Design and Evolution of Large Scientific Experimental Facilities: Strategy and Implementation

by

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Abstract

This thesis is about the design and evolution of large scientific facilities that are used to probe the unknown mysteries of science and create a better future for humanity. These include globally distributed systems for quantum physics, confined fusion and imaging the earliest galaxies that formed after the Big Bang, among others. At the beginning of large scientific project's lifecycle there is often not a clear path to the final use case, a lot of uncertainty with immature technology and budgetary constraints. This thesis aims to gain key insights on how large scale research and development facilities can be optimally designed to take a "long sighted" approach in scientific research. In addition, the research presented has found in looking at a variety of existing, large scale scientific projects and talking with experienced project leaders, tools and techniques that can be leveraged to provide a balanced, system engineering approach to effectively build systems for upgrades and future use cases. Further to the classical system engineering and project management tools, this thesis presents an additional framework, utilizing Technology Roadmapping and Multidisciplinary Design Optimization, MDO, to aid in the foresight and success of large, R&D type projects and their evolution.

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Chapter 1

Introduction

At Lawrence Livermore National Laboratory (LLNL) there regularly arise scenarios in research and development projects, budgeted at hundreds of thousands up to tens of millions of dollars, where the Systems Engineer and/or Project Managers are challenged to make decisions between safely staying within budget and schedule or maximizing value for the future. Typically, these multidisciplinary projects have very expensive, single build deliverables that are needed for very specific experimentation. This situation in not unique to LLNL but occurs in major national and international projects that are described in this thesis.

What is a better use of tax payer money? To deliver something incremental and limited that does not have much growth potential, or something bigger but with the potential for significant future scientific value while risking major budget overruns. Or perhaps, is there a middle ground where stakeholders are satisfied with initial results and the hooks are designed in such that future expandability is made available. In scientific projects where the discovery of new knowledge at the edge of feasibility is at stake this question is particularly acute.

The typical knee jerk reaction of many managers is to expedite the effort by choosing to meet the minimum System Requirements and see what can be added later versus taking the time to evaluate an expanded vision to include future use, growth potential and capabilities. Furthermore, concept selection is often driven by engineering experience with sometimes limited technical, scientific and financial justification. The main driver behind the research presented here is to understand how large scale research and development facilities can be optimally designed to take a "long sighted" approach in scientific research. In addition, answering the following questions:

- How can large, national research facility's projects be optimally designed for future expansion given, uncertain short term fiscal constraints?
- How can the different alternatives ranging from small incremental upgrades to major upgrades to building entirely new facilities be rigorously enumerated and shown as part of a technology roadmap?
- How can this be demonstrated on specific projects such as adding magnetic field seeding at the National Ignition Facility?

In order to answer these questions, firstly, Chapter 2 describes the necessary research that has been conducted on a selection of large scale experimental facilities to understand project evolution and provide examples of success and failure in long term planning. Moreover, project leaders from these facilities were selected and interviewed to extract common patterns and drivers of success and failure. The key learnings summary of which is captured in Chapter 3. In addition, a technology roadmap was created to understand future goals and strategy for a specific technology, Laser Confined Nuclear Fusion and is shown in Chapter 4. As part of the roadmap, an object-process model (OPM) is presented, key figures of merit identified and both technical and financial models developed for the technology. Drilling down a level of abstraction further, an LLNL specific case study - adding a magnetic "booster" (MagNIF) to the National Ignition Facility - is described. This involves the integration of a disruptive sub-technology and has been conducted with a systems thinking approach to understand requirements, risk mitigation and conceptual design selection. Furthermore, a Multidisciplinary Design Optimization, MDO model has been developed for MagNIF to help inform design space, decisions and gain insights into the best architecture and system level tradeoffs. This is described in Chapter 5.

Finally, Chapter 6 summarizes the thesis and aims to draw conclusions on effective strategies for the successful design of large scientific experimental facilities.

Chapter 2

Projects and Facilities

To gain insights and a better understanding of existing, large scientific experimental facilities, a variety of their cutting edge projects and system development, a literature review was conducted. Table 2.1, outlines the eight facilities with their corresponding projects. The following sections describe, in detail facility background information, important technology overviews, project technical challenges and aspects of the project management that led to successes or failures. The projects were chosen such that not only a variety of scientific disciplines in energy, defense and space sectors are covered, but also different scenarios in both the building up of entirely new facilities as well as upgrades to existing systems.

2.1 Sandia National Laboratory, SNL, Z machine and ZR Upgrade

2.1.1 Background & Z Pulsed Power Facility

Established in 1949, Sandia National Laboratory, SNL is a 35.2 km^2 campus located in Albuquerque, New Mexico in the USA. With approximately 12,000 persons on staff and an annual budget of $3.6 billion, SNL is operated for the Department of Energy's National Nuclear Security Administration, NNSA. It's a Federally Funded Research and Development Center (FFRDC) whose primary mission is to design and develop

Table 2.1: Large Scientific Facilities and Projects

Organization/Project	**Description**
Sandia National Laboratory, SNL Z machine	Pulsed Power Facility located in Albuquerque, NM. The Z-machine is the largest high EM wave generator in the world producing 26 million amps with an x-ray output of 2.7 megajoules.
Lawrence Livermore National Laboratory, LLNL National Ignition Facility, NIF	Located at LLNL in Northern California, the NIF is the most powerful and energetic laser in the world. Currently producing 192 beams with a total energy of up to 2 MJ.
French Alternative Energies and Atomic Energy Commission, CEA, France Laser Mega Joule (LMJ)	Laser Mega-Joule in the South of France is based on the architecture of the National Ignition Facility. In the next 5 years, CEA plan to implement a Cryogenic layering Target Positioner into their facility.
Laboratory for Laser Energetics (LLE), Rochester Omega Laser facility	LLE holds one of the most powerful lasers in the world, Omega laser. This is a 60-beam ultraviolet laser which can deliver a total of 60 kJ of energy to targets.
European Organization for Nuclear Research, CERN the Large Hadron Collider, LHC	Largest Particle Physics Laboratory in the world. Provides Particle Accelerators for high-energy physics research.
International Thermonuclear Experimental Reactor, ITER, France	Multi-national Nuclear Fusion project in France using Magnetic Confinement Fusion for plasma physics studies.
James Webb Space Telescope, JWST	NASA funded project. Planned successor of Hubble Space Telescope but observing visible light to the mid-infrared wavelength range.
Deep Space Network, DSN (JPL/NASA)	Largest telecommunications system in the world. International array of giant radio antennas that allow for communication supporting spacecraft missions and provide radar data that improve our understanding of the universe.

nuclear weapon components and cutting edge technologies [117].

Also known as the Z-machine, SNL's Z Pulsed Power Facility is one of the five main technical areas at the Laboratory. The original motivation for this type of facility was to run experiments to help understand the physics of a thermonuclear bomb in a controlled environment. The Z-machine was born in 1996 from an upgrade to the Particle Beam Fusion Accelerator (II), PFBA-II [93] switching to a z-pinch method and enabling a peak current of up to 20 Mega-Amps. After a subsequent upgrade in 2006, the Z-machine is the largest high frequency electromagnetic wave generator in the world producing 26 Mega-Amps with an X-ray output of 2.7 megajoules. Currently, it is primarily used in Inertial Confinement Fusion, ICF experiments creating extremely high pressures and temperatures by utilizing a Z-pinch (or Zeta Pinch). Z-pinch is a term used in fusion research to describe the application of the Lorentz force to compress plasmas. Essentially, high currents are run through plasma over small time scales to cause contractions as the particles are pulled towards one another.

2.1.2 Z Refurbishment, ZR Project upgrade

Owing to the success of the original conversion from the PFBA-II to a Z-pinch machine, there became a need to upgrade other parts of the system which would allow operations throughput increases [123]. Due to archaic, unoptimized hardware that was from the 1985 era, it was hard to support the increasing experiment requests of over 600 a year. For comparison, the yearly shot rate was under 200 during the year 2002 [123]. There was also a need to increase the machine's reliability for ongoing operations as well as a high precision and reproducibility of scientific experiments. Specifically, there was motivation to upgrade the pulsed power drive system to allow for more flexibility and scalability so the system could deliver a larger variety of pulse widths/shapes that were not available prior to this ZR project. Therefore, it was deemed necessary to perform another major system upgrade with implementation and commissioning goals by the end of Fiscal Year 2006. In October 2002, the United States Congress allocated $10 million for the commencement of the ZR upgrade project and other funds were drawn from the NNSA's reliability in Tech base (roughly $50 million for 2003-2005) and Sandia's R&D Pulse Power Technologies (roughly $30 million 2003-2006) [123]. These latter, multi-year funds were planned allocations as of 2002. The ZR Project incorporated key architectural upgrades in three main pulsed power areas; energy storage, pulse forming and vacuum power flow sections. For the energy storage section, the existing capacitors were replaced with 2.6 micro-Farad ones, doubling the stored energy. In addition, a pre-fire protection system was implemented to reduce the likelihood of a Marx generator pre-fire or damage to the capacitors from switch malfunction. There were also many modifications to the pulse forming section which included changes to the intermediate storage capacitors material (Aluminum to Stainless steel), separating out to individual laser triggers and increasing the reliability of the gas switch design to make a more robust system with repeatable timing. Another key architectural change to the pulse forming section was to implement a steeper angled, vertical orientated transmission line to enable horizontal lines of sight and thus allow better diagnostic access. This is shown in the "water" section of figure 2.1.

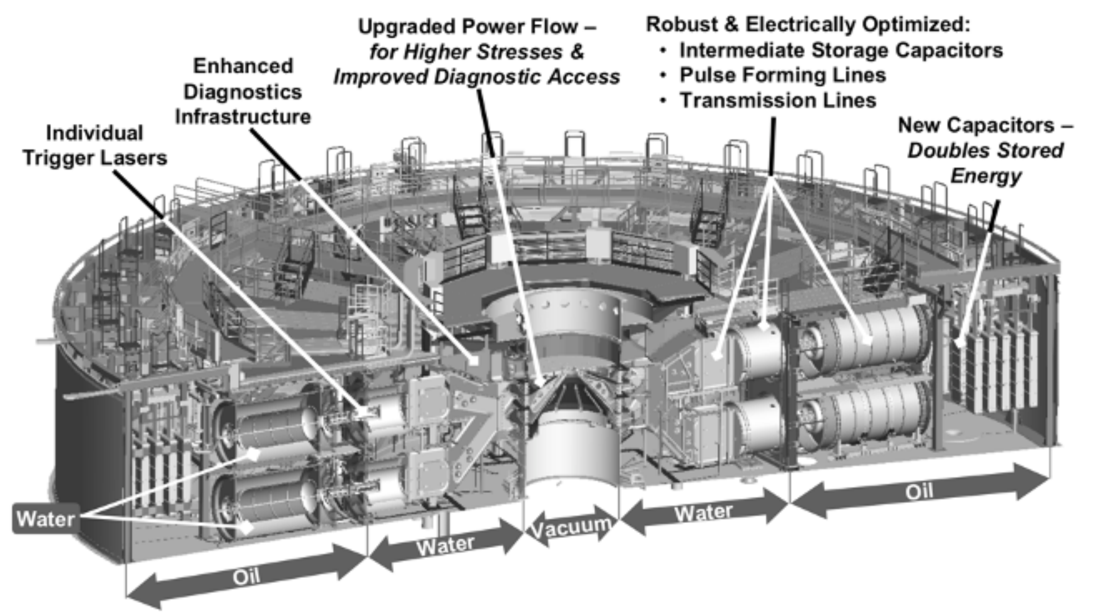


Figure 2-1: Z Refurbishment (ZR) Project Architecture and pulsed power system upgrades [122]

The existing system had horizontal transmission lines that made diagnostic access difficult. The final main section upgraded was the vacuum power flow which is shown at the center of the Z-machine in figure 2-1. In order to satisfy some of the challenging parameters highlighted in table 2.2, the electrical stress of the vacuum insulator stack had to be increased from approximately 105 kV/cm to 140 kV/cm [123].

Table 2.2: Upgrade summary of the Z Refurbishment (ZR) Project [123]

Capability	Z (Present)	After ZR
X-Ray Power Radiated (Nested Arrays)	230 TW	350 TW
Energy Radiated (Single Array)	1.6 MJ	2.7 MJ
T_r for Weapon Physics VH / DH	140 / 220 eV	165 / 260 eV
T_r for ICF VH / DH	75 / 140 eV	90 / 165 eV
P_{Pk} for ICE	2.7 Mbar	>10 Mbar
Flyer plate velocity	21 km/s	> 32 km/s
In band energy 1 keV/ 5 keV/ 8 keV	400 / 100 / 20 kJ	800 / 300 / 80 kJ

VH= Vacuum Hohlraum DH = Dynamic Hohlraum
ICE = Isentropic Compression Experiments

Table 2.2 outlines the major upgraded parameters for the ZR Project. It can be seen that there is an upward trend in all the parameters as a result of the increase in system current from 18 MAmps to 26 MAmps [123].

A major contributor to the success of the ZR project was the clear definition of scope. The primary criteria [123] for the project are shown below and a full suite of requirements flowed down from these three highest level objectives.

1. Enable the facility and diagnostics infrastructure to routinely support a 400 shot per year program while minimizing the impact of implementing improvements on existing experimental programs.

2. Provide Z with enhanced precision, improved timing jitter, and advanced pulse

shaping capability needed for full parameter space assessment for materials of interest to the Stockpile Stewardship Program.

3. Provide a useful increase in current to Z's research community.

The ZR project benefited from utilizing a phased approach and mitigating technical risk as early as possible in the project timeline. Figure 2-2 shows this project timeline and highlights two key items in the risk mitigation strategy. These were, by September 2003, completing the design and build of a single, first article module and then by September 2004, completing a testing program. The module consisted of a completed energy storage and pulse forming sections and was vital in performing tests on these sections before a production design and procurement phase could proceed at the end of 2004. This phase would allow the fabrication of all 36 modules [7] that would be installed and tested by September 2007 in the Z facility.

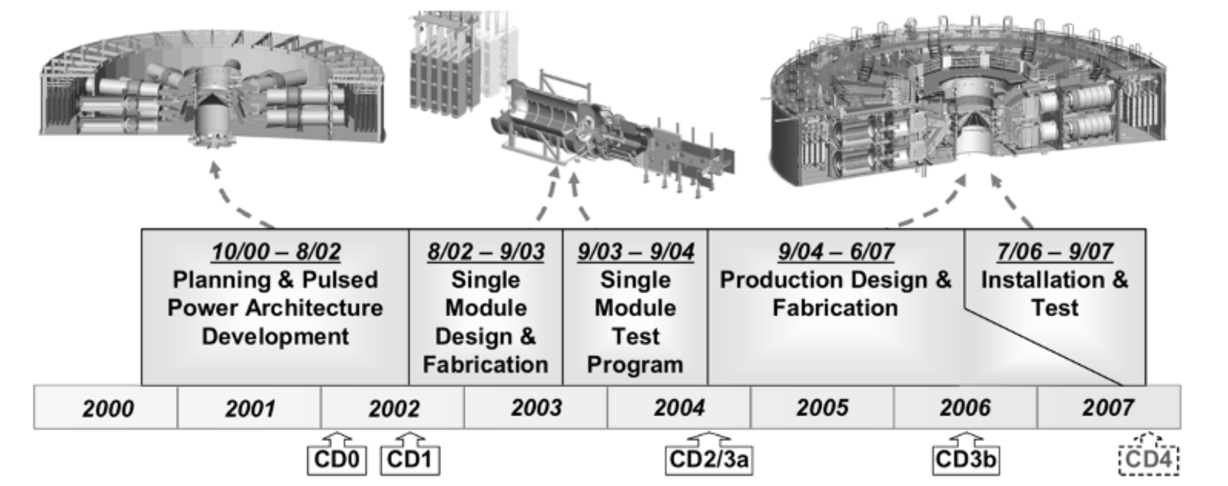


Figure 2-2: ZR Project summary timeline [122]

As this upgrade project had a Total Project Cost, TPC anticipated above $50 million, the Project had to be managed in accordance with the US Department of Energy, DOE Order 413.3, "Program and Project Management for the acquisition of capital assets" [122] [97]. This ensured the project followed classical PM practices including earned value management system, risk and configuration management systems and monthly status reports to NNSA. Figure 2-2 outlines specific, formally mandated Critical Decision, CD points. CD0 was completed in February 2002 and was the approval for mission need, essentially allowing the project to officially begin. CD1 allowed the approval of the single module design, build and test from a critical review of the design and test plan. CD2/3a was the gate for the system final design and allowed the approval for the entire module production. Following on from this, CD3 provided the approval to begin the refurbishment of the upgrade into the facility and the final Critical Decision, CD4 approved the completion of the ZR project.

2.2 Lawrence Livermore National Laboratory, LLNL and the National Ignition Facility, NIF

2.2.1 Background

Lawrence Livermore National Laboratory, LLNL is a federal research facility located in Livermore, California, USA and was founded in 1952. This premier national security facility has a staff of approximately 8,000 persons and sits on a 2.6km^2 campus. Originally a sister laboratory of Lawrence Berkeley National Laboratory, LBNL and run by the University of California, LLNL was built to motivate healthy competition with Los Alamos National Laboratory, LANL in Nuclear Weapon design. On October 1st, 2007, LLNL management transitioned from the University of California [108] to a limited liability company, Lawrence Livermore National Security, LLNS. Similarly to SNL, LLNL is a Federally Funded Research and Development Center (FFRDC) whose mission centers around defense, weapons and energy. One key area of specialized research at LLNL is in laser technology. The Livermore site has hosted the design, construction and operation of ever-increasing energy laser systems culminating in the National Ignition Facility, NIF.

2.2.2 The National Ignition Facility, NIF

The National Ignition Facility, NIF at Lawrence Livermore National Laboratory, LLNL houses the largest and most energetic laser in the world [72]. This Inertial

Confinement Fusion (ICF) machine project was initiated between 1993 and 1996 with completion aim of March 2009 [71]. The multi-billion dollar effort was built for the Department of Energy's, DOE National Nuclear Administration (NNSA) and had many motivations. These included, understanding the complex physics in nuclear weapons to aid in stockpile stewardship; providing the necessary conditions (high pressures and densities) to increase knowledge base of material science and astrophysics; to reach "ignition" yielding net energy gain from a fusion reaction and being the first steps in a potential renewable energy power plant design.

Figure 2-3 shows the layout of the NIF site and highlights the key subsystems. For scale, the length of this building is about three football field widths. It can be seen from figure 2-3 that this is a very complex system and requires many disciplines in both its development and operation. Many of the key subsystems are also shown in figure 2-4 which gives a comprehensive schematic of the high-level laser system architecture.

NIF Architecture

Figure 2-4 shows a CAD model of the main laser sub-systems and components along the beamline in one of the two laser bays. In each laser bay, there are 96 beamlines divided into two clusters with six bundles constituting a cluster. There a two quads or 4 beamlines in a bundle. The Injection Laser System, ILS consists of the necessary subsystems that generate the initial fiber laser, adjust energy, pulse shape and the delivery timing of each beam to the Main Laser System, MLS. The laser pulse is generated in a fiber oscillator located in the Master Oscillator Room, MOR. From here, the approximately 200 pJ pulse is injected into the Preamplifier Modules, PAMs where, in the first sections, the beam is amplified by multiple passes to roughly 10 mJ in energy and is also spatially magnified and shaped [92]. In the second section of the PAM, the multi-pass preamplifier (shown in figure 2-4), the light is amplified up to approximately 6 Joules as it leaves to the Preamplifier Beam Transport System, PABTS. The ISP, Input Sensor Package serves a diagnostic function - in the PABTS first section - to "pick off" small portions of light to understand the power, energy

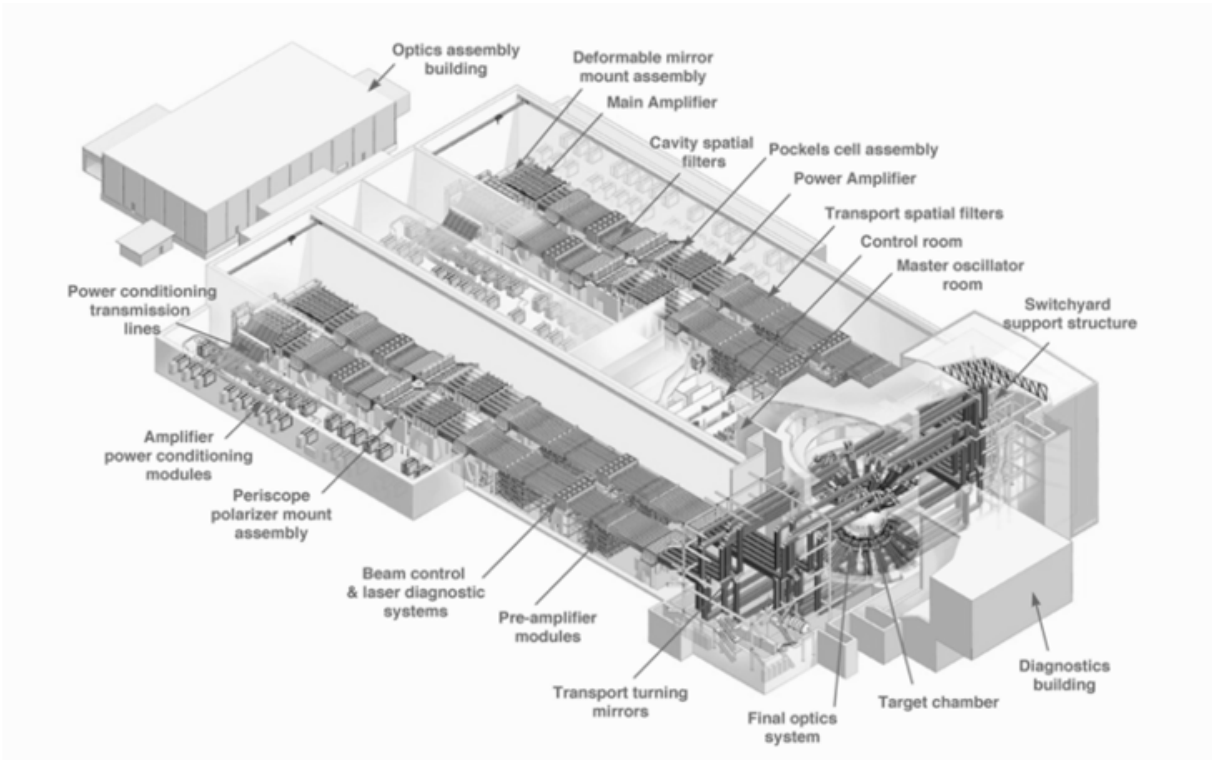


Figure 2-3: A CAD rendering of the National Ignition Facility with major components [72]

and optical profiles. In the second part, the beam is split in four and the PABTS can adjust the amount of light that goes into each beam. The staircase-like vertical laser path outlined in figure 2-4 shows where the light leaves the ILS and enters the Main Laser System. Following the path of just one of the 192 beams, the light heads towards LM3 past the Power Amplifier, PA for initial amplification and then towards the Main Amplifier, MA. The redline at the top of figure 2-4 shows the path of the laser. Between LM1 and LM2 the beam has four passes and on each pass is amplified further. It takes approximately 280 ns for the light to leave and return to the PEPC. The optical switch, called the PEPC (plasma electrode Pockels cell) energizes the KDP (potassium-dihydrogen phosphate) crystal plate to change the light polarization in order to make the required passes. Once no voltage is applied from the PEPC, the light is reflected back up the beam path with one final PA pass and then on towards the switchyard. Once here, the transport mirrors direct the beams toward the NIF

Target Chamber. At the threshold, the Final Optics Assemblies, FOAs convert the light to Ultra violet and focus it onto at target at the chamber center.

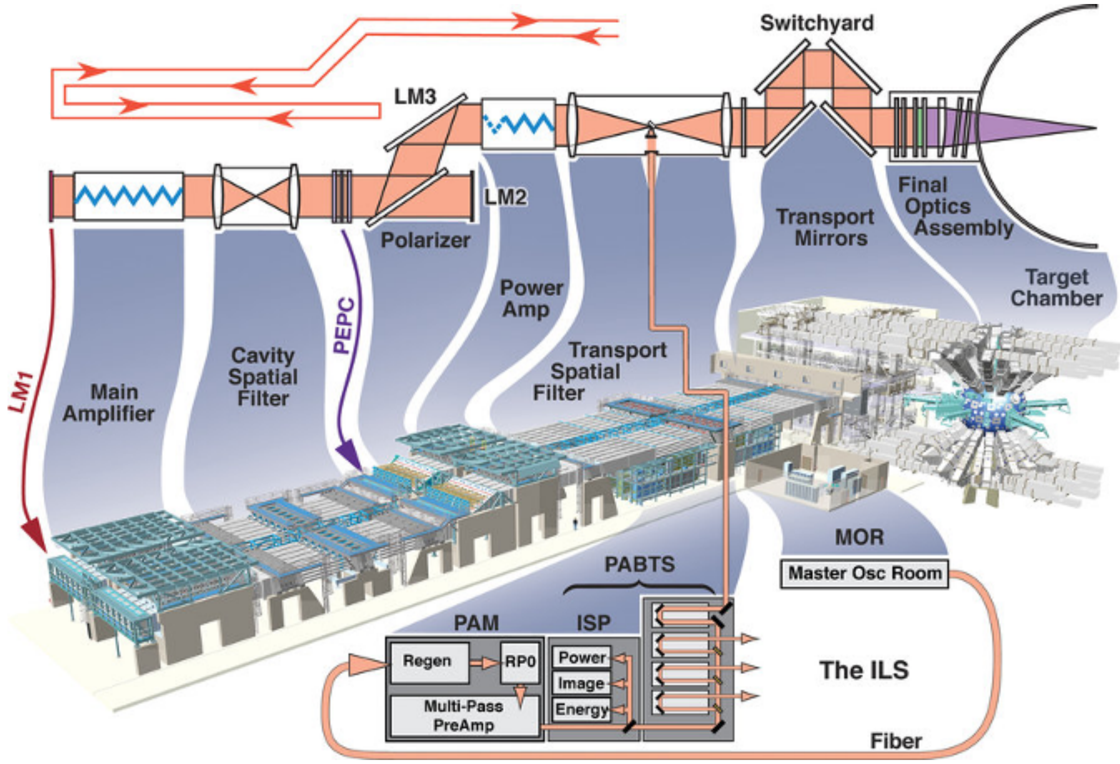


Figure 2-4: NIF laser system schematic view [92]

The primary goal of the NIF is to create self-sustaining nuclear fusion by using inertial confinement to compress frozen Deuterium-Tritium fuel. Ultraviolet light from 192 laser beams is focused onto the wall of a gold cylinder - called a Hohlraum [95] – which converts the light into X-rays. Figure 2-5 illustrates this. These X-rays compress the capsule containing the D-T fuel and accelerate it from approximately 2 millimeters to 60 microns in pico-seconds. The result of the reaction is the production of helium with a substantial neutron yield gained. Currently, the project has not yet achieved net energy gain and continues to conduct experiments to understand the path forward to do so.

In order to freeze the hydrogen isotopes and form spherical ice layers, temperatures below 20 Kelvin are required. These are achieved using Helium Gifford-McMahon cryostats and oxygen free copper as a conduction path to the target. These targets

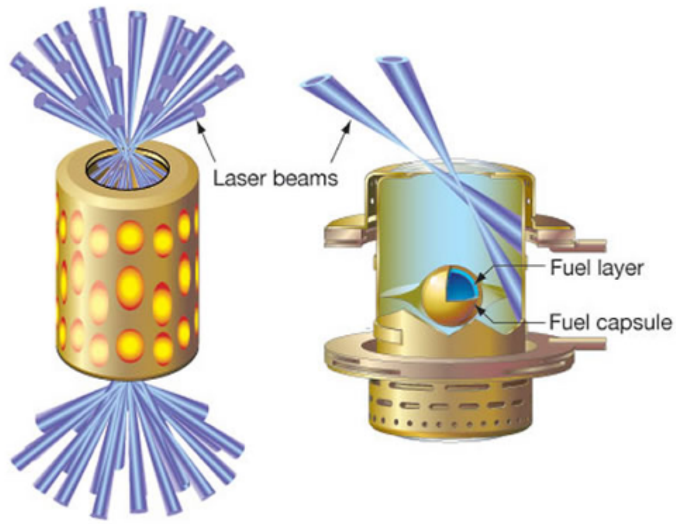


Figure 2-5: NIF laser system schematic view [95]

provide the thermal packaging around the Hohlraum as well as thermometry and heaters to control target temperatures down to the milli-Kelvin level [83]. They are mounted on to "Positioners" in the facility, which provide the isolated environment outside the NIF Target Chamber necessary to prepare for a subsequent experiment. The Positioners are essentially large (5000 liter) vacuum vessels that hold complex mechanical and electrical assemblies. Figure 2-6 shows a shielded cryostat (gold cone) mounted on the end of a Target Positioner's boom. These booms are used as structural members that not only support payloads such as the cryostats but house and protect utility lines that supply helium, air, water and electricity to a desire payload. They are also sized in length to allow adequate reach to the center of the 10 meter diameter sphere that is the NIF Target Chamber (figure 2-7). A 3-D CAD model cut away in figure 2-7 reveals the various components of the Target Bay equatorial level. In addition to the Target Positioners, there are also Diagnostic Positioners that provide the "eyes and ears" of the facility. Diagnostics obtain a variety of experimental data during the fusion implosion, and include optical, nuclear and x-ray detectors thus allowing feedback on such details as laser-capsule drive, neutron yield and x-ray emission.

There are very tight positional requirements for all the Positioners. For example,

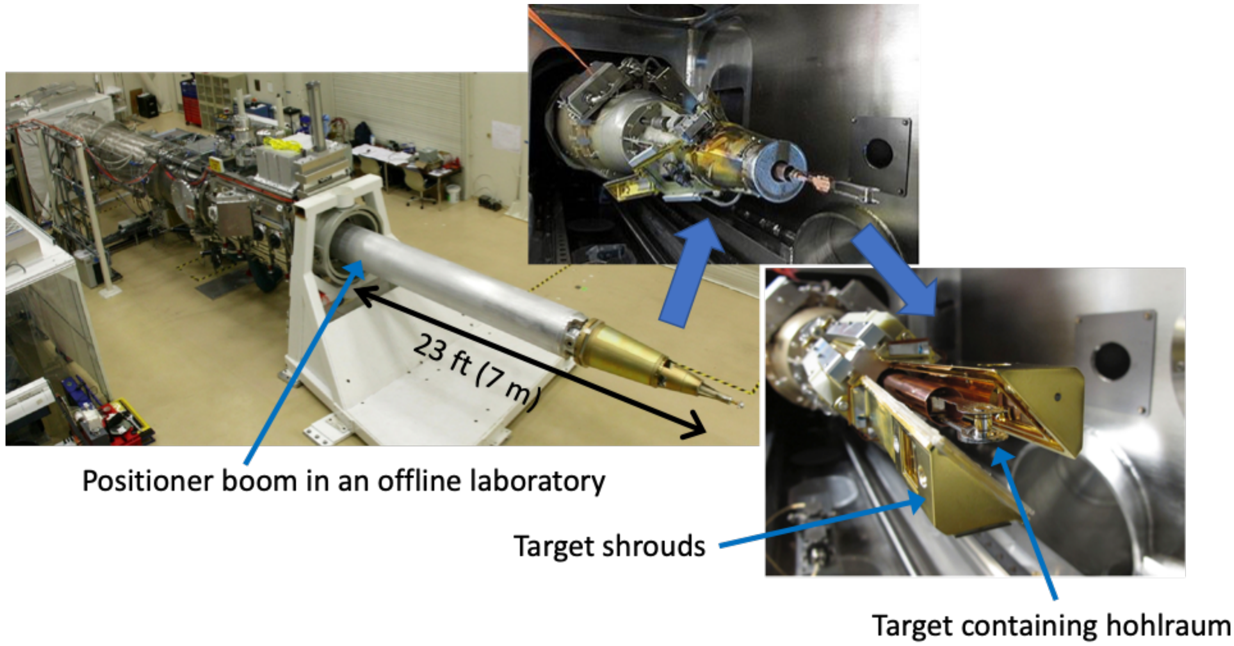


Figure 2-6: A NIF Target Positioner with Cryostat and Target [83]

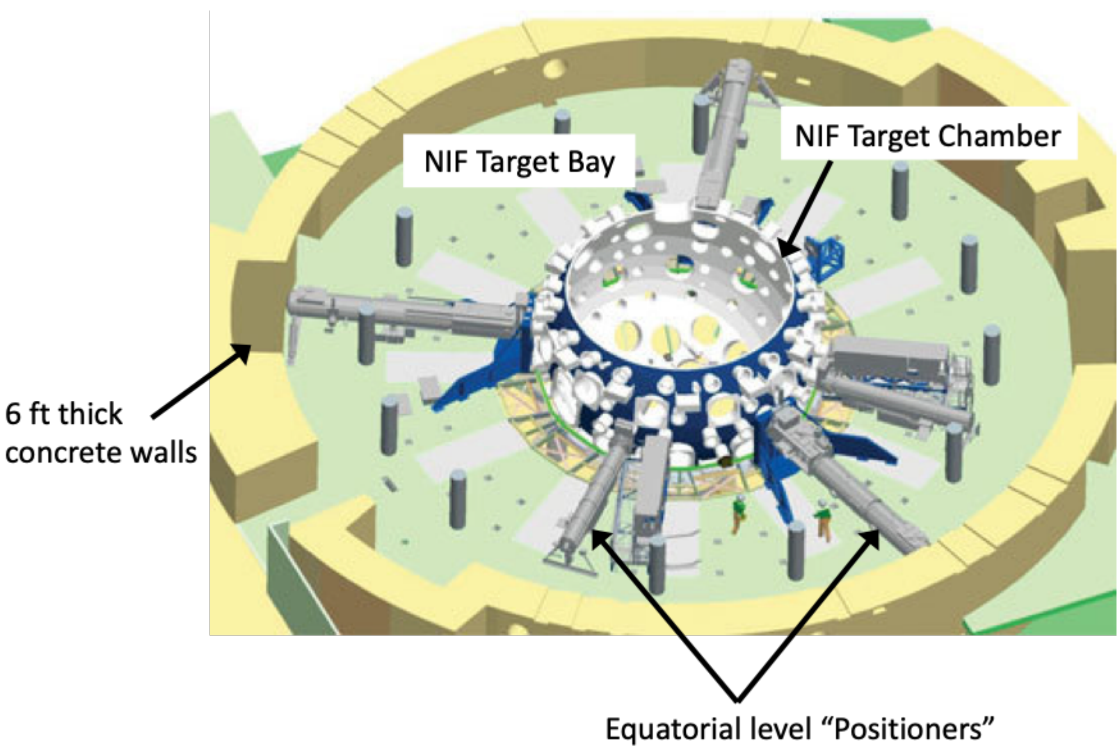


Figure 2-7: CAD rendering of the NIF Target Area cutaway [82]

a Target has to be aligned to the center of the Target Chamber to a tolerance of less than +/- 10 microns and maintain its position for multiple hours with minimum vibrations. This is not a small feat as these booms are approximately 5.5 meters in length implying needs on inherent stiffness and use of materials with low coefficients of thermal expansion for stability. Furthermore, there are requirements on minimizing both the radiation workers are exposed to and facility downtime after neutron-producing laser experiments. Targets and diagnostics currently have to be exchanged manually so it is beneficial that the boom (and vessel) material be chosen with short half-lives and low beta/gamma decay energies in mind. In addition, there are seismic requirements in California for extreme loads, so these must be considered when designing the boom members.

NIF Project System Engineering and Management

The design of NIF's architecture discussed in the previous section was no fluke. It relied on the experience gathered with smaller laser systems developed at LLNL. From as early as the 1970s a number of laser systems were built to understand laser and target interactions for Inertial Confinement Fusion [92]. It took many years to develop the concept for the NIF and downselect from a wide field of candidates to a cost economical, viable laser and target chamber architecture. In the 1980s, design studies were performed for three large ICF laser-driven systems which later informed concepts for the NIF. From these studies two important cost drivers were established; cost scales sub-linearly with the surface area of the amplifier system and that the facility cost scales with the floor area [92]. Therefore it was essentially to define a reasonable set of Primary Criteria, PC that would be in the realms of attainability but also push to the highest laser energy possible. Figure 2-8 shows both the top level criteria and level 2 functional requirements for the laser system. These were developed close to the 1993 conceptual design report that was authorized by the DOE and were driven by the dynamics of an imploding, D-T capsule as well as the anticipated laser interaction with the hohlraum plasma.

As in all good systems engineering, the PC were within the range of 7 +/-2 to

Level 1 Primary Criteria	Description
Laser Pulse Energy	≥ 1.8 MJ
Laser Pulse Pk Power	≥ 500 TW
Laser Wavelength	0.35 μm
Beamlet Power Bal	RMS quad deviation avg over 2 ns, from Rev X pt. design spec
Beamlet Positioning	≤50 μm rms
Direct-Drive	Shall not to be precluded
Laser Safety	Comply with ANSI Z136.1
Recovery Time	≤ 8 h between full system shots

Level 2 Funct Reqm'ts	Description
Laser Pulse Duration	Up to 20 ns
Pulse Dynamic Range	≥ 50:1
Capsule Irrad Symmetry	2 cones/hemisph, ea w ≥ 8 beams
Prepulse Power	< 10^8 W/cm^2 per hemispere
Laser Pulse Spot Size	Design energy within ≤ 600 μm
Beam Smoothness	Shall have ability to do spatial & temporal beam conditioning
Focusing & Pointing	Should have flexibility for users
Diagnostic Capability	See *NIF Laser System Performance*

Figure 2-8: The NIF Primary Criteria and Functional Requirements [92]

not only provide the necessary goals for the system but allow the design team to more easily digest. The recovery time goal drove many of the "ilities" flow down requirements including maintainability, availability and reliability. In order to satisfy this, the NIF project not only incorporated lessons learned from other laser system projects but also designed Line Replaceable Units. The LRUs were an excellent foresight that today allows NIF to be run as a 24/7 operational facility with limited downtime.

Figure 2-9 outlines the original integrated project schedule for the NIF project. Similarly to the Z-machine project, outlined in section 1 of this chapter, the project followed the DOE framework, 413, incorporating many Critical Decision points, CDs in order to ensure effective project management and sponsor agreement with progress. The definitions of each CD can be seen in figure 2-9 and important to note that the anticipated project completion date was at the end of Fiscal Year (FY) 2002 at a Total Project Cost, TPC of 1.08 billion dollars. This is the summation of the Total Estimated Cost, TEC and Other Project Cost, OPC. By reporting in 2011, the NIF project was said to be completed in February 2009 and certified by NNSA on March 27, 2009 with a total project cost of $3.5 billion dollars [71]. What was not captured in the Gantt chart was some of the prior risk mitigation activities such as the utilization of the NOVA laser[1] which was critical in both reducing uncertainties that could scale

[1]NOVA was a 30 kJ UV laser facility built in 1984 at LLNL [70].

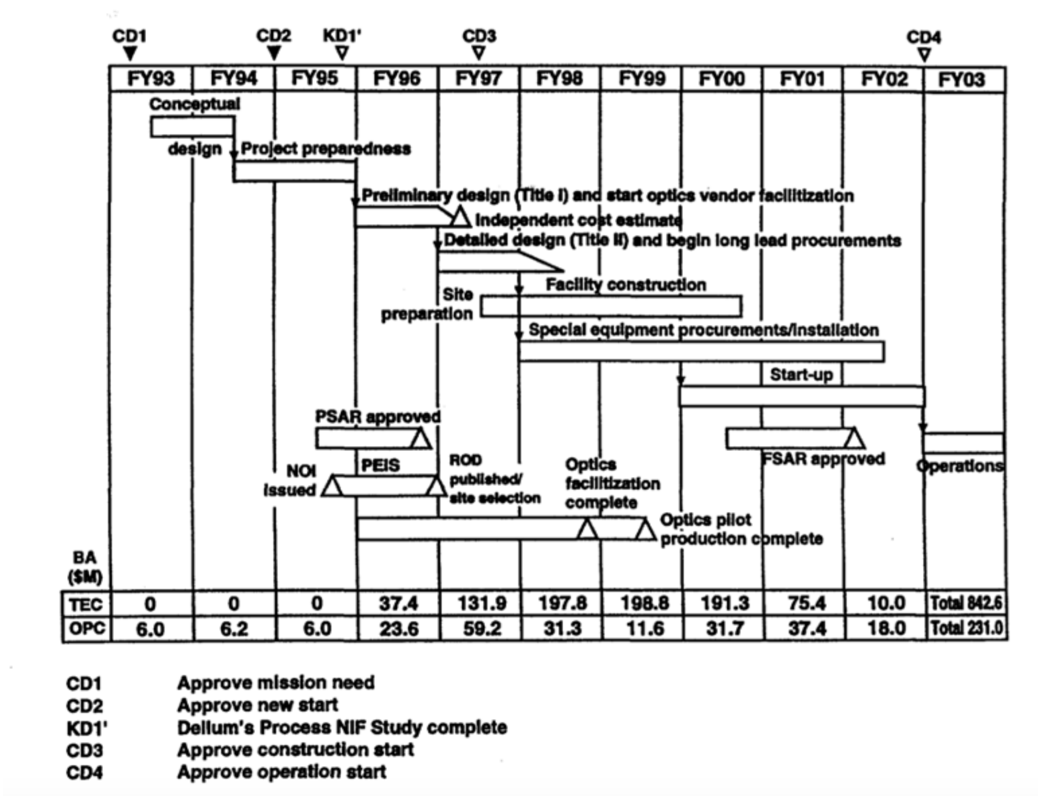


Figure 2-9: Integrated schedule for the NIF project from 1996 acquisition plan documentation [15]

to NIF and refining the primary criteria.

2.3 Alternative Energies and Atomic Energy Commission, CEA and Laser Megajoule, LMJ

2.3.1 Background & Laser Mégajoule, LMJ

The French Alternative Energies and Atomic Energy commission, CEA or the "Commissariat à l'énergie atomique et aux énergies alternatives" is a government funded research organization that specializes in key areas of research and development. These areas include defense, security, renewable energies, nuclear fusion, industrial technological research and scientific fundamental research. CEA has nine research centers across France, employing over twenty thousand people with a total budget of five billion euros [99]. Located at the CESTA Center near Bordeaux in the south of France, Laser megajoule, LMJ is a large laser facility supporting Inertial Confinement Fusion (ICF) research and experiments. This project is entirely funded by the French military budget for about 3 Billion Euro (complete cost) for 15 years [21]. Similar to the NIF in California, LMJ plans to deliver mega-joule level light energy to targets at the center of its vacuum chamber. Furthermore, it also plans to primarily use indirect drive configurations to reach ignition conditions. This can be seen in figure 2-10, below.

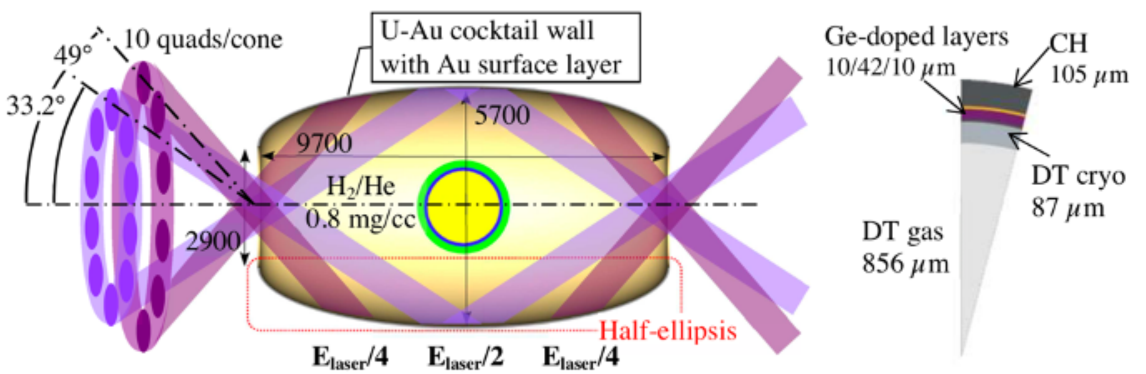


Figure 2-10: Laser Megajoule Facility indirect drive target hohlraum with laser interaction [67]

The baseline design is to deliver 1.8 Megajoules of Ultraviolet light through 240 separate beams to a gold-uranium lined Rugby shaped hohlraum [67]. The beams enter a cryogenically cooled target hohlraum – nominally cooled to 18.3 Kelvin – and contact the inner surfaces causing the D-T fuel capsule to be irradiated and compressed by x-rays generated. The biggest motivation for the LMJ facility was, and is to provide important data on plasma physics to aid in stockpile stewardship for the French Nuclear weapons program. It is a key research facility for the French national security efforts and will allow the validation and modification of physics simulations.

As seen in figure 2-11, the LMJ facility architecture is very similar to the NIF with a few differences such as the laser bay positions relative to the Target Chamber. The top-right image shows a photo from one of the laser bays that include infrastructure for the PETAL beam. This PETawatt Aquitaine Laser is a short pulse, 0.5 pico-seconds to 10 pico-seconds, high power (multi-petawatt), high energy beam that can be used in conjunction with the main LMJ laser or as a stand alone experiment. In the former case, PETAL can provide additional diagnostic capability in target characterization including point projection proton-radiography [16].

