Fusion-neutron measurements for magnetized liner inertial fusion experiments on the Z accelerator

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Abstract. Several magnetized liner inertial fusion (MagLIF) experiments have been conducted on the Z accelerator at Sandia National Laboratories since late 2013. Measurements of the primary DD (2.45 MeV) neutrons for these experiments suggest that the neutron production is thermonuclear. Primary DD yields up to $3 \times 10^{12}$ with ion temperatures ~2-3 keV have been achieved. Measurements of the secondary DT (14 MeV) neutrons indicate that the fuel is significantly magnetized. Measurements of down-scattered neutrons from the beryllium liner suggest $\rho_{\text{liner}} \sim 1 \text{ g/cm}^2$. Neutron bang times, estimated from neutron time-of-flight (nTOF) measurements, coincide with peak x-ray production. Plans to improve and expand the Z neutron diagnostic suite include neutron burn-history diagnostics, increased sensitivity and higher precision nTOF detectors, and neutron recoil-based yield and spectral measurements.

1. Introduction

Measurements of the neutrons produced during magnetized liner inertial fusion (MagLIF) experiments [1]-[2] conducted at the Z pulsed-power accelerator [3] at Sandia National Laboratories suggest that the neutron production is predominantly thermonuclear [4]. Beginning in 2013, these experiments have been performed using deuterium fuel and produced primary DD (2.45 MeV) fusion neutron yields up to $3 \times 10^{12}$ with electron and ion stagnation temperatures in the 2-3 keV range. In section 2, we report several neutron measurements from MagLIF experiments. Plans for improvements to the nuclear diagnostic suite are presented in section 3.

MagLIF is an inertial confinement fusion (ICF) concept that also makes use of magnetic confinement via an externally applied magnetic field. In contrast with standard ICF concepts, pre-magnetizing the fuel is advantageous because this significantly relaxes the required stagnation pressures [1]-[2]. The MagLIF concept utilizes the implosion of a laser-preheated (~ 2.5 kJ), pre-magnetized (10 T) fuel by a solid cylindrical beryllium liner that is compressed by the 17-19 MA delivered by the Z pulsed-power accelerator [1]-[2]. Results from computer simulations using the magneto-hydrodynamics code GORGON are shown in figure 1(a) and illustrate the three main stages of the MagLIF concept. Figure 1(b) shows a time-integrated, self-emission x-ray image of the hot stagnated plasma column from shot 2613 which has a ~ 100 μm diameter and ~ 6 mm length.
Explanations for the helical structure in the column as well as variations in brightness are presently under investigation.

![Diagram](image)

**Figure 1.** (a) Simulation results depict the three main stages of MagLIF: magnetization, laser preheat, and compression. (b) Time-integrated x-ray self-emission from plasma column.

2. Measurements of fusion neutrons on MagLIF experiments

There are several neutron diagnostics on Z used to characterize the primary DD and secondary DT neutron yields and spectra [5]. Neutron yields are principally measured using neutron activation of select materials such as indium $^{115}\text{In}(n,\gamma)^{115m}\text{In}$ with threshold = 336 keV for DD yields which are dominated by neutrons with energies between 2.3-2.6 MeV, but includes the significant contribution from down-scattered neutrons in the ~ 1.5-2.4 MeV range. Copper activation $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ with threshold = 11 MeV is used to measure secondary DT yields which range between 11.8-17.2 MeV. The contribution to the indium activation from higher-energy secondary DT neutrons is << 1%, thus these materials are appropriate for isolating the DD and DT yields. Corrections for neutron attenuation and scattering from Z hardware are preformed using the Monte Carlo MCNP code [6]. Neutron spectra are measured using neutron time-of-flight (nTOF) detectors. Presently, there are two axial nTOF detectors at approximately 7 m and 8 m below the target. Three radial detectors are located at approximately 9.5 m, 11.5 m, and 25 m from the target. All the detectors are composed of a 2.54-cm thick, 7.62-cm diameter, BC-422Q (1%) scintillator coupled to a photomultiplier tube (PMT such as Hamamatsu 5946-mod4). Most of the nTOF detectors utilize extensive collimation and shielding both near the target and around the detectors. This is necessary to limit the amount of neutron down-scatter from hardware and the intense (> 1 MeV) bremsstrahlung-induced signals produced during the experiments that can saturate the detectors. In most cases, the activation-measured yields are compared with the yields inferred from nTOF measurements.

