Shielding Design for the time-resolving Magnetic Recoil Spectrometer (MRSt) on the National Ignition Facility (NIF)

by

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B.S., Rutgers University - New Brunswick (2016)

Submitted to the Department of Nuclear Science and Engineering in partial fulfillment of the requirements for the degree of Master of Science in Nuclear Science and Engineering at the

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Abstract

The National Ignition Facility (NIF) is one of the premier inertial confinement fusion (ICF) experiments active today, with the goal of achieving ignition in a laboratory for the first time. Multiple diagnostics are needed to generate the scientific data necessary for guiding these experiments at the NIF toward this goal. The time-resolving Magnetic Recoil Spectrometer (MRSt) aims to provide time-resolved measurements of the neutron spectrum, to determine time evolution of ion temperature, areal density, and neutron yield, at a time resolution of 20ps and an energy resolution of 100 keV. This would be the first time-resolved measurement of these quantities, and is crucial to understanding the dynamics of the implosion and possible deviations from optimal performance. The MRSt’s unique ability to diagnose the hot-spot formation, fuel assembly, and alpha heating will open a new door to ICF. This work establishes a conceptual shielding design for the MRSt that meets the signal-to-background requirements. The finalized design is composed of 65cm of 30% borated polyethylene shielding for the neutron background, and a 2.5cm layer of tungsten gamma shielding with a 5.5cm layer of shielding on the last 20cm of the pulse dilation drift tube (PDDT) detector. This design reduces the background about 300 times, from 0.12 for the unshielded design to 35 for the finalized shielding design, thus exceeding the requirement of S/B > 5 for the down-scattered-neutron measurement. Neutron background has been reduced nearly to zero, but further gamma reduction could be a future avenue of research, specifically surrounding the graded-Z shielding design.

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A CAD drawing of the MRSt spectrometer on the NIF. The spectrometer consists of a CD foil positioned on the hohlraum, marked as "target" in the figure; a magnet system positioned outside the NIF target chamber, and a detector based on the pulse-dilation-drift-tube (PDDT) technique for detection of the recoil deuterons at the focal plane of the spectrometer. B1 and B2 are the dipole magnets for magnet dispersion, and Q1 and Q2 are the quadrupole magnets for correction of higher-order aberration. An orthogonal view of the dipoles B1 and B2 are shown. At the bottom right is the PDDT detector, surrounded by a thin inner layer of a high-Z shielding and an outer, thick layer of polyethylene shielding.

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Chapter 1

Introduction

Climate change is a hot-button issue that has brought alternative energy sources to the forefront, in the hopes of reducing the use of fuels such as coal, natural gas, and oil to avoid irreversible changes to the environment. While there are numerous alternative energy sources, one of the main branches of energy research revolves around nuclear energy, namely nuclear fusion and nuclear fission. Both involve the conversion of the binding energy of the nucleus into kinetic energy. In nuclear fission, this process takes place when a large nucleus (with mass number $A > 56$) is split into two or more daughter nuclei. This process allows for a massive release of kinetic energy when using heavy elements, and forms the basis for the technology behind today’s "nuclear power plants". Fusion energy, on the other hand, produces energy from the combination of two light nuclei (those with $A < 56$).

While fission has often received much of the fame - and infamy - in nuclear studies as a whole, fusion is increasingly seen as a technology that could provide unlimited clean energy. While fusion has been promising for decades, it has remained elusive due to the high pressures, temperatures, and technological sophistication required, yet advances in research have brought the field closer than ever to its realization.
1.1 Fusion Energy

Thermonuclear fusion occurs when nuclei with $A < 56$ are forced together with high enough speed to overcome the Coulomb barrier. When the nuclei fuse, they release energy and, in many cases, emit highly-energetic neutrons. There are various potential reaction candidates for fusion energy production, but fusion research tends to focus on a select few, namely:

\[ \text{D} + \text{T} \rightarrow ^4\text{He} + n + 17.6\text{MeV} \] (1.1)

\[ \text{D} + \text{D} \rightarrow ^3\text{He} + n + 3.3\text{MeV} \] (1.2)

\[ \text{D} + \text{D} \rightarrow \text{T} + \text{H} + 4.0\text{MeV} \] (1.3)

\[ \text{D} + ^3\text{He} \rightarrow ^4\text{He} + \text{H} + 18.3\text{MeV} \] (1.4)

\[ \text{p} + ^{11}\text{B} \rightarrow ^4\text{He} + 8.7\text{MeV} \] (1.5)

These potential fuels are further evaluated based upon their fusion cross sections - those with larger cross sections at relevant temperatures are easier to fuse, and thus generally of more interest to fusion research. Fig. 1.1 shows the cross section as a function of center of mass energy of the reactants (dictated by the ion temperature), and from this it is clear that the DT reaction is the most ideal candidate.
Figure 1-1: Fusion cross section as a function of reactant center-of-mass energy (CM) for several fusion reactions of interest. As the DT reaction has the highest cross section at a given CM energy (or ion temperature), this reaction is the most viable reaction for fusion research and energy production. Courtesy of ITER [1]

1.2 Approaches to Thermonuclear Fusion

There are several approaches to fusion energy, but most of the research falls into two main categories: magnetic confinement fusion, or MCF[5], which uses magnetic fields to contain particles for sufficiently long periods at the required densities and temperatures; and inertial confinement fusion, or ICF, which uses high-powered lasers to implode a capsule to densities and temperatures required for fusion reactions to occur.

