DEVELOPMENT OF RFQ FOR BNCT ACCELERATOR

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Abstract

An accelerator for Boron Neutron Capture Therapy (BNCT) based on proton Linac has been developed. The accelerator system consists of duo plasmatron as an ion source, low energy beam transport (LEBT), radio frequency quarupole (RFQ) accelerator, Drift Tube Linac (DTL). In order to achieve beam power of 50 kW, the required beam intensity and energy are 50 mA and 10 MeV, respectively. Since high duty rate provides high efficient medical treatment, the design of the RFQ has been investigated to accelerate proton beam from 50 keV to 3 MeV with beam intensity of 60 mA. In this paper, beam dynamics and design of the RFQ are presented in detail.

INTRODUCTION

A-BNCT project has been designed as a facility for the boron neutron capture therapy in Dawonsys. In order to achieve high flux thermal neutron generation of several 10^9 n/cm^2/s, an accelerator system requires high operation duty and high intensity. The A-BNCT consists of duo-plasmatron as ion source, LEBT, RFQ, DTL and Be target system as shown in Fig. 1. The high intensity proton beam would be accelerated by RFQ and DTL up to 3 MeV and 10 MeV, respectively. Since the requirement of beam power at target is 50 mA, RFQ has been designed to be able to accelerate 60 mA proton beam with high transmission rate for A-BNCT. In this paper, we describe the beam dynamics and brief engineering design of the RFQ.

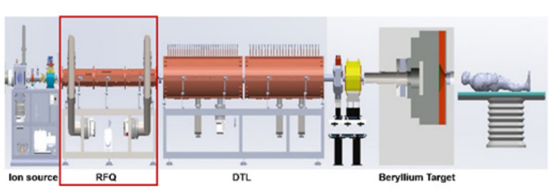

Figure 1: The layout of the A-BNCT.

BEAM DYNAMICS DESIGN

The considerations of designing the RFQ are about 3 meter long, peak power of 500 kW with duty rate of 20 %. The RFQ has design parameters as shown in Table. 1 which satisfies 318.08 cm long of short length, high transmission rate of 93.96 %, bravery factor of 1.72 to minimize RF breakdown. The operation frequency is adopted as 352 MHz for commercialization of RF amplifier system.

Table 1: A-BNCT RFQ Design Parameters

Particle (q/A)	H+ (1/1)
Frequency	352.0 MHz
I/O beam energy	50 keV / 3.0 MeV
Beam intensity	60 mA
Vane voltage	80 kV
Length	318.08 cm
Number of modules	3
Transmission rate	93.96 %
Modulation, m	1 – 2.38
Focusing parameter, B	4.58 - 5.75
Max surface field	31.73MV/m (1.72 kilp.)

The aims of A-BNCT RFQ beam dynamics study are to minimize the RFQ length within reasonable bravery factor, and longitudinal emittance growth by PARMTEQM code [1]. In order to achieve the requirements, we applied varied focusing parameter, *B*, and synchronous phase, Φ_s, and increasing modulation, *m*, in acceleration section as shown in Fig. 2.

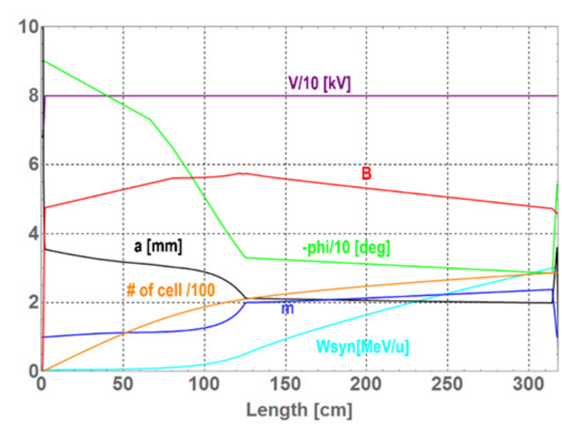

Figure 2: Design parameters of the A-BNCT RFQ.

