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USING AN RFQ TO TRANSPORT INTENSE HEAVY ION BEAMS FROM AN ECR ION SOURCE

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Abstract

In the transport of high intensity, heavy ions from an ECR ion source through a low energy beam transport (LEBT) section, space charge can limit the transmission. It has been proposed to use a Radio Frequency Quadrupole (RFQ) to efficiently address this problem. The stray magnetic field of the ECR ion source can be used to provide focusing against the space charge blow-up by using the Direct Plasma Injection Scheme (DPIS) developed for laser ion sources. The RFQ will focus and transport the injected beam, thus eliminating most of the charge states extracted from the ECR ion source. This narrowing of the charge state distribution is a filter, reducing the low energy beam transport problem as well as the emittance growth for the desired beam. A combined extraction/matching system has been designed for direct injection into a 48.5 MHz RFQ to produce $^{238}U^{40+}$ (0.52 emA) and $^{209}Bi^{30+}$ (1.047 emA) beams. The IGUN code has been used to design the injection directly into the RFQ. The RFQ design has been modified with a pre-buncher built into the vanes to narrow the transmitted charge state distribution as much as possible. The design details of this system will be presented.

INTRODUCTION

Recent emphasis at many accelerator facilities has been to develop, extract and transport intense beams of heavy ions from high performance ECR ion sources into accelerators. The extraction of intense, heavy ion beams is by itself a challenge. Assuming that these highly charged ion beams can be extracted with high intensities, the next biggest challenge is to determine how to transport them for acceleration without large losses.

All high performance, third generation, superconducting Electron Cyclotron Resonance (ECR) ion sources, such as the VENUS(LBNL) [1], SECRAL(IMP) [2], SUSI(MSU) [3], and the SCECRIS (RIKEN) [4], operate at higher frequencies (range?) than second generation sources and hence have higher magnetic fields and plasma densities. A design study of a 56 GHz source at Berkeley showed that such an ECR source can have even higher plasma densities, since the density scales as the square root of the operating frequency [5]. Another next generation ion source, FECRAL [6], being built by the ECR group at Lanzhou, will operate at 45 GHz. In these next generation ECR ion sources, the even higher operating frequencies will result in higher plasma densities. In addition, much higher beam intensities will not only be possible by using extraction voltages higher than the 30 kV in use today in most ECR sources, but also by changing the extraction electrode aspect ratio. The beam intensity for $^{209}Bi^{30+}$ at 45 GHz is expected to be greater than 1 emA at a designed and operable extraction voltage of 50 kV. Since these high performance ECR sources use superconducting solenoids, the stray magnetic field of the source has been used in the DPI scheme to provide more focusing to overcome the space charge blow-up of the high-intensity beams for matching into an RFQ [7].

Assuming the correct matching, the RFQ must then be designed to select the ions of interest for transport and to discard all others. By matching the velocity of the desired charge state to the vane modulation in the RFQ for a given mass, only a limited number of charge states will be accelerated. This property allows the RFQ to be used as a charge/mass (Q/M) filter to obtain a reduced Q/M bandwidth, making the RFQ resemble a Paul quadrupole filter [8] where the action of the dc voltage on the electrodes is replaced by the modulation.

Our initial work on this scheme was reported earlier for uranium ions, which assumed an ion source configured to work at 56 GHz, that was scaled for output currents with data taken from the VENUS ECR ion source operated at 28 GHz [9]. In the present study, a similar high performance ECR ion source is assumed to be directly coupled to an RFQ. We have considered two ion species, uranium and bismuth ions, where the charge state distribution (CSD) data have been taken from their respective ion sources, VENUS and SECRAL II. Although the 4th generation ion source proposed by C. Lyneis *et al.* [Ref 5] would operate at 56 GHz, the FECRAL ion source being built at Lanzhou is designed to be operated at a more modest frequency of 45 GHz to further reduce the complexity as compared to 56 GHz. In this study, the RFQ has been designed to suppress most of the charge states extracted from such an ECR and act as a filter for the desired beams $^{209}Bi^{30+}$ and $^{238}U^{40+}$.

THE ECR-RFQ MATCHING SECTION

It is well known that the RFQ is very efficient for ion acceleration in the energy range from 1 keV/u to 1 MeV/u, but space charge effects dominate at the low RFQ injection energies normally used when employed for higher extracted beam intensities. Therefore, our proposal is to operate the ECR ion source at an extraction voltage of 60-70 kV to overcome the defocusing forces from the space charge in the extracted beam.