1.2.1 Brief Overview of Inertial Confinement Fusion

In ICF, the fusion fuel is heated and compressed by either the direct-drive or indirect-drive method.[2] In direct drive, a spherical capsule containing the fuel is imploded by direct illumination of laser beams focused on the surface of the capsule in a nominally uniform pattern. The outer shell of the target ablates, driving the inner part of the
shell inwards like a rocket, due to conservation of momentum. The shell accelerates, and then, shortly after the laser drive is turned off, it coasts before the deceleration towards peak compression occurs. The goal is to achieve sufficiently high temperatures and densities to generate a self-sustaining thermonuclear burn wave that propagates through the fuel, giving rise to a copious amount of DT reactions, that further produce neutrons that carry most of the released energy. In indirect drive, the capsule is positioned inside a hohlraum, or a high-Z cylinder, which is illuminated on the inside by lasers that produce a radiation field of x rays. It is these x-rays that heat and ablate the outside of the capsule and drive the implosion (see Fig. 1.2). Either way, the desired result is that the implosion generates densities of order 1000 g/cc and temperatures around 10 keV that sparks an ignition burn wave, which propagates outward in the stagnated fuel.

![Figure 1-2: Direct drive (a) and indirect drive (b) approach to ICF. In indirect drive, the laser beams illuminate the inside of a high-Z hohlraum for generation of X-Rays that in turn illuminate and drive the capsule. Courtesy of J. Badziak][2]

During the implosion process, a hot-spot develops at the center of the implosion, surrounded by a cooler and denser layer of fuel. A simplified view of a stagnated ICF implosion (density and temperature profiles) is shown in Fig. 1.3.

In both the direct and indirect-drive approaches it is important to gradually ramp up the intensity of the laser pulse to avoid propagation of strong shock waves through the implosion, which would preheat the fuel and make it harder to compress. The fuel needs to be almost isentropically compressed to achieve the densities required for ignition. At the point of maximum compression, i.e. stagnation, the hot-spot must be
ignited ("hot-spot" ignition) by several correctly timed converging shock waves. To achieve ignition of the hot spot, it needs to have an areal density of 0.3 \( g/cm^2 \) to stop the DT-alpha particles. Under ideal conditions, the alpha-energy deposition generates a nuclear burn wave that expands outward into the surrounding high-density fuel.

![Figure 1-3](image)

Figure 1-3: A simplified view of the density and temperature profiles at stagnation, with the hot spot radius \( r_{hs} \). The "hot spot" is located at the center of the implosion, while the high-density region surrounds the hot spot. Under ideal conditions, the hot spot will have a temperature of order 10 keV, and the surrounding high-density shell will have a density of order 1000 g/cc. Courtesy of B. Zohuri[3]

To effectively burn the fuel in an ICF implosion, it can be shown that the areal density of the implosion must be very high, as described by[6]:

\[
\Phi = \frac{\rho r}{\rho r + 6(g/cm^2)},
\]

where \( \rho r \) is the areal density of the implosion and \( \Phi \) is the burn fraction. For a reasonable burn fraction of 25\%, we need an areal density of 2 \( g/cm^2 \). In the case of solid-density DT fuel with a density of about 0.2\( g/cm^3 \), we need a total mass of around 800 g to obtain a \( \rho r \) of 2 \( g/cm^2 \). This is not practical as the yield of that amount of fuel would be 2.7E14 joules of energy - equivalent to around 1/40th the impact energy of a meteor, which is governed by \( E_{TN} = 3.34 \times 10^{11} J/g \), where \( E_{TN} \) is energy per gram produced by DT fusion[7]. To work with a smaller mass and still achieve a \( \rho r \) of 2 \( g/cm^2 \), we need to compress the fuel to much higher densities of order 1000 g/cc. Given the equation
\[ M = \frac{4\pi (\rho r)^3}{3 \rho^2}, \quad (1.7) \]

this would only require milligrams of fuel to produce megajoules of energy. Based on these values, the yield of an ICF implosion would be easily containable while also providing sufficient energy for effective energy production.

1.3 Obtaining Information About the Implosion Performance

It is evident that experimental information about the fuel assembly is critical for understanding the performance of an ICF implosion. To date, a set of neutron spectrometers, including the standard Magnetic Recoil Spectrometer (MRS)[8], have been used routinely at the NIF for measurements of the time-integrated neutron spectrum, from which time-integrated values of \( \rho r \), ion temperature \( (T_i) \) and yield \( (Y_n) \) have been determined. Although these data have been essential to understand and improve the ignition experiments at the NIF[9], the current diagnostic suite does not provide any detailed information about the hot-spot formation and evolution of the fuel assembly. In the context of optimizing the implosion performance, the impact of the Residual Kinetic Energy (RKE) is also an outstanding issue that needs to be addressed [10]. Simply stated, if the RKE of the implosion kinetic energy is not effectively transferred to hot-spot thermal energy, and thus RKE remains at peak compression, the ignition-relevant plasma conditions will not be achieved. By monitoring the time evolution of \( \rho r \) and \( T_i \), and when the implosion starts to deviate from one-dimensional behavior, RKE can be quantified. This information can be obtained with the next-generation MRS for time-resolved measurements of the ICF neutron spectrum. This new spectrometer, called the MRSt, represents a paradigm shift in our thinking about neutron spectrometers for ICF applications, as it will open a new diagnostic window to ICF implosions.
Chapter 2

