A CONCEPT FOR EMITTANCE REDUCTION OF DC RADIOACTIVE HEAVY-ION BEAMS

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Numerical simulations indicate that it should be possible to use an electron beam to strip 1+ DC radioactive ion beams to 2+ or higher charge states with on the order of 40-80% efficiency. The device, which we call an Electron-Beam Charge-State Amplifier, is similar to an Electron Beam Ion Source, except that it is not pulsed, the beams are continuous. The 2+ beams are obtained in a single pass through a magnetic solenoid while higher charge states may be reached via multiple passes. An unexpected result of the ion optics simulations is that the normalized transverse emittance of the ion beam is reduced in proportion to the charge-state gain. Ion beams with realistic emittances and zero angular momentum relative to the optic axis before entering the solenoid will travel though the solenoid on helical orbits which intercept the axis once per cycle. With an ion beam about 2 mm in diameter and an electron beam about 0.2 mm in diameter, the ion stripping only occurs very near the optic axis, resulting in the emittance reduction.

I. INTRODUCTION

A. Motivation

The creation of accelerated beams of radioactive nuclides far from stability is an area of significant interest in nuclear physics [1,2]. Several laboratories around the world are currently developing methods for the production of high quality radioactive beams based on the extensive experience accumulated in recent years at Isotope Separator On-Line (ISOL) facilities such as ISOLDE [3]. Isotopes of many elements are available with high efficiencies and excellent emittances and energy spreads in 1+ charge states [4,5]. However, the acceleration of radioactive nuclides in the mass 120-240 range with high duty factor and good beam quality from 1+ charge states requires some development, especially at the front end of the post accelerator [6,7,8]. An ionizer capable of efficiently increasing the charge states of very low velocity heavy ions, even if only to 2+, 3+, or 4+, would be of great value in simplifying this process.

B. Background

It has been shown that a 1+ ion beam can be injected into an Electron Beam Ion Source (EBIS), "cooked" to higher charge states, and then extracted [9,10]. This is a batch transfer process with an inherently low duty factor, which is well matched to those nuclides which can be stored in certain ISOL-type ion sources, such as surface ionization sources. Recently, it has been proposed to extend this concept further to increase its efficiency by adding a Penning trap in which to accumulate, store, and cool radionuclides from an ISOL-source before batch transfer to the EBIS charge-state breeder [11]. This concept has the potential for high efficiency and excellent beam quality, but estimates of the number of ions which can be stored in the Penning trap indicate that it may be limited to low average currents [11].

We have developed a concept for a device called an Electron-Beam Charge-State Amplifier (EBQA), an extension of the EBIS-type charge-state breeder, which has the potential for overall efficiencies of 40-80% and operates in a DC mode [12]. In the present paper we describe the EBQA qualitatively and present some of the results of computer simulations with emphasis on the fact that the EBQA reduces the normalized transverse emittance of the ion beam in proportion to the amount of charge state enhancement.

II. THE ELECTRON BEAM CHARGE-STATE AMPLIFIER CONCEPT

A. Qualitative Description

The concept is to pass a DC beam of low energy heavy ions, ^{132}Sn in the numerical examples below, through a strong magnetic solenoid and to use an EBIS-type electron beam to increase the charge state in a single pass. In the single-pass mode, indicated schematically in Fig. 1, the goal is to increase the charge state from 1+ to 2+. It is also possible to use a multipass mode by recirculating the stripped ions back through the solenoid for further charge-state enhancement. With two recirculating beamlines, for example, charge state increase to 4+ would be possible.

Ions extracted from an ion source at 60-100 keV in 1+ charge state are decelerated to 1 keV for injection into the superconducting solenoid located on a high voltage platform. As shown below the ion beam diameter in the solenoid is about 2 mm. An electron beam of about 5 keV energy and about 0.2 mm in diameter is used to strip a fraction of the ion beam to higher charge states. Using reasonable estimates for the initial ion beam emittance and cross sections for electron stripping it is shown below that as much as 40% of the 1+ beam could be stripped to 2+ in a single pass and over 80% could be stripped to 2+ or higher charge states for recirculation.

