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Laser ion source of multicharged ions for ITEP accumulator facility

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Abstract

In this article, we present the results of the laser ion source (LIS) for heavy ion high charge state Institute of Theoretical and Experimental Physics terawatt accumulator facility. This LIS is a duty ion source of C^{+4} for the injector. The main parameters of CO_2 laser, vacuum target chamber, ion beam high voltage extraction system, and low energy beam transport line are shown. The stability of the LIS operation is discussed and measured ion beam parameters (ion current, pulse duration, emittance) for different charge states are presented. After the upgrading of the laser cavity, high voltage capacitors, and spark gaps and the installation of a new catalyst regenerator system, the CO_2 laser became much more stable and allows long term operation. LIS works about 1×10^6 shots without intervention.

Keywords: Catalyst regenerator system; CO_2 laser; Heavy ion accelerator chain; Laser ion source; Vacuum target chamber

1. INTRODUCTION

Modification and upgrading of the existing heavy ion accelerator chain aiming at the production of terawatt power level (100 kJ/100 ns) of intense ion beams is in progress at Institute of Theoretical and Experimental Physics (ITEP) now (ITEP-TWAC (Terawatt Accelerator) project).

The main idea of the project is the accumulation of the nuclei of elements as heavy as possible using non-Liouvillean injection into the accumulator ring. Foil stripper will be used to convert highly charged ions to nuclei. Ions with very high charge states (in the range C-like to He-like ions for different elements) have to be used to minimize losses of ions during non-Liouvillean injection into the accumulator ring. As the accumulation time is restricted, the current of the ion beam at the exit of the source should be higher than 10 mA.

At the present status of ion sources, only Laser Ion Source (LIS) can meet this requirement of intensity for charge states this high. For this reason, it was decided to use LIS for the ITEP-TWAC project.

According to the ITEP-TWAC acceleration-accumulation scenario, the required parameters of LIS are the following:

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- Element—as heavy as possible,
- Ion charge state—in the range C-like to He-like ions,
- Ion pulse length (for 95% of ions with desirable charge state) 10–15 μs,
- The number of ions with desirable charge state—about $5 \cdot 10^{10}$ ions/pulse,
- The emittance of extracted beam—below 500 π mm $\times$ mrad,
- Repetition rate—1 Hz,
- The number of source operation cycles between interventions—10^4.

We plan to use LIS for the ITEP accelerator-accumulator complex in two stages. At the first stage, the existing 4-J/0.5-Hz repetition rate CO_2 laser will be used to put in operation all accelerators and to prove the project principals. At the second stage, a 100-J/1-Hz repetition rate CO_2 laser will be built and used as a driver for LIS.

2. EXPERIMENTAL SETUP

The experimental setup consists of a CO_2 laser, target chamber, expansion tube, high voltage extraction unit, low energy beam transport line, resonance accelerator, bending magnet, and other beam optics (Fig. 1). The CO_2 laser's parameters are shown in Table 1. A pulsed radiation CO_2 laser illuminates the target through the optical focusing system in the vacuum chamber. The estimated spot size and

