Cherenkov Gamma Ray Detectors on High-Energy-Density Systems

Kevin Daniel Meaney

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Cherenkov Gamma Ray Detectors on High-Energy-Density Systems

by

Kevin Daniel Meaney

Honors B.S., University of Wisconsin Madison 2015
M.S., Physics, University of New Mexico, 2017

DISSERTATION

Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctorate of Philosophy
Physics

The University of New Mexico
Albuquerque, New Mexico

May, 2020
Dedication

for Sofi
A great thank you and the highest praise to Yongho Kim, my mentor throughout my PhD experience. Yongho’s guidance, intelligence and patience has helped me grow from a student to a researcher. Likewise, great appreciation to Hans Herrmann, who has been an invaluable mentor and teacher that has helped me grow. Yongho and Hans graciously brought me under their wings and have given me the best graduate experience anyone could ask for. Thank you to Mark Gilmore for his unending support, his willingness to be my liaison between the university and the lab. Mark too, has made my graduate experience smooth and joyful. Thank you to my loving wife Sofi, who has given her support and sacrifice throughout my graduate studies. Thank you to my wonderful parents for their love and support throughout my whole life. Thank you to Hermann Geppert-Kleinrath, whose high spirits, warm personality and intelligence make each day working with him bright. Thank you to Doug Fields and Edl Schamiloglu for agreeing to be on my PhD committee and committing to all the paper work and time that entails.

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Abstract

High energy density (HED) systems are some of the most extreme environments ever created by mankind. Systems with pressures greater than 1 MBar can only be created by a handful of devices on earth, often utilizing high intensity lasers or pulsed power machines. HED systems offer a view into an extreme form of matter only seen in stellar cores, supernovas and other powerful astrophysical systems. Creating HED systems on Earth offer the possibility, if the physics and technology can be matured, to one day create a fusion power plant. If a system is hot and dense enough, the fusion reaction can drive more fusion reactions through the alpha particle depositing its energy. There has been a generation goal of getting this fusion chain reaction to create high yield and gain, however, this regime, called ignition, has remained elusive. Diagnosing HED systems to understand the degradation preventing ignition presents a challenge. HED pockets are often short lived (nanoseconds or picoseconds) and concurrent with a release of a physical blast shock, nuclear particles, a strong electromagnetic pulse and a noisy radiation environment. Cherenkov detectors to
measure energy thresholded, time resolved gamma rays is one such technique that can be applied to these systems to gain insight and understanding to the properties of HED systems. In this dissertation, the fundamentals and background of this diagnostic technique are applied in detail to three HED systems. Gas Cherenkov detectors are applied onto the National Ignition Facility’s inertial confinement fusion ignition campaigns. Inertial confinement fusion uses high powered lasers to compress a capsule full of deuterium-tritium fuel surrounding by a carbon ablator shell, which is used to push the fuel into high densities and temperatures. A technique to isolate a 4.4 MeV carbon gamma ray is introduced and applied to understand the areal density and compression of the outside portion of the inertial confinement fusion pusher. The new data reveals that the outside portion of the pusher followed the expected hydrodynamic predicted trends, while the inner fuel portion of the pusher looks to be degraded and less compressible. This data suggests for specific degradation mechanisms acting on the capsule that preferentially degrade the fuel, such as ablator-ice mix. The time resolution of the gamma detector also gives information about the velocity of the carbon ablator during the fusion burn. Second, gamma ray measure mix studied field on the OMEGA laser system are shared, showing a complicated mix landscape for spherical implosions. Aerogel Cherenkov detectors are fielded on the Mercury pulsed power facility at the Naval Research Lab which creates an accelerated electron beam to create a strong bremsstrahlung x-ray source. The Aerogel Cherenkov detectors are able to characterize and measure time resolved signals of the x-ray pulse, vital information for the x-ray pulse to be feed into a radiography or photofission source. This dissertation presents a body of work that applies a diagnostic technique to an extreme experimental conditions, receives novel measurements and interprets their results.
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<td>$\vec{A}(\vec{k}, \omega)$</td>
<td>3 component magnetic vector potential in SI units of Volts per distance. Note that the Cherenkov light derivation uses Gaussian units.</td>
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<td>$A_n$</td>
<td>Atwood number, defined as the difference of mass densities in the form: $\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$. The value is unitless.</td>
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<td>$A_h, A_l, \bar{A}$</td>
<td>Atomic mass number of the heavy, $h$ or light, $l$, or average, $\bar{A}$, fluid species. Unitless.</td>
</tr>
<tr>
<td>$a$</td>
<td>Dummy variable for the radius of a cylindrical Gaussian surface, measured in length.</td>
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| $\alpha$ | 1) Carbon to non-carbon gamma ray GRH spectrum calibration, is unitless.  
2) Carbon ablator exponential decay constant in the form $e^{-\alpha r}$ in units of inverse distance. |
| $\vec{B}(\vec{k}, \omega)$ | Magnetic field measured in SI units of Tesla. Note that the Cherenkov light derivation uses Gaussian units. |
| $\beta$ | Relativistic $\beta$ defined as the percent of speed of light, $\frac{v}{c}$, is unitless. |
| $b$ | Defined as impact parameter, or perpendicular distance between interacting particles, measured in distance. |
Speed of light with value of \(2.998 \times 10^8\) meters/second. The Cherenkov light derivation uses Gaussian units where additional \(c\) terms are present or removed compared to SI.

Calibration value measured to relate the measured voltage on GRH with the number of carbon gamma rays. Has units of Volts/Number of Carbon Gamma Rays.

Dirac Delta function defined as a function with a zero value for all inputs except \(\delta(0) = +\infty\) as well as \(\int_{-\infty}^{+\infty} \delta(x) = 1\). It has units of inverse its input. When it has inputs of \(\delta(x - vt)\) it has units of inverse volume from each component of the position and velocity vectors. \(\delta(\omega - vk_1)\) has units of time.

Diffusivity of a fluid, measured in area per time.

Elementary charge with value of \(1.602 \times 10^{-19}\) Coulombs.

Electric field measured in SI units of Volts per distance. Note that the Cherenkov light derivation uses Gaussian units.

Energy, measured in joules.

Dynamic friction coefficient which is unitless and has values generally between 1/3 and 1.

Acceleration applied between two fluids in units of length per time squared.

1) \(\epsilon(\omega)\), Electromagnetic permittivity. In free space it holds a value of \(8.85 \times 10^{-12}\) Farad per meter. In materials it holds higher values that vary as a function of frequency. The Cherenkov light derivation uses Gaussian units where additional \(\epsilon\) terms are present or removed compared to SI.
2) Average rate of turbulence kinetic energy dissipation with units of energy per time.

\( \gamma \)  
Relativistic Lorentz factor defined as \( \gamma = \frac{1}{\sqrt{1-\beta^2}} \), is unitless.

\( h \)  
Height of Rayleigh Taylor bubble or finger growth measured in distance.

\( \vec{H} \)  
Magnetic field strength measured in SI in Ampere per distance, in Gaussian units they are related by \( \vec{B} = \mu \vec{H} \).

\( \eta \)  
1) Mass attenuation constant giving the value of the cross section for 14 MeV DT neutrons releasing a carbon gamma, has a value of 0.0106 cm\(^2\)/g.  
2) Kolmogorov length scale, or the smallest turbulent scale, measured in length.

\( h \)  
Planck’s constant with the value 6.626e-34 meters\(^2\)kg/seconds

\( i \)  
Imaginary number defined as \( i^2 = -1 \).

\( I \)  
Laser intensity, measured in power per area.

\( J(\vec{x},t) \)  
Electric current density in SI units of current/distance\(^2\). Note that the Cherenkov light derivation uses Gaussian units.

\( k \)  
1) Wave number with units of inverse length.  
2) Constant in a differential equation.

\( K_n(x) \)  
Macdonald Bessel function of the second kind defined as \( K_n(x) = \int_0^\infty e^{\cosh(nt)}e^{-x\cosh(t)}dt \).

\( l \)  
Length measured in distance.
Glossary

\( \lambda \)

1) Wavelength in units of length.
2) Defined as \( \lambda^2 = \frac{\omega^2}{v^2} - \omega^2\epsilon(\omega) = \frac{\omega^2}{v^2}(1 - \beta^2\epsilon(\omega)) \) as part of the Cherenkov light derivation.
3) \( \lambda_{DeBroglie} \) is the matter wave wavelength, defined as the Planck’s constant over the momentum \( \frac{h}{mv} \).

\( \Lambda \)

Plasma parameter describing the Coulomb scattering logarithm, is unitless.

\( m \)

Mass, measured in kg.

\( \mu(\omega) \)

Electromagnetic magnetic constant. In free space it holds a value of \( 4\pi \times 1e-7 \) Henry per distance. In materials it holds higher values that vary as a function of frequency. The Cherenkov light derivation uses Gaussian where additional \( \mu \) terms are present or removed compared to SI.

\( n(\omega) \)

Index of refraction defining the speed of light in a medium as \( v = c/n \). The index of refraction changes as a function of frequency across materials. When \( n \) is shown alone it means for a specific frequency. Real values of the index of refraction and permittivity have the relation \( n(\omega) = \sqrt{\epsilon(\omega)} \).

\( N \)

Number of particles.

\( P_a \)

Electromagnetic energy flow measured in SI as energy per time. It is determined in the Cherenkov light derivation by integrating the Poynting vector over a surface. Note that the Cherenkov light derivation uses Gaussian units.

\( \Phi(\vec{k}, \omega) \)

Electric potential in SI units of Volts. Note that the Cherenkov light derivation uses Gaussian units.
Glossary

$q$ Charge in Coulombs. Specifically refers to the charge of the particle emitting Cherenkov light in the Cherenkov light derivation. Note the Cherenkov light derivation uses Gaussian units.

$r$ Radius, measured in distance. $r_c$ is used for the radius of the DT ice layer and carbon ablator interface.

$\rho(\vec{x}, t)$ 1) $\rho(\vec{x}, t)$, charge density in SI units of \( \frac{\text{charge}}{\text{distance}^3} \). Note that the Cherenkov light derivation uses Gaussian units.
2) $\rho$, mass density in units of mass over volume.

$\rho R$ Areal density defined as density of a material, $\rho$, times the thickness $R$ measured in units of mass over area.

$\vec{S}$ Poynting vector describing the directional energy flux in SI units of Watts per area. Note that the Cherenkov light derivation uses Gaussian units.

$S_{>n}$ Signal measured by a gamma detector that has an energy threshold of $n$. Value has units of volts.

$\sigma$ Standard deviation of a Gaussian distribution. For time resolved reaction history, $\sigma$ has a unit of time.

$t$ Time, $t_{BT}$ is the time of nuclear bangtime, or maximum fusion rate. $t_C$ is the time of carbon gamma bangtime, or maximum carbon gamma rate.

$T_i$ Ion temperature of the $i$th fluid species, measured in energy.

$\tau_{BW}$ Nuclear burnwidth of the fusion reaction history, measured in units of time.

$\tau_\eta$ Kolmogorov time scale, the smallest turbulent time scale.
Glossary

- $\vec{v}$: 3 component velocity vector in units of length per time.
- $\nu$: Kinematic viscosity measured in units of area per time.
- $\omega$: Angular frequency with units of inverse time.
- $\vec{x}$: 3 component position vector in units of length.
- $Y_n$: Yield, or total number of particles released of neutrons or, for $Y_{\gamma C}$, number of carbon gamma rays.
- $Z$: Atomic number, unitless.
Chapter 1

Introduction

1.1 High energy density systems

High Energy Density (HED) systems are defined as environments that have a pressure larger that 1 MBar, or \(10^{11} \frac{1}{\text{cm}^2}\) [1], [2]. At these pressures, all solids become compressible and behave as ionized, plasma systems. These pressures require extreme temperatures and densities. Compared to the conditions of human experience, HED systems are extraordinarily extreme. In nature, planet cores, star cores, supernovas, neutron stars and the early conditions of the Big Bang can all create HED conditions. The systematic study of HED systems is relatively new, limited by technology able to achieve the intense conditions. The first human created HED conditions occurred in nuclear weapons in the 1940s, but were not able to able to systematically studied. The development of the pulsed power Z-pinch starting in the 1950s as well as the development of intense lasers in the 1970s unlocked the technology to systematically create HED conditions. Figure 1.1 shows the parameter space of density and temperature and the various systems that can create those conditions.

The interest in studying HED physics is three fold. One is the fundamental
Chapter 1. Introduction

Figure 1.1: The density and temperature parameters space showing HED conditions, adapted from [1] and [2]

understanding of a new regime of matter and physics that can help inform planetary and stellar interiors, universe dynamics as well as basic high pressure plasma environments and nuclear processes. Second, HED conditions are hot and dense enough to achieve nuclear fusion. If the physics could be well understood and the technology matured, the hope exists for using HED relevant systems to use nuclear fusion as a clean, carbon neutral, limitless fuel, energy production method [3]. Third, because exploding nuclear weapons pass through a HED regime, paired with the United States adherence to no longer do nuclear weapons tests [4], the United States government supports scientific understanding and systematic study of HED conditions. The physics understanding and developed technology can be used to
support stockpile stewardship\cite{5}, maintaining the nuclear stockpile through science based understanding instead of nuclear weapons tests.

A current generational goal of HED research is to achieve fusion ignition. Ignition is defined as a propagating fusion hot spot. Each deuterium-fusion (DT) releases an 4 MeV alpha particle. The alpha particle deposits its energy in the surrounding fuel, heating it. If a high enough temperature and density are present, enough fusions occurs to deposit enough energy to drive more fusions, thereby causing a feedback loop through a propagating alpha wave, giving high fusion yields for the system only supplying the energy to give the initial spark. Achieving ignition would open a new, categorically different physics environment for fundamental study as well as be able to study more weapons relevant systems. Furthermore, for any reasonable chance for a HED based power plant, ignition type energy gains are required. To date, no controlled experiment has achieved such ignition.

By the nature of the energy concentration needed, creating an HED environment is often a pulsed, single impulse shot that creates the high pressure environment for a short amount of time (nanoseconds to picoseconds). The shot is often accompanied by a resulting blast, a release of nuclear particles, a noisy radiation environment, and an electromagnetic impulse. This creates a difficult diagnostic challenge, as any diagnostic technique must be fast, radiation, shock and electromagnetically hardened and still measure the signal of interest. One of the central diagnostic signatures of interest is the time evolution of DT fusion burn, which provides fundamental measurements on formation and disassembly. The Chereknov process to measure high energy photons is one such technique that meets all the environmental requirements and can measure fusion reaction history as well as other diagnostic signatures of interest. The Cherenkov technique applied to different HED systems and the resulting physics are the purpose of this dissertation.
1.2 High energy density facilities

Three HED environments will be focused on in this dissertation. Inertial confinement fusion (ICF) is the process of heating and compressing a fuel target into high densities and temperatures for nuclear fusion to occur faster than the object can be blown apart. Two facilities, the NIF located in Livermore, California and the OMEGA laser at the Laboratory for Laser Energetics (LLE) located in Rochester New York both use high powered lasers to apply the energy needed to compress fuel. Pinch systems, which, through a fast concentration of a voltage pulse, create a plasma and pinch it to high densities through the Lorentz force can also create HED conditions. One such pulsed power source, Mercury, located at the Naval Research Lab (NRL) in Washington D.C will be highlighted.

1.2.1 Laser facilities

The high power available in lasers offer the opportunity to create HED systems. Many lasers of this type are ultra short pulse lasers, such as BELLA, a 30 fs, 65 J laser, at Lawerence Berekley National Lab, Ohio State’s 40 fs, 15 J Scarlet laser, Stanford’s Matter at Extreme Conditions (MEC) handful mix of joule level lasers, the Jupiter laser Lawerence Livermore which can reach up to a kJ in a handful of nanoseconds and a handful more. However, the two laser systems with the highest amount of energy delivered are the OMEGA laser which can deliver 40 kJ and 60 TW and the 2 MJ, 500 TW NIF laser. These two laser systems have the most energy to drive ICF capsultes to the highest densities and temperatures.

The NIF is the largest, most powerful laser in the world. Figure Focusing 192 lasers in a 6 meter spherical vacuum chamber, the NIF has the ability to shape the laser pulse into complex shapes that would be difficult with pulsed power machines. NIF is an indirect drive system that uses the visible light laser to drive a hohlraum,
converting the light to an x-ray bath that is used to ablate capsules. The conversion to x-ray carries 10% of the input laser energy onto the capsule, but also is more uniform and the x-ray is less susceptible to plasma interactions such as critical densities from ablated matter. The capsules have an initial size of around 1 mm and are composed of an ablator layer - made of carbon or beryllium - with an inner high density DT ice layer surrounding a gaseous DT inner radius at vapor pressure with the DT ice at cryogenic temperature. NIF was constructed with the goal of ignition but, unfortunately, the expected high yields have not been realized. Optimistic simulations did not account for complex, multi-scale effects like initial preheating of the capsule, ablator-DT mix, degradation from the fill tube, tent structure, capsule roughness and laser beam asymmetry and others. All of these effects act to reduce the compressibility of the capsule and remove energy being transferred into the hot spot. The National Ignition Campaign ran from 2009 when the NIF laser
Chapter 1. Introduction

was first operational until 2012. Since then, NIF has expanded its research focus but still studies the sources and mitigation techniques in the hope that ignition will be achieved. As such, diagnostic techniques that can give additional information about the state of the capsule help give insight to the many complicated interactions that prevent higher ICF performance.

The OMEGA laser system has a 4 meter vacuum chamber and uses 60 beams in the UV range to directly ablate the capsule, thereby having the capsule absorb more energy compared to indirect drive, but must content with seeded asymmetries such as laser speckle and overlap. The main advantage to the OMEGA facility is the relatively high shot rate compared to the NIF, where one day allows 10 to 14 capsule implosions, compared to just one for a shot day on the NIF. The high shot rate allows for parameter scans to inform ICF physics that would be prohibitively expensive on the NIF.

1.2.2 Pulsed power

Large pulsed power machines can supply the energy needed to created HED systems. There are a handful of powerful pulsed power facilities around the United States. An incomplete list includes the 1.2 MA Zebra in Reno Nevada, the 1 MA COBRA at Cornell, 1 MA MAIZE at Michigan and University of San Diego’s 1 MA Linear transformer driver. The world’s largest pulsed power source is the Z machine at Sandia National Laboratories in Albuquerque, New Mexico. The Z machine holds 22 MJ of stored energy, delivering around 3 MJ to a load over 100 to 1000 ns with a maximum current of 26 MA. These pulsed power machines use their driving energy to cause a Z pinch, running current through a place inducing a Lorentz force to contract a plasma or a wire array.

A pulsed power machine originally called KALIF-HELA, built in Karlsruhe, Germany and used for light ion beam generation, was purchased, brought over to NRL
and re-named Mercury [6]. It is a 6 stage, magnetically insulated inductive voltage adder. It was originally designed for operation up to 6 MV and 360 kA with a power of 2.2 TW. Its 36 Sandia-style Marx capacitor banks hold 2.2 $\mu F$, 100 kV. The Marx go through a series resistor into four parallel intermediate storage water capacitors that makes up 36 $nH$ which discharge through laser triggered gas switches into three coaxial water pulse-forming lines. Six induction cells are fed by the pulse forming lines where the voltage is added in a vacuum along the magnetically insulated transmission lines. An overview image of the machine is given in Figure 1.3. The voltage is added onto conductor with a vacuum gap with an anode with the front of the device. The strong voltage potential accelerates electrons into the tantalum anode which stops the electron beam and creates a powerful breemmmstraulung x-ray source. Mercury, and other powerful x-ray sources, are often used as radiographic sources or as photofission source [7]. Characterization of the resulting spectrum, especially x-ray photons above specific thresholds of interest, and the time evolution of a such a system is a useful information, especially as feed-in to other radiographic or particle sourced systems.

Figure 1.3: Model of the Mercury pulsed power machine.
1.3 Dissertation overview

This dissertation presents a body of work that applies a diagnostic technique to an extreme experimental conditions and interprets the resulting measurements. Chapter 2 will introduce the theory and background of the Cherenkov process and connect the technique to the application of gamma ray detectors. Chapter 3 will introduce the NIF ICF campaigns, the gamma environment, a technique to isolate fusion neutron induced carbon ablator gamma rays [8], the resulting information on the compression of the NIF pusher [9], [10] and the resulting timing information on the ablator evolution during the fusion burn. Finally, Chapter 4 will introduce the gamma ray diagnosed mix measurements on the OMEGA ICF platform. Chapter 5 will give the results of aerogel Cherenkov detectors fielded on Mercury to characterize its x-ray spectrum and compare with simulations [11]. Chapter 6 will briefly discuss future work with the Cherenkov detectors.
Chapter 2

Gamma rays and Cherenkov Detectors

2.1 Gamma spectrum from HED systems

2.1.1 Gamma rays from nuclear fusion

The binding energy of nuclear particles are on the MeV scale and can be released in gamma rays. The most fundamental fusion reaction is deuterium-tritium (DT), which has the highest reactivity of all fusion interactions. When deuterium and tritium fuse, they create an excited helium-5 atom that immediately decays. In almost all cases, the helium-5 breaks apart and releases a 3.5 MeV alpha particle and a 14.1 MeV neutron. However, there exists a relatively rare branching ratio where instead of breaking apart, the helium-5 releases its excitation energy into a
16.75 MeV gamma ray [12]. This process is shown in Equation 2.1.

\[
D + T \Rightarrow ^5\text{He}^* \rightarrow \begin{cases} 
\rightarrow_1 n(14.1\text{ MeV}) + \alpha(3.5\text{ MeV}) \\
\rightarrow_{4e-5} ^5\text{He} + \gamma_0(16.75\text{ MeV}) \\
\rightarrow_5 ^5\text{He} + \gamma_1(\sim 13.5\text{ MeV})
\end{cases}
\] (2.1)

The gamma ray decay path of the Helium-5 atom has both an excited state and the ground state, giving both a peaked 16.75 MeV gamma ray as well as a broad 13.5 MeV with a full width half max of 3.5 MeV gamma ray. Measuring time resolved direct fusion particles gives the reaction history or fusion burn rate, a measurement of fundamental interest and relevant to performance of fusion systems. The 3.5 MeV alpha particles often don’t escape fusion experiments and the 14 MeV neutrons are Doppler broadened by their ion temperature, requiring a neutron detector to be very close to the fusion hot spot to measure the unperturbed reaction history, which is sometimes not possible on HED experiments. The fusion gamma rays are mostly unperturbed and escape the experiment. These DT fusion gamma rays give the opportunity to measure the fusion reaction history directly. However, the branching ratio presents a challenge with the low number of fusion gammas competing with the strong background of HED experiments. For example, the NIF can release on order of 1e11 DT gammas, OMEGA, 1e9 and a dense plasma focus around 1e5.

