A Fast Pulsed Neutron Source for Time-of-Flight Detection of Nuclear Materials and Explosives

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Abstract. A ~10^6 n/pulse plasma focus was used with two fast detectors and a fast digitizer to test a concept for time-of-flight detection of high explosives and nuclear materials. An iron target was used as a phantom for the high explosives. Preliminary tests showed an inelastic gamma peak that is clearly time separated from the source x-ray peak and the source neutron peak. Additional tests are planned using a high repetition rate source which is under development. A Monte Carlo simulation showed that a larger detector could increase the detection range from ~1 m stand-off to ~5 m stand-off using the existing neutron source.

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INTRODUCTION

AASC has built a fast pulsed neutron source based on the Dense Plasma Focus (DPF). One version [1] stores 500J, fires at 0.5Hz and emits ~3×10^6n/pulse at a pulsed current peak of 130kA. A more advanced version [2] stores only 100J, but fires at ~10-50Hz, and emits ~10^6n/pulse at a peak current of 100kA. Both sources emit 2.45±0.1MeV (DD) neutron pulses of ~25-40ns width. Such fast, quasi-monoenergetic pulses allow time-of-flight detection of characteristic emissions from nuclear materials or high explosives. A test is described in which iron targets were placed at different distances from the point neutron source. Detectors such as Stilbene and $LaBr_3$ were used to capture inelastically induced, 847 keV gammas from the iron target. Shielding of the source and detectors eliminated most (but not all) source neutrons from the detectors. Gated detection, pulse shape analysis and time-of-flight discrimination enable separation of gamma and neutron signatures and localization of the target. A Monte Carlo simulation allows evaluation of the potential of such a fast pulsed source for a field-portable detection system.

EXPERIMENTAL CONFIGRUATION

The plasma focus (PF) is a pulsed plasma device that relies on high currents to produce a hot, dense plasma [3]. To maximize the current for a given stored energy, the inductance in the driver should be minimized. The plasma focus used for this experiment is described in [1]. The anode is a conical SS304 electrode with diameter at the base of 20 mm converging to 10 mm diameter over a 20 mm length. The anode and cathode are separated at the base by an alumina (99.6%) insulator. The 3.2mm cathode rods are located on a circle of 30mm radius. Voltage at the load, dI/dt, and neutron output measured using a calibrated ^{3}He detector were monitored for each pulse. The neutron output is known to exhibit slight anisotropy, favoring the forward direction (along the pinch axis) by about a factor of 2[4]. The focus was fired at 0.2 Hz at a D_2 fill pressure of 9.5 Torr.

Figure 1 is a schematic drawing of the experimental configuration. The detectors used were Stilbene and $LaBr_3$ coupled to fast PMTs. Stilbene is highly neutron sensitive while the neutron sensitivity of the $LaBr_3$ was unknown. A BC408 scintillator placed close to the neutron source was used to the trigger the data acquisition system (PIXIE-500)[5]. To reduce the neutron flux at the detectors, a shield of 15 cm thick HDPE blocks was built around the

detectors. The ~800-900keV photons can penetrate the shield while 2.45MeVneutrons will undergo a single scatter in the low Z shield material. The goal was to reduce the incident neutron energy below the detection threshold.
Iron was used as a phantom for high explosives. Iron emits an inelastic gamma at 847 keV when interacting with D-D (2.45 MeV) neutrons. For explosives detection, the focus would be operated in a DT mixture to generate 14.1 MeV neutrons that would excite the atoms to emit characteristic gammas. The phantom iron target was placed 0.78 m away from the source. The detector package was placed a further 0.78m beyond the target as shown. The goal was to demonstrate time-of-flight separation of the inelastic photons generated by neutron interactions in the target from the hard x-ray pulse inherent to the PF and the neutron burst. Such separation is possible because the focus neutron pulse width is short (~20ns) whereas the time-of-flight for neutrons to the target and that of gammas to the detector is ≈38ns. The neutron pulse takes another 35ns to reach the detectors. Thus one expects an initial gamma signal induced in the stainless steel vacuum vessel walls of the source, followed about 38ns later by the induced gammas from the target, and finally the neutron pulse itself arriving about 70ns after the start.

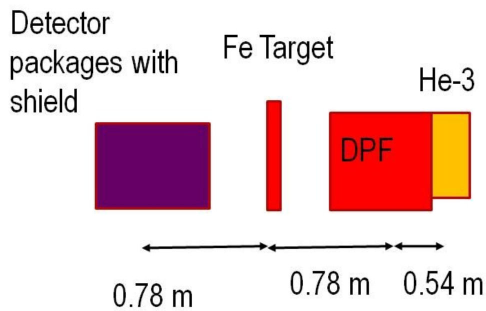

FIGURE 1. Experimental configuration to test Time-of-flight detection scheme.

Before we present the time-of-flight data, we first review the neutron output and stability of the focus source.

