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DESIGN AND COMMISSIONING OF RF SYSTEM FOR SC200 CYCLOTRON

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Abstract

The SC200 proton therapy superconducting cyclotron is currently under construction by ASIPP (Hefei, China) and JINR (Dubna, Russia). The RF (Radio Frequency) system which provides an accelerating electric field for the particles, has been designed and tested in a high-power commissioning. The RF system consists of RF cavity, Low-level RF control system, RF source, transmission network and so on. The main performances of RF cavity meet design and use requirements in the cold test. The RF cavity achieved an unload Q factor of 5200 at the resonant frequency of 91.5 MHz, 65 kV (Center), ~115 kV (Extraction) accelerating voltage and coupling state of S11 < - 30 dB. The low-level RF (LLRF) system has been tested with an amplitude stability of < 0.2% and a phase stability of < 0.1 °C in the high-power commissioning. What's more, the cavity has already operated in a ~50 kW continuous wave state after 4 weeks RF conditioning. Some risks have been exposed at higher power test, but related solutions and improvements have been developed. In future work, the target of RF system is effective operation under the overall assembly of cyclotron after further optimization and RF conditioning.

INTRODUCTION

The SC200 proton therapy superconducting cyclotron is currently under construction by ASIPP (Hefei, China) and JINR (Dubna, Russia). The RF system which provides an accelerating electric field for the particles, has been designed and tested in a high-power commissioning. The key components of RF system are Low-level RF control system, RF source, transmission network, which will be discussed in following paragraphs [1, 2]. The assembled RF system in commissioning stage is shown in Fig. 1.

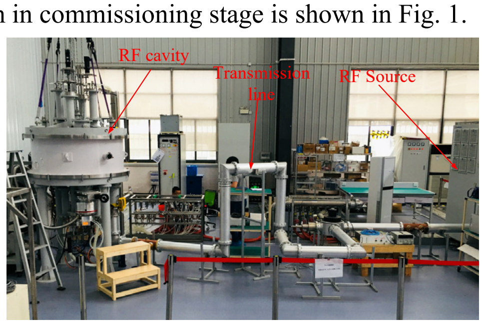

Figure 1: Assembled RF system in commissioning stage.

A high-power commissioning has been performed for the cavity. RF conditioning contributes to improve the performance RF cavity, so as to achieve high power feeding in cavity. Temperature record and X-ray calibration have also made for RF cavity to verify its performance. Moreover, some improvements have been done for cavity to solve related problems.

DESIGN OF RF SYSTEM

The RF system mainly consists of RF cavity, Low-level RF control system, RF source, transmission network. The RF source provides power to RF cavity through 6-inch coaxial transmission line under the control of Low-level RF control system. The RF cavity consists of Dee, Liner, Stems, Trimmers and coupling looping. The layout of RF cavity is shown in Fig. 2. Some optimizations have been made on the cavity based on the original physical model. Therefore, the Dee is optimized to a gradient shape with lighter weight. The inside of Dee has enough space for water cooling pipes. The design and manufacture of water - cooling paths on the rectangular Stem become easy. The new design also provides strong support for Dee to reduce the risk of deformation. The disc of trimmer and Dee form an equivalent capacitance, which is tuned by moving the trimmer up and down. In order to reduce the influence of high temperature under high power, water cooling pipes are also arranged on the outside of the cavity.

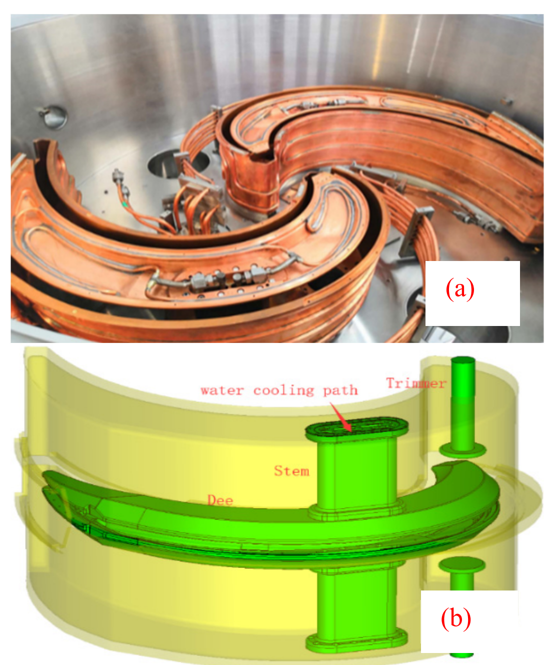

Figure 2: Layout of RF cavity. ((a) is half cavity with up and down symmetry, (b) is half cavity with left and right symmetry).

