ELECTRON BEAM ION SOURCES – NEW PROSPECTS FOR PARTICLE ACCELERATION*

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Abstract

Electron Beam Ion Sources (EBISs) produce highly charged ions (HCIs) in a high density electron beam. Due to their operational principle they have a lot of advantages although limited in ion output. Since the radial source region is given by a narrow electron beam the extracted ion beam features a very low transversal emittance. Moreover, the ions are ionized by a mono-energetic electron beam resulting in a small variation of the ion energy distribution, and thus in a very low longitudinal emittance. Together with a low basis pressure of less than 1E-9 mbar this results in a high quality ion beam. Providing almost any element with any charge state of up to completely ionized species gives a large number of different projectiles and kinetic energies.

INTRODUCTION

The use of EBISs whether based on superconducting magnets or on permanent magnets has been proven in various fields of applications [1]. EBISs feature a lot of advantages which qualify them for accelerator injection, and which compensate for their comparatively low number of particles. In several fields, such as materials research they have already substituted common ion sources such as Electron Cyclotron Resonance Ion Sources (ECRISs) and Liquid Metal Ion Sources (LMISs).

EBIS as injector into an accelerator structure was already started in the late 1970s at the KRION-2 project [2] and has been restated in the early 1990s [3].

Common injectors for accelerator structures are plasma-based sources providing continuous beams of low-charged ions followed by a chopper to produce the required beam bunch sequences. The beam portion which doesn't fit the beam specification of the accelerator is lost. Hadrontherapy facilities whether based on synchrotrons or cyclotrons are primarily based on ECRISs [4-6].

In order to address the need for the distribution of radiotherapy facilities providing access to much larger populations of patients an important point is a significant reduction of costs. Starting point is the implementation of innovative accelerator concepts presented over the last years [7-11].

Another important part is the ion source to be capable of delivering beams of various ion species with sufficient beam properties related to the time structure, beam divergence as well as purity and stability.

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In spite of the fact that the continuous ion output of EBISs is orders of magnitude lower than from plasma ion sources such as ECRISs, extracted ion pulses are close to chopped bunch intensities. EBISs can produce flat-top ion pulses with pulse lengths of 1 µs up to 100 µs as, for instance, required for multi-turn injection into synchrotrons.

Delivering sufficient pulse intensities injection can moreover participate from advantages of EBISs. They originate from the ion production process resulting in a high initial beam quality in regard to beam emittance and energy spread as well as in regard to reduced contributions of unrequested species, ion pulse reproducibility and stability.

Based on the EBIS technology low-energy beamlines are capable to deliver a wide range of projectiles, i.e. almost any available element with charge states up to bare ions with kinetic energies in the range of some tens of eV up to 1 MeV.

In this paper we present the Dresden EBIS family based on permanent magnets resulting in a compact machine set-up. Furthermore, the latest development of the EBIS-SC, based on cryogen-free superconducting magnets for an increased ion output is presented.

ELECTRON BEAM ION SOURCE

Ion production in an EBIS is effected by electron impact ionization in a high density electron beam, which is compressed by a strong magnetic field of a Helmholtz coil geometry. The produced ions are trapped in radial direction by the potential well of the space charge of the electron beam and in axial direction by a positive electrostatic potential offset. The control of this potential offset defines the ionization time and thus the charge state distribution within the trapping region. Typical electron beam diameters are in the range of 100 µm resulting in a comparatively small trap volume on the one hand, but in a narrow ion beam on the other hand.

The ions can be extracted either in leaky mode, i.e. as continuous beam or as ion pulses. In pulsed mode the ions are successively ionized to higher charge states until the trap is opened.

The ionization process is determined by the electron beam current density j_e and the duration of impact, i.e. the ionization time τ. A degree of the ionization process is given by the so-called ionization factor which is the product of both the electron current density and the ionization time

$$j_e \tau . \qquad [1]$$

The ionization process is furthermore influenced by charge exchange and recombination processes as well as particle admission and ion losses. Ion production is thus defined and hence controllable by a set of source parameters such as electron current, electron energy, ionization time and gas admission.

