Design of a 325 MHz half wave resonator prototype at IHEP

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Abstract: A 325 MHz β=0.14 superconducting half-wave resonator prototype has been developed at the Institute of High Energy Physics, Beijing, which can be applied in the low energy section of continuous wave high current proton linear accelerators. The electromagnetic design, multipacting simulation, mechanical optimization and fabrication are introduced in detail. Test results at room temperature and 4.2 K, and a comparison between measured and simulated results, are analyzed in this paper.

Keywords: low beta HWR, high beam proton accelerator, vertical test

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1 Introduction

A superconducting (SC) half-wave resonator (HWR) is an accelerating structure used for low and medium β beams. Compared with SC quarter wave resonators (QWR), the symmetry structure of a HWR cancels the vertical beam steering effect and allows use at higher β. Compared with a spoke cavity, the HWR usually has lower shunt impedance but it can be more cost effective and mechanically stable. Now more and more new facilities propose using HWRs to accelerate the low energy proton beams. Project X at Fermilab proposed using HWRs with 162.5 MHz [1] to accelerate the proton beam from 2.1 MeV up to 10 MeV. The driver of the International Fusion Material Irradiation Facility (IFMIF) at CEA-Saclay also proposed using HWRs with 175 MHz [2] to accelerate the deuteron beam from 5 MeV up to 40 MeV. The driver accelerator for the Facility for Rare Isotope Beams (FRIB) will use β=0.29 HWRs and β=0.53 HWRs with 322 MHz [3] to accelerate all stable ions from 17.2 MeV/u up to 200 MeV/u. A high beam proton accelerator for Accelerator Driven Sub-critical System (C-ADS) plans to use HWRs with 162.5 MHz [4]. A 325 MHz HWR prototype has been developed at the Institute of High Energy Physics (IHEP), Beijing. The main parameters are summarized in Table 1.

2 Design

The electromagnetic (EM) design, multipacting, and mechanical design was optimized, while special attention was paid to make the design compatible with cavity fabrication and surface preparation to get reliable performance.

Table 1. Main parameters of 325 MHz HWR.

requirements	description
particle type	proton
frequency	325 MHz
β	0.14
operating mode	CW
R_{aperture}	35 mm
beam current	10 mA

2.1 EM design

In EM design, $E_{\text{peak}}/E_{\text{acc}}$, $B_{\text{peak}}/E_{\text{acc}}$, R/Q, and G are highly important. The optimization should minimize the peak surface fields ($E_{\text{peak}}/E_{\text{acc}}$ and $B_{\text{peak}}/E_{\text{acc}}$) and maximize the shunt impedance (R/Q) and the geometry factor (G) of the cavity. The software used in these simulations is CST Microwave Studio.

A cylindrical outer conductor and a conical shape inner conductor were chosen for this HWR. Choosing a ratio of 1/3.4 between the top of inner conductor and outer conductor diameter ($D_{\text{t}}/D_{\text{c}}$) allows a good compromise between low peak field values and high accelerating fields. For the electric field region, the cavity outer

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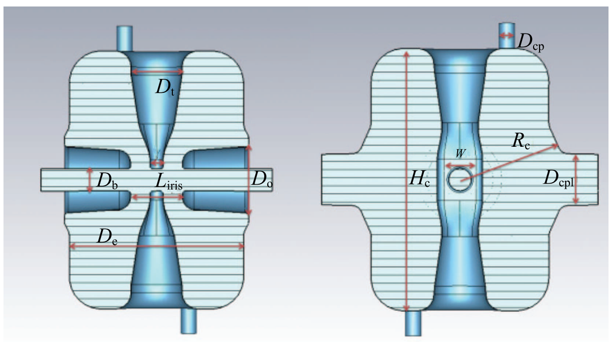
shell middle section is spherical, making the peak surface fields drop significantly, and improving the mechanical stability a lot. The inner conductor has a race-track central section, which allows a better distribution of the surface electric field. For the magnetic field region, the conical shape inner conductor allows more uniform distribution of the magnetic field value. The cover of the cavity is dome shaped which makes the cavity more rigid and minimizes the multipacting effect. The distance between gap centers (MGD) is fixed to approximately half the wavelength at the design $\beta_G = 0.12$ (MGD $= \beta_G\lambda/2$). The optimized cavity geometry is shown in Fig. 1 and the final cavity parameters are summarized in Table 2. All these choices are based on shape optimization.