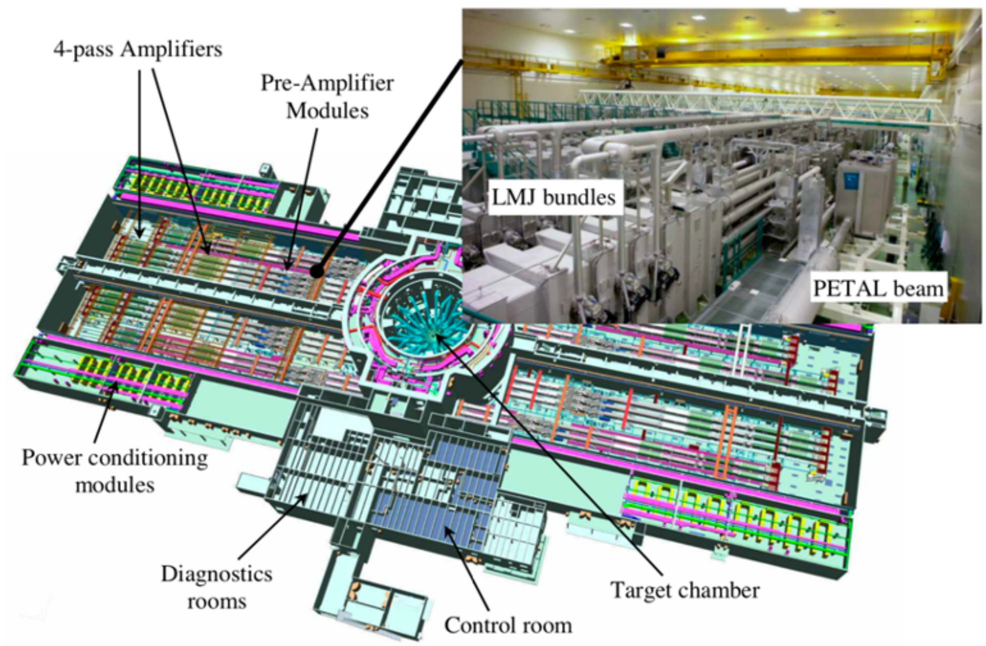


Figure 2-11: Laser Megajoule Facility schematic [67]

In 1999, the LMJ system conceptual design was completed [37]. Although construction commenced in 2003, CEA utilized a prototype called LIL (Ligne d'Intégration Laser) which provided the first test data for one quadruplet (4 beams) of the proposed laser system. The total energy on a target that the LIL laser system could provide was 30 kJ. The LIL was operational in March 2002 and was used as a key risk mitigation activity for the larger project [21]. In addition, the advantage of this staging was not only for allowing initial insights into laser interactions with plasmas but also to validate diagnostic conceptual designs which then could be leveraged for use on LMJ [57]. Figure 2-12 shows the main configuration of the LIL's 5 meter diameter Target Chamber and the variety of diagnostics positioned around it. Essentially, the LIL system architecture was that of a "mini" LMJ. Furthermore, the LIL demonstrated exceedance of performance requirements with 9.5 kJ at 9 nano-seconds delivered by a single beam [37]. This would equate to a total energy of 2.2 MJ for the LMJ and thus, demonstrated additional system margin.

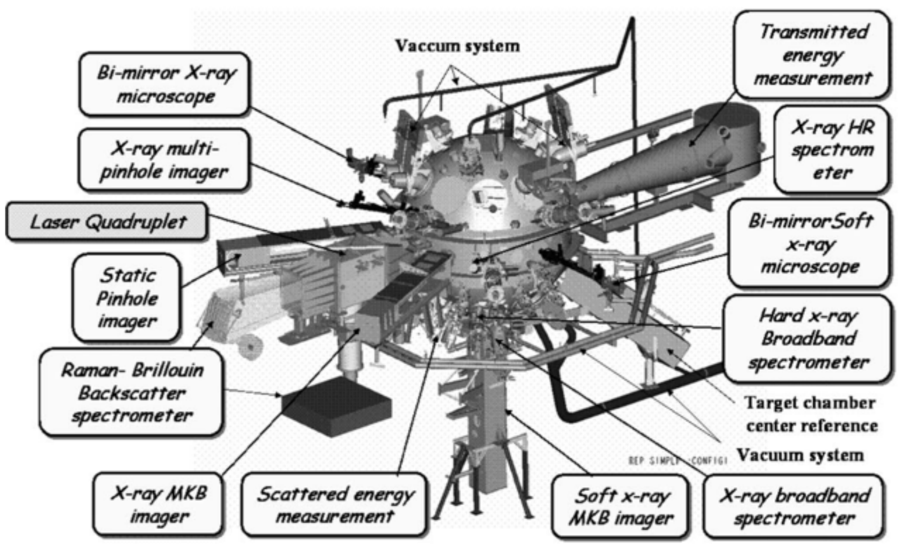


Figure 2-12: LIL system Target Chamber and Diagnostics Schematic [57]

By December 2008, the building construction of the LMJ facility had finished [60]. In 2010, the laser bundles amplification sub-systems were being assembled and the first laser bay assembly had been completed. Ultimately, with the first bundle (2 quads, 8 beams) online, LMJ was commissioned in October, 2014 with subsequent bundles added over time [68]. Table 2.3 below outlines the LMJ facility "Ramp-up" strategy. By more slowly integrating additional bundles and diagnostics, physics experiments can be inter-weaved with the installation and commissioning of the new capability. This is in stark contrast to the NIF ramp up (covered in the previous section), where the majority of or all bundles were installed before meaningful physics experiments were conducted.

Looking at table 2.3, the second configuration of adding and commissioning a second bundle was completed in 2016 [77]. The third and fourth configuration installations were planned to commence 2017 and 2019 respectively [68]. In order to get to

Table 2.3: LMJ ramp up configurations and physics experiments [68]

Configuration	Quads number	Total energy	Diagnostics number	Physics addressed
1st	2	25 kJ	4	Commissioning and 1st hydroradiative experiments
2nd	4 + PW	60kJ	8	Improved hydroradiative experiments. Starting of academic access
3rd	10 + PW	150 kJ	10	Fully diagnosed hohlraum energetics experiments Hydrodynamics and instabilities
4th	14–18 + PW	250–320 kJ	18	~3-order symmetry → 1st implosions (D_2/Ar gas) with neutron production. Fundamental data
5th	22–42 + PW	0.53–1 MJ	26	5-order symmetry. Cryogenic target. More precise diagnostic → fusion studies and ignition preparation
6th	44 + PW	1.5 MJ	>26	Full axial symmetry → ignition studies All experimental topics at high energy

the fifth configuration, a cryogenic target positioner is required. Similar to the NIF project, this cryogenic target positioner (PCC) will be designed to enable target temperatures below 20 Kelvin and the capability of characterizing D-T ice layers before laser shot experiments.

Finally, figure 2-13 shows the high level roadmap for the LMJ facility. It can be seen that the first bundle enabled the commencement of experiments and with ascending configurations, more data and physics understanding is accumulated. The "Full LMJ" vertical line represents the completion of bundle installation and the beginning of an ignition phase where many cryogenic experiments are conducted.

2.4 Laboratory for Laser Energetics, LLE & the Omega facility

2.4.1 Background

Established in 1970, the Laboratory for Laser Energetics, LLE is a world leading laboratory in science, technology education and research with emphasis in laser technology [55]. It is another NNSA funded laboratory located in Brighton, NY in the US on the south campus of the University of Rochester and employs between 400 to 500 members of staff . From its inception, LLE's primary objective has been to study and understand the interaction between radiation and matter to aid in the United States'

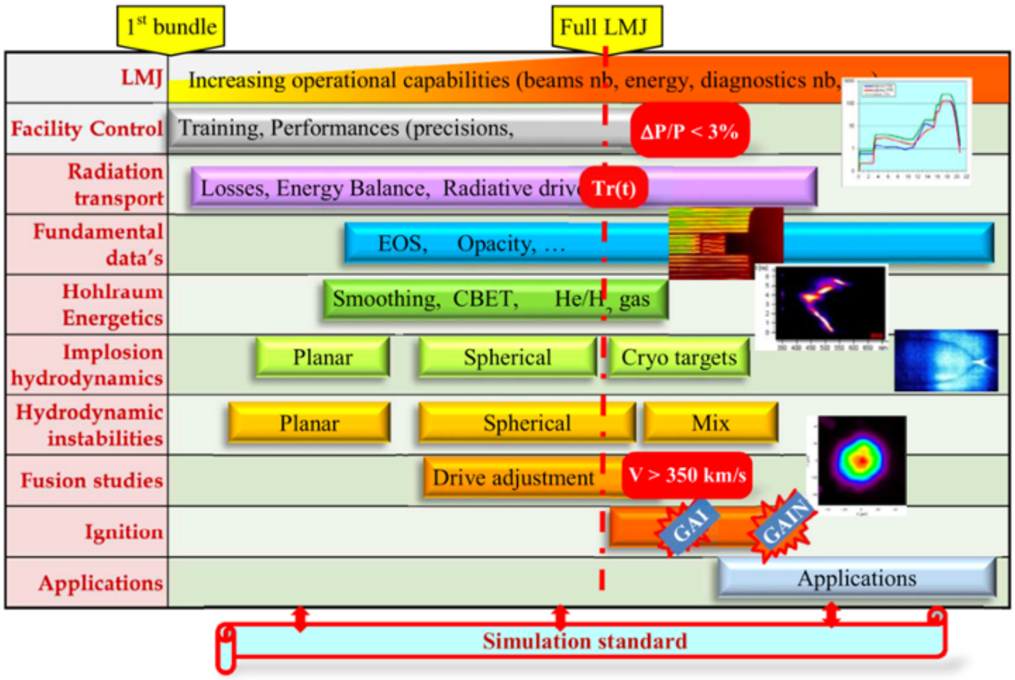


Figure 2-13: LMJ's ignition roadmap and path to full commissioning [68]

stockpile stewardship program [55]. LLE has also been an active contributor in the national ICF program and supports basic physics and implosion experiments with its laser facility. The first laser system built at LLE was in 1972 and named Delta [42]. This 4-beam laser, was one of the first to conduct experiments radiating matter with high power laser light. An additional goal of Delta was to start conducting ICF experiments by using the laser to compress a small fuel target. Following on from Delta, the Zeta laser was built and operation began in 1978, it incorporated 6 beams that focused into a target chamber and provide symmetrical illumination of a fuel target [54]. The first shot in October 1978 created over 300 million neutrons [55]. The Zeta laser system was designed to be the demonstrator and first 6 beams of the 24 beam laser system that was to become Omega. A total of 110 target shots were performed on the Zeta laser through to November 1979 when a suspension period was observed to allow for the commissioning of the remaining 18 Omega beamlines. In 1980 the 24-beam Omega laser became operational.

Figure 2-14: The 24-beamlines of the Omega facility at LLE [55]

2.4.2 Omega Laser Facility evolution

Omega is currently one of the world's most powerful lasers and up until 2005, was the world's most powerful pulsed laser system delivering up to 30 kilojoules of UV light to the center of its 3.3 meter diameter target chamber. In addition, it once held the record for the highest neutron yield produced on a ICF device. To date, the maximum yield Omega can produce per shot is approximately 10^{14} neutrons. Unlike more recently developed ICF systems like NIF and LMJ, Omega utilizes direct-drive where the lasers are directly coupled to the target fuel capsule as opposed to indirectly compressing it using a hohlraum. The first shots on the Omega system used laser light in the infrared range of 1054 nanometers wavelength [55] with a total system long pulse energy of 1.76 kJ. With a new patented technology issued in 1982 and developed at LLE, a frequency-tripling technique enabled conversion to the 351 nm, UV wavelength enhancing the effectiveness of any Nd:glass (neodymium doped, phosphate glass) laser system [25]. This new technology would be utilized in both the future LMJ and NIF architectures allowing more power to be delivered to targets [23]. Further, in 1983, the first six Omega beamlines were converted over to UV and were fully operational. By 1985, all 24-beams of Omega had been converted to the 351 nm wavelength light and the system was successfully commissioned.

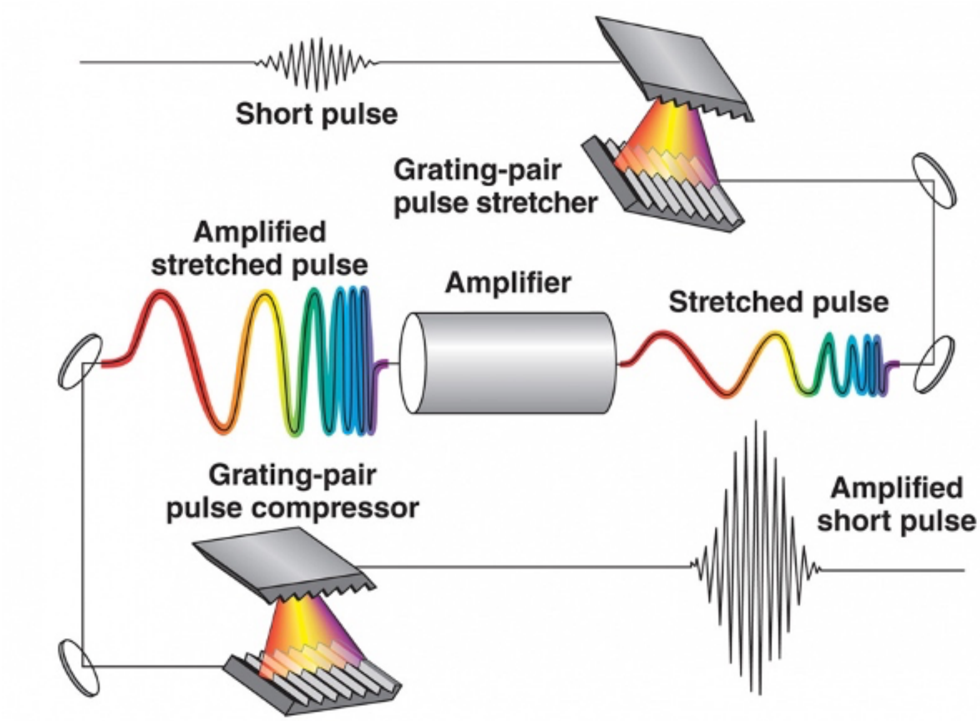


Figure 2-15: Schematic for Chirped Pulse Amplification [94]

Another important invention was made in the same year (1985) which would also have huge implications to ultrahigh power laser technology. This was Chirped Pulse Amplification, CPA, a technique in which very short laser pulses can be stretched, amplified and then compressed [94]. Figure 2-15 shows this process in simplified pictorial form. The laser pulse is stretched out using specialized grating pairs, then amplified more effectively in its longer pulse form. Another pair of gratings combine to shorten the pulse back to its original length. The next development on Omega, was the introduction of the first cyrogenic target system in 1987 allowing the facility to conduct liquid and solid Deuterium-Tritium fuel experiments. However, in early fall of the same year, there were found to be many issues with the introduction of the new cryogenic system, including excessive target vibrations and poor D-T ice layer quality [55]. A lessons learned review was conducted and several systems were redesigned whilst ongoing experiments were suspended. The following year with the new upgrades complete, the Omega system reached a milestone set by DOE to achieve a fuel density of that of 200 times D-T liquid [64]. At the time, this was the highest density of a compressed fuel ever achieved by an ICF experiment and in order to provide accurate measurements a suite of x-ray, neutron and energy spectrum diagnostics had to be employed including utilizing a first of its kind technique of "knock-on" diagnostics [64]. This technique allowed a temperature independent measurement of the implosion density. Smoothing by Spectral Dispersion, SSD was another key invention on Omega during the late-1980s [91]. This technique helps beam profile uniformity as well as reducing intensity peaks so upon arrival at the target, the laser light is absorbed as opposed to reflected with laser-plasma interactions [61].

In June 1989, a National Academy review of Inertial Confinement Fusion programs was conducted which was mandated by the US congress. Driven from the recent milestone and technology successes of fuel density and SSD, the review committee recommended the construction of the Omega upgrade [80] and commented that the glass laser was the only viable candidate for laser-driven ignition[2] demonstration. The US congress appropriated approximately $4 million spread over Fiscal Years 1988 and 1989 to support the initial design efforts for the upgrade [24]. Work began quickly on a preliminary design in 1988 for the Omega 60 system – upgrading to 60 beamlines - which (the review) was completed in the fall of 1989 [24]. Subsequently, DOE conducted two independent reviews of the Omega upgrade in which they concentrated on the technical details in the first and a validation of cost at the management level for the second. These were both completed in FY1990 and the follow on from these were the procurement of long lead items and commencement of the detailed design. The initial estimation was that construction would take approximately four years [55]. In order to decrease risk on the lower technology readiness level (TRL) elements of the Omega 60 project, technology demonstration (prototyping) efforts were continued in the early 1990s including the development of single-segment amplifiers, and a 20 cm diameter disk final amplifier that would increase efficiency, require less maintenance

[2]Ignition being the point at which the fusion energy yield is equal or greater than the laser energy absorbed in the target [84]

and have superior polarization and wavefront characteristics [55]. In December 1992, the 24-beam Omega system fired its last laser shot and operations were suspended whilst the 60-beam, 30-kJ, UV laser upgrades were conducted. The new building construction was completed in 1993 as the laser system build began. The budget provided for the laser system construction was $61 million and the design had to meet a challenging 1 shot per hour requirement. At the end of calendar year 1994 the first beamline had been constructed producing about 600 Joules of UV laser light, all 60 beams were completed in 1995 and the first shot producing 37.2 kJ on target was completed on May 1st 1995. The upgrade was reported to exceed all of its specifications including performing five sequential shots, 1 per hour at an energy at or above 32 kJ [55].

In parallel to the laser system upgrade and driven from the increasing throughput required in the facility – increasing shot repetition rate - a new Cryogenic Target Handling System, CTHS was designed and developed over a seven year period from 1992 to 1999. This project was contracted out from LLE to General Atomics, GA with some additional collaboration from Los Alamos National Laboratory, LANL [55]. The crucial requirements for this upgraded system included supporting up to 12 targets a week; permeation filling through thin membrane polymer capsules (5 to 10 microns in thickness); producing up to 140 micron thick D-T ice layers with tight uniformity specifications; adaptability to a remote (opposing side of the Omega target chamber) shroud pulling system that removes the IR shield less than 100 milliseconds before laser arrival and adherence to a 5 micron positioning tolerance of the target relative to the laser system [4] [5].

Figure 2-16 shows the high level system architecture chosen for the CTHS. The CONOPS are as follows: Four targets are permeation filled with D-T in the permeation cell in the left section of the permeation cryostat. The targets are then cooled to cryogenic temperatures (approximately 18 K) and transferred from the permeation cell to the MCTC where cryogenic temperatures are maintained. In addition to a cryostat, the MCTC houses the shroud assembly and positioning device for the target. The target is “layered” inside the MCTC and shroud assembly, producing

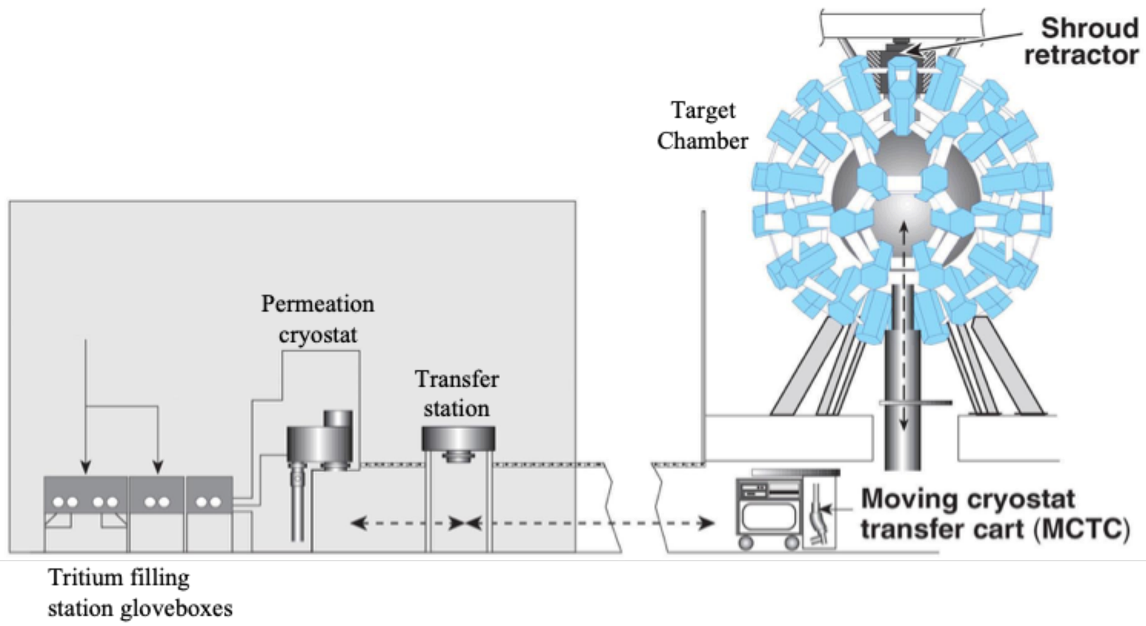


Figure 2-16: Schematic of the Omega Cryogenic Target Handling System [63]

a uniform D-T ice layer on the inside radius of a polymer capsule. Once the layer has been characterized, the target and shroud assemblies are transferred up into the Omega target chamber. After alignment, the shrouds are removed with the shroud retractor (figure 2-16) and the laser beams arrive at the target. General Atomics spent a substantial amount of time prototyping each of the critical CTHS sub-systems to demonstrate the conformity to specifications [5]. This system architecture although suitable for the needs of Omega, is vastly different to the cryogenic design of both the NIF and LMJ.

After the commissioning of the upgraded laser and cryogenic systems, new capabilities were conceived for the Omega facility. Firstly, in 2001, LLE proposed a preliminary design for Omega Extended Performance, EP that would give additional performance and capability with high energy, short pulsed lasers. Figure 2-17 shows the preliminary design, that incorporates 4 ultra-high intensity laser beams, next to the existing facility. This complementary addition would engender new opportunities for the ICF program and high energy density physics. Among its five core missions, Omega EP planned to extend high-energy-density physics research capabilities with

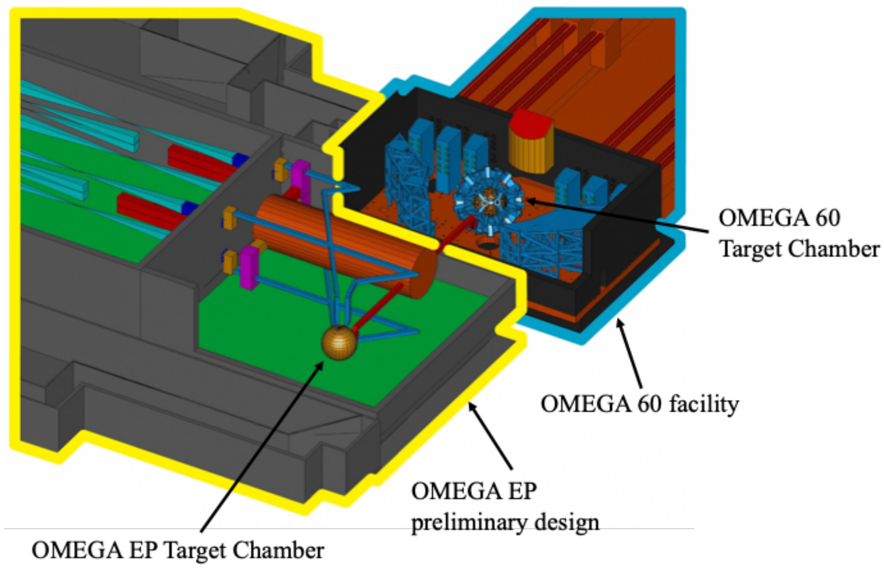


Figure 2-17: Omega EP preliminary design interfacing with Omega 60 [55]

improved, brighter backlighting as well as performing Omega-integrated advanced-ignition experiments [98]. With a shot turnaround of 1.5 hours, 7 to 8 experiments a day could be conducted [121], and flexible diagnostic systems could provide an additional range of experimental configurations. This $90 million effort was completed in 2008 with initial experiments being performed in the fourth quarter of FY08 [79].

A second, notable capability enhancement was the magneto-inertial fusion electrical discharge system (MIFEDS) which was first introduced in 2011 for experiments. Shown in figure 2-18, MIFEDS comprises a stored energy capacitor, a triggering system, sparkgap switches, transmission line and a coil.

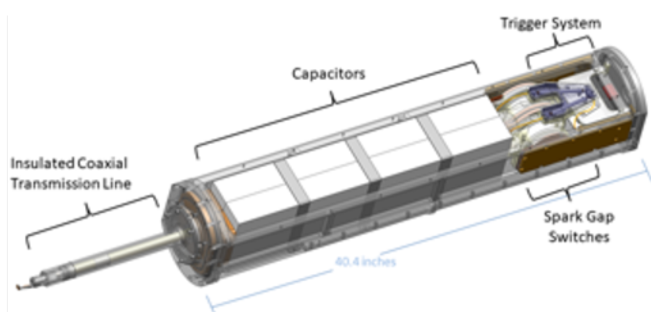


Figure 2-18: MIFEDS coil (left) and Magnetic system (right) [55][88]

For direct drive implosions, the coil (shown in the left of figure 2-18) is positioned around the target and the triggering system is timed such that the peak current is achieved in the target capsule upon the laser arrival. The coupled coil and pulse generation system produces magnetic fields of up to 30 Tesla [88]. By introducing the magnetic seed fields capability in Omega experiments, ion temperature and fusion yields can be increased [20] as well as increasing the experimental permutations and options for physicists to explore new avenues of fusion science.

2.5 The European Organization for Nuclear Research, CERN & the Large Hadron Collider, LHC

2.5.1 Background

Particle accelerators have been around since the 1930s to allow physicists to investigate the sub-structure of atoms and nuclei by accelerating them with electromagnetic fields. These fields increase energies and speeds of charged particles beams while magnetic fields are leveraged to steer and manipulate the beams. Accelerators are useful in fundamental scientific research, aiding in our understanding of how the universe was created and discovering rare sub-atomic particles such as the Higgs-Boson. The European Organization for Nuclear Research, CERN (Conseil européen pour la recherche nucléaire) based in Geneva, was established in 1954 and is the world's largest particle physics laboratory. With currently 23 collaborating member states or countries, the CERN laboratory employees approximately 2,700 people and has hosted around 12,000 users [2]. CERN specializes in building particle accelerators to improve humankind's understanding of the universe, the makeup of matter and the forces which hold matter together. As well as working on fundamental research, CERN brings nations together to collaborate on science for diverse collaborations. In the CERN complex, there are a total of six accelerators and one decelerator. Figure 2-19 provides an overview of them all including the largest, the Large Hadron Collider, LHC and the decelerator, Antiproton Decelerator, AD as well as the commissioning dates.

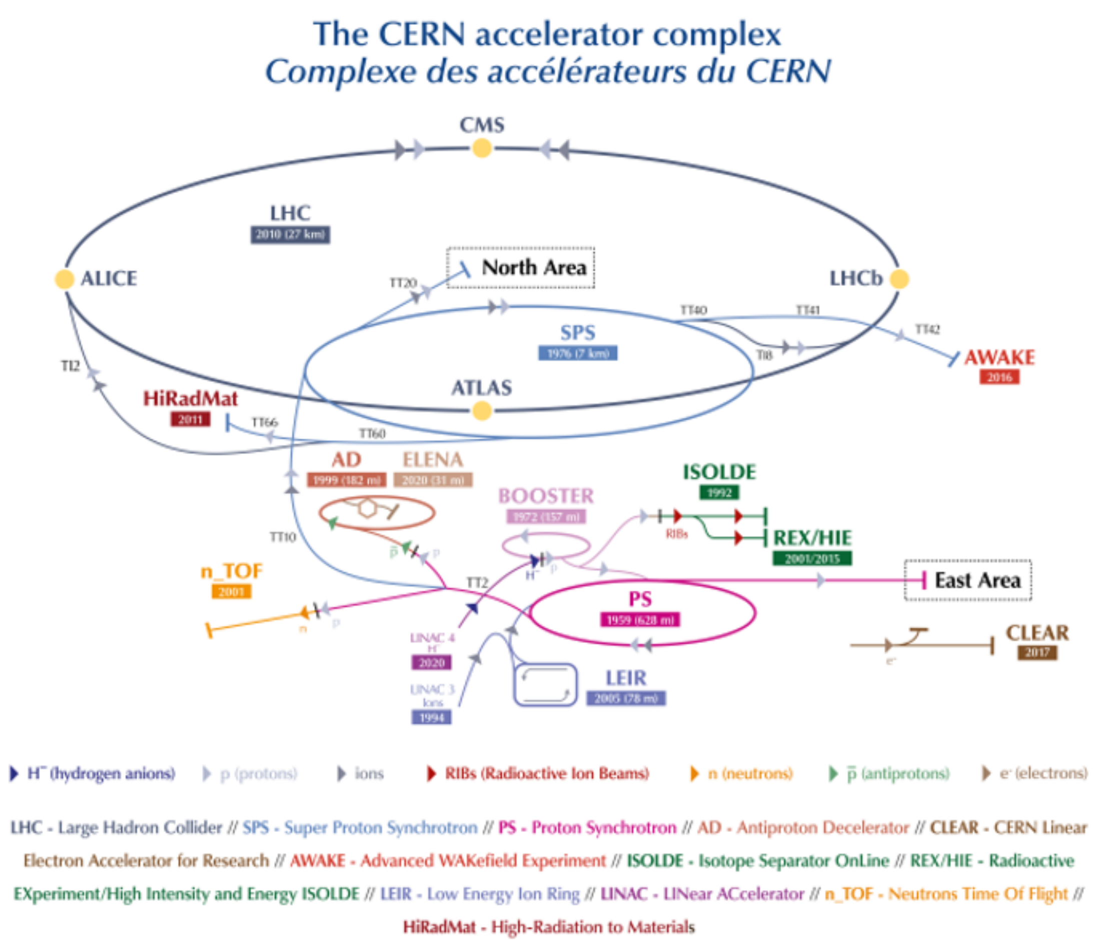


Figure 2-19: Schematic of CERN's accelerators complex [2]

2.5.2 The Large Hadron Collider, LHC

One of the most notable particle accelerators in CERN's purview is the Large Hadron Collider, LHC, which is the world's most powerful accelerator [101]. Utilizing the 3.8 meter wide tunnel constructed by 1988 for the Large Electron-Positron, LEP Collider [101], the LHC was built between 1998 and 2010 with operations starting on September 10th, 2008. Its tunnel has a 27 kilometer circumference and is 175 meters beneath ground level at the France-Switzerland border. The LHC is the final stage of the proton or ion (hadrons) acceleration process at CERN. Although heavy ions can be accelerated, protons are the primary hadrons that are used on the LHC. Initially, a gas bottle supplies hydrogen, electrons are stripped off the atoms to isolate packets of protons by utilizing an electric field [19]. The linear accelerator, LINAC 4, shown in figure 5.1, then accelerates these positively charged particles with an electric field to around one third the speed of light. Next, the protons enter the "Booster", the first circular accelerator in the path which was commissioned in 1972 with a circumference of 157 meters [87]. As they enter the Booster accelerator, the protons have an energy of approximately 50 MeV [19]. A pulsed electric field in combination with magnets are used in the Booster to increase proton energies to around 1.4 GeV. Once this energy is reached, the packets travel on to the Proton Synchrotron, PS which is a 628 meter circumference accelerator that increases proton energy to 25 GeV. Here the protons only need to be accelerated for 1.2 seconds to reach this energy. They are now traveling over 99.9% speed of light and have a mass 25 times greater than a proton at rest. The Super Proton Synchrotron, SPS is the penultimate circular accelerator in the sequence. This accelerator, completed in 1976 has a circumference of 7 kilometers. Once the SPS has increased energies to 450 GeV, proton packets are injected into the LHC in two separate tunnels, in two different directions (clockwise vs anticlockwise) where they reach energies of up to 7 TeV after 20 minutes. At this point, protons are traveling so fast that they circle the 27 km accelerator circumference over eleven thousand times a second [19]. There are four interaction points or detector caverns around the LHC where the two opposing proton beams cross-over. At these points the proton bunches (or packets) are focused down to approximately 20 microns in diameter and even though this is a small cross sectional area, there are only 40 proton-proton collisions per interaction point. However, since there are around three thousand bunches with approximately 100 billion protons in each, and the bunches cross around 30 million times a second, 1 billion collisions are produced a second on the LHC.

A key sub-system in the LHC are the superconducting magnets. There are 50 types of magnets used on the LHC [103] that steer the proton beams in a circular fashion as well as adding stability and positioning. They are all electromagnets, using the world's largest cryogenic system to cool them down to approximately 1.9 Kelvin to maintain their superconductivity [102]. Figure 2-20 shows the conceptual design and cross section for the dipole magnet assembly. There are 1232 of these dipole magnets, 15 meter length each spaced around the LHC accelerator. They generate a steady state magnet field of 8.3 Tesla from over 11 kilo-Amps of current and enable the proton beam to be successfully steered around the 27 kilometer loop. These dipole magnets are wound NbTi Rutherford cables with copper added for stabilization [58]. In order to increase the number of collisions, the proton bunches, or packets need to be as tight as possible. This essentially increases the beam density and number of protons per unit area. The LHC incorporates around 392, six-meter long Quadrupole magnets that enable beam tightening and are of similar make up as the dipoles with an additional 2 poles.

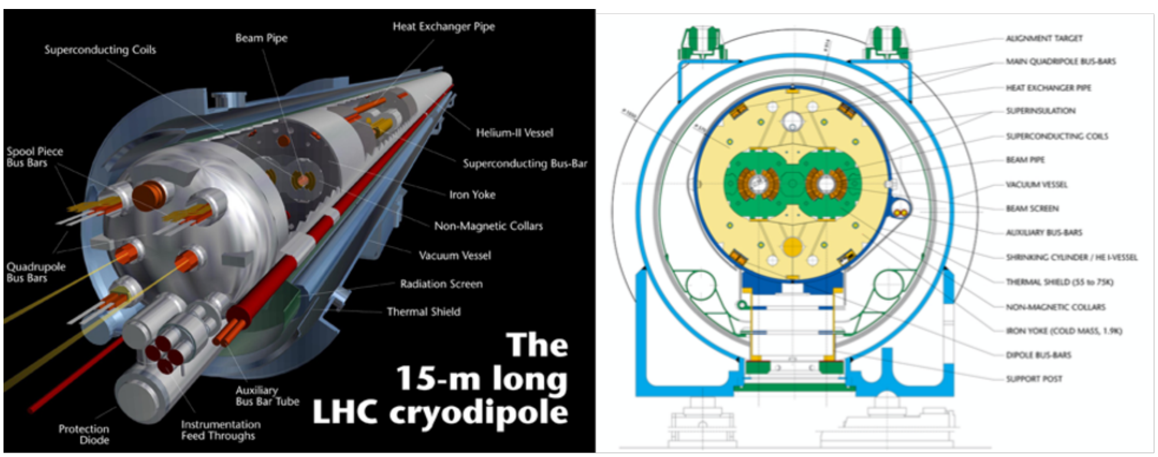


Figure 2-20: The LHC cryo-dipole concept and cross section [46]

As mentioned previously, hadrons travel in opposite directions around the 27 km LHC loop. The LHC has three main vacuum sections, the helium distribution line, cryomagnets insulation and the beam tube vacuum. The latter is required to avoid unwanted particle collisions with gas molecules as the particles travel around the LHC loop. The beam tubes are approximately 56 mm in diameter and are maintained at ultra high vacuum [58], a pressure down to 10^{-13} atm. In order to keep the magnets surrounding the beam tube superconducting, 120 tonnes of helium in a closed liquid circuit is required [102]. The cooling process on the LHC takes weeks to complete and requires three stages, including an initial cooldown of the helium to 80 Kelvin (K) using liquid nitrogen and then a further reduction in temperature to 4.5 K using turbines. In atmospheric pressure, at 4.2 K helium transitions to a liquid state and at 2.17 K becomes a super fluid with very high thermal conductivity and thus high cooling efficiency. This is a desirable to keep the 36,000 tonnes [102] of superconducting magnets at a stable 1.9 K temperature while in operation. Another key technology system in the LHC are the 16 Radio Frequency cavities at intervals around its circumference. These cavities provide the necessary electric field to accelerate the proton beams up to 7 TeV as well as tightening the proton bunching and thus helping increase luminosity. Each of theses RF cavities delivers 2 MJ of energy at 400 MHz [12]. In addition, a number of detectors have been developed and implemented on the LHC. These include ALICE (A Large Ion Collider Experiment), ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid) and the LHCb (Large Hadron Collider beauty) which all provide collision diagnostic data and allow scientists to investigate the largest range of physics possible [101].

LHC project evolution

The CERN council voted and approved the construction of LHC project in December 1994 and the technical design report was published in October 1995 [18]. This technical report outlined the LHC conceptual design and Concept of Operations, CONOPS. One of the advantages for the LHC project was leveraging the existing tunnel circuit of the LEP Collider. However, much civil construction work had to be conducted in order to add the necessary infrastructure for the ATLAS and CMS experiments, as well as the connection to the SPS, and the variety of assembly halls and technical buildings [81]. In 1998, the official ground was broken for the commencement of the construction effort and with the decision to decommission the LEP Collider in December 2000, the LHC project build accelerated. The final excavation of the ATLAS experiment was completed in May, 2002 followed by its inauguration in June 2003

[101]. In 2005, the CMS detector system excavation was completed and the final dipole magnet assembly was taken underground for installation into the beam tube assembly. The last large pieces of both the ATLAS and CMS detectors were lowered into their caverns in February and July 2008 respectively and by September 2008 the LHC started up with its first experiments. Figure 2-21 outlines the costs of the LHC project in millions of Swiss-Francs (CHF) (exchange rate with US dollar in 2021 is about 1:1).

• **Construction costs (MCHF)**

	Personnel	Materials	Total
LHC machine and areas*	1224	3756	4980
CERN share to detectors	869	493	1362
LHC computing (CERN share)	85	83	168
Total	2178	4332	6510

**Includes: Machine R&D and injectors, tests and pre-operation*

Figure 2-21: Summary of costs for the LHC project construction [18]

There was an initial incident in 2008 that delayed ongoing experiments until 2010 with a faulty electrical connection that caused a portion of the magnets to quench which resulted in mechanical damage to the beam path [101]. Fourteen months of repairs and then recommissioning contributed to delayed experiments for higher energies until March 2010 when the 7 TeV proton energy was reached.

Comparatively to the actual costs of the LHC, the initial budget was estimated to be 2230 MCHF in 1993 prices with a predicted timeline of construction between 1995 to 2001 with commissioning in 2002. Subsequent delays with LEP decommissioning and the magnet procurement saw a predicted project completion moved out to 2007 [17]. With additional unanticipated design challenges with some of the detector caverns and the support structure, the LHC operations started in 2008.

2.5.3 The High Luminosity Project, HL-LHC

For physicists, the most important parameter of a particle accelerator is luminosity. With increasing luminosity, the more data can be recorded and rare observations made. The equation below captures the relationship of luminosity to number of events (collisions) per second, dR/dt and the beam cross-section, σ_{p}.

$$Luminosity, L = \frac{1}{\sigma_{\mathrm{p}}}\frac{dR}{dt} \qquad [45]$$

In order to increase the number of collisions every second, the number of particles in a bunch, number of bunches or the complete circuits around the accelerator ring must be increased. The High Luminosity upgrade to the Large Hadron Collider (HL-LHC) aims to increase the luminosity of the LHC close to a factor of five times from 1.2 x 10^{34} cm^{-2} s^{-1} to 5 x 10^{34} cm^{-2} s^{-1} [6]. The project will incorporate 50% margin on the upgraded design to reduce the risk of meeting its primary criteria requirement of the increased luminosity. Figure 2-22 shows the planned HL-LHC project timeline. The red line represents the energy of collisions and the green line, the luminosity. CERN has, and will stop experiments on the LHC for upgrades in Long Shutdown, LS time windows. The first, LS1 was conducted in 2013-2014 to enable increases in beam energy and luminosity in the Run 2 phase. Due to the COVID-19 crisis, the LS2 has been extended and it is now anticipated that Run 3 will begin in March 2022 [101]. Furthermore, LS3 will move to start at the beginning of 2025. This final long shutdown will be used to upgrade sub-systems of the LHC to increase luminosity without increasing beam energy. On the exit side of the LS3, Run 3 will commence (albeit later than the schedule planned in figure 2-22) with a second aim of producing an integrated luminosity of 250 fb^{-1}/year, resulting in 3000 fb^{-1} (1 femtobarn, fb equals 10^{-39} cm^2) including the subsequent dozen years after the upgrade. For reference, all the hadron colliders in the world had created a total integrated luminosity of 10 fb^{-1} before the LHC.

There are many technical challenges with the new, innovative technologies that will be applied to the HL-LHC upgrade. The sub-system technologies include: Su-

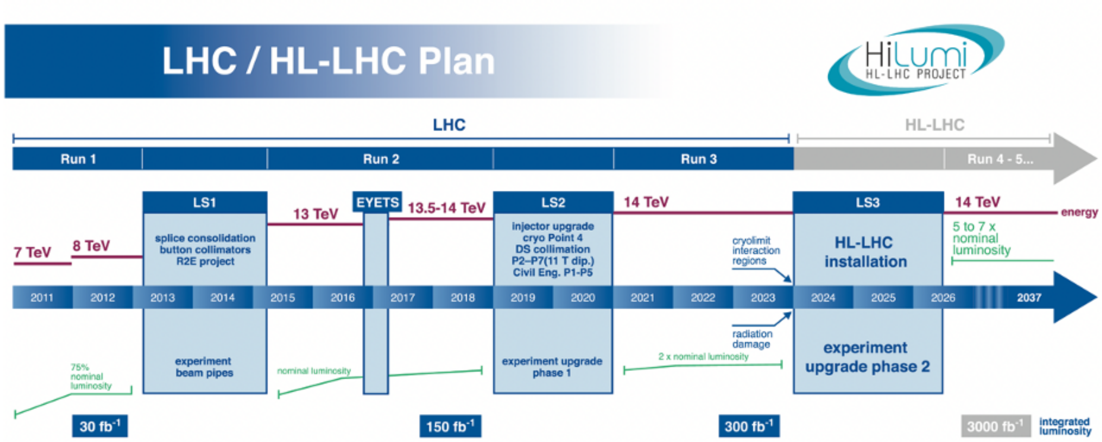


Figure 2-22: The HL-LHC plan for the next decade and beyond [6]

perconducting magnets able to achieve up to 12 Tesla sustained fields, new "Crab Cavities" to steer the beams, beam collimators and connections for high-power superconductors with low energy losses.

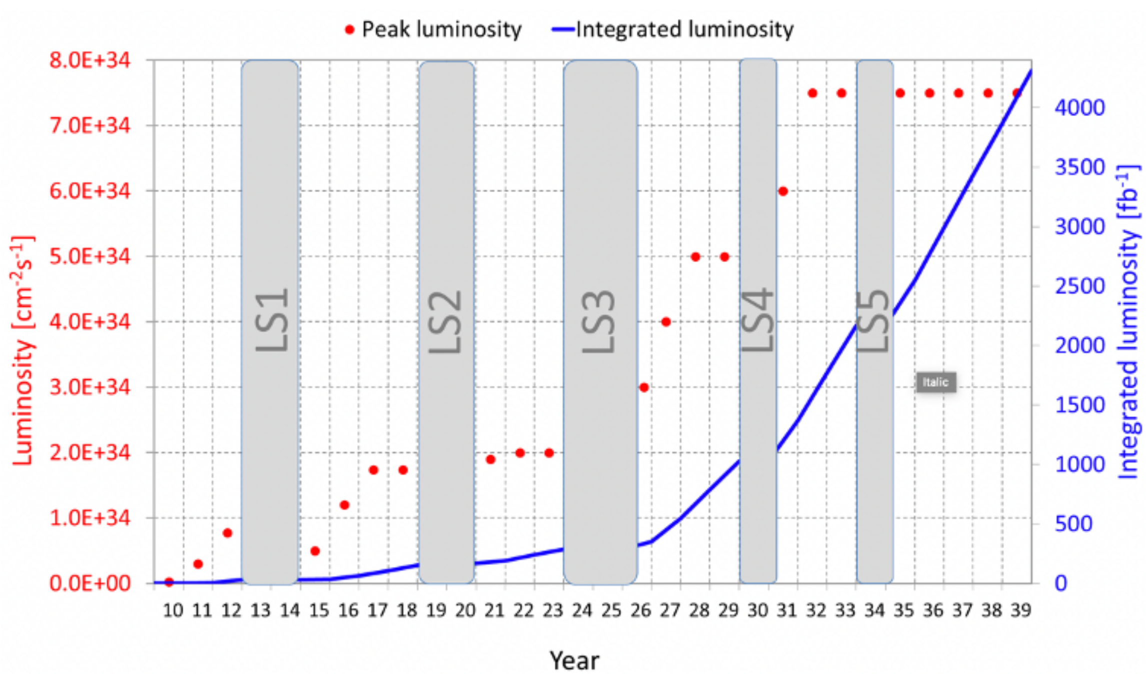


Figure 2-23: LHC peak and integrated luminosity increases with time [6]

Figure 2-23 shows the anticipated increases in luminosity with additional shutdown periods for further upgrades, maintenance and contingency. As of June 2016, the

CERN council had approved a budget of 950 MCHF for the HL-LHC work with an equivalent FTE-years (Fulltime employment-years) of 1600.

2.6 International Thermonuclear Experimental Reactor, ITER

2.6.1 Background

The concept of nuclear fusion power generation fundamentally consists of fusing hydrogen atoms to form heavier ones such as helium with a release of energy through neutrons. There are two main technology branches of confined fusion that have been developed since the 1950s. These are (1) Magnetic and (2) Inertial Confinement Fusion. The latter is discussed earlier in this chapter with the NIF, LMJ and Omega facilities and the former utilizes large magnetic fields to create and sustain high energy plasmas that have both high electrical conductivity and densities. This, Magnetic fusion type is the base technology for the ITER (International Thermonuclear Experimental Reactor) project which will be the world's largest magnetic fusion reactor with assembly completion planned for 2025. Located in Southern France, ITER is a joint venture with 35 nations [48] collaborating to design, develop and build the largest tokamak in the world. ITER is a stepping stone in the development of fusion as a renewable energy source, it aims to act as a feasibility study to prove that Magnetic Confinement Fusion, MCF can be a large scale energy source. The project's main objective is to be the first fusion reactor to produce net energy gain which means there is more output power from a fusion plasma pulse than the power required to heat the plasma.

