DIRECT INJECTION OF INTENSE HEAVY ION BEAMS FROM A HIGH FIELD ECR ION SOURCE INTO AN RFQ

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Abstract

Beam intensities achievable from high performance ECR sources for highly charged ions are limited by the high space charge. For high performance ECR sources, the stray magnetic field of the source can provide focusing against the space charge blow-up of the beam when used with the Direct Plasma Injection Scheme (DPIS) developed for laser ion sources. A combined extraction/matching system has been designed for direct injection into a radio frequency quadrupole (RFQ) accelerator, allowing a total beam current of 12 mA for the production of highly charged $^{238}U^{40+}$(0.49 mA) to be injected at an ion source voltage of 60 kV. In this design, the features of IGUN have been used to take into account the rf-focusing of an RFQ channel (without modulation), the electrostatic field between ion source extraction and the RFQ vanes, the magnetic stray field of the ECR superconducting solenoid, and the defocusing space charge of the ion beam. The RFQ has been designed to suppress most of the charge states extracted from the ECR, acting as a filter for the desired $^{238}U^{40+}$. This reduces the transport problem for the beam line as well as reduces the emittance for the transmitted charge states.

INTRODUCTION

High performance superconducting electron cyclotron resonance (ECR) ion sources such as the 28 GHz VENUS [1], the 24 GHz SECRAL [2] and the 28 GHz source at RIKEN [3] operate at higher frequencies than older sources and hence have higher plasma densities and magnetic fields. A new design study of a 56 GHz source by the ECR ion source group at Berkeley shows that the source can have even higher plasma densities, since the density scales as the square root of the operating frequency [4]. A new type of ECR source has been proposed recently by D. Z. Xie [5] for operation at 50 GHz. Considering the frequency scaling from 28 GHz to 56 GHz and without an increased volume of the plasma chamber, the heavy ion beam of U^{40+} produced earlier by the VENUS source [1] at an intensity of 12 μA can be extracted with an intensity of possibly as much as 0.49 mA at the higher 56 GHz operating frequency. The extraction of these intense highly charged heavy ion beams poses several problems. Generally, accel-decel extraction systems coupled to ECR ion sources have shown inherent problems extracting intense beams of highly charged ions due to sparking at the high voltages required and the poor vacuum conditions, which also limits the extraction of intense beams of highly charged ions. Hence, this type of extraction system generally fails due to problems with the high voltage power supplies. This eventually keeps the ion source from functioning smoothly and increases the downtime of the accelerator. In the applications of laser ion sources, with their much higher plasma densities, severe problems of handling intense beams due to sparking and/or beam loading are avoided by using an ingenious technique, the so-called Direct Plasma Injection scheme (DPI) [6]. This technique was utilized for transporting intense beams directly into a radio frequency quadrupole (RFQ) accelerator using the combined focusing of the gap between the ion source and the RFQ vanes (or rods) and the focusing of the rf fields from the RFQ penetrating into this gap. In this scheme, the plasma expands to the entrance of the RFQ, where the electrons are deflected by the fringe field of the RFQ and only the ions get trapped by the RFQ focusing field. Hence, space charge effects are completely controlled, with the great advantage being the ability to transport very intense beams. This technique was experimentally demonstrated for the acceleration of carbon (C^{3+}, C^{4+}, C^{5+}) and aluminum (Al^{9+}) ions with beam intensities greater than 60 mA [7].

In the case of new ECR ion sources, the development of higher operating frequencies in superconducting ECR ion sources will result in higher plasma densities. Therefore, 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. Operating at these higher extraction voltages will however result in operating the accel-decel systems at relatively higher voltages, increasing the probability of sparking. In order to circumvent this problem in conventional ECR ion source extraction systems, a proposed solution is to couple an RFQ directly to a high performance ECR ion source using the laser ion source DPI scheme. For high performance ECR sources that use superconducting solenoids, the stray magnetic field of the source can be used in the DPI scheme to provide more focusing to overcome the space charge blow-up of the beam [8]. In the present study, the RFQ has been designed to suppress most of the charge states extracted from the ECR, acting as a filter for the desired $^{238}U^{40+}$. This reduces the transport problem for the beam line as well as reduces the emittance for the transmitted charge states.

