Neutron Generation by Laser-Driven Proton Sources

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Ultra-intense lasers have demonstrated the capability of accelerating short pulses of intense ion beams. These ion beams have been used to generate short bursts of neutrons by irradiating a converter in close distance to the source, making this scheme a very compact and bright source of neutrons up to more than 100 MeV in energy. Using novel laser ion acceleration mechanisms directed beams of neutrons can be generated, which increases the brightness of these sources compared to previous attempts. We review the recent research and present experimental data using a mechanism based on relativistic transparency to drive the most intense laser driven neutron source and use them for first applications.

Key Words: Ultra intense lasers, Laser driven neutron sources, Ion beams, Relativistic transparency

1. Introduction

There is a growing need for small and medium sized neutron sources of high brightness\(^1\) and ranging from thermal to multi-MeV particle energies. Applications include basic research, the use in material sciences and further industrial and medical applications. Since the advent of ultra-intense lasers the acceleration of intense ion beams has been one of the most exciting fields of research over the last decade. Those laser systems can accelerate ion beams using fields six orders of magnitude above the highest conventionally available fields and therefore have reduced the required accelerator length from meters to sub-millimeters.

The basic concept of laser driven neutron sources is to replace large conventional accelerator structures by compact laser driven ion sources and use a small converter design to form a compact neutron source. Thus one combines the large cross section for neutron evaporation and related nuclear processes with the spatial and temporal advantage of a laser driven source.

The most widely used mechanism had been discovered in 1999 and is known as the target normal sheath acceleration (TNSA).\(^2,3\) This mechanism is based on the charge separation at the rear surface of thin, micrometer-sized solid foils and results in short bursts of ions up to energies of 60 MeV in an exponential spectrum.\(^4\) The ion beams usually contain protons as the predominant species as those have the highest charge to mass ration and are accelerated most efficiently by the quasi electro-static potential.

The short pulse duration of the ion beam results in a short burst of neutrons with highest brightness and allows for techniques not accessible with conventional drivers.

2. Prior research

Shortly after the discovery of laser driven proton beams by the TNSA mechanism those have been used to generate neutrons. Early experiments include the Li (p, n) Be reaction\(^5\) and obtained \(3 \times 10^8\) n/sr\(^-1\) using the CLF Vulcan laser in the UK and 70 J of laser energy. They also observed an anisotropy with an increased yield in the backward direction towards the laser.

Experiments of our group at the LULI laser system in 2000 resulted in \(4 \times 10^8\) neutrons using the d-d fusion reaction when irradiating a deuterated plastic block with deuterons (see Fig. 1). A clear mono-energetic peak at 2.5 MeV was observed, which was boosted in energy in the forward direction by the beam fusion kinetics.

In 2010 Higginson et al. continued the work on neutron production using the LLNL TITAN laser system\(^6\) and obtained \(1.8 \times 10^9\) n/sr\(^-1\) using LiF as a converter and 120 J of energy. They calculated those numbers to be sufficient enough for neutron resonance spectroscopy as a possible application. A year later the same group succeeded in getting \(8 \times 10^8\) n/sr\(^-1\) via the same reaction using 360 J of laser energy on the same facility.\(^7\) This time they also increased the neutron energy up
the 18 MeV and observed a forward peaked intensity distribution. At a smaller laser system, but at a high repetition rate, the University of Michigan also obtained a directed neutron emission up to $1 \times 10^{14}$ n/sr, energies up to 16 MeV and a conversion efficiency of $10^{-7}$ from laser to neutron energy using $10^{21}$ W/cm$^2$ pulses. Here the group used a deliberate deuterium contaminant layer at the rear surface to enhance the neutron production via the TNSA mechanism. As all the cross sections and the directionality of the emitted neutrons are energy dependent and the use of deuterium instead of protons is advantageous due to the additional neutron present in the latter a novel mechanism was investigated to enhance the neutron emission.

3. Relativistic Transparency

Relativistic transparency occurs, when the motion of the electrons in the laser results in an increased inertia caused by the relativistic mass increase as the electrons approach the speed of light. As the electrons are no longer able to follow the laser oscillation and their number is decreasing due to the expulsion by the ponderomotive force of the laser the target becomes transparent for the laser frequency. More precisely, a target becomes relativistic transparent when $N_e \gamma < 1 < N$ with $N = n_e / n_0$, the normalized target electron density, $n_e = m_e \omega_0^2 / (4 \pi e^2)$ the critical electron density and $\gamma = (1 - v^2/c^2)^{-1/2}$.

At this point the laser interacts with the entire target volume and efficiently accelerates the bulk material. In contrast to the TNSA now all the ions are accelerated, which opens the possibility to use the most efficient neutron conversion reaction.

Two important developments were required to experimentally confirm this new mechanism, the reliable production of sub-micrometer free standing target foils and the enhancement of the laser contrast, i.e. the ratio of unwanted light prior to the main pulse. This mechanism, the so-called Break Out Afterburner (BOA), has been predicted using large scale 3D simulations on the first PFLOP computer at the Los Alamos National Laboratory (LANL) and has meanwhile experimentally demonstrated at several laser facilities.