Figure 2-24 shows the basic schematic of the tokamak concept. Plasma is confined in the tokamak by magnetic fields created by the toroidal and poloidal field coils. The toroidal magnetic field lines run in a donut shape, or torus around the vertical axis of the tokamak and the poloidal field lines run circular around the torus, shown in figure 2-24. As charged particles act to follow magnetic field lines, the plasma follows

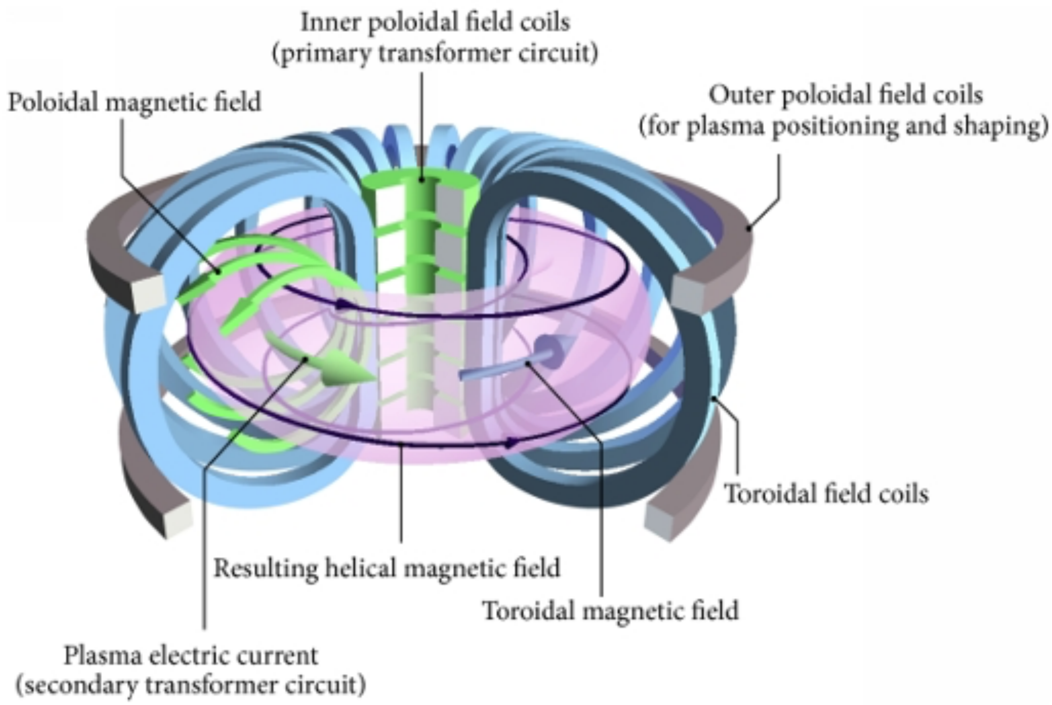


Figure 2-24: Schematic of tokamak and magnetic fields [59]

a helical path around the torus. This results in extremely high temperatures and many collisions between particles. To create the necessary heating power required, typically two methods are used in tokamaks which are either using neutral beam injections or high frequency electromagnetic waves. The latter can be done by two methods according to the ITER project [48]. Ion Cyclotron heating which utilizes radio frequency EM beams, 40-55 MHz to deposit energy into the plasma (similar to a microwave cooker) or Electron Cyclotron heating which runs closer to 170 GHz. For neutral beam injections, Deuterium is shot into the plasma and imparts energy through the collisions made. Both these external heating methods consume the majority of the input power to sustain a fusion reaction and are ratioed with the output power created by the plasma to generate a fusion energy gain factor, Q. Breakeven is the condition when Q = 1, the released fusion energy is equal to the input energy. The highest ever Q was achieved in 1997 by the Joint European Torus, JET in the UK, outputting approximately 16.1 MW of fusion power and resulting in 0.67 Q [49].

In order to assess the current and planned tokamak systems, Table 2.4 was created from various references. Shown in the table are important reactor parameters such as size, magnetic field and actual or predicted Q values. The successor to JET in the European magnetic confined fusion roadmap, is ITER with an aim of reaching a Q value of 10 and being the first reactor to sustain a nuclear fusion reaction.

Table 2.4: Tokamak reactors evolution (in operation and planned)

Tokamak	Commissioning date	Toroidal magfield on axis (T)	Plasma current peak (M-Amps)	Input Power (MW)	Output Power (MW)	Q	Major radius (m)
TFTR	1982	6	3	51	10.7	0.21	2.52
JET	1983	3.45	3.2	24	16	0.67	2.96
DIII-D	1986	2.2	2	27	-	-	1.66
Tore Supra (became WEST)	1988	4.5	1.7	20	-	-	2.25
AUG (ASDEX Upgrade)	1991	3.9	1.6	30	-	-	1.65
C-mod	1993	8	2	6	< 1	0.1	0.67
NSTX	1999	0.3	1.4	11	-	-	0.85
EAST	2006	3.5	1	28	-	-	1.7
KSTAR	2008	3.5	2	16	-	-	1.8
WEST	2018	3.7	1	17	-	-	2.5
ITER	2025	5.3	15	40	500	10	6.2
SPARC	2025	12.2	7.5	25	140	11	1.85
DEMO	2050	5.7	18	50	3000	25	9.1
Ignitor	2024 (estimate)	13	11	24	96	9	1.32
BPX	-	9	11.8	20	100	5	2.59
CIT	-	10	11	20	800	inf	2.1
FIRE	-	10	7.7	20	150	10	2.14

table compiled from various references [30][26][41][53][86][1][89][36][100]

2.6.2 International Thermonuclear Experimental Reactor, ITER tokamak

Similar to the Large Hadron Collider, LHC, the ITER tokamak magnetic system design incorporates superconducting magnets made from either niobium-titanium (Nb-Ti) or niobium-tin (Nb3Sn). There are over ten thousand tonnes of magnets, making ITER the largest integrated superconducting magnetic system in the world [48]. These magnets are also cooled with supercritical Helium in the range of 4 Kelvin to produce zero resistance strands incased in copper. The ITER tokamak, 30 meters in diameter, utilizes eighteen "D" shaped toroidal magnets and six, ring shape poloidal magnets [48]. The former is designed to reach a maximum magnetic field of 11.8 Tesla and the latter, up to 7 Tesla.

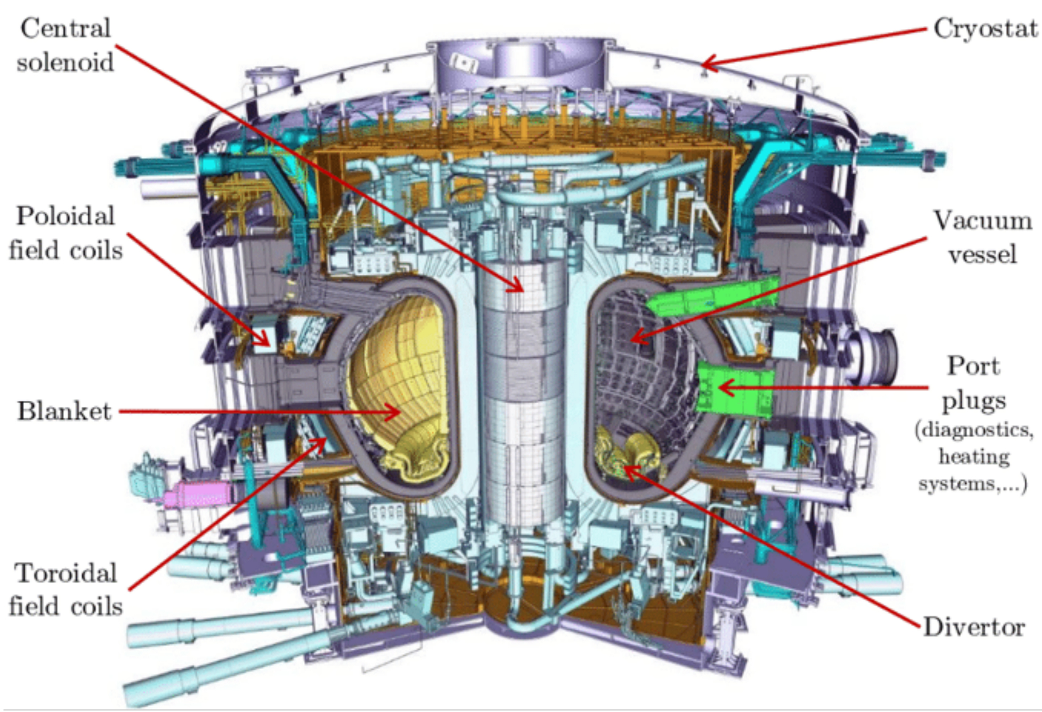


Figure 2-25: Cross section schematic of ITER tokamak and main components [30]

Figure 2-25 shows the 3-D CAD cross section of the ITER tokamak and the central solenoid (inner poloidal), poloidal field coils and toroidal field coils can be seen. The vessel in which the plasma is confined, is evacuated to high vacuum to remove unwanted molecules that may affect experiments. This vacuum vessel container is approximately 840 m^3 in volume and supports both the "blanket" and "diverter" which are also shown in figure 2-25. There are 440 blanket modules which make up the inner wall of the vacuum vessel. These modules act as protection to the steel structure and magnets by absorbing the heat and the neutrons generated from the fusion reactions. In a full nuclear fusion power plant design, the kinetic energy of the emitted neutrons is converted to heat in a water coolant.

The ITER organization was created in 2007 and the project site land was cleared and levelled by 2009. From 2010 to 2014, the support structure and seismic foundations for the tokamak were completed. After which, the construction of the tokamak building began and completion is estimated in 2021 [48]. The tokamak main assembly and integrated commissioning aims to be completed by 2025 with first plasma experiments being conducted in December 2025. The machine will then go into a planned ramp up phase from 2025 resulting in the beginning of Deuterium-Tritium, D-T operations in 2035.

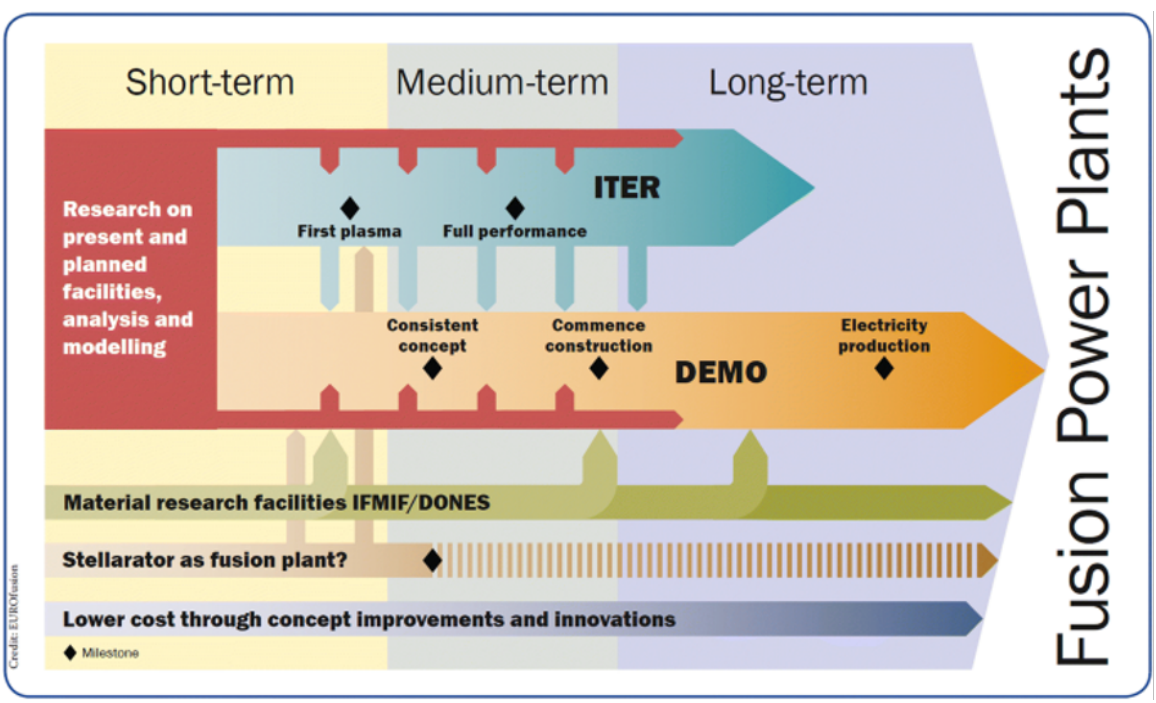


Figure 2-26: European roadmap to fusion energy [29]

Figure 2-26 shows the European roadmap for fusion energy. This is courtesy of EUROfusion, a consortium of European countries concentrating on the development of fusion energy. The longer term vision of MCF in Europe is leveraging ITER to conceptualize and develop the full scale MCF power plant as the first demonstrator. DEMO is planned to be the first, demonstration power plant and is ITER's successor. In addition, the roadmap in figure 2-26 also considers alternate MCF technologies such as a Stellarator as contingency path towards net energy. It is clear from the roadmap strategy that ITER will provide key learnings and insights from its build, testing and operation to inform a more robust design for DEMO. Further to table 2.4, figure 2-27 shows the tokamak technology progress with important scaling parameters. The purpose of ITER is to assess the feasibility of a magnetically confined nuclear fusion reactor and better understand the challenges involved with scaling up plasma volumes, magnetized areas and toroidal magnetic fields. From this, DEMO can be launched with the potential of being the first tokamak to provide electricity to the grid.

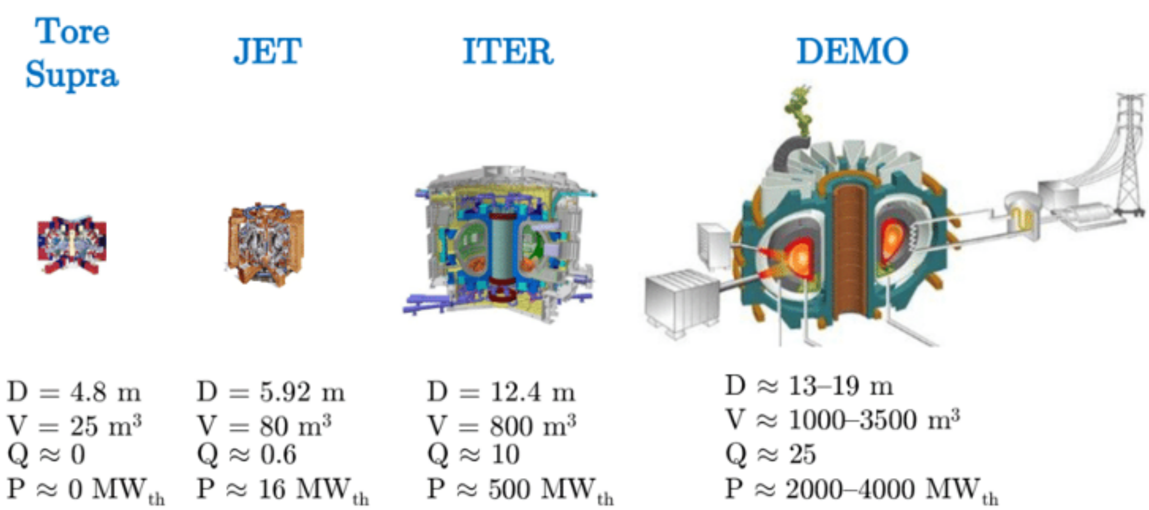


Figure 2-27: Tokamak technology comparison and progression [30]

2.7 James Web Space Telescope, JWST

2.7.1 Background

Located just outside Washington, D.C. to the northeast, the Goddard Space Flight Center, GSFC was established in May of 1959 [111]. Focusing on the building of new space technologies such as spacecraft and instruments to study our solar system and universe, the GSFC is the largest organization of scientists and engineers in the US. It is a critical arm of the NASA organization, fulfilling many core missions in scientific space exploration and discovery. GSFC manages the operations of many NASA international missions including the Hubble Space Telescope, HST which was launched in 1990 to give scientist's a clearer view of the cosmos as well as a better understanding of planets in our solar system. Orbiting 340 miles above the Earth's surface, the HST has played a key role in characterizing discoveries such as the universe expansion, dark energy and the formation of stars [111]. The James Webb Space Telescope, JWST is planned to be the successor of the HST with increased capability to further improve humankinds understanding of the universe. In particular, JWST aims to improve the infrared, IR resolution and sensitivity while HST can still be utilize for UV and visible light studies [114]. Furthermore, with its large mirror, the JWST will be able to detect signals 10 to 100 times fainter than the HST. Table 2.5 compares the two space telescopes and it can be seen that JWST provides additional capability in the infrared wavelength range, finer resolution and further back in time measurements of the first galaxies.

Table 2.5: Comparison between the HST and JWST [114][32]

	HST	JWST
Wavelength observed	0.8 – 2.5 microns	0.6 – 28 microns
Size, mirror area (m^2)	4.5 (2.4 m dia)	26.3 (6.6 m max dim.)
Spatial resolution (FWHM)	0.09 arcsec at 1 µm	0.03 arcsec at 1 µm
Orbit (km)	570	1.5 million
Age of universe observed	1 billion years	0.3 billion years

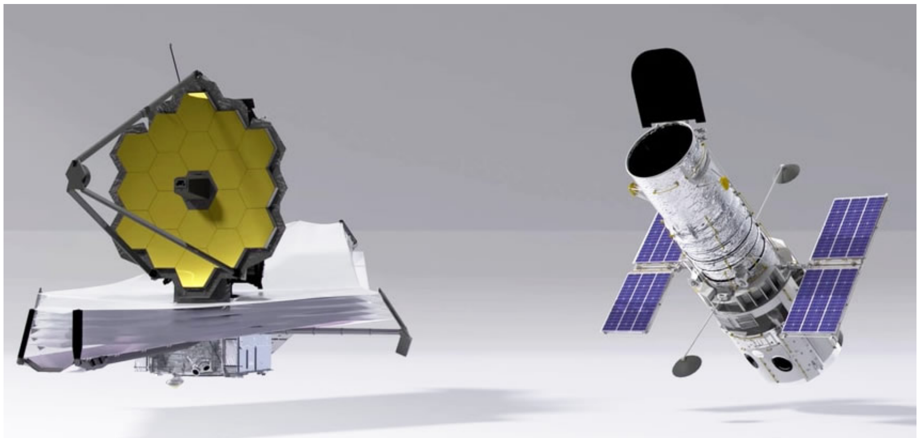


Figure 2-28: Side-by-side comparison of JWST (left) and HST (right) [114]

2.7.2 James Webb Space Telescope, JWST

The JWST is a large (26.3 m^2 mirror) infrared space telescope that is expected to be launched into space in 2021. A complement to the existing Hubble telescope, it will be able to see further into space, utilizing the infrared spectrum and giving scientists more information about the universe's origins and formation of solar systems. With concentration on the near to mid infrared range, the JWST will be able to view high-redshift objects of which visible emissions have been shifted to the IR spectrum due to their distance away and the expansion of the universe. These would be impossible to view from Earth due atmospheric absorption of IR and the HST is not equipped to study these longer wavelengths.

Figure 2-29 highlights the main sub-systems, a number of which have been developed especially for the JWST. The primary mirror consists of eighteen, hexagonal, gold coated beryllium segments that unfold from a stowed position upon deployment and allow for the capturing of very faint IR signals [107]. The secondary mirror, shown in figure 2-29 reflects these signals back to the instrumentation that is contained behind the backplane, in the Scientific Instrumentation Module, ISIM. In this assembly there are four cameras and spectrometers that are sensitive over the optical to mid-IR range and are called the Mid-Infrared Instrument, MIRI, the Near-infrared camera, NIRCam, the Near Infrared Imager and Slitless Spectograph, NIRISS and the

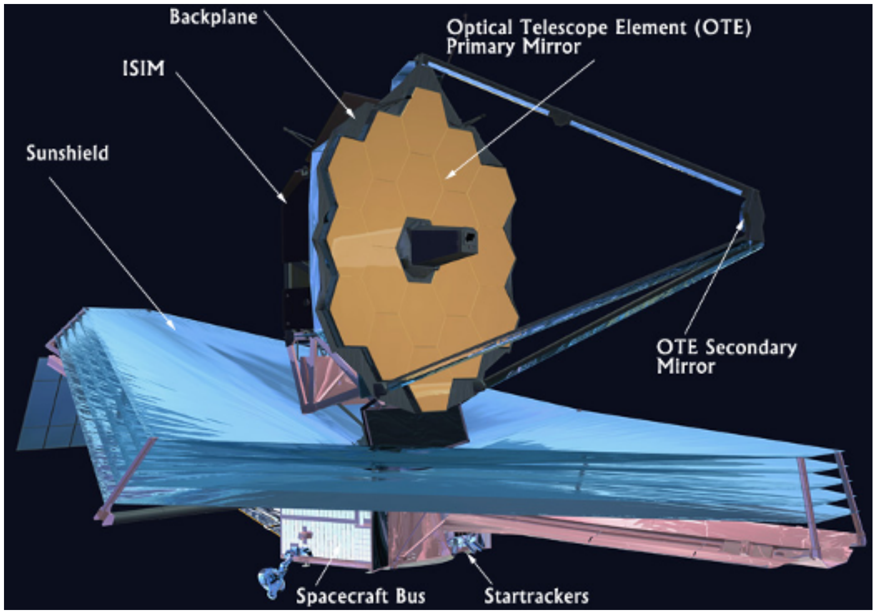


Figure 2-29: JWST main features [114]

Near-Infrared Spectrograph, NIRSpec [120]. The former has to be cooled via a cryogenic system that is housed in the Spacecraft Bus along with control and transport components and is needed to reduce noise. The Sunshield is the largest element of the system and consists of five layers of aluminum coated Kapton (polyimide) material with each having the thickness of a human hair [114]. This assembly provides the necessary protection for the observation components against the heat and light generated by the Sun, Earth and moon and the second Lagrange point, L2 is the chosen orbit in order to maintain the shelter. These observation components (shown on the "topside" of figure 2-29) are kept at temperatures below 50 Kelvin so the instruments aren't overwhelmed with IR from the telescope itself. Additionally, Startrackers are a small collection of telescopes tracking star pattern to aim the observatory.

The project, started in 1996 is a multinational collaboration lead by NASA with the European Space Agency, Canadian Space Agency and the industrial partner, Northrup Grumman. Due to many of the lower TRLs and system design challenges, the JWST project has had multiple delays. In 1998, the project had a planned total budget of $1 billion with a anticipated launch date of 2007 [90]. By 2006, both the anticipated budget and launch date had been changed to $4.5 billion and 2014 respectively. The project successfully completed a Preliminary Design Review, PDR by 2008 and in the prior year had had its technology maturation milestone completed with a successful passing of a non-advocate review into the technology development items [118] which was a big step in the risk mitigation plan. Following in 2010, the project passed an important milestone, the completion of the technical review portion of the Mission Critical Design Review, MCDR signifying that all requirements should be met [112]. More recently, the anticipated launch date has been advertised as October 31st, 2021 with a budget spent of over $10 billion [112]. Further research into these overruns suggests that at least initially, the project team were aiming to rise to the task of building the telescope “faster, better, cheaper” as challenged by the NASA Director, Dan Goldin in 1995 [119]. In addition, the initial feasibility studies projected a budget of $500 million but assumed smaller scope by having only one near-IR camera and also assumed that only one contractor could make the majority of the sub-systems [119]. Both of these assumptions were later proved to be incorrect. Coupled with this, simulations in 1996 suggested that the telescope would have to accommodate mid-IR wavelengths in order to detect galaxies out to higher redshifts [119]. From 2005 documentation [62], Dr John Mather disclosed information on the increases in budget from $3.5 to $4.5 billion citing, amongst other reasons, the causes to be, delay of the transport launch vehicle, Ariane, requirement changes (scope creep) and additional contingency added. Various articles cite the reasons for project delays and budget overruns being due to underestimation of both the technology development and testing as well as lack of funds for expected technical challenge contingency [96] [73]. However, in general, it is thought that once the initial technology milestones were achieved the budget became more predicable [73].

2.7.3 Space Telescope Evolution

The HST and JWST are the preeminent space telescopes that will further our knowledge of cosmos. However, before their missions, over the last several decades there has been a big push to develop these large, infrared space telescopes and to acquire more information about the far reaches of the universe. Having the big advantage of no atmospheric attenuation of IR over ground based telescopes, there are still many challenges in both the design and deployment of such systems including the necessity to have cryogenic cooling for the reduction of local IR emissions from the system itself. If the telescope instrumentation and parts of the structure are not cooled, the detectors will not be able to pick up the faint signals emitted from distant stars and planets. Table 2.6 outlines some of the largest space telescopes from the early 1980s to present day. The general trend for both telescope size and mission duration has increased over the years due to advances in both spacecraft and cryogenic technologies. Initially, many of the early missions utilized a dewar containing a limited volume of coolant that once depleted, would be the end of any data acquisition in the IR spectrum. However, with the incorporation of a cryo cooler for the upgraded HST and the planned JWST project, missions can be extended in to the many year time frame.

Table 2.6: Evolution of space telescopes and instruments [106]

Instrument Name	Year (first operated)	Planned operation lifetime	Wavelength	Aperture/ mirror size	Cooling type
The Infrared Astronomical Satellite, IRAS [109]	1983	11 months	5-100 microns	0.37 m dia	Liquid-helium
Infrared Telescope, IRT [50]	1985	7 days	1.7-118 microns	0.15 m dia	Liquid-helium
Infrared Space Observatory, ISO [105]	1995	2.5 years	2.5-240 microns	0.6 m dia	Liquid-helium
Midcourse Space Experiment, MSX [34]	1996	1 year	8.3-21.3 microns	0.33 m dia	Solid-hydrogen
Submillimeter Wave Astronomy Satellite, SWAS [66]	1998	2 years	538-616 microns	0.54 x 0.68 m	Passive
Odin [104] [38]	2001	2 years	500-600 & 2500 microns	1.1 m dia	Cryogenic cooler
Spitzer Space Telescope [113]	2003	2.5 years (minimum)	3-180 microns	0.85 m dia	Liquid-helium
Akari (Astro-F) [116]	2006	18 months	2-200 microns	0.685 m dia effective aperture	Liquid-helium
Hubble, HST (NICMOS instrument) (WFC3)	1990 (1997) (2009)	3 years before first service	0.8 – 2.5 microns	2.4 m dia	Various
Herschel	2009	3 years	60 – 1250 microns	3.5 m dia	Liquid-helium
JWST [32]	2021 (planned)	5-10 years	0.6 – 28 microns	6.5 m (largest dim)	Passive and cryocooler

2.8 Deep Space Network, DSN

2.8.1 Background

Located next to the San Gabriel mountains in Pasadena, California, the Jet Propulsion Laboratory, JPL has been operating since the mid-1930s [52]. When the National Aeronautics and Space Administration, NASA was formed in 1958, the JPL was transferred from the U.S. Army to NASA and has been managed by California Institute of Technology, Caltech under a contractual agreement since that time. The JPL is a Federally Funded Research and Development Center, FFRDC that specializes in robotic spacecraft and executes Earth science missions. It is a key national research hub that had large contributions to the 1950s and 60s space race with the Soviet Union. These included the build of the United States' first satellite, Explorer 1 (launched in 1958) and the first planetary flyby in 1962. The latter being the Mariner 2 spacecraft that flew past Venus [52]. In addition to concentrating on rockets, payloads and scientific spacecraft, JPL develops and manages the Deep Space Network, DSN.

2.8.2 Deep Space Network, DSN

The DSN is the world's largest scientific telecommunications system [74] and consists of an expansive array of radio antennas that provide communications for interplanetary spacecraft. Its concept was conceived shortly after NASA assumed control of JPL in 1958. The idea was to develop a communication system that could accommodate all deep space (beyond geosynchronous earth orbit) missions thereby making a modular, shared telecommunications system for all spacecraft and missions to share. In addition to its primary function, the DSN gives us insights and understanding into our solar system and universe by utilizing radio and radar technology.

The DSN has three antenna complexes evenly spaced at 120 degrees around the world in the United States, Spain and Australia. As seen in Figure 2-30, the location of the sites allows the DSN to send and receive data consistently to any spacecraft at any unobstructed location that is over 30,000 kilometers away from Earth. All three sites were specially chosen in "bowl shaped" terrain, essentially at the bottom of small valleys to reduce interference from external radio signals. In 1958, the first ground antenna site, the Goldstone complex was built in the Mojave desert, California. The Madrid complex began construction in 1964 with its first 26 meter diameter antenna completed the following year [76]. The third and final site in the DSN is near Canberra and opened in 1965. All 3 complexes have at least four antenna stations that consist of large parabolic dishes with ultra-sensitive receiving systems that detect very faint radio signals from traveling spacecraft [74]. Furthermore, they all have at least one 70 meter diameter dish that is capable of tracking spacecraft that are tens of billions miles away [74]. These faint signals are collected by the quasi-parabolic dishes of the antennas and focused into the microwave equipment that provides amplification [31]. These amplifiers provide special low noise amplification by being cooled to near absolute zero.

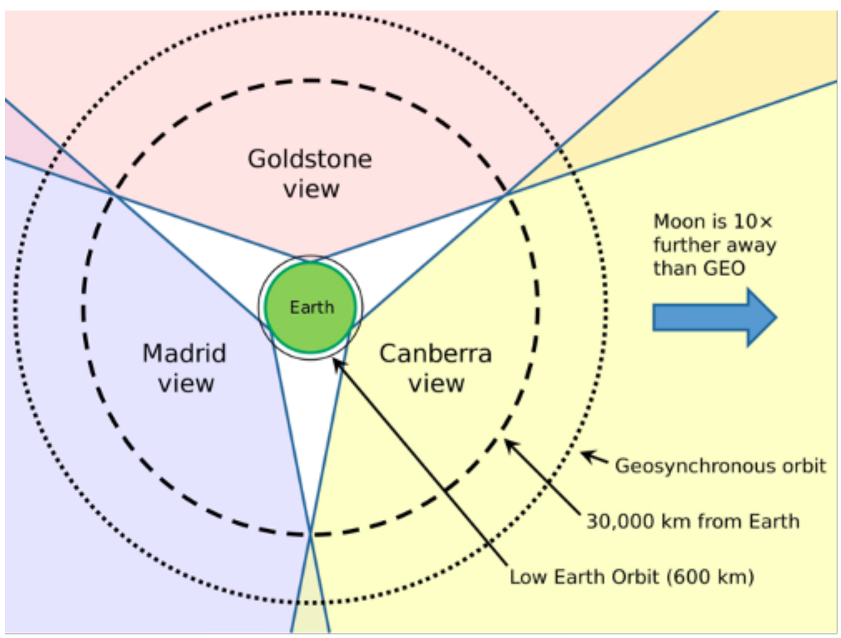


Figure 2-30: North pole view of DSN antenna sites relative to geosynchronous orbit [52]

Antenna evolution of the DSN

As stated previously, each of the DSN sites have a variety of antennas. There are four sizes of antenna used, the 70 and 34 meter ones are used primarily for deep space missions whereas the smaller, 9 and 26 meter antennas service the Earth-orbiting missions [31]. There have been a few design iterations and updates as a result of technology developments that have evolved from NASA mission needs.

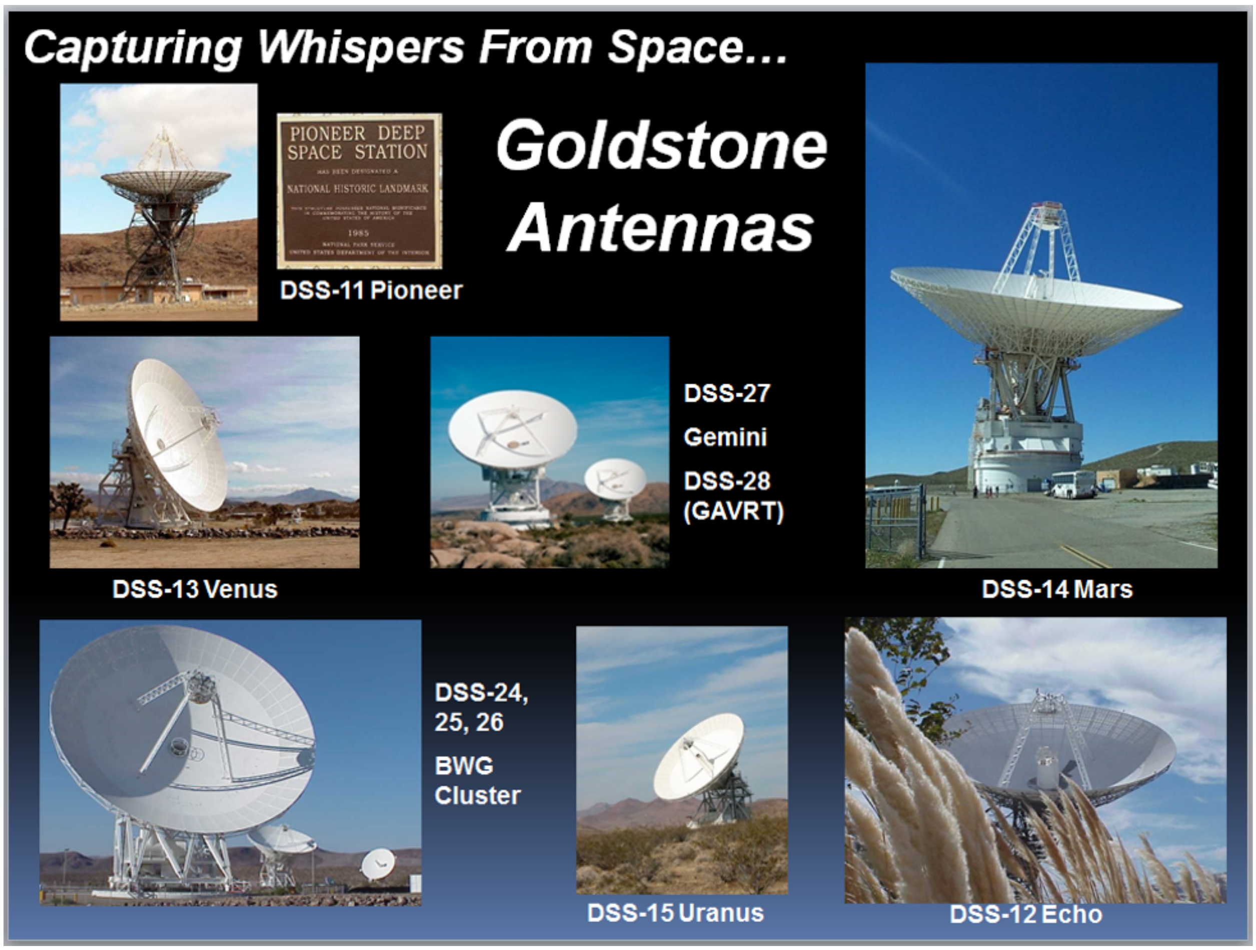


Figure 2-31: DSN antennas at the Goldstone site [75]

Originally, commercial designs were utilized for the DSN that incorporated a parabolic dish into the antenna [31]. As the signals from deep space can be weak, there is an efficiency compromise between picking up as much of the distant signal as possible while minimizing the noise from the surrounding earth. Therefore, in the 1970s, a new design was proposed that would improve performance. This introduced a more optimized, quasi-parabolic dish shape as well as modifications to the secondary reflector that allowed more uniform illumination to the main reflector. This was called the dual-shape design. Upgrades were implemented in the 1980s with the 34 meter diameter high efficiency (HEF) antennas and optimized for the Voyager missions in the X-band (8.4 GHz) frequency range for communications and data transfer [31]. From the Voyager 2 mission toward Neptune it was realized that the signal area for the 64 meter antenna dishes would have to be increased and the dual shape technology introduced hence, the 70 meter antennas were born. Further to these upgrades, in the 1990s new 34 meter antennas were constructed. As well as incorporating the dual shape design, they would also introduce beam waveguides (BWGs) that integrated a suite of secondary reflectors to guide the focal point to the bottom structure or "pedestal" of the antenna. This had big advantages in terms of maintainability, reliability and upgradability of the weather sensitive equipment that had originally been mounted on the feed cone structure of the dish. These BWG antennas had also increased capability of operation in the S- (2 GHz), X- and Ka-bands (32 GHz). Table 2.7 summarizes the evolutionary developments specifically for the Goldstone site.

Table 2.7: Information for the antenna evolution at the Goldstone site [75]

Antenna	**Evolution and important dates**
DSS-12 Echo	34 meter antenna, used for S- and X-band frequencies, built in 1959, decommissioned in 2012
DSS-13 Venus	26 meter antenna built in 1962. Upgraded to 34 meter BWG in 1991
DSS-14 Mars	64 meter in 1966 and upgraded to 70 meter in 1988
DSS-15 Uranus	34 meter HEF in operation from 1984 to 2018
DSS-24,25,26	34 meter BWG antennas constructed between 1992 and 1996
DSS-27, 28	34 meter BWGs. Transferred to DSN in 1994 and DSS-27 is now decommissioned

Figure 2-32 illustrates the DSN's radio frequency technology data rate increases over time and from the graph, the transitions in RF bands can be seen. These advancements are primarily driven by the need to support more extensive missions at greater distances from Earth and in some cases, have been developed from failures with spacecraft communications. An example of this was the advanced communications technology development that adjusted for the loss of the partially opened Galileo antenna in 1991 [74].

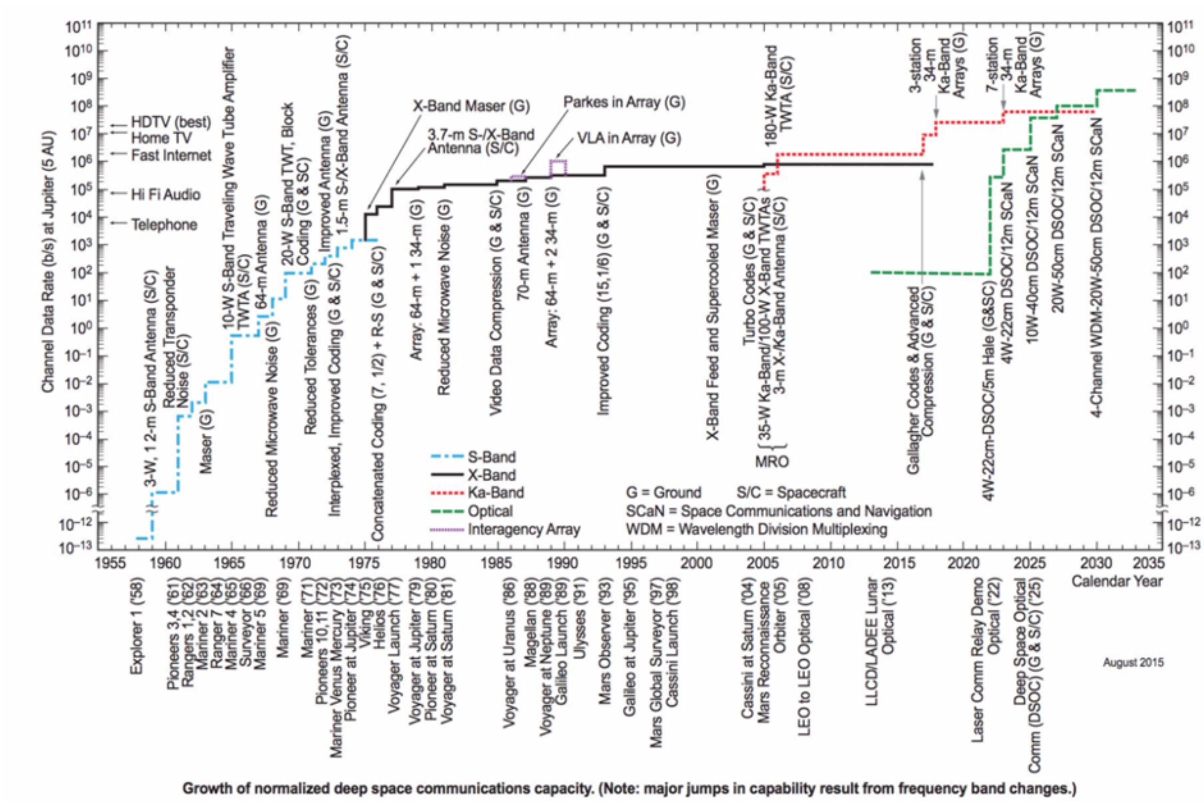


Figure 2-32: DSN rate increases over time. The different colored lines represent different frequency bands [27]

Chapter 3

Project Framework Development

From the organizations and projects identified in Chapter 2, table 2.1, Engineering and Scientific personnel with both involvement in these projects as well as a wealth of experience in the R&D domain and leadership were selected. These key members of staff are shown in table 3.1 with details on their projects, expertise and their experience. Over the course of less than three months - from July to mid-September 2020 - fourteen, approximately 1-hour long interviews were conducted with each person and the generic set of questions shown in Appendix A helped guide the conversation. Due to the large amount of potential questions, not all were asked to each individual but rather, the discussion focused on key insights and learning on both the projects' evolution and strategy. From these individual interviews a more general framework for developing and improving large scientific projects was formed.

3.1 Interview summaries

3.1.1 Gary Mosier

Gary Mosier interview summary

Organization: NASA, JWST

Years of Experience: 30 years

Table 3.1: Project Leaders, Engineering and Scientific staff

Interview date	**Interviewee**	**Current Position**	**Organization / Project**	**Experience**
July 6, 2020	Mr. Gary Mosier	Lead System Engineer	NASA, JWST	30 years experience in Mechanical and Systems Engineering
July 10, 2020	Dr. John Mather	JWST Project Scientist	NASA, JWST	46 years experience in astrophysics and cosmology Nobel Prize in Physics laureate
July 10, 2020	Dr. Leslie Deutsch	Deputy Director, JPL Interplanetary Network Directorate	NASA/JP Deep Space Network, DSN	40+ years experience in communications, digital signaling and project leadership
August 26, 2020	Dr. Lucio Rossi	High-Luminosity LHC project Leader, CERN	CERN, LHC, HL upgrade	40+ years experience in physics and project leadership (20 years at CERN)
August 27, 2020	Dr. Frédérick Bordry	Director for Accelerators and Technology, CERN	CERN, LHC, HL upgrade	35+ years experience at CERN in particle accelerator, technology and personnel/project leadership
August 20, 2020	Mr. Thomas Lanternier	Cryogenic equipment leader	CEA, LMJ	20 years of experience in R&D environment with optics, heat transfer and system engineering
September 8, 2020	Dr. Joseph Snipes	Scientific Expert at ITER	ITER	35 years since PhD experience in plasma physics in tokamaks
September 8, 2020	Dr. Ambrogio Fasoli	Director, Swiss Plasma Center, EPFL	ITER	27 years since PhD experience in plasma physics in tokamaks
August 19, 2020	Mr. Randy Mckee	Senior Engineering Leader	Sandia National Laboratory, ZR upgrade	35 years of experience in Engineering, both at R&D facilities and industry
August 25, 2020	Mr. John Weed	Systems Engineer	Sandia National Laboratory, ZR upgrade	40 years in Mechanical (Vacuum and thin film coatings), Systems Engineering and Project Management
September 4, 2020	Dr. Rick Spielman	Senior Scientific Leader	LLE and SNL, Z-machine initial upgrade	42 years since PhD experience in plasma physics and pulsed power engineering
September 9, 2020	Dr. Jeffrey Paisner	Senior Scientific Leader	LLNL, NIF	46 years experience in laser science and project leadership
September 11, 2020	Dr. Mike Campbell	Director, LLE Laboratory	LLE Omega facility and LLNL, NIF	40 years in R&D laser science at LLNL, LLE and private industry
September 11, 2020	Mr. Ray Scarpetti	Retired (Consultant for NNSA)	LLNL and LANL, DARHT projects	42 years experience in Electrical, Pulsed Power and Systems Engineering

Gary Mosier is a System Engineer who manages the models and simulations group consisting of several dozen people at the GSFC (Goddard Space Flight Center) on the James Webb Space Telescope, JWST project. With a background primarily in the Mechanical Engineering discipline, Mr. Mosier has spent 22 years working on the JWST mission. According to him, the project has spent at least $9 billion so far and was originally presented to the US congress in 1997 to have a total cost of $1 billion with a 2007 launch date. By this original launch date, an updated budget of $3 billion and a 2013 milestone was presented at the Preliminary Design Review, PDR. With the contribution of very tough thermal requirements amongst other things, the JWST project was again re-baselined in 2013, anticipating a new launch date of 2017 and a total cost of $7 billion. A more recent estimation puts the launch date at 2021. Consistent with the JWST and other GSFC assignments Mr. Mosier has experienced, NASA institutes many of the classic System Engineering tools including requirements, FMEA, CONOPS and following the V-model. They also employ a lead system engineer that manages sub-system interfaces and identifies emergent behaviors on the more complex projects like JWST.

Leveraging his experience, the generation and development of requirements follows a fairly common two step approach. Initially, needs, goals and objectives (NGOs) are captured from interactions with stakeholders. These will include the qualitative/functional aspects (the what, who and how) and the quantitative/performance aspects (how much, how often and how well). As the conversations evolve, he says that "we develop use cases, scenarios, and a concept of operations." This is where initial "strawman" concepts and basic architectures start to emerge. He does wonder, if the team then gets wedded to these initial ideas too early in the process such that they preclude better alternatives down the road. However, he acknowledges that these concepts provide better context and allow further discussion to make more sense. In his opinion, it behooves the system engineer to understand that the evolution of stakeholder expectations never really stops although at a first pass, a set of pseudo-requirements can be apparent. The second step to the approach is to generate the formal, engineering requirements expressed as Shall Statements, which must be validated and "shown to be clear, unambiguous, complete, consistent, individually verifiable and traceable". Formal "Measures of Performance" and "Measures of Effectiveness" are captured here as well, generally associated with the most important of the quantitative requirements. Later, when doing trades and optimizations, these are the metrics that are used to make decisions or as mathematical objectives. When asked about requirements that allude to future, non-primary uses cases, Mr. Mosier talked about the capturing of "minimum mission" requirements, the ones that must be met and "stretch goals" that are thought to be "nice to haves", where, without adding cost, schedule and risk, an attempt can be made to try to accommodate them. "Of course we'll add cost, schedule and risk, or at least one of the three no matter how hard we try" and the trick is to convince people that the impact is negligible, if it's not but one is already past some point of no return. As well as having final verifications of requirements by test, analysis, inspection or demonstration, Mr. Mosier sees a lot of value on repeated verification throughout the project lifecycle which can help allow for key decisions to be made earlier and contingencies reallocated.

