REXEBIS – A CHARGE BREEDER FOR THE REX-ISOLDE POST ACCELERATOR

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Abstract

The REXEBIS is an electron-beam ion source developed to trap and further ionise the sometimes rare and short-lived isotopes that are produced in ISOLDE for the Radioactive EXperiment at ISOLDE (REX-ISOLDE). A 0.5 A electron beam is produced in a magnetic field of 0.2 T, and is compressed by a 2 T solenoidal field to a current density of >200 A/cm^2. The 2 T magnetic field is provided by a warm-bore superconducting solenoid, thus giving easy accessibility but no cryogenic pumping. The EBIS is switched between 60 kV (ion injection) and ~20 kV (ion extraction). The EBIS design focused on high injection and extraction efficiencies to the surrounding Penning trap and RFQ in the REX-ISOLDE post accelerator. The design, which required simulation of a complete injection, breeding and extraction cycle, proved viable. Calculations of the back flow of Ar cooling gas from the Penning trap as well as effects of residual gas from the warm-bore vacuum chamber certified that possible outnumbering of the low number of radioactive ions by Ar and residual gas can be handled.

1 INTRODUCTION

The construction of REXEBIS, an Electron Beam Ion Source (EBIS), is part of a larger project, the so-called REX-ISOLDE project [1,2,3], which is an upgrading of the already existing ISOLDE (Isotope Separator On-Line) [4] facility at CERN.

Nuclear physics is now turning its attention to the regions far away from nuclear stability, to the neutron and proton drip-lines, and to physics with radioactive ions. To reach these extreme regions in the nuclear chart innovative accelerator concepts have to be used, and the ISOLDE community has chosen to add a post accelerator to the isotope on-line separator. This will give the physicists access to the already large number of isotopes produced at ISOLDE at higher energies.

The REX-ISOLDE is a pilot project with the aim to demonstrate an efficient scheme for post acceleration of radioactive beams, produced by an on-line mass separator, to energies somewhat below the Coulomb barrier. The ions are first accumulated and cooled in a Penning trap, then charge bred in an EBIS, and finally accelerated in a short linear accelerator to energies between 0.8 and 2.2 MeV/u.

An EBIS charge breeds ions by bombarding singly charged ions with high-energy electrons [5]. The bombarding electrons collide with electrons bound to ions, thus further ionising these ions. After a few milliseconds, the ion has been ionised to a higher charged state.

By introducing an EBIS into the post accelerator chain, the singly-charged ions are ionised to a q/A-value of ~1/4.5, and the length of the succeeding LINAC can be considerably reduced. For the low beam energies delivered by an on-line separator, an EBIS is in principle the only effective alternative. The REXEBIS has features similar to CRYSIS [6], the Stockholm EBIS, but there are some major differences and design challenges that we would like to emphasise in this article. A more extensive article describing the REXEBIS project is foreseen for this autumn.

2 REXEBIS SPECIFICATIONS

The specifications for the REX-ISOLDE post accelerator, together with the limits set by the Penning trap and the mass separator/LINAC, impose strict requirements on the REXEBIS design. The EBIS should be capable to charge-breed elements with mass A<50 to a charge-to-mass ratio of >1/4.5 within a confinement time of 20 ms. This short confinement time is set by the short life-time of the radioactive nuclei. For light elements, however, one has the possibility to use an even shorter cycle time. The number of ions injected per pulse may vary from a few ions to 10^7. The lower limit is set by the production yield at ISOLDE, whereas the space charge inside the Penning trap sets the upper limit. Due to few and costly produced radioactive ions the EBIS has to be efficient, i.e. the injection and extraction efficiency should be higher than 50% [7]. Due to the statistical nature of the ionisation process, the inherent breeding efficiency to a single charge state is less than 30%. Another reason for selecting an EBIS as part of this complex accelerator chain is that this ion source has proved an excellent reliability record at MSL.

To fulfil the above requirements, we have chosen a design utilising a 5 keV electron beam with a current of 0.5 A. The current density is >200 A/cm^2, throughout a 0.8 m long trap region. With these parameters the REXEBIS trap can hold up to ~$6\cdot10^9$ charges at an electron beam charge-compensation of 10%. This large number of ions is more than ten times the maximum number of ions that due to space charge limitations can conceivably be delivered from the Penning trap. Table 1 displays the most dominant charge states for some typical ions that are bred for 20 ms in the REXEBIS.

Table 1: Peak charge state at 20 ms breeding time.