Here, V is the vane voltage (kV), W_{syn} is particle kinetic energy and a is minimum apertures along the RFQ. The synchronous phase becomes -33° at the end of the gentle buncher section and -28° at the end of the acceleration section in order to avoid the space charge effect. Figure 3 shows the results of the beam dynamics for A-BNCT

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RFQ such as rms envelopes for horizontal, vertical and longitudinal emittances in rms and 90 %, and transmission rate along the longitudinal position.

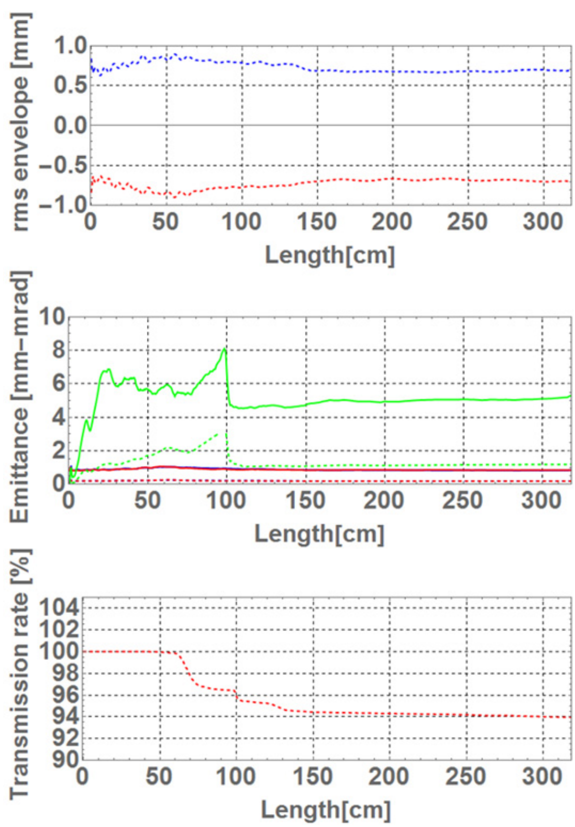

Figure 3: Result of the beam dynamics of the RFQ.

The changes of emittances by the RFQ and output beam parameters are presented in Table 2 which are calculated with 100 k particles to obtain high accuracy. Through the RFQ, we obtained well bunched beam with high captured rate from continuous wave.

Table 2: A-BNCT RFQ Beam Parameters

Emittance (n.r)	Input	Output	Unit
Horizontal	0.2000	0.2003	mm-mrad
Vertical	0.2000	0.1983	mm-mrad
Longitudinal	CW	0.1187	MeV-deg
Twiss, α_x	1.1084	1.6527	
Twiss, α_y	1.1084	-1.6554	
Twiss, β_x	3.5345	20.1442	cm/rad
Twiss, β_y	3.5345	18.5863	cm/rad

RFQ CAVITY DESIGN

Base on the beam dynamics study, cavity design has been studied to provide EM field distribution at the operation frequency as 352 MHz. In the two dimensional cavity design by SUPERFISH code [2], we proposed two types of vane shape as shown in Fig. 4. The difference comes from the existence of vane shoulder for easy manufacturing. Since the shoulder is non-existent in the vane, vane base becomes thicker than the existent case. By comparison the both cases in terms of power consumption and Q-factor, the differences show power consumption of 2.6 % and Q-factor of 1.3 % as shown in Fig. 5. Although existence of vane shoulder has advantages as we mentioned about power consumption and Q-factor, we applied non-shoulder model as simple structure for convenient manufacturing.

