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LIS Carbon Ion Production:
Low laser energy and High Ion currents

N. Lisi, R. Scrivens, F. Varela Rodriguez

We report on the results of ionic current and charge states distributions of carbon ions with the CERN Laser Ion Source. We show how a high pulsed current (>2 mA) of carbon 4^+ ions can be extracted from the source using a low energy CO_2 laser beam ($\lambda = 10.6$ μm, $E < 100$ mJ) focused onto a polyethylene target. The emittance of such source, although in principle small, has not yet been measured. Such ion currents could be utilised for beam alignment of the LEBT at high repetition rate or as a light ion source for light ion synchrotron accelerators such as PIMMS (Proton Ion Medical Machine Study).

1. INTRODUCTION

The CERN laser Ion source is currently being developed in order to provide sufficient currents of high charge states heavy elements [1] for the LHC project.

The generation of high charge to mass ratio ions in the laser plasma sets stringent requirements on a CO_2 laser beam performances in terms of Energy (>100 J) and beam quality (Single Transverse Mode and perhaps Single Longitudinal Mode).

The next stage of LIS development, in collaboration with the TRINITI institute (Moscow Region) is the construction of a novel concept 100 J, 1 Hz repetition rate CO_2 laser amplifier.

The laser system currently under development at CERN and in Russia consists of a Master Oscillator Power Amplifier (MOPA). While the power amplifier is currently under development and construction in Russia, the Master Oscillator was installed at CERN in July 1997 [2].

The new optical configuration allowed some measurement on the scaling of the ion production yield and charge state and at different laser energies and power densities on target [3], in particular both charge states distributions and ion current were found to be higher than expected at low intensity.

Moreover it allows 1 Hz operation of a high current carbon ion beam, by using a plastic target (polyethylene). The $C4^+$ current was found to satisfy some of the parameters for PIMMS, specifically the intensity and the pulse length [4].

2. LASER BEAM: SINGLE MODE AND MULTIMODE

The special feature of the Master Oscillator commissioned at CERN is that it makes possible to switch between Single Longitudinal Mode and Multiple Longitudinal Mode operations (to which we will refer simply as Single Mode and Multimode). Due to the large bandwidth of the active medium several wavelengths can be amplified as neighbour modes of the resonator, this give rise to some amount of randomness in the in the intensity waveform [2]. Our MO features a low pressure gas discharge tube (LPT) in the same cavity and a transverse electric discharge laser head (TED) the effect of the LPT is to narrow down the naturally wide spectral gain profile of the active medium so that single longitudinal mode operation becomes possible. Further closed loop control of the laser cavity length is necessary in order to assure long term stability for single mode operation of the laser.

Although it was predicted that the ion current should be more stable from shot to shot due to the improved reproducibility of the pulse waveform, such strong link was never demonstrated. Rather, slightly higher charge states are observed in correspondence with Multimode beams, as it could be expected due to the higher power density on target.

In the present configuration the MO beam delivers onto target into a spot of 65 μm diameter the energy of about 80 mJ.

Such an energy could be delivered, for Single Transverse Mode but Longitudinal Multimode operation only, by small commercial CO_2 laser systems [5].

3. LASER PRODUCED PLASMA AND DIAGNOSTICS

When the laser is focused onto a target in vacuum a plasma is produced. Due to the high temperatures and densities atoms of the target material are ionised and accelerated into the empty space.

The average ionisation results from the equilibrium between electron impact ionisation and recombination processes (collisional and three body), and strongly depends on electron temperature.

After a drift space electrons and the ions can be separated in an accelerating gap. The drift length is necessary in order to reduce the ion current density due to plasma expansion and render the extraction possible with moderate high voltages (<80 kV). Another effect of the drift length is to increase the pulse duration of the ion current pulse due to the initial velocity spread of the ions.

The experimental apparatus, except for the laser energy voltage is the same as described in [1].

We used a drift length of 1 m and we extract with voltages up to 80 kV (40 kV for the carbon measurements described in this note) in a two gap electrostatic lens. The electrode aperture is 30 mm. The diagnostic for the extracted beam consisted of a Faraday cup with suppression ring at -3 kV. The Electrostatic Spectrometer for charge state distribution measurements was used in the plasma (no extraction voltage) after a drift distance of 2.5 m.

