ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF034



# DEVELOPMENT OF SUPERCONDUCTING RF DOUBLE SPOKE CAVITY AT IHEP*

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*Abstract*

The China Initiative Accelerator Driven System (CiADS) has been approved to transmute long-lived radio-isotopes in used nuclear fuel into shorter-lived fission products. IHEP is developing a 325MHz double spoke cavity at β0 of 0.5 for the CiADS linac. The cavity shape was optimized to minimize Ep/Ea while keeping Bp/Ep reasonably low, while the multipacting was analyzed. Meanwhile, mechanical design was applied to check stress, Lorentz force detuning and microphonic effects, and to minimize pressure sensitivity. A new RF coupling scheme was proposed to avoid electrons hitting directly on ceramic window. The detailed design for the cavity is addressed in this paper.

## INTRODUCTION

The CiADS consists of a high-power proton linac, a spallation target that produces neutrons when bombarded by the high-power beam, and a subcritical core that is neutronically coupled to the spallation target. The linac will accelerate proton beam of 10-5mA up to 250-500MeV, and double spoke cavity is adopted for medium β section.

Spoke cavity evolves from half-wave resonator (HWR) operating in TEM mode. Compared with HWR, Multi-gap structure is possible in spoke cavity, which saves longitudinal space and increase the real-estate gradient. Compared with elliptical cavity, the spoke structure has higher shunt impedance, meanwhile, it is mechanically more stable and exhibit a stable field profile due to the high cell-to-cell coupling [1]. Thus spoke double spoke cavity is a preferred candidate for medium β application.

## ELECTROMAGNETIC DESIGN

Electromagnetic design includes geometry optimization, coupling port design and multipacting (MP) analysis.

### *Geometry Optimization*

The cavity geometry is optimized to achieve maximum accelerating gradient (Eacc) during operation. One limit to the performance of a superconducting cavity is field emission (FE) at where surface electric field is high; another limit is quenching at where surface magnetic field is high. So the peak surface field to gradient ratio, i.e. Ep/Eacc and Bp/Eacc, are the major figure of merits for geometry optimization.

Based on the experience of previous ADS project, SRF cavities seldom quench below Bp of 90mT; though, FE may occur at Ep as low as 30MV/m, and the degradation of FE onset is observed over some time of beam operation. So the main optimization target is to reduce Ep/Eacc, while the Bp/Ep is kept below 2.57mT/(MV/m).

The Ep/Eacc is most sensitive to the central part of the spoke and the end-cover cone shape, i.e. $T_k$, $S_{gl}$, $S_{al}$, and $S_{bl}$, as shown Fig. 1. The base of the spoke has more influence on Bp/Eacc, and it is biased to a racetrack shape in order to further reduce Ep/Eacc [2]. The major geometry parameters optimized are shown in Fig. 1. The final cavity length $C_l$ is 729mm, and the cavity diameter $C_d$ is 560mm.

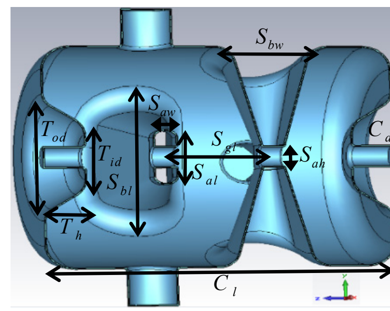
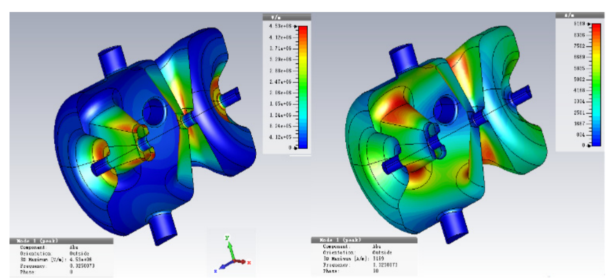



Figure 1: Parameters for optimization.



E-field distribution H-field distribution

Figure 2: Electromagnetic field distribution of double spoke cavity.