NIF and Its Suite of Neutron Spectrometers

The NIF, or National Ignition Facility, is an indirect drive, 192-laser-beam facility capable of delivering up to 2.0 MJ at 500 TW to the hohlraum\[11\]. The laser beams are configured in a polar orientation on the target chamber, enabling these beams to enter the laser-entrance holes at the ends of the vertically-oriented, cylindrical hohlraum. The inner radius of the NIF target chamber is 5 m, and the chamber wall is composed of 10 cm of aluminum and 40 cm of borated concrete\[12\]. The NIF target bay is a 30m $\times$ 30m cylindrical structure made out of 6 feet of concrete, which surrounds the target chamber. The entire facility is shown in Fig. 2.1.
Figure 2-1: The National Ignition Facility (NIF), at Lawrence and Livermore National Laboratory, consists of 192 laser beams capable of delivering up to 2.0 MJ at 500 TW to the hohlraum. Courtesy of LLNL.[4]

2.1 Current Suite of Neutron Spectrometers on the NIF

The current suite of neutron spectrometers on the NIF, consisting of neutron Time-of-Flight (nTOF) spectrometers[9] and a Magnetic Recoil Spectrometer (MRS)[9, 8], have been used extensively to obtain time-integrated information about \( Y_n \) and \( T_i \) from the primary-neutron spectrum around 14 MeV, and time-integrated information of \( \rho r \) inferred from the yield ratio between down-scattered (12-13 MeV) and primary neutrons. These diagnostics are shown in Fig. 2.2.
Figure 2-2: The nTOF spectrometers on the NIF for measurements primary and down-scattered-neutrons. These spectrometers are positioned 20 m from the implosion, and each system consists of collimators and off-axis PMTs/PDs that are shielded. Each LOS is specified in the figure by the polar-azimuthal angles. The Magnetic Recoil Spectrometer (MRS), positioned on the 10-m diameter chamber, is also shown.

Although these spectrometers have been invaluable to the ICF program at the NIF, they do not provide any information about the evolution of the fuel assembly and hot-spot formation. As discussed in the next section, this issue will be addressed by the implementation and use of the MRSt system.
2.2 The MRSt

Figure 2-3: A CAD drawing of the MRSt spectrometer on the NIF. The spectrometer consists of a CD foil positioned on the hohlraum, marked as "target" in the figure; a magnet system positioned outside the NIF target chamber, and a detector based on the pulse-dilation-drift-tube (PDDT) technique for detection of the recoil deuterons at the focal plane of the spectrometer. B1 and B2 are the dipole magnets for magnet dispersion, and Q1 and Q2 are the quadrupole magnets for correction of higher-order aberration. An orthogonal view of the dipoles B1 and B2 are shown. At the bottom right is the PDDT detector, surrounded by a thin inner layer of a high-Z shielding and an outer, thick layer of polyethylene shielding.

The MRSt consists of several components (see Fig. 2.3). The first component is a 20 to 80-μm-thick CD foil with a diameter in the range of 200 to 600-μm. This foil is positioned on the outside of the hohlraum close to the equator, for conversion of neutrons to recoil deuterons [13]. The foil has to be positioned close to the implosion to minimize the time spread of different-energy neutrons (at the foil), which generate recoil deuterons with the same energy. A small aperture (area of 0.2 to 0.8 cm²) is positioned 600 cm from the foil for selection of forward-scattered recoil deuterons.
produced in the foil. The second component is the magnet system consisting of two dipole magnets and three higher-order magnets for momentum analysis of the deuterons.

As shown in Fig. 2.3, the magnet system has an S-shaped design for minimization of the path-length difference and thus time dispersion for same-energy particles (the current MRS does not have this ion-optical geometry, and thus cannot provide time-resolved information of the neutron spectrum). The B-field in both magnets will be 1.20 T. For focusing in the dispersive plane, the dipole inclination and exit angles relative to the particle central trajectory are 27 degrees. The dipole bending angles are 64 degrees. The focal-plane distance is about 60 cm from the exit surface of the last higher-order magnet.

2.2.1 The MRSt PDDT Detector

The third component of the MRSt is an ultrafast pulse-dilation drift tube (PDDT) with a Cesium-Iodide (CsI) cathode for detection of the recoil deuterons at the focal plane of the spectrometer [8]. This CsI cathode covers an energy range of 10.7 - 14.2 MeV, which corresponds to a neutron-energy range of 12 - 16 MeV. Given that the deuterons have different energies and velocities, they will arrive at the focal plane at different times, ranging from 323 ns to 380 ns. A schematic drawing of the PDDT detector is shown in Fig. 2.4.

