Novel Laser Ion Sources

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Development in the field of high-power laser systems with repetition rates of several Hz and energies of few Joules is highly active and opening, giving new possibilities for the design of laser ions sources. Preliminary investigations on the use of four different laser and target configurations are presented: 1) A small CO_2 laser (100 mJ, 10.6 µm) focused onto a polyethylene target to produce C ions at 1Hz repetition rate (CERN). 2) An excimer XeCl laser (6 J, 308 nm) focused onto solid targets (Frascati). 3) A femtosecond Ti:Sapph laser (250 mJ, 800 nm) directed onto a solid targets (Jena). 4) A picosecond Nd:YAG (0.3 J, 532 nm) focused into a dense medium of atomic clusters and onto solid targets (London). The preliminary experimental results and the most promising schemes will be discussed with respect to the scaling of the production of high numbers of highly-charged ions. Different lasers are compared in terms of current density at 1 m distance for each charge state.

I. INTRODUCTION

The CERN laser ion source [1] aims to produce large current pulses (5 mA, 5 µs) of highly-charged heavy elements (25+ Pb, Ta, Au) for single turn injection into a synchrotron (the PS Booster). The CERN accelerator complex runs with a repetition rate of 0.8 Hz and the LIS should run with at least the same repetition rate. Lower ion currents with a higher repetition rate would require an intermediate accelerator for storage and electron cooling. The laser-plasma scaling laws for charge state distribution, plasma density and plasma velocity set requirements on the minimum laser energy necessary for producing the required ion beam parameters [2]. The repetition rate and reliability of the accelerator sets strong constraints on the maximum laser energy that can be available for each active medium due to laser technology and physics. A Nd:Glass or Ruby cannot be used, neither can an electron-beam-pumped CO_2 or Excimer laser. It was decided to test different laser systems with parameters similar to what is currently available on the market in order to compare such results with the CERN CO_2 laser and other large laser systems obtained elsewhere [2,3]. The current density of each charge state (in mA/cm^2) along the target normal was measured at 1m distance for different laser system. The relevant time interval was chosen as the pulsewidth of the current pulse.containing the higher charge states. The range of our measurements was extended to low energy CO_2 laser (100 mJ). Such a source was investigated at CERN and was found to provide enough C^{4+} current to satisfy some of the requirements for proposed medical accelerators [4].

II. C^{4+} FROM A LOW-ENERGY CO_2 LASER ION SOURCE

A high pulsed current (>2 mA, 2 µs) of carbon 4^+ ions can be extracted when using a low energy CO_2 laser beam (λ=10.6 µm, E~100 mJ, dt=70 ns, 3 Hz) focused onto a polyethylene target. Such an ion beam could be utilised either as a test beam at high repetition rate or as an ion source for light ion synchrotron accelerators such as Proton Ion Medical Machines (PIMMS, TERA). In figure 1 and in figure 2 the current waveform and the charge state distribution are reported. The intensity on target was estimated at 5x10^{10} W/cm^2. The measurements in the CERN LIS were performed in a coaxial geometry, where the laser beam is focused onto the target coaxially with the plume expansion and detection system.

By using the same low-energy laser beam some Ta ion measurements were performed and the resulting charge state distribution is in figure 3. It is interesting to mention that for these energies (and higher <12 J) several laser systems with high repetition rate are available in the market at repetition rates up to a few 100Hz.

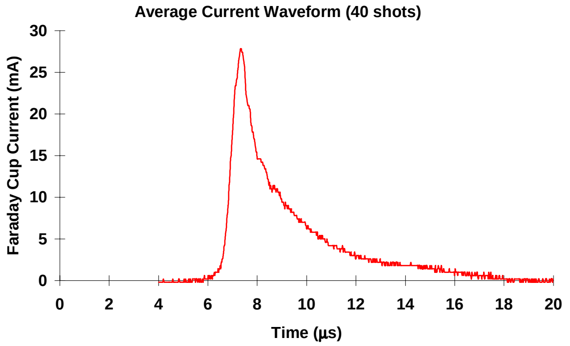

Figure 1 Current waveform for C ions. CO_2 laser, 100 mJ, 70 ns

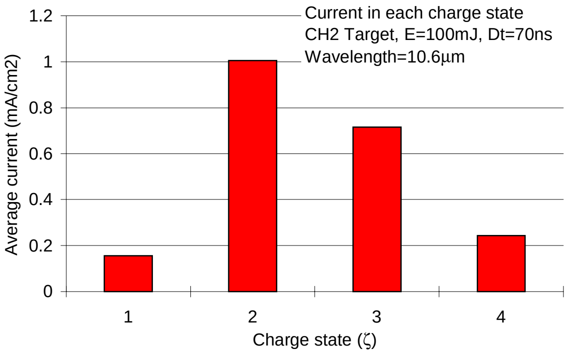

Figure 2 Charge state distribution (CSD) for C ions.

