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BEAM DYNAMICS DESIGN OF A 162.5 MHz SUPERCONDUCTING RFQ ACCELERATOR

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Abstract

Superconducting (SC) RFQ has lower power consumption, larger aperture and higher accelerating gradient than room temperature RFQ. We plan to design a 162.5 MHz SC RFQ to accelerate the 30 mA proton beams from 35 keV to 2.5 MeV, which will be used as a neutron source for BNCT and neutron imaging project. At an inter-vane voltage of 180 kV, the beam dynamics design was carried out with acceptable peak surface electric field, high transmission efficiency, and relatively short cavity length.

INTRODUCTION

In 1995, two SC RFQs have been developed as the injector for the heavy ion linac ALPI in INFN-LNL. Both RFQs are four-rod type and operate at 80 MHz [1]. They have been operated since 2006. The low operating frequency is suitable for accelerating heavy ions with a mass to charge ratio of 8.5. The maximum surface field of the SRFQs is Es,m = 25.5 MV/m. The successful operation of these two RFQs shows the huge application potential of SC RFQ [2]. SC RFQ has lower power consumption, larger aperture and higher acceleration gradient than normal conducting RFQ. It also has a much higher Q value and is more suitable for operating in cw mode.

In this paper we plan to design a 162.5 MHz SC RFQ to accelerate proton beams from 35 keV to 2.5 MeV with a beam current of 30 mA, which will be used as a neutron source for BNCT and neutron imaging project.

DESIGN CONSIDERATIONS

Principle of Beam Dynamics

The SC RFQ is designed to have very high accelerating efficiency and very high beam transmission efficiency. The highest accelerating gradient of a superconducting cavity depends on the peak magnetic field, and the peak surface electric field is about twice the accelerating gradient, which is limited by the field emission. Therefore, in the design process, the surface peak electric and magnetic field of the electrodes should be reduced as much as possible while ensuring the highest accelerating gradient.

The beam focusing force is proportional to the inter-vane voltage, inversely proportional to the aperture [3], because the superconducting RFQ can load a higher voltage between the electrodes, so the aperture is larger than the room temperature RFQ, which has two benefits, on the one hand, it increases the transverse acceptance of the accelerator, which is conducive to the high-efficiency transmission of the high intensity beam, and on the other hand, it reduces the beam instability caused by the beam-cavity interaction. The accelerating gradient of the low-energy beams in the room temperature RFQ can reach about 1 MV/m, while in the SC RFQ it can reach 3 ~ 5 MV/m, which helps shorten the cavity's length and is helpful for the ion beams to quickly leave the low-energy range and overcome the space charge effect. High transmission efficiency, reasonable peak surface electric field and a small growth in emittance can be obtained by selecting the appropriate values of a, m, and φ along the RFQ.

Design Method

We used the traditional four-step method developed at Los Alamos National Laboratory (LANL) for beam dynamics design, and the dynamics simulation was carried out by the code of PARMTEQM and IMPACT-T [4].

An RFQ design is determined when the three independent functions the minimum radial aperture $a(z)$, the modulation parameter $m(z)$ and the synchronous phase $\varphi_s(z)$ are given. When choosing the proper values of these parameters, we can get the desired objectives in terms of adequate radial focusing, capture efficiency, transverse emittance growth, overall length and rf power, etc.

In the superconducting state, it is necessary to ensure that the cavity does not quench, we need to reduce the complexity of the cavity as much as possible, so we adopt a design scheme with a constant focusing strength B. Because the B remains unchanged, the average aperture r0 also remains unchanged, which reduces the difficulty of subsequent processing and facilitates cavity tuning.

BEAM DYNAMICS DESIGN

The design of the SC RFQ with 180 kV inter-vane voltage was completed by PARMTEQM and verified by IMPACT-T. The design parameters are listed in Table 1.

The aperture r_0 is much larger than that of the room temperature RFQ, which can reduce beam loss. And the 30.4 MV/m peak surface electric field will not cause the quench of the superconducting cavity. We finally got proton beams with energy of 2.54 MeV and achieved a transmission efficiency as high as 99.9%.

Figure 1 shows the transverse beam envelope and longitudinal phase envelope along the RFQ. Figure 2 is the phase space projection at the entrance and exit of the RFQ. The full width at half maximum (FWHM) phase spread and energy spread at the exit of the RFQ are approximately 15° and 0.05 MeV.

