Chinese Physics C Vol. 38, No. 7 (2014) 077008

Development of a 325 MHz β=0.12 superconducting single spoke cavity for China-ADS *

LI Han(李菡)[1,2] DAI Jian-Ping(戴建枰)[2;1)] SHA Peng(沙鹏)[2] WANG Qun-Yao(王群要)[2] HUANG Hong(黄泓)[2] LI Li-Hai(李黎海)[2] ZHANG Juan(张娟)[1,2] MA Qiang(马强)[2] LIN Hai-Ying(林海英)[2] SUN Yi(孙毅)[2] PAN Wei-Min(潘卫民)[2]

[1] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[2] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Abstract: Twelve very low Beta superconducting single spoke cavities, whose Beta is only 0.12 (Spoke012) when 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, in collaboration with Peking University and Harbin Institute of Technology, IHEP has successfully designed, fabricated, and tested the Spoke012 prototype cavity. This paper presents the details of the design, fabrication and test results for Spoke012 prototype cavity.

Key words: low beta spoke cavity, EM design, mechanical design, fabrication, cold test

PACS: 29.20.Ej **DOI:** 10.1088/1674-1137/38/7/077008

1 Introduction

A spoke cavity is a TEM-class superconducting resonator with excellent RF performances in the low and middle beta region. Besides the inherent advantages of superconductors, the spoke cavity has smaller dimensions and a stronger mechanical structure than an elliptical cavity with the same frequency, and higher R/Q values than a half-wave resonator [1]. Because of its many advantages in the low energy section, it has become a potential candidate for worldwide high intensity accelerators. Project-X, which is under development at Fermilab, is a multi-MW proton source that includes three types of SC single spoke cavities operating at 325 MHz [2]. The ESS (European Spallation Source) will employ 28 spoke cavities at 352.21 MHz [3]. The HINS (Fermilab High Intensity Neutrino Source) will use single spoke cavities at 325 MHz with β of 0.21 [4].

Therefore, the China-ADS (Accelerator Driven Sub-critical System), based on a 1.5 GeV CW linac, is also proposed to adopt spoke cavities in low Beta regions. Injector Ⅰ of China-ADS linac is shown in Fig. 1 [5]. The normal RFQ cavity accelerates the beam to about 3.2 MeV. Three types of superconducting spoke cavities with operating frequency of 325 MHz, Spoke 012 at β=0.12, Spoke021 at β=0.21 and Spoke040 at β=0.40, are used to accelerate the beam from 3.2 MeV to 178 MeV. Then, the beam is accelerated up to ~1.5 GeV by two types of superconducting elliptical cavities working at 650 MHz.

In these three kinds of spoke cavities, Spoke012, which has the smallest geometry beta, is the first superconducting spoke resonator developed for China-ADS. Its iris length is only 73 mm and the frequency of the small resonance region is very sensitive to elastic end-wall deformation. Consequently, Spoke012 is considered as one of the key challenges because of its high pressure sensitivity value.

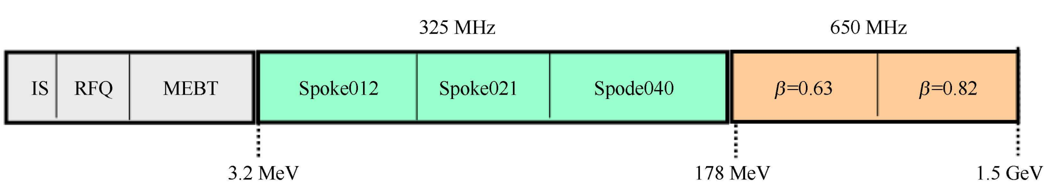

Fig. 1. The layout of China-ADS linac with Injector-Ⅰ.

Received 22 September 2013
∗ Supported by Strategic Priority Research Program of CAS (XDA03020600)
1) E-mail: jpdai@ihep.ac.cn

In this paper, the development of Spoke012 prototype cavity is introduced, including the design, fabrication, and test results.

