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Multipacting analysis for half wave resonators in the China ADS *

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Abstract: In the China ADS (CIADS) proton accelerator, multipacting is an issue of concern for the superconducting cavities. The parallel codes Omega3P and Track3P, developed at SLAC under the support of the DOE SciDAC program, have been used to calculate the electromagnetic field distribution and to analyze the multipacting barriers of such cavities. In this paper, two types of 162.5 MHz half wave resonator cavities, HWR-010 (cylinder type with β of 0.10) and HWR-015 (taper type with β of 0.15) have been analyzed, and the results of the multipacting analyses show that the resonant electrons occur at different regions with different accelerating gradients. The two-point 1st order multipacting on the short plate has also been researched and discussed.

Key words: China ADS, superconducting, HWR, multipacting

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1 Introduction

In Injector II of the China Accelerator Driven Subcritical System(China ADS) project, two types of superconducting HWR cavities (cylinder-type and taper-type) operating at a frequency of 162.5 MHz with β=0.10 and 0.15 [1, 2] will be used to accelerate the proton beam to a minimum energy of 10 MeV. Multipacting (MP) is a resonant process in which a large number of electrons build up an avalanche effect [3] and much RF power is absorbed, so that it is impossible to increase the cavity field by raising the incident power. While most of the MP bands, which are known as soft barriers, may be conditioned with RF, hard MP barriers may persist and prevent the cavities from achieving the design voltage. The potential MP bands have a crucial practical effect on the cavity design. The parallel modules Omega3P and Track3P, for acquiring electromagnetic fields and electron tracking, developed at SLAC under the support of the DOE SciDAC program [4], are utilized to analyze the MP barriers in the two types of HWR cavities.

2 Electromagnetic field distribution for HWR cavities

Prior to the particle tracing, the electromagnetic structures excited by resonant modes need to be obtained. Eigenmode solver Omega3P is one module of the ACE3P suite of finite element codes. The finite element grid with curved elements fitted to the curvature of the boundary allows high-fidelity modeling of the geometry. For the mesh cell setting, tetrahedral cells are used in Omega3P. Figure 1 and Fig. 2 show the cavity models and the electromagnetic field profiles of both the cylinder and the taper type HWRs. From Fig. 2, we can see that the intense electric field is mainly located at the drift tube, while the intense magnetic field is mainly around

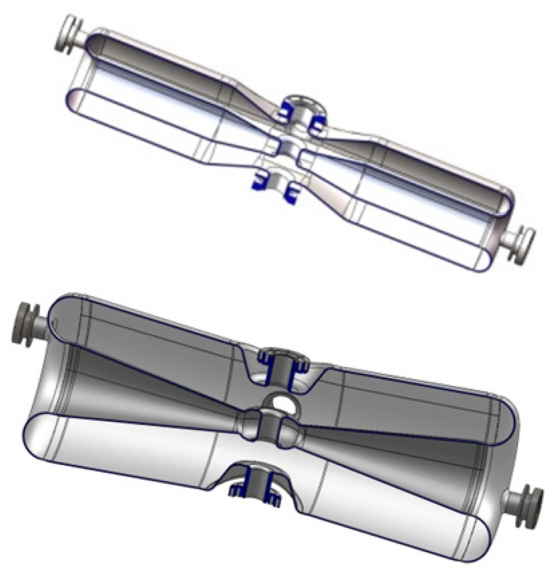

Fig. 1. (color online) Schematics of the HWR cavities (top: cylinder type HWR-010; bottom: taper type HWR-015).

