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GENERAL DESIGN OF 180 MHz RFQ FOR BNCT

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Abstract

Accelerator based boron neutron capture therapy (AB-BNCT) is a promising cancer treatment technology. A general design has been proposed of a 180 MHz radio frequency quadrupole (RFQ) accelerator for BNCT. The particularity of dynamic design of the RFQ is that the average aperture radius changes along the accelerator. Beam dynamics design results show that the length of accelerator which accelerates protons from 35 keV to 2.81 MeV is 5.07 m, and the transmission up to 99.65%. Meanwhile, 20 pairs of Pi-mode stabilizer rods are considered to keep the frequency of dipole mode away from the working quadrupole mode. The simulation results show that a large mode separation of more than 20 MHz between the operating quadrupole mode and nearest dipole mode can be obtained, this is sufficient to deal with the errors caused by machining and misalignment. The initial insertion depth

BEAM DYNAMICS DESIGN

BNCT requires sufficient flux (10^9 n/cm^2/s) of epithermal neutrons (0.5 eV ~ 10 keV), because of this, an RFQ accelerator has been proposed: accelerating 25 mA proton beam (continuous wave mode) to 2.8 MeV to meet the requirements of BNCT. Based on the requirement of high beam transmission efficiency (greater than 99%), the beam dynamic design adopts the idea of making the average aperture variable along the accelerator 0. The beam dynamic parameters are shown in Figure 1.

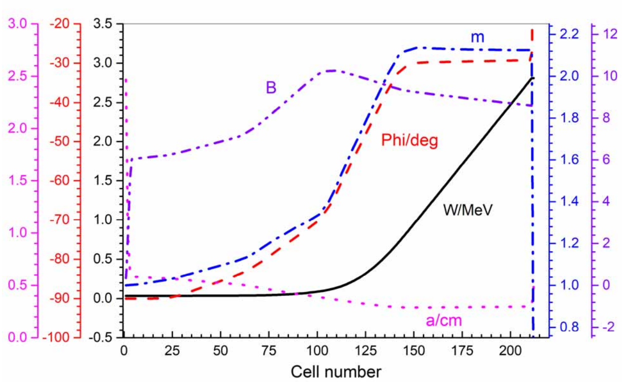

Figure 1: RFQ Accelerator beam dynamic parameters.

As for beam dynamic simulations, 10^5 macro particles with an initial 4D water-bag distribution are simulated with PARMTEQM 0, as shown in Figure 2 and Figure 3.

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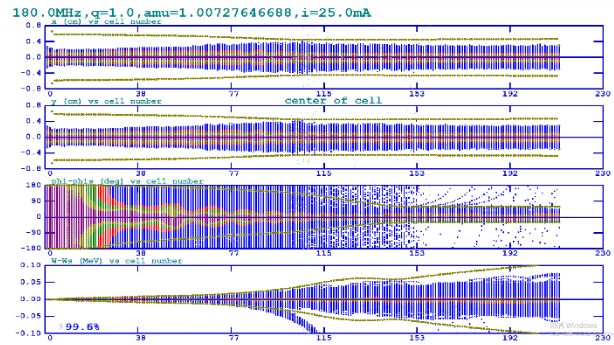

Figure 2: RFQ beam transmission process of the RFQ.

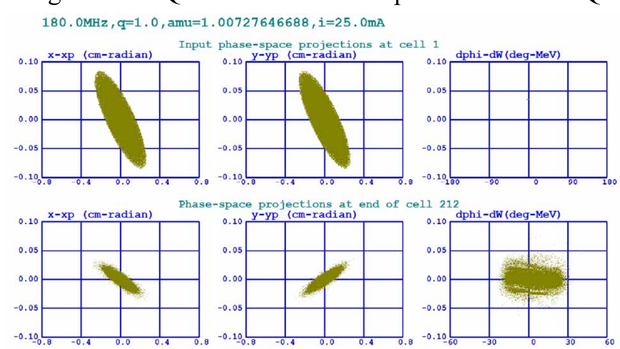

Figure 3: Beam profiles at the entrance and exit of the RFQ.

After simulation, the parameter results are shown in Table 1.

Table 1: Simulation Results

Parameter	Value
Frequency	180 MHz
Input energy	35 keV
Output energy	2.81 Mev
Voltage	72 kV
Current	25 mA
ε_t(norm. rms, entrance)	0.20 π.mm.mrad
ε_t(norm. rms, exit)	0.22 π.mm.mrad
ε_l(norm. rms, exit)	0.62 π.mm.mrad
Vane length	507.73 cm
Transmission	99.65 %

CROSS SECTION DESIGN

The design and simulation of a full length 3D model of whole cavity is usually based on slice cavity. By simulation with slice cavity, some high frequency parameters of the cavity can be obtained easily and the approximate range of cavity size L (shown in Figure 4) can be quickly

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determined when restoring the quadrupole mode frequency to the operating frequency. The 2D cross-sectional structure adopts a quadrilateral structure 0, which has the advantages of easy water cooling and lower cost compared with octagonal cavity. The schematic diagram of the structure and the specific structural parameter values are shown in Figure 4 and listed in Table 2.