2.1. Neutron yield and ion temperature measurement results

As one of the most essential metrics to support the notion of thermonuclear neutron production, the DD neutron yields appear to be isotropic, and the radially and axially measured DD neutron spectral shapes appear to be very similar and have Gaussian shapes from which realistic fusion ion temperatures can be inferred. Figure 2 shows a plot of the primary and secondary neutron yields for several MagLIF shots as well as the ion and electron temperatures. The average primary yield shown in figure 2 is based on several indium activation measurements performed axially (above and below) and radially. The primary DD yields range from $10^{11}$-3$10^{12}$ and all measurements indicate asymmetries less than the measurement uncertainties which are ~ 20%. Secondary DT yields range from $10^9$-5$10^{10}$ and typical uncertainties are also ~ 20%. (It is important to note that the DT yields below $10^{10}$ could not be verified with nTOF measurements.) Ion temperatures are also plotted and range from 1-3 keV with 30% uncertainties.

Figure 3 shows the axially and radially measured nTOF spectra from shot 2591 (2$10^{12}$ DD yield) for data corrected for PMT response, light-output, and direct line-of-sight neutron attenuation and
scattering. The ion temperature ($T_{\text{ion}}$) [7] inferred from these data is determined by fitting a Gaussian to the corrected, energy-transformed data. Significant down-scattered neutrons broaden the nTOF spectra on the lower energy side, hence the Gaussian is fitted to data in the ~2.4-3 MeV range in most cases. In figure 3, a Gaussian fit with corresponding $T_{\text{ion}}$ of 2.5 keV, determined from the average of the spectra shown, is over-plotted and shows good agreement with the data. (We are presently pursuing a forward analysis similar to [8] to infer $T_{\text{ion}}$ that also incorporates more realistic neutron scattering contributions to the nTOF signals.) Overall, the ion and electron temperatures (from x-ray spectroscopy measurements for some experiments) agree within the measurement uncertainties.

![Figure 2](image2.png)  
**Figure 2.** Plot of DD and DT neutron yields and ion and electron temperatures for several MagLIF shots.

![Figure 3](image3.png)  
**Figure 3.** Axial and radial neutron spectra measured for shot 2591 are over-plotted with Gaussian fit.

Based on several filtered, absolutely calibrated x-ray measurements using diamond photo-conduction diodes, the neutron burn duration appears to be $\leq 2$ ns FWHM [4]. Estimates of the neutron bang time from several neutron time-of-flight detectors indicate that the peak neutron production occurs near the time of peak x-ray emission, though uncertainties using the present far-away detectors are ~1 ns. Initial bang-time measurements using CVD diamond detectors show promise for measuring actual neutron burn widths and bang times with sub-ns uncertainties.

### 2.2. Inference of fuel magnetization from secondary DT neutrons

Production of secondary DT neutrons indicates that the fuel is significantly magnetized given the rather low fuel areal density in the radial direction ($\sim 2$ mg/cm$^2$) [9]-[10]. Asymmetry in the DT spectral shapes measured radially and axially, shown in figure 4 for shot 2591, are yet another indicator of the degree of magnetization. The radially measured spectra appear narrower than the axially measured spectra. The asymmetry arises from the high aspect ratio cylindrical geometry where the 1 MeV tritons born in the fuel have increased probability of interacting along the axial direction. The tritons traveling in the axial direction are Doppler-shifted, and this leads to the double peaked structure observed. The inferred magnetization parameter $BR$, where $B$ is the magnetic field and $R$ is the inferred fuel radius, is 0.34 MG-cm. BR, rather than fuel areal density, is the fundamental confinement parameter relevant for MagLIF.

