

A bright neutron source driven by relativistic transparency of solids

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Abstract. Neutrons are a unique tool to alter and diagnose material properties and excite nuclear reactions with a large field of applications. It has been stated over the last years, that there is a growing need for intense, pulsed neutron sources, either fast or moderated neutrons for the scientific community. Accelerator based spallation sources provide unprecedented neutron fluxes, but could be complemented by novel sources with higher peak brightness that are more compact. Lasers offer the prospect of generating a very compact neutron source of high peak brightness that could be linked to other facilities more easily.

We present experimental results on the first short pulse laser driven neutron source powerful enough for applications in radiography. For the first time an acceleration mechanism (BOA) based on the concept of relativistic transparency has been used to generate neutrons. This mechanism not only provides much higher particle energies, but also accelerated the entire target volume, thereby circumventing the need for complicated target treatment and no longer limited to protons as an intense ion source. As a consequence we have demonstrated a new record in laser-neutron production, not only in numbers, but also in energy and directionality based on an intense deuteron beam. The beam contained, for the first time, neutrons with energies in excess of 100 MeV and showed pronounced directionality, which makes then extremely useful for a variety of applications.

The results also address a larger community as it paves the way to use short pulse lasers as a neutron source. They can open up neutron research to a broad academic community including material science, biology, medicine and high energy density physics as laser systems become more easily available to universities and therefore can complement large scale facilities like reactors or particle accelerators. We believe that this has the potential to increase the user community for neutron research largely.

1. Situation

In nuclear-, material-, biology¹ - and related sciences^{2,3}, neutrons have been used to modify and diagnose matter. Their unique properties make them a useful tool to explore areas, where other diagnostics fail. Moreover neutrons produced either by spallation or nuclear reactions (i.e. giant resonance excitation) can serve to mimic reactions usually found in nuclear reactors and therefore help gain a better understanding of aging and stability of present and future nuclear systems. More important as usually the samples to be tested are small in size a compact system is preferential as the total number of neutrons and thereby the required shielding can be minimized. So in general, accelerator based sources and reactors have been used to provide neutrons of high fluxes. Nevertheless, such a scheme is far away from flexible and there are many challenges to face. On the other hand, there is a growing need for flexible, high brightness sources that can be utilized at smaller laboratories⁴, which only could be provided by a laser-accelerated ultra-fast particle source as driver.



As one application in mind, neutron radiography offers complementary information to x-ray diagnostics, especially because of the largely different cross sections for different Z- materials. It therefore can serve as a novel diagnostic, for example in high energy density physics, active interrogation of sensitive materials and laboratory planetary sciences. Ultra intense lasers have been developed to a point, where laser driven particle sources, especially pulsed, intense proton sources, could potentially serve as a laser driven, compact neutron source.

The general concept of a laser driven neutron source is, simplified, to exchange the ten to hundreds of meters long conventional accelerator by approximately 600 μm of laser acceleration and to run an intense burst of ions, e.g. deuterons (pitcher) into a converter material (catcher) to release a directed pulse of energetic neutrons with a pulse duration of less than a nanosecond.

2. Laser ion generation

Laser particle acceleration is an important part of today's high energy and laser physics research. This young field of research has been opened by the advent of the *chirped pulse amplification* (CPA)⁵, which allows laser peak powers up to the petawatt level⁶. Today's laser facilities are able to investigate relativistic laser-matter interaction, or laser-plasma interaction, which is the basis for efficient particle acceleration with lasers. Laser-ion acceleration is primarily driven by relativistic electrons, generated by the interaction of an ultra-intense laser beam with a solid target or a gas jet. The laser peak intensity thereby has to exceed 10^{18} W/cm^2 to immediately accelerate electrons close to the speed of light. Today's lasers are able to reach maximum intensities of more than 10^{21} W/cm^2 ⁷. The dominant ion acceleration starts off the rear, non-irradiated surface by a rapid charge separation. This mechanism is known as *Target Normal Sheath Acceleration*⁸ and has been investigated for about a decade. For proton energies in the few MeV range the cross sections for neutron evaporation by (p,xn) reactions is quite large and conversion efficiencies of 10^{-4} have been measured in first experiments. Ions accelerated by the TNSA mechanism have an exponential energy distribution with an upper cut-off energy determined by the maximum of the accelerating electric potential. So far protons have been accelerated up to roughly 60 MeV⁹ and heavier ions (Carbon) up to 5 MeV/u¹⁰, while it has to be noted that since the discovery of these ion beams 1999, no significant progress has been made in terms of maximum particle energy.

