Fusion neutron detector calibration using a table-top laser generated plasma neutron source

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Abstract

Using a high intensity, femtosecond laser driven neutron source, a high-sensitivity neutron detector was calibrated. This detector is designed for observing fusion neutrons at the Z accelerator in Sandia National Laboratories. Nuclear fusion from laser driven deuterium cluster explosions was used to generate a clean source of nearly monoenergetic 2.45 MeV neutrons at a well-defined time. This source can run at 10 Hz and was used to build up a clean pulse-height spectrum on scintillating neutron detectors giving a very accurate calibration for neutron yields at 2.45 MeV.

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1. Introduction

One of the principal diagnostics in many large-scale inertial confinement fusion (ICF) experiments is a measurement of the absolute fusion neutron yield \cite{1-3}. These ICF experiments are almost always performed on large scale, single shot machines such as the Omega laser at the University of Rochester \cite{4} or the Z machine at Sandia National Lab \cite{5}. The limited repetition rate of these machines requires the use of neutron detectors which are well calibrated to measure the absolute yield on a single shot. This is often achieved with a very large array of detectors which are placed at such a distance that they operate in single neutron counting mode \cite{6}. Alternatively, the yield can be measured with a single detector, if the response of that detector to fusion neutrons is well known.

The calibration of such a neutron detector for fusion experiments needs to be based on the signals from characteristic 2.45 MeV neutrons for dd-fusion or 14 MeV neutrons for dt-fusion. One

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practical way to generate such neutrons would be to use a compact, pulsed source of fusion neutrons and measure the pulse-height response of the detector to single neutrons. To perform a good calibration on one detector, a high rep-rated source of clean fusion neutrons is needed. A promising way to do this easily is to use fusion neutrons generated by a rep-rated, high-intensity laser. Such a source has the advantage of being more compact and portable than accelerator-based sources.

Various methods for neutron generation from laser-produced plasmas have been demonstrated over the past few years [7]. Neutrons can be generated in a secondary process where nuclear reactions occur in a sample material irradiated by energetic electrons or radiation produced in the plasma. This process was suggested as a possible basis for a neutron source by Schwoerer et al. [8] who used the radioactive decay of the sample as a means of measuring hard X-ray yields. Alternatively, neutrons can be created directly by driving \((\gamma, n)\) reactions in an intensely irradiated target [9] or beam-target fusion reactions within the laser-produced plasma itself by accelerating ions on a solid target into the underlying cold target. Neutrons have been measured from this process in both a gaseous deuterium medium [10] and deuterated plastic targets [11]. Pretzler and Hilscher [12,13] irradiated solid deuterated plastic targets with a femtosecond intense laser driving a cylindrical Coulomb explosion within a preformed plasma, accelerating hot deuterons into the surrounding material. In all of these cases, however, the neutron spectrum is not monochromatic, as one expects from a true thermo nuclear plasma and they are often accompanied by a very large burst of hard X-rays which complicate the calibration measurement.

Instead, a pure spectrum of neutrons from the \(D + D \rightarrow ^3\text{He} + n(2.45\text{MeV})\) nuclear reaction in a hot plasma is preferable. We have explored an alternate avenue for calibration of a detector by exploiting the technique of driving fusion by irradiating atomic clusters to drive nuclear fusion between hot deuterons from neighboring cluster explosions [14,15]. Cluster fusion sources are capable of yields up to \(10^5\) fusion neutrons per Joule of incident laser energy using pure deuterium clusters [14,16]. In addition Grillon et al. [17] demonstrated that even higher ion energies can be achieved from deuterated methane clusters.