### 2.3. Inference of liner areal density from down-scattered neutrons

Down-scattered primary neutrons from the highly compressed beryllium liner reveal information about the liner areal density ($p_{\text{R liner}}$). Figure 5 presents axially and radially measured neutron spectra from shot 2591 between 1-3 MeV, both of which reveal small peaks at $\sim 1.6$ MeV which are associated with neutrons down-scattered from beryllium. Results from MCNP simulations are over-plotted with the measured data. These simulations were performed for a 6-mm length, deuterium-fuel line source with a 2.5 keV ion temperature inside a cylindrical beryllium liner with $p_{\text{R liner}}$ of 1 g/cm$^2$. The simulated and measured peaks agree reasonably in terms of the $\sim 1.6$ MeV down-scatter amplitude and the peak location. Additional neutron down-scatter (from hardware, notably between 2-
2.4 MeV) may obscure the down-scatter peak amplitude since this background contribution is not fully understood. What is evident for the measurements and simulations is the subtle energy difference between the ~ 1.6 MeV peak amplitudes for the axial and radial spectra with the axial spectra located at slightly lower energy. It is encouraging that measurements of $\rho_{\text{Rliner}}$ based on x-ray spectroscopy reveal the liner areal density to be ~ 0.9 g/cm², which is very close to the neutron measurement despite the background issues.

![Figure 4](image1.png)

**Figure 4.** Plots of measured and simulated axial (top) and radial (bottom) DT neutron spectra.

![Figure 5](image2.png)

**Figure 5.** Down-scattered primary neutrons from the dense beryllium liner are indicative of $\rho_{\text{Rliner}} \sim 1$ g/cm².

### 3. Future work and summary

One major area of improvement for neutron measurements on Z is to increase the sensitivity and precision for the nTOF measurements. We are presently testing and developing several gated nTOF detectors to gate out the large bremsstrahlung signals to better measure the smaller DT and DD signals. Also, we intend to improve the detector shielding and collimation to enable fielding of closer-in detectors and limit the down-scatter affecting all the detectors. Over the next few years, we will be exploring the incorporation of tritium fuel on Z experiments. In 2-3 years, our goal is to use ~ 1% tritium fuel mixed with deuterium. At this concentration, we expect primary DT yields to be of the same order of magnitude as the primary DD yields. With further improvements to MagLIF experiments (i.e., improved laser preheat coupling, higher magnetic fields, higher accelerator currents), we expect to produce yields in the ~1e13 range (DD and DT). At these higher DT yields, we intend to expand the Z neutron diagnostic suite to include neutron burn-history diagnostics, neutron imaging, and neutron recoil-based spectral measurements.

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### References

[1] S. Slutz *et al.* Phys. Rev. Lett., 108, 025003 (2012).
[2] S. Slutz *et al.* Phys. Plasmas, 17, 056303 (2010).
[3] K. Matzen *et al.* Phys. Plasmas, 4, 1519 (1997).
[4] M. Gomez *et al.* Phys. Rev. Lett. 113, 155003 (2014).
[5] R. J. Leeper *et al.* J. Phys.: Conf. Ser. 112, 032976 (2008).
[6] J. F. Briesmeister. MCNP - A General Monte Carlo N-particle Transport code, Version 4C, Los Alamos National Laboratory, 2000.
[7] V. Yu. Glebov *et al.* Rev. Sci. Instrum., 81, 10D325 (2010).
[8] Hatarik *et al.* J. Appl. Phys. 118, 184502 (2015).
[9] P. Schmit *et al.* Phys. Rev. Lett. 113, 155004 (2014).
[10] P. F. Knapp *et al.* Phys. Plasmas, 22, 056312 (2015).