After optimization, Ep/Eacc achieved 3.4, and the Bp/Eacc is 8.7mT/(MV/m); in case the cavity is operated with Ep of 35MV/m, then the Bp is 90mT, and the gradient can reach 10.3MV/m, which is higher than the project target of 9MV/m. The surface field profile of the cavity is shown in Fig. 2, while detailed design parameters are listed in Table 1.

Table 1: The Major Parameters of Double Spoke Cavity

| Description | Target | Results |
|---|---|---|
| Frequency (MHz) | 325 | 325 |
| R-aperture (mm) | 50 | 50 |
| Epk/Eacc | <3.89 | 3.4 |
| Bpk/Eacc (mT/(MV/m) | <7.78 | 8.67 |
| G*R/Q ( $\Omega^2$) | N/A | 5.08e4 |
| df/dP (Hz/mbar) | <19 | 1.27 |
| LFD factor (Hz/(MV/m)$^2$) | N/A | -9.3 |
| Tuning sensitivity (kHz/mm) | N/A | 78 |
| Cavity rigidity (kHz/kN) | N/A | 26.56 |

* Work supported by the State Key Development Program for Basic Research of China (Grant No. 2014CB845500)
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### *Coupling Port Design*

Three issues have been considered for the coupling port design.

First, the heat load on the stainless steel blank flanges should be low, in order to measure the cavity $Q_0$ accurately during vertical test. The total Q induced by 6 flanges is above $3.5 \times 10^{11}$, by properly choosing the length of the coupling port.

Second, antenna length is selected to reach desired Qe. Assuming the cavity operates at 9MV/m with 10-100mA proton beam, then the matched Qe is 1.5e5-1.5e6 by using equation: $Qe = V_{acc}/(I_{beam} \times R/Q)$. By calculating the Qe vs the antenna length of a 50 Ω coaxial line, it is found that the antenna tip is 3mm away from cavity inner surface at the minimum Qe, which is shown in Fig. 3.

Third, it is important to avoid the FE electrons, which are generated on cavity inner surface, hitting the ceramic window of the coupler. Here a 30 degree bending is applied to the coupling port, so the ceramic window will not see the high electric field region on the spoke centre. The bending angle and the antenna length are carefully checked, to make sure that there is space to insert the antenna into the coupling port.

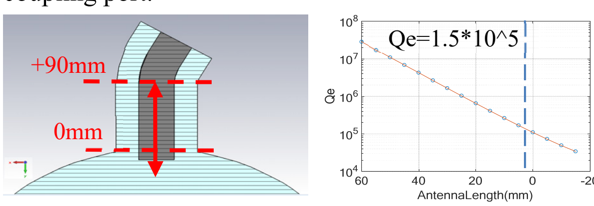


Figure 3: Winding coupling port and Qext versus antenna length.

### *Multipacting*

MP has been analyzed using CST particle tracking solver. Secondary electron yield (SEY), which is the ratio of the number of secondary electrons emitted to the number of incident electrons when the simulation get converged, is adopted to describe how severe the MP is. For each gradient, emitting phases of every 15 degrees are swept to get the maximum SEY.

In order to tell the difference between hard barriers and soft barriers, the same simulation scheme was applied to the ADS spoke021 cavity [3]. The MP of the spoke021 cavity is typically processed in 1 hour during vertical test and before beam operation, while the SEY of the double spoke cavity is lower than that of spoke021, as shown in Fig. 4; thus there should be no hard MP barriers in this double spoke cavity.

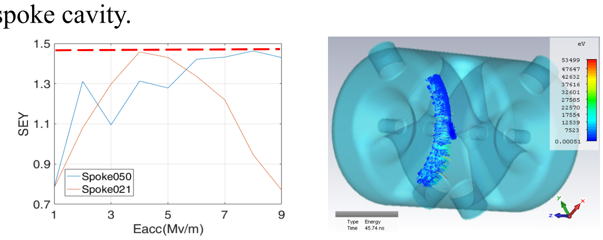


Figure 4: SEY of single spoke cavity and double spoke cavity (left) & typical MP of double spoke cavity (right).

## MECHANICAL DESIGN

Mechanical performance of the cavity was optimized with COMSOL. The simulation results are listed in Table 1 in the last page.

