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TRANSPORT OF INTENSE BISMUTH AND URANIUM BEAMS INTO A RADIO FREQUENCY QUADRUPOLE ACCELERATOR

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Abstract

A 48.5 MHz RFQ has been designed to transport and accelerate $^{238}U^{40+}$ (0.52 emA) and $^{209}Bi^{30+}$ (1.047 emA) beams extracted from a high performance ECR ion source. The RFQ design comprises of a pre-buncher built into the vanes to narrow the transmitted charge state distribution as much as possible. The design parameters as a function of cell length is optimised on $^{209}Bi^{30+}$. It is shown that the losses of various ions without using an inlet aperture are inevitable, but by proper coating of the vanes of the RFQ, sputtering can be minimised to a great extent. Titanium shows better results when compared with gold or copper and this has been verified using the modelling results from SRIM. The design details of matching the ECR and the RFQ and the predicted performance will be presented.

INTRODUCTION

Recent emphasis at many heavy ion accelerator facilities has been to develop, extract and transport intense beams of highly-charged, heavy ions from ECR ion sources. Assuming that these highly charged ion beams can be extracted with high intensities, the next technical challenge is to determine how to transport them without large losses of the desired ion species. All recent 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 than older sources and hence have higher plasma densities and magnetic fields. A 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 [5]. A new type of ECR source has been proposed by D.Z. Xie [6] for operation at 50 GHz. Further, an upcoming new ion source, FECRAL [7], being built by the ECR group at Lanzhou, is designed to be operated at 45 GHz. The enhancement in the beam intensity for $^{209}Bi^{30+}$ at 45 GHz is expected to be greater than 1 emA at an extraction voltage of 50 kV. Considering the frequency scaling for the VENUS ion source from 28 GHz to 56 GHz with an increased volume of the plasma chamber of a factor of 10, the heavy ion beam of $^{238}U^{40+}$ produced earlier by the VENUS source [1] at an intensity of 13 eμA can be extracted with an intensity of possibly as much as 0.52 emA at the higher 56 GHz operating frequency. The extraction of these intense highly charged heavy ion beams, however, poses several problems. Generally, conventional accelerating–decelerating systems coupled to these 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 in turn limit the extraction currents. Therefore, 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 (DPIS) [8]. This technique was utilized for injecting intense beams directly into an RFQ using the combined focusing of the gap between the ion source and 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 RFQ's fringe field and only the ions get trapped by the RFQ focusing field. Hence, space charge effects are efficiently controlled, with the great advantage being the ability to transport very intense highly-charged 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 [9].

In the case of the next generation 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 would result in operating the conventional accelerating–decelerating extraction systems at relatively higher voltages, thus 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 DPI scheme. For high performance ECR sources that use superconducting solenoids, the stray magnetic field of the source can also be used in the DPI scheme to provide more focusing in order to overcome the space charge blow-up of the beam [10].

After the correct matching is accomplished between the ion source and the RFQ, the next task is to design the RFQ to select the ion of interest for further beam transport and to

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discard the unwanted ions. Therefore, the RFQ is in principle be used as a filter in a charge/mass (Q/M) selective mode for a reduced bandwidth of Q/M. By matching the velocity of the desired charge state to the vane modulation in the RFQ, other unwanted charge states will not be focused or accelerated and will be lost in the RFQ. The RFQ will then resemble a Paul quadrupole filter [11] where the action of the dc voltage on the electrodes is replaced by the modulation.

This filtering can be very efficient for ions with larger Q/M, such as carbon and aluminium, but is restricted to several charge states being transported for much lower Q/M ion beams. Some initial work was reported in this direction for the case of uranium ions, which assumed an ion source configured to work at 56 GHz and scaled for currents with data taken from the VENUS ECR ion source operated at 28 GHz [12].

Work on charge state selective ion beam acceleration using a laser ion source directly coupled to an RFQ was reported in Ref. [13]. However, this was for low charge states of bismuth to be used primarily as a driver beam for heavy ion beam inertial fusion (HIF). Other studies, for example Ref. [14], report on use of a DPI scheme mainly for acceleration of C^{5+} ions.