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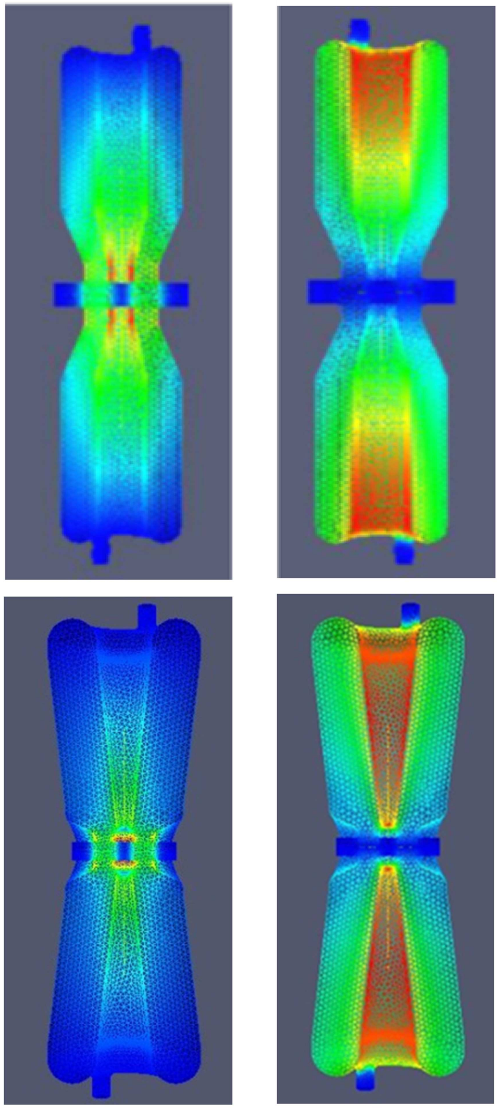

Fig. 2. (color online) The electric (left) and magnetic (right) field distributions of the HWR cavities (top: HWR-010; bottom: HWR-015).

Table 1. Electromagnetic figures of merit for both types of HWR.

parameters	values	
	HWR-010	HWR-015
frequency/MHz	162.5	162.5
β_{opt}	0.10	0.15
$E_{\mathrm{peak}}/E_{\mathrm{acc}}$	5.9	4.9
$B_{\mathrm{peak}}/E_{\mathrm{acc}}/(\mathrm{mT}/(\mathrm{MV/m}))$	12.1	6.1
G/Ω	28.4	51.2
$R_{\mathrm{a}}/Q_0/\Omega$	153	292

the short plate. Some important figures of merit have been listed in Table 1. The sharp reduction of the value of $B_{\mathrm{peak}}/E_{\mathrm{acc}}$ reflects that the taper shape can help increase the storage space of the magnetic field and decrease the surface peak magnetic field value.

3 MP simulations for HWR-010 and vertical test for verification

The MP simulations can be executed after the electromagnetic field calculation. Track3P was used to track the particles and localize the suspicious MP bands; calculations were performed on the NERSC Franklin machine [5]. Due to the symmetry, one half of the HWR cavity was used to do the MP simulations. Seed particles were initiated in the top half (Fig. 3), and they occupy the center of each grid. For the niobium material used in these cavities, the secondary electron yield can change with different surface treatment manners, such as baking and gas charged cleaning (please refer to Ref. [3], Figure 10.5). In order to estimate the MP strength, in this paper the baking treatment curve was used. The accelerating gradient was scanned from 0.1 MV/m up to 6 MV/m with a 0.1 MV/m interval to roughly locate the MP bands. At each field level, 50 RF cycles were used as total running time to obtain the resonant trajectories.

The distribution of resonant particles identified using Track3P showed that there are two potential MP bands, one at field levels below and around 1 MV/m with high impact energies, and the other at field levels of 1.04–1.9 MV/m with low impact energies. No sign of MP is revealed in the range of the operating accelerating gradient of 4 to 5 MV/m. In order to further analyze the accelerating gradient range where MP may occur, a finer scan interval of 0.01 MV/m should be used to expand the suspicious bands. In the following, simulation results of different regions of cavity that may support resonant trajectories are presented.

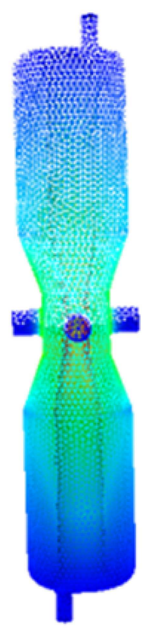

Fig. 3. (color online) Seed particles initiated in top half of HWR-010.

3.1 MP around the beam pipe

Resonant trajectories were found in the beam pipe region (Fig. 4) at accelerating gradient fields from 0.74 to 0.87 MV/m. The impact energies of the trajectories are in the range of 400 to 2500 eV (Fig. 5), which are around the peak of the SEY of niobium. This MP barrier can be surmounted by RF conditioning in view of the sparse resonant electron distribution near the peak of the SEY of niobium.