The CsI cathode is about 50-cm-long, 2 cm-wide, and 1000-Angstrom thick. When the deuterons hit the CsI cathode, secondary electrons (SE) are produced, and a fraction of them are emitted from the backside of the CsI. The distribution of the SE is subsequently accelerated by a spatially- and time-varying electrical field at the cathode that unskews and stretches it, while drifting about 1 m along the tube. At the backend of the PDDT, a Micro-Channel Plate (MCP) is positioned for amplification of the SE signal. The amplified signal is subsequently detected by an array of segmented anodes connected to a multi-channel digitizer. To record the signal with 30 ps time resolution and with a limited set of channels, covering a large energy range, at the PDDT backend, the signal distribution must be unskewed and stretched, as discussed
Figure 2-4: Concept of the pulse dilation drift tube (PDDT) detector for the MRSt. Deuterons hit the CsI cathode and create secondary electrons. A spatially and temporally varying electric field is applied at the cathode, which stretches and unskews the distribution of these electrons as they drift along the magnetic field lines towards an MCP. The MCP amplifies the signal that is recorded on multiple scope channels. The distance from the cathode to the MCP is about 1 meter.

in detail by Hilsabeck et al.[14] From the time-resolved histogram of the detected SE, time-resolved spectrum of the recoil deuterons and the emitted neutrons can be determined.

Taken together, these component comprise the MRSt diagnostic. The final component of the system is the shielding surrounding the PDDT detector.

This shielding is necessary in order to allow for meaningful data to be gleaned from the implosions at the NIF and other ICF experiments. Interactions with the surrounding structure of the MRSt and the NIF target bay itself produce gamma and neutron background, which, left unshielded, will itself interact with the MCP detector. This will prevent a clear signal from being determined, and thus prevent the diagnostic from achieving its goal. To that end, the design and optimization of this shielding constitutes this thesis.
Chapter 3

Design and Optimization of the MRSt Shielding

To successfully implement the MRSt on the NIF, the S/B characteristics must be determined and optimized. This requires a detailed understanding of the S and B distributions at the CsI cathode and MCP and their response to these distributions. This also requires an optimized shielding design that reduces the neutron and gamma background to the required levels. This chapter discusses my work in designing and optimizing the shielding for the MRSt that will meet the requirement of $S/B > 5$ for the down-scattered neutron measurement.

3.1 Signal Distribution at the MRSt Focal Plane

The signal distribution at the CsI cathode was determined by using ion-optical simulations of the MRSt design shown in Fig. 2.3. Results from that modeling are shown in Fig. 3.1 for deuterons generated in a CD foil for a NIF implosion producing $3.6 \times 10^{16}$ neutrons. For this simulation, the MRSt was configured to operate at $\Delta E = 350$ keV and $\Delta t = 40$ ps.
Figure 3-1: (a) Simulated MRSt recoil-deuteron distribution at the CsI cathode for a NIF shot that generated $3.6 \times 10^{16}$ neutrons. For this simulation, the MRSt was configured in the medium-efficiency, medium-energy/temporal resolution ($\Delta E = 350$ keV and $\Delta t = 40$ ps). The binning does not represent the resolution of the system. The recoil deuterons arrive at the CsI during the time window of 326 - 380 ns. (b) Projection of the signal on the time axis. The signal peak originates from primary DT neutrons (in the range of 13-15 MeV), while the subsequent tail is due to down-scattered neutrons at lower energies (12-13.3 MeV), which are generated in the ICF implosion when primary DT neutron elastically scatter off the fuel D and T ions. In this particular case, the primary signal (13-15 MeV) is $\sim 1.8 \times 10^4$ counts and the down-scattered signal (12-13.3 MeV) is $\sim 750$ counts.

3.2 Background Distributions at an Unshielded MRSt Detector

3.2.1 MCNP Model of the NIF Target Bay and MRSt

To determine the optimal shielding design for the MRSt, we must first establish the flux levels and spectra of background neutrons and gammas at an unshielded MRSt. The background neutrons originate from primary DT neutrons that elastically and inelastically scatter off nearby NIF structures, generating a "sea" of ambient background neutrons at the MRSt system, while the background gammas are primarily generated by $(n,n')$ and $(n,\gamma)$ reactions in nearby NIF structures. For successful
implementation of the MRSt, a detailed understanding of these background distributions at the CsI cathode and MCP is required. This was accomplished by developing and using a detailed MCNP model of the MRSt design, shown in Fig 3.2, which was incorporated into the detailed MCNP model of the NIF target bay implemented by H. Khater et al.[15] For an accurate determination of the flux levels and spectra of background neutrons and gammas at the MRSt, the MCNP model includes all major components of the NIF target bay, including the target chamber, with its laser and diagnostic ports, as well as facility flooring and walls, which can be seen in Fig. 3.2(a)

![Figure 3-2](image)

Figure 3-2: (a) 2D cut-through MCNP model of a shielded MRSt in the NIF target bay. The wall of the NIF target chamber is 60 cm-thick (10 cm of aluminum and 40 cm of borated Gunite (b) Zoomed-in view of the MRSt model. In this MCNP model, the MRSt line-of-sight is 73-324 degrees. The CsI cathode and MCP are positioned ∼11 m and ∼10 m from target chamber center (TCC), respectively, and the first quadrupole is located at 5.25m from the TCC.

The results from MCNP modeling of the flux levels and spectra of background neutrons and gammas at an unshielded MRSt are shown in Fig. 3.3 for the same $3.6 \times 10^{16}$ yield implosion used in the signal calculations presented in section 3.1. To
get a better idea about the magnitudes of the neutron and gamma background levels, the data in Fig. 3.3 are projected onto time and energy axes in Fig. 3.4. As shown by the figures, the gamma level dominates the neutron level.

