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DESIGN OF A TWO-CELL C-BAND ACCELERATOR CAVITY WITH HIGHER-ORDER MODE DAMPING*

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Abstract

Higher-order mode (HOM) damping is essential for building large-scale facility linear accelerators, such as a linear collider, because of the need to reduce the wakefield strength inside the accelerating structure. We designed a *C*-band accelerator cavity with distributed coupling and thin HOM-damping waveguides oriented in the radial direction. It was proposed that nickel-chrome (NiCr) coating deposited on the surface of the thin waveguides will be used to increase the surface resistivity and to damp the HOMs. Recently, we designed a two-cell cavity to conduct a concise high power test that will help us understand the fabrication challenges for the cavity with NiCr HOM absorbers, and examine the performance of the NiCr coating under high-power conditioning. This presentation will report the detailed electromagnetic and engineering design of the cavity, the theoretical prediction of the cavity high-gradient performance, the status of fabrication, and plans for high-gradient testing.

INTRODUCTION

Cryo-cooled normal conducting radiofrequency (NCRF) *C*-band accelerator technology is under development for a future electron-positron linear collider [1]. To construct a multi-kilometer linear accelerator, beam instability must be carefully studied. One important factor that can contribute to the beam instability is the long-range wakefield, in the form of higher-order modes (HOM) excited by the beams being accelerated in the RF cavities. HOM damping and detuning are two main approaches to suppressing the HOM in the accelerator cavities [2, 3]. In this paper, we report accelerator cavity design studies for damping the HOM.

The unit-cell design consists of an axisymmetric accelerator cell [4] and four HOM-damping waveguides. Each HOM-damping waveguide is in the form of a thin gap, extending in the radial direction of the accelerator cell and spanning across all accelerator cells in the longitudinal direction. The planar faces of the HOM-damping waveguides will be coated (plated) with a layer of low-electrical-conductivity material, such as nickel-chromium (NiCr). When the HOM fields penetrate into the HOM-damping waveguides, the RF magnetic field of the HOM will interact with the highly lossy coatings, thus getting damped. The plating of NiCr is a developed industrial technology.

At Los Alamos National Laboratory (LANL), in order to test the high-gradient performance of an accelerator cavity designed with the NiCr-coated HOM-damping waveguides, a two-cell standing-wave accelerator cavity was designed at *C*-band (5.712 GHz). The high power test of the cavity will be performed at the CERF-NM facility [5] at LANL.

TWO-CELL CAVITY DESIGN

The mechanical design of the two-cell accelerator cavity with HOM-damping waveguides is illustrated in Fig. 1. The input RF power from the klystron enters the cavity through the WR187 standard waveguide port. The RF power is divided equally and is fed into the two cells from the side. Figure 1(a) shows the HOM-damping waveguide faces, where NiCr coatings will be applied. Figure 1(b) shows the transverse cross section of the cavity and the HOM-damping waveguides. Each HOM-damping waveguide is 0.5-mm thick, and the radial span of the HOM-damping waveguide is 37.0 mm.

The two-cell structure is fabricated in the form of a copper body with four copper quadrants brazed together. The four-quadrant fabrication scheme is essential, because we must machine the thin HOM-damping waveguides, and the waveguide faces need NiCr coatings. Two rounds of mechanical

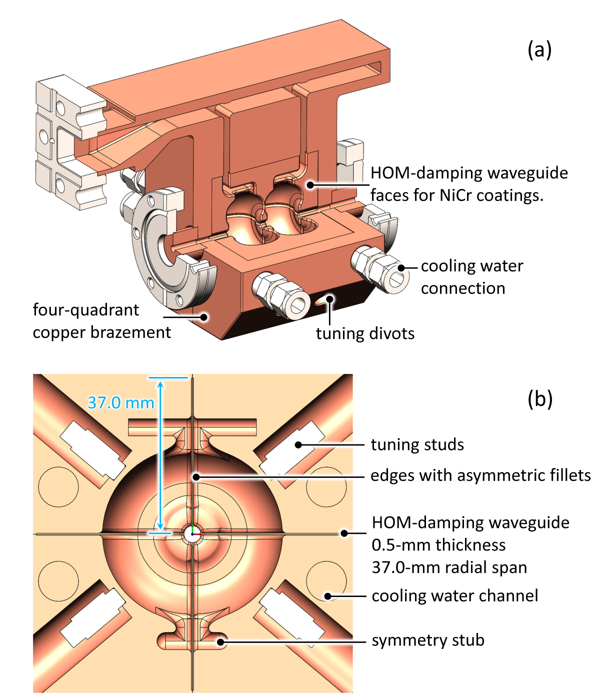

Figure 1: Mechanical design of the two-cell accelerator cavity with HOM-damping waveguides. (a) three-quarter section view; (b) half-section view of one cell.

