Fast Electrons for the Fast Ignitor Scheme of Inertial Confinement Fusion

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1. Introduction

The researches of fast electrons for the fast ignitor scheme of inertial confinement fusion has just now being started in our laboratory. The title above is that of our project within the frames of IAEA which has recently started, actually 1 month ago. Therefore herewith only a brief general summary of recent activities of our so-called HILL laboratory in laser plasma researches is given. Being a new party in this organization first the explanation of the name HILL is given, and the details of the collaboration within Hungary under this title is summarized (Section 2). Then the laser system and the available diagnostics are described in Section 3, including the plans for upgrading the present laser system. A significant part of our previous activity was on the field of high harmonics generation. This is decribed in Section 4 as an example for illustrating nonlinear phenomena in laser plasma interactions. Section 5 describes the possible advantages and disadvantages of using 248 nm radiation for the generation of fast electrons for ICF applications. Being a small laboratory in a small country, scientific collaboration is essential for our activity. In the last part of this report (Section 6) present and future collaborations are described. The aim of these collaborations is not only to participate in the experiments in larger laboratories, but also becoming itself a partner so that even parallel, or rather complementary researches are to be carried out in Hungary, too.

2. The HILL Laboratory

The HILL name is an abbreviation of the High Intensity Laser Laboratory which is situated in Szeged, Hungary at the Department of Experimental Physics of the University of Szeged. The laboratory was and is based on the active collaboration of the above mentioned Department of the University (we shall call it SZU in the following) and the Plasma Physics Department of the KFKI-Research Institute for Particle and Nuclear Physics (Association EURATOM) in Budapest (PPD in the following). The collaboration between the two small groups started in 1994 and since then it is permanently going on.

The tasks are shared between SZU and PPD. SZU is lead by the Head of the Department, Sándor Szatmári, who is well-known for his experiences in generation of ultrashort, high-power laser pulses, especially with systems based on dye- and excimer-lasers. The experience of the SZU extends to short pulse amplification in excimer laser amplifiers. Propagation of short UV laser pulses is and has been investigated in nonlinear, dispersive medium. The group of SZU is responsible for running the laser system, and for the diagnostics of the laser beam, controlling temporal and spectral properties of the laser pulses.

The group of the PPD has experience in laser plasma interactions and plasma diagnotics. The present project is lead by István B Földes. This group is responsible for the interaction chamber for laser plasma experiments and for the diagnostics of laser plasmas. The main interest has been visible, VUV and soft x-ray spectroscopy of laser plasmas. A special interest is toward nonlinear interactions for which the recent external interest for ICF gave a new impetus. Investigations of fast electrons for ICF application are starting in the present year.

3. The KrF laser system and the diagnostics

The details of the laser system are described in [1]. The system is based on a twin excimer laser. The first one pumps a dye-laser chain which in the end delivers a subpicosecond pulse on the 496 nm wavelength. After frequency conversion the pulse is amplified in 3 passes by the off-axis KrF amplifier. Thus a laser pulse of 600 fs duration is obtained with a maximum energy of 15 mJ on the wavelength of 248 nm. In the experiments until now it was focused by a simple f/10 lens on the target which was aligned to 45° of incidence. The maximum intensity obtained this way was 5×10^{15} W/cm^2. An advantage of this laser system is that the pulse is directly amplified, therefore no pulse compression is needed (not a CPA system). Therefore and because of the frequency doubling of the 496 nm laser pulse no pedestal appears, the only possible source of prepulse can be the ASE of the KrF amplifier. Due to the long (10-20 ns) pulse duration and the bad focusability of the ASE the contrast of the beam for our system was better than 10^8. It means that the ASE intensity in the focus is approximately 10^7 W/cm^2. It does not produce a preplasma but it might cause photo-ablation of the target material due to its short wavelength, therefore a further order of magnitude contrast improvement would be needed for optimal performance.

