Status of the CO_2 Laser Ion Source at CERN

P. Fournier, G. Gregoire, H. Kugler, H. Haseroth, N. Lisi, C. Meyer, P. Ostroumov, J.-C. Schnuriger, R. Scrivens, F. Varela Rodriguez, B.H. Wolf
PS Division, CERN, CH-1211 Geneva 23, Switzerland

S. Homenko, K. Makarov, Y. Satov, A. Stepanov
TRINITI, Troitsk, 142092 Moscow Region, Russia.

S. Kondrashev, B. Sharkov and A. Shumshurov
Institute for Theoretical and Experimental Physics, 117257 Moscow, Russia

A laser ion source using a CO_2 laser focused onto a solid target is under study at CERN for the production of high currents of highly-charged heavy ions, for possible use in the pre-injector for LHC. A new expansion and extraction layout was installed in this test facility, improving the alignment and making the target to extraction distance more flexible. A two solenoid beam transport system was studied for providing the matching of the beam to an RFQ. An electrostatic beam transport using gridded electrostatic lenses was designed and constructed as an alternative to a magnetic system. Results show an increased overall current transmission for the electrostatic case. Investigation of the laser parameters required for the production of 1.4×10^{10} Pb^{25+} ions in a 5 µs pulse, has been performed using the TIR-1 laser facility at power densities up to 10^{14} Wcm^{-2} for a focal spot size of 65 µm. The results of the latest scaling are presented.

I. INTRODUCTION

For the highest luminosity in hadron colliders, the injector chain is best served by a source providing a high brightness beam with a pulse length similar to that of the revolution time of the first synchrotron. In this way multi-turn injection and the associated emittance increase is avoided. A source with these characteristics for heavy ions is the Laser Ion Source (LIS). At CERN, the study uses a high power (200 MW), short pulse (70 ns) CO_2 laser beam focused onto heavy metal targets (e.g. tantalum). This creates a hot plasma from which high charge-state ions emerge.

The study's aim is to design a source capable of fulfilling the emittance and intensity for the injection chain of the Large Hadron Collider (LHC) to reach the LHC design luminosity.

The experimental set-up of the source and accelerator (excluding the laser) is shown in Figure 1.

II. PLASMA GENERATION AND EXPANSION

The power for plasma production is supplied by a beam from a 30J CO_2 laser, with a wavelength of 10.6 µm. When focused onto the target surface with a 300 mm focal length copper parabolic mirror, a power density of 2×10^{12} Wcm^{-2} is achieved. The laser repetition rate is 1/30 Hz.

A plasma is formed by the interaction of the intense laser radiation with the target surface. The laser power is then coupled to the plasma by inverse-Bremsstrahlung absorption, which occurs at electron densities up to a critical value where the density is equal to the plasma frequency at the laser wavelength (~10^{19} cm^{-3} for 10.6 µm radiation). The dense high temperature plasma can then cause step-wise ionisation of the heavy ions.

The plasma containing high charge-state ions, is allowed to expand though a 30 mm hole in the final focusing mirror (which is positioned 300mm from the target) and a further 700 mm in vacuum to the extraction system.

III. EXTRACTION OF THE ION BEAM

Before extraction the plasma consists of multiply charged tantalum ions with a current density of 10 mAcm^{-2}. The potential required for extraction can be estimated from the Child-Langmuir law

$$J = \frac{4}{9}\varepsilon_0\sqrt{\frac{2q}{m}}\cdot\frac{U_d^{3/2}}{d^2}$$

where J is the current density, U_d the potential, d the gap spacing and q and m the ion charge and mass. For Ta^{20+} ions and a gap spacing of 30 mm, ~30 kV is required.

The current density may be increased by a factor from 1.25 to 2 in the case that the electrodes have two circular apertures for extraction of the beam [1], and the initial ion velocity in the plasma stream (approximately 10^5 ms^{-1}) leads to an further enhancement of by a factor 1.4 to 1.6 for a streaming energy of 2 kV at a extraction potential of 60 kV [2].

However, the optics of the ions in the acceleration gap is affected by the electric field distribution and the form of the plasma to ion beam boundary. These have been studied for quiescent plasma sources [3] but not for a source with a high ion streaming velocity. These considerations lead to a higher electric field requirement in the accelerating gap. With so many factors affecting the extraction of ions from a LIS, it is necessary to optimise the process by simulation and experiments.

A ray-tracing simulation with the code IGUN [4] for the extraction geometry used on the CERN LIS is shown in Figure 2. A beam of Ta^{20+} ions with a total current of 70 mA is extracted from the plasma. The ions are assumed to have a streaming velocity equivalent to 2 keV per charge in the plasma, and the electron temperature is input as 10 eV. The source is held at a potential of 60 kV.