Figure 3-3: (a) Simulated flux distributions of (a) neutrons and (b) gammas at the unshielded MRSt detector for a $3.6 \times 10^{16}$ neutron yield. The general shape of the distributions is dictated by the surrounding NIF structures.
Figure 3-4: Projection of the flux distributions of neutrons and gammas at the unshielded MRSt detector onto (a) the time axis, and (b) energy axis. The distributions have been normalized per produced source neutron. Statistical uncertainty in the data is about 5%.
3.3 Cesium-Iodide Cathode Response to Signal and Background

3.3.1 Cesium-Iodide Cathode Response to Signal Deuterons

To obtain a fundamental understanding of the MRSt performance, it is important to determine the CsI response to the signal deuterons as well as background neutrons and gammas. As this has been modeled by C. Wink et al.[16], and experimentally verified by A. MacPhee et al.[17], I will only touch upon the key points about the CsI response. Before I go into that discussion, it should also be noted that the CsI plays an insignificant role when it comes to S/B characteristics because the background mainly comes from the MCP at the backend of the detector, as discussed in Sec. 3.4.

The current plan is to use a 75 μm-thick Si substrate in front of the CsI cathode, in which 12.5-MeV deuterons, with an inclination angle of 70 degrees, lose 3.1 MeV. As the deuterons traverse the Si substrate, they exhibit some lateral straggling, which could significantly affect the focus at the CsI cathode, and thus potentially compromise the energy/time resolution of the system if the Si substrate is too thick, but initial SRIM calculations indicate that the lateral straggling for 12.5-MeV deuteron through the Si substrate is of order of 10 microns that is well below the maximum tolerable level of 100 microns (further exploration of the lateral straggling will be conducted in detail in near future. The effect of energy straggling will also be explored).

After traversing the silicon substrate, the deuterons interact with the CsI cathode and deposit their energy in the material according to the Bethe-Bloch formula. As the CsI cathode is 1000 Angstroms thick (the effective thickness is about 3000 Angstroms due to the deuteron inclination angle of 70 degrees), about 4 keV is uniformly deposited by deuterons in the cathode, and this deposited energy generates a cascade of primary electrons with energies on the order of 1 keV [18, 19]. As the CsI cathode is thin, a small fraction of the primary-electron energy is deposited in the material via elastic and inelastic collisions where about half of the energy deposited goes into exciting distant atoms and the other half goes into ionizing more local atomic elec-
trons that generates secondary electrons (SE). The reason for this is that it takes $\sim 20$ eV\[19\] to $\sim 70$ eV\[20\]. For more details of the SE-generation processes and SE transport, the reader is referred to C. Wink’s Master’s thesis\[10\] and references\[18, 19\]. Out of the generated SE, only a small fraction of them are emitted from the backside of the CsI cathode, which can be analytically expressed as

$$P(x) = P_0 e^{x/L}$$

(3.1)

where $P(x)$ is the escape probability of an SE born some distance $x$ from the backside ($x=0$), $P_0$ is the probability for an SE to escape if generated at $x=0$ ($\sim 70\%$ for CsI) and $L$ is the electron escape length ($\sim 90$ Angstroms for CsI)\[19\]. In addition, given that the deuteron energy deposition scales to the first order linearly with the CsI cathode thickness, the number of SE emitted on the backside of the CsI cathode can be expressed as

$$Y_{SE} = \frac{1}{\theta \epsilon} \int_0^{1000} \left( \frac{dE}{dx} \right) P_0 e^{x/L} dx$$

(3.2)

where $\epsilon$ is the energy required to generate an SE, $\theta$ is the inclination angle of the incoming signal deuterons relative to the cathode-surface normal ($\theta = 70$ degrees), and $dE/dx$ is the deuteron stopping power in the CsI material. SE are generated throughout the CsI, but only a fraction of them escape the CsI backside.

To illustrate the fundamentals of the CsI response to deuterons discussed in the previous paragraph, let’s look at an example. In the case of 9.4-MeV signal deuterons (a 12.5-MeV deuteron loses on average $\sim 3.1$ MeV in the silicon substrate in front of the CsI), the stopping power is 1.6 eV/Angstrom and $\sim 60$ SE are produced while $\sim 6.0$ escape. These numbers are in good agreement with Henke model\[18\], which was experimentally tested by Kravchenko et al.\[21\] and experimentally verified by A. MacPhee et al\[17\]. Fig. 3.5 shows the number of deuteron generated SE escaping the backside of the CsI as a function of deuteron energy.
Figure 3-5: The number of SE emitted from the backside of the CsI cathode as a function of original signal deuteron energy using equation 3.2.

Using the SE model described above, the CsI response to the signal deuterons is shown in Fig. 3.6 for the NIF shot producing a neutron yield of $3.6 \times 10^{16}$, where the number of SE emitted at the backside of the CsI cathode is plotted as a function of time. As the down-scattered signal (during the period 350ns-383ns for deuterons) is significantly smaller than the primary signal, S/B calculations and optimization are dictated by the down-scattered signal.
Figure 3-6: The number of SE emitted from the backside of the CsI cathode as a function of time for the NIF shot producing a neutron yield of \(3.6 \times 10^{16}\).