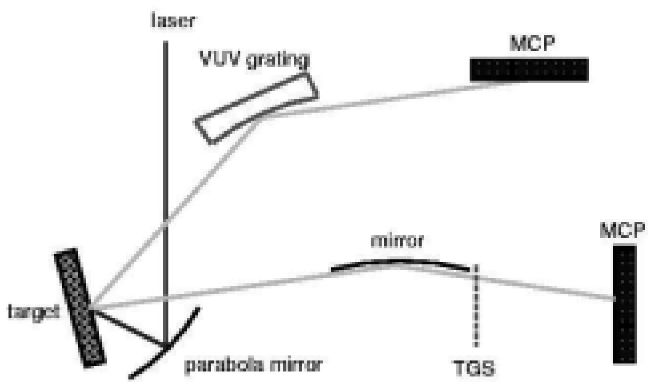

Figure 1. *Experimental arrangement for high intensities.*

In order to obtain higher intensities now the laser beam is focused by an off-axis parabola mirror in a new target chamber. Fig. 1 shows this arrangement with the main diagnostics. This type of focusing allows us to obtain intensities as high as 10^{18} W/cm^2 or even more. As it was demonstrated earlier with a similar laser [2], the good focusability of the UV laser radiation allows one to obtain intensities as high as 10^{19} W/cm^2.

The vacuum system and the target mechanics are now in operation, presently the optimization of laser beam, pointing, and measuring the focal diameter and thus the intensity is going on.

The first experimental data shows that even in this case of f/2 focusing the intensity of the ASE prepulse will not be higher than the above-mentioned 10^7 W/cm^2.

A toroidal holographic grating of 550 lines/mm serves for detecting high-harmonics in the specular direction and for the spectral investigation of the emitted VUV radiation in the 25 to 150 nm range.

Soft x-ray radiation in the 1-25 nm range can be investigated by transmission gratings (1000 and 5000 l/mm) combined with a toroidal mirror [3]. The detector for both spectrometers is an MCP with a phosphor screen. The visible light of the screen is imaged onto a CCD detector.

The above-mentioned arrangement with f/2 focusing and these diagnostics are to be put in operation in year 2001. Further upgrading concerns the laser system as to shorten the laser pulse duration below 100 fs. According to our expectations high-intensity pulses in the 20 fs range can be obtained in the next future. Studies of excimer laser amplifiers give us a hope to be able to increase the laser energy with a factor of 3. For the laser-plasma experiments construction of an electron spectrometer in the 1-100 keV range has started. Besides solid targets gas jet targets will be alternatively used to investigate fast electrons.

4. Generation of high-harmonics

As an example to investigate nonlinear laser-plasma interactions with a short-pulse UV laser, high-harmonics generated on solid surfaces were investigated. In the case of ultrashort laser pulses the plasma generated on a solid surface has not enough time to expand, thus ultrashort pulses can be applied to generate harmonics on steep plasma density profiles. The harmonics can be simply attributed to the current associated with the electrons dragged back and forth across the asymmetric density step [4]. Harmonics were generated with infrared and visible lasers with the shortest observed wavelength of 14 nm by using a relativistic 10^{19} W/cm^2 intensity [5]. As PIC simulations [6] suggested that short wavelength lasers can efficiently produce harmonics of short wavelengths, experiments were carried out with our 248 nm laser beam.

The laser was focused by an f/10 lens onto solid targets (Al, C, CH, Au), up to 5×10^{15} W/cm^2 intensity. The detector was the VUV grating seen in Fig. 1, which gave a spectral resolution of 0.5 nm for a single shot. Second and third harmonics were observed at these nonrelativistic intensities in the specular direction [7]. It was found that harmonics at these intensities and pulse durations (700 fs on target) can be generated both by s- and p-polarized laser beams. The conversion for the second harmonic was – according to the expectations - higher for the p-polarized beam, whereas no difference for the third harmonic generation could be seen. A VUV polarization analyser was built with which it was shown that the harmonics follow the polarization of the laser beam [8]. These findings contradict to the theoretical expectations (and also some of the experiments carried out with shorter laser pulses [9]) from the PIC simulations and the moving mirror model [10]. A local, nonperturbative model suggests the possibility of harmonic generation with s-polarized light caused by the ponderomotive force [8], but it does not give a clue either, how even harmonics of s-polarization can be generated. Present modelling is based on a single electron picture, which shows that harmonics generation by the evanescent laser pulse in the overdense plasma layer may lead to harmonics which follow the polarization of the laser beam.