4. TARGET MATERIAL AND ATOMIC STRUCTURE

For the carbon ion generation we chose polyethylene, which is a polymer, a chemical chain of only carbon and hydrogen (..CH-CH..) which makes it suitable for carbon ion generation [6].

A polyethylene rod was machined in order to fit to the present target mechanism, which makes possible to refresh the target surface to avoid the formation of a crater on the target surface.

In a very simplistic way the electronic structure of the atoms is what determines the ionisation level of the atoms in a plasma of a given temperature and density. In the table 1 we report the ionisation energies of carbon atoms. It can be seen at first glance that there is a large ionisation potential difference between the Li-like (3^+, three electrons left) and He-like ion (4^+, two electron left). We remember that in good approximation, a highly ionised ion has an electronic structure equivalent to its atomic counterpart where the electronic levels have been scaled with Z^2, Z being the residual charge. At first glance we notice that it should be much easier to achieve a $C4^+$ source than a $C5^+$ or a $C6^+$ source.

Table 1: Ionisation Potential of carbon atoms

Ionisation Level	Ionisation Potential
0	10.6
1	26.05
2	50.4
3	67.59
4	374.2
5	475.6

5. CHARGE STATE AND VELOCITY DISTIBUTION

The charge state distribution for the carbon plasma was obtained with the same experimental procedure described in ref. [7] with a curved parallel plates electrostatic spectrometer and a SEM detector.

As for our heavy ion measurements we assumed that the number of secondary electrons generated by the ions at the first dynode is proportional to the ion charge [8].

The Single Mode laser beam was utilised for this experiment. About 80 mJ of the laser energy did reach the target surface. The measured charge distribution in fractional current and particle number is shown in Figs 1 and 2. The charge state distributions were recorded at the distance of 2.5 m from the target. The measurement was gated between (15 to 25) μs as only charge states arriving in this interval were accepted. Such a gate, due to the expansion of the plasma, corresponds to a gating of (6 to 10) μs at the distance of 1 m form the target, were the Faraday cup measurements were taken.

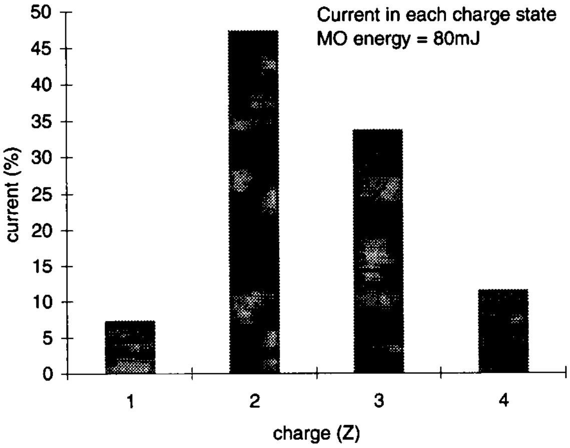

Figure 1 - Fractional Current in each charge state for the first current peak. Single Mode Laser Beam

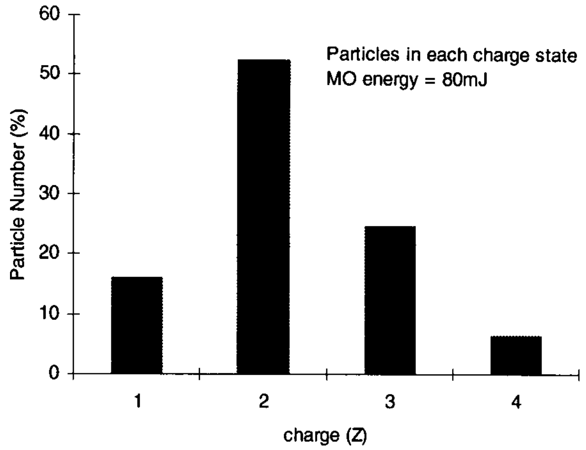

Figure 2 - Fractional Particle Number in each charge state for the first current peak. Single Mode Laser Beam

We note that more than 10% of the total current is due to 4^+ carbon ions. The velocity distribution of the different charge statesis shown in Fig. 3. It should be mentioned that the velocity spread of the source (about 2% after 40 kV extraction) can be compensated to a large extent by modulating the extraction voltage during the current pulse [9].

