STATUS OF ELECTRON BEAM ION SOURCES FOR PARTICLE THERAPY*

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Abstract

The technical performance of ion sources of the Electron Beam Ion Source (EBIS) type has substantially improved during the last years. This is demonstrated by proof-of-principle experiments which have been done using a room-temperature EBIS, a so-called Dresden EBIS-A, which has been in use for several years. A new superconducting EBIS, a so-called Dresden EBIS-SC, has been taken into operation. With the expected higher beam intensities the Dresden EBIS-SC will offer a compact and low-cost solution for applications in particle therapy and will be applicable for synchrotron based solutions (single- or multi-turn injection) as well as other accelerator schemes. It is shown that the introduction of the Dresden EBIS-SC will simplify the injection beam line of medical accelerator facilities.

INTRODUCTION

High-energy ionising radiation has proven to be effective in the treatment of cancerous tumours. In particular protons and light ions (e.g. carbon ions) have the advantage of penetrating the body easily and then depositing their energy at a depth determined by their initial energy, referred to as ”Bragg peak”. Additionally light ions are characterized by an increased relative biological effectiveness. Due to these advantages compared to conventional radiotherapy, hadron therapy facilities are built in an increasing number.

The use of different hadron beams needs the availability of powerful ion sources which are time-stable and provide high-quality beams of different light ions. At the moment ECR ion sources provide the particle beams for hadron therapy. Searching for alternatives, the combination of an electron beam ion source (EBIS) with an RFQ-LINAC facility has been suggested already in the middle of the 1990s [1, 2]. Moreover, recent publications discuss that the use of an EBIS can both simplify the accelerator construction, resulting in a more economical solution for medical accelerators, and provide high-quality hadron beams [3].

In the present paper we will give an overview about recent developments of the EBIS technolgy for applications in particle therapy. We present experimental data measured with a room-temperature EBIS of the Dresden EBIS-A type (for details see [4]) demonstrating different features which are important for the application in synchrotron based accelerator schemes. In addition, we will present a new EBIS type, the Dresden EBIS-SC, a superconducting ion source intended to provide beams of light ions which are sufficient for the application at synchrotrons, CYCLINACs [5], and Rapid Cycling Medical Synchrotrons (RCMS) [6].

REQUIREMENTS

Injectors for synchrotron based solutions consist of a number of ion sources, the low energy transport line, a Linac and the medium energy beam transport line. In order to satisfy the requirements of a medical ion beam a set of demands have to be met. In the following a selection of important requirements is given:

- *Particle number per pulse.* Table 1 lists numbers of hydrogen and carbon ions per pulse for different accelerator types. The particle numbers demanded given by different authors differ more than one order of magnitude.
- *Ion species from the source.* The focus here is on the application of H^+, H_2^+, C^{4+}, and C^{6+}. In the future this will also concern ions such as helium, oxygen, and others.
- *Beam purity.* Beam impurities should not exceed $0.1\,\%$ after the mass spectrometer magnet.
- *Pulse-to-pulse current stability.* The current from the ion source has to be constant within about $\pm 2\,\%$ at the flat top.
- *General beam stability.* The ion source should provide stable and reproducible beams.
- *Beam emittance.* The RMS beam emittance should be $< 40\ \pi$ mm mrad for the applied ion beam.

Table 1: Requirements for the Ion Output for Different Types of Medical Accelerators

Accelerator	Protons	C^{6+}	f/Hz	Ref.
Synchrotron [a] (SIEMENS)	$1 \cdot 10^{11}$	$8 \cdot 10^{9}$	0.1 ... 1	
Synchrotron [b] (MEDAUSTRON)	$1 \cdot 10^{10}$	$4 \cdot 10^{8}$	0.1 ... 1	[7]
CYCLINAC [a]	–	$\leq 10^{8}$	up to 400	[8]
RCMS [a]	$2 \cdot 10^{9}$	$3 \cdot 10^{7}$	30	[6]

The particle numbers are given per pulse. [a] – ion source output; [b] – at the patient.