In the present study, a high performance ECR ion source is assumed to be directly coupled to an RFQ that is designed for charge state selection of heavier ions with higher charge states and very high intensities. We have considered two ion species, uranium and bismuth ions, where the charge state distribution (CSD) data have been reported from existing ion sources for each specie, VENUS and SECRAL II respectfully. Although the 4th generation ion source being proposed by C. Lyneis et al. would be operated at 56 GHz, the FECRAL ion source being built by the ECR group at Lanzhou is designed to be operated at a modest frequency of 45 GHz to reduce the complexity as compared to 56 GHz. 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 [2]. It should be emphasized here that the emerging charge state distribution will be essentially narrowed down by the RFQ. This further reduces the transport problem for the beam line as well as reduces the emittance growth for the transmitted charge states as they are further accelerated.

ECR-RFQ MATCHING SECTION

It is well known that 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 and relatively higher beam intensities that are used for injecting beam into them. Therefore, our proposal is to operate the ECR ion source at an extraction voltage in the range of 60 to 70 kV (i. e., 10.084 keV/u) to overcome the defocusing forces in the extracted beam due to the beam's space charge. New ion sources which are under commissioning, such as FECRAL [7] have designed their extraction systems to be operable at 50 kV [2]. For example, at an extraction voltage of 50 kV, a $V^{3/2}$ enhancement factor of 2.15 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 conventional accelerating–decelerating extraction systems, the gain in the beam intensities are expected to be even higher, when the extraction voltage is further raised above 50 kV.

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 are constant and do not vary with time. Although the PARMTEQ code has 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 matching a time independent beam from the ion source to a time dependent beam inside the RFQ, which poses a serious matching problem. Therefore, a symmetric beam is required which has the same Twiss parameters in both the planes. However, the design of such a combined extraction/matching section can easily be performed using the IGUN code [15]. 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 [16]. In the matched beam condition, as shown in Ref. [16], the effective current becomes zero which is independent of the emittance to acceptance ratio, and the result is a homogenous focusing of the RFQ using unmodulated electrodes. Even in the case of a mismatched condition, the beam envelope will depict betatron oscillations that may finally get damped in the initial acceleration in the RFQ. The code 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. This matching technique of high current beams has been shown to be very effective [17]. An added advantage is that the Kapchinsky–Vladimirsky equations used in the IGUN code can handle axisymmetric charge density distributions of the input beam, which compared to other distributions, has only linear space charge fields and does not contribute to the emittance growth. Although, these are not fully realistic distributions, analytic computation of these fields is possible.

DIRECT INJECTION OF ECR SOURCE INTO AN RFQ

The injector design being proposed implements the matching of the beam from a high performance ECR ion source into a special matching section of an RFQ, which is a section without any vane modulation. The radial matching section of an RFQ is typically 4 to 6 cells in length and has a varying vane tip radius with a constant vane voltage along its length. However, for this design a 6-cell matching section with a constant tip radius was used with no focusing element between the ECR source and the matching section. The ECR source

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axial magnetic field (~4 T maximum value 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.

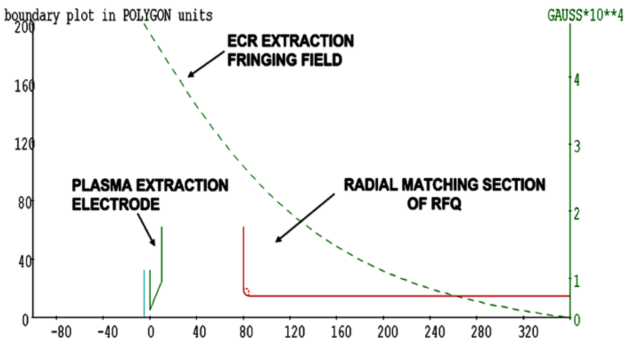

Figure 1: Model of the extraction and matching problem simulated using IGUN.

