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Original Article

Design, fabrication and test of a taper-type half-wave superconducting cavity with the optimal beta of 0.15 at IMP

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ABSTRACT

As a part of R&D work for the high intensity proton linac of China Accelerator Driven Sub-critical System project, a superconducting half-wave cavity with a frequency of 162.5 MHz and an optimal beta of 0.15 (HWR015) has been developed at Institute of Modern Physics (IMP), Chinese Academy of Sciences. In this paper, the design and test results will be described in detail. We introduced a new stiffening strategy for the HWR cavity, the simulation results show that the cavity has much lower frequency sensitivity coefficient (df/dp), Lorentz force detuning coefficient (KL), and can achieve more stable mechanical properties. The performance of the HWR cavity operated in cryostat will be also reported.

1. Introduction

China Accelerator Driven Sub-Critical System (ADS) has been proposed as a part of the “Strategic Priority Research Program” initiated by Chinese Academy of Sciences in 2011, which is a long-term plan of three stages ending in 2040 [1–3]. For the purpose of demonstrating the key technologies, a proton linac with a beam energy of 25 MeV has been designed, constructed and commissioned over the past 7 years at Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS). The linac is composed of an ECR ion source, a low energy beam transport line (LEBT), a 162.5 MHz RFQ cavity, a medium energy beam transport line (MEBT) and the superconducting accelerating section (i.e., three HWR cavity cryomodules with two different optimal beta of 0.10 and 0.15, and one Spoke cavity cryomodule) as shown in Fig. 1, where the output energy of the proton beam of the RFQ cavity and the superconducting accelerating section are 2.1 MeV and 25 MeV respectively.

One of the key accelerating units is superconducting HWR cavity, different designs of which were developed by many laboratories and university around the world, such as ANL, ACCEL, INFN, Juelich, MSU and CEA [4–8]. The Soreq Applied Research Accelerator Facility (SARF) in Israel is the only one facility using the HWR cavities for beam acceleration prior to C-ADS project. There is still a lack of operation experience for this type cavity [9,10], and more research is needed to verify the feasibility of the HWR cavity in an operating linac. In this paper, we will mainly focus on the development of the HWR cavities with the optimal beta of 0.15 labeled as HWR015 cavity. One of the major limiting factors of the HWR cavities for the superconducting linac of CADS project is its mechanical stability. In light of the experience obtained from the development of our previous HWR010 cavities [11–15], a new stiffening strategy for the HWR015 cavities was developed to achieve low frequency sensitivity coefficient (df/dp), low Lorentz force detuning coefficient (KL), and stable mechanical properties. The

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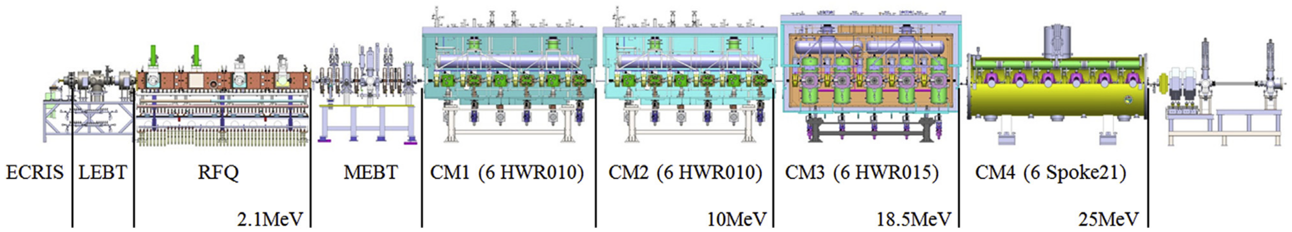

Fig. 1. The schematic of 25 MeV superconducting proton linac of the CADS project.

mechanical design and the corresponding test results of the cavity will be reported in detail, and the performance of the cavity being installed in beamline will also be described.

