

DESIGN AND COMMISSIONING OF A CW HEAVY ION RFQ*

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Abstract

A CW RFQ for heavy ions is designed as the new injector for Separated Sector Cyclotron(SSC) at Institute of Modern Physics, Lanzhou, China. Now the RFQ have been installed in the main hall and the beam commissioning has been done. This paper will introduce the design consideration of the beam dynamics, the HF structure and the cooling structure design, measurement of the cold model, high power test of RFQ and the beam commissioning result.

INTRODUCTION

The Heavy Ion Research Facility in Lanzhou(HIRFL) is an heavy ion accelerator complex at institute of modern physics in Lanzhou, China. This facility can supply most kinds of ions in China. It is composed by superconductor ECR high charge state ion source, Sector Focus Cyclotron(SFC), Separated Sector Cyclotron(SSC) and Radioactive Ion Beam Line(RIBLL). The cooling storage ring(CSR) have been built downstream HIRFL in 2008 and accelerate heavy ion out of HIRFL to 3GeV[1]. HIRFL-CSR complex can supply the beam condition to radioactive nuclear beam physics, material science, life science and aerospace science research. The figure.1 a show the sketch of HIRFL-CSR complex. HIRFL can supply heavy ion beam in these different modes: SFC only, SFC+SSC, SFC+CSR, SFC+SSC+CSR. In all these modes, SFC must be included. SFC was built in 1958 and worked over 7000 hours per year. The output beam from the SFC is very low(just uA). It can't satisfy the current beam requirement of research. So a new SSC-LINAC is considered to work as a new injector for SSC[2]. Both injection to CSR and low energy heavy ion experiment is considered in SSC-LINAC physical design. The CW RFQ is the key part of the SSC-LINAC. Many kinds of ions with different charge-to-mass ratio from 1/3 to 1/7 can be accelerated to 143keV/u by this CW RFQ with 53.667MHz operating frequency. The CW RFQ design means the stricter beam dynamics design, more stable mechanical design. Several CW RFQ have been built and operated[3-5]. The experience of them is helpful for design, measurement and operation of our RFQ. This paper will report the overall design, cold model measurement, high power test and preliminary beam commissioning result.

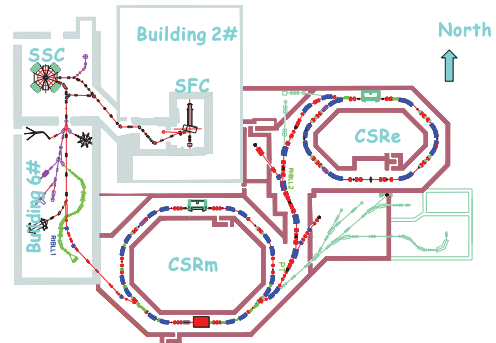


Figure 1: Sketch of HIRFL-CSR complex.

BEAM DYNAMICS DESIGN

The CW RFQ is designed to accelerate different species of ions, which require the RFQ stably operates in a wide range of RF power. The beam dynamics is designed based on the $^{238}\text{U}^{34+}$ with the current of 0.5 pA (17 emA) because the maximal power is needed to accelerate $^{238}\text{U}^{34+}$. Several key points which are considered in beam dynamics design are listed below.

1. The balance between acceptance and inter-vane voltage is considered to choose a proper aperture.
2. The vane modulation factor m is lower than 2 to keep a enough safety margin in CW operation mode.
3. The parametric resonance should be avoided in the design since the parametric resonance of transverse and longitudinal phase advance cause the emittance growth obviously.
4. The space charge of beam should be considered to avoid the beam loss caused by mismatch between the beam and the focusing structure.

The PARMTEQM code is used to design and optimize the beam dynamics. The TOUTATIS is used to check the beam dynamics design. The result of these two code agrees very well. The designed parameter of RFQ is listed in table1. The figure 2 show the changes of main parameter along the longitudinal direction. The transmission efficiency change because of non-ideal beam parameter is also analyzed. The result (figure 3) show that the RFQ are not very sensitive to initial beam parameter and have a very large acceptance.