In the RFQ, the Twiss parameters depend on time (or radio frequency phase), but the Twiss parameters for the injected beam from the ion source do not vary with time. Although the PARMTEQ code is widely used for the design of an RFQ, it cannot be used for designing the proposed DPI matching system because it does not simulate the plasma meniscus and the static accelerating field. The full simulation of this problem requires matching a time independent beam from the ion source to a time dependent

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beam inside the RFQ with the fringe field of the ion source superimposed, which poses a complex matching problem. However, the design of such a combined extraction/matching section has been performed using the IGUN code [10]. The unique features of IGUN take into account the electrostatic field between the ion source and the RFQ, the stray magnetic field of the ECR source, the defocusing space charge of the intense beam, and the RF focusing in the fringe field between the RFQ electrodes and the RFQ flange [11]. In the matched beam condition, as shown in [7], the effective current becomes zero, and the result is a homogenous focusing into the RFQ using an un-modulated matching section.

DIRECT INJECTION INTO AN RFQ

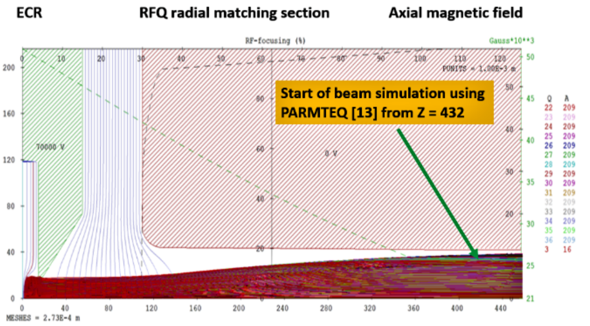
The ECR source axial magnetic field (~ 4 T maximum field generated by the superconducting solenoid) is positioned at the extraction electrode for optimum extracted beam optics, and it defines the beam size at the start of the simulation. Due to the large axial magnetic field necessary in the ECR ion source, the magnetic field extends significantly into the matching section of the RFQ (green dashed line in Fig. 1). The distance between the plasma electrode and the start of the RFQ matching section was chosen to be 28 mm. The source extraction voltage defines the beam injection energy for all extracted charge states. For the simulation, the basic plasma parameters of the electron and ion temperatures were chosen to be 5 eV and 0 eV, respectively. For a matched beam at the entrance of the RFQ channel, the variation of the axial magnetic field gives the smallest radius for different Q/M at different magnetic fields, and the radius and divergence decrease with increasing magnetic fields. Therefore, there is an optimal magnetic field for each charge state of the injected beam.

A total intensity of 25 emA was assumed for bismuth ions, with 1.047 emA of $^{209}Bi^{30+}$ ions, other charge states of bismuth, and ions of the mixing gas. While keeping the beam intensity constant in the simulation (i.e., total ion current of 25 emA), IGUN adjusts the plasma density over many iteration cycles until the loss to the aperture is compensated. The calculated results are shown in Fig. 1 for bismuth and oxygen ions (the mixing gas). The RF focusing parameter (%) for the RFQ is plotted with the values given on the vertical axis in the middle of the plot (shown as black dashed line), and the stray magnetic field from the ECR source is labelled on the right vertical axis.

THE RFQ AS A CHARGE FILTER

The unmodulated RFQ vanes (or rods) in the injection matching region focus the ions without acceleration, so all charge states are transmitted. Selecting only $^{209}Bi^{30+}$ ions for acceleration in the RFQ is not possible, but the aim was to narrow the CSD as much as possible and eliminate the oxygen carrier gas ions.

A number of RFQ design calculations were performed to narrow the output CSD. This task is generally not an easy problem, because in order to have a high current limit, one needs a large focusing force and large RFQ bore, which allows a wide selection of charge states to be focused. A final design that optimized the transmitted current is shown in Table 1.



Start of beam simulation using PARMTEQ [13] from Z = 432

Figure 1: Final IGUN design for a 25 mA $^{209}Bi^{30+}$ beam, including oxygen mixing gas ions, from a 45 GHz ECR injected directly into an RFQ.