2. Electromagnetic design

Considering the experience obtained from the development of our previous HWR cavities with an optimal beta of 0.10 and a same frequency [12–15], we made a reasonable compromise between the optimal electromagnetic performances, acceptable mechanical characteristics, ease of fabrication and surface preparation in the design process of HWR015 cavity. As a first step, the RF properties of the HWR015 cavity was optimized with a goal to get a lower cryogenic heat loading along with a higher accelerating gradient, which are determined by a higher R/Q_0 (R is the shunt impedance and Q_0 is the unloaded quality factor), a higher geometry factor G, and the lower peak surface fields (B_{peak}/E_{acc} and E_{peak}/E_{acc}). This optimization was performed with Computer Simulation Technology-Microwave Studio (CST-MS) software. The final optimized RF parameters were obtained as shown in Table 1.

Table 1
RF parameters of the HWR015 cavity.

Parameters	value
Frequency (MHz)	162.5
β_{opt}	0.15
U_{acc}	1.81
Stored energy @1.81 MV (J)	11.5
E_{peak} @1.81 MV (MV/m)	32
B_{peak} @1.81 MV (mT)	40
R/Q_0 (Ω)	287
$G = Rs^* Q_0$ (Ω)	51.2
Q_0 (4.4 K) @0.78 MV	7.2E8

3. Mechanical design

The detailed analysis of the mechanical properties and the RF design of the HWR015 cavity must be conducted in conjunction, since the cavity wall is impacted by several external loads while operating. A very high electromagnetic field inside the cavity normally results in a strong Lorentz forces and the cavity shape might be deformed by the pressure acting on the cavity wall. When the Eigenmode of the mechanical resonance of the cavity is close to the frequency of the external vibrations, resonant coupling may happen and cause a large deformation of the cavity, so the mechanical eigen modes of the cavity must be taken into account during the integrated design of the cavity.

Microphonics can be mitigated by using the following methods individually, or in combination: (i) provide sufficient RF power from amplifier to compensate the detuning induced by microphonics; (ii) reduce the frequency sensitivity of the cavity to the fluctuation of helium bath pressure, i.e., passive damping; (iii) actively damp the microphonics by using a fast tuner controlled by the frequency feedback of the cavity; (iv) decrease the fluctuation of the helium bath pressure by the cryogenic system design. In our work, we mainly focused on the passive damping scheme for the microphonics, including the impact of the cavity wall pressure, the tuning efficiency and the mechanical eigen vibration. The mechanical properties of the niobium used in our analysis are listed in Table 2.

The mechanical deformations of the cavity due to helium pressure, Lorentz force detuning (LFD) and the mechanical modal vibrations were studied by the multi-physics simulation of ANSYS. The simulation results will be compared with the test results.

3.1. Pressure sensitivity analysis

For the purpose of predicting the frequency shifts, which depend on the accuracy of the simulated electromagnetics and the mechanical deformations of the cavity, we conducted a sequential coupled field analysis, in which two models were used as shown in Fig. 2. The “RF-Model” (see Fig. 2 left) that describes the inner RF-volume of the cavity and the “Mechanical Model” (see Fig. 2 right) represents the mechanical structure of the cavity. Both models were generated within ANSYS. To determine the resonant frequency shift of the cavity, the following steps are necessary: (i) “RF-Model” is used to calculate the resonant frequency and the electro-magnetic field distribution of the non-deformed cavity; (ii) Calculation of the deformation of the “Mechanical Model” by applying the atmospheric pressure as input loads; (iii) Calculation of the resonant frequency of the deformed RF structure by applying the deformations from step (ii) to the “RF-Model".

The simulation results of the frequency shift induced by the deformation of the cavity shape under external pressure show that the critical deformations are located at the areas with strong magnetic field and strong electric field. Therefore, a stiffening structure was applied on the sensitive areas mentioned above as shown in Fig. 3, to reduce the deformation induced by helium bath pressure.

The response of the cavity to a pressure differential of 1 bar was simulated with vacuum inside and ambient pressure outside of the cavity. Because of the symmetry of the structure, in order to reduce the simulation time, 1/4 models were adopted in the simulation process, as shown in Fig. 2. For the different stiffening options, frequency shift of the cavity induced by external helium pressure

Table 2
Mechanical properties of the niobium cavity.

