

Spatially resolved temperature measurement and axial thermal transport assessment of magnetized-liner-inertial-fusion burning plasmas

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In a series of magnetized-liner-inertial-fusion experiments performed at the Z pulsed power facility of Sandia National Laboratories, beryllium liners filled with deuterium gas densities between 0.7 to 1.4 mg/cc and a tracer amount of krypton were imploded. At the collapse of the cylindrical implosion, electron temperatures in the 2–4 keV range and deuterium ion number densities of $\sim 10^{23} \text{ cm}^{-3}$ were expected. Spatially resolved krypton K-shell line emission was recorded with a time-integrated transmission crystal x-ray spectrometer. The spatially resolved data showed $n = 2 \rightarrow 1$ line emission from Be-, Li-, and He-like krypton ions and are characteristic of the highest electron temperatures achieved in the thermonuclear plasma. Detailed modeling of krypton atomic and radiation physics demonstrated that the spectrum is electron temperature dependent, thus allowing for axial temperature distributions to be extracted from the data. Additionally, the electron density (as well as the ion density) of the deuterium compressed plasma was estimated from the relative distribution of narrowband intensity between regions along the z axis. The measurement of axially resolved temperature and density distributions enabled an assessment of thermal transport along the axis of the burning plasma, showing that it proceeded at a much faster rate than local cooling by bremsstrahlung emission. Furthermore, from the pressure distribution, the rate of residual kinetic energy associated with axial plasma flow was evaluated as well.

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I. INTRODUCTION

Magnetized-liner-inertial-fusion (MagLIF) is a concept for controlled thermonuclear energy production [1]. This scheme differs from traditional inertial confinement fusion (ICF) techniques by relaxing certain constraints that hinder both direct- and indirect-drive experiments. For example, the spherical geometry currently used in both direct- and indirect-drive ICF schemes requires implosion velocities around 30 cm/ μs [2]. MagLIF eases this constraint by imposing an axial magnetic field to limit the energy losses due to radial electron thermal conduction. The required implosion velocity drops to roughly 10 cm/ μs if the fuel is also first preheated to a few-hundred eV.

Thermonuclear conditions are achieved by compressing deuterium fuel within a cylindrical beryllium liner with a height of 10 mm and a diameter of ~ 5 mm driven by the Z-machine. There are three distinct stages. First, a ~ 10 T

external axial magnetic field produced from pulsed-coil magnets forces the deuterium to gyrate about the magnetic field lines which are aligned with the axis of the cylinder [3]. This serves to limit the thermal conduction and heat losses from the fuel along the radial direction. Second, the temperature of the deuterium fuel is increased to roughly 500 eV by coupling laser energy from the Z-beamlet laser to the fuel through the top of the beryllium liner [4–6]. Lastly, the Z-machine drives a ~ 20 MA current along the surface of the liner, inducing a $\vec{J} \times \vec{B}$ force to implode the Be liner, compressing the deuterium fuel to thermonuclear temperatures and pressures.

The performance of an ICF experiment depends on the balance of different forms of energy. For MagLIF, the energy balance equation is given by

$$\frac{dU}{dt} = P_{\text{pre}} + P_{\text{pdV}} + P_{\alpha} - P_{\text{rad}} - P_c - P_{\text{end}} + P_{\text{other}}, \quad (1)$$

where U is the total energy in the compressed plasma, P_{pre} is the laser preheat rate, P_{pdV} is the work rate done to the fuel through compression, P_{α} is the heating rate due to α particles, P_{rad} is the cooling rate via bremsstrahlung emission, P_c is the cooling rate due to conductive losses, P_{end} is the energy loss rate for the deuterium fuel escaping out of the ends of the liner, and P_{other} covers all energy source and loss mechanisms that have not been considered in Eq. (1), such as losses due to mixing of liner material into the core and residual kinetic energy (RKE) [7]. To maximize the energy produced in a MagLIF implosion, it is of great importance

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to regulate and minimize the loss mechanisms in the plasma, which are denoted with minus signs in front of the terms in Eq. (1). Quantitative, nonintrusive ways to determine the value of these terms gives insight into the relative importance and magnitude of the losses and allows for further investigation into methods to mitigate its behavior. Additionally, the RKE associated with fluid motion in the implosion core plasma has been of recent interest in ICF experiments [8,9]. In this work, data from axially resolved spectroscopic observations permit an evaluation of axial thermal transport, bremsstrahlung emission, and RKE trapped in axial flow in the column of burning plasma.

Currently, MagLIF has achieved ion temperatures of ~ 3 keV and ion densities of $\sim 1 \times 10^{23}/\text{cc}$. Diagnosing the ion temperature of these experiments through neutron time-of-flight measurements is informative; however, these measurements are often subject to a high degree of variability depending on the lines of sight of the diagnostic and the motion of the plasma. The electron temperature of a plasma is a valuable quantity as it provides a more direct understanding of the thermal state of a high energy density experiment [10]. Determining the electron temperature allows for an understanding of thermal equilibrium when compared to the ion temperature. Also, knowledge of the temperature and the density provides insight into the energetics of the imploded plasma. One method of determining the electron temperature in fusion experiments is through x-ray tracer spectroscopy, where a small amount of a higher Z material is mixed uniformly with the deuterium fuel prior to the implosion and having it follow along with the deuterium as it reaches final temperatures and densities. Previously, argon was used to diagnose the preheat phase, and a two-dimensional, i.e., axial and radial electron temperature, distribution along the length of the liner was obtained [5,6]. However, during the implosion phase of MagLIF, the temperature is expected to reach >2 keV. In this temperature range, argon becomes too highly ionized and loses its diagnostic utility. Alternatively, krypton has been shown to diagnose the conditions of ICF experiments in the range of 2–5 keV [10–12]. The spatially resolved nature of the data collected with the spectrometer in the experiments discussed here allows for axial electron temperature and density spatial profiles to be measured. In turn, this permits a further investigation into an energy analysis at stagnation, including axial thermal transport (P_c), bremsstrahlung power emission (P_{rad}), and the pressure distribution driving the RKE associated with axial plasma flow.

Here, we present the results obtained from krypton K-shell x-ray spectroscopy in MagLIF implosions at Z. We model the emergent krypton line intensity distribution to fit the data with the theoretical spectra. Once the temperature distribution has been determined for a shot, the electron density distribution is found based on the relative narrowband intensity between the different axial regions. Then, we use these temperature and density distributions to assess axial thermal energy transport, bremsstrahlung emission, and RKE in the burning plasma. The paper is organized as follows: Sec. II discusses the details of the experiments that have included krypton as a spectroscopic tracer, Sec. III explains the method in which we model the krypton emission in MagLIF implosion experiments, Sec. IV discusses the procedure with which we determine the

TABLE I. Details of shots with a krypton tracer. Liners for shots Z3371 and Z3377 had a 72 micron plastic coating applied to the external surface of the liner.

Shot	Fill density (mg/cc)	Kr concentration (ppm)	Wall thickness (mm)
Z3079	0.7	5.5	0.465
Z3123	0.7	5.5	0.465
Z3143	1.05	5.5	0.465
Z3210	0.7	5.5	0.465
Z3371	1.4	3.0	0.318
Z3377	1.4	3.0	0.318

conditions of the experiment, Sec. V describes the thermal flux implied by the previous results and RKE, and, lastly, Sec. VI presents conclusions.

II. KRYPTON-DOPED MAGLIF EXPERIMENTS AT Z

In this work, we discuss six MagLIF experiments that included krypton gas mixed with deuterium fuel for diagnostic purposes. The amount of krypton gas in the fuel was between 3.0 and 5.5 ppm. The motivation for such a small amount was to affect the neutron yield as little as possible while also providing a small optical depth of the krypton $\text{He}\alpha$ spectrum (<0.1). The dimensions of the beryllium liner were 10 mm in height with an inner diameter of 4.65 mm. The axial magnetic field utilized to inhibit the radial thermal transport of the fuel radially was 10 T across all six shots. Prior to the collapse of the liner, the Z-beamlet laser preheated the fuel to ~ 500 eV. The same nominal current drive of 17 MA was applied to the surface of each liner. The parameters that varied between the six shots are the initial fill density of the deuterium, the concentration of the krypton gas, and the wall thickness of the Be liner. These values are shown in Table I.