(a) front view (b) side view

Fig. 1. (color online) Section views of the HWR.

Table 2. The optimized geometrical parameters.

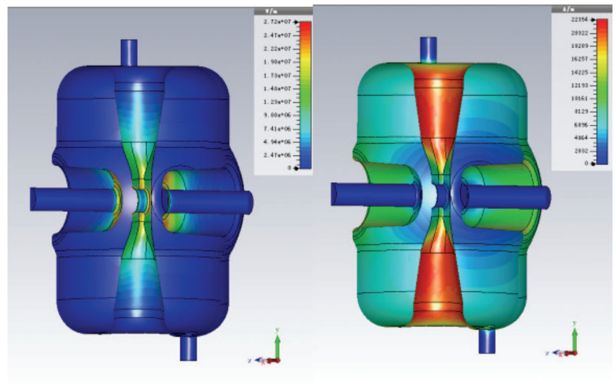
geometrical parameters	value/mm
cavity height H_c	406
cavity diameter D_c	274
cavity center radius R_c	160
inner top diameter D_t	80
racetrack thickness T	20
racetrack width W	50
iris length Liris	82
beam port inner diameter D_b	35
beam port outer diameter D_o	117
coupler port diameter D_{cpl}	80
cleaning port diameter D_{cl}	25

After optimization, the EM parameters reached an excellent result, as listed in Table 3. E_{peak}/E_{acc}=4.2, B_{peak}/E_{acc}=4.9 mT/(MV/m), R/Q=195 Ω and G=74 Ω, which gives a higher accelerating gradient with the same post processing technology. Because the good EM result is obtained at the expense of longer effective longitudinal space, the designers should properly evaluate and find a trade-off between them. The finalized electromagnetic field distribution is shown in Fig. 2, and the longitudinal voltage along the axis of the HWR is shown in Fig. 3.

1E_{acc} is the total accelerating voltage divided by $\beta_G\lambda$.

Table 3. The optimized RF parameters of the HWR.

RF parameters	result
E_{peak}/E^1_{acc}	4.2
B_{peak}/E_{acc}	4.9/mT/(MV/m)
R/Q	195 Ω
G	74 Ω



(a) E-field distribution (b) H-field distribution

Fig. 2. (color online) Electromagnetic field distribution of the HWR.

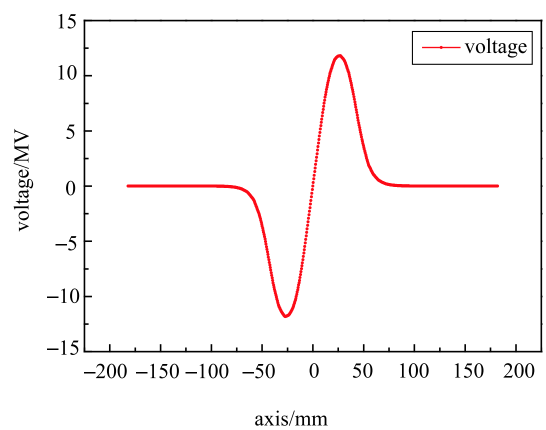
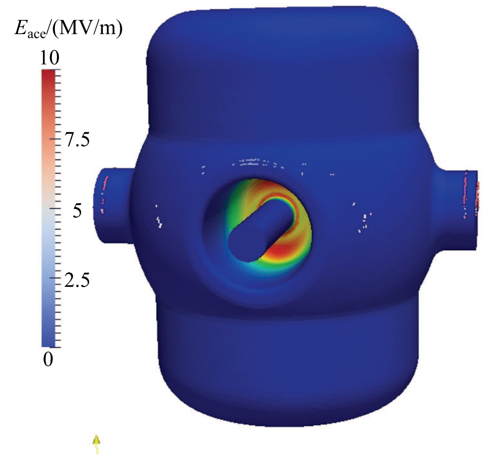


Fig. 3. Longitudinal voltage along the axis.