The geometry of the proposed extraction system 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 (shown as the green dashed line). The distance between the position of 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. The basic plasma parameters of the electron and ion temperatures were chosen to be 5 eV and 0 eV, respectively. Higher values may be more realistic at these higher frequencies since the electron and ion temperatures are expected to increase with frequency. However, as those values are unknown, the values chosen seem to be justified for a first approximation. 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 divergence decrease with increasing magnetic fields. Therefore, there is an optimal magnetic field for each charge state of the injected beam.

For injection of bismuth ions, a total beam intensity of 25 mA was assumed, consisting of 1.047 emA of $^{209}Bi^{30+}$ ions, other charge states of bismuth ions, and ions of the mixing gas used in the ECR. While keeping the beam intensity constant in the simulation (i. e., the total ion current is 25 emA), IGUN adjusts the plasma density over many iteration/convergence cycles until the loss to the RFQ entrance aperture has converged. The final extraction geometry and the calculated results are shown in Fig. 2 for bismuth and oxygen ions (the mixing gas). The RF focusing parameter (%) for the RFQ is plotted as the black dashed line, with the values given on the vertical axis in the middle of the plot, and the stray magnetic field from the ECR source (the green dashed line) is labelled on the right vertical axis.

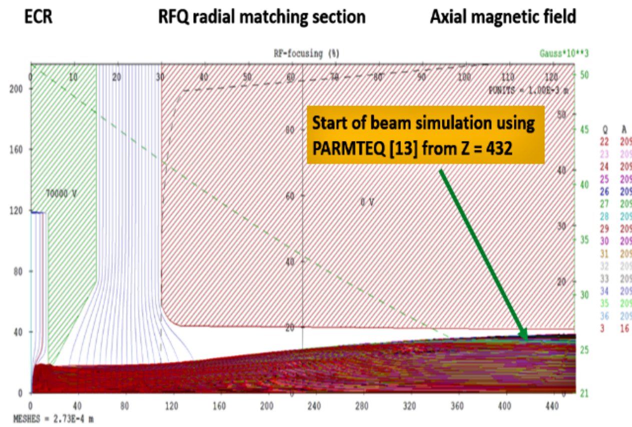

Figure 2: Optimized design using IGUN for transporting 25 emA from 45 GHz ECR ion source, consisting of $^{209}Bi^{30+}$ and other charge states, including oxygen mixing gas ions directly into the RFQ.

THE RFQ AS A CHARGE FILTER

A number of RFQ beam dynamics calculations have been performed using PARMTEQ [18] in order to sharpen the output CSD for $^{209}Bi^{30+}$. However, this is generally not an easy problem. In order to have a high current limit, one needs a large focusing force and large RFQ bore. This allows a wide selection of charge states to be focused. The unmodulated RFQ vanes (or rods) focus the ions with no acceleration, so all the charge states are transmitted. Selecting only $^{209}Bi^{30+}$ 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.

The RFQ design proposed here is a 4-rod RFQ using the constant radius matching section described above as the first stage, which matches the input beam from the ECR as calculated by IGUN. A normal RFQ was then designed to follow this matching section. The performance of this RFQ was calculated for the matched input beam. In order to operate the RFQ as a "charge filter", the normal design of a conventional RFQ with adiabatic bunching will not serve the purpose as a charge filter, since all charge states other than the designed charge state (M/Q) will also pass through the RFQ due to the large longitudinal acceptance. Here we describe the new design of the RFQ called as a charge filter. The RFQ design was modified to use a short buncher section using few cells with modulation in the front end of the RFQ just after the IGUN matching section and then another unmodulated section (drift region) before the RFQ bunching and acceleration begins. It should be noted here, that, the various sections described here are integrated into one complete RF structure. The length of this pre-buncher and drift region was adjusted in such a way that ions with different charge states can be pre-bunched separately in longitudinal phase space. This "pre-buncher" in the beginning of the RFQ was used to reduce the width of the transmitted charge state distribution, but as noted by Fuwa et al. [19], while the pre-bunching slightly reduces the transmission in the lower charge states, it also slightly shifts the transmitted ions toward the higher charge states. A further decrease of the width of the transmitted CSD can be achieved by a slight lowering of the operating vane voltage or by decreasing the modulation. However, this action reduces the $^{209}Bi^{30+}$ transmission slightly. It should be noted that the modified design of the final resulting RFQ with the pre-buncher has the same length and RF power requirement as the original RFQ design without the modifications.

