USING NUCLEAR DATA AND MONTE-CARLO TECHNIQUES TO
STUDY AREAL DENSITY AND MIX IN D₂ INERTIAL CONFINEMENT
FUSION IMPLESIONS

by

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B.A. Physics, University of Montana, 2000

Submitted to the Department of Physics
in partial fulfillment of the requirements for the degree of

Master of Science in Physics

at the

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Abstract

Measurements from three classes of direct-drive implosions at the OMEGA laser system [T. R. Bochly et al., Opt. Commun. 133, 495 (1997)] were combined with Monte-Carlo simulations to investigate models for determining hot-fuel areal density (ρₚ₀ₜ) in compressed, D₂-filled capsules, and to assess the impact of mix and other factors on the determination of ρ₀ₜ. The results of the Monte-Carlo calculations were compared to predictions of commonly used models that use ratios of either secondary D³He proton yields or secondary DT neutron yields to primary DD neutron yields to provide estimates ρ₀ₜ,p or ρ₀ₜ,n, respectively, for ρ₀ₜ. For the first class of implosions, where ρ₀ₜ is low (≤ 3 mg/cm²), ρ₀ₜ,p and ρ₀ₜ,n often agree with each other and are often good estimates of the actual ρ₀ₜ. For the second class of implosions, where ρ₀ₜ is of order 10 mg/cm², ρ₀ₜ,p often underestimates the actual value due to secondary proton yield saturation. In addition, fuel-shell mix causes ρ₀ₜ,p to further underestimate, and ρ₀ₜ,n to overestimate, ρ₀ₜ. As a result, values of ρ₀ₜ,p and ρ₀ₜ,n can be interpreted as lower and upper limits, respectively. For the third class of implosions, involving cryogenic capsules, secondary protons and neutrons are produced mainly in the hot and cold fuel regions, respectively, and the effects of the mixing of hot and cold fuel must be taken into account when interpreting the values of ρ₀ₜ,p and ρ₀ₜ,n. From these data sets, we conclude that accurate inference of ρ₀ₜ requires comprehensive measurements in combination with detailed modeling.

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1. Introduction

For several decades, scientists have been working toward the goal of generating energy using inertial confinement fusion (ICF) [1-4]. Current and near-future experiments utilize lasers to implode capsules filled with gas and ice of mainly deuterium (D), tritium (T), and helium-3 ($^3$He). The inertia of the imploding capsules confines the fuel at high density and temperature, allowing fusion reactions to take place at a high rate.

Because the cross section of the deuterium-tritium (DT) fusion reaction is significantly larger than those of other fusion reactions (Fig. 1.1), DT fuel will probably be used in future practical applications. However, the handling of DT-filled capsules is complicated by the radioactivity of tritium. As a result, many experiments for benchmarking laser and capsule performance in direct- and indirect-drive ICF experiments are performed with D$_2$-filled capsules; deuterium is non-radioactive, and DD reaction rates are relatively large compared to those for other non-DT fuels. Since the reactions themselves have little impact on capsule compression in current experiments, the hydrodynamics of DT capsule implosions can be predicted from measured characteristics of "hydrodynamically similar" D$_2$ capsule implosions.
Figure 1.1: Calculated reactivity of the most relevant fusion reactions according to Ref. 5. At ion
temperatures of interest, the DT reactivity is several orders of magnitude larger than the DD and
D³He reactivities.

One of the most important characteristics of an imploded target capsule is the areal
density ρR, defined as the integral

$$\rho R = \int_0^R \rho(r) \, dr$$

of the radially dependent local density ρ from the center of the capsule to the outer radius. It
provides a measure of how well a capsule is compressed. Although ρR is actually a function of
time, the values we consider here are averaged over time with a weighting factor equivalent to
the fusion burn rate ("burn-averaged"). For D₂-filled capsule implosions, values of hot-fuel areal
density (ρRₜₜ) have often been inferred from the ratios of secondary proton and neutron yields to
primary neutron yields (Y₂p/Y₁n and Y₂n/Y₁n) using simple existing models, which assume a
uniform density and temperature plasma (see Section 2-II for more details). However, these
models have limitations that often result in disagreement between the proton- and neutron-
impelled values of ρRₜₜ.
To understand the limitations of these models, data from experiments and Monte-Carlo simulations were used. Several series of experiments, imploding three types of inertial confinement fusion capsules (Fig. 1.2), were conducted at the OMEGA laser facility [6] to obtain data for implosions with a wide range of $\rho R_{\text{hot}}$. Several charged particle spectrometers [7], positioned at different locations on the OMEGA target chamber (Fig. 1.3), along with neutron diagnostics, were used to obtain data from nuclear particles produced within the imploding capsule (see Section 2-III). A Monte-Carlo code was developed to simulate these experiments and to obtain more realistic pictures of the implosions (see Section 2-IV).

The following sections of this thesis will show that effects of fuel-shell mix, and density and temperature profiles, which are not considered in the existing models, have a significant impact on the production of secondary particles. These factors cause the difference in secondary proton and neutron production and require more complex analysis to infer $\rho R_{\text{hot}}$.

Figure 1.2: Capsules with thin glass shells (left), thick plastic shells (center), and cryogenic shells (right) were used for the study of low, medium, and high $\rho R_{\text{hot}}$ implosions, respectively. They are nominally 900 $\mu$m in diameter.
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The paper “Using nuclear data and Monte-Carlo techniques to study areal density and effects of mix in D₂ implosions,” which has been submitted to Physics of Plasmas, is shown in Section 2. The section has its own appendix (Appendix A) and references. Unsolved problems and future work are described in Section 3. A Monte-Carlo program and the results of the simulations are explained in detail in Appendices B and C, respectively. Experimental data is compiled in Appendix D.
2. Using nuclear data and Monte-Carlo techniques to study areal density and effects of mix in D₂ implosions (paper submitted to Physics of Plasmas)

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ABSTRACT

Measurements from three classes of direct-drive implosions at the OMEGA laser system [T. R. Bochly \textit{et al.}, Opt. Commun. 133, 495 (1997)] were combined with Monte-Carlo simulations to investigate models for determining hot-fuel areal density \( \rho_{\text{hot}} \) in compressed, D₂-filled capsules, and to assess the impact of mix and other factors on the determination of \( \rho_{\text{hot}} \). The results of the Monte-Carlo calculations were compared to predictions of simple commonly used models that use ratios of either secondary D\textsuperscript{3}He proton yields or secondary DT neutron yields to primary DD neutron yields to provide estimates \( \rho_{\text{hot,p}} \) or \( \rho_{\text{hot,n}} \), respectively, for \( \rho_{\text{hot}} \). For the first class of implosions, where \( \rho_{\text{hot}} \) is low (\( \leq 3 \) mg/cm\(^2\)), \( \rho_{\text{hot,p}} \) and \( \rho_{\text{hot,n}} \) often agree with each other and are often good estimates of the actual \( \rho_{\text{hot}} \). For the second class of implosions, where \( \rho_{\text{hot}} \) is of order 10 mg/cm\(^2\), \( \rho_{\text{hot,p}} \) often underestimates the actual value due to secondary proton yield saturation. In addition, fuel-shell mix causes \( \rho_{\text{hot,p}} \) to further underestimate, and \( \rho_{\text{hot,n}} \) to overestimate, \( \rho_{\text{hot}} \). As a result, values of \( \rho_{\text{hot,p}} \) and \( \rho_{\text{hot,n}} \) can be interpreted as lower and upper limits, respectively. For the third class of implosions, involving cryogenic capsules, secondary protons and neutrons are produced mainly in the hot and cold fuel regions, respectively, and the effects of the mixing of hot and cold fuel must be taken into account when interpreting the values of \( \rho_{\text{hot,p}} \) and \( \rho_{\text{hot,n}} \). From these data sets, we conclude that accurate inference of \( \rho_{\text{hot}} \) requires comprehensive measurements in combination with detailed modeling.

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I. Introduction

Maximizing the hot-fuel areal density ($\rho R_{\text{hot}}$) and understanding the effects of mix upon it are fundamental issues of inertial confinement fusion (ICF).\textsuperscript{1-3} One method used to estimate $\rho R_{\text{hot}}$ of D$_2$-filled capsule implosions is to measure the yields of secondary protons ($Y_{2p}$) and/or secondary neutrons ($Y_{2n}$) relative to the primary neutron yield ($Y_{1n}$).\textsuperscript{4-12} These secondary particles result from sequential reactions in which the energetic primary products of reactions,

\begin{align*}
\text{D} + \text{D} & \rightarrow \text{n}(2.45 \text{ MeV}) + ^3\text{He}(0.82 \text{ MeV}), \quad (1) \\
\text{D} + \text{D} & \rightarrow \text{p}(3.02 \text{ MeV}) + ^1\text{T}(1.01 \text{ MeV}), \quad (2)
\end{align*}

undergo fusion reactions with thermal deuterons in the fuel

\begin{align*}
^3\text{He}(\leq 0.82 \text{ MeV}) + \text{D} & \rightarrow \text{p}(12.5 - 17.4 \text{ MeV}) + ^4\text{He}(6.6 - 1.7 \text{ MeV}), \quad (3) \\
^1\text{T}(\leq 1.01 \text{ MeV}) + \text{D} & \rightarrow \text{n}(11.9 - 17.2 \text{ MeV}) + ^4\text{He}(6.7 - 1.4 \text{ MeV}). \quad (4)
\end{align*}

These processes produce secondary particles with spectra spread over significant energy intervals due to the kinetic energy of the primary reactants. The secondary particle yields are typically two to three orders of magnitude lower than the primary yield, and the ratios $Y_{2n}/Y_{1n}$ and $Y_{2p}/Y_{1n}$ (which are linearly dependent on $\rho R_{\text{hot}}$ in certain plasma regimes) can each be used to infer a value of $\rho R_{\text{hot}}$ for implosions of D$_2$-filled capsules in both direct- and indirect-drive experiments.\textsuperscript{12-15} In those studies, the simple "hot-spot" and/or the "uniform" models were used to relate these ratios to $\rho R_{\text{hot}}$. Although these simple models have been widely used to infer a value of $\rho R_{\text{hot}}$, they have some serious limitations which can result in misinterpretation and errors (as described in Section II); one manifestation of these problems is often disagreement between the proton- and neutron-inferred values of $\rho R_{\text{hot}}$ calculated from experimental data (see Fig. 1). These deviations are related to a combination of mix, temperature profile, and the difference between the cross section for secondary reactions (3) and (4). These factors can cause
secondary protons and neutrons to be produced in different regions of the compressed capsules (Fig. 2). In addition, other workers have noted some puzzling issues with recent secondary neutron measurements in indirect drive implosions on OMEGA. In that work, the authors observed a factor-of-three larger $Y_{2n}/Y_{1n}$ ratio and a narrower secondary neutron spectrum than predicted for these low-convergence implosions (where mix should be relatively unimportant). In contrast, for high-convergence implosions, they found better agreement between measured and predicted $Y_{2n}/Y_{1n}$ values.

![Graph](image)

**FIG. 1.** Secondary proton- and neutron-implied values of $\rho R_{\text{hot}}$ are compared for implosions of small $\rho R_{\text{hot}}$ (squares), medium $\rho R_{\text{hot}}$ (triangles), and cryogenic (circles) capsules at the OMEGA laser facility. For small $\rho R_{\text{hot}}$ implosions, the values of $\rho R_{\text{hot}}$ inferred from secondary protons and neutrons using the simple hot-spot model agree well. It is also shown that values of $\rho R_{\text{hot}}$ are larger for implosions with \~{}12-kJ laser energy (open squares) than for implosions with \~{}23-kJ laser energy (closed squares) (Fig. A.1). For these dramatically overdriven implosions, it is possible that the effects of mix are coming back into play, as indicated by the observation that $\rho R_{\text{hot,2n}}$ is larger than $\rho R_{\text{hot,2p}}$. However, for implosions with larger $\rho R_{\text{hot}}$, the values inferred from secondary neutrons are always larger than the values from secondary protons. The error bars shown are typical of each type of implosion; they include uncertainties in the measurements and in the assumed values of the density.
FIG. 2. Calculated radial distributions of primary and secondary birth positions per unit length for (a) low $\rho R$ implosion 30981, (b) medium $\rho R$ implosion 27443, and cryogenic implosion 28900. For low $\rho R$ implosions, where $\rho R_{2p}$ and $\rho R_{2n}$ agree reasonably well, birth positions of secondary protons and neutrons are virtually identical. However, for medium $\rho R$ and cryogenic implosions, where $\rho R_{2n}$ is always larger than $\rho R_{2p}$, secondary neutrons are produced in more outer regions compared to secondary protons. Note that calculated radial distributions of primary birth rates per unit volume (as opposed to unit radius) are shown in FIGs. A.3, A.4, and A.5 for these three implosions.

In previous work, high-resolution secondary-proton spectra were obtained during experiments at the OMEGA laser facility. The yields were used with measured neutron yields to estimate $\rho R_{\text{hot}}$ with the hot-spot and uniform models and it was shown that the $Y_{2p}/Y_{1n}$
inferred $\rho R_{\text{hot}}$ was often lower than the $Y_{2n}/Y_{1n}$-inferred $\rho R_{\text{hot}}$. This was attributed to the effects of fuel-shell mix, and it was suggested that the two inferences might be considered lower and upper limits, respectively. In this paper, that work is extended to cover a wider range of implosion types and to include Monte-Carlo simulations that allow a detailed study of the implications of more realistic models of the compressed core on the secondary production. Section II describes the hot-spot and uniform models and their limitations. Section III describes the experiments and the range of parameters that are measured. Section IV describes a Monte-Carlo program that has been developed to model the implosions to understand how particle production occurs. Results from both experiments and Monte-Carlo calculations are discussed in Section V, with an emphasis on how $\rho R_{\text{hot}}$ is related to the yields of primary and secondary particles. The results are summarized in Section VI.
II. Primary and secondary products

The hot-spot and uniform models have been commonly used to relate $Y_{2p}/Y_{1n}$ and $Y_{2n}/Y_{1n}$ to $\rho R_{\text{hot}}$. The hot-spot model assumes that an imploded capsule is a sphere of uniform density and temperature and that all primary reactions occur at the very center of the capsule. A fraction of the primary $^3$He (tritons) fuse with thermal deuterons, producing secondary protons (neutrons) as they move radially outward. As the primary particles travel through the D plasma, they lose energy and the probability for producing secondary particles along the path varies greatly since the secondary D$\text{D}^3$He and DT fusion cross sections ($\sigma_{\text{D}^3\text{He}}$ and $\sigma_{\text{DT}}$) are strong functions of the primary $^3$He and T energies (Fig. 3a). $^{18} \sigma_{\text{D}^3\text{He}}$ peaks at $\sim 0.65$ MeV, close to the $^3$He birth energy (0.8 MeV), while $\sigma_{\text{DT}}$ peaks at $\sim 0.18$ MeV, significantly lower than the triton birth energy (1.0 MeV). As a result, secondary protons are mainly produced near the $^3$He birth position, while secondary neutrons are mainly produced further away from the triton birth position (see Fig. 3b). This information is used to calculate $\rho R_{\text{hot}}$ from $Y_{2p}/Y_{1n}$ and $Y_{2n}/Y_{1n}$, and the resulting dependencies are shown in Fig. 4 for D plasmas with different temperatures and densities. The ratios each saturate at different values of $\rho R_{\text{hot}}$ for different temperatures and densities, because the primary $^3$He and tritons generally have significantly different ranges in the plasma. If either particle stops before leaving the fuel, it will not sample the entire $\rho R_{\text{hot}}$, and the implied value of $\rho R_{\text{hot}}$ underestimates the actual value. $Y_{2p}/Y_{1n}$ does not depend on temperature until it starts to saturate, while $Y_{2n}/Y_{1n}$ is sensitive to temperature well below the saturation level. Therefore, without a reasonable estimate of plasma temperature, $Y_{2n}/Y_{1n}$ cannot be used to accurately infer $\rho R_{\text{hot}}$. 
FIG. 3. (a) Dependence of the secondary $^3$He (DT) reaction cross section on the energy of the primary $^3$He (T) in a cold D plasma. The $^3$He reaction cross section is peaked close to the birth energy of $^3$He, while the DT reaction cross section peaks dramatically after T has lost most of its energy. (b) As a result, secondary protons are created close to the birth points of primary $^3$He (here defined as $\rho_R=0$) while secondary neutrons are produced away from the birth points of primary T ($\rho_R=0$). Although this plot is for a 1 g/cc, 3 keV D plasma, it looks similar for plasmas with different densities and temperatures.

FIG. 4. (a) $Y_{2p}/Y_{1n}$ and (b) $Y_{2n}/Y_{1n}$ as functions of $\rho_{R_{hot}}$ for a 1, 3, and 8 keV D plasma of 1 g/cc (solid line) and 10 g/cc (dashed line) using the hot-spot model. The energy losses of primary $^3$He and T were calculated according to Ref. 19, and the fusion cross sections were calculated according to Ref. 18. $Y_{2p}/Y_{1n}$ is temperature independent until it reaches the saturation levels. In contrast, $Y_{2n}/Y_{1n}$ is temperature dependent well below saturation levels.
The uniform model assumes that the primary particles are produced uniformly in a sphere of constant density and temperature. The $Y_{2p}/Y_{1n}$ and $Y_{2n}/Y_{1n}$ dependencies show similar behavior to the hot-spot model. The primary difference is that values of $\rho R_{\text{hot}}$ implied by the uniform model are always larger than values from the hot-spot model because the mean path length of primary particles in the D plasma is shorter by 25% in the uniform model, when saturation has not occurred. The simulations described in Section V indicate that the hot-spot model gives more meaningful values of $\rho R_{\text{hot}}$ than the uniform model. Thus, the hot-spot model will be used throughout the remainder of the paper.

Both models have limitations which can introduce errors into the analysis of $\rho R_{\text{hot}}$. These include the saturation of $Y_{2p}$ and $Y_{2n}$ and the uncertainty introduced by the temperature dependence of $Y_{2n}$. The shapes of temperature and density profiles, and the presence of fuel-shell mix$^{20-22}$ can have substantial impact on secondary particle production. In reality, the temperature is highest and the density is lowest at the center of the implosion. As the temperature decreases and the density increases, the rate of energy loss of primary particles becomes larger. This typically causes a reduction of the secondary proton production rate and an enhancement of the secondary neutron production rate (see Fig. 3a). Fuel-shell mix lowers the temperature in the mix region, which increases the energy loss rate and results in a further reduction of the secondary proton production rate and an enhancement of the secondary neutron production rate. Shell material mixed into the fuel can directly affect secondary production by increasing the energy lost by T and $^3$He after traveling through a given amount of D, due to the higher effective charge of the shell material mixed in.
III. Experiments

In the direct-drive experiments described here, distributed phase plates,\textsuperscript{23} polarization smoothing using birefringent wedges,\textsuperscript{24} and 1-THz, two-dimensional smoothing by spectral dispersion\textsuperscript{25} were applied to smooth the OMEGA laser beams in order to enhance implosion uniformity and the nuclear reaction rate. Three types of capsules were used to study implosions with a wide range of areal densities. Low-$\rho R_{\text{hot}}$ implosions were studied using thin ($\sim 3$ $\mu$m) glass (SiO$_2$) shells filled with $\sim 15$ atm of D$_2$. Some of these capsules were irradiated with a 1-ns square pulse delivering 23 kJ of on-target energy, while others were irradiated with a shorter ($600 - 800$ ps) pulse with on-target energy of $\sim 12$ kJ.\textsuperscript{26} Medium and large $\rho R$ implosions were studied using capsules with thick ($\sim 20$ $\mu$m) plastic (CH) shells filled with $\sim 15$ atm of D$_2$, and cryogenic capsules with a $\sim 100$ $\mu$m layer of D$_2$ ice enclosed within a 3–5 $\mu$m thick CH shell, respectively. They were all irradiated with 1-ns square pulses, delivering 23 kJ of on-target energy.

