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OBSERVATION OF MEV-IONS IN LONG PULSE LARGE-SCALE LASER PRODUCED PLASMAS

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A new approach for the investigation of generation of fast ions and hot electrons inside the same plasma volume in laser produced plasmas is proposed. It is based on the spectroscopic observation of line radiation from single and double excited levels with simultaneous high spectral and spatial resolution. The experimental results demonstrate the observation of fast ions from highly charged target material inside the plasma volume and suggest that the generally accepted scaling relations are serious invalid under certain conditions. Even for rather modest intensities ions with several MeV-energy are observed.

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When laser radiation interacts with solids a significant amount of particles, both light (electrons) and heavy (ions) can be accelerated to velocities of directed motion essentially exceeding thermal ones. This effect was found at the beginning of 60tes [1]. At present times such acceleration was seen in plasmas created by laser pulses of various duration, wavelengths and intensities. The analysis of quite a number of different experiments carried out on 25 laser installations, allowed to obtain the empirical dependence of the mean energy of fast particles on the parameter $q\lambda^2$ (q is the laser flux density and λ is laser wavelength) in the wide range: $q\lambda^2 = (10^{10} - 10^{18})\,\mathrm{W}\cdot\mu\mathrm{m}^2/\mathrm{cm}^2$ [2]. For parameters $q\lambda^2 < 10^{13}\,\mathrm{W}\cdot\mu\mathrm{m}^2/\mathrm{cm}^2$ this dependence was defined from the results of experiments [3–13]: at $q\lambda^2 = 10^{13}\,\mathrm{W}\cdot\mu\mathrm{m}^2/\mathrm{cm}^2$ the mean energy of fast ions does not exceed values of about 1 keV/amu. This empirical estimation agrees quite well with known theoretical mechanisms of fast ion generation [14–16]. However there are known also experimental results [17, 18] which do not fit into the generally accepted scaling relations: at $q\lambda^2 = 10^{13}\,\mathrm{W}\cdot\mu\mathrm{m}^2/\mathrm{cm}^2$ a mean energy of fast ions of about 10 keV/amu was observed. At present there is not available a comprehensive theory which can explain fast particles outside the scaling relations [2].

In all these previous experiments the mean energy of the fast ions was defined through time of flight measurements with Faraday cups from the arrival of the peak signal of the fast ions. It is however not obvious, that energy measurements outside the plasma correspond directly to the energy of the fast particles inside the plasma volume where the laser interaction takes place. The same drawback relates to the measurements of hot electrons.

The present paper reports about experiments employing a quite different approach for the measurement of fast particles: registration of the emission lines from the target ions by means of spherically bent mica crystals [19] providing simultaneous high spectral and spatial resolution and non-Maxwellian spectra analysis [20–22]. The experimental results obtained show that even for rather modest intensities it is possible to accelerate ions to energies of directed motion of up to 100 keV/amu inside the plasma volume.

Experiments were carried out at the "nhelix-laser" installation (nano second high energy laser for heavy ion experiments) at GSI in Darmstadt, Germany. The "nhelix" is a Nd-glas/Nd-Yag laser ($\lambda_{las} = 1.06\mu\mathrm{m}$) with the duration of pulse of 15 ns and an energy up to 100 J. The present experiments however were performed with an energy of 17 J. The laser radiation is focused with a plane-convex lens (diameter 100 mm, focal length $f = 130$ mm) onto a solid teflon target (CF_2). In order to obtain different laser intensities onto the target, the distance between the lens and the target was changed (movement of lens). Investiagtion of the intensity inside the focus showed that no hot spots appeared.

Soft X-ray line radiation was recorded simultaneously by two spectrographs with spherically bent mica crystals. The mutual arrangement of laser beam, targets and spectrographs is shown schematically in Fig. 1a. The curvature radii of both crystals were 150 mm (No.1 in Fig.1b) and 100 mm (No.2 in Fig.1b). Both spectrographs were installed in the FSSR-2D scheme [19, 23]. This allowed to record spectra with spectral resolution of $\lambda/\Delta\lambda = 3000 - 5000$ and spatial resolution (with one-dimension) of $\delta x = 25 - 45\mu\mathrm{m}$. The first spectrograph recorded the plasma radiation in the direction parallel to the target surface, and the second one at an angle of 55°. Spectrographs were tuned on the spectral range $\lambda = (14 - 15)$ Å, containing the resonance line Ly_α (the transition $2p - 1s$) of the H-like ion FIX and the He_β-line (transition $1s3p^1P_1 - 1s^2$) of He-like FVIII. Examples of the spectrograms are shown in Fig.1b. The diameter of the emission area parallel to the target surface (x-coordinate) was $540\mu\mathrm{m}$ (FWHM) for the Ly_α-line and 810 μm for the He_β-line. Investigations with a pinhole camera show that the Ly_α-emission region is about a factor of 2 smaller than those measured with the pinhole. Moreover the observed long extended halo (up to about 1 cm) was identified as the emission of the He-like resonance and intercombination line ($\mathrm{He}_\alpha = 1s2p^1P_1 - 1s^2$ and $\mathrm{Y}_\alpha = 1s2p^3P_1 - 1s^2$ respectively). We note that for a spot size of 540 μm we obtain an averaged Intensity of $5\cdot10^{11}\,\mathrm{W/cm}^2$ onto the target.

