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DESIGN OF A CONTINUOUS WAVE HEAVY ION RFQ FOR BISOL

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Abstract

The Beijing isotope separation online (BISOL) facility will be used to study the new physics and technologies at the limit of the nuclear stability. The post accelerator for BISOL facility aims to accelerate radioactive beams to 150 MeV/u. As an injector for the downstream superconducting linac, a 4-vane RFQ operating at 81.25 MHz is needed to accelerate high-charge-state ions such as $^{132}Sn^{22+}$ from 3 keV/u to 500 keV/u in CW mode. We have compared two kinds of beam dynamics of BISOL RFQ with and without a Multi-Harmonic Buncher (MHB) bunching the continuous wave beam up-stream of the RFQ. The results indicate that it is possible to keep transverse emittance growth within tolerable limits while the longitudinal emittance is much smaller than the design without an external buncher. The acceleration of multi-charge beams simultaneously in the RFQ is also discussed in this paper.

INTRODUCTION

Peking University (PKU) and China Institute of Atomic Energy (CIAE) are jointly proposing to construct the Beijing Isotope-Separation-On-Line Neutron-Rich Beam facility [1]. This facility aims at both basic science and application goals, and is based on both reactor and accelerator-driven systems, as shown in Fig. 1. The reactor-driven system is relying on the existing China Advanced Research Reactor (CARR) at CIAE. The accelerator-driven system, accelerating high intensity deuteron beams to 40 MeV, will run as an intense accelerator-driven neutron source [2]. The radioactive ion beam comes from the ISOL target will be highly charged and accelerated to 150 MeV/u by the post accelerator. This radioactive beam can further be going under in-flight fragmentation to generate most neutron rich beams.

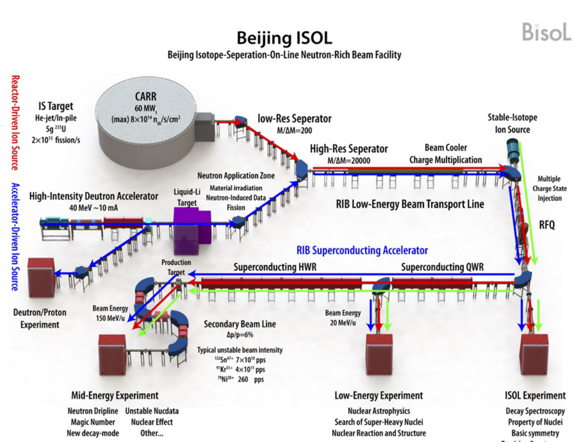

Figure 1: Layout of BISOL project.

The main components of the post accelerator will consist of a Stable Beam Ion Source (SBIS), a Charge State Breeder (CSB), a Low Energy Beam Transport line (LEBT), a Radio Frequency Quadrupole accelerator (RFQ), a Medium Energy Beam Transport line (MEBT), a Superconducting (SC) linac including Quarter-Wavelength Resonators (QWR) and Half-Wavelength Resonators (HWR), and a High Energy Beam Transport line (HEBT). The BISOL RFQ will operate as a CW injector for high-charge-state heavy-ion beams.

RFQ DYNAMICS DESIGN

After the RFQ, the ion beam will be transported and matched into the SC linac by the MEBT. The longitudinal emittance at the exit of the RFQ is an important parameter for the operation of the following accelerator. The design goals are the minimization of the longitudinal and transverse emittance.

The beam dynamics simulations of the RFQ were performed with the PARMTEQ code [3]. In previous designs of the RFQ [4], the reference particle was $^{132}Sn^{21+}$ and the output energy was 300 keV/u. The low output energy of the RFQ will increases the design difficulty of the SC linac. In addition, the longitudinal output emittance was larger without pre-bunching.

To obtain a low output emittance, an external harmonic buncher will be used to generate a small longitudinal emittance beam. In order to get credible simulation results, the output from the LEBT was used as the input beam distribution for PARMTEQ, as shown in Fig. 2. The RFQ will only accept the well-bunched core particles for further acceleration avoiding capture of the small fraction particles in the tails of the distribution.

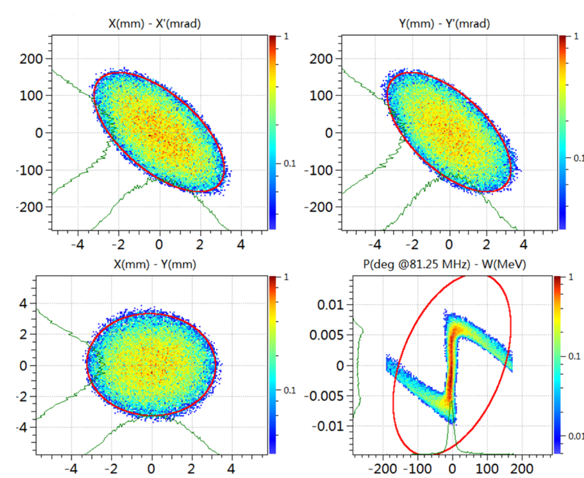

Figure 2: Input beam distribution.