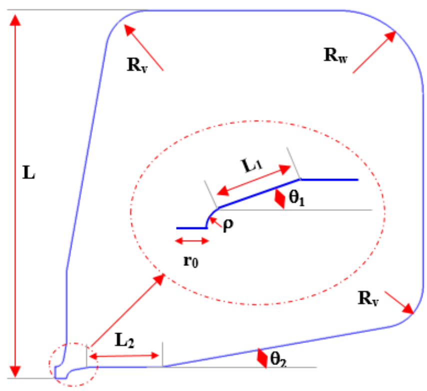

Figure 4: 2D cross-sectional structure schematic.

Table 2: Cross-sectional Parameters of RFQ

Parameter	Value
r_0	Decided by beam dynamics
ρ/r_0	0.75
θ_1	10 degree
θ_2	10 degree
R_v	20 mm
R_w	40 mm
L_1	20 mm
L_2	20 mm
L	Decided by r_0

L is the only tuning parameter to change the operating frequency to 180 MHz, so it is depend on the variable average aperture r_0. Based on the beam dynamics design, The simulation results of high frequency parameters of a slice cavity with a thickness of 50mm with respect to r_0 are shown in the Figure 5. With the increase of the r_0, the quality factor Q and L increase linearly, while the power loss per unit length P and the maximum surface electric field decrease. On average, L is about 160mm and Q is 16150 with respect to variable r_0.

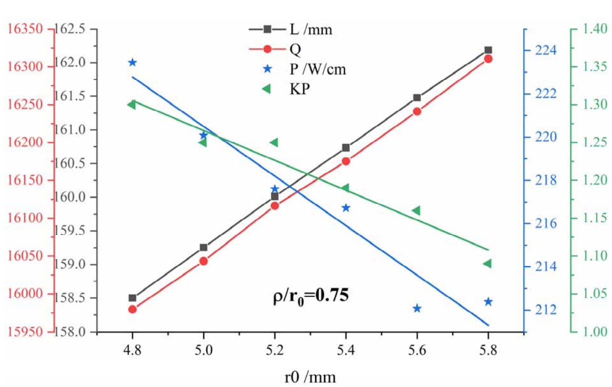

Figure 5: High frequency parameters with respect to r_0.

PI-MODE STABILIZER LOOPS (PISL) AND TUNER DESIGN

From a beam dynamics point of view, the RFQ accelerator is about 5m long, so it is divided into 5 modules. In order to save computer resources and reduce computation time, it is decided to perform the 3D simulation of full length RFQ model without modulation. With this condition, it was found that the frequency difference between adjacent dipole mode and working mode was less than 1MHz after whole cavity simulation with CST MICROWAVE STUDIO 0. Therefore, special structure must be considered to keep the frequency of dipole mode away from working quadrupole mode. Dipole stabilizing rods have been considered firstly. It is shown from the simulation result that a frequency interval about 12 MHz can be reached, this requires extremely high accuracy for the accelerator manufacturing. So it was decided finally to add 20 pairs of Pi-mode rods to separate the dipole mode and operating mode. The key factor determining the frequency interval is the distance between a pair of Pi-mode rods. In order to ensure sufficient redundancy, the distance was finally determined to be 55 mm, resulting in a frequency interval more than 20 MHz. Afterwards, 100 tuners are also accepted to deal with field errors caused by accelerator assembly. Meanwhile, it is also used to change the distribution of voltage in this design.

The initial insertion depth is set to 20mm according to common accelerator devices.

The detailed PISL and tuner parameters are shown in Figure 6.

