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INVESTIGATION ON THE TRAPPED MODES OF CPMU AT HEPS

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Abstract

The Cryogenic Permanent Magnet Undulator (CPMU) is a crucial component in synchrotron radiation sources. Due to the small magnet gap of CPMU, the interaction between the beam and its surroundings is strong, which can result in a significant contribution to coupling impedance. In this work, the influence of CPMU on coupling impedance was investigated using wakefield and eigenmode solvers. The results indicate that some of the transverse impedance resonances in CPMU were much stronger than the impedance threshold determined by synchrotron radiation damping, which could cause vertical beam instability. To address this issue, different types of damping materials were investigated through simulations to suppress the resonances.

INTRODUCTION

The in vacuum undulator (IVU) is a device, whose magnet is put inside in the vacuum box, and thus the magnet gap can be designed as much small as possible [1]. CPMU is a kind of undulator, whose magnet is working at cryogenic. Compared with IVU, it can provided a stronger magnetic at the same magnet gap, which can help to increase the frequency of synchrotron radiation generated by electron beams.

Due the small gap, the interaction between beam and its surroundings can be strong. Recently, multiple light sources, such as the Canadian Light Source [2], the Australian Light Source [3], and SLAC's SPEAR3 [4], have all discovered beam instability phenomena caused by the trapped mode inside the IVU.

In the first phase of the High Energy Photon Source (HEPS) project, 6 CPMUs will be installed in the storage ring. The CPMU have a longitudinal length of approximately 2.6 m, with a standard magnet gap of 5 mm. Therefore, the evaluation of its influence on beam is crucial to ensure the stable operation of the beam within the storage ring.

VERTICAL IMPEDANCE

Due to limited computational resource, the three-dimensional model of CPMU need to be simplified. Its unnecessary detailed structures were removed, and the length of mangnet was reduce to 1 m, to reduce the mesh number for a short simulation time. Figure 1 shows the simplified model, and the right figure depicts the transverse cross section of CPMU, which similar to a circular ridge waveguide.

Compared to circular waveguide, the ridge waveguide has a lower cutoff frequency. As the size of beam pipe is large compared to the magnet gap, the cutoff frequency formed by the magnet and vacuum cavity is lower than that of the beam pipe. As a result, some modes with low-frequency can be trapped in CPMU, and it is also called as trapped modes.

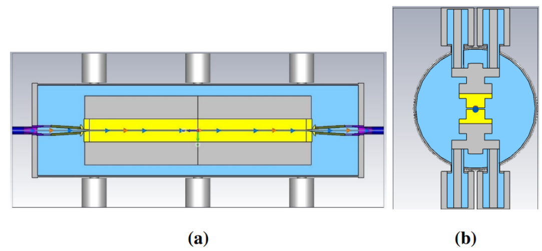

Figure 1: The simplified model of CPMU. (a): vertical cross section; (b): transverse cross section.

Through the CST wakefield solver, the vertical coupling impedance of the simplified model is shown in Fig. 2. In the simulation, the RMS length of the beam bunch was set to 100 mm, and the calculation length of the wakefield is 20 m.

Figure 2 shows that there are mainly two obvious impedance peaks at 96 MHz and 189 MHz. The real part impedance of these two peak are 2.1 and 0.6 MΩ/m, respectively. Due to these two peaks have a high Q factor, the wakefield is hard to convergence. Thus, the magnitude of the vertical impedance is smaller than expected value.

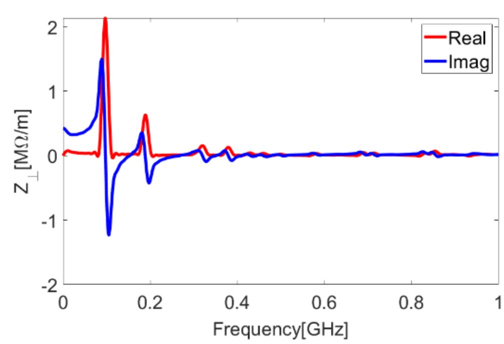

Figure 2: The vertical coupling impedance.

TRAPPED MODES

Although the CPMU model has been simplified, the simulation still takes nearly one month to obtain the impedance results in Fig. 2. As the simulation time is proportional to the wakefield length, it will require a large amount of time and computational resources, to obtain a converged result. Therefore, the eigenmode solver is adopted to analyze these two impedance peaks, which requires little computational resources and time.

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The relationship of five eigenmodes, between the R/Q and the vertical displacement, is shown in Fig. 3. The eigenmode frequency of Mode 1 and Mode 3 are 96 MHz and 189 MHz, respectively, which is consistent with the frequency of impedance peak in Fig. 2. The relationship curves for Mode 1 and Mode 3 resemble parabolic shape, which is agree with the relationship between the transverse impedance's R/Q and its transverse displacement. Therefore, Mode 1 and Mode 3 can be thought as the vertical impedance mode, and it is also called as trapped modes.