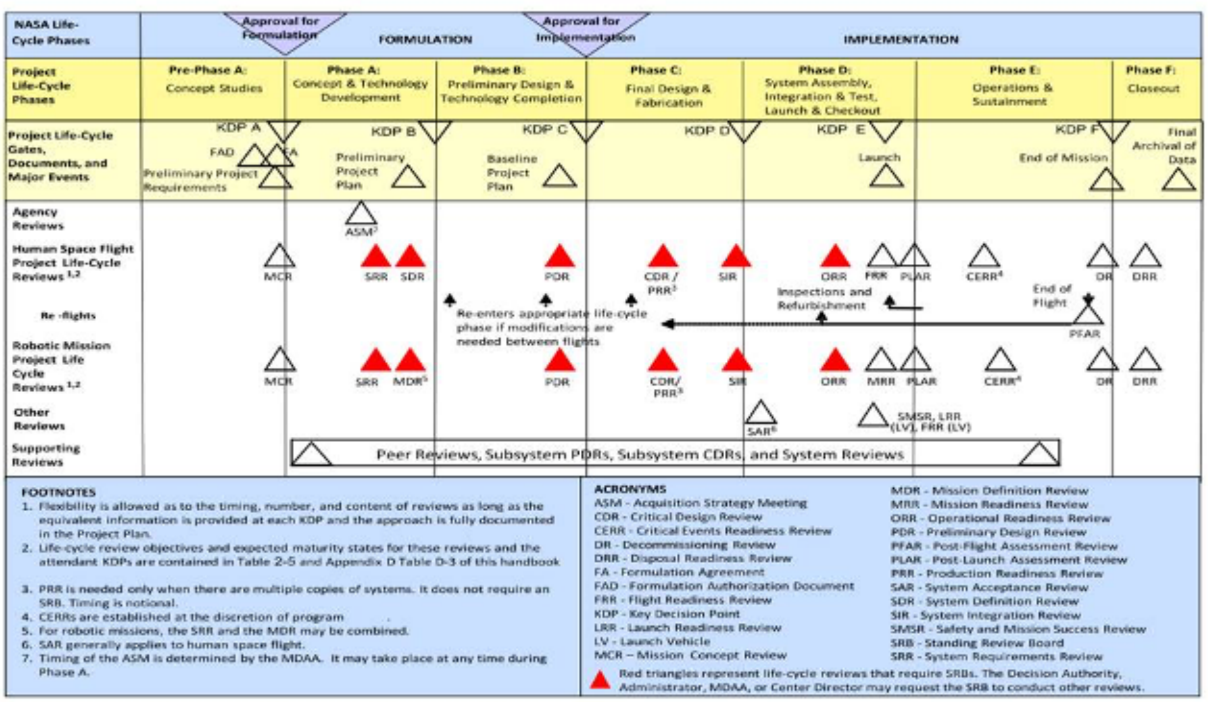


Figure 3-1: the NASA Program/Project Life Cycle [112]

Figure 3-1 shows the NASA Program/Project (P/p) Life Cycle. Mr. Mosier discussed the life cycle as consisting of seven phases – in which the influence of the system engineering V model can be seen – and identifies a number of Life Cycle Reviews. The ones shaded in red require the involvement of a Standing Review Board (SRB), which is independent of the P/p and tracks it throughout the life cycle. For projects such JWST, a rigorous design process is followed including PDRs and CDRs. Consistent with figure 3-1, the development of mission concepts is the focus of Pre-Phase A (or Pre-Formulation). "What we want and need to do is develop a number of credible alternatives for missions", according to Mr. Mosier, and this is before the team can proceed to trades and down-selection to develop one chosen architecture. He finds it very useful to spend time to develop the suite of candidates, all of which should satisfy the stakeholder NGOs, and although there will still be lacking details, large uncertainty factors must be applied. By doing so, these efforts go a long way towards making credible and justifiable down-selects from the candidate solutions. In order to make a downselect, each candidate can be ranked against the cost, schedule and performance metrics – "we assess robustness in terms of the three metrics" - and more often than not, there are many performance metrics which have to be considered.

In regards to strategies to mitigate project risks, Mr. Mosier advises a number of ideas. Primarily, going after the lower TRL technologies first, saying it is essential to "develop critical technology at the earliest possible date". In his experience, a technology cannot be considered to be successfully developed purely in terms of hardware demonstration but a validated analytical model of the hardware is a must. In addition, technology demonstrations, testbeds and engineering models should be done at the largest physical scale possible relative to the size of the flight hardware, and operated under the most "flight-like" conditions where possible, in order to minimize scaling and extrapolations. There could be a scenario where a prototype provides limited advantage as the final use case and conditions are far different from the ones of those being tested. For large and complex projects like JWST, "we will build testbeds and pathfinders" to demonstrate a new technology. Although these demonstrations are not in a true space environment, they provide valuable sub-system performance risk reduction. An interesting insight Mr. Mosier shared was regarding an initial proposed phasing approach to the JWST strategy, where a smaller telescope, Nexus could have been built and tested in space to understand some of the challenging sub-system design performance such as maintaining cryogenic temperatures behind the sunshield. Nexus was cancelled due to the estimated $350 million price tag but in Mr. Mosier's opinion, and when looking at the resulting JWST costs, this would have been a good idea. Another key risk mitigation strategy is regarding peer review and for cases where requirements are verified by analysis, an independent analysis should be performed to confirm the results. The secondary analysis is completely independent of the first and does not use any part of the modeling and analysis performed by the primary path. This extends to correlation and calibration performed to validate the models used in the analysis. He highlighted the use of different modeling tools as being a plus, providing an extra level of independence. Mr. Mosier also encourages that all aspects of the full life cycle are considered at all times, "a project can easily increase risk by focusing on the finished system, in operation", which can be at the expense of understanding the system in other, intermediate states and environments. He provided relevant space exploration examples of these additional states as any point during integration and test, when being transported, or during launch, ascent and trajectory to the final operational orbit. This really helps highlight the need and value of the various stages of the system's CONOPS. He also advocates for subsystems development to be in parallel to the extent possible. "Some of JWST's cost and schedule overruns can likely be attributed to the late development of the spacecraft relative to the development of the telescope and the science instruments". What also potentially hindered here was the procurement of critical components such as the Beryllium mirrors had to be made way ahead of time. Finally, Mr. Mosier sees a lot of value in technical reviews, and programmatic reviews to get different perspectives and secondary critique on critical aspects of the design and project engineering.

3.1.2 Dr. John Mather

Dr. John Mather interview summary

Organization: NASA, JWST

Years of Experience: 46 years

Dr. John Mather is an American astrophysicist and cosmologist who currently works on the JWST at the GSFC in Maryland. A recipient of the Noble Prize in Physics for his work on the Cosmic Background Explorer Satellite, Dr. Mather's has 46 years of experience working at NASA. Since 1995, he has held the position of senior project scientist on the JWST mission where he leads the science team and represents scientific interests at the project management level.

In our discussion, Dr. Mather highlighted three key lessons learned over his career. The first, saying "if you don't test something it won't work" in the R&D space because when you are building a first of its kind, you need to employ a key risk mitigation testing strategy. For the JWST project, offline tests are vital but you cannot test everything and warm and cold sub-systems have to be tested separately. The second being that as a PI of a project, you are essentially the systems engineer and it's your responsibility to implement the necessary tools and organization to produce results. Thirdly, "if something really matters to you, you should get two suppliers", there should be redundancy in procurement and Dr. Mather's mentioned concerns with the lack of it for the JWST cryo system. He also highlighted technological challenges with the JWST mission such as the CCDs and stability requirements knowing that vibrations are a big deal. What he found quite effective was getting all technologies to at least a TRL of 6 before committing to a final design. Often times in these projects, a schedule and final design are committed to before there is a realistic chance of a mature, feasible technology. Although, it can be seen as potentially disorganized, this obviously has large potential cost savings as without, there could be a lot more investment into a non-feasible system designs and the team will have to accommodate many changes after a PDR or CDR.

The JWST process for requirements development involved the scientists writing the initial document and then engineers flowing down a substantial set of more specific ones. According to Dr. Mather, there was "a lot of back and forth" with the engineers needing to understand what can be done versus what's really required. Often times one has to understand the differences between stakeholder needs instead of wants and in his/her mind, this iterative process was essential in resolving conflicting requirements, which will increase expense if not correctly managed. He brought up a specific example with the JWST regarding the launch vehicle sizing saying that the design had to fit this vehicle but other spatial requirements drove this fit to be very tight. They found issues with this tight fit and so a balance had to be struck to alleviate the conflict. Furthermore, there have been many technological challenges with the JWST project and when sending equipment up into space, it has to work first time and have redundancies for any failures. Dr. Mather discussed many problems that the team had encountered throughout the effort with some specific examples. For low noise, the IR detector amplifier electronics need to run at 7 Kelvin, and there were challenges with both reducing the radiative loads and also issues with cable length. The latter emerging from preliminary testing that discovered running a signal over the baseline design cable length was unacceptable. In addition, there were challenges with the sun shade and ultimately the risk reduction of testing first, on Earth has been hugely beneficial.

3.1.3 Dr. Leslie Deutsch

Dr. Leslie Deutsch interview summary

Organization: NASA/JPL, Deep Space Network, DSN

Years of Experience: 40+ years

After gaining his PhD, Dr. Leslie Deutsch joined the Jet Propulsion Laboratory, JPL in 1980 in the communications discipline as a coding theorist. Over the subsequent years, he progressed as a Digital Signaling processing lead all the way up to the Head of Deep Space Network, DSN technology as well as serving for a year at JPL as

Chief Technologist. This latter position involved establishing JPL's strategy for technology development. His current role is as the Deputy Director for the Interplanetary Network Directorate where he interfaces with a multidisciplinary team that support communication systems to spacecraft. A large part of this Directorate is the DSN project. According to Dr. Deutsch, the DSN has a yearly budget of approximately $250 million and if one was wanting to build it over again in today's money, the capital investment would be $10 billion or so. Started in the early 1960s and driven by the US's first moon mission, there was foresight in the DSNs architecture. Dr. Deutsch emphasized that a key strategy to its evolution was the intent to make it scalable. In addition, limits and costs associated with mass on spacecraft forced the development of antennas on Earth. The fact that the DSN is still used today, Dr. Deutsch credits the variety of antennas used, versatile hardware developed and the multi/different missions that drove its development. In the early 1990s, Dr. Deutsch had large, leadership involvement in the Galileo mission where he introduced advanced communications technology that adjusted for the loss of the partially opened Galileo antenna. He also played key roles in subsequent missions including the Huygens Probe mission to Saturn where communications issues emerged that had to be solved with spacecraft en route. He commented that a lot of failures with spacecraft communication systems drove the development of the DSN technology. Dr. Deutsch has managed small teams (20-25 persons) focused solely on research to much larger ones of up to 180 persons in his more recent capacity. Although he doesn't utilize many traditional system engineering tools, Dr. Deutsch has had extensive experience in creating theoretical models to solve communication issues. He considers risk management and balancing risk a key aspect of successful projects that he has managed. A specific example of a risk mitigation strategy that the DSN has employed is designating a 34 meter antenna at the Goldstone site for non-operation, R&D prototype testing. This has allowed upgrades and new technologies to be test run before deploying them into the commissioned network. A specific example of this use was - as he recited - a faux-pas regarding the optimization of the hyperbolic mirror that sits on top of the antenna. For potential cost and weight savings the team went to a lighter wave antenna material (400kW X-band radar transmitter) but the changed material melted when using the radar.

The DSN is funded under the Congressional line item, “Space Operations” and NASA Headquarters can move funds between sub-line items. Dr. Deutsch is a staunch proponent of automation of various aspects of the DSN in order to save on operations funds. This then allows focus on furthering technologies such as the DSN aperture enhancement project which will increase the capability of the DSN.

3.1.4 Dr. Lucio Rossi

Dr. Lucio Rossi interview summary

Organization: CERN

Years of Experience: 40+ years

Dr. Lucio Rossi is the Project Leader for the Large Hardon Collider (LHC) High Luminosity (HL) upgrade at CERN. With over 40 years of experience since gaining his PhD in plasma physics from the University of Milan, he is an expert in superconducting magnets and their application in particle accelerators. Dr. Rossi joined the CERN organization in 2001 leading the Magnet Superconductor and Cryostat Group until 2011 when he became the project leader for the HL upgrade. According to Dr. Rossi, the project budget with contingency is estimated to be around $3 billion which is 40% of the original LHC costs. The integrated personnel effort is about 3000 FTE-years with installation planned (pre-COVID) in 2025. Although the HL project is to increase the number of particle collisions with an aim of up to ten times the number of Higgs-Bosons currently produced, there are two other beneficial “prongs”. The first is the technology breakthroughs that will come from developing 40% more powerful superconducting magnets which Dr. Rossi says are currently at a TRL 2 or 3. These will need to be developed to at least a TRL 6 before getting to implementation on the LHC. The second benefit is the aspect of community interest and keeping the particle physics community together, Dr. Rossi stated “there is less interest if we don’t develop new capabilities”.

As any large project leader should, Dr. Rossi utilizes classical PM tools such as EVM and Configuration Management and the project employs its own custom data management system. Because of the technology intensive nature of the upgrade project, there is also emphasis on documentation of testing and manufacturing. Regarding requirements for the project, high level objectives were driven from the luminosity increases and physics needs. From these, functional requirements were generated and specifications for each component could be flowed down. Dr. Rossi believes that it is vital to fix the goal of the project at the beginning and get to a baseline or nominal design early. In addition, build in margin to project performance goals to allow contingency in anticipation that the physics goals may require higher numbers than initially conceived. For example, the HL upgrade is designed with a 50% margin on its key performance requirement so that its ultimate performance will far exceed the physics needs.

Dr. Rossi observes that it is very important to have a good organizational structure to manage projects well. In the case of the HL he has divided the project into 20 discrete work packages driven from his experience (see figure 3-2). Each functional work package, WP has a leader with the 1st WP covering the project management and others for magnetics, cryogenics and accelerator parameters. It is his expectation that each WP leader should master the entire package. His management strategy is to find a balance between many meetings and no meetings dedicating time he spends with each WP leader on project steering/budget meetings and then a purely technical coordination meeting with all the leads. Each lead is expected to have around 20 internal technical reviews a year. As Dr. Rossi says "Everyone reports to someone, apart from the pope!", he has to report to the higher CERN organization management with a cost and schedule review every 18 months which focuses on the less technical aspects of the project. He finds technical cost optimization a continuous action to maximize budget efficiency and focus it on the highest priority items.

Dr. Rossi sees a key part of his role in assessing and managing risk. Similar to previous successful projects, the plan for the HL project is to implement an offline prototype approach. This type of risk minimization plan involves building an initial

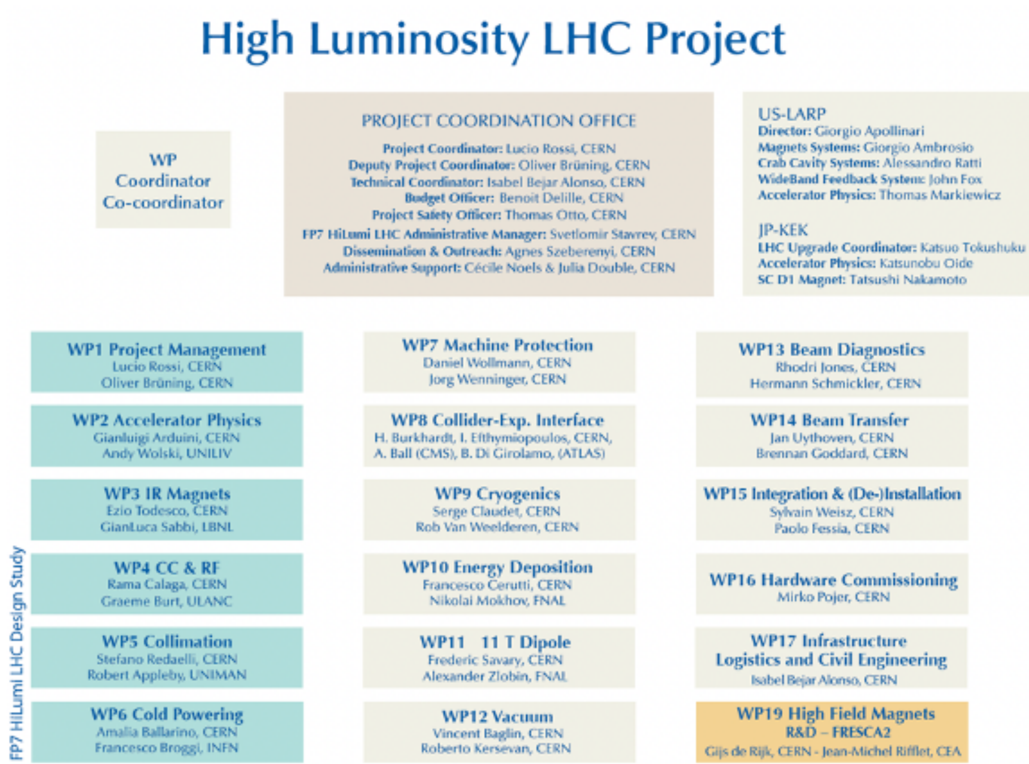


Figure 3-2: High Luminosity Project organizational structure showing the Project Coordination Office and individual Work Packages (WP) [6]

prototype that will test all of the functionality required to get to higher magnetic fields and serve as a spare when the primary four sub-system modules are built for deployment in the LHC.

A particular interesting insight from Dr. Rossi in respect to the project management side of phasing a project is that with an upgrade like HL, you can take more risk than a brand new project. If the HL upgrade fails initially, you still have an operational system that can be used for ongoing experiments. This may be a good driver for R&D facilities to deploy projects faster with higher TRL related requirements to start the learning process and plan to phase in upgrades. The early learnings in large scale R&D projects can be key and could even advocate to canceling any further work or expediting it to get to the end game goals sooner.

3.1.5 Dr. Frédérick Bordry

Dr. Frédérick Bordry interview summary

Organization: CERN

Years of Experience: 35+ years

With over 35 years of experience, Dr. Bordry has had multiple engineering roles in the CERN organization specializing on particle accelerator technologies. Dr. Bordry earned his PhD in Electrical Engineering from the Institut National Polytechnique in Toulouse and then spent the early part of his career conducting energy conservation research. In 1986, he joined CERN working on the power conversion systems for the LHC's predecessor, the LEP project. During this time, he gained operational experience leading the control room activities. Once the LHC project reached the approval stage in 1994, Dr. Bordry moved to lead the Power Converters Design and Construction group until 2008 and then took over as the head of CERN's technology department. This role focused on particle accelerator specific technologies in disciplines such as cryogenics, vacuum and electromagnetics. In 2014, he moved on to his current role as the Director for Technology and Accelerators at CERN. This higher level view role involves many responsibilities including looking at the state of the art technologies and new capabilities including the HL upgrade project. In this capacity, Dr. Bordry is responsible for over 1400 full time employees with overseeing the High Luminosity project one level in management above Dr. Rossi.

He has a keen eye on risk driven from his experience and says that project management is all about risk, "[we] must manage the risk with projects". For a project like the HL upgrade, the risk register is so important that he employs a risk officer to keep the document "living" and assesses these risks in the FMEA format by assigning explicit probably and consequences to each item. One has to have a measure of the risk scope, generate the list, set the priorities, assign owners to each mitigation and "attack it". It is then the owner's responsibility to develop the mitigation as the project progresses. One of the challenges he finds some PMs have is achieving the good balance between reporting out and actually performing the work. The HL project organization was developed with Work Packages, driven from the work breakdown structure to (sub system) leads that then helped defined the schedule. The project management of the interfaces between the groups is done at a higher level and employs a rigorous engineering change request structure. For example, if there are changes in a specification of the vacuum system then the interfacing sub-systems are aware and have to sign off on the update. When discussing his experience with the original LHC project, Dr. Bordry is very cognizant of the ilities involved with designing an operational facility. The project plans big shut down periods at two year intervals for both upgrades as well as time for maintenance for many subsystems. He was heavily involved in optimizing the LHC to reduce the mean time between failures (MTBF). A lot of time and effort was spent obtaining a good measurement of this in order to correct and reduce it. Following on from the conversation summary with Dr. Rossi, the Cost-and-Schedule review every 18 months was implemented per Dr. Bordry's instruction. He sees the importance of this formal reporting and frequency having a two fold effect. Firstly, it helps avoid tunnel vision and enables more external, independent review in a three day meeting setting. Secondly, he sees it as a powerful management tool to guide the team to a deliverable and to assess performance and changes in direction or strategy. In this venue all costs, schedule, EVM and risk register are reviewed. He does not advocate for every R&D project to have this level of rigor and appreciates that a graded approach with smaller projects should be taken. Again, this ties in with the balance of reporting versus performing the detailed work - for smaller projects less time is needed to report out. In terms of not precluding future advancements, adding margin in the system's performance is something that a project leader should have in their back pocket. For the HL upgrade, the energy primary criteria is to run at 14keV but Dr. Bordry has the team aiming for the design to go to 15keV. However, he advises that it is important to understand the extra cost to do this, in some project cases it may be too costly to have the luxury of this added margin. The question becomes, "Do we implement it from the beginning or take the risk later?".

From the discussion with Dr. Bordry, he summarized the evolutionary chronology of the LHC project summary:

- 1983 – First idea
- 1994 – Initial demonstration and approval
- 2006 – Equipment installation (majority completed)
- 2010 – Commencement of operations (2008 was first beam)
- 2024 – Anticipated end of use without any upgrades
- 2040 – Anticipated end of use with High Luminosity (HL) extension

He sees the LHC project as a phased approach and the intent is to always look ahead to the next avenue of increasing energy and data thinking beyond the next project (HL upgrades) timeframe. In his mind the CERN organization "must keep thinking ahead! We're thinking of next use case in particle accelerators while building the initial ones". He is heavily involved in the development of the European roadmap and strategy for particle physics. What does the Future Circular Collider look like? Is a 100km circumference or a 100 keV energy accelerator feasible? What is the time line for upgrades looking past the HL project? These are some of the question's Dr. Bordry intends to answer in the near future.

3.1.6 Thomas Lanternier

Thomas Lanternier interview summary

Organization: CEA, LMJ

Years of Experience: 20 years

Thomas Lanternier is an Engineering Manager working with CEA at the CESTA Center. When discussed, he alluded to the two funding streams for CEA projects, one is civilian and the other is defense-centred. The French Ministry of Defense funds the

LMJ project and as a result there is great care taken in spending tax payers' money as responsibly as possible he emphasized. Funding is on a yearly basis and there are many processes in place to guarantee that everything is done by the book.

For the first part of his career, Mr. Lanternier worked in optics manufacturing and understanding optics production in different laser facilities. He specialized in optics material properties and metrology in the infrared domain. He commented that there are many challenges with optics, especially the specifications required with respect to laser damage tolerance and spectral bandwidth (photometric) issues. From being a more specialized research expert, Mr. Lanternier has increased his responsibilities, becoming a laboratory engineer and more recently, a team leader. The typical size of projects he has led are between 4 to 6 FTEs that have a 2 to 5 year life cycle. With his current role, he is the person in charge of LMJ's cryogenic equipment. Specifically, he is responsible for leading the engineering team in designing, developing and implementing a new Cryogenic Target Positioner called the PCC (Porte-Cible Cryogénique) into the LMJ facility. As are many aspects of the LMJ project, this employs a phased approach to implementation and risk mitigation. Furthermore, there will be initial operations conducted at room temperature as the cryogenic systems are brought online and purposeful delays incorporated in deployment of tritium systems that supply fuel to the targets mounted on the PCC. Mr. Lanternier talked extensively about the details of the offline testing of new systems before deployment into the LMJ facility and in his mind, "...offline testing is key before bringing systems into LMJ". As Mr. Lanternier and his team develop the new cryogenic positioner, they are trying to make it as versatile as possible, attempting to anticipate the future use(s) and not trying to take the specifications "too seriously". Alluding to an example, the operational temperature range is set for the cryostat but he is cognizant of additional, future uses including those at lower temperatures. Mr. Lanternier is familiar with the philosophy not to preclude specifications or requirements and says that the system engineer should make an assessment of what is required to increase any given specification range. If this is very costly, one really needs to nail down the specification. Relating back to the cryostat example, he is trying to read the future and add additional utility such as target temperature sensors and heaters – these come at little cost and could avoid much higher costs later on when interfacing with a mature architecture. In Mr. Lanternier's experience, project requirements are driven by physicists and often times they don't know what they really need. More often than not he adopts an interviewing strategy to help really understand the needs of the main stakeholders. He says that it is "always a negotiation" in requirements between what experts think they want and what is actually possible. Once the requirements have been developed and agreed upon, the next step – according to Mr. Lanternier - is to lock them down. In order to make edits and additions, a configuration controlled, change process should be implemented. Additionally, for every requirement a verification method is identified and although one tries and does the smart thing, everything is really driven by cost so there has to be a compromise. In his experience, some requirements may become irrelevant if other interfacing systems change so it is essential that there is also a change process between interfaces. Due to the scale of the LMJ project, a structured process for specification (requirement) writing and guidelines on flow-down specifications to sub-systems has been developed. Following on from the requirement generation phase of a project, Mr. Lanternier encourages creative concept generation. Although often times his R&D projects are very complex he thinks it is good to have several concepts and it can be dangerous to eliminate too many of them early on. The worry here is that you have no contingency and potentially no concepts at all. Concept down selection on LMJ is generally a qualitative process but there are feasibility assessments for the concepts early on where they are compared against requirements and specifications.

Regarding reduction of project risk, Mr. Lanternier advocates for a balance between testing and true solutions (proven) and then prototyping as much as possible. There are also big advantages with working in phases and trying to validate an R&D project step by step.

3.1.7 Dr. Joseph Snipes & Dr. Ambrogio Fasoli

Dr. Joseph Snipes & Dr. Ambrogio Fasoli interview summary

Organization: ITER

Years of Experience: 27+ years

Dr. Joseph Snipes and Dr. Ambrogio Fasoli have a combined experience of over 60 years in the field of plasma physics and fusion energy since their respective PhDs. Both have roles in the development and build of the ITER tokamak. Previously, Dr. Snipes was in charge of magnetic diagnostics at the Joint European Torus, JET and commented that since university, he has been involved in tokamak based fusion "all the way!". He has been working on ITER since 2008 and the typical budget for his project group is a few million annually whereas the entire ITER effort runs over $200 million annually, closer to $1 million a day according to Dr. Snipes. Dr. Fasoli specializes in plasma physics and fusion energy and has had a variety of positions in these fields. Included in his resume is working as an assistant professor at MIT, becoming a physics professor at the Swiss Plasma Center, SPC and similar to Dr. Snipes, he spent time working on the JET tokamak in Oxford, UK. Since 2015, his current position is Director of the SPC which is part of the Ecole Polytechnique Fédérale de Lausanne, EPFL basic sciences program. The SPC performs a lot of work with the EuroFusion Consortium which is a European collaboration on fusion research with many EU members and Switzerland. At the SPC, Dr. Fasoli controls a budget of approximately $30 million/year and oversees around 150 people. As the SPC does a lot of development work for the ITER project including magnetic systems testing, Dr. Fasoli is heavily involved with ITER as well as driving the higher level European roadmap for fusion energy. In addition to providing feasibility for the Demostration, DEMO tokamak – the predicted first tokamak to supply electricity to the grid – from Dr. Fasoli's perspective, projects like JET and ITER are a driving force for new culture and foster creative solutions with diversity that a multinational collaboration can bring.

Regarding System Engineering and Project Management specific tools, Dr. Snipes focused on the plasma control system which he is working on and commented that requirements recording and tracking are very important. There are a lot of trade-offs that have to be made between science and engineering and sometimes it's a question of cost. Due to the aggressive goals of ITER, there is not much margin as either costs have to be kept down or engineering is being pushed to the limits. Dr. Snipes mentioned an example of the former regarding the ITER main vessel vacuum system. Originally, the baseline design had eight cryogenic vacuum pumps and this was cut to six. However, these pumps need to regenerate (warm up and evaporate trapped gases) and so there are times where only four of these pumps are available. It really is essential to keep a systems thinking view even when trying to reduce costs. From Dr. Snipes' experience on smaller tokamaks, one of his big concerns with the ITER project is magnetohydrodynamic (MHD) instabilities resulting in disruptions and generating run away electrons. "Plasma current can drop to zero very quickly" Dr. Snipes stated and because of the high electric field by disruption, high speed electrons act like a beam, depositing energy on the tokamak walls. A little bit of melting on the internal beryllium wall tiles on the JET tokamak doesn't matter but as the electron runaway scales exponentially with the current, he is worried about ITER and the increased likelihood that electron beams could burn through the wall tiles and penetrate water tanks. For reference, the JET machine runs at 5 MAmps and the current baseline design for ITER is to get up to 15 MAmps. ITER's strategy here is conservatively ramp up the current from 3 MAmps.

The central integration office provides SE and PM guidelines for work on ITER. The project also utilizes a rigorous, formal design process and for Dr. Snipes' project, the plasma control system, there will be a Final Design Review, FDR in July 2021. Typically there are CDRs, PDRs, FDRs, procurement reviews and readiness reviews and Dr. Fasoli commented that this is a framework that he is instituting in academic research as well. However, he understands that this is dependent on size and scope, meaning that not all projects require this level of rigor and a graded approach should be applied. As projects are defined by the three elements of the iron triangle, cost, schedule and scope, Dr. Snipes' has observed that engineers will act to always cut scope first as the other two elements are more externally set. In terms of Project Charters, ITER utilizes them to layout the research plans, project goals, identifying key achievements and helping the team understand the high level aims such as how many shots will have on ITER and the phasing of construction and operations. Furthermore, Dr. Fasoli added that ITER has a central unit in Munich that oversees project related activities and is managed with PM professionals.

Both Dr. Fasoli and Dr. Snipes' emphasized the importance of assessing "risks and opportunities" on scientific mega projects and on ITER, there is a designated team to identify and assess these. Dr. Fasoli has observed that risk registers have become very "sexy and relevant" and are incredibly useful in identifying schedule tasks but also offers that one should evaluate the risk level and type of risk to understand its importance. This type of thinking is something he has implemented in the research and scientific area in addition to project management. On the aggressive schedule to start ITER operations in 2030-2035 timeframe, a lot of risks will be better understood at this commissioning stage. Sometimes the full machine has to be built to really understand these emergent behaviors although prototyping is also a large lever. Smaller tokamaks such as JET and TCV (Tokamak à configuration variable based in Switzerland) have acted as these more prototypical models as energy is increased in ITER. Dr. Snipes' highlighted the importance of "electro- and magnetic- field stability as well as soak through" but this won't be fully understood until the machine is operated in the regimes that could cause issues.

3.1.8 Randy Mckee

Randy Mckee interview summary

Organization: Sandia National Laboratory

Years of Experience: 35 years

Randy Mckee has over 35 years experience as an engineer in both the private industry sector and the R&D environment. During earlier parts of his career, he spent time at Rocketdyne, Caterpillar and Ktech Corporation in the semiconductor industry. He has substantial experience in the scientific R&D environment at Savannah River National Laboratory and Sandia National Laboratory, SNL. Throughout his career he has gained increasing experience in project management, has lead teams of up to 200 persons with more typical project scales closer to 50 engineers and budgets in the tens of millions dollars. At SNL he worked as a lead on the manufacturing engineering side of the ZR upgrade project. In addition to this, there were subsequent, smaller upgrades that were required in order to introduce plutonium for Z-machine experiments as well as more reliable gas switches in the triggering system. Although utilization of the classical PM tools such as EVM, MS Project schedules and requirement management are very useful, Mr. Mckee advocates for a graded approach, insisting that the rigor in which the project is managed is increasingly proportional to the scale (scope, budget and schedule). He is very sensitive to scope creep due to a lot of the low TRL projects he has worked on. Generally, on the smaller ($<$ \$1 million), scope creep can be accommodated, however when it comes to larger ones, it must be avoided. "PIs [Principal Investigators] want every opportunity to change things at the last minute" due to the fact that they often are learning as they go. His way of tackling this is to "freeze" the design or certain aspect of the project to force progress and get the team on the same page. A mechanism in which he finds useful to do this are reviews. Not only do they get the team presenting consistently but they also allow for the outside view and different perspectives to provide input. He also leverages a Change Control Board, CCB to ensure that changes are not taken lightly and that there are costs to deviations from the baseline. He cautions on the term "not to preclude" in any requirement as this can lead to defocused efforts and potentially a lack of direction and discipline. Three critical areas that Mr. Mckee highlighted during the discussion are requirements, risk management and concept development. Firstly, requirements are often an overlooked and more of a box to check in projects but done right, are the essential starting piece. At a minimum, he recommends interviews with the PI to generate needs and a useful method to drive flow down requirements incorporates conducting, and keeping relevant a Failure Modes

Effect and Analysis, FMEA table. Furthermore, the V&V approach needs to be incorporated. Secondly, in his experience, projects have failed without the running of a tight risk register and being strict in the management of these risks helps reduce the overall project risk. Finally, system engineering tools are used infrequently to identify and choose leading concepts and instead, in the R&D domain, expert engineers are relied upon to make decisions based on their experience base. An interesting insight gained from speaking with Mr. Mckee was that working on large scale R&D scientific projects is really on the "bloody edge of technology" and a lot of those bloody edge findings happen with last minute changes. This type of environment demands that engineering and operation organizations have to be amenable and dynamic to further progress technology.

3.1.9 John Weed

John Weed interview summary

Organization: Sandia National Laboratory

Years of Experience: 40 years (1980 start)

John Weed is a senior systems engineer at Sandia National Laboratory which is where he gained approximately 40 years' experience in the R&D environment. Initially working on thin film deposition and vacuum technologies, Mr. Weed developed into systems engineering full time in 2005. As one of two Project Manager deputies on ZR upgrade, the approximately $60 million project outlined in the previous chapter, he was responsible for all pulsed power components as well as leading the commissioning of the upgrade. The project was very hardware intensive, contributing to half of the costs and approximately 30 people worked over a six year period. Due to the estimated budget on a tight schedule, the DOE order 413.3 was enacted for the ZR upgrade project according to Mr. Weed. This increased the rigor in which Project Management tools were used. These included Earned Value Management, Critical Path and multiple decision points along the project timeline for external reviewers to assess progress. Mr. Weed credits the success of the ZR upgrade project

– which was reported to be on time and on budget – to be down to several key aspects. These include the clear and well defined requirements, the identification of risks areas early, prototyping a complete "arm" of the system and adding contingency into both the schedule and budget. For the latter, Mr. Weed commented that "in large advanced technology system development projects, if you do not have schedule and cost contingency built into your plan, you do not have a plan". Although the schedule incorporated both a standard Conceptual Design Review, CDR and Final Design Review, FDR an essential component of the risk mitigation was to prototype and build a first article, single module or arm of the upgraded machine. Even though the primary criteria flowed down a factor of two increase in the machine's current, the architecture of ZR was very similar to Z and it was thought that prototyping one arm of the machine would mitigate the majority of risk and that few emergent behaviors would result upon the 18-month installation and commissioning period. Once the 1st article demonstrated satisfaction of single arm requirements, this design would be copied to all thirty six arms of the machine. For the duration of the project, Mr. Weed praises the standard engineering approach through using V&V and emphasized that having the rationale (validation) and verification method are essential to success. A big takeaway is insisting upon contingency in planning an R&D project because zero contingency is equal to infinite risk. Having a high quality schedule is very important but not sufficient, it needs to be backed up with realism and contingency and the team must buy into it. In Mr. Weed's experience things never go as planned and so having a staff with substantial experience helps immensely due to the "experience of scars".

3.1.10 Dr. Rick Spielman

Dr. Rick Spielman interview summary

Organization: SNL, Z-machine & LLE

Years of Experience: 42 years

Since completing his PhD, Dr. Spielman has spent the majority of his 42 year career in the scientific R&D sector at national laboratories. Initially, he was a staff member at SNL, working on electron transport and pulsed power for fusion and weapons applications. He was responsible for building sub-systems for the Saturn accelerator, the largest pulsed power machine at the time and was a manager for a small team of four persons. Here, he gained expertise in x-ray diagnostics and z-pinch techniques. From beginning as a technical staff member he rose quickly to become a distinguished member of technical staff and was then selected as the Chief Scientist and Project Manager for the Z-machine project in 1993. The scope of the project was to upgrade the Particle Beam Fusion Accelerator (II), PFBA-II to the Z-machine with a budget of $25 million and a staff of 25 persons. This was a prior upgrade to the ZR project which was conducted later on (see previous chapter). The project had a timeline of 3 years and the Z-machine came online in September of 1996. Dr. Spielman credits the success to a number of things. "In a project, it's the beginning that defines success, you must have an explicit understanding of programmatic and technical expectations" meaning that as the project lead, he had to understand what time he had and what could be done. Demanding a clear set of roles and responsibilities and a clear understanding of the project scope were essential as well as the budget authority so that he was able to choose and change personnel. Dr. Spielman emphasized that in order to start off on the right foot, "roles and responsibilities, budget and deliverables are essential". His developed WBS provided the work packages with a simple reporting structure and he held only 45 minute weekly status meetings to allow the team to focus on the technical challenges. Although throughout the project he utilized traditional management tools he did say that "tools are no better than the people that use them" and the two best are "your brain and experience which matter most". Moreover, he thinks that there is no substitute for experience and most people's real learning is by making mistakes. He was able to leverage a lot of his knowledge base from previous projects including the Saturn accelerator to mitigate risk and prototyped parts when he deemed the risk to be high. In pulsed power systems "failures scale with voltage" and it depends on the TRLs on whether one should adopt a phased approach.

The team, under his leadership, completed the requirements very quickly due to the well-defined scope and he tried to think of the system holistically considering the minimum amount of effort required in each puzzle piece (sub-system) to be successful. The organizational structure was kept fairly flat, having leads for each work package and he insisted on having dedicated staff to manage and track procurements. Dr. Spielman assessed the engineering TRLs to be high, around 7/8 whereas the pulsed power at the 3 to 4 level, so that's where more effort was concentrated. He made sure that the major problems were understood and the more challenging systems were built with the best understanding at the time. For the project review format, Dr. Spielman had both a CDR and FDR for Z upgrade. In his opinion, the value of these reviews is to force the project lead to solidify his/her thoughts and in particular for the CDR, it helped him by getting the team on one page. However, on smaller projects, these reviews have provided nothing of value to Dr. Spielman and he has seen attempts to institute the same rigor regardless of scope and scale which is not a good use of time and resources. Due to the success of the Z-machine project, both in performance and delivering on time, Dr. Spielman was offered the same position for the ZR project. However, he declined due to not having the complete budget and personnel authority. He finished as the manager of the Z machine in 2001.

3.1.11 Dr. Jeffrey Paisner

Dr. Jeffrey Paisner interview summary
Organization: LLNL, NIF (Currently at LANL)
Years of Experience: 46 years

Dr. Paisner joined LLNL in 1974 after graduating from Stanford University with a PhD in Physics. Throughout his career he was heavily involved with laser technology initially researching novel materials for high powered lasers. From 1975 to 1991, he worked on the Atomic Vapor Laser Isotope Separation (AVLIS) project and developed the classified patents on isotope separation with lasers. The AVLIS system enriches Uranium by using finely tuned laser light to extract the fissile isotope, Uranium-235 from natural or depleted Uranium. Dr. Paisner credits this project – where he eventually managed a \$100 million budget and 200 people – as "cutting my teeth" working with multidisciplinary teams and top notch engineering staff. He quickly rose to become the Associate, and then the Deputy Program Leader for the project where he was responsible for all of the technology. In 1992, Dr. Paisner was pulled off of the AVLIS project to start the Inertial Confinement Fusion project, the NIF. In the early days of the project, he was responsible for the laser system clusters and bundles. By the time of the CD0 DOE milestone in January 1993, Dr. Paisner had become the Deputy Director of the NIF and months later, the Project Manager. As the Chief Architect, he was responsible for a \$600 million yearly budget and would remain as the leader until 1999. The primary criteria (previous chapter) did not specify the number of beams but rather to total required energy and frequency: 1.8 MJ of 3 omega light with a power balance on each beam. According to Dr. Paisner, the original NIF baseline design had 240 beams but later on, two conceptual designs were developed to the point that all drawings were made. The second concept architecture of 192 beams eventually won out due to some infeasibilities with the larger number of beams. With cutting edge technology sometimes decisions are made as "Nature puts a limit on what you do". He mentioned numerous times, that he credits the success of NIF to its architecture. In order to solve the big problems, he thinks it is essential to develop the right architecture and then you are left with solving the right problems. "You need to ensure that the physics and engineering go hand-in-hand" and one of the major strengths to do this is the architecture. Coupling this with the right, self-motivated staff will ensure you succeed. According to Dr. Paisner, a project like the NIF is not a 9 to 5 activity, where you really have to work 24/7 constantly thinking about strategy and you must have people that drive it. In addition to a strong team and architecture, Dr. Paisner credits the well-disciplined use of some key system engineering and project management tools to aid in the building of a facility as large as the NIF. "There was enormous pressure to keep costs down" and utilizing a well-thought out WBS was crucial in understanding the necessary tasks that had to be completed. Furthermore, there was continuous cost optimization, many reviews and a very formal threat list (risk list) was developed and monitored. He also mentioned that it is very hard to estimate costs in R&D domain, especially with low TRLs and developing an activity based, logically linked, resource loaded schedule helps the manager understand this better with every activity costed in a schedule. Specifically on the NIF project, the risk mitigation for tackling the lower TRLs was to “prototype everything”. For example, between 1994 and 1997 a single beamline prototype system called Beamlet was in operation and demonstrated many of the techniques required for the NIF laser. Demonstrators like this are essential in any good R&D project to reduce risk and increase TRLs.

He commented that the NIF Project utilized a top down build approach with the high level Primary Criteria identified early and the work packages generated from the sub-systems needed to meet the flow-down requirements. He employed a configuration management system early on in the project and had 15 system engineers that were responsible for the system requirements which took up two bookshelves. There were big advantages from lessons learned from other facilities that gave insight into both what some requirements had to be and how to meet them. For example, alignment systems techniques were learned from accelerators (CG changes from Earth’s magnetic field had to be considered in tolerances) and laser amplification technologies from earlier laser systems. Dr. Paisner insists that one has to understand all interfaces and requirements before the design although good engineering staff realized that we don’t have all the answers upfront in R&D projects. A typical pitfall of more junior engineers is to try to design immediately where experience helps ask the right questions first and develop the real needs before wasting time building something no one wants.

The NIF building design was sub-contracted out and tight tolerances drove up the cost. Oftentimes in projects, the method of accomplishment can change cost by large numbers and so putting large uncertainty on things helps accommodate this. One of the early decision’s Dr. Paisner had to make as project lead was regarding the Transport Spatial Filters. Due to costs and fast tracking the building, a back of the envelope decision was made to cut them down to 65 meters from 80 meters. Although there were frequent cost challenges, he was an advocate of modularity in the laser system design, insisting for kinematic placement of assemblies so they could be exchanged more easily as well as developing a line-replaceable-unit (LRU) approach to the optical systems. As well as modularity aspects to the design, there are often times when design choices preclude certain future operations or upgrades and when designing the NIF Target Chamber, special thought was considered as to not preclude future diagnostics. In addition to the penetrations for the 192 laser beam entry points, the Target Chamber incorporated many ports, as shown in figure 3-3, to allow for the maximum amount of future utilization. To this day, the Target Chamber can still support upgrades for new diagnostics.

Figure 3-3: NIF Target Chamber internal view and installation [110][115]

When asked about the laser technology progression at LLNL, Dr. Paisner referred to a time when he "Spent Christmas with NOVA". NOVA was the preeminent laser facility at LLNL, capable of delivering a total energy of 30 kJ with its 10 beams. Before the NIF project, there were plans to perform a NOVA upgrade to increase its total energy into the megajoule magnitude. The main, three high level goals from the National Academy of Sciences at the time included this NOVA upgrade. However, Dr. Paisner recalls a period over Christmas in 1992 when he analyzed the proposed upgrade plans and deemed them to be shortsighted with insufficient spatial considerations for the laser architecture needed to get to the megajoule level. He was responsible for writing the memorandum that turned off the NOVA upgrade and sparked the beginnings of work on the NIF technologies.

3.1.12 Dr. Mike Campbell

Dr. Mike Campbell interview summary

Organization: LLNL & LLE

Years of Experience: 40 years

Dr. Mike Campbell has been leading the LLE organization as Director since 2017. With around 40 years of experience, the majority of which in the R&D laboratory environment, Dr. Campbell has a unique perspective on fusion science. After the initial part of his career at LLNL, Dr. Campbell has had experiences in the private sector, running the nuclear programs at General Atomics in San Diego and also spending time with a small startup company. For the latter he provided an analogy to his R&D experiences as "landing the plane and building the runaway at the same time". In addition, he worked on pulse power systems at SNL and finally accepted a position in his current role at LLE.

Starting as a staff scientist at LLNL, Dr. Campbell immediately started work with indirect drive fusion experiments beginning on the Argus laser, a demonstration system to prove out the scalability of neodymium glass fusion lasers. He also was given the principal milestone for delivering the Shiva laser – a follow-on 10 kJ, Infrared ICF laser system - which was successfully completed under his leadership. He continued to advance at LLNL, becoming heads of firstly the Advanced Lasers Division, then the ICF program and up to the Associate Director of the laboratory. An advocate for diversity in teams, Dr. Campbell was the first at LLNL to bring foreign national (non-US citizens) scientists to LLNL. He also became involved in, not only single projects, but the ICF program builds working with both DOD and DOE. When Dr. Campbell first arrived, lasers and the national weapons program were separate and his vision was to encourage the collaboration of disciplines and fund laser projects through weapons in addition to, at the time, current streams. In order to do so, he mentioned that he had to build a network and constituency a lot bigger than just himself or the laboratory. He had a vision and saw there were more opportunities to do things and it was necessary to build the advocates to get it done. After the Cold War, however, not many people wanted to work on weapons. Dr. Campbell was part of the cohort that convinced the right leaning politicians that NIF was needed for nuclear weapons tests and the left for "dealing with the bad guys". Establishing trust with DOE Headquarters staff was essential to project success and his advice is that the sponsor must be treated as a partner, not a customer. Furthermore, keep stakeholders and committee members informed of your technical progress, one has to be transparent and "don't oversell a project". Dr. Campbell highlighted three important aspects for the program (and project) ramp up:

1. Get the constituency together
2. Turn opposition into advocates
3. Build up the infrastructure (supply chain set up for huge projects is complex)

He sees the whole ICF program, from early laser systems to the NIF, as a phased approach that is required to push the bounds of physics and technology. For example, if the same technologies were used as on NOVA, the cost per Joule (with inflation) extrapolated is $25 Billion for NIF which would be an unacceptable cost. Beamlet played a big part in this and was an essential prototype to reduce NIF TRL risks, developing the required technologies further. In turn, he sees the NIF as an intermediate machine and part of the roadmap to get to giga-joules worth of emitted neutron energies. He emphasized that "higher convergence and lower adiabat is needed to get to ignition" and the three potential solutions to do this are with bigger lasers, improvements in target quality such as making better hohlraums and capsules, and potentially utilizing one of the NIF project's "not to precludes" of changing the laser configuration to Direct Drive. He also thinks we "need to get the quality of energy right not just the quantity", essentially the efficiency, which when looking at NIF developments over recent years can be seen as improving over time.