As the liner compresses and heats the fuel, the krypton ionizes and emits K-shell radiation in the energy range of 12.8–13.2 keV, which includes the $\text{He}\alpha n = 2 \rightarrow 1$ transition and satellite lines in Li- and Be-like krypton ions. For each shot, the emission was collected with the axially resolving, compact, rugged, in-chamber, transmission-type (CRITR-AR) spectrometer [13]. The instrument uses a quartz 10-11 transmission-type cylindrically bent crystal to spatially and spectrally resolve photons in the range of 7–28 keV. The data are collected on a Fuji TR image plate with an intrinsic resolution of $75 \mu\text{m}$ [14]. Near the krypton $\text{He}\alpha$ spectral feature, the CRITR-AR spectrometer has a resolving power of $\frac{\lambda}{\Delta\lambda} \approx 750$, which is sufficient for detailed spectroscopic analysis. The instrument provides an axial resolution of ≈ 0.5 mm, allowing for a spatial analysis of the conditions reached in the compressed fuel. Additionally, each shot fielded diagnostics to record total neutron yield. An example of the krypton K-shell line emission recorded with the CRITR-AR spectrometer is shown in Fig. 1, along with the lineout of region 4.

While the spectrometer is able to record emission across the entire length of the liner, only in specific areas does the krypton reach temperatures that are hot enough to emit K-shell radiation. We can see from Fig. 1 that there is bright emission

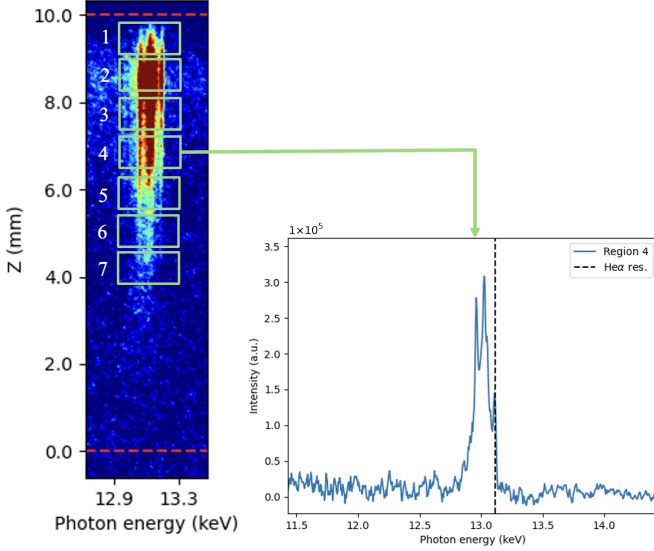


FIG. 1. Image of shot Z3377 with axially resolved regions denoted with green boxes. The image on the left is the spectra as collected via the image plate. The red dotted lines on the lower and upper ends of the image denote the 0 and 10 mm positions of the liner, respectively. The plot on the right shows the lineout of region 4. The three-peak structure of the He α spectral feature is displayed with the black dotted line indicating the He α resonance line on the high-energy end of the spectrum. The underlying continuum is seen slightly decreasing from left to right. The central peak is dominated by Li-like transitions and the He-like intercombination line, while the peak on the low-energy side is mainly due to Be-like transitions.

near the top of the liner (i.e., near the laser entrance hole), but almost no observable emission as we look further down the length. Accordingly, we can extract a collection of spatially resolved spectra associated with each one of these bright regions, but we cannot assess the regions that lack sufficient krypton K-shell emission. The regions where the spectra can be analyzed are labeled in increasing numerical order from top to bottom.

III. KRYPTON ATOMIC PHYSICS MODEL

The goal is to compare the experimental data to the theoretical emission of krypton across a range of relevant electron temperatures and densities. First, each shot is grouped into regions that align with the spatial resolution of the instrument and capture intensity changes along the axis of the plasma column. The data allows between 5 and 7 regions to be identified, depending on the experiment. The spectra of each region are then integrated along the length of the vertical direction to produce lineouts. We isolate the krypton line emission by removing the underlying continuum from each shot. The experimental continuum is fit to an exponential function by fitting the slope on each side of the krypton line emission along with a curve that is one standard deviation above and below the best fit. This provides a preliminary estimation of the temperature as well as a source of uncertainty due to background determination that will be incorporated later in the

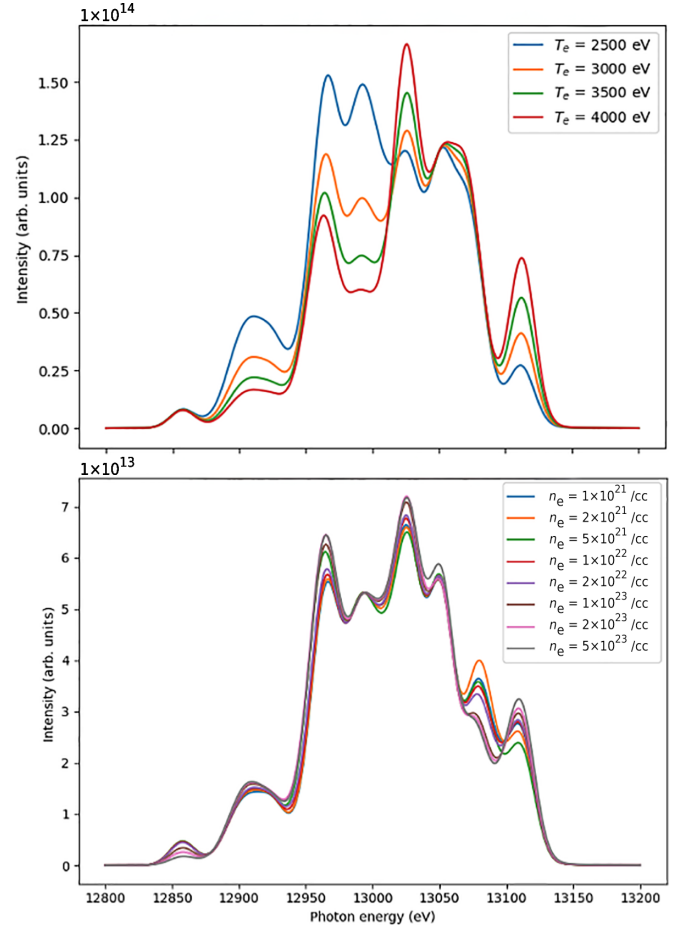


FIG. 2. Plots of the emergent intensity distributions of krypton K-shell emission at various electron temperatures and densities. The top plot shows the sensitivity of the spectrum to electron temperature with density held constant at $1 \times 10^{23}/\text{cc}$. The bottom plot shows the lack of sensitivity to electron density in the krypton He α feature with temperature held constant at 3000 eV. Both figures have been normalized to the Li-like feature at 13 051 eV for illustrative purposes.

analysis. A detailed explanation of this process is described in Appendix.

An emergent intensity distribution (EID) for a collection of electron temperatures and densities is needed to compare to the experimental data. The theoretical spectra are produced via integration of the radiation transport equation along the line of sight of the spectrometer. Photon-energy resolved emissivities and opacities are calculated via the procedure outlined in [15].

The line shapes are calculated with the multi-electron radiator line shape (MERL) code, which allows for the effects of Stark broadening to be taken into consideration [16]. We can identify the prominent He-like, Li-like, and Be-like emission from the experimental data. Thus, line shapes are calculated for the He α resonance and intercombination lines, Li-like $n = 2, 3, 4$ satellites, and Be-like $n = 2$ satellites. While the Stark broadening of the line shapes is dependent on the electron density of the plasma, these experiments have not reached electron densities large enough to significantly impact the data.

The Einstein coefficients for each transition are computed with the Flexible Atomic Code (FAC) [17]. The upper and lower state level populations are obtained from a PrismSPECT calculation [18]. The PrismSPECT atomic and radiation physics model is used to compute the krypton level populations at conditions relevant to the expected stagnation conditions of MagLIF implosions. The model includes over 8000 levels from H-like through Ne-like ions of krypton. The program solves the collisional radiative system of atomic kinetics rate equations in order to obtain the level population distribution. This includes contributions from the following atomic processes: electron collisional excitation-deexcitation, electron collisional ionization-recombination, radiative recombination, spontaneous emission, photoexcitation-stimulated emission, photoionization-stimulated recombination, and autoionization-dielectronic recombination. The calculation is run under a uniform slab geometry with a thickness of 67.5 μm and a deuterium and krypton concentration determined by the experimental filling conditions. The thickness of the slab was chosen based on the average chord length through a circle with a radius equal to that of the stagnation column of 50 μm as extracted from x-ray images in MagLIF implosions [19]. The independent variables are electron temperature and electron density. The EIDs for various electron temperatures and densities after convolving with the instrumental broadening are shown in Fig. 2. The synthetic spectra show a high degree of sensitivity to electron temperature, but very little sensitivity to electron density. In the range of densities achieved in MagLIF implosions, there is little to no effect on the krypton K-shell line shapes due to Stark broadening. Therefore, the relative intensity distribution of the krypton He α spectral feature can be used to determine axial temperature distributions, but a different method is needed to determine axial density distributions.

We note that to account for small differences in the location of transition energies between the model produced in EID and the experimental spectra, the emission from each charge state is allowed to block-shift in photon energy to more closely match the experimental line transitions. This is done to compensate for the spectral calibration of the instrument to better match the theoretical transition locations. The emission of each charge state is shifted no more than 5 eV in either direction, which is less than 0.1% of the original position of the levels, so the corrections are quite small.