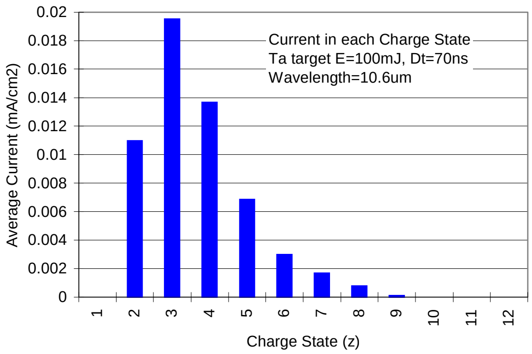

Figure 3 Ta CSD with CO_2 laser, 100 mJ, 70 ns.

III. EXCIMER LASER MEASUREMENTS IN FRASCATI

Ions flowing from targets irradiated by short wavelength lasers (Visible, UV) have been measured before, see for example [3,5]. These measurements were performed first in order to use a homogeneous experimental set-up, that is the same instrumentation that is currently in use at CERN. Secondly, the investigation of a regime of laser energies and pulse duration where laser systems at repetition rates up to a few Hz are commercially available, was possible with the view to developing a source that will have to run at 1 Hz or more. Thirdly, highly charged ions were measured in the past in the plasma close to the target (~1 mm) by means of x-ray spectroscopy [6]. At ENEA (Frascati, Italy) the large aperture excimer laser, HERCULES, could be used [6]. It can provide a near diffraction limited beam with the following parameters in the near UV, at the wavelength of 308 nm: The energy, 6 J, is delivered in a pulse 140ns long when the laser is equipped with an unstable resonator with magnification M=7 ($I=9x10^{12}$ W/cm^2). Alternatively an output of 2.5 J in a pulse of 10ns is achieved by a MOPA (master oscillator, power amplifier) configuration ($I=5x10^{13}$ W/cm^2). Such a beam is routinely focused on various targets in order to provide strong emission of characteristic soft x-rays in the keV and sub-keV region [7]. The target chamber was pumped with turbomolecular pumps down to 5x10^{-6} mbar.

In this experiment the laser was focused onto the target at 45^o to the normal while the detection system was along the target normal.

In figures 4 and 5 the measured charge state distribution are shown. Lower charge states were observed as compared to similar laser energy CO_2 Laser (figure 6) at CERN.

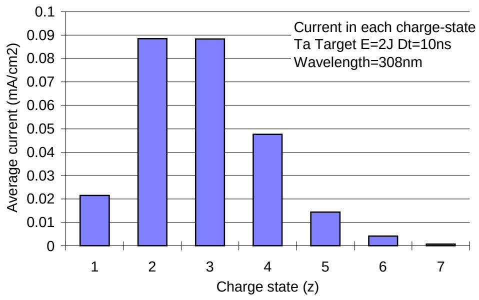

Figure 4 Ta CSD with excimer laser. 2 J,10 ns.

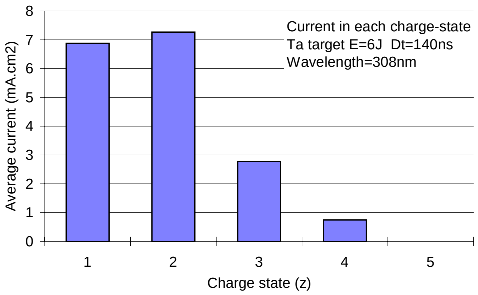

Figure 5 Ta CSD with excimer laser, 5J,140ns

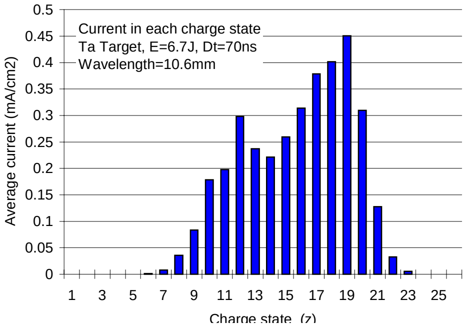

Figure 6 Ta CSD with CO2 laser,6.7 J, 70 ns

IV. FEMTOSECOND LASER PRODUCED PLASMA IN JENA

In November 1998 a one-week visit was organised to the Institute of Optics and Quantum electronic of the University of Jena in order to investigate the production of high charge state of high Z elements following the irradiation of solid targets. The laser [8] has the following parameters: wavelength 800 nm, energy 200 mJ and pulse duration 100 fs. Although the nominal intensity is 2.5x10^{18} W/cm^2, the estimated experimental value is 5x10^{17} W/cm^2. The vacuum could be brought down to below 10^{-5} mbar after few days of pumping.