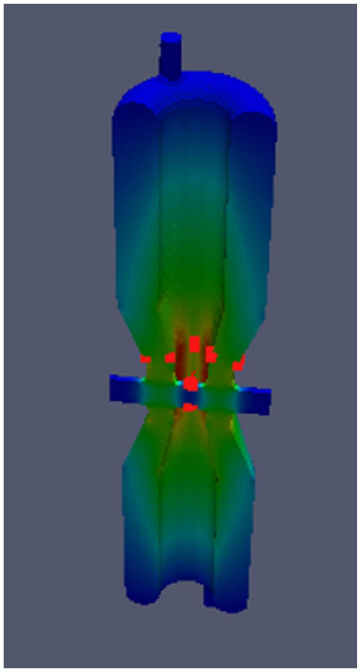

Fig. 4. (color online) MP location around the beam pipe.

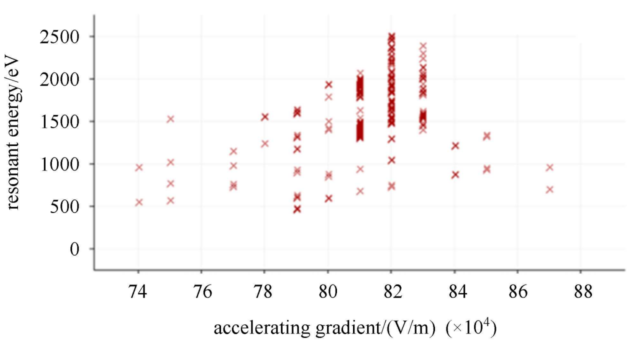

Fig. 5. (color online) MP resonant energy vs. accelerating gradient around the beam pipe.

3.2 MP on cavity shorting plate

Resonant electrons were observed on the shorting plate at accelerating gradient field levels from 1.04 to 1.9 MV/m (Fig. 6, Fig. 7). These are two-point first-order MP. The impact energies of the resonant electrons are below 100 eV and are not at the peak SEY for niobium, so such an MP band can normally be passed through without much difficulty.

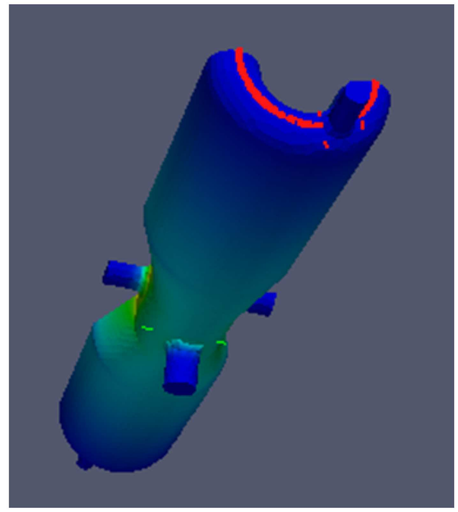

Fig. 6. (color online) MP location on the cavity shorting plate.

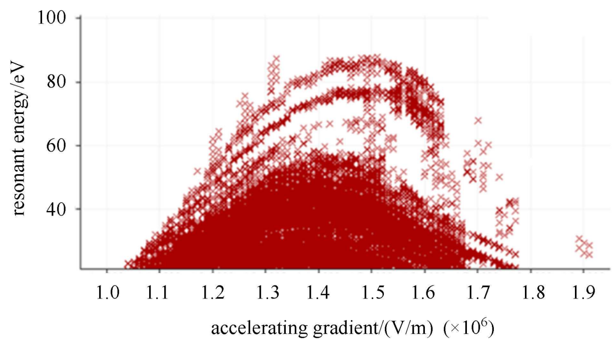

Fig. 7. (color online) MP activity resonant energy vs. accelerating gradient in the rinse port.

3.3 HWR-010 vertical test and MP result analysis

In the vertical test of HWR-010, the performance of the cavity was verified [6]. Fig. 8 shows the cavity fixed on the support stand prepared for the vertical test. The actual test results show that some MP does happen at certain accelerating gradients (Fig. 9). When MP occurred, a large number of secondary electrons consumed the RF power so that it became impossible to increase the cavity fields by raising the incident power; the impedance of the resonator also changed, which caused loss of the matching between the resonator and the transmission system and a considerable amount of forward power to be reflected.

