PRELIMINARY DESIGN OF RF SYSTEM FOR SC200 SUPERCONDUCTING CYCLOTRON

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Abstract

The SC200 is a compact superconducting cyclotron, which is designed under the collaboration of ASIPP (Hefei, China)-JINR (Dubna, Russia), for proton therapy. The protons are accelerated to 200 MeV with maximum beam current of ~500 nA. The very high mean magnetic field of 2.9 T-3.5 T (center-extraction) challenges the design of radio frequency (RF) system because of the restricted space. The orbital frequency of the protons is ~45 MHz according to the magnetic field and beam dynamics. The RF system is supposed to operate at 2rd harmonic of ~90 MHz. Two RF cavities located at the valley of the magnet have been adopted. The preliminary design of RF system, which consists of active tuning, coupling and so on, is presented. The computation and simulation showed good results to ensure the RF cavities operating at the 2rd harmonic and the proper variation of acceleration voltage versus radius.

INTRODUCTION

The SC200 superconducting proton cyclotron is designed under the collaboration of ASIPP and JINR for proton therapy. The RF cavity is the critical and complex component of SC200. The RF cavity works as a resonator to generate necessary voltage between Dee gaps to accelerate protons continuously. The half-wavelength coaxial resonant cavity has been adopted in SC200. It is mainly composed of stem, Dee, coupling loop, tunable shorted terminal, cavity, as shown in Fig. 1.

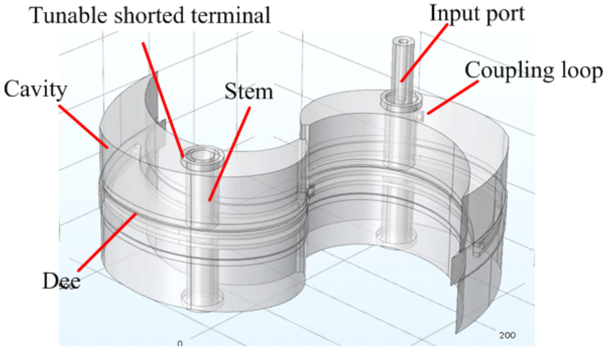

Figure 1: RF cavity structure.

According to the physical design requirements of SC200 Superconducting Proton Cyclotron [1-3] the main technical parameters of RF cavity are described in Table 1.

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Table 1: Technical Parameters of SC200 RF Cavity

Parameter	Value
Frequency	90 MHz(2 harmonic)
Cavity number	2
Source power	~100 kW
Cavity type	λ/2 coaxial
Accelerate voltage	60 kV(Center)~ 120 kV(Extraction)
Dee azimuthal extension	40°
Dee Cavity azimuthal extension	50°

Due to the high magnetic field of cyclotron， the compact structure has challenged the requirements of RF design. First, the resonance frequency and correct voltage distribution have to fit the requirements of acceleration, especially in the central region and extraction region. What's more, the proper coupling and tuning method should be found to cover possible working frequency. Finally, the operation stability and thermal consideration need to be taken into account.

ACCELERATION

Resonance frequency (f) and quality factor (Q value) are the important characteristic parameters to describe the performance of the resonant cavity (RF cavity). Table 2 shows the simulation results from different codes, respectively. The simulation results show good agreement.

The eigen-frequency of ~90 MHz has been found with correct voltage distribution along the radius of Dee, as shown in Fig. 2. The Q value has been estimated with and without the surface loss of cavity. The typical value of Q is ~7000 which is reasonable and acceptable. The Q value (~4500) has decreased as the surface of cavity was set up to loss material (copper).