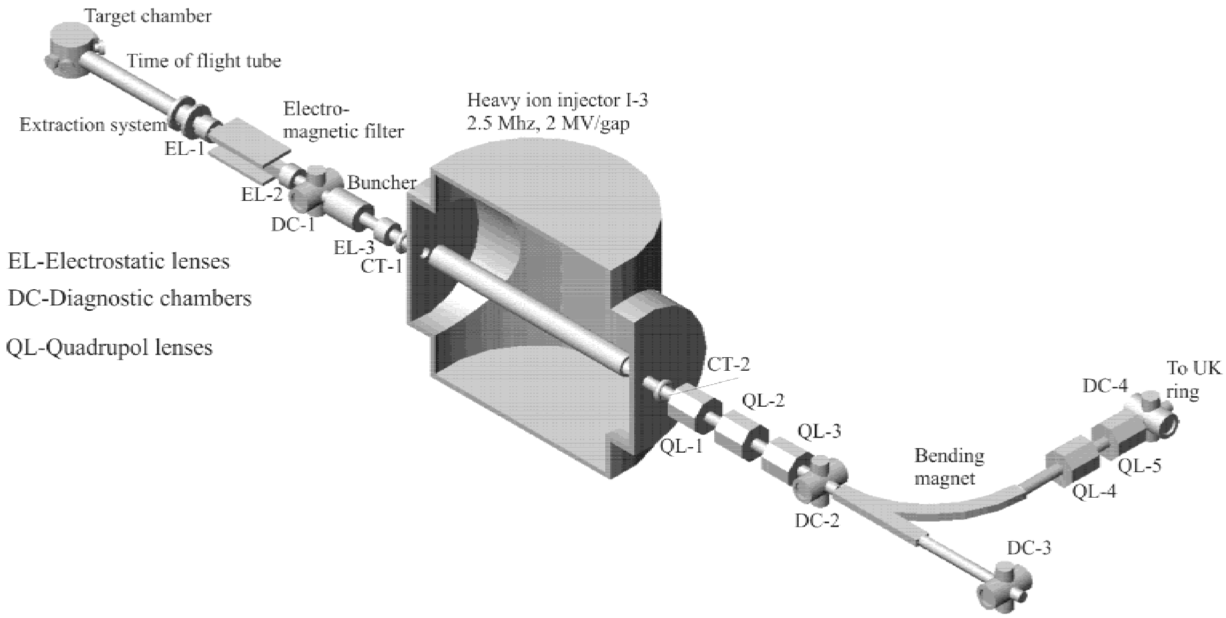

Fig. 1. Experimental setup.

power density are $d = 70\ \mu$m and $q = 1 \times 10^{11}$ W/cm^2. Plasma expands from the target with velocities of 6×10^6–5×10^7 cm/s. The extraction system has two electrodes with diameters of 80 mm. The extraction voltage is 50 kV.

The low energy beam transport line consists of three electrostatic lenses and an electromagnet filter which separates ion beam components with a fixed ratio of charge-state z to momentum p by means of transverse electric E and magnetic B fields. The efficiency of the electromagnetic filter and its interference to emittance as well as total beam current need further investigation. The buncher (2.5 MHz, 10 kV) feeds the ion beam into accelerator I-3. I-3 is the two-gap resonator accelerator with frequency 2.5 MHz and voltage 2 MV/gap. In these conditions, the ions of C^{+4} accelerate up to the energy of 1.33 MeV/n.

At present, the laser ion source fully satisfies the requirements from injector I-3 (number of particles and ion pulse duration). The transmission of I-3 for C^{+4} is restricted by the charge of the beam at the value of 80–100 mA peak current in the bunch and 2–3 mA of average current. Taking into account the efficiency of 10% for I-3 one can obtain the value of 20–30 mA C^{+4} ion current at the entrance of I-3.

During the last year, some improvements on LIS were made, namely,

- high voltage capacitors and spark gaps were charged to increase the lifetime of the high current discharge circuits;
- new cavity mounting was installed;
- the catalyst unit was inserted into the lasing mixture circulator.

Lasing mixture CO_2:N_2:He = 1.5:1:10 now is sealed in the CO_2 laser and circulates through catalyst and cooler where dissociated molecules recover. Now the routine operation cycle of LIS is 1×10^6 pulses and the only restriction is the pollution of the Cu mirror inside the vacuum chamber and the necessity of recovering the catalyst. It needs to be mentioned that all measurements were done after a duty cycle of 1×10^6 shots.

Table 1. *The main parameters of the CO_2 laser*

Wavelength	10.6 μm
Pulse energy	4 J
Pulse duration	100 ns/1.5 μs
Beam divergence	5×10^{-4}
Pulse structure	multimode
Lasing mixture	CO_2:N_2:He = 1.5:1:10
Gas pressure	1 Barr
Operating voltage	42 kV
Repetition rate	0.5 Hz
Operation without intervention	1×10^6

Table 2. *The main parameters of the electrostatic analyzer*

Geometry of plates	Cylindrical
Deflection angle	90°
Mean radius of the deflection plates, R_0	100 mm
Gap between the plates, ΔR	10 mm
Geometric factor of the analyzer $k = R_0/(2\Delta R)$	5
Maximum potential of deflection plates, U	5 kV
Input slit, Δb_{in}	100 μm
Output slit, Δb_{out}	100 μm
Detector (electron multiplier)	SEM
Coefficient of multiplying, up to	10^6
Applied voltage, up to	2.5 kV
Pressure in the analyzer itself	1×10^{-7}

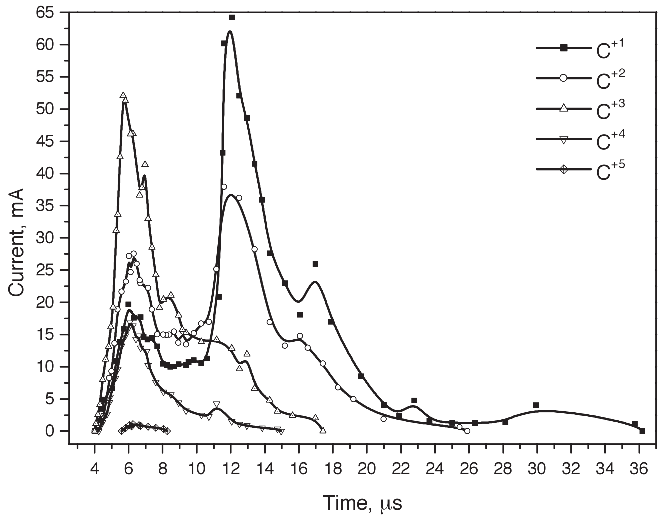

Fig. 2. Time-of-flight spectra.