The potential of the high voltage side of the source is fixed to 60 kV by the input energy requirements of the RFQ. In order to optimise the ion optics, a series of measurements were performed where the ion beam transmission into a 30 mm Faraday cup, 300 mm downstream of the extraction system was measured as a function of the applied source potential. The current density of ions in the plasma was then varied by changing the distance from the target to the extraction system.

A plot of the transmitted current as a function of the applied source voltage is shown in Figure 3. The plot shows a linear increase in current as a function of voltage until saturation is reached. The potential at which this turning point occurs can be measured for each source current (*I in* Amperes), and is found to follow the equation I=1.0x10^{-8} $(z/A)^{1/2}$ $U^{3/2}$,where ζ and A are the ion beam average charge-state and mass number, and U is the total potential across the first two electrodes of extraction (in Volts).

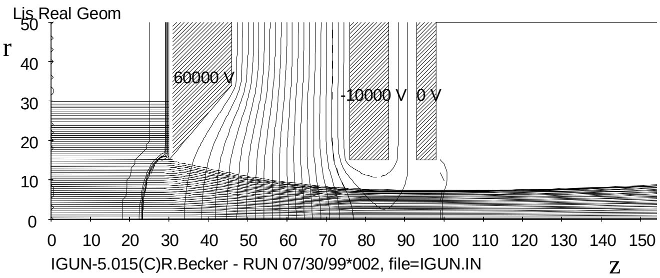

Figure 1. Cylindrically symmetric simulation of the extraction of Ta^{20+} ions, using IGUN. r & z co-ordinates are in millimetres.

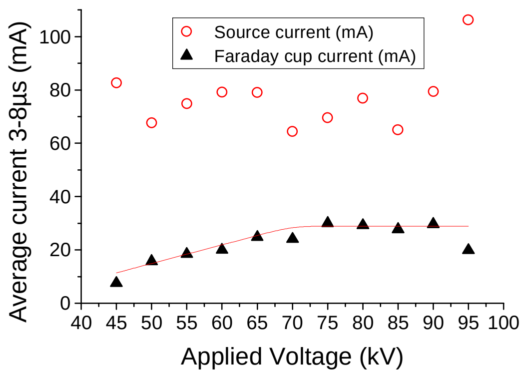

Figure 2. Transmitted ion current into a Faraday cup 300 mm downstream of the extraction systems, as a function of the applied source high voltage. Not all of the source current can be transported to the Faraday cup without a focusing lens.

IV. LOW ENERGY ION BEAM TRANSPORT AND ION BEAM ACCELERATION

The most pressing problem for the LIS is the transport of the ion beam at low energy from the source outlet to the Radio Frequency Quadrupole (RFQ) accelerator. The RFQ requires a small diameter beam at the input (6.5 mm), and hence the ion beam emerging from the 30 mm aperture extraction electrodes must be tightly focused and matched. This is difficult due to the high beam self space-charge field. Moreover, the space-charge is time dependent (due to the variation in current) and hence the static focusing system cannot achieve the same ion beam optical parameters at all times.

Two different focusing systems have been tested. The first uses two 120 mm aperture solenoids with peak on axis fields of 1.4 T. The second [a Gridded Electrostatic Line (GEL)] uses a set of high-voltage electrodes (up to 40 kV) separated by grids (see Figure 4).

The use of the two solenoid line has already been reported [5] where 2.0 mA of Ta^{20+} could be focused into a 6.5 mm aperture Faraday cup. The current appears to be limited by the non-linear space charge forces [6] which are produced when the ion beams of different charge-state are separately focused by the magnetic field of the solenoid. In this case the ion beam quality is compromised and only a small fraction of the beam can be focused into the cup aperture. The emittance of the beam cannot be realistically measured, as all charge-states will be measured together and therefore the phase-space occupied will be very large.

The GEL was installed in January 1999 and could be optimised to transport a total current of 33 mA into the same Faraday cup. The ion trajectory in the GEL should be independent of the charge-state and hence the ratio of the ion charge-states should remain unchanged (12% of Ta^{20+}). In this case a current of 4.7 mA of Ta^{20+} ions can be supposed.

