ZR Neutron Diagnostic Suite

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Abstract. The ZR facility, a major refurbishment of Sandia National Laboratories' Z facility, is in the final stages of becoming operational. A number of neutron experiments are planned for this facility including deuterium gas puff z-pinch loads as well as indirect drive capsule experiments. As part of this effort, a new suite of neutron diagnostics is being developed. This suite will include improved neutron activation and neutron time-of-flight diagnostics for initial experiments. Future diagnostics being planned for ZR include neutron imaging, neutron bang time, neutron reaction history, and a neutron-proton recoil magnetic analyzer.

1. Introduction

The U. S. Department of Energy is supporting research at Sandia National Laboratories (SNL) to investigate the possibility of using pulsed power driven magnetic implosions (z-pinches) to drive inertial confinement fusion (ICF) targets [1]. This research is being conducted on SNL's ZR facility that is capable of delivering peak currents of 26 MA and electrical powers of 100 TW. The present paper will focus on a new suite of neutron diagnostics that are assuming an ever-increasing importance in conducting these experiments. An important issue in developing these diagnostics is that they must operate in an intense hard x-ray bremsstrahlung background of some 10^9-10^{10} rads/s. Diagnostics that are presently being developed for initial experiments include neutron yield detectors and neutron time-of-flight detectors that are fielded at several polar and azithmuthal angles to measure neutron total yield, neutron velocity and energy, and ion temperature.

Previous neutron measurements conducted at current levels of 20 MA on the Sandia's Z facility using gas puff loads produced DD neutron yields of 3.7 x 10^{13} into 4π [2,3]. Indirect capsule experiments on Z using a dynamic hohlraum (DH) load produced DD yields up to 2.7 x 10^{11} into 4π [4,5]. Based on these results, we expect DD gas puff neutron yields on ZR to scale to yields of order 1 x 10^{14} into 4π and DH capsule experiment yields to be up by a factor of several. Additionally, we are now considering going to DT gas fills in these experiments that should yield DT neutron yields that are of order 100 times higher relative to these DD yields. Given the possibility of these higher yields,

we are now considering a number of new future neutron diagnostics that will be added to our core neutron diagnostic suite. These include neutron imaging, neutron bang time, and neutron reaction history. Finally, we are also investigating the feasibility of an n-p recoil magnetic analyzer for high precision neutron spectroscopy measurements.

2. Total Neutron Yield Measurements

Indium and copper activation will be used on ZR for the measurement of total neutron yield of 2.45 MeV DD neutrons and 14.1 MeV DT neutrons, respectively. The indium diagnostic is based on the inelastic neutron scattering reaction: ^{115}In (n, n′)^{115m}In [5,6]. This reaction has a 336 keV threshold and is a standard for the measurement of DD neutrons in ICF experiments.   A competing ^{115}In(γ,γ′)^{115m}In reaction must be taken into account due to the hard bremsstrahlung background on Z. The ^{115m}In metastable state emits a 336 keV gamma ray, which is measured with a high-purity germanium detector. Cylindrical (2.5 cm diameter by 1.25-cm thick) indium samples will be placed on axis, on the side at 90 degrees, and on the bottom. The ^{115m}In metastable state has a 4.5 hours half-life. The copper diagnostic is based on the nuclear reaction: ^{63}Cu(n, 2n)^{62}Cu(β+) [5]. This reaction has an 11 MeV threshold, so it is sensitive to DT neutrons but not DD neutrons.   The induced ^{62}Cu positron activity has a 9.74 minute half-life and is measured using a NaI gamma-gamma coincidence system.