From Fig. 1b we can see the anisotropy of the spectral characteristics of the plasma radiation. Spectral lines recorded by the first spectrograph and, consequently, radiated in direction parallel to the target surface (i.e. in direction perpendicular to the direction

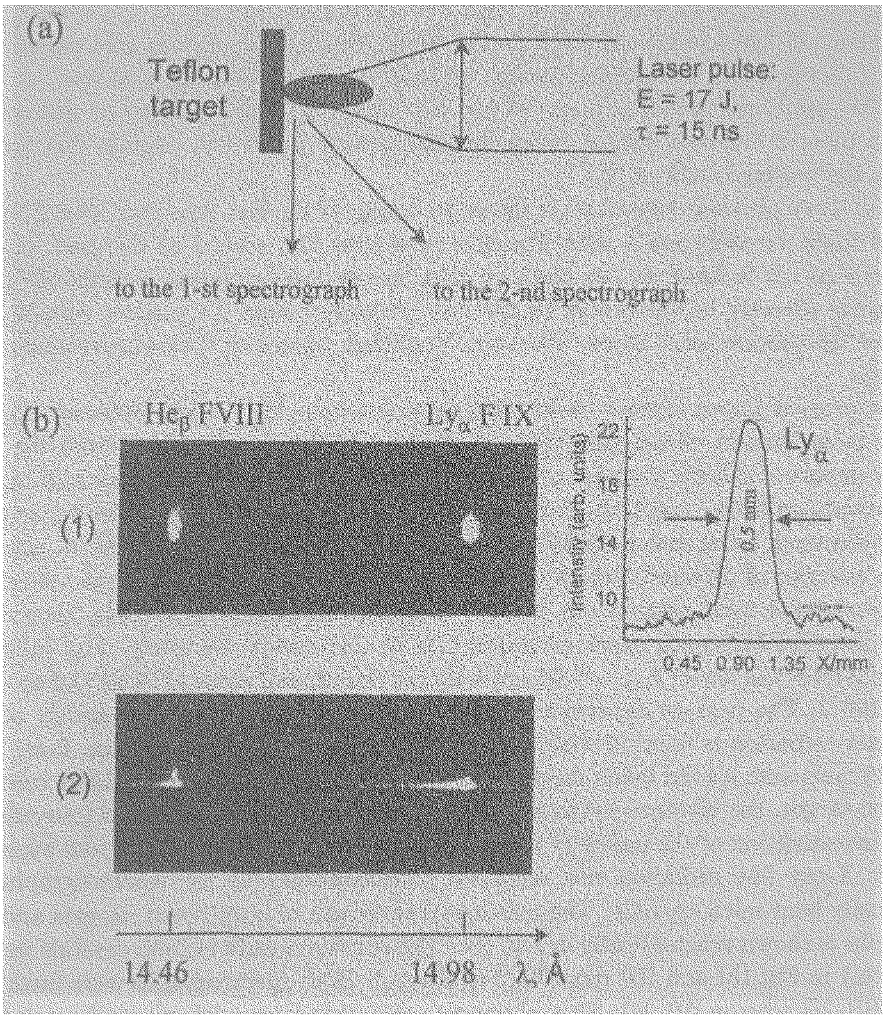

Fig.1. The scheme of experiment (a) and examples of spectrograms (b) obtained for different directions of observation: *1* – parallel to the target surface, *2* – at an angle of 55° relative to the target surface

of the predominant plasma expansion), are rather narrow and have the symmetrical line shape (see also Figs.2 and 3). Contrary to this, spectral lines recorded by the second spectrograph have strongly asymmetric profiles with enhanced shortwavelength wings.

