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OPTIMIZING COUPLING SLOT DESIGN FOR Pi-MODE STRUCTURE CAVITY IN CSNS II DEBUNCHER*

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Abstract

This paper proposes a new coupling slots design for the Pi-Mode structure high-frequency cavity in the China Spallation Neutron Source (CSNS) Phase II. Through simulation calculations and experimental verification, it was found that the new coupling slots design significantly improves the Q value and transmission efficiency of the high-frequency cavity. This study is of great significance for improving the performance of the high-frequency cavity in CSNS II, and thus improving the accuracy and efficiency of neutron scattering experiments.

INTRODUCTION

Neutron scattering experiments play a crucial role in fields such as materials science, biology, and chemistry, providing insights into the structure and properties of materials. CSNS II, constructed by the Institute of High Energy Physics of the Chinese Academy of Sciences, aims to provide a high-brightness, high-energy resolution, and high-time resolution neutron beam for scientific research. To increase energy dispersion and adjust the injection angle, CSNSII plans to use a 648 MHz PI model high-frequency cavity as a Debuncher. The PI model high-frequency cavity has advantages such as high Q value, uniform electromagnetic field, and low cost. The design parameters of the coupling slots in the PI model high-frequency cavity are crucial. By optimizing the size and position of the coupling slots, the electromagnetic field distribution of the cavity can be adjusted, thereby enhancing the scattering effect and improving the performance and stability of the accelerator.

PROCESS OF RESEARCH

Choosing Work Model

Pi-model and pi/2-model high-frequency cavities are commonly used in particle accelerators. Pi-model cavities have large effective shunt impedance but are sensitive to perturbations and errors due to small spacing between adjacent modes. In contrast, pi/2-model cavities have lower sensitivity to perturbations and errors but relatively small shunt impedance.

In CSNS II, the debuncher cavity requires high stability and effective shunt impedance for changing the injection phase and accelerating the beam. Coupling slots are an important parameter for reducing sensitivity, and optimizing them can improve the stability and reduce the sensitivity of pi-model cavities. Therefore, studying the optimization of pi-model high-frequency cavities and their coupling slots is crucial for designing an efficient debuncher in particle accelerators.

Designing PIMS Units with SUPERFISH

When particles are ejected from the linear superconducting accelerator, β reaches 0.65. The size of the PIMS unit was designed by SUPERFISH, as shown in Fig. 1, with a frequency of 648 MHz and β of 0.65. Figure 2 is a 3D view of a PIMS unit, and each PIMS module contains 7 units.

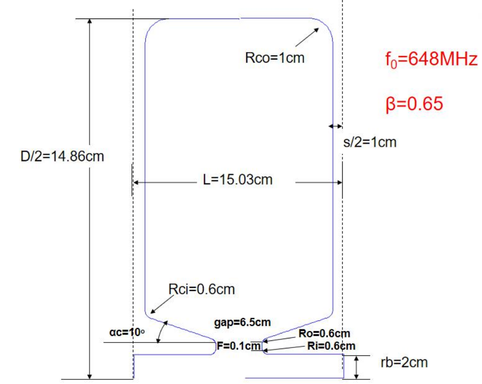

Figure 1: Dimension of PIMS debuncher.

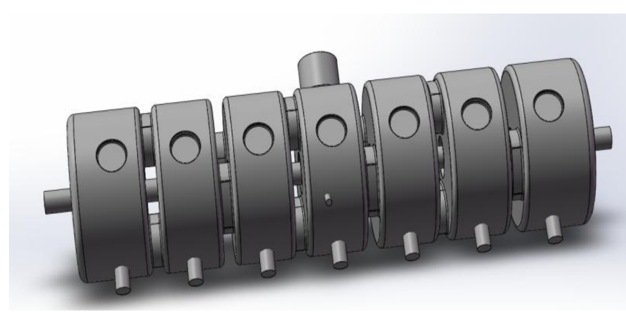

Figure 2: 3D view of a PIMS module.