Table 1: Design and Operating Parameters of the RFQ

Parameter	Value
Mass (M)	209
Input Energy	10.084 keV/u
Charge (Q)	30
Frequency	48.5 MHz
Aperture	1.15 cm
Vane voltage	94.0 kV
Electric field (surface)	11.45 MV/m
Bravery factor	1.3
Capacitance/m	75 pf/m
Power/m (at voltage = 90.56 kV)	0.0061 MW/m
Stored energy/m	0.3575 joules/m
Quality factor	17768
Maximum vane modulation	1.45
Focusing strength	4.354
Accelerating efficiency	0.2841
Focusing efficiency	0.7566
Vane length (incl.IGUN matching)	298 cm
Beam current limit	59.8 emA
Normalized acceptance	0.40 cm-mrad
Max capture efficiency of $^{209}Bi^{30+}$	94 %

Next, the RFQ design was modified to use a short buncher section in the front end of the RFQ just after the IGUN matching section and then another unmodulated section before the RFQ bunching and acceleration begins. This "pre-buncher" was used to reduce the width of the transmitted charge state distribution. The modified design of the final RFQ with the pre-buncher has the same length and RF power requirement as the original RFQ design without the pre-buncher.

This RFQ for $^{209}Bi^{30+}$ is almost identical to the earlier reported 48.5 MHz RFQ designed for $^{238}U^{40+}$ [9], which also had a length of 298 cm for input ions at 10.084 keV/u and output energy of 60 keV/u with an RF power of 18 kW. For the calculations that are reported here, the emittance and rms ellipse parameters were calculated using IGUN at the position Z = 432 meshes in the matching section as indicated in Fig. 1, and these values were used as input parameters to PARMTEQ [12] for calculation of the beam bunching and acceleration through the RFQ. The transverse and longitudinal beam parameters have been computed through the final RFQ design as a function of the cell number. The RFQ beam transmission, shown in Fig. 2, has a narrower charge state distribution than the beam extracted from the ECR ion source. Finally, the two assumed ECR charge state distributions are shown in Fig. 3, along with the predicted RFQ output beam current distributions for bismuth and uranium beams.

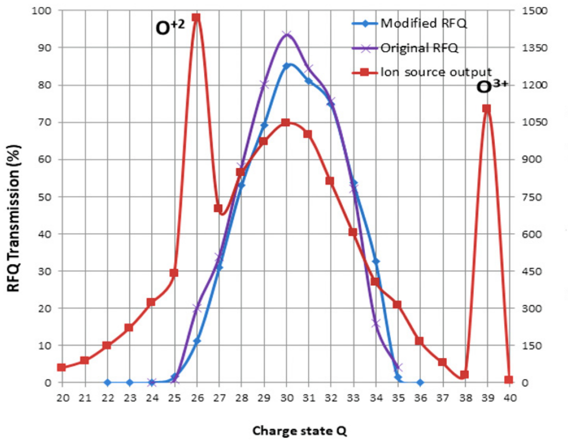


Figure 2: Transmission of ^{209}Bi ions through the modified RFQ design compared with the original design as a function of the input charge state distribution.

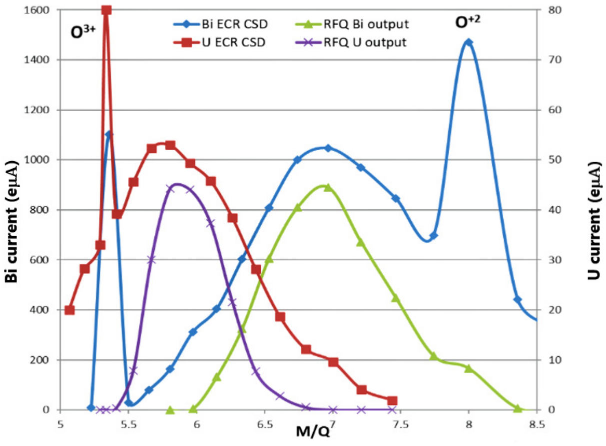


Figure 3: Input and output RFQ current distributions calculated for both bismuth and uranium beams.

DISCUSSION AND CONCLUSION

It has been shown in this study that an RFQ can be used as a charge filter to efficiently transport highly charged heavy ion beams from an ECR ion source with low emittance growth. One emphasis here has been to narrow the emerging charge state distributions. In the case of filtering a ^{209}Bi^{30+} beam, the transmission through the RFQ is 94%, while the resulting charge state distribution shows a narrowed FWHM of 60 % of the original distribution. For the case of ^{238}U^{40+}, the transmission is slightly above 90%, and the FWHM of the resulting charge state distribution has narrowed to ~62 % of the original distribution.

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