Recent advances at TRIDENT show a very efficient conversion efficiency using the Break Out Afterburner (BOA)¹¹ mechanism and show peak energies approaching 200 MeV. The BOA mechanism only requires 10^{20} W/cm^2 and linear polarization. Therefore, this mechanism can be used using present laser facilities having pulse length of 500 fs and energies of about 100 J on target. The main difference between TNSA and BOA is the de-coupling of the ion acceleration from the driving laser field due to the thickness of the target. In contrast, for the BOA mechanism the electrons that are accelerating the ions are still interacting with the laser field.

With compact, laser ion acceleration, energies the regime of spallation will become accessible in the near future and consequently the conversion efficiency will rise by several orders of magnitude. Regardless of the production mechanism, the neutron pulse length resembles the initial proton beam pulse length and can be in the picosecond regime and due to the focusability of laser driven proton beams the source size can be made very compact. Apart from the target area, none of the components require shielding and the sample to be exposed to the neutron beam can be mounted very close to the source, gaining a large factor simply by the solid angle.

3. Experiments

We have been able to perform the first laser driven neutron source based on the BOA regime, powerful enough for a first test on fast neutron radiography. These results have been recently

published in Physical Review Letters¹² and highlighted in numerous journals (like e.g. NATURE¹³, La Recherche, Physicsworld.com etc). We could demonstrate the production of beamed neutrons ranging from a few MeV all up to 150 MeV dependent on the laser parameter and could provide a first radiograph of dense objects¹⁴. We used an F/1.5 off-axis parabolic mirror to typically focus 80 J of 1.053 μm laser light in a 600 fs pulse. The on-target focus has been measured to be around 3 μm in radius ($1/e^2$ -condition, containing $>60\%$ of the laser energy) with a peak intensity of $1 \times 10^{21} \text{ W/cm}^2$. The laser pulse duration and beam parameters were carefully recorded during the whole campaign. Thin, freestanding, plastic (CH₂) and deuterized plastic (CD₂) foils with thicknesses from 200 nm to 3.2 μm were used to generate proton and deuteron beams. The high temporal contrast of the Trident laser with 10^{-7} at -4 ps (ratio of preceding laser irradiation compared to the peak intensity)¹⁵ enables interaction of the laser with a highly overdense target even for nm-scaled targets and hence very efficient acceleration of deuterons through the BOA mechanism. The proton and deuteron beams were deposited in a Beryllium converter, providing a high cross section for neutron production and at the same time minimizing generation of unwanted high-energy bremsstrahlung photons.

We also have implemented and calibrated numerous diagnostic systems to detect the ion and neutron beams in these laser experiments. We have a calibration curve for BTI Bubble detectors¹⁶ extended to higher neutron energies, shielded, used and calibrated neutron time of flight detectors (nToF), successfully implemented nuclear activation techniques and fielded a suite of additional neutron diagnostics (^3He detectors, scintillating fibers, ^{10}B detectors) to short pulse laser experiments. Thus, in recent experiments we demonstrated the full characterization of the laser driven neutron field.