The resulting realistic 48.5 MHz 4-rod RFQ has a total length of 298 cm and an average vane bore radius of 11.5 mm. Its performance was calculated using PARMTEQ, assuming an injection beam energy of 10.084 keV/u for a beam of $^{209}Bi^{30+}$ (M/Q =6.966). The results showed that >94 % transmission could be achieved for this beam, and a total beam current of 8 mA could be accelerated to a final energy of 60 keV/u. At these energies, the short RFQ cells are advantageous since the stable phase and accelerating field change very slowly over the length. Therefore, the dc beam from the ion source is 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 RFQ requires an input RF power of ~18 kW. The concept of a "variable energy" RFQ can also be easily adopted here, especially in the case of using a 4-rod RFQ as compared to using the 4-vane RFQ, since the electrodes and the driving inductances are practically separable [20].

This RFQ for $^{209}Bi^{30+}$ is almost identical to the earlier reported 48.5 MHz RFQ designed for $^{238}U^{40+}$ [12], 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 input rf power of 18 kW. The design and operating parameters of the $^{209}Bi^{30+}$ RFQ are shown in Table 1. Table 2 lists the energy and velocity levels at various sub-sections of the RFQ calculated for $^{209}Bi^{30+}$. In this table, β is defined as the ratio of the particle velocity, v to the velocity of light, c ; β = v/c. Figure 3 shows the design parameters of the RFQ as a function of cell number. This matching section replaces the normal radial matching section used in most RFQ's. For the calculations that are reported here, the emittance and rms ellipse parameters were calculated using IGUN at the position Z = 432 meshes (4.32 cm) in the matching section as indicated in Fig. 2, and these values were used as input parameters to PARMTEQ 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. These are shown in Fig. 4 for the case of $^{209}Bi^{30+}$. The RFQ beam transmission, shown in Fig. 5, has a narrower charge state distribution than the beam extracted from the ECR ion source.

Similarly, the case is shown for the $^{238}U^{40+}$ RFQ in Fig. 6, again clearly depicting the selection of a much narrower charge state distribution than the beam extracted from the ECR ion source. In both cases, as shown, the modified RFQ with the pre-buncher has a narrower charge state distribution than the original design. Finally, the two assumed ECR output current distributions are shown in Fig. 7, along with the predicted RFQ output beam current distribution for the $^{209}Bi^{30+}$ and $^{238}U^{40+}$ peaks.

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 vane voltage of 90.56 kV)	0.0061 MW/m
Stored energy/m	0.3575 J/m
Quality factor	17768
Maximum vane modulation	1.45
Focusing strength	4.354
Accelerating efficiency	0.2841
Focusing efficiency	0.7566
Vane length (including IGUN matching section)	298 cm
Beam current limit	59.8 mA
Normalized acceptance	0.40 cm·mrad
Maximum capture efficiency of $^{209}Bi^{30+}$	94 %

Table 2: Energies and Velocities Through the Various Subsections of the RFQ Calculated for $^{209}Bi^{30+}$

RFQ subsection	W [MeV]	W/u	W/Q [MeV]	β=v/c
Initial (beam entry point)	2.10	0.0101	0.0600	0.0046
Shaper	6.90	0.033	0.230	0.0084
Buncher	11.19	0.0535	0.373	0.0107
Final	12.54	0.060	0.418	0.0114
Accelerator	40.	0.191	1.333	0.018

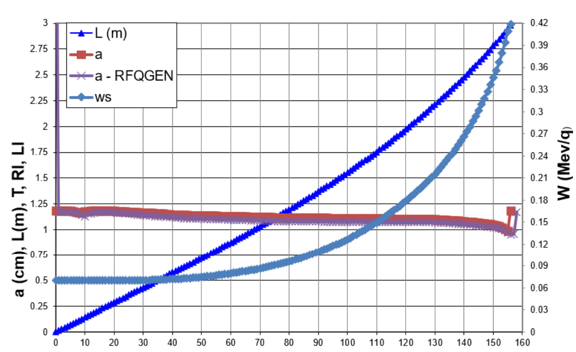

Figure 3: RFQ design parameters as a function of cell length for $^{209}Bi^{30+}$.