It is possible to show that observed line profiles can not be explained by Stark effect in a dense plasma. For example, the theoretical results obtained for Ly$_\alpha$- line of FIX are presented in Fig.4. The line profiles were calculated with account of the quasistatic ion microfield Stark broadening, broadening due to the elastic collisions with electrons, and the Doppler shifts in the form

$$S_{21}(\omega) = \frac{1}{\pi^{1/2}\gamma_D A_{21}} \sum_{\alpha} A_{\alpha 1} \int\limits_0^\infty V\left(\frac{\omega - \omega_{21} - \Delta\omega_\alpha \beta}{\gamma_D}, \frac{\gamma_\alpha}{\gamma_D}\right) P_\alpha(Z_i, \beta) d\beta$$

here $A_{\alpha 1}$ is the transition probability for the sublevel with the parabolic quantum numbers $\alpha \equiv (n_1, n_2, m)$, $V(x, y)$ is the Voigt function with the Doppler width γ_D and the collision

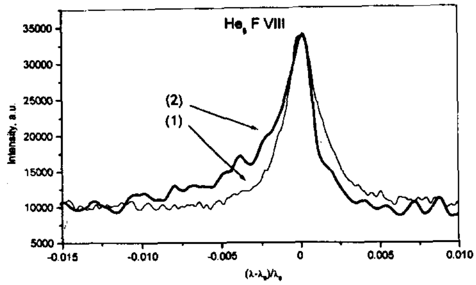

Fig.2. The profile of the He$_\beta$-line of ion FVIII radiated by laser-produced plasma in the direction parallel to the target surface *(1)* and at an angle of 55° relative to the target surface *(2)*

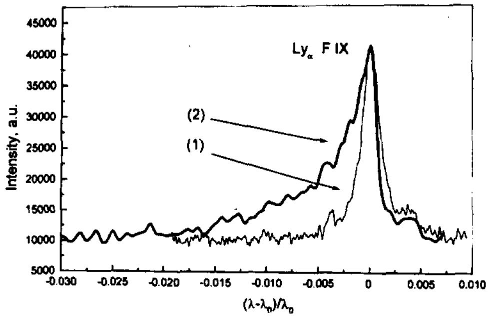

Fig.3. The profile of the line of $2p-1s$ of ion FIX radiated by laser-produced plasma in the direction parallel to the target surface *(1)* and at an angle of 55° relative to the target surface *(2)*

width γ_α for each sublevel (according to [24]), $\Delta\omega_\alpha$ is the linear Stark shift of the sublevel in the field $F_0 = Z_i e/r_0^2$, $r_0 = 0.62 N_i^{-1/3}$ is the mean separation between ions, Z_i and N_i are the mean ion charge and density, $P_a(Z_i, \beta)$ is the distribution function of the ionic field $F = F_0\beta$, which account for the Debye screening and ion correlation effects [25]. The parameter $a = r_0/r_D$, and r_D is the Debye length.

It can be seen from Fig.4 that even at plasma density $N_e = 10^{21}\,\mathrm{cm}^{-3}$ Stark effect is not essential both for line width and shift, and can not explain the experimental results obtained.

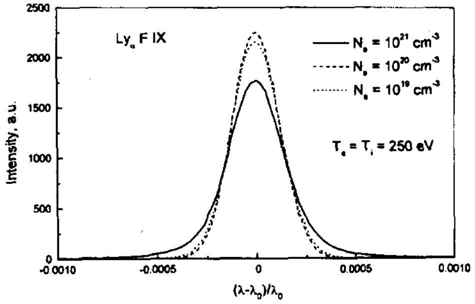

Fig.4. The profiles of the line $2p-1s$ of ion FIX calculated with account of the quasistatic ion microfield Stark broadening, broadening due to the elastic collisions with electrons, and the Doppler broadening for plasma with $T_e = T_i = 250\,\mathrm{eV}$

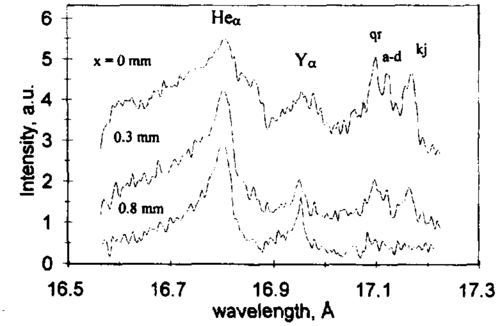

Fig.5. Space resolved He$_\alpha$ emission. The laser beam was perpendicular to the target, the angle between target and spectrometer was 45 degrees, x – the distance from the target surface

The only and very evident reason explaining such difference of spectra, is Doppler shift (increasing) of frequencies of photons radiated in the direction of the predominant motion of ions. In this case photons recorded by the first spectrograph, practically do not experience the frequency shift (transversal Doppler effect is negligible). The asymmetry of lines recorded by the second spectrograph is connected with anisotropy of macroscopical movements of plasma from the flat massive target (plasma can expand only from target, i.e. in direction to spectrograph). From the densitograms presented in Figs.2 and 3 it is seen that a significant number of photons show a relative frequency shift of $(\lambda-\lambda_0)/\lambda_0 =$