Parameters	value
Poisson's ratio	0.38
Young's modulus (GPa)	105
Yield strength[a] (MPa)	50
Yield strength[b] (MPa)	140
tensile strength (MPa)	400

[a] Room temperature, 300 K.
[b] Low temperature, 4.2 K.

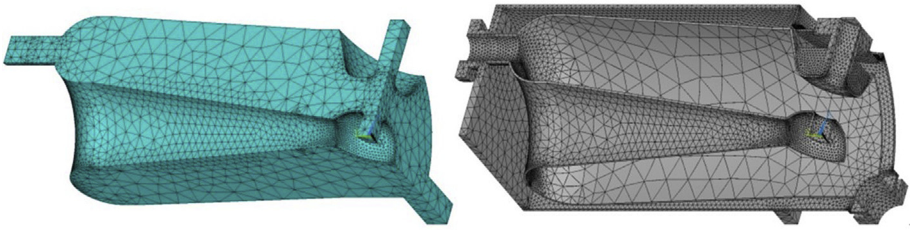

Fig. 2. RF model (left) and mechanical model (right) of the HWR015 cavity used in the simulation process.

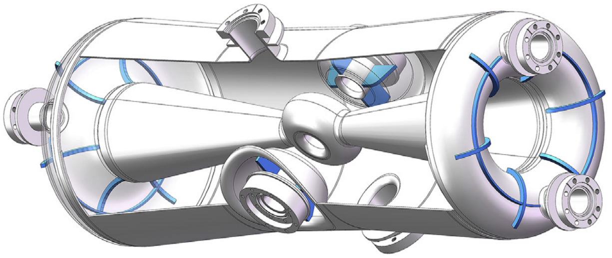

Fig. 3. HWR015 cavity with stiffing ribs.

with non-constrained tuner and with fixed tuner were simulated. Two options of tuner constrain have been explored due to lack of data of tuner stiffness, it allowed us to predict the range of df/dp determined by tuner stiffness and the quality of the tuner joints to the external supports. Fig. 4 gives the simulation results of df/dp and its dependence on the tuner stiffness.

3.2. *Lorentz force detuning (LFD) effect*

The cavity wall is deformed by Lorentz force that leads to the frequency shift proportional to the square of the accelerating gradient (i.e., Lorentz force detuning (LFD) effect). In our work, LFD was also simulated with ANSYS following a procedure similar to that performed for the df/dp simulation, in which a pressure load simulated from the Lorentz forces on the cavity wall was used. Generally, The Lorentz force induced pressure (i.e., Lorentz pressure) at beam pipe region results in the vacuum volume reduction in high electric field region, which in turn will increase the equivalent capacitance and reduce the frequency of the cavity. The vacuum volume at the dome region enlarged in the high magnetic field by the Lorentz pressure will increase equivalent inductance, thus, reduce the frequency of the cavity as well. Therefore, both the Lorentz pressure at the dome region and the beam pipe region reduce the frequency of the HWR015 cavity. The simulation results are summarized as shown in Fig. 4.

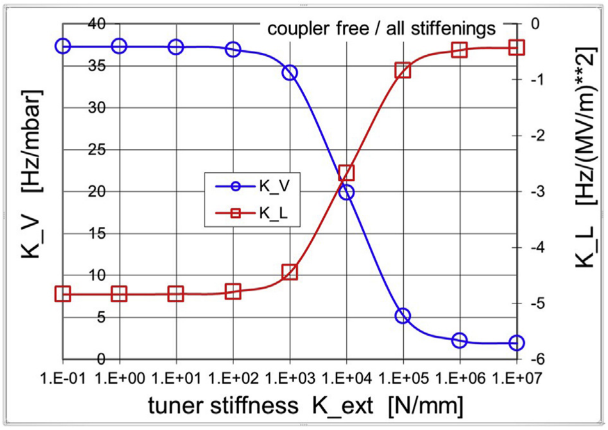

Fig. 4. Frequency sensitivity coefficient (K_V) and Lorentz force detuning coefficient (K_L) as a function of the tuner stiffness of the HWR015 cavity.

