High-currents of multi-MeV protons and fusion neutrons produced by 3-TW sub-nanosecond laser beam

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Abstract — Multi-MeV ions and fusion neutrons were generated by focused radiation of the 3–TW Prague Asterix Laser System (PALS). In our experiments a maximum proton energy of about 4 MeV was generated by a laser irradiance $I \lambda^2 \approx 5 \times 10^{16}$ W cm$^{-2}$ µm$^2$ on target, which is nominally reachable at $I \lambda^2 \approx 3 \times 10^{18}$ W cm$^{-2}$ µm$^2$ for picosecond-class lasers [1,2]. This value of 4 MeV well correlates with the proton scaling law obtained experimentally at the Omega EP facility from 10-ps laser pulses [3]. When a massive deuterated polyethylene target was exposed to the laser intensity of about $3 \times 10^{16}$ W/cm$^2$ a neutron yield of about $3 \times 10^8$ neutrons per shot was recorded. Moreover, the deuterons emitted from the target front surface had enough energy to produce high energy neutrons through the $^7$Li(d,xn) reaction when impinging a LiF slab.

A number of phenomena occur in the plasma produced by intense lasers. Their most important applications consist e.g. in acceleration of charged species, excitation of nuclear reactions, driving of strong shock waves, generation of coherent secondary radiation ranging from THz to high harmonics, that all have been extensively investigated during the last three decades.

Ions with multi MeV energy were produced in experiments performed with lasers irradiating targets with high-intensity pulses of duration from nanoseconds down to femtoseconds [1-8]. A novel approach in the use of time-of-flight techniques allowed us to observe 4–MeV protons emitted from the rear surface of a 17-µm thick Si target exposed to the intensity of $I \lambda^2 = 3.6 \times 10^{16}$ W cm$^{-2}$ µm$^2$ delivered in a 300 ps pulse from the PALS iodine laser [5,6]. The comparison of our experimental results with those obtained at other two laser systems with fairly similar contrasts ($\sim 10^{-6}$ to $>10^{-8}$) is shown in Fig. 1. It is surprising that the PALS data correlate with the Omega EP data as shown by the power-law fit with an exponent of 0.44 [3].
Both the PALS and EP data are shifted upwards in comparison with the most of data obtained at the Helios, Vulcan, and other fs-class lasers [1-4,7,8]. This fact supports the statement that “the EP laser is out-performing all other lasers in the world in terms of proton energy at a given intensity” [3], but in the case of the PALS laser it indicates that the non-linear processes occurring in the laser-produced plasma, such as self-focusing, can enhance substantially the focused intensity. Despite of a large spread in the proton velocities, it is evident that maximum proton energy of 4 MeV reached at the PALS corresponds to $I \lambda^2 \sim 2 \times 10^{18}$ Wcm$^{-2}$μm$^2$. Thus, for the resultant effective target irradiance it holds $I_{EF} \sim 55 \times I_0$. The self-focusing in the plasma produced with the PALS laser was reported when the laser beam was focused in a range of about ±400 μm around the target front surface. In such conditions Ta$^{4+}$ and Au$^{8+}$ ions with the maximum charge state of ~ 50 were observed [9,10].

The irradiation of a massive deuterated polyethylene foil by the intensity of ~2×10$^{16}$ W/cm$^2$ delivered by the PALS laser resulted in a yield of 2×10$^8$ neutrons per laser shot, i.e. ~4×10$^5$ neutrons/J [11]. It is known that the laser intensity does not scale the yield of neutrons from d(d,n)$^3$He reaction induced in a solid deuterated target as summarized in [12,13].

In addition to the direct measurements of laser-driven production of fusion neutrons from bulk deuterated plastic targets the pitcher-catcher target scheme using an identical laser and detector arrangement has been used to compare the efficiency of both these schemes [14]. The “catcher” is a secondary LiF or deuterated target and the “pitcher” is a primary target emitting the fast ions. The generation of high-energy neutrons through the $^7$Li(d,xn) nuclear reaction with $Q=15.03$ MeV [14-18] has been demonstrated experimentally using the deuterons accelerated from the rear surface of the deuterated foil via the so-called target-normal sheath acceleration mechanism. These experiments confirmed the theoretical

![Proton scaling as a function of laser intensity](image-url)
prediction that deuterons with energy of a few MeV can generate high-energy neutrons. Nonetheless, the deuterons are not accelerated with the same force during the same period as the protons, which leads to a reduction of their number and energy [16]. The cut-off energy of deuterons emitted from the front surface of a deuterated target irradiated with the PALS laser was a few MeV [11].

The 3-TW PALS laser system was used for our deuteron acceleration experiment. The neutrons produced through the $^7$Li(d,xn) nuclear reaction were detected with bubble dosimeters and time-of-flight detectors composed of a fast plastic scintillator BC408 type and of a photomultiplier tube. The deuterated polyethylene target was exposed to the intensity of $\sim 3 \times 10^{16}$ W/cm$^2$. The deuterons accelerated in the backward direction struck a LiF slab with surface area of 17.6 cm$^2$, which was positioned 10.3 cm from the pitcher $(\text{CD}_2)_n$ target. The signal of a scintillation detector induced by the neutrons from the d(d,n)$^3$He and $^7$Li(d,n)$^8$Be reactions is shown in Fig. 2. The delay in production of neutrons from the $^7$Li(d,xn) reaction and their longer flight distance caused an increase in the flight time up to $\sim 25$ ns. To obtain the energy range of these neutrons, the time-of-flight signals observed in various directions were evaluated. The maximum energy of neutrons was found to be $E_{\text{max}} \sim 15$ MeV. The maximum number of neutrons from both the d(d,n)$^3$He and $^7$Li(d,xn) reactions was $\sim 3.4 \times 10^8$ neutrons per shot. The maximum number of ($^7$Li$d$) neutrons was estimated to be $\sim 5 \times 10^7$ per shot. When considering the full angular distribution of the expanding plasma, the possible maximum yield of the ($^7$Li$d$) neutrons could be as high as about $1 \times 10^9$ per shot. The occurrence of the deuterons with energy of 2.4 MeV was confirmed by the tracks observed on CR-39 track detector protected with Al foil of 40 μm in thickness. The number of fusing deuterons having energy of $\sim 2.5$ MeV has been estimated to be about $10^{12}$ per shot.
In conclusion, the reported results confirm usefulness of the concept of using the plasma produced by “long” (sub-nanosecond) pulses of kJ-class lasers for generation of secondary particles. In particular, the experiments conducted at PALS demonstrate that in the laser-produced plasma expanding in the backward direction with a broad angular distribution a large number of multi-MeV deuterons suitable for beam-target experiments can be generated. Our experiments indicate that the yield of neutrons from the d(d,n)³He reaction reaches up to $2.5 \times 10^8$ neutrons/shot and the possible maximum yield of the 15-MeV neutrons from the $^7$Li(d,xn) reaction could be as high as about $1 \times 10^9$ neutrons/shot.

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