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Moreover, a cold (no feeding power) test has been made on a mock-up cavity to verify its main parameters. The test results are shown in Table 1. The Resonant frequency is adjusted by 4 capacitance trimmers with moving distance of 100 mm. The tuning range in cold test is similar to the design. The Accelerating voltage is also the same. Due to a certain roughness on the mock-up cavity, the unload Q factor is lower than the design. But it also meets the requirements [3].

Table 1: Main Parameters of RF Cavity in Cold Test vs. Design

Parameter	Design	Cold Test
Frequency	91.5 MHz	91.5 MHz
Tuning range	±100 kHZ	91.4 MHz +180 kHz
Accelerating voltage	60 kV (Center) ~120 kV (Extraction)	65kV (Center) ~115 kV (Extraction)
Unload Q factor	5500	5200
Coupling state	$S_{11} < -30$ dB	$S_{11} < -30$ dB

The RF source is a Solid Amplifier with full power of 120 kW at frequency 91.5 ± 1 MHz. The Solid Amplifier signal flow is shown in Fig. 3. The Solid Amplifier consists of RF Gate, Driver module, Splitter, RF sub-Modules, Combiner and cooling auxiliary system. There are 48 RF sub-Modules and every Modules provides a redundant full power of 2.8 kW. The Low-level RF control system (LLRF) controls the Solid Amplifier to feed power to RF cavity. The composition chart of LLRF system is shown in Fig. 4. The adjustment process is implemented by three main loops. The amplitude loop compensates fast distortions for amplifier with a stability < 0.2%. The phase loop keeps the phase of cavity field to the desired value with a stability < 0.1°. The tuning loop contributes to automatic turning for cavity. The stabilities mentioned have been tested in the high-power commissioning.

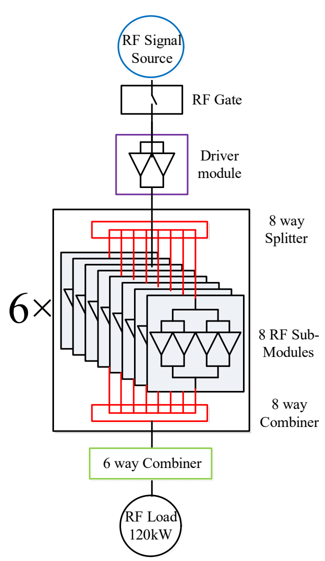

Figure 3: Amplifier signal flow.

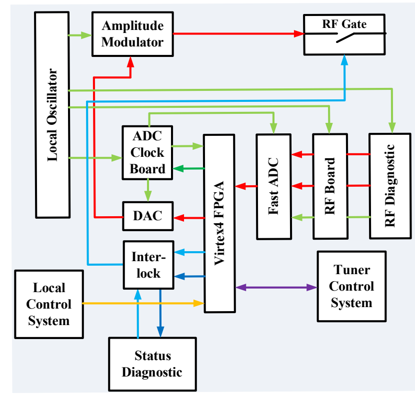

Figure 4: The composition chart of LLRF system.

THE COMMISSIONING OF HIGH-POWER TEST

We have made a high-power test for the prototype SC200 cyclotron under a suitable condition. The current of superconducting coil was 140 A with a magnetic field of ~3 T. The vacuum degree of cyclotron host is 1×10^{-4} Pa. The Pulse wave mode was used for RF conditioning under the control LLRF system [4]. The interface of LLRF system for RF conditioning is shown in Fig. 5. For RF conditioning, we increased the pulse wave power gradually under good coupling state. Amplitude in LLRF becomes stable gradually after a certain time. Pick-ups contributed to detect the multipactor in cavity in once RF conditioning [5]. Finally, the cavity could be fed ~50 kW continuous wave power without reflection after 4 weeks of RF conditioning. In the whole RF conditioning process, we recorded the temperature of RF cavity. Thermal resistances detected three different points on the outside surface of RF cavity liner. The temperature rise of RF cavity is no more than 30 °C due to good cooling effect. The frequency deviation of cavity caused by temperature rise is estimated no more than -40 kHz based on previous multi-analysis [6].

