

ELECTRON BEAM ION SOURCES, ION OPTICAL ELEMENTS AND BEAM DIAGNOSTICS FOR PARTICLE ACCELERATORS

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Abstract

Electron Beam Ion Sources (EBISs) provide highly charged ions (HCIs) for a variety of investigations and applications, e.g. amongst others as injection source for particle accelerators. EBISs feature a lot of advantages which qualify them for accelerator injection, and which partly compensate for their comparatively low number of particles.

DREEBIT GmbH provides a family of compact EBISs based on permanent magnets. A more sophisticated version is based on cryogen-free superconducting magnets providing a significantly higher ion output.

Based on this ion source technology complete low-energy beamlines provide a wide range of projectiles, i.e. almost any available element with charge states up to bare ions with energies of some tens of eV up to 1 MeV. Due to their specific application the beamlines comprise a variety of ion optical elements as well as various ion beam diagnostics.

INTRODUCTION

Beams of HCIs are important tools in various fields of basic and applied research. They are used for atomic and nuclear physics experiments, for investigations of the processes in laboratory and astrophysical plasmas [1]. In materials science and nanotechnology they are used both for surface modification as well as for surface analysis [2]. Another growing field is their application in biotechnology, such as molecule fragmentation or cancer therapy. In particular radiation therapy with protons and carbon ions has proven to be a highly advantageous alternative to photon radiation therapy [3]. The proton and ion beams applied for have to meet a set of requirements, such as beam purity, low beam emittance and high beam brightness.

Since the region in which the ions are produced is small and the temperature of the created ions is low EBISs are ideally suited for high beam quality. In several fields, such as materials research they have already substituted common ion sources such as electron cyclotron resonance ion sources (ECRIS) and liquid metal ion sources (LMIS) [4]. However, due to the limited ion currents that can be delivered by EBISs applications such as focused ion beam (FIB), ion beam lithography, and cancer therapy still rely on LMIS and ECRIS systems. Nevertheless, an increased ion output from EBISs promises advantages also in these fields.

Improvements in EBIS technology will make them more feasible for high-current applications. Recently, the Dresden EBIS-SC has been developed which

complements a series of sources of HCIs with a unique concept in terms of tabletop size and resource efficiency [5].

Featuring an enhanced electron current density resulting in an increased trap capacity the EBIS-SC is designed to meet the required ion numbers per pulse for cancer therapy. In order to compete with ECRISs in this field the beam quality has to be sufficient enough to reduce ion losses within the accelerator.

In this paper, we present latest improvements proving the feasibility of producing beams of HCIs with convenient beam properties such as low transversal and longitudinal emittance.

In addition, we present a variety of ion optical elements as well as ion beam diagnostics that have been developed the last years. The DREEBIT Wien filter allows for the charge mass separation. The DREEBIT pepper-pot emittance meter allows for emittance measurements of beams of a wide range of particle intensity. Other beam diagnostics are provided, such as beam imaging systems, retarding field analyzers and different kinds of Faraday cups.

ELECTRON BEAM ION SOURCES

Electron Beam Ion Sources (EBISs) produce highly charged ions in a high density electron beam. The ions are trapped radially by the negative space charge potential of the electron beam, while axial trapping is realized by additional electrostatic potentials. The control of these potentials allows for a definite production and extraction of the ions. 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 an approximately monoenergetic electron beam resulting in a small variation of the ion energy distribution, and thus in a very low longitudinal emittance. This results in connection with a low base pressure of less than 10^{-9} mbar in a high quality ion beam.



Figure 1: Dresden EBIS-A, based on permanent magnets.

The ions can be extracted as continuous beam as well as ion pulses with distinct pulse shapes. The electron beam can be loaded with atoms or ions by direct gas injection. Volatile compounds can be used to inject metal atoms. Injection from external ion sources is possible using a quadrupole beam bender. This allows to provide almost any element which can be ionized to charge states of up to completely ionized ions. Hence a large number of different projectiles at different kinetic energies is available.

The use of EBISs either based on permanent magnets (Dresden EBIS-A, see Fig. 1) or on cryogen-free superconducting magnets (Dresden EBIS-SC, see Fig. 2) has been proven in a variety of fields and applications [6]. In addition, their compact design makes them transportable, low in operational costs and guarantees easy handling.

The EBIS-SC is a more sophisticated EBIS version based on superconducting magnets with a liquid helium free cooling system. The compression of an electron beam of up to 1 Amp is realized by a magnetic field of up to 6 Tesla. This leads in connection with an ion trap length of 20 cm to a high output of highly charged ions.