Element	Charge-state
$_{8}O$	+7
$_{11}Na$	+9
$_{12}Mg$	+9
$_{18}Ar$	+11
$_{19}K$	+11
$_{20}Ca$	+12
$_{36}Kr$	+16
$_{37}Rb$	+18

3 SOLENOID

The superconducting magnet will provide a 2 T magnetic field, both for focusing of the electron beam and to facilitate trapping at ion injection. To optimise the performance of the EBIS, the magnetic field straightness, homogeneity, and stability must be carefully controlled. We have developed a simple method to verify the field straightness, and found the traced central field-line to be within a cylinder of radius 0.1 mm for the full EBIS length (-800<z<800 mm). The axial field has a specified homogeneity of 0.3% over ±400 mm, and we measured the homogeneity to be within 0.25%. The specified relative field stability is $5\cdot10^{-6}$ h^{-1}.

The REXEBIS has a warm bore, i.e. the inner cylinder containing the drift structure is held at room temperature, despite the cryogenic temperatures of the superconducting solenoid. We chose this concept to avoid the memory effect in which gases frozen to a cryogenic surface may re-enter the vacuum by the thermal load from the electron beam going astray. Furthermore, keeping the vacuum chamber at room temperature enhances the accessibility to the inner structure, and should allow good reliability. The main difficulty with this concept is to substitute the inherently efficient cryogenic pumping from a cold bore with NEG pumps and turbo-molecular pumps positioned at relatively poor conductance outside the solenoid.

4 ELECTRON GUN

The electron gun is of immersed type, positioned at 0.2 T. This design is uncomplicated, relatively insensitive to axial displacement, current and current-density is easy to control, and the design is well proved in EBIS constructions. Apart from a modest electron current compression, the main drawback is the unavoidable scalloping (periodical beam diameter variations along the beam propagation) which we have proved is insignificant for the working of the REXEBIS.

The electron gun will deliver a current of ~0.5 A at a cathode current density of 25 A/cm^2. The perveance of the gun is 0.87 μA/V$^{3/2}$. A 1.6 mm diameter LaB_6 cathode will be used. Figure 1 shows an EGUN simulation of the beam propagation in the gun region.

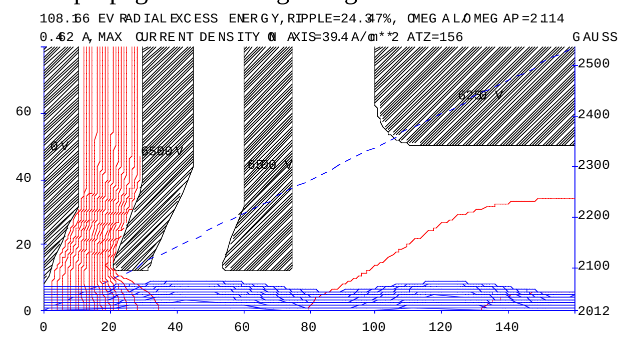

Figure 1. Cylindrical geometry simulation of the electron beam in the gun region. One unit of length corresponds to 0.1 mm.

4 INNER STRUCTURE

The inner structure consists of drift tubes, a support structure and NEG strips. All these elements are placed in UHV and close to room temperature (warm bore ~15 °C). We have chosen to manufacture most of these details in titanium due to its gettering property. To further improve pumping efficiency, we have considered drilling holes radially in the drift tubes.

The drift tubes have a radius of 5 mm. The REXEBIS has three trapping tubes: 100, 230 and 464 mm long with 2 mm spacing, which can be combined to trap lengths of 100, 230, 332, 464, 696 and 798 mm. With a full length the charge trapping capacity for a 10% electron beam compensation amounts to $6\cdot10^9$ electrical charges.

The electron beam energy will be 5 keV, and the beam radius 0.25 mm. The potential depth of the electron beam will amount to 107 V, which is significantly larger than the potential ripple (±5 V) caused by beam scalloping. Ions are injected with a ~10 μs long pulse from the Penning trap, and are ejected by their inherent kinetic energy upon lowering the end-tube trap potential. Utilising this method, virtually no extra energy spread will be introduced.

5 ELECTRON COLLECTOR

A cylindrical iron shield surrounds the copper collector. The iron reduces the magnetic field drastically inside the collector, causing the electron beam to expand rapidly onto the collector surface. The design of the collector is tailored to the electron impact angle so that back-scattering is minimised (see Figure 2). Simulations show that the fraction of electrons that re-entered the trap region is about 0.25%. The collector has a large opening towards the combined injection/extraction beam optics. This minimises ion beam aberrations and increases pumping conductance.

