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Alcator C-Mod Design and Engineering

J.H. Irby, D. Gwinn, W. Beck, R. Vieira

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

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Contact author: J.H. Irby, 190 Albany Street, Cambridge, MA 02139

Fax: 617-253-7227

Email: irby@psfc.mit.edu

19 Pages / 5 Figures

Abstract:

Alcator C-Mod is the high field, high density, divertor tokamak in the world fusion program. We describe in this paper some of the innovative engineering solutions required to produce a diverted tokamak capable of operation at the 8 T, 2 MA level. Some design details of the TF magnet, the OH coax, and power and cooling systems are discussed, as well as the instrumentation required to verify proper operation of these components. Vacuum, vessel bake, boronization, and wall cleaning systems are also discussed.

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I. Introduction

Alcator C-Mod is a compact, high field tokamak, with an advanced divertor and metal walls. C-Mod operates at toroidal fields of more than 8 T and with plasma currents greater than 2 MA. These high fields and currents, together with the forces expected during full current disruptions, required novel engineering design concepts to be developed throughout the design process. An overall description of the design of Alcator C-Mod will be presented here. More detailed information can be found in papers from several conference proceedings presented during the design and operation phases of Alcator C-Mod [1-6].

A table of machine and achieved plasma parameters is shown in table I.

TABLE I

Major Machine Parameters for Alcator C-Mod

Major Radius (m)	0.68
Minor Radius (m)	0.21
Max Elongation	1.85
Max Triangularity	0.85
Max Toroidal Field (T)	8.1
Max Plasma Current (MA)	2.01
Plasma volume (m^3)	1
Max Discharge Length (s)	<5
Vessel Volume (m^3)	4
TMP Pumping Speed N2 (l/s)	2000
Effective Pumping Speed N2 (l/s)	500
Ohmic Heating Power (MW)	2.7
ICRF Source Power (MW)	8
Lower Hybrid Source Power (MW)	3
Peak Utility Power (MW)	24
Peak Power Alternator/Fly	400
Total Stored Energy Alternator/Fly (GJ)	2
Experimental Cell size (m)	15.2 W × 15.2 L × 12.2

II. Alcator C-Mod Design

Figure 1 shows a cutaway view of Alcator C-Mod. The 304L stainless steel vacuum vessel provides a large portion of the mechanical support for the PF and OH magnets. The vessel is constructed of welded cylindrical and annular components. The inner most cylinder comprising the inner vessel wall was machined to high precision and provides support for critical diagnostics and plasma facing components. The inner wall is 1.5 cm thick, but other sections of the vacuum vessel are considerably thicker to provide strength in high stress regions. There are no toroidal electrical breaks in the vacuum vessel. The EF1, EF2, EF3, and EFC magnets are secured into pockets formed from extensions of the cylindrical sections with a system of G10 blocks and wedges. 3.8 cm thick stainless steel mounting plates cover the pockets and attach firmly to the vessel. These plates are keyed into the 316 LN stainless steel wedge plates that support the TF horizontal arms as well as the vacuum vessel. The EF4 magnets are supported from the retaining cylinder which is discussed below.

The TF magnet consists of 120 rectangular turns of C-10700 copper with a 250 MPa yield strength. Each turn is made up of four structurally separate straight conductor bars. The innermost bars are wedge shaped and are bonded together to form a robust cylindrical structure which is adequate to react the local in plane and out of plane electromagnetic loads internally. The horizontal and vertical conductor sections are arranged into twenty bundles of six bars each. The in plane and out of plane loads of each bundle are reacted by the heavy stainless steel superstructure. The TF core bars consist of wedged copper plates reinforced by thin 216 stainless steel plates. These stainless plates keep the copper from continuing to yield and flow under the extreme stresses near the bore region of the core. Forty TF horizontal arms interlock into the core, and twenty TF vertical legs interlock into the arms with sliding joints to form the TF magnet. Both the arm and leg bundles are formed with six copper plates. During high field operation up to 230 kA of current flows in this magnet.

The TF generates up to 110 MN of in-plane force acting to expand the magnet against the external superstructure. These forces are taken up by the retaining cylinder and upper and lower covers which are forged and machined from 316LN stainless steel. This superstructure operates at 77K. At this temperature, the yield and ultimate strength is adequate to carry the applied loads. The covers are 0.66 m thick and 4.9 m in diameter. The cylinder is 0.15 m thick and 2.34 m high. The in-plane loads are carried from the covers to the cylinder by ninety-six 718 inconel draw bars with a yield strength of 1 GPa. They are pretensioned to 2.2 MN each during assembly. During high field operation the domes can deflect as much as 3 mm. Forty 718 inconel taper pins secure the cylinder to the wedge plates, and ninety six stainless steel dowel pins prevent rotation of the covers relative to the cylinder. The out-of-plane loads of the radial conductor bars of the TF are carried through the wedge plates and taper pins into the cylinder. The TF core and arms interlock with slots in the covers to provide additional support for out-of-plane loads.

