FEASIBILITY OF SHORT WAVELENGTH, SHORT PULSE LASER ION SOURCE FOR THE LHC INJECTOR

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Abstract

Results of experimental investigations of characteristics of ion streams generated from laser plasma after focusing the laser beam either with an aspheric lens or with a parabolic mirror (allowing an observation of the ion emission in the direction of the target normal) are presented. The photodissociation iodine laser PERUN operating with $\lambda = 1.315\mu m$ and delivering energy up to $50J$ was exploited in the experiment. In this contribution we restricted ourselves to the results of ion emission measurements from $Ta-$, $Pb-$ and $Bi-$ plasma.

Introduction

Present studies of the emission of ions from the laser produced plasmas are mainly motivated by a growing interest in the physics of heavy ion accelerators. In the application of the laser plasma as a source of multiply charged heavy ions high current densities are required. From this viewpoint, as numerous experiments show, the laser plasma sources seem to be very promising. In comparison with the electron cyclotron resonance ion sources, which are employed for heavy ion injectors at present, higher current densities of highly charged ions are expected. Thus the charge state of ions, the ion velocity (or the ion energy) and the ion current density were the basic parameters of interest. However, it is evident that whilst the ECR sources are nowadays highly developed as far as their reliability and simplicity of operation is concerned, the laser sources still face major technological and even scientific problems.

PERUN Experiment and Results

Ion emission experiments were mainly performed with the photodissociation iodine laser system PERUN [1]. Ion collectors (IC), a cylindrical electrostatic energy analyzer (IEA) and a Thomson mass spectrometer (TS) were applied to monitoring the emission of the ions [2]. The ion species, their energy, abundance and/or velocity distribution were explored in dependence on the laser power density, focus setting with respect to the target surface and the changing the angle of observation. The collectors are based purely on the time-of-flight effect, the spectrometers combine time-of-flight with the action of electric or magnetic field on the ions. The collectors first separate the electron component and then they measure the ion current. The outcome is, however, influenced by the secondary emission, which is adding to the net current. Since the secondary emission coefficient, which is specific for any cathode material, may be energy and charge dependent, it introduces a certain degree of uncertainty in the results. This is the main source of error in the absolute estimates of the ion number. In the following it was assumed that for each ion charge unit impinging on the collector cathode one extra secondary electron is struck out.

The analyser devices use either an electric field alone to separate the ion species as in the IEA or the combined electric and magnetic field in the TS. The geometry of IEA is that of a cylindrical capacitor segment, where the radial electrostatic field separates the ions entering through a slit. The sensor is a vacuum windowless electron multiplier. An IEA requires a repetitive laser operation (typically 20 shots) to determine the charge energy spectrum.

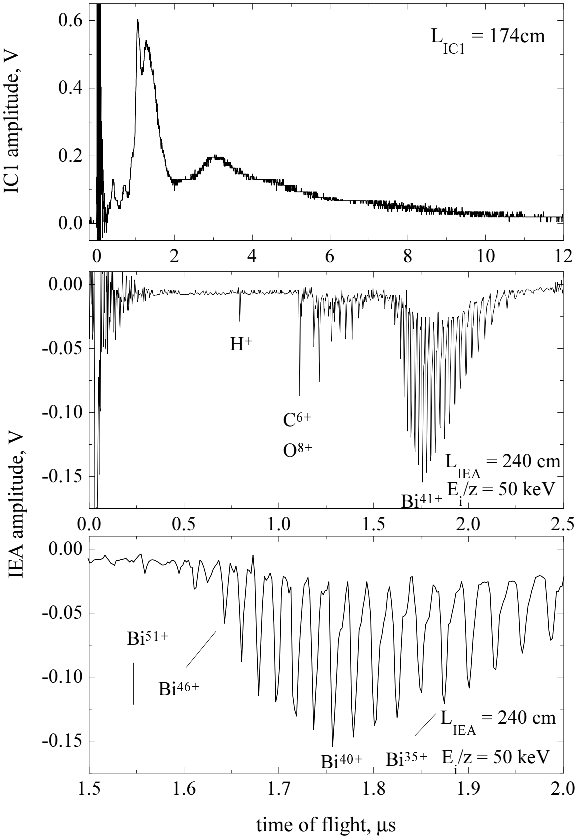

Figure 1: IC signals and IEA record of Bi.