In order to optimize harmonic conversion, experiments were carried out with controlled prepulses using geometrical splitting of the laser beam [11]. A 10^{13} W/cm^2 pulse served as a prepulse and a delay of 0-40 ps was applied to vary the initial plasma profile. C targets were preferentially used in these experiments because of their lower photo-ablation rate for the ASE prepulse. It was found that at certain delay times, i.e. at about 5 ps the conversion to harmonics was significantly increased. Fig. 2 shows the results with a p-polarized laser beam but results with s-polarized beam were similar. Taking into account the plasma expansion velocity, it can be stated that conversion to harmonics is the highest when the plasma scale length is L/λ=0.2-0.3. In the case of our 45° angle of incidence it is the same than the optimal scale length for resonance absorption.

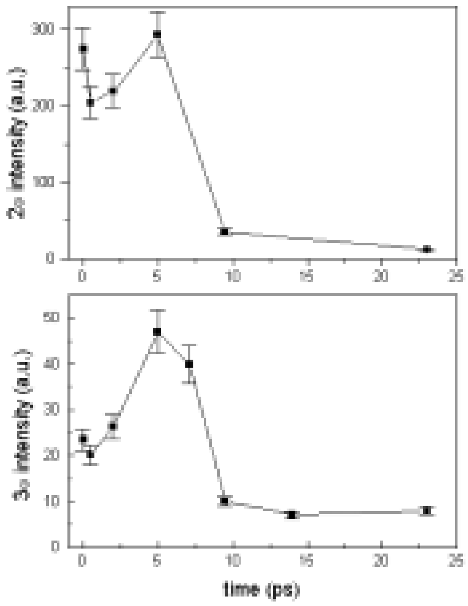

Figure 2. *Dependence of harmonics generations on prepulse time for C target.*

Our planned future experiments have to clean whether higher UV laser intensities can efficiently be used for efficient high-harmonics generation of short wavelength by this method which was not found in a previous experiment with a high-intensity but unclean KrF laser pulse [12]. It must be mentioned however that if harmonics generation is really optimized – even for higher intensities – at these scale lengths, then the optimal pulse duration of a 248 nm laser pulse for efficient harmonics generation is ~50 fs at 10^{18} W/cm^2 and ~20 fs at 10^{19} W/cm^2 intensity.

5. Possibilities of fast electron generation with 248 nm radiation

It is not the purpose of the present work to give details about the possibilities of fast electron generation for the fast ignitor scheme of ICF. Its concept goes back to the idea of Tabak [13]. In the case of fast ignition a portion of the precompressed DT pellet is heated above 6 keV during a time of 10-30 ps by a laser beam of more than 10^{19} W/cm^2 intensity, mostly by the laser generated intense electron beam.

As a consequence of the well-known $I\lambda^2$ scaling of nonlinear interactions much lower electron energies are expected for 248 nm than for a 800 nm or 1 μm laser beam. Fig. 3 compares the expected electron energies as a function of intensity for 248 and 800 nm wavelengths. It can be seen that for 10^{19} W/cm^2 infrared laser intensity MeV electron energies are expected and were observed in several laboratories, as e.g. by Gahn et al. [14]. In the case of higher, 10^{20} W/cm^2 intensities, which is assumed to be necessary for hole boring to the critical density [13], electron energies of up to 10 MeV are expected. These energies might be on the one hand too energetic for an efficient ignition. On the other hand some recent simulations give the results that even these electrons may be too strongly slowed down in the preformed plasma.

It can be clearly seen that the energy of fast electrons generated by a KrF laser will be around 1 MeV for this high intensity, which might be optimal for fast ignition.

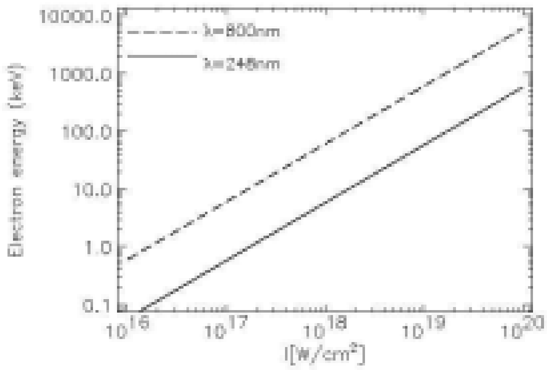

Figure 3. *Scaling of electron energies vs laser intensity.*

A further advantage of carrying out experiments with KrF lasers is, that due to the above-mentioned scaling law, less nonlinearities will be present, therefore the electron accelerating mechanisms can be investigated under cleaner conditions, i.e. separately. It can also be seen in Fig. 3, that the expected electron energies for 10^{19} W/cm^2 intensities - i.e. for the range available for us in the next future - remain below 100 keV. That is why we are going to build an electron spectrometer up to this energy only.