Deuterium-deuterium (DD) fusion is another common fusion fuel that is a lot easier to work with compared to tritium systems. There exists an analogous DD fusion gamma ray releasing a 23.8 MeV gamma ray [13], however, the branching ratio at a few keV is around 1e-7. The combination of DD reactivity being 100x less at 1 to 10 keV thermal temperatures compared to DT fusion combined with the branching ratio being another factor of 100x less compared to DT fusion pushes measurement of the DD gamma rays often too low to be experimentally practical. For example, NIF could release 1e7 DD fusion gammas, OMEGA and the Z Machine, 1e5 and a dense plasma focus around 10 gamma rays.
There are also a few other fusion reactions that preferentially release gamma rays instead of charge particles. These fusion fuels can be chosen specifically for diagnostic information. Hydrogen-Tritium (HT) fusion \[15\] releases nearly 100\% in a 19.8 MeV fusion gamma line and Deuterium Helium-3 fusion release a 16.6 MeV gamma line with a branching ratio of 1.2e-4 \[14\]. The HT gamma ray is used in separated reactant experiments discussed in Chapter 4. All the fusion reaction rates of the four fusion processes of interested are plotted in Figure 2.1 and summarized in Table 2.1.

The time scale of these fusion emissions are very short, around 100 to 150 ps for

![Figure 2.1: Fusion rates for keV thermal temperatures for fusion reactions of interest that can create a strong gamma ray signal. HT releases primarily only in a gamma ray. Reactivity measurements provided by Jerry Hale.](image)
Table 2.1: Some fusion reactions that release gamma rays of interest. The reactivities given are at thermal temperatures of 3 keV.

<table>
<thead>
<tr>
<th>Fusion Reaction</th>
<th>Gamma Ray Energy</th>
<th>Branching Ratio</th>
<th>Total Fusion Reactivity at 3 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT</td>
<td>16.7 MeV</td>
<td>4.2e-5</td>
<td>1.87e-18 cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>D$^3$He</td>
<td>16.6 MeV</td>
<td>1.2e-4</td>
<td>2.68e-22 cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>HT</td>
<td>19.8 MeV</td>
<td>1</td>
<td>2.43e-24 cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>DD</td>
<td>23.8 MeV</td>
<td>~1e-7</td>
<td>1.60e-20 cm$^{-2}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

NIF and OMEGA. Z Machine and dense plasma focus have burn pulse widths on the order of 10s of nanoseconds.

2.1.2 Non-fusion gamma rays

HED environments also create high energy photons through other mechanisms. For laser driven systems, the brightest gamma ray signal comes from inelastic scattering from fusion released particles. Specifically, DT generated neutrons scattering off surrounding material transfers some of the MeV energy of the neutron into the nuclei of the surrounding material, which then de-excite by releasing a gamma ray. In laser driven systems like OMEGA and NIF, the surrounding material can be the ICF capsule itself, often made out of carbon, beryllium, or silicon. Alternative designs like the single pushered shell or the double shell campaign use higher Z material like tungsten, molybdenum or copper. NIF, being an indirectly driven system, has the capsule surrounded by the hohlraum and its supporting structure, known as the thermal mechanical package (TMP). The hohlraum is made up of gold and sometimes uranium. The thermal mechanical package is made up of aluminum and silicon primarily. At the Z machine, the target center is surrounded by a massive amounts of material which has roughly been estimated as a large block of copper. The tabulated nuclear database output of 14.1 MeV neutrons incident on a handful of materials of
interest is shown in Figure 2.2. Lower Z atomic numbers, such as carbon and silicon, have nuclear excitation levels where specific gamma ray lines are present. As the Z number increases, the spectrum becomes more of a continuum as the many nuclear levels in the nuclei blur together. The higher the Z of the material, the sharper the slope with more of the gamma ray being lower energy. The time evolution of these neutron induced gamma rays follows the fusion burn history convolved with the neutron time of flight geometry outlay of the material. For materials that are in the capsule, for example carbon or tungsten, the shell is on the order of 50 $\mu m$ away from the center of fusion emission and maybe 50 $\mu m$ thick, causing a neutron time of flight and signal broadening of 2 ps. Therefore, for static shell material the
Besides nuclear particles create gamma rays, the high energy of the thermal environment itself can sometimes create gamma rays. The Maxwell-Boltzmann temperatures of the HED systems sit around a few keV, too low to generate any MeV photons. In laser systems, the powerful electric fields can accelerate electrons to high
energies and can reach 10s and 100s of keV electrons which can convert their energies to powerful x-rays, but still below the MeV levels of gamma rays of interest. For this reason, laser systems like OMEGA and NIF when driving capsules are relatively quiet and clean in the MeV gamma ray range, allowing reproducible measurements at these high energies. When the NIF laser energy is focused to accelerate electrons specifically, such as the Advanced Radiographic Source (ARC) laser, which uses a few picosecond pulse on a gold cone to accelerate electrons and create a strong x-ray and gamma pulse can create photons above 10 MeV. The measurements are shown in Chapter 5. Pulsed power machines, have MegaAmpere currents have sufficient
voltages and acceleration potentials to accelerate electrons to high enough energies for them to produce MeV photon energies. The Mercury pulsed power machine, for example, creates an electromagnetic pinch that accelerates electrons that creates a MeV bremsstrahlung signal with no nuclear processes at all. Mercury has a bremsstrahlung endpoint of around 5 MeV, discussed in detail in Chapter 5. The Z Machine, not discussed in detail in the dissertation, due to the massive power and currents, can accelerates electrons and create massive bremsstrahlung signals, in addition to the fusion particles. The bremsstrahlung endpoints for the Z machine are not known in detail, but could be between 7 to 14 MeV. Cherenkov detectors are in the process of being fielded on Z to better understand this non-nuclear emission.

2.2 Cherenkov Light

The fastest velocity for casual interaction in the universe is $c$, the speed of light in a vacuum, which is constant. When photons move through materials, the interactions of the light with the surrounding dielectric causes the speed of light to slow down. Conceptually, the surrounding atoms act as approximate dipoles that are driven back and forth by the propagating light wave. Driven dipoles at a non-resonance causes the dipoles to emit the same frequency with a delay. The interaction between the propagating wave and the surrounding atoms combine to decrease the velocity of the wave. When a charged particle moves through a medium with a velocity faster than the speed of light in that material, it emits Cherenkov (also transliterated as Cerenkov) light. As the charged particle is going faster than the speed of light, the polarization and resultant re-emission create a field that continues to emit at far distances. Consider Figure 2.5, adapted from Jelley [16], where a slow moving charged particle creates a symmetric polarization of the surrounding dipoles. However, at a speed comparable to the light in the medium, the symmetry along the axis the particle is traveling is violated, which creates a resulting dipole field at large distances.
from the electron track. A common conceptual analogy is drawn between a jet plane making a sonic boom and a charged particle emitting light, both catching up to its self generated wave front and merging them into a single shock wave. The effect was first observed by Cherenkov in 1934 [17] and a classical electromagnetism derivation of the effect was done by Frank and Tamm in 1937 [18]. All three were awarded a Nobel prize in 1958 [19]. Frank and Tamm were able to capture the observed characteristics of Cherenkov light using a derivation with Maxwell’s equations and a few assumptions. The derivation will be reproduced, loosely following Jackson [20], to highlight the assumptions made with an additional focus on the clarity of the logic. Consider an electron moving with some velocity, the charge density and current can be described in Gaussian units as:

\[ \rho(\vec{x}, t) = e\delta(\vec{x} - \vec{v}t) \quad \vec{J}(\vec{x}, t) = \vec{v}\rho(\vec{x}, t) \]  \hspace{1cm} (2.2)

In SI units, where \( \rho(x, t) \) is the charge density in units of charge per volume, \( e \) is the charge of the electron in Coulombs, \( \delta \) is the Dirac Delta function, which has units of inverse distance - cubed for the 3D vectors. \( \vec{x} \) is the 3D position vector measured in distance and \( \vec{v} \) is the 3D velocity vector measured in distance per time. \( J(\vec{x}, t) \) is the electrical current density in units of current per area. When an electron is moving
through a medium with index of refraction \( n(\omega) = \sqrt{\epsilon(\omega)} \), Maxwell’s equations can be used to calculate the resulting electromagnetic waves that are released from the particle’s interaction with the dielectric medium. The Fourier form of Maxwell’s equations (in Gaussian units) take the form:

\[
\left(k^2 - \frac{\omega^2}{c^2} \epsilon(\omega)\right) \Phi(\vec{k}, \omega) = \frac{4\pi}{\epsilon(\omega)} \rho(\vec{k}, \omega) \quad (2.3)
\]

\[
\left(k^2 - \frac{\omega^2}{c^2} \epsilon(\omega)\right) \vec{A}(\vec{k}, \omega) = \frac{4\pi}{c} \vec{J}(\vec{k}, \omega) \quad (2.4)
\]

In SI, \( k \) is the wave number in inverse length, \( \omega \) is the angular frequency in inverse time, \( c \) is the speed of light, \( \epsilon \) is the permittivity in units of Farad/meter as a function of frequency, \( \Phi \) is the electric potential in Volts, \( \vec{A} \) is the 3D magnetic vector potential in units of Volt time per length. The Gaussian units remove the additional permittivity and speed of light terms (\( \epsilon_0, \sqrt{\epsilon_0} c \)). Substituting the particle’s density and current into Maxwell’s equations and solving for the Fourier-form potentials:

\[
\Phi(\vec{k}, \omega) = \frac{2q}{\epsilon(\omega)} \frac{\delta(\omega - \vec{k} \cdot \vec{v})}{k^2 - \frac{\omega^2}{c^2} \epsilon(\omega)} \quad \text{and} \quad \vec{A}(\vec{k}, \omega) = \epsilon(\omega) \frac{\vec{v}}{c} \Phi(\vec{k}, \omega) \quad (2.5)
\]

We can relate the Fourier-form potentials to their electric and magnetic field:

\[
\vec{E}(\vec{k}, \omega) = i \left( \frac{\omega(\omega)}{c} \frac{\vec{v}}{c} - \vec{k} \right) \Phi(\vec{k}, \omega) \quad \text{and} \quad \vec{B}(\vec{k}, \omega) = i \epsilon(\omega) \vec{k} \times \frac{\vec{k}}{c} \Phi(\vec{k}, \omega) \quad (2.6)
\]

\( \vec{E} \) is the electric field measured in Volts/distance in SI and \( \vec{B} \) is the magnetic field measured in Tesla. To find the radiated energy, one must first express the electric field as a function of frequency at some distance, or impact factor, \( b \) from the particle’s path. We arbitrarily set the particle to move in the x-axis and \( b \) to be in the y axis. Taking the Fourier inverse of equation 2.6:

\[
\vec{E}(\omega) = \frac{1}{(2\pi)^{3/2}} \int d^3k \vec{E}(\vec{k}, \omega) e^{ib\vec{k}_2} \quad (2.7)
\]

First we compute the \( x \) component of \( E_1 \) of the electric field (parallel to \( \vec{v} \)):

\[
E_1(\omega) = \frac{2iq}{\epsilon(\omega)(2\pi)^{3/2}} \int d^3k e^{ib\vec{k}_2} \left( \frac{\omega \epsilon(\omega) v}{c^2} - k_1 \right) \delta(\omega - v k_1) \frac{\delta(\omega - v k_1)}{k^2 - \frac{\omega^2}{c^2} \epsilon(\omega)} \quad (2.8)
\]
To simplify we can make the definition \( \lambda^2 = \frac{\omega^2}{v^2} - \frac{\omega^2}{c^2} \epsilon(\omega) = \frac{\omega^2}{v^2} (1 - \beta^2 \epsilon(\omega)) \). Breaking the integral apart into the \( k_1, k_2, k_3 \). The \( k_1 \) integral can immediately be integrated by the definition of the Dirac Delta:

\[
E_1(\omega) = -\frac{2iq\omega}{v^2(2\pi)^{3/2}} \int_{-\infty}^{\infty} dk_2 e^{ibk_2} \int_{-\infty}^{\infty} \frac{dk_3}{k_2^2 + k_3^2 + \lambda^2} 
\]

The \( k_3 \) integral has the value \( \frac{\pi}{(\lambda^2 + k_2^2)^{1/2}} \)

\[
E_1(\omega) = -\frac{iq\omega}{v^2 \sqrt{2\pi}} \int_{-\infty}^{\infty} dk_2 e^{ibk_2} \frac{1}{(\lambda^2 + k_2^2)^{1/2}} 
\]

The \( k_2 \) integral is in the form of a modified, Macdonald Bessel function \( K_0(x) \), giving the evaluated parallel field:

\[
E_1(\omega) = -\frac{iq\omega}{v^2} \left( \frac{2}{\pi} \right)^{1/2} \left( \frac{1}{\epsilon(\omega)} - \beta^2 \right) K_0(\lambda b) 
\]

Following a similar pattern for the components of the field:

\[
E_2(\omega) = \frac{q\omega}{v} \left( \frac{2}{\pi} \right)^{1/2} \frac{\lambda}{v} K_1(\lambda b), \ E_3 = 0 \text{ and } B_1 = B_2 = 0, \ B_3(\omega) = \epsilon(\omega)\beta E_2(\omega) 
\]

We would like to calculate the radiated energy \( dE \) per particles traversed distance \( dx_{\text{particle}} \). It can be expressed through the electromagnetic energy flow \( P_a \) through the surface of an infinite cylinder of radius \( a \) around the path of the moving particle, which is given by the integral of Poynting vector \( \vec{S} = \frac{\epsilon}{4\pi} \vec{E} \times \vec{H} \) over the cylinder surface:

\[
\left( \frac{dE}{dx_{\text{particle}}} \right)_{\text{rad}} = \frac{1}{v} P_a = -\frac{c}{4\pi v} \int_{-\infty}^{\infty} 2\pi a B_3 E_1 dx 
\]

The integral over \( dx \) at one instant of time is equal to the integral at one point over all time. Using \( dx = vdt \):

\[
\left( \frac{dE}{dx_{\text{particle}}} \right)_{\text{rad}} = -\frac{ca}{2} \int_{-\infty}^{\infty} B_3(t) E_1(t) dt 
\]
Because our electric and magnetic fields are in frequency domain, we can swap the integral to the frequency domain:

\[
\left( \frac{dE}{dx_{\text{particle}}} \right)_{\text{rad}} = -ca \int_{0}^{\infty} B_3^*(\omega) E_1(\omega) d\omega \tag{2.15}
\]

Consider a diagnostic measuring Cherenkov radiation with the detector perpendicular distance \(b\) from the radiation where \(b\) is far, defined as greater than the atomic distances in the medium, that is \(|\lambda b| \gg 1\). Within this limit we can expand the Bessel functions into their asymptotic form:

\[
E_1(\omega) \rightarrow \frac{iq\omega}{c^2} \left(1 - \frac{1}{\beta^2\epsilon(\omega)}\right) e^{-\lambda b} \sqrt{\lambda b} \tag{2.16}
\]

\[
E_2(\omega) \rightarrow \frac{iq}{v\epsilon(\omega)} \sqrt{\frac{\lambda}{b}} e^{-\lambda b} \text{ and } B_3(\omega) = \epsilon(\omega)\beta E_2(\omega) \tag{2.17}
\]

Plugging in our electric and magnetic field forms into the energy per distance:

\[
\left( \frac{dE}{dx_{\text{particle}}} \right)_{\text{rad}} = \Re \left( \int_{0}^{\infty} \frac{q^2}{c^2} \left(-i\sqrt{\lambda^*\lambda}\omega\left(1 - \frac{1}{\beta^2\epsilon(\omega)}\right)e^{-\left(\lambda^*+\lambda\right)a}\right) d\omega \right) \tag{2.18}
\]

When \(\lambda = \frac{\omega^2}{v^2} \left(1 - \beta^2\epsilon(\omega)\right) > 0\) (positive and real) this expression is suppressed by the exponential and vanishes, meaning no electromagnetic energy is emitted by the charged particle at far distances. When \(\lambda\) is purely imaginary, the exponential becomes 1 (independent of \(a\)) and therefore electromagnetic energy is released at a far distance. For \(\lambda\) to be imaginary, assuming \(\epsilon(\omega)\) is real (true for common materials) \(\beta^2\epsilon(\omega > 1)\), that is,

\[
v > \frac{c}{\sqrt{\epsilon(\omega)}} = \frac{c}{n} \tag{2.19}
\]

Therefore, for electromagnetic energy to be released to far distances by a charged particle, the particle’s velocity must be larger than the phase velocity of the electromagnetic fields in the medium at frequency \(\omega\). This is the Cherenkov condition.

With the purely imaginary \(\lambda\) condition, \(\sqrt{\frac{\lambda^*}{\lambda}} = i\) the integral can be simplified to:

\[
\left( \frac{dE}{dx_{\text{particle}}} \right)_{\text{rad}} = \frac{q^2}{c^2} \int_{\epsilon(\omega)>\frac{1}{\beta^2}} \omega \left(1 - \frac{1}{\beta^2\epsilon(\omega)}\right) d\omega \tag{2.20}
\]
Converting from Gaussian units to SI units and re-including the magnetic permittivity, $\mu(\omega)$, gives us the Frank-Tamm formula:

$$\left( \frac{dE}{dx_{\text{particle}}} \right)_{\text{rad}} = \frac{q^2}{4\pi} \int_{\epsilon(\omega) > \frac{c}{n(\omega)}} \mu(\omega) \omega \left( 1 - \frac{c^2}{v^2 \epsilon(\omega)} \right) d\omega$$

(2.21)

This derivation, although accurately capturing the representative electromagnetic characteristics, makes some nonphysical assumptions, for example, a particle moving at a constant velocity will not emit radiation, as it will violate Galilean relativity. Also, the conservation of energy and momentum are not considered in the derivation. More precise derivations have been done [21] taking into consideration the full interaction with the surrounding medium. Quantum mechanical derivations using perturbation theory, which include energy and momentum conservation, give additional terms that are minor corrections, but recapture the Frank Tamm formula in the limit $h \rightarrow 0$ [22].

The Frank-Tamm formula does not diverge because mediums are dispersive ($\epsilon(\omega)$) and the index of refraction eventually goes to 1 as light frequencies approach x-ray and gamma ray frequencies, therefore making the integral converge.

The angle dependence of the Cherenkov light can be determined through a geometric Huygens principle argument, sketched in Figure 2.6. The charged particle moves with velocity $\beta c$. The Cherenkov light emitted moves at a velocity $\frac{c}{n}$. Therefore, the emitted light is emitted at the angle $\cos(\theta) = \frac{1}{\beta n}$. This is consistent with the Cherenkov condition, as the angle of light when $v < \frac{c}{n}$ becomes imaginary. Doing a more detailed derivation includes a quantum correction in the form:

$$\cos(\theta) = \frac{1}{\beta n} + \frac{\lambda_{\text{DeBrogile}}}{2\lambda} \left( 1 - \frac{1}{n^2} \right)$$

(2.22)

However, because the DeBrogile wavelength for a relativistic electron is around 2.5 picometers, second term is on the order of $1e-6$ and is negligible. From the above information, Cherenkov light can be characterized by the following:

- Cherenkov light is emitted when a charged particle is moving faster than the speed of light in a medium, determined by $n(\omega)$
Figure 2.6: Huygens sketch of Cherenkov emission. The Cherenkov light is emitted at \( \cos(\theta) = \frac{1}{\beta n} \)

- Cherenkov light’s spectrum is proportional to \( \propto \frac{1}{\lambda^2} \), or, equivalently, \( \left( \frac{d^2N}{dl\lambda} \right) \propto \frac{1}{\lambda^2} \) or \( \left( \frac{d^2N}{dl\omega} \right) \propto \text{const.} \). For common materials, this light is in the 200 to 800 nm range.

- Cherenkov light is a fast process. Light is emitted by the charged particle (with an interaction length of wavelength, \( \lambda \), which is on the scale of 100s of nm) with the surrounding atoms in the medium through the interaction of the passing particle. A single light pulse should occur on the approximate time scale of
  \[
  \frac{\text{Interaction length scale}}{\text{Time for charge particle to transit}} \approx \frac{500\text{nm}}{c} \approx 2 \text{ femtoseconds.}
  \]
  The duration of the full Cherenkov pulse instead comes from the dispersion of the medium and spread from the particle’s transit, which are both subject to diagnostic design.

- The number of photons emitted is dependent on the charge of the transiting particle, \( q \), the length of transit of the charged particle, \( x \), and the dispersion relation of the medium, \( n(\omega) \)

- The emitted light is released in a cone, with the angle of the cone dependent on the energy of the particle, \( \beta \), and the index of refraction of the medium \( n(\omega) \).
Chapter 2. Gamma rays and Cherenkov Detectors

2.3 Cherenkov diagnostics

The goal of nuclear diagnostics is to covert high energy (>MeV) particles to a low energy state that can be recorded on a digitizer. The Cherenkov process is an attractive technique to convert high energy charged particles to visible/UV light which can be directly related back to properties of the charged particle. Measuring gamma rays, because they are neutral, must first be converted to a charged particle, almost exclusively an electron. The diagnostic values of interest are often total number of gamma rays and their spectral distribution, resolved both temporally and spatially. The Chereknov process applied on electrons resulting from gamma rays can give some information on all values of interest, if properly designed. The Cherenkov technique can be contrasted with scintillators, which likewise covert MeV particles to eV range photons. Scintillators rely on molecular transitions to convert nuclear particles and gamma rays to visible light. In current mode, both these processes provide a proportional signal, where more gamma rays result in more recorded visible light signal. Both diagnostics often record the resulting released visible/UV photons with a photodiode, if there is a lot of signal, or a photomultipler tube (PMT), when there is less signal. Scintillators cover a wide range of parameter space, but often have higher efficiency (defined as photons/incident particle), a slower response time (due to metastable decay), have characteristic line spectrum and emit in $4\pi$ instead of directional compared to Cherenkov light. For HED systems, unique properties of the Cherenkov provide a direct diagnostic advantage compared to scintillators for the following situations:

1. Fast counting of charged particles

2. Direct determination of velocity (magnitude and direction) and energy (if mass is known) of charged particle.

3. Threshold discrimination through selection of high energy particles against
4. Uniform response for counting over large areas.

