

# SIMULATION OF CARBON ION EXTRACTION AND LOW ENERGY BEAM TRANSPORT SYSTEM FOR RFQ AT THE LINAC I-100

B.A. Frolov

State Research Centre of Russia Institute for High Energy Physics,  
142281, Protvino, Moscow Region, Russia

## *Annotation*

For the carbon ion injection into the radio frequency quadrupole, the laser ion source and the low energy beam transport (LEBT) system has to deliver 20 mA of  $C_{12}^{5+}$  ion beam with 80 keV at the input of RFQ within normalized emittance of  $0.39\pi$  mm-mrad. An extraction system and a low energy transport line should be optimized to reduce the beam emittance as much as possible. The results of computer simulation are presented for extraction and LEBT system: the combination of the tetrode extraction system and the electrostatic focusing lens from three electrodes with middle grid electrode negative voltage.

## INTRODUCTION

In the last two decades the methods of ion radiation therapy have been investigated very dynamically. The proton and especially carbon ion beams are a superior tool in treating cancer. Proton-ion radiation therapies hospital medical centers are being actively built in Japan, Germany and Italy. In the nearest future the construction of such centers is planned in the USA, France, Austria and China. For today more than 5500 patients have already been treated with carbon-ion beam at Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan. Patients' treatment was first implemented at Heidelberg Ion Beam Therapy Center (HIT), Germany 2008. The project of the proton-ion beam therapy center in SRC IHEP was developed in 1998-2000 [1]. In the course of experiments held in 2000-2001 stable acceleration of carbon ion was achieved in linac I-100 [2]. In the last few years a large volume of work has been done regarding the modernization of the linear accelerator I-100 and the circular accelerator (booster) U-1.5, the transportation channel of ion beam from I-100 in the booster was built and successfully tested. Experimental researches on acceleration and accumulation of protons and deuterium ions in the circular accelerator U-70 in 2008-2009 revealed the feasibility of using IHEP acceleration complex in medical purposes: for proton-ion radiation therapies [3].

Before 1985 the linear accelerator I-100 was used as a standard proton injector directly into the big synchrotron U-70. Currently I-100 is used as injector of light ions with the energy of 16.7 MeV/u and/or as a reserve injector of protons with the energy of 72.7 MeV/u into the synchrotron-booster U-1.5 [3]. To switch to the carbon ions acceleration mode the gas-discharge source of

duaplasmatron type should be replaced with the laser ion source. It seems reasonable to keep the possibility of a fast switch from the proton or deuteron acceleration mode to the carbon ions acceleration and visa versa. The scheme of carbon ion injection into the linac I-100 with the help of radio frequency quadrupole (RFQ) accelerator which is fixed at an angle to the protons injections route was developed in IHEP. The carbon ions acceleration in I-100 happens at the second multiplicity. The switch to the second multiplicity determines the number of restriction at the ratio  $Z/A$  for the accelerated ions (where  $Z$  is ion charge,  $A$  – is its mass). The work [4] shows that the ions with the ratio  $Z/A=0.4-0.5$  can be accelerated in I-100 because of the complex of few restrictions. The percentage of carbon with  $Z=6$  generated by the laser ion source is small [2]. That's why the RFQ parameters calculation was done for the ions beam  $C_{12}^{5+}$  at the current of 20 mA and at the injection energy of 80 keV/u. To transport the ions from the source and to modify the beam parameters in accordance with the required at the input to the RFQ the ion-optic system (IOS) of beam matching is to be design.

## OPTICAL SYSTEM SIMULATION

The matching of intensive beam of highly charged ions with the input of the linear accelerator is a complicated and not yet completely solved problem. To the large extent it is due to the strong effect of the space charge forces for the low energy region. IOS calculation is complicated by a full range of other important factors. The laser ion source is used to get the highly charged carbon ion beams. Such source was created in IHEP in 2000 [2]. The duration of multicharged ions formation is a few dozens of nanoseconds. The beam with the needed for future usage duration of a few microseconds is formed due to thermal spread of ions speed in plasma at the drift gap of  $L=1340$  mm length from the laser focusing point till the extraction plane. The experimental investigations [2] showed that the output beam had a complicated time and charge structure. In the beam there are the ions from the first till the fifth charge inclusively. In the initial part of the current pulse ( $\sim 5\div 10$   $\mu$ s) mainly there are ions with the charge  $Z=5$  and  $Z=4$ . During the pulse the profile together with the intensity of the beam with the given charge change. Also the ratio between the currents for ions with different  $Z$  changes. As a result of the given above features of the carbon ion beam generated by the