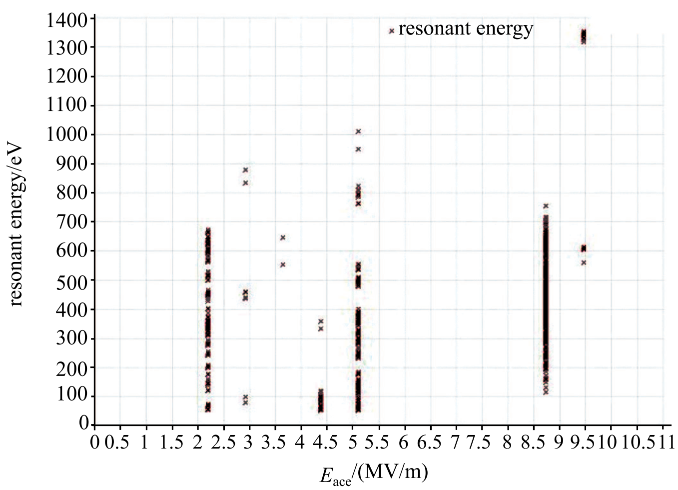
2.2 Multipacting

Multipacting in RF structures is a resonant process, in which a large number of electrons building up from multipacting discharge, absorb RF power so that it becomes impossible to increase the cavity fields by raising the incident power [2]. A proper cavity geometry and perfect surface preparation can stop multipacting from happening in the cavity.

Using the Track3P module developed by SLAC, the multipacting of the 325 MHz β=0.14 HWR prototype was simulated for E_{acc} from 1 MV/m to 11 MV/m. Resonant trajectories were observed at the regions around the nose cup (from 2.2 MV/m to 5.1 MV/m) and coupler ports (from 8.7 MV/m to 9.4 MV/m), as shown in Fig. 4. When the accelerating gradient is larger than 9.4 MV/m, no multipacting happens.



(a) location of resonant points



(b) the impact resonant energy VS. E_{ace}

Fig. 4. (color online) The multipacting results from Track3P.

2.3 Mechanical design

The mechanical performance of the 325 MHz HWR prototype was optimized using SolidWorks CAD and ANSYS code. The cavity rigidity, tuning range, pressure sensitivity, Lorentz force detuning (LFD), and microphonic detuning were studied. Stiffening rings were used to enforce the nose cups around beam ports. The thickness of the cavity wall is determined to be 3.2 mm.

The allowable stresses for niobium RRR300 based on the yield strength are 47 MPa at RT and 212 MPa at 4 K.The stresses on the cavity were simulated and are summarized in Table 4. The results indicate the cavity is safe at the evacuation, cool down and tuning conditions.

The cavity frequency dependence on changes in external pressure is called pressure sensitivity (df/dp). Different boundary conditions at the beam and coupler ports (a fully fixed condition and a completely free condition) of the HWR are calculated. The cavity deformations under one atmosphere pressure are shown in Fig. 5. During operation the boundary is balanced between the fixed and free conditions, so df/dp is between -6.3 Hz/mbar and -95.3 Hz/mbar. From experience at IHEP, the fluctuation range of the helium bath pressure is about ± 2 mbar, so the frequency drift will vary in the range of ± 12.6 Hz to ± 190.6 Hz. This frequency drift should be considered during tuner design.

Table 4. The optimized stress of the HWR.

parameter	boundary	stress/MPa
evacuation (1 bar, RT)	ports fixed	15.2
	ports free	20.1
cool down (4.2 K)	beam ports fixed	134
tuning (2 kN, RT)	coupler ports free	36

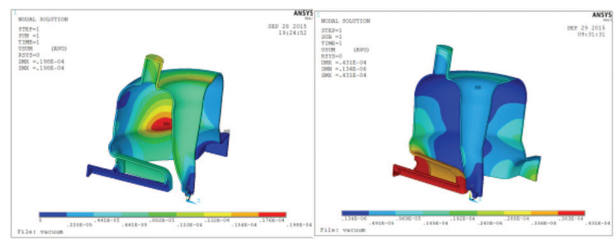


Fig. 5. (color online) The deformation results of HWR with beam and coupler ports fixed (left) and free (right).

The tuning force is applied on the flange of the beam pipe. The tuning range R and the tuning force F are related to the stiffness k and the tuning sensitivity s [5].

$$R = \frac{s}{k} F. \tag{1}$$

The simulation results show that $s = 1.1$ MHz/mm, and $k = 17.3$ kN/m. So 1.6 kN is needed for 100 kHz tuning range.