More detail on the variations of different type of Cherenkov detectors can be found in [16]. Cherenkov detectors have a long history of being used throughout physics diagnostic applications. Ring imaging Cherenkov (RICH) detectors, which measure specific Cherenkov angles to determine charge and velocity of particles are a commonly used diagnostic in particle physics and high energy physics. In colliding beam experiments, single count aerogel Chereknov detectors were used for particle identification, first as light collection (experiments including TASSO, EDR, Belle), also as RICH detectors (HERMES, LHCb, and AMS-02) and possibly varying indices of different aerogels for future detectors [23]. Specifically, two RICH detectors based on both fluorinated gas and aerogels run at CERN’s Large Hadron Collider B to distinguish pions, kaons and protons [24]. Stanford Linear Accelerator (SLAC) uses fused silica and water RICH detectors to study cosmic data [25]. Cosmic neutrinos are studied using PMTs measuring Cherenkov light coming for muons in Antarctic ice, first in the AMANDA [26] and then IceCube projects [26]. RICH based atmospheric particle showers are studied by using large tanks of water [28] as Cherenkov mediums, such as the HAWC observatory [29]. The thresholding capability of quartz Cherenkov detectors could be used for active interrogation gamma ray readings [30]. Cherenkov detectors are used in a myriad of other locations.

2.3.1 Principals of current-based Cherenkov gamma ray detectors

Almost all the uses of Cherenkov detectors mentioned above were single count detectors, often capturing a handful of photons to identify specific particles. As mentioned in the introduction, HED systems are pulsed, with an extremely strong signal in a
short amount of time (picoseconds and nanoseconds). These signals received are give milliAmps of recorded current (> 1e5 photons) where specific photon counting is not the goal. The design of current collection detectors is distinct and has different design choices than single count detectors. The pieces of such detectors will be stepped through, highlighting the fundamental processes and considerations that go into the design of such detectors.

**Gamma ray to relativistic electron conversion**

Cherenkov detectors requires a charged particle and so a converter is placed before the Cherenkov medium. Gamma rays hit the converter and either Compton scatter or pair produce, transferring the photon energy to the kinetic energy of the electron and position. A simple diagram showing this process is shown in Figure 2.7. The goal of the converter is to have a high conversion efficiency (number of electrons in Cherenkov gas/incident gamma ray) as well as preserve the incoming gamma ray energy and not to disturb or downscatter the incoming gamma ray spectrum. At the MeV gamma ray energy level, the interaction with the converter is a combination of Compton interaction and pair production. Because pair production cross section goes as $\propto Z^2$, Compton scattering becomes dominant with lower Z material, such as carbon or beryllium. For Compton scatter, the relationship between the energy
transferred and the resulting gamma ray scattered angle $\theta$ follows:

$$E_{e'} = E_\gamma \left( 1 - \frac{1}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos(\theta))} \right)$$

(2.23)

Which implies that a gamma scattered at 180 degrees transfers the maximum amount of energy $\left( \frac{E_\gamma}{m_e c^2 + 2E_\gamma} \right)$ while a barely scattered gamma transfers no energy. The Klein-Nishina formula gives the differential cross section of photons off free electrons. Pair production, on the other hand, creates an electron and a positron very nearly in the same, forward, direction. The creation of the electron-positron pair requires $2m_e c^2 \approx 1.02$ MeV and spreads the remaining energy to both particles, giving each particle, on average $\bar{E} = \frac{1}{2} (E_\gamma - 2m_e c^2)$. An example electron spectrum for a gamma ray incident on a 1 cm graphite converter calculated with MCNP is given by Figure 2.8, showing the spread from the Compton and pair production spectrum from the gamma ray. There is a skew towards low energy electrons, but about 1/3 of the electrons have above 1/2 the energy of the incident gamma ray. Once the scatter occurs, the electron continues through the material until it reaches the gas. Adding a thicker converter increases the interaction chance, but the stopping power acts on the created electrons. There is an optimal thickness, depending on the gamma ray spectrum, of best conversion efficiency with minimal perturbation of the gamma ray spectrum. The limiting case of an extremely thick converter collects only the edge electrons.

**Relativistic electron to Cherenkov light**

Once the relativistic electron is in the Cherenkov medium, the medium will emit Cherenkov light if the electron has enough velocity. For HED systems, three Cherenkov mediums will be considered, a solid piece of fused silica, aerogels and gas systems. The two values of interest are the dispersion of the material, $n(\omega)$, and the optical transparency. Using the Frank-Tamm eq 2.21 and setting the energy deposited to 0 to find the threshold at which photons are created, the equation sim-
plifies to \(0 = 1 - \frac{v^2}{c^2 n(\omega)}\). Using the total relativistic energy \(E = (\gamma - 1)m_e c^2\), one can rearrange these equations to find the energy threshold in the form:

\[
E_{e^{-\text{thr}}} = \left(\frac{1}{\sqrt{1 - n(\omega)^{-2}}} - 1\right)m_e c^2
\]  

(2.24)

Solids and liquids have an index of refraction (for \(\lambda \approx 600 \text{ nm}\)) greater than 1.33, corresponding to an electron threshold energy of 0.26 MeV and lower. Some of the reasonably densest gas systems, such as fluorinated gas at 200 psia and room temperature, can reach an index of refraction as high as \(n = 1.014\), which corresponds to a lowest electron threshold energy of 2.6 MeV. Going to higher pressures make most gasses undergo a phase transition to a liquid, thereby pushing their index of refraction up to solid-liquid values. Using a heater to warm the gas is one possible way to continue to push the pressure and index of refraction lower for a gas system. However, aerogels offer indices of refraction within the middle range \((n = 1.02 \text{ to } 1.07)\), corresponding to a 0.9 to 2 MeV electron threshold energy. Due to the effect of the

Figure 2.8: The resulting electron spectrum from incident gamma rays going through a 1 cm graphite converter calculated with MCNP. There is a skew towards low energy electrons, but about 1/3 of the electrons have above 1/2 the energy of the incident gamma ray.
In terms of optical and UV transparency, fused silica and the gas systems are nearly completely transparent across 200 to 800 nm. Aerogels, however, are more absorptive, especially in the UV range. Moreover, how absorptive specific aerogels are depends on the precise fabrication techniques and varies across different densities and batches of aerogels. Because of this, fused silica and gas systems continue to increase the Cherenkov production as they increase their thickness (until the stopping power has slowed the electron below the threshold), while aerogels have an optimum that balances more Cherenkov photons and the UV/optical absorption.

The values of the index of refraction above are given for one specific wavelength value, when in reality each medium has a dispersion relationship. The dispersion of a material depends on the polarizability of the medium. One simple model for material dispersion is the Lorentz-Lorenz equation, relating the index of refraction to the polarizability of the material. In reality, there are many layers of complication and...
a whole field that models dielectrics across frequency ranges, nevertheless, empirical
models such as the Sellmeir equation, which models dispersion relations in the form:

\[ n^2(\lambda) = 1 + \sum_i B_i \frac{\lambda^2}{\lambda^2 - C_i} \approx 1 + \frac{B_1 \lambda^2}{\lambda^2 - C_1} + \frac{B_2 \lambda^2}{\lambda^2 - C_2} + \frac{B_3 \lambda^2}{\lambda^2 - C_3} \]  \hspace{1cm} (2.25)

are reported commonly in the literature. Such semi-emperical models have tabulated
values for fused silica [31]. Likewise, for aerogels, some measurements give approxi-
mate dispersion relationships [33] and the index of refraction can be approximated
by shifting linearly in proportion to the aerogel density [34]. For gas systems, such as
CO2, the dispersion relationship has also been tabulated [35], as well as the variation
in terms of density [36]. Some representative dispersion relations have been plotted
in Figure 2.9.

Finally, when the Cherenkov light is emitted, it is emitted at the Cherenkov angle
given in equation 2.22. When designing Cherenkov detectors, the optical properties of
the light transfer must be considered to maximize light collection. For the 16.75 MeV
gamma ray, a 16 MeV relativistic electron has a \( \beta = 0.9995 \), so the Cherenkov angle
is approximately \( \arccos(\frac{1}{n}) \). For gas systems which have incidences \( (n) \) of around
1.01, Cherenkov light is emitted at around 8 degrees, which is forward directed. Inc-
cident gamma rays/electrons with lower energies have more forward emitting angles.
Materials with lower index of refraction emit at wider emitting angles. Plot 2.10
summarizes some emittance angles as a function of electron energy and the index of
refraction, showing that the angle very quickly levels off at the \( \arccos(\frac{1}{n}) \) level. For
gamma detectors currently used in ICF, discussed in the next section, the emittance
angle is relatively unimportant. The optics systems are often inefficient and sample
a small amount of the emitted Cherenkov photons. With different gamma ray spec-
trum or Cherenkov medium, the optics instead sample another angular distribution
space of emitted Chereknov photons with a similar efficiency. The poor optimization
of the focusing of the optics, although losing detector sensitivity, allows for similar
sensitivities across gamma spectrum, Cherenkov mediums and exact alignment and
collimation of the detector, thereby making it more consistent.
Figure 2.9: Example of dispersion relation for CO2 gas, aerogel and fused silica. Although there is some dispersion across each type of material, materials with a larger index of refraction has more variation across wavelengths. In this comparison, the CO2 has variation on the 9th decimal point, the aerogel on the 3rd decimal point and so the dispersion relation of the fused silica completely dominates compared to the other two.

2.3.2 Gas Cherenkov Detectors for NIF and OMEGA

With all these characteristics, Gamma Cherenkov detectors have been designed specifically for different HED systems. This concept for a reaction history gamma detector on ICF facilities was first published by Lerche and Cable in 1996 in the ICF Annual Report [37], a more updated concepts published by Herrmann et al [38]. The first gas Cherenkov detector for ICF was designed for the OMEGA laser system, introduced briefly in the introductory chapter. The gamma diagnostic was designed to be placed into a target chamber inserter that places the detector 20 cm from the
target chamber center (TCC) [39]. The original design was made to fit into this constraint which resulted in a tapered nose that held a 7 cm radius, 1.5 cm thick beryllium converter which widened to a 10 inch diameter sized tube that extended 1 meter back. To collect the light into a PMT while still in a co-axial design, a large tungsten slug was placed in front of the PMT in order to protect it from direct interaction of gamma rays. Cassegrain optics collect the Cherenkov light generated in the front of the tube, bounce around the tungsten slug and focus it on the photocathode of the PMT. The Cassegrain optics has the advantage of both moving light around the protective slug and creating a time delay of 0.5 to 0.75 ns between the direct gamma ray interaction and the light path of the reflecting Cherenkov light, thereby time separating the signal and the precursor background. Figure 2.11 shows this detector, designated GCD1 for the 1st generation of the Gas Cherenkov Detector. The GCD1 was brought to the Idaho State University electron beam and Cherenkov thresholds were measured [40], matching closely with Integrated Tiger Series (ITS)
ACCEPT code simulations of the full detector.

The GCD1, however, was limited in its time resolution, with a Hamamastu PMT that has an impulse response function of 300 ps for DT burn histories of 150 ps. The PMT technology was improved with the Photek 110 series that gave an impulse response function of 110 ps [41], [42], allowing reasonable deconvolution of reaction histories. One attempt to further increase the time resolution was to couple the Cherenkov light to a streak camera, which has an impulse response of around 10 ps. However, because of the susceptibility of the phosphor in the streak camera to background radiation, the light must be coupled many meters away outside the chamber through an optical relay, shown in Figure 2.12. A second GCD (GCD2) was created with this goal in mind, however, the efficiency of coupling to light so far away was poor and signal levels were too low to be useful. Instead, the GCD2 was retrofitted to also hold a Photek PMT. A separate technique was pursued to develop a pulse-dilation PMT that, through stretching the signal, is a radiation hardened PMT that also has a 10 ps impulse response [43].

A third coaxial GCD (GCD3) was developed to improve on GCD1 as a fielding detector for the newly developed photomultiplier tube. The GCD3 improved on GCD1 by lengthening the optical path by 4 cm, thereby delaying the signal from the precursor and additional 0.25 ns, a stronger gas vessel rated to go up to 400 psia,
as well as enhanced shielding [44]. Figure 2.14 shows the GCD3 diagram which was designed specifically for use at OMEGA. The GCD3 at this time is now located at the NIF[45] fielding the pulse dilation PMT technology studying anomalous excitation of the gas, a new phenomenon likely caused by the extremely noisy environment the detector is located in.

GCD 1 through 3 were the three generations of coaxial, insertable gamma ray detectors. These detectors battle with the strong background signal released with the strong pulse and require in-line shielding with a large tungsten slug in center of the Cherenkov light generating tube. An alternative design that is instead mounted and

Figure 2.12: Diagram showing GCD2 designed to transfer the Cherenkov light out to streak camera located far away in a shielded location

Figure 2.13: Diagram showing GCD3. Picture adapted from [44].
Figure 2.14: Two diagrams showing GRH. Picture on the left is meant to highlight the path of the Cherenkov light path reflection through the off axis parabolic mirrors (OAP)s. The figure on the right shows the full integrated detector.
<table>
<thead>
<tr>
<th>Detector</th>
<th>Notes</th>
<th>Geometry</th>
<th>Pressure + Threshold</th>
<th>Locations &amp; Solid Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCD1</td>
<td>First ICF γ detector Co-Axial</td>
<td>&lt; 100 CO2, &gt; 6.3 MeV</td>
<td>OMEGA @ 20 cm: 1.1e-2</td>
<td>6.3 MeV OMEGA @ 20 cm: 1.1e-2</td>
</tr>
<tr>
<td>GCD2</td>
<td>Intended for streak camera Co-Axial</td>
<td>&gt; 100 CO2, &lt; 6.3 MeV</td>
<td>OMEGA @ 20 cm: 1.1e-2</td>
<td>6.3 MeV OMEGA @ 20 cm: 1.1e-2</td>
</tr>
<tr>
<td>GCD3</td>
<td>Improved GCD1 for PD-PMT Co-Axial</td>
<td>&lt; 400 CO2, SF6, C2F6</td>
<td>OMEGA @ 40 cm: 3.0e-4</td>
<td>1.8 MeV OMEGA @ 40 cm: 3.0e-4</td>
</tr>
<tr>
<td>Ω GRH</td>
<td>Mounted outside chamber Pretzel</td>
<td>&lt; 200 CO2, SF6</td>
<td>OMEGA @ 2.8 m: 2.9e-4</td>
<td>NIF @ 2.8 m: 2.9e-4</td>
</tr>
<tr>
<td>NIF GRH</td>
<td>Mounted outside chamber Pretzel</td>
<td>&lt; 200 CO2, SF6</td>
<td>OMEGA @ 2.8 m: 2.9e-4</td>
<td>NIF @ 2.8 m: 2.9e-4</td>
</tr>
</tbody>
</table>

Table 2.3: Overview of the gas Cherenkov diagnostics fielded on OMEGA, NIF and, in the future, the Z machine.
fixed on the outside edge of the vacuum chamber offers the ability to have a larger converter, 12.7 cm diameter, and have a folded geometry that points the sources of background (direct interaction with the PMT, PMT quartz window, and pressure window) in the opposite direction of the Cherenkov signal. Because these fixed detectors focus on measuring the DT fusion gamma reaction history, they are called (somewhat confusingly) Gamma Reaction History (GRH) diagnostics, as opposed to the co-axial GCD detectors. The GRH used a pretzel twisted geometry to bounce the generated Cherenkov signal 4 times to the PMT photocathode located in the reverse direction of the incident gamma rays [46]. Figure 2.14 shows a diagram of GRH. The first GRH was fielded on the OMEGA chamber at 2.8 meters, and then four nearly identical cells were placed on the NIF chamber at 6 meters. The OMEGA GRH is currently being modified to be placed on Sandia’s Z machine to hopefully measure DT fusion reaction history when some tritium is added to Z machine implosions. The summary of these gas systems is shown in Table 2.3.2.

2.3.3 Aerogel Cherenkov Detectors

Gas systems use the low index of refraction for a relatively high threshold in order to specifically isolate the DT fusion gamma rays. Another system, aerogel Cherenkov detectors have been applied to a lower energy (few MeV) bremsstrahlung photon source, such as the Cygnus radiographic source located at the Nevada National Security Site and the Mercury pulsed power machine located at the Naval Research Lab in Washington D.C. With these x-ray sources having an endpoint of 2 or 5 MeV, gas systems have too high of an energy threshold to be useful. Aerogel Cherenkov mediums span the appropriate range of energies. Detectors fielded at pulsed power machines have less restrictions that those fielded on large vacuum chambers. A simple modular design, first designed and built for the Cygnus x-ray source, to hold a thin, aluminum converter in front of an aerogel or fused silica Cherenkov medium
followed closely with two off axis parabolic mirrors that bounce the UV/visible light into a PMT that is out of the collimated x-ray beam. A thick collimator sits in front of the modules. These detectors are called Aerogel Cherenkov Detectors for Cygnus (ACDC). When these detectors are applied to other systems, they are still called ACDC or shorted to ACD. A diagram showing this layout is given in Figure 2.15. The advantage of this design is that they are relatively mobile and modular and more ACDCs can be added linearly. The first generation of two ACDC modules, collimator and housing box were made out of aluminum. The second generation of an additional two were made out of tungsten to minimize internal scatter. A third
generation added additional features like easy placement of tungsten filters and an
gas inlet valve for feeding dry air to avoid aerogel water absorption. Each module
of the ACDC can fit aerogels of different densities and therefore different thresholds.
Using multiple modules or swapping aerogels between shots allows one to measure
separate cuts of the x-ray spectrum.
Chapter 3

Diagnosing Inertial Confinement Fusion Ablator Physics

In inertial confinement fusion (ICF), understanding the dynamics of the ablator is a key to understanding the source of performance degradation. The ablator follows the energy budget, reflects the compressibility of the capsule and is a source of mix. The ablator mass remaining gives a metric of the rocket efficiency created by the laser ablation. As the ablator becomes more compressed, and its areal density increases, it compresses the fuel and makes the hot spot hotter and denser. There have been very few diagnostics that have looked at the final state of the ablator. The process of fusion neutrons inelastically scattering off carbon, emitting a 4.4 MeV gamma ray, gives the opportunity to investigate the ablator areal density during the fusion burn. The areal density, also referred to as carbon $\rho R$, is the density of carbon integrated along a line radially outwards from the center of the capsule. Charged particles have been used on the OMEGA laser facility to measure the shell areal density using either a stopping power model or knock on particles[47]. However, the higher areal densities of the ablator at the National Ignition Facility (NIF) makes detection of escaped charged particles difficult. The Diagnostic for Areal Density (DAD) uses a
quartz Cherenkov medium to measure shell areal density at OMEGA as well [48]. There have been little diagnostic data on the ablator at the NIF.

Isolating the carbon portion of the gamma ray spectrum can get at this information. Previously, a simultaneous forward fit[49] across the four gas cells was preformed to isolate the carbon gamma peak by using a simulated gamma spectrum and time evolution by using a Monte Carlo N-Particle (MCNP)[50] simulation of the surrounding hohlraum/TMP. Values generated from the forward fit in combination with neutron images were used to constrain areal density of both the fuel and ablator[51]. However, the MCNP simulation turned out to be non-predictive, needing the introduction of more free parameters in the forward fit, such as the signal strength ratio of the elements in the hohlraum/TMP signal. The high number of degrees of freedom led the fit to often be sensitive to input parameters and have many local minima. The local minima combined with the uncertainties in gas cell timing and absolute scaling prevented the forward fit from being used routinely.

3.1 Isolating neutron induced carbon gamma rays

This work was published in [8]. As ICF capsules compress to high temperatures and densities, nuclear fusion of the DT fuel occurs. The resulting 14 MeV neutrons inelastically scatter with the carbon atoms of the ablator shell, exciting the 1st nuclear metastate of the 12C nucleus, subsequently (20 fs) emitting a 4.4 MeV gamma ray. In a monoenergetic instantaneous point source approximation, the intensity of the 4.4 MeV gamma ray signal is directly proportional to the areal density of the carbon ablator. Simulations suggest this assumption is accurate to 5 to 12% [52]. The 14 MeV fusion neutrons continue past the capsule, travel 3 to 6 mm (in 50 to 120 ps) and inelastically scatter with the surrounding hohlraum and TMP. The neutron interaction with the supporting structures of the indirect drive ICF experiment creates a continuum gamma spectrum that acts as a background to the carbon gammas.
of interest. As said above, the GRH has multiple gas cells that select the photon energy threshold. The GRH places two thresholded channels to isolate the carbon gamma peak. Gas cell B is set at 200 psia of SF6, the densest gas and pressure the GRH is designed for, setting the lowest index of refraction of n=1.0136 that GRH can operate at, corresponding to a gamma threshold of 2.9 MeV. Gas cell B signal consists of the 4.4 MeV carbon gamma peak, the hohlraum/TMP background and a small (approx. 5% of the total signal) amount of 17 MeV fusion gammas. Gas cell C is set at 187 psia CO2, giving n= 1.0058 corresponding to a 4.5 MeV gamma threshold, eliminating all carbon gamma signal contribution. The 4.5 MeV threshold signal is dominated by the hohlraum/TMP background (fusion gammas approx. 9% of signal). Gas cell A and D are set to isolate the DT fusion gammas.