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COMBINED EXTRACTION/MATCHING SYSTEM

Since the RFQ is very efficient for acceleration in the energy range from 1 keV/u to 1 MeV/u, but space charge effects are dominant at the low energies (10 to 30 kV) and relatively higher beam intensities used for injecting beam into them, our proposal is to energize the ECR ion source to 60 kV to overcome the defocusing forces in the extracted beam due to the beam's space charge. At this extraction voltage a $V^{3/2}$ enhancement factor of 2.8 in the beam intensity is expected as compared to extraction at 30 kV. Since most existing superconducting ECR ion sources operate at ~30 kV with accel-decel extraction systems, the gain in the beam intensities is expected to be even higher at 60 kV using an improved extraction system design.

In the RFQ, the beam Twiss parameters depend on time (or radio frequency phase), but the injected beam from the ion source has constant Twiss parameters that do not vary with time. Although PARMTEQ is generally 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 one to match a time independent beam from the ion source to a time dependent beam inside the RFQ, which poses a serious matching problem. However, the design of such a combined extraction/RFQ matching section can easily be performed using the IGUN code [9]. 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 vanes and the RFQ flange [10]. It allows the user to simulate the beam from the plasma meniscus of the ECR source to the position in the RFQ where the axial acceleration starts with the modulation of the electrodes. An added advantage is that the Kapchinsky-Vladimirsky equations used in IGUN can handle axisymmetric charge density distributions of the input beam.

DETAILS OF THE DIRECT INJECTION DESIGN

The design being proposed implements the matching of the beam from a high performance 56 GHz superconducting ECR source into the matching section of an RFQ (a section without any modulation). The radial matching section of a normal RFQ is typically 4-6 cells in length and has a varying vane tip radius with a constant vane voltage along its length. For this design, a 6 cell matching section with a constant tip radius was used. No focusing element was used between the ECR source and this matching section. The ECR source extraction axial magnetic field of maximum value ~ 4 T (generated by the superconducting solenoid at the extraction side of the ECR source) is selected at the extraction electrode position for optimum extraction conditions, and it defines the beam size at the start of the simulation. The geometry of the problem as simulated in IGUN is shown in Fig. 1. 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. The distance between the plasma electrode and the start of the RFQ matching section was chosen to be 25 mm. The source extraction voltage (60 kV) defines the beam injection energy for all extracted charge states. The basic plasma parameters of the electron temperature and ion temperature were chosen to be 5 eV and 0 eV, respectively. Higher values may be more realistic at these higher frequencies as the electron temperature and ion temperature are expected to increase with frequency. However, for a first approximation, these values seem to be justified.

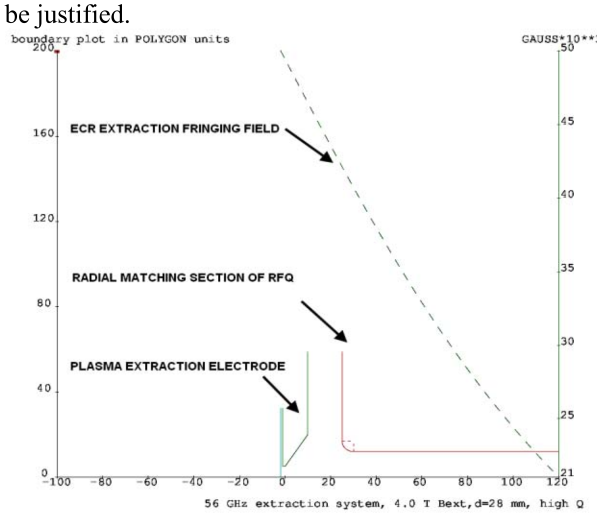

Figure 1: Geometry of the problem simulated with IGUN.

