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DEVELOPMENT OF A SUPERCONDUCTING DOUBLE-SPOKE CAVITY AT IMP*

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Abstract

Superconducting multi-spoke cavities are well-known optional choice for acceleration of heavy ions in medium energy. This paper describes the RF design, mechanical design, and test results of the superconducting double-spoke cavity developed at IMP. After Buffered Chemical Polishing and High Pressure Rinsing, one cavity has gone through high gradient RF testing at 4.2 K in the Vertical Test Stand. We present measurements of the quality factor as a function of accelerating field and maximum field on the surface. Accelerating gradient of more than 15 MV/m is reached with peak electric field of 61 MV/m, and peak magnetic field of 118 mT.

INTRODUCTION

The superconducting spoke cavity is based on one or more loaded structures where each loading element supports a TEM mode. As the interest in spoke cavities has increased and their design advanced, more and more spoke cavities have been developed and tested not only for low and medium beta particle [1], but also for high velocity application [2]. The use of spoke cavities is planned for substantial projects, such as the main driver accelerator of the Proton Improvement Plan-II (PIP-II) [3] and the superconducting part of the European Spallation Source (ESS) [4]. Applications of the Accelerator Driven System (ADS) for nuclear waste transmutation or for tritium production also propose the use of spoke cavities [5].

Based on the scheme of China ADS, we have done researches on spoke cavities and designed an optimal β = 0.52 double-spoke cavity as an alternative option for the medium velocity regimes.

RF DESIGN

The main goal in the RF design of superconducting cavity is to get a higher accelerating gradient and a lower heat load, which are determined by lower peak surface fields and a higher $G*R/Q_0$. According to the state of the art, we require that the maximum peak surface electric and magnetic field be under 35 MV/m and 70 mT. For our application, the accelerating gradient is about 9 MV/m, thus the normalized electric field E_p/E_{acc} and the magnetic field B_p/E_{acc} are less than 3.89 and 7.78 mT/MV/m.

This work has been done using the electromagnetic design software CST Microwave Studio [6]. Figure 1 shows a cut-away view of the cavity model in MWS and the main geometric parameters used for the optimization.

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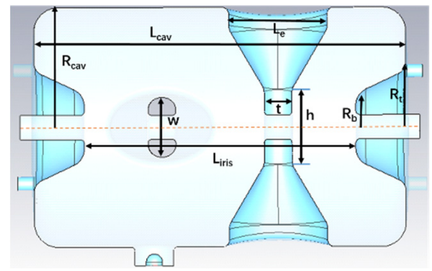

Figure 1: The cut-away view of double spoke cavity model in MWS and main parameters.

The length between iris (L_{iris}) and cavity's radius (R_{cav}) are relatively determined by the desired β_0 and the operating frequency. All data have been obtained in the process of optimization under conditions of the desired β_0 and frequency, which means that the iris-to-iris length and the radius of cavity are varied along with the parameters.

The magnetic field of the operating mode in a spoke cavity is more concentrated near the surface of the outer conductor and surrounds the spokes, thus the dimension and shape of the spoke base have a great influence on the maximum surface magnetic field. To uniform the surface magnetic field on the spoke base, the elliptic column is used to replace the cylindrical one. The major axis of the ellipse is along the beam pipe.

Besides, the cavity total length should be considered, which has a great effect on the flatness of the electric field, which plays an important part in both the position of the peak surface field and the shunt impedance, especially for multi-spoke cavities. We found that better RF properties can be achieved if the field is stronger in the end cell than the middle cell for the double-spoke cavities.

Table 1: The RF Properties of the Double-Spoke Cavity

RF Properties	Value
Frequency [MHz]	325
Optimal β	0.52
Effective length $3\beta\lambda/2$ [mm]	581.2
E_p/E_{acc}	3.77
Bp/E_{acc} [mT/MV/m]	7.64
G [Ohm]	114
R/Q_0 [Ohm]	499
Voltage(β_0) @E_{acc}=9 MV/m [MV]	5.23
Pdiss (@R_s=60 nΩ, E_{acc}=9MV/m) [W]	44
Aperture [mm]	50
Diameter of cavity [mm]	506
Length of cavity [mm]	785

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Table 1 summarizes all the RF parameters of the cavity design; the effective length is defined as $L_{eff} = 3\beta_0\lambda/2$. The electromagnetic simulation gives the optimum parameters *Ep/Eacc* of 3.77 and *Bp/Eacc* of 7.64 mT/(MV/m), which meet the requirement of China ADS. Figure 2 shows the electric and magnetic fields distribution in the double-spoke RF volume with all the HPR and coupler ports.