IV. DATA ANALYSIS

The synthetic spectra are sampled against the spatially resolved spectra for each shot to find the electron temperatures. A standard, weighted χ^2 minimization procedure is used to determine the temperature that best represents the experimental data. The probability distribution for a measurement of T_e is given by

$$P(T_e) \propto e^{-\chi^2/2}, \quad (2)$$

where $\chi^2 = \sum (aI_{e,i} - I_{t,i})^2 / \sigma_i^2$, a is a scaling constant to convert from the units of the experimental data to the units of the EID, $I_{e,i}$ is the data point of the experimental spectrum, $I_{t,i}$ is the data point of the EID, and σ_i is the uncertainty of a data

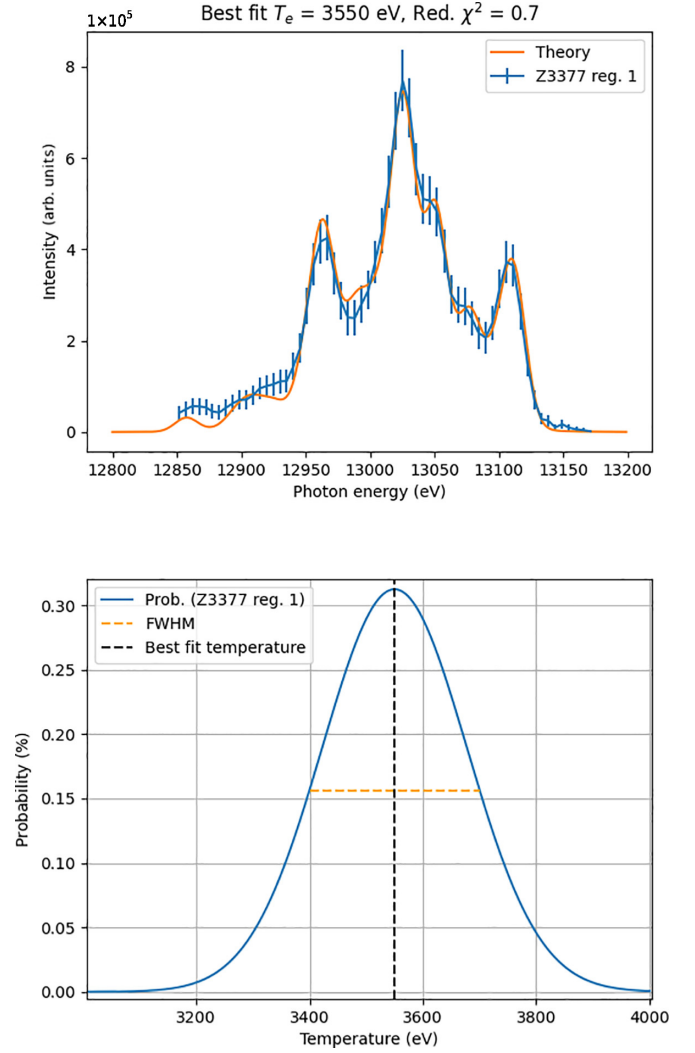


FIG. 3. Fit to data and reduced χ^2 value (top), and probability distribution (bottom) for region 1 of shot Z3377. The top plot shows the experimental data in blue and the best-fit spectrum from the EID in orange. The plot below shows the resultant probability distribution in blue. The dotted black line is the most probable value of T_e and the dotted orange line is the FWHM of the distribution.

point in the experimental spectrum. The uncertainties are derived from the fluctuations about the mean in the experimental spectrum through an iterative procedure and accounting for the Poisson statistical nature of the signal recorded in these experiments [20]. Assuming that the probability distribution is Gaussian (which is a good approximation in our case), the peak of the distribution is the most probable value of T_e and represents the best estimate of the measurement of T_e . The full width at half maximum (FWHM) of the distribution is $\sim 2.4\sigma$, where σ is the standard deviation. We take the upper and lower uncertainties as the half width at half maximum ($\pm$ HHWM) of the distribution. Hence, the error bars give a 76% confidence interval that the measurement is within this range.

The best-fit temperature to the experimental spectrum and its associated probability distribution for region 1 of shot Z3377 is shown in Fig. 3. We can see that the theory and data

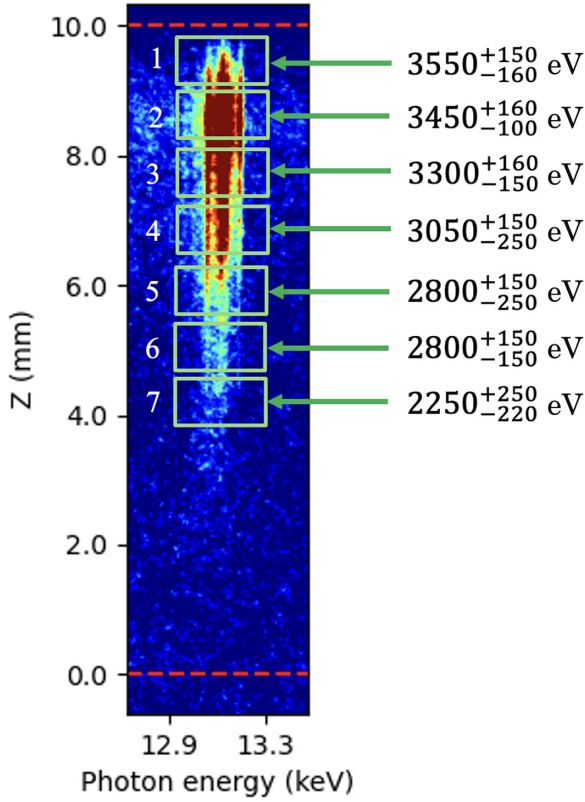


FIG. 4. Image of shot Z3377 with axial temperature distribution values and associated uncertainties.

are in good agreement. The HWHM of the probability distribution is used as the contribution to the overall uncertainty due to data statistics, while the other source of uncertainty comes from the continuum subtraction of the data. The upper and lower bounds of the continuum level are also fed into the minimization procedure and provide slightly different best-fit temperatures. The full axial temperature distribution for shot Z3377 along with an image of the data are displayed in Fig. 4. Since the amount of krypton in the liner is of the order of parts per million, all of the transitions, including the $\text{He}\alpha$ resonance line, have small optical depths and therefore the effect of radiation transport is small.

Although the relative intensity distribution of the krypton $\text{He}\alpha$ feature is quite insensitive to electron density (see Fig. 2), we can still find useful density information in the photon-energy integrated intensity across the $\text{He}\alpha$ spectrum. Indeed, the narrowband intensity of this spectral feature is a function of temperature and density, as shown in Fig. 5. Hence, once the temperatures have been determined, a relative distribution of electron densities can be extracted from the ratios of narrowband intensities between regions. Furthermore, absolute densities can be determined if a suitable constraint is applied. To this end, we constrain the average density to match an estimate obtained from a mass conservation argument based on initial filling conditions and size of the stagnated plasma column from imaging measurements.

This idea for electron density determination can be effectively implemented in an iterative algorithm. First, the narrowband intensity of each region in the data is calculated.

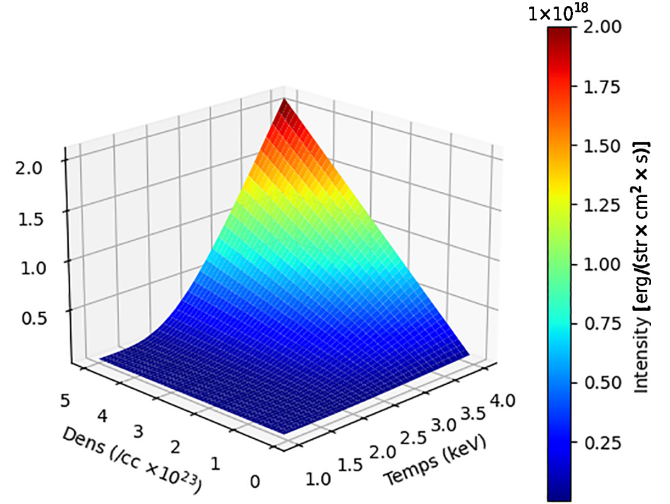


FIG. 5. A plot of integrated narrowband intensity values for different temperatures and densities. The integration is from 12.85 to 13.15 keV, covering the complete krypton $\text{He}\alpha$ spectral feature.