Table 2: Eigen Mode Analysis Results

Software	f (MHz)	Q (without loss of cavity)	Q (with loss of cavity)
CST	90.6	7230	4590
HFSS	89.6	6880	\
COMSOL	89.46	\	4067

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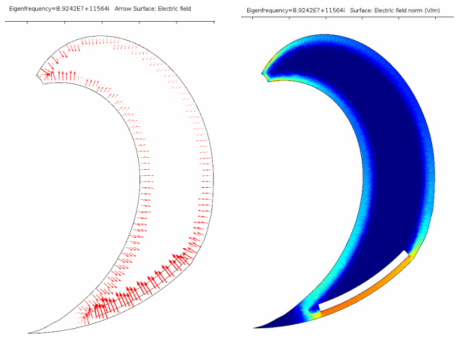

Figure 2: The electric field vector diagram at f=89.24 MHz.

Voltage Analysis

The function of the RF cavity is to generate the high-frequency electric field in the gap between the electrode and the ground. Each turn the proton cross the gap, it will be accelerated by the electric field. Therefore, it is extremely essential to analyze the distribution of the Dee voltage.

Accelerating voltage was obtained according to the integral of azimuthal component of the electric field in the accelerating gap on a fixed radius. Comparing with the simulating results from various codes: HFSS, CST, COMSOL, the bilateral voltage distribution along the radius was shown in Fig. 3.

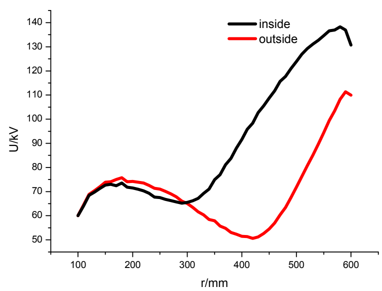

Figure 3: The analysis results of COMSOL.

Based on the good consistency of above simulation results, the 60 kV at central region and 120 kV at extraction region have been achieved.

Power Loss

Due to the lossless of energy in vacuum, the power loss of the RF cavity just involves the surface loss of the conductors. Thus, the power loss can be written as:

$$P_W = \frac{1}{2}\sqrt{\frac{\pi \mu f}{\sigma}} \int |H|^2 \partial S \qquad (1)$$

Where μ is the copper permeability, $\mu = 4\pi \times 10^{-7}$ H/m, f is the working frequency, $f = 9.07 \times 10^7$ Hz, σ is the conductivity of the cavity materials, $\sigma = 5.8 \times 10^7$ S/m(copper); H is the magnetic intensity vector, which is calculated by MICROWAVE STUDIO [4].

In order to design the water cooling system, the cavity is divided into several parts to consider the loss of each part. According to the above formula of the cavity power loss, the magnetic intensity vector H of the corresponding position has been integrated on the surface of each part. Then the total power loss of the cavity is 84.2 kW. The proportion and the distribution of power loss of each part have been calculated, as shown in Table 3.

Table 3: The Power Loss of Each Part

Part	Power Loss(kW)	Proportion(%)
Stem	21.06	25.01
Dee	34.33	40.77
Cavity	28.59	33.96
Coupling loop	0.1516	0.18
ALL	84.2	\

TUNING

Because of the RF power loss, the increasing temperature must influence the resonance frequency of Dee cavity. To cope with such frequency shift, the inductance tuning (tunable shorted terminal) has been adopted， as shown in Fig. 4. The tuning system is designed to cover the resonant frequency of 90 MHz with bandwidth of ±1 MHz.

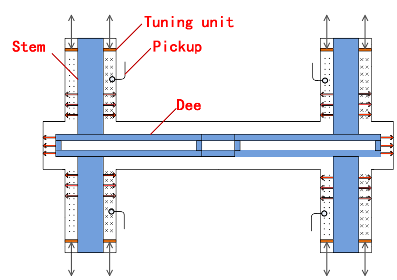

Figure 4: Double cavity structure.

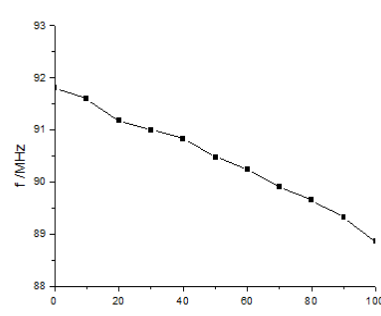

Figure 5: Resonance frequency as a function of mobile distance.