### 3.3.2 Cesium-Iodide Cathode Response to Background Neutrons and Gammas

As it has been shown by C. Wink et al. that the background generated in the CsI is negligible in comparison to other sources, we will not elaborate upon this and only refer to their work.[10, 14]

### 3.4 Microchannel-Plate Response to Signal and Background

#### 3.4.1 Microchannel-Plate Response to Signal Deuterons

As shown in Fig. 3.1, the signal-deuteron distribution (10.7-11.6 MeV) at the CsI cathode stretches over a time period of 350-383 ns. The SE distribution generated
by these deuterons in the CsI cathode will be dilated (or stretched) about $25\times$, accelerated to $\sim 2$ keV, and transported $\sim 1$ m to the backend of the PDDT, which takes about 50ns. In addition to dilating the signal distribution, it is unskewed when it has reached the backend of the detector (see T. Hilsabeck et al.\cite{14} for how the dilation-unskew method works). Given that the duration of the neutron emission from an ICF implosion is $\sim 100$ ps and the MRSt dilates the signal $25\times$, the signal time window at the detector is $\sim 2.5$ ns long, at 420-422.5 ns. A microchannel plate (MCP) will be used at the PDDT backend to provide gain before the SE distribution is detected by an array of segmented anodes (along the energy axis). Typically about 90\% of the signal SE distribution, shown in Fig. 3.6, will be detected and amplified by the MCP. The reason for this is that the MCP consists of an array of small glass channels for amplification, and these channels cover about 90\% of the MCP area. At the time of writing this thesis, it is not clear if a single-stage MCP or Chevron-style MCP will be used for the MRSt. In the context of determining the S/B, this is, however, not important.

For the optimization of the shielding surrounding the PDDT detector and for maximizing the S/B, a clear understanding of the MCP response to the down-scattered-deuteron signal and neutron/gamma background must be obtained.

3.4.2 Microchannel-Plate Response to Background Neutrons and Gammas

As the down-scattered signal is detected over an area that is about $125 \times 10mm^2$ (the width of the signal distribution in the plane perpendicular to the dispersive plane is $\sim 10$ mm) and time duration that is $\sim 2.5$ ns, an assessment of the MCP-induced background during this space-time window must be made.

Neutrons mainly generate electrons through $(n,p)$ and $(n,\alpha)$ reactions in the MCP glass. The neutron-induced ions in the MCP, which typically have a range of order 100 microns, may strike the channel walls and generate electrons that are multiplied along the channel. C. Parker et al. found that a borosilicate MCP efficiency for
detecting 14-MeV neutrons with perpendicular incidence is $(5.1 \pm 1.9) \times 10^{-3}$ electrons per incoming neutron\cite{22}. This number is critical for the assessment of the MRSt neutron background.

Gammas interact with the MCP through the photoelectric effect, Compton scattering and pair production, producing primary electrons and positrons. In a similar fashion as for the ions produced by neutron-induced nuclear reactions, gamma-induced primary electrons/positrons can strike the MCP-channel wall and generate a cascade of electrons emitted at the exit of the MCP. C. Parker et al. found that the efficiency of the borosilicate MCP for detecting 1.5-MeV gammas with perpendicular incidence is $(4.9 \pm 3.1) \times 10^{-3}$ electrons per incoming photon with perpendicular incidence\cite{22}. In their work, they also concluded that a borosilicate MCP is a much better choice than the standard lead-based MCP for a system measuring signal in the presence of a large gamma background.

To determine the number of electrons generated by the background neutrons and gammas in the MCP (integrated over the down-scattered-deuteron-signal time window of 420-422.5 ns), a simple model was created in which it is assumed that each interaction, generating a charged particle, produces a recordable signal. To account for the fact that background neutrons and gammas are isotropic at the MRSt MCP, a multiplication factor of 0.5 was also used to approximate the MCP response to particles with different angles of incidence\cite{10}.

In the case of the neutron background (for which the fluence spectrum is shown in Fig. 3.7(a)), the cross section Fig. 3.7(c) for generating charged particles and gammas were used to determine the spectrum-weighted interaction probabilities in the borosilicate-glass MCP for an unshielded MRSt, and the results are shown in Fig. 3.7(g). Since neutron-induced ions always interact with the MCP material, these events totally dominate over neutron-induced gammas and thus constitute most of the background shown in Fig. 3.7(g).

In the case of the background gammas interacting with the borosilicate-glass MCP (fluence spectrum shown in Fig. 3.7(b)), cross sections for generating photoelectrons, Compton electrons, and pair-produced electrons/positrons Fig. 3.7(d), and the prop-
Properties of the borosilicate-glass were used to determine the gamma-spectrum-weighted interaction probabilities and thus the number of electrons generated in the MCP. The results from that calculation is shown in Fig. 3.7(h), from which an interaction probability of $5.2 \times 10^{-3}$ was calculated for 1-MeV gammas with perpendicular incidence on the MCP. This result agrees with the result to be published by C. Parker et al.[22]. It is also clear from Figs. 3-7(g) and (h) that the generated background in the MCP is totally dominated by the gamma interactions in the glass.