Optimization of the Coupling Slots

In the design of linear particle accelerators, power coupling between units is crucial. In accelerators, power coupling between adjacent units is achieved through coupling slots. The design of coupling slots directly affects the performance and stability of the accelerator. In this study, we propose a new design scheme for coupling slots to achieve power coupling between units. The

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coupling slot design scheme in this study has two coupling slots between two units. The two coupling slots between adjacent units are distributed vertically at 90 degrees to reduce their sub-near-field coupling to the next unit. This design scheme can effectively achieve power coupling between units and improve the performance and stability of the accelerator [1]. In this design scheme, the coupling coefficient kc is an important parameter. We use the following formula to calculate the coupling coefficient kc:

$$k_c = \frac{f_m^2 - f_p^2}{f_m^2 \cdot \cos\left(\frac{m\pi}{N}\right) - f_p^2 \cdot \cos\left(\frac{p\pi}{N}\right)}$$

m, p represents the number of modes, and f is the frequency, N=7.

The coupling coefficient kc and effective shunt impedance Zeff=ZT^2 are the two most important indicators for optimizing the coupling space. In a PI-mode high-frequency cavity, the coupling coefficient kc describes the strength of energy transfer between adjacent cavities, and its magnitude affects the energy transfer and phase relationship between cavities, thereby affecting the performance of the accelerator. The effective shunt impedance Zeff represents how much energy gain the structure can provide to ions under a given high power loss, directly describing the efficiency of converting high-frequency power into particle energy in the structure. Both of these parameters are related to the unloaded quality factor Q, which is an important parameter describing the rate of energy decay inside the cavity. By optimizing the shape of the coupling slot, the energy transfer and decay inside the cavity can be improved, thereby improving the unloaded quality factor Q of the cavity, which is crucial for the stability and continuous operation of the accelerator.

In this study, three shapes were analysed based on a three-cell model, as shown in Fig. 3 for the standard slot and previous optimized slot, and Fig. 4 for the comparison between the previous optimized slot and the newly designed optimized slot in this article. Two shapes were analysed based on a seven-cell model after optimization. After optimization, a new coupling slot shape was obtained, whose coupling coefficient kc and effective shunt impedance Zeff were both superior to those of the standard slot and modified slot. This new shape can improve the performance and stability of the accelerator. By optimizing the coupling coefficient kc and effective shunt impedance Zeff, the energy transfer and particle acceleration efficiency of the high-frequency cavity can be improved.

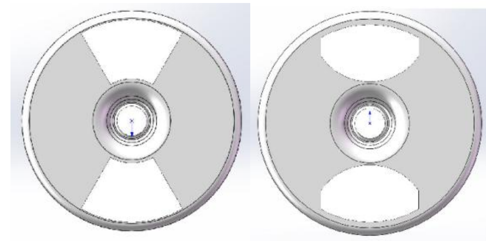

Figure 3: The standard slot and the previous optimized slot.

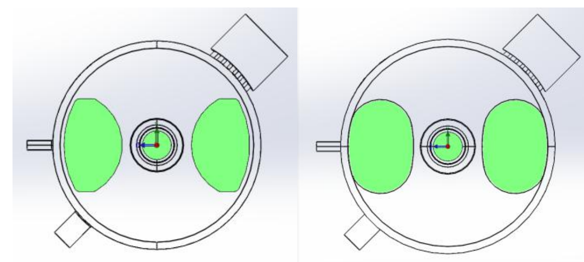

Figure 4: The previous optimized slot and the new optimized slot.

To optimize the design of coupling slots, this paper used SolidWorks and CST software for model building and simulation calculation. Specifically, we first used SolidWorks to build a 3-cell model and set the parameters of the coupling slots as variables for subsequent simulation calculations. Then, we adopted a design method based on the deformation of standard slots, as shown in Fig. 5. By finding a suitable annular slot and retaining the central angle and radius of the outer arc AD, as well as the endpoints B and C of the inner arc BC, we connected the endpoints of the outer and inner arcs with three tangent arcs to achieve a more complex and accurate coupling effect, as shown in Fig. 5.

This design method can make the shape of the coupling slots more complex, thus achieving a more accurate coupling effect. By importing the SolidWorks model into CST for simulation calculation, we can predict the coupling effect more accurately and optimize the design of the coupling slots.