Charged-particle data were collected with two types of spectrometers. Wedge-range-filter proton spectrometers\textsuperscript{12,27} provided secondary-proton spectra from up to six different directions simultaneously. These spectra were used to calculate the yield and mean energy of secondary protons. Two magnet-based charged-particle spectrometers\textsuperscript{27} provided the spectra of primary protons and tritons for low $\rho R$ implosions. Neutron data were obtained from three diagnostics. Neutron time-of-flight detectors\textsuperscript{26} provided primary and secondary neutron yields as well as primary-neutron-yield-averaged ion temperature ($<T_i>_{Y_{1n}}$), and a neutron temporal diagnostic\textsuperscript{29} measured the peak primary neutron production time and the DD burn duration. In addition, secondary-neutron spectra were obtained from the 1020-scintillator array\textsuperscript{30} on some of the more recent implosions.
The data from each implosion then includes the five quantities, \( Y_{1n} \), \( Y_{2n} \), \( Y_{2p} \), \( <T_i>_{Y_Ln} \) and \( <E_{2p}> \), which will be matched to simulations in the next section. In addition, the spectral energy distributions of the secondary protons (and sometimes secondary neutrons) will be compared with the simulations. The yields and \( <T_i>_{Y_Ln} \), together with a realistic plasma density, can also be used to determine what the simple hot-spot and uniform models imply for values of \( \rho R_{\text{hot},2p}^{\text{exp1}} \) and \( \rho R_{\text{hot},2n}^{\text{exp1}} \) (where the superscript exp1 refers to use of the measured \( <T_i>_{Y_Ln} \) as the characteristic ion temperature).
IV. Monte-Carlo simulations

A Monte-Carlo program was developed to model the experiments described in Section III. This allows us to use more realistic temperature and density profiles than those in the hot-spot and uniform models. The burn-averaged ion temperature profile \[ T_i(r) \] and the shell (or cold fuel, for cryogenic capsules) density profile \[ \rho_{\text{cold}}(r) \] are assumed to have super- or sub-Gaussian profiles, and the six input parameters are: \( T_{i0}, T_{iw}, T_{ip}, S_{r0}, S_w, \) and \( S_p \) characterizing the temperature and density profiles

\[
T_i(r) = T_{i0} \exp[-(r/T_{iw})^{T_{ip}}] 
\]

and

\[
\rho_{\text{cold}}(r) = \rho_{\text{cold}0} \exp\left(-[(r-S_{r0})/S_w]^{S_p}\right). 
\]

These parameters are varied to produce simulated particle production that best fits the measured data for each implosion. The hot-fuel density profile \[ \rho_{\text{hot}}(r) \] is calculated assuming that the plasma is isobaric out to the peak shell pressure region; with this constraint \( \rho_{\text{cold}0} \) is then adjusted in order to conserve the fuel mass. (The initial fuel mass is calculated based on the initial fuel pressure and the size of the capsule.)

For computational purposes, each primary particle is assumed to produce a secondary particle, and a spectrum of particles per unit energy \( dN_2/dE \) is obtained. Since only a small fraction of the primary particles actually undergo secondary reactions, the secondary yield and spectrum need to be normalized according to \( Y_2 = <P_2>Y_1 \) and \( dY_2/dE \approx <P_2>Y_1(dN_2/dE)/N_2; \)

\[
<P_2> = \int n_0(l)\sigma_{sec}(l)dl > 
\]

is the probability of primary-to-secondary conversion, calculated in the program as the primary-yield-weighted mean value of the line integral of the D number density \( n_D \) times the secondary fusion cross section \( \sigma_{sec} \) for all possible primary particle trajectories. The primary particle production is determined by the density and temperature profiles. The
particles are followed along their trajectories through the capsule until either they escape or lose all of their energy. The probability of a secondary fusion reaction is calculated along the path of the primary particle, and then the birth position, direction, and energy of the secondary particle are calculated. The energy loss of the secondary particles is calculated to determine its contribution to a secondary spectrum. In addition to these spectra, the radial distributions of the primary and secondary particle birth positions are recorded to illustrate the effects of profiles and fuel-shell mix.

Since the model is static, the primary yield is calculated by multiplying the burn profile by the burn duration (full-width-half-maximum of the neutron production rate); therefore, the error in the measurement of the burn duration is included in the error of the primary yield. $<E_{2p}>$ is calculated from the secondary-proton spectrum, and $<T_{i}Y_{1n}>$ is determined in the region where the primary particles are produced. $^{31}$ Each of the six input parameters is varied over a large range, initially using large steps to identify the region of small $\chi^2$. This region is then more carefully explored using finer grids; as a result, the six-dimensional parameter space is explored completely. For each set of model parameters, the predicted values of the experimentally-measured quantities are calculated and the quality of agreement with the data from a particular implosion is characterized with the total $\chi^2$, which takes account of uncertainties in the experimental measurements. For each implosion, it is found that multiple local minima exist within the space of model parameters but that there is one clear region with the smallest values of $\chi^2$. Errors on the values of individual model parameters are then estimated by asking how much they can be changed without causing the total $\chi^2$ to increase by more than one. Although the widths and shapes of secondary-proton spectra are not used as fit criteria, it will be seen that

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the predicted spectra match the measured spectra quite well; this fact provides extra confidence that the best-fit model parameters are realistic.

The characteristics of the best-fit model for each implosion were used to determine how realistic the hot-spot-model inferred values of $\rho R_{\text{hot}}$ are. Values of $Y_{2p}/Y_{1n}, Y_{2n}/Y_{1n}, <T_i>_{Y_{1n}}$ and plasma density from the simulations were used to infer $\rho R_{\text{hot,2p}}^{\text{sim1}}$ and $\rho R_{\text{hot,2n}}^{\text{sim1}}$ according to Fig. 4 (the superscript sim1 indicates that $<T_i>_{Y_{1n}}$ was used as the characteristic ion temperature). The values of $\rho R_{\text{hot,2p}}^{\text{sim2}}$ and $\rho R_{\text{hot,2n}}^{\text{sim2}}$ were calculated assuming that the appropriate temperatures are averages weighted by secondary yields ($<T_i>_{Y_{2p}}$ and $<T_i>_{Y_{2n}}$, respectively). These values were then compared with $\rho R_{\text{hot}}^{\text{int}} \equiv \int \rho dr$, integrated over the hot-fuel region.
V. Results

A. Low areal density implosions

For low-\(\rho R_{\text{hot}}\) implosions, the primary \(^3\text{He}\) and \(T\) traverse the entire hot-fuel region, and the values of \(\rho R_{\text{hot}}\) inferred from secondary protons and neutrons using the hot-spot (or uniform) model generally agree with each other and usually give a reasonable estimate of the actual value of \(\rho R_{\text{hot}}\). This is shown experimentally by the square points in Fig. 1, which compares values of \(\rho R_{\text{hot,2p}}^{\text{exp}}\) and \(\rho R_{\text{hot,2n}}^{\text{exp}}\). These values were inferred according to Fig. 4 assuming a D plasma with a a temperature of \(<T_\|>_{Y_{1n}}\) keV and a density of 1.5 g/cc (obtained from a typical best-fit simulation, as discussed below). Fig. 1 also illustrates that \(\rho R_{\text{hot,2p}}^{\text{exp}}\) and \(\rho R_{\text{hot,2n}}^{\text{exp}}\) are larger for implosions with lower (\(~12\) kJ) on-target laser energy (open squares) than for implosions with full (\(~23\) kJ) laser energy (closed squares). This could be explained by a larger amount of glass shell being ablated away in full energy implosions, resulting in less material to drive the fuel inward.\(^{32,33}\) (Fig. A.1). In addition, these values of \(\rho R_{\text{hot}}^{\text{exp}}\) from D\(_2\) implosions with full laser energy show reasonable agreement with values from similar thin-glass shell DT implosions,\(^{34,12}\) for which the knock-on method\(^{35}\) was used to determine the \(\rho R_{\text{hot}}\).
FIG. 5. Parameters from the best-fit Monte-Carlo simulation of shot 30981 (3.1 μm SiO₂ shell filled with 14.7 atm D₂). (a) Tᵢ(r) and ρ(r). Fuel mass is fully conserved, while 11 % of the shell mass remains. (b) Radial distributions of the birth positions of primary and secondary particles indicate that secondary protons and neutrons are produced in a virtually identical region of the capsule. (c) Measured and simulated secondary-proton and (d) secondary-neutron spectra. Note that the shape and width of the simulated proton spectrum are very similar to those of the measured spectrum, even though these were not part of the fitting procedure. The difference in calculated and measured secondary yields are within the measurement uncertainties. Measured and simulated values of implosion characteristics are summarized in Table I. Fig. A.3 indicates how the radial profiles of Tᵢ and ρ can change without changing the quality of the fit to the data too much.
For implosion 30981, which involved a 3.1 μm glass shell filled with 14.7 atm of D₂ gas, Fig. 5a shows simulated density and temperature profiles from the best-fit simulation. Fig. 5b shows radial distributions of the primary and secondary particle birth positions; secondary protons and neutrons are produced in virtually identical regions of the capsule. In addition, a high plasma temperature and a low ρRₜₜ result in similar values of ρRₜₜ from the simulated secondary yields. Values of ρRₜₜ are inferred using the hot-spot model and assuming a plasma temperature of <Tᵢ>ᵣ₁₈ keV and a plasma density of 1.5 g/cc (obtained from simulation). In addition, values of ρRₜₜ agree with ρRₜₜ obtained from the fuel density profile shown in Fig. 5a; this indicates that the small amount of fuel-shell mix in this type of implosion does not have much impact on the accuracy of the simple model. Results of the simulation along with measured data are summarized in Table I.

Simulated secondary spectra are in good agreement with measured spectra as shown in Figs. 5c and 5d. The measured secondary proton spectrum is an average of five spectra obtained simultaneously at different angles from implosion 30981.
Table I. Measured and simulated values of yields and $\rho R$ for OMEGA implosion 30981. Experimental data were fitted by adjusting $\rho(r)$ and $T_i(r)$. Total $\chi^2$ along with parameters specifying the cold ($SiO_2$) temperature and density Gaussian profiles [peak temperature ($T_{i0}$), 1/e radius ($T_{iw}$), power of the exponent ($T_{ip}$), peak density radius ($S_{r0}$), 1/e radius ($S_w$), and power of the exponent ($S_p$)] are also listed. $\rho R_{\text{cold}} = \int \rho_{\text{cold}} dr$, integrated radially over the $SiO_2$ shell region, and $\rho R_{\text{hot}} = \int \rho_{\text{hot}} dr$ integrated radially over the hot-fuel region of the simulated profiles. Values of $\rho R_{\text{hot, 2n}}$ and $\rho R_{\text{hot, 2p}}$ were deduced using measured (left column) and simulated (right column) yield ratios assuming a 1.5 +/- 1 g/cc (obtained from Fig. 5a) D plasma at $<T_i>_{Y_{1n}}$ +/- 0.5 keV.

<table>
<thead>
<tr>
<th>Shot 30981</th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{1n}$</td>
<td>(1.5 +/- 0.15) E+11</td>
<td>(1.5 +0.23 -0.18) E+11</td>
</tr>
<tr>
<td>$Y_{2n}/Y_{1n}$</td>
<td>(5.1 +/- 0.98) E-4</td>
<td>(5.1 +1.1 -0.57) E-4</td>
</tr>
<tr>
<td>$Y_{2p}/Y_{1n}$</td>
<td>(7.9 +/- 1.1) E-4</td>
<td>(7.5 +1.0 -0.96) E-4</td>
</tr>
<tr>
<td>$&lt;E_{2p}&gt;$ (MeV)</td>
<td>14.47 +/- 0.1</td>
<td>14.64 +0.14 -0.16</td>
</tr>
<tr>
<td>$&lt;T_i&gt;<em>{Y</em>{1n}}$ (keV)</td>
<td>8.2 +/- 0.5</td>
<td>8.2 +0.7 -0.5</td>
</tr>
</tbody>
</table>

$\chi^2$ | ... | 0.1 |
$T_{i0}$ (keV) | ... | 20.5 +2.5 -10 |
$T_{iw}$ (\mu m) | ... | 34 +14 -4 |
$T_{ip}$ | ... | 2 +5 -0 |
$S_{r0}$ (\mu m) | ... | 62 +6 -10 |
$S_w$ (\mu m) | ... | 3.5 +3 -3.3 |
$S_p$ | ... | 2.5 +2.5 -2 |

$\rho R_{\text{cold}}$ (mg/cm$^2$) | ... | 4.5 +4.3 -4.2 |
$\rho R_{\text{hot}}$ (mg/cm$^2$) | ... | 3.7 +0.8 -0.4 |
$\rho R_{\text{hot, 2n}}$ (mg/cm$^2$) | 4.6 +0.9 -1.2 | 4.6 +1.0 -0.6 |
$\rho R_{\text{hot, 2p}}$ (mg/cm$^2$) | 4.3 +0.6 -0.8 | 4.1 +/- 0.5 |
B. Medium areal density implosions

Correctly inferring the value of $\rho R_{\text{hot}}$ is more difficult for implosions of capsules with thick plastic shells because $Y_{2p}$ reaches saturation when $\rho R_{\text{hot}}$ is sufficiently large, and $Y_{2n}$ is enhanced in the presence of increased fuel-shell mix. The triangles in Fig. 1 show that the values of $\rho R_{\text{hot,2p}}$ are often smaller than values of $\rho R_{\text{hot,2n}}$, as previously reported in Ref. 12. Values of $\rho R_{\text{hot,2p}}$ and $\rho R_{\text{hot,2n}}$ are inferred assuming a temperature of $<T_i>_{Y_{1n}}$ keV and a D plasma with a density of 2 g/cc.

Fig. 6a shows the temperature and density profiles that result in the best fit to the measured data for implosion 27443 (19.4 $\mu$m plastic shell filled with 15 atm of D$_2$ gas), and Fig. 6b shows the resulting radial distributions of primary and secondary particle birth positions. About 32% of the initial CH mass remains, and $\sim$ 1.3 $\mu$m of the initial CH layer has mixed into the fuel (which is similar to the amount of mix reported in Refs. 20-22.$^{36}$ The $^3$He are ranged out before traversing the entire fuel region. Fig. 6b also illustrates an enhancement of $Y_{2n}$ by fuel-shell mix; the increased energy loss of $T$ per unit $\rho R_{\text{hot}}$, due to the cooler, dense shell material, results in an enhanced DT fusion cross section (Fig. 3), which causes $Y_{2n}/Y_{1n}$ to overestimate $\rho R_{\text{hot}}^{\text{int}}$. In addition, $Y_{2n}/Y_{1n}$ is more sensitive to temperature in this $\rho R_{\text{hot}}$ range; using $<T_i>_{Y_{1n}}$, which is always higher than $<T_i>_{Y_{2n}}$, results in a larger inferred value of $\rho R_{\text{hot}}$. 

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FIG. 6. Best-fit parameters from the Monte-Carlo simulation for shot 27443, which involved a 19.4 μm CH shell filled with 15 atm D2. (a) T_e(r) and ρ(r). Fuel mass is fully conserved, while 32% of the shell mass remains. (b) Radial distributions of the birth positions of primary and secondary particles show that secondary proton production is diminished, while secondary neutron production is enhanced in the region of significant fuel-shell mix. This causes secondary protons to underestimate, and secondary neutrons to overestimate the actual value of ρR_\text{hot}. (c) Measured and simulated secondary proton spectra are compared, and (d) simulated secondary neutron spectrum is shown. The secondary proton spectra show more energy downshift, and the width of the secondary spectra are slightly narrower, than the low ρR_\text{hot} case because the average primary particle energy is smaller at the time of secondary reaction. Experimental and simulated values of implosion characteristics are listed in Table II, while other fits are illustrated in Fig. A.4.
Simulated yields and additional parameters characterizing the implosion are summarized and compared with measurements in Table II. This table shows that the values of $\rho R_{hot}^{siml}$ implied by secondary protons and neutrons are smaller and larger than the value of $\rho R_{hot}^{int}$, respectively. The hot-spot model was used to obtain values of $\rho R_{hot}$ using $<T_i>_{Y_{1n}}$ keV for the temperature and assuming the density of the D plasma was 2 g/cc.

Table II. Measured and calculated values of implosion characteristics for OMEGA implosion 27443. Values $\rho R_{hot}$ were calculated assuming a 2 +/- 1 g/cc D plasma at $<T_i>_{Y_{1n}}$ +/- 0.5 keV. Results from simulation (right column) indicate that the $\rho R_{hot,2p}$ underestimates and $\rho R_{hot,2n}$ overestimates the actual value.

<table>
<thead>
<tr>
<th>Shot 27443</th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{1n}$</td>
<td>(1.5 +/- 0.15) E+11</td>
<td>(1.6 +0.1 -0.25) E+11</td>
</tr>
<tr>
<td>$Y_{2n}/Y_{1n}$</td>
<td>(1.5 +/- 0.24) E-3</td>
<td>(1.4 +0.16 -0.12) E-3</td>
</tr>
<tr>
<td>$Y_{2p}/Y_{1n}$</td>
<td>(1.0 +/- 0.14) E-3</td>
<td>(1.0 +0.1 -0.15) E-3</td>
</tr>
<tr>
<td>$&lt;E_{2p}&gt;$ (MeV)</td>
<td>13.1 +/- 0.1</td>
<td>13.07 +/- 0.1 -0.11</td>
</tr>
<tr>
<td>$&lt;T_i&gt;<em>{Y</em>{1n}}$ (keV)</td>
<td>4.1 +/- 0.5</td>
<td>4.1 +0.2 -0.4</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>...</td>
<td>0.5</td>
</tr>
<tr>
<td>$T_{io}$ (keV)</td>
<td>...</td>
<td>11 +0 -5.5</td>
</tr>
<tr>
<td>$T_{iw}$ (\mu m)</td>
<td>...</td>
<td>20 +18 -0</td>
</tr>
<tr>
<td>$T_{ip}$</td>
<td>...</td>
<td>0.8 +1.2 -0</td>
</tr>
<tr>
<td>$S_{io}$ (\mu m)</td>
<td>...</td>
<td>54 +/- 2</td>
</tr>
<tr>
<td>$S_{iw}$ (\mu m)</td>
<td>...</td>
<td>16 +2 -6</td>
</tr>
<tr>
<td>$S_p$</td>
<td>...</td>
<td>1.2 +0 -0.2</td>
</tr>
<tr>
<td>$\rho R_{cold}$ (mg/cm$^2$)</td>
<td>...</td>
<td>42.3 +3.9 -2.1</td>
</tr>
<tr>
<td>$\rho R_{hot}$ (mg/cm$^2$)</td>
<td>...</td>
<td>8.9 +1 -0.4</td>
</tr>
<tr>
<td>$\rho R_{hot,2n}$ (mg/cm$^2$)</td>
<td>12.8 +/- 1.9</td>
<td>11.6 +1.2 -1</td>
</tr>
<tr>
<td>$\rho R_{hot,2p}$ (mg/cm$^2$)</td>
<td>5.0 +/- 0.7</td>
<td>5.2 +0.5 -0.7</td>
</tr>
</tbody>
</table>

The simulated secondary proton spectrum is compared with the measured spectrum in Fig. 6c. The measured secondary proton spectrum is an average of three spectra simultaneously obtained at different angles from implosion 27443, and shows more downshift than spectra from
the low \( \rho R_{\text{hot}} \) implosions. The widths of the secondary proton and neutron spectra (Fig. 6d) are slightly narrower than in the previous case because the average energy of the primary particle, at the time it undergoes secondary fusion, is smaller.\textsuperscript{12}
C. Cryogenic implosions

For cryogenic implosions, the interpretation of inferred values of \( \rho R_{\text{hot}} \) is even more subtle, since there is a high-temperature, low-density fuel region and a low-temperature, high-density fuel region. If most of the secondary particles are produced only in the hot-fuel region, then \( Y_2/Y_{1n} \) can be used to infer \( \rho R_{\text{hot}} \). On the other hand, if secondary particles are mainly produced in the inner part of the cold fuel region, the inferred \( \rho R \) is larger than \( \rho R_{\text{hot}} \), but smaller than \( \rho R_{\text{total}} \). (Even the more penetrating T cannot traverse the entire cold fuel region since the range of T in a 8 g/cc, 1 keV D plasma is ~ 15 mg/cm\(^2\), and we usually calculate \( \rho R_{\text{total}} > 40 \) mg/cm\(^2\) from the downshift of the average secondary proton energy for cryogenic implosions). Fig. 1 shows that values of \( \rho R_{\text{hot}} \) implied by measured \( Y_{2n}/Y_{1n} \) are always larger than values from measured \( Y_{2p}/Y_{1n} \) for those implosions (values were inferred assuming a \( <T_i>_{Y_{1n}} \) keV, 3 g/cc D plasma).