Figure 2 shows details of a TF sliding joint. The sliding joints allow the TF magnet to maintain contact with the supporting cylinder and domes. As the joint surfaces move during a discharge current densities of up to 5 kA/cm^2 must be carried across the joint. To carry this current effectively requires the use of a material that can conform well to its mating surface with very low contact resistance. On C-Mod feltmetal is used to serve this purpose. It consists of 0.051 mm diameter chopper cut copper wire sintered onto a 0.127 mm thick copper substrate to produce a 1 mm thick pad. The feltmetal is vacuum baked and then plated with 0.013 mm of silver before use. The pads are laser cut and then inductively soldered to the magnet arms. Four pads with a combined area of 80 cm^2 are used at each TF joint. At installation the feltmetal surface is coated with graphite. The graphite provides both immunity to atmospheric gases that can infiltrate the cryostat seals and a lower coefficient of friction for the joint. Sliding tests of uncoated joints cooled to 77 K under the loads expected in the experiment indicated that the addition of room air and more specifically oxygen to an otherwise pure nitrogen atmosphere caused rapid failure of the feltmetal relative to the 50,000 pulse design goal. The application of graphite provided reliable operation well beyond the design goal. The use of graphite on similar room temperature joints was first used on the MAST experiment at Culham [7].

Springplates are hydralically driven into position between the TF fingers to provide the required contact pressure. The springplates also provide the compliance needed as the joint slides and distorts during normal operation and during distruptions. Force deflection curves are recorded during installation of all 960 springplates, and the data is used to estimate the feltmetal compression (typically 5.5 MPa). Springplate spacers, either G10 or stainless steel, depending on location, are adjusted if the compression pressure is found to be out of bounds.

In figure 3 the TF coax used to make the transition from the parallel bus to the first-to-last turn TF vertical leg is shown. Forces not supported in the coax structure are reacted against the retaining cylinder. The coax provides both a very strong structure through which to conduct the large currents and a natural way to minimize field errors.

A drawing of the OH coil stack adn TF core is shown in figure 4. The OH coil stack is wound over the TF core, but following fabrication, the removal of Teflon coated stainless steel strips allowed it to be free to move relative to the core. The OH stack is keyed to the vacuum vessel with a set of mounting blocks that attach to the inner vessel cylinder. A system of pins and belleville washers ensure proper alignment while allowing movement over of the stack over a wide temperature range. Full-hard C-107000 copper bar with at 16 X 21 mm^2 cross-section is used for all three OH magnets. The OH1 extends the full length of the stack while the OH2U and OH2L are wound on the upper and lower 1/4 of the stack. The OH magnets not only drive plasma current, but also provide a great deal of plasma shaping and positional control.

Well over 30 kA of current has been driven through the OH magnets during high field, high current operation. To supply this current in very space restricted regions of C-Mod where the magnetic field exceeds 17 T requires a novel engineering approach. Figure 5 shows one of the three OH coaxes used to feed current to the OH magnets. The coaxial design allows the forces on the inner and outer conductors to react against each other in a very strong structure. Contact to the OH magnet terminal plates is made with feltmetal pads on both the inner and outer coax connections. A unique feature of the design includes a coax foot with electric discharge machined 25 um high slots that act as springs. A belleville washer stack compresses the foot against the feltmetal and maintains contact during a discharge even as the OH terminal pocket moves relative to the feed coax. Overturning forces on the foot required very tight tolerances on the foot and pocket into which the foot slides (~0.025 mm). Also shown in figure 5 are the thermocouples used to measure the temperature on each side of the inner coax feltmetal pads.

Coaxial feeds are used for all C-Mod PF magnets except EF4 which is located outside the retaining cylinder. The coaxes are fabricated such that the inner coax can rotate relative to the outer coax. The center coax screws into the magnet terminal block with a righ-handed thread, and the outer coax screws into the block with a left-handed thread. When locked together, outside the retaining cylinder, the coax can not rotate in either direction without becoming better engauged and more difficult to rotate. LN2 flows through the center coax to cool the coax and the terminal blocks.

A unique feature of the C-Mod EF1, EF2, EF3, and EFC magnet design is the use of an electroforming technique to join the magnet terminals to the coil [8]. This process produces a stress free joint with properties as good as the base metal. Localized annealing of the copper during the more standard techniques of welding or brazing made these processes unacceptable in this application.