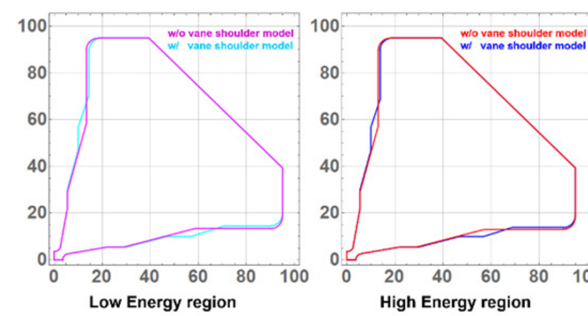

Figure 4: The geometry study of vane in two dimensional.

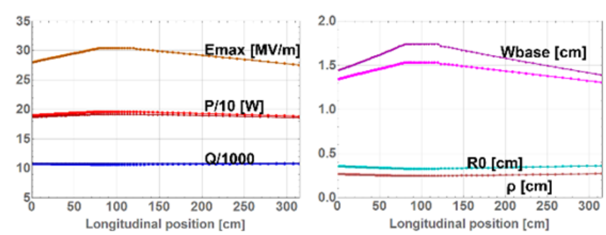

Figure 5: The results of vane design on the geometry.

We obtained vane structures which have 10700 of Q factor, 61.45 kW of a quadrant power at the resonant frequency by SUPERFISH code. The total power consumption would be estimated as [3]

$$P_{total} = P_{SF} \bullet \alpha_{3D} + P_{beam} \quad \text{(Eq. 1)}$$

where α_{3D} = 1.3 is a factor that accounts for the 3D losses which includes RF transmission loss and difference between SUPERFISH and experience result, P_{beam} is the beam power. We obtained a 3D power consumption of peak power of 467.04 kW and average power of 93.41 kW in the RFQ cavity including beam power. Due to high power and high duty operation, cavity cooling is important issue in cavity design. In order to obtain larger coolant channels in vane-tip region, half blank width, B_w, is applied as 5.5 mm and blank depth, B_D of 29 mm, to take up 6 Φ cooling channel in vane-tip and it is positioned close to vane-tip. To protect vane from leak by cooling channel, gap of 3 mm between vane edge and cooling channel is considered as a limitation.

The fluid flow in cooling channel has been studied to confirm pressure, velocity and temperature change by cavity cooling. In order to apply convection condition in vane cooling for heat transfer method, turbulent flow is

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selected. Zigrang-Sylvester of Equation is applied to understand turbulent flow dynamics in Eq. 2 [4] and related equations are described in Eqs. 3 and 4.

$$\frac{1}{\sqrt{f}} = -4.0\log_{10}\left[\frac{\varepsilon / D}{3.7} - \frac{5.02}{\mathrm{Re}}\log_{10}\left(\frac{\varepsilon / D}{3.7} + \frac{13}{\mathrm{Re}}\right)\right] \quad \text{(Eq. 2).}$$

$$\mathrm{Re} = DV/\nu \;, \quad \Delta P = 2f\frac{L}{D}\rho V^2 \quad \text{(Eq. 3).}$$

Here, f is friction factor, ε is $1.50{\cdot}10^{-3}$ mm of pipe roughness, ν is $1.13{\cdot}10^{-6}$ m^2/sec of kinematic viscosity, ρ is 1000 kg/m^3 of water density, ΔP is pressure drop, Re is Reynolds number, D is diameter of pipe, V is velocity of water and L is pipe length. Calorimetry RF power measurement method is used to estimate temperature change by cavity cooling by Eq. 5.

$$\Delta T \;\; [^{\circ}C] = 14.3 \times Power \;\; [kW] / flow \;\; rate \;\; [LPM] \quad \text{(Eq. 5).}$$

Figure 8 shows the results of the turbulent flow dynamics. Since cooling diameter are designed two cases for efficient cooling as semi-circle of 6 x 14 mm in vane-tip and circle of 15 mm in vane base. Since the cross-sectional area is important parameter in fluid dynamics, both cases have been studied. 7.00 LPM in vane-tip and vane base for up to 2.4 kW of cooling power and are needed. In these cases, pressure drop are estimated as 4.8 kPa of pressure drop and 13140 of Reynolds number for vane-tip and 0.7 kPa and 8760 for vane base, respectively.

