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IMPLEMENTATION OF A SUPERCONDUCTING ELECTRON BEAM ION SOURCE INTO THE HIT ION SOURCE TESTBENCH

E. Ritter*, A. Silze, DREEBIT GmbH, Großröhrsdorf, Germany
G. Zschornack, TU Dresden and Helmholtz-Zentrum Dresden-Rossendorf e.V., Dresden, Germany
R. Cee, T. Haberer, A. Peters, T. Winkelmann, HIT, Heidelberg, Germany

Abstract

Cancer therapy with light heavy ions is now a well proven technology. Almost all facilities are running Electron Cyclotron Resonance Ion Sources (ECRIS) to produce carbon ions and protons as well. In the 1990's the idea of using a Electron Beam Ion Source (EBIS) was proposed [1]. Some proof of principle measurements were carried out [2] but the application of EBIS ion sources in radiation facilities has not been established. We present results from the implementation of a superconducting EBIS, the Dresden EBIS-SC, at an RFQ accelerator at the testbench of the Heidelberg Ion Therapy Center (HIT).

First results from C^{4+} ions produced by the Dresden EBIS-SC [3] and injection in an RFQ accelerator at the HIT testbench are shown. Furthermore, emittance measurements as well as investigations of the ion energy and the transmission through the RFQ were done. The emittance of the EBIS source is lower by a factor of nine compared to an ECRIS, which improves the transmission through the RFQ.

With the current setup the ion output from the EBIS-SC is lower by a factor of 7 compared to an ECRIS to fulfill the requirements of the highest irradiation level (see Table 1). Further improvements are discussed.

SETUP

The testbench at HIT normally consists of an ECRIS, a dipole analyzing magnet for the charge state separation, ion optical elements like a quadrupole triplet, quadrupole dublets, steerers as well as a Radio Frequency Quadrupole accelerator (RFQ). The injection energy of the RFQ is 8 keV/u. The Low Energy Beam Transport line (LEBT) also features a set of beam diagnostics like Faraday cups, grid profile monitors, and phase probes for the kinetic energy determination of the ions. For the presented experiments the ECRIS was substituted by a Dresden EBIS-SC. The full setup of the testbench with the EBIS ion source is shown in Figure 1.

The EBIS-SC was set on a high voltage platform providing up to 20 kV positive potential additional to the potential of the drift tubes which defines the energy of the extracted ions. The extraction energy of the ions without the platform potential was 6.9 keV. To reach the injection energy for the RFQ the platform was set on 17.1 kV resulting in an overall energy of 24 keV/q, where q is the charge state of the ions, or 8 keV/u for C^{4+} ions.

Optimizing Source Parameters

To commission the ion source for highest output of C^{4+} some preparational investigations were carried out by measuring the charge state distribution via A/q spectra for different ionisation times and gas pressures. The highest yield of C^{4+} ions was found using a pressure of 1.5×10^{-7} mbar and an ionisation time of 15 ms. As an example, a C^{4+} ion dominated spectrum measured at $p = 8 \times 10^{-8}$ mbar is shown in Figure 2. The fraction of C^{4+} ions in this spectrum is about 26 %.

Measured Pressure vs. Real Pressure

From earlier experiments and from simulations of the charge state distribution within an Electron Beam Ion Source it is known that the optimal gas pressure for C^{4+} production in the drift tube section is in the range of 8×10^{-10} mbar to 3×10^{-9} mbar [3]. The measured pressure within the ion source at HIT was in the range of 1×10^{-7} mbar. Due to the fact that the ratio of the C^{4+}/C^{5+} decreases and the ratio of C^{4+}/C^{3+} increases with further gas injection, the pressure in the drift tube region must be on the order of 1×10^{-9} mbar. The measured pressure is a result of the position of the vacuum gauge far away from the drift tube section and possibly by a shunt in the gas inlet capillary, which provides a higher gas pressure at the vacuum gauge than in the drift tube region.

RESULTS

In the following we provide results from the investigation of C^{4+} ions extracted from the EBIS-SC and injected in the RFQ accelerator at the HIT testbench.

Emittance Measurements

To proof the lower emittance of an EBIS compared to an ECRIS a pepper pot emittance meter [4] was mounted behind the dipole magnet directly in front of the second Faraday cup. A typical pepper pot image is shown in Figure 3. The obtained rms-emittance of the beam was

$$\begin{aligned} \epsilon_{x,\mathrm{rms}} &= 33.5 \pm 6.6\,\mathrm{mm\,mrad}, \\ \epsilon_{y,\mathrm{rms}} &= 31.7 \pm 6.0\,\mathrm{mm\,mrad}. \end{aligned}$$

The emittance values are smaller by a factor of nine compared to the emittance values from an ECRIS mounted on the testbench before [5]. Despite the smaller ion current, the brightness of the EBIS (4×10^{-9} $A^2\,mm^2\,mrad^2$) is higher by a factor of six than the brightness of the ECRIS (6×10^{-10} $A^2\,mm^2\,mrad^2$) [5].