Figure 3.1 shows a MCNP calculated NIF gamma spectrum with the DT fusion gammas, an example carbon gamma signal as well as the hohlraum/TMP background signal. The MCNP simulation was done in 2011 with a 14.1 MeV monoenergetic neutron source going into a 5.75mm gold hohlraum with the surrounding TMP structure. The geometry of a 5.75mm hohlraum and TMP is believed to be an accurate representation of the geometry and elemental composition of current hohlraum/TMP design. The gamma spectrum is dominated by aluminum (40%), silicon (16%) and gold (32%). However, when rolled with the 2.9 MeV GRH response, which has been absolutely calibrated[124], the measured spectra is dominated by only aluminum (63%) and silicon (31%), which is mostly located in the TMP, not the hohlraum. However, compared to experimental data, the simulated gamma spectrum over predicts the high energy portion of the hohlraum/TMP spectrum – giving 40% larger 2.9 MeV threshold/4.5 MeV signal ratio. The simulation also predicts that the high energy portion of the hohlraum/TMP gammas should corrupt an 8 MeV threshold DT measurement, broadening the signal by 20%. However, this isn’t observed as 8 MeV, 10 MeV and 12 MeV signals are all identical, suggesting no high energy contribution. This suggests that the 14 MeV neutron induced gamma spectrum may
Figure 3.1: An MCNP calculated NIF gamma spectrum comprised of the DT fusion gammas, the carbon gammas and the hohlraum/TMP gammas. The responses of the gas cells used to isolate the 4.4 MeV gamma line are plotted on top.

be incorrectly estimating high energy components, specifically for aluminum, and motivates re-verifying the nuclear databases, which in the past have observed data points\cite{54} lower than the verified database’s prediction or counts too low to distinguish at the high gamma energy level\cite{55}. Both the simulation and experimental GRH data show that including depleted uranium in the hohlraum has very little change on the spectrum, as most of the mass neutrons interact with comes from the TMP, which is standard across all shots. Experimental data also shows changing hohlraum geometry (5.75 vs 6.75 mm) also has no measurable effect. Because of the
MCNP gamma spectrum being non predictive, using a method independent of any assumed spectra was pursued, using the directly measured 4.5 MeV threshold as a background measurement. The gamma rays induced by carbon are believed to be well understood, with MCNP simulations of puck shots following the expected trends. Calibration of 14.1 MeV neutrons off of carbon has been used for calibrating GCD detector responses [56]. The correct subtraction of the 2.9 MeV and 4.5 MeV signal can isolate the carbon gammas.

Phrasing it mathematically, the symbol $R_{\text{thr}}(E)$ expresses the photon-energy-integrated response of a GRH cell with a certain threshold to a given photon energy spectrum. Note the photon-energy-dependent response of the GRH does not change with time, while the photon energy spectrum does. For the two gas cells situated around the carbon peak, as explained above, the signals of the two cells can be expressed as [53]:

$$S_{>2.9}(t) = R_{>2.9}(E_{\gamma C})Y_{\gamma C}(t) + R_{>2.9}(E_{\text{Hohlr\+DT}})Y_n(t)$$  \hspace{1cm} (3.1)

$$S_{>4.5}(t) = R_{>4.5}(E_{\text{Hohlr\+DT}})Y_n(t)$$  \hspace{1cm} (3.2)

That is, the measured 2.9 MeV signal is made up of carbon gamma spectrum applied onto the 2.9 MeV gas cell response plus the non-carbon gamma spectra, which is proportional to the neutron yield, also applied onto the 2.9 MeV response function. The 4.5 MeV signal picks up only the non-carbon components. $Y_{\gamma C}(t)$ and $Y_n(t)$ represent the yield of carbon gammas and fusion neutrons respectively. The 2.9 MeV threshold response to the carbon gammas, $R_{>2.9}(E_{\gamma C})$, has been measured with the puck calibration shots and can be replaced with the constant $C_{\text{puck}}$. If we introduce a scaling factor defined as the ratio of the responses to the non-carbon components of the gamma spectrum, $\alpha = \frac{R_{>2.9}(E_{\text{Hohlr\+DT}})(t)}{R_{>4.5}(E_{\text{Hohlr\+DT}})(t)}$, we can apply this factor to the 4.5 MeV threshold cell, subtract the two signals and have the relation:

$$S_{>2.9}(t) - \alpha S_{>4.5}(t) = C_{\text{puck}}Y_{\gamma C}(t)$$  \hspace{1cm} (3.3)
Which then isolates the carbon gamma peak as a function of time, allowing conversion to carbon $\rho R$. Implicit in this formulation is that the signals have been corrected for their respective PMT gain and quantum efficiency.

### 3.1.1 Beryllium ablators as null calibration and subtraction routine

The NIF beryllium campaign\[57][58\] offers an opportunity to measure the ratio of the two gas thresholds when there is no ablator gammas present, and hence a measurement of the scaling factor $\alpha$. Beryllium produces negligible neutron induced gammas\[17\] and so the emitted spectrum is only the hohlraum/TMP gamma background and the DT fusion gammas. Four beryllium shots with DT fuel occurred in 2017-18, shots N170702-001, N171112-001, N180121-002 and N180618-001. These were used to calibrate the ratio of the 2.9 MeV threshold signal to the 4.5 MeV threshold with no carbon gammas. To find the relative strength of the 4.5 MeV threshold against the 2.9 MeV threshold signal when no carbon is present, the 4.5 MeV threshold is multiplied by a scaling factor until it matches the 2.9 MeV threshold. Because of uncertainty in the cell to cell timing, the timing was also allowed to vary $\pm 15$ ps in order to better match the two signals when the 4.5 MeV is scaled. Varying the scaling factor and the relative timing, the residual between the two signals is minimized. A weight is also applied to minimizing the residual where the highest signal to noise is measured.

Figure 3.2 shows an example of the optimal scaling and timing shift on a beryllium shot along with the residual minimization landscape. The four optimal scaling factors found were 3.05, 2.70, 2.88 and 2.70 respectively with an average of 2.83. The four optimal timing shifts, -4, 4, -13 and 8 ps, are on the order of the $\pm 8$ ps measured standard deviation of the statistical cell to cell timing variation. The source of variation (7%) in the scaling factor is unknown, but thought to be mainly a combination
Figure 3.2: Example of finding a calibration scaling factor of 2.7 for a beryllium shot. The average scaling factor of all four shots, 2.8, is used as a calibration for other shots that have carbon. The residual landscape from shifting the timing and the scaling factor are shown in the upper right.

of different downscattered neutron spectrum changes and PMT gain correction. The found scaling factor is rounded to 2.8 and then applied to other NIF shots with the extra signal remaining on the 2.9 MeV threshold after subtraction being the isolated carbon gammas. Indirect drive exploding pushers also give an opportunity to measure a low carbon $\rho R$ signal. Three exploding pusher shots with a carbon ablator were recorded but all have a relatively higher 2.9 MeV threshold signal, suggesting that enough carbon is left over to contaminate a clean, no carbon, signal. Because of the higher signal relative to the beryllium shots, the exploding pushers were not used as part of the null carbon ratio. Using the ratio determined from beryllium
shots, the indirect drive exploding pushers are measured to have a carbon $\rho R$ in the range of 70 to 150 $\frac{\text{mg}}{\text{cm}^2}$.

Taking the scaling factor from the beryllium shots makes the assumption that gamma spectra emitted from all shots, besides the carbon, is nearly identical. However, it is observed that the 4.5 MeV threshold signal varies with a standard deviation of 15%. The exact source of this variation is not known. As said above, different hohlraum diameters (5.75, 6.75 mm) or hohlraums composition (gold or uranium) are observed to have no correlation with 4.5 MeV signal. The number of photons is $> 10^7$ and so photon statistics is negligible and empty gas background shots show that photons less than the Cherenkov threshold, such as x-ray and laser plasma interaction photons, produce a background signal $< 100x$ than the Cherenkov photons. Another possible source of gamma spectrum variation is tungsten or silica dopants placed into the carbon ablator. However, estimating the $\rho R$ of the dopant near bang-time suggests it’s too low to be noticeably detectable by any energy threshold. For example, a full scale high density carbon shot with 0.33% W dopant and an effective increase from initial to final dopant $\rho R$ to be around 20, we estimate there to be a tungsten $\rho R$ of around $10 \frac{\text{mg}}{\text{cm}^2}$, which would contribute less than 1% to the 4.5 MeV gas threshold signal. If the tungsten was replaced with silicon, this too would be less than 1%. There also is no observed correlation of the 4.5 MeV signal and the dopant concentration. Downscattered neutrons could change the hohlraum/TMP gamma spectrum by changing the interaction cross sections as well as the output gamma energies. A loose correlation is seen in the total 4.5 MeV signal increasing with increasing downscatter ratio (DSR), suggesting that that lower energy neutrons create more background gammas. However, the relative strength between the gamma rays measured from the 2.9 MeV threshold and the 4.5 MeV threshold is comparable, and so using the ratio between the two threshold channels should account for the approximate spectrum change. The carbon gamma line cross section itself doesn’t change much across MeV neutron energies. The four beryllium shots have a DSR range of
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2.3 to 3.2 and the found ratio does not correlate with the DSR. As a whole, the effect of downscattered neutrons is estimated to be on the order of 10% and taken to be included in the error. Another possible source could be neutron asymmetry, where some shots happen to shoot a higher flux of neutrons towards regions of higher or lower hohlraum/TMP mass. However, observed neutron asymmetry happens on the 5% level, making the effect is not large enough to significantly shift the gamma ray spectrum. The most likely source of error may be correcting by the gain and quantum efficiency (QE) of the PMT – as each calibrated measurement of the response of the PMT has variation on the 15% level. The DT measurement (>10 MeV), which should have a constant and simpler gamma ray spectrum, still has scattered signal variation on the 10% level. The reasons of the observed PMT sensitivity variation are not known, but the scatter would explain some of the variation in the observed signals.

Directly applying the 2.8 scaling factor to the 4.5 MeV threshold signal and subtracting it from the 2.9 MeV threshold gives a reasonable subtracted carbon gamma across many shots. Because of the hohlraum/TMP signal arriving about 100 ps after the DT and carbon signal, subtracting the scaled 4.5 MeV signal subtracts the late time signal, leaving only an earlier and narrower signal with a similar burnwidth to the DT signal. However, for a number of shots the resulting subtracted signal goes negative in the late time, which is unphysical. To improve the analysis and prevent against negative carbon signal, the scaling factor and the relative timing were allowed to vary within uncertainty constraints in order to minimize the amount of negative carbon signal - weighted by the signal to noise of the peaks. The allowed scaling factor variation reflects the scatter observed in the scaling factor found from the 4 beryllium shots and the allowed timing variation reflects statistical timing variation between the two cells. The scaling factor and timing are varied until the resulting subtracted signal’s negative portion makes up less than 1% of the max 4.5 MeV threshold signal. Changing the timing is prioritized more than the scaling factor.
The arbitrary cut-off of 1% was chosen to give results that look consistent with reasonable negative going noise and deconvolution artifacts. The resulting carbon $\rho R$ values are not very sensitive to this specific cut off, changing the cut off criteria to 2% or 0.5% has little effect on most shots and only changes the more sensitive carbon $\rho Rs$ by 10% – considered within our error.

Figure 3.3 shows two examples of typical subtraction routines, one where almost no change from direct scaling is needed, one where changing the timing and scaling factor gives a more realistic carbon gamma signal. The exact cause of the negative going carbon is unknown, but is expected within the signal variation we see in the $\alpha$ ratio and the background 4.5 MeV signal. The quoted uncertainty captures the variation with or without the subtraction routine and the ad-hoc correction we apply is to move the isolated carbon peak closer to a correct and realistic value.

Of the 44 shots analyzed, 72% have the unchanged 2.8 scaling factor. The remaining 28% of shots have an average of 2.6 with a standard deviation of 0.2. The average scaling factor found across all shots is 2.73 with a standard deviation of 0.16. This variation is similar to what is observed and expected from the beryllium shots. The average found time shift is -12 ps with a standard deviation of 11 ps. This agrees with the expected cell to cell timing statistical variation.

The signal obtained after subtraction is the carbon gamma signal as a function of time. The timing of the carbon gamma peak compared to the DT burn holds information about the velocity and energy of the shell and will be investigated in detail elsewhere. The integral of this peak gives the total charge collected from carbon gammas which is calibrated to a known amount of carbon $\rho R$ through a number of shots done with a carbon puck placed near the implosion. For all shots of major campaigns after the start of 2015 where the GRH was operating, the carbon gamma signal was generated, integrated and a carbon $\rho R$ value was generated.
Figure 3.3: Examples of the subtraction algorithm for two shots. The most left figures show the resulting carbon signal after direct subtraction using the 2.8 factor from the beryllium shots, the center figures show the subtraction after the optimal point found to give 1% negative carbon. The right figures show the landscape of how the negative carbon signal changes with varying timing and scaling factor. a) Shows an example which has a very similar pattern to 70% of analyzed shots, with very little change from directly applying the beryllium scaling. b) Shows an example of the remaining 30% where a larger time shift or scaling factor variation is needed to correct a late negative carbon signal, indicated by the arrow. Time shift has no effect on the resulting carbon $\rho R$, but every decrease in 0.1 scaling factor results in 25 mg/cm$^2$ less carbon $\rho R$. The 30% with a different scaling have an average scaling factor of 2.6$\pm$ 0.2.
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3.1.2 Method verification and uncertainty estimation

The forward fit has been run and generated carbon $\rho R$ for two shots that have occurred after 2015. For shot N170601-002, the forward fit generated a value of $339 \ \text{mg/cm}^2$ and the subtraction method here generated a value of $365 \ \text{mg/cm}^2$. For shot N171015-001 the forward fit got $347 \ \text{mg/cm}^2$ and the subtraction method got $378 \ \text{mg/cm}^2$. These agree within error. The fact that both these methods reproduce similar values gives confidence that using the beryllium scaling factor is consistent with modeling the expected hohlraum/TMP spectrum. This subtraction method, however, has less reliance on spectral assumptions. Using predicted signals directly from the MCNP spectrum with a $350 \ \text{mg/cm}^2$ carbon capsule fed directly into the subtraction routine, it predicts a $305 \ \text{mg/cm}^2$ due to the MNCP simulation overestimating the hohlraum/TMP signal background signal.

A number of implosions have been very similar and so the expected carbon $\rho R$ should be comparable. For these similar implosions, a near identical carbon $\rho R$ has been measured. For example, Bigfoot shot N180909-003 was a repeat of the best performer N180128-002 and a near identical carbon $\rho R$ of $330$ and $324 \ \text{mg/cm}^2$ respectively was found. Other shots where the performance was very similar and observables agreed within error between the two shots also observed a constant carbon $\rho R$. For example, the Highfoot shots N150218-003 and N160509-002 have similar yields, bang-times, burnwidths, downscatter ratios and also observed an identical carbon $\rho R$. A separate, independent, preliminary analysis developed by Prav Patel[59] from Lawrence Livermore National Laboratory estimates the optical depth, defined as $\tau$ in $I(\tau) = I_0 e^{-\tau}$, of the ablator at bangtime by calculating the attenuation of the x-ray signal at 11 and 22 keV energies along one specific line of sight with an error estimated to be around 17%. The optical depth is directly proportional to the $\rho R$ of the ablator. Figure 3.4 shows the estimated optical depth vs the calculated carbon $\rho R$ having a strong correlation across many shots. This correlation gives confidence that the estimation of the ablator $\rho R$ through two independent techniques agree.
Figure 3.4: Prav Patel’s preliminary estimations of ablator optical depth using 11 keV and 22 keV x-ray lines correlate with the measured carbon $\rho R$.

The differences may be caused in part to the $4\pi$ global average the carbon gammas emit compared to one specific line of sight the x-ray sees. Also, the contribution the dopants adds to the x-ray attenuation but is not observed through carbon gammas.

All these factors: similar values to the forward fit, repeatability and comparison with estimated optical depth gives us confidence that our algorithm and method gives reasonable values. Comparison of carbon $\rho R$ values against 8 high density carbon 2D post-shot HYDRA simulations have agreed within error at the 15% level and follow observed trends.

The error can be broken into 1) statistical or comparative error which defines, for a set of generated carbon $\rho R$ values, what difference is needed for two values to be distinct and 2) systematic error, where all generated carbon $\rho R$ values may be higher or lower by a scaling factor. The exact breakdown of statistical vs systematic error.
depends specifically on what two shots are being compared, however, for simplicity, an estimation of error is done here to be applied on all generated carbon $\rho R$ values.

Above 2.9 MeV, for a typical carbon $\rho R$ of $350 \text{ mg/cm}^2$, the total gamma flux is estimated that 20% of the gammas come from carbon while 80% comes from hohlraum/TMP and DT gammas. However, through the Cherenkov process, the signal of Cherenkov photons are estimated to be 60% carbon compared to the background hohlraum/TMP and DT. This makes the signal to noise in absolute signal to be just above 1:1. However, the signal is time resolved with carbon signal is partially time separated from the background, with the early time evolution of the carbon peak being essentially unperturbed and the late time arrival of the carbon eventually becoming 100% hohlraum/TMP. Because of the time separation, the signal to noise is time weighted is a little larger than 2:1, depending on the carbon $\rho R$ of the shot. By the nature of the signal being on the same level of the background, any uncertainty in the background transfers to uncertainty in the signal level.

The first factor introducing significant error is correcting the observed signal for the PMT gain and quantum efficiency to compare equivalent Cherenkov photon counts. All shots analyzed have 1 of 3 different PMT biases, one for each of the $10^{14}$, $10^{15}$ and $10^{16}$ neutron yield ranges. Gain curves and quantum efficiency is provided from the Photek manufacturer and gain curves are remeasured occasionally using a calibrated laser as well as comparing against neutron yield corrected signal comparisons across 120 shots since 2015. Nevertheless, the PMT sensitivity has significant scatter each time it is measured. The PMT correction is estimated to contribute 15% systematic error as well as 10% statistical error when comparing across PMT biases i.e across yield ranges.

The observed background variation as well as the determined cell response ratio from the beryllium shots introduces an error. The 4.5 MeV threshold signal has a standard deviation variation of 15%, believed to be dominated by the PMT gain correction, the changing downscattered neutron spectra and the neutron asymmetry.
The hohlraum diameter and composition, dopants, photon statistics, non-Cherenkov background and deconvolution uncertainty are all believed to be negligible in comparison. The downscattered neutron and neutron asymmetry are estimated to have a 10% statistical and systematic level effect. The four scaling factors found from beryllium shots have a standard deviation of ±0.17. A ±0.2 scaling factor corresponds to a systematic change in carbon $\rho R$ of about 50 $\text{mg cm}^{-2}$, which is estimated as a 15% systematic error. Timing shift has a negligible effect on the carbon $\rho R$ value.

Estimating the effective error from the subtraction routine is a difficult process. As said above, the chosen timing shifts have effectively no change on the resulting carbon $\rho R$ and so determining the effective error from the routine comes from estimating the possible variation from determining what scaling factor is chosen. The 1% negative carbon signal cut off was selected to be placed in a landscape that is not highly sensitive to changing scaling factor as well as give carbon signals where the negative components look by eye to be reasonable from devolution artifacts and noise. If we allow twice as much negative carbon signal, setting the cutoff to 2%, there is an average shift of 3% larger carbon $\rho R$ across 50 shots analyzed, suggesting that the 1% cut off is indeed in region that is not too sensitive. However, tightening the requirement to 0.5% negative carbon signal, the found average carbon $\rho R$ is 10% smaller with a 10% standard deviation, suggesting that 0.5% tolerance is in a more sensitive landscape. To be conservative, we take the 10% variation from doubling the tolerance as our estimate for the statistical error and systematic error for the subtraction algorithm.

Finally, converting the integrated carbon signal to carbon $\rho R$ using the puck calibration introduces error as well. The puck calibration value is found by using the weighted average of 5 puck shots that occurred between 2012 and 2018. Three of the puck shots had laser problems with cross beam energy transfer, resulting in a low signal and a high error. Two of the puck shots have high signal to noise and dominate the weighted average. The weighted statistical average of the puck shots is
calculated to be 6%. Systematic error estimated by the determination of the known $\rho R$ puck value and the gamma directional dependence are calculated to be 5%.

Taking the statistical and systematic errors in quadrature, we approximate the error of the carbon $\rho R$ to have a statistical error of 15% and a systematic error of 30%. Steps are being taken to better calibrate the PMTs to have a more consistent gain and QE measurements. More beryllium shots will increase the statistics of the cell response ratio while more puck calibrations will give more statistics on the carbon gamma to carbon $\rho R$ value. In the future, increased filtering to increase the carbon signal vs the hohlraum/TMP signal as well as installation of a faster pulse dilation PMT[60] may improve the consistency of the subtraction algorithm and reduce uncertainty. A better understanding of the effect of downscattered neutron spectra will be conducted in the future in order to better apply corrections.

### 3.2 National Ignition Facility ablator trends

This work was published in [9]. Across the layered shots analyzed, the observed values of carbon $\rho R$ vary from 180 $\frac{mg}{cm^2}$ to 620 $\frac{mg}{cm^2}$. A handful of the Bigfoot and HDC capsules are part of the subscale campaign and so have with smaller, 910 $\mu m$ radius capsules, 64 $\mu m$ thick ablator, with lower laser energy, 1 to 1.2 MJ, all have values between 175 to 300 $\frac{mg}{cm^2}$. The majority of the capsules fall into the middle range, with full scale capsules having a 1000 $\mu m$ total radius, the HDC and Bigfoot with a 72 $\mu m$ thick ablator while the CH campaign has a 160 $\mu m$ thick ablator. The Highfoot campaign have large 1120 $\mu m$ radius, 175 $\mu m$ ablator thickness with a higher adibat. All these middle range capsules range across 1.5 to 1.8 MJ total laser energy and have carbon $\rho R$ ranging from 300 to 500 $\frac{mg}{cm^2}$. Finally, the Hybrid B capsules and one oversized HDC capsule have a radius around 1100 $\mu m$ total and use the maximum laser energy of 1.8MJ but are designed for even higher energies. These oversized capsules have the highest values ranging from 550 to 650 $\frac{mg}{cm^2}$. Figure 3.5
Figure 3.5: Carbon $\rho R$ loosely correlates with total input laser energy, but generally falls into three major buckets. Subscale (small capsule, low energy), full scale (designed for nominal NIF laser energy) and oversized capsules (designed for more laser energy). The high $\rho R_C$ of the oversized capsules reflects the larger mass remaining shows the values found against input laser energy with the three buckets highlighted.