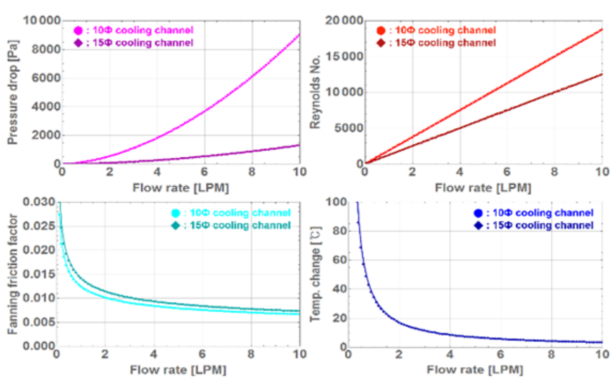

Figure 6: The fluid flow dynamics on flow rate.

By applying the cavity design and cooling system, three dimensional analysis of the RFQ cavity was carried out to study three dimensional RF analysis such as undercut design, cavity tuning, mode analysis and thermal analysis such as temperature distribution and cooling design as well as vacuum system design by CST code [5].

Fig. 6 shows the three dimensional model which includes undercut system, vacuum grid and tuner. The undercut system is designed as triangular type of 23.6 mm of height, depth of 40.6 mm with angle of 12.5 ˚ for low energy section and height of 14.0 mm, depth of 37.2 mm with angle of 12.5 ˚ for high energy section. Tuners position are various depth from 2 to 7 mm at each position to obtain uniform field distribution. Vacuum grid consists of 9 slits with width of 260 mm and height of 50 mm on the cavity wall. In order to compensate the frequency shift by hole, the grids are inserted by 2.5 mm. Through the three dimensional cavity design, we obtained uniform field distribution and temperature distribution with cooling as shown in Fig. 8.

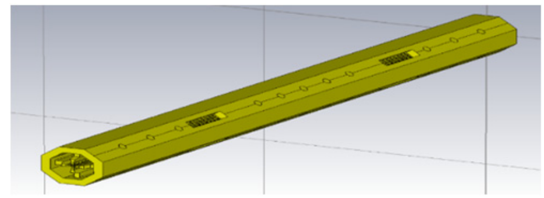

Figure 7: The model of A-BNCT RFQ.

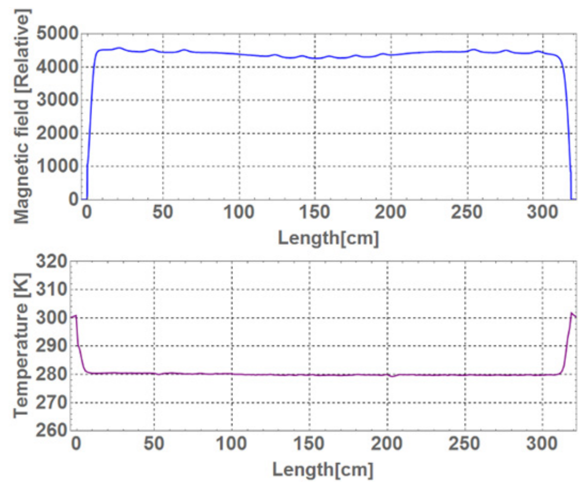

Figure 8: The magnetic field and temperature distributions along the beam axis.

CONCLUSION

A high power and high duty rate RFQ accelerator for A-BNCT has been designed to accelerate proton beam from 50 keV to 3 MeV with up to 60 mA of beam intensity and 20 % of duty rate. Since high power operation requires high power cooling, we designed RFQ has large cooling channel and fluid flow dynamics has been studied. Through two dimensional and three dimensional cavity design, RFQ cavity construction is launched from April 2017 by Dawonsys.

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