The emittance increase caused by the passage of the beam through the GEL was measured by two methods. A multi-slit single-shot measurement [2] (using a slit plate with 100 µm slits separated by 5 mm, followed by a P47 phosphor screen and a gateable CCD camera) was employed but could not be used near the beam focus as the ion beamlets emerging through each slit overlap. In this case the measurement was performed without the full potentials on the three GEL electrodes, and an un-normalised 4xRMS emittance from 600 to 700 mm.mrad was found. Simulation [7] predicted an emittance growth of a factor 1.5, while the experiments indicate a factor 2 - 2.5.

The first RF acceleration stage for the heavy ion Linac at CERN, is an RFQ, which accelerates ~100 µA of Pb^{27+}. As the space-charge is very significant at the RFQ injection energy for the LIS, a test RFQ was designed and built [8] to accelerate ions with a minimum charge to mass ratio of 0.0865, with an output energy of 100 keV per nucleon, for a total current of 60 mA.

The diagnostic line after the RFQ consists of a quadrupole doublet, a current transformer and a 77^{o} spectrometer magnet after which a phosphor screen or Faraday cup may be mounted. In addition, a large aperture bending magnet is available for selection of only the fully accelerated ion beam, which may be captured in a large aperture Faraday cup.

The RFQ is found to transmit a range of high charge states and a significant amount of beam that is not accelerated to the full energy. The most recent results use the

GEL upstream of the RFQ. With a Faraday cup positioned at the output of the RFQ, currents as high as 6 mA can be found, but after transport through the large aperture bending magnet the full accelerated current is found to be 2.7 mA. The shot to shot fluctuation of the ion current is only 8.4% at this position.

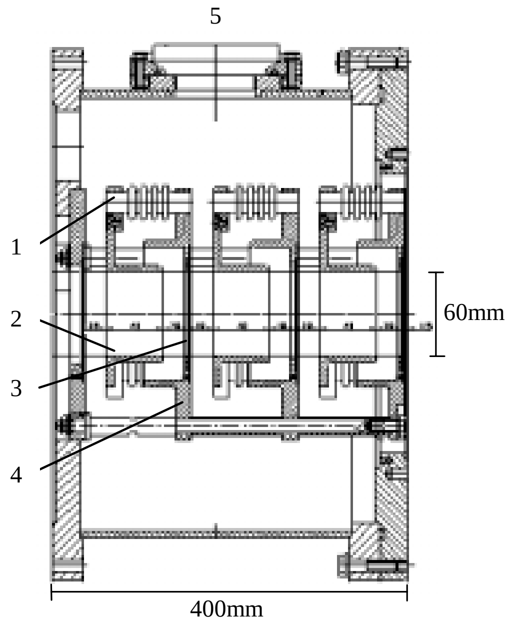

Figure 3. Drawing of the Gridded Electrostatic Line (GEL). 1- Ceramic isolator, 2- High Voltage electrode, 3- Grid, 4- Ground electrode, 5- HV feedthough mounting port.

V. STATUS OF THE HIGH ENERGY LASER

A project is underway to build a 100 J CO_2 laser with a pulse length of 20 ns and a repetition rate of 1 Hz. The original laser parameters were extrapolated from measurements with different CO_2 laser systems and with simulations. Significant work has been performed with the TIR-1 CO_2 laser system in TRINITI to build a single shot laser delivering the correct beam parameters onto a target, to study the plasma parameters.

With the latest scheme a Master Oscillator - Power Amplifier (MO-PA) configuration is used to provide 82 J pulses with a full width half maximum pulse length of 20 ns. The laser beam focal spot is estimated as 130 µm after focusing off-axis onto the target with a 1.5 m focal length copper mirror. The power density in this case is approximately $2x10^{13}$ Wcm^{-2}.

Measurements of the plasma current density and charge state distribution 3 m from the target suggest that the source could be configured to give $1.3x10^{10}$ Pb^{25+} ions with a pulse length of 5.5 µs. However, the shape of the ion pulse will require extraction of a peak current of 120 mA. Production of ions has also been observed with power densities up to 10^{14} Wcm^{-2} after focusing with a 600 mm focal length spherical mirror, and Pb^{29+} was seen as the highest abundance charge-state.

VI. CONCLUSION

The CO_2 LIS has demonstrated that high current, high charge-state beams can be produced and accelerated by an RFQ. The beam parameters at the RFQ output still fall short of those required for the injector chain to reach the LHC design luminosity.

Attention continues to be focused on the extraction and transport sections to the RFQ. The next step may involve reducing the space-charge effect by increasing the beam energy by a higher source potential and thereby reducing emittance blow-up and increasing the transmission from the source to the RFQ. In this case a new RFQ will be required.

The 100 J, 1Hz CO_2 power amplifier is scheduled for delivery at the end of 2000. This upgraded source should be producing ions in the middle of 2001.

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