The collector is placed at a +2000 V potential relative to the cathode, yielding that the 0.5 A electron current dissipates 1000 W at the collector surface. The power density in the affected region of the collector is below 8 mA/cm^2. Estimations of out-gassing caused by electron bombardment yields a rest gas pressure inside the collector of the order of 10^{-11} mbar.

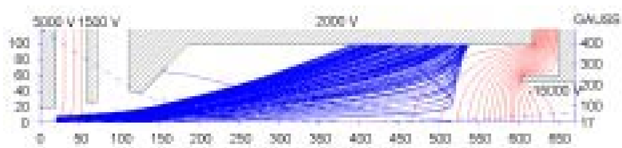

Figure 2. EGUN simulation of the absorbed electron beam. One unit of length corresponds to 0.25 mm. Only the upper cylindrical part of the collector region is shown.

6 HIGH VOLTAGE SWITCHING

The REXEBIS is situated at a 60 kV potential during injection, allowing captured of cooled 60 keV ions from the Penning trap. The potential is decreased to about 20 kV during the breeding time (figure 3). The RFQ is optimised for an ion energy of 5 keV/u, which with the EBIS output q/A~1/4.5 gives an ion extraction voltage of around 20 kV.

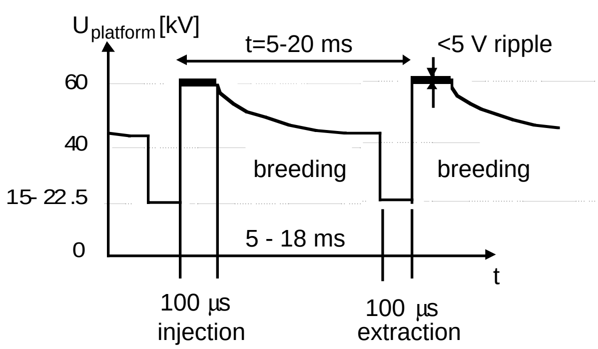

Figure 3. REXEBIS platform potential relative ground during two cycles.

7 VACUUM AND REST GAS SPECTRUM

The REXEBIS requires an extremely good residual gas pressure (10^{-11} mbar) inside the trap region to avoid a complete outnumbering of the few radioactive ions. The backbone in the pumping system is one turbo molecular pump on each side of the EBIS. These two pumps will together with a hexagonal pattern of NEG strips replace the needs for cryogenic pumping (traditionally used in cold bore EBIS).

The main vacuum concerns are out-gassing from the inner structure and gas load from the electron collector due to the impacting electrons. Moreover, there will be an argon gas load from the Penning trap, which has an argon buffer gas pressure of 10^{-3} mbar. A 7-stage differential pumping transfer line will provide an argon pressure of ~10^{-14} mbar inside the REXEBIS.

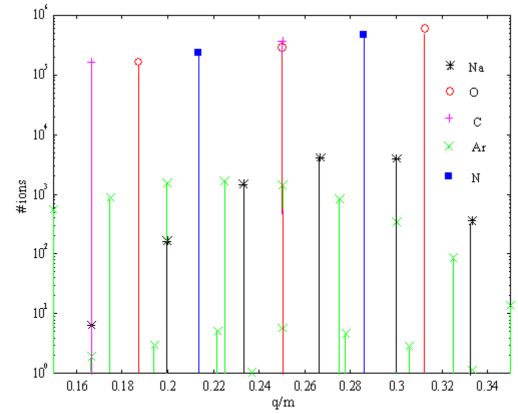

Figure 4. Calculated q/A spectrum showing the absolute number of extracted residual and radioactive ions per pulse. Breeding time 13 ms; 10 000 injected ^{30}Na ions.

Figure 4 shows a calculated q/A spectrum as produced from rest gas, gas from the collector and injected charge-bred ions. It is clear that the ions of interest may display a much lower intensity than nearby rest-gas peaks. To make a clean beam of the isotopes of interest, a mass separator is clearly needed.

Table 2 summarises the design properties of the REXEBIS.

Table 2: The REXEBIS design parameters.

Maximum central magnetic field	2.0 T
Electron gun type (Semi-immersed)	LaB_6
Electron beam current I_e	0.46 A
Electron beam current density	>200 A/cm^2
Electron beam energy E_e	5000 eV
Electron gun perveance P	0.87 A/V$^{3/2}$
Electrons re-entering the trap	<0.25%
Trap length	<0.8 m
Trap capacity (10% compensation)	~$6\cdot10^9$ C

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