The capacity to trap positive ions is given by the negative space charge of the electron beam defining an upper limit of the number of ions that can be produced. Assuming a constant and homogeneous electron beam it simply results from the electron current I_e, the electron velocity v_e and the length of the trap L, and can be given by the following unit-based formula

$$C_{Trap}[\mathrm{As}] = 10^{13}\ I_e[\mathrm{A}]\ L[\mathrm{m}] / \mathrm{sqrt}(\ E_e[\mathrm{eV}]) \ . \qquad [2]$$

A family of EBISs have been developed the last decade which are based on permanent magnets resulting in a compact table-top design [12]. It started with the so-called Dresden EBIT with a maximum axial magnetic field of 250 mT and a trap length of 2 cm. The largest version, the Dresden EBIS-A, features an axial magnetic field of 600 mT and a trap length of 6 cm (see Fig. 1).

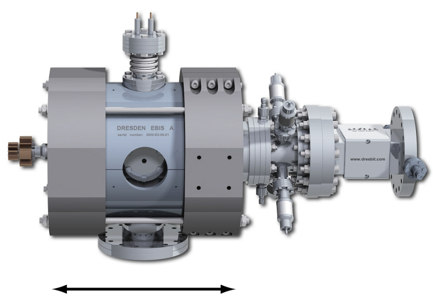

Figure 1: Dresden EBIS-A, based on coils of permanent magnets with upstream Wien filter (on the right).

Beside the fact that EBISs can deliver highest charge states their high beam quality which is due to their small radial source extension, the low basis pressure and the mono-energetic electron beam came into focus for their application as injector source. Typical beam emittance values are in the range of several mm mrad. The mean energy spread of the ions has been determined up to several tens of eV.

The demand for higher ion output related to this gave rise to the development of the Dresden EBIS-SC [13]. Their axial magnetic field of 6 T is based on cryogen-free superconducting technology still keeping the set-up compact (see Fig. 2). The combination of an increased electron current of up to 1 A and the trap length of 20 cm results in a corresponding increased ion output (see Equ. 2) which is sufficient to meet the requirements of an injector for accelerators.

Working gases are admitted through a gas injection valve, which also allows for the admission of metals embedded in volatile compounds. Metals can alternatively be admitted from external ion sources such as LMISs as shown for example for charge breeding experiments [14].

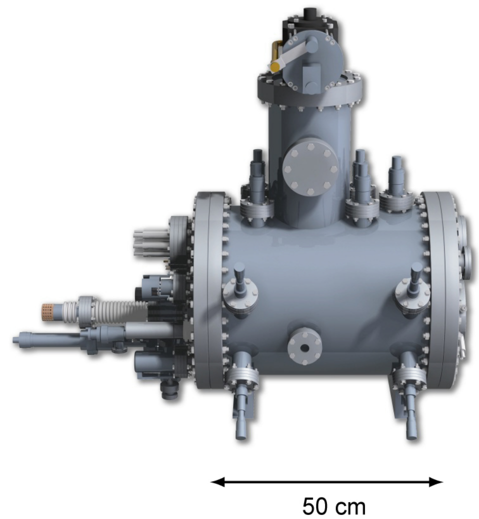

Figure 2: Dresden EBIS-SC, based on cryogen-free superconducting magnets.

The EBISs either based on permanent magnets or on superconducting coils can be connected to low-energy beamline structures for beam formation, charge-to-mass separation and beam diagnostics. The simplest set-up is the combination with an ExB (Wien) filter, as pictured in Fig. 1, providing mass and charge separated particle beams in a very compact assembly.

Fig. 3 pictures a standard beamline with the Dresden EBIS-SC, an analyzing magnet and a target chamber comprising a set of beam diagnostics such as a pepper-pot emittance meter and a retarding field analyzer.

In order to give access to the whole range of kinetic energy of up to 1 MeV the beamline can be put on a high voltage terminal allowing for both ion deceleration and acceleration.