Radial profiles of temperature and density calculated for implosion 28900 (89-\( \mu \)m D\(_2\) ice layer inside of 5.1-\( \mu \)m CH shell) are shown in Fig. 7a, and simulated and measured spectra are shown in Figs. 7c and 7d. As indicated in Fig. 7d, the secondary-neutron spectrum is much narrower than the secondary-neutron spectra from Figs. 5d and 6d (Fig. A.2) because the primary T are, on average, less energetic when they fuse with thermal D.\(^{12}\) Measurements of secondary-neutron spectra from more recent cryogenic implosions also show the same characteristics.
FIG. 7. (a) Simulated profile of shot 28900 (cryogenic capsule with a 5.1 \mu m CD shell and 89 \mu m D_2 ice layer) which gives the best fit to the measurement. 31% of the total mass remains. (b) Radial distributions of the birth points of primary and secondary particles show that most of the secondary protons are produced in the hot-fuel region, while secondary neutrons are mainly produced in the cold fuel region. (c) Measured and simulated secondary proton spectra. (d) Simulated secondary neutron spectrum is narrower than the spectra in Figs. 5d and 6d because primary T are less energetic at the time they undergo secondary reactions; \rho R of cold fuel is large enough to stop primary T (Fig. 7.b), and the cross section increases as T loses energy (Fig. 3a). Important implosion characteristics are summarized in Table III, while other fits are illustrated in Fig. A.5.
The radial distributions of the primary and secondary birth positions shown in Fig. 7b indicate that secondary protons and neutrons are born mainly in the hot and cold fuel regions, respectively. Therefore, the $\rho R$ obtained from secondary protons gives an estimate of $\rho R_{\text{hot}}$, while the secondary neutron yield provides a lower limit on $\rho R_{\text{total}}$. In this type of implosion, effects of mix or exchange of hot and cold fuel play significant roles in determining the radial distribution of secondary birth positions.

Simulated values of yields and other important implosion characteristics are compared with experimental results in Table III. The secondary-neutron, hot-spot-model-inferred $\rho R_{\text{siml}}$ is close to $\rho R_{\text{total}}^{\text{int}}$, but this does not mean that the hot-spot model describes the implosion accurately. The agreement is an accidental consequence of using the wrong temperature, $<T_i>_{Y1n}$, which samples the hotter central region rather than the cooler fuel region where most of the secondary neutrons are produced.

This implosion has also been analyzed using a combination of x-ray and neutron measurements, without the use of secondary proton data. These results are discussed in Ref. 37. While the best-fit profiles were somewhat different, they agree within the uncertainties of the two simulation techniques.
Table III. Measured and calculated values of implosion characteristics for OMEGA implosion 28900. \( \rho R_{\text{total}} = \int p_d r \, dr \), integrated radially over the entire simulated profiles. \( \rho R_{\text{hot}} \) is defined as the \( \rho R \) that includes 90% of primary production. Values of \( \rho R_{\text{hot}} \) were calculated assuming a 3.0 +/- 1.5 g/cc D plasma at \( < T_i >_{\gamma_{1n}} +/- 0.5 \) keV. Results from the simulation (right column) suggest that value of \( \rho R_{\text{hot,2p}} \) provides a good estimate of \( \rho R_{\text{hot}} \). Secondary neutron implied \( \rho R_{\text{hot}} \) is similar to \( \rho R_{\text{total}} \), but this is because the value of the temperature used to infer \( \rho R_{\text{hot}} \) is too large. If the temperature of the cold fuel region (1 keV instead of 3.6 keV) were used, a much smaller and physical value of \( \rho R_{\text{hot}} \) would be implied.

<table>
<thead>
<tr>
<th>Shot 28900</th>
<th>Measured</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Y_{1n} )</td>
<td>((1.2 +/- 0.12) E+11)</td>
<td>((1.3 +0.12 -0.14) E+11)</td>
</tr>
<tr>
<td>( Y_{2n}/Y_{1n} )</td>
<td>((9.4 +/- 1.4) E-3)</td>
<td>((9.1 +1.0 -1.1) E-3)</td>
</tr>
<tr>
<td>( Y_{2p}/Y_{1n} )</td>
<td>((1.8 +/- 0.26) E-3)</td>
<td>((1.6 +0.0 -0.2) E-3)</td>
</tr>
<tr>
<td>( &lt;E_{2p}&gt; ) (MeV)</td>
<td>(13.31 +/- 0.10)</td>
<td>(13.28 +0.15 -0.11)</td>
</tr>
<tr>
<td>( &lt;T_i&gt;<em>{\gamma</em>{1n}} ) (keV)</td>
<td>(3.6 +/- 0.5)</td>
<td>(3.5 +0.6 -0.3)</td>
</tr>
<tr>
<td>( \chi^2 )</td>
<td>...</td>
<td>0.6</td>
</tr>
<tr>
<td>( T_{i0} ) (keV)</td>
<td>...</td>
<td>(8.5 +9.5 -2.5)</td>
</tr>
<tr>
<td>( T_{iw} ) (( \mu )m)</td>
<td>...</td>
<td>(18 +10 -8)</td>
</tr>
<tr>
<td>( T_{ip} )</td>
<td>...</td>
<td>(1.2 +0.6 -0.4)</td>
</tr>
<tr>
<td>( S_{r0} ) (( \mu )m)</td>
<td>...</td>
<td>(52 +22 -2)</td>
</tr>
<tr>
<td>( S_{w} ) (( \mu )m)</td>
<td>...</td>
<td>(32 +16 -12)</td>
</tr>
<tr>
<td>( S_{p} )</td>
<td>...</td>
<td>(9 +1 -7.5)</td>
</tr>
<tr>
<td>( \rho R_{\text{total}} ) (mg/cm(^2))</td>
<td>...</td>
<td>(48.2 +3.2 -6.0)</td>
</tr>
<tr>
<td>( \rho R_{\text{hot}} ) (mg/cm(^2))</td>
<td>...</td>
<td>(7.9 +0.2 -1.7)</td>
</tr>
<tr>
<td>( \rho R_{\text{hot,2n}} ) (mg/cm(^2))</td>
<td>(49.8 +5.0 -6.9)</td>
<td>(48.0 +4.9 -4.0)</td>
</tr>
<tr>
<td>( \rho R_{\text{hot,2p}} ) (mg/cm(^2))</td>
<td>(9.3 +1.9 -1.5)</td>
<td>(7.8 +0.5 -0.6)</td>
</tr>
</tbody>
</table>
VI. Conclusions

The hot-spot and uniform models have been used to infer the areal density of the hot-fuel region ($\rho R_{\text{hot}}$) of D$_2$ implosions, but disagreements between the values of $\rho R_{\text{hot}}$ inferred from secondary proton and neutron yields have often been observed, indicating limitations in these models. Results from direct-drive experiments at the OMEGA laser system and Monte-Carlo simulations provided a deeper understanding of the relationship between $\rho R$, the capsule structure, and secondary particle production. Experiments show that values of $\rho R_{\text{hot}}$ inferred from the ratios of secondary proton and neutron to primary neutron yields ($Y_{2p}/Y_{1n}$ and $Y_{2n}/Y_{1n}$) using the hot-spot model agree well for low $\rho R_{\text{hot}}$ implosions (thin-glass shell capsules), and simulations indicate that they give a good estimate of the actual value of $\rho R_{\text{hot}}$. The results from implosions of D$_2$-filled thin-glass shells also show reasonably good agreement with results from implosions of similar capsules filled with DT gas. For thick-plastic-shell capsule implosions, where the $\rho R_{\text{hot}}$ of an implosion becomes sufficiently large, $Y_{2p}/Y_{1n}$ underestimates $\rho R_{\text{hot}}$ since the primary $^3$He are ranged out before sampling the entire hot-fuel region. In addition, fuel-shell mix increases the rate of energy loss of $^3$He and causes $Y_{2p}/Y_{1n}$ to further underestimate $\rho R_{\text{hot}}$. The fuel-shell mix also causes $Y_{2n}/Y_{1n}$ to overestimate $\rho R_{\text{hot}}$ by slowing down the primary T, thereby increasing the secondary DT fusion reaction cross section. As a result, values of $\rho R_{\text{hot}}$ for medium $\rho R_{\text{hot}}$ capsules inferred from $Y_{2p}/Y_{1n}$ and $Y_{2n}/Y_{1n}$ using the hot-spot model should be interpreted as estimates of the lower and upper limits on the actual $\rho R_{\text{hot}}$, respectively. For cryogenic capsules, secondary protons are produced mainly in the hot-fuel region, and the proton-implied value of $\rho R$ provides a good estimate of the hot-fuel $\rho R$. In contrast, secondary neutrons are mostly produced in the inner part of the cold fuel region, and the neutron-implied $\rho R$ gives a lower limit on the total $\rho R$ when calculated correctly using the secondary-neutron-
birth-point average temperature and density. Naive use of the simple hot-spot or uniform model, with a burn-averaged temperature, often results in inaccurate inference of \( \rho R_{\text{hot}} \). More thorough analysis, such as the use of complete data sets and simulations for determining the secondary birth positions and the effects of mix, as presented herein, or the use of detailed analysis of secondary neutron spectra both from experiments and simulations\(^{10} \), is required in order to obtain a realistic estimate of \( \rho R_{\text{hot}} \).

**Acknowledgement**

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Appendix A: Additional figures

FIG. A.1. 1D clean LILAC simulations for low \( \rho R \) implosion 30981 indicate hot-fuel \( \rho R \) starts to decrease as the capsule is significantly overdriven. This trend agrees with measurements where \( \rho R_{\text{hot}} \) are lower for full-laser energy (~23 kJ) driven thin-glass shell capsules than for low laser energy (~12 kJ) driven capsules (Fig. 1).

FIG. A.2. The simulated secondary neutron spectrum is narrower than the spectra in Figs. 5d and 6d because the primary T are less energetic at the time they undergo secondary reactions; \( \rho R \) of cold fuel is large enough to stop primary T (Fig. 7.b), and the cross section increases as T loses energy (Fig. 3a). Note that detailed analysis of secondary neutron spectra was used to study areal density in Ref. 10.
FIG. A.3 Samples of temperature, density, pressure, and burn profiles which produced fits to the data which were not as good as the best fit for implosion 30981. Bold lines represent the best-fit profiles; dashed and dotted lines represent the fits having the highest and lowest peak temperature, respectively, in the group of fits for which the total $\chi^2$ is within one of its minimum value.
FIG. A.4 Samples of temperature, density, pressure, and burn profiles which produced fits to the data which were not as good as the best fit for implosion 27443 (as described in the caption of Figure A.3). The width of the burn profile is narrower than the width for implosion 30981, indicating more compression.
FIG. A.5 Samples of temperature, density, pressure, and burn profiles which produced fits to the data which were not as good as the best fit for implosion 28900 (as described in the caption of Figure A.3). The width of the burn profile is narrower than the width for implosion 30981, indicating more compression.
References


26. Short laser pulses (< 1 ns) imploding thin-glass shell capsules prevent significant nuclear production while the laser is on. This is important if $\rho R_{\text{total}}$ is to be studied, because the capsule can be charged to a significant potential relative to the target chamber wall due to laser-plasma interactions. The potential can cause an upshift of measured proton energies, making it difficult to determine how much energy the protons lost while leaving the capsule (necessary for calculating $\rho R_{\text{total}}$). The potential decays away rapidly after the laser is turned off, so it does not affect measurements of protons from implosions in which the nuclear burn occurs after the pulse (such as those involving thick-plastic-shell or cryogenic capsules). This affects only the study of $\rho R_{\text{total}}$; measurements of yields are unaffected by capsule potentials.


31. Primary-neutron-yield-weighted-average ion temperature is calculated by two methods, each yielding a virtually identical temperature. First, the product of the temperature and the primary neutron birth rate per unit length at each radius is integrated and divided by the primary neutron.
yield. Second, the primary neutron spectrum is calculated, and the width of the spectrum was used to obtain an ion temperature.


34 M. J. Canavan, *et al.*, to be submitted to Rev. Sci. Instrum. (2004); herein the laser energy was \( \sim 30 \text{ kJ} \) for these DT implosions.


36 Radha *et al.*, 20 Li *et al.*, 21 and Regan *et al.* 22 reported \( \sim 1 \text{ \( \mu \)m}, \sim 0.5 \text{ \( \mu \)m}, \) and \( \sim 0.4 \text{ \( \mu \)m} \) of the initial shell layer mixed into the fuel, respectively.


3. An unsolved problem and future work

I. Energy losses of primary particles

For thin-glass capsule implosions, we obtain some primary charged particle spectra in addition to secondary proton spectra, since the imploding capsule does not have enough $\rho R_{\text{tot}}$ to completely stop primary particles. However, the energy loss of the primary particles ($\Delta E$) is smaller than or comparable to the $\Delta E$ of the secondary protons. Calculations according to Ref. 8 predict a larger $\Delta E$ for primary particles than secondary protons for temperatures and densities of interest, because their energy is much smaller than that of secondary particles. We held discussions and performed calculations, but, so far, we have not reached a conclusion. Examples of this problem can be seen in spectra from implosions 30981, 30982, and 30983 in Appendix D.

II. Improvements to the Monte-Carlo program

There are three obvious directions that could be taken in generalizing and improving the analysis procedures described in this thesis. The first involves enhancements of the Monte-Carlo program, the second involves incorporation of additional data constraints into the fit procedures, and the third involves improvements in the rigor of the statistical analysis.

At least two changes could be explored for the Monte-Carlo program. The first is to incorporate asymmetries into capsule structures; this is important because we often have evidence of significant asymmetries in the data sets (see Appendix D). The second is to investigate whether the normalization technique described in Section 2-IV introduces any errors in the shapes of secondary spectra, and whether improvements are worth pursuing in this area.

For comparing simulations with data, use could be made of experimental constraints that were not imposed in the work described here. For example, we made use of the yields and mean

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energies of secondary protons, but we didn't compare the detailed shapes of the measured and simulated spectra as part of the quantitative goodness-of-fit procedure. In addition, other diagnostic measurements provide relevant information. X-ray data provide additional constraints on temperature and density profiles. The neutron temporal diagnostic, the proton temporal diagnostic, and time-resolved x-ray measurements provide information about time dependence that could be modeled by using the Monte-Carlo program to simulate successive time slices.

Finally, it would be interesting to explore more complete approaches to quantifying the statistical analysis of data-simulation comparisons. One approach would be to use the "bootstrap" method to evaluate goodness of fit and uncertainties in best-fit parameters. A set of artificial data sets is generated from an actual data set. In each artificial data set, each "measurement" is assigned a value gotten by adding to the actual measured number an amount determined randomly from the Gaussian distribution implied by the measurement uncertainty. For each data set, a new set of "best-fit" model parameters is calculated, and the distribution of values of these parameters generated by a large number of "data sets" is used to study the probability distributions of the inferred parameters.
Appendix B: Details of Monte-Carlo code

A Monte-Carlo code was developed to understand the effects of fuel-shell mix and density and temperature profiles on secondary yields, as explained in Section 2-IV. This program produces spectra of primary, secondary, and knock-on particles (fuel and shell ions elastically scattered by DT neutrons) according to density and temperature profiles specified by the user. The profiles are assumed to be static throughout the burn duration and to be spherically symmetric. A flow chart of the code is shown in Figure B.1, and details of the program are explained in the following sections.

B.1 Input parameters

When modeling any real inertial confinement fusion experiment, it is critical to conserve the fuel mass and to know how much shell mass remains. In order to calculate the initial mass, the program prompts the user for the initial capsule conditions (Figures B.2 and B.3). It requires the user to specify the type of gas, fill pressure, shell material, shell thickness, and capsule diameter. In addition, for cryogenic capsules, the user must specify the ice layer thickness. The program calculates the initial mass of the fuel and shell and displays them on the user interface.

There are two ways to specify the burn-averaged density and temperature profiles. In the multi-ramp model, an imploded capsule is modeled by a central sphere and several shells (or zones) surrounding it (Figure B.2). Within each zone, the density of fuel and shell materials and the temperature can be constant or vary linearly. The program requires the user to specify the radius of the sphere and the thickness of the zones, as well as the density and temperature at the center of the sphere and at the inner and outer edges of each zone. Up to eight shells can be used to specify the density and temperature profiles of the implosion.
Figure B.1 Flow chart of the Monte-Carlo code
Figure B.2 User interface for the multi-ramp model. The radius of the sphere and the thickness of each zone, as well as the density and temperature at the center of the sphere and at the inner and outer edges of each zone, need to be specified for up to eight zones. The program plots profiles, birth points and spectra next to the user interface.
Figure B.3 User interface for the Gaussian model.

In the Gaussian model, the temperature and shell density profiles \([T_i(r)\) and \(\rho_{\text{col}}(r)\) are specified using Gaussian functions,

\[T_i(r) = T_{i0} \exp \left[ -\left( \frac{r}{\sigma_{Ti}} \right)^{p_{Ti}} \right], \quad \text{and} \quad (B.1)\]
\[ \rho_{\text{cold}}(r) = \rho_{c0} \exp \left[ -\left( \frac{r - r_{c0}}{\sigma_c} \right)^{p_c} \right], \] (B.2)

where \( T_{i0}, \sigma_{Ti}, p_{Ti}, r_{c0}, \sigma_c, \) and \( p_c \) are variables specified by the user (Figure B.3). For cryogenic implosions, the plastic shell surrounding the ice layer is assumed to be ablated completely, and the density of the cold fuel is expressed using \( \rho_{\text{cold}}(r) \). The pressure within the shell (or cold fuel) is calculated using \( T_i(r) \) and \( \rho_{\text{cold}}(r) \), and the position of peak shell pressure is determined. The density of the hot fuel [\( \rho_{\text{hot}}(r) \)] is calculated, assuming that the hot fuel region (inside the peak shell pressure) is isobaric. To fully conserve the hot fuel mass, \( \rho_{c0} \) is adjusted accordingly. Once the hot and cold density and temperature profiles are determined, they are plotted next to the user interface (Figure B.2) along with the pressure profile. The amount of mass remaining in the profile, as well as the \( \rho R \), is calculated and shown on the user interface (Figure B.2).

The user selects a fusion product (test particle): primary, secondary, or knock-on. The full-width-half-maximum of the primary neutron production rate (burn width or \( t_b \)) is used to calculate the primary yield \( (Y_1) \). This value is obtained from the neutron temporal diagnostic (NTD) [9]. Other parameters to be specified by the user include an upper limit on the energy range \( (E_{\text{max}}) \) and the energy resolution \( (dE) \) of the resulting spectrum, the distance between successive calculations \( (dr) \), and the number of test particles \( (N_{\text{testp}}) \). For computational reasons, \( N_{\text{testp}} \sim 10^4 \) particles (instead of \( Y_1 > 10^{10} \)) is used to obtain a spectrum, which is then normalized to determine the final spectrum.
B.2 Primary particle

The radial burn profile (fusion reaction rate per unit volume) of the primary fusion reaction can be calculated using density and temperature profiles. For a fusion reaction $A + B \rightarrow C + D$, the burn profile $[R_1(r)]$ is given by,

$$R_1(r) = n_A(r)n_B(r) < \sigma v >_{AB}(r)$$

(B.3)

where $n_A$ and $n_B$ are number densities of reacting particles A and B, respectively, and $<\sigma v>_{AB}$ is the rate coefficient averaged over the velocity distribution of both species. $<\sigma v>$ is a function of ion temperature and is calculated according to Ref. 5 and shown in Figure 1.1. For the DD fusion reaction, $R_1$ is given by,

$$R_1(r) = \frac{1}{2} n_D(r)^2 < \sigma v >_{DD}(r)$$

(B.4)

Then the primary yield ($Y_1$) is calculated by integrating $R_1$ over the volume of the compressed capsule and multiplying by the burn width ($t_B$),

$$Y_1 = t_B \int R(r) \, dV.$$  

(B.5)

Since the radial burn profile is effectively the probability of a primary fusion reaction at each radius, the birth position of primary particles ($r_{1\text{birth}}$) is randomly generated using the Monte-Carlo technique: the radial profile is integrated over the radius and normalized to one. Then a random number between zero and one is used to select the radial position of primary fusion reaction. The polar ($\theta_1$) and azimuthal ($\phi_1$) angles of a primary birth position as well as the direction of a primary particle ($\vec{v}_1$), which is defined by two angles ($\theta_{v1}$ and $\phi_{v1}$), are also determined by random numbers, since a primary particle is produced isotropically in the spherically symmetric capsule.
The energy of the primary particle is determined according to Ref. 10, assuming that the velocity of the reacting ions is a three-dimensional Maxwellian distribution of temperature $T_i(r_{\text{birth}})$. The energy distribution of fusion product C is then given by a Gaussian,

$$f(E_c) = \frac{\langle E_c \rangle}{\sqrt{2\pi} \sigma_{E_c}} \exp \left[ -\frac{(E - \langle E_c \rangle)^2}{2\sigma_{E_c}^2} \right], \quad (B.6)$$

where $\langle E_c \rangle$ is the mean energy of fusion product C and $\sigma_{E_c}$ is the standard deviation of the Gaussian. $\langle E_c \rangle$ is given by,

$$\langle E_c \rangle = \frac{1}{2} \frac{m_e}{m_e + m_D} \left[ Q + \langle K \rangle \right], \quad (B.7)$$

where $\langle V^2 \rangle$ and $\langle K \rangle$ are the center-of-mass velocity and relative kinetic energy of the reacting particles averaged over the Maxwellian distribution and given by,

$$\langle V^2 \rangle = \frac{3T_i}{m_A + m_B}, \quad (B.8)$$

and

$$\langle K \rangle \approx \left( \frac{\pi^2 e^4 m}{2\hbar^2} \right)^{\frac{1}{3}} T_i^{2/3} + \frac{5}{6} T_i, \quad (B.9)$$

where $m$ is the reduced mass of the reacting particles. $Q$ is the nuclear energy release of the reaction. $\sigma_{E_c}$ is given approximately as,

$$\sigma_{E_c} \approx \frac{2m_c m_D}{(m_A + m_B)(m_C + m_D)} Q T_i. \quad (B.10)$$

Once the birth position, direction, and energy of the primary particle are determined, it is followed until it either escapes the capsule or loses all its energy. The energy loss of the primary particle is calculated according to Ref. 8 along its path, and a simulated primary particle
spectrum \([N_1(E)]\) is obtained \((\int_0^{E_{\text{max}}} N_1(E) dE = N_{\text{testp}})\). The primary spectrum \([Y_1(E)]\) is obtained by normalizing \(N_1(E)\) by,

\[
Y_1(E) = \frac{Y_1}{N_{\text{testp}}} \cdot N_1(E).
\]  

(B.11)

**B.3 Secondary and knock-on particles**

For computational purposes, each primary particle is assumed to produce a secondary particle. As explained in the previous section, each primary particle is followed, and its energy loss is calculated along its path. The secondary fusion reaction cross section \((\sigma_{\text{sec}})\) is a function of the primary particle energy and is calculated according to Ref. 11. The probability of a secondary fusion reaction per unit length \([R_2(r)]\) is obtained by,

\[
R_2 = n_\text{D}(r)\sigma_{\text{sec}}(r),
\]  

(B.12)

where \(n_\text{D}\) is number density of D. \(R_2\) is then integrated and normalized to one so that a random number between zero and one can be used to determine the birth position of secondary particles.

