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RESEARCH AND DEVELOPMENT OF RF SYSTEM FOR SC200 CYCLOTRON

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Abstract

A 200MeV compact isochronous superconducting cyclotron, named SC200, for proton therapy is under development by collaboration of ASIPP (Hefei, China) and JINR (Dubna, Russia). The radio frequency (RF) system as one of most significant subsystems in cyclotron consists of acceleration cavity, low level RF, RF source and transmission network. SC200 has two cavities connected in the centre, which are operated at 91.5 MHz with second harmonic. To meet the required acceleration voltage, the cavities have been carefully designed with comprised choices between several aspects, such as Q factor, mechanic stability and so on. The low-level RF (LLRF) system has been implemented by using the FPGA to achieve the significant accelerating voltage with an amplitude stability of <0.2% and a phase stability of < 0.1 degree. The cavity and LLRF system have been tested outside of cyclotron, the results will be presented. For future, the commissioning of whole RF system will be started after the assembly of SC200 at the end of 2018.

INTRODUCTION

The 200 MeV isochronous Superconducting cyclotron (SC200), as a high-energy proton source of radiotherapy system, is an international joint research project between Institute of Plasma Physics Chinese Academy of Sciences(ASIPP) and Joint Nuclear Research Institute (JINR), which is scheduled to be ready for the first beam in the first half year of 2019 [1~3].

The radio frequency (RF) system, as the significant component of the accelerator, is designed to provide a specific frequency of electric field for the protons and maintain the stability of the acceleration voltage. Two cavities are located at valleys of the magnet. The system is operated at the frequency of 91.5MHz with second harmonic. The voltage of 60kV at the centre and 110kV at the extraction region are requested so as to have a good extraction of internal ion source of cyclotron, respectively. The main parameters are described in Table 1. And the main aspects of RF system design consisting of RF cavity, LLRF and so on, which will be discussed in following paragraphs and some test results will be also presented.

Table 1: Main Parameter of the RF Cavity

Resonance frequency:	91.5MHz
Cavity numbers:	2
Harmonic number:	2th
Accelerating voltage:	Centre: 60 kV
	Extraction: 120 kV
Cavity type:	λ /2
Outer diameter:	1280mm
Height:	500mm

RF CAVITY DESIGN

The RF cavity is located at the valleys of the magnet, and the geometry of the RF cavity is restricted by the size of spiral sectors. The operating frequency of the RF cavity is 91.5 MHz, and the second harmonic is used to accelerate the beam.

Determining the angular width between Dee and cavity wall, i.e. the accelerating gap, is one of the priorities in the cavity design. The Q factor and the efficiency of accelerating voltage are mainly controlled by this parameter. Based on a positive correlation between the Q factor and the accelerating gap, and a negative correlation between the efficiency of the accelerating voltage, the gap was found according to simulations. Thus, to get a suitable value of the parameter is very important. The optimized angular width for the accelerating gap of the SC200 cyclotron is 7°.

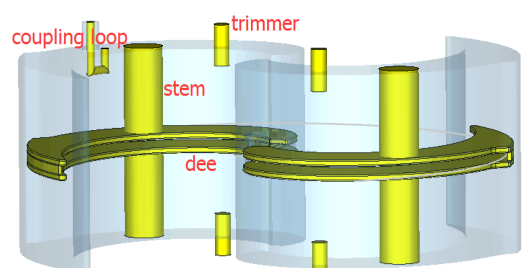

Figure 1: SC200 cyclotron cavity design.

The RF cavity resonator solution for the SC200 cyclotron is given in Fig.1. The RF cavity is ½ λ coaxial resonator with a single stem. It is equipped with 4 capacitance tuning trimmers and an inductive coupling loop.

The resonator frequency of the cavity can be adjusted by capacitance trimmers. In order to avoid sparking between the dee and the trimmer, the distance was limited from 50 mm to 110 mm, and the tuning range was 180 kHz, as shown in Fig.3. Besides, the resonant frequency of cavity can also be changed by changing the size of some components of the cavity if the resonant frequency is totally out of the tuning range of trimmers. For instance, the size of stem will have a strong effect on the resonant frequency. While the radius of the stems increases by 1mm,

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the resonance frequency increases by 0.25MHz. Moreover, milling the up and down walls of the RF cavity will also give an obvious change on the resonant frequency.