For example, shot Z3377 has a set of seven narrowband intensity values. As a starting point, an initial density value is chosen for one of the axial regions. Then, the theoretical narrowband intensity for that region can be calculated since we know both the temperature and density. The density is obtained by setting the theoretical narrowband ratio equal to the ratio between two regions in the data. The algorithm provides a set of axially resolved ion density values. These are then averaged and compared to the estimated average density. The initial density is iterated until the constraint is satisfied. A flow chart of the algorithm is seen in Fig. 6. This algorithm is repeated by selecting other regions as the initial region in order to check the uniqueness and consistency of the solution found for the distribution of densities. We note that because the deuterium fuel dominates the composition of the plasma

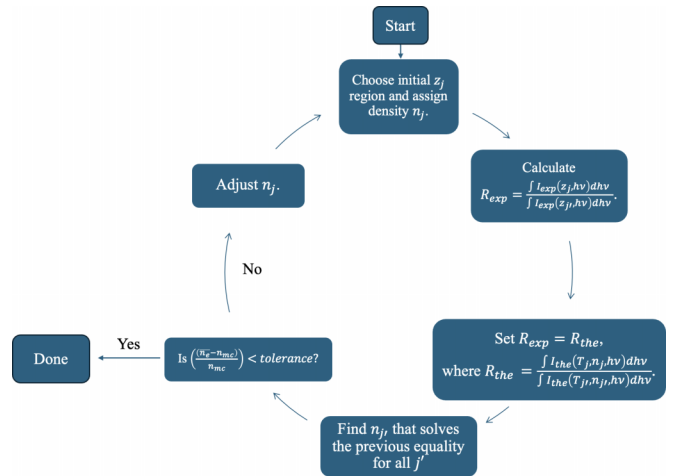


FIG. 6. Flow chart describing the iterative algorithm to determine the axial electron density distribution. Here, n_j refers to the initial density value for the algorithm, $\bar{n}_e$ is the emissivity weighted average electron density for the entire axial range, and n_{mc} is the electron density found through the mass conservation argument.

TABLE II. Temperature, density, and energy results. The shot number and the region numbering are shown in the two leftmost columns. The axially resolved electron temperature, electron density, pressure, thermal flux rate, bremsstrahlung power emission, and rate of residual axial kinetic energy produced from the analysis are shown in the right columns. Note that the rate of change of residual axial kinetic energy and thermal flux are in units of terawatts, while bremsstrahlung emission is in gigawatts.

Shot	Region	T_e (eV)	n_e (No./cc $\times 10^{23}$)	Pres. (GBar)	Therm. flux (TW)	Brem. em. (GW)	R.O.C. of R.K.E. (TW)	Length (mm)
Z3079	1	2500 ⁺⁴⁷⁵ ₋₁₄₀	3.96 ^{+0.54} _{-0.36}	2.66 ^{+0.41} _{-0.31}	-17 ⁺² ₋₂	221 ⁺⁶¹ ₋₄₁	1.07 ^{+1.28} _{-1.01}	1.0
	2	2050 ⁺¹⁵⁰ ₋₁₅₀	0.76 ^{+0.15} _{-0.10}	0.50 ^{+0.11} _{-0.08}	+235 ⁺²⁴ ₋₂₅	10.5 ^{+4.2} _{-2.8}	4.05 ^{+5.14} _{-3.74}	1.3
	3	2800 ⁺²⁰⁵ ₋₁₆₀	0.28 ^{+0.10} _{-0.09}	0.25 ^{+0.09} _{-0.08}	-598 ⁺³² ₋₂₅	1.92 ^{+1.37} _{-1.23}	29.5 ^{+42.6} _{-24.4}	1.5
	4	2200 ⁺¹⁵⁰ ₋₁₅₀	5.33 ^{+0.33} _{-0.71}	3.76 ^{+0.35} _{-0.56}	+655 ⁺³² ₋₂₃	370 ⁺⁴⁸ ₋₉₉	9.27 ^{+10.35} _{-8.65}	0.9
	5	2750 ⁺²⁰⁰ ₋₁₅₀	0.17 ^{+0.03} _{-0.05}	0.15 ^{+0.05} _{-0.05}	-409 ⁺³⁷ ₋₃₈	0.47 ^{+0.28} _{-0.28}	59.7 ^{+81.8} _{-50.7}	1.0
Z3123	1	2850 ⁺¹⁵⁵ ₋₁₅₀	1.60 ^{+0.29} _{-0.28}	1.46 ^{+0.28} _{-0.27}	-56 ⁺⁵ ₋₅	63.2 ⁺²³ ₋₂₂	0.48 ^{+0.59} _{-0.43}	1.5
	2	2750 ⁺¹⁵⁰ ₋₂₅₀	2.71 ^{+0.30} _{-0.27}	2.39 ^{+0.30} _{-0.32}	+56 ⁺⁵ ₋₅	142 ⁺³² ₋₂₉	0.33 ^{+0.38} _{-0.31}	1.2
	3	2750 ⁺¹⁰⁰ ₋₁₆₀	2.59 ^{+0.24} _{-0.20}	2.28 ^{+0.23} _{-0.22}	-125 ⁺⁷ ₋₁₁	217 ⁺⁴⁰ ₋₃₄	0.09 ^{+0.11} _{-0.09}	2.0
	4	2450 ⁺¹⁵⁰ ₋₁₅₀	1.95 ^{+0.11} _{-0.10}	1.53 ^{+0.13} _{-0.12}	-52 ⁺⁷ ₋₁₁	81 ^{+9.5} _{-8.7}	0.08 ^{+0.09} _{-0.08}	1.4
	5	2250 ⁺¹⁵⁰ ₋₁₅₀	1.65 ^{+0.19} _{-0.18}	1.19 ^{+0.16} _{-0.15}	-74 ⁺⁷ ₋₇	52 ⁺¹² ₋₁₁	0.06 ^{+0.06} _{-0.05}	1.3
Z3143	1	2950 ⁺²⁸⁰ ₋₁₀₀	5.17 ^{+0.67} _{-0.18}	4.89 ^{+0.79} _{-0.24}	-50 ⁺⁷ ₋₃	268 ⁺⁷¹ ₋₁₉	2.54 ^{+2.95} _{-2.52}	0.6
	2	2900 ⁺¹⁰⁰ ₋₁₆₀	1.84 ^{+0.18} _{-0.26}	1.71 ^{+0.18} _{-0.26}	+50 ⁺⁷ ₋₃	56.2 ⁺¹¹ ₋₁₆	20.7 ^{+23.1} _{-18.2}	1.0
	3	2900 ⁺²¹⁰ ₋₁₅₀	3.60 ^{+0.25} _{-0.15}	3.34 ^{+0.34} _{-0.22}	-128 ⁺¹⁴ ₋₁₀	172 ⁺²⁵ ₋₁₅	2.63 ^{+2.83} _{-2.55}	0.8
	4	2750 ⁺¹⁵⁰ ₋₁₅₀	2.77 ^{+0.10} _{-0.20}	2.44 ^{+0.16} _{-0.22}	-150 ⁺¹⁴ ₋₁₀	99 ^{+7.7} _{-14.6}	0.03 ^{+0.05} _{-0.03}	0.8
	5	2400 ⁺³⁵⁰ ₋₁₄₀	2.33 ^{+0.16} _{-0.30}	1.79 ^{+0.29} _{-0.25}	-278 ⁺²⁴ ₋₂₄	82 ⁺¹³ ₋₂₁	0.21 ^{+0.23} _{-0.19}	1.0
Z3210	1	2750 ⁺²¹⁰ ₋₂₉₀	0.44 ^{+0.14} _{-0.07}	0.39 ^{+0.13} _{-0.07}	-157 ⁺²⁰ ₋₂₆	3.13 ^{+1.99} _{-1.01}	0.06 ^{+0.08} _{-0.06}	1.0
	2	2500 ⁺³⁵⁰ ₋₂₅₀	0.31 ^{+0.08} _{-0.10}	0.25 ^{+0.07} _{-0.08}	-89 ⁺²⁰ ₋₂₆	1.48 ^{+0.77} _{-0.96}	51.0 ^{+67.6} _{-42.2}	1.0
	3	2400 ⁺¹⁵⁰ ₋₁₅₀	4.67 ^{+0.38} _{-0.31}	3.59 ^{+0.37} _{-0.33}	-69 ⁺¹⁵ ₋₁₁	329 ⁺⁵⁵ ₋₄₅	6.58 ^{+7.52} _{-6.58}	1.0
	4	2400 ⁺¹⁵⁰ ₋₁₅₀	3.86 ^{+0.31} _{-0.25}	2.97 ^{+0.30} _{-0.27}	0	270 ⁺⁴⁴ ₋₃₆	0.52 ^{+0.56} _{-0.49}	1.2
	5	2400 ⁺¹⁵⁰ ₋₁₅₀	4.91 ^{+0.34} _{-0.83}	3.77 ^{+0.35} _{-0.68}	326 ⁺²⁸ ₋₂₉	255 ⁺³⁶ ₋₈₇	4.70 ^{+5.26} _{-4.25}	0.7
	6	2850 ⁺¹⁵⁰ ₋₁₅₀	0.41 ^{+0.11} _{-0.10}	0.37 ^{+0.10} _{-0.09}	+385 ⁺²⁸ ₋₂₉	2.77 ^{+1.49} _{-1.35}	30.9 ^{+42.4} _{-27.7}	1.0
	7	2900 ⁺¹⁶⁰ ₋₃₅₀	0.10 ^{+0.21} _{-0.04}	0.09 ^{+0.20} _{-0.04}	-41 ⁺³ ₋₃	0.2 ^{+0.7} _{-0.1}	1.03 ^{+4.45} _{-0.94}	1.0
Z3371	1	2750 ⁺²¹⁰ ₋₂₁₀	2.57 ^{+0.37} _{-0.31}	2.26 ^{+0.37} _{-0.32}	+200 ⁺²² ₋₂₄	139 ⁺⁴⁰ ₋₃₄	15.2 ^{+17.9} _{-14.4}	1.3
	2	3000 ⁺¹⁵⁰ ₋₁₅₀	8.06 ^{+0.76} _{-1.54}	7.75 ^{+0.83} _{-1.53}	-256 ⁺²² ₋₂₂	1210 ⁺²²⁹ ₋₄₆₂	14.1 ^{+15.6} _{-11.9}	1.1
	3	2950 ⁺²⁰⁰ ₋₂₁₀	3.06 ^{+0.09} _{-0.30}	2.89 ^{+0.21} _{-0.35}	+687 ⁺⁶⁰ ₋₅₅	157 ⁺¹¹ ₋₃₁	9.46 ^{+10.15} _{-9.46}	1.0
	4	3350 ⁺¹⁶⁰ ₋₁₀₀	1.10 ^{+0.11} _{-0.15}	1.18 ^{+0.13} _{-0.17}	-840 ⁺⁶⁵ ₋₆₃	24 ⁺⁵ ₋₇	45.1 ^{+50.0} _{-39.7}	1.1
	5	3150 ⁺¹⁶⁰ ₋₁₀₀	5.59 ^{+0.18} _{-0.18}	5.64 ^{+0.33} _{-0.26}	-296 ⁺⁶⁰ ₋₆₄	594 ⁺³⁹ ₋₃₉	8.12 ^{+8.44} _{-8.12}	1.1
	6	2350 ⁺²¹⁰ ₋₂₁₀	4.75 ^{+0.35} _{-2.45}	3.58 ^{+0.41} _{-1.87}	+502 ⁺⁴⁴ ₋₂₈	337 ⁺⁵² ₋₃₄₈	0.81 ^{+0.88} _{-0.72}	1.0
Z3377	1	3550 ⁺¹⁵⁰ ₋₁₆₀	2.46 ^{+0.61} _{-0.75}	2.84 ^{+0.71} _{-0.87}	-240 ⁺¹⁷ ₋₁₉	56 ⁺²⁸ ₋₃₄	2.13 ^{+2.77} _{-1.75}	0.5
	2	3450 ⁺¹⁶⁰ ₋₁₀₀	3.92 ^{+0.12} _{-0.10}	4.33 ^{+0.24} _{-0.17}	+20 ⁺¹⁶ ₋₁₀	222 ⁺¹⁵ ₋₁₂	1.74 ^{+1.88} _{-1.74}	0.8
	3	3300 ⁺¹⁶⁰ ₋₁₅₀	3.90 ^{+0.13} _{-1.31}	4.12 ^{+0.24} _{-1.40}	-167 ⁺²⁹ ₋₃₂	188 ⁺¹³ ₋₁₂₇	0.21 ^{+0.22} _{-0.16}	0.7
	4	3050 ⁺¹⁵⁰ ₋₂₅₀	4.54 ^{+0.09} _{-0.23}	4.51 ^{+0.24} _{-0.43}	+24 ⁺¹⁵ ₋₉	212 ⁺¹⁰ ₋₂₃	0.34 ^{+0.35} _{-0.34}	0.6
	5	2800 ⁺¹⁵⁰ ₋₁₂₀	4.55 ^{+0.17} _{-0.42}	4.08 ^{+0.27} _{-0.52}	+411 ⁺³¹ ₋₅₂	203 ⁺¹⁶ ₋₃₉	1.41 ^{+1.48} _{-1.32}	0.6
	6	2800 ⁺¹⁵⁰ ₋₁₅₀	5.92 ^{+0.38} _{-0.88}	5.31 ^{+0.44} _{-0.84}	+366 ⁺³¹ ₋₅₂	343 ⁺⁴⁵ ₋₁₀₂	3.21 ^{+3.45} _{-2.82}	0.6
	7	2250 ⁺²⁵⁰ ₋₂₂₀	4.04 ^{+0.28} _{-0.48}	3.17 ^{+0.39} _{-0.47}	-366 ⁺³² ₋₃₂	124 ⁺¹⁸ ₋₃₀	2.66 ^{+2.90} _{-2.48}	0.5