2 Design of Spoke012 cavity

As 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 $2/3^{*}\beta\lambda$.

In order to maximize the shunt impedance and minimize the ratio of $E_{\rm peak}/E_{\rm acc}$ and $B_{\rm peak}/E_{\rm acc}$, 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 analyzed using the CST_MWS software (Microwave studio) [6].

Finally, compared with the round and race-track shapes, an elliptical spoke base has been chosen due to its 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. When 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.

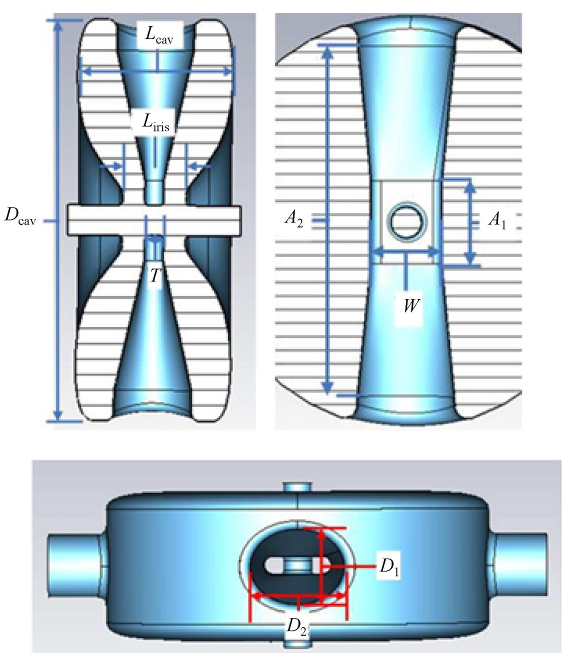

Fig. 2. The cross section of Spoke012 cavity. ($L_{\rm cav}$- cavity length, $L_{\rm iris}$- iris to iris length, T- spoke thickness, W- spoke width, $D_{\rm cav}$- cavity diameter, D_1- minor axis of spoke base, D_2- major axis of spoke base.).

The 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.

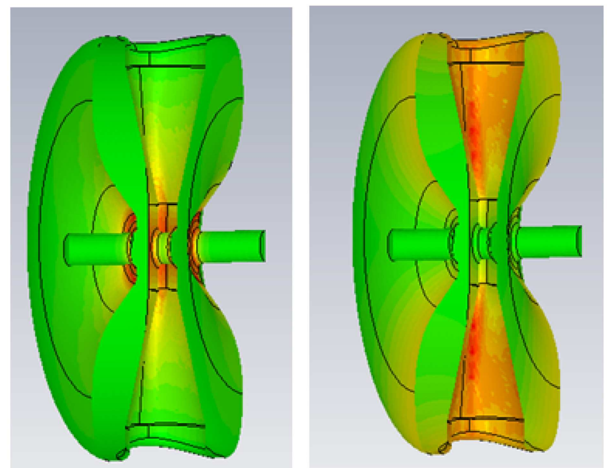

Fig. 3. (color online) The surface electric field (left) and magnetic field (right), the field increases with the color changing from green to red.

Table 1. Main parameters of Spoke012 cavity.

cavity length ($L_{\rm cav}$)/mm	180
cavity diameter ($D_{\rm cav}$)/mm	468
iris-to-iris length ($L_{\rm iris}$)/mm	73
major axis of spoke base (D_2)/mm	112.5
minor axis of spoke base (D_1)/mm	90
spoke thickness at aperture (T)/mm	22
spoke width at aperture (W)/mm	82
spoke race-track higher (A_1)/mm	94
spoke lofting higher (A_2)/mm	398
aperture diameter/mm	35
coupler port diameter/mm	80
operating frequency/MHz	325
$E_{\rm peak}/E_{\rm acc}$	4.5
$B_{\rm peak}/E_{\rm acc}$/mT/(MV/m)	6.4
G/Ω	63
$(R/Q)/\Omega$	142
geometrical beta	0.12
$L_{\rm eff}=\beta\lambda$/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 of the stiffeners are made of reactor-grade niobium. The circumferential ribs have a thickness of 10 mm, while others are 6 mm in thickness. A view of the stiffeners is shown in Fig. 4.