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THE DRESDEN EBIS ION SOURCES

The basic idea of an EBIS is to generate a high-density electron beam by magnetic beam compression. The magnetic field is produced either by superconducting coils [9] or by room-temperature permanent magnet configurations [10], respectively. Incoming atoms are ionized and trapped by the electron beam and successively ionized by electron-impact ionization. The extraction of the ions is realized by switching the electric axial trap potentials asymmetrically. The time characteristics of the extracted ion pulses depends on the pulsed extraction field along the z-axis of the ion trap.

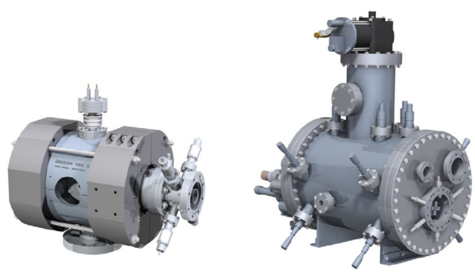

Figure 1: 3D Drawing of the Dresden EBIS-A (left) and the Dresden EBIS-SC (right). In each case the ion extraction can be seen on the right.

Three generations of high-innovative room temperature EBIS/EBIT ion sources have been developed by the collaboration of the Technische Universität Dresden and the DREEBIT GmbH since 1999 [4]. They differ in the extractable currents of highly charged ions. Fields of application are research, industrial technologies as well as medicine. A new class of high-current ion sources for particle therapy, the so-called Dresden EBIS-SC, is currently under test and the following results have been obtained so far:

- a 6 T magnetic field for electron beam compression,
- an electron beam current of 750 mA,
- extraction of first H^+ and $C^{(4,6)+}$ ion pulses.

The EBIS-SC will feature beam parameters which satisfy the requirements of medical synchrotrons [11]. This leads to a compact and low-cost solution for medical applications in particle therapy. 3D drawings of both ion sources are shown in Fig. 1.

MEASUREMENTS WITH THE DRESDEN EBIS-A

In this section we report on proof-of-principle experiments at the Dresden EBIS-A to demonstrate the general ability of EBIS sources to cope with the demands for particle therapy.

Particle Numbers per Pulse

Table 2 lists particle numbers per pulse extracted from the Dresden EBIS-A at different operation conditions.

Table 2: Ions per Pulse Extracted from the Dresden EBIS-A. C_{trap} – Electrical Trap Capacity of the EBIS-A

Ion	**Ions per pulse**	**percent C_{trap}**
H^+	$2.1 \cdot 10^8$	42
H_2^+	$5.7 \cdot 10^7$	12
C^{4+}	$5.6 \cdot 10^7$	32
C^{6+}	$3.3 \cdot 10^7$	40

For the Dresden EBIS-SC the number of extracted ions will be increased to meet the requirements mentioned in Table 1.

Ion Species

The Dresden EBIS-A as well as the Dresden EBIS-SC can provide any required ionzation stage of all relevant elements up to fully stripped ions (q/A = 0.5; not valid for heavy ions). For injection into a linac elements with q/A = 0.5 are available up to calcium.

Beam Purity

All ion production processes occur in a finite rest gas atmosphere, i.e. slight fractions of oxygen and nitrogen contribute to the q/A-ratio of fully stripped ions which cannot be distinguished by a magnetic analyzer. For direct injection of C^{6+} ions into a synchrotron it is therefore of great importance to produce C^{6+} beams which are as pure as possible. The Dresden EBIS-A has been demonstrated to limit the impurity of C^{6+} beams at a level of $< 1\%$ at standard operation conditions. Measured spectra gave the following ratios

$$\frac{N^{7+}}{C^{6+}} \approx 3 \cdot 10^{-3} \quad \text{and} \quad \frac{O^{8+}}{C^{6+}} \approx 9 \cdot 10^{-3} \, .$$

The higher contribution of bare oxygen ions arises from embedded oxygen in the construction materials of the source. Selection as well as preprocessing of the used construction materials should further reduce the oxygen fraction.

Pulse-to-Pulse Stability

Figure 2 pictures the pulse-to-pulse stability of carbon ion pulses. The switching velocity of the ion trap potential (SLEW rate) was 100 μs while the ion extraction frequency was 77 Hz resulting from 12 ms ionzation time and 1 ms duration for switching off of the trap potential. Fig. 2 shows that the pulses are reproducible with only small variation (typically $\Delta Q/Q \approx 1\%$). The widths of the pulses extracted from the Dresden EBIS-A have been demonstrated to span from about 1 μs up to 60 μs.