and the minimal amount of krypton in the liner, $n_e \approx n_i$. A complete list of the temperatures and densities determined in the analysis for all six shots is shown in Table II.

An advanced neural network application utilizing Bayesian statistics has allowed for the determination of the spatially integrated ion temperature T_i through neutron yield and time-of-flight diagnostics [21]. This T_i analysis did not include information extracted from the krypton data. Hence, it is in-

formative to compare spatially integrated T_i and T_e . To obtain a spatially integrated T_e to compare with T_i , we define an emissivity-weighted average for T_e across the axial extent of the regions of a given shot [22]. This is expressed as

$$\bar{T}_e^{\epsilon_v} = \frac{\int \int T_e(z) \epsilon_v(z) A(z) dz dv}{\int \int \epsilon_v(z) A(z) dz dv}, \quad (3)$$

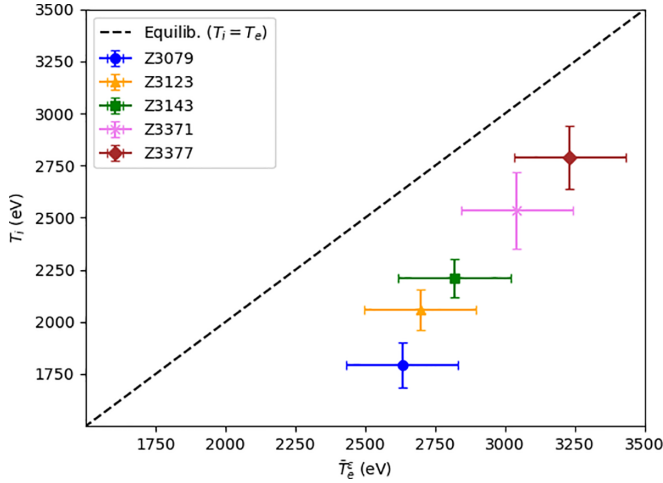


FIG. 7. A plot of the emissivity-weighted average electron temperature diagnosed through krypton spectroscopy vs the ion temperature determined from neutron diagnostics.

where $T_e(z)$ is the diagnosed electron temperature for a given axial region, $\epsilon_\nu(z)$ is the monochromatic emissivity calculated by our spectral model for a z coordinate, $A(z)$ is the surface area of a volume element at a z coordinate, dz is the axial height of the given region, and $d\nu$ is the photon frequency element. The photon frequency integration is over the 12.85–13.15 keV of the He α spectrum. Describing the temperature in this way accounts for the different weights each region contributes based on its emissivity. This also considers changes in the height of a region that can vary between shots.

The ion temperature values have been determined for five of the six shots presented here and are compared to the diagnosed emissivity-weighted average electron temperature in Fig. 7. First, we note that both temperature measurements demonstrate that hot, deuterium burning plasmas with temperatures in the 1.75 to 3.5 keV range have been produced in the MagLIF experiments at Z. Second, ion and electron temperatures are strongly correlated and they monotonically increase as a function of initial fill density. Third, we can also see that the electron temperature for each shot is larger than the ion temperature. Usually, in ICF experiments, the ion temperature is expected to have a greater value than the electron temperature. However, the temperature measurements displayed in Fig. 7 are space and time integrated and, in particular, the time intervals of integration may not completely overlap in time, thus effectively sampling slightly different states of the plasma. We further note that the rate of 13 keV x-rays has a steeper dependence on temperature than from neutrons of the deuterium-deuterium nuclear fusion reaction recorded with neutron time-of-flight measurements [19].