![Fluence spectra of background neutrons and gammas at the unshielded MRSt MCP, integrated over the 2.5 ns time (420-422.5 ns for down-scattered signal deuterons); charged-particle and gamma producing cross sections for neutrons and gammas in the borosilicate-glass MCP; number of SE produced as a function of neutron and gamma energy.](image)

Figure 3-7: Fluence spectra of (a) background neutrons and (b) gammas at the unshielded MRSt MCP, integrated over the 2.5 ns time (420-422.5 ns for down-scattered signal deuterons); charged-particle and gamma producing cross sections for (c) neutrons and (d) gammas in the borosilicate-glass MCP; number of SE produced as a function of (g) neutron and (h) gamma energy. See text for additional details.
3.4.3 Signal-to-Background Generated by the Microchannel Plate for an Unshielded MRSt

Having established the signal and background levels generated by the borosilicate-glass MCP, an assessment of the S/B for the MRSt down-scattered-neutron measurement can now be made. From Fig. 3.6, the number of SE generated by the down-scattered deuteron signal is \( \sim 750 \) events. This should be contrasted to the background-induced electron spectra shown in Fig. 3.7(g) and (h). Integrating and summing the neutron- and gamma-induced electron spectra results in the S/B ratio of 0.12, which is clearly too small for a successful MRSt measurement of the ICF down-scattered-neutron spectrum, and thus indicate that shielding surrounding the spectrometer is required. To achieve a S/B \( > 5 \) for this measurement, the background needs to be reduced, at minimum, \( \sim 40 \) times.

3.5 Optimized Design of the MRSt Shielding

As demonstrated in previous section, the MCP constitutes the main source of background, clearly indicating that shielding must be used to enclose the MRSt detector and effectively shield the MCP.

After several iterations using MCNP transport code, an MRSt shielding design has been found that reduces the ambient background of neutrons and gammas to the required level of S/B \( > 5 \) for the down-scattered neutron measurement (see Fig. 3.9(b)). This design practically encloses the PDDT detector that has a volume of \( 50 \times 100 \times 10 \) cm\(^3\). The first layer surrounding the PDDT detector consists of 2-cm thick stainless steel (the detector vacuum housing). The stainless steel housing is in turn surrounded by a 2.5-cm thick layer of tungsten. An extra 3-cm thick layer of tungsten surrounds the last 20 cm of the PDDT detector. This shielding made of high-Z material has been incorporated into the design to reduce the gamma background to the required level. Outside the gamma shielding there is a neutron shielding, which is composed of a 65-cm thick layer of 30% borated polyethylene (the thickness of
polyethylene can possibly be reduced to $\sim 35$ cm as discussed later).

The principle of this shielding is to first reduce the neutron background through absorption as well as moderating the neutrons through a low density, low Z material. Borated polyethylene serves both of these purposes. Then, a layer of high-Z material acts to reduce the gamma background, as gammas are not effectively moderated by the low-Z neutron shielding. By increasing the layer of high-Z shielding around the detector itself, the gamma background is further reduced where it is most relevant for the S/B.

To illustrate the effectiveness of the shielding design, the neutron- and gamma-fluence maps (time-integrated over the down-scattered signal time window) are shown in Figs. 3-8(a) and (b). As shown by these maps, the neutron and gamma fluence is reduced about two orders of magnitude at the MCP location. It is also notable that the neutron fluence drops significantly immediately inside the polyethylene, while the gamma fluence is not visually reduced until they reach the tungsten layer. The remaining gamma (or rather x-ray) background at the MCP is mainly due to tungsten fluorescence, because neutrons and gammas excite K shell electrons that generate $\sim 60$ keV photons. Some of those photons are absorbed by the stainless steel vacuum housing.
Figure 3-8: MCNP-modeled maps of neutron fluence and gamma fluence around the MRSt system, which have been integrated over the down-scattered signal time (420-422.5 ns).
Fig. 3.9 shows the spatial source distribution of the background gammas and x-rays, clearly indicating that significant amount of photons are produced both in the polyethylene and tungsten shielding. As discussed in Chapter 4, improvements to the gamma shielding will be explored, where the tungsten will be replaced by graded-Z design with progressively lower-Z materials towards the PDDT detector. Reducing the thickness of polyethylene would increase fluence level of higher-energy neutrons at the tungsten, which would increase the level of background gammas produced by \((n,\gamma)\) reactions. Although this will reduce the S/B, it might be a solution from a practical point of view, such as space constraints. This will be touched upon later.
Figure 3-9: Spatial source distribution of the background gammas and neutrons, clearly indicating the origin of the background in the MRSt measurement.
As the signal is recorded over the time window of 420-422.5 ns, the neutron and gamma background were evaluated over this time period. This was done by going through the same exercise as for the unshielded MRSt case, and the resulting data are shown in Figs. 3-11(a)-(h). The results are contrasted to the unshielded MRSt case to illustrate the effectiveness of the shielding. From these data, the S/B ratio have been derived (see Table 3.1).

Figure 3-10: Fluence spectra of background neutrons and gammas at the shielded MRSt MCP (red), integrated over the 2.5 ns time (420-422.5 ns for down-scattered signal deuterons); charged-particle and gamma producing cross-sections for (c) neutrons and (d) gammas in the borosilicate-glass MCP; number of SE produced as a function of (g) neutron and (h) gamma energy. The data for the unshielded case (blue) is also shown for comparison.