To optimize Q factor, the edges of the Dee are corner-angled and smoothed, which will reduce distributed capacitance between them. And, the Q factor can also be raised by ~600 for our case if the shape of stem adopted the elliptic cylinder instead of the cylinder. In addition, the Q factor will be significantly deceased if the cavities and Dee are not connected well, so the wires and contact fingers are adopted to ensure the good electric touch.

From the simulation and the optimization of design, we achieved the unloaded Q factor of ~6100 at the frequency of 91.5MHz and the average acceleration voltage of 65 kV at the centre and 115 kV at the extraction, respectively with the total power dissipation of ~80kW in the RF cavity.

TEST OF CAVITY

The deviation of real RF cavity from the simulations is mainly induced by the manufacturing errors and installation tolerance. The simulations showed that the maximum deformation of the cavity is less than 0.33mm when the cavity is fed into ~100kW, and the thermal deformation will cause the frequency drift of -31.6 kHz, which can be compensated by trimmers.

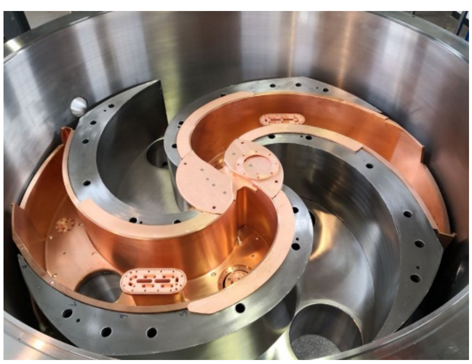

Figure 2: RF cavity.

The test of the cavity outside of the cyclotron has been proceeded to ensure the performance and improve the deviation from the design, as shown in Fig. 2. Due to the error of manufacturing and assembly, the resonant frequency drifted with 0.2 MHz, which has been offset by slight change on the gap between the Dee and cavity wall. The measured result of unloaded Q factor is ~5200, while the simulation result is ~6100. Besides, the critical coupling is approached by rotating the coupling loop. All trimmers are moved at the same time with considering the field balance. Comparing the simulation result with the test result, we can see a good agreement, as shown in Fig. 3.

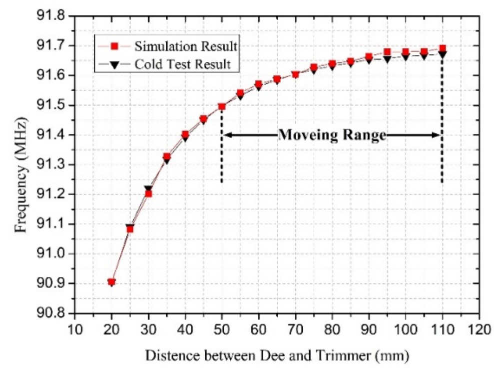

Figure 3: The frequency tuning range.

The voltage distribution along the acceleration gap was calculated according to the shunt resistance and the power dissipation of whole cavity. A special probe with a 50 Ohm resistor in parallel was adopted to measure the shunt resistance [4]. The calculation results of acceleration voltage are presented in Fig. 4.

The difference between the simulation and the test results is induced by this measurement method itself and the limitation of probe connection. The test results proved that the cavity could give the necessary acceleration voltage along the radius, especially at the centre and extraction region.

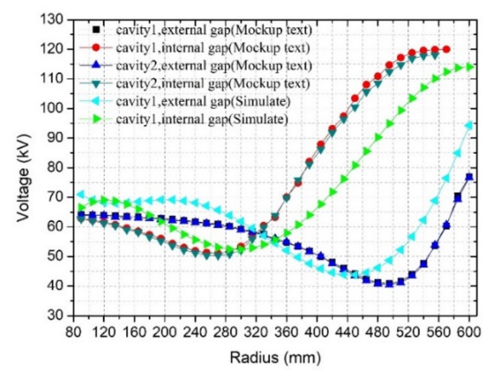

Figure 4: Voltage distribution of test and simulation normalized to the centre of ~60kV.

LOW LEVEL RF SYSTEM

The purposes of the LLRF design are to achieve stable operation of RF system and handle several kinds of commissioning, such as cavity conditioning, automatic start-up of cavity operation, and so on.

