ACCELERATION OF INTENSE BEAMS OF HIGHLY-CHARGED IONS USING DIRECT PLASMA INJECTION SCHEME*

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Abstract

Laser Ion Source (LIS) is the most intense source of highly-charged ions of different elements capable of being providing beams with current 10-100 mA and pulse durations 1-10 μs [1]. Such parameters well meet the requirements of single turn injection into synchrotron and FFAG rings. A few years ago the Direct Plasma Injection Scheme (DPIS) was proposed to extract and accelerate intense beams of highly-charged ions from laser produced plasma [2]. By this approach extraction of ions from plasma happens almost inside the first cell of an RFQ, eliminating severe space charge problems in a low-energy-beam-transport (LEBT) and the LEBT itself.

About 35 mA/1.5 μs ($6\cdot10^{10}$ ions/pulse) of $^{12}C^{4+}$ ions were accelerated by RFQ up to 100 keV/u using DPIS with amplitude of total current up to 60 mA [3]. 17 mA/0.4 μs ($6\cdot10^{9}$ ions/pulse) of $^{12}C^{6+}$ ions has been accelerated up to 100 keV/u as well [4]. The results obtained well meet the requirements of small scale synchrotron or FFAG accelerators for carbon cancer therapy.

The latest results on ^{27}Al ions acceleration using DPIS are presented. The results obtained show that DPIS is, probably, the best choice as high current injector of highly-charged ions for FFAG accelerator.

DIRECT PLASMA INJECTION SCHEME

Laser-produced plasma is a very intense source of highly-charged ions of almost all elements of the periodic table. As far as the time of plasma generation is much shorter than time-of-flight of ions up to the extraction system and the initial size of the plasma is much less than distance L to extraction system, ion pulse duration τ and current I are defined by following relations [5]:

$$\tau \propto L\,,\; I \propto L^{-3}. \qquad (1), (2)$$

Possible recombination losses of highly-charged ions during plasma expansion into vacuum are neglected here.

Ion current and pulse duration strongly depend on the parameters of the laser and elements used. As an example, $^{12}C^{4+}$ ion current into 1 cm^2 aperture and corresponding ion pulse duration measured at 3.7 m from the target and scaled according to relations (1) and (2) to other distances are presented in Fig. 1 for the case of a 3J/30ns Nd-glass laser and 10^{11} W/cm^2 power density on the target surface. One can see that ion current can reach 1 A at the short distances from the target; this is much higher than the current limit of the subsequent RFQ.

In a conventional LIS with LEBT, the distance from the target to the extraction system is defined by the required ion pulse duration τ according to relation (1). Very often the required τ is more than few μs and that brings the total extracted ion to the value of about 100 mA which is of the order of current limit of the subsequent RFQ. In this case, a LEBT can not be avoided if it is desired to inject as many ions as possible into the RFQ acceptance. However, it is not possible to fully avoid losses as space charge is very high and time variations of current are very big. The best value of extracted ion beam transmission into RFQ acceptance is, typically, less than 50% [6].

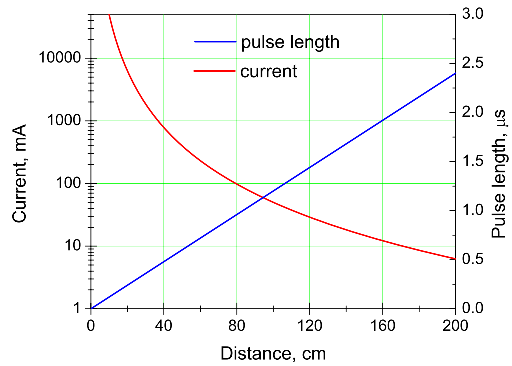

Figure 1: Dependences of $^{12}C^{4+}$ ion current into 1 cm^2 and corresponding ion pulse duration on the distance from the target.

If the required ion pulse duration required does not exceed 1-2 μs (small synchrotron or FFAG rings), there is a different possibility for injecting highly-charged ions from LIS to the subsequent RFQ. The extracted ion current is so high (typically, much more than 100 mA) that even without matching of beam emittance to RFQ acceptance (without LEBT), the RFQ can be filled by ions up to space charge limit and, thus, RFQ output current will reach its maximal possible value. DPIS realizes such an approach.

^{27}AL IONS ACCELERATION USING DPIS

Experimental Set-up

The lay-out of the DPIS ion source part used for acceleration of ^{27}Al ions is presented in Fig.2. A moveable planar target under high potential up to +90 kV was placed inside the grounded vacuum chamber with

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residual gas pressure 10^{-6} Torr. A 3D manipulator allowed moving the target with minimal step of about 10 μm in three perpendicular directions. The target was electrically connected to the surrounding metal box which prevents plasma flow outside it to grounded walls of vacuum chamber. Breakdown will happen without this protection box. A focussing mirror with focal length of 100 mm was used to focus 2.3J/6ns Nd-YAG laser beam onto a target surface at an incident angle of 10 degrees. Maximum laser power density at the target surface reached 10^{13} W/cm^2.