To gain a deeper understanding of the performance of the coupling slots, we further investigated the mechanism of different parameters on their performance. We found as the central angle α of arc AB increases, kc and Zeff exhibit opposite characteristics, i.e., an increase in α leads to an increase in kc and a decrease in Zeff, as demonstrated in Fig 6. Additionally, we observed that the distance of OB also has an impact on kc and Zeff, where an increase in OB distance leads to a decrease in kc and Zeff values. Therefore, selecting an appropriate central angle α of arc AB is crucial for achieving optimal coupling efficiency in the design of the coupling slot. At the same time, attention should be paid to the distance of OB to ensure that the values of kc and Zeff can reach a good level.

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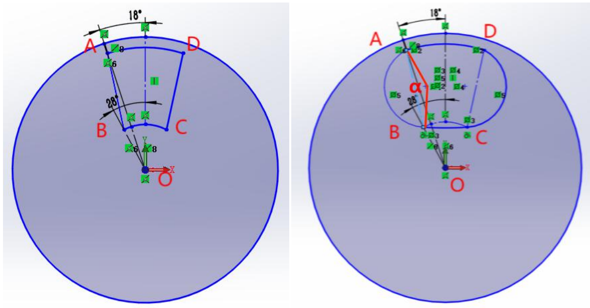

Figure 5: A design method based on the deformation of standard slots.

By using this method, we can easily achieve the dual optimization of Zeff＞28 and kc＞5% for the cavity. We applied this type of coupling slots to the 7-cell cavity and conducted CST simulation. Compared with the original modification method, the simulation results showed that the TS parameter (tilt sensitivity) of this type of coupling slots was smaller, at 192.88%, while the TS parameter of the original coupling slots for the entire cavity was 228.70% [2]. In addition, simulation data also indicated that in the new design, the frequency interval between the various modes was larger than before, which means that the modes were less likely to interfere with each other.

To meet the requirements of injection phase and energy spread expansion in the fast cycling synchrotron, the beam aperture in the downstream debuncher will be enlarged to achieve higher momentum jitter compression ratio. This new coupling hole design can achieve the required Zeff and kc values with a smaller aperture area. This feature is very important for optimizing the performance and stability control of high-frequency cavities in the accelerator and neutron source fields.

CONCLUSION

Using SolidWorks and CST software, we employed a design method based on standard slot deformation to enhance coupling slot complexity, achieving accurate coupling effects. We investigated parameter effects on slot performance and found that selecting an appropriate arc AB central angle α achieves optimal coupling. Attention to OB distance ensures favorable kc and Zeff values. This method enables dual optimization for the entire cavity. When applied to a 7-cell cavity, the new slot design exhibited a smaller TS parameter and larger frequency interval between modes, indicating reduced interference. Thus, this method effectively optimizes coupling slot performance and cavity efficiency.

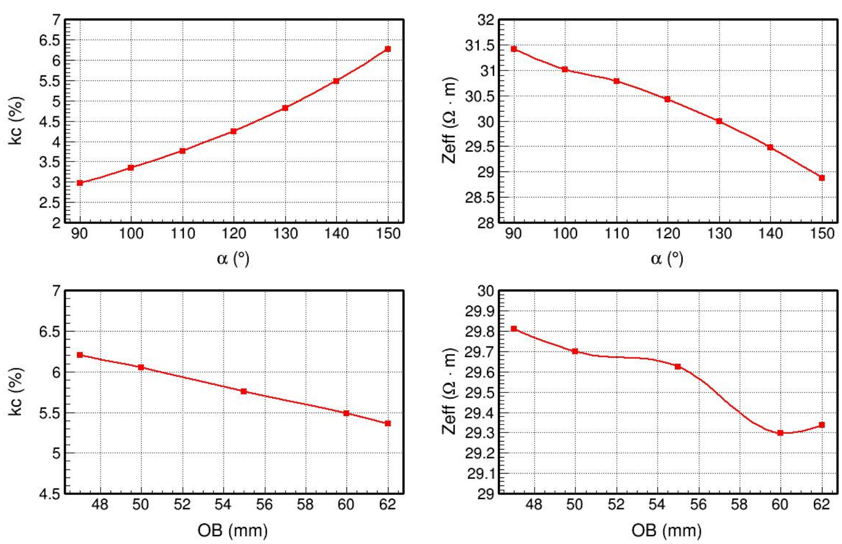

Figure 6: The trend of kc and Zeff.

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