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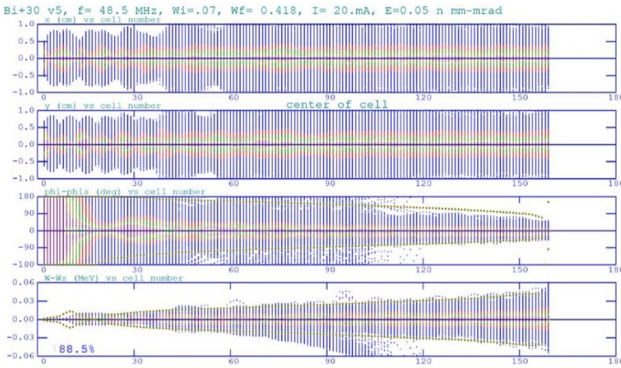

Figure 4: Transverse and longitudinal beam parameters as function of cell number in the final RFQ design for $^{209}Bi^{30+}$.

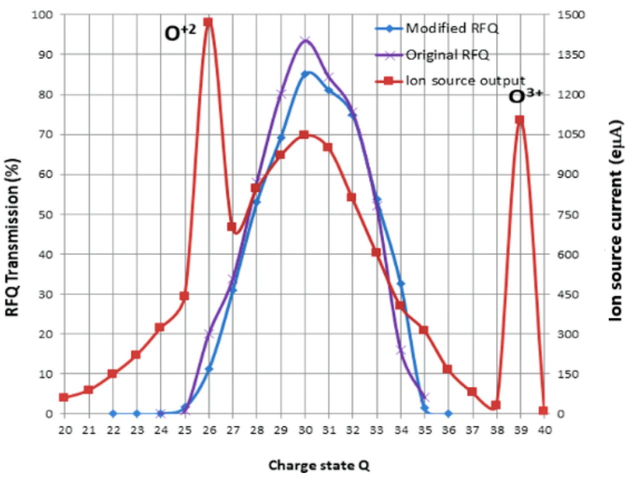

Figure 5: Transmission of ^{209}Bi ions through the modified RFQ design compared with the original design as a function of the input charge state distribution.

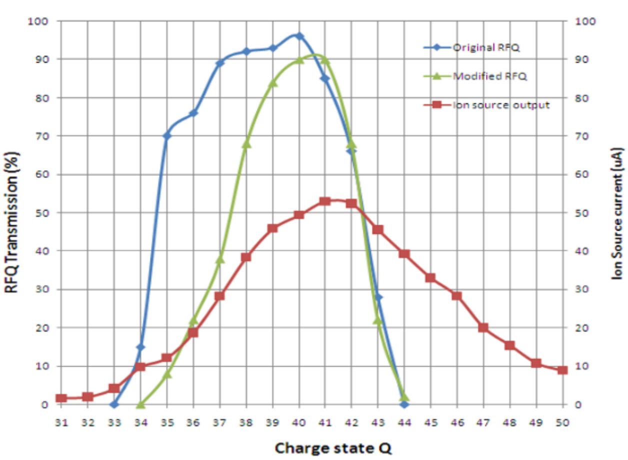

Figure 6: Transmission of ^{238}U ions through the final modified RFQ design compared with the original design as a function of the input charge state distribution.

It is to be noted here, that both the charge state distributions have been obtained from two different ion sources and the resulting widths of the emerging charge state distributions after the RFQ will be different, although the difference in their M/Q values are not substantial.