A common theme with R&D project planning is adding contingency which Dr. Campbell concurs with stating that "if you try and do things for the first time you need to add more contingency". However, one has to appreciate the evolutionary aspects to a project and not add so much contingency that it never gets off the ground. Moreover, Dr. Campbell mentioned many important lessons learned from the "100x campaign" of increasing energy of laser systems from Janus (100J) to Shiva (10kJ). There was too much reliance on numerical modeling and simulations with not enough physics testing being conducted in the regimes of interest. He thought theoretical physics staff were overconfident in the simulations and there was not enough peer review. The project leadership missed a key expertise element that would complement the facility experts and design physicists, this was an experimental physicist leader: "Experimentalists bring reality and you need both design and experimentalist physicists to strike a balance". In addition, diagnostics were also not adequate, this technology fell behind and perhaps a more parallel approach was required. Similarly, these mistakes were repeated again for the NIF project, with no experimental physicist leadership and an inadequate planned diagnostic suite. There was also additional learning in the NIF on how to operate a very complex machine, which took longer than expected. In summary, from Dr. Campbell's experience in the ICF program, modeling, theory and experimental expertise are all necessary components in a successful program.

3.1.13 Ray Scarpetti

Ray Scarpetti interview summary

Organization: LLNL & LANL

Years of Experience: 42 years

With a background in Nuclear Engineering, Electronics and Systems Engineering, Mr. Scarpetti joined LLNL in 1978 and started work on weapons testing systems, laser facilities such as Shiva and Nova and then isotope separation technology in AVLIS. Before he left LLNL, he had gained extensive experience in pulsed power, electric lighting systems (fuses) in weapons and project management. In 2002, Mr. Sarpetti joined Los Alamos National Laboratory, LANL in Albuquerque where he became the Group Leader for the Dual-Axis Radiographic Hydrodynamic Test, DARHT facility. Presently consisting of two large x-ray machines that image imploding materials, the DARHT facility is a high energy, short pulse system that aids scientists in the understanding of weapon detonation ensuring that the nation's stockpile is safe and effective. Initially, Mr. Scarpetti was a reviewer for the DARHT-1, the first radiography axis and then became the Project Manager for the upgrade, a second axis, DARHT-2. During this project, Mr. Scarpetti ran a budget of approximately $90 million with between 200-250 FTEs and a schedule of 5 years from 2003 to the delivery of the system at the end of May 2008. All the requirements and goals of the project were either met or exceeded. Shortly afterwards, Mr. Scarpetti retired in 2010 and now works as a consultant reviewing projects for NNSA.

When discussing the DARHT-2 project upgrade, Mr. Scarpetti highlighted some lessons learned from the experience. "You should never down play the risks" - which was done initially for the project - as the budget will not be set properly and you will end up having to cut corners. He also mentioned that the original DARHT-1 project had to water down requirements such as peak voltage from 20 MV to 12 MV due to external "forcers" such as cost. In comparison, there were different challenges with the DARHT-2 project including poor documentation and existing constraints that couldn't be changed, "in some respects it is harder to upgrade than a clean sheet of paper". He compared this upgrade to remodeling a house and found the lack of as-built drawings of the existing system a major challenge. Due to money restraints, in-situ field fits and revisions for DARHT-1 components were not truly catalogued. In Mr. Scarpetti's R&D domain experience, one will never have a complete set of prints so you must appreciate that before you go in to an upgrade project. Related to this, one should be completely honest with the sponsor, when you have a problem be transparent and don't hide it. In his Project Director role for the DARHT-2 project, Mr. Scarpetti was not only responsible for personnel and budget but also all the risk management and took the teamwork development very seriously saying "the hardest problems you find are sociological". His advice to leaders is that you should understand the competency and motivation of your team members to ensure you get the best out of them and put them in a position to effectively contribute to the team.

He also advocates for situational leadership where one has to tailor their style to fit the team dynamic and in terms of the team members, “you really work for them” and have to give them tools and environment to get the job done. In addition to the external sponsor, Mr. Scarpetti thinks it is essential to be transparent internally to your team. “You must own your mistakes, if you mess up, say it” and be honest with your management to avoid bigger project delays, “never delay bad news”. Another important aspect of PM that he highlighted is risk management stating “projects are all about risk management”. For DARHT-2, he was very disciplined in managing the risk register and thinks it’s not only key to identifying risks but also stating how you are going to manage them. “You need a living document with low/medium/high risk characterization” and knowing that these will grow during the project lifecycle, then peak and then reduce. A crucial risk mitigation that Mr. Scarpetti employed on DARHT-2 was prototyping, in particular to understand reliability of the 68 high current cells which would make up the DARHT-2 beamline. By offline testing six different, 2 meter long cells on over 200,000 shots, the team were able to qualify a leading candidate and ensure that reliability was beyond satisfactory. Furthermore, there was a ramp up plan to get to the high current required for DARHT-2, starting at lower energies and slowly increasing helped assess the system stability and identified any shortcomings.

3.2 Key learnings and themes

From the interviews conducted and summarized in this chapter, some common themes that apply to project successes and failures become apparent. Among these are the obvious, classical tools project leaders employ to effectively manage and guide interdisciplinary teams in addition to more subtle techniques. What is quite interesting is that regardless of project size (in terms of scope and budget) the same tools are applied but with different levels of rigor. Figure 3-4 provides some of the key elements that resonated through both literature research and discussions with technical staff leaders. Quoting Dr. Spielman "it’s the beginnings that define the success", many of the interviewees emphasized the importance of getting the right primary criteria and requirements from stakeholders. Dr. Campbell, although talking specifically to higher-level programs, in the same manner advocates for involvement and communication with the broader community and stakeholders. Furthermore, many of the project leaders emphasized transparency, especially when working with external funding entities as it helps develop both trust and allows them to be part of the solution. Also, one should appreciate that stakeholder needs will evolve over time and understanding that the "customer is always wrong", meaning that they may know what they want but don't necessarily know what they really need. This is amplified in the scientific, R&D domain. Constant communication is required even once interviews and discussions have been conducted and the initial NGOs are realized. From my own experience leading R&D projects at LLNL, often times more junior staff want to act fast with good intentions to get into the design space and provide solutions to a problem when they are not really sure of what is actually required. Although it is good practice to develop requirements and concepts in a parallel strategy, for more complex sub-systems, a lot of time must be spent understanding the constraints before one can fully enter the design space. For instance, drawing from the MagNIF experiences - a project covered in detail later - design choices were made quickly in the initial phases with a poor understanding of requirements and the design ultimately failed and had to be upgraded multiple times. These lessons learned were applied effectively to the final phase of the project which is discussed further in Chapter 5.

From figure 3-4, a credible schedule is another obvious enabler for project success and is captured under classical tools. It is a very useful instrument but more often than not is a check box rather than a effectively, resource loaded timeline. On quite a few of the projects reviewed, there were a number of occasions where the end of the project was defined as commissioning with little foresight into the adoption time that the operations staff will need. This is a common trend, especially in implementation of upgrades into an existing facility such as the NIF amongst others. Once a capability is deployed there has to be a large scheduled window to bring the system "fully" online. Even though typically not intrinsically linked to the schedule, diagnostics made the

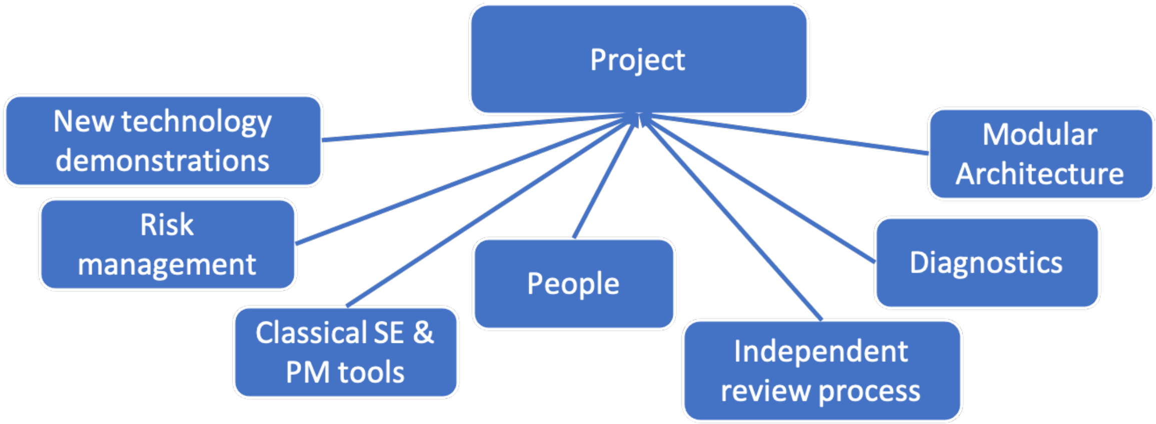


Figure 3-4: Essential elements to success in large scientific R&D facility projects

list of the essential project elements. This is due in part to the ICF machines (Omega, NIF and LMJ) - but also found in many of the other project leadership experiences - that have shown the need for diagnostics but are often an afterthought. However, as nothing ever goes as planned in scientific research, anticipation of what could go wrong or needs further inspection could add to the likelihood of success. In addition, diagnostics are key in validating and improving any models or simulations. When NIF came online in 2009, there was inadequate thought for the diagnostic suite needed to assess implosion symmetry and high resolution x-ray imaging. As a result, to this day the NIF engineering team are still avidly designing and fielding new diagnostics to support experiments.

Stressed by Dr. Paisner and acknowledged by most is the importance of selecting the right architecture that meets the requirements and outweighs all others under the iron triangle constraints. What was noticeable in the conversations was the lack of quantitative analysis regarding this. However, Mr. Mosier talked in detail about the process at GSFC (Goddard Space Flight Center) and its effectiveness with choosing the right path forward. Furthermore, as part of the LLNL magnetic booster case study which is described in Chapter 5, a quantitative approach of scoring concepts was taken and the recommendation to follow a similar framework for assessing concepts is given in Chapter 6.

Another input branch into a successful project, is people. Although important, it is not merely a matter of staffing appropriately but a large experience base is advantageous in addition to a diverse team. However simple it may seem, it is necessary to ensure all disciplines are represented, especially at the project leadership level. In the discussion with Dr. Campbell he cited this as a big error in the ICF program at the NIF and earlier laser facilities that lacked from the balance of having an experimental physics leadership role. This has since been rectified. Collaborations are also an effective way of knowledge transfer and expediting research efforts such as the tactic CERN is employing for its upgraded superconducting magnets development. Also, discussions with many of the project leaders highlighted the need to generate and review lessons learned in order to avoid previous mistakes. Perhaps not a formal review is required but it behooves us to understand the mistakes of similar projects and what worked well.

Perhaps considered as part of a classical system engineering process, all of the interviewees saw the merit of technical and project reviews with a graded approach methodology. Internal benefits included aligning and adding consistency within the team and getting new perspectives and critique, whereas the external facing benefits include the transparency with sponsors and the communication with stakeholders. At LLNL, a convenient byproduct of creating the NIF, the Integrated Product Review Board, IPRB process has been the established systems engineering guideline for many years. The process utilizes a chairperson for reviews as well as, through a checklist, selects the right reviewers and level of review rigor. This is an incredibly useful tool to guide all levels of experience through the various stages of a project lifecycle. In addition to formal reviews, it is good practice to conduct more everyday peer reviews, as simple as one-on-one meetings to validate calculations with analytical or empirical methods.

Having a modular architecture was mentioned by many of the interviewees and especially with R&D projects, it is key in allowing for future expansions and upgrades. The ability to swap out modules such as LRUs for inspection, repair and maintenance seems essential and was seen in both the NIF and CERN. Furthermore, this type of architecture also benefits the ongoing operations phase of a project even if the baseline design doesn't need to be changed. For the NIF, this modularity is still paying dividends, not only in allowing the facility to operate 24/7 but also in increasing laser power with higher quality optics and the adaptability of disruptive technologies like the MagNIF system.

The last two project success elements that are closely linked are risk management and new technology demonstrations. One may consider that the latter is really part of the former but it was brought up so many times in conversations it warranted its own, separate element. In order to validate models and get an expedited look at potential issues, demonstrators or prototypes can be greatly advantageous especially with the lower TRLs. The system engineer should identify these lower TRLs early in the process to understand the allocation of resources in the risk mitigation strategy. For many of the projects discussed, demonstrations have taken a variety of scales. For NIF and SNL one module or beamline provided the vetting of the architecture as well as making improvements to a more sizable system so that the TRL was increased. Omega, LMJ and the LHC at CERN have adopted a more staged approach, implementing upgrades at shutdown intervals and continuing the running of experiments between these periods. JWST has thoroughly utilized first article testing to mitigate a lot of sub-system emergent behaviors and hone critical designs such as the unfolding mirror assembly that has to work first time. One regret on the JWST project is to have canceled the Nexus small scale on-orbit demonstration project, which might have helped contain project cost overruns by avoiding unnecessary redesigns. Most of the project leaders credit success to a thorough assessment and development of a risk register and a disciplined CCB style management of it. FMEAs are also a tool that can be leveraged to great effect in the R&D environment. Linked to the management of risks, there also has to be a disciplined approach to requirements and interfaces ensuring that the consequences are understood with scope creep or interface changes and managers have to follow a formal process.

Finally, an element not highlighted in figure 3-4 but that certainly is evident from project leader interviews and the following chapter, is the future project vision. One needs to look ahead at what is next whilst working on the project at hand, because if you wait, it will be too late. This was particularly noticeable in conversations with Dr. Bordry and Dr. Fasoli with their respective visions for LHC upgrades and the future of fusion power in Europe.

Chapter 4

Laser Confined Nuclear Fusion Technology Roadmap

4.1 Roadmap Overview

Facilities that utilize the main two types of Nuclear Fusion, Magnetically and Inertially confined, have been discussed in Chapter 2. These mega-machines are designed to fuse hydrogen isotopes together to produce helium and neutrons. This chapter takes a closer look at the second type of potential future power generation, which is Inertial Confinement Fusion, ICF using lasers to drive the reaction (Laser Confined Nuclear Fusion). In order to assess the viability for fusion to become the next major power generation source, a technology roadmap can be developed that will help understand progress and future developments in this exciting field. This roadmap not only sets goals for the LCNF technology but also a credible, projected path in which to reach them. Furthermore, Figures of Merit, FOMs and demonstrator projects are identified, a patent research conducted and both technical and financial models are developed to add fidelity to the roadmap.

4.2 Dependency Structure Matrix, DSM & Roadmap model

At the top level 1 we place nuclear fusion as a future class of carbon-free energy generation technologies. In order to understand the connectivity of the level 2 technology, Laser Confined Nuclear Fusion, LCNF, a Design Structure Matrix, DSM and technology tree were created and are shown in figure 4-1. Level 1 represents the Fusion power technology and decomposes in the two possible methods highlighted above.

		1FUS	2LCNF	3LAS	3TAR	3DIA	3CTP	3CHB	4LCF	4OPT	4SIM	4CPT	4POS	4PRE	4EMG
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1FUS	1	1													
2LCNF	2		2	1	1	1	1	1							
3LAS	3		1	3					1	1					
3TAR	4		1		4						1				
3DIA	5		1			5						1			
3CTP	6		1				6						1	1	
3CHB	7		1					7							1
4LCF	8			1					8						
4OPT	9			1						9					
4SIM	10				1						10				
4CPT	11					1						11			
4POS	12						1						12		
4PRE	13						1							13	
4EMG	14							1							14

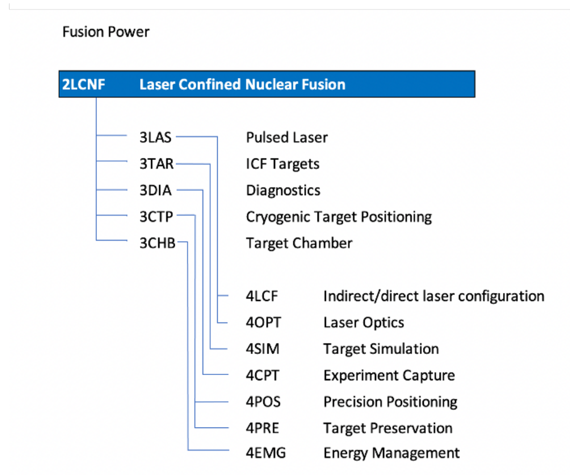


Figure 4-1: LCNF DSM and technology tree

The 2LCNF tree shows us that Laser Confined Nuclear Fusion is part of a larger global Nuclear Fusion Power initiative to harness fusion power. The DSM and tree both show that 2LCNF requires the following technologies at the subsystem level 3: 3LAS Laser, 3TAR ICF Targets, 3DIA Diagnostics, 3CTP Cryogenic Target Positioning, and 3CHB Target Chamber. Each level 3 subsystem also requires enabling technologies shown as level 4 systems in figure 4-1. Each branch in the technology roadmap tree is identified by a unique three or four-letter code or ID number, e.g. 4OPT. This is done so that technologies and their associated roadmaps can be uniquely stored and identified, thus avoiding confusion between similar and yet distinct technologies.

Breaking down the LCNF with an Object-Process Methodology, figure 4-2 shows the high-level OPD (Object-Process Diagram). Highlighted are the essential processes and forms required for the technology. The fuel, Deuterium and Tritium (D-T) is injected by a filling system, is frozen and "layered" with the cryostat and contained inside a target capsule that is in an evacuated environment. Utilizing the laser drive, the fuel is fused and the products can be seen in the figure. In order to capture energy from the fusion process, a liquid bath surrounding the target chamber could be used and interacts with the neutrons, creating heat for steam generation and thus electricity production. Captured on the right hand side of the figures are four Figures of Merit, FOM, that are used to assess and benchmark the technology. These are covered in detail in the next section.

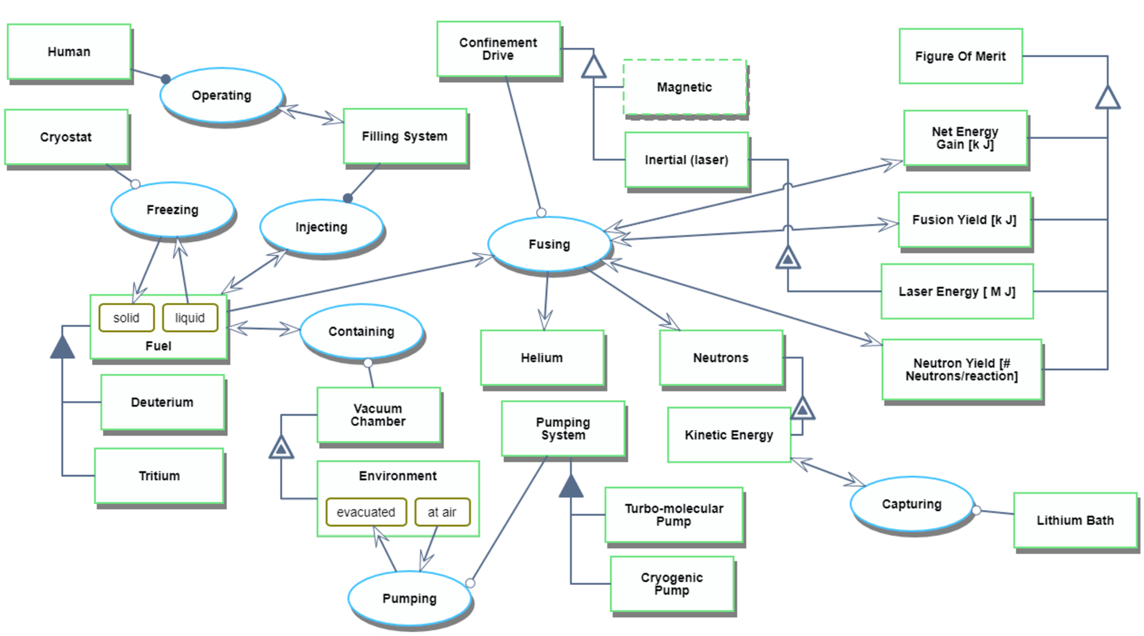


Figure 4-2: OPM System Diagram of Laser Confined Nuclear Fusion technology

4.3 Figures of Merit

From research conducted in the LCNF technology field, Figures of Merit were generated and are shown in table 4.1.

A major update to the key Figures of Merit, FOMs from the OPD is the removal of

Table 4.1: Figures of Merit, FOMs for Laser Confined Nuclear Fusion

ID	FOM	Units	Description
1	**Fusion yield**	**[kJ]**	Yielded energy from the fusion reaction
2	**Neutron Yield**	**[# of neutrons/reaction]**	Number of neutrons produced from a fusion experiment
3	**Implosion velocity**	**km/s**	Rate at which the capsule implodes from x-ray compression
4	**Laser Energy**	**[MJ]**	Energy that the laser system can deliver to the target
5	**ITFX (Experimental Ignition Threshold Factor)**	**[#]**	A measure of proximity to "ignition" (net energy gain)
6	Number of Reactions	[#/day]	Number of Fusion reactions produced each day
7	Cost	[$/reaction]	Total cost for each reaction
8	Capital from other sources	[$]	Funds provided for customer experimental time on the Fusion machine
9	Waste by-products	[kg/reaction]	Amount of radioactive and disposable waste produced from each reaction
10	Fuel mass required	[kg/reaction]	The amount of D-T fuel required for each reaction

the Net Energy Gain (KJ) and the addition of the implosion velocity (km/s). It was decided that the former is not completely relevant for the state-of-the-art technology and can be derived from a combination of the Fusion yield, Laser energy and inefficiencies. This becomes a key FOM once the Laser Based Nuclear Fusion technology reaches ignition (more energy out than in) and beyond. Researching the literature more, it becomes apparent that the implosion velocity is really a more appropriate, key FOM. In addition, the ITFX, Experimental Ignition Threshold Factor has been added. This provides a metric of how close an experiment or system is believed to be to ignition, expressed as a fraction.

It is important to understand the inputs, outputs and related equations from research into Laser Confined Nuclear Fusion to aid in the building of the roadmap technical model. The equations for implosion velocity and ITFX [78] are shown below:

$$v_{imp} = (\frac{r_{cap}}{r_{hohl}})(\frac{E_{laser}}{m_{cap}})^{0.5} \quad Eqn1$$

Implosion velocity leverages the radius of both the capsule and Hohlraum as well as laser energy and capsule mass.

$$ITFX = [(\frac{DSR}{0.071})^{2.1}(\frac{Y_{13-15}}{4e15})(\frac{170}{m_f})] \quad Eqn2$$

The ITFX metric relies upon empirical values for Down Scatter Ratio, DSR, neutron yield and D-T (Deuterium-Tritium) fuel mass. The DSR is a ratio of certain energy neutrons produced from a fusion reaction.

The relationship table relating the FOMs and equations is shown below.

Table 4.2: Relationships for Laser Confined Nuclear Fusion FOMs

Inputs	Key Relationships/Equations	Outputs
Laser Energy *Capsule diameter* *Hohlraum diameter* *Capsule material*	$v_{imp} \sim \left(\frac{r_{cap}}{r_{hohl}}\right)\left(\frac{E_{laser}}{m_{cap}}\right)^{0.5}$	**Implosion Velocity**
		Cost
	Simulations – Experiments	**Fusion energy and Neutron yield**
Neutron yield	$ITFX = \left[\left(\frac{DSR}{0.071}\right)^{2.1}\left(\frac{Y_{13-15}}{4e15}\right)\left(\frac{170}{m_f}\right)\right]$	**ITFX (Experimental Ignition Threshold Factor)**
Fuel mass required		

Relevant Figure of Merit: Fusion yield [kJ]

Figure 4-3 shows the increase in Fusion yield (kilojoules, kJ) on the NIF by varying different laser and target parameters over time. The energy yield trend is increasing over time however, it does have a theoretical limit. This limit is related to the amount (mass) of the reactants and therefore also the laser drive energy and capsule materials. As the reduction in mass releases energy (based on Einstein's special relativity equation), the greater the mass, the more energy. However, at a certain point the laser energy required becomes too great than is achievable with optics and amplification technology. In addition, the material of the capsule that holds the D-T fuel will not be able to withstand the pressures involved with increasing the laser energy.

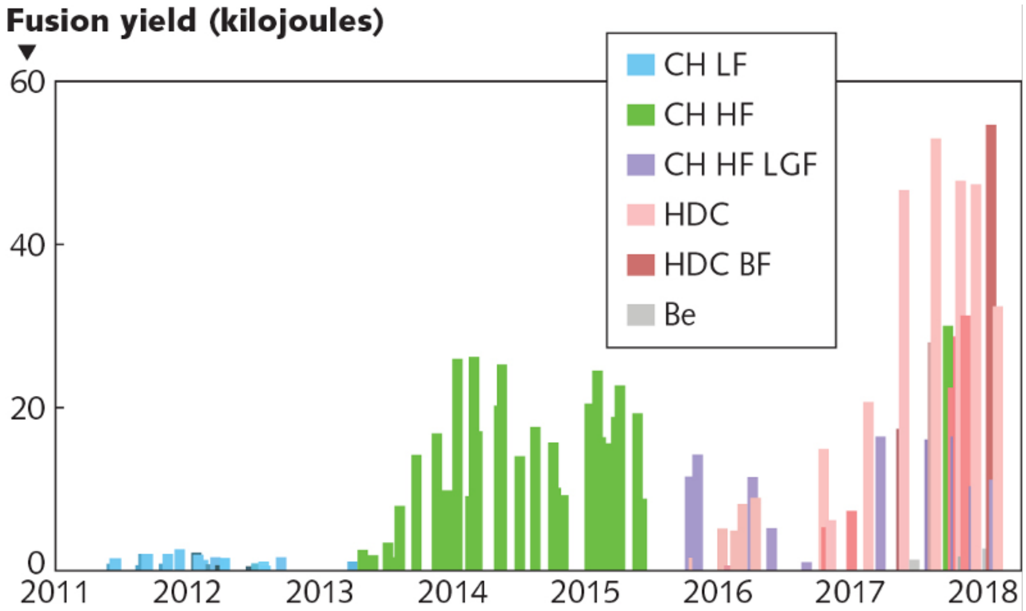


Figure 4-3: National Ignition Facility, NIF Fusion yield over time [44]

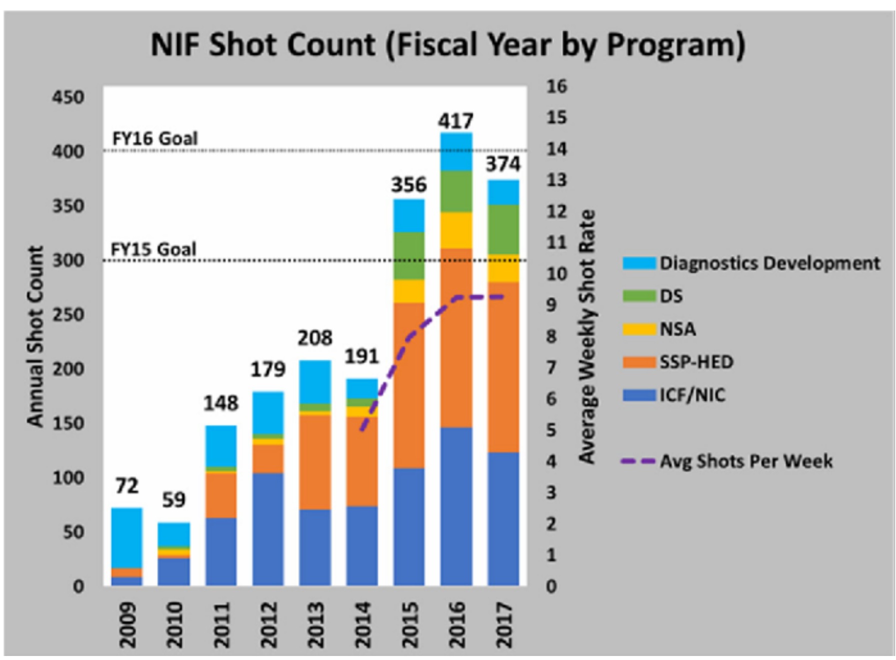


Figure 4-4: National Ignition Facility (NIF) annual target shot count [56]

The Fusion Yield FOM is a quality measurement implying an efficiency of a LCNF experiment. Figure 4-4 captures the annual shot (experiment) count for the NIF from 2009 through part way of 2017 and shows the increasing trend as the facility increases throughput and capability. This quantity measurement of the technology is also in table 4.1 as the number of reactions per day.

4.4 Alignment with Strategic Drivers

Taking the perspective as a government contractor that is looking to improve near term efficiencies and gains in Laser Confined Nuclear Fusion as well as develop the next generation world-class laser facility, strategic drivers with targets can be generated. This will not only aid in further development of harnessing fusion as an alternative renewable energy source but also allow for a suite of improved quality experiments for stockpile stewardship. Table 4.3 shows the three main strategic drivers and the necessary alignment of the 2LCNF technology roadmap with them.

These three drivers capture the near, medium and long term goals for the LCNF technology. Initially, leveraging existing facilities such as NIF, smaller gains and prototype developments can be made to understand further the tuning parameters to maximize neutron yield. These include some of the improvements listed in a subsequent section - Demonstrator Projects – such as Target and Optics improvements along with a disruptive technology. Similar to what EuroFusion are planning to phase in with ITER and DEMO, the LCNF technology should plan to apply learnings from the NIF to a 10 MJ laser energy, power plant adaptable facility. From this proof of ignition, the first of its kind LCNF power plant can be conceived, developed and built.

4.5 Positioning and Competitive Analysis

As mentioned earlier, Laser Confined Nuclear Fusion (LCNF) and Magnetic Confined Fusion are primary branches of nuclear fusion research. In LCNF devices, high-powered, high-energy laser systems are used to drive the fusion reactions are typically

Table 4.3: LCNF Strategic drivers

ID	Strategic Driver	Alignment & Targets
1	To further utilize a state-of-the-art facility to understand the necessary conditions for ignition and baseline a conceptual system architecture, budget and timeline for an upgraded fusion facility by 2025.	This 2LCNF Technology Roadmap is targeting a neutron yield of greater than 2e17 with lower < 425 km/s implosion velocities.
2	To design and develop a Laser Confined Nuclear Fusion facility capable of delivering the laser energy and temporal pulse shapes to produce approximately 100x energy gain by 2045.	For this new facility, the targeted FOMs will be at least 10 MJ of laser energy and an ITFX (Ignition threshold) of > 1
3	Provide initial estimates of a fusion power plant design to be implemented to produce power in 2060.	This will require similar targets in FOMs as #2 but with the added Reactions/second target of 10. The conceptual design review aim is for 2040 with more finalized reviews after the 2045 ignition milestone.

Note: This is the opinion of the author in the context of this thesis work and not the official LLNL/NIF timeline

so costly to design, build, and maintain that LCNF devices are typically government funded ventures. The three most prominent devices/facilities are NIF, LMJ, and SG-III. SG-III, consisting of only a fraction of the beam lines and energy delivery capabilities of its two competitors, was designed to study fusion parameters, not to achieve net fusion gain. Therefore, in this technology-intensive proto-market, NIF and LMJ can be considered a competitive duopoly as the only two facilities capable of performing experiments with the possibility of achieving ignition.

As a duopoly, both NIF and LMJ exhibit monopoly elements as the only firms with the ability to conduct both High-Energy Density (HED, typical for national nuclear security development) and fusion experiments. Each offer a unique product in terms of the parameters of the experiments such as laser power, temporal pulse shape, diagnostics, and target design resources. They are unique in that they are run by two governments, each with a contingent of loyal facility users in the queue hoping to verify their physics models. NIF and LMJ appear to be exhibiting behavior consistent with both the Cournot's Model and the Bertrand's Model [28], as firms that definitely respond to each other's moves (Bertrand model) but not likely to reach a Nash Equilibrium due to the lack of predictable best response functions. This industry is in its infancy in terms of demonstrating fusion viability and focuses mainly on exploring alternative methods of creating a fusion environment rather than solely focusing on responding to competing partner "moves".

Table 4.4: NIF and LMJ Facilities at a glance

	National Ignition Facility	**Laser Megajoule**
Location	U.S.	France
Construction costs	~$3.5B USD	~$3B USD
Construction completed	Yes	No
Year operational	2009	2014
Indirect or Direct Drive	Potential for both	Potential for both
Fast Ignition Capable	No	Yes
Shock Ignition Capable	No	Yes
Magnetically assisted	Yes	No
Shots per year	500 - 600	50
Primary laser energy (as designed)	1.8 MJ	was 1.0 MJ, now 1.8 MJ
Primary laser energy achieved	2 MJ	Unknown
Secondary laser energy (as designed)	None	I KJ
Secondary laser power	None	1.2 Petawatt
Neutron Yield	1.90E+16	Unreported
Fusion Energy Output	54 KJ	Unreported
Beam lines fielded	192	176
Beam lines when fully constructed	192	240

Although NIF and LMJ do not seemingly engage in sequential game play, they do appear to actively respond to each other's achievements or advancements with initiatives of their own. When LMJ was first announced, the system was designed to reach 1MJ (starting point B-LMJ shown in Figure 4-5). After NIF attained their energy goal of 1.8MJ (A-NIF in Figure 4-5) but did not reach their neutron yield expectations, LMJ increased their energy goal to 1.5MJ (B1 point shown in Figure 4-5). NIF then pushed the boundaries of their laser driver up to the optics damage threshold to produce 2.2 MJ. LMJ likely realized that for them to be seen by their supporters as a leader in this industry, they announced that their design goals are now 1.8MJ (B2 point in Figure 4-5) [78] [67] [22].

LMJ then announced the addition of a Petawatt laser to supplement the laser driver that positions them to attain the B2 point which would dominate the A-NIF point (current NIF position). In response to LMJ's secondary laser, NIF is exploring two strategy options:

- A1- Longer term venture of improving target design inefficiencies (introducing magnetically assisted devices) to raise neutron yield while understanding that the laser driver can only produce so much energy before optics damage is cost prohibitive.

- A2- Shorter term venture of either improving the optics damage threshold or living with the costs associated with operating the laser at higher fluences to reach greater energy levels.

4.6 Technical Model

4.6.1 Morphological Matrix

In order to understand important design decision variables for Laser Confined Nuclear Fusion, research was conducted. It was found from data that there are at least seven key variables that must be considered. The table below shows these along with the unique choices for each.

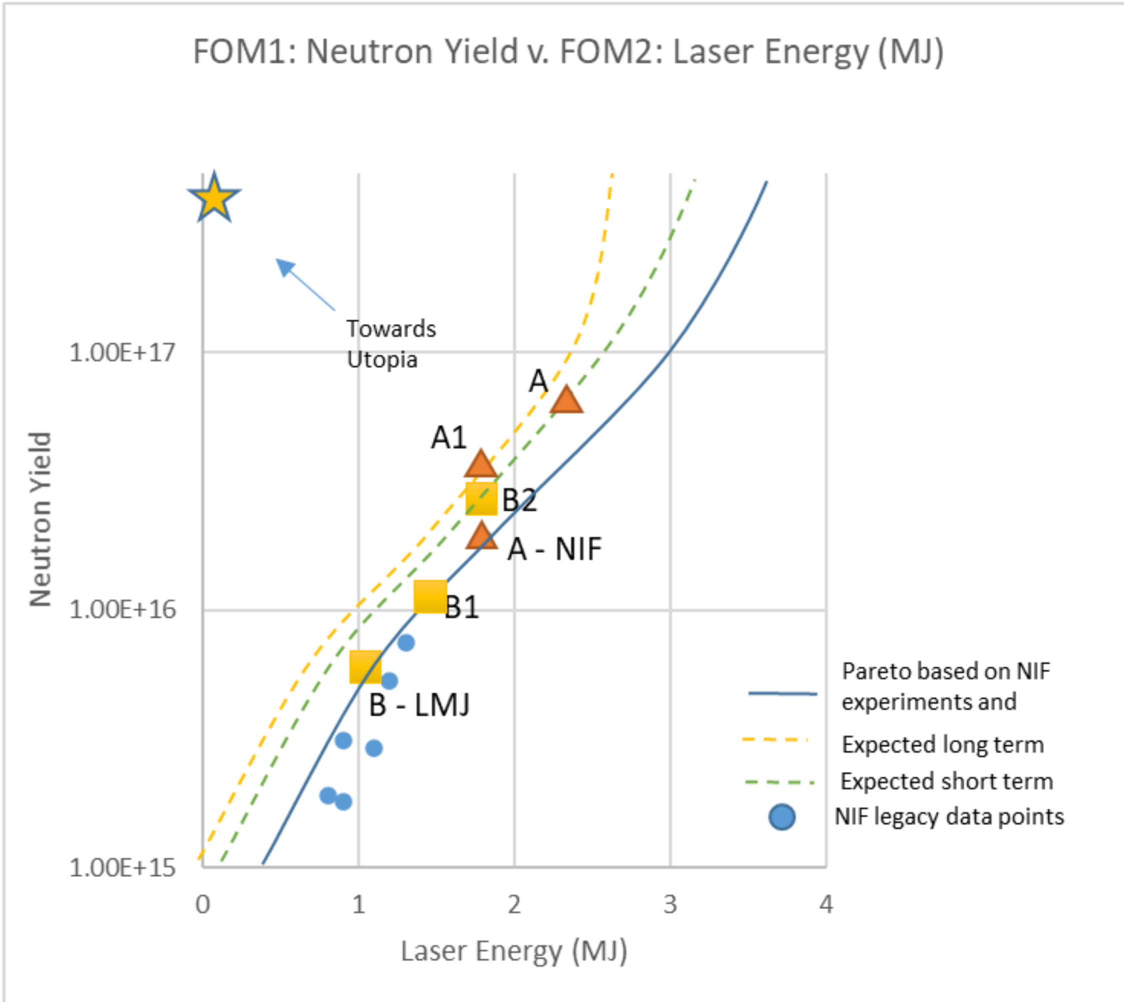


Figure 4-5: Potential tradespace for a two-player game along a two-dimensional Pareto Front using Neutron Yield and Laser Energy between NIF and LMJ [78] [67] [22]

Figure 4-6 was created to better explain each of decision variables in pictorial form. There are 2 variables for the laser system. These are the UV light energy delivered to the target and the temporal shape at which this energy is delivered. A further two variables pertain to the Hohlraum structure in terms of size (scale) and design shape. The Hohlraum is utilized in indirect drive laser confined nuclear fusion experiments to covert the UV light into x-rays that compress the fuel capsule. The remaining three variables cover the capsule radius, material, and a variable for the D-T (Deuterium-Tritium) fuel ice-layer known as the K-factor. This factor provides a normalized number for the summation of all defects and sphericity of the ice layer.

Table 4.5: LCNF Morphological Matrix (color bars represent experiments highlighted in table 4.6) [78]

Decision variable	1	2	3	4
Laser Pulse shape (temporal)	Low foot	High foot	Hybrid	
Laser energy (MJ)	1.4	1.6	1.8	1.9
Hohlraum shape/design	Hohlraum	Rugby	Frustraum	I-raum
Hohlraum scale, *Diameter.Length* (microns)	Nominal: 575.949	Sub-scale: 470.900	Enlarged: 600.1124	
Capsule inner radius (microns)	910	930	950	1100
Capsule Material	HDC	CH (plastic)	Be	
K-factor	0.8	1	1.2	1.5

It essentially indicates a fuel quality with 1 being optimal.

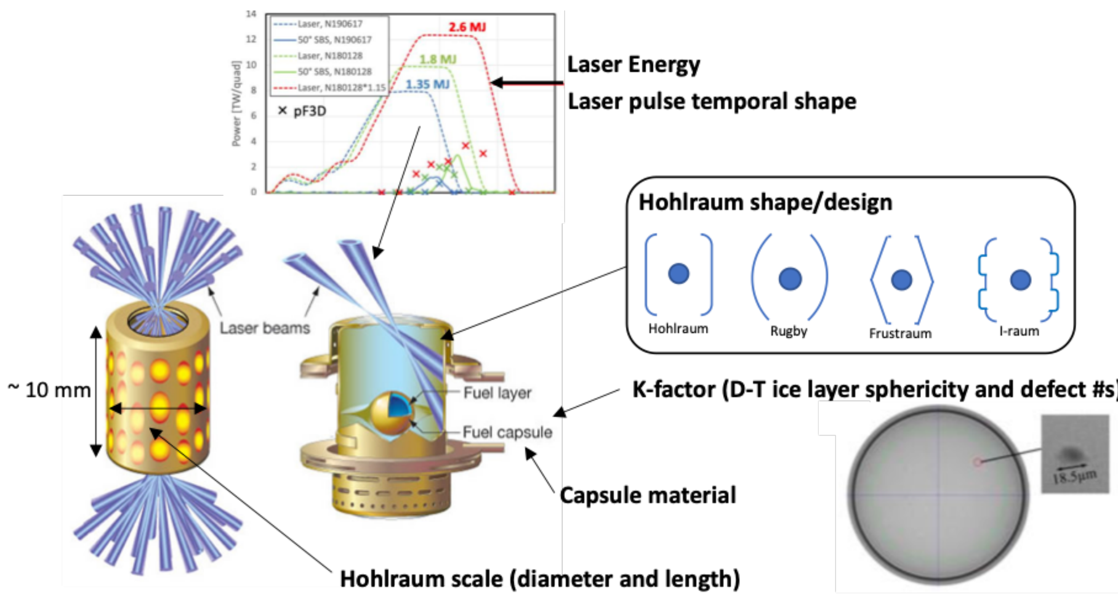


Figure 4-6: NIF target Hohlraum (Au cylinder) with laser interaction and important decision variables (figure developed from multiple references, [78] [95]

As the National Ignition Facility, NIF is at the forefront of Laser Confined Nuclear Fusion, the subsequent data gathered is all from NIF. No other facility is currently able to produce anywhere near the laser energies and neutron yields. Table 4.6 shows three experiments conducted over the last 7 years, important decision variables and the resulting neutron yield and implosion velocity FOMs. These are colored keyed such that they relate back to the variables shown in table 4.5.

Table 4.6: Experimental data from the NIF [78]

Experiment ID	Capsule IR (microns)	Hohlraum IR (microns)	Hohl/Cap ratio	Capsule material	Laser Energy (MJ)	Pulse shape	Implosion velocity (km/s)	Neutron yield
N140120	930	2372	2.55	CH	1.9	High-foot	360	9.30E+15
N170827	910	2885	3.17	HDC	1.8	Low-foot	408	1.90E+16
N191110	1100	2981	2.71	HDC	1.9	Hybrid	366	2.00E+16

4.6.2 Sensitivity Analysis

Implosion velocity and neutron yield were the two FOMs that were explored for a sensitivity analysis. To assess the former FOM, the partial derivatives with respect to the capsule inner radius, Hohlraum inner radius and laser energy using the equation below were calculated. This has been assumed to be an equality equation versus an approximation for the purposes of the analysis.

$$v_{imp} = (\frac{r_{cap}}{r_{hohl}})(\frac{E_{laser}}{m_{cap}})^{0.5} \quad Eqn3$$

This yielded the following set of equations:

$$\frac{\partial v_{imp}}{\partial r_{cap}} = (\frac{1}{r_{hohl}})(\frac{E_{laser}}{m_{cap}})^{0.5} \quad Eqn4$$

$$\frac{\partial v_{imp}}{\partial r_{hohl}} = -(\frac{r_{cap}}{{r_{hohl}}^2})(\frac{E_{laser}}{m_{cap}})^{0.5} \quad Eqn5$$

$$\frac{\partial v_{imp}}{\partial E_{laser}} = (\frac{1}{2m_{cap}})(\frac{r_{cap}}{r_{hohl}})(\frac{E_{laser}}{m_{cap}})^{-0.5} \quad Eqn6$$

From these partial derivative equations, one can calculate the change in implosion velocity from unit changes of each variable. These are shown in table 4.7. It is important to note that the NIF experiment, N180128 was used as the benchmark. This experiment had an implosion velocity of 425 km/s and neutron yield of 1.8e16.

Table 4.7: Sensitivity results for implosion velocity FOM

Implosion Velocity	delta velocity (m/s)	change of one unit	Velocity change percentage	normalized ratio
Capsule IR	450062.84	105.26%	105.26%	1.00
Hohlraum IR	-153082.60	35.80%	-35.80%	-1.00
Laser Energy	0.12	5.56E-07	2.78E-07	0.50
Laser Pulse shape	45000.00	*Estimated from experimental data*		0.11

When understanding the neutron yield sensitivity to these same four parameters, experimental data gathered from NIF over the last 10 years had to be used. This data is shown in figure 4-8 for two different types of laser pulse shape. The implosion velocity changes from table 4.7 were used along with figure 4-8 trend line equations to generate the change in neutron yield per unit change of the variable. These values were then ratioed and normalized. The results of the sensitivity analysis for implosion velocity and neutron yield are shown below in figure 4-7.