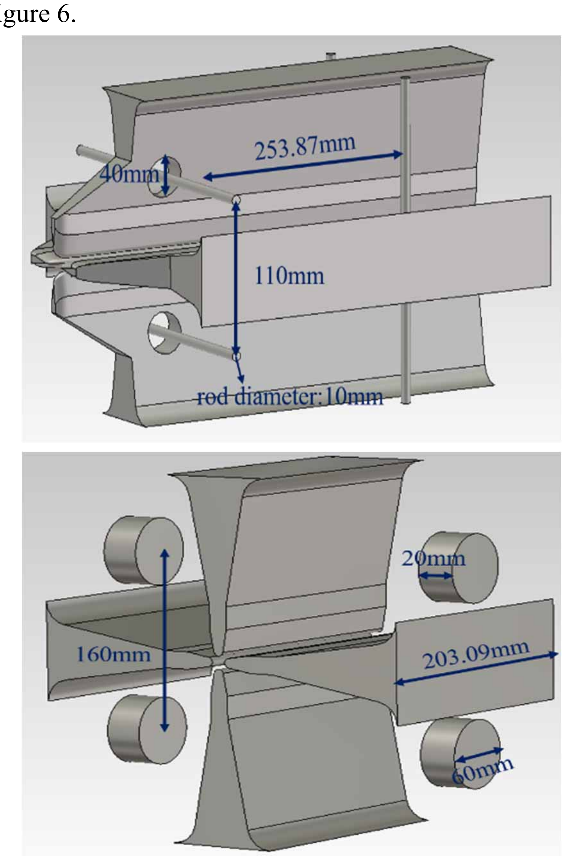

Figure 6: Detailed PISL and tuner parameters.

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Results of whole cavity simulation are listed in Table 3. The presence of the other quadrupole mode can deteriorate the longitudinal beam dynamics, so they must also be carefully considered. But the frequency separation between nearest quadrupole mode and operating mode in this design is greater than 2 MHz, no additional consideration such as coupling structure is required.

Table 3: Whole Cavity Simulation Results

Parameter	Value
Working mode frequency f_q	180.00 MHz
Nearest quadrupole frequency f	182.26 MHz
Nearest dipole frequency f_d	200.95 MHz
$\|f_q - f\|$	2.26 MHz
$\|f_q - f_d\|$	20.95 MHz
L	155.70 mm
Q factor	13766.20

ADJUSTMENT OF FIELD FLATNESS

After the entire cavity structure is established, the adjustment of the field flatness is crucial in the design of RFQ accelerator. For conventional RFQ accelerator with constant average aperture, field flatness is typically characterized by measuring the longitudinal distribution of the transverse electric field. In this particular design, however, the average aperture is not constant, the measurement of electric field are no longer applicable. Fortunately the inter-vane voltage remains constant. Therefore, the field flatness is evaluated by measuring the longitudinal distribution of the transverse inter-vane voltage. Due to the quadrupole symmetry of the cavity model, four tuners in different quadrants at the same position always have the same depth in the tuning process. By adjusting the undercut and the tuners and evaluate the transverse voltage by utilizing the macro in CST, the fluctuation of the field is less than ±2.5% finally. The dimension of undercut is shown as Figure 7 and the voltage distribution before and after tuning are shown as Figure 8.

CONCLUSION

The final beam dynamic design results of the 180 MHz RFQ accelerator is that the accelerator length is 5.07 m and the beam transmission efficiency is 99.65%. In terms of cavity structure, cross-sectional structure adopts a quadrilateral structure and the 3D cavity model adopts 20 pairs of Pi-mode rods to achieve a frequency separation of 20 MHz between dipole mode and the quadrupole mode, this prevents the beam dynamics from deteriorating transversely and is beneficial for the construction work of the RFQ accelerator. At the same time, by changing the depth of tuner, the unflatness of voltage distribution is less than ±2.5%, which basically meets the project requirements and further adjustment and optimization of voltage flatness are still ongoing.

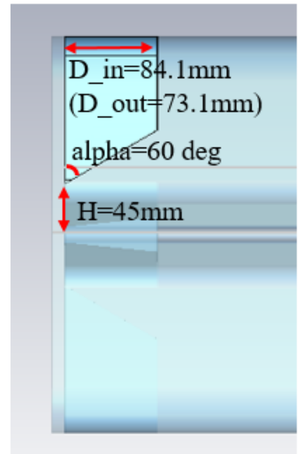

Figure 7: Final Dimension of undercut.

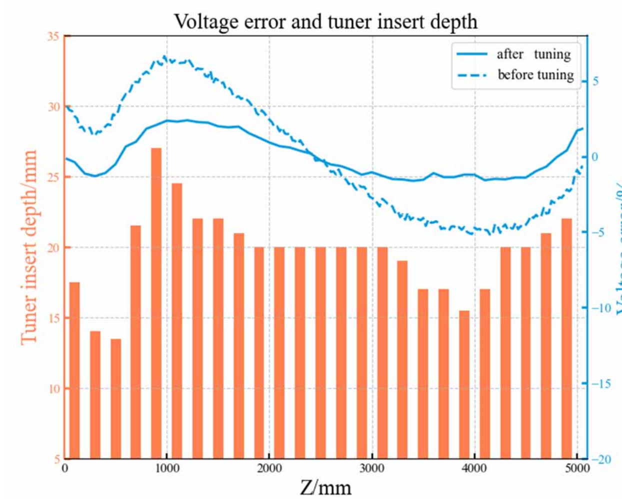

Figure 8: Transverse inter-vane voltage distribution before and after tuning.

ACKNOWLEDGMENTS

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