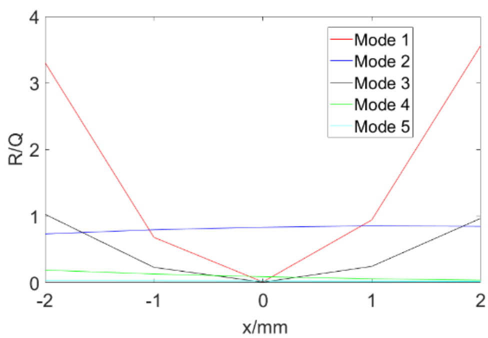

Figure 3: The R/Q of five eigenmodes at different vertical displacement.

According to the eigenmode results, the coupling impedance for these two modes were calculated and presented in Table 1. The transverse shunt impedance for Mode 1 and Mode 3 can reach 150 and 32.6 MΩ/m, respectively. However, the vertical impedance threshold in HEPS, determined by synchrotron radiation (SR) damping, is approximately 4.7 MΩ/m. When the frequency of trapped modes is overlap with the beam spectrum, the impedance of trapped modes can be a huge value, and thus some measures need to be adopted to inhibit it.

Table 1: Eigenmode Results of Trapped Modes

	f [MHz]	$\frac{R}{Q}_\perp$ [MΩ/m^2]	Q	R_s [MΩ/m]
Mode1	96	0.78	773	150
Mode3	189	0.22	1154.8	32.6

The Q factor of trapped mode can be damped by placing damping materials at specific locations inside the model, which would result in a decrease in the magnitude of its coupling impedance. Therefore, in this section, two approaches are proposed to suppress these trapped modes: electric damping and magnetic damping.

Electric Damping

To achieve a good mode damping effects, it is usually necessary to place the damping materials in the region with strong field distribution. Taking the mode of 96 MHz as an example, its electric field distribution is shown in Fig. 4, and the field distribution at 189 MHz is similar to that at 96 MHz.

The electric field at 96 MHz is strong in the magnet gap and near the girder. Considering the influence of damping materials on the magnetic field at the magnet pole, we only consider placing it on the girder and study its damping effects on the trapped modes.

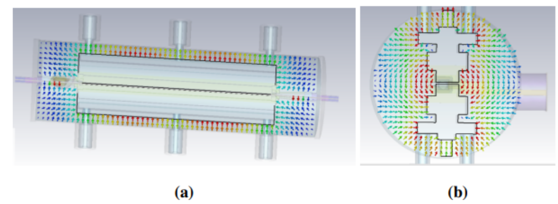

Figure 4: The electric field distribution of the eigenmode at 96 MHz. (a): vertical cross-sectional view at its center; (b): transverse cross-sectional view.

The size of the electric damping material, placed at the girder, is 60*30*20 mm, and a total of 4 pieces are used, as shown in Fig. 5. In order to study the influence of its electromagnetic properties on the Q factor, a parameter sweep is conducted on the dielectric constant and magnetic permeability: ϵ', ϵ'', μ', μ''.

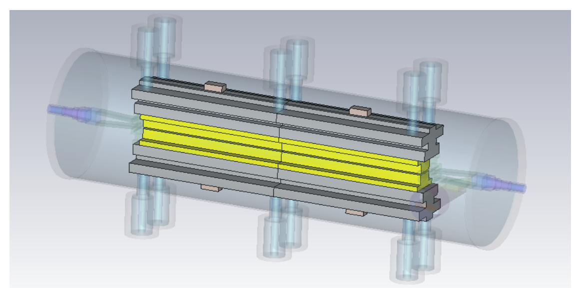

Figure 5: The location of electrical damping material, and it is the earthy yellow elements on the girder.

The default electromagnetic parameters for the electric damping material at 100 MHz are set as $\epsilon' = 5$, $\epsilon'' = 2.5$, $\mu' = 5$, $\mu'' = 2.5$. When scanning one variable, the other parameters remain unchanged. The scanning range for variable ϵ' and ϵ'' is 5, 10, and 20, and that for μ' and μ'' is 2.5, 5, 7.5, and 10. Figure 6 shows the sweep results of Q factor at 96 MHz. To facilitate comparison, four air blocks were placed at the location of the damping material, whose electromagnetic properties is $\epsilon = \mu = 1$.

In Fig. 6, the electric damping material can effectively reduce the Q factor of trapped mode, compared to the case without damping material. Increasing the value of μ'', especially for ϵ'', can significantly enhance its damping effect on Q factor. That suggests that, the damping material with a large value of ϵ'', can help to suppress the trapped modes in the model.