TS renders the whole spectrum in a single shot, but the resolution power for highly charged species is poor. The output picture formed either on an ion sensitive foil or a multichannel plate is composed of a set of parabolas, each corresponding to a single value of e/m. Whereas for light elements like contaminants in the vacuum of the target chamber the parabolas are quite distinct, the higher charges usually coalesce. In practice it is thus imperative to use an IEA to get a quantitative answer. However, if the recordings of the TA are processed numerically, in particular, a grid of precalculated parabolas is overlapped with the output the identification of ion groups is fast and convincing. Both the devices are difficult to calibrate absolutely, but placing a coaxial IC in the path of flight of an IEA makes an absolute calibration possible. Examples of ion collector signals and electrostatic analyser spectra for Bi is shown in Fig. 1. Two groups of ions (fast and thermal) are clearly discernable on the charge-integrated and time-resolved signal from an ion collector, which was located in a far expansion zone. The spectra in Fig. 1 clearly prove the existence of ions with charge states about $50+$. We registered fully stripped Al, or nearly stripped Co and Ni, and ions with charge state higher than $48+$ of heavy elements: Ta, W, Pt, Au, Pb and Bi. In principal, the mass-to-charge ratios, energies and abundance of the emitted ions can be determined from the spectra. The ions are not only generated, but also accelerated. The maximum energy of the ions increases with the laser power density. In our experiments with high-Z targets the highly ionized ions with energies up to several MeV were registered. Keeping in mind a two group electron model [3] the fast ion expansion velocity can be interpreted as a sound speed with the hot electron temperature.

Estimates of the ion current density and the number of ions with a given charge state produced during a single laser shot were performed by processing of the IC signal with the use of the data from IEA spectra. The total maximum ion current density attained $12mA/cm^2$ with lense and $\sim\ 22mA/cm^2\ 94cm$ from a Ta target (recalculated value according to r^2 law) using the parabolic mirror. An evaluation of the experimental data pointed out that about 30% of the ions of their total amount are in a high charge states (from 35+ to 45+). When recalculated to the number of the particles our measurements give thus at least 10^8 of ions in a single charge state within a single pulse lasting about $1\mu s$. The maximum values are observed in the direction of the normal to the target, as it follows from the measurements with the parabolic mirror. To obtain the entire ion energy distribution for a single value of the laser energy a series of measurements changing the analyzer voltage was made. As the measurements are fairly laborious and time consuming they were performed only for $Ta-$ ions, see [3].

Exploiting the theoretical considerations in [4-8] a dependence of the average charge state of ions on electron temperature was constructed, which is shown in Fig. 2. It is seen that an average charge state of Ta-ions 45 is attainable at an electron temperature of about $1.0 - 1.5keV$, while at the same temperature the average charge state of Au- and Bi-ions is 51 and 55, respectively. This corresponds to the electronic structure of the heavy ions, which unlike the neutral atoms tend to form a closed electron shell with 28 electron left (Ni-like ions). For a further ionization a fairly high potential barrier would have to be overcome. In this sense it is easier to achieve a higher ionization degree starting from heavier elements.

The generation of the ions in the laser plasma, as far as their charge states and numbers are concerned, is very sensitive to the position of the laser focus with respect to the target surface. The results of our studies of the effect of focus setting on the ion emission is summarized in Fig. 3. There is a position of the target lying behind the true focus (aim in front of the target surface), which is most favourable not only for generation of the highly ionized particles but also for attaining a maximum yield of the ions. Then it is most likely that the laser shots aimed repeatedly in the same point on the target surface deteriorate both the amount and the average charge state of the emitted ions. It was found that after the 3rd laser shot the plasma parameters are so changed that the energetic highly charged ions are missing and the total ion emission is much weaker.