The trends observed between the experimental parameters that varied across the six shots and the diagnosed emissivity-weighted average electron temperatures are shown in Fig. 8. We can see that the shots with higher initial filling pressures resulted in higher peak temperatures. Similarly, the thinner Be liners resulted in higher peak temperatures as well. As a consistency check, the total neutron yield scales with the electron temperature. It should be noted that while the neu-

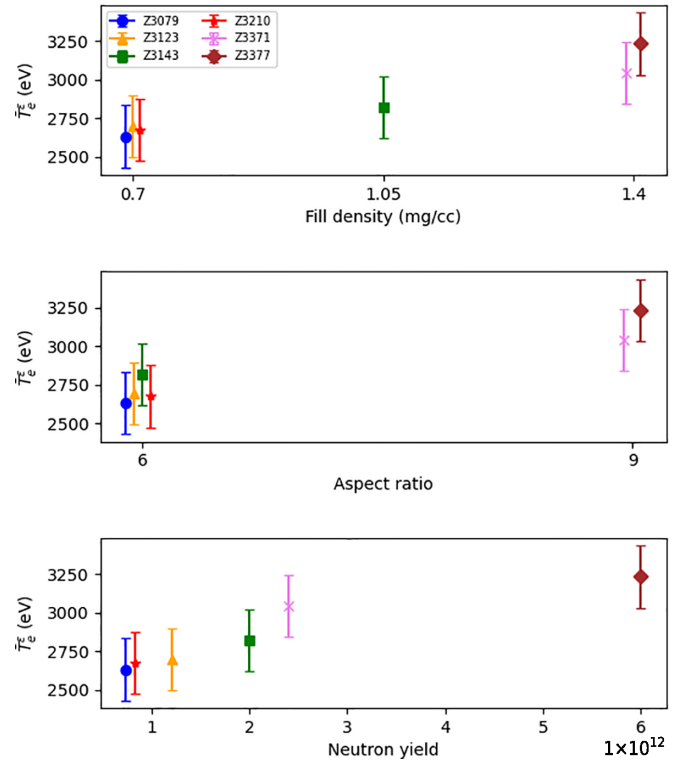


FIG. 8. Plots of the trends of emissivity-weighted average electron temperatures vs the parameters that varied between the shots. The plot at the top shows the electron temperature of each shot vs the shots initial gas fill. The middle plot shows the trends vs the aspect ratio of the liner. The bottom plot shows the trend vs total neutron yield on a logarithmic scale. The data points with the same aspect ratio or initial density are slightly separated from each other for illustrative purposes.

tron yield is directly related to the ion temperature, a higher ion temperature would imply a higher electron temperature, which follows the result shown in Fig. 8.

In the analysis of the preheating phase of MagLIF, the electron temperature was largest near the laser entrance hole and decreased with the depth of the liner [5,6]. Here, a similar trend appears across the six experiments, but the peak temperatures typically are located closer to the center of the liner. For example, shot Z3079 had a peak temperature located at the top of the liner and decreased with depth, whereas shot Z3143 was hottest in the center of the liner and decreased away from the center. The temperature reached in the experiments appears to correlate more on the compression along the plasma column distribution than the depth of the preheat energy deposition. Lastly, shot Z3377 had the brightest krypton emission as well as the largest neutron yield of the six krypton-doped experiments and also resulted in the highest electron temperatures. Taking advantage of the spatial resolution of the instrument has provided a better understanding of the structure and temperature distribution of the imploded MagLIF burning plasma.

V. THERMAL FLUX AND RKE ASSESSMENT

Knowledge of axial electron temperature and density distributions enables the analysis of thermal transport along

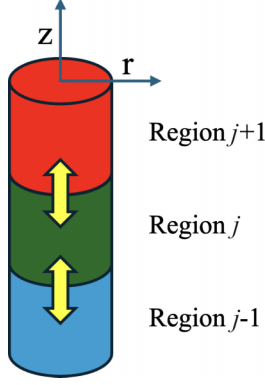


FIG. 9. Illustration of imploded cylinder divided into discrete regions. The arrows indicate the movement of energy into or out of a given region or zone.

the axis of the plasma column and the relative importance of energy lost via bremsstrahlung emission. Moreover, investigating the axial thermal transport of energy is of specific interest to MagLIF because the axial magnetic field is included to inhibit thermal flux radially, but does not constrain transport axially.

In order to assess the thermal flux of energy across axial boundaries, we employ the schematic shown in Fig. 9. We can treat the imploded plasma as a collection of discretized cylinders stacked on top of one another. The height of each cylinder is determined by the spatial resolution of the instrument and the radius is $\sim 50 \mu\text{m}$. These volumes are allowed to exchange energy via thermal transport across the cross-sectional area that connects the zones together. In this way, we can quantitatively assess energy transfer and loss mechanisms that occur in the plasma. It should be noted that given the time-integrated nature of the measurements, the results we discuss for the energy transport mechanisms represent time-averaged effective values.

The thermal flux is given by

$$\vec{q} = -\kappa_{\parallel} \nabla T_e, \quad (4)$$

where $\kappa_{\parallel} = \frac{3.2(4\pi\epsilon_0)^2 \sqrt{m_e} T_e^{3/2}}{4\sqrt{2\pi} \ln \Lambda e^4}$ is the Spitzer thermal conductivity for thermal flux parallel to the lines of the magnetic field [23]. The Spitzer conductivity is valid when $n_i \lambda_D^3 \gg 1$, where λ_D is the Debye length of the plasma. For the temperatures and densities determined in this analysis, this product is always much greater than one. Also, the electron mean free path is in the range from 0.2 to 2.0 μm ; these values are much smaller than the spatial length scale of T_e , which is a few-hundred microns. There is a large dependence on electron temperature, but a lesser (logarithmic) dependence on electron density. Here we are only considering the thermal transport along the axis of the liner because we do not have any spectral data resolved radially. The rate of thermal energy into or out of a region is calculated by multiplying the thermal flux by the surface area created by the boundary between adjacent regions.

Bremsstrahlung power emission is related to the temperature and density through

$$P_{Br} = 1.76 \times 10^{17} \sqrt{T_e} Z_i^3 \rho^2 V / A^2, \quad (5)$$

where Z_i is the net charge of the emitting plasma, ρ is the final mass density, V is the volume of the emitting element, and A is the mass number of the plasma [24].

Recent efforts have been made to characterize the RKE in ICF spherical implosions remaining in the implosion core fuel [8,9]. However, no assessment has been done to evaluate the RKE trapped in the axial flow of a cylindrical MagLIF implosion core. Here, we infer the axial RKE of the plasma from the vertical flow that can be driven by the axial pressure distributions calculated using the temperatures and densities obtained from the spectroscopy data analysis. The pressure is given by the ideal gas law as

$$P = (n_e + n_i) k T_e, \quad (6)$$

where $n_e \approx n_i$ since the amount of krypton mixed in the fuel is minimal. We can compare the pressures computed here with values published elsewhere for three other MagLIF experiments [25]. While those three experiments differ in laser preheat energy and have a larger axial magnetic field of 15 T compared to the six experiments discussed here, those results can still be used as an order-of-magnitude consistency check against the pressures determined through the temperatures and densities from the krypton spectroscopy analysis. The pressures in the two independent studies agree well.

In order to compare the thermal flux and bremsstrahlung emission rates to the RKE, we look at the rate of change of the axial RKE. For a given axial region j , this quantity is calculated as

$$\frac{d(\text{RKE})_j}{dt} = m_j \vec{v}_j \cdot \vec{a}_j, \quad (7)$$

where m_j is the mass, and v_j and a_j are the velocity and acceleration, respectively, of the region. The mass of a region is found through $m_j = \rho_j V_j$, where ρ_j is the mass density of the deuterium in region j found by multiplying the ion density by the mass of deuterium and V_j is the volume of region j . To calculate the accelerations and velocities, we start with the axial pressure distributions mentioned previously. We first calculate the net pressure exerted on a region from the axial pressure differentials, $\Delta P_{j,j+1} = [P_j - P_{j+1}]$. The net force on a region is the sum of the pressure differentials pushing into j and exerting outward on adjacent regions, $\vec{F}_j = (\Delta P_{j,j+1} + \Delta P_{j,j-1}) \vec{A}$, where $\vec{A}$ is the surface area connecting two zones together. Here we are assuming a constant radius of $\sim 50 \mu\text{m}$, $\vec{A} = \vec{A}_j = \pi (50 \mu\text{m})^2$ for all j . The net forces are related to the accelerations through Newton's Law, $\vec{F}_j = m_j \vec{a}_j$. Finally, we estimate the velocity from the acceleration and a timescale which we take as given by the burn width, $\tau = 2.5 \text{ ns}$. The latter is taken from values measured in similar MagLIF experiments [19].

The list of results is shown in Table II. We can see that the dominant source of axial energy transport originates from the thermal transport up and down the imploded plasma column, which is $\sim 10^3$ larger than the energy released in the form of bremsstrahlung radiation, i.e., axial energy transport through thermal flux proceeds at a much faster rate than the energy that is lost through bremsstrahlung emission. The values calculated for the RKE have relatively large uncertainties, i.e., effectively they represent ranges. Interpreted in this way, the rate of RKE in vertical plasma flow can be comparable and

larger than Bremsstrahlung emission, but smaller than that of axial thermal transport.