For stable operation, the LLRF system defined three feedback control loops: amplitude loop, phase loop and frequency tuning loop. The system is operated at 91.5 MHz with Direct Digital Synthesizer (DDS) generation. The amplitude loop is used to compensate fast distortions by smooth the injection power of the solid state power amplifier (SSA), as shown in Fig.5. The phase loop keeps the phase of the field in the cavity to the desired value by keeping the difference phase between the local oscillation and pick-up signals. In order to tune the cavity resonance frequency to the master oscillator frequency, the LLRF

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system generates a tuning signal to drive the trimmers of different DEEs simultaneously according to the phase difference between the cavity pick-up signal and the forward power signal. Figure 6a showed the test bench, and the LLRF system has achieved the accelerating voltage with an amplitude stability of<0.2% and a phase stability of <0.1°, as shown in Fig. 7.

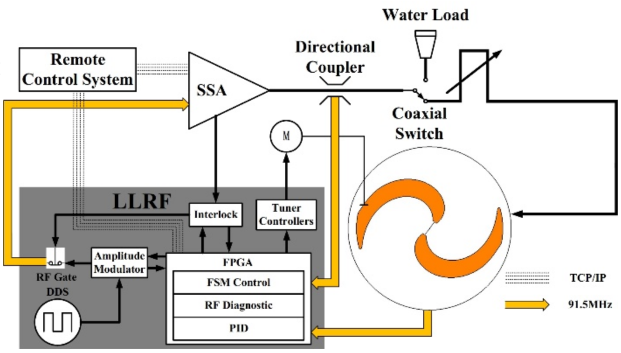
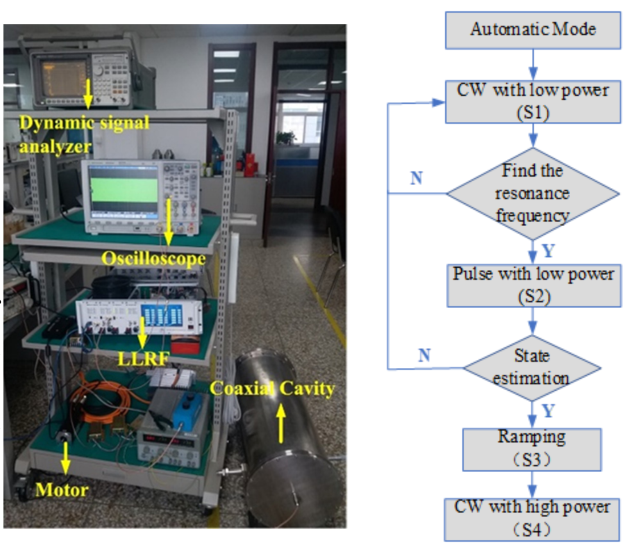


Figure 5: Block diagram of SC200 RF system.



(a) (b)

Figure 6: (a) LLRF test platform (b) Start-up procedure.

The logic to start up the LLRF is present in Fig.6b. In the state S1, the frequency tuning loop is closed. When the resonance frequency of cavity is close to 91.5 MHz, the state changes to S2. In this state, the LLRF tries to increase the injection power under pulsed mode to overcome the multipacting region. The power will go higher step by step. If the estimation is good according to the reflection coefficient, the whole system will go to the full power operation through the S3&S4. And then, the phase loop and the amplitude loop will be closed.

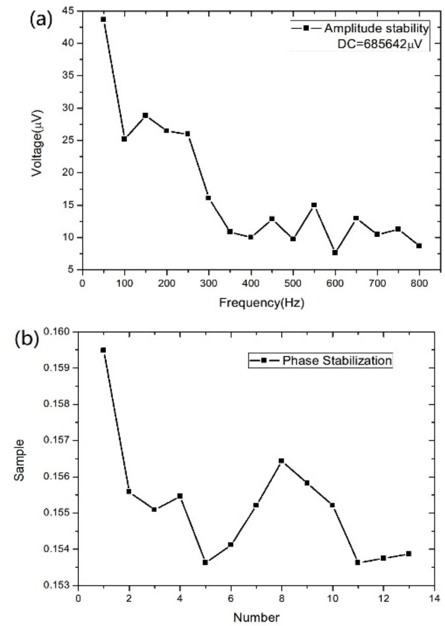


Figure 7: Measurement of (a) amplitude and (b) phase stability.

The LLRF system also has a sophisticated procedure for the cavity conditioning. The algorithm is similar to the state S1 and S2. Together with the built-in protection system, the LLRF system could do the RF conditioning automatically and speed up the process extremely.

CONCLUSION

The RF system, which consists of the RF cavity and the LLRF system, has been developed for the SC200 Superconducting Proton cyclotron. The test results showed that the performance of the cavity and the LLRF could meet the design requirements. For future, the RF system will be assembled in the cyclotron and proceed the RF conditioning at the end of 2018.

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