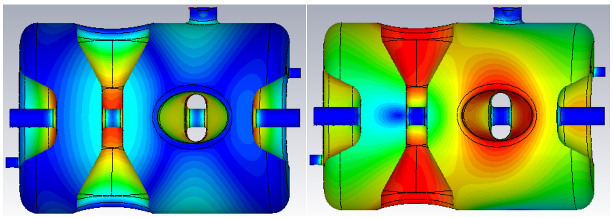

Figure 2: The electric (left) and magnetic (right) field distribution in the double-spoke RF volume. The field strength increases as the color changes from blue to green to yellow to red.

MECHANICAL DESIGN AND FABRICATION CONSIDERATIONS

For the bare cavity, we take less attention to the sensitivity to helium pressure fluctuation than protecting against plastic collapse, which means avoiding unbounded displacement in each cross-section of the double-spoke cavity due to the plastic hinge. There are six beam pipe ribs welded on each of the two end cap and two ring ribs with six connecting ribs between two rings welded at the end of the two end walls, with which the cavity can be bolted connection between two aluminium plates when checking the leak rate. All the stiffeners are made of 6 mm thick reactor grade niobium.

The cavity has been simulated under a one atmosphere external load, while both the ribs between the two rings of each end are fixed. Figure 3 shows the equivalent results of Von Mises stress and displacement distribution for the stiffened cavities during the leak check conditions. Other mechanical properties of the stiffened double-spoke cavity are listed in Table 2.

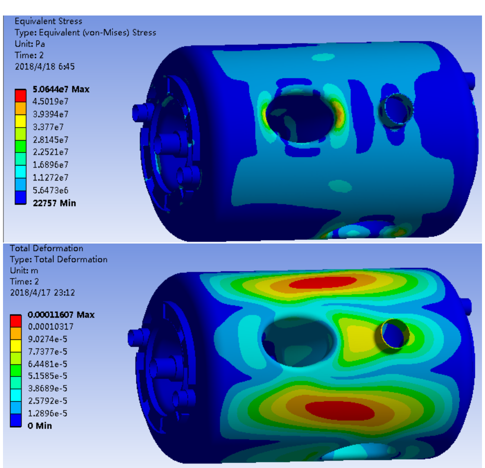

Figure 3: The Von Mises stress (up) and displacement (down) distribution of the stiffened cavity under one atmosphere external load.

Table 2: The Mechanical Properties of the Double-Spoke Cavity

Mechanical Properties	Value
Thickness of the cavity walls [mm]	3
Critical pressure [bar] @ Room temperature	1.8
Max Von Mises [MPa]	51
Max Displacement [mm]	0.12
Sensitivity to helium pressure fluctuation KP [Hz/mbar]	75.1

The overall mechanical design including minimizing the K_p and Lorentz force detuning (K_L) will be done with the helium vessel and the tuner soon.

To simplify the manufacturing, the length of the major axis of the ellipse should be limited. In our design, the cavity can be divided into two single spoke cavity from the center of the dual spokes, as shown in Fig. 4. All the components of the double-spoke cavity, are formed and machined of high purity niobium (Nb), and connected by electron-beam welding (EBW).

Two prototype double-spoke cavities were fabricated in Harbin at the end of 2016.

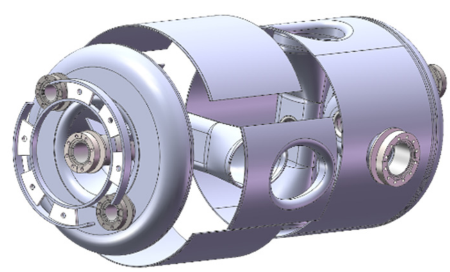

Figure 4: The explosive view of the double-spoke cavity.

SURFACE PREPARATION

The interior surface of DSR052-01 was prepared for vertical test after the cavities delivered to IMP. The cavity was immersed in a bath of ultra pure water with a degreasing agent and ultrasonically cleaned. It was then received its Buffered Chemical Polishing (BCP), followed by a High Pressure Rinse (HPR).

The BCP used the standard $HF:HNO_3:H_3PO_4$ (1:1:2) acid mixture. During BCP, acid flow and temperature were controlled by the automatic BCP system. To ensure the uniformity of etching, two BCP runs were made, each with the cavity in vertical orientation, sending the acid in via the lower HPR ports and beam pipe port, and taking the out coming fluid from all the upper ports back to the closed acid circulation system, as shown in Fig. 5.

