Laser particle acceleration and accompanying nuclear processes: experimental and theoretical study

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Nuclear reactions initiated by fast particles and hard x-rays emitted by plasma under interaction of powerful femtosecond laser pulses attract enormous attention during last decade [1,2]. Mostly such reactions take place outside the plasma volume due to extremely high energies of accelerated ions, electrons and x-rays. The idea of triggering nuclear reactions by accelerating ions with a powerful ultrashort laser pulse in a plasma [3] became one of the milestones of high field laser science [4]. The underlying conception of the suggested compact ''reactor'' is utilization of high-energy ions accelerated by the laser triggered charge-separation electrostatic field for compact source of fast neutrons and neutrons of intermediate energies for generating various short- and long-lived, light and heavy isotopes, for generating gamma radiation over a broad energy range, for making sources of light ion and induced radioactivity. The suggested technique for triggering nuclear reactions provides a practical tool for studies of nuclear transformation on the pico- and nanosecond scales, which cannot be achieved by using other methods. In this paper we present our theoretical and experimental results on particle acceleration and nuclear excitation by them.

It has been proposed recently to use small targets with all dimensions less or comparable to the laser spot size. These so-called mass limited targets can enhance the efficiency of laser energy transformation into hot electrons and correspondently to the fast ions. In our experiments such mass limited micro-targets naturally appeared in vapor jet at the surface of liquid metal irradiated by laser prepulse. The 3D PIC simulations of interaction of short high-intense laser pulses with mass-limited target homogeneous targets consisted of heavy and light ions have been performed. The numerical simulations were implemented through multidimensional fully relativistic particle-in-sell (PIC) code MANDOR [5]. At the first stage of interaction the well-collimated beam of hot electrons is generated. The electrons oscillating in the laser field expel from the target ages and accelerate in the longitudinal electric filed in the focal spot of the Gaussian laser pulse. Under action of laser radiation significant part of electrons leaves target. It results in Coulomb explosion of uncompensated positive charge of target. At the same time, almost all protons are escaped from a target in forward direction forming proton bunch which accelerated by electric field created by hot electrons. Explosive heavy ion core behind proton bunch acts as a pusher improving its quality. As result, the monoenergetic proton beam has been generated by the laser pulses.

It is well understood now that the "low intensity" radiation heating up the solid target before the main femtosecond pulse has serious impact not only on the efficiency of laser-plasma interaction but also on the physical mechanisms of radiation absorption by hot electrons. This issue becomes of special importance if the laser pulse intensity approaches and/or exceeds the so-called relativistic threshold since new mechanisms of electron acceleration come into play. Hence investigations made in a such a transient regime of interaction could provide more insight into the physical origin of the fast electron production mechanisms. Besides hard x-rays produced could be very useful as a reliable and simple micro-source for different application areas. We achieved efficient control on hot electrons generation applying small pre-pulse advancing the main pulse by 13 ns. Huge increase in hard x-ray production and electron energies were obtained using standard flat targets and melted metal targets.

In our experiments we used 0.3 TW radiation from Ti:sapphire laser system (15 mJ, 805 nm, 50 fs, 10 Hz) focused in vacuum by off-axis parabolic mirror (F/D~5, full pulse energy) or aberration free objective (not more than 2 mJ) to the spot of 3-4 μm in diameter onto the surface of solid target (silicon, silica, tungsten, melted metals, etc.). Estimated peak intensity at the target surface of $2x10^{18}$ W/cm^2 in case of focusing with off-axis parabola was proved by deducing hot electron temperature of 140 keV from hard x-ray measurements within 0.1-1 MeV range.

Temporal shape of the pulse was measured within 1-100 ns range using fast diode and within 0-50 ps using third order correlation function. This reveals that ASE contrast changes from 10^5 on picosecond scale to higher than 10^7 on nanosecond one. Few low intensity pre-pulses were detected advancing main pulse by 7 ps (contrast 10^4) an 13 ns (contrast $4x10^6$). The latter pulse is due to the radiation leakage from the regenerative amplifier. Its arbitrary amplitude can be easily tuned from 10 to $4x10^6$ by adjusting polarizers in the Pockels cells of the laser system, so we used this pulse to understand the role of the pre-pulse in our experiments.

Our measurements showed that the difference between s- and p-polarized radiation becomes small if intensity exceeds 100 PW/cm^2. The most unusual behavior appears if melted gallium is used as a target. In this case hard x-ray yield and hot electron temperature exhibit huge increase at low contrast, while in the case of silica and silicon targets changes are detectable but small. We also observed that high energy ions are accelerated mostly along the reflected beam and not along the target normal. Fig.1 presents how pre-pulse amplitude affect interaction at intensities up to 1500 PW/cm^2. Tungsten target was used in this experiments. The mean energy of hot electrons was estimated from hard x-ray measurements in 50–2000 keV range using 50 mm thick NaI scintillator based detector. In this case more than twofold increase in the mean electron energy was observed if the pre-pulse amplitude was chosen high enough. We attribute this behavior to relativistic self-focusing in low density plasma created by pre-pulse.

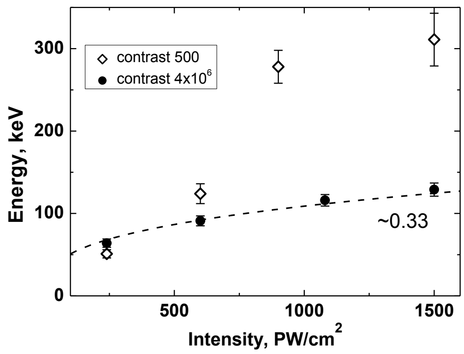

Fig.2. Mean energy of hot electrons dependence on the laser pulse intensity at different contrasts. Dashed line represents data fit by power function.

In the case of nuclear excitation due to laser-plasma interaction the most probable but yet not detected channel of low energy nuclear isomeric level decay is internal conversion through atomic shell. This process yields delayed electrons with energy equals to the differences between nuclear level energy and binding energy of an electron at the given atomic shell. In special experiments silicon plate with thin layer of ^{57}Fe on its top was placed on the path of plasma emission 40 cm away from the plasma in such a way that plasma emission directly irradiated ^{57}Fe layer at an incidence angle of approximately 45^o. Energy spectra of electrons emerging from the secondary target were measured with electrostatic time-of-flight semi-cylindrical analyzer having 10% energy resolution. Analyzer sensitivity was enough to detect single electron with signal-to-noise ratio of 5-6. Electron spectrometer was placed to witness only charged particles emerging or scattered from the ^{57}Fe layer. In this study we present first evidence for experimental detection of internal conversion decay of 14.41 keV isomeric level of ^{57}Fe isotope excited due to femtosecond laser plasma interaction.

We observed internal conversion decay of ^{57}Fe 14.41 keV isomeric nuclear level excited by emission from plasma, created at the solid target surface by femtosecond laser pulse. Our results open new possibilities and perspectives for investigation of novel schemes of low energy nuclear level spectroscopy.

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