3.3. *Mechanical modes*

Mechanical resonance of the cavity installed in the cryostats can be excited by the external vibration. If the eigen mode of the mechanical resonance is close to the frequency of the external vibrations, resonant coupling between the cavity and the external vibration will happen and cause a large deformation of the cavity. The detailed investigations of mechanical resonance of the cavity were conducted by using the different simulation models of the half of the cavity and with the structural constraints in two directions as shown in Fig. 5, the z-half model is in the left and x-half model is in the right of Fig. 5. The fundamental frequencies and the associated mode shapes are mainly focused in the process of modal analysis [16]. The frequency of the first mechanical mode for the z-half model is 190.9 Hz and the frequency of the first mechanical mode for the x-half model is 112.8 Hz (see Fig. 5 left and right respectively). Table 3 gives the frequencies of the first five modes for the two different simulation models. As one can clearly see the highest cavity flexibility is determined by the central electrode, the helium vessel and its supporting plate. Still, the frequencies of the two lowest modes are rather far from 60 Hz.

The HWR015 cavity has been made of 3 mm thickness niobium sheets, the final wall thickness will be about 2.8 mm after several surface treatments. The simulation results of the mechanical parameter of the cavity with 2.8 mm in wall thickness are shown in Table 4.

4. HWR015 fabrication

An exploded view of the HWR015 bare cavity is shown in Fig. 6. The cavity consists of an inner conductor, an outer conductor, the top and bottom covers, two beam pipes, two coupler pipes, four processing pipes and stiffening ribs. The inner conductor, outer conductor and top/bottom covers were fabricated from high-purity niobium sheets of 3 mm thick by deep drawing and electron-beam welding. The beam pipes, coupler pipes, and the pipes of the processing ports were fabricated from high-purity niobium rods by machining. Eight flanges on the cavity, through which it interfaces with the helium vessel, are made of niobium-titanium alloy (Nb55Ti45) connected to the niobium by means of electron-beam welding. The stiffening ribs are made of reactor-grade niobium, and welded with the cavity by electron-beam welding.

Prior to the electron-beam welding, the inner surface of the cavity parts was inspected visually, all visible local defects were polished by a hand-held rotary tool. All cavity parts were degreased by ultrasonic water rinsing, and a layer of 10 μm was removed by light BCP, followed by drying in clas-100 clean room. It is of great

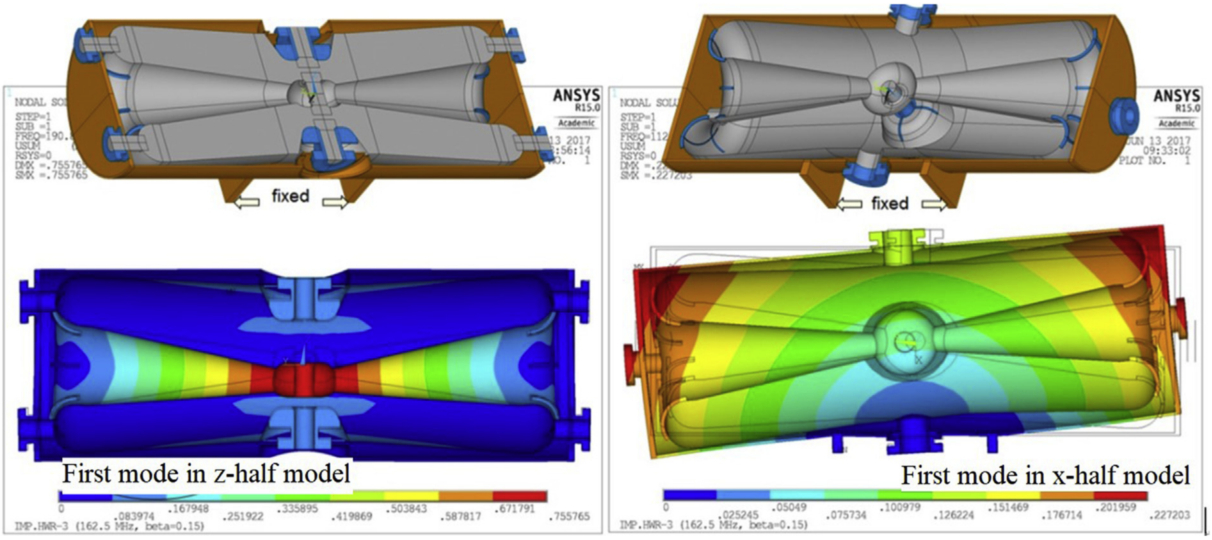

Fig. 5. The HWR015 cavity models used for the mechanical eigen vibration simulation, and the corresponding first modes for z-half (left) and x-half (right) models respectively.