**B.3.1 Secondary particle energy and direction**

The direction of a secondary particle \((\vec{v}_2)\) is calculated by,

\[
\vec{v}_2 = \vec{v}_{\text{CM}} + \vec{u}_2,
\]  

(B.13)

where \(\vec{v}_{\text{CM}}\) is the center of mass (CM) velocity, and \(\vec{u}_2\) is the velocity of the secondary particle in the CM system. \(\vec{v}_{\text{CM}}\) is calculated using the velocities of primary particles and thermal D, and \(|\vec{u}_2|\) is calculated using energy conservation:
\[ |\vec{\mu}_2| = \left[ \frac{2}{m_c + m_d} \left( Q + K \left( \frac{m_d}{m_c} \right) \right)^2 \right]^{1/2} \]  \hspace{1cm} (B.14)

and the direction of \( \vec{\mu}_2 \) is determined using random numbers, since the distribution of the angle between \( \vec{v}_{cm} \) and \( \vec{\mu}_2 \) is isotropic. The energy of the secondary particle is calculated using \( \vec{v}_2 \).

The secondary particle is followed until it either exits the imploding capsule or loses all its energy. If the particle escapes, the energy is recorded, and a spectrum of particles per unit energy \( dN_2/dE \) is obtained. Since only a small fraction of the primary particles actually undergo secondary reactions, the secondary yield and spectrum need to be normalized according to \( Y_2 = \langle P_2 \rangle Y_1 \) and \( dY_2/dE \approx \langle P_2 \rangle Y_1 (dN_2/dE)/N_2 \); \( \langle P_2 \rangle = \langle \int n_D(l) \sigma_{sec}(l) dl \rangle \) is the probability of primary-to-secondary conversion, calculated in the program as the primary-yield-weighted mean value of the line integral of the D number density \( n_D \) times the secondary fusion cross section \( \sigma_{sec} \) for all possible primary particle trajectories.

B.3.2 Knock-on particle energy and direction

The program also calculates the spectra of knock-on particles (fuel or shell particles elastically scattered by primary neutrons), which are of great interest for DT-filled capsule implosions. As is the case of secondary particles in D_2-filled capsules, each primary DT neutron is assumed to elastically scatter a particle. Each neutron is followed, and the probability of an elastic scattering per unit length \( [R_{ko}(r)] \) is obtained by,

\[ R_{ko} = n(r) \sigma_{ko} \], \hspace{1cm} (B.15)

where \( n \) is number density of the elastically scattered particle, and \( \sigma_{ko} \) is the total scattering cross section. Since DT neutrons are assumed to scatter only once, \( \sigma_{ko} \) is constant. \( R_{ko} \) is then
integrated and normalized to one, so that a random number between zero and one can be used to determine the birth position of knock-on (KO) particles.

The energy of the KO particle ($E_2$) is calculated first. The differential cross section for elastic scattering of DT neutrons off protons, deuterons, or tritons (Figure B.4) is integrated and normalized to one, then a random number is used to select the energy of the knock-on particle.

![Differential cross-section](image)

Figure B.4 Differential cross section of elastic scattering of DT neutron off D, T, and p.

The angle between the primary neutron velocity ($\vec{v}_1$) and the direction of the knock-on particle in the DT neutron frame ($\theta'$) is given by,

$$\cos \theta' = \left[ \frac{(A+1)^2 \ E_2}{4A \ E_1} \right]^{\frac{1}{2}}. \quad (B.16)$$

The distribution of the angle around $\vec{v}_1$ ($\phi'$) is isotropic, so a random number is used to determine the value of $\phi'$. Figure B.5 shows the relationships between $\vec{v}_1$, $\theta'$, and $\phi'$. Since these angles are with respect to $\vec{v}_1$, a rotation matrix is used to obtain the direction of the KO particle in the coordinate system of the imploding capsule. After the direction and energy of the knock-
on particle is determined, the same processes are used to obtain the spectrum of knock-on particles, as were used for the secondary particles.

![Diagram of DT neutron and knock-on particle](image)

Figure B.5 Relationships between directions of DT neutron and knock-on particles.

**B.4 Ion temperature**

There are two methods to calculate the primary-neutron-yield-weighted temperature ($<T_i>_{Y_{1n}}$). One way is to integrate the product of the ion temperature and primary reaction rate per unit length ($dY_{1n}/dr$) over the radius and divide by the primary yield.

$$<T_i>_{Y_{1n}} = \frac{\int T_i(r) \frac{dY_{1n}(r)}{dr} dr}{Y_{1n}}$$  \hspace{1cm} (B.17)

Another way is to use the Full-Width-Half-Maximum of the primary neutron spectrum. For the neutron branch of the DD fusion reaction, the FWHM is related to the ion temperature by

$$\text{FWHM} = 82.5 \sqrt{T_i}$$  \hspace{1cm} (B.18)
where FWHM and T<sub>i</sub> are in keV [12]. Ion temperatures obtained from the two methods are compared and shown to be virtually identical.

**B.5 Best-fit profile**

The temperature [T<sub>i</sub>(r)] and density [ρ(r)] profiles are adjusted to find the best fit between the measured and calculated values of Y<sub>1n</sub>, Y<sub>2n</sub>/Y<sub>1n</sub>, Y<sub>2p</sub>/Y<sub>1n</sub>, secondary proton mean energy (<E<sub>2p</sub>>)<sub>,</sub> and <T<sub>i</sub>><sub>Y1n</sub>. The range and the grid size of the six parameters (T<sub>io</sub>, σ<sub>Ti</sub>, p<sub>Ti</sub>, r<sub>0</sub>, σ<sub>c</sub>, and p<sub>c</sub>) of the Gaussian profiles (equations B.1 and B.2) are defined by the user. The χ² for each fitting parameter is calculated as follows:

\[
\chi^2_{Y_{1n}} = \frac{(Y_{1n}^{\text{meas}} - Y_{1n}^{\text{sim}})^2}{\Delta Y_{1n}^2}
\]  

(B.19)

where \( Y_{1n}^{\text{meas}} \) and \( Y_{1n}^{\text{sim}} \) are the measured and simulated values of Y<sub>1n</sub>, respectively, and

\[
\Delta Y_{1n} = \sqrt{\left(\frac{\Delta Y_{1n}^{\text{meas}}}{Y_{1n}^{\text{meas}}}\right)^2 + \left(\frac{\delta T_B}{T_B}\right)^2 Y_{1n}^{\text{meas}}}
\]  

(B.20)

where \( \Delta Y_{1n}^{\text{meas}} \) is the absolute error on the measured Y<sub>1n</sub>, and \( T_B \) and \( \delta T_B \) are the measured burn duration and its error, respectively. Since \( T_B \) is used to calculate Y<sub>1n</sub>, it is necessary to include \( \delta T_B \) in the error of Y<sub>1n</sub>.

\[
\chi^2_{Y_{2/Y_{1n}}} = \frac{\left(Y_{2/Y_{1n}}^{\text{meas}} - Y_{2/Y_{1n}}^{\text{sim}}\right)^2}{\Delta\left(\frac{Y_{2/Y_{1n}}^{\text{meas}}}{Y_{1n}^{\text{meas}}}\right)^2}
\]  

(B.21)

where \( Y_{2/Y_{1n}}^{\text{meas}} \) and \( Y_{2/Y_{1n}}^{\text{sim}} \) are the measured and simulated ratios of secondary to primary yields, respectively, and

\[
\Delta\left(\frac{Y_{2/Y_{1n}}^{\text{meas}}}{Y_{1n}^{\text{meas}}}\right) = \sqrt{\left(\frac{\Delta Y_{1n}^{\text{meas}}}{Y_{1n}^{\text{meas}}}\right)^2 + \left(\frac{\delta Y_{2/Y_{1n}}^{\text{meas}}}{Y_{2/Y_{1n}}^{\text{meas}}}\right)^2 \left(\frac{Y_{2/Y_{1n}}^{\text{meas}}}{Y_{1n}^{\text{meas}}}\right)}
\]  

(B.22)
where $\delta Y^{measured}_2$ is the absolute error on the measured $Y_2$. The same equation is used for $Y_{2p}/Y_{1n}$ and $Y_{2n}/Y_{1n}$.

$$\chi^2_{E_{2p}} = \frac{(E_{2p}^{meas} - E_{2p}^{sim})^2}{\delta E_{2p}^2} \quad (B.23)$$

where $E_{2p}^{meas}$ and $E_{2p}^{sim}$ are the measured and simulated values of the average secondary proton energy, respectively, and $\delta E_{2p}$ is the error on $E_{2p}^{meas}$, which is typically $0.10 - 0.15$ MeV.

$$\chi^2_{T_i} = \frac{(T_i^{meas} - T_i^{sim})^2}{\delta T_i^2} \quad (B.24)$$

where $T_i^{meas}$ and $T_i^{sim}$ are the measured and simulated values of the primary-neutron-yield-averaged temperature, and $\delta T_i$ is the error on $T_i^{meas}$, which is typically $0.5$ keV.

The total $\chi^2$ is a sum of the five individual $\chi^2$ for each measurable ($Y_{1n}$, $Y_{2n}/Y_{1n}$, $Y_{2p}/Y_{1n}$, $<E_{2p}>$, and $<T_i>/Y_{1n}$). The program first calculates $Y_{1n}$ and $<T_i>/Y_{1n}$ from the burn profile, then goes through the Monte-Carlo process for the secondary proton spectrum ($Y_{2p}$ and $<E_{2p}>$ are obtained) and the secondary neutron spectrum ($Y_{2n}$ is obtained) as explained in Section B.3. Therefore, after each measurable is calculated, its $\chi^2$ is calculated and added to the total $\chi^2$. Once the total $\chi^2$ becomes significantly larger compared to the minimum value of $\chi^2$, the program skips the remaining calculations for that profile and begins a new calculation for the next profile. If the total $\chi^2$ of a particular profile is within some range of minimum $\chi^2$, the values of yields, energy and temperature along with the parameters specifying the profiles are recorded in a file. If the total $\chi^2$ of a profile is smaller than the minimum $\chi^2$, it becomes the new minimum. Although multiple local minima exist within the parameter space, for all simulations there is one clearly defined region with the smallest values of $\chi^2$. 

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Appendix C: Details of simulated results

In this section, details of the results of simulations of three types of OMEGA implosions are presented. Figure C.1 shows the range of parameters for which total $\chi^2$ is within one of the minimum $\chi^2$ for the low $\rho R$ implosion 30981. Results for the medium $\rho R$ implosion 27443 and the cryogenic implosion 28900 are shown in Figures C.2 and C.3, respectively.
Figure C.1 Range of parameters which produced reasonably good fits to the data for implosion 30981. Large square points represent the best-fit parameters, while other points represent parameters for which total $\chi^2$ were within one of the minimum value. (a) Peak ion temperature ($T_{i0}$) and $1/e$ radius of ion temperature Gaussian ($T_{iw}$), (b) $T_{i0}$ and power of exponent of ion temperature Gaussian ($T_p$), and (c) position of peak shell density ($S_{\rho}$) and $1/e$ radius of shell density Gaussian ($S_w$) show strong correlations. (d) Since $S_w$ is small, nuclear production is insensitive to the power of the exponent of shell density Gaussian ($S_p$). $S_p > 10$ was not explored since the shape of Gaussian does not show any significant change. Ranges of burn-averaged profiles are shown in Fig. A.4.
Figure C.2 Range of parameters which produced reasonably good fits to the data for implosion 27443. (a) $T_{i0}$ and $T_{iw}$, and (b) $T_{i0}$ and $T_{ip}$ show strong correlations. (c and d) $S_{r0}$, $S_w$, and $S_p$ are tightly constrained because the amount of mix has a significant impact on secondary yields. (d) Super-Gaussian shell profile is required to mix enough shell material into the fuel to match secondary yields. Range of acceptable profiles are shown in Fig. A.5.
Figure C.3 Range of parameters which produced reasonably good fits to the data for implosion 28900. (a) $T_{i0}$ and $T_{iw}$, (b) $T_{s0}$ and $T_{p}$, and (c) $S_{s0}$ and $S_{w}$ show strong correlations. Range of acceptable profiles are shown in Fig. A.6.
Appendix D: Compilation of experimental data

Shot information and spectra from various types of D\textsubscript{2} implosions have been compiled for reference purposes. Figs. D.1 and D.2 show the spread of secondary proton energy and yield, respectively. Experimental conditions and measured data are summarized in Table D.1, which is followed by a set of spectra from magnet-based charged-particle spectrometers (CPS1 and CPS2) and wedge-range-filter proton spectrometers (WRFs) for each implosion. Definition of relevant variables is listed prior to the table and the compilation of spectra.

Figure D.1 Relative scatter in measured average secondary proton energy for each shot. The energy spread is small for thin shell implosions because most of shell material is ablated away. For thick shell and cryogenic implosions a significant amount of shell (cold fuel) remains, and the amount of secondary proton energy loss depends heavily on the direction of secondary protons and the amount of shell material remaining in that direction.
Figure D.2 Relative scatter in measured secondary proton yield for each shot. Yield measurements for thin-shell capsules irradiated with ~23 kJ laser energy, in which nuclear production begins during the laser pulse (while there is a potential difference between the capsule and the target chamber wall), and other types of implosions, in which nuclear production begins after the laser is off, have a similar amount of scatter. This indicates that the potential does not affect charged particle yield measurements.
Definitions of variables:

Shot #: shot number
Target: fill(pressure in atm)shell[thickness in \( \mu \)m] diameter in \( \mu \)m
Pulse Shape: nominal pulse shape
  SG1018: 1 ns square pulse
  SG0801: 800 ps pulse*

Laser energy: measured laser energy delivered to target in kJ
Bang time: measured time in ps when primary neutron production is at its peak (t = 0 occurs when laser is turned on)
Burn width: measured full-width-half-maximum of primary neutron production rate curve in ps

\( Y_{1n} \): measured primary neutron yield and its absolute uncertainty and its statistical and absolute errors
\( Y_{2n} \): measured secondary neutron yield and its absolute uncertainty and its statistical and absolute errors

\( <T_i>_{Y_{1n}} \): measured primary-neutron-yield-averaged ion temperature in keV
\( \rho R_{\text{hot},n}^{\exp 1} \): hot-fuel \( \rho R \) inferred from \( Y_{2n}/Y_{1n} \) using the hot-spot model assuming a \( <T_i>_{Y_{1n}} \) plasma and its error in mg/cm\(^2\)**

\( <T_i>_{Y_{2n}} \): calculated secondary-neutron-yield-averaged ion temperature for the type of implosion in keV
\( \rho R_{\text{hot},n}^{\exp 2} \): hot-fuel \( \rho R \) inferred from \( Y_{2n}/Y_{1n} \) using the hot-spot model assuming a \( <T_i>_{Y_{1n}} \) plasma and its error in mg/cm\(^2\)**

\( <Y_{2p}> \): measured average secondary proton yield and its absolute error
\( \sigma_{Y_{2p}} \): standard deviation of secondary proton measurements for each implosion
\( \sigma(\sigma_{Y_{2p}}) \): standard error in secondary proton measurements
\( \rho R_{\text{hot},p}^{\exp 1} \): hot-fuel \( \rho R \) inferred from \( Y_{2p}/Y_{1n} \) using the hot-spot model assuming a \( <T_i>_{Y_{1n}} \) plasma and its error in mg/cm\(^2\)**

\( <T_i>_{Y_{2p}} \): calculated secondary-proton-yield-averaged ion temperature for the type of implosion in keV
\( \rho R_{\text{hot},p}^{\exp 2} \): hot-fuel \( \rho R \) inferred from \( Y_{2p}/Y_{1n} \) using the hot-spot model assuming a \( <T_i>_{Y_{2p}} \) plasma and its error in mg/cm\(^2\)**

\( <E_{2p}> \): measured average secondary proton energy and its error in MeV
\( \sigma_{E_{2p}} \): standard deviation of average secondary proton energy for each implosion
\( \sigma(\sigma_{E_{2p}}) \): standard error in secondary proton energy measurements

* pulses with asterisks maintained the pulse shape but were truncated to \( \sim 650 \) ps

** D densities of 1.2 +/- 1, 2 +/- 1, and 3 +/- 1.5 g/cc were assumed for thin-glass, thick-plastic, and cryogenic implosions, respectively
<table>
<thead>
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Table D.1
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Table D.1
Definitions:

Shot #: shot number
Target: fill (pressure in atm) shell [thickness in μm] diameter in μm
On-Target Energy: energy delivered to target in kJ
Pulse Shape: nominal pulse shape
SG1018: 1 ns square pulse
SG0801: 800 ps pulse*

Y_{1n}: primary neutron yield and its absolute error
<T_{i}Y_{1n}> primary-neutron-yield-averaged ion temperature in keV
Bang Time: time in ps when primary neutron production is at its peak (t = 0 when laser is turned on)
Burn Width: full-width-half-maximum of primary neutron production rate curve in ps
Y_{2n}: secondary neutron yield and its absolute error
<T_{2p}>: average secondary proton yield over all WRFs and its absolute error
ρR_{hot,2p,hot-spot}: hot-fuel areal density inferred from Y_{2p}/Y_{1n} using the hot-spot model**
ρR_{hot,2n,hot-spot}: hot-fuel areal density inferred from Y_{2n}/Y_{1n} using the hot-spot model**
ρR_{hot,2p,uniform}: hot-fuel areal density inferred from Y_{2p}/Y_{1n} using the uniform model**
ρR_{hot,2n,uniform}: hot-fuel areal density inferred from Y_{2n}/Y_{1n} using the uniform model**
<E_{2p}> average secondary proton energy over all WRFs and its absolute error
ρR_{total}: total areal density inferred from secondary proton energy downshift***

Charged-particle-spectrometry (CPS) data

Port: CPS-1 or CPS-2 (width of collimator in mm)
Particle detected: particle type detected on CPS
Yield: yield of charged particle
Yield (Gaussian): yield of charged particle under best-fit Gaussian to the spectrum
<E>: average energy of particle
<E> (Gaussian): average energy of particle under best-fit Gaussian to the spectrum
σ (Gaussian): standard deviation of Gaussian fit
<T_i>: ion temperature determined using standard deviation of spectrum

Wedge-range-filter (WRF) spectrometer data

Port: position of WRF in OMEGA chamber (TIM 1-6 and KO 1-3) and its distance from target chamber center in cm
Y_{2p}: yield of secondary protons****
<E>: average energy of secondary protons in MeV*****

* pulses with asterisk maintained the pulse shape but were truncated to ~ 650 ps
** ion temperature of <T_{i}Y_{1n} +/- 0.5 keV and D densities of 1.2 +/- 1, 2 +/- 1, and 3 +/- 1.5 g/cc were assumed for thin-glass, thick-plastic, and cryogenic implosions, respectively
*** ion temperature of 1 keV, and SiO₂, CH, and cold D densities of 5, 10, and 7 g/cc were assumed for thin-glass, thick-plastic, and cryogenic implosions, respectively. For implosions in which nuclear production began during the laser pulse, the error is not calculated because secondary proton energy was upshifted by unknown amount due to charging of capsule.