In the first series of simulations for this design, the ECR stray magnetic field was varied from low to high values to determine its effect on the focusing at the entrance of the RFQ matching section. 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 the divergence decrease with increasing magnetic fields. Therefore, there is an optimal magnetic field for each charge state of U. A total beam intensity of 12 mA consisting of 0.49 mA of $^{238}U^{40+}$ ions, other charge states of U ions and ions of the mixing gas were used, with all the beam intensities scaled from Ref. 1. While keeping the beam intensity constant in the simulation (i.e., the ion current is 12 mA), IGUN adjusts the plasma density over a number of iteration/convergence cycles until the loss to the aperture is compensated. The calculated results are shown in Fig. 2. The rf focusing parameter (%) for the RFQ is plotted with the values given on the vertical axes in the middle of the plot, and the stray magnetic field from the ECR source are labelled on the right vertical axes. In Fig. 3, the current densities and RMS emittances of the U^{40+}ions, other U^{+} charge states, and oxygen mixing gas components are shown inside the RFQ matching section (units for 1 micron = 1 mm.mrad).

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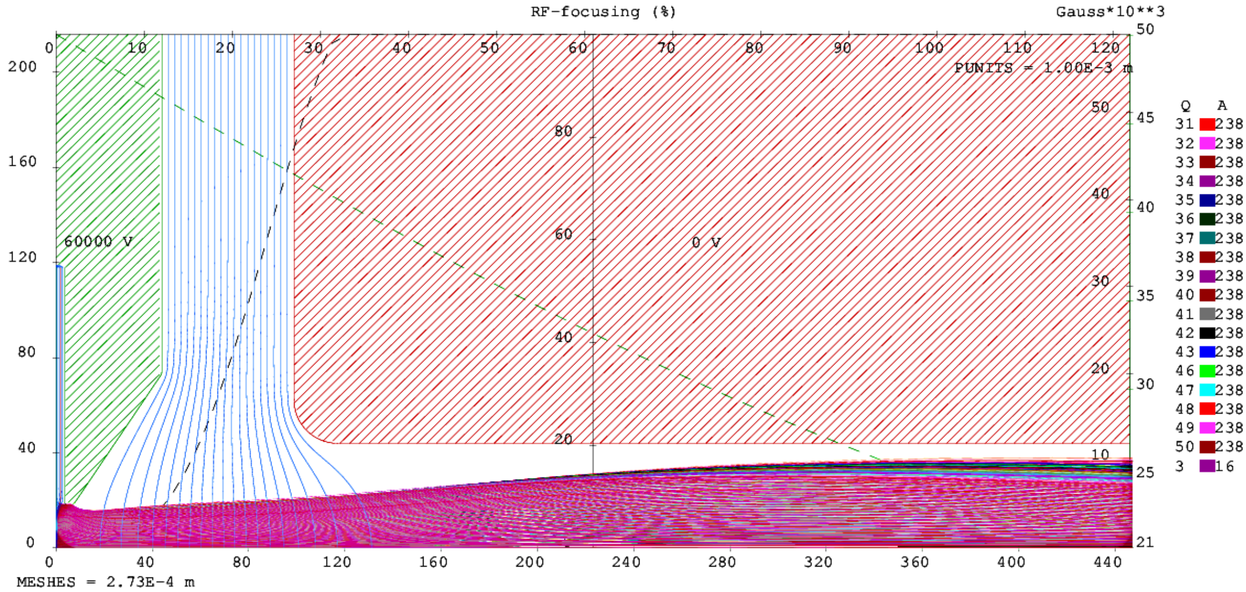

Figure 2: Optimized design for transporting a total current of 12 mA (from 56 GHz ECR source), consisting of U^{40+}, other U^{+} charge states, and oxygen mixing gas ions directly into an RFQ.