The interaction of the surface electromagnetic field with the induced surface currents and charges results in a Lorentz force on the cavity wall [6]. This force will result in a deformation of the cavity wall, and then cause the resonant frequency shift. The definition of the LFD coefficient is as follows:

$$K_{\mathrm{L}} = \Delta f / E_{\mathrm{acc}}^2. \tag{2}$$

The numerical analysis for the LFD effect has been done, and the deformation results at different boundary conditions at beam and coupler ports (a fully fixed condition and a completely free condition) are shown in

Fig. 6. The relationship between frequency shift and accelerating gradient is plotted in Fig. 7. The maximum deformation is located near the high electric field region. The K_L is -2.1 Hz/(MV/m)^2 with ports fixed and -12.7 Hz/(MV/m)^2 with ports free.

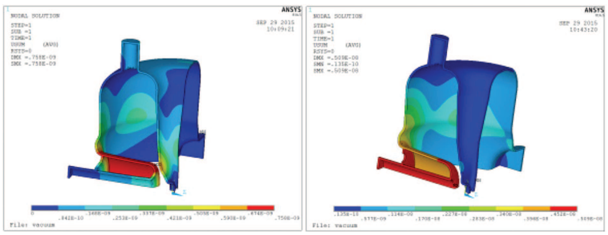


Fig. 6. The deformation results at 1 MV/m with beam and coupler ports fixed (left) and free (right).

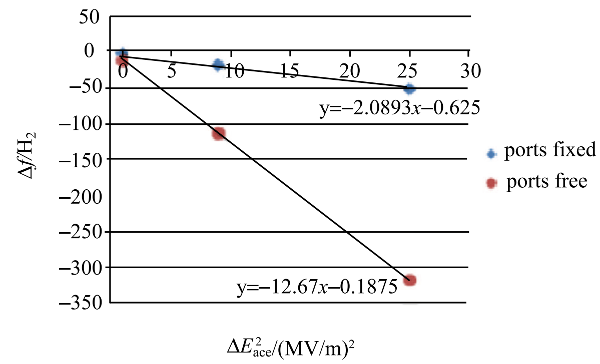


Fig. 7. (color online) The LFD coefficient of the HWR.

Frequency changes should be studied to get an accurate 325 MHz at 4.2 K, and the results are listed in Table 5. The buffer chemical polishing (BCP) and cooling down to 4.2 K increase the resonance frequency, while the evacuation and LFD lower it. The cavity frequency after fabrication should be 323.8 MHz.

Table 5. The frequency changes of the HWR.

performance	boundary	Δf/kHz
BCP (200 μm)	ports free	+886
evacuation		
	ports fixed	−6.33
	ports free	−95.29
$\varepsilon_{air} \rightarrow \varepsilon_{vacuum}$	ports free	−94.65
cool down (to 4.2 K)	ports fixed	+492.35
LFD (operating E_{acc})		
	ports fixed	−0.10
	ports free	−0.62

The cavity was analyzed for mechanical resonance modes. Low frequency modes around 250 Hz and below lead to microphonic resonances which must be avoided. Figure 8 and Table 6 show the lowest mechanical frequency is 369 Hz, indicating there is no danger from microphonic resonances.

3 Fabrication

The cavity and stiffening rings are made of niobium RRR300, while the flanges are made of Nb-Ti alloy. An exploded view of the 325 MHz HWR is shown in Fig. 9.

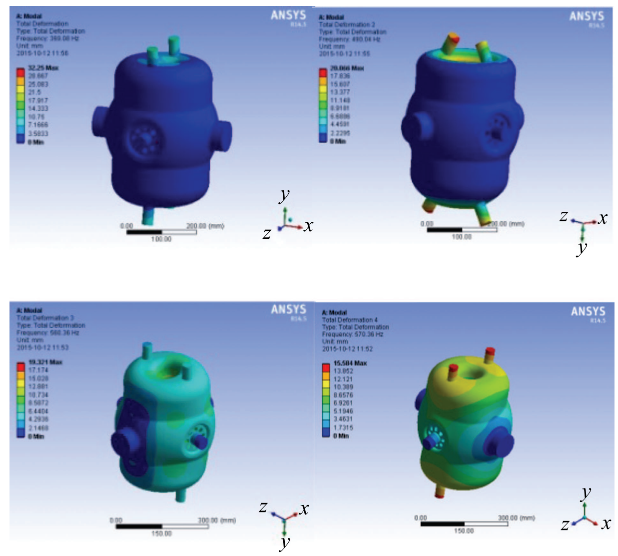


Fig. 8. (color online) The lowest eigenvector modal shapes.

