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Towards a compact Laser based Neutron source

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Abstract. Several experiments for neutron generation using high intensity laser sources, with a power exceeding 10^{19} W/cm² via TNSA (Target Normal Sheath Acceleration) or other similar methods, have been performed in recent years in different laboratories. However, so far there is no one running neutron source based on such a technology. We have just started a study of the advantages and limits of this novel technique, trying to identify the critical points in order to pave the way for future experiments.

1. Introduction

The need for accelerating gradients orders of magnitude larger than existing ones drives the research in particle accelerators towards plasma based accelerators [1],[2]. These machines can sustain fields greater than tens of GV/m paving the way for the realization of table top accelerators. In every considered scheme under investigation a PW class laser is used.

Likely these lasers will be not considered uniquely to drive the main accelerator but they will also be devoted to other several activities. The interaction of such a laser with matter produces a large number of electrons, ions, positrons, protons via several different mechanisms depending on the laser intensity and the target material compositions and dimensions [3]. While a lot of effort is dedicated nowadays to improving the quality of these charged or neutral beams of particles to use them, up to now there is not yet a user facility using these kind of beams while there are several studies concerning neutron production via laser-matter interaction (for instance among others [4],[5], [6]).

2. Methodological analysis

Our interest is to focus mainly on a very compact neutron source. In order to achieve it we consider a moderator with the Bedogni design [7], implemented already in a thermal neutron irradiation facility with extended and very uniform irradiation area (HOTNES at ENEA-INFN, Frascati). A neutron source is located on the bottom of a large cylindrical cavity (30 cm diameter, 70 cm in height) delimited by polyethylene walls. Owing on a polyethylene shadow-bar, only multiple-scattered neutrons can reach the irradiation volume. The resulting neutron spectrum is highly thermalized (Cd-ratio about 10). Irradiation planes are disks (30 cm in diameter) showing very uniform thermal field



(1-2%) over their whole surface. The moderating efficiency (thermal fluence per primary neutron) is about $2 \cdot 10^{-4} \text{ cm}^{-2}$.

HOTNES was designed using the Monte Carlo MCNPX 2.7 Monte Carlo code [8] using the ENDF/B-VII cross section library [9] for neutrons with energies below 20 MeV and the room temperature cross section tables for thermal neutrons in polyethylene, $S(\alpha,\beta)$. In our case we replace the radionuclide neutron source with the laser compact source.

3. Conventional source

We use as a master reference the parameter of the Eupraxia collaboration [10], a European design study to produce the first conceptual design report of a plasma based accelerator. Eupraxia is still considering several alternatives, and we focus on the case where the beam is produced in a conventional accelerator and later plasma-accelerated. An electron beam of 1 GeV energy, with bunch charge 100 pC, a repetition rate of 10 Hz and an average current of 1 nA is foreseen. We consider the production of neutrons via bremsstrahlung, using a tungsten target of $5 \times 5 \times 9 \text{ cm}^3$, being 9 cm the maximum yield. We can obtain about 0.4 neutrons for each primary electron. With the Eupraxia design values we can have about $2.5 \cdot 10^9$ neutrons/s. This number sets the lower limit of any laser based neutron compact source that can be considered interesting at such a facility.

Using a moderator like [7] we conclude that we can have about $2.32 \cdot 10^{-4}$ neutrons per primary particle. We are not considering the beam collimation because it has an impact less than an order of magnitude in terms of lost neutron flux, and it does not change the results of our analysis. With these figures we estimate about $9.3 \cdot 10^{-5} \text{ n/cm}^2$ per primary on the sample.

4. Laser based source

When a high intensity laser (10^{19} W/cm^2 or larger) is focused on a solid target several effects can be triggered, like for instance Target Normal Sheath Acceleration (TNSA) [11], Radiation Pressure Acceleration (RPA) [12], collisionless shock acceleration [13] and Break Out Afterburner (BOA) [14], depending on target material, thickness and surface contaminations for instance. Let us focus on TNSA. Fast electrons are accelerated through the material by the laser. These electrons penetrate the target, ionizing other particles and escaping from the other side. In this moment they build up a very strong electric field, in the order of TV/m. This field extracts protons and ions from the rear surface, producing an intense beam of particles. A sketch describing the physics of the interaction can be found in [15]. While there are scaling laws of the process, it is very difficult to define the energy spectrum, the flux intensity, and the particle geometrical distribution in a general case, as the emission is strongly linked to the target material, surface contamination, laser energy and intensity, and laser contrast. To better underline this argument the reader can have a look to the spectra of Figure 1 produced from very different lasers. While their energies are quite different, the intensities are much more similar. The increasing of the energy increases both proton number and average energy. However this dependence is not followed very strictly, mainly due to some particular experimental arrangement of the target, as well as the use of different kind of targets triggering different mechanisms.