In ICF research, many different threshold conditions have been proposed to determine the onset of the self-heating regime[61]. One well-known condition, the Lawson criterion, balances the fusion energy gain and energy losses. The criterion establishes a minimum threshold based upon the product of the peak hot spot pressure and confinement time, $P\tau$, for ignition onset. Following Betti et al[62], in an ICF experiment, fuel internal energy comes from the shell kinetic energy and can be
estimated in a one-dimensional thin shell approximation as:

\[ 2\pi P_s R_s^3 \frac{\theta}{2} M_{sh} v^2 \]  

(3.4)

Where \( P_s \) and \( R_s \) are the pressure and radius at stagnation; \( \theta \) is the fraction of the shell kinetic energy transferred to the fuel internal energy; \( M_{sh} \) is the mass of the shell and \( v \) is the peak velocity of the shell. At stagnation, the velocity of the shell vanishes \( (\dot{R} = v = 0) \). The only force applied to the shell is the hot spot pressure, i.e. \( M_{sh} \ddot{R} = 4\pi R_s^2 P \). Using this relationship, along with the shell kinetic energy, one can define the confinement time and write it as:

\[ \tau \equiv \sqrt{\frac{R}{\ddot{R}}} \sim \sqrt{\frac{M_{sh}}{4\pi P_s R_s}} \sim \frac{R_S}{v} \sqrt{\frac{1}{\theta}} \]  

(3.5)

Combining both equations (3.4) and (3.5) to estimate the Lawson Criterion:

\[ P\tau = (\rho R)_{\text{shell}} v \sqrt{\theta} \]  

(3.6)

This simple derivation suggests that in an idealized implosion, a large areal density of the shell should translate into a higher hot spot pressure or a longer confinement time. Since the remaining shell, or pusher, consists of the dense DT ice layer and the remaining ablator, usually carbon, the total pusher areal density is \( (\rho R)_{\text{shell}} = \rho R_{\text{DT}} + \rho R_C \). The areal density of the ice portion of the pusher is derived from the total DT areal density as measured by the neutron downscatter ratio (DSR) [63], [64]. The DT \( \rho R \) is a vital metric for driving fusion, generating a hot spot, and bootstrapping alpha heating [65]. The carbon portion of the pusher drives the DT fuel [66]. The carbon gamma ray measurement provides the carbon portion of the pusher’s areal density and completes a full pusher areal density measurement.

The ablator loses more than 90% of its mass through the acceleration phase of the implosion. The ablation of the mass, which provides the force to drive the DT payload of a spherical rocket, determines the maximum velocity of the shell. The shell velocity in turn fixes the energy that can be transferred into the fuel to form the hot spot[67]. However, tradeoffs must be made between less mass and more velocity
which leads to more mix. A small amount of mass remaining has been shown to seed a high amount of mix and other degradation mechanisms that cause the neutron yield to fall off a performance cliff\cite{68}. More capsule mass remaining adds a buffer layer than can help protect against ablation front growth feeding through to ablator mixing into the hot spot\cite{69}. For recent shots, designs that leave more than 4% mass remaining produce no significant mix (<20% of total x-ray emission) in the hot spot\cite{70}, [71]. When the carbon $\rho R$ measurement is made during the fusion burn, the relevant carbon is both the remaining mass and some ‘piled up’ mass that was ablated when the capsule implosion speed exceeds the exhaust velocity during deceleration and stagnation. Almost all recent NIF/ICF shots have about 0.1 to 0.2 mg of carbon remaining. To maximize the hot spot pressure and confinement, designers should try to maximize the carbon $\rho R$ compression, while leaving enough mass remaining as a buffer against a high amount of mix or x-ray preheat of the fuel.

### 3.2.1 Expected density profile of ablator at bangtime

To understand the measured carbon $\rho R$ values, it is valuable to have a qualitative model of the state of the ablator when this measurement is made. When ablator areal density is measured, it has gone through its full evolution. First, the acceleration phase, where x-rays create an ablation front that drives the capsule inward and ablates the majority of the mass of the carbon shell. Second, the deceleration phase, where the internal energy of the inner gas becomes comparable to the energy imparted into the shell and slows the incoming shell. Around the deceleration phase, the input laser energy is turned off and the capsule enters the coast time, where the hohlraum begins to cool, decreasing the ablation pressure. Finally, the hot spot reaches peak fusion output and the carbon $\rho R$ measurement is made. Because of the ablation process, the density profile of the ablator near bangtime can be broken into two components – first, a free expansion region where the outward boundary of the ablator exponentially decreases as it freely expands and stretches off into the
Figure 3.6: Typical 2D HYDRA simulation output of a high-density carbon campaign NIF shot showing the $4\pi$-averaged density and temperature profile at bangtime. The carbon $\rho R$ measures the integral of the ablator, which is made up of the shoulder and the free expansion region. A density model that smooths the profile is plotted alongside the ablator for comparison.
surrounding space. Second, a density shoulder of carbon shell that the ablation front has not reached or was caught and piled up as the capsule decelerates and stagnates. This ablator shoulder pushes onto the DT ice layer and communicates the ablation pressure on the fuel. In reality, the ablator is hydrodynamically mixed and blurred through the Rayleigh-Taylor and other fluid instabilities instead of being two discrete layers\[72\. Figure 3.6 shows a typical 2D HYDRA [73] simulation of a High Density Carbon (HDC) campaign[74], [75], [76] NIF shot with a typical angle averaged density profile at bangtime. The shoulder of the carbon as well as a free expansion region can be identified. Since the GRH diagnostic measures the total number of gamma rays emitted from carbon-scattered fusion neutrons, this introduces a $\frac{1}{r^2}$ dependence as the flux of the neutrons decrease per unit of area as they move farther into a region of carbon mass spread out over a larger radius. However, with the expected carbon density profile, the unablated shoulder and nearby expansion region make up 90% of the areal density, while the further free expansion region is under-sampled by the carbon gamma measurement, thereby weighting the carbon gamma measurement to the ablator that is still close to the fuel. Nevertheless, the $\frac{1}{r^2}$ dependence is seen as a higher order correction of the mono-energetic instantaneous point source approximation[53] (MIPS) used to connect the carbon gamma ray measurement to ablator $\rho R$, estimated to be accurate within 5% to 10% of the true areal density. This dependence is included in the quoted experimental uncertainties. With the MIPS assumption, the measured number of carbon gamma rays is proportional to the integral of the carbon region.

Consider the expectation of the measurement under this density profile. Cerjan et al[51] used a static model of the density profile by assuming a quadratically decreasing exponential tail fit against the edge of the DT ice layer. In this picture, the shoulder and the free expansion portion were smoothed together into a steadily decreasing profile. Figure 3.6 shows a comparison between a fit of this form and the HYDRA simulation. Within the uncertainties and constraints of the gamma ray measurement,
this form is a reasonable approximation. Written explicitly the density profile can be approximated as:

\[
\rho_C(r) = \rho_0 \left( \frac{r_c}{r} \right)^2 e^{-\alpha(r-r_c)} \Theta(r - r_c) \tag{3.7}
\]

Where \( \rho_0 \) is the density at the DT ice layer-carbon interface, \( r_c \) is the radius of this carbon-ice interface, \( \alpha \) is the decay length scale and \( \Theta(r - r_c) \) is the Heaviside function, starting the carbon density at the interface radius. The measured carbon \( \rho_R \) would have the form:

\[
\rho_R = \frac{m_r \alpha}{4\pi r_c} \left( 1 + \alpha r_c e^{\alpha r_c} Ei(-\alpha r_c) \right) \tag{3.8}
\]

This expression is derived from the definition of \( \rho_R = \int_{r_c}^{\infty} \rho_c(r)r^2dr \) combined with an expression for spherical mass remaining \( m_r = 4\pi \int_{r_c}^{\infty} \rho_c(r)r^2dr \). The maximum density at the interface is \( \rho_0 = \frac{m_r \alpha}{4\pi r_c^2} Ei(t) = \int_{-\infty}^{t} e^{t} \frac{dt}{t} \) is the exponential integral function. The components that make up the measurement of the carbon \( \rho_R \) are: 1) mass remaining of the ablator, 2) the decay length 3) the radius and 4) the density of the DT ice layer-carbon interface. With this density model, when three of these components are set, the fourth is automatically determined.

The carbon \( \rho_R \) is a convolved measurement that involves all these components. With the carbon \( \rho_R \) measurement and two other observables of the contributing components, the ablator density profile can be approximated with this model. The mass remaining is estimated using a shell velocity scaling based on surrogate non-DT implosions that are radiographed to measure the shell trajectory until bang time[67]. These scalings are then applied to DT shots where x-ray radiography cannot be used. The cold fuel layer-carbon interface is estimated by the Los Alamos Neutron Image Team’s downscattered neutron images which draw a 17% contour to estimate the radius[78], [79]. This radius, as the approximate edge of the DT ice layer, has been determined to be a reasonable estimate of the location of the DT ice-carbon interface radius because of the mixed nature of the region and agreement with simulations.
3.2.2 Ablator trends across NIF shots

There is handful of models to estimate $P\tau$, such as Cheng et al.[80] We use the yield equation $Y_{\text{DT}} = n^2 \langle \sigma v(T) \rangle V\tau$ along with the ideal gas law for pressure $P = nkT$ to estimate the Lawson criterion in the form $P\tau \propto \sqrt{\frac{T_{\text{DT}}}{V(\sigma v(T))}} kT$. It is known that burnwidth is not confinement time[81], but the Betti et al. definition in equation (3.5) uses hydrodynamic simulations to argue they may be proportional[62] and so for simplicity it is used here as an approximation ($\tau \propto \tau_{\text{BW}}$). With these assumptions we can make an estimation for relative $P\tau$ for the Highfoot, Bigfoot and HDC NIF campaigns compare them with the carbon $\rho R$, as shown in Figure 3.7. The combination of both the theoretical expectation along with experimental trend showing that the carbon $\rho R$ does help hot spot confinement motivates understanding the various experimental input parameters that affect the final state of the ablator.

Figure 3.10 shows the measured $\rho R$ as a function of four different metrics: max shell velocity, mass remaining, cold fuel ice layer radius and picket intensity. Collectively, across all campaigns, there is no apparent correlation with the measured carbon $\rho R$ for any of these metrics. There is a suggestive correlation with the Highfoot campaign and velocity. While almost all implosions have an estimated mass remaining between 0.1 to 0.25 mg, the Hybrid B campaign has 0.25 to 0.3 mg. The relatively higher mass may explain the higher carbon carbon $\rho R$ values for the Hybrid B campaign specifically. For almost all campaigns, the cold fuel outer radius varies between 40 to 50 $\mu$m. For looking at all campaigns collectively, the lack of global correlations suggests that these effects, mass remaining and DT-carbon radius, are not as important as the last remaining variable in the model of the ablator – the thickness of the ablator, which is set primarily by the $\alpha$ as part of $\rho(r) \propto \left(\frac{r}{r_c}\right)^2 e^{-\alpha r}$. 
Figure 3.7: The remaining carbon $\rho R$ generally correlate across the estimated $P\tau$, a measure of the hot spot performance through energy balance. The $P\tau$ metric is approximated by $P\tau \propto \sqrt{\frac{T_{\text{DT}}T_{\text{GW}}}{V\langle \sigma v(T) \rangle}} kT$

Dopants and laser foot

High Z dopants, such as tungsten or silicon, are added to ablators in order to reduce preheat at the ablator-ice interface (by increasing opacity and heat capacity) to provide a better density (Atwood number) match of the ablator to the DT ice layer through the capsule evolution. Berzak Hopkins et al. have shown the addition of tungsten dopants to the HDC ablator improved stagnation pressure and fusion output. Carbon $\rho R$ measurements are systematically higher and have decreased final thickness as dopants are added. Consider four HDC subscale shots as a comparison set: N160120-003 and N160418-001 were undoped while N160223-001 and N161023-001 had a 0.23% atomic percentage tungsten dopant added. Each pair were designed to reach a specific velocity, the slower set shots N160120-003 and N160223-001 were
Figure 3.9: 2D HYDRA density profiles at bangtime for the doped and undoped comparison. The doped case shows higher density ablator with a similar radius.
Figure 3.10: Carbon $\rho R$ has no global correlation with a) max shell velocity b) mass remaining, c) cold fuel radius, or d) laser picket intensity.
experimentally inferred to have a max velocity of $353 \, \mu m/\mu s$ with an ablator mass remaining of 0.24 mg, and the faster set shots N160418-001 and N161023-002 were estimated to have a max velocity of around $376 \, \mu m/\mu s$ with a mass remaining of 0.18 mg. The slower pair has a coast time of 1.8 ns while the faster pair has a coast time of around 1.5 ns. The trend across the comparison set sees increased yield and fuel $\rho R$ when dopants are added.

Likewise, Figure 3.8 shows that the carbon $\rho R$ sees a 50% increase between the doped and undoped case, from $200\pm50 \, \text{mg/cm}^2$ to $300 \pm 50 \, \text{mg/cm}^2$. This is consistent with Berzak Hopkins et al. radiography measurements on non-DT capsules seeing a 50% increase in the in-flight aspect ratio (ratio of imploding capsule radius to thickness) with the addition of dopants. The carbon $\rho R$ does not change with increased shell velocity, consistent with the global trends. The relative change in carbon $\rho R$ between

![Figure 3.8](image-url)

**Figure 3.8**: For a specific comparison case on the HDC subscale campaign, carbon $\rho R$ is insensitive to a velocity increase but sensitive to dopants. 2D HYDRA simulations with a limited mix model capture the observed increase.
doped and undoped subscale capsules is larger than any other measurement besides neutron yield. Adding dopant increases the compression of the ablator distinctly from velocity, mass remaining, and ablator radius. In another comparison case, Bigfoot shots N170524 and N171015 were near identical shots that both have a 1 ns coast time but increased the tungsten dopant from 0.13% to 0.21% as well as an increase of 10% higher peak laser power. These two shots observe an increase in carbon $\rho R$ from $315\pm 47$ to $378\pm 56 \ \text{mg cm}^{-2}$, consistent with the increase seen in the HDC shots with more dopants. The observation of increased carbon $\rho R$ verifies that the addition of dopants creates an improved ablator piston that continues until the end of the capsule evolution when the fusion occurs.

Post shot simulations using 2D HYDRA follow the same observed trend. The simulated carbon $\rho R$ values are included in Figure 3.8. Figure 3.9 shows the simulation’s output of the angle averaged density as a function of radius for two of the simulated shots, showing that the addition of the dopant predicts higher carbon density. The simulation handles the addition of the tungsten dopant by changing the density and opacity, however, a pure HDC equation of state is used. The change in absorbed energy and improved Atwood number (better density matching) is enough to capture the observed increased compression, despite only calculating low hydrodynamic modes (up to 8) and so not resolving any features of high order mix.

A series of three Bigfoot campaign implosions varied the duration of the laser foot, defined as the first pulse of the shaped laser drive. The first foot of the laser drive sends the first shock into the capsule and, setting the initial conditions, makes the largest contribution to the adiabat for the implosion[83],[84]. For the Bigfoot campaign, the first and second shock merge within the fuel. Historically, NIF implosions have moved to higher capsule adiabats by increasing the laser foot amplitude. The adiabat has increased from the Lowfoot[85], to Highfoot, and then Bigfoot campaign. Increasing the laser foot amplitude has indeed produced increased adiabat, improving capsule stability, allowing for higher shell velocity and improved capsule
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performance. Lengthening the laser foot likewise is believed to lower the adiabat of the capsule, by moving the first and second shock merger farther into the fuel. The laser picket intensity, shown in the global trends, has no correlation with the carbon $\rho R$.

In this parameter scan, the nominal Bigfoot laser pulse shapes have a foot length of 1.1 ns with a design capsule adiabat of 4. Two implosions used a foot duration of 1.4 and 1.65 ns with an expected design adiabat of 3.5 and 3. All three shots had total laser energy of 1.8 MJ and a similar coast time of 0.9 ns. The measured carbon $\rho R$ trends with the laser foot lengthening, possibly following the ablator on a lower adiabats, giving higher compression resulting in higher carbon $\rho R$. Figure 6 shows the laser pulses and fusion reaction history measured the GRH diagnostic[90] as well as the measured carbon $\rho R$ versus the foot length. Changing the laser foot, however, did not systematically change the yield, hot spot and downscattered neutron radius, fuel $\rho R$, ion temperature, or burnwidth, suggesting that lengthening the laser foot and reducing the capsule adiabat did not improve fuel confinement or hot spot performance in general. Nevertheless, the outer most edge of the capsule responds as expected to the lengthened laser foot. This trend is consistent with other data showing that the compression of the ablator by itself does not improve fuel performance.

3.2.3 Pusher compression

This work was published in [10]. The dopant and laser foot does not explain the majority of ablator areal density. Besides all the other factors, the strongest correlation of carbon $\rho R$ is with coast time, the time between the end of the laser drive and peak fusion rate. The comparison against coast time across the campaigns, seen plot a) of Figure 1, shows a suggestive downward correlation for each of the campaigns, with an exception for the Highfoot campaign. Our primary interest here, however,
Figure 3.11: For a specific comparison case on the HDC subscale campaign, carbon $\rho R$ is insensitive to a velocity increase but sensitive to dopants. 2D HYDRA simulations with a limited mix model capture the observed increase.

is the effect of the coast time on the compression of the carbon portion of the pusher near stagnation time. This late time evolution is convolved with the mass remaining of the carbon ablator, which is set earlier in the capsule evolution. Typically, $>90\%$ of the mass of the carbon shell is ablated off throughout the capsule’s evolution. However, most of the ablation occurs before laser drive turn off. The smaller ablator surface area (approximately 0.16 mm$^2$ imploded compared to the initial 4mm$^2$) and relatively shorter amount of time (0.4 to 1.8 ns of coasting vs the 7 ns of laser drive) makes the coast time contribute a negligible amount of ablator mass loss.
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Figure 3.12: a) The measured carbon $\rho R$ at peak fusion rate has a suggestive correlation against laser coast time within most campaigns. b) When corrected by the mass remaining to isolate late time evolution, carbon $\rho R$ sees a decreasing correlation with coast time across all campaigns. This effect dominates the carbon $\rho R$ value more than any other metric investigated.
Therefore, to better understand the ablator evolution as a function of coast time, we compare the carbon $\rho R$ normalized by the mass remaining. The mass remaining is inferred by input energy and velocity scaling of capsules, which is calibrated through surrogate, non-cryogenic capsules and then applied to the shots that have the DT ice layer [67],[69]. Areal density has units of $\text{mg/cm}^2$ and represents the amount of mass integrated radially outward from the center of the capsule. For the normalized, unit mass considered here, the units of $\frac{1}{\text{cm}^2}$ represent an amount of interaction integrated along a path with a set number of carbon atoms. A higher value represents a set number of atoms within a smaller volume and so this value is proportional to the compression of the shell. As an example, the high $\rho R$ values in the Hybrid B campaign are due to its higher mass remaining. Correcting by the mass remaining makes it consistent with other campaigns of similar coast time— thus isolating the effect of late-time evolution. Correcting by the mass remaining shows a clear dependence of coast time against carbon $\rho R$ across many campaigns, plot b) of Figure 1. The correlation is direct experimental verification that additional late time laser energy continues to maintain a significant pressure on the capsule, in agreement with Hurricane et al. [65] and Berzak Hopkins et al. [86].

In series of experiments, laser energy is often increased by extending the laser pulse as opposed to solely increasing peak power. Although coast time is strongly coupled with total laser energy, it is not always a 1-1 relation and the carbon $\rho R$ has a better correlation against coast time than input laser energy ($R^2$ of 0.7 vs 0.5). This correlation suggests that the laser coast time itself has a direct effect on the ablator compression beyond simply additional laser energy. During the coast time, the hohlraum cools, decreasing the ablation pressure. Decreasing ablation pressure at earlier time, relative to the peak fusion, causes deceleration and inflight decompression when the shell is at a larger radius. As suggested in stopping power experiments [87], if an early-time decrease of ablation pressure causes the implosion to come in later relative to the coalesced shock, it creates a longer time gap
between the shock yield and the compression yield. The rebounding shock then hits the incoming shell at an earlier time (larger radius) and could reduce compression and final areal density. Apart from coast time, increasing dopant percentage is also observed to increase the carbon $\rho R$ and overall compression [82]. These effects – increased laser energy, less hohlraum cooling, rarefaction wave and possibly the rebounding shock hitting the ablator at a larger radius – are all possibilities to contribute to the observed correlation.

The ablator is only part of the total pusher, which is comprised of both the remaining ablator and the DT ice layer. The DT ice layer makes up approximately 80% of the total DT $\rho R$. One may naturally hypothesize that the increasing pressure of the ablator, due to shorter coast time and/or more laser energy, should then be communicated to the DT ice layer. The DT $\rho R$ is measured by five neutron time of flight instruments [88], which infer the neutron energy spectra. The amount of downscattered neutrons can be related to the total DT $\rho R$ through the scattering cross section [64]. However, the DT $\rho R$ is uncorrelated with coast time (and laser energy) across all the campaigns, show in figure . The Highfoot campaign uses larger capsules that have more initial DT mass, and this is reflected in a higher DT $\rho R$. Once normalized by the DT mass, the Highfoot campaign has an average fuel $\rho R$ consistent with other campaigns. The comparison is shown in Figure 3.14.