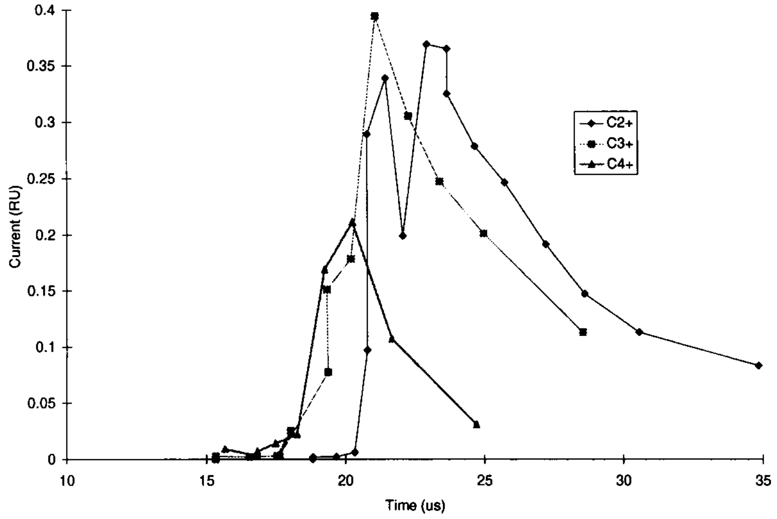

Figure 3 - Velocity distribution for $C2^+$, $C3^+$ and $C4^+$, 2.5m from the target.

6. ION CURRENT AND CURRENT STABILITY

The stability of the source is one of the major concerns for its application as real source for an accelerator. Instabilities, or at least causes for ion current fluctuations, can rise almost everywhere: due to the laser pulse generation, the laser interaction with the target, during the plasma expansion and extraction and finally in the high current multicharge beam transport in the LEBT line. We note that the high charge state heavy ion production sets a far more stringent set of demands on the stability of the system than the carbon ion production described in this report. This is due to the higher laser energy, higher laser intensity on target, the higher plasma velocity and finally the higher current.

The current was extracted with 40 kV across the extraction electrode gap at the distance of 1 m from the target. The extraction aperture was 30 mm.

In order to test the stability of the carbon laser ion source, about 80 current waveforms were recorded in similar conditions. This was done for Single Mode that for Multimode Beam.

In order to improve the reproducibility of the system, a new target surface was used every 10 shots in order to avoid effects from the formation of a crater on the polyethylene surface.

Some reproducible differences between Single Mode and Multimode laser beam were found.

The "average" current waveform for single mode and Multimode beam is shown in Figs. 4 and 5. This average waveform is obtained by averaging all the acquired waveforms at each time point.

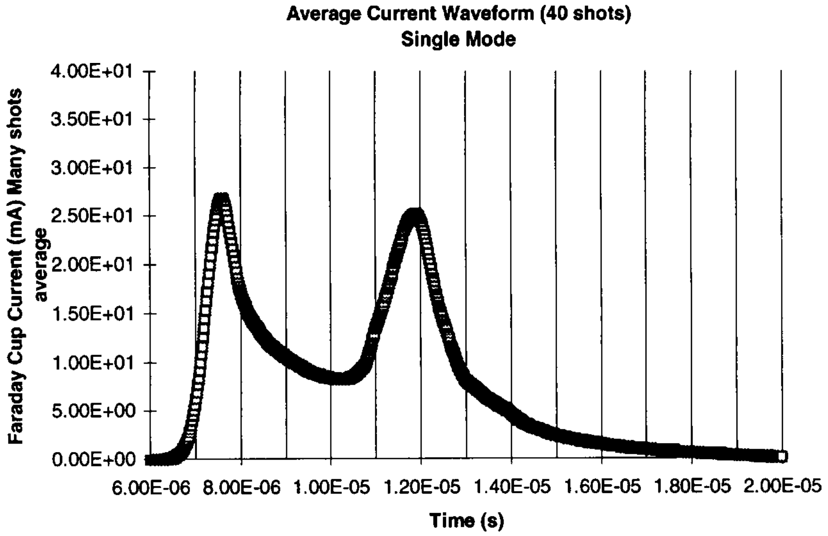

Figure 4 - Average ion current waveform for Single Mode beam. Faraday cup measurement at a distance of 1 m from the target. A second bump is a consistent feature of a single mode laser beam.