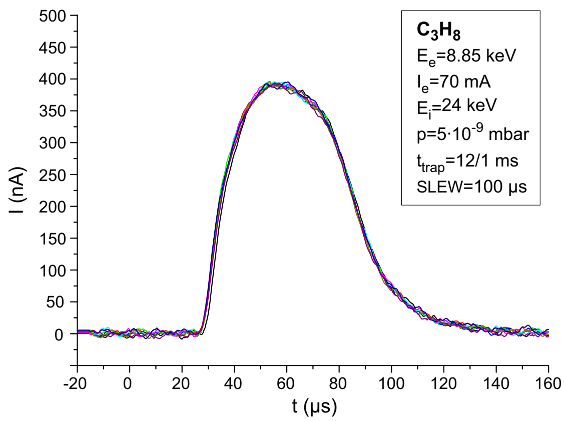

Figure 2: Pulse-to-pulse stability for C^{4+} ion pulses at a propane working gas pressure of $5 \cdot 10^{-9}$ mbar.

General Beam Stability

Fig. 3 pictures the 12-h long-term stability of a C^{4+} ion current. The measurements show that the beam current varies at most by 2 % and is correlated with the change of the temperature of the source environment.

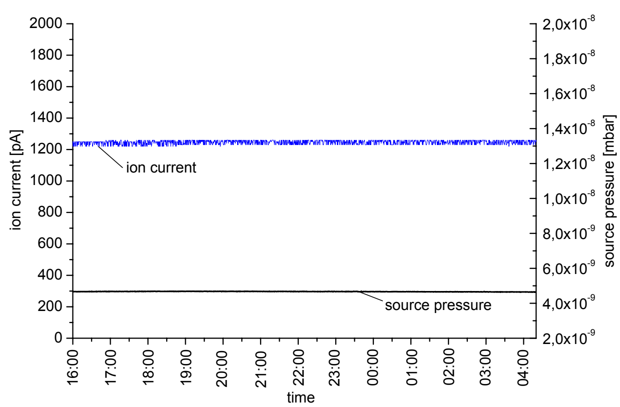

Figure 3: 12-h long-term stability of C^{4+} ion pulses from a propane working gas atmosphere. The source operation parameters are given in Fig. 2. The working gas pressure of the ion source is given supplementary (black line).

Beam Emittance

Measurements using a recently developed pepperpot emittance meter [4] have shown that the RMS emittance of the extracted carbon ion beams is in the range of 2 to 8 π mm mrad. In contrast to ECR sources the distribution of the beam cross-section is homogenous and nearly circular compared to the triangular aberrations known from beams of ECR ion sources (see for instance [12]). Fig. 4 gives an example of an x- and y-RMS-emittance of a carbon beam. The left picture shows a phase space plot of the beam parallelized by an Einzel lens while the right picture gives the beam emittances at different Einzel lens potentials.

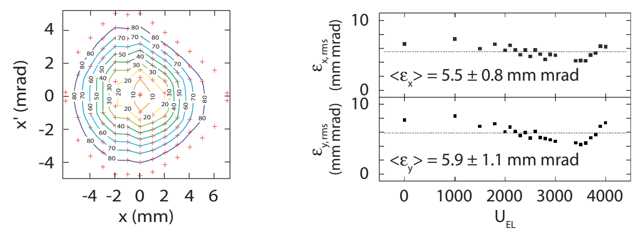

Figure 4: Emittance measurements of a carbon beam extracted from the Dresden EBIS-A. See text for explanation.

DRESDEN EBIS-SC: A NEW ION SOURCE GENERATION FOR MEDICAL PARTICLE THERAPY

The prototype of the Dresden EBIS-SC is a compact superconducting EBIS with a specially designed electron optics. The overall source length is 70 cm while the source body is based on CF350 flanges. The most important design parameters are given in table 3.