**** error on each WRF yield measurement is a percentage of the total yield (10 – 15% depending on statistics)

***** error on each WRF energy measurement is 0.1 – 0.15 MeV depending on statistics
Summary of thin shell implosions
<table>
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<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>Y_{1n} (x10^{11})</th>
<th>&lt;T_{p1n}&gt; (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tr>
<td>27817</td>
<td>D_{2}(15) SiO_{2}[2.1] 904.2 um</td>
<td>21.5</td>
<td>SSD: SG1018</td>
<td>2.0 ± 0.4</td>
<td>8.4 ± 0.5</td>
<td>Not Available</td>
<td>Not Available</td>
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CPS-1 (1mm slit)

DD protons
Yield (Gaussian): \((1.8 \pm 0.2) \times 10^{11}\)
\(<E>\) (Gaussian): 3.26 ± 0.02 MeV
\(\sigma\) (Gaussian): 0.10
\(<T_p>\): 6.3 keV

CPS-2 (1mm slit)

DD protons
Yield (Gaussian): \((2.0 \pm 0.2) \times 10^{11}\)
\(<E>\) (Gaussian): 3.31 ± 0.02 MeV
\(\sigma\) (Gaussian): 0.12
\(<T_p>\): 9.2 keV

Note:
### Secondary proton spectra from WRF

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<th>Shot #</th>
<th>$&lt;Y_{2p}&gt;$ (x10^7)</th>
<th>$Y_{zn}$ (x10^7)</th>
<th>$\rho R_{hot, 2p}$, hot-spot (mg/cm²)</th>
<th>$\rho R_{hot, 2a}$, hot-spot (mg/cm²)</th>
<th>$\rho R_{hot, 2p}$, uniform (mg/cm²)</th>
<th>$\rho R_{hot, 2a}$, uniform (mg/cm²)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm²)</th>
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<td>2.9 +/- 0.4</td>
<td>3.5 +/- 0.8</td>
<td>0.8 +/- 0.2</td>
<td>1.6 +/- 0.5</td>
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**TIM2, 12.5cm**

$Y_{2p}$: 2.8x10^7  
$<E>$: 15.2

**TIM3, 12.5cm**

$Y_{2p}$: 3.5x10^7  
$<E>$: 15.39

**TIM4, 12.5cm**

$Y_{2p}$: 3.5x10^7  
$<E>$: 15.26

**TIM5, 12.5cm**

$Y_{2p}$: 2.4x10^7  
$<E>$: 15.20

**TIM6, 12.5cm**

$Y_{2p}$: 2.5x10^7  
$<E>$: 15.21
CPS-1 (1mm slit)

DD protons
Yield (Gaussian): \((1.9 \pm 0.2) \times 10^{11}\)
\(<E>\) (Gaussian): \(3.27 \pm 0.02\) MeV
\(\sigma\) (Gaussian): 0.13
\(<T_p>\): 11.2 keV

DD tritons
Yield (Gaussian): \((1.7 \pm 0.2) \times 10^{11}\)
\(<E>\) (Gaussian): \(1.11 \pm 0.02\) MeV
\(\sigma\) (Gaussian): 0.13
\(<T_p>\): 11.0 keV

CPS-2 (1mm slit)

DD protons
Yield (Gaussian): \((2.1 \pm 0.2) \times 10^{11}\)
\(<E>\) (Gaussian): \(3.34 \pm 0.02\) MeV
\(\sigma\) (Gaussian): 0.11
\(<T_p>\): 7.7 keV

DD tritons
Yield: \((2.1 \pm 0.2) \times 10^{11}\)
\(<E>\): \(1.15 \pm 0.02\) MeV
Standard deviation: 0.14

Note:
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<th>Shot #</th>
<th>$\langle Y_{2p} \rangle$ (x10^7)</th>
<th>$Y_{2a}$ (x10^7)</th>
<th>$\rho R_{\text{hot-spot}}$ (mg/cm^2)</th>
<th>$\rho R_{\text{hot-spot}}$ (mg/cm^2)</th>
<th>$\rho R_{\text{uniform}}$ (mg/cm^2)</th>
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Secondary proton spectra from WRF

TIM2, 12.5cm
$Y_{2p}$: 2.7x10^7
$<E>$: 15.54

TIM3, 12.5cm
$Y_{2p}$: 2.3x10^7
$<E>$: 15.30

TIM4, 12.5cm
$Y_{2p}$: 2.8x10^7
$<E>$: 15.2

TIM5, 12.5cm
$Y_{2p}$: 2.6x10^7
$<E>$: 15.2

TIM6, 12.5cm
$Y_{2p}$: 2.6x10^7
$<E>$: 15.15
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<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1n}$ ($x10^{11}$)</th>
<th>$&lt;T_{i}\gamma_{1n}&gt;$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<td>D$_2$(15) SiO$_2$(3.3) 925 μm</td>
<td>22.9</td>
<td>SSD: SG1018</td>
<td>4.5 +/- 0.9</td>
<td>6.1 +/- 0.5</td>
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CPS-1 (1mm slit)

**DD protons**
- Yield (Gaussian): $(5.0 \pm 0.5) \times 10^{11}$
- $<E>$ (Gaussian): $3.03 \pm 0.02$ MeV
- $\sigma$ (Gaussian): 0.11
- $<T_i>$: 7.7 keV

**DD tritons**
- Yield (Gaussian): $(5.0 \pm 0.5) \times 10^{11}$
- $<E>$ (Gaussian): $1.01 \pm 0.02$ MeV
- $\sigma$ (Gaussian): 0.12
- $<T_i>$: 9.5 keV

CPS-2 (1mm slit)

**DD protons**
- Yield (Gaussian): $3.4 \times 10^{11}$
- $<E>$ (Gaussian): $3.11$ MeV
- $\sigma$ (Gaussian): 0.13
- $<T_i>$: 10.9 keV

Note: DD proton yield from CPS-2 is lower than yield from CPS-1 because of track overlap problem.
### Secondary proton spectra from WRF

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<th>$&lt;Y_{zp}&gt;$ (x10^8)</th>
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<th>$\rho R_{bot, 2p}$ hot-spot (mg/cm²)</th>
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**TIM1, 12.5cm**

- $Y_{zp}$: 3.0x10^8
- $<E>$: 14.82

**TIM2, 12.5cm**

- $Y_{zp}$: 2.5x10^8
- $<E>$: 14.86

**TIM3, 12.5cm**

- $Y_{zp}$: 2.8x10^8
- $<E>$: 14.91

**TIM4, 12.5cm**

- $Y_{zp}$: 2.5x10^8
- $<E>$: 14.82

**TIM5, 12.5cm**

- $Y_{zp}$: 3.0x10^8
- $<E>$: 14.81

**TIM6, 12.5cm**

- $Y_{zp}$: 2.6x10^8
- $<E>$: 14.87
### Table

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<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>( Y_{1a} ) (( x 10^{11} ))</th>
<th>( &lt;T_{\gamma} &gt; Y_{1a} ) (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29833</td>
<td>D_2(15) SiO_2[2.6] 912 μm</td>
<td>22.7</td>
<td>SSD: SG1018</td>
<td>4.1 +/- 0.8</td>
<td>7.0 +/- 0.5</td>
<td>900 +/- 50</td>
<td>160 +/- 25</td>
</tr>
</tbody>
</table>

### CPS-1 (1mm slit)

**DD protons**
- Yield (Gaussian): \((4.2 \pm 0.4) \times 10^{11}\)
- \(<E>\) (Gaussian): \(3.12 \pm 0.02\) MeV
- \(\sigma\) (Gaussian): 0.13
- \(<T_{\gamma}>\): 10.9 keV

**DD tritons**
- Yield (Gaussian): \((3.9 \pm 0.4) \times 10^{11}\)
- \(<E>\) (Gaussian): \(1.04 \pm 0.02\) MeV
- \(\sigma\) (Gaussian): 0.13
- \(<T_{\gamma}>\): 11.0 keV

### CPS-2 (1mm slit)

**DD protons**
- Yield (Gaussian): \(2.8 \times 10^{11}\)
- \(<E>\) (Gaussian): 3.10 MeV
- \(\sigma\) (Gaussian): 0.13
- \(<T_{\gamma}>\): 1.2 \times 10^{11}

**DD tritons**
- Yield: 1.07 MeV
- standard deviation: 0.14

---

Note: DD proton and triton yields from CPS-2 is lower than yields from CPS-1 because of track overlap problem.
### Secondary proton spectra from WRF

<table>
<thead>
<tr>
<th>Shot #</th>
<th>$&lt;Y_{2p}&gt;$</th>
<th>$Y_{2n}$</th>
<th>$\rho R_{hot, 2p}$, hot-spot (mg/cm²)</th>
<th>$\rho R_{hot, 2n}$, hot-spot (mg/cm²)</th>
<th>$\rho R_{hot, 2p}$, uniform (mg/cm²)</th>
<th>$\rho R_{hot, 2n}$, uniform (mg/cm²)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29833</td>
<td>1.1</td>
<td>1.2</td>
<td>+0.3</td>
<td>+0.7</td>
<td>+0.4</td>
<td>+0.8</td>
<td>15.09</td>
<td>+0.1</td>
</tr>
<tr>
<td></td>
<td>+/-</td>
<td>+/-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>0.1</td>
<td>0.2</td>
<td>-0.4</td>
<td>-1.1</td>
<td>-0.6</td>
<td>-0.6</td>
<td>-1.1</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

**TIM1, 12.5cm**

- $Y_{2p}$: $1.0 \times 10^8$
- $<E>$: 15.06

**TIM2, 12.5cm**

- $Y_{2p}$: $9.1 \times 10^7$
- $<E>$: 15.17

**TIM3, 12.5cm**

- $Y_{2p}$: $1.1 \times 10^8$
- $<E>$: 15.05

**TIM4, 12.5cm**

- $Y_{2p}$: $1.1 \times 10^8$
- $<E>$: 15.08

**TIM5, 12.5cm**

- $Y_{2p}$: $9.7 \times 10^7$
- $<E>$: 14.97

**TIM6, 12.5cm**

- $Y_{2p}$: $1.2 \times 10^8$
- $<E>$: 15.18
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{18}$ (x10$^{14}$)</th>
<th>$&lt;T_{18}&gt;_{18}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30979</td>
<td>D$_2$(14.7) SiO$_2$(2.9) 911 μm</td>
<td>20.5</td>
<td>SSD: SG0801</td>
<td>3.9 +/-</td>
<td>8.3 +/-</td>
<td>900 +/-</td>
<td>160 +/-</td>
</tr>
</tbody>
</table>

### CPS-1 (1mm slit)

**DD protons**
- Yield (Gaussian): (5.0 ± 0.5) x10$^{11}$
- $<E>$ (Gaussian): 3.03 ± 0.02 MeV
- $\sigma$ (Gaussian): 0.11

**DD tritons**
- Yield: (5.0 ± 0.5) x10$^{11}$
- $<E>$: 1.01 ± 0.02 MeV
- Standard deviation: 0.12

### CPS-2 (1mm slit)

**DD protons**
- Yield (Gaussian): 3.4 x10$^{11}$
- $<E>$ (Gaussian): 3.11 MeV
- $\sigma$ (Gaussian): 0.13

Note: DD proton yield from CPS-2 is lower than yield from CPS-1 because of track overlap problem.
<table>
<thead>
<tr>
<th>Shot #</th>
<th>$&lt;Y_{2p}&gt; (x10^8)$</th>
<th>$Y_{2p} (x10^5)$</th>
<th>$\rho R_{\text{hot}}$ for hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{\text{hot}}$ for uniform (mg/cm$^2$)</th>
<th>$\rho R_{\text{total}}$ (mg/cm$^2$)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{\text{total}}$ (mg/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30979</td>
<td>1.3</td>
<td>9.0</td>
<td>2.7</td>
<td>3.2</td>
<td>3.6</td>
<td>4.2</td>
<td>15.03</td>
</tr>
<tr>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>+ 0.4</td>
<td>+ 0.4</td>
<td>+ 0.5</td>
<td>+ 0.6</td>
<td>+/-</td>
</tr>
<tr>
<td>0.1</td>
<td>1.4</td>
<td>- 0.5</td>
<td>- 0.6</td>
<td>- 0.7</td>
<td>- 0.8</td>
<td>0.1</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Secondary proton spectra from WRF**

**TIM2, 12.5cm**

$Y_{2p}$: 1.2x10$^8$

$<E>$: 15.06

**TIM3, 12.5cm**

$Y_{2p}$: 1.3x10$^8$

$<E>$: 15.17

**TIM4, 12.5cm**

$Y_{2p}$: 1.3x10$^8$

$<E>$: 15.05

**TIM5, 12.5cm**

$Y_{2p}$: 1.1x10$^8$

$<E>$: 15.08

**TIM6, 12.5cm**

$Y_{2p}$: 1.5x10$^8$

$<E>$: 14.97

**Energy (MeV)**
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>( \gamma_{1S} ) (x10^{11})</th>
<th>( &lt;T_P&gt;<em>{\gamma</em>{1a}} ) (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30980</td>
<td>D_2 (14.7) SiO_2 [2.9]</td>
<td>13.2</td>
<td>SSD: SG0801</td>
<td>2.9 +/-</td>
<td>6.2 +/-</td>
<td>1050 +/-</td>
<td>170 +/-</td>
</tr>
</tbody>
</table>

**CPS-2 (0.5mm slit)**

- **DD protons**
  - Yield (Gaussian): \((2.6 \pm 0.3) \times 10^{11}\)
  - \(<E>\) (Gaussian): \(2.87 \pm 0.02\) MeV
  - \(\sigma\) (Gaussian): \(0.14\)
  - \(<T_P>\): \(12.7\) keV

- **DD tritons**
  - Yield (Gaussian): \((2.5 \pm 0.3) \times 10^{11}\)
  - \(<E>\) (Gaussian): \(0.94 \pm 0.02\) MeV
  - \(\sigma\) (Gaussian): \(0.1\)
  - \(<T_P>\): \(6.5\) keV

*Note: No CPS-1 data*
<table>
<thead>
<tr>
<th>Shot #</th>
<th>$&lt;Y_{Zp}&gt;$</th>
<th>$Y_{Zp}$</th>
<th>$\rho R_{bot, Zp}$</th>
<th>$\rho R_{bot, Zn}$</th>
<th>$\rho R_{bot, Zp}$</th>
<th>$\rho R_{bot, Zn}$</th>
<th>$E_{2p}$</th>
<th>$\rho R_{total}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(x10^8)</td>
<td>(x10^8)</td>
<td>(mg/cm^2)</td>
<td>(mg/cm^2)</td>
<td>(mg/cm^2)</td>
<td>(mg/cm^2)</td>
<td>(MeV)</td>
<td>(mg/cm^2)</td>
</tr>
<tr>
<td>30980</td>
<td>2.2</td>
<td>1.5</td>
<td>5.0</td>
<td>+0.7</td>
<td>+0.8</td>
<td>+0.9</td>
<td>7.8</td>
<td>14.68</td>
</tr>
<tr>
<td></td>
<td>+/-</td>
<td>+/-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+/+/+</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Secondary proton spectra from WRF

TIM2, 12.5cm

$Y_{Zp}$: 2.1x10^8
$\langle E \rangle$: 14.66

TIM3, 12.5cm

$Y_{Zp}$: 2.0x10^8
$\langle E \rangle$: 14.72

TIM4, 12.5cm

$Y_{Zp}$: 2.2x10^8
$\langle E \rangle$: 14.71

TIM5, 12.5cm

$Y_{Zp}$: 2.3x10^8
$\langle E \rangle$: 14.68

TIM6, 12.5cm

$Y_{Zp}$: 2.3x10^8
$\langle E \rangle$: 14.97
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>Y_{1\theta} (x10^{11})</th>
<th>&lt;T&gt;<em>{Y</em>{1\theta}} (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30981</td>
<td>D_{2}(14.7) SiO_{2}[3.1] 927</td>
<td>13.1</td>
<td>SSD:</td>
<td>1.5 +/-</td>
<td>8.2 +/-</td>
<td>1090</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SG0801</td>
<td>0.2</td>
<td>0.5</td>
<td>+/-</td>
<td>+/-</td>
</tr>
</tbody>
</table>

**CPS-1 (1mm slit)**

**DD protons**

Yield (Gaussian): \((1.5 \pm 0.2) \times 10^{11}\)

\(<E>\) (Gaussian): 2.63 \pm 0.02 MeV

\(\sigma\) (Gaussian): 0.12

\(<T>\): 9.2 keV

**DD tritons**

Yield (Gaussian): \((1.9 \pm 0.2) \times 10^{11}\)

\(<E>\) (Gaussian): 0.73 \pm 0.02 MeV

\(\sigma\) (Gaussian): 0.14

\(<T>\): 12.8 keV

**CPS-2 (1mm slit)**

**DD protons**

Yield (Gaussian): \((1.4E \pm 0.1) \times 10^{11}\)

\(<E>\) (Gaussian): 2.67 \pm 0.02 MeV

\(\sigma\) (Gaussian): 0.16

\(<T>\): 16.7 keV

**DD tritons**

Yield (Gaussian): \((1.3 \pm 0.1) \times 10^{11}\)

\(<E>\) (Gaussian): 0.77 \pm 0.02 MeV

\(\sigma\) (Gaussian): 0.11

\(<T>\): 7.9 keV

---

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### Secondary proton spectra from WRF

<table>
<thead>
<tr>
<th>Shot #</th>
<th>(&lt;Y_{2p}&gt; (x10^8))</th>
<th>(Y_{2p}) (x10^8)</th>
<th>(\rho R_{hot, spot, 2p}) (mg/cm²)</th>
<th>(\rho R_{hot, 2n}) (mg/cm²)</th>
<th>(\rho R_{hot, 2p}) (mg/cm²)</th>
<th>(\rho R_{total, uniform}) (mg/cm²)</th>
<th>(&lt;E_{2p}&gt;) (MeV)</th>
<th>(\rho R_{total}) (mg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30981</td>
<td>1.2</td>
<td>7.9</td>
<td>4.3</td>
<td>4.6</td>
<td>5.6</td>
<td>6.1</td>
<td>14.57</td>
<td>12.9</td>
</tr>
<tr>
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<td>+/-</td>
<td>+/-</td>
<td>+ 0.6</td>
<td>+ 0.6</td>
<td>+ 0.8</td>
<td>+ 0.8</td>
<td>+/-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>1.3</td>
<td>- 0.8</td>
<td>- 0.9</td>
<td>- 1.1</td>
<td>- 1.2</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

**TIM2, 12.5cm**

\(Y_{2p}: 1.3x10^8\)

\(<E>: 14.56\)

**TIM3, 12.5cm**

\(Y_{2p}: 1.3x10^8\)

\(<E>: 14.60\)

**TIM4, 12.5cm**

\(Y_{2p}: 1.3x10^8\)

\(<E>: 14.54\)

**TIM5, 12.5cm**

\(Y_{2p}: 1.1x10^8\)

\(<E>: 14.48\)

**TIM6, 12.5cm**

\(Y_{2p}: 1.2x10^8\)

\(<E>: 14.66\)
### CPS-1 (0.5mm slit)

**DD tritons**

Yield (Gaussian): \((1.7 \pm 0.2) \times 10^{11}\)

\(<E>\) (Gaussian): \(0.72 \pm 0.02\) MeV

\(\sigma\) (Gaussian): 0.12

\(<T_i>\): 9.4 keV

### CPS-2 (0.5mm slit)

**DD tritons**

Yield (Gaussian): \((1.7 \pm 0.2) \times 10^{11}\)

\(<E>\) (Gaussian): \(0.83 \pm 0.02\) MeV

\(\sigma\) (Gaussian): 0.12

\(<T_i>\): 9.4 keV

Note: Both CR-39 were etched for only two hours because track density is very high. DD proton tracks are too small to be scanned because of that.
<table>
<thead>
<tr>
<th>Shot #</th>
<th>$&lt;Y_{2p}&gt;$ (x10^7)</th>
<th>$Y_{2p}$ (x10^8)</th>
<th>$\rho R_{hot, Zn}$, hot-spot (mg/cm^2)</th>
<th>$\rho R_{hot, Zn}$, uniform (mg/cm^2)</th>
<th>$\rho R_{hot, Zn}$, uniform (mg/cm^2)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30982</td>
<td>1.1 +/- 0.5</td>
<td>7.3 +/- 0.5</td>
<td>4.0 + 0.6</td>
<td>4.5 + 0.6</td>
<td>5.3 + 0.7</td>
<td>14.64 +/- 0.1</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>1.2</td>
<td>4.0 + 0.6</td>
<td>4.5 + 0.6</td>
<td>5.3 + 0.7</td>
<td>14.64 +/- 0.1</td>
<td>10.7</td>
</tr>
</tbody>
</table>