A gold coated off-axis parabola focused the laser onto the target surface at 45^o from the target normal, while the detection system was placed normal to the target surface. The measured charge state distribution is shown in figure 7.

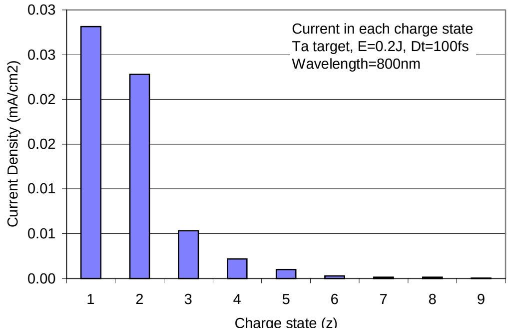

Figure 7 Ta CSD with Ti:Sapphire laser 200 mJ,100 fs

V. PICOSECOND LASER PRODUCED PLASMA AT IMPERIAL COLLEGE

Highly-charged ions have been observed in the interaction of short laser pulses with a medium of atomic clusters (for example Ar and Xe) [9]. The Nd:Glass laser system at Imperial College can provide 1 to 2ps pulses of up to 1 J. The 2nd harmonic of the laser was used (0.3 J at 527 nm) and focused using a f/10 lens onto various targets. The final focusing and target area were placed inside a 1.2 m diameter cylindrical tank, which could be pumped to <10^{-5} mbar. The high vacuum pumping consisted of an oil diffusion pump, a turbo pump and an LN$_2$ cooled surface.

Solid tantalum and a dense medium of atomic clusters formed in a high-pressure gas jet were investigated as target media. The results obtained by using solid Ta target were similar to those of Jena and charge states up to 9+ were observed in small quantities, together with traces of oil covering the target surface. In order to provide enough clusters for the source to be attractive in terms of current, the jet pressure had to be increased (up to 5 Bar backing pressure). As the valve had to be opened for at least a few ms, the chamber pressure would rise considerably (up to 0.1 mbar in the nearest gauge). Such a pressure is too high for the ions to travel to the detection system without recombining. Only an UV signal was measured with a SEM tube but no ions could be detected. In the previous experiments with clusters [9], the cluster density was much lower and hence the pressure in the chamber could be kept low. Whether it is possible to generate a large amount of clusters while maintaining surrounding high vacuum conditions is an experimental challenge.

VI. VACUUM AND IMPURITIES

All the experiments performed at CERN had carefully controlled vacuum conditions. The experiments were performed with background pressures of less than 10^{-6} mbar and clean components were used.

Further experiments performed at CERN indicate that highly charged ions freely expanding into a background pressure of 10^{-5} or above over a distance of few meters will start to recombine (loosing a few charge states). It is difficult to believe that the results that have been presented would be substantially different in the case that the vacuum could have been improved.

Concerning the Jena preliminary experiment, the situation is different since a layer of oil was observed on the target surface. Due to the presence of a prepulse-formed plasma and the absorption mechanisms for femtosecond light [10], it is not excluded that for different vacuum and cleanness conditions the result could have been different. On the other hand, from the results obtained in Imperial College, it was concluded that solid-target fs-laser interaction is not a dramatically convenient way of producing large amounts of highly charged ions in the present source scheme.

VII. CONCLUSIONS

The aim of this investigation was to find out whether in the near future a laser ion source based on a short wavelength, short pulse duration laser, could replace the present CO$_2$ scheme advantageously. This means providing the needed number of heavy ions in the correct time interval.

The most immediate conclusion is that at present no laser system except the TEA CO$_2$ laser can provide a large current of highly-charged ions. The advantage of the CO$_2$ wavelength is in the higher plasma temperature and lower plasma density, together with a hot corona that probably provides the mechanism to propel the outer layers of the plasma. Moreover it is particularly interesting to study the ion production with low-energy CO$_2$ lasers where high repetition rate systems exist.

However the experiments of Frascati and Jena should be continued, in Jena with higher vacuum and lower energy prepulse and in Frascati with a coaxial illumination scheme.

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