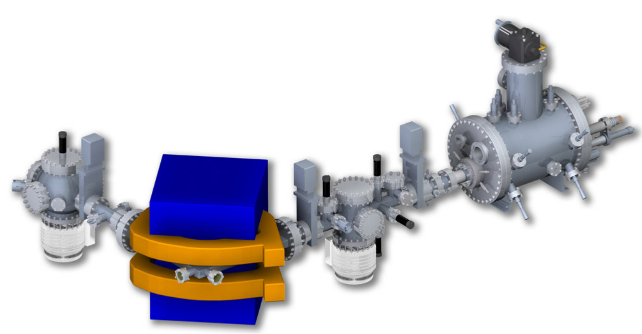

Figure 3: Beamline with Dresden EBIS-SC, 90 degree bending magnet, and reaction chamber.

Fig. 4 pictures an extraction spectrum of iodine ions from the EBIS-SC measured in leaky mode, i.e. the ions left the trap continuously over a reduced axial trap potential. Maximum charge state is I^{28+} which is nickel-like iodine. Highest charge state is argon-like I^{35+}. The carbon ions arise from CH_3I which was used for particle admission into the ion source.

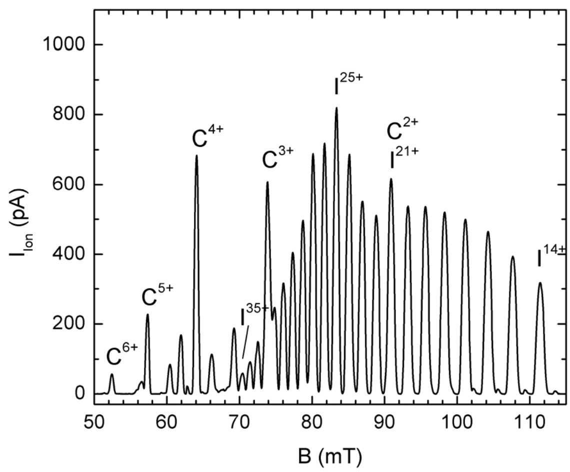

Figure 4: Iodine extraction spectrum from the EBIS-SC measured in leaky mode. Iodine was admitted as CH_3I.

The extraction spectrum in Fig. 5 shows C^{4+} in the maximum after an ionization time of 10 ms. The C^{4+} pulse was measured to about 500 pC which corresponds to about $8x10^8$ ions per pulse.

The ion output of highest charge states, such as neon-like Xe^{44+} have been measured up to 10^6 ions per pulse and per second. Low Z elements, which are especially of interest for radiotherapy facilities, can also be extracted as continuous beam currents with high ion output. Proton currents from the EBIS-SC have been measured with more than 1 µA.

Other applications are of increasing interest which is related to more exotic projectiles, such as high charge states of rare radioisotopes, low charged molecular fragments and clusters that can be delivered by corresponding admission from volatile compounds or external ion sources.

CONCLUSION

Due to their beam properties EBISs present an alternative to plasma-based ion sources for injection into accelerator structures. Their advantages related to the lateral and transversal beam emittance, beam purity and stability as well as the large variety of available projectiles and their starting energy compensate for their low continuous ion output. The formation of ion pulses with comparable intensities to chopped beam bunches provide their application as injector sources, especially in combination with innovative accelerator structures.

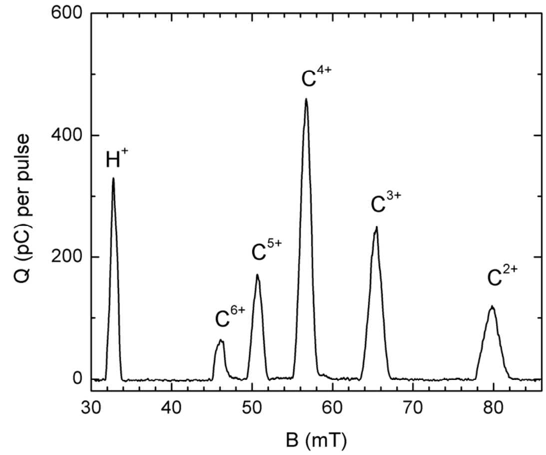

Figure 5: Carbon extraction spectrum from the EBIS-SC measured in pulsed mode after 10 ms ionization time. Carbon was admitted as propane (C_3H_8).

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