Secondary proton spectra from WRF

TIM2, 12.5 cm

$Y_{2p}$: 1.1x10^8  
$<E>$: 14.63

TIM3, 12.5 cm

$Y_{2p}$: 1.1x10^8  
$<E>$: 14.56

TIM4, 12.5 cm

$Y_{2p}$: 1.0x10^8  
$<E>$: 14.67

TIM5, 12.5 cm

$Y_{2p}$: 1.1x10^8  
$<E>$: 14.60

TIM5, 12.5 cm

$Y_{2p}$: 9.6x10^7  
$<E>$: 14.71
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1e}$ ($10^{11}$)</th>
<th>&lt;$T_{P}$&gt; &lt;$Y_{1e}$&gt; (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30983</td>
<td>D$_2$(14.7) SiO$_2$(2.9) 912</td>
<td>11.5</td>
<td>SSD: SG0801</td>
<td>1.7 +/- 5.9 +/-</td>
<td>1060 +/- 5.2 +/-</td>
<td>170</td>
<td>+/-</td>
</tr>
</tbody>
</table>

**CPS-1 (0.5mm slit)**

**DD tritons**

Yield (Gaussian): \((1.5 \pm 0.2) \times 10^{11}\)

$<E>$ (Gaussian): \(0.68 \pm 0.02\) MeV

$\sigma$ (Gaussian): 0.10

$<T_i>$: 6.5 keV

**CPS-2 (0.5mm slit)**

**DD tritons**

Yield (Gaussian): \((2.1 \pm 0.2) \times 10^{11}\)

$<E>$ (Gaussian): \(0.84 \pm 0.02\) MeV

$\sigma$ (Gaussian): 0.11

$<T_i>$: 7.9 keV

Note: Both CR-39 were etched for only two hours because track density is very high. DD proton tracks are too small to be scanned because of that.
<table>
<thead>
<tr>
<th>Shot #</th>
<th>$&lt;Y_{2p}&gt;$ ((x10^8))</th>
<th>$Y_{2p}$ ((x10^8))</th>
<th>$\rho R_{bot, 2p, hot-spot}$ ((\text{mg/cm}^2))</th>
<th>$\rho R_{bot, 2n, hot-spot}$ ((\text{mg/cm}^2))</th>
<th>$\rho R_{bot, 2p, uniform}$ ((\text{mg/cm}^2))</th>
<th>$\rho R_{bot, 2n, uniform}$ ((\text{mg/cm}^2))</th>
<th>$&lt;E_{2p}&gt;$ ((\text{MeV}))</th>
<th>$\rho R_{total}$ ((\text{mg/cm}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>30983</td>
<td>1.2</td>
<td>6.3</td>
<td>3.9</td>
<td>3.4</td>
<td>5.1</td>
<td>5.1</td>
<td>14.62</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Secondary proton spectra from WRF

TIM2, 12.5cm
$Y_{2p}$: 1.2$x10^8$
$<E>$: 14.51

TIM3, 12.5cm
$Y_{2p}$: 1.4$x10^8$
$<E>$: 14.69

TIM4, 12.5cm
$Y_{2p}$: 1.2$x10^8$
$<E>$: 14.59

TIM5, 12.5cm
$Y_{2p}$: 1.1$x10^8$
$<E>$: 14.61

TIM6, 12.5cm
$Y_{2p}$: 1.3$x10^8$
$<E>$: 14.70
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>Yield ($Y_{1s}$) ($x10^{11}$)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30984</td>
<td>$\text{D}_2(14.7)$ SiO$_2[2.4]$ 927</td>
<td>11.1</td>
<td>SSD: SG0801</td>
<td>2.3 +/- 6.3 +/-</td>
<td>920 +/-</td>
<td>160 +/-</td>
</tr>
</tbody>
</table>

**CPS-1 (1mm slit)**

DD protons
Yield (Gaussian): $(2.9 \pm 0.3) \times 10^{11}$

$\langle E \rangle$ (Gaussian): $2.97 \pm 0.02$ MeV

$\sigma$ (Gaussian): 0.13

$\langle T_p \rangle$: 10.9 keV

DD tritons
Yield (Gaussian): $(2.7 \pm 0.3) \times 10^{11}$

$\langle E \rangle$ (Gaussian): $1.01 \pm 0.02$ MeV

$\sigma$ (Gaussian): 0.11

$\langle T_p \rangle$: 7.9 keV

**CPS-2 (1mm slit)**

DD protons
Yield (Gaussian): $(2.7 \pm 0.3) \times 10^{11}$

$\langle E \rangle$ (Gaussian): $3.02 \pm 0.02$ MeV

$\sigma$ (Gaussian): 0.12

$\langle T_p \rangle$: 9.2 keV

DD tritons
Yield (Gaussian): $(2.5 \pm 0.3) \times 10^{11}$

$\langle E \rangle$ (Gaussian): $1.02 \pm 0.02$ MeV

$\sigma$ (Gaussian): 0.11

$\langle T_p \rangle$: 7.9 keV
<table>
<thead>
<tr>
<th>Shot #</th>
<th>$Y_{\text{2p}}$ (x10^6)</th>
<th>$Y_{\text{2n}}$ (x10^5)</th>
<th>$\rho R_{\text{hot, 2p}}$ (mg/cm²)</th>
<th>$\rho R_{\text{hot, 2n}}$ (mg/cm²)</th>
<th>$\rho R_{\text{hot, 2p}}$ (mg/cm²)</th>
<th>$\rho R_{\text{hot, 2n}}$ (mg/cm²)</th>
<th>$\rho R_{\text{total}}$ (mg/cm²)</th>
<th>$&lt;E_{\text{2p}}&gt;$ (MeV)</th>
<th>$&lt;E_{\text{2n}}&gt;$ (MeV)</th>
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</thead>
<tbody>
<tr>
<td>30984</td>
<td>1.4 +/-</td>
<td>5.2 +/-</td>
<td>3.4 + 0.5</td>
<td>2.3 + 0.3</td>
<td>4.5 + 0.6</td>
<td>3.0 + 0.4</td>
<td>14.72 +/-</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

**Secondary proton spectra from WRF**

**TIM2, 12.5cm**
- $Y_{\text{2p}}$: 1.4x10^8
- $<E>$: 14.68

**TIM3, 12.5cm**
- $Y_{\text{2p}}$: 1.6x10^8
- $<E>$: 14.65

**TIM4, 12.5cm**
- $Y_{\text{2p}}$: 1.3x10^8
- $<E>$: 14.84

**TIM5, 12.5cm**
- $Y_{\text{2p}}$: 1.3x10^8
- $<E>$: 14.74

**TIM6, 12.5cm**
- $Y_{\text{2p}}$: 1.2x10^8
- $<E>$: 14.69
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>( V_{18} ) (x10^{11})</th>
<th>( \langle T_p \rangle_{\gamma_{18}} ) (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30985</td>
<td>( \text{D}_2(14.7) ) SiO_2[2.3] 909</td>
<td>11.0</td>
<td>SSD: SG0801</td>
<td>2.0</td>
<td>+/-</td>
<td>8.5</td>
<td>+/-</td>
</tr>
</tbody>
</table>

CPS-1 (0.5mm slit)

DD protons
Yield (Gaussian): \((2.7 \pm 0.3) \times 10^{11}\)
\(\langle E \rangle\) (Gaussian): \(2.95 \pm 0.02\) MeV
\(\sigma\) (Gaussian): \(0.14\)
\(\langle T_p \rangle\): \(12.7\) keV

DD tritons
Yield (Gaussian): \((2.7 \pm 0.3) \times 10^{11}\)
\(\langle E \rangle\) (Gaussian): \(1.01 \pm 0.02\) MeV
\(\sigma\) (Gaussian): \(0.12\)
\(\langle T_p \rangle\): \(9.4\) keV

CPS-2 (0.5mm slit)

DD protons
Yield (Gaussian): \((2.2 \pm 0.2) \times 10^{11}\)
\(\langle E \rangle\) (Gaussian): \(3.0 \pm 0.02\) MeV
\(\sigma\) (Gaussian): \(0.12\)
\(\langle T_p \rangle\): \(9.2\) keV

DD tritons
Yield (Gaussian): \((2.1 \pm 0.2) \times 10^{11}\)
\(\langle E \rangle\) (Gaussian): \(1.02 \pm 0.02\) MeV
\(\sigma\) (Gaussian): \(0.11\)
\(\langle T_p \rangle\): \(7.9\) keV
### Secondary Proton Spectra from WRF

<table>
<thead>
<tr>
<th>Shot #</th>
<th>(&lt;Y_{2p}&gt;) (x10^8)</th>
<th>Y_{2n} (x10^3)</th>
<th>(\rho R_{\text{hot}, 2p, \text{hot-spot}}) (mg/cm^2)</th>
<th>(\rho R_{\text{hot}, 2n, \text{hot-spot}}) (mg/cm^2)</th>
<th>(\rho R_{\text{hot}, 2p, \text{uniform}}) (mg/cm^2)</th>
<th>(\rho R_{\text{hot}, 2n, \text{uniform}}) (mg/cm^2)</th>
<th>(\text{E}_{2p}) (MeV)</th>
<th>(\rho R_{\text{total}}) (mg/cm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30985</td>
<td>1.1</td>
<td>6.2</td>
<td>3.0</td>
<td>2.9</td>
<td>4.0</td>
<td>3.9</td>
<td>14.69</td>
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<td>+/-</td>
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<td>+0.4</td>
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<td>1.1</td>
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<td>-0.6</td>
<td>-0.8</td>
<td>-0.8</td>
<td>0.1</td>
<td>N/A</td>
</tr>
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</table>

**TIM2, 12.5cm**

- \(<Y_{2p}>\): 1.1x10^8
- \(<E>\): 14.60

**TIM3, 12.5cm**

- \(<Y_{2p}>\): 1.1x10^8
- \(<E>\): 14.60

**TIM4, 12.5cm**

- \(<Y_{2p}>\): 1.0x10^8
- \(<E>\): 14.86

**TIM5, 12.5cm**

- \(<Y_{2p}>\): 1.0x10^8
- \(<E>\): 14.55

**TIM6, 12.5cm**

- \(<Y_{2p}>\): 1.0x10^8
- \(<E>\): 14.85

95
Summary of thick shell implosions
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{\text{in}}$ (x10^11)</th>
<th>$&lt;T_p&gt;$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27443</td>
<td>D2(15) CH[19.4]</td>
<td>22.0</td>
<td>SSD: SG1018</td>
<td>1.5 (+/-)</td>
<td>4.1 (+/-)</td>
<td>1870 (+/-)</td>
<td>150 (+/-)</td>
</tr>
<tr>
<td></td>
<td>934.8 μm</td>
<td></td>
<td></td>
<td>0.2 0.5</td>
<td></td>
<td>50</td>
<td>25</td>
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</table>

<table>
<thead>
<tr>
<th>$&lt;Y_{2p}&gt;$ (x10^8)</th>
<th>$Y_{2p}$ (x10^8)</th>
<th>$\rho R_{\text{hot-spot}}$ (mg/cm^2)</th>
<th>$\rho R_{\text{hot-spot}}$ (mg/cm^2)</th>
<th>$\rho R_{\text{hot-spot}}$ (mg/cm^2)</th>
<th>$\rho R_{\text{uniform}}$ (mg/cm^2)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{\text{total}}$ (mg/cm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2.3</td>
<td>5.0</td>
<td>12.8</td>
<td>6.8</td>
<td>16.4</td>
<td>13.1</td>
<td>57.1</td>
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<td>+/-</td>
<td>+/-</td>
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<td>+1.8</td>
<td>+0.8</td>
<td>+1.8</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>0.2</td>
<td>0.3</td>
<td>-1.0</td>
<td>-2.6</td>
<td>-0.7</td>
<td>-2.7</td>
<td>0.1</td>
<td>2.9</td>
</tr>
</tbody>
</table>

**Secondary proton spectra from WRF**

**TIM1, 12.5 cm**

$Y_{2p}$: 1.7x10^8  
$<E>$: 12.56  

**TIM3, 12.5 cm**

$Y_{2p}$: 1.3x10^8  
$<E>$: 13.27  

**TIM4, 12.5 cm**

$Y_{2p}$: 1.5x10^8  
$<E>$: 12.98  

**TIM5, 12.5 cm**

$Y_{2p}$: 1.5x10^8  
$<E>$: 13.53  

**TIM6, 12.5 cm**

$Y_{2p}$: 1.5x10^8  
$<E>$: 13.15
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>Yield$_1$ (x10$^{10}$)</th>
<th>$&lt;T_{\gamma}&gt;$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27444</td>
<td>D2(15) CH[19.2] 935.4 µm</td>
<td>21.8</td>
<td>SSD: SG1018</td>
<td>1.1</td>
<td>4.7</td>
<td>1870</td>
<td>160</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$&lt;Y_{2p}&gt;$ (x10$^7$)</th>
<th>$Y_{2\alpha}$ (x10$^6$)</th>
<th>$\rho R_{\text{bot, 2p}}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{\text{bot, 2n}}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{\text{bot, 2p}}$, uniform (mg/cm$^2$)</th>
<th>$\rho R_{\text{bot, 2n}}$, uniform (mg/cm$^2$)</th>
<th>$&lt;E_{1p}&gt;$ (MeV)</th>
<th>$\rho R_{\text{total}}$ (mg/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>1.1</td>
<td>3.3</td>
<td>9.0</td>
<td>4.2</td>
<td>11.4</td>
<td>13.55</td>
<td>44.0</td>
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</tr>
<tr>
<td>1.0</td>
<td>0.2</td>
<td>-0.8</td>
<td>-2.1</td>
<td>-1.0</td>
<td>-3.1</td>
<td>0.1</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Secondary proton spectra from WRF

**TIM1, 12.5cm**

- $Y_{2p}$: $6.0 \times 10^7$
- $<E>$: 13.12

**TIM3, 12.5cm**

- $Y_{2p}$: $7.8 \times 10^7$
- $<E>$: 13.76

**TIM4, 12.5cm**

- $Y_{2p}$: $6.8 \times 10^7$
- $<E>$: 13.55

**TIM5, 12.5cm**

- $Y_{2p}$: $6.6 \times 10^7$
- $<E>$: 13.89

**TIM6, 12.5cm**

- $Y_{2p}$: $6.9 \times 10^7$
- $<E>$: 13.43
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1n}$ ($\times 10^{19}$)</th>
<th>$&lt;T_{1n}&gt;<em>{Y</em>{1n}}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27445</td>
<td>D2(15) CH[19.2] 939.4 µm</td>
<td>22.2</td>
<td>SSD: SG1018</td>
<td>7.7</td>
<td>3.6</td>
<td>1860</td>
<td>170</td>
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<table>
<thead>
<tr>
<th>$&lt;Y_{2p}&gt;$ ($\times 10^3$)</th>
<th>$Y_{2p}$ ($\times 10^4$)</th>
<th>$\rho R_{hot, 2p}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2a}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2a}$, uniform (mg/cm$^2$)</th>
<th>$\rho R_{total}$, uniform (mg/cm$^2$)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm$^2$)</th>
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</thead>
<tbody>
<tr>
<td>5.2</td>
<td>7.1</td>
<td>3.4</td>
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<td>10.3</td>
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<td>+0.9</td>
<td>+1.8</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>0.8</td>
<td>1.2</td>
<td>-0.8</td>
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<td>-1.2</td>
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<td>0.1</td>
<td>3.0</td>
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</table>

**Secondary proton spectra from WRF**

**TIM1, 12.5cm**

$Y_{2p}$: $4.5 \times 10^7$

$<E>$: 12.97

**TIM3, 12.5cm**

$Y_{2p}$: $5.2 \times 10^7$

$<E>$: 13.88

**TIM4, 12.5cm**

$Y_{2p}$: $6.3 \times 10^7$

$<E>$: 13.75

**TIM5, 12.5cm**

$Y_{2p}$: $4.5 \times 10^7$

$<E>$: 13.97

**TIM6, 12.5cm**

$Y_{2p}$: $5.3 \times 10^7$

$<E>$: 13.52
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1p}$ (x10^{18})</th>
<th>&lt;T&gt;$_{\nu\nu}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27446</td>
<td>D2[15]</td>
<td>SSD: SG1018 939.6 μm</td>
<td>+/-</td>
<td>5.1</td>
<td>4.0</td>
<td>1850</td>
<td>+/-</td>
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<table>
<thead>
<tr>
<th>$&lt;Y_{2p}&gt;$ (x10^{18})</th>
<th>$Y_{2p}$ (x10^{18})</th>
<th>$\rho_{R_{hot}, 2p}$ (mg/cm^2)</th>
<th>$\rho_{R_{hot}, 2n}$ (mg/cm^2)</th>
<th>$\rho_{R_{shock}, 2p}$ uniform (mg/cm^2)</th>
<th>$\rho_{R_{shock}, 2n}$ uniform (mg/cm^2)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho_{total}$ (mg/cm^2)</th>
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</thead>
<tbody>
<tr>
<td>2.7</td>
<td>4.4</td>
<td>2.7</td>
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<td>3.6</td>
<td>9.8</td>
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<td>36.8</td>
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<td>+/-</td>
<td>+/-</td>
<td>+0.5</td>
<td>+1.6</td>
<td>+0.6</td>
<td>+2.0</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>0.4</td>
<td>0.9</td>
<td>-0.7</td>
<td>-2.2</td>
<td>-0.9</td>
<td>-2.9</td>
<td>0.1</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Secondary proton spectra from WRF

TIM1, 12.5cm

$Y_{2p}$: 2.7x10^7
$<E>$: 13.39

TIM4, 12.5cm

$Y_{2p}$: 2.7x10^7
$<E>$: 13.72

TIM5, 12.5cm

$Y_{2p}$: 2.5x10^7
$<E>$: 14.23

TIM6, 12.5cm

$Y_{2p}$: 2.9x10^7
$<E>$: 13.83
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1n}$ ($x10^{11}$)</th>
<th>$&lt;T_{11}&gt;$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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</thead>
<tbody>
<tr>
<td>27447</td>
<td>D2(15) CH[19.3] 930.6 μm</td>
<td>21.6</td>
<td>SSD: SG1018</td>
<td>1.4 +/- 0.1 0.5</td>
<td>3.6 +/- 0.5</td>
<td>1840 +/- 50</td>
<td>160 +/- 25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$&lt;Y_{2p}&gt;$ ($x10^8$)</th>
<th>$Y_{2p}$ ($x10^8$)</th>
<th>$&lt;E&gt;$</th>
<th>$Y_{2p}$ ($x10^8$)</th>
<th>$&lt;E&gt;$</th>
<th>$Y_{2p}$ ($x10^8$)</th>
<th>$&lt;E&gt;$</th>
<th>$Y_{2p}$ ($x10^8$)</th>
<th>$&lt;E&gt;$</th>
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</thead>
<tbody>
<tr>
<td>1.7 +/- 0.2</td>
<td>2.9 +/- 0.4</td>
<td>5.9</td>
<td>0.8</td>
<td>2.2</td>
<td>8.7</td>
<td>2.0</td>
<td>20.5</td>
<td>12.83</td>
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</tr>
</tbody>
</table>

**Secondary proton spectra from WRF**

TIM1, 17.5cm

$Y_{2p}$: 1.9x10^8  
$<E>$: 12.79

TIM3, 17.5cm

$Y_{2p}$: 1.4x10^8  
$<E>$: 12.87

TIM4, 17.5cm

$Y_{2p}$: 1.8x10^8  
$<E>$: 12.03

TIM5, 17.5cm

$Y_{2p}$: 1.7x10^8  
$<E>$: 13.06

TIM6, 17.5cm

$Y_{2p}$: 1.9x10^8  
$<E>$: 13.38
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{18}$ ($x10^{14}$)</th>
<th>$&lt;T_{p}&gt;_{18}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tbody>
<tr>
<td>27448</td>
<td>D2(15) CH[19.2] 930.4 µm</td>
<td>21.6</td>
<td>SSD: SG1018</td>
<td>1.4 +/- 0.1</td>
<td>3.8 +/- 0.5</td>
<td>1790 +/- 50</td>
<td>160 +/- 25</td>
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<table>
<thead>
<tr>
<th>$&lt;Y_{2p}&gt;$ ($x10^{8}$)</th>
<th>$Y_{2n}$ ($x10^{8}$)</th>
<th>$\rho R_{bot, 2p}$ (mg/cm²)</th>
<th>$\rho R_{bot, 2n}$ (mg/cm²)</th>
<th>$\rho R_{bot, 2p}$ uniform (mg/cm²)</th>
<th>$\rho R_{bot, 2n}$ uniform (mg/cm²)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm²)</th>
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</thead>
<tbody>
<tr>
<td>1.9 +/- 0.2</td>
<td>2.0 +/- 0.3</td>
<td>7.2 +/- 1.4</td>
<td>11.7 +/- 2.5</td>
<td>9.9 +/- 1.8</td>
<td>15.3 +/- 2.3</td>
<td>13.10 +/- 0.1</td>
<td>57.1 +/- 2.9</td>
</tr>
</tbody>
</table>