III. Power Systems

Primary utility power for Alcator C-Mod is provided by a 24 MVA peak power 13.8 kV line. This line is used to directly power the ICRF and lower hybrid systems, long pulse diagnostic neutral beam, and the EF2 magnet supply. This line also powers the 2 MVA drive motor for the MIT 225 MVA, 14.4 kV alternator and its 72 ton flywheel. The flywheel and alternator provide 2 GJ of stored energy to power the remaining ten magnetic supplies, most of which goes to drive current in the TF magnet. 325 MJ of energy is extracted from the alternator in approximately 2.3 s during an 8T, 2 MA discharge in Alcator C-Mod. However, storage and conversion systems have been designed to supply up to 500 MJ at up to 400 MVA peak to the experiment.

Eleven power converters provide power to the 14 C-Mod magnets. A major advantage of liquid nitrogen cooling of the magnets is that the magnet resistances are about a factor of six lower than room temperature magnets, and low voltages can be used to drive the required currents. Lower voltages allow switching, commutation, and crowbar functions to be done with extremely reliable, low maintenance, solid-state components. We list the converter parameters in table II.

TABLE II

Power Convertor Properties

Supply	**Output Voltage (V) (open circuit/full load)**	**Maximum Current (kA)**	**Additional Comments**
TF	1550/800	260	2 Quadrant, auto-tap-changer, OV, IOC, bypass protection
OH1	932/500	±50	4 Quadrant-Lockout, OV, IOC, crowbar, varistor protection
OH2U /OH2L	243/100	±50	4 Quadrant-Circulating Current, OV, IOC, crowbar, varistor protection
EF1U	648/492	±15	4 Quadrant-Circulating Current, OV, IOC, crowbar, varistor protection
EF1L	648/492	±15	4 Quadrant-Circulating Current, OV, IOC, crowbar, varistor protection
EF2U	600/500	6	2 Quadrant, IOC, varistor protection
EF2L	600/500	6	2 Quadrant, IOC, varistor protection
EF3	3645/2400	22	2 Quadrant, OV, IOC, crowbar (Fire-All), varistor protection
EF4	1023/900	±10	4 Quadrant-Lockout), OV, IOC, crowbar, varistor protection
EFC	900/750	3	2 Quadrant, IOC, varistor protection
EFC Chopper	900/750	3	IOC, varistor protection
OH2 Comm Sw	2kV MAX	50	OV, crowbar protection (parallel operation)
OH1 Comm Sw	4kV MAX	50	OV, crowbar protection (series operation)
EF1 Comm Sw	2kV MAX	15	OV, crowbar protection
non-axisymetric	600/500	3	2 Quadrant, IOC, varistor protection

IV. Liquid Nitrogen Cooling System

All C-Mod magnets and supporting structures are cooled with liquid nitrogen. The entire machine is housed inside a large cryostat consisting of fiberglass shells enclosing approximately 10 cm of foam insulation. The cryostat is well sealed against outside air intrusion to protect the machine from the formation of condensation and ice, and the access of oxygen to the sliding joint feltmetal. Liquid nitrogen is supplied from a 73,000 l storage tank to C-Mod at the rate of 32,500 l/day. The nitrogen first fills a 1000 l sump from which a pump supplies a manifold and valve system that feed the magnets and a panel used to cool the upper superstructure. A programmable logic controller monitors approximately 250 thermocouples and uses that information to control the supply valves for the magnet and the superstructure cooling. Liquid nitrogen exhausted by the magnets flows to the bottom of the cryostat and then back into the sump where is filtered and recirculated. LN2 boil-off at the bottom of the cryostat quite effectively cools the lower superstructure.

The TF core is cooled by nitrogen flow both down the central bore of the core and through channels on the outer surface of the core. TF arm and leg bundles are cooled by nitrogen flow between the edge of the copper plates and the G10 housing. Some of the TF arm cooling exhaust flows directly onto the core sliding joints, giving extra cooling to these critical components.

Liquid nitrogen flows through the OH center coax conductor to directly cool the feltmetal joints and terminal plates. Nitrogen also flows into a manifold at the base of the OH stack and then upward over the outer surface and back down along the inner surface to cool OH stack conductors.

The remaining magnets are cooled by liquid nitrogen flow between the edges of the magnets and the G10 housings.

Following an up-to-air period, and several days before cooldown, a GN2 purge of the cryostat is begun. LN2 is not allowed into the sump until the water vapor content within the cyrostat drops below 200 parts/million. A differential measurement of the cyrostat pressure relative to the ambient atmospheric pressure is used to maintain a positive over pressure in the cryostat of approximately 300 Pa.