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machining are required for the fabrication. In the first round, the four copper quadrants are machined with the features of the HOM-damping waveguides. The quadrants are then sent out for NiCr coatings. The fabrication method of the NiCr coatings was developed at SLAC: a 800-nm nickel layer and a 200-nm chromium layer are deposited in one pass, and there are a total of seven passes, resulting in a total thickness of 7 to 10 µm. In the second round of the machining, the RF features of the accelerator cavity will be machined to precision, followed by the final brazing processes. During the brazing processes, the separately deposited nickel and chromium layers are annealed, forming the NiCr alloy.

We carefully examined the edge blending where the HOM-damping waveguides meet the accelerator cells, in order to ensure that the pulsed temperature rise on the NiCr coating layer stays low. Please note that because the second round of the machining happens after the deposition of the nickel and chromium layers, during the machining, copper will be exposed to form the curved faces of the fillets. In other words, the edge-blending faces will not be covered by nickel or chromium. In the current design, the pulsed temperature rise on the NiCr coating stays below 20 K, when the accelerating gradient is at 100 MV/m, lasting for a time duration of 1 µs. The applied fillet was asymmetric, and the fillet dimensions were 1.02 mm and 0.75 mm. The copper wall thickness separating the two cells measures 1.5 mm. Therefore, the maximal fillet size allowed between the two cells over that copper wall is 0.75 mm. However, a circular, 0.75-mm fillet is not enough to bring the pulsed temperature rise to below 20 K, which requires that the fillet size towards the inside of the cells should be increased to 1.02 mm.

Theoretically, with a yield strength up to 400 MPa, NiCr is expected to present a cyclic-fatigue damage threshold much higher than that from a pulsed temperature rise of 20 K. However, in our study, we would like to ensure a relatively safe condition for the NiCr coatings, when the desired accelerator operation is achieved.

RF SIMULATION RESULTS

The two-cell accelerator structure designed with HOM-damping waveguides was studied using the CST High Frequency Solver [6]. As mentioned above, the HOM-damping waveguides have a thickness of 0.5 mm and a radial span of 37.0 mm. It is worth noting that additional, unwanted modes can be excited inside the HOM-damping waveguides; those modes are not the higher-order modes of the accelerator cells. Instead, they are exclusively related to the thin, HOM-damping waveguides. Therefore, at the initial stage of the RF design, we varied the radial-span dimension of the HOM-damping waveguide to ensure that the eigenmode-frequency of those parasitic, thin-waveguide-related modes were at least 300 MHz below or above the accelerator operating frequency of 5.712 GHz. Eventually, we decided that the radial span of the HOM-damping waveguide should be 37.0 mm, which meanwhile yielded satisfactory results from the wakefield simulations.

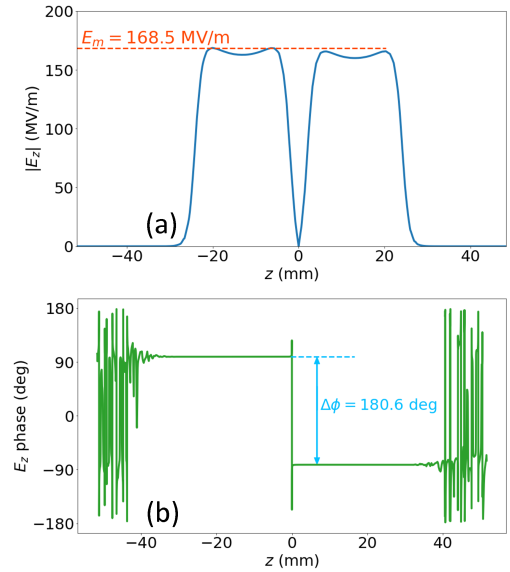

Figure 2: RF simulation results of the on-axis electric field in the two-cell standing-wave accelerator cavity with HOM-damping waveguides, at a gradient of 100 MV/m. (a) equal accelerating field magnitude in the two cells. (b) 180-degree phase difference between the two cells.

In our RF design of the two-cell cavity, critical coupling of the structure at 5.712 GHz was achieved. Meanwhile, the structure showed identical field magnitude in the two cells as well as an RF phase difference of 180 degrees, indicating operation in a π-mode, as indicated in Fig. 2. The contour distributions of the RF electric and magnetic fields are provided in Fig. 3, which show the π-mode operation, when the structure is operating at an accelerating gradient of 100 MV/m.

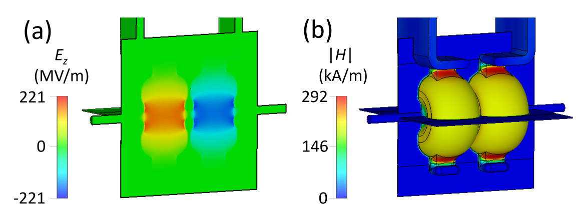

Figure 3: (a) Longitudinal electric field plotted on the cavity longitudinal cross section, and (b) magnetic field magnitude contour on the cavity inner faces, calculated for 100-MV/m accelerating gradient.