The Bigfoot subscale shots have a small amount of DT mass (90 $\mu$g compared to 130 $\mu$g) but are observed to have the same fuel $\rho R$ as the full scale shots (around 550 $\frac{mg}{cm^2}$) and consequently indicate an increased efficiency for compressing fuel compared to the other groups. The detailed reason why these subscale shots show increased efficiency is unclear, but the subscale shots also have some of the smallest observed downscattered neutron radii (35 $\mu$m compared to 45 $\mu$m for other campaigns) suggesting that these have some of the highest fuel convergence. The overall trend implies that the effects that compress the ablator do not translate directly to the fuel.
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Focusing on the HDC campaign, 2D, integrated, HYDRA post-shot simulations that include delivered laser power, as-built hohlraum, capsule and fuel resolved to mode eight with no added preheat successfully capture the carbon $\rho R$ variation within the 15% carbon $\rho R$ diagnostic measurement uncertainty. Eight HDC post-shot simulations were selected to compare carbon $\rho R$ values spanning the coast times and, for these shots, laser energy [89]. Both the absolute values and the observed trend of the carbon $\rho R$ and mass corrected carbon $\rho R$ are matched by the simulations. However, these 2D HYDRA simulations over-predict the fuel $\rho R$ compared to the experimentally inferred values, being on average 30% systematically larger. The fuel $\rho R$ has an approximate 7.5% uncertainty as estimated by the chi squared weighted average from five lines of sight. This overestimation has historically been noted in other ensembles of 2D simulations with the addition of preheat to the simulated ice layer needed to bring the fuel $\rho R$ into agreement with measurements [91]. Similarly, Clark et al.’s [92] high-resolution, 3D Hydra simulations with 60 J adiabatically added to the ice layer to replace high-resolution hydrodynamic mix match the experimentally measured fuel $\rho R$. The simulated comparison for both the carbon $\rho R$ and the DT $\rho R$ corrected by mass are shown in Figure 3.13. Two-dimensional HYDRA simulations over-predict the ice layer compression but successfully capture ablator compression. These results imply that the mechanisms that prevent expected compression of the fuel do not degrade the ablator $\rho R$. Cheng et al. [81] and Clark et al. [92] highlight three potential sources of degradation of fuel compression and yield: mix/preheat in the DT ice layer, perturbations induced by the fuel fill tube, and 3D asymmetricities. Experiments have been executed to isolate the effect of different fill tube sizes as well as low mode asymmetricities. It is impossible experimentally to isolate the effects between 2D and 3D in the simulations. Therefore, to estimate the effects of 3D asymmetricities, large low mode asymmetricities, prolate and oblate shapes in both the hot spot and cold fuel, are used as an approximation. These experimental comparisons indicate that neither the fill tube nor asymmetricities decrease fuel and carbon $\rho R$. Experiments changing fill tube sizes (2.5 $\mu$m, 5 $\mu$m or 10 $\mu$m) or having
Figure 3.13: The compression of the carbon ablator generally correlates with the hot spot ion temperature. Despite the fuel density not having any correlation, increased ablator compression may still improve hot spot confinement, resulting in a higher temperature.
Figure 3.14: a) Unlike the carbon $\rho R$, the fuel $\rho R$ has no correlation across coast time. b) Comparing compression by correcting the fuel $\rho R$ with DT mass still shows no correlation with coast time. This implies that the increased compression of the ablator is not being transferred to the rest of the pusher.
large low mode asymmetries (P2/P0 of +35%, -27% or -2%) all produce the same carbon $\rho R$ and fuel $\rho R$ within uncertainty. Because these two effects do not notably decrease pusher compression, it suggests ablator-ice mix to be the main degradation source for the fuel.

Ablator-ice mix has been simulated [72], growth rates of preimposed modulation have been measured [95], and experimental designs seek to minimize its effect [82]. Previous 3D simulations suggested that higher mode resolution ablator-ice mix did not have a significant effect on Highfoot shots [93], but these simulations did not include equation of state variation due to the mix [94]. A DT-carbon mixed material equation of state would be less compressible. In simulations of Highfoot and HDC implosions that match the fuel $\rho R$, 60 J of energy are added to the ice layer adiabatically, with no additional energy added to the ablator portion of the pusher. This evidence supports the practice of adding energy to simulate ablator-ice mix solely to the fuel layer and not to include the remaining ablator portion of the pusher. Adding energy to the carbon portion of the shell would decrease the carbon compressibility and give lower carbon $\rho R$ than observed. The data suggests that the ablator mix with the DT fuel reduces the compressibility of the fuel but does not significantly affect the remaining ablator compressibility. This observation presents a constraint on the extent and method of ablator-ice mix and models should reflect this observation.

It was shown earlier that the ablator areal density’s generally does correlate with the hot spot confinement, that is, the Lawson Criterion. However, across these experimental series, the carbon portion of the pusher has continued to increase its compression while the fuel compression remains constant. It is not immediately clear whether increasing pressure from the outer portion of the pusher should then communicate to the hot spot. The hot spot pressure depends mainly on the DT areal density and the ion temperature. Because the DT areal density has remained constant, the increase in hot spot pressure is due to an increased hot spot temperature. The correlation between ion temperature and the carbon areal density is shown in
Figure 3.15: The compression of the carbon ablator generally correlates with the hot spot ion temperature. Despite the fuel density not having any correlation, increased ablator compression may still improve hot spot confinement, resulting in a higher temperature.
Even though the DT areal density has not increased, it is consistent with theoretical analysis by Hurricane et al. [65] suggests that ablation pressure at late time transfers to hot spot, regardless of the density profile or pusher compressibility. This correlation suggests that better ablantor compression improves capsules performance through better confinement, increasing temperature while not necessarily increasing the fuel areal density. Further compression trends along with yield were published in [96]. In summary, measurements of the gamma rays scattered from the carbon atoms in the ablantor show that the compressibility of the ablantor is determined primarily by the laser coast time, a feature captured by 2D HYDRA simulations. This observation verifies that late-time laser energy transfers into an ablation pressure that directly compresses the outer edge of the fuel layer which then communicates with the hot spot pressure. Therefore the highest performing capsules must be designed with short coast times. The fuel $\rho R$, however, is largely constant and is overestimated by 2D HYDRA simulations, requiring added energy to the simulated ice layer to reduce its compressibility and match measurements. These data shows that the ablantor-ice mix does not significantly affect the ablantor areal density, an observation that should help constrain mix models.

**HELIOS ablantor-fuel mix simulations**

There are many complex processes for the physical mechanism causing the degradation of NIF ICF capsules, such as asymmetries, hot electrons from the hohlraum heating, ablantor-hot spot mix and ablantor-DT ice mix. However, to be consistent in the observation that the DT fuel is being degraded while the ablantor is not affected as much, it suggests a mechanism that preferentially degrades the DT ice layer but not the ablantor. One immediate candidate is the ablantor-DT ice mix. The entropy of a mixed element plasma is more than the entropy of two separated layers. The carbon ablantor and DT ice are Atwood unstable and so Rayleigh Taylor instabilities, as well as all other associated instabilities, mix the ablantor into the DT ice layer as
Figure 3.16: The density as a function of radius during peak fusion for increasing amounts of carbon mix.

the capsule evolves. A mixed DT ice layer has a higher entropy and has changed thermodynamic properties, specifically is less compressible compared to a non-mixed layer. Doing a representative calculation or well measured experiment to measure distributions, time evolution and extent of the mixing has been the challenge of the HED field since its creation. Here we analyze one possible explanation for the source of degradation with the understanding that there are many complicating variables and that this analysis to match the data is not unique.

HELIOS [97], a simple hydrodynamic simulation software, was used in combination with PrOpacEOS, an equation of state calculation tool - both of which made by PRISM Computation Sciences, Inc [98] to estimate the effect of mix on the compression of the pusher. A mix parameter scan was done with increasing carbon being
mixed into the DT ice layer. As an initial condition, an increasing atomic percentage of the carbon is uniformly mixed through the DT ice layer. An equation of state data table is calculated used PrOpacEOS for each mixed carbon-DT plasma. The summary is shown in Figure 3.16 and 3.17. Increasing the mix amount decreases the areal density of the DT ice layer while the ablator areal density is unchanged, consistent with the NIF observational study. A modest amount of carbon needs to be mixed in to see the observed 15% decrease in DT areal density. This amount of carbon mass is basically negligible for the carbon ablator and so the main structure of the carbon ablator remains unchanged. This simple simulation tool shows the trend that ablator-ice mix would degrade the DT ice portion while the majority of the carbon ablator would remain relatively unchanged, similar to the data and trends observed on the NIF.
3.3 Time dependent ablator areal density

The analysis of the carbon ablator, its trends and the compression of the pusher all are the result of the integral of the carbon gamma ray peak. The GRH measures a time resolved signal and therefore holds time information of the ablator. Such information provides stringent observational constraints on the residual kinetic energy near peak burn, on possible shock mistiming and on fuel-ablator mix.

Consider a fusion burn reaction history in a Gaussian form:

\[ Y_{\text{DT}}(t) = \frac{Y_{\text{DT}}}{\sigma_{\text{DT}} \sqrt{2\pi}} e^{-\frac{(t-t_{BT})^2}{2\sigma_{\text{DT}}^2}} \]  

(3.9)

Where \( Y_{\text{DT}} \) is the total neutron yield, \( \sigma_{\text{DT}} \) is the standard deviation related to the measured burnwidth, defined as the full width at half maximum, as, \( \sigma_{\text{DT}} = \frac{r_{\text{FWHM}}}{2\sqrt{2\ln 2}} \) and \( t_{BT} \) is the bangtime, or time of maximum fusion rate. If a DT fuel volume is surrounded by a shell containing carbon, the 4.4 MeV gamma rays are produced by elastic scattering of the DT fusion neutrons on the 12C atoms. With the monoenergetic instantaneous point source (MIPS) approximation, carbon gamma rays are proportionally produced at the rate \( Y_{\gamma C}(t) = \eta Y_{\text{DT}}(t) \left( \rho R_C(t) \right) \) where \( \eta \) is the mass attenuation coefficient with a value of 0.0106 cm\(^2\) g\(^{-1}\). Through the GRH diagnostic, we measure both the \( Y_{\text{DT}}(t) \) and the \( Y_{\gamma C}(t) \) and so through direct division can measure \( (\rho R)_C(t) \). However, the hydrodynamic evolution of the shell evolves on timescales of nanoseconds while the nuclear burn has burnwidth values of 130 to 150 ps for cryogenic implosions. During the maximum fusion burn, we make the further approximation that the evolution of the areal density of the ablator can be well approximated by a linear time dependence, that is, a constant slope over the duration of the DT burn. This assumption is reinforced by the experimental data, as direct division often gives a straight line over regions with good signal and allows simplifying the result. The areal density of the carbon can then be expressed as:

\[ (\rho R_C)(t) = \rho R_{C0} \left( \frac{t - t_1}{t_{BT} - t_1} \right) \]  

(3.10)
Where \( t_1 \) is a chosen time to define the time interval for the slope. That is, the value \( \frac{1}{t_{BT}-t_1} \) is the normalized \( \rho_R \) slope value, i.e. \( \left( \frac{\frac{d}{dt} \rho_R}{\rho_R} \right) \). Note that at \( t = t_1 \) the expression goes to zero as this becomes inaccurate. We only apply the slope around the peak DT burn at \( t \approx t_{BT} \). Experimentally, we will use \( t_1 = t_{BT} \pm 75 \text{ ps} \).

With two these expressions substituting into the carbon gamma ray output, it may be written as

\[
t_c = t_{BT} + \frac{t_{BT} - t_1}{2} \left( \sqrt{1 + \frac{4\sigma^2}{(t_1 - t_{BT})^2}} - 1 \right)
\]  

(3.11)

The carbon gamma rays arrive at a later time the DT neutrons \( (t_C > t_{BT}) \) as long as the \( \rho_R \) slope is positive \( (t_{BT} > t_1) \). Using the carbon gamma isolation routine, we have measurements of the fusion bangtime time as well as the peak carbon gamma time and can easily take their difference. Using the previous relation that the normalized slope is \( \left( \frac{\frac{d}{dt} \rho_R}{\rho_R} \right) = \frac{1}{t_{BT}-t_1} \), we can then relate the normalized slope to the time difference between the fusion peak and the carbon gamma ray peak.

Inverting equation (4):

\[
\frac{1}{t_{BT} - t_1} = \frac{t_C - t_{BT}}{\sigma_{DT}^2 - (t_2 - t_{BT})^2} \rightarrow \left( \frac{\frac{d}{dt} \rho_R}{\rho_R} \right) = \frac{\Delta t_{C-DT}}{\sigma_{DT}^2 - (\Delta t_{C-DT})^2}
\]  

(3.12)

Therefore, with a Gaussian burn history, the carbon gamma ray peak time compared to the DT fusion bangtime (the carbon-DT) time shift is proportional to the slope of the ablator areal density changing with time.

This carbon \( \rho_R(t) \) information can be used in combination with the density profile form, repeated here:

\[
\rho(r) = \rho_0 \left( \frac{r_c}{r} \right)^2 e^{-\alpha(r-r_c)}
\]  

(3.13)

In order to estimate the approximate velocity and kinetic energy of the ablator during the fusion burn. As a reminder, in the MIPS approximation, the measured carbon gamma signal is a product of the ablator \( \rho_R \) and the fusion as a function of time:

\[
Y_{\gamma C}(t) = \eta(\rho R)_C(t) Y_{nDT}(t)
\]  

(3.14)
We measure the carbon gammas, \( Y_{\gamma C}(t) \), and the fusion reaction rate, \( Y_{nDT}(t) \), and so by direct division we can obtain the ablator \( \rho R(t) \). The full width half max of the fusion burn is around 150ps while the hydrodynamic evolution of the ablator plasma is on the order of nanoseconds. We make the approximation, which is supported by simulations, that the \( \rho R_C(t) \) takes a linear form over this time period. We can experimentally determine this by doing direction division of the DT peak and the carbon gammas and then fitting a linear line to the result. The figure below gives an example for an HDC subscale shot that observed a 10 ps shift of the carbon gamma peak against the DT signal.

This shot observed a slope of \( \frac{d}{dt}(\rho R_C) = \rho \dot{R}_C = 466 \text{ mg cm}^{-2} \text{ ns}^{-1} \). Across shots, fitting the linear line from direct division to find normalized slope \( \left( \frac{\rho \dot{R}_C}{\rho R} \right) \) follows the algebraic prediction from bang time difference between the carbon gammas and DT peak, as predicted by Hoffman. See the below image for comparison across the NIF database:
Now that we have measured areal density slopes, we would like to calculate the velocity and kinetic energy located in the remaining ablator. Assuming spherical and angular symmetry, equation (2) predicts the mass remaining as

\[ m = 4\pi \int_{r_c}^{\infty} \rho(r)r^2dr = 4\pi \frac{r_c^2}{\alpha} \rho_0. \]

The \( R_C \) measurement takes the form:

\[ (\rho R)_C = 4\pi \int_{r_c}^{\infty} \rho(r)rdr = \frac{m\alpha}{4\pi r_C} \left( 1 + \alpha r_c e^{\alpha r_c} Ei(-\alpha r_c) \right) \] (3.15)

The max density at the DT ice-ablator interface is set as \( \rho_0 = \frac{m\alpha}{4\pi r_c^2} \). \( Ei(t) = \int_{-\infty}^{x} \frac{e^t}{t} dt \) is the exponential integral function. The carbon ablator density profile evolves over time during the burn as the capsule continues to move inwards. To approximate this, we make the assumption that the decay length, \( \alpha \), is constant over this burn region, the thought being that there is very little ablation that occurs during the 150 ps of fusion burn as the laser has been turned off for 0.5 to 1.8 ns, the hohlraum has cooled, and the capsule has a very small surface area (about 0.04 mm²). The assumption says that the \( \rho R_C \) change is all due to the radius decreasing over this time. With this assumption we can rewrite equation (3) as a function of time as:

\[ (\rho R)_C(t) = \frac{m\alpha}{4\pi r(t)} \left( 1 + \alpha r(t) e^{\alpha r(t)} Ei(-\alpha r(t)) \right) \] (3.16)

We measure a constant value of \( \frac{d(\rho R_C)}{dt} = \rho \dot{R}_C \), and so can take the derivative of equation 5 to find an expression:

\[ \frac{d}{dt} (\rho R)_C(t) = \frac{\alpha^3 m}{4\pi} e^{\alpha r(t)} r'(t) Ei(-\alpha r(t)) + \frac{\alpha^2 m r'(t)}{4\pi} - \frac{\alpha m r'(t)}{4\pi r(t)} \] (3.17)

This is now an exact, separable, nonlinear, differential equation that can be solved. Taking an integral we get a solution as:

\[ k + \frac{4\pi}{\alpha m} (\rho \dot{R}_C) t = \alpha e^{\alpha r(t)} Ei(-\alpha r(t)) + \frac{1}{r(t)} \] (3.18)
Where \( k \) is the integration constant with units of \( \frac{1}{\text{cm}} \). Given the measured \((\rho \dot{R}_C)\), this equation can be used to solve for a radius (and corresponding \( \rho R_C \)) at each time step. The change in the radius across the time steps gives us our velocity.

As an example, consider the specific HDC subscale shot N160223-001 which was observed to have a \( \rho R = 278 \frac{\text{mg}}{\text{cm}^2} \), a \( \rho \dot{R}_C = 466 \frac{\text{mg}}{\text{cm}^2 \text{ns}} \), a burn-weighted cold fuel radius of 48.6 \( \mu \text{m} \) and a remaining mass of 0.23 mg. This sets the \( \frac{1}{\alpha} = 55.6 \mu \text{m} \). At \( t = 0 \) for bangtime, we find the initial condition of \( k = 0.0088 \). We can then calculate the density profile at any time relative to the bangtime, with the burnweighted average giving the observed carbon. Here is a plot of 3 calculated profiles \( + = -75 \) ps after bangtime:

![Calculated ablator density profile evolution for N160223-001](image)

From this, we can calculate estimate velocity as an average from these two points, \( \frac{55.6 - 48.7}{0.075} = 92 \frac{\mu \text{m}}{\text{ns}} \) and \( \frac{48.7 - 44.9}{0.075} = 51 \frac{\mu \text{m}}{\text{ns}} \), so:

\[
\begin{align*}
\nu_{C@BT} & \approx 71.5 \frac{\mu \text{m}}{\text{ns}} \\
KE_{C@BT} & \approx 590 \text{J}
\end{align*}
\]  

(3.19)

For comparison, the ablator is estimated to have a maximum velocity of around \( v_{\text{max}} = 415 \frac{\mu \text{m}}{\text{ns}} \), or about 19.8 KJ of energy. This would imply that the ablator...
has decelerated and lost 97% of its energy and the capsule is very close to a stagnation state at bangtime. Using the thin shell approximation predicts a velocity at bangtime of around $140 \frac{\mu m}{ns}$, about double the estimated velocity and quadruple the energy compared to using this more involved method.

Preliminary analysis on the NIF dataset shows that the carbon timing shift is about 10 to 20 ps for all shots across all campaigns. The carbon is still moving inward at bangtime, in agreement with simulations. The carbon has lost the majority of its velocity and energy and looks as though it is close to stagnation. The amount of energy in the carbon layer is around 0.5 kJ, which is not a significant source of the energy budget. In conclusion, the velocity and kinetic energy of the carbon ablator can be approximated by using the measured carbon gamma and DT reaction history as well as a exponential decreasing profile assumption.
Chapter 4

Diagnosing Inertial Confinement Fusion Mix

As introduced in the previous chapter, mix is one of the central problems of ICF systems. Driving a higher density shell into a lower density fuel is an inherently unstable system. With all the free energy of HED systems, instabilities transfer energy away from shell velocity, hot spot pressure and convergence into non radial velocity, turbulence, heating of different portions of the capsule and other forms of residual kinetic energy. Radiation losses, primarily from bremsstrahlung radiation is propotional to $Z^2$, and so a small amount of mix of higher Z materials can greatly increase the radiation losses as well as the heat conductivity, both acting to dull the hot spot formation. The extent of this mix is notoriously extremely difficult to calculate, with a full systematic treatment needing to include spatial scales down to the Kolmogorov length scale $\eta = \left( \frac{\nu^3}{\epsilon} \right)^{1/3}$ where $\nu$ is the kinematic viscosity and $\epsilon$ is the average rate of turbulence kinetic energy dissipation as well as the Kolmogorov time scale $\tau_\eta = \left( \frac{\nu}{\epsilon} \right)^{1/2}$. In HED systems like a NIF ICF capsule, this would require simulating a millimetre sized system down to nanometers; 6 orders of magnitude. This is currently untenable, and so experimental studies are used to make suitable
4.1 Types of mix in inertial confinement fusion

In ICF systems, one must drive a higher density shell into a lower density DT gas. This drives a Rayleigh-Taylor (RT) instability which drives interpenetration of fluid regions with different densities. The perturbations of the surface at first grows exponentially (in linear theory with no viscosity) with a growth rate of \( \propto e^{\sqrt{A_n k g}} \) where \( A_n = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \) is the Atwood number, \( k \) is the mode number and \( g \) is the acceleration between the two fluids. The RT instability eventually saturates out with a fully turbulent mixed layer in the non-linear regime with the height of the bubble (or depth of a finger) growing quadratically (\( h \propto t^2 \)). The transition from linear growth to non-linear growth and time needed to pass for all the modes to reach a fully turbulent mixed layer are active areas of research and modeling. Furthermore, the laser pulse creates shock waves that move through the capsule, which instigates Richtmyer-Meshkov instabilities, which are the impulse, shock driven form of the RT instability. Multiple shocks pass through the capsule as well as their reflections while the sustained pulse of the laser applies acceleration driving RT instabilities. Furthermore, when any form of non-radial motion occurs, either through asymmetries in the implosion, the flowing plasma creates a shear force that drives a Kelvin Helmholtz instabilities, which move radial motion into disperse energy and create oblique shocks. All three of these instabilities are coupled together and feed on each other and evolve across different modes. In spherical implosions these instabilities are compounded by the convergence effects, where high convergence factors amplify the mix and instabilities. In this dissertation, the combination of all these effects is collectively referred to as hydrodynamic mix. This is opposed to other types of mix that occur from capsule defects such as specks or dust on the surface, the stalk that is used to hold the capsule in the center of the chamber, the fill tube that is inserted
into the capsule, or the tent which is used to hold the capsule in the center of the hohlraum. All these engineered effects can cause jets of material to be shot across the hot spot and can create blobs of cooler material that degrade the implosion. This type of mix is sometimes referred to as chunk mix. There are also other forms of mix, such as diffusion, or high energy particles escap

4.2 Separated Reactant Experiments

In order to have an experimental measurements of the integrated effects of the various mix effects, a diagnostic technique is used that separates nuclear fusion reactants in the shell of capsule. The most common tool is to place deuterated plastic (CD as opposed to standard CH plastic) with some tritium fuel fill. If DT yield is observed, the deuterium in the fuel must have been mixed into the hot spot, atomized and undergone fusion reaction. Separated reactant experiments were done back on the Nova laser in the late 90s [99], using a deuterated plastic and a H2 gas fill. Separated reactants were used to diagnose OMEGA implosion performance after install polarizing smoothing [100] and as a function of shell recession [101]. Separated reactant studies have been used to understand the effect of mix on shell thickness and fit mix models to the observations [102]. Because of the higher shot rate, the majority of separated reactant experiments have been done on OMEGA as a surrogate for ICF conditions generally. However, a handful of experimental campaigns have been run on the NIF in symcap designs and been used to validate mix models [103],[104].

