Hard x-rays and nuclear reactions from laser produced plasmas

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Abstract

We report on a fully angular resolved spectrum of hard x-rays emitted from a laser produced plasma, which is generated by a laser intensity of $5 \times 10^{18} \text{ W/cm}^2$ on a tantalum surface. MeV x-rays were utilized to generate photoneutrons via photofission of beryllium.

1 Introduction

In the last decade it has become possible to generate focused laser light intensities exceeding $10^{18} \text{ W/cm}^2$ within a few tens of femtoseconds. This enormous peak intensity focussed onto a solid target creates relativistically moving electrons in a hot and dense plasma spot which radiates in the entire spectral range up to several MeV. Electrons and ions are emitted with rather high energies and even nuclear reactions (e.g. fusion, photofission) can take place \cite{1,2,3,4,5,6,7}. We show measurements of the spectral composition and the angular distribution of the emitted hard x-rays (10 keV to 2 MeV). The absolutely calibrated x-ray spectrometers used allow us to measure absolute photon numbers in 16 channels. We report for the first time about laser nuclear fission with a table top laser system.

2 Experimental setup and x-ray measurements

The experiments described here were performed with the multi Terawatt Ti:Sapphire laser system in Jena. The laser generated pulses of 60 fs duration, center wavelength of 800 nm, an energy of 250 mJ and a repetition rate of 10 Hz. The pulses were focused with a f/2 parabolic mirror to $4 \times 7 \text{ μm}^2$, containing 50% of the energy. The laser impinged under 45° onto the 1.0 mm thick smoothed tantalum ($Z=73$) target. A peak intensity of $5 \times 10^{18} \text{ W/cm}^2$ was reached. The hard x-ray spectrum was measured using 12 spectrometers based on thermoluminescence detector (TLD) stacks\cite{8} (see Fig.1). These spectrometers allowed the absolute measurement of the photon fluence for photon energies between 10 keV and 2 MeV with a spectral resolution of 20%. It was carefully verified that no scattered x-rays and no electrons excite the TLDs. Fig. 2 displays two x-ray spectra, detected by TLD spectrometers in the direction of specular reflection (solid circles) and in forward direction (open squares) with respect to the incident laser pulse. The absolute photon yield is given in number of photons per laser shot, keV and sr. From the exponential decrease of the x-ray spectrum at high photon energies (solid line), we calculated a hot electron temperature $T_e$, supposing Bremsstrahlung is generated by electrons with a Maxwellian energy distribution.
Deconvolution of the TLD readings using a SAND II algorithm[8] yields $T_e = 700$ keV in specular direction and $T_e = 300$ keV for the forward laser direction on the back side of the tantalum. Spectra similar to Fig. 2 were recorded in twelve directions within the plane of incident laser and target normal. Fig. 3 shows the angular distribution of the electron temperatures.

3 Discussion of the results and theoretical considerations

The transverse electric field of the laser pulse forces the electrons to a wiggling motion. Therefore the electrons gain the so called quiver energy. PIC simulations show that this quiver energy equals - derived for perpendicular incidence - the hot electron temperature $k_B T_e$

$$k_B T_e \sim m_e c^2 \left( \sqrt{1 + 7.28 \times 10^{19} (I \lambda^2)} - 1 \right)$$  

(1)

For 45° angle of incidence and p-polarized light a similar scaling law ($k_B T_e \propto (I \lambda^2)^{1/3}$) is in good agreement with several experiments[9]. Equation (1) predicts an electron temperature of 420 keV for a laser intensity of $5 \times 10^{18}$ W/cm$^2$ which is consistent with our measurement, where the hot electron temperature varies between 200 keV and 700 keV (see Fig. 3).