There are three design targets. The first is to minimize He pressure sensitivity (df/dp); the second is to make sure the cavity will not plastically deform in any possible boundary condition during post processing, testing, and operation; the third is to make sure the lowest intrinsic vibration frequency is above 100Hz.

### *Pressure Sensitivity*

The structure of the cavity is shown in Fig. 5. The cavity helium vessel is made of Ti, and the cavity end-cover is connected with the helium vessel by a Nb55Ti ring. Nb ribs inside the spoke are used to reduce df/dp and stress. For naked cavity, Ti blocks on end-cover are used to support the cavity with a fixture.

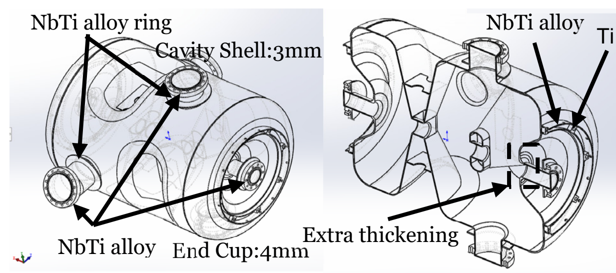


Figure 5: Mechanical design of double spoke cavity.

It is well known that geometry deformation will cause frequency deviation, and the frequency change can be calculated by Slater's theorem [i.e., Eq. (1)]. When the cavity beam port is free, the frequency deviation induced by pressure change inside the helium vessel is balanced by properly placing the stiffening rings and ribs. A df/dp of 1.27Hz/mbar is achieved, and Fig. 6 illustrate that the frequency change induced by electric field and magnetic field dominated zone cancel each other.

$$df \propto (\varepsilon_0 E^2 - \mu_0 H^2)dV \qquad (1)$$

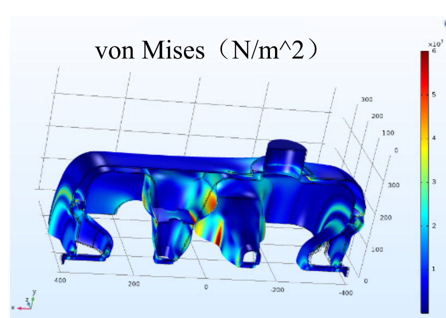


Figure 6: Stress & deformation (×100) with beam pipe free.

### *Stress Analyses*

There are typically three different boundary conditions to be analysed, as shown in Fig. 7 and Table 2. During leak

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check there is maximum stress on the cavity body, which is shown in Fig. 8, and it is still below the allowable stress of 47MPa [4]. For naked cavity, the fixture hold the stiffening ring on end-cover, and the stress is below allowable stress too.

Table 2: Boundary Conditions for Stress Analyses

| | In | HeV | Out | BP |
|---|---|---|---|---|
| Leak check | Vac. | 1 atm | 1 atm | Free |
| Cooling down | Vac. | 1 atm | Vac. | Free |
| Tuning | Vac. | 1 atm | Vac. | Free+Push |

*HeV is short for helium vessel, and BP is for beam pipe

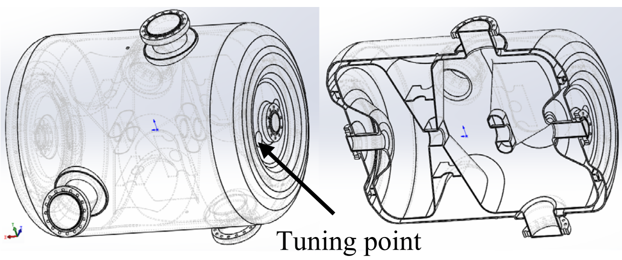


Figure 7: Double spoke cavity with helium vessel.

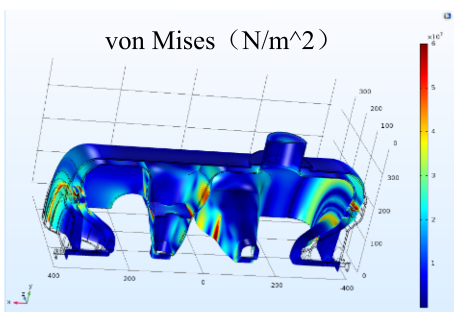


Figure 8: Surface von Mises stress of leakage detecting & Displacement (×50).