In this paper we demonstrate a novel method of calibrating a neutron detector designed for single-shot operation. To do this we use a table-top laser-driven exploding cluster neutron source utilizing pure deuterium clusters first presented by Ditmire et al. [14]. Upon irradiation by a short intense laser pulse, a gas of deuterium clusters can exhibit extremely efficient deposition of energy creating a plasma with energy densities reaching \(\approx 10^5 \text{Jcm}^{-3}\) [18]. The instantaneous ejection of almost all electrons from the clusters results in a Coulomb explosion of the clusters in which the ions gain sufficient energy to undergo dd-fusion [15]. This is an attractive method for producing fusion neutrons due to its high repetition rate, its inexpensive and compact design and its easy handling. Most important for the application described here is the fact that the neutrons are very monochromatic. We have, previously, ascertained that the neutron spectrum has an energy width \(\Delta E/E < 0.1\). In addition, the neutron burst is ultra-short [19] and scales favorably with increasing laser pulse energy [20]. Furthermore, the source is very clean with a very low accompanying yield of X-rays. This results from the fact that very few fast electrons are produced in the cluster explosion and most of the deposited laser energy is transferred to the deuterons. In fact, for many experiments it was unnecessary to shield the detectors with lead; the neutron signal was well resolved from the small X-ray pulse near \(t = 0\).

We employed this source to calibrate a high-sensitivity neutron detector [21] designed for operation on experiments performed on the Z facility [22,23] at Sandia National Laboratories. This detector will be used in single shot dd-pellet ignition experiments [24] in which a relatively small fusion neutron signal must be distinguished from a strong flux of bremsstrahlung radiation. With this in mind, the detector has been constructed with a unique shielding geometry. An absolute neutron yield is desirable so that a detailed knowledge of the detector’s response to the fusion neutrons can be obtained.
2. Experimental setup

The calibration was performed by driving the cluster fusion source with a Ti:sapphire CPA laser system providing 40 fs pulses at a wavelength of 800 nm and a repetition rate of 10 Hz. The schematic of the calibration is illustrated in Fig. 1. The laser pulse with energy of 0.1–0.5 J was focused into a dense plume of deuterium clusters by an f/10 spherical mirror to an intensity of \( \sim 10^{17} \text{ W cm}^{-2} \). Clusters were generated using a gas jet consisting of a 24 mm long conical nozzle with an opening angle of 10° and an orifice of \( d = 750 \mu \text{m} \). The deuterium gas reservoir backing the jet was cryogenically pre-cooled to \( \sim 100 \text{ K} \) with liquid nitrogen and expanded from a pressure of 70 bar into vacuum to form clusters of radius approximately 3–10 nm (with a rather broad size distribution). The clusters were irradiated approximately 2–3 mm under the nozzle where the average atomic density was \( \sim 10^{19} \text{ cm}^{-3} \). In principle, neutrons can be produced at the 10 Hz repetition rate of the laser. However, in this experiment, the gas jet was operated once every 6 s because of the limited pumping capability of the vacuum system.

The calibrated detector consists of a scintillator and a microchannel plate photomultiplier tube (MCPPMT). The scintillator has a surface area of 100 mm \( \times \) 25 mm and has a thickness of 75 mm, which is close to the 77 mm mean free path of dd-fusion neutrons. Since this detector is operated far below its saturation level, the signal produced in the scintillator is proportional to the total neutron yield. The bias voltages of the photomultiplier tube were varied from 2800 to 3500 V to observe the effects on the signal. During the calibration the detector was positioned at a distance of 2.0 m from the laser focal spot. This distance assured that, with an appropriately lowered fusion yield, neutrons were observed in single particle detection mode with roughly one neutron observed every 10 shots. The signal was recorded with a 5 GHz oscilloscope and the small initial X-ray pulse was easily distinguished from the much larger neutron pulse which arrived \( \sim 100 \text{ ns} \) later. The total neutron yield was also monitored with four additional neutron detectors placed at distances of 0.40, 2.21, 2.40 and 6.10 m. These detectors were composed of a cylindrical plastic scintillator with a diameter of 12.7 and 15.0 cm length and a photomultiplier tube with 12.7 cm diameter, connected by a conical Plexiglas light guide.