Figure 5 shows the simulation result, the x-coordinate represents the tunable distance of the shorted terminal, the y-coordinate represents the resonance frequency of the cavity. The minimum and maximum frequency can be found: Fmin=88.8 MHz and Fmax=91.8 MHz.

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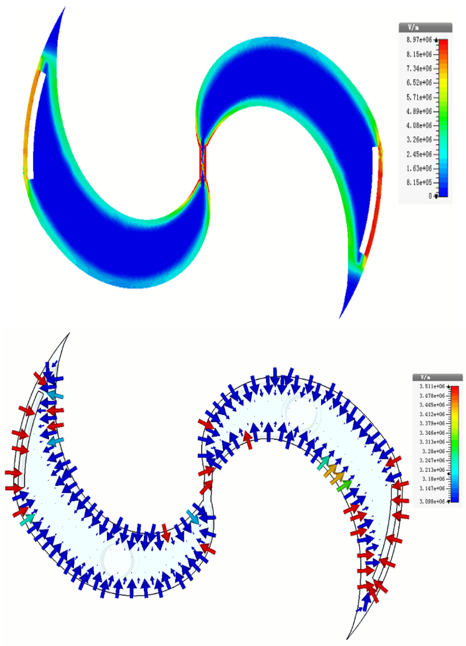

Figure 6: Electric field distribution.

What's more, In the case of double cavity, there are four tuning units, as shown in Fig. 4. The electric field of the left and right cavities will be unbalanced if the positions of the tuning units are not symmetrical. Figure 6 shows the simulation results of such unbalanced electric field with the asymmetrical position of tuning units. It can be easily found that the electric field of the right cavity is significantly larger than the left one. Therefore, the pick-up signals of each tuning unit need to be calibrated to achieve the feedback control in the low level radio frequency (LLRF) system to keep the balance of electric field.

COUPLING

The role of the coupling device is to transmit the RF power into the RF cavity [5]. In SC200, the cavity is a high impedance device, which should be matched to the characteristic impedance (50 ohm) of the transmission line through coupling loop, as shown in Fig. 7. The stem has been used as the outer conductor of coaxial transmission line, meanwhile the inner conductor of transmission line goes through the stem and forms a coupling loop in the RF cavity. Due to the compact and integral design of stem and coaxial line, there are no additional holes on the magnet yoke for coupling design.

In order to achieve the matching at the working frequency of 90 MHz, the shorted terminal is turned to ensure that the resonant frequency of the RF cavity is 90 MHz. And then, the coupling loop area has been changed to achieve the minimum of the scattering parameter S11. The matching point can always be found by changing the area of coupling loop, and the reflection coefficient is significantly related to the resonant frequency of the RF cavity and the position of the shorted terminal, see Figs. 8 and 9.

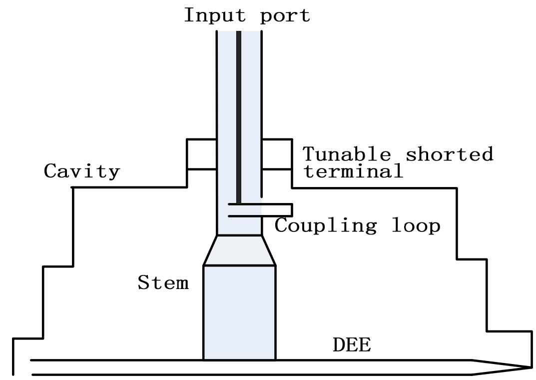

Figure 7: Coupling loop within the stem.