Table 3
HWR015 modal analyses results.

Mode	1	2	3	4	5
Frequency (Hz) (mounting plate fixed) Z-half	190.9	197.8	203.5	274.4	277.0
Frequency (Hz) (mounting plate fixed) X-half	112.8	113.8	145.1	169.6	219.2

Table 4
Mechanical Parameters simulation results of the HWR015 cavity.

parameters	value
Cavity wall thickness (mm)	2.8
df/dp (Hz/mbar) @beam pipe free	37
df/dp (Hz/mbar) @beam pipe fixed	2
LFD (Hz/(MV/m)^2) @beam pipe free	−5
LFD (Hz/(MV/m)^2) @beam pipe fixed	−0.5
Mech.mode-1 frequency (Hz)	128.3

importance to obtain the weld seams with high quality between inner conductor, outer conductor and top/bottom covers, which are welded from the outside, and by using a reliable method.

It is imperative to check the frequency of the cavity before and after trimming the length of the inner conductor and the outer conductor, which have an allowance in length. The frequency error caused by forming error was compensated by cutting the length of the inner and the outer conductors. The most critical requirement is the mechanical tolerance for the concentricity of the two beam pipes required by beam dynamics. Therefore, a metal bar closely matched and passing through the two beam tubes was used to ensure the concentricity in the welding process.

In order to obtain the high surface quality, welding quality and dimensional accuracy etc., the strict quality controlling procedures were established before the niobium cavity fabrication. The high purity niobium with residual resistivity ratio RRR >250 were procured from domestic suppliers (Ningxia OTIC). The first batch of four niobium HWR015 cavities were manufactured by two vendors (i.e., Harbin Institute of Technology and Ningxia OTIC), each vendor provided two of the cavities. Different welding schemes were adopted for the welding of inner conductor by two vendors as shown in Fig. 7. The second batch of eight HWR015 cavities was fabricated by Harbin Institute of Technology. A total of twelve HWR015 cavities were manufactured for the 25 MeV proton linac demo of CADS project, followed by surface preparation and RF testing. Fig. 8 shows a picture of two manufactured HWR015 cavities.

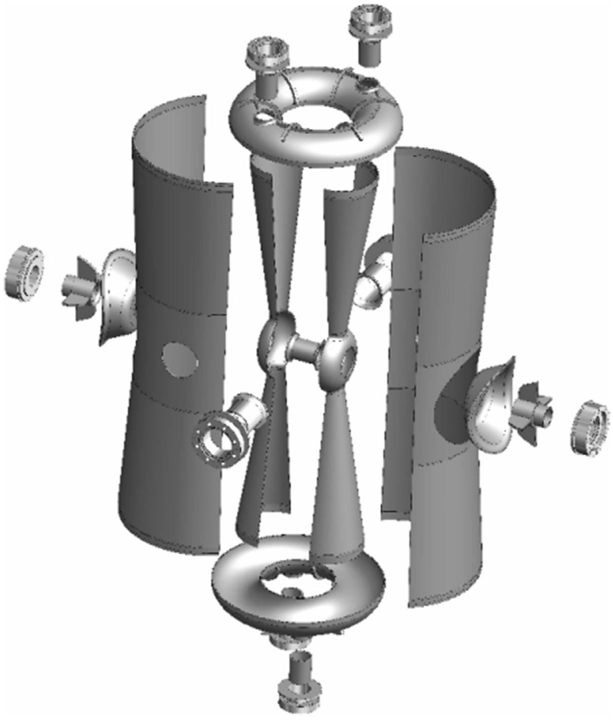

Fig. 6. Exploded view of the HWR015 cavity.