The mechanical design with a 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 bellows.

Distortions of Spoke012 due to vacuum load and thermal shrinkage have been predicted by the ANSYS MECHABICAL software [7]. By optimizing the radius of circular ribs and bellows connecting the cavity with the vessel, the sensitivity of helium pressure ($\mathrm{d}f/\mathrm{d}p$) is decreased. In the calculation of external pressure loading, one beam pipe flange is considered for "hard fixing" to the helium vessel. The final mechanical properties are shown in Table 2.

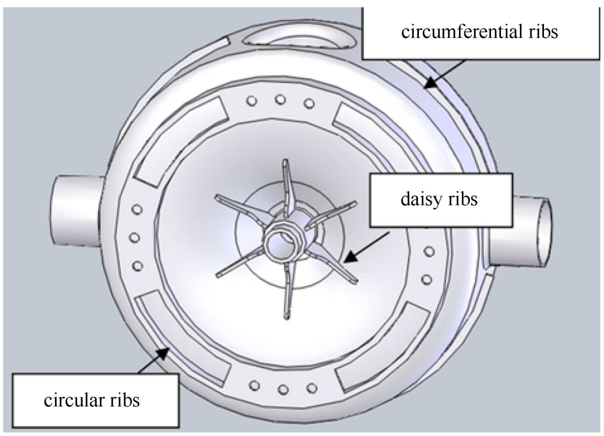

Fig. 4. The stiffener design of the Spoke012 cavity.

Table 2. The mechanical property of Spoke012.

$\mathrm{d}f/\mathrm{d}P$(pipe free)/(Hz/torr)	−156
$\mathrm{d}f/\mathrm{d}P$(pipe fixed)/(Hz/torr)	+40
tuning sensitivity/(MHz/mm)	1
the static Lorentz coefficient/(Hz/(MV/m))^2	−1.3
cooling down (300 to 4.2K)/kHz	+463

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

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

3 Fabrication

For fabrication, the cavity body is enclosed by a high RRR niobium with a thickness of 3.5 mm. The niobium materials come from Ningxia Orient Tantalum Industry Co., Ltd. After pro-processing, the 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 exploded view of Spoke 012 is shown in Fig. 5.

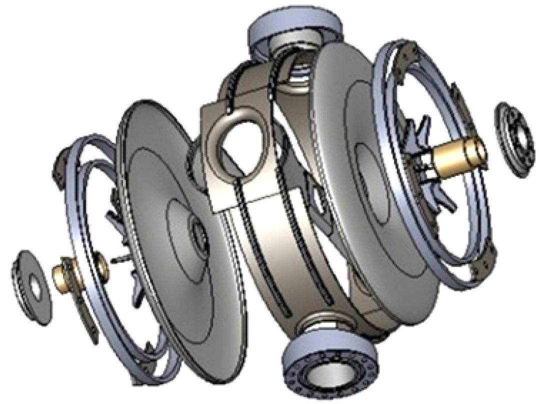

Fig. 5. An exploded view of Spoke012.

All of the cavity components were made by stamping technology with a 3510 kN punching machine. Some experiments were done with copper sheets to understand the shrinkage and deformation in the stamping. To make the cylindrical portion easy to weld, it was separated into four sheets, while the end-walls were stamped from a bulk niobium.

All of the 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 the 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, which is close to the 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.

During the fabrication, all of the 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.

Fig. 6. A frock clamp for the Spoke012 tuning.

Fig. 7. Two bare Spoke012 prototype cavities fabricated in November 2012.

4 Surface processing and vertical testing

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 Ref. [8].