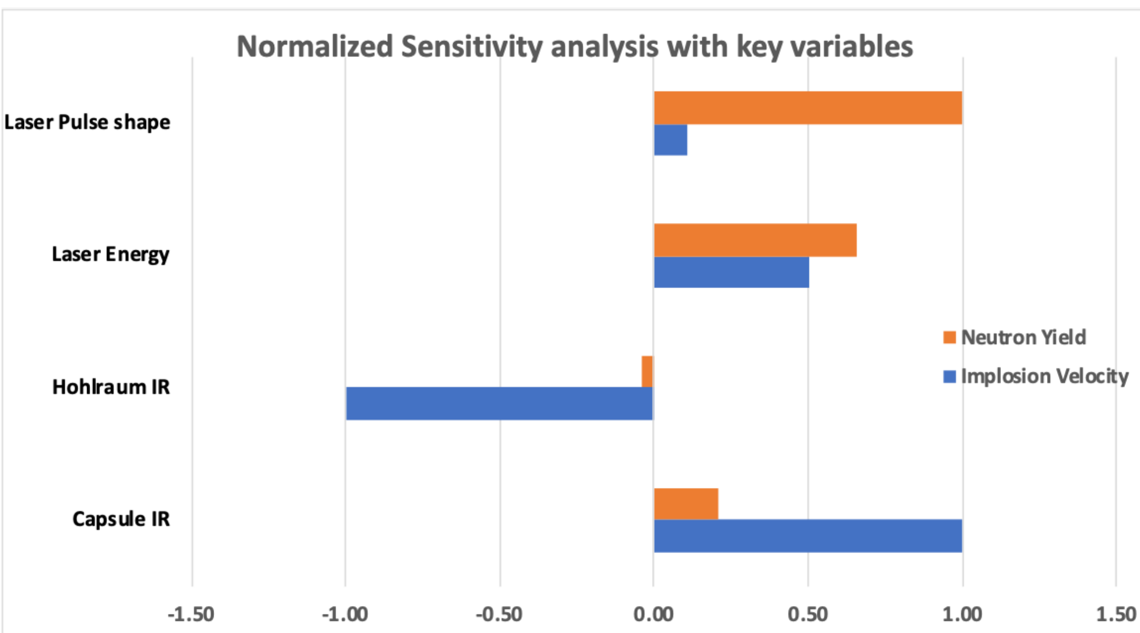


Figure 4-7: Sensitivity analysis plot for the two key FOMs

Laser pulse shape (temporal) is the only discrete variable and as this technology develops, more types of pulses can be studied. It is interesting to confirm that both laser energy and temporal pulse shape are the most sensitive variables for neutron yield. The least sensitive is the unit change of hohlraum radius. The analysis holds true for a constrained, range of values. However, as fusion is a relatively new and complicated technology some of the constraint values are not actually known. Although implosion velocity is affected by all the variables, the capsule and hohlraum radii have equally the same magnitude of change on this FOM. From the plot above, a hohlraum increase in radius acts to reduce the velocity of the implosion. This makes sense as there will be less compression and more heat loss with a large hohlraum assuming all other parameters/variables remain the same. Conversely, the plot shows that an increase in capsule size will increase implosion velocity. This will start to break down at a certain capsule diameter - for example when the capsule radius is greater than the hohlraum radius - and further work is required to assess a constraint for the capsule and hohlraum radius ratio.

Figure 4-8 below shows the initial tradespace of data for Laser Confined Nuclear Fusion. The Utopia point is in the left top corner of the graph because, with lower velocity and higher neutron the fusion reaction would be more efficient. In addition, lower implosion velocities may have a positive implication on cost and a better laser pulse shape could be developed potentially utilizing lower total laser energy.

4.7 Financial Model

An analysis was conducted to understand the financial prospects of high-gain LCNF power highlighting the extensive investment required and the eventual value of energy produced. Since the project is federally funded, and does not generate sales or income, the analysis presented forecasts a timeline where the project begins to generate a “profit” or break-even point as the value of the energy produced exceeds annual project costs in 2068. Obviously, an NPV analysis would show a significant loss but the value of energy produced is just a fraction of the true value of demonstrating a "profitable" fusion plant. LCNF technology is in early development where current FOMs need to see significant improvement for the project to begin construction of

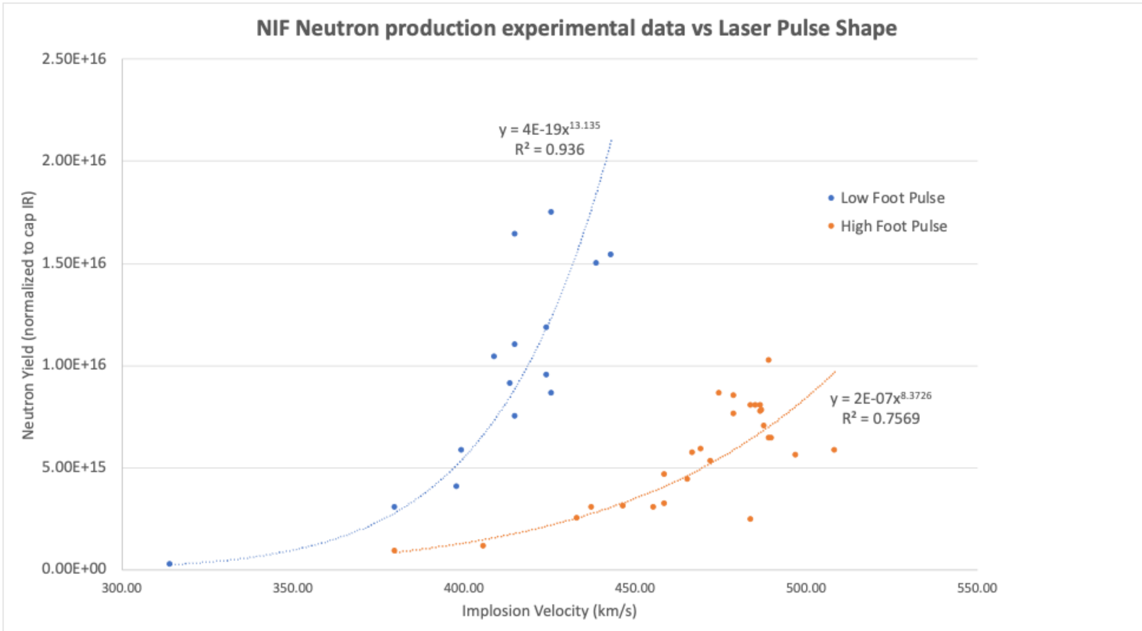


Figure 4-8: Initial tradespace plot from 10 years of NIF experiments [78]

fusion power plants. Moreover, most of the enabling fusion power plant technologies such as neutron energy capture, low-cost target fabrication, and high repetition rate laser drivers are at low readiness levels. The forecast shown below represents a future scenario where fusion FOM levels improve significantly from 2020 - 2035 after constructing the next generation B-NIF facility and federal funds begin to move towards the development of a fusion plant in 2035.

4.7.1 Future Scenario

The following scenario represents a potential set of milestones in the development of commercial laser fusion power generation. This is only one of a set of potential future scenarios:

- 2025 – 2035 Construction of B-NIF as the next generation facility to significantly improve on key fusion FOMs and show energy gains exceeding 1000, prompting push for fusion plant development using R&D Expenditures
- 2040 – 2050 Construction of 1st fusion plant with significant R&D Expenditures

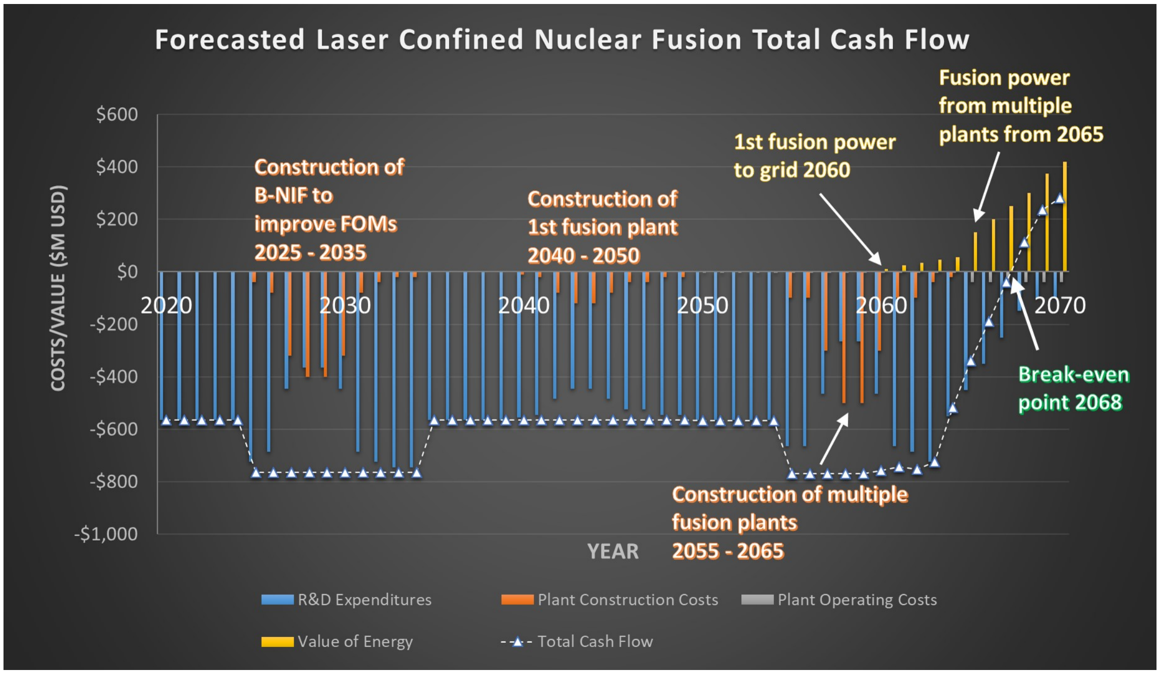


Figure 4-9: LCNF Financial model cash flow

improving fusion power plant technologies

- 2050 – 2055 Significant use of R&D Expenditures to refine the fusion plant in preparation for demonstration of power to the grid
- 2055 – 2065 Construction of multiple fusion power plants based on lessons learned from 1st fusion plant
- 2060 – First power to the grid achieved
- 2065 – Significant value from energy reached prompting end of project and reduction in overall federal funds for research
- 2068 – Break-even point as the annual value of energy generated exceeds the annual costs

Total Cash Flow:

- U.S. laser confined fusion development budget currently at approximately $565M (FY20) including all costs offset by energy value produced by its fusion power plants

Cost Assumptions:

• R&D Expenditures – U.S. laser confined fusion research budget currently at approximately $565M (FY20) that fluctuates based on construction projects
• Plant Construction Costs – Anticipated future construction costs based on current power plant costs, approximately $1,500/kWe (USD)
• Plant Operating Costs – Anticipated future operating cost based on current nuclear power plant operating costs of approximately $20/kWe-yr (USD)

Value of Energy Assumptions:

While fusion power may offer many benefits to society, its levelized cost of electricity (LCOE) may drive future adoption. In an optimization study performed by Hawker [43], an LCOE of less than $25/MWh – the price point needed to compete with other renewable sources of energy – could be attained with the parameters shown in table 4.8.

Table 4.8: LCOE parameters for fusion power plants [43]

LCOE of ~$25/MWh (USD) design point [Hawker,2020]	
Facility Availability	80%
Laser Driver Lifetime	40M shots
Discount Rate	4%
Plant Cost	1.5k/kWe
Operations & Maint.	$20 USD/kWe-yr
Driver Cost	$3/J
Target Cost	$2 USD/target
Reaction Frequency	0.05 Hz
Gain (Energy Out/Energy In)	1000

• 1st Fusion Plant – 1.2M reactions/yr, 1.4E6 MWh/yr, $25/MWh
• Multiple Fusion Plants – Scaling of the 1st Fusion Plant based on redirected funds to construct multiple plants from 2055 - 2065

4.8 Demonstrator Projects

Consistent with the strategic drivers for the LCNF technology, table 4.9 outlines the R&D portfolio requirement to align with the roadmap goals.

Table 4.9: LCNF demostrator projects

Project	Description	FOM targets	Budget (USD)	Timeline
Optics Improvements	A number of projects aim to improve optics related FOMs to increase the laser driver's maximum power. One FOM limiting laser power is the optic damage threshold in J/cm2. These projects include exploration of optics conditioning methods, improving surface quality, improving optical material purity, and management of scattered light to significantly improve the overall damage threshold to allow for higher fluences of UV laser light.	Optics damage thresold 15 J/cm^2	$75M	2021 - 2023
Target Optimization	Target design consists of many variables thought to be sensitive to fusion yield FOMs. Modeling has shown that one design variable in particular that can have a profound effect is the Hohlraum shape. A number of promising shape candidates are being modeled and explored including some resembling rugbies. Since laser power is directed to the Hohlraum inner surfaces, these new geometries offer a way to manipulate the plasma generated and imparted to the fuel capsule.	Neutron yield, 10E6	$50M	2021 - 2023
Magnetically assisted drive	Currently, inertial confinement fusion experiments are purely driven by laser energy, but recent developments have demonstrated major benefits with the addition of a disruptive technology, a magnetic (B) field. Physics models suggest that both the energy output and the neutron yield will both increase with the introduction of large seed magnetic fields at the time of implosion. It involves implementing a magnetic system capable of generating ~ 50 Tesla fields, with a cryogenic system that holds the 2mm D-T ice ball at 18K (inside a target assembly), stable within less than 1 milli-Kelvin. There are many possible system architectures and approaches to take for both the magnetic system design as well as integration mechanism into the facility.	Neutron yield, 10E7	$50M	2020 - 2024
Diagnostics improvements	Developing a clearer understanding of NIF implosions under extreme conditions is one of the biggest challenges facing fusion technological advancement. A number of new nuclear diagnostics are continuously developed adding to the extensive suite of NIF on-board diagnostics. One major diagnostic is the scattered array of real-time neutron activation detectors that sample neutron yield from strategically placed locations within the target chamber.	Op. Cost Reduction, 10%/year	$30M	2020 - 2025
Laser driver facility improvements	Increasing the laser drive power enables new and promising experimental shot configurations. To increase the laser power delivered to the target, a number of facility enhancements by way of a significant plant construction effort to scale up the laser system is required.	Laser Energy, 10 MJ	$4B	2035 - 2045

4.9 Key patents, publications, presentations

For the patent analysis, an initial search was conducted using the U.S. Trademark and Patent Office search application but it was challenging to find international fusion technology patents such as those related to the large-scale ITER (originally the International Thermonuclear Experimental Reactor) fusion facility development effort [48]. Ultimately, the search and analysis was performed using the World Intellectual Property Organization's (WIPO) international patent database to better understand the international patent landscape for the broader nuclear fusion technology field (as opposed to our more specific laser-confined variant). A Boolean search using "AND" phrases such as: nuclear fusion, confined fusion, and fusion reactor, yielded 9,181 published patents in the last 30 years (1990 – 2020). To better understand the technological interest and progress in the field, the patents published by year were charted. The patents published steadily increase from 1990 – 2010 and can perhaps be attributed to the increase in worldwide fusion research investments as it becomes more apparent that the world's future energy needs may exceed the existing fossil-fuel based infrastructure.

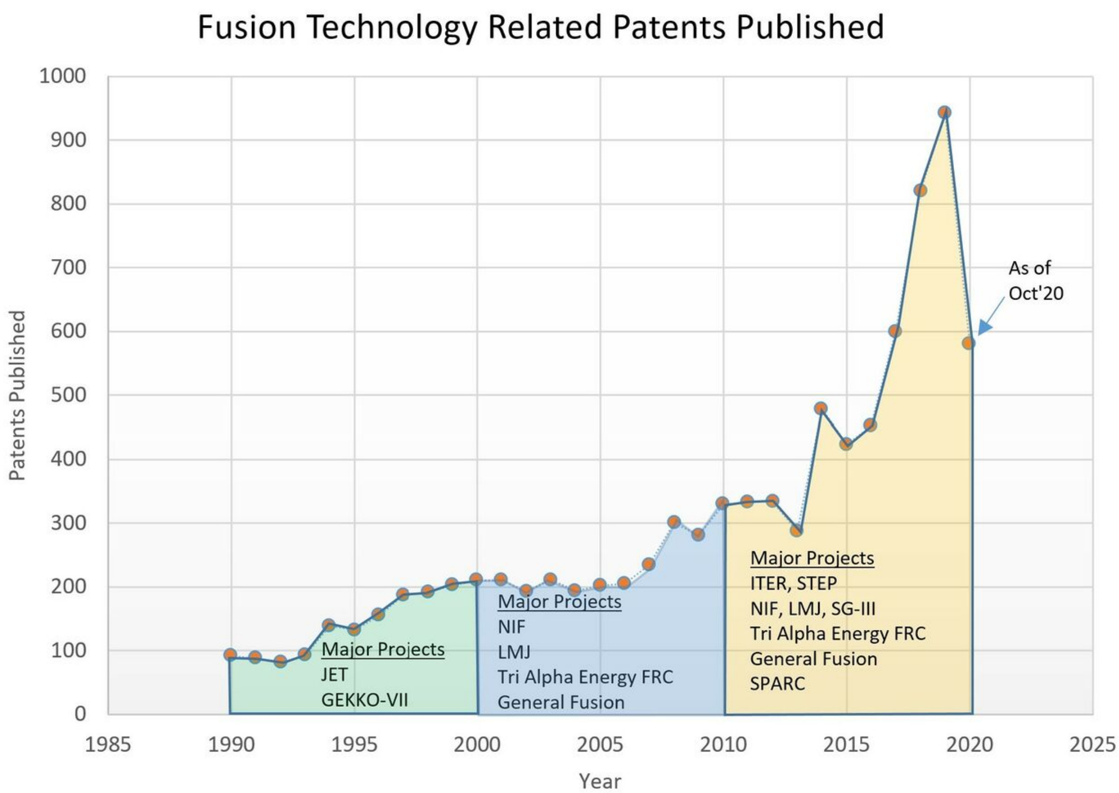


Figure 4-10: Fusion technology related patents published over the past 30 years, compiled using the WIPO international IP database search application

In 2016, the U.S. based Advanced Research Projects Agency – Energy (ARPA-E) commissioned a nuclear fusion technology global IP landscape study that helps to validate our search results. When comparing Figure 4-10 and Figure 4-11, the steady increase trend from 1985 to 2013 are similar in both plots but our IP analysis (Figure 4-10) reports roughly twice the number of patents. This significant deviation is likely attributed to the variation in parameters (and definition) used to identify "fusion technologies". The key takeaway however is that the fusion technology IP trend indicated by both figures indicate that this field is undergoing significant technological growth.

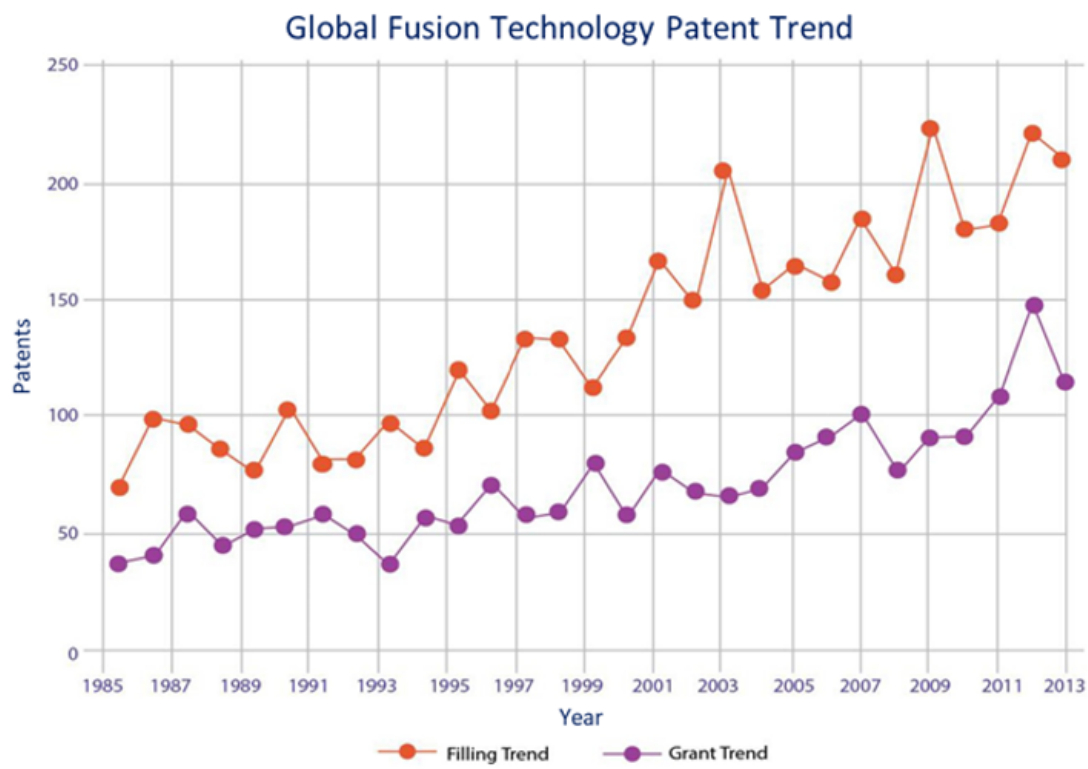


Figure 4-11: Global IP grant trend of IP assets in nuclear fusion technology as analyzed and reported (based on Questel Orbit data) by iRunway in 2016 for ARPA-E [56]

Unfortunately, the IP landscape study performed by iRunway only reports data up to 2013 where in our IP analysis, the trend begins to increase significantly over the next 7 years. New developments on the ITER and the UK-based Spherical Tokamak for Energy Production (STEP) projects in addition to the on-going efforts at the National Ignition Facility (NIF) and Laser Megajoule (LMJ) may have helped with the spike that started in 2013.

iRunway's report in 2016 postulates that magnetic confinement and inertial confinement methods dominate nuclear fusion technology patenting activity and reports that the United States leads the IP space, holding the most fusion technology IP assets (1982). As shown in Figure 4-12, a significant cluster of IP assets are collectively held by European countries as well.

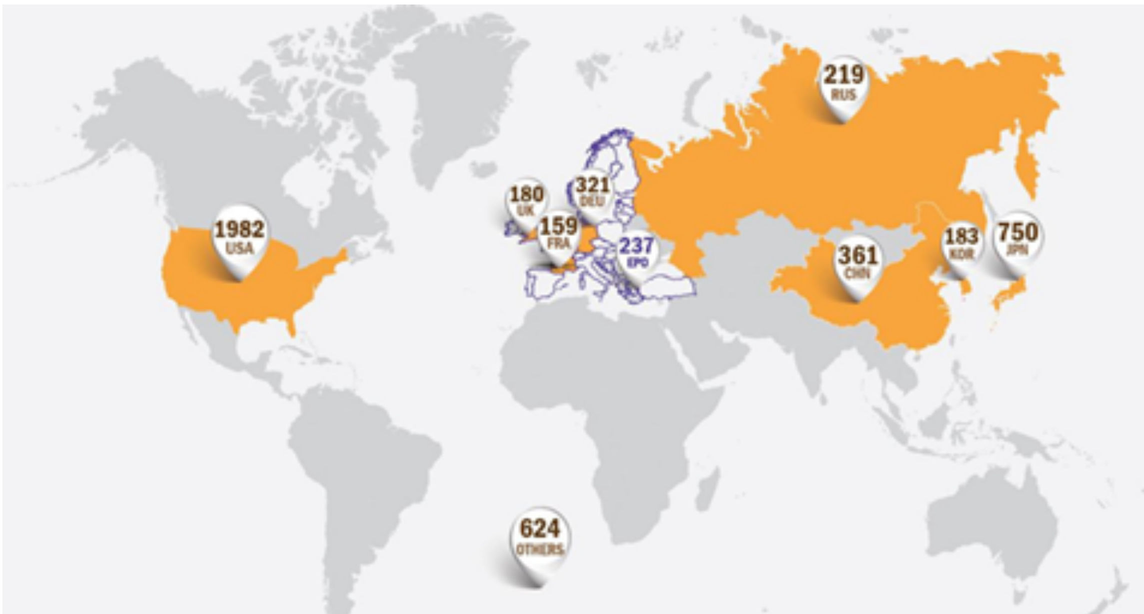


Figure 4-12: Geographical ownership of nuclear fusion technology assets globally as reported by iRunway in 2016 for ARPA-E [47]

Two of the more interesting patents reviewed involve the design of a NIF-based fusion-fission power plant (US 9,171,646 B2 [33]) and the design of magnetically assisted targets (US 10,134,491 B2 [35]) both of which belong to the Lawrence Livermore National Laboratory. Curiously, there was not a patent claiming the design of the laser-based fusion reactor (reactor to prove efficacy of fusion power, not the power generating plant). The lack of a design-protecting patent may be why the LMJ facility in France and the Shenguang-III facility in China closely resemble the physical architecture of the NIF.

The "Control of a Laser Inertial Confinement Fusion-Fission Power Plant" patent depicted in the schematic shown in Figure 4-13 drew our attention for its forward-looking mentally as the vehicle to eventually extract energy from fusion reactions based on learnings from NIF experiments. The patent itself describes the fusion plant driver (laser-based), reaction outputs (fusion neutrons), an energy collecting fission blanket, and a coolant system that transfers the energy from the fission blanket as heat. This may be one of just a few large-scale designs protected for a laser-based confined fusion power plant. Conversely, some ITER member nations are already planning for Tokamak-based fusion power plants with the expectation that ITER will provide the technical knowhow.

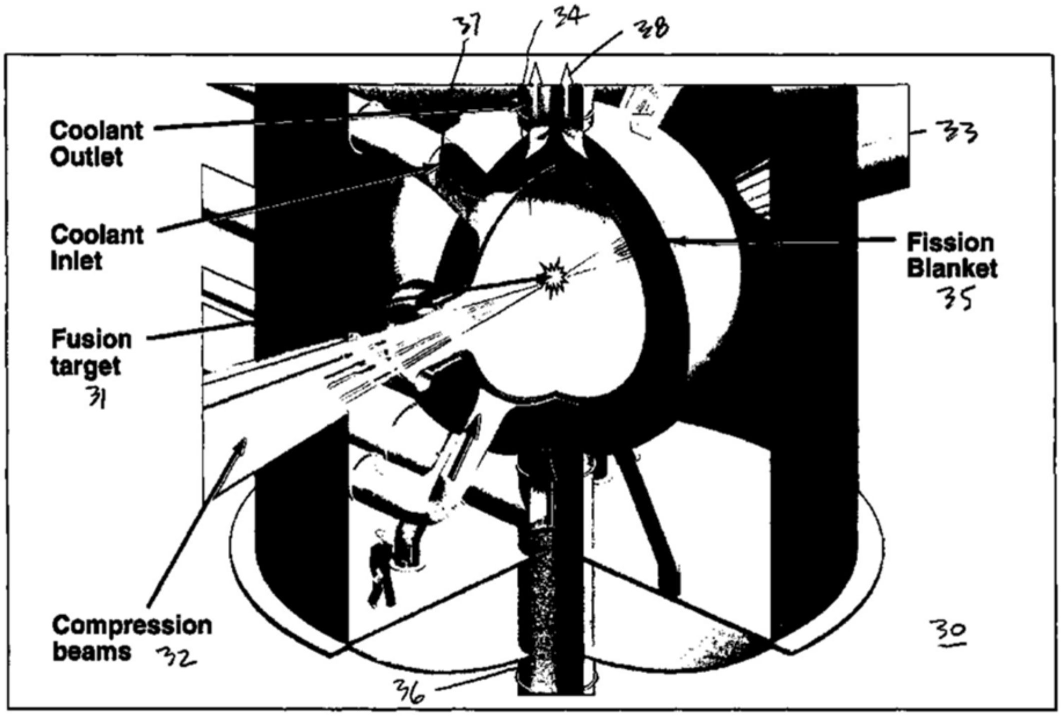


Figure 4-13: U.S. Patent claiming the design of a nuclear fusion power plant that used lasers for compression and a fission blanket to capture energy [33]

Although NIF facility design patents appear to be lacking, patents that describe the design of the fusion targets (typically a D-T fueled filled capsule housed in a Hohlraum) are more plentiful. An example of a target design claim within a patent is the device shown in Figure 4-14 designed to produce axial seed magnetic fields that in theory will help ease the stringent environmental conditions required for ignition.

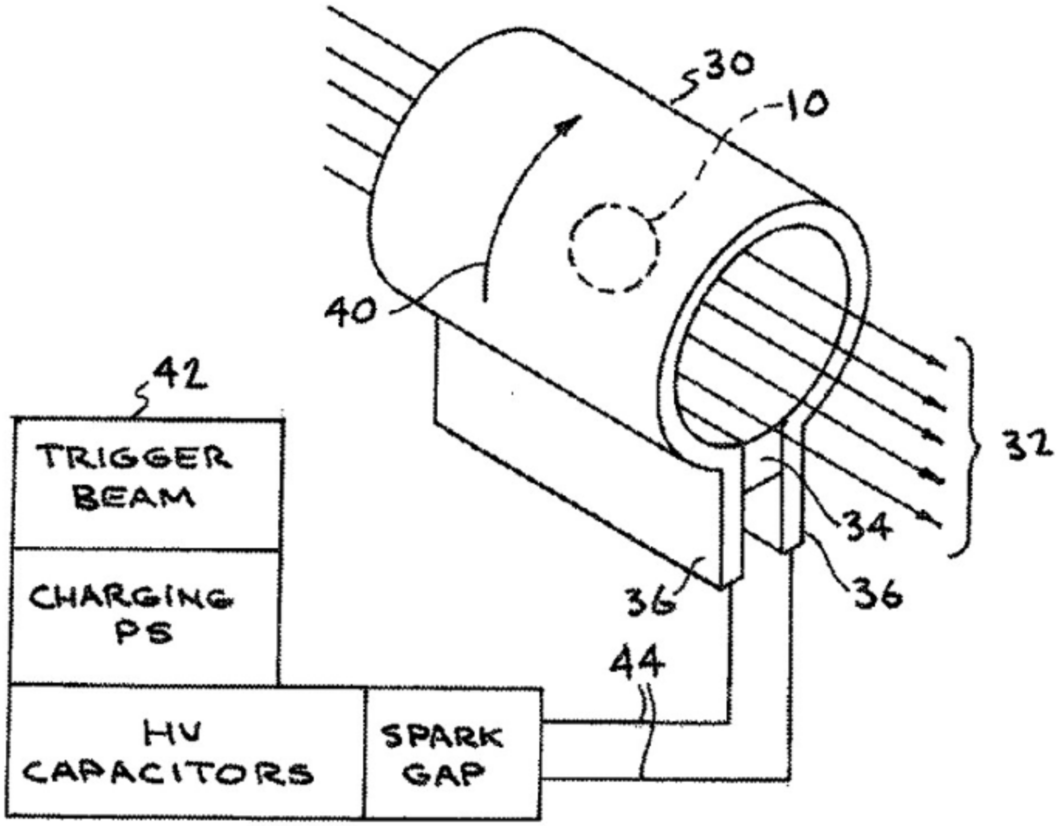


Figure 4-14: U.S. Patent claiming the design of a device to produce axial seed magnetic fields to help create conditions for ignition and propagating burn in the NIF fusion targets [35]

To dive deeper into the laser confined fusion technology branch (our technology roadmap topic) within the broader fusion technology landscape, a review was conducted of a paper recently published in 2019 by the International Atomic Energy Agency titled "Progress of indirect drive inertial confinement fusion in the United States" that provides an update to U.S. based ICF development. To learn more about the ICF competitive landscape, a paper describing LMJ and the PETawatt Aquitaine Laser (PETAL, a multi-Petawatt beam coupled to LMJ [67]) laser's status titled "The Laser Mega-Joule: LMJ & PETAL status and Program Overview" was also reviewed. NIF and LMJ (including PETAL) are known as two of the premier ICF research facilities in the world. An article published in Science Magazine in 2015 explores the differences between the 2 facilities [22].

NIF has been operational for over a decade now and is known as one of the most energetic laser systems capable of producing greater than 2MJ peak during ICF shot operations. Designed for 1.8MJ, the facility expected to reach ignition in 2013 but did not reach that ambitious goal due to unexpected target compression uniformity issues. Since then, the focus has been to better understand the efficacy of the NIF to achieve ignition by exploring several design variables that are thought to be sensitive to one of the key objectives – neutron yield [51]. Among the variables considered are: Hohlraum (cylindrical shell used to produced x-rays when irradiated) geometry, capsule (containment for D-T fuel) size, capsule structural support and fill devices, and lastly, the laser output power and temporal beam shape directed to the Hohlraum. Modeling results shown in Figure 4-15 attempt to predict the relationship between laser energy input and neutron yield and the change in the curve when the capsule is scaled up in size.

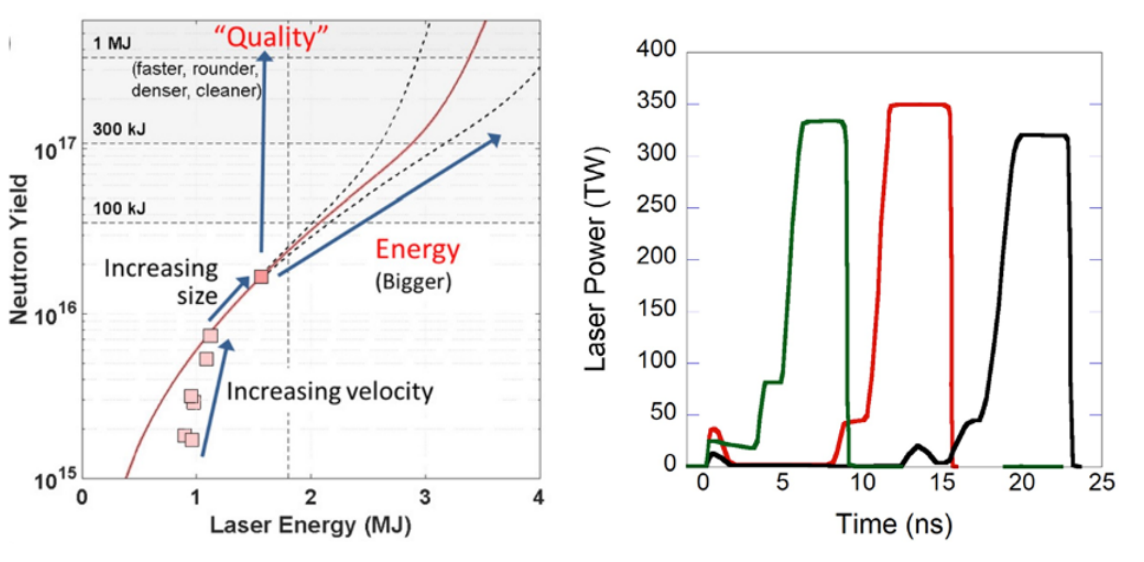


Figure 4-15: (Left) Notional relationship between laser energy and neutron yield and the expected curve changes due to capsule upsizing. (Right) Temporal beam shape design variable considerations [51]

Since the Hohlraum produces the x-rays needed for implosion, it is critical that the shape/geometry is optimized. Various Hohlraum geometries are under exploration as part of a design space that will hopefully be optimized for neutron yield.

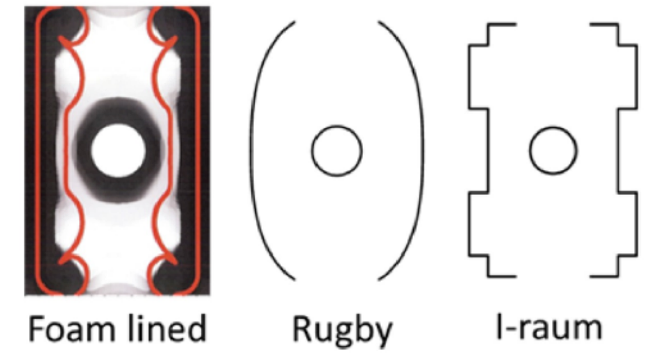


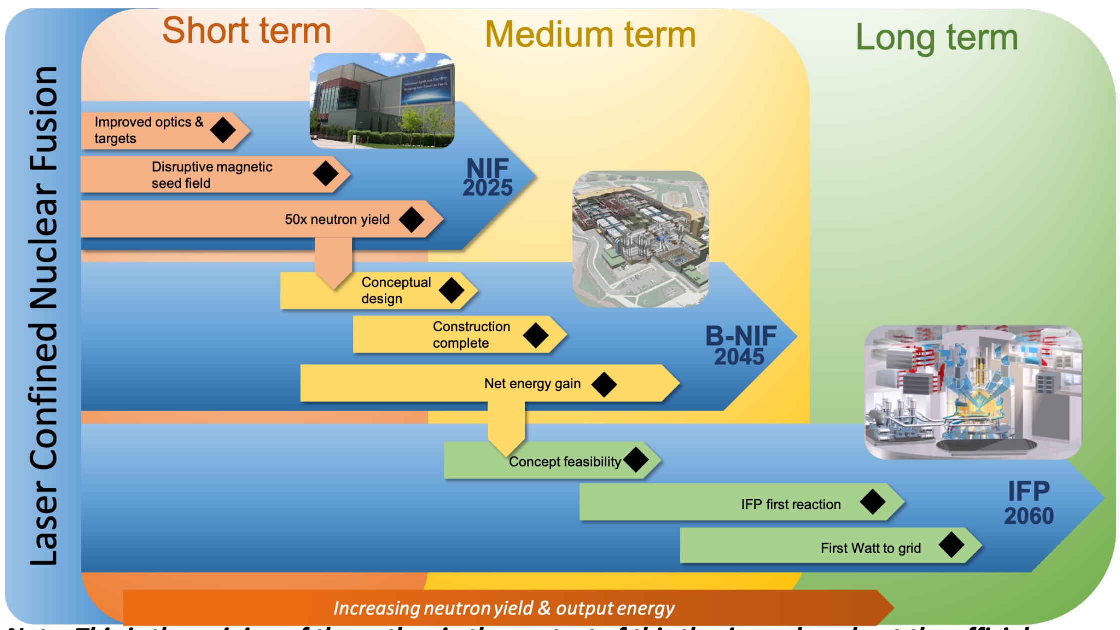
Figure 4-16: Hohlraum design considerations/variables to improve compression symmetry in hopes of generating a more favorable environment for ignition [51]

LMJ is currently operational but is still under construction with 176 of the 240 designed beams installed and commissioned. The expectation is that the laser system will reach maximum energy of 1.5 MJ and a maximum power of 400 TW. It's architecture closely resembles NIF except for a novel, short-pulsed (500 fs to 10 ps) ultra-high-powered, high-energy laser that enables "fast ignition" and "shock ignition" experiments where lasers like PETAL can potentially help trigger the chain of implosions needed for ignition. Although developments to date at LMJ and PETAL look promising, it is still years away from realizing its full potential as an ICF facility [67] [22] [51].

4.10 Technology Strategy Statement

The target is to develop the first Laser Confined Nuclear Fusion Power Plant and be inputting power into the US national grid by 2060. In order to achieve this, the roadmap is divided into three phases as shown in the high level roadmap chart below. A first phase could be to leverage a suite of R&D projects on the existing NIF system and make improvements to reach a factor of 50x in neutron yield by 2025. The second phase, leveraging the first, will drive the design, development and build of a new, "Bigger" NIF to increase the laser energy delivered to a target by a factor of 5

(10 MJ +). This will also allow the continued R&D of new optics, diagnostics and larger, more optimized targets. This second phase aims to reach net energy gain by 2045 and has aspects (enabling technologies) incorporated to provide insights into a power plant design. The third and final phase is to design and build Inertial Fusion Plants, IFPs to utilize fusion energy and provide a renewable power source to the grid. Figure 4-17 outlines the strategy in chart form.



Note: This is the opinion of the author in the context of this thesis work and not the official LLNL/NIF timeline

Figure 4-17: LCNF high-level roadmap (images from [124] [14] [65])

Chapter 5

LLNL Case Study: Integrating Magnetic seed fields in Laser Confined Nuclear Fusion

5.1 Project Motivation

As discussed in Chapter 2, The National Ignition Facility (NIF) is located at the Lawrence Livermore National Laboratory (LLNL) in Northern California. It contains the world's largest and most energetic laser that compresses frozen deuterium-tritium (DT) fuel to create nuclear fusion reactions [72]. Ultraviolet light from 192 laser beams is focused onto the wall of a 12 mm tall, gold hohlraum which converts the light into x-rays as illustrated in Figure 5-1. The result of this rapid compression is a fusion reaction that produces helium and neutrons. Currently, inertial confinement fusion experiments are purely driven by laser energy, but recent developments have demonstrated major benefits with the addition of a disruptive technology, a magnetic (B) field [69]. Physics models suggest that both the energy output and the neutron yield will both increase with the introduction of large seed magnetic fields at the time of implosion. Figure 5-1 also shows the increasing predicted yield energy versus seed magnetic field with the introduction of this disruptive technology. The theory behind this concept is, as the charged particles (such as helium nuclei) are released from the implosion, instead of immediately being ejected, they act to follow the magnetic field lines and drive back into the fuel mix. This causes more reactions, an increase in reaction temperature and thus, increases in both neutron and energy yield.

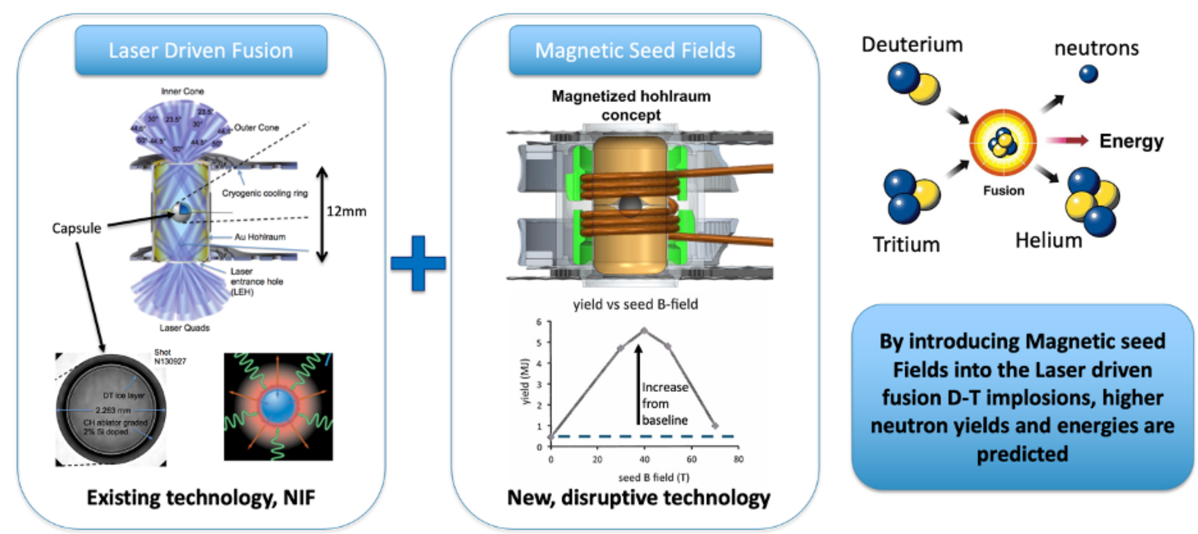


Figure 5-1: Introducing magnetic fields to Inertial (Laser Driven) Confinement Fusion [95] [8] [10]

Magnetically assisted fusion on the National Ignition Facility is in the second phase of a three-phase project. The final goal of the effort is to add this "seed" field to the cryogenic fusion experiments and observe an increase in neutrons and energy yield. Phase 3 of the project is the most challenging, integrating a multidisciplinary team of electrical engineers, cryogenic engineers, mechanical engineers, physicists, operations staff and managers. It involves implementing a magnetic system capable of generating ~50 Tesla fields, with a cryogenic system that holds the 2mm D-T ice ball at 18K (inside a target assembly), stable within less than 1 milli-Kelvin. There are many possible system architectures and approaches to take for both the magnetic system design as well as integration mechanism into the facility with the project likely being 3 to 5 years in duration and having an estimated budget ranging between \$30 and \$40 million. There are a large amount of design variables, parameters, and constraints (highlighted ones are shown in Table 5.5) and it is essential that the design is optimized with both magnetic field performance and cost considerations in mind.

5.2 Application of systems thinking and engineering approach

5.2.1 Project Management & phased approach

As mentioned previously, the MagNIF project consists of three phases. The first phase was a demonstration platform for simple room temperature experiments and involved a fast track implementation on one of the NIF Positioners, TANDM348 (Target and Diagnostic Manipulator at the angle of 348 degrees on the horizontal plane around the NIF Target Chamber). The second phase, also utilizes TANDM348 but with increases in both voltage and current as well as a specialized target design that will also provide some risk mitigation and learning for the final phase. Both phases 1 and 2 are captured under the Warm B-Field, WBF system shown in figure 5-2 as a subsidiary of the MagNIF project. The Cryo B-Field, CBF effort will result in the system required to complete phase 3, the final phase of the project and will utilize the Cryogenic Target Positioner, CryoTARPOS with an external pulser (pulse generator assembly).

Further to the basic system decomposition, figure 5-3 ties in the high level roadmap for the MagNIF project. It can be seen from the figure that initial, non-magnetic field experiments were conducted in parallel with the development of the initial pulser and coil (solenoid) subsystems. From December 2018 through 2019 the WBF system was implemented and ramped up in the NIF facility. "Gas Pipe" experiments were conducted with and without seed magnetic fields to assess the influence of laser burn-through with the additional technology. These Gas Pipe experiments use only one quad (4 laser beams) that travel through a gas filled, plastic cylinder and produce x-rays from the UV light interaction with the room temperature gas. The results of the seed magnetic field introduction demonstrated a faster burn-through (~1 nano-second) as well as particle confinement – a compressed (tighter) x-ray illumination

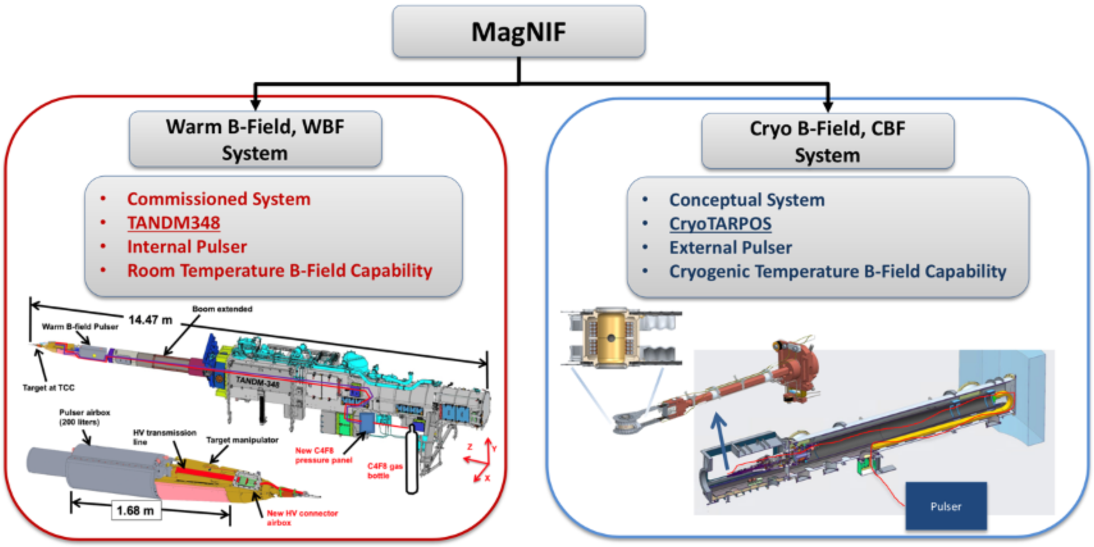


Figure 5-2: MagNIF definition and sub-projects [3]

column.