**Secondary proton spectra from WRF**

**TIM1, 17.5cm**

$Y_{2p}$: $1.7x10^8$

$<E>$: 12.97

**TIM3, 17.5cm**

$Y_{2p}$: $1.8x10^8$

$<E>$: 12.92

**TIM4, 17.5cm**

$Y_{2p}$: $2.2x10^8$

$<E>$: 13.05

**TIM5, 17.5cm**

$Y_{2p}$: $2.0x10^8$

$<E>$: 13.58

**TIM6, 17.5cm**

$Y_{2p}$: $2.0x10^8$

$<E>$: 12.97
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>(Y_{1n} \times 10^{11})</th>
<th>(&lt;T_{1n}&gt;) (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27449</td>
<td>D2(15) CH[19.3]</td>
<td>23.3</td>
<td>SSD: SG1018</td>
<td>1.6 +/-</td>
<td>4.2 +/-</td>
<td>1810 +/-</td>
<td>160 +/-</td>
</tr>
<tr>
<td></td>
<td>939.6 (\mu)m</td>
<td></td>
<td></td>
<td>0.2 0.5</td>
<td></td>
<td>50</td>
<td>25</td>
</tr>
</tbody>
</table>

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|}
\hline
<Y_{2p}> \times 10^8 & Y_{2n} \times 10^8 & \rho R_{\text{hot-spot}} & \rho R_{\text{hot-spot}} & \rho R_{\text{uniform}} & \rho R_{\text{uniform}} & <E_{2p}> (MeV) & \rho R_{\text{total}} (mg/cm^2) \\
\hline
1.6 & 2.3 & 4.9 & 11.8 & 6.8 & 15.6 & 13.21 & 54.0 \\
+/- & +/- & +/- & +/- & +/- & +/- & +/- & +/- \\
0.2 & 0.3 & -0.9 & -2.5 & -1.0 & -3.2 & 0.1 & 2.9 \\
\hline
\end{array}
\]

Secondary proton spectra from WRF

TIM1, 12.5cm

\(Y_{2p}: 1.8 \times 10^8\)
\(<E>: 12.75\)

TIM3, 12.5cm

\(Y_{2p}: 1.6 \times 10^8\)
\(<E>: 13.47\)

TIM4, 12.5cm

\(Y_{2p}: 1.5 \times 10^8\)
\(<E>: 13.14\)

TIM5, 12.5cm

\(Y_{2p}: 1.5 \times 10^8\)
\(<E>: 13.45\)

TIM6, 12.5cm

\(Y_{2p}: 1.5 \times 10^8\)
\(<E>: 13.22\)
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>Y1n (x10^1)</th>
<th>&lt;T1&gt;Y1n (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
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<tbody>
<tr>
<td>27450</td>
<td>D2(15) CH[19.3] 933.6 µm</td>
<td>22.1</td>
<td>SSD: SG1018</td>
<td>1.0 +/- 0.1</td>
<td>4.3 +/- 0.5</td>
<td>1810 +/- 50</td>
<td>160 +/- 25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>&lt;Y2p&gt; (x10^3)</th>
<th>Y2n (x10^3)</th>
<th>ρRhot, 2p, hot-spot (mg/cm²)</th>
<th>ρRhot, 2p, hot-spot (mg/cm²)</th>
<th>ρRhot, 2p, uniform (mg/cm²)</th>
<th>ρRhot, 2n, uniform (mg/cm²)</th>
<th>&lt;E2p&gt; (MeV)</th>
<th>ρRtot, (mg/cm²)</th>
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<tbody>
<tr>
<td>8.9 +/- 0.9</td>
<td>1.3 +/- 0.2</td>
<td>4.4 +/- 0.6</td>
<td>10.9 +/- 1.7</td>
<td>6.0 +/- 0.9</td>
<td>14.3 +/- 2.3</td>
<td>13.51 +/- 3.1</td>
<td>45.2 +/- 3.0</td>
</tr>
</tbody>
</table>

**Secondary proton spectra from WRF**

- TIM1, 12.5 cm
  - Y2p: 7.9x10^7
  - <E>: 12.79

- TIM3, 12.5 cm
  - Y2p: 8.7x10^7
  - <E>: 13.79

- TIM4, 12.5 cm
  - Y2p: 8.6x10^7
  - <E>: 13.47

- TIM5, 12.5 cm
  - Y2p: 9.5x10^7
  - <E>: 14.01

- TIM6, 12.5 cm
  - Y2p: 9.8x10^7
  - <E>: 13.49

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### Table

<table>
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<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>Y₁₈ (x10⁹)</th>
<th>&lt;T&gt;₂₈ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tbody>
<tr>
<td>27454</td>
<td>D2(15) CH[19.4]</td>
<td>22.2</td>
<td>SSD: SG1018</td>
<td>1.4</td>
<td>3.3</td>
<td>1870</td>
<td>160</td>
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<tr>
<td></td>
<td>942.8 µm</td>
<td></td>
<td></td>
<td>+/-</td>
<td>+/-</td>
<td>0.5</td>
<td>50</td>
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<th>&lt;Y₂₈&gt; (x10⁹)</th>
<th>Y₂₈ (x10⁹)</th>
<th>ρR₂₈, 2n, hot-spot (mg/cm²)</th>
<th>ρR₂₈, 2n, hot-spot (mg/cm²)</th>
<th>ρR₂₈, 2n, uniform (mg/cm²)</th>
<th>ρR₂₈, 2n, uniform (mg/cm²)</th>
<th>&lt;E₂₈&gt; (MeV)</th>
<th>ρR₂₈, total (mg/cm²)</th>
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<td>6.2</td>
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<td>9.9</td>
<td>16.7</td>
<td>13.13</td>
<td>56.3</td>
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<td>+/-</td>
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<td>+1.8</td>
<td>+3.7</td>
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<td>0.3</td>
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<td>-2.2</td>
<td>-3.2</td>
<td>0.1</td>
<td>2.9</td>
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</table>

---

### Secondary proton spectra from WRF

**TIM1, 12.5cm**

Y₂₈: 1.8x10⁸

<σ>: 13.09

**TIM3, 12.5cm**

Y₂₈: 1.8x10⁸

<σ>: 13.18

**TIM4, 12.5cm**

Y₂₈: 1.7x10⁸

<σ>: 12.69

**TIM5, 12.5cm**

Y₂₈: 1.5x10⁸

<σ>: 13.33

**TIM6, 12.5cm**

Y₂₈: 2.0x10⁸

<σ>: 13.15

---

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### Table

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{2p}$ ($x10^8$)</th>
<th>$&lt;T&gt;$</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tbody>
<tr>
<td>27455</td>
<td>D2(15)</td>
<td>21.7</td>
<td>SSD:</td>
<td>1.1</td>
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<td>140</td>
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<td></td>
<td>CH[19.3]</td>
<td></td>
<td>SG1018</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>940.6 μm</td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.5</td>
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<td>25</td>
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<th>$&lt;Y_{2p}&gt;$ ($x10^8$)</th>
<th>$Y_{2n}$ ($x10^8$)</th>
<th>$\rho R_{hot, zp, hot-spot}$ (mg/cm³)</th>
<th>$\rho R_{hot, zp, uniform}$ (mg/cm³)</th>
<th>$\rho R_{hot, 2p, uniform}$ (mg/cm³)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm³)</th>
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<td>1.0</td>
<td>1.4</td>
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<td>-2.5</td>
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<td>-3.2</td>
<td>0.1</td>
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### Secondary Proton Spectra from WRF

- **TIM1, 12.5cm**
  - $Y_{2p}$: $1.1x10^8$
  - $<E>$: 12.39

- **TIM3, 12.5cm**
  - $Y_{2p}$: $1.1x10^8$
  - $<E>$: 13.52

- **TIM4, 12.5cm**
  - $Y_{2p}$: $9.6x10^7$
  - $<E>$: 13.49

- **TIM5, 12.5cm**
  - $Y_{2p}$: $1.1x10^8$
  - $<E>$: 13.21

- **TIM6, 12.5cm**
  - $Y_{2p}$: $9.3x10^7$
  - $<E>$: 13.34
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<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{ln}$ ($10^{14}$)</th>
<th>$&lt;T_{R}&gt;_{vis}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tbody>
<tr>
<td>30621</td>
<td>D2(15.0) CH(19.4) 937.8 µm</td>
<td>N/A</td>
<td>SSD: SG1018</td>
<td>1.5 +/- 0.2 0.5 3.6 +/- 50 1890 170 +/- 25</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

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<tr>
<th>$&lt;Y_{2p}&gt;$ ($10^8$)</th>
<th>$Y_{2p}$ ($10^8$)</th>
<th>$\rho R_{hot, 2p}$, hot-spot (mg/cm²)</th>
<th>$\rho R_{hot, 2n}$, hot-spot (mg/cm²)</th>
<th>$\rho R_{hot, 2p}$, uniform (mg/cm²)</th>
<th>$\rho R_{hot, 2n}$, uniform (mg/cm²)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm²)</th>
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<tbody>
<tr>
<td>2.3 +/- 0.2</td>
<td>0.3</td>
<td>-1.1</td>
<td>-2.6</td>
<td>12.6</td>
<td>17.2</td>
<td>13.3</td>
<td>51.3</td>
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</tbody>
</table>

Secondary proton spectra from WRF

**TIM1, 12.5cm**

$Y_{2p}$: $2.1\times10^8$

$<E>$: 13.47

**TIM3, 12.5cm**

$Y_{2p}$: $2.3\times10^8$

$<E>$: 13.33

**TIM4, 12.5cm**

$Y_{2p}$: $2.5\times10^8$

$<E>$: 13.11
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<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>Pulse Length (x10^11)</th>
<th>T&lt;sub&gt;1n&lt;/sub&gt; (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tr>
<td>30626</td>
<td>D2(15.0)</td>
<td>CH(19.1) 948.2 µm</td>
<td>SSD: SG1018</td>
<td>22.5</td>
<td>1.9 +/- 0.3</td>
<td>4.1 +/- 0.5</td>
<td>1900 +/- 50</td>
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<table>
<thead>
<tr>
<th>&lt;Y&lt;sub&gt;2p&lt;/sub&gt; (x10^8)</th>
<th>Y&lt;sub&gt;2n&lt;/sub&gt; (x10^8)</th>
<th>ρ&lt;sub&gt;hot, 2p, hot-spot&lt;/sub&gt; (mg/cm^2)</th>
<th>ρ&lt;sub&gt;hot, 2n, hot-spot&lt;/sub&gt; (mg/cm^2)</th>
<th>ρ&lt;sub&gt;hot, 2p, uniform&lt;/sub&gt; (mg/cm^2)</th>
<th>ρ&lt;sub&gt;hot, 2n, uniform&lt;/sub&gt; (mg/cm^2)</th>
<th>&lt;E&lt;sub&gt;2p&lt;/sub&gt;&gt; (MeV)</th>
<th>ρ&lt;sub&gt;total&lt;/sub&gt; (mg/cm^2)</th>
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</thead>
<tbody>
<tr>
<td>4.1</td>
<td>3.8</td>
<td>11.1</td>
<td>-16.1</td>
<td>2.5</td>
<td>12.78</td>
<td>20.6</td>
<td>66.3</td>
</tr>
<tr>
<td>+/-</td>
<td>+/-</td>
<td>+/3.4</td>
<td>+/-2.7</td>
<td>+/3.2</td>
<td>+/-3.2</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>-2.3</td>
<td>-3.8</td>
<td>-11.4</td>
<td>-4.6</td>
<td>0.1</td>
<td>2.8</td>
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</table>

Secondary proton spectra from WRF

- TIM1, 12.5cm
  - Y<sub>2p</sub>: 4.3x10<sup>8</sup>
  - <E>: 12.69

- TIM3, 12.5cm
  - Y<sub>2p</sub>: 4.2x10<sup>8</sup>
  - <E>: 12.68

- TIM4, 12.5cm
  - Y<sub>2p</sub>: 3.8x10<sup>8</sup>
  - <E>: 12.96

Energy (MeV)
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>Y_{1q} (x10^{11})</th>
<th>&lt;T&gt;<em>{Y</em>{1q}} (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30627</td>
<td>D2(15.0)</td>
<td>22.5</td>
<td>SSD: SG1018</td>
<td>1.8</td>
<td>3.7</td>
<td>1890</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>CH[19.4]</td>
<td></td>
<td></td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td></td>
<td>941.8 μm</td>
<td></td>
<td></td>
<td>0.3</td>
<td>0.5</td>
<td>50</td>
<td>25</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Y_{2q} (x10^{8})</th>
<th>\rho_{\text{bot, 2q, bot-spot}} (mg/cm^2)</th>
<th>\rho_{\text{bot, 2q, uniform}} (mg/cm^2)</th>
<th>\rho_{\text{bot, 2q, uniform}} (mg/cm^2)</th>
<th>&lt;E_{2p}&gt; (MeV)</th>
<th>\rho_{\text{total}} (mg/cm^2)</th>
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<tbody>
<tr>
<td>3.7</td>
<td>4.3</td>
<td>10.7</td>
<td>18.5</td>
<td>23.1</td>
<td>12.67</td>
</tr>
<tr>
<td>+/-</td>
<td>+/-</td>
<td>+4.3</td>
<td>+2.9</td>
<td>+3.5</td>
<td>+/-</td>
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<td>0.4</td>
<td>0.5</td>
<td>-2.4</td>
<td>-4.2</td>
<td>-5.2</td>
<td>0.1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.8</td>
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</table>

**Secondary proton spectra from WRF**

- **TIM1, 12.5cm**
  - Y_{2p}: 4.0x10^8
  - <E>: 12.66

- **TIM3, 12.5cm**
  - Y_{2p}: 4.0x10^8
  - <E>: 12.68

- **TIM4, 12.5cm**
  - Y_{2p}: 3.2x10^8
  - <E>: 12.65
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1e}$ $(x10^{11})$</th>
<th>$&lt;T_1&gt;$ $Y_{1e}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tbody>
<tr>
<td>30628</td>
<td>D2[15.0]</td>
<td>22.5</td>
<td>SSD:</td>
<td>2.0</td>
<td>4.0</td>
<td>1880</td>
<td>160</td>
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<td></td>
<td>CH[19.3]</td>
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<td>SG1018</td>
<td>0.3</td>
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<th>$Y_{2p}$ $(x10^8)$</th>
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<th>$\rho R_{hot, 2p}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{hot, 2p}$, uniform (mg/cm$^2$)</th>
<th>$\rho R_{hot, 2p}$, uniform (mg/cm$^2$)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm$^2$)</th>
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<tr>
<td>4.4</td>
<td>4.1</td>
<td>11.6</td>
<td>16.6</td>
<td>28.6</td>
<td>20.9</td>
<td>12.81</td>
<td>65.4</td>
</tr>
<tr>
<td>+/-</td>
<td>+/-</td>
<td>+4.5</td>
<td>+2.7</td>
<td>+</td>
<td>+2.6</td>
<td>+/-</td>
<td>+/-</td>
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<tr>
<td>0.4</td>
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<td>-3.9</td>
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<td>-3.8</td>
<td>0.1</td>
<td>2.8</td>
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Secondary proton spectra from WRF

TIM1, 12.5cm
$Y_{2p}$: 4.4$x10^8$
$<E>$: 12.43

TIM3, 12.5cm
$Y_{2p}$: 4.5$x10^8$
$<E>$: 13.12

TIM4, 12.5cm
$Y_{2p}$: 4.2$x10^8$
$<E>$: 12.88

Energy (MeV)
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{18}$ ($\times 10^{11}$)</th>
<th>$&lt;T_{\mu}Y_{18}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tbody>
<tr>
<td>30629</td>
<td>D2(15.0) CH[20.6] 945.2 $\mu$m</td>
<td>22.9</td>
<td>SSD: SG1018</td>
<td>1.5 +/- 3.5 +/- 0.2 0.5</td>
<td>1950 +/- 50</td>
<td>180 +/- 25</td>
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</table>

<table>
<thead>
<tr>
<th>$&lt;Y_{2p}&gt;$ ($\times 10^8$)</th>
<th>$Y_{2p}$ ($\times 10^8$)</th>
<th>$\rho R_{\text{hot, 2p}}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{\text{hot, 2a}}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{\text{hot, 2a}}$, uniform (mg/cm$^2$)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{\text{total}}$ (mg/cm$^2$)</th>
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<tbody>
<tr>
<td>3.7</td>
<td>3.1</td>
<td>13.9</td>
<td>16.4</td>
<td>N/A</td>
<td>20.4</td>
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<td>+/-</td>
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<td>+</td>
<td>+2.2</td>
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<td>-3.1</td>
<td>N/A</td>
<td>-3.8</td>
<td>0.1</td>
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</table>

**Secondary proton spectra from WRF**

![Secondary proton spectra from WRF](image)

**TIM1, 12.5cm**

$Y_{2p}$: $3.4 \times 10^8$

$<E>$: 12.78

**TIM3, 12.5cm**

$Y_{2p}$: $3.9 \times 10^8$

$<E>$: 12.27

**TIM4, 12.5cm**

$Y_{2p}$: $3.7 \times 10^8$

$<E>$: 12.47

**Energy (MeV)**
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1p}$ ($x10^{11}$)</th>
<th>$&lt;T_1&gt;$ from (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tbody>
<tr>
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<td>D2(15.0)</td>
<td>CH[19.1]</td>
<td>24.2</td>
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<td>CH(878.2)</td>
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<td>+/-</td>
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<td></td>
<td></td>
<td>0.4</td>
<td>0.5</td>
<td>50</td>
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<table>
<thead>
<tr>
<th>$&lt;Y_{2p}&gt;$ ($x10^8$)</th>
<th>$Y_{2n}$ ($x10^8$)</th>
<th>$\rho R_{hot, 2p}$, hot-spot (mg/cm²)</th>
<th>$\rho R_{hot, 2n}$, hot-spot (mg/cm²)</th>
<th>$\rho R_{hot, 2p}$, uniform (mg/cm²)</th>
<th>$\rho R_{hot, 2n}$, uniform (mg/cm²)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm²)</th>
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<tr>
<td>5.7</td>
<td>4.1</td>
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<td>14.2</td>
<td>N/A</td>
<td>18.0</td>
<td>12.74</td>
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<td>+/-</td>
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<td>+</td>
<td>+2.4</td>
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<td>67.4</td>
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</tbody>
</table>

Secondary proton spectra from WRF

TIM2, 15.0cm
$Y_{2p}$: $6.1x10^8$
$<E>$: 12.62

TIM3, 15.0cm
$Y_{2p}$: $5.7x10^8$
$<E>$: 12.81

TIM4, 15.0cm
$Y_{2p}$: $6.1x10^8$
$<E>$: 12.54

TIM6, 15.0cm
$Y_{2p}$: $5.1x10^8$
$<E>$: 12.97

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Secondary proton spectra from WRF

TIM3, 15cm
Y_{2p}: 4.2x10^8
\langle E \rangle: 12.99

TIM4, 15cm
Y_{2p}: 4.6x10^8
\langle E \rangle: 12.8

TIM6, 15cm
Y_{2p}: 4.0x10^8
\langle E \rangle: 12.56
### Table

<table>
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<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1a}$ $(x10^3)$</th>
<th>$&lt;T_i&gt;$ $(keV)$</th>
<th>Burn Time (ps)</th>
<th>Burn Width (ps)</th>
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### Table (continued)

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<th>$\rho R_{hot, 2a, hot-spot}$ $(mg/cm^2)$</th>
<th>$\rho R_{hot, 2p, uniform}$ $(mg/cm^2)$</th>
<th>$\rho R_{hot, 2a, uniform}$ $(mg/cm^2)$</th>
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### Secondary proton spectra from WRF