Table 6. The modal analysis.

mode	frequency/Hz
1	369
2	490
3	560
4	570

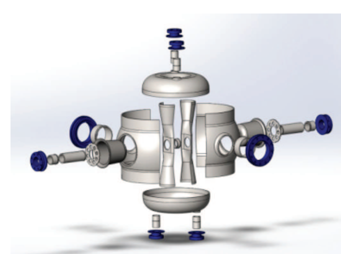


Fig. 9. (color online) Exploded view of the HWR.

Spinning forming and deep drawing covers, and nose cups are made by spinning forming, while the inner conductor and the cleaning holes in the cover are made by deep drawing technology. The annealing of components is necessary to eliminate residual stress, because it would be harmful to the machining dimension accuracy and assemble.

Electron beam welding (EBW) is used to join all components together. The fabrication sequence is shown in

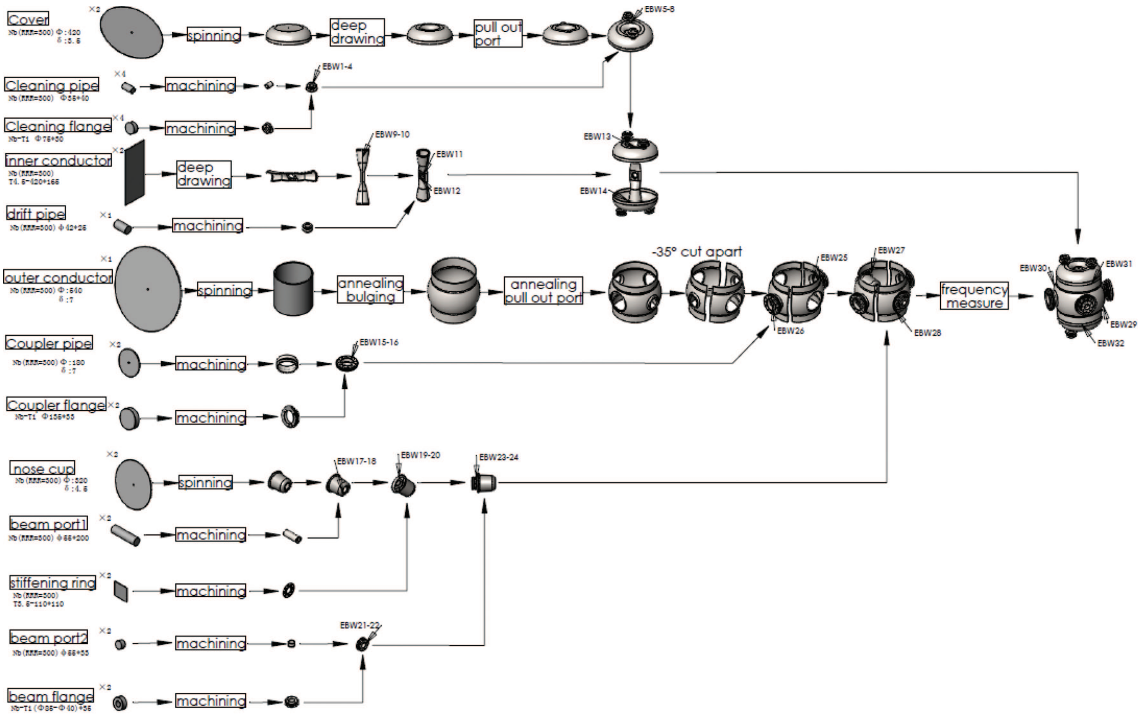


Fig. 10. The fabrication sequence of the HWR.

Fig. 10. Before the final EBW, the inner surface of the cavity was examined carefully, and the defects removed completely. Every component underwent a chemical polish to wipe off the oxide layer at the weld region. In order to guarantee the weld quality, the wall thickness of the weld region should be within 3.2 mm, and the thickness tolerance should be less than 0.1 mm. The estimated weld shrinkage value was 0.6 mm. The finished bare HWR prototype is shown in Fig. 11.

Fig. 11. (color online) The 325 MHz bare HWR prototype.