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

LOW ENERGY BEAMLINES

The EBISs can be connected to different beamlines providing beams of HCIs for specific experiments and applications. The simplest set-up is a room-temperature EBIS followed by a Wien filter and a small reaction chamber resulting in a very compact table-top assembly.

In order to use the whole range of ion species and their kinetic energies a beamline can comprise a bending magnet, a high voltage terminal, corresponding ion beam optics and diagnostics, a deceleration lens system, a target reaction, a target preparation and a target transfer chamber. An example of such a beamline is pictured in Fig. 3. Typical range of kinetic energy is 100 eV times q

up to 40 keV times q which for high charge states of heavy ions, such as Xe^{44+} exceeds 1 MeV kinetic energy. Typical beam emittance is about 10 mm mrad.

Depending on the EBIS extraction mode the beamlines can provide continuous beams as well as ion pulses with controllable pulse length. In addition fast switching control of the trap opening potential allows for shaping the ion pulses, i.e. providing flat top pulses of a distinct length for injection into accelerator structures.

Although the ion output of the highest charge states of heavy ions is limited, e.g. $10^6 Xe^{44+}$ ions per pulse and per second, much more ions can be extracted as continuous beam currents of low Z elements. The EBIS-SC for instance is capable to provide proton currents of more than 1 μA .

Moreover, exotic projectiles, such as high charge states of rare radioisotopes or low charged molecular fragments can be produced by corresponding injection from volatile compounds or external ion sources.

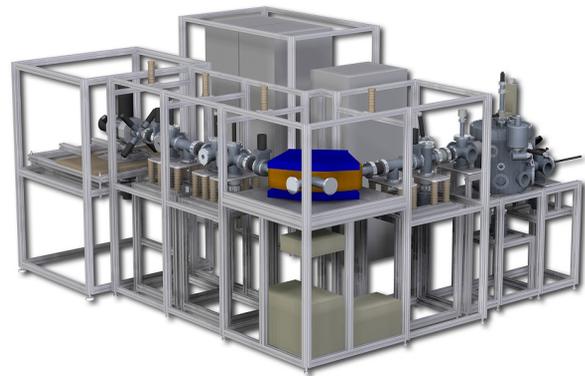


Figure 3: Ion irradiation facility with Dresden EBIS-A, high voltage platform, 90 degree bending magnet, target and transfer chamber.

PARTICLE BEAM OPTICS AND DIAGNOSTICS

Due to their specific applications the beamlines comprise various ion optical elements that are needed to realize high quality beams. Amongst others these are mass separation systems (bending magnet, Wien filter), Einzel lenses, deflection systems, deceleration lens systems, slits and Faraday cups.

The Wien filter as pictured in Fig. 4 is a particle separator with crossed magnetic and electric field configuration providing mass and charge separated particle beams. With the Wien Filter as an ion source add-on a very compact device is available substituting a complete standard beamline setup.

Another example is a quadrupole beam bender that for instance allows for the external injection of ions into an EBIS which has been demonstrated for charge breeding of Gold ions [7]. The quadrupole beam bender provides for the 90 degree deflection, gating and switching of particle beams with energies of typically up to 20 kV times particle charge. It consists of four bended electrodes with potentials to be set independently. Fast switching of the electrode potentials is provided by a fast high voltage pulse generator.



Figure 4: Wien filter based on CF100 flanges.

In order to characterize the low energy particle beams various diagnostic systems are available. The Pepper-pot emittance meter as pictured in Fig. 5 allows for emittance measurements of beams of a wide range of particle intensity. It creates an image of the beam after passing a pepper-pot like mask by amplification and converting the incident beam into visible light which can be monitored through a glass vacuum window. After passing the pepper-pot mask the beam is separated into several spots with equal distance. The emittance of the beam can be calculated from the position, the size, and the shape of these spots. After mass separation the emittance of an Ar^{16+} beam from the Dresden EBIS-A has been measured to be 3 mm mrad.

The Retarding field analyzer can be used to determine the transversal energy spread of the extracted particles. It consists of a Faraday cup with 3 grid meshes, with the center mesh on retarding potential, and an upstream collimator with exchangeable aperture plates.

The charged particles are decelerated by a static electrical field. The ions passing this retarding field are detected by the Faraday cup resulting in a measured particle current which is dependent on the decelerating voltage.

If the incoming beam is decelerated only particles with a higher kinetic energy than the retarding potential are detected as current. Tuning the deceleration voltage results in an integral spectrum of the energy distribution. Differentiation of this spectrum gives the energy distribution of the charged particle beam.

The transversal distribution of a Xe^{44+} beam from the Dresden EBIS-A has been determined to have a Gaussian shape with a full width half maximum of about 30 eV.



Figure 5: Pepper-pot emittance meter with water-cooled shutter based on CF160 flange.

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