* erik.ritter@dreebit.com

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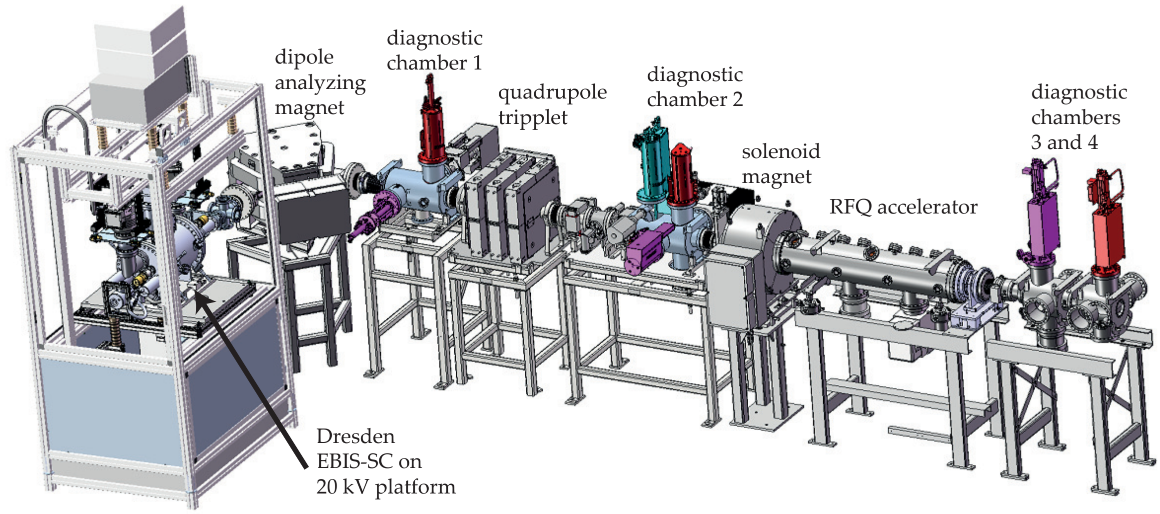

Figure 1: 3D CAD model of the testbench with the Dresden EBIS-SC (from left: EBIS-SC with 20 kV-platform, dipole analyzing magnet, diagnostic chamber one with profile grid 1, analyzing slits, and Faraday cup 1, quadrupole tripplet, diagnostic chamber two with pepper pot, profile grid 2, and Faraday cup 2, solenoid magnet, RFQ accelerator, diagnostic chambers three, and four with a set of 3 phase probes, profile grid 3, and Faraday cup 3). The Faraday cups are colored in red, the grid profile monitors are colored in purple, and the pepper pot is colored in blue.

Transmission through RFQ

The transmission of ions passing the RFQ accelerator was determined by the ratio of ion pulse currents in Faraday cup 3 behind the RFQ and Faraday cup 2 in front of the RFQ. The highest reached transmission was about 61 %, as shown in Figure 4.

Energy Determination

The kinetic energy of the accelerated ions was measured using a set of three phase probes [6]. The ions left the RFQ with a kinetic energy of 400 keV/u while the RFQ was running with a high frequency power of 198 kW. The peak current in the third Faraday cup was measured to 12 µA (i.e. Q = 130 pC).

Intensity Measurement

Due to the losses in the accelerator structure a much higher primary current of ions has to be produced than needed at the patient. Table 1 shows the number of ions at each irradiation level from level I3 to the highest level I10. The table also shows the minimum current of ions behind the RFQ accelerator to reach the required amount of ions for the irradiation.

At the HIT testbench the maximum charge of C^{4+} ions produced by the EBIS ion source and measured behind the RFQ was Q = 130 pC which equals a mean ion beam current of 6.5 µA (at a pulse length of 20 µs) while higher ion extraction pulses of up to 560 pC had already been measured at the Dresden EBIS-SC [7]. These 6.5 µA are a factor of about 7 lower than needed for I10 and would satisfy the irradiation level I5 (see Table 1). This factor shows, that presently the Dresden EBIS-SC cannot completely fulfill the requirements of the ion output for the HIT medical accelerator.

Table 1: The table shows the ions per second needed for the irradiation levels I3 up to I10. The mean ion current at the RFQ exit needed to fulfill the required ion yield at the patient is also given

irradiation level	ions/s	$I_{\text{RFQ-exit}}$ [µA]
I3	5.0×10^6	2,9
I4	8.0×10^6	4,7
I5	1.0×10^7	5,9
I6	1.5×10^7	8,8
I7	2.0×10^7	11,7
I8	3.0×10^7	17,6
I9	5.0×10^7	29,4
I10	8.0×10^7	47,0

OUTLOOK

The results demonstrate that because of the low rms emittance of the produced ion beams an EBIS can provide C^{4+} ion pulses to be effectively injected into a RFQ accelerator in a medical synchrotron based particle therapy facility. By using a 20 kV platform, the required injection energy for the RFQ is easily achieved. The lower measured extraction current of the EBIS compared to an ECRIS limits the application of this ion source at the current state to the irradiation level I5. The measurements show that an EBIS is a possible candidate as an ion source for cancer therapy facilities but the ion output has to be increased. Possible solutions to expand the ion beam currents from the Dresden EBIS-SC are to rise the electron beam current as well as to lengthen the ion trap. For the current investigation at the HIT testbench we will install a larger cathode to increase the electron beam current.