After post processing, the Spoke 012-2# prototype cavity was successfully vertically-tested at IHEP.

The vertical test system consists of a 325 MHz signal generator, a 1 kW solid state amplifier, a LLRF control system and a DAQ system, and classical vertical test method was used [9].

In the vertical test, Spoke012-2# reached $E_{\rm acc}$ of 8 MV/m at 4.2 K, the residual surface resistance ($R_{\rm s}$) is 50 nΩ. Here, $E_{\rm acc}$ is defined as the total accelerating voltage divided by $\beta\lambda$ (110 mm). 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.

When the accelerating gradient reached 8 MV/m, it was hard to grow because of a serious multipacting effect. Although an additional six hours of RF conditioning was carried out, the maximum accelerating gradient improved very little.

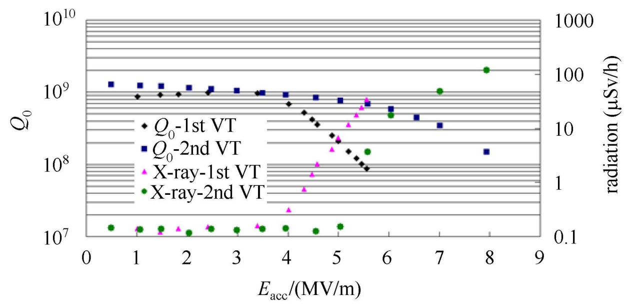

Fig. 8. VT summary of Spoke012-2# cavity.

5 Horizontal test

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

Fig. 9. The cryomodule of Spoke012 with cavity.

Fig. 10. The LLRF equipment of Spoke012.

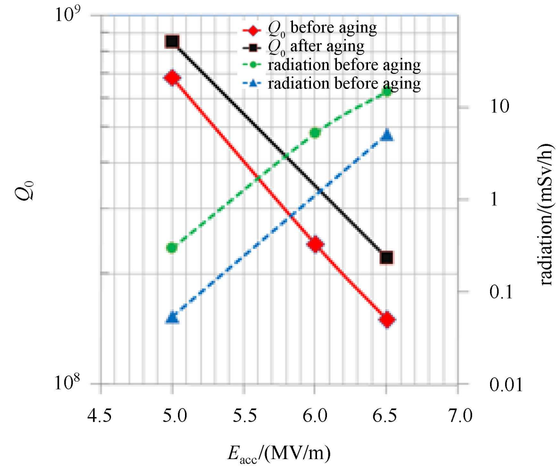

Fig. 11. HT performance of the Spoke012-02# cavity.

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

The authors wish to thank our collaborators from PKU and HIT for the design and fabrication of the Spoke012 prototype cavities, and the colleagues from RF, vacuum and cryogenic groups of IHEP for their hard work on the cavity tests.

References

1 Shepard K W et al. Phys. Rev. ST Accel. Beams, 2003, **6**: 080101
2 Gonin I et al. Single Spoke Cavity For Low-energy Part of CW Linac of Project X. Proc. of the 2010 International Particle Accelerator Conference.Japan: Kyoto, WEPEC057
3 Karl McFaul. ESS Corporate Presentation. Proc. LINAC 2012. Isreal: Tel-Aviv
4 Lanfranco G et al. Production of 325 MHz Single Spoke Resonators at FNAL. Proc. of the 2007 Particle Accelerator Conference. USA: Albuquerque, New Mexico
5 LI Z H et al. General Design of C-ADS Accelerator Physics. Internal Report
6 CST MICROWAVE STUDIO. www.cst.com
7 ANSYS MECHANICAL^{TM} of Ansys Inc
8 WANG Qun-Yao et al. Surface Processing Facilities for Spoke Cavities at IHEP. Proceedings of SRF2013. France: Paris, September 2013
9 DAI Jian-Ping, ZHANG Juan et al. LLRF and Data Acquisition Systems for Spoke012 Cavity Vertical Test at IHEP. Proceedings of SRF2013. France: Paris, September 2013