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The main RFQ parameters are described in Table 1. The nominal inter-vane voltage is 70 kV and the maximum peak field value is kept at a conservative level of 1.58 Kilpatrick [5], lower than FRIB [6] which also works in CW mode. The average aperture has been maintained constant to simplify the machining. The transmission is better than 95% and no transverse emittance growth is observed in the simulation. The longitudinal rms emittances are equal to 0.20 keV/u·ns for the $^{132}Sn^{22+}$.

Table 1: Key Parameters of RFQ

Parameter	Value
Reference particle	$^{132}Sn^{22+}$
Q/A	1/6
Frequency [MHz]	81.25
Input beam energy [keV/u]	3
Output beam energy [keV/u]	504
Vane length [mm]	5604
Peak beam current [pmA]	0.1
Duty factor [%]	100
Inter-vane voltage [kV]	70
Maximum peak electric field [MV/m]	16.70
Kilpatrick coefficient	1.58
Minimum aperture radius [mm]	3.60
Average aperture [mm]	5.73
Synchronous phase [deg]	-90~-25
Modulation factor	2.07
Trans. output nor.rms.emit. [pi mm·mrad]	0.19
Long. output nor.rms.emit. [keV/u·ns]	0.20
Longitudinal emittance [keV/u·ns] @99.9%	5.31
Transmission efficiency [%]@elimit=1.5MeV	95.6

It can be seen from Table 2 and Fig. 3 that the pre-bunched scheme will shorten the length of the RFQ by nearly 1 m and can produce a smaller longitudinal output emittance. But the transmission efficiency of this scheme is only about 80% (LEBT+RFQ).

The pre-bunched scheme can be more suitable for the simultaneous transmission of multi-charge-state beams. And at this time, different charge-state particles are in different rf cycles. Finally, we adopt the dynamics design with an external buncher.

Table 2: Comparison of RFQ Parameters

Parameter	Value	
MHB	No	Yes
Output energy [keV/u]	506	504
Vane length [mm]	6567	5604
Trans. input nor.rms.emit. [pi mm·mrad]	0.25	0.20
Trans. output nor.rms.emit. [pi mm·mrad]	0.23	0.19
Long. output nor.rms.emit. [keV/u·ns]	0.31	0.20
Long. emittance [keV/u·ns] @99.9%	5.33	5.31
Long. emittance [keV/u·ns] @98.0%	3.11	2.24
Long. emittance [keV/u·ns] @95.0%	2.18	1.45
Long. emittance [keV/u·ns] @90.0%	1.50	0.95
Transmission efficiency [%]	98.1	95.6

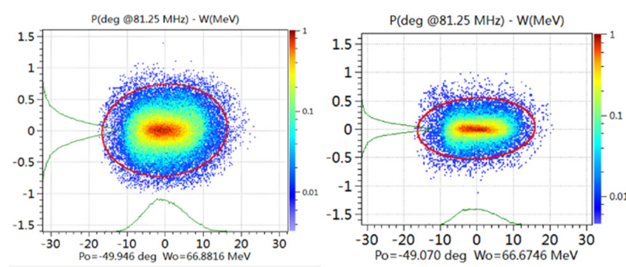

Figure 3: Longitudinal phase space at the exit of the RFQ without MHB (left) and with MHB (right).

The main RFQ parameters along the RFQ are plotted in Fig. 4, where B is the radial focusing strength, a is the minimum radial aperture, φ_s is the synchronous phase, w_s is the kinetic energy of the synchronous particle and m is the vane modulation factor. The beam transmission along the accelerating cells simulated by PARMTEQM is shown in Fig. 5.

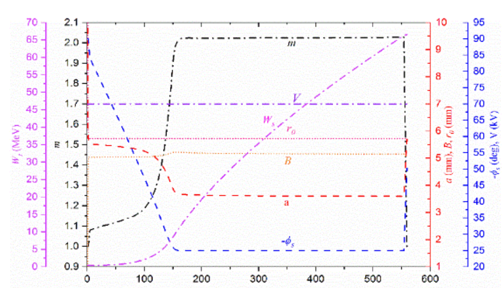

Figure 4: Main RFQ dynamics parameters.

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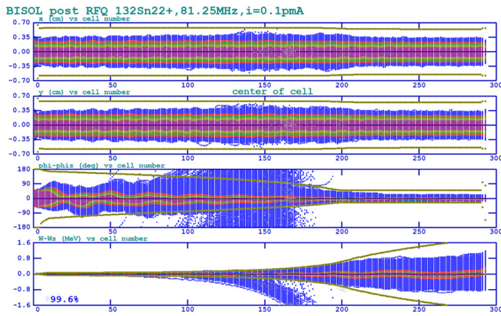

Figure 5: Beam transmission along the RFQ (Plots from top to bottom are the beam profiles in x and y planes, phase and energy spectrums respectively).