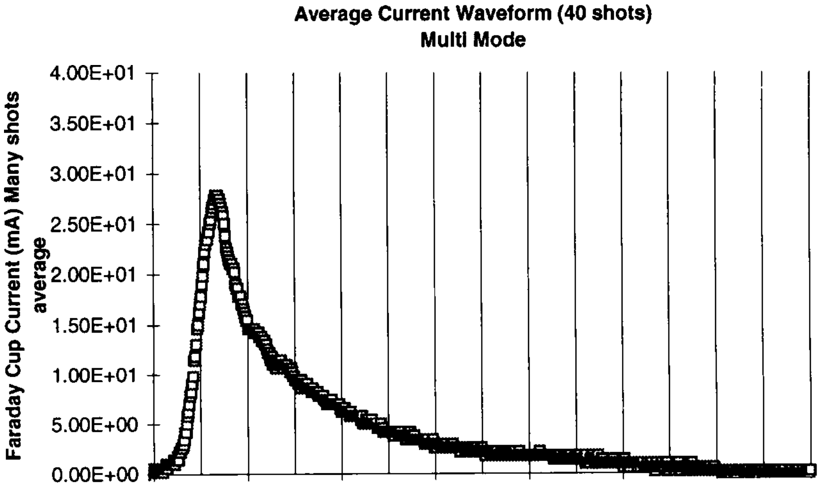

Figure 5 - Average ion current waveform for Multimode beam. Faraday cup measurement at a distance of 1 m from the target. The ions are slightly faster.

By using a similar procedure we can obtain the fractional "standard deviation" waveform which tells us about the current shot to shot stability as a function of time. Such waveforms can be seen in Figs. 6 and 7.

