DEVELOPMENT OF A VERY LOW BETA SUPERCONDUCTING SINGLE SPOKE CAVITY FOR CHINA-ADS LINAC*

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Abstract

Twelve very low Beta superconducting single spoke cavities whose Beta is only 0.12 (Spoke012) operating at 325 MHz, are adopted in Injector I for China-ADS linac. This type of spoke cavity is believed to be one of the key challenges for its very low geometric Beta. So far, collaborated with Peking University and Harbin Institute of Technology, IHEP has designed, fabricated and tested the spoke012 prototype cavity successfully. This paper presents the details of the design, fabrication and test results for Spoke012 prototype cavity.

INTRODUCTION

Spoke cavity is a TEM-class and generally superconducting resonator. In addition to the inherent advantages of superconductors, the spoke cavity has more compact structure with the same frequency than the elliptical cavity, and higher shunt impedance than the half-wave resonator, etc. Therefore, many large-scale accelerators, which need high power and high intensity protons, have been purposed to adopt spoke cavities, and the China-ADS linac is one of them [1].

Figure 1 is the layout of China-ADS linac. With the scheme of Injector I, the proton beam originates from an ECR ion source, and then accelerated to 3.2 MeV by a CW normal conducting RFQ. From 3.2 MeV to 178 MeV, the beam is accelerated by three different types of superconducting spoke cavities (Spoke012, Spoke021, Spoke040). After that, the beam is accelerated by two types of superconducting elliptical cavities.

Among the three spoke cavities, Spoke012 is believed to be the most challenging one since it is of very low geometric Beta, which is only 0.12. In this paper, the development of Spoke012 prototype cavity is introduced, including the design, fabrication and vertical test results.

DESIGN OF SPOKE012 CAVITY

Required by beam dynamics, the frequency of 325 MHz, β of 0.12 and beam aperture diameter of 35 mm are chosen for Spoke012 cavity, and the iris-to-iris distance is defined to be 2/3βλ.

In order to maximize the shunt impedance and minimize ratio of Epeak/Eacc and Bpeak/Eacc and then get a higher accelerating gradient, the RF parameters of spoke012 with different shapes and dimensions of spoke base and end-wall were simulated and analysed, using the CST_MWS software (Microwave studio) [2] .

Finally, compared with round and race-track shape, elliptical spoke base has been chosen due to a more uniform magnetic field distribution. A camber end-wall has been selected for a better RF performance and stronger structure. The resonator structure of Spoke012 is very sensitive to the pressure variations because of the very low geometry Beta. Contrasted to a conventional flat end-wall, the camber end-wall encloses the RF region with entire curves. Curved design could decentralize the force of helium fluctuation, which could improve the mechanical property and is easier to design the stiffeners.

Cross section and field distribution of spoke012 cavity are shown in Fig. 2 and Fig. 3, meanwhile the main geometric parameters and RF results are presented in table 1.

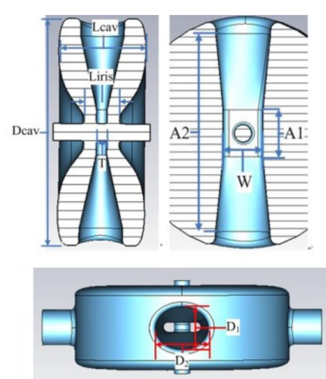

Figure 2: Cross section of spoke012 cavity.

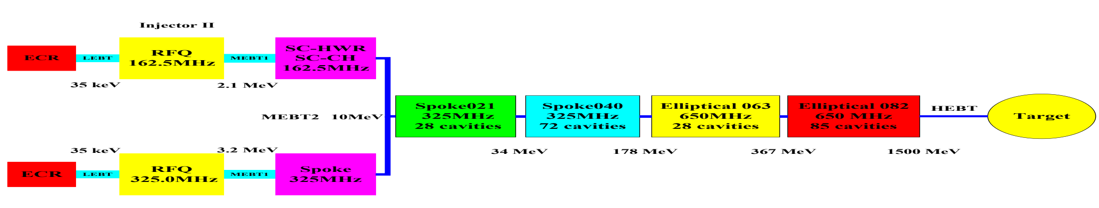

Figure 1: Layout of the China-ADS linac.

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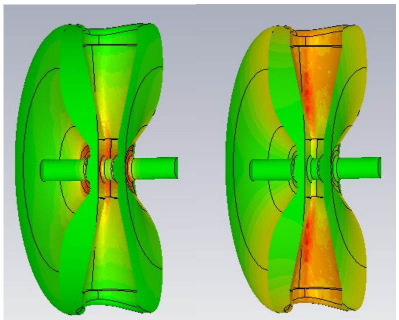

Figure 3: Surface electric field (left) and magnetic field (right), the field increases with the colour changing from green to red.