4 Testing

4.1 Post processing

The post processing of the 325 MHz HWR includes ultrasonic cleaning, BCP, annealing, high pressure rinsing (HPR), clean assemble and low temperature baking. The post processing sequence and the setup of HRP are shown in Fig. 12 and Fig. 13.

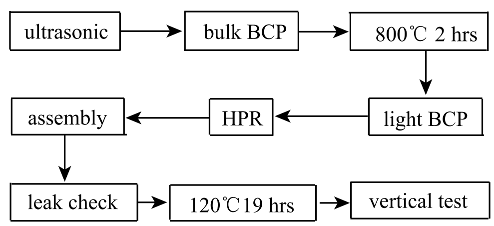


Fig. 12. Post processing sequence of the HWR.

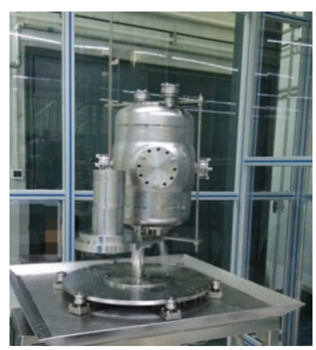


Fig. 13. (color online) The setup of HPR.

4.2 Vertical test

In the vertical test (VT), the forward and pick-up couplers are fixed length antenna. The external Q is 1×10^9 at RT and 3×10^{10} at 4.2 K, respectively, as shown in Fig. 14.

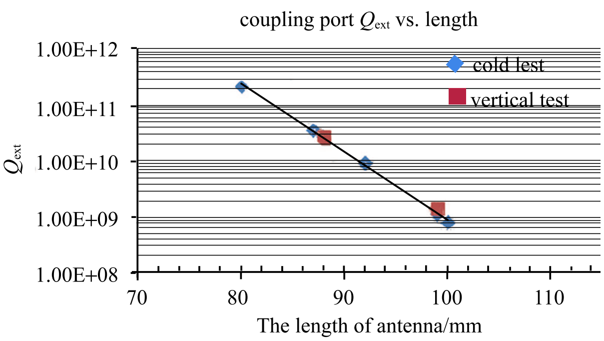


Fig. 14. Q_{ext} versus antenna length of the HWR.

Temperature sensors were connected to the top, center and bottom of the cavity to detect temperature changes caused by insufficient cooling. Liquid helium (LHe) level sensors, helium gas pressure sensors, cavity vacuum gauges and X-ray radiation were also monitored online. A 1kW solid-state amplifier and low level radio frequency (LLRF) control system were used. The HWR cooled down in a dewar is shown in Fig. 15.

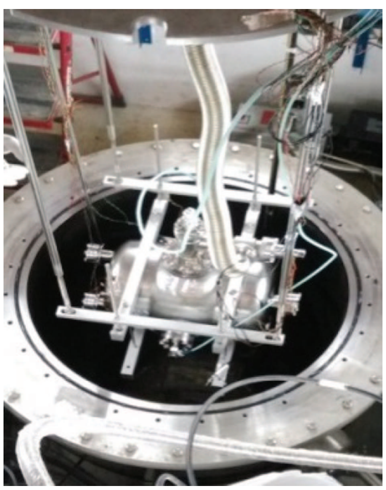


Fig. 15. (color online) The HWR and dewar.

In the vertical test, the multipacting effect occurred in low field (around 0.1 MV/m, 1.4 MV/m and 4.4 MV/m) and high field (10.5 MV/m, 13–15 MV/m) at 4.2 K. The test results agree with simulations at low field well. From the experiences of spoke cavity at IHEP, there were no multipacting above 10 MV/m and the simulation of HWR was to 11 MV/m, so the reason of multipacting observed at high field needs to be further studied. RF conditioning can overcome the multipacting and improve cavity performance. The conditioning phenomenon is shown in Fig. 16. After an hour of RF conditioning at 4.2 K, the multipacting barriers were soft and reduced greatly. But at 2 K, after several hours of RF conditioning, the multipacting was insurmountable, so the test had to be stopped. The reason still needs to be further studied.