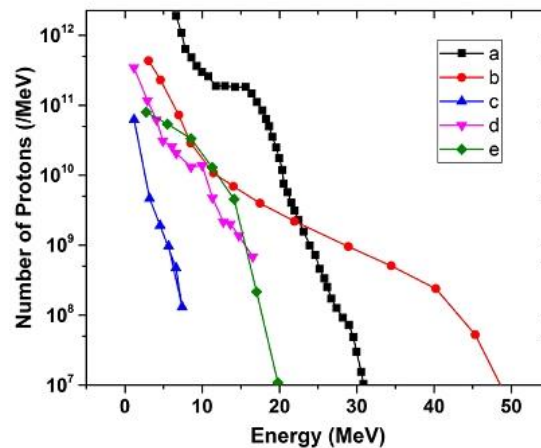


Figure 1. Comparison of proton spectrum emerging in different experiments. For the symbol caption see the Table 1.

Table 1. Symbol caption for spectrum in Fig. 1.

Label	Name	Intensity(W/ cm ²)	Energy(J)	Reference
a)	Vulcan	$2.0 \cdot 10^{20}$	200	[16]
b)	Trident	$1.5 \cdot 10^{20}$	80	[17]
c)	Arcturus	$1.0 \cdot 10^{20}$	3	[18]
d)	Vulcan	$1.0 \cdot 10^{20}$	42	[19]
e)	Astra Gemini	$1.0 \cdot 10^{21}$	10	[20]

What is really important is the number of protons in an energy range below 10-20 MeV, because even a laser with energy around or below 40 J can already produce a proton number in the order of 10^{11} in such energy range. Once that the primary beam is produced, the protons/ions hit a material like for instance LiF or Be, in order to produce a neutron flux. This scheme is usually called pitcher-catcher scheme. In [6] there is a comparison between results obtained with different lasers and target materials. This kind of comparison is very difficult because the properties of the proton or ion beams are not completely and uniquely linked to the laser but also to the target material, geometry and thickness.

5. Expected flux

We focus on a typical catcher target of lithium fluoride. Different yields are found in the literature for the same reaction. For this simulation and for the following, the neutron production yield was generated using a custom LabviewTM based software based on a continuous projectile slowing down in the target. The stopping power data were generated from PSTAR (NIST) [21] for protons and SRIM 2011 [22] for deuterons. Cross sections data were taken from ENDFB VII [9] and EXFOR (protons) [23] or TENDL2009 (deuterons) [24]. The differences in the yield in the range of the tens-few tens of MeV are only about a factor 2-4, much less than an order of magnitude, making appealing also protons of lower energy that can be produced by smaller laser with higher repetition rate. The thickness of the target was also optimized in order to maximize the neutron flux. With 0.2 cm of LiF target, the typical

moderation yields in thermal neutron flux per primary fast neutron is about $1.55 \cdot 10^{-4}$ n/p per proton of 5 MeV.

We also considered the case of a Beryllium target (0.3 mm thick) with a deuteron beam, because usually the targets are hydrogenated on the surface to increase the deuteron number. Considering 7 MeV deuterons we can have a moderation yield in thermal neutron flux per primary fast neutron of about $1.24 \cdot 10^{-4}$ n/d.

6. Conclusions

Looking at Table 2 we can compare the results of the several cases examined.

Table 2. Neutrons from different scenarios.

Primary	Energy	Yield (n/prim)	m(moderation efficiency)	Y x m
Electrons	1 GeV	$4.0 \cdot 10^{-1}$	$2.32 \cdot 10^{-4}$	$9.3 \cdot 10^{-5}$
Protons	5 MeV	$8.67 \cdot 10^{-4}$	$1.55 \cdot 10^{-4}$	$1.4 \cdot 10^{-7}$
Ions	7 MeV	$7.64 \cdot 10^{-4}$	$1.24 \cdot 10^{-4}$	$9.4 \cdot 10^{-8}$

It is clear that to be competitive, in a lab where there is already an accelerator with GeV energy beam, this kind of source must have a flux of primary particles at least 3 orders of magnitude greater. Let us consider now some specific applications for such a laser based neutron source such as Prompt Gamma Activation Analysis (PGAA) and neutron radiography. Usually a series of many techniques is used to study the objects in this field like THz, IR, X-ray radiation and neutron based techniques. There is a particular interest in considering new plasma accelerators for cultural heritage, because for instance in the Eupraxia project, all of these sources are foreseen. Adding also, with the same instrumentation, a neutron source could be very interesting, giving the possibility of having on the same site all these techniques together. Neutron radiography requires parallel beam or divergent beam of low energy neutrons having intensity in the range of only $10^4 - 10^6$ neutrons/cm²/s to avoid formation of significant amount of long-lived radioactive isotope from neutron absorption within the specimen. PGAA are less demanding considering that even conventional portable sources are used for this end, giving flux on the sample in the order of 10^3 n/cm²/s.

These kind of numbers are in the some order of several CANS [25]. For a laser based neutron source, with such a high efficiency and compact moderator the required initial flux of primary particles is in the order of 10^{11} - 10^{12} particles/s in an energy range around tens of MeV. This number is really very close to the existing results of several experiments. In particular, while it is already achieved in a single shot, it must be demonstrated for lasers with lower energy, let's say less than 30 J, that can operate with a repetition rate of 1-10 Hz. The gap can be filled in the next years with improvements in the targets and laser technologies.

Laser plasma based neutron sources are very promising CANS. The reduced dimensions, the absence of RF devices, the small number of personnel needed to operate them, are all in favor of further development in this field. The state of the art is really close to consider interesting these kind of sources in some particular applications.

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