Table 3.1 illustrates the S/B ratio for each of the different designs considered in the course of this thesis. The finalized design was obtained after comparing each of these different configurations.
Table 3.1: S/B for the optimized design of the MRSt shielding, contrasted to other options to illustrate the impact of geometry and material on the S/B. The optimized design is discussed in the second paragraph of Section 3.5. Using standard polyethylene instead of borated polyethylene reduces the S/B by about 25% (from S/B of 35 to 26); using lead for the inner high-Z layer instead of tungsten reduces the S/B by about 24% (from S/B of 35 to 27); using no extra 3-cm thick layer of tungsten that surrounds the last 20 cm of the PDDT detector reduces the S/B by about 6% (from S/B of 35 to 33); using a 35-cm thick polyethylene shielding instead of 65-cm thick shielding reduces the S/B by about 44% (from S/B of 35 to 20). A thinner polyethylene might be the optimal solution when all space constraints have been fully considered.

<table>
<thead>
<tr>
<th>Material</th>
<th>Extra Shield</th>
<th>Final S/B</th>
<th>Final Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0.12</td>
<td>27</td>
<td>35</td>
</tr>
<tr>
<td>Lead</td>
<td>27</td>
<td>20</td>
<td>33</td>
</tr>
<tr>
<td>Thin Poly.</td>
<td>No Extra γ</td>
<td>33</td>
<td>26</td>
</tr>
<tr>
<td>Non-borated Poly.</td>
<td>Final Design</td>
<td>Final Design</td>
<td></td>
</tr>
</tbody>
</table>

Each of these choices was based on the physics of neutron and gamma interaction, and verified through modelling with MCNP. For neutron shielding, low-Z materials are often used, as the interactions of neutrons with particles of similar masses allows them to lose their kinetic energy more rapidly. For instance, the number of elastic collisions a neutron needs to go from 2 MeV to 0.25 MeV from collisions with hydrogen dense materials is around 18, as compared to 115 for collisions for materials with $A = 12^{[23]}$. In order to complement this, low-Z materials are often doped with highly-absorbing materials. For this reason, I used a 30% borated polyethylene material for the neutron shielding, as this not only reduced the neutron background through elastic collisions, but also through absorption by the boron atoms in the material. This increased the S/B by an additional 9 compared to the case with regular polyethylene. Additionally, increasing the thickness of the polyethylene layer from 35cm to 65cm significantly improved the S/B, by 77%.

For the gamma shielding, there were two main choices: the material type, and extra shielding around the MCP. For material type, a high-Z material was selected, as there is a higher number - and a higher density - of electrons for gammas to interact with via the photoelectric effect, Compton scattering, and pair production. To that end, both lead and tungsten were looked at. In this case, density proved more important, and tungsten performed 32% better than lead. Lastly, an increased layer of tungsten around the very end of the PDDT, where the MCP is located, was
implemented to further reduce the gamma background. The S/B increase in this case was much less pronounced than the other changes, offering only a \( \sim 6\% \) increase in the S/B, but did prove effective nonetheless.

Overall, the optimal shielding design provides an improvement of the S/B from 0.12 for the unshielded PDDT to 35 - an improvement of \( 293 \times \). This S/B is more than sufficient in comparison to the initial goal of an S/B > 5. This is ideal, as it allows for continued high performance of this diagnostic even the case where the MRSt is operated at lower efficiency and higher resolution.
Chapter 4

Summary

The MRSt system will provide for the first time time-resolved information about the ion temperature $T_i$, the neutron yield $Y_n$, and the areal density $\rho r$ in an ICF implosion, which has never before been possible before. This information will be obtained with the MRSt through time-resolved measurements of the neutron spectrum in the range of 12-16 MeV. Information about $Y_n$ and $T_i$ is obtained from the primary-neutron spectrum (13-15 MeV), while $\rho r$ is inferred from the yield ratio between down-scattered (12-13 MeV) and primary neutrons.

To successfully implement the MRSt on the NIF for a S/B > 5 measurement of the down-scattered neutrons, a fundamental understanding of the signal and background distributions at the MRSt detector must first be obtained. Then, the CsI cathode and MCP response to signal deuterons and background neutrons/gammas must be determined, followed by minimization of the background in the MRSt data. This was done in this thesis in a two-step approach.

In the first step, an MCNP model of the MRSt in the NIF target bay was implemented and used to assess the signal and background distributions at the MRSt detector at an unshielded MRSt system. Models of the CsI and MCP response to the signal and neutron/gamma background were then implemented to assess the S/B for the unshielded MRSt case. It should be noted that these models were benchmarked by existing data to raise the fidelity of the modeling. From this exercise, it is clear that the borosilicate-glass MCP constitutes a major source of background that
needs to be mitigated. As discussed in Section 3.4.3, the total neutron and gamma background generated by the MCP needs to be reduced, at minimum, \(\sim 40\times\).

In the second step, a shielding design, consisting of polyethylene, tungsten and stainless steel, practically enclosing the PDDT detector, was developed to reduce the background to the required level. This design reduces the background \(292\times\) and improves the S/B from 0.12 for the un shielded case to \(\sim 35\) for the optimal shielding case, which meets the requirement of a S/B > 5 for the down-scattered neutron measurements.

Going forward, we will explore the graded-Z shielding design, in which several layers of decreasing Z are placed around the PDDT detector. This would attenuate higher energy gammas before they enter the next layer of shielding, where they would be attenuated further.
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