$= (0.5 - 1.5) \cdot 10^{-2}$. These values corresponds to ion velocities in the direction of observation of $V_{obs} = (1.5 - 4.5) \cdot 10^{8}\,\mathrm{cm/s}$. From these figures we can also see, that the velocities of fast H-like ions FIX and their concentration is higher than for He-like ions FVIII. The symmetrical shape of the profiles of lines recorded by the first spectrograph means that the motion of fast ions occurs normal to the target surface. It means that the perpendicular velocity component of their motion is $1/\cos 55^{\circ} = 1.74$ time more than V_{obs}. Hence, the energy of fast ions FIX in our experiments was about 2.5 MeV.

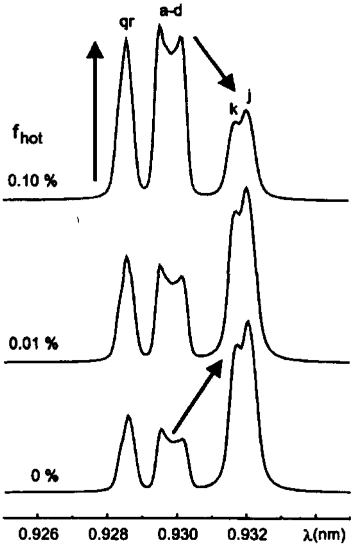

Fig.6. Hot electron diagnostic based on the relative intensities of the Li-like dielectronic satellites qr, $a - d$, kj. The parameters for the non-Maxwellian collisional radiative MARIA modelling [20] are: nuclear charge $Z_n = 12$, bulk electron temperature $kT_{bulk} = 100\,\mathrm{eV}$, electron density $n_e = 10^{21}\,\mathrm{cm}^{-3}$, plasma size $L_{eff} = 500\mu\mathrm{m}$, beam "temperature" $kT_{beam} = 3\,\mathrm{keV}$. With increasing fractions of hot electrons, the qr-satellites rise relative to the jk- satellites

Fig. 5 shows the space resolved He$_{\alpha}$-line, the intercombination line Y$_{\alpha}$ and the Li-like dielectronic satellite spectra $1s2lnl' - 1s^{2}2l$ (registration with a third spherically bent mica crystal, $R = 100$ mm, same shot like in Fig.1b, No. 1). Even for distances $x \approx 0.8$ mm strong Doppler shifted wings at the He$_{\alpha}$-line are observed and more close to the target the wing structure is even more pronounced (we note that the so called "blue satellites" [26] cannot be a reason for the observed line wing asymmetry in our case). The spectral distribution of the dielectronic $1s2l2l'$-satellites (indicated as qr, $a - d$, jkl, for satellite designations see [27]) is sensitive to hot electrons. Fig.6 shows the non-Maxwellian collisional-radiative calculations for an optically thick plasma carried out with the MARIA-codes [20]. It can clearly be seen that with an increasing fraction f_{hot} (relative to the bulk electrons with density n_e(bulk)) of hot electrons (with density n_e(hot))

$$f_{hot} = \frac{n_e(\mathrm{hot})}{n_e(\mathrm{hot}) + \mathrm{n_e(bulk)}}$$

the intensity of the qr-satellites increases relative to the jk-satellites. This effect is based on the increased collisional inner-shell excitation of the qr-satellites from the Li-like $1s^{2}2l$-states through hot electrons whereas for the jk-satellites the dielectronic capture channels still dominates. Note that ion abundances are simultaneously calculated for non-Maxwellian electrons to take into account the shifted ionic populations for different charge states. As can be seen from Fig.6 the shift to higher ionization states (caused by increased ionisation processes through hot electrons) does not compensate the increased inner-shell excitation. Density variations showed that for our range of parameters redistribution effects inside the $1s2l2l'$-satellite structure can not be made responsible for the qr/jk intensity interplay shown in Fig.6.

In conclusion we have developed a new diagnostic for the investigation of fast ion and hot electron generation by means of space resolved high-resolution X-ray spectroscopy. Fast ions and hot electrons can be investigated inside the plasma and also inside the same plasma volume. The experimental results demonstrate that MeV-ions can be generated at intensities much lower as predicted by scaling relations. In accordance with available today's theoretical considerations based on the quite a number of experimental results (see review [2]), such energies of ions can arise only at essentially higher values (two orders of magnitude of parameter $q\lambda^2$).

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