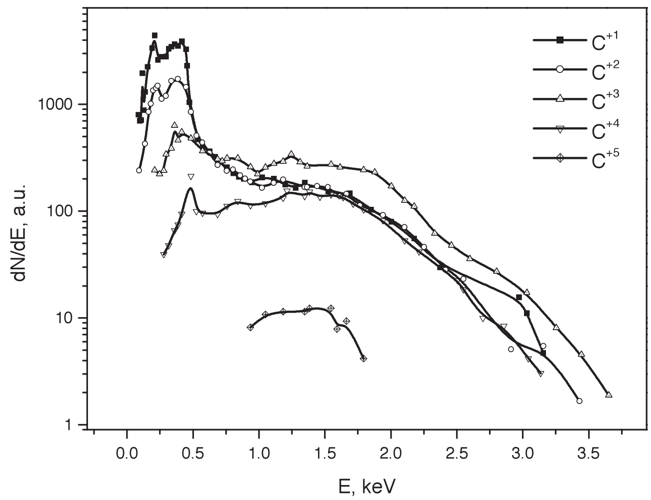

Fig. 4. Carbon ion energy spectra.

3. CHARGE AND ENERGY SPECTRA OF IONS

For energy spectra measurements, an electrostatic analyzer was used. The main parameters of the analyzer are presented in Table 2. The SEM was tested to find the correct operating voltage for real plasma density at the analyzer position (in our case 2.4 kV). To find the ion current for different charge states we need to know secondary emission coefficients $\gamma(E,z,M)$, where E is the energy of ions, z is the charge state, and M is the mass of ions. Then from the formula

$$\frac{dN_i}{dt} = k\cdot\gamma(E,z,M)\cdot\frac{dN_e}{dt},$$

one can find the ion particle current dN_i/dt into SEM, by measuring the electron current dN_e/dt from SEM, where k is the gain of SEM. The values of $\gamma(E,z,M)$ were taken from Cano (1973). Ion spectra are shown in Figures 2, 3, and 4, and Table 3 shows the main parameters of the beam for different charge states.

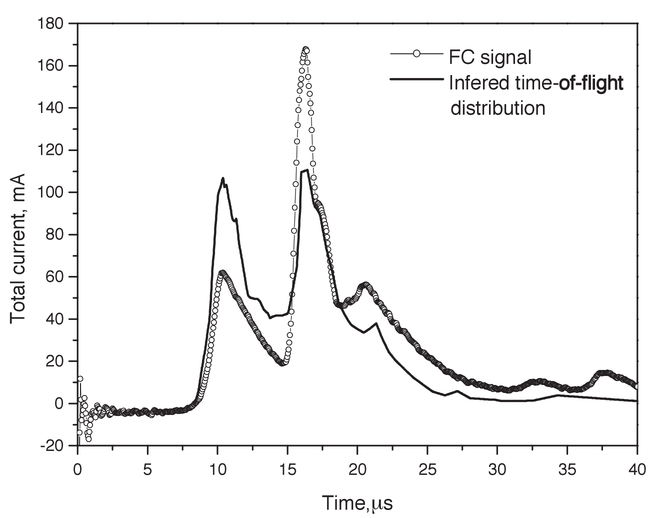

Fig. 3. Carbon ions.

It was shown that for inverse bremsstrahlung adsorption of laser radiation (at laser flux intensities $I_l\lambda^2$ below 10^{15} W/cm$^2\mu$m^2) the plasma electron temperature T_e can be found (Roudskoy, 1996) as

$$T_e = 100\cdot\left(\frac{z\cdot P_e}{d}\right)^{1/3} \approx 60 \text{ eV}$$

for $\lambda = 10.6$ μm, if focal sport d (mm), average charge states z, and the power of the laser pulse P_e (GW) are known.