5. HWR015 testing

5.1. Vertical testing

Each cavity underwent an incoming inspection to verify conformity with the specifications upon their arrival at IMP. The inner surface of all the cavities was visually inspected by industrial

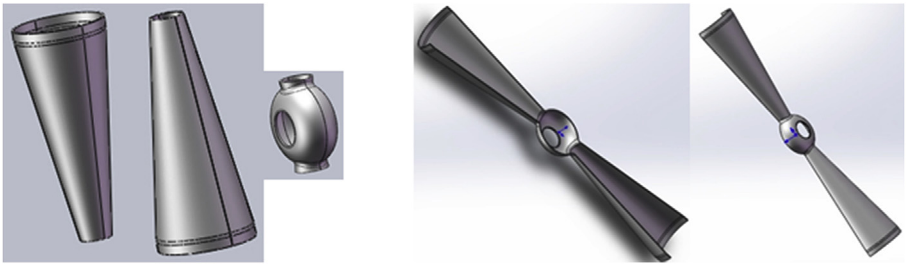

Fig. 7. Inner conductor welding scheme adopted by Harbin Institute of Technology (left) and Ningxia OTIC (right).

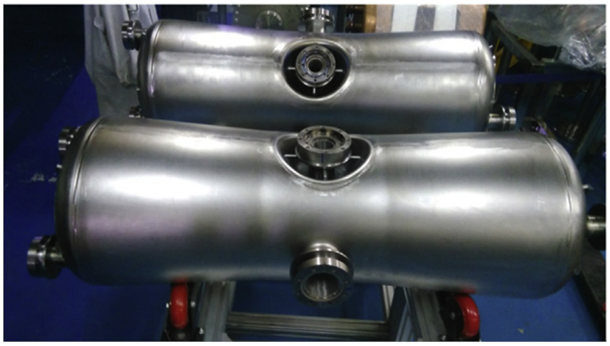

Fig. 8. Picture of the manufactured HWR015 cavities.

endoscope, the dimensions of all the cavities were measured by the coordinate measuring machine and the vacuum tightness of the cavities were also checked. The inner surface of the cavity was treated by a standard surface process, which is similar to the surface processing protocol adopted for the high beta cavities [17–19]. The main surface treatment for the HWR015 cavity consists of ultrasonic cleaning, heavy chemical etch by BCP, heat treatment, high-pressure rinsing, and 120 °C baking before RF testing.

All twelve HWR015 cavities have been welded with helium vessel and performed RF testing at 4.4 K at the vertical testing stand (VTS) of IMP [20]. The performance of all the cavities with helium vessel meets the design specification as shown in Fig. 9. The minimum residual resistance (R_{res}) among the cavities is 2.3 nΩ at low field region, and 7.7 nΩ at $E_{peak} = 32$ MV/m for the cavities labeled as HWR015-7 and HWR015-8, respectively. The performance of the HWR015 cavities during the vertical test is mostly limited by quench. The maximum and the minimum achieved E_{peak} are 90 MV/m and 47 MV/m. No X-ray radiation was detected during the test of the cavities obtained the lowest E_{peak} labeled as HWR015-2 and HWR015-9, more experiments are needed to be conducted to study the issues of the HWR015-2 and HWR015-9 cavities.

5.2. Resonant frequency pressure sensitivity measurement

As one can see in Fig. 1, one cryomodule with five HWR015 cavities installed inside is used in the 25 MeV proton linac demo for CADS project to accelerate proton beam from 10 MeV to 18.5 MeV. The pressure sensitivity of frequency (df/dp) of the HWR015 cavity being installed in beamline with beam ports fixed by tuner was measured by slowly varying the helium pressure by several mbar and observing the change of the cavity frequency. The measured result of df/dp is 14.7 Hz/mbar as shown in Fig. 10, which is in accordance with the simulation result. Table 5 gives the comparison of the measured and simulated results of df/dp.

