ELECTRON BEAM CHARGE STATE AMPLIFIER (EBQA)-- A CONCEPTUAL EVALUATION*

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Abstract

A concept is presented for stripping low-energy, radioactive ions from 1+ to higher charge states. Referred to as an Electron Beam Charge State Amplifier (EBQA), this device accepts a continuous beam of singly-charged, radioactive ions and passes them through a high-density electron beam confined by a solenoidal magnetic field. Singly-charged ions may be extracted from standard Isotope-Separator-Online (ISOL) sources. An EBQA is potentially useful for increasing the charge state of ions prior to injection into post-acceleration stages at ISOL radioactive beam facilities. The stripping efficiency from q=1+ to 2+ (η_{12}) is evaluated as a function of electron beam radius at constant current with solenoid field, injected ion energy, and ion beam emittance used as parameters. Assuming a 5 keV, 1 A electron beam, η_{12} = 0.33 for 0.1 keV, ^{132}Xe ions passing through an 8 Tesla solenoid, 1 m in length. Multi-pass configurations to achieve 3+ or 4+ charge states are also conceivable. The calculated efficiencies depend inversely on the initial ion beam emittances. The use of a helium-buffer-gas, ion-guide stage to improve the brightness of the 1+ beams [1] may enhance the performance of an EBQA.

1 INTRODUCTION--MOTIVATION FOR THE EBQA

The production and acceleration of radioactive nuclides far from stability is an area of significant interest in nuclear physics [2,3]. Generating these nuclides in specific charge states selectively and efficiently are important goals in the development of a cost-effective Radioactive Ion Beam (RIB) facility. To increase efficiency and reduce cost, it is desirable to strip singly-ionized species to higher charge states while still at low energy in the post-accelerator. RIBs typically employ low charge state ions (usually 1+) at the front end of the post-accelerator; these ions are often generated within Isotope Separation On-Line systems (ISOLs) [4]. For A>30-60 amu, higher charge states are desired to simplify the post accelerator. For example, ISAC [5] presently under construction at TRIUMF, requires a source capable of generating heavy ions with charge to mass ratios (q/A) greater than 1/30. Elevated charge states are available at low energy from Electron Cyclotron Resonance Ion Sources (ECRIS) [6] and Electron Beam Ion Sources (EBIS) [7]. The ISOL-MAFIOS [8] system combines properties of both ECRIS and EBIS by electrostatically "catching" singly-charged ions injected into the minimum B-field ECR region; stripped ions then effuse continuously. However, ECR sources tend to generate beams of relatively large emittance and produce a broad range of charge states. The EBIS is typically a pulsed machine which generates higher charge states by first trapping ions in an electrostatic well then "cooking" them in an electron beam for a period of time. A large EBIS is planned for the REX ISOLDE facility at CERN [9]. If the 1+ ions are first accelerated by a low q/A structure, such as an RFQ, they can be stripped afterwards to higher charge states. A post accelerator based on this concept is being developed at Argonne [2,10,11]. The EBQA concept discussed here is an alternative method of increasing the charge state of a DC beam at ion source energy.

The primary components of an EBQA are presented in Figure 1. Though in principle it should be possible for the EBQA to generate ions of arbitrarily high charge state by recirculating the beams, the present analysis focuses on advancing q from 1+ to 2+.

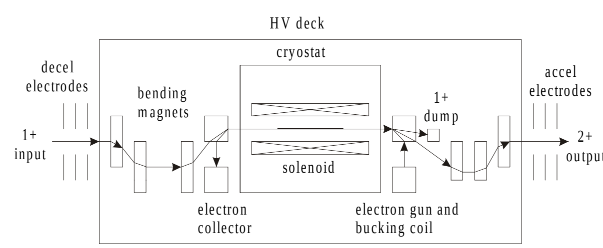

Figure 1: The EBQA in single-pass mode.

2 EBQA ANALYSIS

Simulating the detailed ion and electron orbits within the solenoid requires a full 4-D emittance distribution (e.g., f(x,x',y,y')). Angular momentum effects arise from xy' and x'y phase-space pairs. A Kapchinsky-Vladimirsky (K-V) distribution is chosen for the injected beam [12]. The solenoid is modeled as an ideal cylindrical coil. All ion trajectories are assumed to be near the axis; therefore, analytical expressions for B_z and B_r can be obtained.

2.1 Matching

To optimize stripping efficiency and minimize envelope oscillations, the ions and electrons must be

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properly matched into the solenoid. Assuming the ion starts from a shielded source (**B**=0), the matched beam radius is just twice the Larmor radius, $r_m = 2\rho_o$,

$$r_m = \left[\frac{2\varepsilon_n m_o c}{qB_{zo}}\right]^{1/2} \qquad (1)$$

where the normalized emittance is $\varepsilon_n = \beta\gamma\varepsilon_o$. Note that the matched radius is not a function of injected energy.