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Table 1: Main Parameters of 180 kV SC RFQ

Parameters	Value
Frequency [MHz]	162.5
Input beam energy [MeV/u]	0.035
Output beam energy [MeV/u]	2.54
Focusing parameter B	9.0
Average aperture r_0 [mm]	8.5
Minimum aperture a [mm]	5.4
Modulation m	1 ~ 2.069
Synchronous phase φ [°]	-90 ~ -30
Number of cells	184
Peak beam current [mA]	30
Inter-vane voltage [kV]	180
Peak surface electric field [MV/m]	30.4
Kilpatrick coefficient	2.24
Acceleration gradient [MV/m]	0.77
Input transverse normalized RMS emittance [mm·mrad]	0.200
Output longitudinal normalized RMS emittance [MeV·deg]	0.120
Transmission efficiency [%]	99.9
Length [m]	3.27

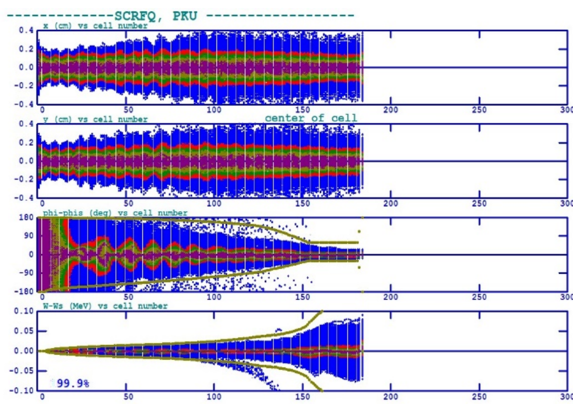

Figure 1: Evolution of beam envelopes along the RFQ. From the top to bottom are the beam envelope in the x and y planes and phase and energy spectrums, respectively.

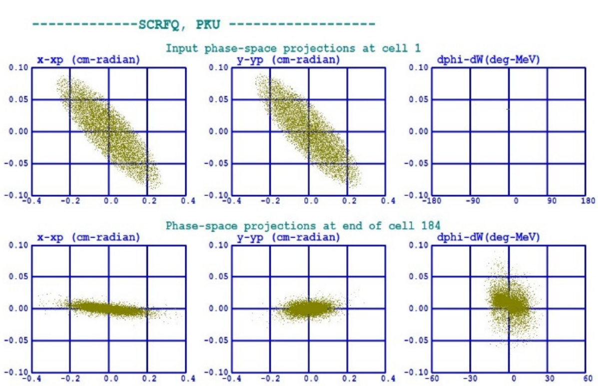

Figure 2: Particles phase-space distribution at the entrance and exit of RFQ.

Both the transverse and longitudinal emittance growth are reasonable as shown in Fig. 3. The normalized rms transverse emittances of the output beam are $\varepsilon_x = 0.28$ mm·mrad and $\varepsilon_y = 0.27$ mm·mrad, the longitudinal emittance is $\varepsilon_z = 0.120$ MeV·deg, which indicate a good beam quality is realized. Figure 4 shows the peak surface field distribution along the RFQ, the maximum peak surface field is 30.4 MV/m at cell 72. Because of the large average aperture of the SC RFQ, the maximum peak surface field is significantly reduced to this value that will not cause the cavity quench, and the transmission efficiency is increased accordingly.

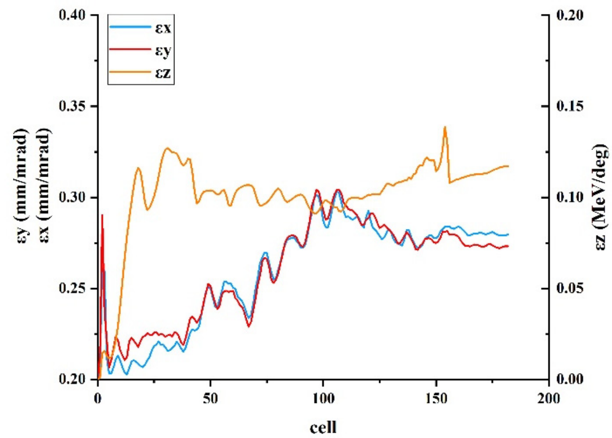

Figure 3: Emittance growth along RFQ.

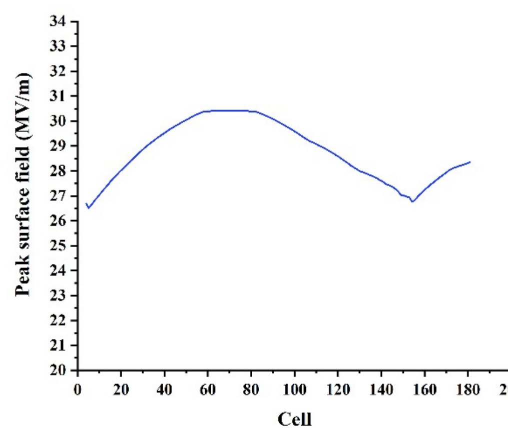

Figure 4: Peak surface field distribution.