PLASMA FOCUS NEUTRON OUTPUT AND REPRODUCIBILITY

The neutron output is an important consideration for determining the dose to the target and thus, the return signal from the target. Ideally, one desires a return of one count per shot from the target to each detector. However, the intense neutron pulse activates the vacuum chamber walls which radiate photons that act as background to the desired target pulse. Energy discrimination and time-of-flight are used to discriminate these background photons from target photons. The key to our time-of-flight detection technique is that the neutron pulse is shorter than the typical neutron flight times to the target and the gamma/neutron return times from the target. Since these times are known for a given target range, it is possible to gate the detectors and hence significantly reduce background. For example, for the configuration of Fig. 1, since we know that the time scale for all three events (source region gammas, target gammas and source neutrons) reaching the detectors is <100ns, all gamma events that lie outside this window are rejected. This dramatically reduces background clutter, allowing even a low target gamma count rate to be statistically significant. Background reduction is important, but so also is optimization of desired signal. Pulse pile up by definition eliminates the benefit of time-of-flight separation and impairs the analysis routine's ability to determine the photon energy. Therefore, the most desirable case from a detection stand point is a high repetition rate, low output source. However, as stand-off distance between the target and source increases, the neutron output must increase. The problem of interest is on the scale of ~1 m so a neutron output of ~10^6 n/pulse is acceptable. Over the course of the experiments, the average neutron output was 2.3×10^6 n/pulse. The standard deviation was 96%. Despite the large variation in shot to shot neutron output over the course of the experiments, the cumulative dose of many of the individual experiments followed a similar trend (see Figure 2a). Experiment 179a is the obvious outlier.

Given a large set of data on the voltage, dI/dt and neutron output, statistically relevant correlations between the neutron output and the terminal measurements are possible. A clear correlation exists between the minimum in the dI/dt and the neutron output. The deviation around the trend is significant, but the peak current was fixed at 130 kA ±2%. The measured results suggest that a deep 'bite' in the current is preferred over a shallow current 'bite' to produce neutrons.

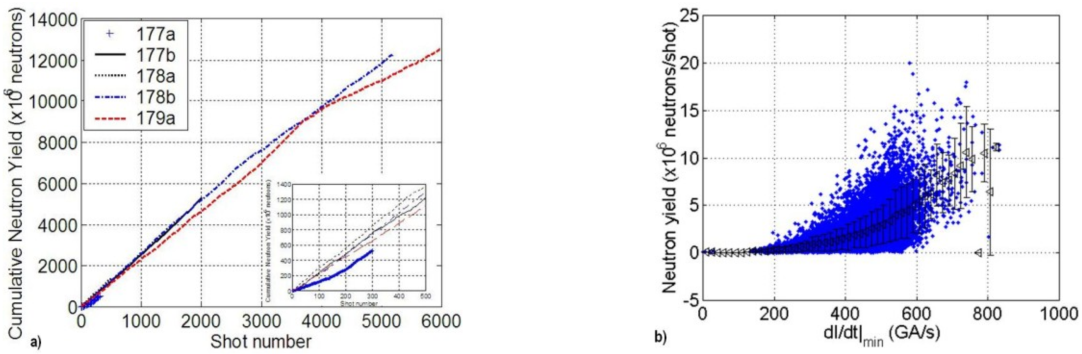

FIGURE 2. a) The cumulative neutron output over five different experiments. b) Neutron output vs. the minimum in the dI/dt.

The spread in the neutron outputs suggests a high pinch voltage (or equivalently a deep dI/dt) is only a necessary condition for high neutron yield. The process by which the high pinch voltage leads to neutron production is complicated. The pinch voltage supports the creation of fast ion beams that flow near the axis of the pinch (where the magnetic field is weak). A given pinch voltage may result from rather different pinch currents for the same peak current, since the dI/dt source term for the pinch voltage may be generated by a small but steep drop in current, or conversely, a larger but more gradual drop. If the pinch current is so different for the same peak current, then it is plausible that the ion beam spectrum and target density (both of which depend upon pinch current) could fluctuate. Last but not least, the ion beam spectrum might also vary for a fixed pinch voltage, because the pinch voltage is only an integral of the electric field along its entire length. For a given integral, the variation in local fields at different points along the pinch could lead to different ion spectra. For DD fusion, the neutron output is very sensitive to the spectrum, since for the typical mean ion beam energy in the range of 50keV, the cross-section is far below its peak and varies strongly with energy. Hence it is not surprising that although the current varies by only 2%, the neutron output varies by as much as 55%. Additional improvements to the source are required. The neutron output deviation should be reduced and the repetition rate needs to increase toward 100 Hz. A high repetition rate pulse power system has been demonstrated at the 70 kA level but needs to be scaled up to the 100-200 kA level.