2.2 Electron Injection

Magnetic field at the cathode plays an important role in determining the matched e-beam radius. Because of the relatively low electron energy and high field intensity, electron rigidity is low. The cathode immersion field can be used to control the beam size within the solenoid to maximize stripping efficiency or brightness. High field and low rigidity mean that both electron gun emittance and gun alignment errors must be small.

The EBQA requires a large perveance from the electron gun; thus, space charge neutralization must occur over a short distance. The doubling distance of a 5 keV, 1 A electron beam extracted through a 1 cm^2 aperture is approximately 4 cm. The necessary neutralization of the e-beam space charge is facilitated by dc extraction. Employing a background hydrogen gas at a pressure of 10^{-6} Torr, the neutralization time, $\tau_n = (n_b \langle\sigma_{01} v\rangle)^{-1}$, is on the order of 1 ms for 5 keV electrons [13].

2.3 Stripping Efficiency--Analytical Results

Stripping efficiency in the EBQA depends upon solenoidal field intensity, beam energies, emittances, ion charge state, and stripping cross sections. Cross sections are estimated using empirical formula [14,15] or from data [16] where available. Multi-step ionization is ignored as are cross sections for excited states. Assuming uniform density profiles for both ions and electrons, stripping efficiency can be estimated. The stripping efficiency for singly-charged ions, fully immersed in the e-beam can be expressed as,

$$\eta_s(t_i) = 1 - \exp\left[-\frac{L_s \sigma_{12} I_e \beta_e}{e\pi r_e^2 \beta_i c \beta_{e\parallel}}\right] \qquad (2)$$

To determine actual efficiency, overlap of the electron and ion beams must be included (this does not take into account orbital effects). For a matched ion beam radius, r_m the efficiency is given as,

$$\eta_{12} = \eta_s(t_i)\frac{r_e^2}{r_m^2} \qquad r_e < r_m \qquad (3a)$$

$$\eta_{12} = \eta_s(t_i) \qquad r_e > r_m \qquad (3b)$$

The effect of nonlocalized charge on stripping efficiency is discussed in the following section with simulation results. In the limit where stripping efficiency is relatively weak (<10 percent) and $r_e \le r_m$, the efficiency can be approximated by Equation 4. In this case, the efficiency is roughly independent of r.

$$\eta_{12} \approx \frac{L_s \sigma_{12} I_e \beta_e}{e\pi r_m^2 \beta_i c \beta_{e\parallel}} \qquad (4)$$

Continued stripping of the 2+ beam to higher charge states must also be considered. If interest is in q=2+ only, ions stripped to higher charge states would be considered lost. The time it takes to maximize the q=2+ state may be expressed as,

$$t_{max} = \frac{\ln(\sigma_{12}/\sigma_{23})}{n_e \beta_e c(\sigma_{12} - \sigma_{23})} \qquad (5)$$

Using ^{132}Xe as an example, $\sigma_{12} = 1.5\times10^{-21}$ m^2 and $\sigma_{23} = 0.84\times10^{-21}$ m^2 at 5 keV, t_{max} = 215 µs (r_e = 0.7 mm). Inserting t_{max} into the 2+ rate equation, the maximum efficiency for the production of Q=2+ is 47.9 percent; at this time the density of q=3+ is 21.4 percent. In the single-pass mode, this represents the maximum theoretical efficiency; however, in a multipass system, one could do better if trying to attain q>2+.

2.4 Stripping Efficiency and Orbit Effects

Stripping efficiency is found to be maximized when electron and ion beam diameters are the same; however orbital effects complicate the picture. Figure 2a shows an x-y projection of two ion orbits entering the solenoid.