4. EMITTANCE MEASUREMENTS

In our experiment, the extraction system consist of two flat electrodes with an aperture of 80 mm. The first electrode has a grid with mesh of 1 × 1 mm. The wire in this grid has a diameter of 100 μm. The grid is used to fix the plasma boundary for stable operation of the ion beam in space and time. The second electrode has a grid with a wire mesh of 2 mm. The wire diameter is 100 μm also. This wire makes

Table 3. *The main parameters of the carbon beam*

Z	Number of particles	Peak current (mA)	Pulse duration (μs)	E (keV)	ΔE (keV)
1	2×10^{12}	62	30	0.3	0.3
2	9×10^{11}	37	18	0.3	0.3
3	4×10^{11}	51	12	0.8	1.6
4	8×10^{10}	16	10	1	1.5
5	2×10^{9}	1	2	1.3	0.9

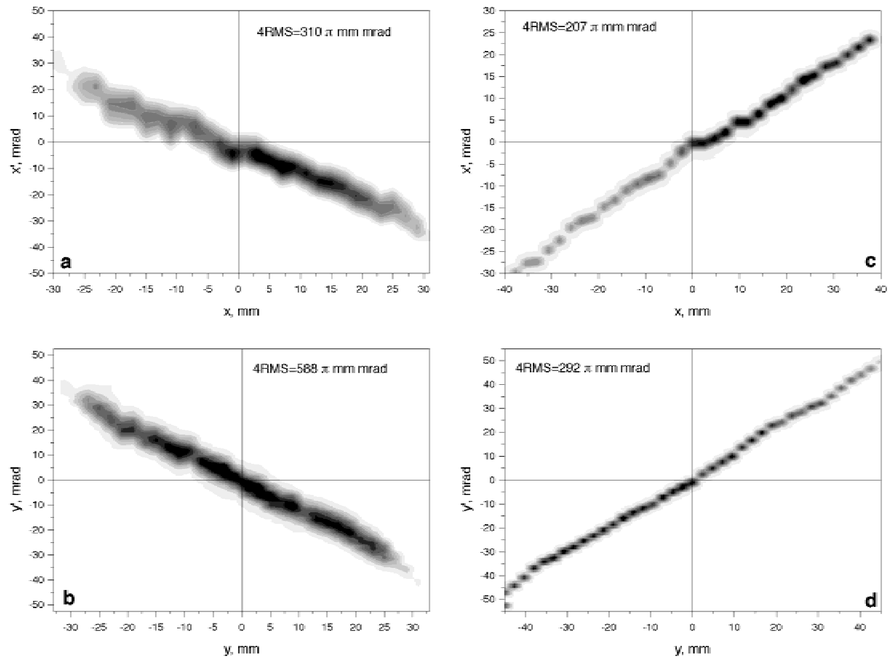

Fig. 5. The emittance diagram.

electric field distribution more homogeneous in the extraction gap. High voltage applied to the gap is 50 kV and gap distance is 40 mm. The emittance of the beam has been measured in two planes. The first plane was perpendicular to the last extraction grid and the second was parallel to it. For emittance measurements we used the 100-μm slit. It could be moved transverse to the beam. To detect an ion beam behind the slit, scintillate CsJ was used. Scintillate was placed at a distance of 81 mm from the slit. A readout system based on CCD camera and computer were used to get the image of the beam. In the measurement of the ratio of the transverse velocity to the longitudinal one after the slit we have to take into account the interference of a space charge. The estimation shows that with a slit size of 100 μm, the influence of the space charge will be below measurement accuracy. Then the RMS emittance we calculate by the formula

$$\varepsilon_{RMS} = \frac{1}{N} \cdot \sqrt{\sum r^2 \cdot \sum r'^2 - \left(\sum r \cdot r'\right)^2}$$

where r and r' are the coordinates and angles, respectively, to the central trajectory of the beam. At the exit of the extraction system, the ion beam diverges and there was no possibility to measure emittance of the whole beam. Then the beam was focused by an einzel lens to get it into measuring unit. The results of the emittance measurements are shown in Figure 5.

5. CONCLUSION

The use of LIS for the ITEP accelerator-accumulator facility since last year shows that the duty cycle is 97% with nonstop operation of 1×10^6 shots. At the moment the general obstacle for long term operation is the pollution of the focusing mirror by target material in the vacuum chamber. To increase the duty cycle to close to 100%, we are planning to change the focusing and target chambers to install new optics with focal lengths of 1600 mm. This new vacuum chamber will let the modified CO_2 laser beam of 100 J/15 ns with a 160-mm diameter go onto the target. With all of these improvements and with the new catalyst unit, the whole LIS will work without intervention up to 10^7 shots.

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