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Table 1: Parameters of Beam Dynamic Design

parameter	values
frequency (MHz)	53.667
ion	$^{238}\text{U}^{34+}$
Charge to mass ratio	1/7
Current (pmA)	0.5
Input energy (keV/u)	3.728
Output energy (keV/u)	143
Duty factor	100%
Inter-vane voltage (kV)	70
Maximum surface field (MV/m)	14.0928
Kilpatrick factor	1.523
Minimum aperture a (cm)	0.472
Modulation factor m	1.94
Synchronous phase ϕ_s	$-90^\circ \sim -30^\circ$
Length of the vanes (cm)	250.846
Transmission efficiency	94.1%

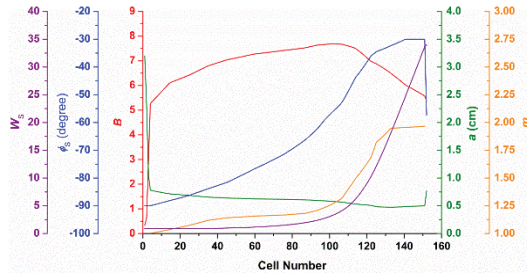


Figure 2: Curves of RFQ's main parameters along the longitudinal direction.

RF AND MECHANICAL DESIGN

The MWS software is used to simulate the four-rod RFQ cavity. The target of RF design is to decrease the power loss, to tune the field distribution along the longitudinal direction and to give the design of tuner and power coupler. Two model is built for simulation of RFQ.

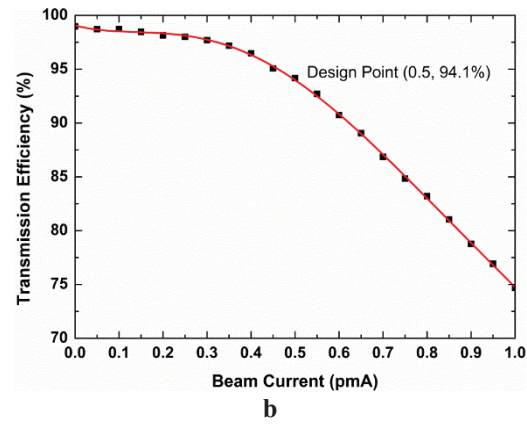
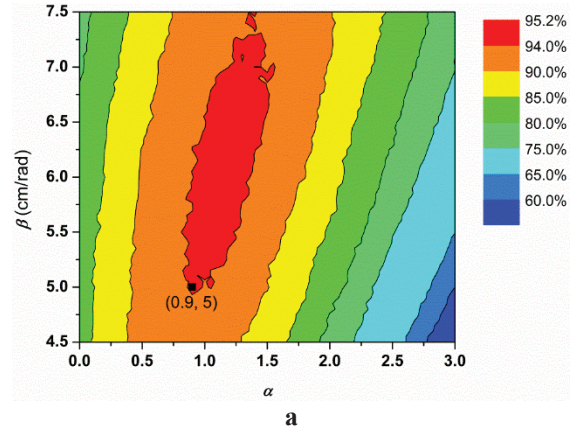


Figure 3: transmission efficiency versus the a) twiss parameter b) beam current c) energy spread d).

Table 2: Simulation Results of Two Model

Vane	Parameters	Values
Modulation	Frequency / MHz	52.967
	Q_0 Value	6560
	Shunt Impedance / $\text{k}\Omega \cdot \text{m}$	399.9
	Power Loss / kW	31.0
	Dipole component ratio	9%
Yes	Frequency / MHz	52.801
	Q_0 Value	7300

One model has non-modulation electrode, the other has electrode with modulation. The simulation results are shown in table 2.