Table 1: Main Parameters of Spoke012 Cavity

Cavity length(Lcav)/mm	180
Cavity diameter(Dcav)/mm	468
Iris-to-iris length(Liris)/mm	73
Major axis of spoke base (D2)/mm	112.5
Minor axis of spoke base (D1)/mm	90
Spoke thickness at aperture(T)/mm	22
Spoke width at aperture(W)/mm	82
Spoke race-track higher(A1)/mm	94
Spoke lofting higher(A2)/mm	398
Aperture diameter/mm	35
Coupler port diameter/mm	80
Operating frequency (MHz)	325
E_{peak}/E_{acc}	4.5
B_{peak}/E_{acc} mT/(MV/m)	6.4
G (Ω)	63
R/Q (Ω)	142
Geometrical Beta	0.12
Leff= β λ (mm)	110

In order to meet the requirements of helium pressure sensitivity and lower the von stress of cavity, the structure of Spoke012 cavity is enhanced by three types of stiffeners, including two circular ribs in the end-wall outer region ,six daisy ribs in the inner region and eight circumferential ribs on the cylindrical portion of the cavity. All stiffeners are made of reactor-grade niobium. Circumferential ribs have a thickness of 10mm, while others are 6 mm. A view of stiffeners is shown in Fig. 4.

Mechanical design with helium vessel is studied. Titanium (TA2) is chosen as the material of Spoke012 helium vessel. One beam port is welded to the helium vessel, the other one is connected with a bellow.

Distortions of Spoke012 due to vacuum load and thermal shrinkage have been predicted by the ANSYS MECHABICAL software [3]. By optimizing the radius of circular ribs and bellows connecting the cavity with the vessel, the sensitivity of helium pressure (df/dp) is decreased. In the calculation of external pressure loading, one beam pipe flange is considered “hard fixing” to the helium vessel. The final mechanical properties are shown in Table 2.

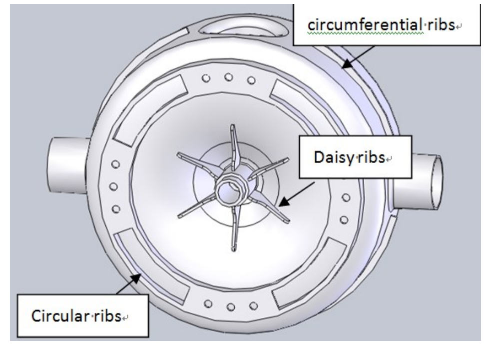

Figure 4: Stiffener design of Spoke012 cavity.

Table 2: Mechanical Property of Spoke012

df/dP(pipe free)	-156 Hz/torr
df/dP(pipe fixed)	+40 Hz/torr
Tuning sensitivity	1 MHz/mm
The static Lorentz coefficient	-1.3 Hz/(MV/m)^2
Cooling down (300 to 4.2K)	+463 kHz

Note: “pipe free” means unconstrained at the tuning side, while the tuner give a longitudinal constraints for “pipe fixed”. The von stress of cavity is all below 40MPa at 1 atmosphere standard.

About 460 kHz increase when the cavity is cooled down from room temperature to 4.2 K. The cavity is designed to be tuned only from the bellow side. With a tuning sensitivity of 1 MHz/mm and a 60 kHz / 100 kgf spring constant of the end wall, the Spoke012 cavity meets the requirement for the tuning range of 200 kHz easily.

FABRICATION

For fabrication, the cavity body is enclosed by a high RRR niobium with the thickness of 3.5mm. The niobium materials come from Ningxia Orient Tantalum Industry Co., Ltd. After pro-processing, thickness of the cavity was reduced to an average of 3.2 mm. Four beam flanges, including two beam pipe flanges, a vacuum flange and a coupler port flange are made of Nb-Ti alloy. An explode view of Spoke012 is shown in Fig. 5.

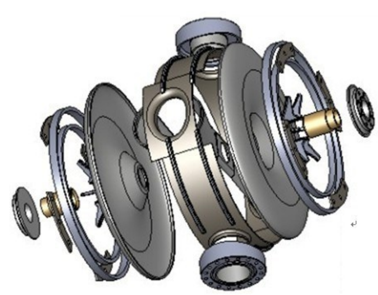

Figure 5: Explode view of Spoke012.

All the cavity components were made by stamping technology with a 3510 KN punching machine. Some experiments were done with the copper sheets to understand the shrinkage and deformation in the stamping.

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To make the cylindrical portion easy to weld, it was separated into four pieces of sheets, while the end-walls were stamped from a bulk niobium.

All components were joined using electron beam welding (EBW). It is noted that the thickness of weld region was reduced to 2 mm to meet the demand of final back forming welds between the end walls and the shells. Before EBW, every component underwent a brief chemical polish to wipe off the oxide layer from weld region.