4. Results

In the main part of the experiment, we generated proton beams in excess of 135 MeV and deuteron beams above 180 MeV total particle energy. These ion beams were dumped in a beryllium converter. The converter was placed at distances of 5 mm up to 5 cm behind the driver target to control the size of the neutron source. The lateral dimensions of the converter were adjusted accordingly to capture the full ion beam, which had an average cone half-angle of about 30° (see Ref. 14); the length of the converter was typically 5cm, sufficiently long to stop protons and deuterons with energies of 135 MeV and 180 MeV, respectively.

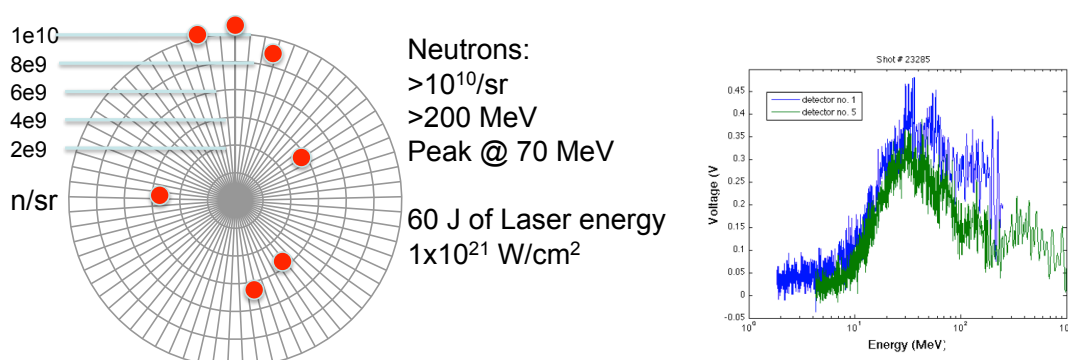


Figure 1: Neutron results: A clear, forward peaked energy distribution of the neutrons is visible, when using sub-micron CD targets and the BOA mechanism. The neutron energies extend to above 100 MeV peaking at 50-70 MeV.

The neutron beam distribution measured with the bubble detectors showed two components: an isotropic component from (p,n) and (d,n)-reactions and a peaked forward component from deuteron breakup-reactions (see Fig. 1). The neutron yield in the forward direction was one order of magnitude higher with up to $1.2 \times 10^{10} \text{ n/sr}$. All other directions measured much lower neutron fluxes of up to $4 \times 10^9 \text{ n/sr}$. The nToF-detectors detected the same forward directed neutron distribution as the bubble

detectors. The ones placed orthogonal to the laser beam and parallel to its counter propagation direction still measured the peak neutron flux at 8 MeV with maximum energies of up to 25 MeV. However, in the direction of the driving ion beam, the neutron flux peaked at energies of up to 50 MeV with maximum energies of 100 MeV to 150 MeV. A typical spectrum is shown in Fig. 1 (blue and green lines from two detectors behind each other). The high maximum neutron energies imply that other neutron generating mechanisms are present such as pre-compound reactions¹⁷.

5. Summary

We experimentally demonstrated a high power, laser-driven neutron source. The driving ion beam consisting of either only protons from CH targets or protons and deuterons from CD targets with maximum energies of 135 MeV and 178 MeV, respectively. The beam was dumped in a Be-converter for the generation of neutrons via (p,n), (p,2n), and (d,n) reactions and via deuteron break-up reactions. The neutron beam has been characterized with a set of diagnostics consisting of a dozen bubble detectors, 3 nTOF detectors, and a neutron imager. With CD targets of 600 nm thickness, where efficient acceleration of deuterons takes place in the BOA regime, the neutron distribution has a strong, forward directed, component with 1.2×10^{10} n/sr and maximum neutron energies of up to 150 MeV. This constitutes two orders of magnitude higher flux and 6 to 8 times higher maximum neutron energies than previously reported by other groups. The ability to generate dense MeV-neutron beams with lasers also opens the field of neutron and neutron-assisted research to a much broader community, including small-scale laboratories as well as universities and also paves the way to new compact and cost-efficient neutron-based applications.

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