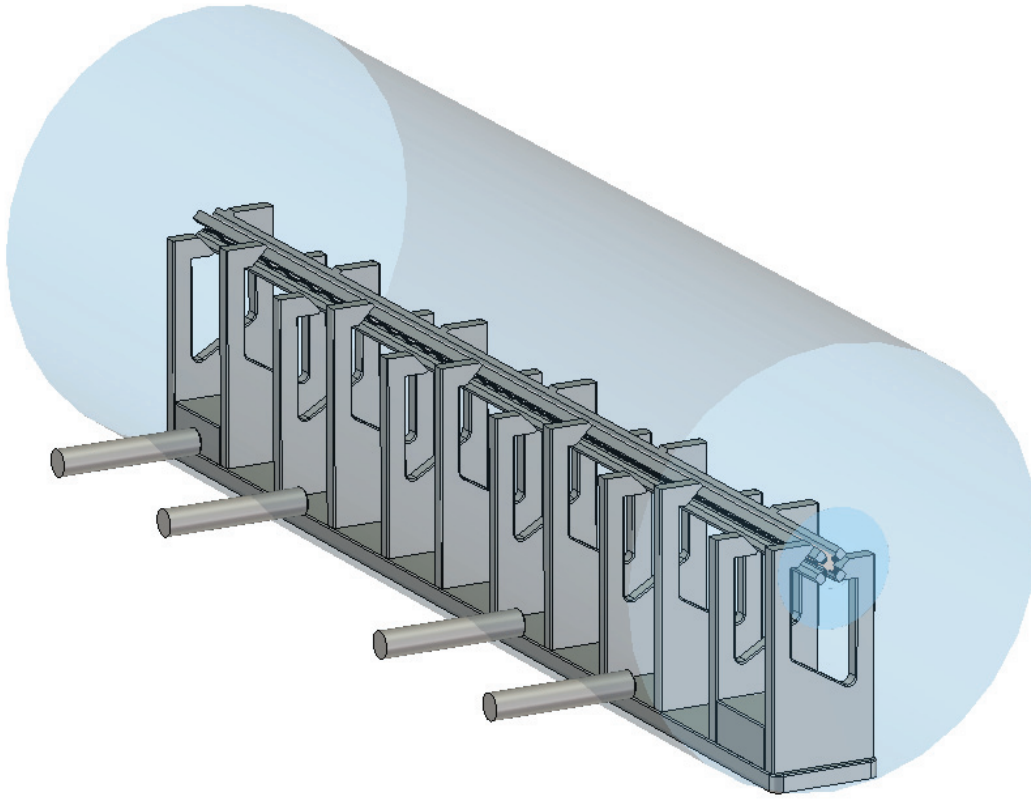


Figure 4: Sketch of RFQ cavity.

The frequency difference between two models are very small. The modulation electrode can cause the field distribution along longitudinal direction uneven. This unflatness can be compensate by the tuning block inserted between stems. The tuning block can increase the frequency of RFQ cavity. It is the reason that frequency of model is designed a little lower than 53.667MHz(frequency of beam dynamics design). The frequency is easy to be tuned to 53.667MHz by tuning block. Four frequency tuners(figure 4) are used in this RFQ cavity. Simulation result show that these tuners have little effect on the field distribution when these tuners step in cavity equally. The maximum tunable value of frequency is 125kHz when all tuners are inserted into RFQ cavity. Power coupler is co-axial type with a ceramic vacuum window. The inner conductor loop can be rotated to a proper position to keep the coupler in critical coupling condition.

In cooling structure design, a full 3d model is built using the CST multiphysics studio, the power loss obtained from RF simulation is applied as thermal boundary condition. On the support arm of stems, the power loss is high. So in the cooling structure design, the cooling channel in stem have a specific design. The cooling channel go up into the arm and then return back out the arm. Every arm will be cooled by two cooling channel to ensure the sufficient cooling capacity. At the end of the rods, the U type cooling channel is machined so that the end of the rods can be cooled by water. This method is more efficiency than cooling rods by heat conduction without water channel at

the end of rods. The pressure difference between inlet and outlet of cooling channel is set for 0.3MPa. The water temperature at inlet is 20 °C . According to the hydrodynamics formula, the flow rate and film coefficient of every cooling channel is estimated. The temperature distribution is simulated. The maximum temperature is 49.3°C and the temperature at the arm is higher than the bottom of stems. Temperature is similar with power distribution. Mechanical analysis is done base on the temperature distribution. The maximum deformation is 81.1um occurred at the rods. It is below the tolerance of deformation since average aperture of RFQ is relative large. This will be examined in beam commissioning.

BEAM COMMISSIONING OF RFQ

The beam commissioning experiment system for RFQ accelerator was set up(shown in figure 4). It is consist of a high charge state ECR ion source using evaporative cooling technology, LEBT, RFQ and beam diagnostics instruments. LEBT include a solenoid, bending magnet, four quadrupole magnets, two solenoids in sequence. Two solenoid can adjust the shape of beam emittance to match the acceptance of RFQ. Between two solenoids closed to entrance of RFQ, a faraday cup and a profile monitor is installed. At the exit of RFQ, a faraday cup, an ACCT+FCT, and a FCT were installed.