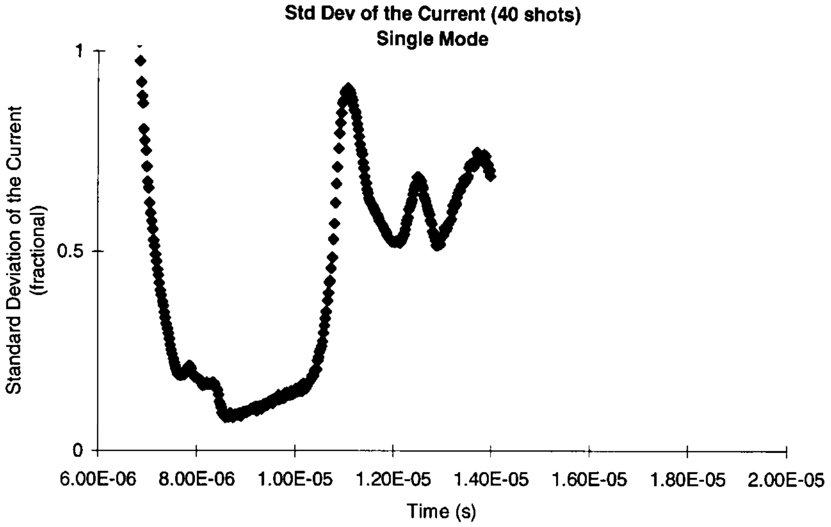

Figure 6 - "Standard deviation" waveform for Single Mode laser beam

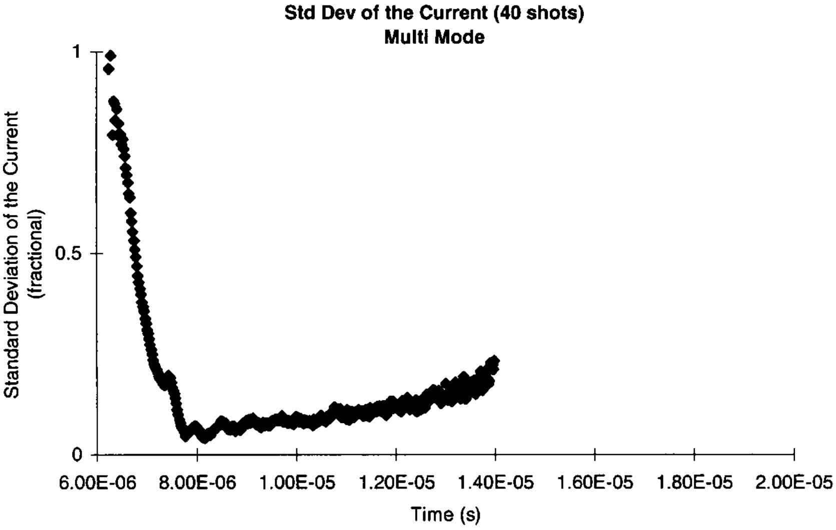

Figure 7 - "Standard deviation" waveform for Multimode laser beam

In order to interpret more easily the implication of current stability of the previous figures we can integrate the current waveforms in a given interval and calculate the standard deviation of such values for all the waveforms. This analysis is reported in Fig. 8.

We can see that for a Multimode beam we can obtain a current stability approaching 5% in some time windows. The stability during the rising edge of the current waveform, where most of the $C4^+$ ions are is worse, at about 15%. The large fluctuations of the current between 6.5 and 7.5 μs are caused by the shot to shot fluctuations of the ion velocity (thus the arrival time of the ions) as the integration interval includes the rising edge of the current pulse.

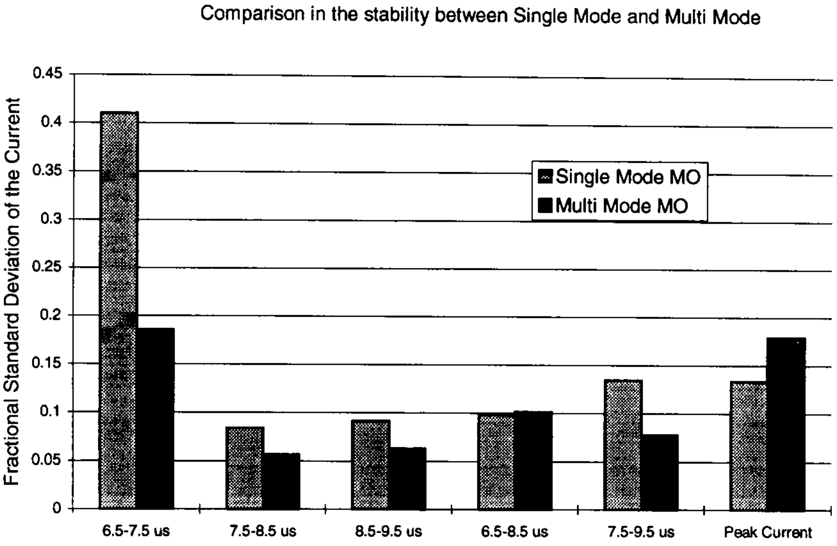

Figure 8 - Ion current stability for different intervals. Single Mode and Multimode comparison.

The peak current in the same window averages at more then 20mA (Figs. 4 and 5). If the fraction of C4$^+$ is approximately 10% of the total current (Fig. 1), we can produce more than 2 mA of C4$^+$ with a stability figure of around 10%.

The charge state distribution has not yet been measured with Multimode beam. It is probable that in this case a higher ratio of C4$^+$ will be found.

7. CONCLUSIONS

In conclusion, by using a low energy CO$_2$ laser beam and a polyethylene target, a carbon ion source delivering more than 2 mA of C4$^+$ was obtained. Such a source could be of use for beam alignment in the LEBT of the LIS source for LHC. Moreover it achieves more than required for ion current in the correct charge state, pulse length and repetition rate for the PIMMS (Proton Ion Medical Machine Study) where the source should provide about 0.5 mA of C4$^+$ for a duration of about 2 μs [4] at the LINAC exit.

Other advantages of such Carbon Laser Ion Source are, no gas load, no power required at high voltage platform and a relatively simple configuration of vacuum vessel.

Moreover the Ion current was found to be stable within 10% (RMS) from shot to shot.

Still open points are: The emittance of the source and the stability of the emittance of the source.

Emittances for the LIS source of heavy ions, are found in the range 100-300 mm.mrad depending on the extraction configuration. We believe that it is likely that the emittance of the C4$^+$ ions could be less than 100mm.mrad but further measurements will be necessary to demonstrate such figure.

Finally a Multimode laser beam was found to give a current output of similar stability, if not better, compared to a Single Mode beam. This is interesting in itself and moreover makes the construction of a Carbon LIS more simple as small reliable lasers available on the market can be utilised.

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