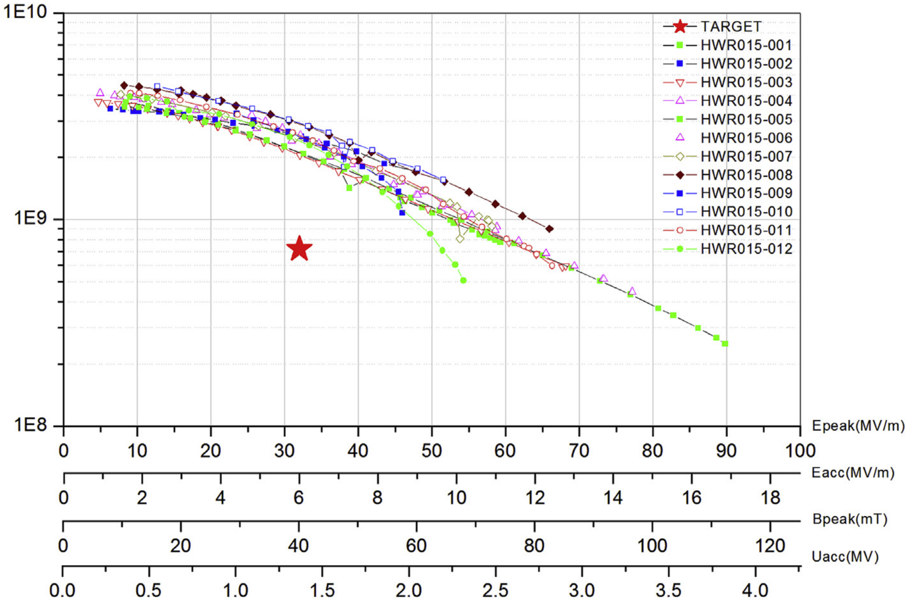

Fig. 9. Q0 versus gradient during vertical testing of the twelve HWR015 cavities.

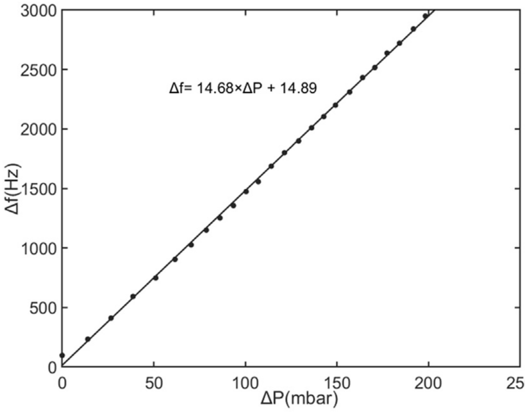

Fig. 10. Resonant frequency pressure sensitivity (df/dp) measurement results of the HWR015 cavity being installed in beamline.

Table 5
Mechanical Parameters measurement and simulation results of the HWR015 cavity.

parameters	Simulation beam ports free/fixed	Measurement tuner fixed
Cavity wall thickness (mm)	2.8	2.8
df/dp (Hz/mbar)	37/2	14.7
LFD (Hz/(MV/m)^2)	−5/-0.5	−3.6

5.3. *Lorentz force detuning (LFD) effect measurement*

The Lorentz force detuning (LFD) effect of the HWR015 cavity being installed in beamline was also measured by slowly increasing the accelerating gradient and observing the change of the cavity frequency. The measured result is $-3.6\text{Hz}/(\text{MV/m})^2$ as shown in Fig. 11, which is also consistent with the simulation result. Table 5 gives the comparison of the measured and simulated results of LFD.

6. Performances of HWR015 being installed in beamline

The 25 MeV proton linac demo for CADS project was tested with beam in May 2017, a picture of cryomodule in tunnel is shown in Fig. 12. Four cryomodules have been installed for the acceleration of proton beam from 2.1 MeV to 25 MeV (i.e., two cryomodules with six HWR010 cavities in each (2.1–10 MeV), one cryomodule with HWR015 cavities (10–18.5 MeV), and one cryomodule with six Spoke021 cavities (18.5 MeV–25 MeV)).