The acid filling time is 270 s, and the emptying time with nitrogen is about 350 s. Fresh acid circulated for about 180 minutes through the cavity. For the second run the flanges were detached, and the cavity was flipped top to bottom before the flanges were re-attached again. The wall thickness reduction averaged 109.2 µm after a total etching time of 225 minutes, which was about 10 µm less than we expected.

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Figure 5: The BCP set-up of the double-spoke cavity.

After a 850 °C heat treatment for 3.5 hours and light BCP of 15 µm etching, the DSR052-01 was shifted to the class 100 clean room for HPR with ultra pure water at the pressure of 84 bars. The HPR system distribution involved a long wand with a nozzle at the end that produces three water jets, fan-shaped to the wand axis, which is designed for HWR cavity [7]. For HPR, the wand rapidly spins about the axis and moves into or out of the cavity at the speed of 40 mm/min. For the sake of a jet to directly spray on all the interior cavity surfaces, including all four HPR ports and beam pipes, the position of the DSR052 is changed six times with the HPR lasting about 1 hour at each orientation for a total of 7 hours.

After completing HPR, the double-spoke cavity was dried in a class 100 clean room for more than 24 hours and then all auxiliary parts (i.e. the antenna, the adjustable coupler, the pick up, the pump out port with valve and the blank flanges) were assembled in class 100 clean room.

COLD TEST RESULTS

The DSR052-01 was mounted in the VTS cryostat with the the beam pipe along the vertical axis because of lack of space (radially). Preparation of the cavity for insertion into the VTS dewar included attaching thermo-elements, installing a siphon for removal of helium gas from the lower end cap, installing RF lines for power coupling and for the field probe, line for vacuum pump, etc. A 120 °C baking for 48 hours have been done before cooldown.

First cooldown revealed a leak that developed in the adjustable coupler flange. After the coupler flange was replaced, a second VTS test was performed.

A 500 W RF power amplifier was used to feed power into the cavity. We used a adjustable capacitive coupling in the lower beam port and transmitted power was picked up with an antenna attached to the upper beam port.

As expected, we observed a very strong electron activity starting at around 1.5 MV/m, when initially raising Eacc, but it was easily processed.

The quality factor as a function of accelerating gradient, maximum electric and magnetic field on the surface of the DSR052-01 is shown in Fig. 6. The accelerating gradient of more than 15 MV/m is reached with peak electric field of 61 MV/m, and peak magnetic field of 118 mT. Enventually, the accelerating grident is limited by quench of the cavity. The X-rays emission started from the accelerating gradient of 12 MV/m, as the red curve in Fig. 6. The field emission source supposed to be from the adjustable coupler flange replacement without HPR.

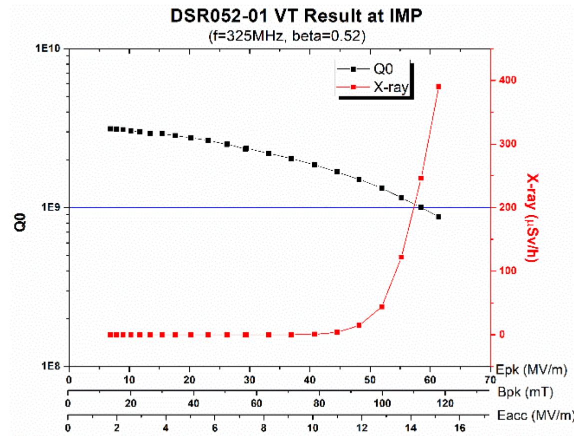

Figure 6: The quality factor as a function of accelerating gradient, maximum electric and magnetic field on the surface of the DSR052-01. The red curve is X-rays detected during the Q_0 versus E_{acc} scans.

The overall surface resistance at E_{acc} = 9 MV/m is about 54.3 nΩ for the quality factor of 2.1E9. The BCS resistance is 33.3 nΩ, so the residual resistance is about 21 nΩ.

CONCLUSION

A superconducting double-spoke cavity with the optimal $\beta = 0.52$ has been designed as an alternative option for the China ADS medium energy part at IMP. The accelerating gradient of more than 15 MV/m is reached with peak electric field of 61 MV/m, and peak magnetic field of 118 mT in the vertical test.

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