For the single-pass mode, as indicated in Fig. 1, the 2+ beam is accelerated from the platform to approximately twice the energy of the original beam. As discussed below, the normalized transverse emittance is reduced by a factor of two, so the overall ion beam brightness is increased by a factor of three (assuming 40% efficiency).
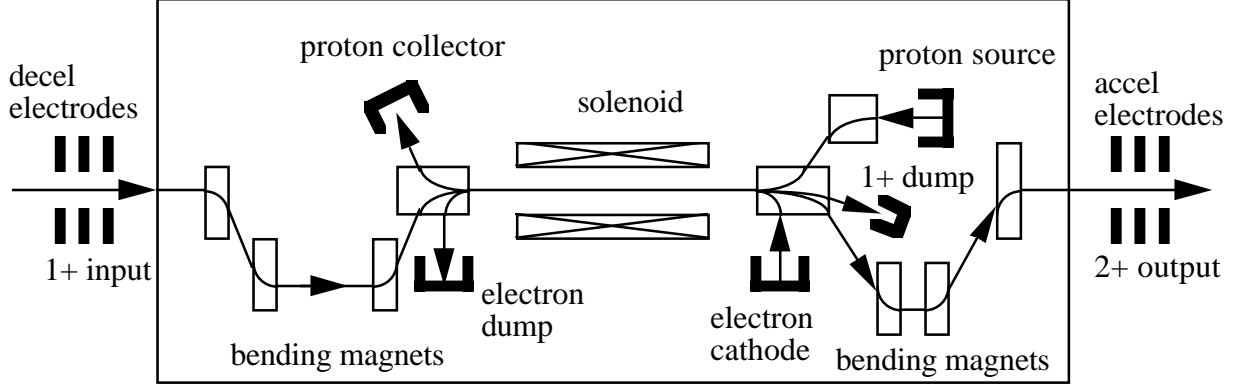

Figure 1: Electron Beam Charge State Amplifier (EBQA) single-pass configuration

The space-charge potential of the small diameter electron beam can be quite high, on the order of 1 kV, so it must be neutralized. It may be possible to use residual gas or a copropagating low energy proton beam for neutralization. The layout in Fig. 1 indicates the possible configuration of a proton beam used for this purpose.

B. Ion Orbit Dynamics

The efficiency of the EBQA for charge stripping depends critically on properly matching the ion beam into the solenoid. A simple derivation, confirmed by the simulations shown below, gives a relationship for the properly matched ion beam radius (r_o) in the solenoid in terms of the ion charge (qe), mass (m_o), ion source normalized emittance (ε_n), and solenoid strength (B):

$$r_o = \left[\frac{2\varepsilon_n m_o c}{Bqe}\right]^{1/2},$$

where c is the speed of light.

Several types of ISOL 1+ ion sources have emittances (unnormalized) in the 2-10 π mm-mr range at 30 keV beam energy [5]. In the numerical simulations below we have used 5π mm-mr at 60 keV for the Sn beam from the ion source. From the equation above, the ion beam orbit in the solenoid scales as the square root of the ion source emittance.
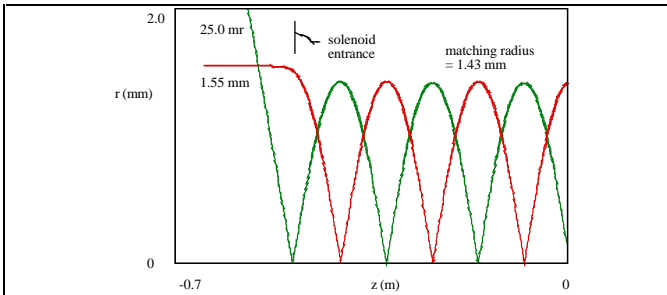
Based on conservation of generalized angular momentum, any ion which has zero angular momentum relative to the beam axis before entering the solenoid will spiral through the magnetic field on helical orbits which pass through the solenoid axis once per cycle. Numerical (ray tracing) simulations show that it is possible to match the emittance ellipse of the ion beam into the solenoid so that all ions at the perimeter of the ellipse have the same diameter helices while in the magnet, and the radius of the resulting envelope of the ion beam is given by the equation above. Results of these simulations for the ions with maximum x-value and maximum x'-value at injection are shown in Fig. 2.

C. Emittance Reduction

Figure 3 shows a calculation for the same beam as Fig. 2, but with twice the charge and half the emittance. Note that the vertical scale in Fig. 3 is one half that of Fig. 2, i.e. the projected orbit diameters are a factor of two smaller due to the higher charge state. If the charge of an ion from Fig. 2 is changed due to stripping by an electron near the solenoid axis, then its orbit changes discontinuously to one with half the projected radius, as in Fig. 3. Ions which enter the solenoid with emittance and orbits as in Fig. 2 will leave with the emittance as shown in Fig. 3, as long as the stripping occurs at radii small compared to the overall ion beam radius.