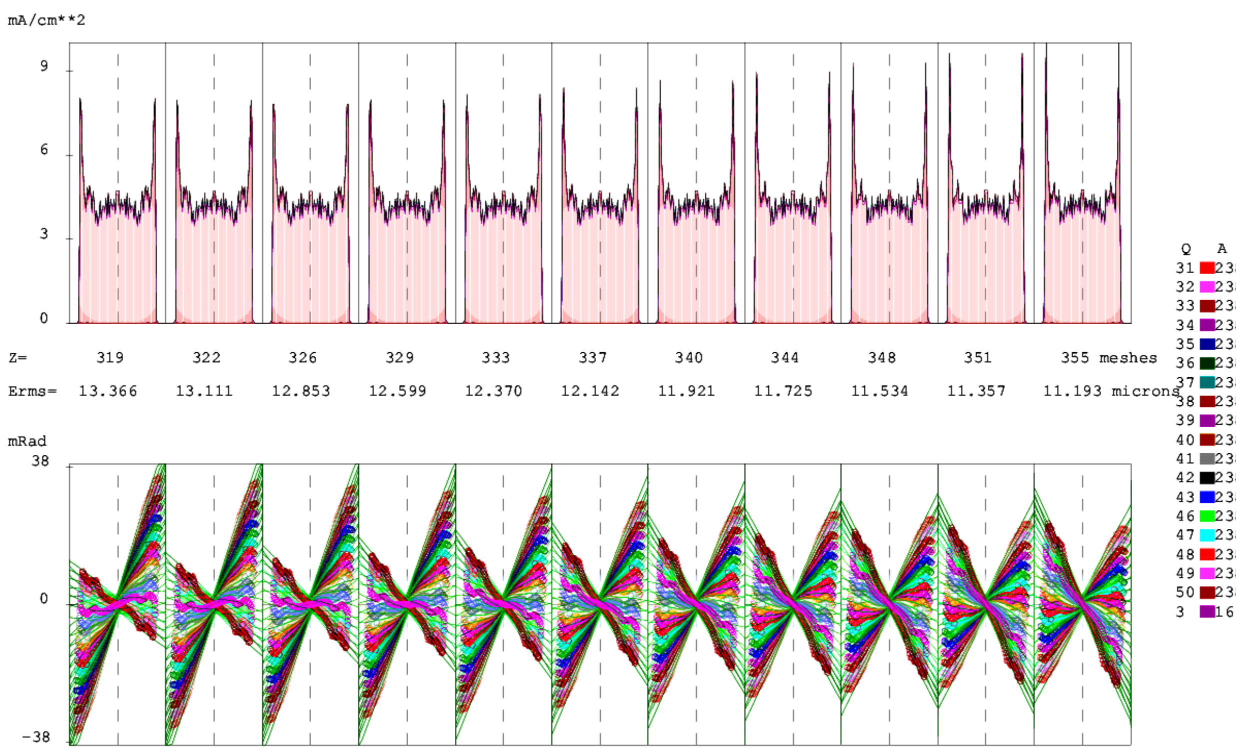

Figure 3: Current densities and RMS emittances of the U^{40+}ions, other U^{+} charge states, and oxygen mixing gas components inside the RFQ matching section.

PERFORMANCE OF THE RFQ DESIGN

The RFQ design being proposed for the 56 GHz superconducting ECR source with its extraction and direct injection uses the constant radius matching section designed above as the first section of the RFQ. The RFQ vanes then have a short modulated section with no acceleration followed by an unmodulated section, and then a gentle bunching section is used to accelerate the beam to the final output energy. The slight bunching caused by the first modulation enhances the loss of the unwanted charge states in the main acceleration, while preserving the emittance of the transmitted charge states.

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A realistic 48.5 MHz RFQ with a total length of 2.98 m and average aperture radius of 12 mm was calculated by PARMTEQ [11] assuming an injection beam energy of 10.084 keV/u for a beam of $^{238}U^{40+}$ (A/q =5.95). The results showed that > 89% transmission could be achieved for this beam and a total beam current of 12 mA can be accelerated to a final energy of 60 keV/u. Shorter RFQ cells are advantageous since the stable phase and accelerating field change very slowly over the length, resulting in the dc beam from the ion source being bunched by the RFQ with minimum emittance growth. Since the characteristic impedance of the structure depends on its type, design parameters and operating frequency, a lower operating frequency of 48.5 MHz and shorter length were chosen to minimize the RF power requirements. This 4-rod RFQ requires an rf power of only 9.2 kW. The concept of a variable energy RFQ can be easily adopted especially in the case of the 4-rod RFQ as compared to the 4-vane RFQ where the electrodes and the driving inductances are practically separable [12].