Magnetic Damping

Figure 7 illustrates the magnetic field distribution at 96 MHz. In addition to the strong field distribution at the magnet gap, there is also a significant field distribution near

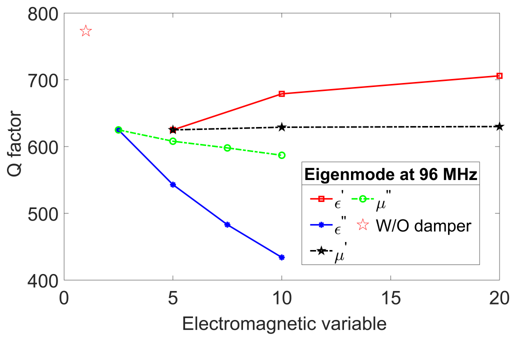

Figure 6: The damping effect of electric damping material with different electromagnetic variables on the Q factor.

the linked rods. To avoid interference with the magnetic field at the magnet gap, the magnetic damping material is selected to be placed around the linked rods.

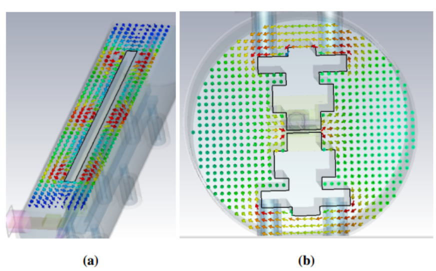

Figure 7: The magnetic field distribution of the eigenmode at 96 MHz. (a): horizontal cross-section at the girder; (b): transverse cross-section.

The location of the magnetic material in the model is shown in Fig. 8, with dimensions of 50*50*5 mm for each of the 12 pieces.

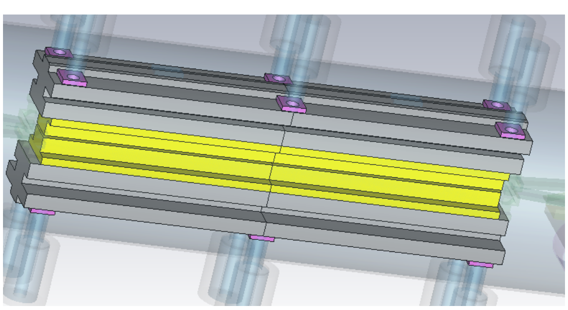

Figure 8: The location of magnetic damping material, and it is the magenta components around linked rods.

The influence of four electromagnetic parameters on the damping effect of Q factor was also investigated, using the same parameter sweep settings as mentioned in the section of *Electric Damping*. Figure 9 displays the Q factor results under different electromagnetic variables.

According to Fig. 9, the variable μ'' has the most significant suppression effect, and it can decrease the Q factor from 773 to 10. This indicates that the damping effect of magnetic material is significantly better than that of electric material.

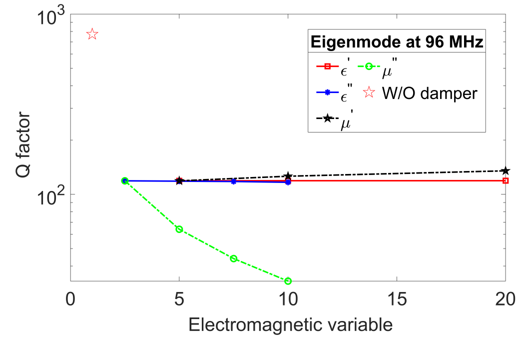

Figure 9: The damping effect of magnetic damping material with different electromagnetic variables on the Q factor.

Therefore, the magnetic damping material is finally selected to suppress the trapped modes in CPMU.

Considering the practical conditions, the ferrite material of HOM absorber in RF cavity is selected as the magnetic damping material to suppress the trapped mode. The eigenmode results with ferrite material are shown in Table 2.

Table 2: Eigenmode Results with Ferrite Material

	f [MHz]	$\frac{R}{Q}_{\perp}$ [MΩ/m^2]	Q	R_s [MΩ/m]
Mode1	96	0.94	17.7	4.5
Mode3	189	0.24	52.6	1.6

Compared with Table 1, the ferrite material significantly reduces the Q factor of these two trapped modes, whose value is decreased from 773 and 1154.8 to 17.7 and 52.6, respectively. The transverse impedance finally decreases to 4.5 and 1.6 MΩ/m, which is less than the impedance threshold determined by SR damping. Considering the bunch by bunch feedback system, the influence of trapped modes on beam is acceptable.

CONCLUSION

In our study, we observed that the trapped mode in CPMU can lead to large vertical impedance. When the frequency coincides with beam spectrum, it will significantly exceed the impedance threshold. To address this issue, two types of material: electric material and magnetic material, are proposed to suppress it, and the magnetic material has an excellent performance.

After implementing ferrite material, the Q factor as well as the transverse impedance are significantly reduced. That indicates ferrite materials can effectively suppress the influence of trapped modes on beam.

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