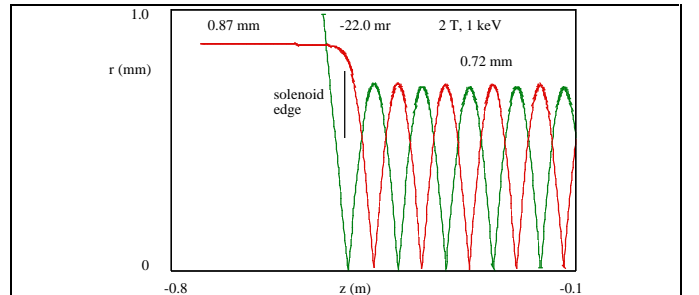Figure 4 is an end view of the ion and electron orbits in the solenoid. The projected orbits of q=1 ions are circles

Figure 2. The orbits of ions with maximum x displacement and maximum x' divergence matched into a 2 T solenoid for a ^{132}Sn^{1+} beam with 38.7π mm-mr emittance at 1 keV.

Figure 3. The orbits of ions with maximum x displacement and maximum x' divergence matched into a 2 T solenoid for a ^{132}Sn^{2+} beam with 19.1π mm-mr emittance at 1 keV.

with diameters determined by the normalized emittance of the initial ion beam (the largest circle in this diagram). All orbits pass through the axis of the solenoid due to the conservation of angular momentum. The electron beam is contained within the smallest circle in this diagram. Charge state changing occurs within the small circle. Hence, ion orbit diameters decrease in proportion to the charge state increase, and orbits continue to pass through the axis of the solenoid in the approximation that the electron beam is contained within a circle which is small relative to the ion helical orbits. It is the selective stripping of ions only very near the axis which leads to the emittance reduction effect.
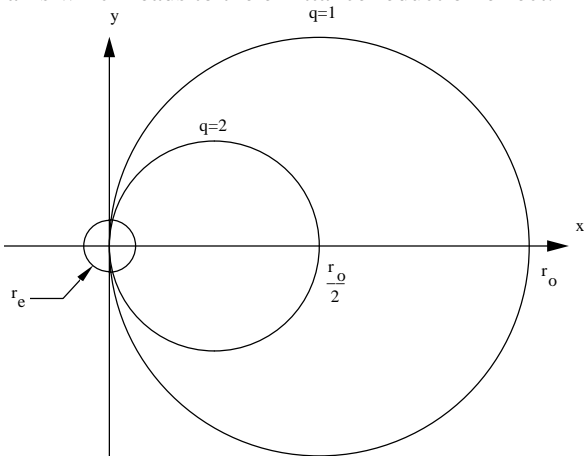

Figure 4. End view of ion and electron orbits in the solenoid.

D. Stripping Probabilities

The EBQA is potentially useful only if a significant fraction of the 1+ ions are stripped at least once in a single pass through the solenoid. With parameters given above the ions spend on the order of 30 μsec in the solenoid, so with the relative orbit diameters also given above, cross sections estimated from the Lotz formulation [13], an 8 T, 1 meter long solenoid, and an assumed 1 ampere electron beam the calculated stripping of the 1+ beam is over 50% in a single pass. For single-pass operation the peak in the 2+ yield is predicted to be about 40% as the distribution evolves from 1+ to 2+ and then to 3+ and above. For multiple-pass operation the theoretical yield into the 4+ charge state is as high as 80%.

III. SUMMARY AND DISCUSSION

The EBQA concept is potentially very useful for an advanced, high intensity accelerated radioactive beam facility such as the one under study at Argonne [14]. It would reduce the electric fields required at the front end of the post accelerator by a factor of 2-4 for single-pass or multiple-pass configurations, respectively. It also relaxes the design specifications of this section of the post accelerator due to the increased beam brightness (reduced transverse emittance) and the higher ion velocity at the accelerator entrance.

Further simulations of the intense electron beam required for the EBQA must be carried out to determine its ultimate limitations. Trade-offs between solenoid strength and length and electron beam energy and intensity will have to be studied. The stripping cross sections are higher for low energy electron beams, but injection dynamics issues are more difficult at these low energies. Since conventional EBIS devices are dedicated to the achievement of very high, nearly fully stripped ions, most experience has been accumulated for the higher energy beams required by such applications.

Detailed neutralization of the intense electron beam is required especially to avoid energy spread in the stripped ion beam due to variation in the potential across a partially neutralized e-beam.

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