Figure 5: The interface of LLRF system for RF conditioning.

Moreover, X-ray measurement has been made for cavity to the maximum accelerating voltage on Dee based on principle of bremsstrahlung. The detectors were suitable to collect the X-ray spectrum from Dee. The detectors were calibrated to acquire the relationship between energy and channel by Am241 source. The shunt impedance in test

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meets the design value 90 kΩ. The Dee voltage deviation between the two cavities is no more than 7 % [7].

IMPROVEMENTS FOR THE CAVITY

The high-power test stopped after running ~30 hours at ~50 kW continuous wave power due to the breakdown of RF window. We made some improvements for cavity to solve the problem. The structure of RF window was optimized to reduce the risk of multipactor. Venting holes (or gaps) were designed to increase gas circulation between RF window and the cavity to improve the vacuum degree. Cooling pipes were arranged on RF window and coupling to reduce thermal stress as shown in Fig. 6.

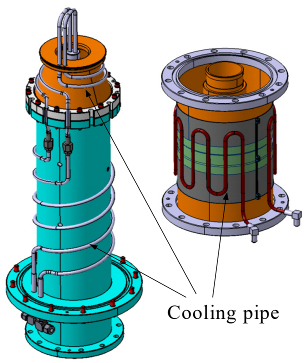

Figure 6: Cooling pipes on RF window and coupling.

We improved the electrical contact situation on Dee and Stem. The copper rings were used on Stem instead of the original copper braid. The “L” type RF contact fingers which have better condition within 2.5 mm are used between two Dees as shown in Fig. 7.

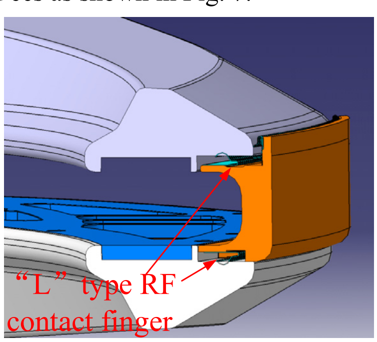

Figure 7: “L” type RF contact finger for Dee.

Last but not least, the water-cooling paths were modified on cavity. We designed semicircular groove for cooling pipes on Dee to increase heat dissipation area as shown in Fig. 8. A three-way connector was added to fix pipe on Dee.

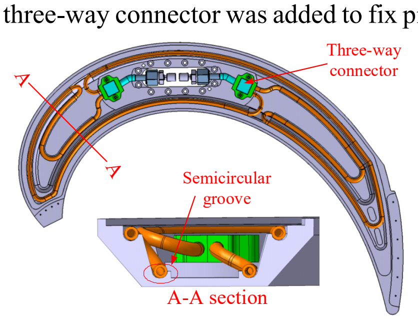

Figure 8: Water cooling optimization on Dee.

SUMMARY

The RF system of SC 200 mainly consists of RF cavity, Low-level RF control system, RF source and so on. The main parameters of RF cavity have been verified in a cold test. The RF cavity achieved an unload Q factor of 5200 at the resonant frequency of 91.5 MHz, 65 kV (Center) ~115 kV (Extraction) accelerating voltage and coupling state of S11 < -30 dB. The LLRF system has been tested with an amplitude stability of < 0.2% and a phase stability of < 0.1 degree. The cavity could be fed ~50 kW continuous wave power without reflection after 4 weeks of RF conditioning. Temperature record has contributed to thermal and frequency deviation analysis. The X-ray measurement has calibrated the maximum accelerating voltage on Dee. The improvements which are mainly about RF window, electrical contact and cooling system have been made to solve related problems. The future goal is to achieve 80 kW power smooth injection after the formal RF conditioning.

ACKNOWLEDGEMENTS

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