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MULTIPOLE FIELD OPTIMIZATION OF X-BAND HIGH GRADIENT STRUCTURE

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Abstract

The X-band constant gradient acceleration structure plays a crucial role in the VIGAS project. However, the presence of a multipole field component in the structure's coupler leads to an increase in ray bandwidth and a decrease in yield, ultimately affecting the quality of the generated rays. Through calculations, it has been determined that the quadrupole field component is particularly prominent in the original structure, accounting for 29.5% of the fundamental mode strength. Therefore, it is necessary to modify the cavity structure of the coupler. By altering the shape of the cavity to two staggered circles, the objective of reducing the quadrupole field is achieved. The optimized quadrupole field component now accounts for approximately 0.3% of the fundamental mode strength. Subsequently, the non-resonant perturbation method was employed to simulate and experimentally measure the magnitude of the multipole field component in the actual acceleration cavity.

INTRODUCTION

In 2021, Tsinghua University introduced the Very Compact ICS Gamma-ray Source project, known as the VIGAS project. The primary objective of the VIGAS project is to develop the world's first compact quasi-monochromatic gamma-ray source operating in the megaelectronvolt range. The gamma-ray energy generated by this project can be continuously adjusted within the range of 0.2 to 4 MeV.

The accelerator structure utilized in the project is based on the X-band technology and comprises an input coupler and an output coupler positioned at its ends. However, the inclusion of these couplers disrupts the circular symmetry of the accelerator structure, resulting in the emergence of multipole fields within the electromagnetic field. These multipole fields, present within the accelerator structure, have the potential to increase the beam emittance. Consequently, this may have an impact on the beam dynamics, ultimately affecting the bandwidth and yield of the produced gamma rays [1].

To analyze the beam dynamics, comprehensive simulations were conducted for the entire accelerator structure. These simulations took into account three-dimensional field distributions for the various components, specifically focusing on comparing the effects of one-dimensional and three-dimensional field distributions within the X-band accelerator structure. The results demonstrate that the emittance, which characterizes the size of the beam, increases by approximately 14% in the presence of three-dimensional field distributions, compared to the case of one-dimensional field distributions. This indicates that the presence of multipole fields indeed leads to an increase in the emittance.

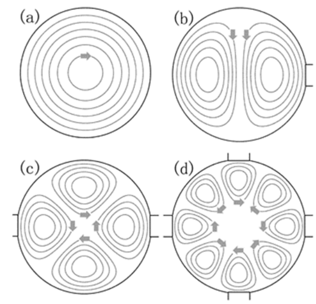

Figure 1: Different drilling situation in the cavity and the distribution of the multi-pole magnetic field.

The emergence of multipole fields within the couplers is a result of the symmetry breaking of the cavity, as shown in Fig. 1 [2]. In the absence of any deviations from perfect circular symmetry, the occurrence of multipole fields can be avoided. However, the introduction of a hole in the cavity wall gives rise to the generation of multipole fields, with the dipole field being the most dominant component. In the case of a pair of symmetric double holes, the quadrupole field becomes the strongest component of the multipole fields. When there are four symmetric holes, the octupole field emerges as the most significant component.

In the existing X-band accelerator structure's couplers, two symmetric holes are present, resulting in the quadrupole field being the most prominent among the multipole fields. It constitutes approximately 30% of the intensity of the fundamental mode. Hence, it becomes crucial to suppress the quadrupole field component effectively.

OPTIMIZATION

The most effective method to suppress the quadrupole field component is by introducing two additional holes in the vertical direction of the previously symmetrical double holes, forming a symmetric four-hole structure. This modification effectively mitigates the quadrupole field. However, the process of punching additional holes has a considerable impact on the structure. Therefore, a compromise approach was adopted. The entire cavity of the coupler was transformed from a circular structure to two staggered circular structures, creating a racetrack-type structure, as shown in Fig. 2. This approach provides a satisfactory solution to reduce the quadrupole field.

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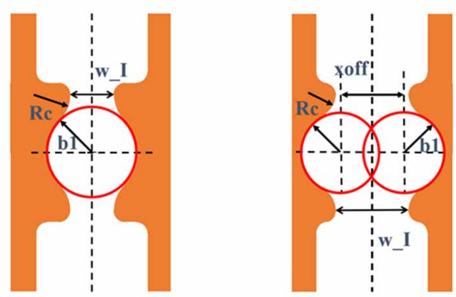

Figure 2: Schematic diagram of coupler structure optimization.

The modified structure of the coupler resembles a symmetrical four-hole structure, which effectively suppresses the quadrupole field without the need for additional drilling. However, the changes in the coupler structure result in an increase in the surface magnetic field. The maximum value of the surface magnetic field occurs at the chamfer on both sides of the feed inlet. To prevent excessive surface magnetic field, it becomes necessary to adjust the size of the chamfer at this location. Additionally, the structural modifications introduce a mismatch between the coupler and the accelerating cavity, necessitating a rematching process.

By conducting parameter scanning, the optimized parameters for the modified structure are obtained, as presented in Table 1. These optimized parameters ensure improved performance and alignment between the coupler and the accelerating cavity.