The MP barrier we met below 1 MV/m of accelerating gradient led to Q_0 dropping dramatically; it took a very long time to be conditioned and eliminated with

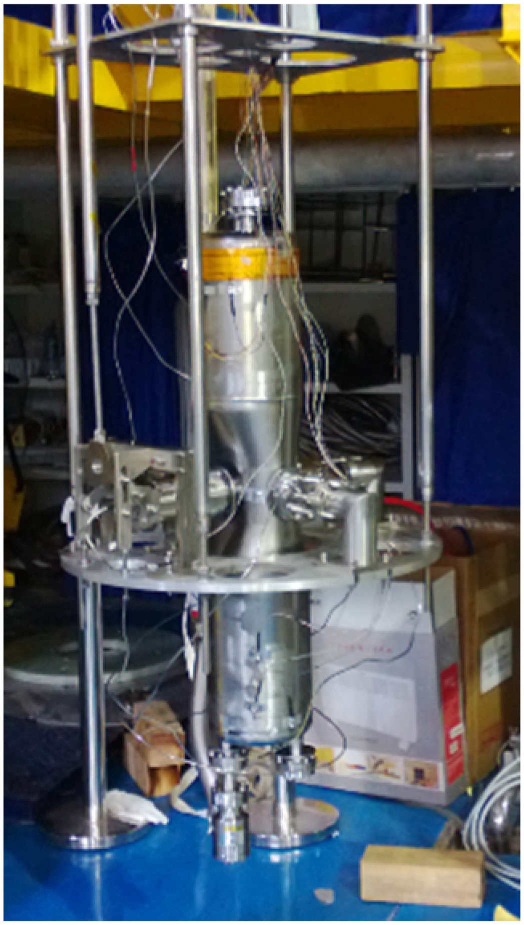

Fig. 8. (color online) HWR-010 cavity installed in vertical test stand.

RF power, which is in accord with the MP simulation results.

4 MP simulations for taper HWR-015

The taper HWR-015 cavity has been developed for the acceleration of protons from about 4 MeV to 10 MeV and is in the fabrication stage. In order to predict the MP occurrence in this kind of cavity, the same simulation process as was used for the cylinder type HWR-010 has been applied. Firstly, the Omega3P module of the ACE3P code was used to implement the electromagnetic field calculation; the field distribution result is shown in Fig. 2 (bottom). In the next step, the Track3P module was launched to do the simulation of resonant electron tracking in the electromagnetic field surroundings obtained from the first step. Analogously, resonant electrons appeared on the cavity waist and on the shorting plate (Fig. 10 and Fig. 11). To make a comparison of the MP activities of the two kinds of HWR cavities, it can be found that in the taper-shaped HWR-015, more serious resonant electron aggregation happens in the waist part of the cavity, and the impact energy of resonant electrons on the shorting plate is closer to the SEY peak of niobium.

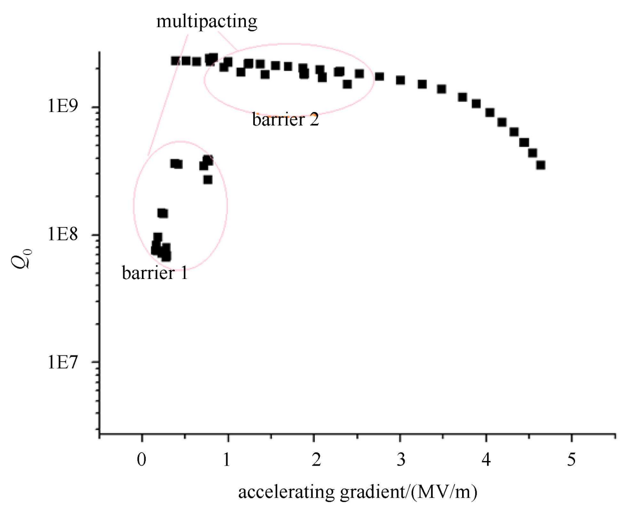

Fig. 9. (color online) Vertical test quality factor vs. accelerating gradient for HWR-010.