However, the total yield of electrons, photons or secondary particles created depends on various experimental parameters such as target element, target surface properties, density scale-length of plasma generated by laser prepulses and finally laser polarization and direction of emission. The angular distribution of the x-rays points to some interesting features. Bremsstrahlung from weakly relativistic electrons ($E_\gamma \leq 0.5$ MeV) shows no significant deviation from isotropic emission. This behavior changes distinctly for x-ray energies greater than the electron rest mass ($E_\gamma > 0.5$ MeV). Bremsstrahlung emission of electrons in this energy range is peaked in the propagation direction of the electrons. This suggests that the detected angular distribution of MeV radiation resembles the distribution of the highly relativistic electrons. Our data therefore imply the existence a jet of highly energetic electrons close to the specular reflection direction of the laser. Similar effects - but for other conditions and due to different mechanisms - were seen by other groups using laser powers as low as 0.5 TW (50mJ, 120fs) [10] and as powerful as 100TW (50J, 500fs)[11]. As experimentally verified by ref.[1] and [10] we assume 0.5-1% energy transfer from the laser pulse to suprathermal electrons. Yu et al.[12] performed PIC simulations with parameters similar to
our experiment, but with perpendicular incidence. They found more than half of the suprathermal electrons that are created in the interaction were accelerated in back direction by the reflected laser light. Assuming a similar fraction of electrons was accelerated in the specular direction for our geometry and taking into account the measured $T_e$, one finds that the plasma density in front of the target, required to generate the measured x-ray yield in the specular direction is $n_i \approx (10^{20} - 10^{21})$ cm$^{-3}$, for a plasma volume of (10 $\mu$m$^3$ (laser focus $\times$ the preplasma expansion within a few ps). This is a realistic preplasma density generated by the unavoidable prepulse of TW Ti:sapphire laser systems.

4 Application of the MeV x-rays: photoneutrons

We used the MeV x-rays to initiate photonuclear reactions. Neutrons were produced by a ($\gamma$,n)-reaction in Beryllium via $^9$Be + $\gamma$ $\rightarrow$ $\alpha$ + $\alpha$ + n. The Beryllium was split by $\gamma$ (i.e. hard x-rays from the laser produced plasma) exceeding the threshold energy of 1.67 MeV. We placed a Beryllium disk (12 mm thick, 70 mm diameter) 4.5 cm away from the laser plasma in specular direction of the incident laser (Fig. 1). The Be disk was mounted on the surface of a polyethylene sphere of 12.5 cm diameter. About 40% of the neutrons generated in the Be disk entered the Bonner sphere and were thermalized by inelastic scattering with hydrogen and carbon nuclei. The neutron thermalization efficiency of the Bonner sphere was absolutely calibrated for the relevant neutron energies. A gold disk ($^{197}$Au, 16 g) was placed

Fig. 2: Spectrum of hard x-rays; specular direction (circles) and behind the target (squares)

Fig. 3: Angular distribution of hot electron temperature is distinctly peaked between specular direction and target normal
in the center of the Bonner sphere, capturing thermal neutrons $^{197}\text{Au} + n \rightarrow ^{198}\text{Au}$ with a cross-section of 99 barn. $^{198}\text{Au}$ decays by emission of a 411.8 keV $\gamma$ with a half-life of 2.7 d. The $\gamma$-spectrum was collected by a Ge-detector. After 20,000 laser shots the activity of the $^{198}\text{Au}$ due to thermalized photoneutrons exceeded the natural background activation of gold by a factor of 2.5. This corresponds to about 100 photoneutrons per shot after correction for solid angles, thermalization probability in the Bonner sphere, capturing cross-section of Au and Ge-detector response. To our knowledge this was the first observation of a ($\gamma$,n)-disintegration with a laboratory size laser system. From the number of neutrons generated in the Beryllium disk, one can infer the total number $N_P$ of photons with energies larger than 1.67 MeV emitted from the relativistic plasma: Using an averaged photoneutron cross-section of 0.5 mbarn above 1.67 MeV, we calculated $N_P = 2.5 \times 10^4$ (sr$^{-1}$), which corresponds well to the integrated photon yield of $N_{TLD} = 1 \times 10^5$ in the hot electron wing above 1.67 MeV achieved in the TLD measurement in specular direction. In our measurement the neutron yield was used to cross-check the TLD readings, whereas in interactions with more energetic laser pulses (resulting in a higher photon flux) and higher intensities (increased hot electron temperature) the photon fluxes above 2 MeV will dramatically increase. Since the detection range of the TLDs ends at about 2 MeV one has to think of a different method. Photonuclear reactions with well-defined thresholds and well-known reaction cross-sections are an interesting substitute.

5 Conclusion

In conclusion we have performed the first measurement of the angular distribution in the plane of incidence of the hard x-ray spectrum. The x-rays were emitted by a relativistic, laser produced plasma, generated with a laser intensity of $5 \times 10^{18}$ W/cm$^2$. We showed the strongly anisotropic x-ray emission characteristics at relativistic photon energies by Bremsstrahlung generation of hot electrons reflected on the target surface. Utilizing the detailed knowledge of the x-ray spectra we induced the photonuclear reaction $^9\text{Be} + \gamma \rightarrow \alpha + \alpha + n$ by MeV photons from the laser produced tantalum plasma and demonstrated the neutron capture reaction $^{197}\text{Au} + n \rightarrow ^{198}\text{Au}$ with our compact laser neutron source.

References