V. Critical Instrumentation

There are 480 sliding joints with 1920 feltmetal pads on the TF magnet. These are critical locations that are monitored for changes in resistance both between and during discharges. Since both sides of the joints are not easily accessible at the TF core, the two joints at this location are monitored in series, resulting in 360 voltage measurements for the TF magnet. Between discharges, 1 kA of current is driven through the TF magnet so that resistance measurements at the 360 locations can be recorded. In addition, 16 easily selectable joint locations can be monitored during a discharge with results recorded in CAMAC.

The OH coax connections are also carefully monitored. Leads from thermocouples attached on either side of the feltmetal contact plate are brought back to isolation amplifiers. Both the thermocouple temperatures and the voltage across the contacts are recorded during a discharge.

The OH signals are processed following a discharge and alarms are sent to both engineering and physics operators if the signals are out of bounds. The TF signals must be checked by the engineering operator before another shot is allowed.

All magnet currents are measured with Rogowski coils and precision integrators and a redundant set of shunts. Bus voltages are measured using precision voltage dividers and isolation amplifiers. Several amperes of current are driven through the magnets between shots to monitor magnet resistance and thus average temperature. All C-Mod magnet supplies have their own set of shunts and voltage dividers to monitor supply performance.

VI. Vacuum and Wall Conditioning Systems

Two 1000 l/s turbo-molecular pumps located at a single horizontal port provide the primary pumping system for C-Mod. The effective pumping speed for nitrogen is approximately 500 l/s once relevant conductances are taken into account. Typical base pressures are in the low 10^-6 Pa range. The vacuum vessel, including port extensions, has a volume of 4060 l. The main chamber has a surface area of about 10 m^2. The horizontal port extension primary seals are racetrack Helicoflex seals. Secondary indium seals provide enhanced leakchecking capability and can also backup the primary seals if a leak develops.

Following an up-to-air period, Alcator C-Mod is baked for several days at a temperature of 130 C. 450 kapton heaters monitored by 500 thermocouples at power levels of up to 120 kW are required to bake C-Mod [9]. The magnets must be cooled, typically to -25 C, during the bake to protect the epoxy resin bonding layers from the high temperatures. During the bake period, electron cyclotron discharge cleaning (ECDC) in deuterium is applied to clean the vessel walls. ECDC power levels of 2.5 kW at 2.45 GHz are used. The TF magnet current is swept during ECDC to move the resonance from the inner wall out into the ports.

The ECDC system is also used for boronization. Diborane gas (90% He, 10% B2D6) is metered into the vessel at pressures of a few mTorr through a manifold that extends completely around the machine toroidally. The gas is broken down in the ECDC discharge with a 50% duty cycle over a 1 s period. During the time the rf is off the gas is allowed to fill the chamber uniformly. A boron coating of 1200 A is typically applied over a several hour long deposition period. This process is repeated after about 200 discharges to maintain acceptable plasma performance.

Glow discharge cleaning capability is also available on C-Mod. Its primary purpose has been for the removal of heavy boron compounds before an up-to-air period. A glow discharge in helium breaks down these compounds and allows fast safe access to the vessel following the up-to-air. The system has also been used very successfully in support of wall pumping and fueling experiments. Two glow discharge electrodes are located in the upper chamber 10 cm away from the vessel wall. Voltages up to 1000 V, and currents up to 1 A can be supplied to the electrodes. Ballast resistors can be switched in and out and current and voltages regulated by PLC control. IGBT switches can interrupt power to the electrodes on a time-scale short enough to greatly limit damage to vessel surfaces if arcing occurs.

VII. Acknowlegements

Many engineers have contributed greatly to the design and fabrication of Alcator C-Mod including Herb Becker, Bruce Montgomery, Steve Fairfax, Matt Bessen, Bob Childs, Frank Silva, and Joe Daigle.

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Figure Captions:

1) Cut-away view of Alcator C-Mod. Cryostat, TF and PF magnets, vacuum vessel, and inner wall hardware are shown. Not shown are the retaining cyclinder and domes, and the EF4 magnet which attaches to the cylinder.
2) Details of the TF magnet sliding joints. Four feltmetal pads provide the low resistance contacts for 250 kA of current flow. The spring plates supply the contract pressure required together with the necessary compliance.
3) Current to the TF magnet is supplied by a coax structure that has great strength while minimizing error fields.
4) The OH stack surrounds the TF core. Coaxial connections to all three coils allows reliable 50 kA connections to be made in magnet fields of 17 T.
5) Details of the OH coax connection are shown. Feltmetal pads soldered to either side of a 1.58 mm copper plate provide a low resistance connection. Thermocouples monitor the temperature on either side of the junction and the voltage across it. Slots EDM’d into the central coax foot provide additional compliance to the joint.