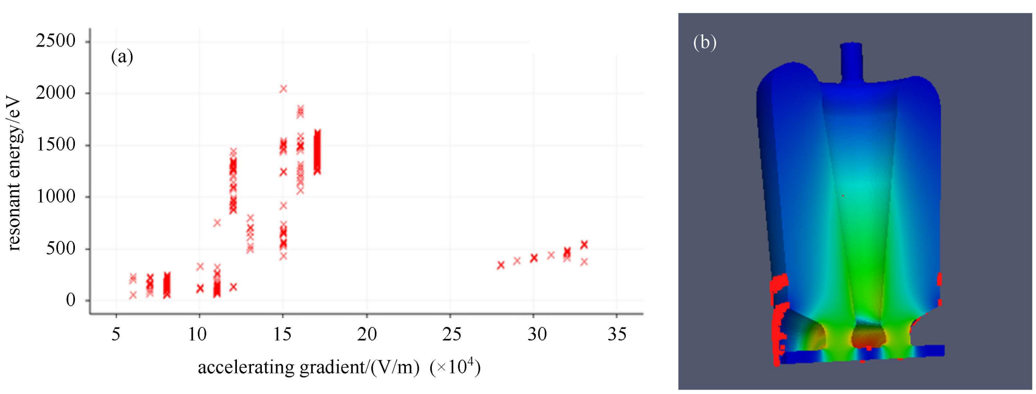

Fig. 10. (color online) Resonant energy vs. accelerating gradient (a) and relevant MP location on the waist part (b).

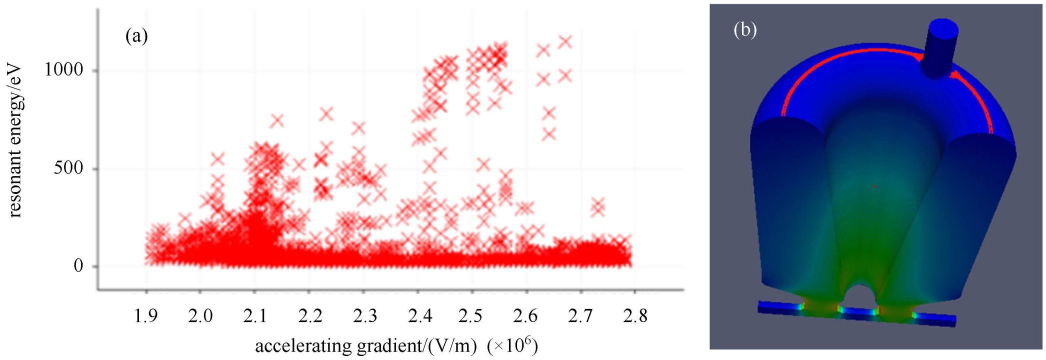

Fig. 11. (color online) Resonant energy vs. accelerating gradient (a) and relevant MP location on the shorting plate (b).

5 Discussion

From the above simulations, the two-point 1st order MP at the shorting plates in the HWR cavity is significantly stronger than other kinds of MP. More specifically, this kind of MP can be presented as in Fig. 12. The dominant motion of the electron is determined by the magnetic field, which leads to cyclotron motion with the radius R given as:

$$R=\frac{\sqrt{mK_{\text{impact}}}}{B_0 e}. \tag{1}$$

in which m and e are the mass and electric charge of the electron respectively, B_0 is the approximately uniform magnetic field magnitude near the short plate and K_{impact} is the impact energy of the electron [7, 8].

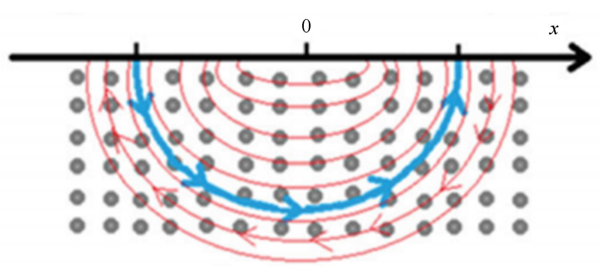

Fig. 12. (color online) Schematic view of the two-point 1st order MP on the shorting plate (red line: electric field, dark point: magnetic field, blue line: electron trajectory). From Ref. [7], Fig. 14.