We used IMPACT-T to verify the design results of the SC RFQ given by PARMTEQM and the simulation results show that they were consistent as shown in Fig. 5.

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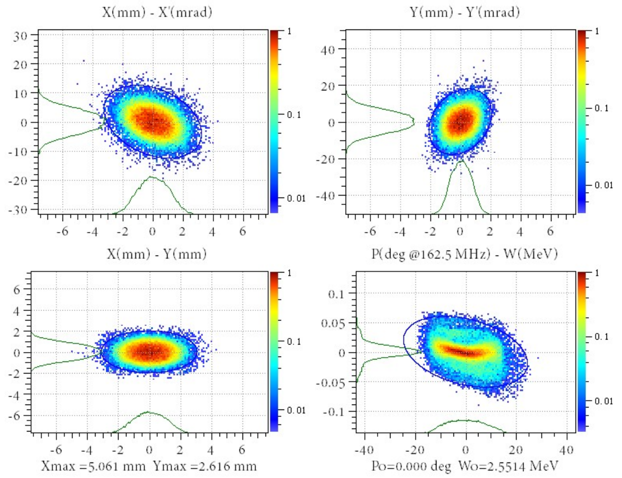

Figure 5: Particles phase-space distribution at the exit of RFQ.

REDUNDANCY STUDY

In order to further prove the reliability of the beam dynamics design, the effects of input beam mismatch on transmission have been carried out to evaluate the tolerance of the RFQ dynamics design, including Twiss parameters and normalized emittance [5], as shown in Figs. 6 and 7. For the mismatch of input Twiss parameters (α, β), we can see from the picture that for a wide range of α and β values near the design point, the transmission efficiency can be maintained above 95%, so we have a large redundancy of Twiss parameters. Meanwhile, the transmission remains above 99% when the transverse normalized rms emittance is less than 1.25 mm · mrad.

The redundancy study shows good results that appropriate deviation of the input beam parameters will not have a significant impact on the transmission efficiency. Therefore, the dynamics design is reasonable, and the subsequent structural design can be carried out accordingly.

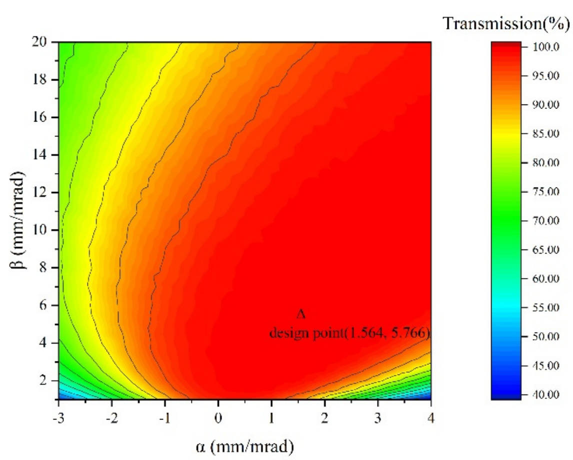

Figure 6: Transmission efficiency of the RFQ versus the input beam Twiss parameters.

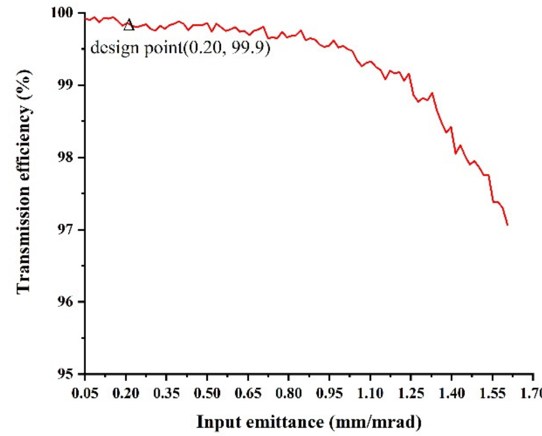

Figure 7: Transmission efficiency of the RFQ versus the input transverse emittance.

CONCLUSION

SC RFQ is proven to have the ability to accelerate ions with lower power consumption, larger aperture and higher acceleration gradient, and many of its applications are underway. In this paper, the dynamics design of a 162.5 MHz SC RFQ which accelerates 30 mA proton beams from 35 keV to 2.5 MeV has been completed, the final result shows that this RFQ can accomplish the acceleration with the length of 3.27 m and the transmission efficiency of 99.9%. A redundancy study was also carried out, and indicates that this dynamics design has sufficient redundancy, so it is reliable. Later, we plan to carry out the structural design of this SC RFQ on the basis of this paper's work.

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