3. Method and results

To discern the dd-neutrons we plotted a time of flight histogram of the measured data. A representative TOF spectrum from the Z neutron detector is illustrated in Fig. 2. This shows the separation between X-rays and fusion neutrons. The zero time point was determined from the

![Fig. 1. Experimental setup: the incoming beam is focused to the middle of the chamber by a spherical mirror. Four scintillation neutron detectors observe changes in the total yield. The calibrated detector is marked with a “D”.](image-url)
arrival of the initial X-ray pulse. We identify the peak in the histogram at \(92.8 \pm 3.7\) ns as the \(2.45\) MeV neutrons from the \(dd\)-fusion reaction. This time of arrival is consistent with the expected time of flight of \(92.38\) ns for a 2.00 m distance. The low-energy tail of the neutron peak is due to scattered neutrons from the surrounding walls of the lab. The small peaks before 20 ns are caused by ballistic X-rays from the plasma and scattered X-rays from the chamber walls.

A typical operating voltage for the detector will be a MCPPMT bias voltage of 2800 V. We recorded 7000 shots at this setting. A discrimination threshold was set at 0.55 mV and only peaks above this limit were taken into account. We assumed that signals occurring in a time window of 22 ns were generated by unscattered neutrons. Using this condition, a total number of 643 shots showed fusion neutrons with energy of 2.45 MeV.

The number of neutrons produced in the deuterium plasma was regulated by varying the laser-pulse energy so that less than every tenth laser pulse resulted in a signal on the detector. Previous experiments have shown that the fusion yield in these deuterium cluster plasmas varies roughly as the square of the laser energy [16]. With a laser energy of \(\sim 0.2\) J the total neutron yield was about \(2 \times 10^3\) neutrons per shot, confirmed by the detector furthest away from the target assuming an isotropic neutron distribution. This yielded a suitable neutron flux level for the calibration. At a 2.0 m distance from the fusion plasma this corresponds to \(< 700\) neutrons during 7000 shots on an area equal to the detector's scintillator surface area assuming an isotropic neutron distribution. This is in good agreement with the number of signals recorded.

For every fusion neutron signal above the threshold value and within the 22 ns TOF window, the peak areas were calculated. The signals were integrated for a time window of 60 ns to reduce the errors arising from ringing in the acquisition circuit. None of the signals showed a second peak from scattered neutrons or other rays during this time interval. Fig. 3 shows the histogram of peak areas. Its shape results from the distribution of energy that the neutrons transfer to the scintillating material. The average peak area was found to be \(22.08 \pm 0.87\) mV ns. It is expected, that the detector will interact with \(245 \pm 16\) neutrons [21] on Z leading to a statistical uncertainty of \(\approx 8\%\).

With higher MCPPMT voltages, the peak areas increase exponentially. Though the statistics in this analysis were not as good as above, the measured
sensitivity on this voltage agreed with the normalized single photoelectron MCPPMT gain stated by the manufacturer. Fig. 4 shows the average peak height as a function of MCPPMT voltage. The average pulse height appears to vary linearly with bias voltage.

4. Conclusions

We have presented a novel method to calibrate neutron detectors designed to measure total fusion neutron yield from single-shot fusion experiments. We used 2.45 MeV neutrons from the plasma created by laser-irradiated deuterium clusters. It should also be possible to operate the cluster source with a deuterium–tritium mix for examination of 14 MeV dt-fusion neutrons. The higher energy of these neutrons would push the signal closer to the X-ray flash. However, this potential problem could easily be avoided by employing greater flight distances at the expense of signal or by using heavier detector shielding to eliminate the already low radiation signals. We find that this cluster fusion source is an ideal neutron source for this application, as it is very monochromatic, is largely clean from X-rays and drives from a point like pulsed source with well-defined flight time to the detector. The source provided neutrons at a high enough repetition rate to achieve statistics that limit the error for measurements using the detector almost completely to the statistical uncertainties of the total yield.

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