laser ion source (complicated charge structure, plasma flow instability during the pulse, wide spread of ions energies, significant influence of the space charge effect) it is difficult to design the matching channel. It is worthy of note that the method of direct beam injection from the source into the RFQ was suggested and successfully realized in [5,6]. The stage of the target cell was at high voltage and was connected to RFQ linac directly.

IOS should provide the minimal deviation of the effective output ellipse parameters at IOS output from those of the ellipse matched with accelerator input. The calculation value of the normalized emittance of carbon beam at the RFQ input is  $0.39 \pi$  mm·mrad. The beam emittance from laser ion source depends on the transverse impulse of plasma ions at drift gap output and the aberrations of beam extraction system. Due to the aberration in the matching channel the emittance increases and the beam loss at the accelerator input can be quite significant. That's why the extraction system and a low energy transport line should be optimized to reduce the beam emittance as much as possible. In course of experimental research of the laser source created in IHEP there was used the scheme of carbon ions beam extracting which consisted of a double-grid plasma diode with the voltage between the grids  $10 \div 30$  kV [2]. If the beam is postaccelerated up to 80 kV using additional third electrode, the matching channel is to consist of at least two lenses. The matching beam IOS should have at least two degrees of freedom to provide the setting of two output beam parameters (radius and the angle of slope).

IOS in which the systems of beam extracting from ion emitter, acceleration till the given energy and matching are a complete union is suggested below. It is shown on the figure 1 and it consists of six electrodes. It is known that the acceptable ion optics parameters of the beam from the source are achieved upon the condition of emission uniformity over the whole area and its stability in time. The grid should be allocated to fix the plasma border in the plasma electrode surface because of plasma flow nonstationarity for the laser ion source. To extract ions from plasma and for their acceleration to the injection energy the system consisting of four electrodes is used. The length of the first gap (extraction gap) and its voltage should correspond to the given plasma density and provide the initial beam formation. In calculation the formula for optimal gap [7] can be used. In the four electrode system in distinction from the three electrode system the extraction and acceleration voltages do not depend from each other and there already is one freedom degree for the beam parameters formation (third electrode potential). Such optic system allows combining transverse beam matching with postacceleration and transportation with less aberrations. In this case for the beam matching with the RFQ it's enough using one focusing lens.

IOS calculation was done with the help of 2-D code of modeling the optics for positive ions extraction for the system with plasma emitter [8]. Current density at the extraction surface was considered constant and equal to

$22 \text{ mA/cm}^2$ . It was suggested that plasma contained only the carbon ions with the charges  $Z=5$  and  $Z=4$ , besides the concentration of five-charged ions was 33%, of the four-charged ions - 67%, and this balance remains unchangeable during the pulse. In real situation both ion current density incoming to the emission surface and beam charge structure change quite significantly during the pulse. As it was revealed in experiments in the head part of the beam during the first  $10 \mu\text{s}$  of the current pulse there were only high-charged ions with  $Z=5$  and  $Z=4$ . It's also worth mentioning that the approximate twice decrease of five-charged ions amount during the first  $5 \mu\text{s}$  is accompanied by the increase of the four-charged ions amount (see figures [2]). As the time dependence of the current pulse charge composition is complicated, when holding on calculations the current density and percentage of five- and four-charged ions are considered constant.

Poisson equation was solved in cylindrical coordinates. When simulating the method of large particles was used (taking 1000 particles of five-charged and four-charged ions each). The initial axial ion energy ( $\sim 300$  eV) was distributed at a random way (the estimation of the axial velocity was done basing on the drift gap passing time [2]). The initial transverse velocities of ions were also distributed in accordance with the random normal numbers (transverse ions energy in the end of drift gap received from qualitative evaluation is  $\sim 10$  eV).