VI. CONCLUSIONS

We present krypton K-shell spectroscopy experiments from MagLIF implosions at Z. A tracer amount of krypton was added to the deuterium fuel of the order of parts per million. Accordingly, the inclusion of this small amount of krypton had a minimal effect on the neutron yield and provided a low optical depth for the lines present in the K-shell spectrum, including the $\text{He}\alpha$ of <0.1 . An imaging transmission spectrometer equipped with a cylindrically bent quartz crystal was employed to record time-integrated axially resolved krypton K-shell emission spectra in the range from 12.5 to 13.5 keV with a spatial resolution of 0.5 mm and a spectral resolving power of 750. In this photon-energy range, the spectrum is dominated by Be-, Li-, and He-like krypton ions.

Detailed atomic and radiation physics modeling of the spectrum for the conditions expected in the hot dense deuterium burning plasma demonstrates that the relative intensity distribution is electron temperature dependent, but weakly sensitive to density. As a result of the temperature dependence and the spatially resolved nature of the observation, we were able to extract the axial distribution of temperature from the burning plasma. Once the temperature distribution is determined, the distribution of density was extracted from the relative brightness of narrowband intensities. The electron temperatures and densities obtained from the spectroscopic analysis showed that the burning plasma had temperatures in the range of 2.0–3.6 keV, and electron number densities from $1 \times 10^{22}/\text{cc}$ to $6 \times 10^{23}/\text{cc}$. The largest electron temperatures were located in the top and central regions of the plasma column. Additionally, a comparison with the T_i independently diagnosed with nTOF data shows a strong correlation with the T_e presented in this work. However, the electron temperatures are larger than the ion temperatures.

The availability of both the electron temperature and density measurements enabled an energy analysis including axial thermal flux, bremsstrahlung power emission, and the time rate of change of RKE. The analysis shows that the axial thermal flux proceeds at a much greater rate ($\sim 10^3$) than both the bremsstrahlung emission and the rate of change of RKE. In spite of the large uncertainties associated with the rate of change of RKE, the estimations provide a range of values that can be comparable or greater than the bremsstrahlung emission, but still smaller than the axial thermal flux.

The largest sources of error arise from propagating the density determination into the expressions for bremsstrahlung emission and the RKE. The error bars for density are modest, but propagating this uncertainty through each calculation can cause the error bars in energy to be quite high. For example, the bremsstrahlung emission is proportional to ρ^2 , which means that the errors will be necessarily larger compared to the ion density.

The measurements presented here are time integrated. Using a time-gated spectrometer would allow for a view into the temporal evolution of the stagnating plasma. Additionally, since the data are time integrated, we do not have access to

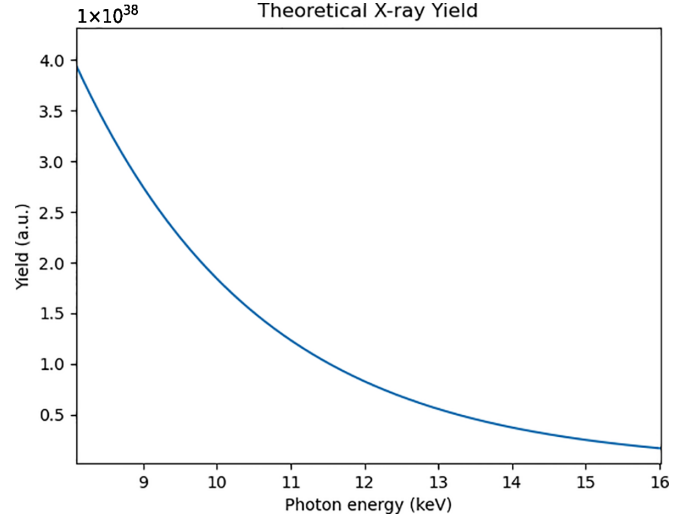


FIG. 10. The theoretical x-ray yield as a function of photon energy for a plasma with $n_D = 5 \times 10^{22}/\text{cc}$, $T_e = 2.5$ keV, $R = 50 \mu\text{m}$, $L = 1$ mm, and $\tau = 2.5$ ns.

the burn time of the fuel and the time history of the krypton line emission in this experiment. This is necessary when calculating the RKE. Instead, we calculate the rate of change of RKE by estimating the burn width from previous MagLIF experiments with similar parameters.

While the axial density distributions were determined through the relative narrowband intensities of the axial regions and a mass conservation constraint, considering an alternative spectroscopic measurement may produce better values. In addition, fielding a second radially resolving spectrometer would allow one to record spectra that could be used to diagnose the radial distribution of the temperature. The latter would be useful for comparison with the axial measurement as well as to assess the magnetic field effect at stagnation on axial and radial thermal transport.

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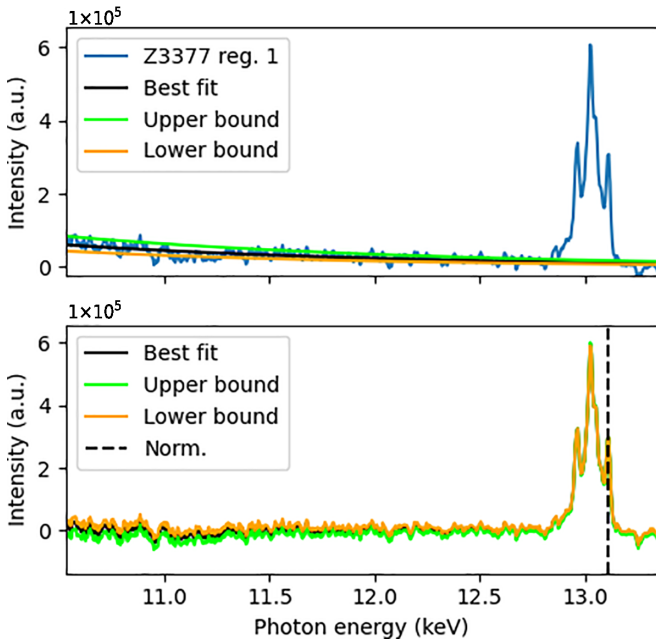


FIG. 11. Figures of experimental continuum subtraction procedure. The top plot shows the experimental data from region 1 of shot Z3377 in blue with the best-fit exponential function and $\pm 1\sigma$ of the fit in green and orange, respectively. The bottom plot shows the resulting three lineouts of the He α line emission from shot Z3377 region 1 after the three different continuum levels are subtracted. The krypton line emission with the best fit to the continuum is shown in black and the upper and lower bounds of the subtraction are shown in green and orange, respectively. The black dotted line located at 13.114 keV shows the position chosen to normalize the three lineouts.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: CONTINUUM SUBTRACTION PROCEDURE

Each shot discussed here had an underlying continuum that needed to be removed in order to isolate the krypton line emission. The x-ray yield in an ICF experiment is proportional to $Y_{hv} \propto n_D^2 R^2 L \tau \exp[-h\nu/k_b T_e]/T_e^{1/2}$, where Y_{hv} is the total

x-ray yield as a function of photon energy, n_D is the deuterium atom number density, R is the stagnation radius, L is the length of the plasma column, and τ is the burn width [19]. A plot of the x-ray yield as a function of photon energy between 8 and 16 keV for a MagLIF plasma with $n_D = 5 \times 10^{22}/\text{cc}$, $R = 50 \mu\text{m}$, $L = 1 \text{ mm}$, $T_e = 2.5 \text{ keV}$, and $\tau = 2.5 \text{ ns}$ is shown in Fig. 10. We can see that this function is always exponentially decaying above 8 keV. It is, therefore, a good approximation to fit the continuum in the data to an exponentially decaying function and then using it to remove all but krypton line emission. An example of the krypton emission with the underlying continuum for shot Z3377 region 1 is shown in the top plot of Fig. 11. Here we can see a slight drop with increasing photon energy. The shape of the function is set by the electron temperature of the plasma and is found through a least-squares polynomial fit. The data on the left- and right-hand sides of the krypton line emission are sampled against the theoretical x-ray yield with varying electron temperatures until a solution is found via the least-squares minimization. The upper and lower bounds of the continuum fit are then taken from the sum of squared residuals of the fit.

The next step is to subtract the continuum from the data to isolate the krypton line emission. As is seen in the lower plot of Fig. 11, the different continuum subtractions provide slightly different relative intensity distributions. The upper bound of the subtraction will necessarily decrease the lower end of the spectrum relative to the higher end, and vice versa for the lower bound estimation. Although the differences between the three traces may be slight, they provide a nonzero contribution to the total uncertainty.