   A new approach to measuring neutron yields that is being developed for the ZR Facility is the Beryllium Rod Detector. This detector is based on the threshold reaction ^{9}Be(n,α)^{6}He and has been developed to measure bursts of DD or DT fusion neutrons. The ^{6}He activity produced can be directly related to the neutron yield. To measure the activity of the 0.8-second half-life, beta particles emitted from ^{6}He are counted using a plastic scintillator (BC-418) which is closely coupled to twelve, 0.635 cm diameter Be rods embedded in it, and mated to a 3.81 cm diameter R5946 fine mesh photomultiplier tube.   The output signal is passed through a constant fraction discriminator to a multichannel scaler.   The reaction has a threshold of 670 keV (making it insensitive to thermal neutrons); the data is obtained in real time (~ 3 seconds), by using multi-channel scaling to obtain the decay curve. Thus, with a properly calibrated detector, one can determine the neutron yield from the scaling of the decay curve in a matter of seconds.

3. Neutron Time-of-Flight Measurements

Four plastic scintillation detectors will be used in pairs as neutron time-of-flight (NTOF) detectors [4,5]. A schematic of the paired scintillation detectors for NTOF and indium activation measurements is shown in Fig. 1. The scintillation detectors consist of 2.54 cm thick by 7.6 cm diameter Bicron BC-418 plastic scintillator coupled to Hamamatsu R5946 photomultiplier tubes. Two of these "side-on" detectors A and B will be located along a single line-of-sight at 102 degrees with respect to the pinch z axis and at distances of 750 cm and 950 cm, respectively, from the ICF capsule. Another pair of "on-axis" detectors C and D will be located on a single line of sight along the Z axis at distances of 750 cm and 850 cm, respectively, below the target chamber center.

   The goals of paired detector configurations in the neutron time-of-flight technique are the absolute determination of the neutron average velocity and birth time. The configuration of paired side-on and paired on-axis neutron time-of-flight detectors improves our ability to identify ion beams as a contributing source of DD or DT neutrons. From simple kinematical considerations such ion beams, if present, are expected to be axially directed and would result in higher observed neutron energies (> 2.45 MeV or > 14.1 MeV) in the axial direction. But neutrons from axially directed ions, observed side on (near 102 degrees relative to the z axis) will have an energy consistent with 2.45 MeV in the case of DD targets or 14.1 MeV in the case of DT targets.   Thus, by measuring neutron energies axially and nearly orthogonally to the pinch z axis, ion-beam contributions to the neutron production are readily identified.

The neutron time-of-flight detectors also enable the measurement of reaction-weighted ion temperature of the fuel. As long as the detector is far enough away from the source, the spread in the arrival time of the neutrons corresponds to the spread in the initial velocity of the neutrons caused by the ion temperature. Therefore, the ion temperature is obtained from the NTOF spread by

$$T_i = (c_1 w/d)^2$$

where T_i is the ion temperature in keV, w is the full width at half-maximum (FWHM) of the neutron time distribution at the detector in ns, d is the neutron flight path in m, and c_1 is 1.30 for 2.45 MeV neutrons and 8.20 for 14.1 MeV DT neutrons. For a given temperature and distance, the DD neutron time spread will be more than 6 times larger than the DT neutron time spread. As a result, DD ion temperature measurements will typically be measured using detectors located at ~8 m and DT ion temperature measurements will typically employ detectors located at ~20 m.
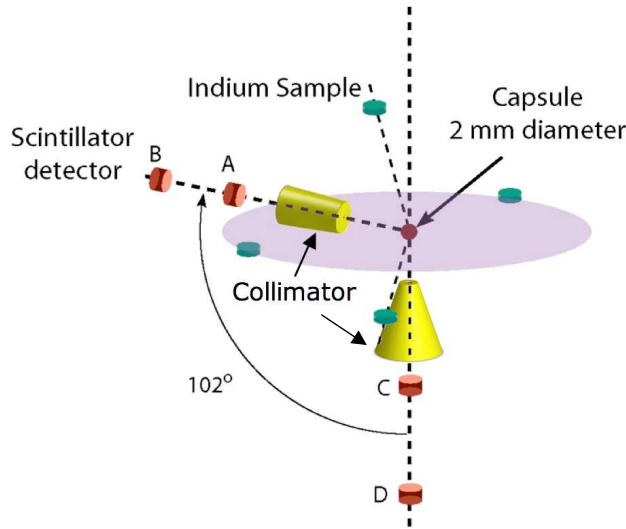

Fig 1. Schematic of initial ZR neutron diagnostic suite showing the two pairs of collimated neutron time-of-flight scintillation detectors and the layout of the indium activation samples.