A frock clamp was used to clamp the end wall to the cylindrical shell during pre-weld tuning, as shown in Fig. 6. The trimming was done by removing material from both the end walls and the central shell. According to the calculation, trimming sensitivity increases about 450-800 kHz/mm when the cavity length becomes shorter. This is consistent with the frequency measured in the cavity length cutting. The final frequency before the last welding was 325.75 MHz, and close to theoretical estimate of 325.42 MHz. The expected value of shrinkage along the cavity axis due to the last EBW was 1.2 mm, yet the actual value after welding was about 2 mm, and the frequency of the cavity after fabrication is about 500 kHz lower than expected. This will be further studied next.

Figure 6: A frock clamp for Spoke012 tuning.

During the fabrication, all mechanical errors were carefully considered, including the total cavity length, the asymmetry of both gaps, the parallelism of the end-walls and shrinkage occurs at the round edges of the last EBW. Two bare Spoke012 prototype cavities are shown in Fig. 7.

Figure 7: Two bare Spoke012 prototype cavities fabricated in November 2012.

POST SURFACE PROCESSING AND VERTICAL TEST

The post surface processing of Spoke012-2# prototype cavity was finished in December, 2012, including ultrasonic cleaning, BCP and HPR. More details may be found from reference [4]

After post processing, the Spoke012-2# prototype cavity was vertical-tested successfully at IHEP.

The vertical test system consists of 325 MHz signal generator, 1 kW solid state amplifier, LLRF control system and DAQ system, and classical vertical test method was used [5] .

In the vertical test, Spoke012-02# reached Eacc of 8 MV/m at 4.2 K, the residual surface resistance (Rs) is 50 nΩ.Here, Eacc is defined as the total accelerating voltage divided by $\beta\lambda$(110mm).The X-ray appeared at 5 MV/m, and the maximum surface field was limited to 36 MV/m. The measured Q_0 of the cavity as a function of accelerating gradient is shown in Fig. 8.

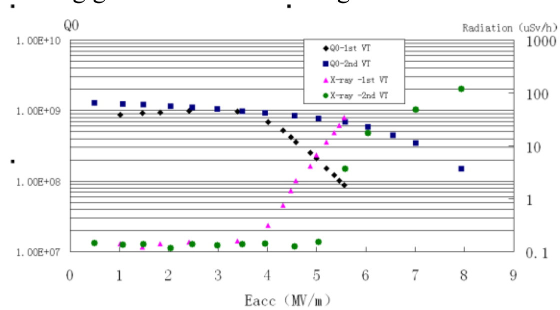

Figure 8: VT summary of Spoke012-02# cavity.

When accelerating gradient reached 8 MV/m, it was hard to grow up because of a serious Multipacting effect. Though additional 6 hours' RF conditioning was carried out, the maximum accelerating gradient improved very little.

HORIZONTAL TEST

After integrated with the high power input coupler, cryostat and tuner successfully, Spoke012-2# cavity with helium vessel was horizontally tested in the beginning of September 2013 at IHEP. The cryomodule of Spoke012 and LLRF equipments are shown in Fig. 9 and Fig.10.

In this test, a serious Multipacting effect played a critical role in the limitation of increasing the accelerating gradient. The performance then improved much after sufficient RF aging, while the radiation reduced obviously. As shown in Fig. 11, the maximum accelerating gradient under CW reached 6.5 MV/m, and at this gradient, Q_0 of the cavity is 2.2×10^8.

Figure 9: The cryomodule of Spoke012 with cavity in it.

Figure 10: The LLRF equipments of Spoke012

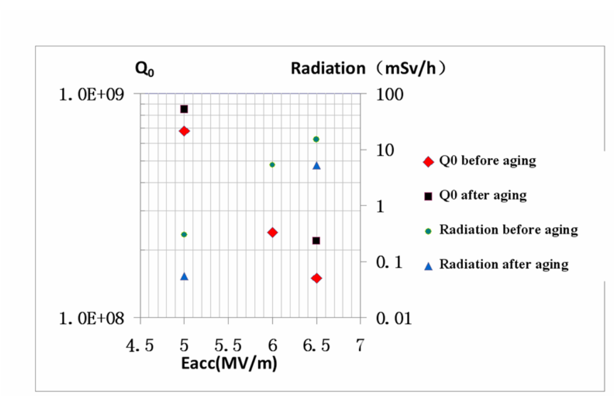

Figure 11: Performance of Spoke012-02# cavity in HT.

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REFERENCES

[1] Zhihui Li et al., "General Design of C-ADS Accelerator Physics", internal report.
[2] CST MICROWAVE STUDIO, www.cst.com
[3] ANSYS MECHANICAL™ of Ansys Inc.
[4] Qunyao Wang et al., "Surface Processing Facilities for Spoke Cavities at IHEP", Proceedings of SRF2013, Paris, France, September 2013.
[5] Jianping Dai, Juan Zhang et al., "LLRF and Data Acquisition Systems for Spoke012 Cavity Vertical Test at IHEP". Proceedings of SRF2013, Paris, France, September 2013.

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