The performance of the final RFQ is shown in Fig. 4, which shows the scaled charge state distribution from the 56 GHz superconducting ECR source and the calculated final charge state distribution from the RFQ at 60 keV/u. For this calculation, the emittance parameters calculated in IGUN at the end of the fourth cell in the matching section were injected directly into the rest of the RFQ. The RFQ output has a much narrower charge state distribution than the beam extracted from the ECR ion source and does not transmit any of the O^{3+} ions extracted from the ion source carrier gas. The output phase space of the $^{238}U^{40+}$ions in the x and y planes are respectively shown in Fig. 5 and 6. The normalized RMS emittance is only 0.52 microns (mm.mrad) in the X-plane and 0.71 microns in the Y-plane.

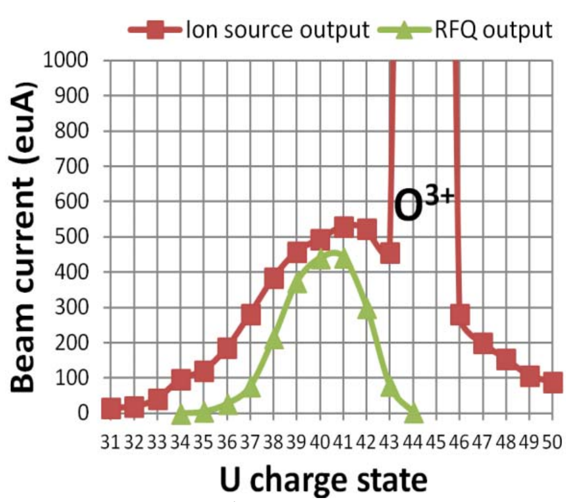

Figure 4: The scaled U^+ charge states extracted from the 56 GHz ECR and the calculated charge states transmitted through the RFQ.

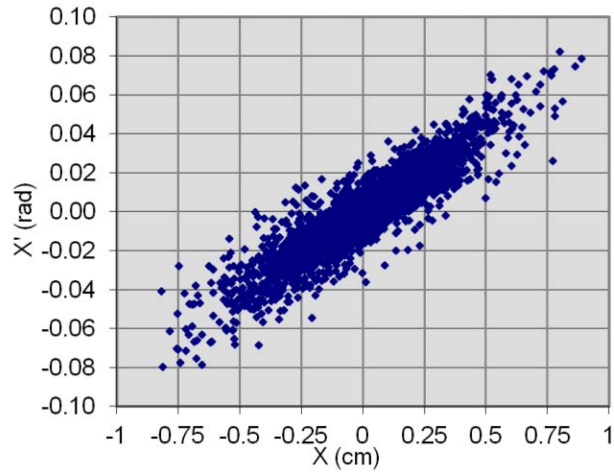

Figure 5: The calculated output phase space in the x plane of the U^{+40} charge state extracted from the 56 GHz ECR and transmitted through the RFQ.

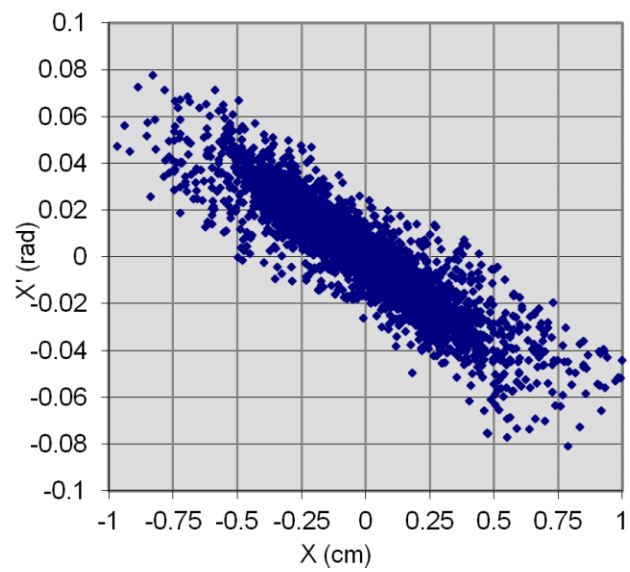

Figure 6: The calculated output phase space in the y plane of the U^{+40} charge state extracted from the 56 GHz ECR and transmitted through the RFQ.