Figure 6 presents the beam loss distribution along the RFQ with position and energy. Most of the lost particles are in low energy section, the deposited power is small.

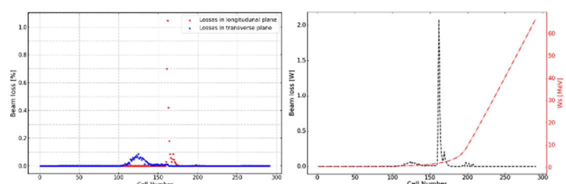

Figure 6: Lost particles (left) and deposited power (right) along the RFQ accelerating cells.

ERRORS STUDY

Non-ideal input beams have been simulated using PARMTEQM code. We evaluated the transmission efficiency under different input beam parameters, including the input beam Twiss parameters, beam tilt, beam current and beam emittance. The results are shown in Fig. 7.

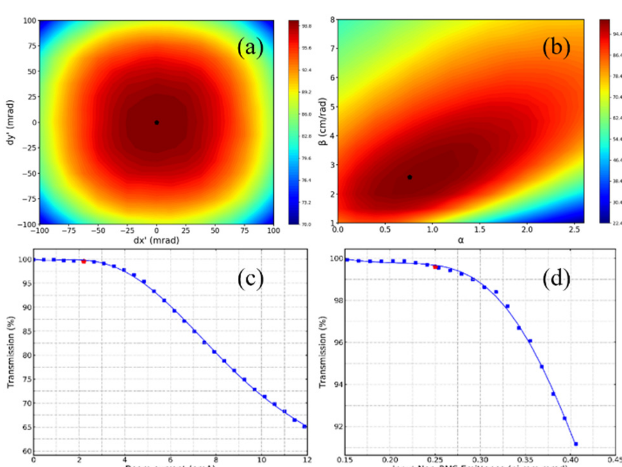

Figure 7: Transmission efficiency of the RFQ behavior versus (a) beam Twiss parameters; (b) beam tilt; (c) beam current; (d) beam emittance.

The results of error analysis show that this design is not very sensitive deviations from the ideal input beam parameters, and this design has a large redundancy.

MULTI-CHARGE-STATE BEAMS ACCELERATION

The high-charge-state ions have close charge-to-mass ratios, and can be simultaneously injected into the RFQ to improve beam intensity. They have similar transverse parameters at the entrance of the RFQ. Therefore, we assume that the transverse parameters for each ion beam are the same. The phase space of the multi-charge-state beams at the RFQ exit is plotted in Fig. 8, where $^{132}Sn^{22+}$, $^{132}Sn^{21+}$ and $^{132}Sn^{23+}$ were plotted in the same spaces, although they were separated.

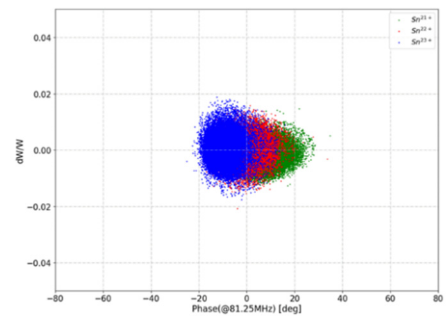

Figure 8: Phase space distributions of multi-charge-sate beams at the exit of RFQ.

CONCLUSION

A CW RFQ operating at 81.25 MHz has been designed for the BISOL post-accelerator. Beam dynamics simulations show the RFQ can produce low output emittance with the input from the LEBT. The error analysis has shown that the design has a wide compatibility margin. Additionally, we studied the transmission of multi-charge-state beams in this RFQ.

REFERENCES

[1] Baoqun. Cui *et al.*, "The Beijing ISOL initial conceptual design report", *Nuclear Instruments and Methods in Physics Research,* vol. 317, pp. 257-262, Dec. 2013. doi:10.1016/j.nimb.2013.07.059

[2] S.X. Peng, F. Zhu, *et al.*, "The deuteron accelerator preliminary design for BISOL", *Nuclear Instruments and Methods in Physics Research*, vol. 376, pp. 420-424, Jun. 2016. doi:10.1016/j.nimb.2016.01.008

[3] K. R. Crandall and T. P. Wangler, "PARMTEQM-A beam dynamics code for the RFQ linear accelerator", LA-UR-88-1546. doi:10.1063/1.37798

[4] P. P. Gan, H. P. Li, Z. Wang, *et al.*, "CW RFQ design and investigation for multi-charge-state acceleration of radioactive beams from BISOL", *Journal of Instrumentation*, vol. 13, no. 9, p. T08002, Aug. 2008. doi:10.1088/1748-0221/13/08/t08002

[5] W. D. Kilpatrick, "Criterion for Vacuum Sparking Designed to Include Both rf and dc". *Review of Scientific Instruments*, vol. 28, pp. 824-826, 1957. doi:10.1063/1.1715731

[6] G. Pozdeyev *et al.*, "FRIB front end construction and commissioning", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 58-62. doi:10.18429/JACoW-IPAC2018-MOZGBF1