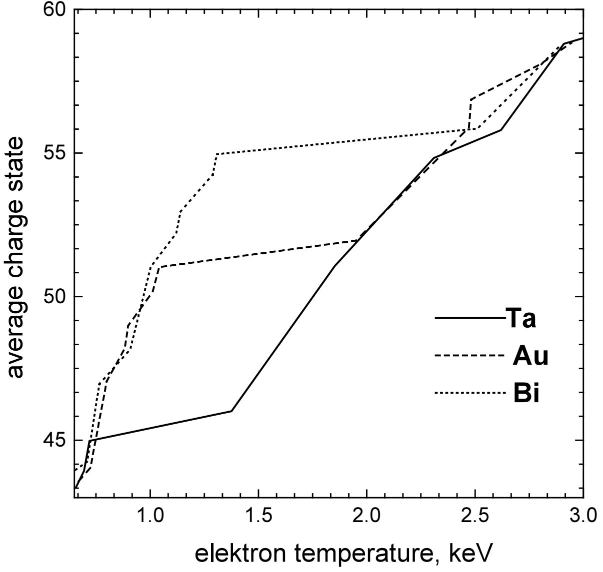

Figure 2: Calculated mean charge of Ta, Au and Bi dependent on the electron temperature

Discussion and Conclusions

It is interesting to compare the requirements of an ideal LHC injection at CERN with the performance of the short pulsed lasers as potential ion source drivers. Since these lasers appear to be more costly and less practical then the CO_2 these drawbacks must be balanced by specific advantages offered by them. A principle advantage might well be skipping of the first stripper in the Linac line. Also the number of ions and the timing of their arrival should be such, as to allow for a single turn booster operation and possibly to avoid the use of LEAR (which would, however, be the purpose of any laser source). The requirements of CERN are summarized as follows:

For the lead ions experiment an ideal source should yield

$Pb45+$	$3.6mA$	$6\mu s$	$(= 3 \times 10^9$ ions$)$	$17.3keV/u$
$Pb54+$	$4.3mA$	$6\mu s$	$(= 3 \times 10^9$ ions$)$	$20.8keV/u$

In deriving these numbers it was assumed that the extraction voltage is set to $80kV$ and no stripper. This compares with the numbers obtained e.g. with the iodine laser using a Ta target

$Ta42+$	$22.8mAcm^{-2}$	$1\mu s$	$(= 10^8$ ions$)$	$12.7keV/u$

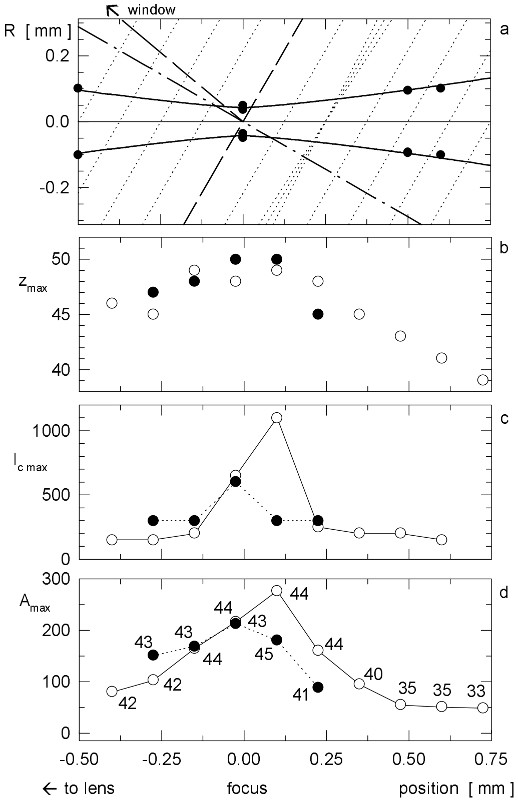

Figure 3: Dependence of the ion current and of the mean charge on the focus setting

In the last line the second number is the current density in the collector current maximum of the fast ion group (about 30% of the total) obtained with the mirror focus measured in reality by a coaxial IC $174cm$ from the target, but transformed using a quadratic law to a distance of $94cm$ (to make it compatible with the lens focusing). The fast group involves about 10 ion species and the pulse is short. Although the estimate of 10^8 ions available for the extraction is fairly conservative, it is difficult to see, how especially the pulse timing could be extended to the required $6\mu s$ tempering just at the laser. Looking at the charge-energy spectra a natural spreading of the pulse by the time-of-flight would dictate an intolerably long flying path.

A certain improvement might be expected resorting still to shorter wavelenght laser. Then there is a less acceleration and the energy spectrum is narrower. Equally a larger focus, while keeping the power density constant, might supply more ions, but at the cost of a disproportionate increase in the pulse energy, since not only the focus area grows, but also the pulse should be prolonged, see [1]. But it is unlikely that the timing of the pulse might be reconciled with the LHC injection demands without a major change in the subsequent acceleration regime,

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