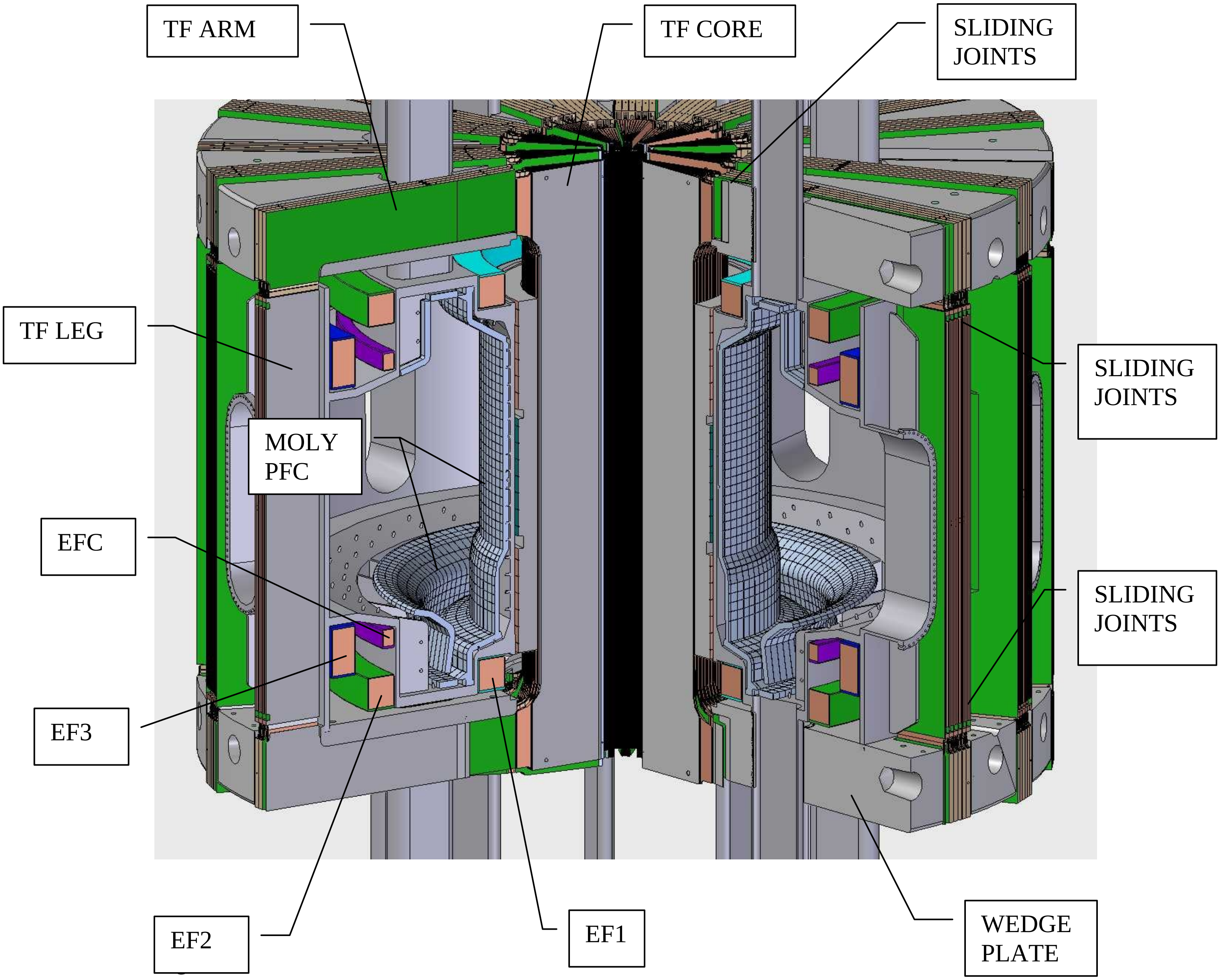
TF ARM
TF CORE
SLIDING JOINTS
TF LEG
SLIDING JOINTS
MOLY PFC
EFC
SLIDING JOINTS
EF3
EF2
EF1
WEDGE PLATE