IRON PHANTOM DETECTION

The iron target for these experiments consisted of five 13.5" conflat flanges placed into a mount between the source and the detector. The target was range thick to the neutrons and the stimulated inelastic photons. Despite the less than ideal configuration, a peak is visible between the two source peaks shown in Figure 3. The stilbene detector has more counts as it had a larger volume. The source photon and source neutron peaks are nearly of the same magnitude. The $LaBr_3$ detector showed a lower sensitivity to neutrons, perhaps because it contains more higher-Z material than does the stilbene. Pulse shape analysis (PSA) performed on the stilbene detector separates the neutron counts from the photon counts based upon the longer tail of the neutron counts. Neutron events in the detector leave long tails skewing the pulse to long times while the photons produce more symmetric counts. The first source peak and the target peak were identified to be from a photon source while the third peak was primarily from neutrons. Improvements to the test configuration are planned to improve the target peak intensity and resolution.

A MORE PRACTICAL ARRANGEMENT

Monte Carlo simulations were used to model the efficacy of the same neutron source, but with a detector array 100 cm by 100 cm by 2.5 cm thick. The large detector is more representative of a likely detector to be used in large stand off scenarios. The geometry for the simulation is shown in Figure 4a. The results at the detector for 5 shots are shown in Figure 4b. With a 3 m stand-off from the target used in the experiments and another 1m from the detector, the target gamma peak is clearly distinguished in time from the source peak and the reflected neutrons. In this geometry the neutron peak can be suppressed since neutrons are not likely to back scatter from the target into the detector. This simulation helps to validate the concept while showing that a ~10^6 n/pulse source might be sufficient to address a ~3m stand-off problem.

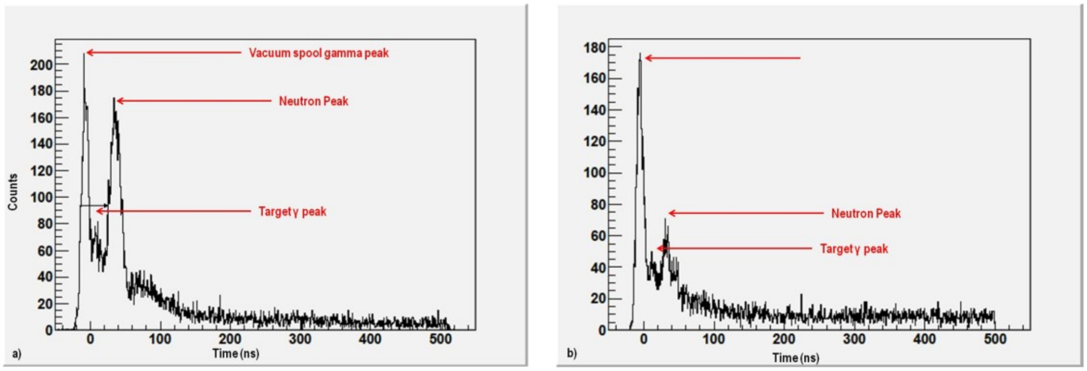

FIGURE 3. Detector counts in time a) Stilbene b) $LaBr_3$

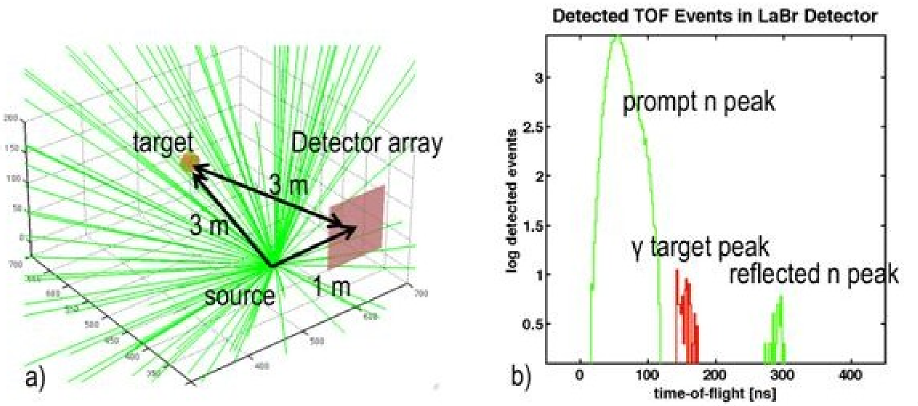

FIGURE 4. Monte Carlo Simulation a) geometric configuration b) Detector counts

CONCLUSIONS

A potential new approach to high explosives and nuclear materials detection was demonstrated. The approach relies on a fast pulse of neutron generated by a plasma focus. The stimulated emission from the target material was detected using a set of fast detectors and a fast digitizer. The approach showed time-of-flight separation of the source radiation peaks and the target radiation peaks. Initial numerical simulations show promise for scaling up the approach to large stand-off applications using a larger detector array. A more intense neutron source is already demonstrated and a high repetition rate pulse power system is under development to allow 100 Hz operation.

ACKNOWLEDGEMENTS

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