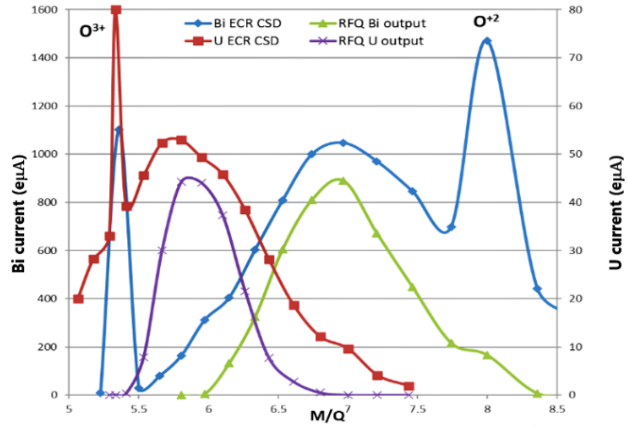

Figure 7: Input and output RFQ current distributions calculated for both bismuth and uranium beams.

BEAM LOSSES AND COOLING REQUIREMENTS

The distance between the plasma electrode of the ECR ion source and the start of the matching section of the RFQ is such that the extraction flange of the ECR extraction system can be attached to the entrance flange of the RFQ. Hence the beam power of the extracted beam, which is estimated to be a maximum of 1.5 kW assuming a total extracted ion current of 25 mA, extracted at 60 kV, is mostly deposited in the entrance of the RFQ. It is important to use an aperture at the entrance of the RFQ to avoid unwanted ions getting sputtered on the RFQ rods and further damaging them and at the same time increasing the beam transmission through the RFQ. This is a possible measure to be adopted or to be considered for improving the lifetime of the RFQ rods. Figure 8 depicts the calculated beam losses (charge states 24^+ to 35^+) all through the RFQ, considering an input of 10000 macroparticles, without using an input aperture and this may possibly result in sputtering of the RFQ rods. It is to be noted that 24^+ is predominantly lost in the first 10 cells of the RFQ and the higher charge states up to 25^+ are about 25 % of the total loss of 24^+ throughout the remaining cells

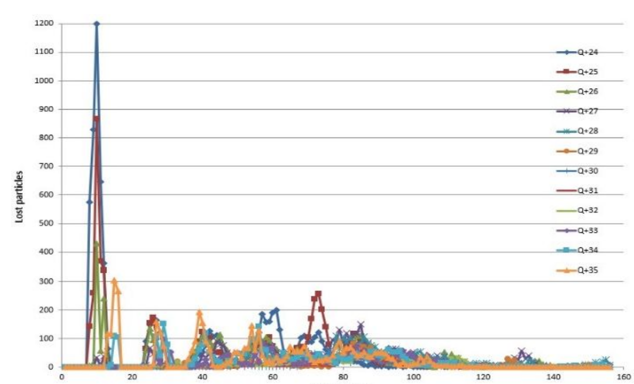

Figure 8: Beam losses calculated (charge states 24^+ to 35^+) all through the RFQ using 10000 macroparticles, without using an input aperture, and may result in sputtering of the RFQ rods.

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of the RFQ. Figure 9 shows the transmission achieved for $^{209}Bi^{30+}$ as a function of cell length. It may be important to perform a hard metal coating of the RFQ rods (instead of a thin metal coating of nickel of few mils which eventually gets sputtered out [21]) to mitigate sputtering effects resulting from the use of heavy ions. High-gradient experiments [22] suggest that titanium vane tips support higher surface fields compared to copper, up to 40 MV/m, and are more resistant against beam irradiation. In the worst case scenario, the damaged RFQ rods may be replaced with new RFQ rods, which may cause downtime of the accelerator. It should be noted that sputtering of the RFQ rods is inevitable and the suggested measures mentioned above should be seriously considered.

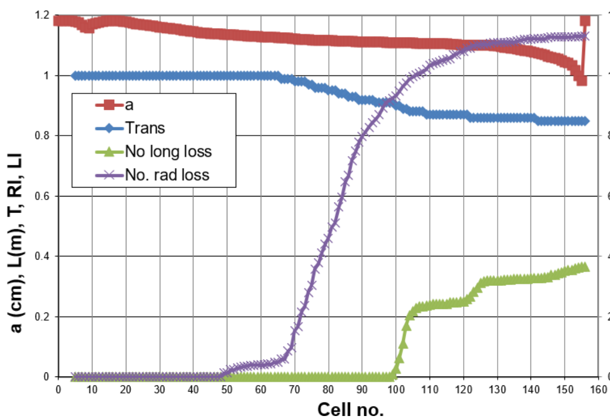

Figure 9: Transmission of $^{209}Bi^{30+}$ as a function of cell length.