Figure 1

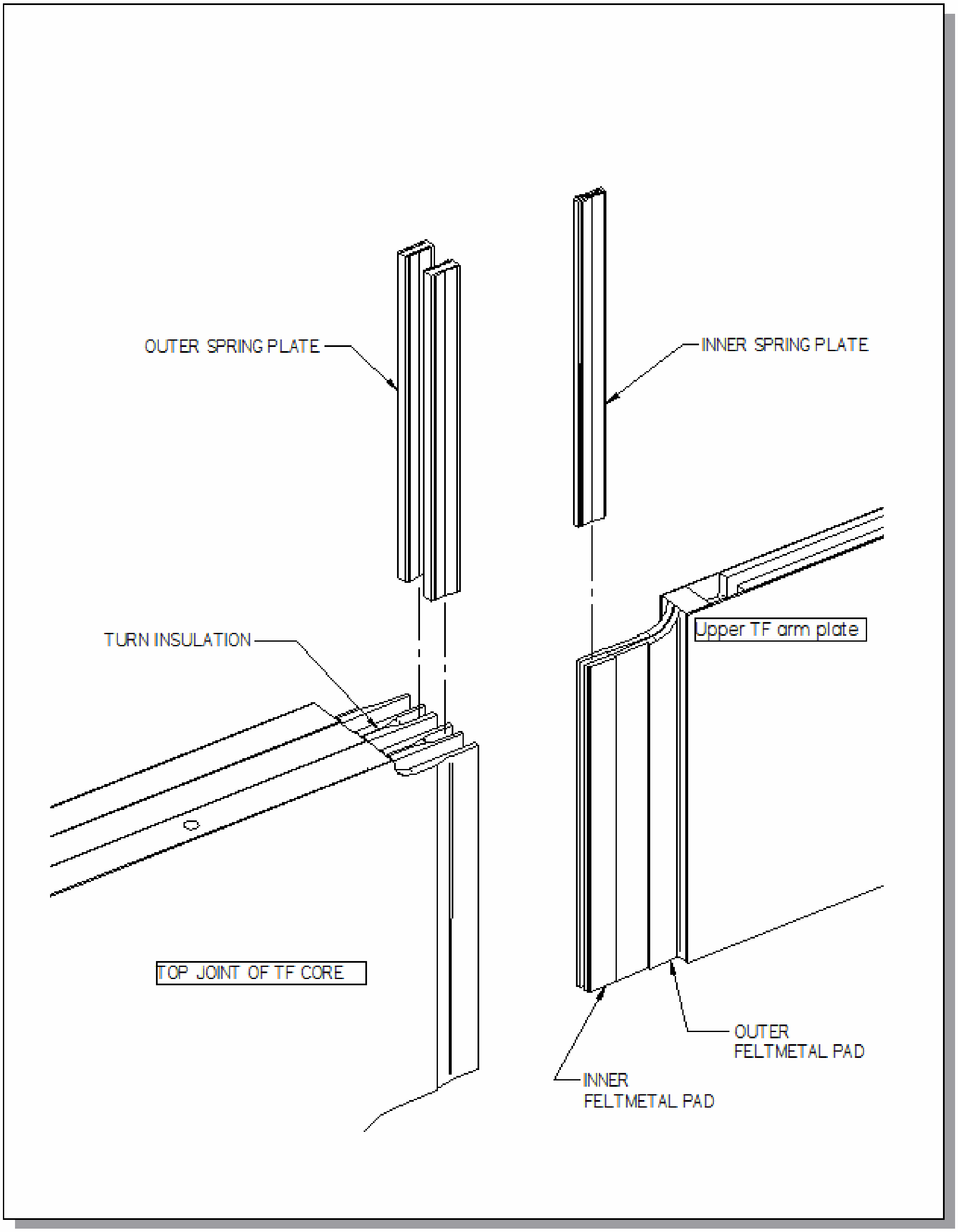
OUTER SPRING PLATE
INNER SPRING PLATE
TURN INSULATION
Upper TF arm plate
TOP JOINT OF TF CORE
OUTER FELTMETAL PAD
INNER FELTMETAL PAD