The numerical calculations showed that the emittance value is minimal when the middle electrode of the matching lens is a grid with negative potential (Fig 1). If for the beam matching einzel lens is used, then bigger aberrations are typical of such IOS as well as the normalized emittance (at the level of 95 % particles) a few times increase the needed at the RFQ input. IOS which consisted of six electrodes was analyzed numerically. As a result of calculations IOS geometry (electrodes radiuses, distances between them) was optimized and were selected the electrodes potentials with which should be guaranteed the maximum particles entry into the calculated ellipse at the RFQ input corresponding to the optimal capture with the injection energy 80 keV. Plasma electrode aperture radius equals to 10 mm, RFQ flange radius is 18 mm, other IOS electrodes radiuses are 15 mm. Gap lengths between the first and the second, the second and the third, the third and the fourth electrodes are 8.5 mm, 20 mm and 12 mm accordingly. The distance between the grid and the electrodes is 11mm. The widths of the second and third electrodes are 4 mm, and the widths of the fourth and sixth are 20 mm. RFQ flange width is 48 mm, and the distance from the flange to RFQ electrodes is 8 mm. Carbon ions calculated trajectories and the electrodes potentials are shown on the figure 1. The figure 2 demonstrates the emittance pattern at IOS output. The normalized 4-rms emittance for 95 % beam particles is  $0.316 \pi$  mm·mrad. The emittance pattern shows that the beam is similar to the laminar one.

The described IOS is space effective and well manageable. It allows matching the beam with RFQ input by regulating third electrode and grid potentials in the same IOS geometry if the beam intensity changes. The extraction voltage should also be changed with the change of the current density.

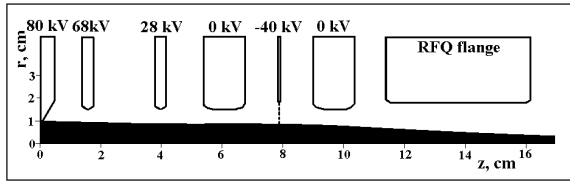


Fig.1. Geometry of the IOS and trajectory of carbon ions.

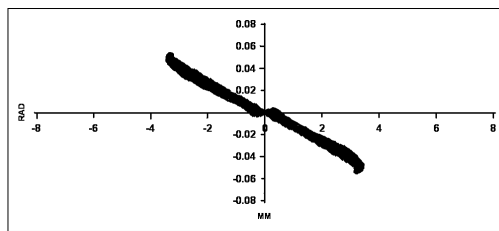


Fig.2. Emittance pattern.

## REFERENCES

- [1] Yu.M. Antipov, A.V. Vasilevskiy, A.P. Vorobiov et al., Proc. of XVI Charged Particle Accelerator Conference, Protvino, 1998, v. 2, p. 212-219; Yu.M. Antipov, A.V. Vasilevskiy, A.P. Vorobiov et al., Proc. of XVII Charged Particle Accelerator Conference, Protvino, 2000, v. 2, p. 302-307.
- [2] Yu.M. Antipov, B.A. Frolov, Yu.P. Gorin et al., Proc. of XVII Charged Particle Accelerator Conference, Protvino, 2000, v. 2, p. 385-389; Yu.M. Antipov, N.E. Anferov, V.A. Batarin et al., Preprint IHEP, 2001-52, Protvino, 2001, p.10.
- [3] Yu.M. Antipov, N.E. Anferov, V.A. Batarin et al., Preprint IHEP, 2003-14, Protvino, 2003, p.14.
- [4] Yu.M. Antipov, S.V. Ivanov, *Novosti I problemy fundamental'noj fiziki*, Protvino, 2008, N3, p. 1-11.
- [5] M. Okamura, H. Kashiwagi, K. Sakakibara et al., *Rev. Sci. Instrum.* **77**, № 3, Part II, 03B303 (2006).
- [6] H. Kashiwagi, M. Fukuda, M. Okamura et al., *Rev. Sci. Instrum.* **77**, № 3, Part II, 03B305 (2006).
- [7] G.D. Alton and H. Bilheus, *Rev. Sci. Instrum.* **75**, № 5, p.1431-1435 (2004).
- [8] B.A. Frolov, Proc. of XIX Charged Particle Accelerator Conference, Dubna, 2004; Preprint IHEP, 2004-43, Protvino, 2004, p.8.