### Tuning Sensitivity

The tuning force is applied on a single side of the cavity near the beam pipe, as shown in Fig. 7, and the displacement by pushing the end-cover is defined as positive. The stress and displacement are simulated at various tuning force, and it is found that the stress on cavity is smaller when pushing the cavity compared with pulling, as shown in Fig. 9.

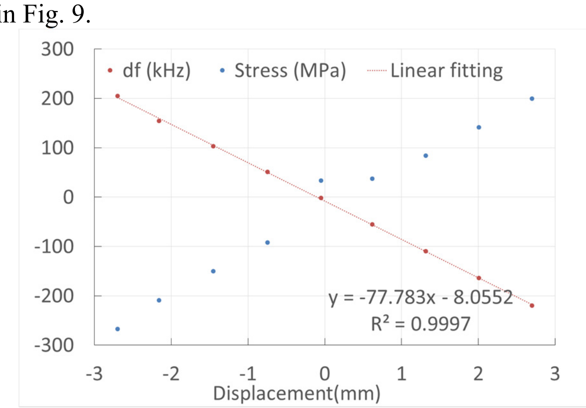


Figure 9: Stress and freq. change vs tuning force.

### Lorentz Force Detuning

The interaction of the cavity field with the induced surface currents and charges results in an electromagnetic surface forces in RF cavities [5]. The induced frequency shifting effect is called Lorentz force detuning (LFD), and it has to be considered and corrected by low level control system. The definition of LFD coefficient is as following:

$$K_L = \Delta f / E_{acc}^2 \quad (2)$$

Frequency shift at various gradient are simulated to fit the LFD coefficient, as shown in Figure 10. The maximum deformation is located near the high electric field region, The $K_L$is-9.3 Hz/(MV/m)^2 with ports free

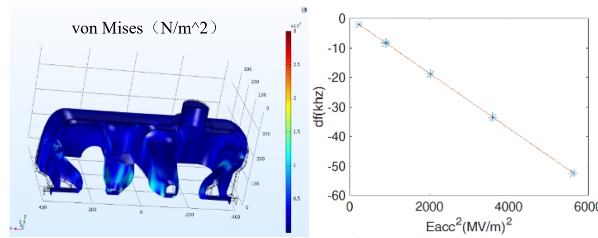


Figure 10: Displacement (×300) caused by Lorenz force@75MV/m (left) and LFD coefficient fitting (right).

### Vibration Mode

The mechanical resonance modes are analysed with cav-ity beam pipe free and sitting on the center of its helium vessel. The lowest vibration frequency is 215Hz, as shown in figure 11, indicating there is no danger of

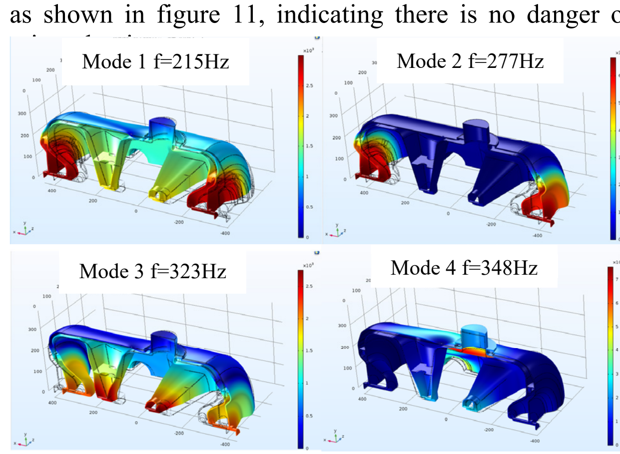


Figure 11: The lowest vibration modes.

## CONCLUSION

The systematic design of the double spoke cavity has been accomplished, including RF parameters optimization, coupling port design, MP analysis, structure design, pressure sensitivity optimization, stress analysis, tuning simulation, LFD analysis, and vibration mode analysis. Now the fabrication is on going, and the delivery of the prototype cavity is planned on August 2018. Vertical test and horizontal test will be applied to the cavity.

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