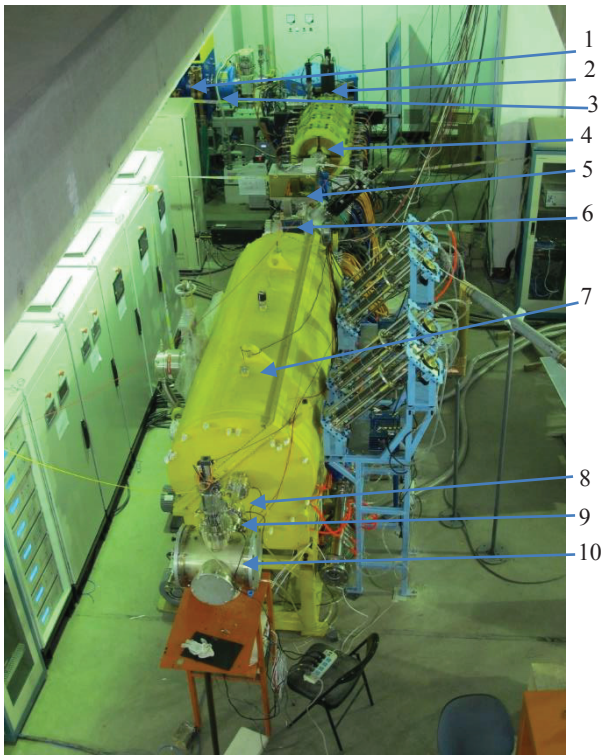


Figure 5: layout of the beam experiment system for RFQ.
1. Ion source 2. Bending magnet 3. Solenoid 4. Quadrupoles 5. Solenoid 6. Faraday cup and profile monitor 7. RFQ 8. ACCT+FCT 9. FCT 10. Faraday cup.

The cw $^{16}\text{O}^{5+}$ ion beam is used in the beam commissioning experiment due to the current condition of ion source and RFQ. The extraction beam at exit of bending magnet is about 200-220uA. After optimization of strength of quadrupole magnets and solenoids, the faraday cup at exit of RFQ obtained 150uA current when the current on the faraday cup at the entrance of RFQ is 180uA. The transport efficiency is about 83%. But the real transport efficiency is higher. There are two reasons: 1. The beam current obtained by faraday cup at entrance of RFQ is higher than beam current injected into RFQ. There are some beam loss between the faraday cup and the entrance of RFQ since a solenoid is inserted between them. 2. The faraday cup at the exit of RFQ is small, so part of the beam is not collected by the faraday cup. The energy of ion is measured by time of flight method. Beam signals of two FCT is measured by an oscilloscope. The time difference of two signals is ion's flight time. The beam energy can

obtained since the distance and flight time are known. In figure5, the sketch of FCTs and the measured signals are shown. The time delay Δt of two signals is 8.68ns. The flight time is $t = \Delta t + nT$. The T is the RF period. When $n=2$, the energy of ion is 141.89keV/u, it is lower than the designed energy for 0.77%. The error of measurement comes from two reason: 1. The length of FCTs is measured by vernier calipers, the precision is $\pm 0.01\text{mm}$. 2. The oscilloscope's sample rate is 20GHz/s, the measure error is $\pm 50\text{ps}$. The error of ion energy is $\pm 0.15\text{keV/u}$ from the error formula.

CONCLUSION

A high charge state cw RFQ accelerator is designed, fabricated and tested to improve the beam efficiency of the HIRFL. In the design and fabrication, various improvements were made to increase the performance of this RFQ accelerator. The fabrication error is measured and discussed in detail. After high power test, the maximum pulse power can reach 35kw with 30% duty factor with seldom sparking. The stable operation condition prove that the cooling structure design works very well. The transport efficiency of $^{16}\text{O}^{5+}$ beam is over 83%. The simulation result of the RFQ cavity agrees very well with the measurement result. Beam with higher charge to mass ratio will be tested in the near future.

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