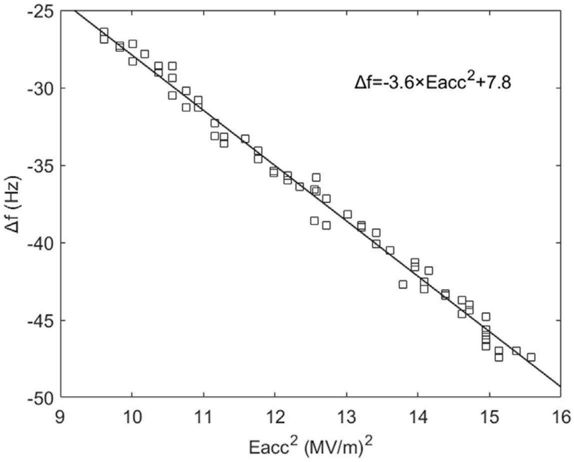

Fig. 11. Lorentz force detuning coefficient measurement results of the HWR015 cavity being installed in beamline.

Fig. 12. Picture of the cryomodules with the HWR cavities installed in tunnel.

The HWR015 cavities in cryomodule show severe multipacting effect in low field region [21], making it difficult to lock the resonant frequency and feed RF power to the cavity, since the bandwidth of the cavity is broadened by multipacting effect. The conditioning of the cavities was started by sweeping the frequency of the signal generator within several kHz range around the resonant frequency of the cavity, while its output power was slowly increasing. Once the multipacting barriers are conditioned and disappeared, pulse conditioning method is used with progressive increase of power level and pulse length under certain constraint of vacuum.

The performance of the HWR015 cavities being installed in beamline is mainly limited by field emission instead of quench observed during vertical test. Compared to the vertical test of the cavity, the integration of the cavities with power couplers, solenoid and other accessory equipment in cryomodule makes apparently the cavities less clean. The average E_{peak} of the HWR015 cavities in the first cryomodule is about 25 MV/m, which is much lower than the corresponding value in vertical test. One of the reasons for the low average E_{peak} is that the HWR015 cavity string was reassembled 5 times because of the vacuum leak in 2018. The second cryomodule of the HWR015 cavities was assembled successfully once, and the average E_{peak} of 32 MV/m was achieved, Fig. 13 gives the X-ray radiation induced by field emission as a function of the E_{peak}.

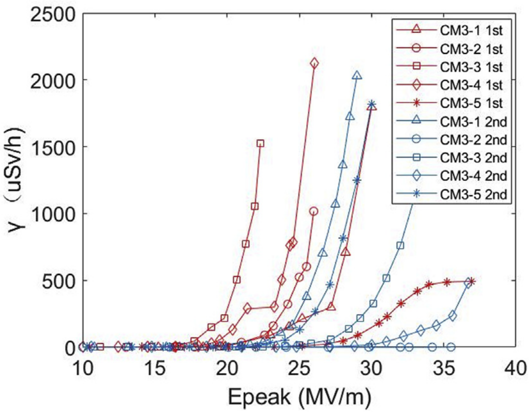

Fig. 13. Radiation as a function of Epeak of the HWR015 cavities being installed in beamline.

7. Conclusion

Superconducting half-wave cavities with a frequency of 162.5 MHz and an optimal beta of 0.15 (HWR015) are one of the essential components for 25 MeV proton linac demo for CADS project. In light of the experience obtained from the development of our previous HWR010 cavities [11−15], Diverse engineering efforts from RF to mechanical have been pursued, and we made the reasonable compromise between the optimal electromagnetic performances, acceptable mechanical characteristics, ease of fabrication and surface preparation in the design process of HWR015 cavity. A new stiffening strategy has been designed and adopted for the cavity, the simulation results show that the cavity has much lower frequency sensitivity coefficient and Lorentz force detuning coefficient, which are verified by the measured results. To date, a total of twelve HWR015 cavities welded with helium vessel have been manufactured, and conducted vertical testing at 4.4 K at IMP. Two cryomodules with the HWR015 cavities have been assembled and commissioned with proton beam over the past three years. The average Epeak of the cavities in each cryomodule was improved from 25 MV/m to 32 MV/m due to the improvement of the assembly procedures. The performance of all the cavities meets the design specification.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.01.014.

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