6. Collaboration for the investigation of fast electrons

As our possibilities in our small laboratory and with our UV laser is strongly limited for accelerating electrons, international collaboration is essential for us. We have a long existing collaboration with the Max-Planck-Institut für Quantenoptik (MPQ). Within the frames of this collaboration we take part in an experiment with the ATLAS laser system which aims to investigate fast electron transport in preformed plasmas.

Fig. 4 illustrates the experimental arrangement of Kaluza and Tsakiris[15] for these studies. In the previous experiments [14] a gas jet was used for investigating fast electrons. In these series the electrons will be accelerated in preformed plasmas. Electron spectra will be directly measured by the electron spectrometer, similarly to [14]. Information about electron spectra will be obtained from the hard x-ray spectra of the decelerating electrons in different materials. In order to see the spatial structure of the electrons, and see, whether filamentation occurs according to the calculations of Honda et al [16], we suggested visible light from the transition radiation of fast electrons as a possible diagnostics.

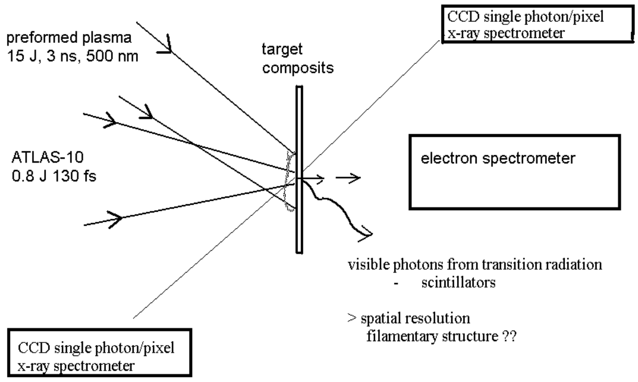

Figure 4. *Experimental arrangement of MPQ for investigating fast electron transport.*

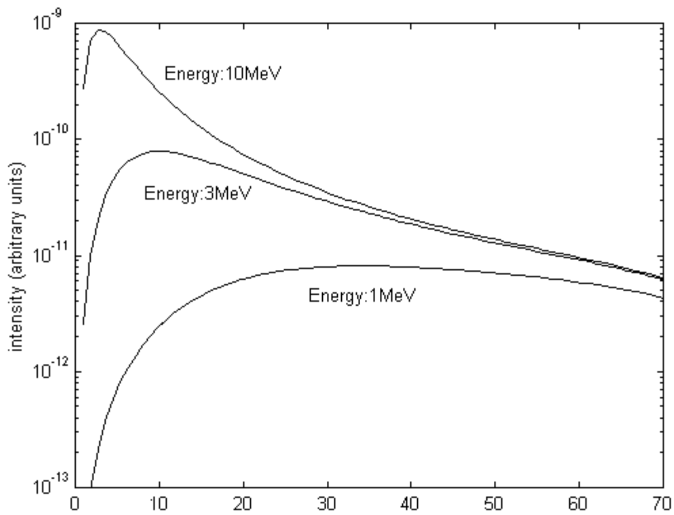

Figure 5. *Angular distribution of transition radiation integrated for the visible range.*

As an illustration of the expectations for detecting transition radiation, the angular distribution of the frequency-integrated intensity (from 0.2 to 0.8 μm wavelength) is plotted in Fig. 5 for Cu. It can be seen that both the intensity and the angular distribution strongly depends on the electron energy. In the previous experiments in gas jets [14] the electron temperature was determined to be about 3 MeV, and approximately 2×10^{10} fast electrons were generated. Assuming similar conversion efficiency in preformed plasma it means that approximately 10^7 photons are expected from transition radiation. Thus we assume to obtain a detectable but week signal. In order to have a better spatial resolution to be able to observe the filaments of submicron thicknesses [16] detection in the VUV range must be considered, too. As the expected signal is low, scintillators will be used to, which will have a more limited spatial resolution.

Our further plan for the future is to develop a more intense collaboration with the Photonics Institute of the Technical University of Wien in order to investigate electron acceleration mechanisms with ultrashort ~20 fs laser pulses. Within this collaboration parallel experiments in Wien and in Szeged with 800 and 248 nm wavelengths, respectively, are planned.

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