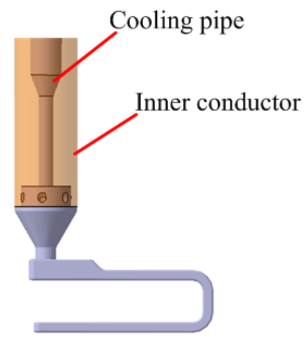

Figure 8: Inductive coupling loop.

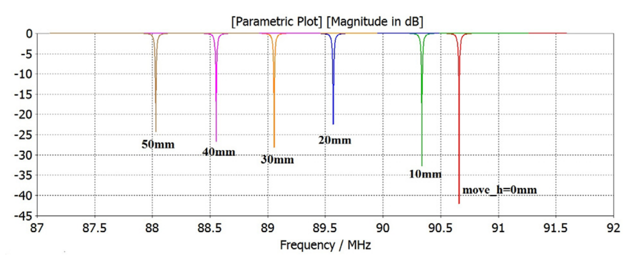

Figure 9: Reflection coefficient at various positions

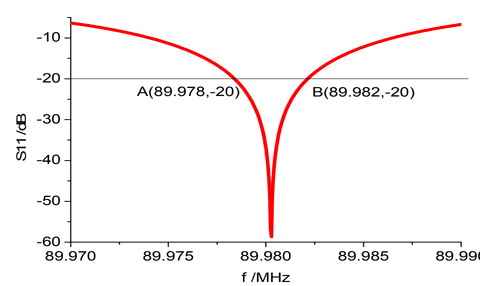

Figure 10: Reflection coefficient.

The bandwidth approximates 4 kHz, as shown in Fig. 10. The reflection coefficient S11 can be optimized to -40 dB by adjusting the area of coupling loop carefully.

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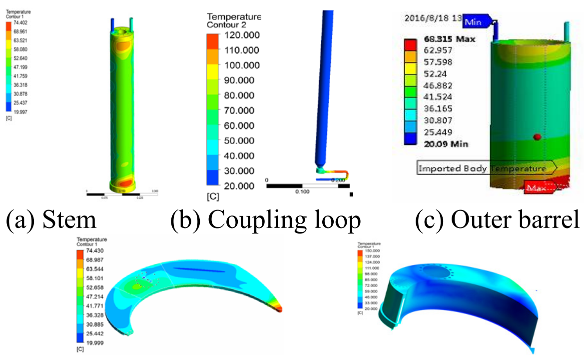
THERMAL ANALYSIS

As we know, the thermal deformation of RF cavity caused by the power loss significantly affects the resonance frequency. What is worse, the deformation of Dee will impact on the balance of acceleration electrical field and the proton orbit.

Due to the complexity of RF cavity, each component of the RF cavity has been simulated respectively. The simulation results of power loss (Table 3) are used as the boundary condition of these components in ANSYS codes.



(a) Stem (b) Coupling loop (c) Outer barrel

(d) Dee (e) Cavity

Figure 11: Temperature distribution.

Thermal analysis has been done, but the results are not very good and satisfactory. The temperature distribution is extremely nonuniform, and the local temperature is too high to operate stably, as shown in Fig. 11. Therefore, the water cooling system needs to be further optimized to achieve acceptable and stable operation temperature of each part.

DISCUSSION AND CONCLUSION

The characteristic parameters of RF cavity have been accomplished based on the simulation. The accurate eigen mode at the working frequency of 90 MHz has been found. The Q value is about 7000 that can meet with the design requirement. The tuning system is designed to cover the resonant frequency of 90MHz with bandwidth of ±1 MHz, and the adjusting range of frequency is 88.8 MHz ~ 91.8 MHz. The coupling design has been completed through inductive coupling.

The 60 kV at central region and 120 kV at extraction region have been achieved, which can prove the needed acceleration voltage at the central and extraction region. The total power loss of the cavity is 84.2 kW, and then the RF source with maximum power of ~100 kW was designed to meet the requirement.

For future work, the mockup design and measurement have been put on the agenda, besides the cooling system.

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