4. Neutron production

The most promising neutron generating reactions are the p (Be, xn) B reactions, widely used in conventional accelerator driven sources. A highly efficient converter is therefore made of beryllium, where the length of the converter matches the range of the incoming ion beams. To further enhance the converter performance and to increase the directionality the Be converter is often surrounded by a cylinder of tungsten. If initially the proton beams is replaced by a deuteron beam the additional neutron generating breakup reaction of the deuteron yields a directed neutron beam in addition to the isotropic Be (p, n) B reaction.

The conversion of the incident ion beam into neutrons therefore is governed by the following processes (see Fig. 2): 1. breakup of the deuteron as it enters the converter material, 2. neutron emission due to the Be (p(d), xn) B processes according to the energy dependent cross sections, 3. energy loss of the ions inside the converter material, 4. pre-compound reactions in the converter material for the highest neutron energies, 5. neutron scattering and W (n, xn) W reactions in the tungsten wall of the converter casing.

5. Recent Experiments

Whereas initial experiments on neutron production using the TNSA mechanism have resulted in neutron numbers that made them suitable for resonance spectroscopy, a higher conversion efficiency is needed for more demanding applications. Recently, our group used the BOA mechanism to generate an intense beam of energetic deuterons from the bulk of deuterized plastic foils at the LANL Trident facility. The BOA mechanism also offers the possibility to efficiently accelerate ions independent of their charge to mass ratio, preferential for accelerating deuterons. Different converter materials were tested, starting with copper and then changed to an encapsulated beryllium target, about 5 mm behind the plastic foil. The BOA mechanism required a precise target thickness control as if the target is too thin the target becomes transparent too soon, before the laser pulse reaches maximum intensity and the interaction is inefficient. If the target is too thick the regime of relativistic transparency cannot be reached and the ions are accelerated by the less favorable TNSA mechanism (see also Fig. 5). A typical experimental setup is shown in
The neutron yield and distribution is made of two parts. a) The neutron converter has to have a sufficient length according to the requirements in the previous chapter, the neutron converter has to have a sufficient length according to the driving ion beam for these parameters including an ion Wide Angle Spectrometer (iWASP),\textsuperscript{21} Radiochromic Film Imaging Spectroscopy (RIS)\textsuperscript{22} and Nuclear Activation Imaging Spectroscopy (NAIS).\textsuperscript{23} During the experiments at LANL in 2012, the optimum target thickness was approximately 650 nm for the CH and CD targets at which peak energies of up to 150 MeV have been measured for protons and deuterons, respectively. With thinner or thicker targets, particle energies and numbers drop rapidly (for more details, see Ref.\textsuperscript{24}).

Neutrons can be measured using activation techniques in different materials (In, Cu, Ag), neutron time-of-flight (nTOF) methods in different directions, neutron imaging camera systems\textsuperscript{25,26} and BTI bubble detectors.\textsuperscript{27} Details about our experimental setup can be found in\textsuperscript{19}.

According to the requirements in the previous chapter, the neutron converter has to have a sufficient length according to the stopping range of the deuterons, but not too long in order not to scatter or absorb too many neutrons in the desired forward direction.

Laterally, the converter can be limited in order to maintain a small source size, e.g. for point projection imaging using high energy neutrons, but this reduces the total amount of neutrons, as the ion beam diverges and more deuterons start to miss the converter material.

The neutron yield and distribution is made of two parts. a) The $4\gamma$ emission of neutrons from the $^9\text{Be} (p,n)^8\text{B}$ reaction for lower energetic protons and the $^9\text{Be} (p,2n)^7\text{B}$ reaction at higher proton energies, b) the forward peaked emission from the breakup if deuterons were used.

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\textsuperscript{19} See http://www.bubbletech.ca for BTI, Bubble Technology Industries.
\textsuperscript{20} F. Smecka and M. Hajek, AIAU Paper No. 2007-27607, Technische Universität Wien, 2007.
The high brightness, directionality and compact format of the neutron source opens up a multitude of applications. The neutron source was demonstrated as a tool for neutron radiography, the test of detector systems and the use in active interrogation have opened the field to those compact sources. As this states the very early results of this new technique and given the rapid development of short pulse laser systems this will become an exciting field of research with many useful applications.

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The generation of neutrons using laser driven ion beams has made significant progress in the recent years. The initial experiments using the TNSA mechanism to drive an ion beam have been followed by new acceleration mechanisms based on relativistic transparency of solids with the advantage of selected ion species at very high brightness. Using the most favorable reaction of deuterium on beryllium high brightness neutron sources driven by laser systems of a few Joules of energy have been realized and the unique neutron beam characteristics have been measured. First applications like neutron radiography, the test of detector systems and the use in active interrogation have opened the field to those compact sources. As this states the very early results of this new technique and given the rapid development of short pulse laser systems this will become an exciting field of research with many useful applications.
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