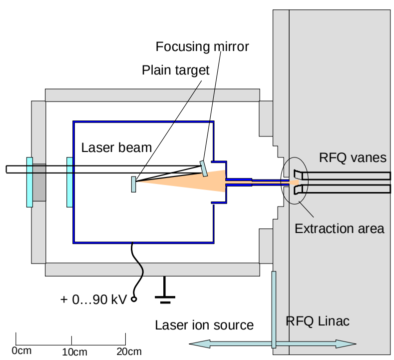

Figure 2: Lay-out of DPIS experiment.

Laser-produced plasma can flow out of the protection box only through the pipe (diameter 6 mm, length 100 mm) perpendicular to the target surface and on the axis of the RFQ electrodes. The distance between the target and the pipe output was 300 mm. The gap between pipe output and RFQ electrodes input has been adjusted to avoid breakdowns between them. As the pipe output is placed very close to the RFQ input plane, extraction of ions happens almost inside the first cell of the RFQ.

The main parameters of the RFQ used in these experiments are listed in Table 1.

Table 1: Main Parameters of RFQ

Length of Vane Modulated Area	1.42 m
Frequency	100 MHz
Radius of Aperture	6.55 mm
Nominal RF Voltage	120 kV
Nominal RF Power	200 kW
Ion Charge State-to-Mass Ratio (Z/A)	≥ 1/3
Input Energy	20 keV/u
Output Energy	100 keV/u
Output Current for 100 mA $^{12}C^{4+}$ Ion Injection (Result of Simulations)	76 mA

A current transformer placed just behind of the RFQ output was used to measure the total accelerated current. Before measurements, the current transformer was calibrated by comparison with the current measured by a Faraday Cup (FC). As a large aperture magnetic spectrometer was not available, an Electrostatic Ion Analyzer (EIA) has been used for charge states analysis of accelerated ion beam. EIA is a 90 degree cylindrical capacitor sector which allows only ions with a given energy-to-charge state ratio to pass through [7]. As the energy of all ions accelerated by RFQ is approximately the same, it was possible to resolve the different charge states using the EIA. Ion currents downstream of the EIA were measured by a FC with a ring under negative potential to suppress secondary electrons emitted from the FC.

Results on ^{27}Al ions acceleration

At first, RFQ output current has been optimized with respect to target-focussing mirror distance and the best distance has been kept for all further measurements.

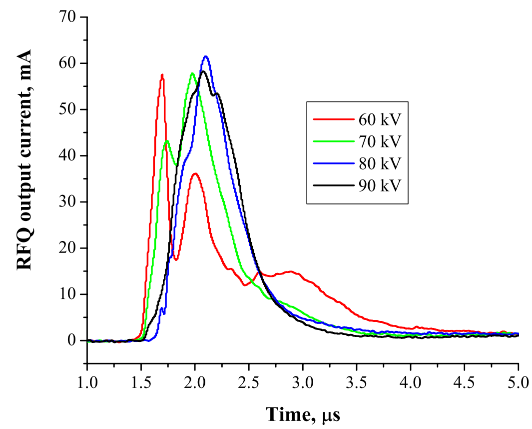

Figure 3: Time dependences of RFQ output currents for different extraction potentials.

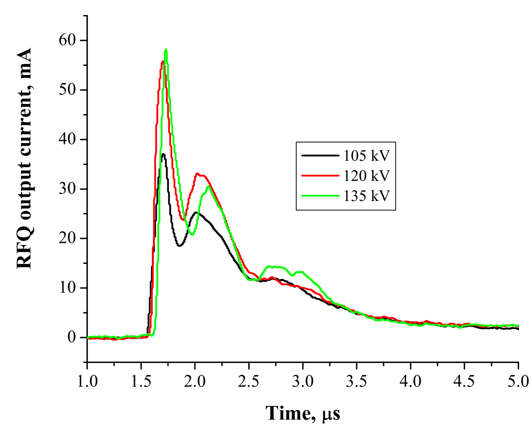

Figure 4: Time dependences of RFQ output currents for different RF voltage amplitudes.

Time dependences of RFQ output currents are presented in Fig. 3 for different extraction potentials and 120 kV RF voltage amplitude and in Fig. 4 for different RF voltage amplitudes and 60 kV extraction potential.