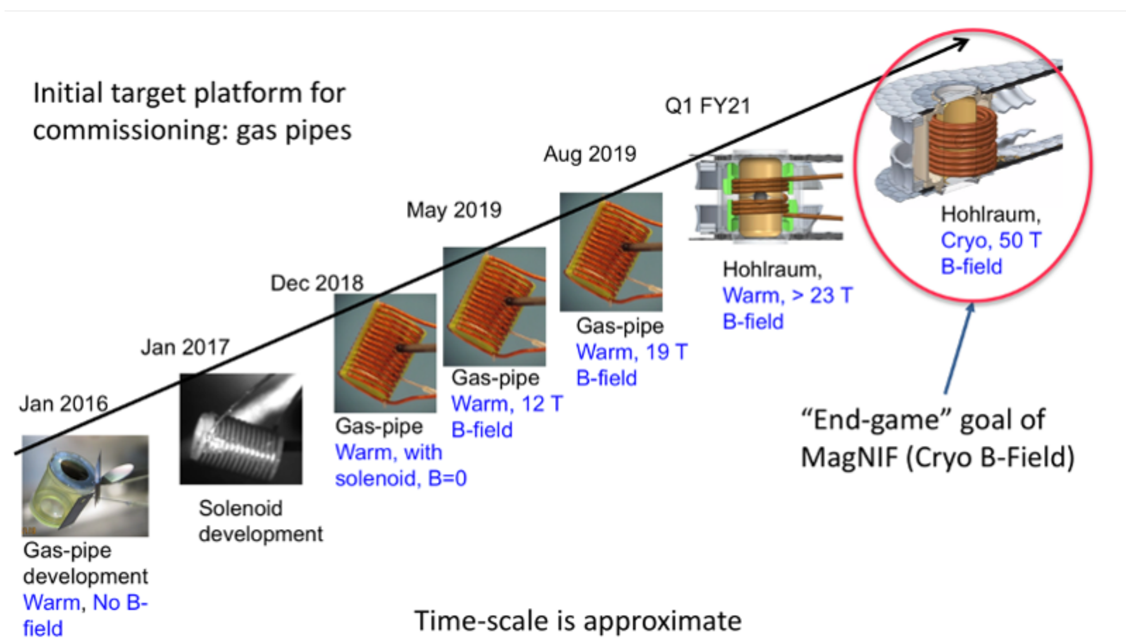


Figure 5-3: MagNIF timeline and phasing [9]

The first experiment for phase 2 of the project, shown in figure 5-3 as the Q1 FY21 milestone has been delayed to Q2. This phase will not only test the new target design and materials with 192 NIF laser beams but will also provide diagnostic data to understand any increases in hotspot (compressed capsule fuel) temperature as well as neutron yield. The final "End-game" milestone is shown in FY23 when the experiments on the CryoTARPOS commence and predicted neutron yields are increased.

Risk mitigation strategy

The phased approach discussed is a large part of the MagNIF risk mitigation strategy. Staging in this manner not only reduces the risks for the final, end-game implementation but also provides both a new capability for different NIF users and motivation/priority for the final project from initial experimental results. Table 5.1 shows the high-level risk register for the final phase of the project, CBF. In addition to taking credit for the other phases, the register highlights the top risks (red boxes) that were presented at the Conceptual Design Review, CDR in September 2020.

Table 5.1: MagNIF high-level risk register [3]

Subsystem	Technical Risk	Mitigation Plan
System level	Integration and emergent system behaviors	Early end-to-end test for CBF and learnings from RT platform
Target	Coil influence on layering 1. Layer forming operations (slow) and 2. Layer heating near shot time (fast)	Thermal simulations to quantify and understand Early measurements and tests with (1) ITPS prototype targets and (2) Hohlraum wall temperature 1. Thermal control of coil (heat switch) for layering operations 2. Quenching before shot (more impactful: limit amplitude of B-Field or Hohlraum material)
	Field soaking through hohlraum & wall motion	AuTa design RT designs and test/measurements
	Target Assembly	Experience w/RT target assy, (1) Design (incorporating RT platform learnings) (2) Early prototyping & test target builds
	Cryogenic target integrity (and material compatibility)	Testing (Cryo cycling and ITPS) and Design
Magnetic System	Coil breakdown	Insulation and coil design Coupled early coil tests with simulations
	Coil motion	Simulation Tests with high speed camera Circuit and Coil design
	Transmission line cryo performance	Early stripline/twin leads cryo cycling and testing
	Transmission line (cabletrack) performance	Design and test in cabletrack tester
	Pre-fire	MOR tie-in concept and switch design (reliability)
	Connection breakdown/failure	Multiple design/build/test cycles Prototyping connections early and testing in B141 (E-gun pulser)
	Impedance matching	Early component and full system test (potentially using WBF Pulser)
Cryo System	Cryogenic system thermal capacity and adequate margin for layering operations	Twin lead design & thermal sinking Assessment of L-TIC/LRU thermal margin with baseline design
	Connection #3 spatial limitations	Mag-Target LRU design and test

These include the acknowledgement of the emergent behaviors from bringing the sub-systems together, such as the cryogenic and target systems as well as the structural and magnetic systems. A key risk mitigation strategy here is to prototype early and plan on iterative designs. For the magnetic system, the primary concern – brought about from experience with the WBF system – is the connections. In an ideal electrical world these would be eliminated but for the operational context of the NIF, they are essential in allowing for ongoing operations and feasible turnaround times for experiments. So, the connections are prioritized to be prototyped early in the project lifecycle and contingency is put in place to allow for iterative designs. The schedule in figure 5-4 was developed from the risk mitigation testing in addition to the stakeholder needs and priorities discussed later.

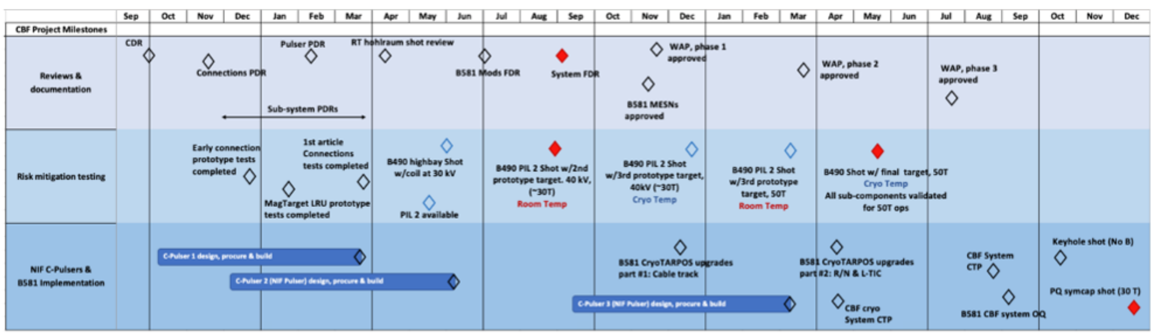


Figure 5-4: MagNIF schedule presented at the Conceptual Design Review, CDR [3]

Sub-system Preliminary Design Reviews, PDRs are leveraged to focus and drive the team to the prototype build milestones. For example, the connections PDR was scheduled in November 2020 to allow enough for at least two design iterations and procurement to meet the first magnetic system milestone in May 2021 ("B490 highbay shot w/coil at 30 kV"). Furthermore, early connection prototype tests by the end of calendar year 2020 enable the team to appreciate the installation and operation of the connections with "mock-up" assemblies of the operations equipment in an offline facility. Another strategy incorporated to help ensure success of the connections is designing with margin. The baseline circuit of the magnetic system is for 40kV operation but the connections are designed to withstand voltage drops of up to 60 kV for future scalability and impedance mismatching emergent behaviors.

In the middle swimlane of figure 5-4, titled "Risk mitigation testing", another phased approach strategy is utilized. The first red diamond milestone in August 2021, shows a 10kV increase in voltage from the May 2021 milestone and the introduction of a prototype target. However, to not over complicate the offline testing and to reduce the risk from procurement, the tests are at room temperature. The introduction of the cryogenic system comes towards the end of the calendar year 2021 so that magnetic system issues can be addressed ahead of time while the team are waiting for longer lead, cryogenic components to arrive. The following year, testing to get to higher magnetic fields will be conducted offline with any required upgrades and a staged integration into the NIF facility (B581) will be observed. Instead of trying to install all new systems over one maintenance period, the strategy is to get some confidence in operations for some sub-systems before full deployment. For example, the cable track upgrade will take place the December before and the team are aiming to install and commission the new cryogenic system in the April timeframe, several months before the magnetic system will be commissioned.

5.2.2 Stakeholder analysis, requirements and concept development

Prior to developing the risk mitigation strategy, the Cryo B-Field, CBF Primary Criteria was developed from conversations with Physicists and NIF management to guide the beginnings of the project. Table 5.2 shows the seven Primary Criteria that added specifications to allow for the ideation phase and generation of viable concepts for CBF.

As a result of the ideation development phase, eight conceptual solutions were generated. These are shown in figure 5-5 and are captured into four different categories. Concepts 1A and 1B have an internal pulser in CryoTARPOS architecture, while Concepts 2A and 2B have an external pulser on CryoTARPOS but different ways of transporting the high energy pulse. Concepts 3A and 4A utilize a two Positioner approach with either internal or external pulser systems and Concepts 3B

Table 5.2: MagNIF, CBF Primary Criteria [3]

FRPC No.	Requirement Title	Requirement Text
1	B-Field for Cryo targets	The B-Field shall be applied to targets fielded on CryoTARPOS
2	Performance	The Cryo B-field system shall support up to 600 scale Cryogenic Hohlraum targets. The magnetic field shall be generated using a coil able to provide: - Up to 50 Tesla for up to 600 scale Cryogenic Hohlraum targets The B-field platform performance shall be compared to existing NIF shot N180128, or equivalent, with the addition of a seed B-field
3	Functionality	The drive electronics & coil shall be adjustable to achieve a user-requested B-Field: For the 600-scale Cryogenic Hohlraum target, a user selected field ranging from 20 T to 50 T
4	Operations	Hardware shall be designed such that the time required to reconfigure target positioners to-and-from using magnetic fields shall be less than 12 hours with a goal of less than 8 hours
5	Target debris & backscatter	Additional debris and backscatter risk associated with the addition of the B-field generator platform shall meet NIF requirements
6	NIF integration	Cryo B-field capability shall be consistent with ongoing NIF shot operations: alignment, diagnostic imaging and safety of workforce and equipment
7	Design	Cryo B-field system shall be designed to NIF standards, including reliability, and such that initial deployment does not require major disruption to ongoing operations

and 4B utilize a similar approach but with the magnetic field generating coil on the completely separated Positioner.

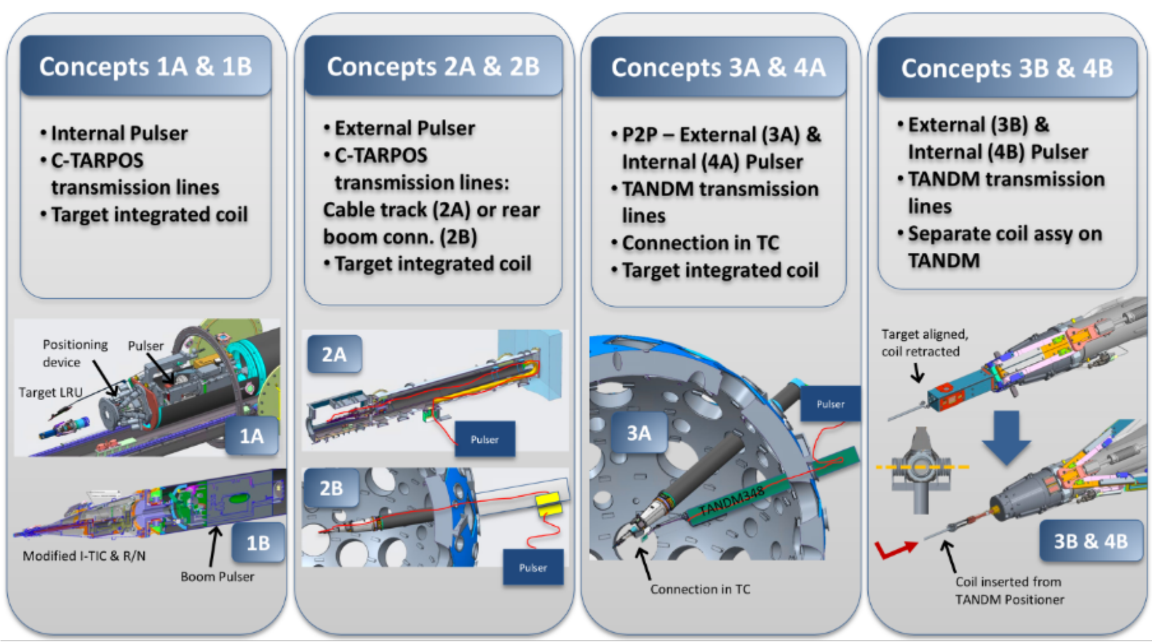


Figure 5-5: MagNIF concepts summary [11]

In order to generate a thorough, well informed set of requirements and downselection from this large suite of potential architectures for the CBF project, a stakeholder analysis was performed. This involved firstly identifying the important stakeholders, then presenting the concepts and plan to them in a large meeting forum, then discussions with them in a more private, one-on-one setting to understand their needs and perspectives on the concepts. Finally, consolidating their input into a ranking system to make an initial downselect to a few concepts that could be developed further and then again paired down to a primary and secondary option. Figure 5-6 shows the Stakeholder Value Network, SVN that was generated with knowledge of the NIF organization and working with experienced members of staff.

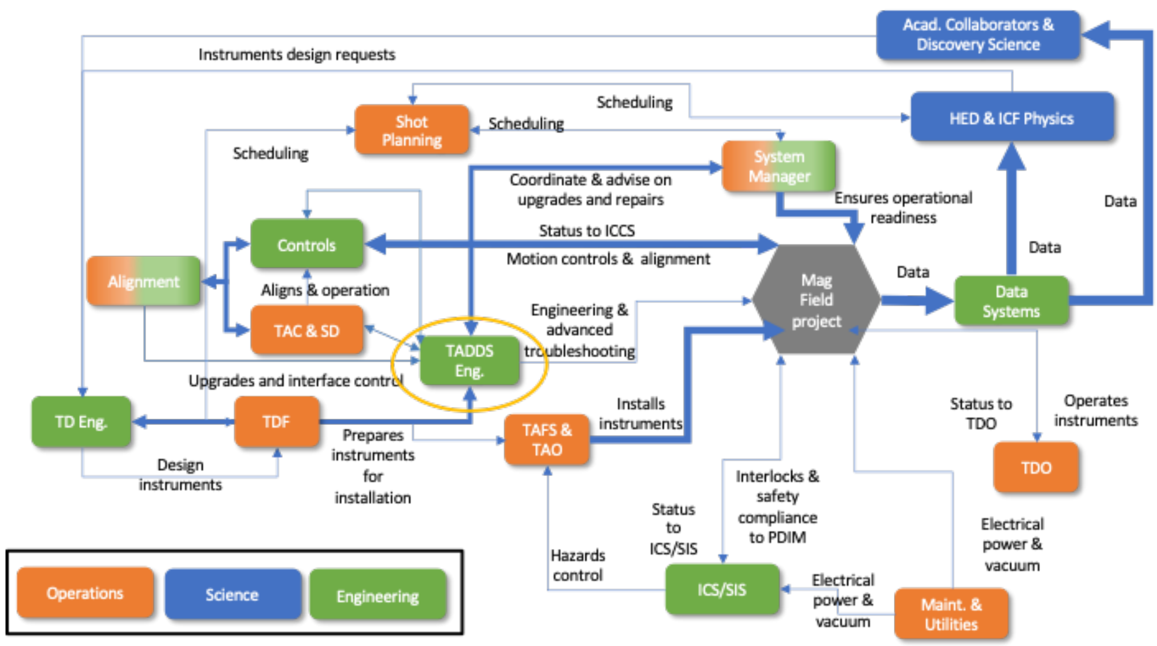


Figure 5-6: MagNIF Stakeholder Value Network, SVN [39]

The Target and Diagnostic Delivery Systems, TADDS team circled above are responsible for the management and implementation of the MagNIF project. Following the introductions of the concepts to the stakeholders, interviews were conducted over a month long window. Table 5.3 shows the 17 primary stakeholders involved in the discussions throughout the month of April in 2020.

Resulting from these conversations, a list of the top eight needs was synthesized for the project. These are shown in table 5.4.

Subsequently, each of these needs or evaluation criteria were assigned a weighting

Table 5.3: MagNIF, CBF Stakeholder interviews summary [11]

#	Stakeholder Groups	Representatives	Attendees	Discussion Date
1	NIF Director	Mark Herrmann	Ayers, Herrmann, Hsing, Kalantar, Kilkenny, Larson, Moody, Bruno V et al., Boehm, Fry, Tang	4/6/2020
2	NIF Facility	Doug Larson & Bruno Van Wonterghem		
3	Physics	Warren Hsing & Andy Mackinnon		
4	NIF Target Diagnostics	Perry Bell & Steven Ross	Bell, Boehm, Fry, Tang	4/10/2020
5	NIF Target Experimental Operations	Tom Kohut	Kohut, Boehm, Fry, Tang	4/9/2020
6	NIF Radiation Safety Officer	Richard Beale	Beale, Fry	*via email*
7	Target Fabrication	Abbas Nikroo & Becky Butlin	Abbas, Butlin, Kroll, Fry	4/14/2020
8	Cryogenic Layering	Suhas Bhandarkar & Bernie Kozioziemski	Bernie, Suhas, Boehm, Fry, Tang	4/15/2020
9	TALIS	Dean Latray	Kalantar, Latray, Masters, Boehm, Fry, Tang	4/17/2020
10	Debris & Shrapnel	Nathan Masters		
11	NIF Cleanliness	Liang-Yu Chen	Chen, Fry	*via email*
12	NIF ICS & SIS	Jeremy Dixon	Brunton, Dixon, Boehm, Fry	4/16/2020
13	Integrated Computer Control System	Gordon Brunton		
14	Alignment	Shannon Ayers & Dan Kalantar	Ayers, Kalantar, Boehm, Fry, Tang	4/17/2020
15	REMS	Shannon Ayers		
16	System Engineering	Tom Parham & Terry Malsbury	Malsbury, Parham, Boehm, Fry, Tang	4/23/2020
17	NIF User Office	Kevin Fournier	Bond, Fournier, Hsing, Kalantar, Boehm, Fry	4/28/2020

Table 5.4: MagNIF Stakeholder needs

ID	Needs (Evaluation Criteria)	SH group
1	Satisfy performance objectives: - Peak B-Field of 50 Tesla - Range of B-Fields from 20 to 50 Tesla	Physics, Facility, All
2	Minimize shot operations impact: - Aim: NIF shot rate unaffected by MagNIF capability	Alignment, Operations, Facility, User Office
3	Minimize time to implementation (shorter schedule)	Physics, Facility, NIF Director
4	System quality attributes, "ilities" (Reliability, Scalability, Maintainability etc.)	Facility, Pulser team, Operations, System Engineering
5	TRL, Technical Readiness Level - Technical Challenge	Cryogenic engineering, Pulser team, ME team
6	CryoTARPOS downtime	Operations, Facility
7	Software & controls development	CEM (ICS/ICCS), Alignment, Operations
8	Project Cost	Facility, TASE (TADDS)

factor that summed to 1. Then, a scoring system of 0 to 3 was used to evaluate how well each concept satisfied each need. The weighting factor was then multiplied by the score and the eight weighting factor-score products were summed to give a total concept score. Figure 5-7 shows the results of the analysis and the three, clear front-running concepts.

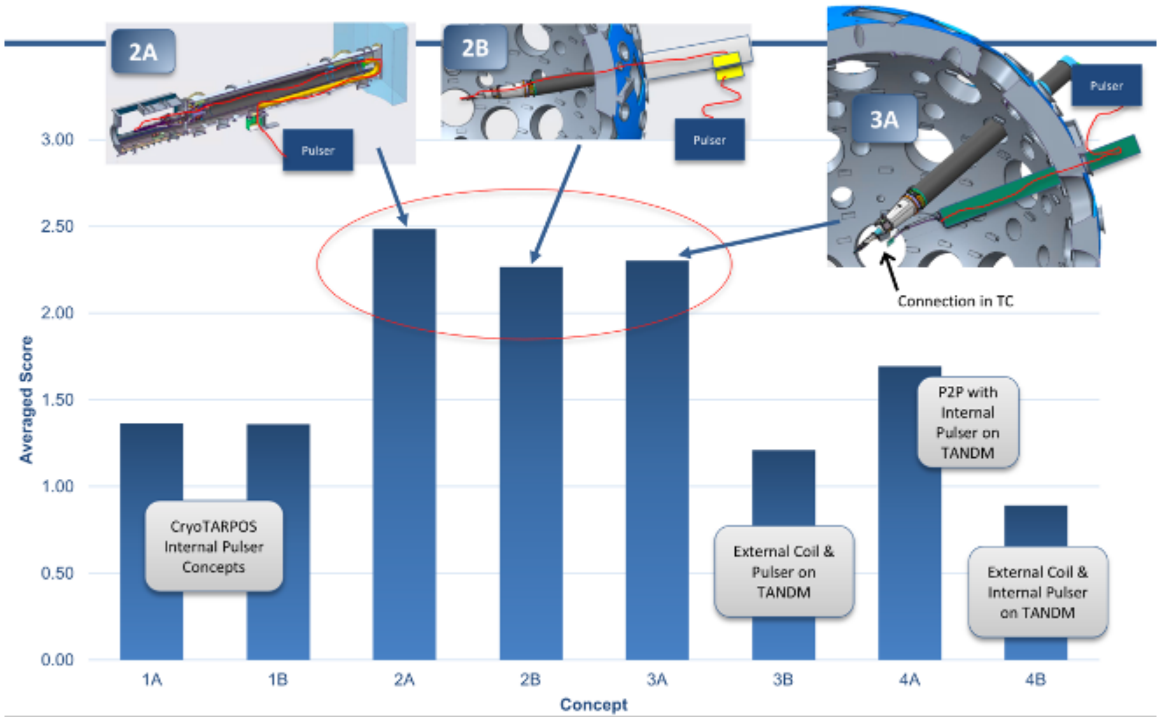


Figure 5-7: MagNIF concepts ranking and initial downselect [11]

Over the following months from June through July 2020, these three concepts were developed further to understand both feasibility in the designs and the balance of risks each had. With input from the Multidisciplinary Design Optimization, MDO study and a more qualitative assessment of the risks, benefits and negatives of each were presented to NIF senior management with the selection of concept 2A as primary and concept 2B as the secondary path forward. The main drivers for this primary path selection were the risks with a remote connection device, the ease of end-to-end qualification preparation testing before experiments and the minimal disruption to interfacing systems.

5.2.3 Concept of Operations, CONOPS

One often overlooked system engineering tool is understanding the use cases and operational context of systems as the design is progressing. For the CBF project, care and time was taken to understand the CONOPS for the system and the high level steps of which are shown in figure 5-8.

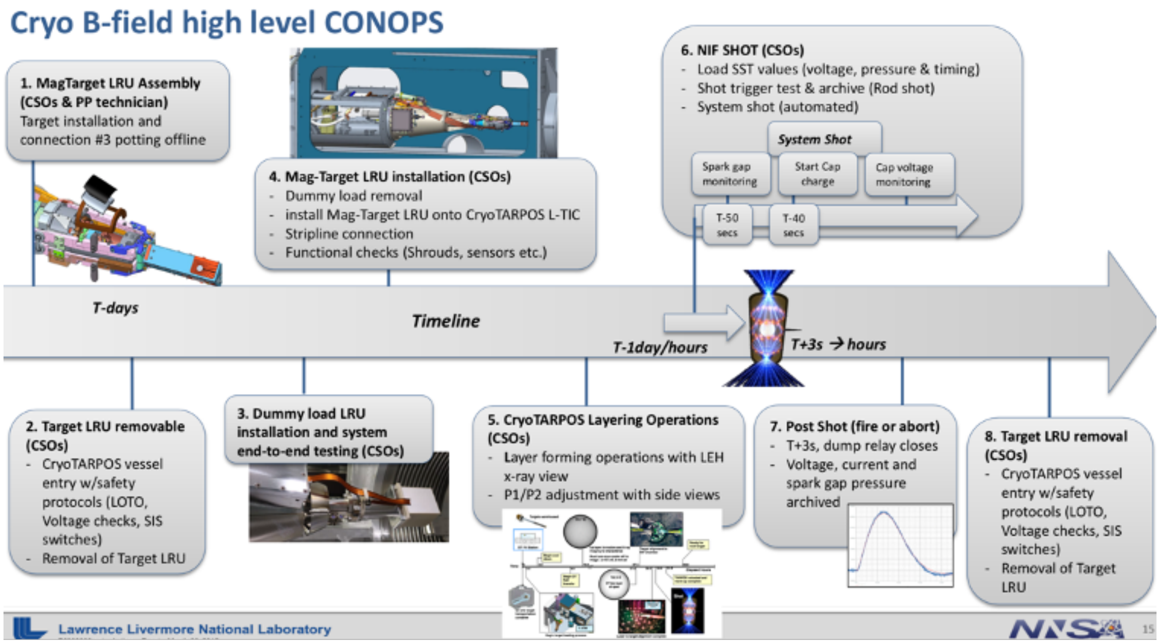


Figure 5-8: MagNIF, Cryo B-Field Concept of Operations [3]

Not only do they provide insight into the online operation of the system, but also the preparation and decommissioning (or removal) phases. For the CBF, this was key in uncovering the pre-installation work that is required to support the assembly of the target and magnetic coil system prior to experiments. Now that this is known, the team can concentrate on the offline facility support to accommodate and understand the roles of interfacing teams to coordinate efforts. Working the CONOPS in parallel with Failure Modes and Effects Analysis, FMEA proved to be hugely beneficial in identifying late, near shot time (laser arrival) failure modes. For example, the worst being a pre-fire of the magnetic pulser system milliseconds before the 192 beams arrive. This has potentially disastrous consequences with backscatter and was deemed to be in the "Significant Program Impact" category meaning that a failure to mitigate could result in a laser downtime of 6 months and millions of dollars' worth of recovery efforts. As a result, the teams are designing a control system to mitigate this failure mode.

5.3 MagNIF Multidisciplinary Design Optimization

5.3.1 Disciplines & Key Sub-systems

For Phase 3 of the NIF Magnetic Field project, there are four main disciplines involved with integration into Laser Driven Fusion. They are all highly coupled and provide the main modules for the system simulation:

1. **Electrical Engineering** – Pulsed Power design of the Magnetic System. This consists of the three sub-systems shown in Figure 5-9: The Pulser, Transmission Lines and Coil. The key components of the Pulser are the high voltage charging supply, capacitor and switch. The capacitor voltage drives its size and the switch allows for the release of charge near shot time. The transmission line consists of two main elements, a flexible stripline or coaxial line and smaller, more delicate twin leads that are closer to the target. Lastly, the coil is wrapped around the hohlraum.

2. **Thermal Engineering** – The cryogenic system shown in Figure 5-9, contains the Helium Gifford-McMahon cooler as well as a conduction path to the target to reach temperatures as low as 14K. The hohlraum and capsule must be kept at 18K for long periods of time, so thermal stability, cooling capacity and cryogenic system margin are all key in providing a robust design. The coil twin leads (transmission lines) are additional sources of heat load to the target. These have to be optimized in order to tradeoff between the thermal and magnetic systems.

3. **Structural Engineering** – The boom structure shown in Figure 5-9, must be adequately designed for low deflection and greater than 3.0 factor of safety

on yield. The mass and location of both the thermal and electrical (magnetic system) flow into this discipline's design and the size of the payload that has to be accommodated.

4. **Project Management** – All three of the disciplines above provide information on volumes, mass and complexity. These have to be managed appropriately, balancing project risk. This is assessed through the implementation costs generated as a result of the magnetic system, cryogenic system and boom structure design.

Figure 5-9 (below) illustrates the main sub-systems that are involved in this multidisciplinary effort.

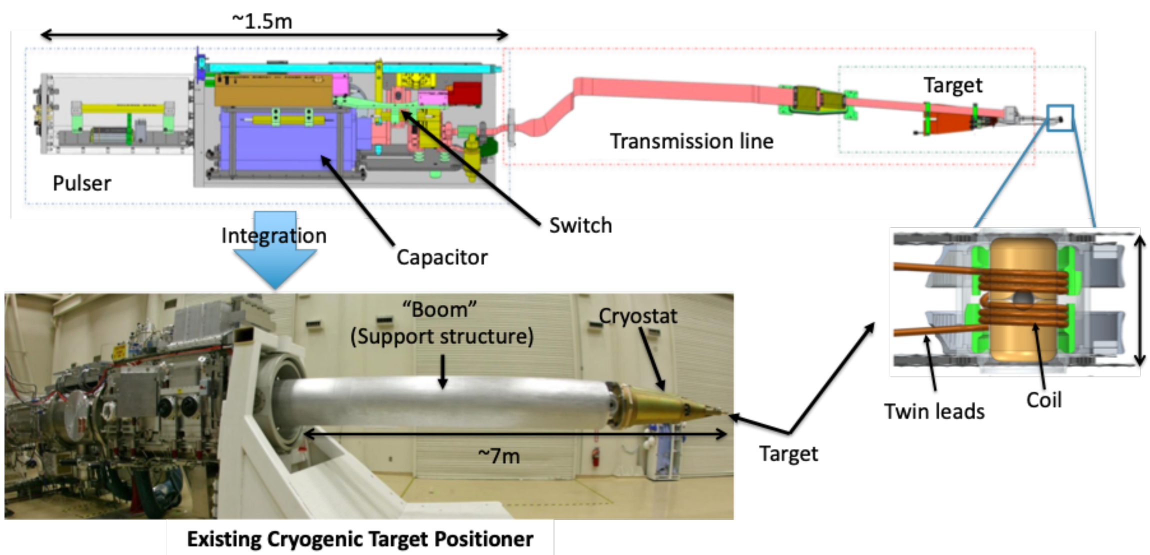


Figure 5-9: Main sub-systems in the magnetic field integration project [83] [13]

5.3.2 Problem Formulation and Models

The purpose and scope of this effort is to minimize the project cost (C) while maximizing the magnetic field (Bpeak) produced by appropriately sizing the magnetic system, cryostat, and boom assemblies using MDO (multidisciplinary design optimization) techniques while satisfying constraints such as a minimum magnetic field within the target capsule volume.

Objectives, Design Variables, Constraints, and Parameters

Table 5.5 highlights the main, identified design variables, constraints and objectives for the MagNIF optimization model.

Table 5.5: Primary Magnetic-NIF Design Variable, Constraint & Objective Table

Symbol	Description	Upper or lower bound/nominal or initial value	Relevant Module	Units	Type
C	Cost	N/A	Cost	$M	Objective
B_{peak}	Magnetic Peak Field	>50	Coil	Tesla	Constraint/Objective
t_{peak}	Circuit risetime	>0.5, <4	Pulser	micro-sec	Constraint
l	Transmission line wire length	0.1 to 0.5	Input	Meters	Design variable
x	Wire gauge	20, 22, 24, 26, 28, 30	Input	Gauge	Design variable
M	Wire material	Cu, Au, Ag, BeCu Sstl	Input	dimensionless	Design variable
N	Number of coil turns	3, 4, 5, 6, 7, 8, 9, 10	Coil	dimensionless	Design variable
V_{charge}	Capacitor charge voltage	20,000 to 80,000	Pulser	V	Design variable/Constraint

Model Diagram and module construction

Figure 5-10 outlines the six module MDO model developed for the MagNIF system. The multidisciplinary modules include structural, thermal (cryogenics) and electrical (pulsed power) engineering disciplines as well as Project Management.

i. Pulser Module

For the Pulser and subsequent modules, multiple references were used to generate and derive the necessary analytical equations [88] [85] [40]. MATLAB was used to model the magnetic system circuit and a lumped sum approach as an RLC (Resistance, Inductance, Capacitance) circuit was adopted. Each element or module was assigned a parameter or dependent variable. The Magnetic System Circuit is shown in Figure 5-11. This module combines the system inductance and resistance to calculate the peak current and circuit rise time (time to peak current). The equations below are

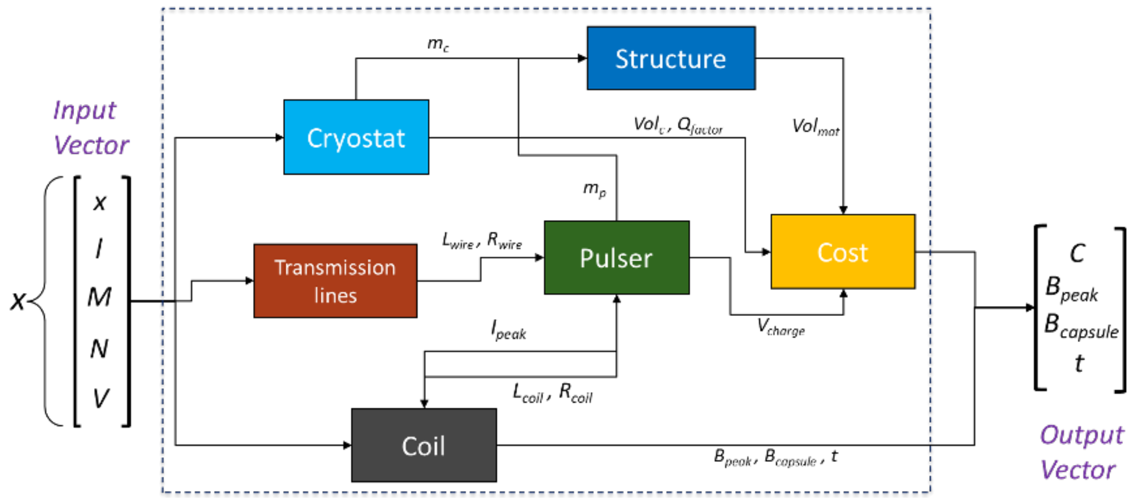


Figure 5-10: Magnetic field integration project MDO model

used to calculate the resultant current delivered to the coil per unit time. The inputs for this module are from both the Transmission Lines and Coil module outputs.

This last equation is not directly utilized in the model, but it gives the energy efficiency of the coupled Pulser-coil system. This also provides another verification that the simulation model is producing an efficient design.

ii. Transmission Line Module

The equations below allow the calculation of the area, inductance and resistance for the transmission line wires. The design variables gauge, wire length and material effect either the resistance or inductance of the twin leads. The stripline section of the transmission line have a far smaller effect on the circuit parameters and are therefore combined in the Pulser resistance and inductance totals.

iii. Coil Module and introduction of ohmic heating

This module provides the coil resistance and inductance that feeds into the Pulser module. In addition, the peak magnetic (B) field can also be calculated and is constrained in subsequent optimizations (next section). The resistance is calculated from the coil wire length, diameter and resistivity (from material). The inductance is a

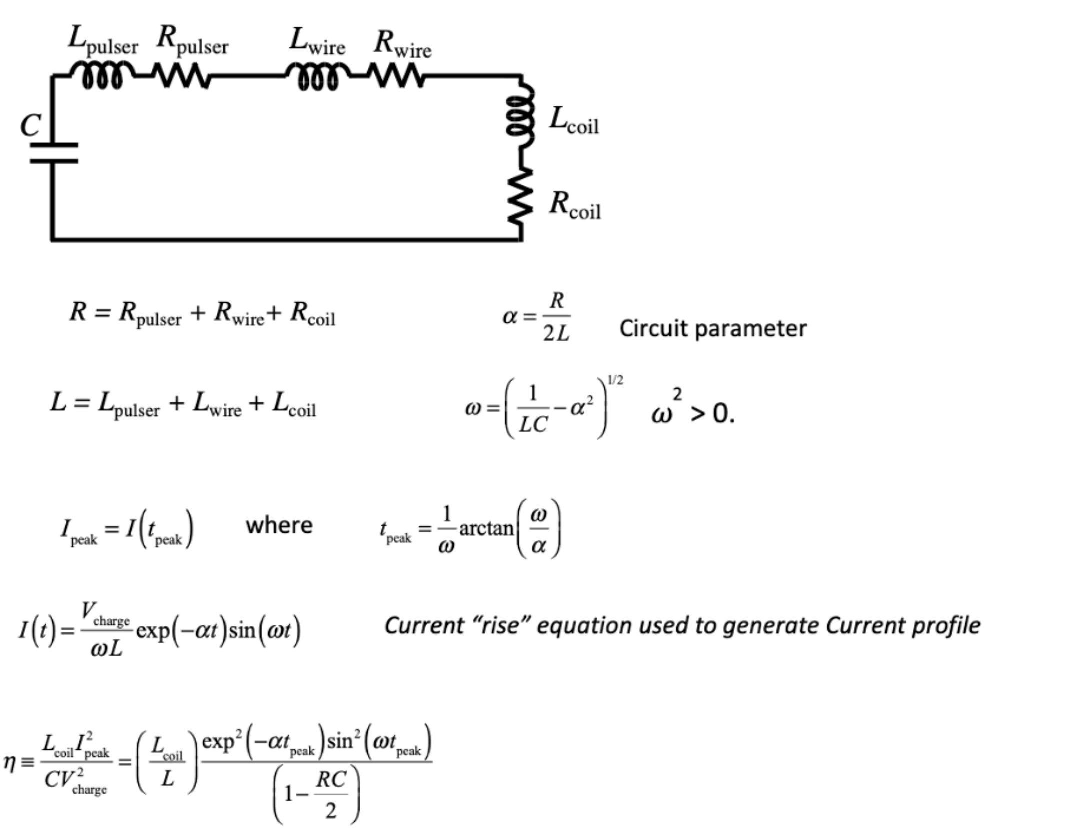


Figure 5-11: Magnetic System RLC Circuit and equations (Circuit diagram from Bill Stygar).

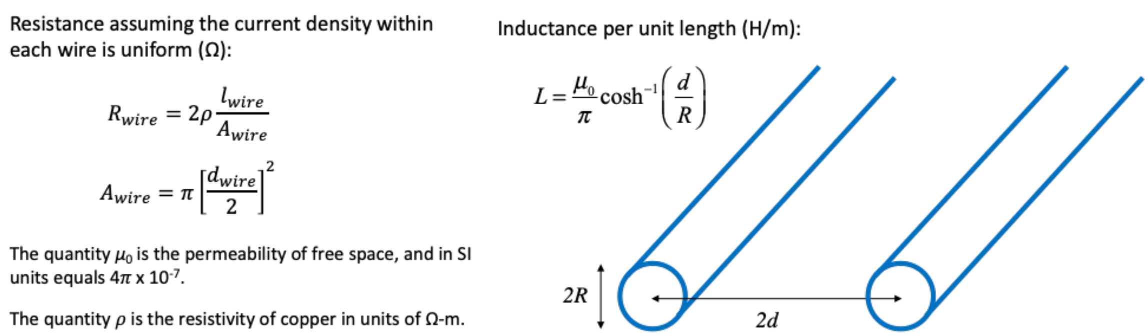


Figure 5-12: Calculating the transmission line (twin leads) dependent variables

complicated calculation that analytically estimates the self-inductance of a system of n coaxial circular loops connected in series and the mutual inductance. In Figure 2.4 below, the coil axis is horizontal and the blue circles represent the cross section of the coil wire turns.

$$L = \sum_{i=1}^{n} L_i + 2\sum_{i=1}^{n}\sum_{j=i+1}^{n} M_{ij}$$

$$L_i = \mu_0 a_i \left[\ln\left(\frac{8a_i}{R_i}\right) - 1.75 \right]$$

$$M_{ij} = \mu_0 \sqrt{a_i a_j} \left[x_{ij} \ln\left(\frac{8\sqrt{a_i a_j}}{r_{ij}}\right) - y_{ij} \right]$$

$$x_{ij} = 1 + \frac{3\alpha_{ij}}{2^4} - \frac{15\alpha_{ij}^2}{2^{10}} + \frac{35\alpha_{ij}^3}{2^{14}} - \frac{1575\alpha_{ij}^4}{2^{22}}$$

$$y_{ij} = 2 + \frac{\alpha_{ij}}{2^4} - \frac{31\alpha_{ij}^2}{2^{11}} + \frac{247\alpha_{ij}^3}{3(2^{15})} - \frac{7795\alpha_{ij}^4}{2^{24}}$$

$$\alpha_{ij} = \frac{r_{ij}^2}{a_i a_j}$$

$$r_{ij}^2 = (a_i - a_j)^2 + d_{ij}^2$$

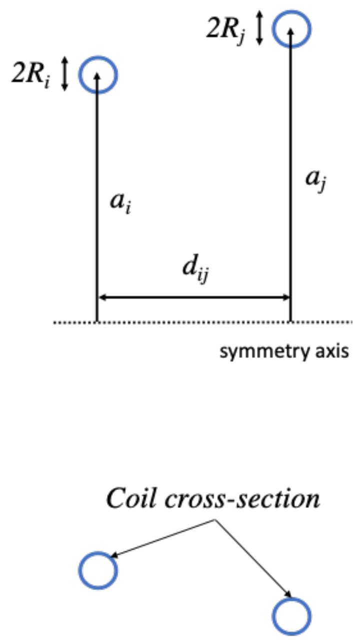


Figure 5-13: Coil inductance calculation and geometry

In order to calculate the magnetic field peak, one needs to estimate the magnetic field along the axis of a system of n coaxial circular current loops using coil loop radius, a, current, I, and distance from the loop, z. This "z" term is included as the outer windings will contribute to the peak field at the coil center. Essentially sum the contributions from each winding to the central, peak B-Field. In addition, the magnetic field at the 3mm diameter capsule wall can be calculated.

When running initial simulations and comparing peak currents to the open source circuit modeler SCREAMER, there was approximately a 4% error in values. An important aspect of the coil physics as the current increases is Ohmic or Joule heating. As the current increases, the wire temperature does as well, thus increasing the resistance. Although this effect seems small, it has large cost implications. In order to calculate current as a function of time, the following second order differential equation was devised.

Figure 5-15 shows two high speed camera video images taken before (2 µs) and after (20 µs) after peak current has reached the coil. The image to the right shows substantial coil motion and plasma from the melted coil. The previous equations can

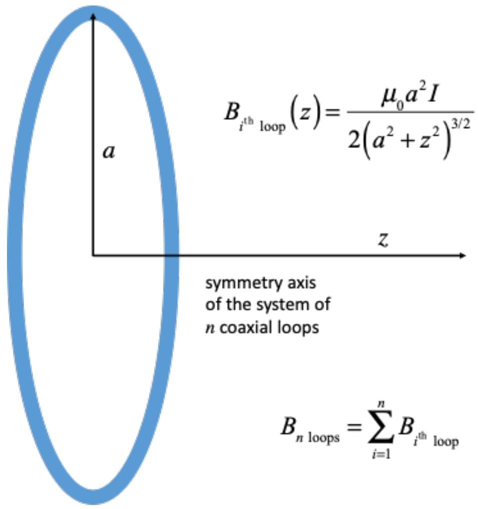


Figure 5-14: Calculating B-Field from coil windings and geometry

$$\left(L_{\text{pulser}} + L_{\text{coil}}\right)\frac{d^2Q}{dt^2} + \left(R_{\text{pulser}} + R_{\text{coil}}\right)\frac{dQ}{dt} + \frac{Q}{C} = 0$$

where $$I(t) = \frac{dQ(t)}{dt} \qquad R_{\text{coil}}(t) = f\left(\int_0^t I^2 R_{\text{coil}}\, dt\right)$$

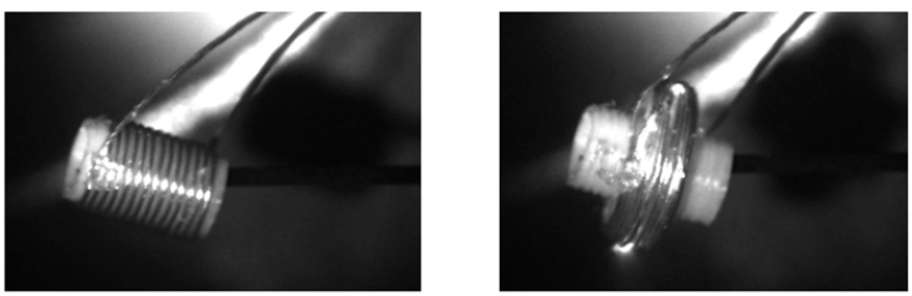


Figure 5-15: Second order differential equation and high speed video images for a test coil pulse experiment [13] (Coil video stills from E. Carroll).

be expressed in the discretized form given below. These discretized equations can be used to calculate numerically the current at time step n+1, given circuit parameters at time step n. They are combined in a for loop in MATLAB to output the charge, Q, resistance, Rcoil, Current, I and Ohmic energy in the coil, E.

The more accurate, resultant current is then used to calculate the magnetic field.

$$I_{n+1} = \frac{\left(\frac{-Q_n}{C} - \left(R_{\text{pulser}} + R_{\text{coil},\,n} \right) I_n + \left(L_{\text{pulser}} + L_{\text{coil}} \right) \frac{I_n}{\Delta t} \right) \Delta t}{\left(L_{\text{pulser}} + L_{\text{coil}} \right)}$$

$$Q_n = Q_{n-1} + \frac{\left(I_n + I_{n-1} \right) \Delta t}{2}$$

$$R_{\text{coil},\,n} = f\left(E_n \right)$$

$$E_n = E_{n-1} + \frac{R_{\text{coil},\,n-1} \left(I_n + I_{n-1} \right)^2 \Delta t}{4}$$

$$I_0 = 0 \qquad Q_0 = CV_{\text{charge}} \qquad E_0 = 0$$

$$R_{\text{coil},\,0} = \text{the initial coil resistance}$$

Figure 5-16: Discretized form equations

iv. Magnetic System Validation

The magnetic system modules were validated by using both circuit modeler software (SCREAMER) and empirical data obtained from b-dot probe measurements.

For current wave forms generated at different capacitor charge voltages (Figure 5-17), the MATLAB outputs were compared to the SCREAMER simulation software. Before the ohmic heating action addition, these were in agreement within 4 percent. However, this dropped down to much less than 0.1 percent deeming the module to be very accurate.