The beam power of the filtered ions through the RFQ is expected to be smaller than the remaining part of the non-filtered ions. Since the beam power is very high, it is important that the RFQ entrance flange is water cooled to dissipate the heat. This will further reduce the outgassing and discharges in the extraction area. The RFQ itself will have good pumping to evacuate the gas load coming from the non-filtered ions in addition to the pumping system installed between the extraction and RFQ flanges.

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 of interest with a reduced emittance growth. It should also be obvious that the proposed RFQ structures could be designed to filter other charge states of uranium and bismuth (i. e., $^{209}Bi^{31+}$ and $^{238}U^{41+}$). It is emphasized here that the emerging charge state distributions have narrowed down. 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 down to ~62 % of the original distribution. This clearly demonstrates that the RFQ is acting as a charge filter by removing the unwanted ions and at the same time, preserving the transmission and improving the emittance with acceleration. The filtered ions, consisting of the unwanted charge states and the carrier gas ions, are lost inside the RFQ.

This technique has the advantage that axisymmetric forms of charge density distributions can be properly matched from the ECR directly into the RFQ. It is evident that such an RFQ channel is very effective and less M/Q sensitive for the extraction system of all high performance ECR ion sources. This technique has promising applications for injecting and transporting very intense beams into RFQ accelerators for research, Accelerator Driven Sub-critical Systems (ADSS), and more efficient, compact neutron generators [23]. The 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. The charge breeding concept can be utilized with a powerful ECR ion source directly coupled to this RFQ charge filter and then injected into another higher frequency LINAC for additional acceleration.

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REFERENCES

[1] C. Lyneis, D. Leitner, M. Leitner, C. Taylor, and S. Abbott, "The third generation superconducting 28 GHz electron cyclotron resonance ion source VENUS", *Rev. Sci. Instrum.*, vol. 81, p. 02A201, 2010. doi:10.1063/1.3271135

[2] H.W. Zhao *et al.*, "Superconducting ECR ion source: From 24-28 GHz SECRAL to 45 GHz fourth generation ECR", *Rev. Sci. Instrum.*, vol. 89, p. 052301, 2018. doi:10.1063/1.5017479

[3] G. Machicoane *et al.*, "First Results at 24 GHz with the Superconducting Source for Ions (SuSI)", in *Proc. ECRIS'14*, Nizhny Novgorod, Russia, Aug. 2014, paper MOOMMH03, pp. 1-4. https://jacow.org/ECRIS2014/papers/moommh03.pdf

[4] Y. Higurashi, H. Haba, M. Kidera, T. Nakagawa, J. Ohnishi, and K. Ozeki, "Recent Developments of RIKEN 28 GHz SC-ECRIS", in *Proc. ECRIS'16*, Busan, Korea, Aug.-Sep. 2016, pp. 10–13. doi:10.18429/JACoW-ECRIS2016-MOBO04

[5] C. Lyneis, P. Ferracin, S. Caspi, A. Hodgkinson, and G.L. Sabbi, "Concept for a fourth generation electron cyclotron resonance ion source". *Rev. Sci. Instrum.*, vol. 83, p. 02A301, 2012. doi:10.1063/1.3655527

[6] D.Z. Xie, "A new structure of superconducting magnetic system for 50 GHz operations", *Rev. Sci. Instrum.*, vol. 83, p. 02A302, 2012. doi:10.1063/1.3655530

ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-TUP13

[7] G. Machicoane *et al.*, "Recent Advance in ECR Ion Sources", in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 31–36. doi:10.18429/JACoW-NAPAC2019-MOYBB2

[8] M. Okamura, T. Katayama, R.A. Jameson, T. Takeuchi, and T. Hattori, "Simulation of direct injection scheme for RFQ linac", *Rev. Sci. Instrum.*, vol. 73, p. 761–763, 2002. doi:10.1063/1.1430044

[9] M. Okamura *et al.*, "Simulation of direct injection scheme for RFQ linac", *Rev. Sci. Instrum.*, vol. 79, p. 02B314, 2008. doi:10.1063/1.1430044