In continuation of this technique, a similar platform was used that instead used ultra thin deuterated plastic layers. Previous experiments used layers that were often a micron or thicker, in this experimental campaign 15 µm OMEGA capsules were used with a placed 150 nm deuterated layer, the layout of the capsules are given in Figure 4.1. These capsules have HT as a fuel to create the HT gamma ray discussed in Chapter 2, as well as using the pure TT fusion yield as the 'clean'
Figure 4.1: Capsule design for the thin separated reactant history capsules for 2017 and 2019 OMEGA mix campaigns. The primary focus was on 15 \( \mu m \) shell thickness with 415 \( \mu m \) inner radius. The deuterated plastic was recessed at different locations further from the location.
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Figure 4.2: Integrated DT yield data (mix metric) obtained in OMEGA mix campaign in 2017, PI’d by Zylstra, revealed a complicated mix landscape previously unseen with experiments that had thicker deuterated layers. The blue points show the collected data, showing the mix signal falls off immediately at 0.3 $\mu$m, stays at a low level at 0.6 $\mu$m and then appears to increase at the 0.9 $\mu$m depth. The dashed lines were preshot simulated expectations of the mix landscape based on previous thicker deuterated layer experiments and a wider hydodynamic mix width. Turning off the turbulent model and leaving only the ZPKZ diffusion model matches the fast fall off of the mix signal up close to the fuel, suggesting that the up close mix is best explained through a diffusion dominated mix with no hydodynamic mix effects. However, the increase in the mix signal at 0.9 $\mu$m presets an unknown mix mechanism that preferentially pulls material from further away from the fuel. If both these affects were integrated together with a thick deuterated layer, it would look like the preshot simulated data and previous experimental observations.
burn of the fuel as the tritium is present only in the initial gaseous fuel. The first experimental set with the thin deuterated layers taken in 2017 and revealed a complex mix landscape that was previously unseen in the thicker deuterated layers. All the capsules, regardless of recession depth, gave a similar TT yield, showing that the placement of the deuterated layers doesn’t have an affect on the performance of the fuel fusion itself. The integrated mix values are shown in Figure 4.2.

4.2.1 Diffusion dominated mix and transition to hydrodynamic mix

When the deuterated layer is right up against the fuel (at recession depth of 0), a high mix value is seen. As soon as the deuterated layer is recessed 0.3 µm, the amount of deuterium mixed to the hot spot falls to a null result, meaning no significant amount of deuterium is mixed in. This fast fall off can best be explained through a diffusion dominated mix mechanism where any hydrodynamic mix mechanisms are negligible or not yet developed. These results were published in [106]. From Kagan and Tang [107], the diffusion in a binary mixture can be expressed as:

\[
D = 747 \frac{T_i^{5/2}}{F_{lh}\rho ln(\Lambda)} \sqrt{\frac{1}{A_l} + \frac{1}{A_h} \frac{\bar{A}}{Z_l^2 Z_h^2} \frac{\text{cm}^2}{s}} 
\]

where \( A_l \) and \( A_h \) are ion masses in atomic mass units, \( Z_l \) and \( Z_h \) are the ion charges of the light, \( l \), and heavy, \( h \) species. \( \bar{A} \) is the number-weighted mean ion mass, \( T_i \) in keV is the ion temperature and \( \rho \) in \( \frac{g}{\text{cm}^3} \) is the mass density. \( F_{lh} \) is a dynamic friction coefficient which generally has a value between 1/3 and 1. For the specific case of deuterium in the shell the plasma conditions can be estimated as \( F_{lh} = 1 \), \( \ln \Lambda = 6 \), \( T_i = 1.5 \text{ keV} \) and \( \rho = 1 \ \frac{g}{\text{cm}^3} \), with the background material as carbon (\( A_h = 12 \), \( A_l = 2 \), \( Z_h = 6 \), \( Z_l = 1 \), \( \bar{A} = 7 \)), we find \( D_{CD} \approx 5.1 \ \frac{\mu m^2}{\text{ns}} \). Once in the fuel, the plasma conditions are \( T_i = 4.0 \text{ keV} \) and \( 0.5 \ \frac{g}{\text{cm}^3} \), with the tritium background now \( A_h = 2 \), \( Z_h = 2 \) and \( \bar{A} = 2 \). The fuel diffusivity is \( D_{HT} \approx 1590 \ \frac{\mu m^2}{\text{ns}} \). With a diffusion distance of \( \sqrt{D_\tau} \), within 100 ps around maximum compression, deuterium
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Figure 4.3: Output of 1D hydrodynamic simulation showing the ion fractions as a function of radius output for the 0 $\mu$m and 0.3 $\mu$m recession depth cases for both the turbulent and diffusion model and the diffusion model only. When the turbulent model is turned on, both the 0 $\mu$m and 0.3 $\mu$m recession depth are pulled into the hot spot and see similar DT burn values. For the diffusion only case, when the deuterium is right up against the full, it diffuses into the hot spot from the temperature and density gradient and sees a high yield. However, when recessed, the CH plastic in between the hot spot and the deuterium blocks the deuterium from diffusing into the hot spot and so very minor amount of DT yield is seen. Figure adapted from [106].
could possibly diffuse 0.7 $\mu m$ in the CD shell and 13 $\mu m$ in the HT fuel. This rough calculation doesn’t fully take into account the density and temperature gradients that actually occur but instead show that that diffusion scale length has the ability to pull nearby deuterium into the fuel which can then be pulled into the central hot spot. 1D hydrodynamic simulations with an turbulent mix model that has an adjustable scale length \[108\] as well as the Zimmerman-Paquette-Kagan-Zhdanov (ZPKZ) diffusion model \[109\], \[110\] were run to capture the sharp drop off. The ZPKZ model incorporates thermodiffusion of multiple species, frictional ion heating, advective transport of ion enthalpy, density diffusion, barodiffusion, electrodiffusion and has no free parameters. The output of the simulation is shown in comparison to the data in Figure 4.2, with the dashed lines were preshot expectations based on thicker deuterated layer data with a wider mix depth and the solid black line is with no turbulent model and only the ZPKZ diffusion model. Figure 4.3 shows the ion fractions as a function of radius output for the 0 $\mu m$ and 0.3 $\mu m$ recession depth cases for both the turbulent and diffusion model and the diffusion model only. When the turbulent model is turned on, both the 0 $\mu m$ and 0.3 $\mu m$ recession depth are pulled into the hot spot and see similar DT burn values. For the diffusion case, when the deuterium is right up against the full, it diffuses into the hot spot and sees a high yield. However, when recessed, the CH plastic in between the hot spot and the deuterium blocks the deuterium from diffusing into the hot spot and so very minor amount of DT yield is seen. This mix mechanism best explains the fast fall off of the mix over such short spatial scales. Note that the same diffusion model is still turned on in the turbulent mix case, but the blurring from the hydrodynamic mix removes any substantial gradients and therefore makes the diffusion a minor effect compared to the hydrodynamic processes. Therefore, for these moderate convergence (12x), 6 keV, OMEGA capsules seem their dominant mix mechanism is diffusion.

Denser and cooler systems that are more compression driven (as opposed to shock) would be expected to have less gradients to drive diffusion. Compression
Figure 4.4: Mix data for 15 \( \mu m \) thick capsules focusing on the up close recession depths for both 2017 and 2019. 2017 had data at recession depths at 0, 0.3 and 0.6 \( \mu m \) while 2019 had recession depths located at 0 and 0.15 \( \mu m \) and unfortunately did not have any data at 0.3 and 0.6 \( \mu m \). 2017 had a gas fill of 9 atm while 2019 had a gas fill of 11.5 atm and had 1 kJ of energy less delivered to the capsule. The higher gas fill and less energy delivered likely made the 2019 implosions more compressively driven compared to shock driven, thereby giving more time for hydrodynamic instabilities to grow and create less gradients to drive diffusion, making the mix signal 1/2 compared to 2017 at the 0 \( \mu m \) recession depth and the observed slope of the mix decrease, approximated by exponential fits, to be less sharp.
driven capsules have a deceleration phase where the dense shell stagnates on the hot spot and is highly RT unstable. Data taken in 2019 continued the investigation into the sharp, diffusion mix. Compared to 2017, the capsules shot in 2019 had a higher pressure fill (12.5 atm of HT compared to 9) and had 1 kJ of energy less delivered. The 2019 data was taken at 0 $\mu m$ and in between the fall at 0.15$\mu m$ in order to get more information on the diffusion length scale. No data was taken at the 0.3 and 0.6 $\mu m$ recession depth. Both the 2017 and the 2019 data up close is shown in Figure 4.4. The amount of mix observed at the 0 $\mu m$ recession depth had decreased by a factor of 2 and the mix drop from 0 to 0.15 $\mu m$ is steeper than would be predicted from hydrodynamic mix, but not as sharp as observed in 2017. This is currently explained by the higher gas fill and less energy delivered, making the capsules more compressive with longer hydrodynamic development, marking the start of some hydrodynamic mix. The cooler implosions likewise decreased the gradients that drive the diffusion. Capsules were also shot that had 27 $\mu m$ thick ablator instead of 15$\mu m$. The 27 $\mu m$ capsules were designed to be much cooler, more dense and more compression dominated compared to the 15 $\mu m$ capsules. All the 15 $\mu m$ capsules and some of the 27 $\mu m$ were all shot with a simple square 1 ns laser pulse. The other few 27 $\mu m$ shell capsules were shot with a triple picket which sends three timed shocks before sending the main pulse and so have a higher convergence (around 20) than the square pulse implosions but the hot spot is cooler [112]. These four conditions, 15 $\mu m$ at 9 atm gas fill pressure, 15 $\mu m$ at 11.5 atm gas fill pressure, 27 $\mu m$, 11.5 atm square pulse and 27 $\mu m$ triple picket pulse present a scan across the hydrodynamic growth of the implosions. Fitting an exponential fit against the data taken in 2019 is shown in Figure ?? shows the slope relaxing as the capsules move to a more compressive implosion. This trend is in the process of being simulated.

In conclusion, using the platform of thin separated reactant layers revealed a diffusion dominated mix process for the fuel-shell interface. As one transitions to more compressive, either through higher gas fill or higher convergence pulse shaping
Figure 4.5: Mix data for both 15 $\mu$m and 27 $\mu$m thick capsules focusing on the up close recession depths for both 2017 and 2019. Compared to 15 $\mu$m, 27 $\mu$m shells are more compressively driven and using a triple picket pulse further increases the convergence. As implosions get more compressively driven, the mix mechanism transitions from a sharp, diffusion driven mix to a hydrodynamically driven mix that has a slower mix slope as it moves further away from the gas-shell interface.
sees a transition from sharp, diffusion driven mix to a hydrodynamically driven mix that has a slower mix slope as it moves further away from the gas-shell interface.

### 4.2.2 Anomalous inversion mix

Revisiting to original data collected in 2017, shown in Figure 4.2, shows a surprising result that at 0.9 \( \mu m \) recession depth sees an order of magnitude increase in the mix signal, suggesting that some material is being pulled into the hot spot that is preferentially being pulled from further away with a layer in-between that is not pulled or mixed in. This ‘inversion mix’ presents a puzzle on what mix mechanisms would preferentially create this affect. Two initial hypothesizes were 1) that the stalk which holds the OMEGA capsules in the center of the chamber can create a jet that shoots material from the outer portion of the shell into the hot spot and likewise 2) an asymmetry in ablation pressure, creating what’s called a P1 asymmetry, could also create a jet of material that again could pull material on the edge of the capsule into the hot spot. These hypothesizes were tested in 2019 when capsules at the 0.9 \( \mu m \) recession depth were re-created and shot both with additional stalks (1, 2 and 4 - called porcupine targets), shown in Figure 4.6 as well as physically offsetting the capsule from the target chamber center at 0, 50 \( \mu m \) and 100 \( \mu m \) offset in order
to create a laser asymmetry and amplify the P1. These test were done with the expectation that if they were the cause of the observed inversion mix, putting multiple stalks or amplifying the P1 asymmetry would see a corresponding increase in the mix yield at the 0.9 $\mu m$ recession depth. Furthermore, further recession depths at 1.4 $\mu m$ and 2$\mu m$ were also taken to see the trend even further. The results are shown in Figure 4.7, with multiple stalks or offset have no affect on the mix amount at the 0.9 $\mu m$ recession depth. Going further out sees a steady decline in mix amount. The multiple stalk and offset capsules also had a 10.5 atm fill. The 2019 capsules that have the 10.5 atm fill have slightly less mix (DT/TT ratio of 1) than the 2017 capsules (DT/TT ratio of 1.2 and 1.5), but still very close. The addition of stalks have a slight increase in the mix metric, spanning ratios of 1.1 and 1.3, however, offsetting the capsules had no noticeable effect, with the mix ratio still being 1. The minor change in mix ratio eliminates the hypothesis that the stalk or a possible P1 are the main driver of the observed inversion mix. Pre-shot xRAGE simulations of the stalk were done, however, the amount of shell mix was always too small to see the observed yield increase and the mix rate was always smooth and gradual as a function of depth, with no inversion seen. The observations were consistent with these experimental measurements and further simulations are ongoing to understand the mix sensitivity change observed. The steady drop off going further out suggests that the inversion mix peaks close, around 1 $\mu m$, implying a very specific and narrow boundary that is not mixed within the 0.3 to 0.8 $\mu m$ depths. As mentioned in the description of in Figure 4.2, the observed amount of mix in the thin deuterated layers, even with the complex mix landscape, is still consistent with the thick deuterated layer experiments done before. If the landscape was integrated and averaged over, it would arrive at the data and simulations done before.

With the initial hypothesizes experimentally excluded, the mystery still remains on what mechanism could cause such preferential mixing. One considered, passing explanation was that high energy tritons, located on the thermal tail of the
Figure 4.7: Mix data for 15 $\mu m$ capsules focusing on the further out (>0.8 $\mu m$) recession depths for both 2017 and 2019. The 2019 capsules, including all the stalk, offset and recession variations all had the higher gas fill. Likely because of this gas fill, the repeated nominal shots at 0.9 $\mu m$ recession depth have slightly lower mix metric than the 2017 capsules. The addition of additional stalks have a slight effect on the amount of mix while the capsule offset has no noticeable change. The low sensitivity of these effects to the mix eliminate them as the main driver of the observed inversion mix. The steady drop off going further out suggests that the inversion mix peaks close, around 1 $\mu m$, implying a very specific and narrow boundary that is not mixed within the 0.3 to 0.8 $\mu m$ depths.
Boltzmann-Maxwell distribution, could escape the hot spot and create enough fusions in part of the deuterated shell to create a Bragg peak from the stopping power of the plasma and give the observed inversion shape. Nevertheless, the measured DT ion temperature is constant as a function of recession depth and the product rates are too low to see the observed yields. Another hypothesis was a dominate, single mode RT finger or bubble could preferentially pull material from a preferential layer and create the inversion shape. High resolution simulations of RT growth in a convergent geometry have been done with varying modes, initial perturbation size and many other input variables, but the mix as a function of recession depth has always been observed to be smooth, with no kink or inversion mix ever seen. As of the writing of this dissertation, no clear explanation is known for this observed inversion mix, but investigation continues.

The possibility always remains that the original data taken in 2017 were somehow errors or capsule problems. The possibility of this was always believed to be low, as tracing back the shipping and fabrication process revealed no problems. Furthermore, 0.3 and 0.6 $\mu$m recession depths were fabricated in separated batches and filled and shipped in different containers. So for two sets of capsules (four implosions) to be fabricated incorrectly or having another problem that would give the data observed would be unlikely. The 2019 data, although suggestive, did not definitively re-observe the mix dip observed in 2017. If we take the 2019 data without the context of the 2017 data, it would still have an anomalous quick slope at the fuel-shell interface but then may otherwise be a smooth decrease. To resolve any doubts, the 2017 data is planned to be repeated in an upcoming OMEGA shot day.

4.3 Gamma inferred time resolved mix

The results so far have been from the integrated total yield. The HT gas fill was chosen specifically for the strong gamma ray signal distinct from the DT gamma ray
line. As mentioned in Chapter 2, the HT fusion gamma line is peaked at 19.8 MeV with the DT gamma line at 16.7 MeV with a broad 2nd energy level focused at 12 MeV. Gas Cherenkov detectors can then be used to differentiate these two gamma lines and, because of the fast time response, could have a measurement of the HT fuel burn and the DT mix burn. Measuring whether the material in the shell, located at specific distances from the fuel, was mixed in before the fuel burn, during or later would be a powerful diagnostic technique that would constrain and inform the mix mechanisms. Charged particle separated reactants experiments were done using 20 $\mu$m thick OMEGA capsules with 1 $\mu$m thick separated reactant layer which showed the mix occurred late relative to the fuel burn [113]. However, the charged particle technique requires a low enough shell $\rho R$ for the charged particles to escape, thereby making it unsuable on NIF and other denser systems. Charged particles also requires multiple shots, one to measure the pre-mixed fuel burn reaction history signal and one to measure the deuterated shell mix signal with shot reproducibility connecting the two shots. A gamma technique would be available regardless of the shell areal density and can occur on the same capsule implosion simultaneously.

The technique of using the Cherenkov response to isolate the HT and DT gamma rays for time resolved gamma rays was published by Zylstra et al. [115]. As briefly mentioned, the HT/DT sensitivity ratio becomes more skewed towards the 19.8 MeV HT gamma ray as one goes to higher thresholds (lower pressures). At 20 psia CO2, the HT/DT sensitivity ratio is a factor of 6 while a 100 psia of CO2 the HT/DT sensitivity of 2. Going to even denser (up to 400 psia) and fluorinated gases can continue to push the ratio even lower. When an implosion occurs, two gamma detectors with different thresholds measure signals that are combinations of the HT and DT gamma rays. In a real experiment, it is likely one detector would also completely see all HT and another seeing a mix of HT and DT. Using a forward fit routine with a minimization routine [115] can isolate the HT and the DT gamma reaction histories, in a very similar technique to the carbon timing isolation.
Attempts to measure this time resolved mix signal occurs in both the 2017 and 2019 shot days. Unfortunately, neither were successful as both shot days had different forms of systematic jitter on the ± 50 ps time scale that scrambled the baseline timing measurement and hid the observable signal, giving contradictory and inconsistent results. In 2017 there was an inconsistent and anomalous time shift that caused repeat shots or shots that should have the same gamma shift to have significant variation. One noticeable problem was the electrical attenuators used for changing signal strength each had their own, specific time shifts that needed to be recorded in order to be accounted for. In 2019, special focus was used to keep the attenuator and wiring set up constant, however, fast transient digitizer (FTD) were used for the first time that we believe somehow caused a jitter that caused difficulty for isolating our timing signal. Furthermore, the yield ratios of DT and HT in 2019 were not conducive to good timing signal, as the DT yield was relatively too low compared to the HT yield. Both GCDs signals were comprised of over 85% HT gamma rays, too low to isolate. The timing data for 2019 in shown in Figure blah. For future shots, special detail will be taken to minimize and isolate jitter, specifically using high speed digital phosphor oscilloscope, protected from high voltages by a Mach-Zehender system.
Chapter 5

Rough Gamma Spectroscopy using Cherenkov detectors

The focus of the dissertation so far has been on ICF systems and using gamma ray diagnosed information to inform on degradation mechanisms. The Cherenkov technique, however, can be applied to varied HED systems. Specifically, the high pass, thresholding capability of the Cherenkov technique gives some information on the gamma ray energy spectrum. Using multiple Cherenkov channels, one can either do a forward fit or a rough deconvolution to approximate the gamma ray energy spectrum. This will be expanded on two systems, the NIF Advanced Radiography Capability (ARC) laser and a pulsed power x-ray source, Mercury. The determination of the energy spectrum of these systems gives insight to their physical mechanisms as well as being useful feed in information for radiography systems or photofission inputs.
5.1 MeV gamma ray measurements on the NIF ARC system

At the NIF, x-ray radiography has been a long use powerful diagnostic tool. Historically, the x-ray source was created with joules to kJ of laser energy making 1 to 10 keV photon beams. However, for strong shocks or very dense, high Z pusher ICF concepts like the double shell campaign, higher photon energies are needed. The ARC laser was designed to deliver a kJ in a picosecond scale pulse to create these high energy pulses. NIF has converted one quadruplet (a group of 4 beamlines, or a quad) among the 48 available into ARC beams, more technical details given in [116]. Work on the ARC system goes back to 2010 [117] and earlier but the last few years have seen successful fielding and operation of the ARC laser.

When short, ultra intense ($I > 1e17 \frac{W}{cm^2}$) are incident on solids, the laser light is absorbed efficiently near the critical surface, so a large amount of the laser light can potentially be absorbed by the material. The laser light transfers energy to the plasma through oscillating electrons in the electric field of the laser. The pressure associated with these types of lasers can be larger than the plasma pressure. The high pressure can accelerated ions inward on a surface, creating a snowplow that can push densities above the original solid density. The accelerated electrons can spread their energy through inverse bremsstrahlung through collisions with ions or resonance absorption. Other types of energy transfer, such as other off-resonance absorption and $J \times B$ heating also act to transfer the energy coupled by the laser to other sources. Besides highly accelerated electrons and many positrons [119], the ARC short pulse laser can couple lots of its energy to photons. ARC x-ray measurements in the 70 to 200 keV range have an approximate convergence efficiency, defined as the ratio between x-ray yield and the total laser energy, to be around 4 to 9e-4 [120]. For an MeV radiographic source, the current baseline design has the 10 ps short pulse ARC laser is shot onto a gold focusing cone onto a 2 mm thick gold foil. Four lasers are
Chapter 5. Rough Gamma Spectroscopy using Cherenkov detectors

Figure 5.1: Cartoon of ARC MeV source target. The gold cones are self-focusing the laser light onto the 2mm thick gold. Two laser beams go into each cone for a total of four beams with a total laser energy of 600 J. For maximum gamma ray yield, all the lasers are co-timed. For taking multiple radiographic images, the lasers can be delayed from each other arbitrarily.

used in total, with two lasers each into two cones, the total energy of the laser is 600 J. The lasers are nominally co-timed and pointed into the self-focusing cones. Figure 5.1 shows a small cartoon of the ARC MeV source target.