To further interpret K_{impact} in terms of electric and magnetic field, E_0 of the approximately uniform electric field magnitude near the short plate is introduced and the kinetic energy which can be obtained from one time resonant motion by the electron is:

$$K_{\text{impact}}=E_0\pi R. \tag{2}$$

Substituting (2) into (1), we can get:

$$K_{\text{impact}}=\frac{mE_0^2\pi^2}{B_0^2}. \tag{3}$$

The cyclotron period T of the electron is:

$$T=\frac{2\pi m}{B_{\text{average}}e} \tag{4}$$

$$T=T_{\text{rf}}\frac{2\pi}{\omega}, \tag{5}$$

T_{rf} is the RF period, and B_{average} is assumed to be $1/\sqrt{2}$ of B_0, which can be deduced as:

$$B_0=\sqrt{2}\frac{m\omega}{e}, \tag{6}$$

which is the electron resonant condition. The MP predictions for HWR cavities from different analysis tools are compared in Table 2.

Table 2. MP predictions for HWR cavities.

cavity	analytical prediction	Track3P simulation
HWR-010	$E_{\text{acc}}\sim$0.71 MV/m ($B_0\sim$8.2 mT)	$E_{\text{acc}}\sim$[0.77 MV/m, 1.8 MV/m]
HWR-015	$E_{\text{acc}}\sim$1.61MV/m ($B_0\sim$8.2 mT)	$E_{\text{acc}}\sim$[1.9 MV/m, 2.8 MV/m]

According to this cyclotron model, the condition of the two-point 1st order MP is:

$$W_1<K_{\text{impact}}<W_2. \tag{7}$$

In terms of electric and magnetic field:

$$\frac{1}{\pi}\sqrt{\frac{W_1}{m}}<\frac{E_0}{B_0}<\frac{1}{\pi}\sqrt{\frac{W_2}{m}}, \tag{8}$$

where $[W_1,\ W_2]$ is the region of impact energy corresponding to SEY>1 in Fig. 4.

As for the two types of HWR cavities, the HWR-015 cavity with the taper shape can decrease the magnetic field strength further than the HWR-010 of the cylinder type, therefore, the MP impact energy for the HWR-015 cavity is higher than that of the HWR-010 cavity and is closer to the peak of the niobium SEY curve. According to our analysis, the two-point 1st order MP in the taper type HWR-015 may be a terrible barrier which cannot be conditioned easily. Vertical testing needs to be done on the prototype cavities, and the cavity may be redesigned if the MP cannot be overcome by conditioning.

In this paper, the MP simulations have been done for HWR-010 and HWR-015 cavities using Track3P. According to the simulation results, there is no sign of MP during the operating accelerating gradient range. However, several MP traps may exist in the low and medium fields, and the places where MP may occur vary with different accelerating gradients.

The vertical test for the HWR-010 has also been implemented, showing that the test results are in accordance with the simulation values. In the future, Track3P can be applied as a powerful tool to predict the occurrence of MP and then to suppress it in the preliminary design stage if necessary.

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References

1 YUE W M, HE Y, ZHANG S H et al. Proceedings of Linac 2012, Tel-Aviv, Israel, TUPB055, 2012, 600–602

2 YUE W M, HE Y, ZHANG S H et al. Proceedings of SRF 2013. Paris, France, THP016, 2013, 917–919

3 Padamsee H, Knobloch J, Hays T. RF superconductivity for Accelerators. John Wiely and Sons, Inc. 2008, 179–197

4 https://confluence.Slac.Stanford.edu/ display/AdvComp/ Materials+for+cw11

5 https://www.nersc.gov/

6 CHANG W, HE Y, WEN L H et al. Chinese Physics C, 2014, **38**(5): 057001

7 ZHENG Z, Facco A, LIU Z, Popielarski J, Saito K, WEI J, ZHANG Y. Nuclear Instruments and Methods in Physics Research A, 2014, **735**: 596–601

8 Park G T. Proceedings of SRF 2013. Paris, France, THP027, 2013, 955–958