**TIM3, 15cm**
- $Y_{2p}$: $2.5 \times 10^8$
- $<E>$: 12.73

**TIM4, 15cm**
- $Y_{2p}$: $2.4 \times 10^8$
- $<E>$: 12.04

**TIM6, 15cm**
- $Y_{2p}$: $2.5 \times 10^8$
- $<E>$: 12.94

**Energy (MeV)**
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<th>( Y_{1a} ) (x10^9)</th>
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<th>Burn Width (ps)</th>
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<th>( Y_{2p} ) (x10^9)</th>
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<th>( \rho R_{\text{bot, } 2n} )_bot-spot (mg/cm^2)</th>
<th>( \rho R_{\text{bot, } 2p} )_uniform (mg/cm^2)</th>
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Secondary proton spectra from WRF

TIM3, 15.0cm
\( Y_{2p} \): 2.8x10^8
\( <E> \): 13.39

TIM4, 15.0cm
\( Y_{2p} \): 3.5x10^8
\( <E> \): 12.76

TIM6, 15.0cm
\( Y_{2p} \): 3.2x10^8
\( <E> \): 12.53

Energy (MeV)
Summary of cryogenic implosions
### Table

<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1n}$ ($10^6$)</th>
<th>$&lt;T_{1n}&gt;$V1s (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<th>$&lt;Y_{2p}&gt;$ ($10^3$)</th>
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<th>$\rho R_{bot, 2n}$</th>
<th>$\rho R_{bot, 2p}$</th>
<th>$\rho R_{bot, 2n}$</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
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### Secondary proton spectra from WRF

- **TIM1, 15.0cm**
  - $Y_{2p}$: $1.4 \times 10^7$
  - $<E>$: 13.44

- **TIM3, 18.0cm**
  - $Y_{2p}$: $1.7 \times 10^7$
  - $<E>$: 14.26

- **TIM4, 15.0cm**
  - $Y_{2p}$: $1.7 \times 10^7$
  - $<E>$: 13.74

- **TIM6, 15.0cm**
  - $Y_{2p}$: $1.4 \times 10^7$
  - $<E>$: 14.12
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<thead>
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<th>Shot #</th>
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<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1a}$ ($x10^{11}$)</th>
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<td>3.6 +/- 0.5</td>
<td>1620 +/- 50</td>
<td>170 +/- 25</td>
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$$<Y_{2p}> \quad Y_{2a} \quad \rho R_{hot, 2p, \text{spot}} \quad \rho R_{hot, 2a, \text{spot}} \quad \rho R_{hot, 2a, \text{uniform}} \quad \rho R_{hot, \text{total}}$$

$$\rho_{\text{hot, spot}} \quad \rho_{\text{hot, spot}} \quad \rho_{\text{hot, uniform}} \quad (\text{mg/cm}^2)$$

<p>| | | | | | | | |</p>
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### Secondary proton spectra from WRF

**TIM2, 12.5cm**

$Y_{2p}$: $2.4x10^8$

$<E>$: 12.92

**TIM3, 12.5cm**

$Y_{2p}$: $1.7x10^8$

$<E>$: 13.49

**TIM4, 12.5cm**

$Y_{2p}$: $2.2x10^8$

$<E>$: 13.53

**TIM6, 12.5cm**

$Y_{2p}$: $2.5x10^8$

$<E>$: 13.28

Energy (MeV)
### Secondary proton spectra from WRF

**TIM3, 18.0cm**
- \( Y_{2p} \): 1.3\( \times 10^7 \)
- \( <E> \): 14.0

**TIM4, 15.0cm**
- \( Y_{2p} \): 1.2\( \times 10^7 \)
- \( <E> \): 13.72

**TIM6, 15.0cm**
- \( Y_{2p} \): 9.9\( \times 10^6 \)
- \( <E> \): 14.14
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1a}$ ($\times 10^{10}$)</th>
<th>$&lt;T_p&gt;$ ($Y_{1a}$) (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<th>$Y_{2a}$ ($\times 10^9$)</th>
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<th>$\rho_{R_{hot, 2n, hot-spot}}$ (mg/cm$^2$)</th>
<th>$\rho_{R_{hot, 2n}}$ uniform (mg/cm$^2$)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho_{R_{total}}$ (mg/cm$^2$)</th>
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Secondary proton spectra from WRF

TIM2, 15.0cm

$Y_{2p}$: $4.1 \times 10^7$

$<E>$: 13.82

TIM3, 18.0cm

$Y_{2p}$: $3.4 \times 10^7$

$<E>$: 14.01

TIM4, 15.0cm

$Y_{2p}$: $3.4 \times 10^7$

$<E>$: 13.72

TIM6, 15.0cm

$Y_{2p}$: $3.1 \times 10^7$

$<E>$: 13.83
Secondary proton spectra from WRF

**TIM2, 15.0cm**
- $Y_{zp}: 1.4 \times 10^8$
- $<E>: 13.33$

**TIM3, 18.0cm**
- $Y_{zp}: 1.4 \times 10^8$
- $<E>: 13.63$

**TIM4, 15.0cm**
- $Y_{zp}: 1.3 \times 10^8$
- $<E>: 13.92$

**TIM6, 15.0cm**
- $Y_{zp}: 1.4 \times 10^8$
- $<E>: 13.21$
### Table

<table>
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<th>Bang Time (ps)</th>
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### Parameters

- $<Y_{2p}>$ ($10^9$)
- $Y_{2p}$ ($10^9$)
- $\rho R_{hot, 2p}$, hot-spot (mg/cm$^2$)
- $\rho R_{hot, 2a}$, hot-spot (mg/cm$^2$)
- $\rho R_{hot, 2p}$, uniform (mg/cm$^2$)
- $\rho R_{hot, 2a}$, uniform (mg/cm$^2$)
- $<E_{2p}>$ (MeV)
- $\rho R_{total}$ (mg/cm$^2$)

|        | 3.1  | 1.2  | 16.3 | 53.3 | N/A  | 56.2 | 13.62 | 43.6 |
|        | +/-  | +/-  | +    | +5.2 |    | +5.7 | +/-   |    |
|        | 0.3  | 0.1  | -4.8 | -7.2 |    | -7.0 | 0.1   | 3.1 |

### Secondary Proton Spectra from WRF

**TIM2, 15.0cm**

- $Y_{2p}$: $2.8 \times 10^8$
- $<E>$: 13.79

**TIM3, 18.0cm**

- $Y_{2p}$: $3.2 \times 10^8$
- $<E>$: 13.38

**TIM4, 15.0cm**

- $Y_{2p}$: $3.4 \times 10^8$
- $<E>$: 13.41

**TIM6, 15.0cm**

- $Y_{2p}$: $3.1 \times 10^8$
- $<E>$: 13.88

### Energy (MeV)

---

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Secondary proton spectra from WRF

<table>
<thead>
<tr>
<th>Shot #</th>
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<th>Pulse Shape</th>
<th>$Y_{1e}$ ($x10^{10}$)</th>
<th>$&lt;E&gt;_{V1e}$ (keV)</th>
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<th>$\rho_{R_{bot}, 2n}$ hot-spot (mg/cm$^2$)</th>
<th>$\rho_{R_{bot}, 2p}$ uniform (mg/cm$^2$)</th>
<th>$\rho_{R_{bot}, 2n}$ uniform (mg/cm$^2$)</th>
<th>$&lt;E&gt;_{2p}$ (MeV)</th>
<th>$\rho_{R_{total}}$ (mg/cm$^2$)</th>
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<td>On-Target Energy (kJ)</td>
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<td>( &lt;T_{1e}&gt; ) (keV)</td>
<td>Bang Time (ps)</td>
<td>Burn Width (ps)</td>
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<th>( Y_{2p} \times 10^9 )</th>
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<th>( \rho_{R_{bot, 2n}, \text{bot-spot}} ) (mg/cm²)</th>
<th>( \rho_{R_{bot, 2p}, \text{uniform}} ) (mg/cm²)</th>
<th>( \rho_{R_{bot, 2n}, \text{uniform}} ) (mg/cm²)</th>
<th>( &lt;E_{2p}&gt; ) (MeV)</th>
<th>( \rho_{\text{total}} ) (mg/cm²)</th>
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</table>

**Secondary proton spectra from WRF**

**TIM2, 15.0cm**
- \( Y_{2p}: 3.3\times10^7 \)
- \( <E>: 13.83 \)

**TIM3, 18.0cm**
- \( Y_{2p}: 3.3\times10^7 \)
- \( <E>: 13.88 \)

**TIM4, 15.0cm**
- \( Y_{2p}: 4.3\times10^7 \)
- \( <E>: 13.92 \)

**TIM6, 15.0cm**
- \( Y_{2p}: 3.9\times10^7 \)
- \( <E>: 13.41 \)
<table>
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<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1e}$ ($x10^{19}$)</th>
<th>$&lt;T_p&gt;V_{1e}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
<th>$&lt;Y_{2p}&gt;$ ($x10^3$)</th>
<th>$Y_{2p}$ ($x10^8$)</th>
<th>$\rho R_{bot, 2p, \text{hot-spot}}$ (mg/cm²)</th>
<th>$\rho R_{bot, 2a, \text{hot-spot}}$ (mg/cm²)</th>
<th>$\rho R_{bot, 2p, \text{uniform}}$ (mg/cm²)</th>
<th>$\rho R_{bot, 2a, \text{uniform}}$ (mg/cm²)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
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<td>3.1 +/-</td>
<td>1705</td>
<td>131</td>
<td>2.5 +/-</td>
<td>2.9 +/-</td>
<td>4.4 +0.8</td>
<td>48.1 +5.5</td>
<td>6.1 +1.1</td>
<td>49.6 +6.3</td>
<td>14.21</td>
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<td>0.3 0.5</td>
<td>0.5 0.5</td>
<td>50</td>
<td>25</td>
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Secondary proton spectra from WRF

**TIM2, 15.0cm**
- $Y_{2p}$: 3.0x10$^7$
- $<E>$: 14.17

**TIM3, 18.0cm**
- $Y_{2p}$: 3.1x10$^7$
- $<E>$: 14.33

**TIM4, 15.0cm**
- $Y_{2p}$: 2.0x10$^7$
- $<E>$: 14.20

**TIM6, 15.0cm**
- $Y_{2p}$: 2.0x10$^7$
- $<E>$: 14.15
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<tr>
<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>( Y_{1a} \times 10^{10} )</th>
<th>( &lt;T&gt;<em>{Y</em>{1a}} ) (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tr>
<td>32845</td>
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<table>
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<th>(&lt;Y_{2p}&gt; \times 10^8)</th>
<th>(Y_{2a} \times 10^8)</th>
<th>(\rho R_{hot, 2p, hot-spot}) (mg/cm²)</th>
<th>(\rho R_{hot, 2a, hot-spot}) (mg/cm²)</th>
<th>(\rho R_{hot, 2p, uniform}) (mg/cm²)</th>
<th>(\rho R_{hot, 2a, uniform}) (mg/cm²)</th>
<th>(&lt;E_{2p}&gt;) (MeV)</th>
<th>(\rho R_{total}) (mg/cm²)</th>
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<td>1.7</td>
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<td>+5.5</td>
<td>+7.8</td>
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<td>0.2</td>
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<td>-7.2</td>
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<td>3.1</td>
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**Secondary proton spectra from WRF**

KO1, 20.0cm

\(Y_{2p}: 1.8 \times 10^8\)

\(<E>: 13.41\)

TIM3, 18.0cm

\(Y_{2p}: 1.6 \times 10^8\)

\(<E>: 14.00\)

TIM4, 15.0cm

\(Y_{2p}: 1.9 \times 10^8\)

\(<E>: 13.51\)

TIM6, 15.0cm

\(Y_{2p}: 1.4 \times 10^8\)

\(<E>: 14.10\)
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<th>Shot #</th>
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<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{16}$ ($10^{16}$)</th>
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<th>Burn Width (ps)</th>
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<td>33412</td>
<td>CRYO</td>
<td>21.5</td>
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<th>$Y_{2p}$ (x10^7)</th>
<th>$\rho R_{bot, 2p, hot-spot}$ (mg/cm^2)</th>
<th>$\rho R_{bot, 2n, hot-spot}$ (mg/cm^2)</th>
<th>$\rho R_{bot, 2p, uniform}$ (mg/cm^2)</th>
<th>$\rho R_{bot, 2n, uniform}$ (mg/cm^2)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm^2)</th>
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<tr>
<td>2.1</td>
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<td>19.1</td>
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<tr>
<td>0.3</td>
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<td>-1.1</td>
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Secondary proton spectra from WRF

KO1, 20.0cm
$Y_{2p}$: 2.0x10^7
$<E>$: 15.07

TIM3, 18.0cm
$Y_{2p}$: 1.9x10^8
$<E>$: 14.82

TIM4, 15.0cm
$Y_{2p}$: 2.4x10^7
$<E>$: 14.88

TIM6, 15.0cm
$Y_{2p}$: 1.9x10^7
$<E>$: 14.74

Energy (MeV)

Yield / MeV (x10^6)
<table>
<thead>
<tr>
<th>Shot #</th>
<th>Target</th>
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<th>Pulse Shape</th>
<th>$Y_{1a}$ ($\times10^8$)</th>
<th>$&lt;T_{1a}&gt;$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tr>
<td>33413</td>
<td>CRYO</td>
<td>22.0</td>
<td>SSD: SG1018</td>
<td>6.7 (+/-)</td>
<td>3.2 (+/-)</td>
<td>1614 (+/-)</td>
<td>204 (+/-)</td>
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<table>
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<th>$Y_{2a}$ ($\times10^8$)</th>
<th>$\rho R_{\text{hot, 2p, hot-spot}}$ (mg/cm$^2$)</th>
<th>$\rho R_{\text{hot, 2a, hot-spot}}$ (mg/cm$^2$)</th>
<th>$\rho R_{\text{hot, 2a, uniform}}$ (mg/cm$^2$)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{\text{total}}$ (mg/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3 (+/-)</td>
<td>7.2 (+/-)</td>
<td>10.8 (+/-)</td>
<td>49.8 (+/-)</td>
<td>37.9 (+/-)</td>
<td>51.5 (+/-)</td>
<td>13.66 (+/-)</td>
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<tr>
<td>0.1 (+/-)</td>
<td>0.8 (+/-)</td>
<td>-2.4 (+/-)</td>
<td>-7.2 (+/-)</td>
<td>-29.1 (+/-)</td>
<td>-7.4 (+/-)</td>
<td>0.1 (+/-)</td>
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Secondary proton spectra from WRF

KO1, 20.0cm

$Y_{2p}$: $1.1\times10^8$

$<E>$: 13.37

TIM3, 18.0cm

$Y_{2p}$: $1.4\times10^8$

$<E>$: 14.09

TIM4, 15.0cm

$Y_{2p}$: $1.4\times10^8$

$<E>$: 13.60

TIM6, 15.0cm

$Y_{2p}$: $1.2\times10^8$

$<E>$: 13.56

Energy (MeV)
### Table

<table>
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<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{18}$ ($x10^8$)</th>
<th>$&lt;T&gt;_{Y18}$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<tbody>
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<td>33415</td>
<td>CRYO</td>
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<td>SSD: SG1018</td>
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<td>4.0</td>
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<td>251</td>
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<th>$&lt;Y_{2p}&gt;$ ($x10^7$)</th>
<th>$Y_{2p}$ ($x10^7$)</th>
<th>$\rho R_{bot, 2p, hot-spot}$ (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2n, hot-spot}$ (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2p, uniform}$ (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2n, uniform}$ (mg/cm$^2$)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm$^2$)</th>
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<td>5.4</td>
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<td>9.0</td>
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<td>+4.3</td>
<td>+1.8</td>
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<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>0.8</td>
<td>0.3</td>
<td>-1.6</td>
<td>-6.3</td>
<td>-1.5</td>
<td>-6.3</td>
<td>0.1</td>
<td>3.1</td>
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### Secondary proton spectra from WRF

**KO1, 20.0cm**
- $Y_{2p}$: 5.5x10^7
- $<E>$: 13.68

**TIM3, 18.0cm**
- $Y_{2p}$: 5.5x10^7
- $<E>$: 14.44

**TIM4, 15.0cm**
- $Y_{2p}$: 5.7x10^7
- $<E>$: 14.03

**TIM6, 15.0cm**
- $Y_{2p}$: 4.7x10^7
- $<E>$: 14.08

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<table>
<thead>
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<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1a}$ ($10^8$)</th>
<th>$&lt;T_{1a}&gt;$ (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<td>CRYO</td>
<td>22.7</td>
<td>SSD: SG1018</td>
<td>6.5 +/- 0.7</td>
<td>2.9 +/- 0.5</td>
<td>1654 +/- 50</td>
<td>191 +/- 25</td>
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<th>$Y_{2a}$ ($10^8$)</th>
<th>$\rho R_{bot, 2p}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2a}$, hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2p}$, uniform (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2a}$, uniform (mg/cm$^2$)</th>
<th>$&lt;E_{2p}&gt;$ (MeV)</th>
<th>$\rho R_{total}$ (mg/cm$^2$)</th>
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<td>1.4 +/- 0.8</td>
<td>6.9 +/- 0.8</td>
<td>&gt; 9.2</td>
<td>46.6</td>
<td>+5.6</td>
<td>N/A</td>
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<td>0.1</td>
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<td>-7.1</td>
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<td>+/1/</td>
<td>+/1/</td>
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</table>

**Secondary proton spectra from WRF**

KO1, 20.0cm

Y$_{2p}$: 1.7x10$^8$

$<E>$: 13.58

KO2, 15.0cm

Y$_{2p}$: 1.5x10$^8$

$<E>$: 13.69

TIM3, 18.0cm

Y$_{2p}$: 1.5x10$^8$

$<E>$: 13.72

TIM4, 15.0cm

Y$_{2p}$: 1.4x10$^8$

$<E>$: 13.56

TIM6, 15.0cm

Y$_{2p}$: 1.1x10$^8$

$<E>$: 13.48
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<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>( Y_{1n} \times 10^{10} )</th>
<th>( &lt;T&gt;_{y1n} ) (keV)</th>
<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<td>33603</td>
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<td>3.9 +/-</td>
<td>3.2 +/-</td>
<td>1672 +/-</td>
<td>179 +/-</td>
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\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\( <Y_{2p}> \) (x10^7) & \( Y_{2n} \) (x10^7) & \( \rho R_{bot, 2p, \text{hot-spot}} \) (mg/cm^2) & \( \rho R_{bot, 2n, \text{hot-spot}} \) (mg/cm^2) & \( \rho R_{bot, 2n, \text{uniform}} \) (mg/cm^2) & \( \rho R_{bot, 2n, \text{uniform}} \) (mg/cm^2) & \( <E_{2p}> \) (MeV) & \( \rho R_{total} \) (mg/cm^2) \\
\hline
7.7    & 3.5   & 11.4                   & 45.6        & 43.8            & 47.2            & 13.76         & 39.2           \\
+/-    & +/-   & +                      & +5.1        & +               & +5.7            & +/-           & +/-            \\
1.2    & 4.4   & -2.8                   & -6.8        & -36.4           & -6.7            & 0.1           & 3.1            \\
\hline
\end{tabular}

Secondary proton spectra from WRF

TIM3, 18.0cm
\( Y_{2p}: 7.2\times10^7 \)
\( <E>: 14.22 \)

TIM4, 15.0cm
\( Y_{2p}: 7.6\times10^7 \)
\( <E>: 13.95 \)

TIM6, 15.0cm
\( Y_{2p}: 8.3\times10^7 \)
\( <E>: 13.12 \)
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<th>Shot #</th>
<th>Target</th>
<th>On-Target Energy (kJ)</th>
<th>Pulse Shape</th>
<th>$Y_{1n}$ (x10$^{10}$)</th>
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<th>Bang Time (ps)</th>
<th>Burn Width (ps)</th>
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<th>$&lt;Y_{2p}&gt;$ (x10$^7$)</th>
<th>$Y_{2n}$ (x10$^8$)</th>
<th>$\rho R_{hot, 1p}$ hot-spot (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2n}$ uniform (mg/cm$^2$)</th>
<th>$\rho R_{bot, 2p}$ uniform (mg/cm$^2$)</th>
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<td>3.1</td>
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Secondary proton spectra from WRF

KO1, 20.0cm

Y$_{2p}$: 9.8x10$^7$

$<E>$: 14.0

TIM3, 18.0cm

Y$_{2p}$: 7.4x10$^7$

$<E>$: 13.86

TIM4, 15.0cm

Y$_{2p}$: 8.0x10$^7$

$<E>$: 13.76

TIM6, 15.0cm

Y$_{2p}$: 7.7x10$^7$

$<E>$: 13.69

Energy (MeV)
Bibliography