Table 3: Design Parameters of the Dresden EBIS-SC

Parameter	Value
Magnetic field	$\leq$ 6 T
Max. electron beam current	1 A
Max. electron energy	30 keV
Eff. electron beam density	$>$ 1000 A/cm^2
Max. eletrical trap capacity	$5 \cdot 10^{10}$ e
Distance cathode-anode	variable (controllable from outside)
Trap length	20 cm
Number of drift tubes	8 (individually controlled)

The EBIS SC is designed to meet the demands for the application in particle therapy. The implementation of the Dresden EBIS-SC will allow a redesign of the injector beamline of medical accelerators in order to reduce the complexity and installation costs of the beam line. This is pictured in Fig. 5. The upper part shows the scheme of an ECR-based injection beam line. Here, the production of C^{6+} ions is usually realized by the extraction of C^{4+} ions from an ECR ion source. After following pre-acceleration, the C^{4+} ions are stripped to C^{6+} ions. The ion beam is then chopped into pulses of some tens of microseconds in order to allow multi-turn ion injection into the synchrotron. However, single pulses of C^{6+} ions and protons with appropriate particle numbers are ideal for a therapy irradiation facility.

The middle part of Fig. 5 pictures the simplification of the injection beam line using an EBIS-SC. In principle, an EBIS-SC directly will provide sufficient and pure pulses of C^{6+} ions with variable time structures needed for single-turn and multi-turn injection, respectively. Moreover, the EBIS-SC also will provide pulses of H^+ and H_2^+ ions as well as a variety of fully stripped ions with q/A=0.5 in particular. This favours their application in both clinical and non-clinical research.

A next step to simplify the ion injection scheme of a synchrotron can be the application of a compact Wien filter (EBIS-SC(W); overall filter length of about 20 cm) [13] as shown in the lower part of Fig. 5. The Wien filter which is directly mounted behind the ion extraction lens system replaces the magnetic analyzer.

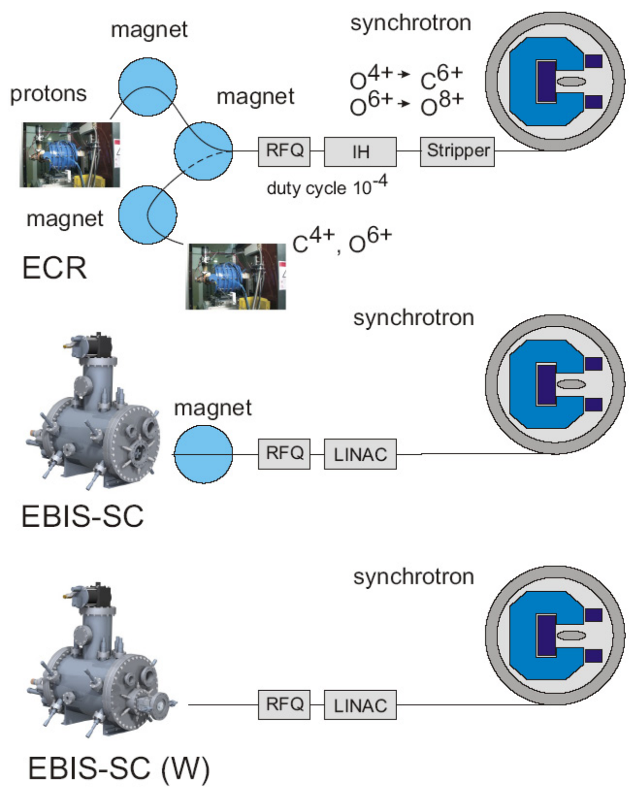

Figure 5: Possible simplification of the ion injection beam line of a synchrotron. The "classical" ion injection scheme using ECR ion sources is shown in the upper part. The injection scheme with a Dresden EBIS-SC is shown in the middle part. The application of a Dresden EBIS-SC(W) is shown in the lower part.

SUMMARY

Experiments at the Dresden EBIS-A have demonstrated that the EBIS technology will be capable of delivering ions meeting the demands of particle therapy in near future. Moreover, it has been shown that an EBIS has a variety of advantages compared to standard sources at present used for beam injection into different accelerator set-ups.

The Dresden EBIS is designed to provide sufficient ion numbers and pulse shapes that are applicable to different solutions of medical accelerator schemes. Finally, the application of an EBIS will simplify the ion injection beam line.

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