Figure 2

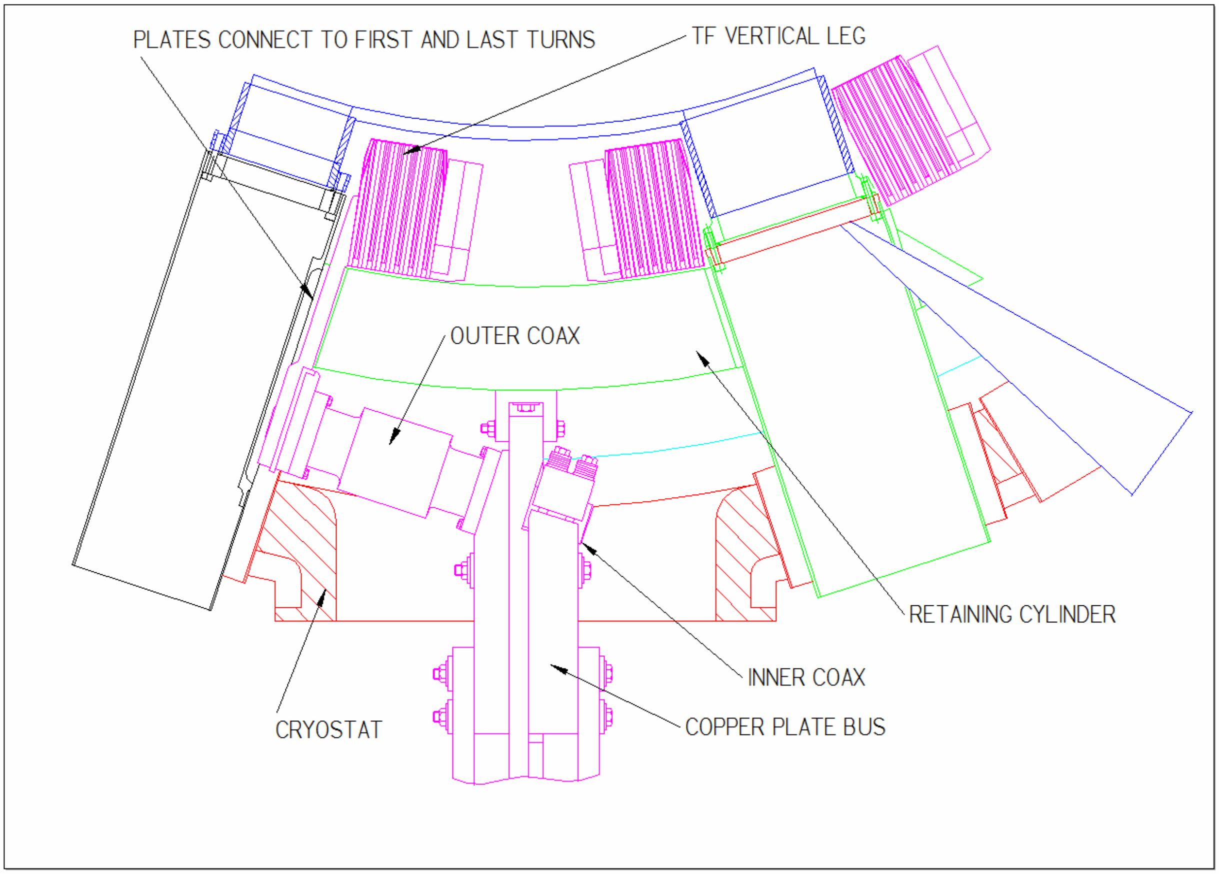
PLATES CONNECT TO FIRST AND LAST TURNS
TF VERTICAL LEG
OUTER COAX
RETAINING CYLINDER
INNER COAX
COPPER PLATE BUS
CRYOSTAT