CONCLUSION

It has been shown that a high performance ECR ion source can be coupled to an RFQ to transport intense beams of highly charged heavy ions without the problems of space charge beam blow-up and/or sparking in the extraction region. It was shown that the stray magnetic field of the ECR source is critical for a matched beam. The rf focusing in IGUN shows its versatility and simplicity to directly match the beam from the ECR source to the matching section of the RFQ.

The added advantage is that axisymmetric forms of charge density distributions can be properly matched. It is evident that such an rfq-channel might be very effective and less q/m sensitive for the extraction system of all high

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performing ECR ion sources. This technique has promising applications for injecting and transporting very intense beams into RFQ accelerators for research, ADSS and more efficient, compact neutron generators [13]. The accelerator driven sub-critical system (ADSS) being developed at various laboratories around the world to create nuclear energy may also benefit from this technique, both in terms of transporting intense beams of protons and making the low energy segment more compact. This RFQ is essentially a buncher configured as a charge filter, so RIB facilities can take advantage of this technique. The charge breeding concept can be utilised with a powerful ECR ion source directly coupled to this RFQ charge filter and then injected into an another higher frequency RFQ for additional acceleration

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REFERENCES

[1] C. Lyneis, D. Leitner,M. Leitner,C. Taylor and S. Abbott, Rev. Sci. Instrum., 81, 02A201 (2010).

[2] H. W. Zhao, W. Lu, X. Z. Zhang, Y. C. Feng, J. W. Guo, Y. Cao, J. Y. Li, X. H. Guo, S. Sha, L. T. Sun and D. Z. Xie, Rev. Sci. Instrum., 83, 02A320 (2012).

[3] Y. Higurashi, J. Ohnishi, T. Nakagawa, H. Haba, M. Tamura, T. Aihara, M. Fujimaki, M. Komiyama, A. Uchiyama and O. Kamigaito, Rev. Sci. Instrum., 83, 02A308 (2012).

[4] C. Lyneis, P. Ferracin, S. Caspi, A. Hodgkinson and G. L. Sabbi, Rev. Sci. Instrum., 83, 02A301 (2012).

[5] D. Z. Xie, Rev. Sci. Instrum., 83, 02A302 (2012).

[6] M. Okamura, T. Katayama, R. A. Jameson, T. Takeuchi, T. Hattori, Rev. Sci. Instrum., 73, 761 (2002).

[7] M. Okamura, T. Takeuchi, R. A. Jameson, S. Kondrashev, H. Kashiwagi, K. Sakakibara, T. Kanesue, J. Tamura, T. Hattori, Rev. Sci. Instrum., 79, 02B314 (2008).

[8] G. Rodrigues, R. Becker, R.W. Hamm, R. Baskaran, D. Kanjilal and A. Roy, Rev. Sci. Instrum., 85, 02A740 (2014).

[9] R. Becker, W. B. Herrmannsfeldt, Rev. Sci. Instrum.63, 2756 (1992).

[10] R. Becker, R. A. Jameson, Nucl. Instrum. Methods A558, 20 (2006).

[11] PARMTEQ, Los Alamos National Laboratory, http://laacg1.lanl.gov/laacg/services/serv_ann.phtml #parmteq

[12] A. Schempp, Nucl. Instrum. Methods, B40/41, 937 (1989).

[13] R. W. Hamm and R. Becker, Int. J. Modern Phys. Conf. Series, Vol. 27, 1460126 (2014).

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