[10] G. Rodrigues, R. Becker, R.W. Hamm, R. Baskaran, D. Kanjilal, and A. Roy, "The direct injection of intense ion beams from a high field electron cyclotron resonance ion source into a radio frequency quadrupole", *Rev. Sci. Instrum.*, vol. 85, p. 02A740, 2014. doi:10.1063/1.4861405

[11] W. Paul and H. Steinwedel, "Notizen: Ein neues Massenspektrometer ohne Magnetfeld", *Z. Naturforsch. A*, vol. 8, no 7, pp. 448–450, 1953. doi:10.1515/zna-1953-0710

[12] G. Rodrigues, R. Becker, R.W. Hamm, and D. Kanjilal, "Direct Injection of Intense Heavy Ion Beams from a High Field ECR Ion Source into an RFQ", in *Proc. ECRIS'14*, Nizhny Novgorod, Russia, August 2014, paper MOPPH006, pp. 52–56. https://jacow.org/ECRIS2014/papers/mopph006.pdf

[13] Y. Fuwa, S. Ikeda, T. Kanesue, M. Okamura, and Y. Iwashita, "Charge State Selective Ion Beam Acceleration Using the RFQ Linac", *RIKEN Accel. Prog. Rep.*, vol. 48, p. 198, 2015. https://www.nishina.riken.jp/researcher/APR/APR048/pdf/198.pdf

[14] J. Tamura, Y. Fuwa, T. Kanesue, and M. Okamura, "Charge State Selective Ion Beam Acceleration with RFQ Linac", in *Proc. HIAT2015*, Yokohama, Japan, Sep. 2015, paper WEPB11, pp. 216–218. doi:10.18429/JACoW-HIAT2015-WEPB11

[15] R. Becker and W.B. Herrmannsfeldt, "IGUN–A program for the simulation of positive ion extraction including magnetic fields", *Rev. Sci. Instrum.*, vol. 63, p. 2756, 1992. doi:10.1063/1.1142795

[16] R. Becker and R.A. Jameson, "Emittance growth as mesh artefact", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 558, pp. 32-35, 2006. doi:10.1016/j.nima.2005.11.009

[17] R. Becker, "RFQ Matching for Current Dominated Ion Beams", in *Proc. EPAC'92*, Berlin, Germany, Aug. 1992, pp. 816–818. https://jacow.org/e92/PDF/EPAC1992_0816.PDF

[18] K.R. Crandall and T.P. Wangler, "PARMTEQ—A beam dynamics code for the RFQ linear accelerator", *AIP Conf.Proc.*, vol. 177, pp. 22-28, 1988. doi:10.1063/1.37798

[19] Y. Fuwa, S. Ikeda, M. Kumaki, T. Kanesue, M. Okamura, and Y. Iwashita, "Beam Dynamics of Multi Charge State Ions in RFQ Linac", in *Proc. LINAC'14*, Geneva, Switzerland, Aug. 2014, paper MOPP112, pp. 317–319. https://jacow.org/LINAC2014/papers/mopp112.pdf

[20] A. Schempp, "RFQ ion accelerators with variable energy", *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 40/41, pp. 937–942, 1989. doi:10.1016/0168-583X(89)90511-9

[21] J. Staples, "Beam dynamics and vane geometry in the LBL heavy ion RFQ", in *Proc. PAC'83*, Santa Fe, NM, USA, March 1983, pp. 3533–3535. https://jacow.org/p83/PDF/PAC1983_3533.PDF

[22] H.W. Pommerenke, G. Bellodi, A. Grudiev, S. Kumar, and A.M. Lombardi, "Beam Dynamics and RF Design Studies for the New RFQ for CERN Linac4 Upgrade", in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 430–433. doi:10.18429/JACoW-LINAC2022-TUPOPA10

[23] R.W. Hamm and R. Becker, "The Design of a Compact RFQ Neutron Generator", *Int. J. Modern Phys. Conf. Series*, vol. 27, p. 1460126, 2014. doi:10.1142/S2010194514601252