As mentioned, the shape of the exponential function is determined by the electron temperature of the plasma. Therefore, the process of subtracting the continuum provides another consistency check for the electron temperature diagnosed through the krypton line emission. For each shot and region, the electron temperature found through the continuum subtraction is within $\pm 15\%$ of the value reported in Table II.

The end result is three lineouts for a given region of the data, i.e., one along the best fit and two slightly adjusted for the different continuum level subtractions. As seen in Fig. 11, these can be very small differences, but when used through the least-squares minimization, the best-fit temperatures can vary up to 50 eV. The analysis is done for each individual lineout, and the changes in the results lead to another contribution to the uncertainty when added in quadrature to the uncertainties from the FWHM.

- [1] S. A. Slutz, M. C. Herrmann, R. A. Vesey, A. B. Sefkow, D. B. Sinars, D. C. Rovang, K. J. Peterson, and M. E. Cuneo, Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field, *Phys. Plasmas* **17**, 056303 (2010).
- [2] J. Lindl, P. Amendt, R. Berger, S. Glendinning, S. Glenzer, S. Haan, R. Kauffman, O. Landen, and L. Suter, The physics basis for ignition using indirect-drive targets on the National Ignition Facility, *Phys. Plasmas* **11**, 339 (2004).
- [3] D. C. Rovang, D. C. Lammpa, M. E. Cuneo, A. C. Owen, J. McKenney, D. W. Johnson, S. Radovich, R. J.

- Kaye, R. D. McBride, C. S. Alexander, T. J. Awe, S. A. Slutz, A. B. Sefkow, T. A. Haill, P. A. Jones, J. W. Argo, D. G. Alton, G. K. Robertson, E. M. Waisman, D. B. Sinars, *et al.*, Pulsed-coil magnet systems for applying uniform 10–30 T fields to centimeter-scale targets on Sandia’s Z facility, *Rev. Sci. Instrum.* **85**, 124701 (2014).

- [4] P. Rambo, I. Smith, J. Porter, M. Hurst, C. Speas, R. Adams, A. Garcia, E. Dawson, B. Thurston, C. Wakefield, J. Kellogg, M. Slattery, H. Ives, R. Broyles, J. Caird, A. Erlandson, J. Murray, W. Behrendt, N. Neilson, and J. Narduzzi, Z-Beamlet:

- A multikilojoule, terawatt-class laser system, *Appl. Opt.* **44**, 2421 (2005).
- [5] K. Carpenter, R. Mancini, E. Harding, A. Harvey-Thompson, M. Geissel, M. Weis, S. Hansen, K. Peterson, and G. Rochau, Magnetic field impact on the laser heating in MagLIF, *Phys. Plasmas* **27**, 052704 (2020).
- [6] K. R. Carpenter, R. C. Mancini, E. C. Harding, A. J. Harvey-Thompson, M. Geissel, M. R. Weis, S. B. Hansen, K. J. Peterson, and G. A. Rochau, Temperature distributions and gradients in laser-heated plasmas relevant to magnetized liner inertial fusion, *Phys. Rev. E* **102**, 023209 (2020).
- [7] D. E. Ruiz, P. F. Schmit, D. A. Yager-Elorriaga, C. A. Jennings, and K. Beckwith, Exploring the parameter space of MagLIF implosions using similarity scaling. I. Theoretical framework, *Phys. Plasmas* **30**, 032707 (2023).
- [8] K. M. Woo, R. Betti, O. W. Mannion, C. J. Forrest, J. P. Knauer, V. N. Goncherv, P. B. Radha, D. Patel, V. Gopalaswamy, and V. Y. Glebov, Inferring thermal ion temperature and residual kinetic energy from nuclear measurements in inertial confinement fusion implosions, *Phys. Plasmas* **27**, 062702 (2020).
- [9] T. J. Murphy, The effect of turbulent kinetic energy on inferred ion temperature from neutron spectra, *Phys. Plasmas* **21**, 072701 (2014).
- [10] H. Chen, T. Ma, R. Nora, M. A. Barrios, H. A. Scott, M. B. Schneider, L. B. Hopkins, D. T. Casey, B. A. Hammel, L. C. Jarrott, O. L. Landen, P. K. Patel, M. J. Rosenberg, and B. K. Spears, On krypton-doped capsule implosion experiments at the National Ignition Facility, *Phys. Plasmas* **24**, 072715 (2017).
- [11] J. T. Clapp, R. C. Mancini, E. C. Harding, M. A. Schaeuble, and A. J. Harvey-Thompson, Observation and diagnostic application of Kr K-shell emission in magnetized liner inertial fusion experiments at Z, *Rev. Sci. Instrum.* **93**, 103532 (2022).
- [12] E. Gallardo-Diaz, R. C. Mancini, D. T. Cliche, and R. Tommasini, Design of a multi-monochromatic x-ray imager (MMI) for Kr K-shell line emission, *Rev. Sci. Instrum.* **93**, 113525 (2022).
- [13] D. B. Sinars, D. F. Wegner, S. A. Pikuz, B. Jones, M. Geissel, S. B. Hansen, C. A. Coverdale, D. J. Ampleford, M. E. Cuneo, L. A. McPherson, and G. A. Rochau, Compact, rugged in-chamber transmission spectrometers (7–28 keV) for the Sandia Z facility, *Rev. Sci. Instrum.* **82**, 063113 (2011).
- [14] G. Dunham, E. C. Harding, G. P. Loisel, P. W. Lake, and L. B. Nielsen-Weber, Cross-calibration of Fuji TR image plate and RAR 2492 x-ray film to determine the response of a DITABIS super micron image plate scanner, *Rev. Sci. Instrum.* **87**, 11E301 (2016).
- [15] E. Gallardo-Diaz, R. C. Mancini, J. T. Clapp, P. Adrian, T. E. Evans, J. Frenje, R. Florido, M. K. G. Kruse, and T. Nagayama, First observations from the Kr multi-monochromatic x-ray imager for time and spatially resolved diagnosis of hot implosion cores, *Phys. Plasmas* **31**, 072701 (2024).
- [16] R. C. Mancini, D. P. Kilcrease, L. A. Woltz, and C. F. Hooper, Computational aspects of the Stark line broadening of multielectron ions in plasmas, *Comput. Phys. Commun.* **63**, 314 (1991).
- [17] M. F. Gu, The flexible atomic code, *Can. J. Phys.* **86**, 675 (2008).
- [18] J. MacFarlane, I. Golovkin, P. Wang, P. Woodruff, and N. Pereyra, SPECT3D – A multi-dimensional collisional-radiative code for generating diagnostic signatures based on hydrodynamics and PIC simulation output, *High Energy Density Phys.* **3**, 181 (2007).
- [19] S. B. Hansen, M. R. Gomez, A. B. Sefkow, S. A. Slutz, D. B. Sinars, K. D. Hahn, E. C. Harding, P. F. Knapp, P. F. Schmit, T. J. Awe, R. D. McBride, C. A. Jennings, M. Geissel, A. J. Harvey-Thompson, K. J. Peterson, D. C. Rovang, G. A. Chandler, G. W. Cooper, M. E. Cuneo, M. C. Herrmann, *et al.*, Diagnosing magnetized liner inertial fusion experiments on Z, *Phys. Plasmas* **22**, 056313 (2015).
- [20] E. C. Harding, T. Ao, J. E. Bailey, G. Loisel, D. B. Sinars, M. Geissel, G. A. Rochau, and I. C. Smith, Analysis and implementation of a space resolving spherical crystal spectrometer for x-ray Thomson scattering experiments, *Rev. Sci. Instrum.* **86**, 043504 (2015).
- [21] W. E. Lewis, P. F. Knapp, S. A. Slutz, P. F. Schmit, G. A. Chandler, M. R. Gomez, A. J. Harvey-Thompson, D. J. A. M. A. Mangan, and K. Beckwith, Deep-learning-enabled Bayesian inference of fuel magnetization in magnetized liner inertial fusion, *Phys. Plasmas* **28**, 092701 (2021).
- [22] I. E. Golovkin and R. C. Mancini, High-order satellites and plasma gradients effects on the Ar He β line opacity and intensity distribution, *J. Quantum Spectrosc. Radiat. Transfer* **65**, 273 (2000).
- [23] L. Spitzer and R. Harm, Transport phenomena in a completely ionized gas, *Phys. Rev.* **89**, 977 (1953).
- [24] S. Atzeni and J. Meyer-Ter-Vehn, *The Physics of Inertial Fusion* (Oxford Science, Oxford, 2004).
- [25] M. R. Weis, D. E. Ruiz, M. R. Gomez, A. J. Harvey-Thompson, C. A. Jennings, D. A. Yager-Elorriaga, W. E. Lewis, S. A. Slutz, L. Shulenburg, D. J. Ampleford, K. Beckwith, and J. N. Koning, Assessing the performance of MagLIF with 3D MHD simulations, *Phys. Plasmas* **32**, 022708 (2025).