In order to validate the peak magnetic field that the MDO model was predicting, a 6-turn copper coil output was compared to empirical data. These were in agreement to approximately 3 percent. This was likely in the bounds of the measurement error.

v. Cost Module

This module utilizes the output of the Pulser Module, the required charge voltage. From an electrical standpoint, the main cost driver in this system design is the capacitor volume and the amount of high voltage connections needed. The capacitor volume

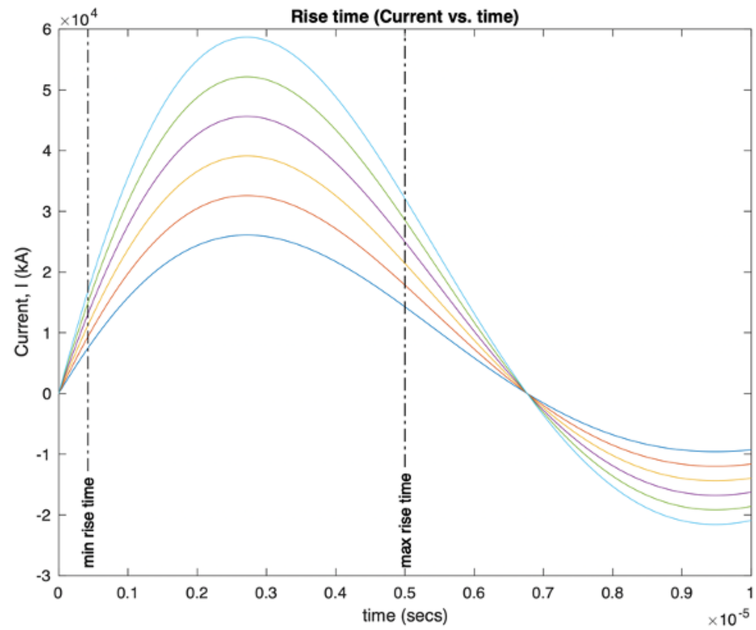


Figure 5-17: MATLAB output graphs of current versus time for different charge voltages

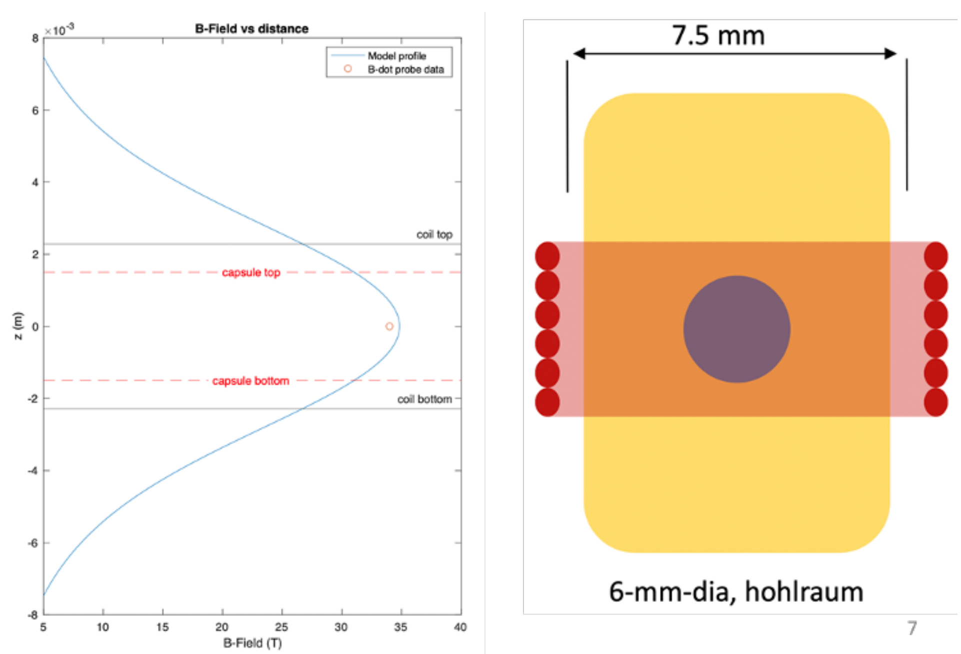


Figure 5-18: MATLAB output graph of B-field along hohlraum axis compared to empirical peak data (Hohlraum sketch from Bill Stygar).

is proportional to the square of the charge voltage. As a baseline, the warm (room temperature) platform of this project has a 0.012 m^3 ICAR capacitor with a maximum charge voltage of 40 kV. The project design and implementation (total project) cost for this baseline capacitor is known and can be scaled with voltage squared. However, if the charge voltage exceeds 40 kV, there will be additional expenses incurred for more connection development as the capacitor (and Pulser system) will have to be positioned outside of the vacuum vessel and at least 200 ft from the target coil.

$$Cost_{\text{Pulser}} = Cost_{\text{factor}} * Vol_{\text{cap}} + Con * Con_{\text{factor}}$$

$\text{Cost}_{\text{factor}}$ gives $\$/\text{m}^3$, Vol_{cap} is the volume derived from a squared voltage ratio with the existing capacitor. Con is the number of connections (=0 if required charge voltage < 40 kV). $\text{Con}_{\text{factor}}$ is a cost generated from project experience for the design, development, testing and implementation of a new connection design.

From the additional modules one can generate a new total cost output and the single objective function:

$$Cost_{\text{Total}} = Cost_{\text{Pulser}} + Cost_{\text{Cryostat}} + Cost_{\text{Boom}}$$

vi. Cryostat & Structural Modules

The Cryostat Module's purpose is to determine the cryostat mass, volume, and thermal capacity. The design variables material, wire length, and gauge provide input to the module algorithm to determine heat energy and the heat energy factor (against a 50% margin). Depending on the heat energy factor, the algorithm selects the cost and mass of the cryostat unit from five discrete options.

$$Q = \frac{2A_{\text{wire}}\kappa\Delta T}{l_{\text{wire}}}$$

The Structural Module's purpose is to incorporate the cost of the cantilevered, tubular boom structure to the overall cost of the project. It accepts payload (mass) inputs from the cryostat and Pulser modules and outputs the boom cost to the cost module. The cost of the structure varies by mass (using historical cost data from similar structures) and depends on the load applied by the cryostat and the Pulser. The boom structure's factor of safety (von Mises), cross-sectional shape (circular), interior diameter, material (aluminum), were considered parameters while the wall thickness varied in response to the payload input to meet the factor of safety.

$$Safety\ Factor, SF = \frac{\sigma_{\text{yield-Al}}}{\sigma_{\text{von-mises}}} = 3$$

$$where\ M_{\text{B}} = l_{\text{B}} P_{\text{payload}}$$

$$\sigma_{\text{b}} = \frac{M_{\text{B}} c}{I}$$

$$\tau_{\text{max}} = \frac{2P_{\text{payload}}}{A}$$

$$\sigma_{\text{vm}} = \sqrt{{\sigma_{\text{b}}}^2 + 3{\tau_{\text{max}}}^2}$$

5.3.3 Single Objective Optimization of Cost

Initial Design of Experiments Exploration

The Parameter Study technique was chosen for the initial exploration of the design space. Table 5.6 below shows the changing of levels and factors. For this technique, one variable (factor) is changed at a time to a different level. For the initial model, 3 levels for each of 3 design variables were chosen for a total of 7 experiments. Parameters were set as shown in Table 5.6 for each simulation.

To determine the best design, comparisons were made with experiments in sets where only one parameter was changed. The experiment set containing 1, 2, 3, showed that wire gauge has a small effect ($0.53M across the range) on cost. The experiment set containing 1, 4, 5, showed that wire length has a significant cost effect ($14.37M across the range). Lastly, the experiment set containing 1, 6, 7, showed that the material also has a significant cost effect ($75.59M across the range). The higher the gauge, the smaller the cross-sectional area and the more voltage is required to push the current through the coil. Material has potentially a significant effect as resistivity can change dramatically from material to material. Stainless steel wire requires a very high, likely infeasible voltage to generate the required field and thus the cost is also excessive. The best design at the time and a good starting point for optimization was the configuration – 24 wire gauge, 155 mm wire length, and Cu material.

Table 5.6: DOE, Initial Parameter Study table for MagNIF

Expt #	Wire gauge	Wire length (mm)	Material	COST ($M)	B-Peak (T)
1	24	155	Cu	8.19	53.29
2	25	155	Cu	8.42	53.47
3	26	155	Cu	8.72	53.65
4	24	500	Cu	17.66	53.29
5	24	1000	Cu	22.56	53.29
6	24	155	Au	8.46	53.29
7	24	155	Sstl	83.78	53.29

Exploring a Gradient-based Method

As three of the five design variables are discrete (x_g, M and N) it was not possible to initially utilize a gradient-based algorithm to explore and minimize the objective function, Cost. However, by modifying the gauge to represent the wire diameter, it could be used as a continuous variable with lower and upper bounds. This, along with the continuous variable, length (l) could be used with an SQP algorithm (fmincon in MATLAB) to identify the Cost local and global minima with the following for an initial run:

- Material, M was initially set to copper [resistivity of 1.68x10^{-8} ohm-meters, thermal conductivity integrals 1520 W/cm (300k) and 61.4 W/cm (15K)].
- Number of turns was initially set to N = 10.
- Coil inner diameter, d was set to 7.5 mm.
- Peak current, I was set to 48 kA and charge voltage was allowed to float.

At first Sequential Quadratic Programming (SQP) was chosen as the optimizer because it is considered one of the best gradient-based algorithms as well as being fast to converge. In addition, it is a convenient function to use in MATLAB. There are weaknesses similar to other gradient-based methods of potentially selecting a local minima depending on the initial starting point design variables. In addition to the SQP algorithm, it was decided to test the Nelder-Mead simplex direct search in MATLAB (fminsearch) with the same variables/parameters listed above.

For the SQP optimization, the single (pseudo) objective function was:

$$z(x_g, l) = Cost_{\text{Pulser}} + Cost_{\text{Cryostat}} + Cost_{\text{Boom}} + p((\frac{B_{peak}}{50} - 1)^2)$$

The B-field peak constraint of being at least 50 Tesla was normalized and added to the total cost utilizing the quadratic penalty function. The lower and upper bounds of the wire diameter and length were controlled in the fmincon script below. Various initial points, x0 were used in each optimization, and the results are shown in Table 5.7.

Table 5.7: SQP optimization with different initial points

Initial guess, x0	**Optimized variables, x***	**Objective function (z) (g in the code)**	**Actual Cost (f)**
[0.00035, 0.6]	[0.0006, 0.6]	3.51934×10^{37}	$18.768M
[0.000175, 0.3]	[0.0006, 0.4954]	3.51934×10^{37}	$17.933M
[0.0006, 0.3]	[0.0006, 0.3]	3.51935×10^{37}	$10.095M
[0.0001, 0.25]	[0.0006, 0.255]	3.51934×10^{37}	$9.7450M

Unlike heuristic methods, this gradient-based function is extremely dependent on the starting point as it converges on local minima and stationary points. The difference seen is an almost halving in cost. What is also interesting is that the optimum x* is not at a length of 0.2 m. The wire diameter being at its maximum makes sense but the cryogenic vs. pulse power trade off definitely favors the electrical discipline but there is compromise so that there is not the largest, most expensive undertaking by the cryogenic engineering team.

The MATLAB function fmincon was used to conduct the sensitivity analysis. X* is left at the optimum and multiple parameters and constraints are changed one by one to understand which have the greatest effect on the cost. Table 5.8 shows the results:

B-Field, coil internal diameter and wire gauge (diameter) are the main active constraints. In fact, increasing the internal diameter of the coil has major implications

Table 5.8: SQP optimization with varying parameters

Initial guess, x0	Coil Material variable (M)	Coil diameter constraint value (d)	B-Field constraint value (T)	# of coil turns, N	Optimized variables, x*	Objective function (z) (g in the code)	Actual Cost (f)
[0.0001, 0.25]	Copper	7.5mm	50	10	[0.0006, 0.255]	3.51934×10^{37}	$9.7450M
[0.0001, 0.25]	SSTL	7.5mm	50	10	[0.0006, 0.255]	3.51934×10^{37}	$83.828M
[0.0001, 0.25]	BeCu	7.5mm	50	10	[0.0006, 0.255]	3.51934×10^{37}	$17.483M
[0.0001, 0.25]	Copper	10.5mm	50	10	[0.0006, 0.255]	9.3928×10^{37}	$87.687M
[0.0001, 0.25]	Copper	7.5mm	60	10	[0.0006, 0.255]	7.71597×10^{37}	$72.074M
[0.0001, 0.25]	Copper	7.5mm	40	10	[0.0006, 0.255]	1.0508×10^{39}	$9.7430M
[0.0001, 0.25]	Copper	7.5mm	50	6	[0.0006, 0.255]	4.3295×10^{38}	$58.73M
[0.0001, 0.25]	Copper	7.5mm	50	3	[0.0006, 0.255]	1.6577×10^{39}	$49.822M

on cost as expected. Also, material has a large effect as the increase in resistivity can really hinder the current, thus requiring a bigger, more expensive electrical system. What is quite surprising is the change in cost from 40 to 50 Tesla (magnetic field) vs. 50 to 60 Tesla. Getting above 50 Tesla costs an order of magnitude more whereas below 50 Tesla does not make much of a difference in terms of cost.

Although the coil internal diameter is the most active constraint, the B-field peak is the most interesting and the second most active. The optimizer was re-ran for 45T and 55T peak B-field constraints respectively. At 45T, the optimal point is [0.0006, 0.2547] - $9.8M, and at 55T, this is at [0.0001, 0.2500] - $72M. It is hard to intuitively understand this large cost jump and the minima at such a small size of wire for the 55T case. However, the costs of both the boom (supporting structure) and Cryostat must start dominating and so the optimizer tries to compromise on the electrical side (smaller wires = less cryogenic capacity).

Relaxing the coil internal diameter is impossible as the spatial constraints cannot change. In addition, to have successful physics results the full 50T is required. There could be errors in physics models that mean that this could be potentially +/-10% but the more margin the better, so 50T is also a hard constraint. The real conflict in this model is the wire lead length. The cryogenic subsystem wants it to be as long as possible where the opposite is true for the electrical, pulse power system.

Settling on a Heuristic Method

After exploring the SQP gradient-based method, the SA (Simulated Annealing) technique was ultimately selected as a reliable search method for good (as opposed to true optimal) design options that will satisfice the needs. With both discrete and continuous design variables, a heuristic method allowed for full exploration of the design space (unlike the SQP study where some variables were changed to parameters) to help solve - a believed to be - complex, nonlinear, non-convex problem. SA was particularly appealing due to its search options such as the annealing schedule of temperatures to broadly search the design space at first and then focus on a smaller zone later in the run. The perturbation function also played a factor in the selection as it was felt to be comfortable with managing the discrete variable design options in that manner. Cost (z in pseudo-objective below) was selected as the objective function for which to optimize the system because unit cost plays a prominent role in design selection for the primary stakeholder due to project funding constraints (see discussion in Chapters 2 and 3). Tuning parameters were explored and are shown in Table 5.9 below by selecting a range of inputs to explore for each parameter. After exploring each parameter's impact to the peak magnetic field and cost, the parameter set shown as Trial 27 in Table 5.9 was settled on. Significant cost variances were observed suggesting that tuning the search parameters and finding the right settings are key to confidently locating potential design configurations. In particular, it was found that increasing the schedule parameter was the most effective in getting to the lowest cost complying with constraints. Trial 27 initially had the most optimal solution at $9.43 million.

After that initial SA parameter tuning study, the model was further refined to include ohmic heating in the Coil module and converted the Pulser charge voltage from a dependent variable to a design variable. The final objective function utilizes a quadratic penalty to enforce the peak B-field ($\geq$ 50 Tesla) and charge voltage ($\leq$ 80kV) constraints and is formulated as:

Table 5.9: Simulated Annealing, SA parameter tuning

		Simulated Anealing Tuning Parameter Study													
		SA Options								xbest					
		To	schedule	dT	neq	nfrozen	diagnostics	B_peak	Cost	gauge of wire	length of transmission	Wire Material Cu=1; Au=2; sstl=3; Ag=4; BeCu=5;	Coil Turns	Coil ID	Iterations
Trial	Parameter Exploration									x_g	l	M	N	d	
1	To	100	1	0.5	10	3	0	51.67	1.84E+07	2	0.203	2	7	0.007	113
2	To	1	1	0.5	10	3	0	8.44	4.63E+07	5	0.207	1	6	0.041	20
3	To	10	1	0.5	10	3	0	50.25	1.19E+08	2	0.201	3	7	0.007	102
4	To	200	1	0.5	10	3	0	50.14	1.69E+07	2	0.204	5	7	0.008	109
5	To	500	1	0.5	10	3	0	49.26	2.81E+07	1	0.206	1	7	0.008	107
6	schedule	100	0.1	0.5	10	3	0	48.53	1.72E+07	4	0.241	2	8	0.007	120
7	schedule	100	1	0.5	10	3	0	51.67	1.84E+07	2	0.203	2	7	0.007	113
8	schedule	100	10	0.5	10	3	0	50.80	9.68E+06	4	0.231	4	7	0.007	109
9	schedule	100	100	0.5	10	3	0	51.52	2.81E+07	2	0.202	1	7	0.007	105
10	schedule	100	200	0.5	10	3	0	50.51	9.86E+06	1	0.202	5	7	0.007	126
11	dT	100	1	0.1	10	3	0	48.28	9.06E+06	2	0.219	4	8	0.007	106
12	dT	100	1	0.5	10	3	0	51.67	1.84E+07	2	0.203	2	7	0.007	113
13	dT	100	1	1	10	3	0	47.77	9.40E+06	1	0.241	2	8	0.007	105
14	dT	100	1	1.5	10	3	0	49.20	2.80E+07	1	0.202	1	7	0.008	104
15	dT	100	1	2	10	3	0	51.83	2.45E+08	4	0.201	3	7	0.007	112
16	neq	100	1	0.5	0.1	3	0	NC	NC	NC	NC	NC	NC	NC	>350
17	neq	100	1	0.5	50	3	0	NC	NC	NC	NC	NC	NC	NC	>350
18	neq	100	1	0.5	10	3	0	51.67	1.84E+07	2	0.203	2	7	0.007	113
19	neq	100	1	0.5	5	3	0	46.08	2.80E+07	5	0.201	4	7	0.008	68
20	neq	100	1	0.5	2	3	0	Error	Error	Error	Error	Error	Error	Error	Error
21	nfrozen	100	1	0.5	10	0.1	0	51.63	1.04E+07	1	0.212	4	7	0.007	109
22	nfrozen	100	1	0.5	10	1	0	48.56	2.78E+07	5	0.201	4	7	0.008	65
23	nfrozen	100	1	0.5	10	3	0	51.67	1.84E+07	2	0.203	2	7	0.007	113
24	nfrozen	100	1	0.5	10	5	0	50.70	1.25E+07	5	0.211	2	7	0.007	161
25	nfrozen	100	1	0.5	10	10	0	50.75	2.78E+07	5	0.213	1	7	0.007	248
26	diagnostics	100	1	0.5	10	3	0	51.67	1.84E+07	2	0.203	2	7	0.007	113
27	diagnostics	100	1	0.5	10	3	0.1	50.30	9.43E+06	4	0.207	4	7	0.008	102
28	diagnostics	100	1	0.5	10	3	0.5	47.91	1.85E+08	3	0.204	3	8	0.007	112
29	diagnostics	100	1	0.5	10	3	1	48.33	1.86E+07	3	0.222	5	8	0.007	125
30	diagnostics	100	1	0.5	10	3	10	49.93	1.04E+07	1	0.223	1	7	0.007	104

$$z(x_g, l, M, N, V) = \begin{matrix} Cost_{\text{Pulser}} + Cost_{\text{Cryostat}} + Cost_{\text{Boom}} + \\ + p[max\{0, (1 - \frac{B_{peak}}{50})\}^2 + max\{0, (\frac{V_{charge}}{80000} - 1)\}^2] \end{matrix}$$

The SA based optimization minimized cost to \$10.3M dollars with the design variables set to: 22 wire gauge, .255m wire length, copper material, 10 coil turns, with a 40kV pulser voltage. To better understand the cost sensitivity of the design variables, the full range of each variable, one at time was explored. The variable under exploration remained a variable while all others were set as parameters to the values shown in Figure 5-19.

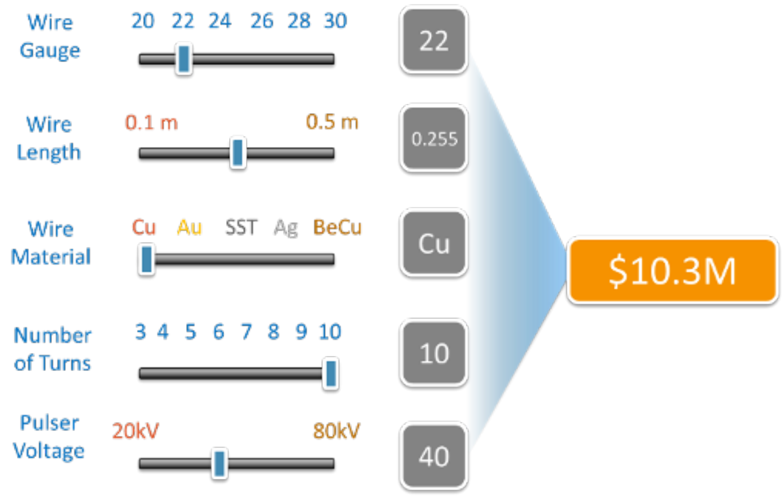


Figure 5-19: Recommended design of $10.3M based on Simulated Annealing cost optimization

Although these plots only represent small slices of the design/objective space, they were found to be insightful. One of the more sensitive variables is wire length. The plot to the left in Figure 5-20 shows cost versus wire length and suggests that cost varies from ~$10M to ~$30M depending on the wire length selected. The 0.255m recommendation makes sense because it is the shortest option before the thermal system needs a significant upgrade, shifting to a much more expensive unit. Another interesting plot is cost versus voltage, shown in Figure 5-20 (right), where cost increases significantly when the voltage selected is above approximately 40kV. The 40kV recommendation also makes sense as it represents the largest voltage just before a significant cost increase represented by the increased slope between 40kV and 42kV. If the Pulser system requires more than 40kV, the Pulser has to move to an external location. This dramatically increases design costs (at least 1.5x). However, an interesting insight here is that although the external Pulser may have a greater upfront cost, there are huge benefits in accessibility, maintainability and reliability (the "illities") which are hard to quantify in a cost without having prior experience fielding a similar system. This ties in nicely with the Spring 2020, 16.888 class, MDO guest lecture by Prof. Quim Martins who highlighted that "Optimization is really an exploration" and is not necessarily the complete answer but is a vital tool to get us close to a final design. There is high confidence that a good low-cost design near a true global optimum is found due to the broad initial search space explored by the annealing schedule.

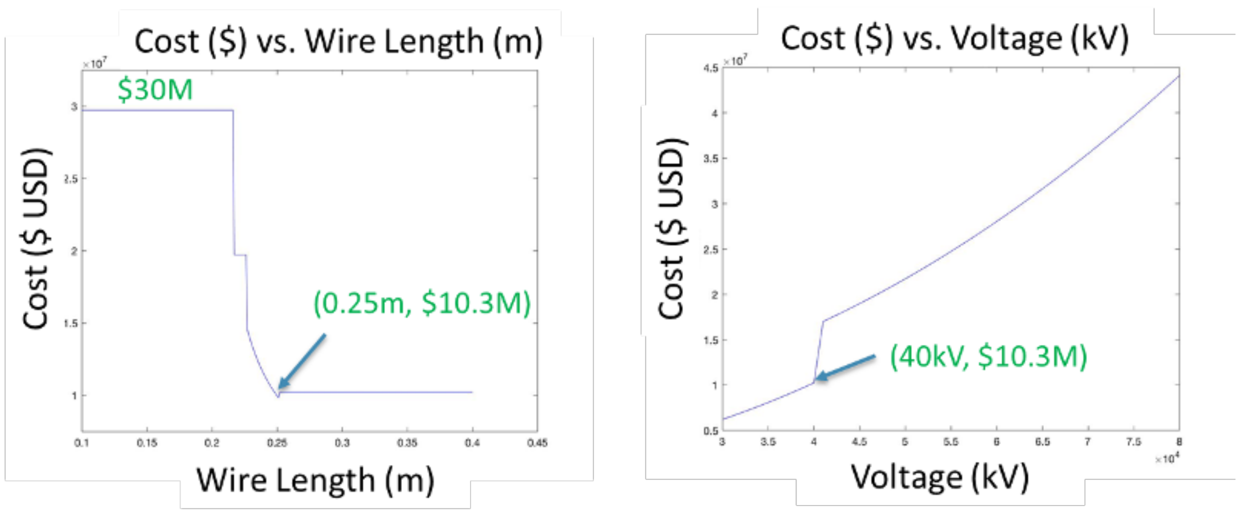


Figure 5-20: Sensitivity exploration plots of the recommended $10.3M design

5.3.4 Multi-Objective Optimization of Cost and B-Field

The two objective functions, Cost (J_1 - original objective) and B-Field (J_2 - new objective), were strategically selected to study the tension-type relationship between the most critical performance objective (B-Field) and the greatest real-world constraint (Cost). B-Field was selected as the most important performance type objective due to the desire to consider a wide range of optimal designs for varying B-Field values. This allowed the potential architecting of the system for multiple configurations to run experiments at varying B-Field values. To optimize the system for both objectives simultaneously, the heuristic method of Simulated Annealing was selected with the Weighted Sum approach due to its ability to analyze the mix of discrete and continuous variables. The total objective function (J) below was formulated by adding the two scaled (with α and β) pseudo-objective functions using the quadratic penalty function to incorporate the two scaled inequality constraints placed on the maximum voltage and minimum B-Field. Varying lambda values were used to step through the optimal points (design options) on the Pareto frontier. A full factorial plot was generated to validate the direct Pareto method. The B-Field inequality constraint was reduced from ≥ 50 to ≥ 30 Tesla to explore lower cost options in the 30 Tesla performance range. A charge voltage inequality constraint was again used to limit the design space to ≤ 80 kV. The pseudo-objective function:

$$J = \begin{array}{l} \frac{\lambda J_1}{\alpha} - \frac{(1-\lambda)J_2}{\beta} + \\ \quad + p[max\{0,(1-\frac{B_{peak}}{30})\}^2 + max\{0,(\frac{V_{charge}}{80000}-1)\}^2] \end{array}$$

was formulated for the multi-objective optimization. Greater than 80 kV charge voltage would significantly complicate the design, introduce other challenges and require additional cost drivers. To meet project goals, one does not likely need these extremely high magnetic fields, so the charge voltage was constrained accordingly. In order to scale the two competing objectives, alpha and beta were chosen and honed from multiple runs. These resulted in $\alpha = 1\times10^6$ and $\beta = 5$. The full factorial objective space and shape of the Pareto frontier is shown in Figure 5-21. The tradespace plot shows blue x points that represent weighted sum output points and the red trace represents an interpolation of those points that represents the Pareto frontier. Overall, the shape is convex with several local non-convex (concave) regions that appear to be related to the discrete variable dependent cost module.

Further examination of the plot reveals that the SA optimizer with the Weighted Sum approach did not output any points in the region of magnetic field ~50 to ~70 Tesla. The Adaptive Weighted Sum technique would have been advantageous here for better distribution but there would be difficulties with the discrete variables. To validate the interpolation, the full factorial was plotted, shown as the square points and they appear to match up fairly well to the Weighted Sum outputs. It can also be seen that the full factorial enumeration of designs produced a few points more optimal than the Pareto front in the high field regions. This could be due to the resolution of the SA and potentially the convergence parameters that were tuned. In

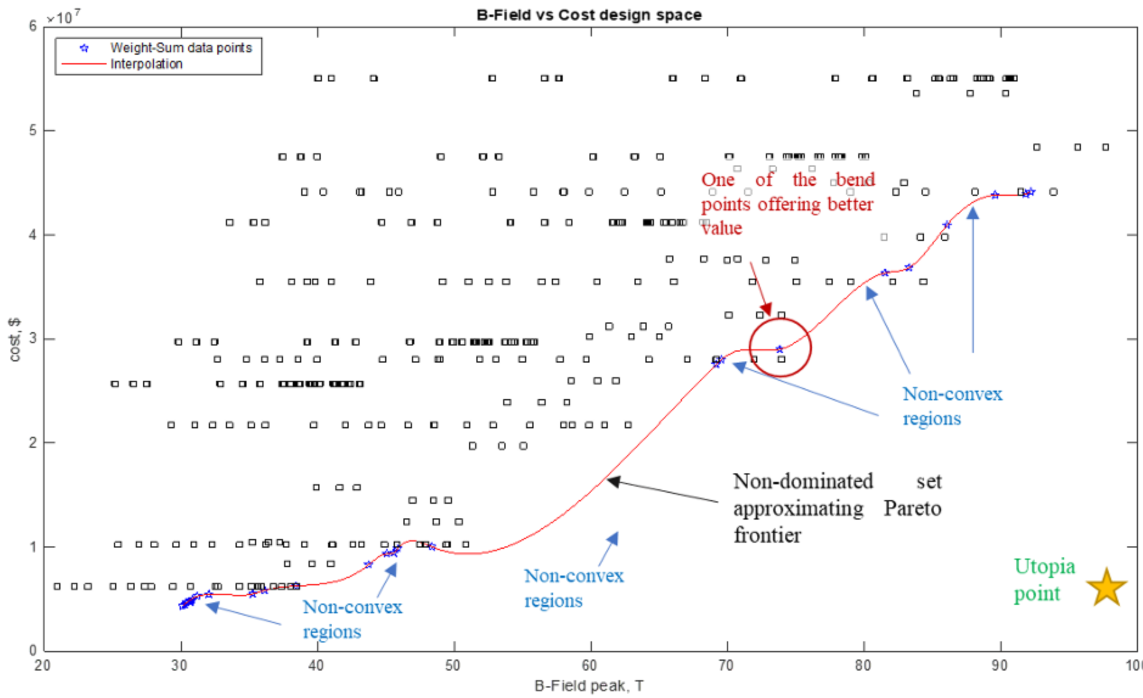


Figure 5-21: Full factorial enumeration of the objective space – B-Field [T] vs. Cost [$] showing the Pareto frontier

addition, this region requires more work as the analogous costing function used could be less accurate with this higher TRL type implementation. With the selection of the Weighted Sum method, scaling of the weights was critical to truly explore the optimal relationship between the two objectives. The model was run over 25 times to explore the full range of λ values from 0 to 1, in 0.05 increments with additional points closer to concave areas. Without proper scaling with $\alpha = 1\times10^6$ dollars, and $\beta = 5$ Tesla, the weights assigned would be ineffective. Varying the weights had a significant impact in the trial runs. When exploring the lower λ values, cost carried little weight and allowed the optimizer to search for larger B-Field options with almost no regard for cost. When exploring the higher λ values, B-Field carried little weight and allowed the optimizer to search for lower cost options while meeting minimum B-Field values. However, the cost influence was a little greater as the algorithm seemed to favor it over B-Field when λ was close to ~0.35, not at the midway point. It would be hard to get this perfect due to the rapid change of cost from single digit millions to tens of millions and would potentially require different scaling at different areas of the Pareto front. This exploration of the design space for the MagNIF design of a magnetic booster system showed that even small design changes at the subsystem level can generate large differences in programmatic outcomes in terms of cost and overall system complexity.

5.3.5 Final Recommendation

To select the final design options, the bends along the Pareto front that represent large performance gains with minimal added costs were explored. In the representation of the tradespace shown in Figure 5-21, the bend points furthest to the right represent excellent value. To provide a range of B-Field options (46 – 76 Tesla), 4 design options shown below in Table 5.10 were selected. There is hesitation to recommend any design options greater than approximately 75 Tesla because the added fusion benefits in this range are undetermined. The baseline physics model suggests that there are no more benefits above approximately 60 Tesla. Design point 1 and 2 are similar, representing the lower cost range and offer 2 wire material options – copper or gold. Design options 3 and 4 offer greater B-Field values but with significantly more cost. Ideally, one would recommend design option 4 due to its large B-field capability but offer a list of excellent design choices for a range of budgetary constraints. Although this option is more costly, an external Pulser has huge benefits in accessibility, maintainability, reliability (the "illities") as well as scalability.

5.3.6 Learnings and Future Work

Throughout this modeling exercise, the importance of validation was highlighted. Although there was confidence in the model, ways to validate were found before adding too many layers of complexity to ensure the effects of each change were understood. Studying sensitivity plots like those shown in Figure 5-20 to observe model behavior can serve as model checks prior to adding the next layer of complexity. As for future

Table 5.10: List of proposed design options on the Pareto frontier

Design	cost (USD)	B-Field (Tesla) B_{peak}	gauge of wire x_g	length of transmission (m) l	Wire Material Cu=1; Au=2; SST=3; Ag=4; BeCu=5 M	Coil Turns N	Voltage (V) V
1	$ 9,359,800	46.02	2	0.343	1	10	38034
2	$ 10,105,000	47.93	2	0.316	2	10	39701
3	$ 31,129,000	76.47	2	0.243	2	10	64318
4	$ 21,640,000	60.01	2	0.241	4	9	49866

work, the addition of more complex coil geometries (conical, double-wrapping, etc.), and perhaps more wire cross-sectional shapes should be considered. Also, the incorporation of an impedance (1D) circuit model that integrates well with MATLAB would be advantageous. This would give a more realistic simulation and considers effects such as the energy-pulse-wave transit time and impedance matching of transmission line elements and connections. This becomes more important with the recommended external Pulser architecture as wave effects and reflections in transmission lines are more prevalent with increased length. Finally, the inclusion of a AWS (Adaptive Weighted Sum) direct Pareto method would provide benefits and potentially new insights, in particular to better explore the concave regions of the design space.

Chapter 6

Conclusions

From Chapter 2, a number of large, scientific projects and facilities have been reviewed with emphasis on technical, technology development as well as their evolution. Leveraging this, Chapter 3 provided insights into the necessary tools and techniques that have aided experienced project leaders in their careers with a concluding synthesis of common themes and enablers for successful project engineering in the R&D domain. The technology roadmap presented in Chapter 4 helps provide an answer to the question of how large research facility's projects can be optimally designed for future expansion and the preceding Chapter 5 dives further down into a specific case study that gives us insight into critical tools that can be utilized.

It was found that mega-project leaders in the scientific sector use the classical system engineering and project management tools to aid them in project development and implementation. Summarizing Section 3.2, a graded approach should be taken depending on scale, and the experience drawn upon tells us that there are many enablers that contribute to success. These include, amongst others, a disciplined technical review process, a living risk management strategy, a balance of disciplines in analysis and test, and an aggressive stance on prototyping. The latter being a key aspect to really increase the low TRLs that are found in the R&D environment. It is understood that any one tool will not save a project if other deficiencies are apparent, a balance of these things is required. Ultimately the quality of staff in the project will provide great benefit but it is essential for this staff to be set up and utilized in the most effective manner possible.

To maintain and enable funding streams, looking ahead to the next project or upgrades to the existing system must be prioritized. It is this foresight that can aid in the necessary scalability of the designed architecture or decide where to limit the scope for the existing concept. The use of modularity in architecture was found to be a particularly effective way to allow large scientific facilities to be maintained and upgraded over time.

There is a fine balance between implementing something that is adequately scoped to maximize benefit in the short term rather than biting off more than one can chew and having significant project delays which have the potential to erode stakeholder confidence. Contingency must be utilized in R&D projects in both schedule and cost forms. Furthermore, Chapter 4 presents a more specific example of how large scale scientific organizations can build in this foresight and plan for a more holistic strategy. The technology roadmap described for Laser Confined Nuclear Fusion, LCNF allows us to see the bigger picture plan and direction for this nascent power potential generator. It covers different alternatives ranging from small incremental upgrades to major upgrades to building entirely new facilities which can be rigorously enumerated, and without such a roadmap, there will not be efficient future progress in this field. It is essential to project a future vision and timeline as scientific R&D projects differ from short term commercial projects in several important ways, see Table 6.1. In general, the TRLs are far lower, thus driving up costs and requiring more contingency along with a dynamic approach to adapt to changes. This is compared to a more defined scope and higher TRLs in commercial projects. Furthermore, it can be seen from table 6.1 that these scientific projects anticipate a far longer lifecycle due to the time to design, develop and build cutting edge technologies as well as upgrading and getting further use out of the system(s).

Although it is known that a model by itself is not satisfactory in providing a fool proof answer, there are many important insights gained by performing MDO on an R&D project such as MagNIF. Without taking the time to build and develop the model, there could have been shortsighted decisions made such as choosing an

Table 6.1: Comparison of large commercial and scientific R&D projects and technologies in terms of technology planning and project execution

Aspect	**Commercial Projects**	**Scientific Projects**
Time horizon	3-5 years	20-40 years
Starting TRL	6-9	3-5
Technology Availability	Mainly reliance on existing supply-chain (buy)	Mainly custom-build-in-house (make)
Priority	Cost efficiency	Cutting-edge performance
Financing	Self-funded	Public funds
Project budgets	10-100 [$M]	50-10,000 [$M]

architecture that provides near term experimental benefit, but lacks the long term vision. For instance, the generated MDO tradespace allowed a wholesome view of all the options rather than discrete design points and enabled the comparison of architectures in one place. It allowed the team to understand the cost additions for an external pulser but also the significant benefits in terms of the "ilities". One may argue that the shortest path to initial experiments may be an internal pulser architecture but, if we consider the right, forward thinking approach, and consider costs of having to maintain it, it is very likely that the external pulser will save money and increase capability in the longer term. Furthermore, a critical subsystem that the MDO model unveiled was the twin leads and the importance of their geometry. The strong, interdisciplinary tension with this component is apparent as both the cryogenic and electrical systems have opposing requirements and the optimizer acts to reach a compromise with these disciplines while still adhering to magnetic field and cost constraints. It is acknowledged that more empirical data will have to be gathered but the point is, this model provides an expedited look at what's important and what emerges as the disciplines are combined, something that provides great advantage before money is sunk into making the same discovery with a prototype build.

In summary, it is necessary that large scale facilities not only incorporate the suite of systems engineering and project management tools available but also leverage roadmaps and MDO to understand the bigger picture as well as gaining critical insights to provide the best design solutions to low TRL problems. A blended balance of these are required in order to evolve and progress most efficiently.

Figure 6-1 shows an integrated framework for Design and Evolution of large Scientific Facilities. This framework integrates strategic planning and technology roadmapping (top), multidisciplinary design optimization (MDO) (middle) and project management and execution (bottom) into a coherent whole. Organizations such as LLNL, CERN and others discussed here need to adopt such an integrated view to achieve future success in pushing the boundaries of scientific discovery. Developing the strategy and technology roadmap is essential for any successful R&D program and is likely more important in this domain versus the commercial one due to the lack of definition. It forces the thought progression of where the low TRL based project is headed, even if ultimately it isn't really known until half way through the journey. Figure 6-1 also shows the inter-connectivity over the three pillars of this integrated framework. Prioritizing the development of models, both benefits and ties in with the MDO design as well as informing required high-level budgets needed for the various phases of project to allow for a graded approach. In addition, the creation of goals and technology direction in tandem with definition of resources can provide huge benefit and feed into the project strategy. The MDO pillar along with system engineering tools enables the development of the project architecture and aids in the understanding of key trade-offs and costs. These in-turn feed into the development of a modular architecture and a more insightful awareness of project scope and costs. Indicated under the project management and execution section, risk management and the identification of lower TRLs work to devise the technology demonstration or prototyping strategy, an essential R&D tool. Furthermore and highlighted earlier, a disciplined design review process must be instituted and the right, well balanced team with all disciplines accounted for, must be assembled. By following this framework, scientific R&D facilities and organizations can increase the likelihood of project success and gleam great insights into technologies and architectures that could have potentially eluded them previously.

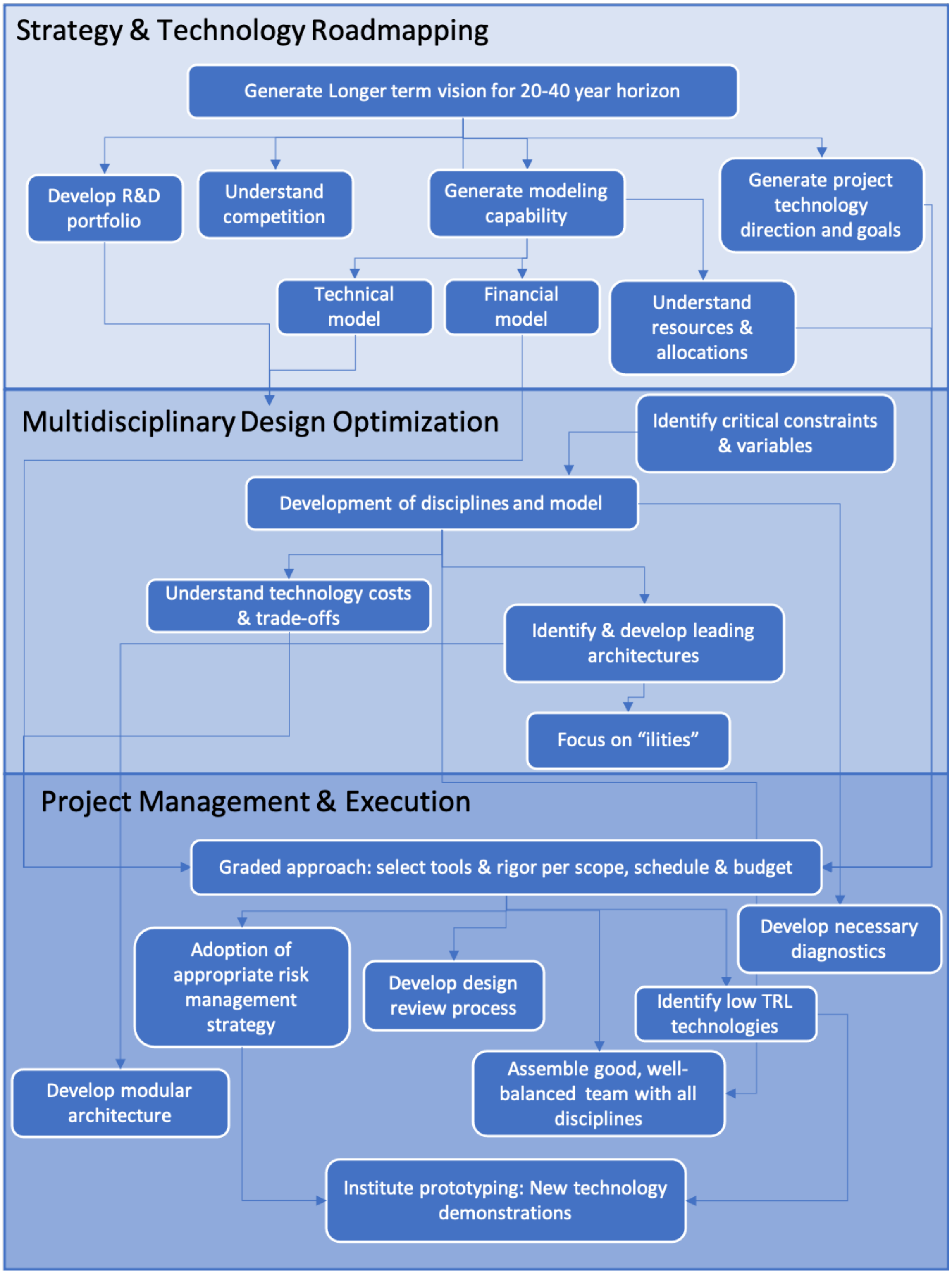


Figure 6-1: Integrated framework for large scientific R&D facility projects

6.0.1 Future work

In order to develop the framework further, future steps are suggested. Firstly, as diversity was touched on by a few of the interviewees, and with the knowledge that the most successful teams are those with a good balance of the technical disciplines as well as having members with different perspectives, it is recommended that more interviews should be conducted to gain insights from a diversified set of project leaders. These would include international project leaders with different, diverse backgrounds and experiences which will bolster the framework and even provide more unique insights into successful project parameters. In addition, this will also potentially provide another set of R&D projects to research and draw comparisons from. It is also suggested that further analysis should be drawn on comparing commercial projects to the ones covered in the research presented here. This can build on table 6.1. Moreover, a deeper dive into some of the case studies provided in Chapter 2 could be taken to uncover more key details on the important techniques employed.

From the MDO study presented in Chapter 5, future steps can be performed to develop the MagNIF model further and provide more detail with the incorporation of an impedance (1D) circuit model. However, a better use of time maybe to develop an MDO model for one of the other R&D projects presented in Chapter 2. For example, an optimization study could be run to assess the options for the HL-LHC project at CERN or even for the next particle accelerator. Great insights and understanding could be gained from a well-thought out MDO model and complimented with a technology roadmap, the most viable solution for the future particle physics machine could be discovered.

Finally, with the further development of the MagNIF project and the evolving landscape for Laser Confined Nuclear Fusion, both the MDO study and the technology roadmap must be regularly revisited over future years. This will allow for the comparison of project outcomes, the validation of models and the optimization of the project path required to attain carbon-free energy.

Appendix A

Questionnaire template

Name:

Organization:

Years of Experience:

Project experience: *types/scales of projects worked on*

What typical size of project have you led?

What System Engineering & Project Management tools do you employ?

What do you find effective in thinking about the final use case?

What techniques do you use to maximize project value?

Current Project information:

Requirements

How do you generate and write requirements?

How do you understand what the project endgame is?

How do you incorporate "not to precludes" and future use cases into your planning?

- Do you have examples of this going well?

- Do you have examples of shortsightedness?

How do you validate requirements?

Are the requirements verified at the completion of the project?

Concept down-selection

How do you generate concepts?

What techniques/tools do you use to choose leading concepts?

How do you justify the selected concept?

How do you communicate and get buy-in for your vision to upper management?

Can you provide examples of how the concept selection process lead to long term success or failures?

Do you utilize staged deployment in a phased or staged approach?

Do you utilize phased approaches? Do these provide jumping off points to reduce long term costs?

General

Do you use any design review processes?

Do you have a System Engineering/PM guideline or institutional manual for the projects you work on?

Do you utilize Project Charters?

How does the funding process work at your institution?

What do you find effective in order to reduce project risk?

How do you plan in redundancy to avoid project delays?

Is there anyone else you think I should talk to?

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