Figure 3

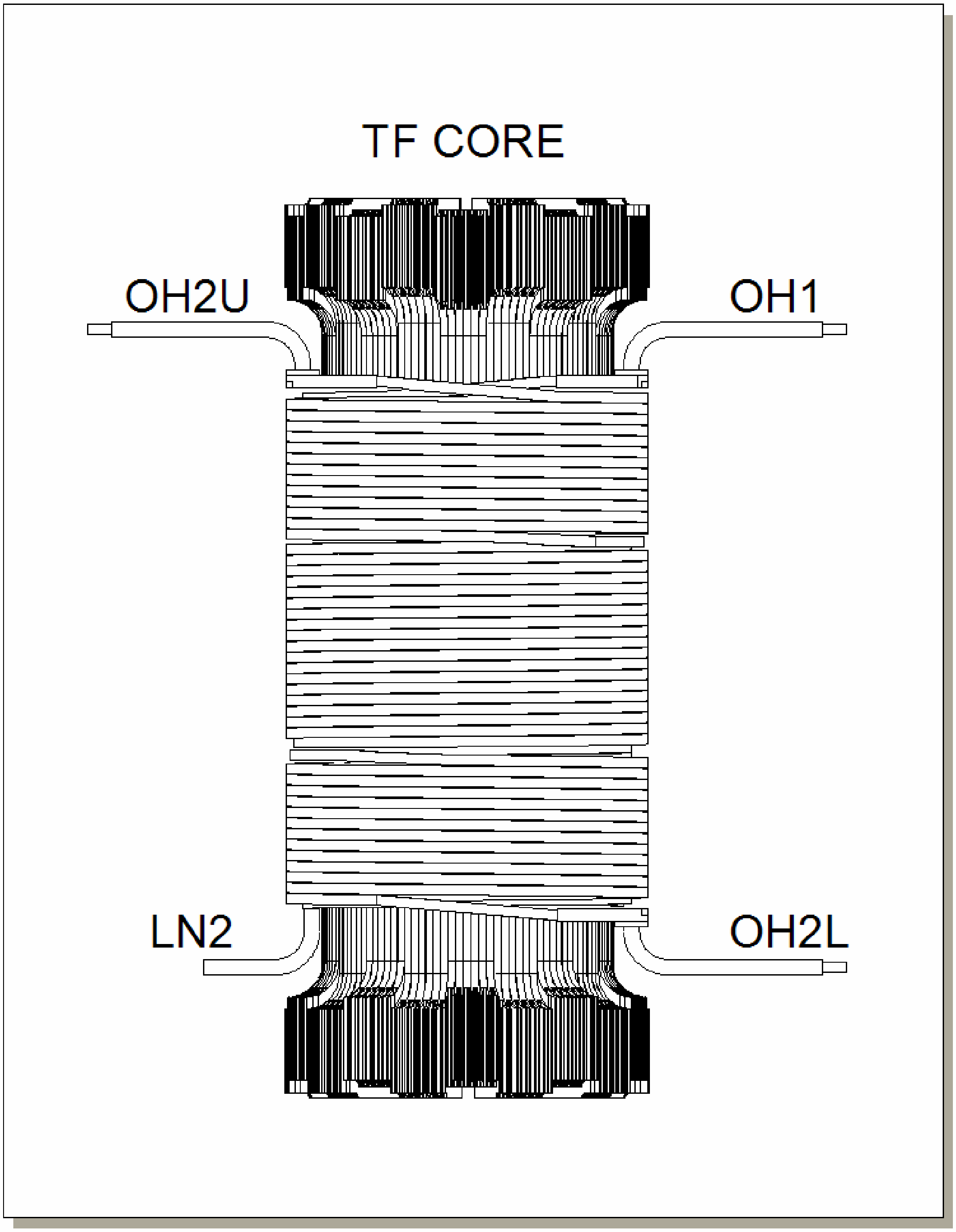

Figure 4

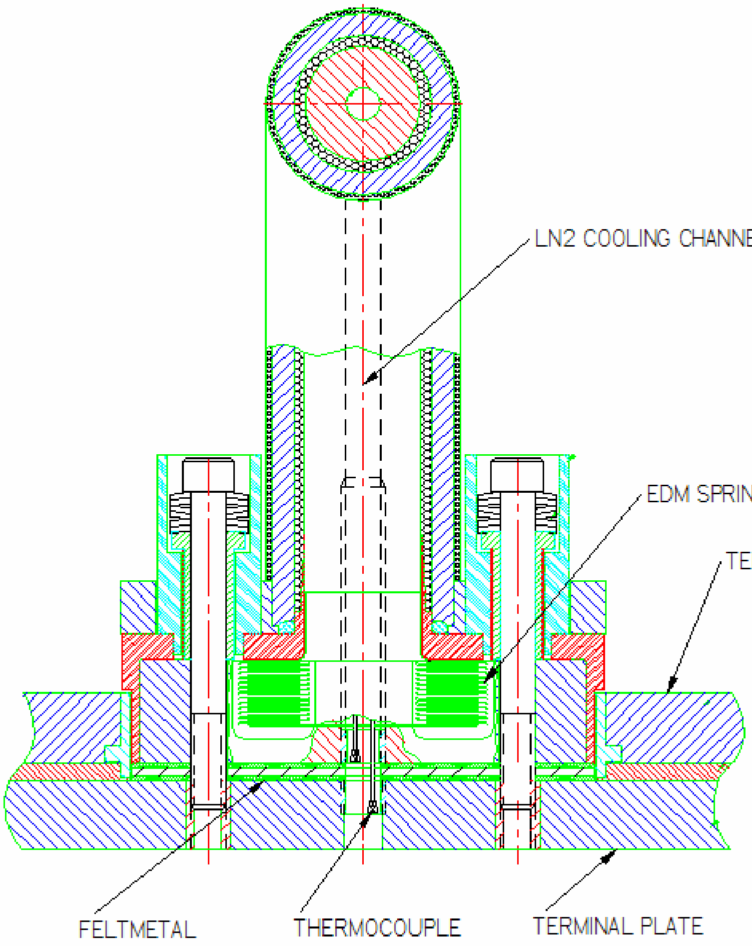
LN2 COOLING CHANNEL
EDM SPRING SLOTS
TERMINAL PLATE
FELTMETAL
THERMOCOUPLE
TERMINAL PLATE

Figure 5