GRH has measured high energy (> 2.9 MeV) gamma rays from these ARC shots and has received strong signals. Figure 5.2 shows GRH measurements for a nominal ARC MeV radiography shot, N191223-001, Fa NDD ARC MeV Source S11. Because the GRH collected four gas cells, the relative change between the gas cells can be used to approximate the bremsstrahlung temperature. If one roughly approximates the bremsstrahlung photon spectrum as the exponential integral function $Ei(E/T)$ with a set electron temperature, we can fit the model to our four gas cell responses and measurements to find a best fit of the photon spectrum. The results of this fit are shown in Figure 5.3, with an electron temperature of 2.4 MeV found, similar to other fits found for high intensity ARC shots used in the pair production campaign (2.3 MeV) [119]. More complex functional forms can be used or even a rough deconvolution with a more physical model can be done to better constrain the spectrum. The estimation of the spectrum can be a vital input to radiography measurements from the ARC laser on high Z experiments. The thresholded mechanism of the Cherenkov detectors give absolute certainty to the existence of high energy gamma rays and give detector sensitivity for the high energy photon components.
Figure 5.2: GRH data showing a strong signal of photons > 2.9 MeV threshold and a decreasing signal as the GRH threshold increased. The >10 MeV threshold was multiplied by 10 to have all peaks appear on the same scale, nevertheless, a good signal to noise of gamma rays > 10 MeV was observed.

5.2 Constraining Mercury x-ray spectrum with aerogels

The Mercury pulsed power generator, located at the Naval Research Laboratory (NRL), is a six-stage magnetically insulated inductive voltage adder that can nominally run at 6 MV, 360 kA, and 2.2 TW [6]. Mercury was run in a mode that releases a bremsstrahlung-like photon spectrum with a 4.8 MeV end-point energy from a large-area 33 cm diameter diode. The high voltage pulse accelerates electrons from the cathode, creating a high temperature electron plasma that gets magnetically focused, accelerating electrons into a tantalum converter, creating a x-ray pulse. Mercury and other high-energy x-ray radiation sources, such as Cygnus, a similar
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Figure 5.3: Using the absolute signals of the GRH measurements, a simple spectrum fit to the exponential integral function finds an electron temperature of 2.4 MeV. Plotted on the left is the resulting spectrum in absolute terms with the assumption that the photons are emitted in $4\pi$, which is known to be an incorrect assumption for short pulse driven x-ray source.

Pulsed power machine, can be used as inputs to other systems such as radiography or used to create a photo-neutron source [7], [121]. For both these applications, quantifying the shot-to-shot reproducibility of the photon spectrum as well as photon flux, and time evolution of the photon pulse is vital to understanding the radiography image or the resulting neutron pulse. Specifically, radiography and photo-neutron source are interested in x-rays above a specific energy threshold. Aerogels have an index of refraction of around 1.02–1.07 spanning 1.1–2.3 MeV threshold energies, making them appropriate for these systems. Aerogels have been used previously as a Cherenkov medium in particle physics, often as single particle counters [23]. The Aerogel Cherenkov Detector for Cygnus (ACD/C) was able to characterize the Mercury machine’s x-ray pulses using multiple aerogels. This work was reported in
The fast Cherenkov process is limited in time resolution is often limited to the time response of the photomultiplier tube (PMT). The ACD/C has an aluminum converter that Compton scatters incoming photons into relativistic electrons, which causes the Cherenkov medium to emit light as they pass through. The Cherenkov light is then coupled through off-axis parabolic mirrors to a Hamamatsu R5946 PMT located off the axis of the incoming beam. The x-ray beam continues through a mirror and out an exit hole covered with a thin (1 mm) aluminum light cover to the second module. For Mercury, aerogels of five different densities were fabricated at Los Alamos National Lab and their densities were measured within 1% [122]. The index of refraction was determined by a linear density scaling of \( n = 1 + 0.279 \times \rho \left[ \frac{g}{cm^3} \right] \) [34]. The Cherenkov kinetic electron energy threshold was found using equation 2.24. Finally, the quoted photon energy threshold is determined by applying a correction to electron energy threshold using the Klein–Nishina formula and assuming an incident, average energy photon. Applying a correction from electron energy threshold to photon energy threshold introduces some uncertainty. We assume incident photons when line traces suggest a ±9 degree spread, and depending on the energy of the incident gamma, the gamma to electron energy loss can vary between 80% and 85%. Propagating the variation in this energy loss to the threshold energy results in variation of ± 0.15 MeV which we quote as our uncertainty. The summary is shown in Table 5.1. Previously, aerogels were tested at an electron beam [123] to measure their Cherenkov response; however, the incident electron energy was not known and only a relational response was measured. Response curves were calculated using an Integrated Tiger Series (ITS) ACCEPT Monte Carlo code simulating the geometry of the ACD/C detector [126]. The response curves include the slight attenuation from the x-ray beam going through the mirror and the exit port for the second module. Response curves generated for gas Cherenkov detectors using the same code and physics packages for research on inertial confinement fusion have been benchmarked.
Table 5.1: The densities of the measured aerogels and the resulting gamma energy threshold.

<table>
<thead>
<tr>
<th>Aerogel density [ \text{mg/cm}^3 ]</th>
<th>Index of refraction</th>
<th>Electron kinetic energy threshold [MeV]</th>
<th>$\gamma$ threshold [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>260 ± 3</td>
<td>1.0726</td>
<td>1.4</td>
<td>1.1± 0.15</td>
</tr>
<tr>
<td>206 ± 3</td>
<td>1.0575</td>
<td>1.6</td>
<td>1.3± 0.15</td>
</tr>
<tr>
<td>164 ± 3</td>
<td>1.0458</td>
<td>1.7</td>
<td>1.5± 0.15</td>
</tr>
<tr>
<td>118 ± 3</td>
<td>1.0329</td>
<td>2.0</td>
<td>1.8± 0.15</td>
</tr>
<tr>
<td>72 ± 3</td>
<td>1.0201</td>
<td>2.6</td>
<td>2.3± 0.15</td>
</tr>
</tbody>
</table>

in the past [124].

ACD/C was designed for and used at the Cygnus x-ray source at the Nevada National Security Site. The comparatively lower dose and high background because of aluminum modules not sufficiently blocking internal scattering resulted in ACD/C achieving a marginal signal-to-noise ratio (S/N≈1) with only one aerogel density [125]. With the Mercury machine, which has a higher energy photon endpoint, higher dose, and updated tungsten modules that reduced internal scatter, we were able to achieve a high S/N across five different aerogel densities.

Normally, the 33 cm diameter diode of Mercury creates a toroidal 11 cm beam spot. This was attenuated down with 15.2 cm of lead and 15.2 cm of tungsten down to an 11.25 mm diameter collimated beam. This placed exit of the collimated beam at a distance of 91.4 cm from the source diode. Another diagnostic, the Compton spectrometer, was placed at the exit of this collimation. The ACD/C was placed at the exit port of the Compton spectrometer, about 178.6 cm away from the large emitting diode. With 30.5 cm of collimation on Mercury, ACD/C was 155.6 cm away from the exit collimation point. Because of the upstream Compton spectrometer, the x-ray beam was attenuated by a 12 mm plastic converter and two 6 mm beryllium flanges. The front of ACD/C has a 10 cm thick tungsten collimator with a 1 cm diameter aperture, which underfills the 2.5 cm diameter, 1 cm thick aerogel medium. The
ACD/C was surrounded on all sides with 10 cm of lead bricks to reduce background signal. See Fig. 5.4 for the layout. For each Mercury shot, channel 1 of ACD/C rotated through five different density aerogels, while channel 2 consistently held a fused silica Cherenkov medium to act as shot-to-shot dose measurement. This paper focuses on 14 specific Mercury shots where conditions remained constant. This shot series includes six shots (2 each) with aerogels at the 1.1, 1.3 and 1.8 MeV thresholds: four shots with the 1.5 MeV threshold aerogel, one at the 2.3 MeV threshold aerogel and one thicker (2.5 cm) aerogel at the 1.3 MeV threshold, and two background shots (no aerogel or fused silica).

Each time Mercury completes a pulse, ACD/C picks up a signal in the two channels, an aerogel and the fused silica. An example of pulse shapes from a shot is given in Fig. 5.5. For each given shot, the aerogel signal gives a shorter pulse than the fused silica. The photon signal often narrows as the energy threshold increases. About 90 ns after each Mercury main pulse, a voltage reflection in the generator causes another smaller peak that is observed with the fused silica 0.3 MeV threshold but not the 1.5 MeV aerogel threshold, suggesting that the photon spectrum of the second peak is much softer. The noise was measured by removing the Cherenkov medium and was used to subtract from each pulse; however, because of the high signal to noise level,
the background had negligible effect on the pulse widths. The Hamamatsu R5946 PMT has an impulse response of about 4 ns, which would consequently broaden the observed pulses by about 0.5 ns. Because this broadening is smaller than the observed shot-to-shot variation, we consider this small enough to neglect. A summary of the observed FWHMs across different aerogels is given in Table 5.2 with the uncertainty of the FWHM capturing all observed FWHMs for that energy threshold. The voltage on the Mercury diode must be high enough for higher-energy photons to be generated. As the machine pulses through the input voltage ramp, photons of higher energy start later and end sooner, correspondingly. It has previously been observed that an x-ray beam directionality changes with time [127]. The accelerated electron beam impinges on the side of the machine instead of the converter early in
Table 5.2: The average FWHM across different aerogel thresholds. The pulse becomes narrower as the photon threshold increases. The uncertainty on the FWHM captures the range of all shots at that threshold.

<table>
<thead>
<tr>
<th>Photon threshold [MeV]</th>
<th>Average FWHM [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3 ± 0.05</td>
<td>25.2 ± 1.3</td>
</tr>
<tr>
<td>1.1 ± 0.15</td>
<td>24.6 ± 0.5</td>
</tr>
<tr>
<td>1.3 ± 0.15</td>
<td>22.4 ± 0.5</td>
</tr>
<tr>
<td>1.5 ± 0.15</td>
<td>22.6 ± 0.9</td>
</tr>
<tr>
<td>1.8 ± 0.15</td>
<td>20.7 ± 1.8</td>
</tr>
<tr>
<td>2.3 ± 0.15</td>
<td>20.6 ± 2.0</td>
</tr>
</tbody>
</table>

The voltage ramp. As the current and voltage become high enough, the electron beam becomes more forward directed and the electrons are accelerated to higher energy. As the voltage ramp drops, the beam becomes less forward directed again. Both of these effects (beam angle and accelerating voltage) can contribute to the observed narrower pulses for higher-energy photons.

A primary reason the ACD/C was brought to Mercury was to measure the shot-to-shot variation of each pulse. Mercury quotes 10% shot-to-shot variation as measured using thermoluminescent dosimeters (TLDs). In the collimated setup, a handful of TLDs were placed on the Mercury diode. The ACD/C successfully captured shot-to-shot variation as the fused silica signal follows the reported Mercury dose output from the average of TLDs at 12 cm radius on the diode, the radial distance of the collimated x-ray beam that ACD/C observed. The error bars of the TLDs are the standard deviation across all the TLDs at 12 cm radial distance. The correlation across six shots with identical upstream Compton spectrometer conditions is shown in Fig. 5.6. The collimated x-ray beam ACD/C observed was at a particular location on the diode. Due to the angular and radial dependence of Mercury, the average dose across the diode at that radial distance may not exactly match ACD/C observations of the collimated down-stream beam. The TLDs were prepared to read krad level dose, so the few TLDs that were placed in-line with the collimation at the exit of
Figure 5.6: TLD and fused silica signal correlation across six shots with identical upstream conditions.

the ACD/C received too low of a signal to be useful.

A Mercury shot creates high radiation and radio frequency in the room; nevertheless, the ACD/C was successfully able to achieve a high S/N across all five aerogel densities. Background shots were taken by removing the Cherenkov mediums. The ACD/C had about 200x signal level from the fused silica compared to the no Cherenkov medium, 27x for 1.1 MeV threshold, and about 3x for the lowest signal 2.3 MeV threshold. Figure 5.7 shows the summary. The drop in the signal level as the threshold increases reflects the slope of the photon spectrum. Using the inputs of the current and voltage of the diode, a particle-in-cell simulation was used to generate the electron population at Mercury’s tantalum converter [128]. The electron population was then fed into a 2D ITS Monte Carlo code to output a predicted photon flux and spectrum at the position of the ACD/C aluminum converter. The output of the simulation is shown in Fig. 5.8 along with our ITS ACCEPT calculated detector responses. Folding the calculated response curves with the simulated spectrum gives a predicted signal that can be compared with our observed signal. The absolute signal difference between the simulation and our observed data varies from
Figure 5.7: Signal level observed across different aerogel thresholds compared against a background signal (no Cherenkov medium).

a factor of 2 for the fused silica to a factor of 5 for the 2.3 MeV energy threshold. To compare relative spectra, we scale the output of the simulation by a factor of 2 to match the observed fused silica. Figure 5.9 shows the summary with the uncertainty in the relative signal shown. The difference seen between the simulated and the measured spectral shape is within the uncertainty of both the measured value and the simulations.

The observed integrated signal and the simulated signal using the predicted Mercury spectrum disagree by an absolute factor of 2 for the fused silica up to a factor of 5 for the highest energy threshold. This absolute signal difference could be in part from scaling factors like the PMT gain and quantum efficiency correction or the absolute flux prediction from the simulation. The simulated signal seems to have a steeper slope than the observed signal—this is within the uncertainties, but it may suggest a harder Mercury spectrum than simulated. Later in the experimental run, an attenuation study using varying thicknesses of lead focused on the higher-energy
Figure 5.8: Particle-in-cell simulated Mercury photon spectrum with ACCEPT response curves.

portion of the Mercury spectrum. With the lead-attenuated spectrum, there again is an observed discrepancy between the calculated signal and the experimental signal, another suggestion of a harder Mercury spectrum. However, the sources of uncertainty in the experiment and calculation must be understood and reduced before any definitive statement can be made.

Aerogel fabrication can leave voids and non-uniformities throughout the aerogel. Voids can cause transition radiation, and density variations would likewise spread the energy threshold and make it less of a sharp threshold. Both effects would
Figure 5.9: Measured ACD/C signal along with the simulated signal scaled by 2x to match fused silica signal. The uncertainty on the measured signal captures the shot to shot variation while the uncertainty on the simulated signal estimates the variation due to the uncertainty in the input parameters.

cause the aerogel response curves to pick up more signal and make our simulated result closer to the measured signal. Voids and density variations should likewise be worse for lower-density (higher-energy threshold) aerogels, where we observe a larger discrepancy. Visual inspection of the aerogels can reveal occasional cloudy areas and cracks. The five aerogels used for this experimental run were chosen to be visually the clearest and most uniform. To better match previous relative response curves obtained at an electron beam,7 we introduced density variation within the aerogels. Applying a Gaussian density profile with a 1% variation instead of a uniform specific density better fits the electron beam data. However, response curves which were recalculated with this variation were not significantly different in this case. Another concern is that aerogels can absorb water, possibly changing their density and their response curves. Aerogels with a supercritical methanol fabrication process have been observed to absorb <2% by weight of water over 30 days [125].
Nevertheless, during our experimental run, we placed the aerogels in a bell jar with dry CO2 air when they were not in the ACD/C, thus limiting their exposure to humid air to several hours. Because of this process, we believe that water absorption was minimal. Furthermore, the aerogel response curves, although generated with the code used for gas Cherenkov response curves that have been bench-marked at a known gamma source at High Intensity Gamma Source (HIGS), have not themselves been calibrated. It is difficult to estimate the amount of error that these different sources of uncertainty can cause. By taking our calculated responses curves and estimating various optical transition floors as well as shifting the energy thresholds lower by ±0.15 MeV, the resulting spectrum can vary around 70%, which is used as the estimation of our uncertainty. We plan to take the ACD/C to the HIGS to measure response curves instead of relying on simulations. Better characterization and fabrication of aerogels is also being investigated to minimize voids and cracks.

The simulation to generate the photon flux also has some sources of uncertainty. The current input into the diode is measured at four different locations that have often given different values with a 5% standard deviation. This variation is due to azimuthal asymmetries on the machine; however, for the simulation, the average of the four values is used. Neglecting these asymmetries can affect the peak current and the resulting beam directionality. The collimated photon flux at the ACD/C converter was found through ray tracing, which neglects scattering and other spectrum-changing effects. The 2D ITS code used to generate the photon spectrum may be missing additional effects that a 3D MCNP simulation may capture. Finally, there was a small geometric difference between the particle in cell (PIC) simulation and the hardware actually fielded in the experiment. The cumulative effects of all these factors may contribute in part to the discrepancy between the simulation and observation. The Compton spectrometer that was upstream from the ACD/C holds potential to collect another independent spectral measurement. So far, the qualitative comparison that has been performed agrees. A more detailed investigation and
The ACD/C was brought to Mercury and achieved high signal to noise, temporally resolved thresholded photon curves. By rotating out five different aerogels, the ACD/C was able to obtain spectral information. The S/N for aerogels was as high as 27 for 1.1 MeV threshold and about 3 for the lowest signal, the 2.3 MeV threshold. Using the fused silica Cherenkov medium, the ACD/C also followed the shot-to-shot dose variation of the Mercury machine. The high-energy photon curves were observed to be narrower than the lower threshold curves. The calculated Mercury spectrum and the simulated aerogel response curves also agree within error to the measured response. Reducing uncertainty can be achieved by better characterization of the aerogels through better quantification of effects like cracks, voids, and density variations. Likewise, direct measurement of aerogel response curves at HIGS can further help reduce uncertainty. In the future, the ACD/C is planned to become a standard diagnostic for the Cygnus pulsed power machine, measuring shot to shot variation for radiography. Aerogel Cherenkov detectors are planned to be deployed to laser fusion facilities like the OMEGA laser in order to measure cross sections relevant to big bang nucleosynthesis.
Chapter 6

Conclusion and Future Work

6.1 Summary of work completed

The work in this dissertation humbly contributes, in its small part, to the understanding of HED systems. In the goal of gaining high yield through the ignition process, one must diagnose ICF systems to understand their degradation mechanisms. Gamma rays, emitted both by fusion processes and non-fusion processes are one doorway into the physics of the capsule convergence. A new technique to isolate the fusion neutron induced 4.4 MeV carbon gamma line was presented. The result of this isolation routine reveals the trends of the ablator areal density across the NIF ignition campaigns. They reveal that the carbon ablator is not significantly degraded in the same way the fuel portion of the pusher is, suggesting specific degradation mechanisms that preferentially degrade the fuel and not the ablator, such as ablator-DT ice mix. Mix studies carried out on surrogate OMEGA capsules, also utilizing Cherenkov gamma techniques, reveal a complex mix landscape that inform understanding of moderate convergence ICF systems. The gamma techniques being practiced on the OMEGA system can be applied to NIF systems in the future. Furthermore, the Cherenkov diagnostics are also used in parallel to support radiography
systems, such as the NIF ARC and the Mercury pulsed power machine to understand the approximate energy spectrum as feed-in to radiography of HED systems.

The result of this work has resulted in four first author publications [8], [9], [10], [11] with four more in the process of being written (Carbon gamma timing on NIF, MeV spectrum characterization on the ARC laser, Transition from diffusion to hydrodynamic mixing on OMEGA, Stalk and offset mix sensitivity on OMEGA). It has resulted in seven co-author publications [43], [60], [45], [96],[56] [106], [115] and a few more in the review process. This work was presented at an invited talk at APS DPP 2019, an oral presentation at 49th Anamalous Absorption Conference, and a handful of poster presentations. The aerogel Cherenkov detector work characterizing Mercury, as part of the Brazos team, was awarded the Los Alamos 2018 Distinguished Program Award and the 2017 Defense Program Award.

6.2 Future work

The techniques of using Cherenkov detectors to gain deeper physics insight into HED systems has the potential to give much more high resolution, specific information about many systems. Aerogel development has been moving along with the creation of clear (by eye) aerogels at low densities ($6 \text{ mg/cm}^3$) which would correspond to a 6.2 MeV gamma ray threshold. If aerogels can continue to be made with lower densities with good characteristics, the possibility exists of replacing complex gas pressure systems with simpler, solid aerogel system. Currently, the GRH, previously fielded on the OMEGA system is being adapted to be fielded on the Z machine, with the hope that the addition of tritum to their systems will allow fusion reaction histories to be observed in a new HED system. The GCD3 at the NIF with pulse-dilation PMT currently observes an anomalous long tail in the DT reaction history signals which is currently understood to be excitation and florescence of the gas system itself. Steps are being taken to improve the system with the hope to
sometime soon get the first, high resolution fusion reaction history measurements, allowing for the investigation into the fusion burn shape. The GRH systems on the NIF are currently being reviewed for the possibility to add a pulse-dilation PMT, which would remove the PMT as the source of instrument time resolution. A faster time resolution should allow better separation between the carbon gamma and the hohlraum/TMP, increasing the sensitivity for the carbon $\rho R$ as well as the carbon gamma timing. Further analysis is ongoing with the collected carbon $\rho R$ data, as in HYDRA 2D simulations, the carbon is able to differentiate between the simulation knobs of preheat and mix, allowing further refinement of the simulation tools and identification, and hopefully mitigation, of degradation of the ICF capsules. The Los Alamos program is ramping up the double shell campaign, which envisions a high Z tungsten or molybdenum inner shell that can reach areal densities of 3 or 5 $g/cm^2$. The same techniques applied to the carbon gamma line should also be able to be applied, with possibly better optimized Cherenkov thresholds, to these other pushers. The long term goal of fielding a gamma ray detector at a much closer location to the center of NIF, which could increase the detector sensitivity by up to 400x. The higher sensitivity would allow multiple orders of magnitude of fusion reaction history to be observed, possibly seeing both the shock yield and compression yield components of NIF capsules. The higher sensitivity would also allow for time resolution mix studies, similar to those done on OMEGA, to be done at NIF, giving a high spatial and temporal resolution of the mix and burn. At OMEGA, shot days are planned to repeat the 2017 data to confirm the existence of the mix dip and the inversion mix as well as get good time resolved mix data through reducing system timing jitter. Further down the line, shot plans are in the idea stage to start measuring gamma induced mix on high Z materials, such as tungsten, in preparation for double shell like campaigns on the NIF. Aerogel systems are being considered and designed for characterizing radiographic x-ray sources in Nevada.
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