4. Future Planned Neutron Measurements

Several classes of new neutron measurements are being considered for ZR. The first of these is a measurement of fusion reaction history. The issues are similar to the reaction history measurements being proposed for NIF [8]. Fusion reaction rate provides information about compressed fuel core in an ICF target. Two quantities are of interest in performing these measurements. The first is bang time which is defined as that time interval between the 50 % rise-time of on target power and the time of peak thermonuclear emission from the target. The other quantity of interest is the time history of the thermonuclear emission from the target. Both of these quantities depend on detailed target hydrodynamics, plasma conditions, and are a sensitive indicator of modeling accuracy.

Several prototype neutron bang time detectors for the ZR facility have been tested. The current approach is to use three CVD diamond detectors of different sizes and sensitivities placed in a lead-shielded housing. These detectors will be located in a reentrant tube 50 cm from the center of the target. Neutron induced signals from the CVD diamond detectors will be recorded by a 3 GHz, 10 Gsamples/s, Tektronix TDS-694 oscilloscope. This diagnostic should be able to measure bang time for yields about 1×10^{10} for DT and above 5×10^{10} for DD implosions on ZR.

The reaction burn history can be determined by monitoring the 16.7 MeV gamma rays from the DT reaction, $T(d,\gamma)^5He$. Since gamma-ray temporal distribution at a point distant from a target (point source) is unaffected by either distance or temperature, it may be possible to use them for fusion history measurements. The largest challenge is the low branching ratio of 5 x 10^{-5} for gamma production. Our current plan is to use a gas Cherenkov detector similar to that developed by Los Alamos National Laboratory [9]. In this detector system, fusion gamma rays interact with a converter and produce forward-directed, relativistic electrons at the entrance to a high-pressure (~ 100 psi) gas cell containing CO_2. The electrons generate Cherenkov light when they travel faster than the speed of light through the CO_2 gas. By changing the gas pressure, the index of refraction can be adjusted to set the gamma detection energy threshold and discriminate against lower-energy gamma and hard x-ray bremsstrahlung backgrounds.

In collaboration with Lawrence Livermore National Laboratory, a neutron pinhole camera is being developed for the ZR facility. Images of both the primary and downscattered neutron distributions will provide valuable diagnostic information about the implosion core of ICF targets. This diagnostic operates by pinhole imaging the neutron source onto a scintillating fiber array that is imaged onto a CCD camera. Initial tests on the Z facility were successful in imaging the hard bremmsstrahlung produced by a wire array z-pinch. Work to further develop this diagnostic for the ZR facility is ongoing.

We are presently investigating a class of neutron diagnostics that are based on the measurement of recoil protons from the interaction of 2.45 MeV and 14.1 MeV neutrons in thin CH_2 foils (of order 10-mg/cm^2-thick). These diagnostics would operate by detecting the proton recoils at near forward angles in either time-integrated detectors or time-resolved current mode detectors. The protons may be energy resolved using range filter or by magnetic analysis using a magnetic spectrometer arrangement similar to one presently being developed by the MIT group for NIF [10]. An attractive feature of these types of neutron diagnostics is that the neutron energy E_n and the proton energy E_p at an angle θ relative to the original neutron direction is simply related by $E_p = E_n \cos^2(\theta)$. Additionally, the elastic n-p cross section is very well known at both 2.45 MeV and 14.1 MeV. These diagnostic techniques offer a very clean measurement of neutron yield that can be almost entirely free of scattered neutron backgrounds. At higher neutron yields, measurements of time-resolved ion temperature and reaction burn time may become possible.

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