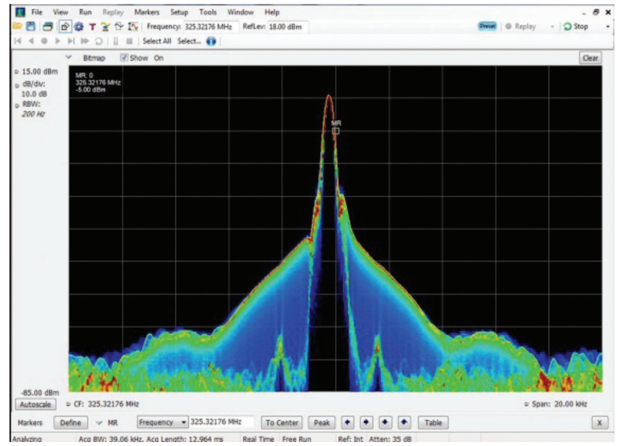


Fig. 16. (color online) The multipacting spectrum during vertical test aging.

At 4.2 K, the Q factors are 1.4×10^9 at $E_{\mathrm{acc}}=7$ MV/m and 4.3×10^8 at $E_{\mathrm{acc}}=15.9$ MV/m. The test result is shown in Fig. 17. The curve of Q_0 vs. E_{acc} is very flat. The maximum peak fields are 66.2 MV/m and 77.6 mT, and X-ray radiation appears at 11 MV/m. Though the highest accelerating gradient obtained is 15.9 MV/m, the maximum peak fields are still not too high at this field level, which helps in depressing the field emission. So the cavity performance still has much room for improvement after further processing.

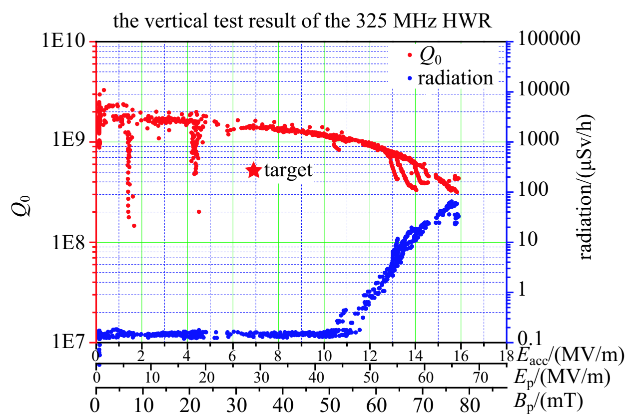


Fig. 17. (color online) The vertical test results of the HWR.

The HWR was tested at both RT and 4.2 K. The results are listed in Table 7. The Δf error between simulation and measurement after BCP may cause by the non-uniformity of removal from the inner wall of the cavity. The measured Δf was larger than simulation at same tuning force, and the reason may be the geometry error in fabrication. The simulated results of the coupler antenna, cooling down, $\mathrm{d}f/\mathrm{d}p$ and LFD agree well with the measured results.

Table 7. Comparisons between measured and simulated results of the HWR.

parameter	simulation	measurement
forward/pickup coupler	1.2e9/2.7e10	1.5e9/2.7e10
BCP(20μm)	+886 kHz	+1024 kHz
tuning	1.1 MHz/mm	1.2 MHz/mm
	68.8 kHz/kN	125 kHz/kN
cooling down	+492.4 kHz	+645 kHz
$\mathrm{d}f/\mathrm{d}p$	−95.3 Hz/mbar	−116.3 Hz/mbar
LFD	-12.7 Hz/(MV/m)^2	-17.5 Hz/(MV/m)^2

5 Summary

A 325 MHz β=0.14 HWR prototype has been successfully developed for CW high current proton linear accelerators. The EM parameters of the HWR have been optimized to an excellent result (very low peak field, high R/Q and G), at the expense of longer effective longitudinal space. The optimized mechanical design gives the cavity a reasonable tuning range, low $\mathrm{d}f/\mathrm{d}p$ and LFD coefficient. The maximum acceleration gradient obtained in the test is 15.9MV/m with $Q_0=4.3\times10^8$ at 4.2 K, and the curve of Q_0 vs. E_{acc} is fairly flat. As the maximum peak fields (E_{peak}, B_{peak}) are not too high at this condition, it is possible to improve the performance further by future processing. All the multipacting barriers during VT at 4.2 K are soft, and consistent with the simulations. In the next steps, further surface processing (including roll grinding and polishing, plasma cleaning) will be done for better HWR performance, and tests will be done at 2 K.

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