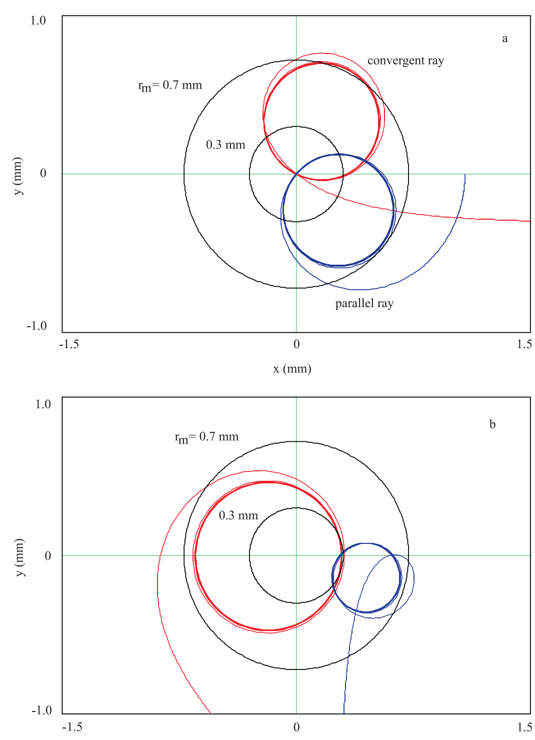

Figure 2: a) End-on view of matched orbits within the solenoid (x-y plane) starting with zero angular momentum, and b) with finite angular momentum.

The electron beam is contained within a circle of radius r_e. The ion trajectories are matched into the solenoid with a radius r_m=0.71 mm. Both trajectories enter the solenoid with zero angular momentum; however, they are separated in phase space to indicate maximum displacement and divergence. In Figure 2b, trajectories are shown which include angular momentum satisfying the K-V distribution. Stripping can only take place while ions are within the region occupied by the electron beam; i.e. $r<r_e$. Because of the complex orbits that result from the inclusion of angular momentum, it is necessary to use a numerical model to determine the stripping efficiency within an EBQA.

3 NUMERICAL MODEL

A random number generator is used to produce a set of Cartesian input phase space coordinates satisfying the K-V distribution. A predictor-corrector algorithm is employed to step each trajectory through the solenoid; this method has been benchmarked against a Runge-Kutta algorithm to insure accuracy. Depending upon initial positions in phase-space, some ions never encounter the e-beam and therefore cannot be stripped. For those ions that do enter the e-beam, a finite stripping probability is assigned. Total efficiency is determined by summing the probability for all trajectories and then dividing by the total number of particles. The trajectories possessing a nonzero stripping probability are used to calculate the emittance of the stripped, doubly-charged beam. Stripping efficiencies, determined in simulations of 2000 particles per electron beam radius are presented in Figure 3 for ion beam emittances of ε_n=0.005, 0.010, and 0.020 π-mm-mrad (ε=39, 77.5, and 155 π-mm-mrad at 1 keV, A=132 amu). The results in Figure 3 are obtained for constant e-beam current and energy (1 A, 5 keV) assuming a stripping cross section of 1.5×10^{-21}m^2. In the case of 0.1 keV injection into an 8 T field, the maximum efficiency is 38.6 percent with a charge state distribution of 33.4 percent in 2+, 4.9 percent in 3+, and 0.3 percent in 4+ and above. The stripping efficiency is seen to be inversely proportional to injected ion beam emittance.

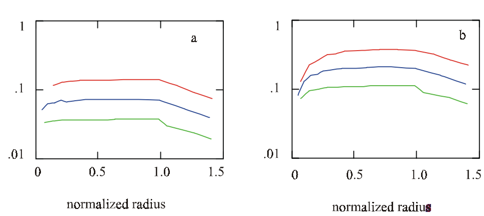

Figure 3: Stripping Efficiency versus electron beam radius at 0.005, 0.010, and 0.020 π mm mrad a) 1.0 keV, 8 T and b) 0.1 keV, 8 T.

A comparison of numerical and analytical stripping efficiency is presented in Figure 4. In this case, the injected ion beam energy and emittance are 1.0 keV and ε_n=0.005 π-mm-mr and the solenoid field strength is 8 T. Efficiency is plotted against electron beam radius assuming constant current. Near the matched radius, good agreement exists between both efficiency models; however, away from matched radius, the numerical result is larger. The deviation of the numerical result from Eq. 3 is indicative of orbital effects within the solenoid. Similar behavior is observed for the other injection cases.

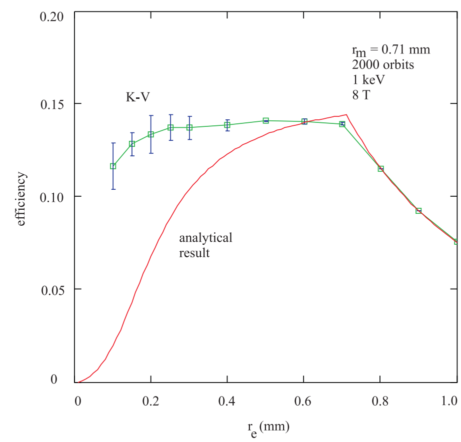

Figure 4: Comparison of numerical and analytical stripping efficiency models with electron beam radius.

4 ACKNOWLEDGEMENTS

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