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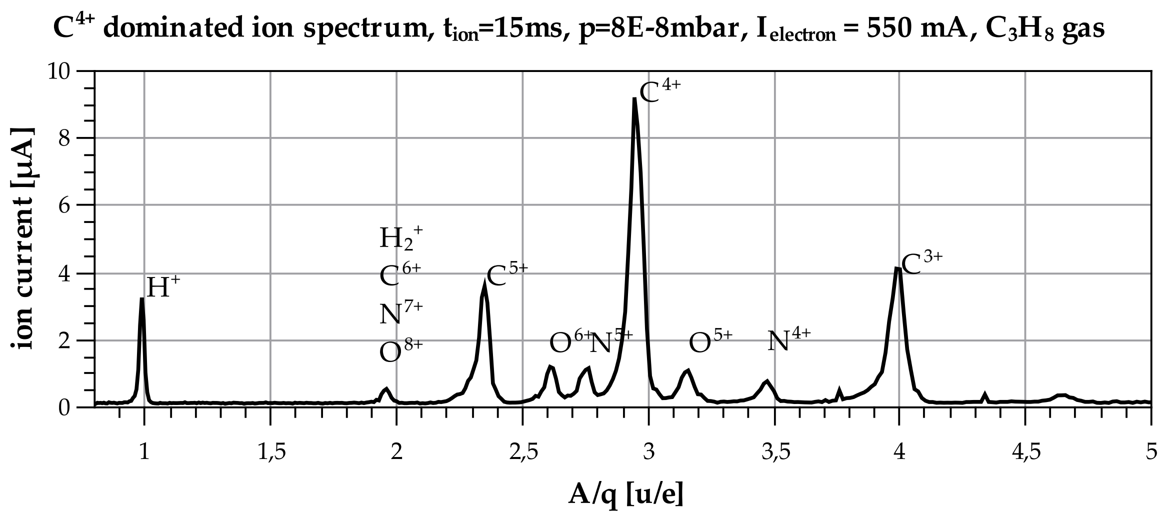

Figure 2: Ion spectrum with dominant C^{4+} ion peak measured at Faraday cup 1 at a pressure of 8×10^{-8} mbar, an ionisation time t_{ion} of 15 ms, an electron beam current of 550 mA and an analyzing slit width of 10 mm. The fraction of C^{4+} ions results in 26 %.

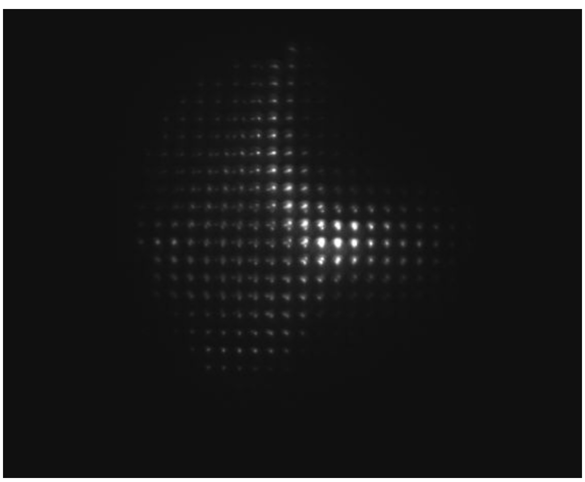

Figure 3: Pepper pot image captured from C^{4+} ions at the pulse ion current of 12 µA on the RFQ exit. The optical focus was set to the solenoid (Fig. 1), not to the pepper pot.

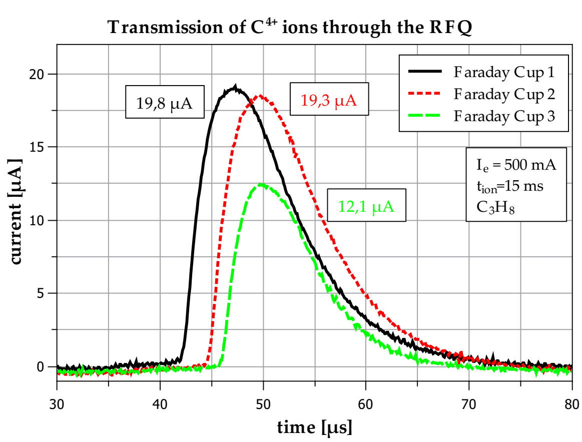

Figure 4: Transmission of a C^{4+} ion pulse from Faraday cup 1 (black solid line) to Faraday cup 2 (red dotted line) passing the RFQ to Faraday cup 3 (green dashed line).

ACKNOWLEDGMENT

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