Table 1: Coupler Optimization Structural Parameters

Parameters	**Value [mm]**
Rc	4.0
xoff	7.0
b1	5.891
w_I	9.173

By utilizing the optimized parameters in simulation calculations, it is determined that the strength of the quadrupole field component in the input coupler of the X-band acceleration structure is reduced to 0.28% of the fundamental mode strength. The variation of the tangential magnetic field within the entire cavity of the coupler, both before and after optimization, is shown in Fig. 3.

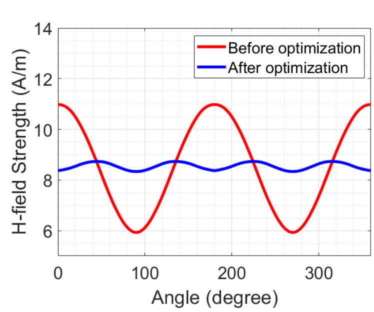

Figure 3: Simulation distribution of tangential magnetic field on r = 2 mm at the cavity of X-band accelerating structure coupler.

MEASURE

The non-resonant perturbation method is employed to measure the quadrupole field in the X-band acceleration structure [3]. This method involves introducing a perturbation object into the acceleration structure and measuring the reflection coefficient S11 at the input port. By analyzing the S11 measurement, the electromagnetic field at the location of the perturbation object within the acceleration cavity can be obtained. One of the advantages of the non-resonant perturbation method is its ability to measure the electromagnetic field of traveling wave acceleration structures accurately. It enables precise tuning and analysis of the acceleration structure.

Furthermore, the non-resonant perturbation method ensures minimal contact between the measurement system and the interior of the acceleration structure. This eliminates any potential impact on the internal components of the structure. The measurements conducted in this study specifically focus on the coupler structures prior to optimization.

Simulation

In the unoptimized coupler model, a copper material perturbation object is introduced to simulate the actual scenario. The perturbation object is moved along a circular path centered around the coupler's center, and the reflection coefficient of the coupler's input port is simulated at each position of the perturbation object. By calculating the difference in reflection coefficients between the perturbed and non-perturbed cases, it is possible to assess the electromagnetic field at the location of the perturbation object. Therefore, by analyzing the difference in reflection coefficients, the magnitude of the multipole field component can be determined. The measured data resulting from these calculations are presented in Fig. 4.

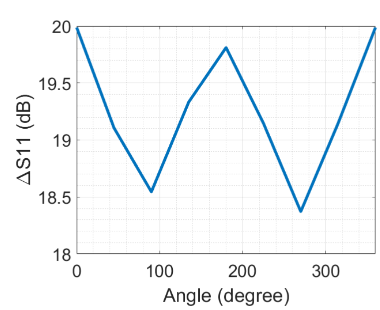

Figure 4: Simulation results of the relationship between the difference in reflection coefficient and the position of the perturbation object.

Experiments

During the actual measurement process, a pair of eccentric original plates was designed and fabricated to securely position the perturbation object. The purpose of these plates is to ensure that the perturbation body remains in a fixed position throughout the measurement. The design and arrangement of the eccentric original plates can be observed in Fig. 5.

Figure 5: Eccentric disc and fitting between disc and coupler hole.

Throughout the measurement process, the eccentric position of the perturbation object is continuously rotated, and the reflection coefficients are individually measured at different positions. A comparison is then made between the measurement results with the perturbation object and the results without it. By analyzing the relationship between the difference in reflection coefficients and the eccentricity position, valuable insights into the impact of the perturbation object can be obtained. This relationship is visually depicted in Fig. 6.

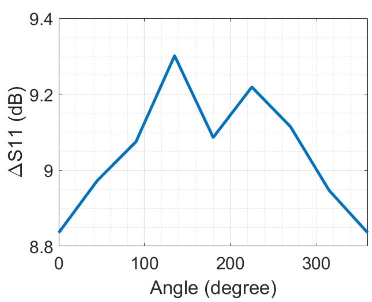

Figure 6: Experiment results of the relationship between the difference in reflection coefficient and the position of the perturbation object.

Through analysis, it has been discovered that the magnitude of the quadrupole field obtained through simulation is approximately 0.0382, while the magnitude of the quadrupole field component obtained through experimentation is around 0.0054. These values exhibit noticeable differences between the simulation and experimental results. The disparities can be attributed to various factors, such as variations in the models and parameters employed in the simulation and experimental setups. Further discussion and analysis are necessary to comprehensively understand and reconcile these disparities.

CONCLUSION

The optimization of the X-band acceleration structure has successfully suppressed the strength of the multipole field in the coupler. The strength of the quadrupole field component, which initially accounted for approximately 30% of the fundamental mode strength, has been reduced to just 0.28% after the optimization process.

The non-resonant perturbation method has been employed to measure the electromagnetic field within the X-band acceleration structure, both through simulation and experimental approaches. This method has provided initial insights into the multipole field within the coupler. However, there exist certain differences between the experimental and simulation results, indicating the need for further analysis and calculations to fully understand and reconcile these discrepancies.

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