100 MHz RF noise has been filtered numerically for all curves.

One can see that the pulse become smoother and current amplitude rises with increasing extraction potential. Maximum current and pulse duration are 60 mA and 0.65 μs for extraction potentials in the range of 70-90 kV. Increasing the RF voltage amplitude increases the current, but doesn't change the time structure of the current pulse.

The charge state distribution obtained using the EIA is presented in Fig. 5 for 60 kV extraction potential and 120 kV RF voltage amplitude. One can see that accelerated ion beam mainly contains ions with nominal charge state 9+.

Shot-to-shot fluctuations of output RFQ current amplitude and pulse duration over 150 shots are presented in Fig. 6. One should note that RF frequency has been tuned manually. In case of automatic tuning the statistics should become better.

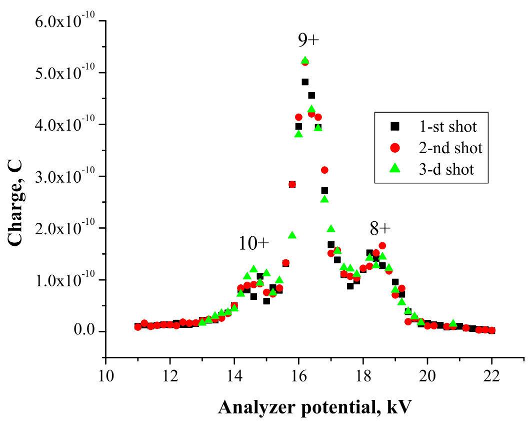

Figure 5: Charge state distribution (extraction potential – 60 kV, RF voltage amplitude – 120 kV, 3 shots for each analyzer potential).

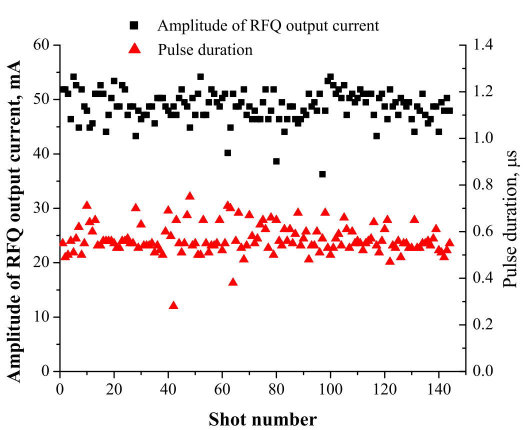

Figure 6: Shot-to-shot fluctuations of output RFQ current amplitude and pulse duration (extraction potential – 60 kV, RF voltage amplitude – 120 kV).

DISCUSSION AND CONCLUSIONS

After tests with protons FFAG accelerators will certainly demand heavier ion species. The main ion source requirements of FFAG accelerators are:

- Current of desirable charge state – about 10 mA
- Ion pulse duration – less than 1 μs
- Rep-rate – 10-100 Hz.

At present, only LIS can provide such intense beams of highly-charged ions of almost all elements of the periodic table. As the required ion pulse duration is short, DPIS is, probably the best choice to meet FFAG accelerator requirements. Up to now, the LIS has not ever been tested for rep-rates higher than 1 Hz, but 10-100 Hz operation looks visible with the use of modern powerful vacuum pumps.

The main results of this work are:

- ^{27}Al ion beam with total current up to 60 mA and pulse duration up to 0.65 μs has been accelerated by a (charge-to-mass ratio 1/3) RFQ using DPIS up to 100 keV/u
- The accelerated beam consists of 3 charge states; the most abundant is $^{27}Al^{9+}$ with a current fraction of about 65%.
- Good stability of the RFQ output ion beam parameters has been found: ±6% - for total current amplitude, ±11% - for ion pulse duration; improvement is possible with tight RF frequency control and other measures.
- DPIS is, probably, the best choice as high current injector of highly-charged ions for FFAG accelerators.

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REFERENCES

[1] S. Kondrashev et al, "New Developments of a Laser Ion Source for Ion Synchrotrons", EPAC'04, Lucerne, July 2004, p. 1402.

[2] M. Okamura et al, Laser and Particle Beams, 20, 2002, pp. 451.

[3] H. Kashiwagi et al, Rev. Sci. Instrum., 75, 2004, p. 1569.

[4] H. Kashiwagi et al. Rev. Sci. Instrum., 77, 03B305 (2006).

[5] B. Sharkov and S. Kondrashev, Matching of the Intense Laser Ion Source to the RFQ Accelerators", EPAC'96, Sitges, June 1996, p. 1550.

[6] P. Fournier et al, Rev. Sci. Instrum., 71, 2000, p. 924.

[7] N. D. Mescheryakov et al, Laser and Particle Beams, 20, 2002, p. 455.