We calculated the RF loss in the NiCr coating, when the accelerator cells are operating with the desired TM_{010} mode. According to the CST simulation results, when the NiCr coatings are applied, the unloaded quality factor of the cavity is 13573; when the NiCr coatings are not present, i. e., when the HOM-damping waveguides have entirely copper faces, the unloaded quality factor is 13574. When the two-cell structure operates at 100-MV/m accelerating gradient, the RF power needed is 4.6 MW, in which 0.42 kW is dissipated in the NiCr coatings. We plan to operate the high power test with a RF pulse (1-µs pulse length) repetition rate of

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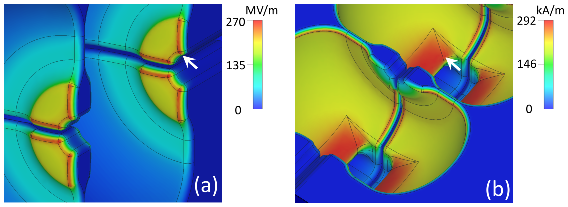

Figure 4: RF simulation results of the (a) electric and (b) magnetic magnitude distributions, when the two-cell accelerator cavity operates at an accelerating gradient of 100 MV/m. Peak-field locations are marked with arrows.

100 Hz, and the time-average RF power dissipation in the NiCr coatings is 42 mW. Therefore, NiCr causes minimal concern for the nominal operation of the accelerator cavity.

The electric and magnetic field peak values and locations are indicated in Fig. 4, assuming an accelerating gradient of 100 MV/m. In Fig. 4(a), the peak electric field is found along the blended edges on the re-entrant features. In Fig. 4(b), the peak magnetic field is found on the fillets at the RF coupling ports and at the symmetry stubs.

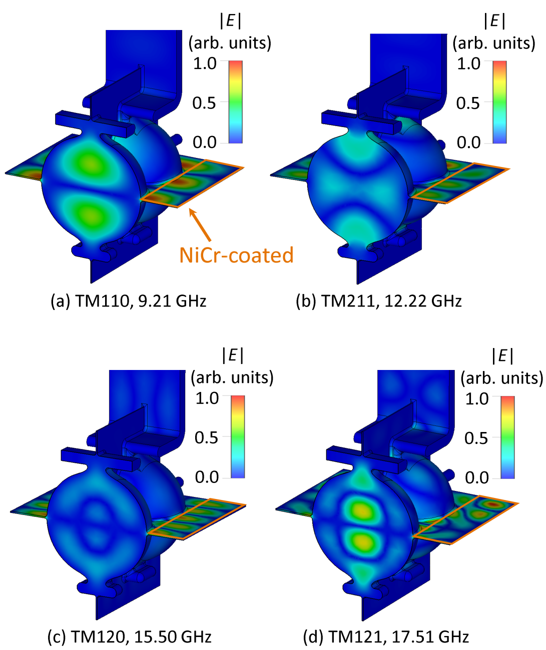

Figure 5: Qualitative, normalized presentation of the HOM electric field magnitude inside the two-cell accelerator cavity, demonstrating the HOM dissipation by the NiCr coatings. (a) TM_{110} mode at 9.21 GHz; (b) TM_{211} mode at 12.22 GHz; c) TM_{120} mode at 15.50 GHz; (d) TM_{121} mode at 17.51 GHz.

In the accelerator cavity, when operating at a gradient of 100 MV/m, with 1-µs RF pulses at a 100-Hz repetition rate, the peak temperature rise in copper is 26 K, the location of which is indicated by the arrow in Fig. 4(b). The peak temperature rise in NiCr is found on the boundary of the coatings, towards the accelerator cells. Along the NiCr-copper boundary, the pulsed temperature rise in NiCr is found in the range of 0.02 to 20 K.

Lastly, Fig. 5 provides a qualitative illustration of the expected penetration of the HOM electric fields inside the HOM-damping waveguides. The CST eigenmode simulation results are provided. The transverse cross section of one cell is shown, for identifying the HOM. The HOM magnetic field sufficiently interacts with the NiCr inside the HOM-damping waveguides, and the HOM is thus damped.

The two-cell accelerator cavity designed with HOM-damping waveguides is currently under fabrication, and will be tested under high power at the CERF-NM facility. The high power test will be an RF test, without involving an electron beam. When the cavity is in normal operation, there will be no HOM excited; when breakdowns occur, during the intense power release, a portion of the power may take the form of the higher-order modes, which will penetrate into the HOM-damping waveguides and interact with the NiCr layers. We will perform post-mortem examination to study the influence of RF breakdowns on the NiCr layers.

CONCLUSION

A two-cell standing-wave accelerator structure was designed at 5.712 GHz for studying the use of the nickel-chromium (NiCr) coatings inside the thin waveguides for damping the higher-order modes (HOM). The structure is currently in fabrication and will be tested for the high-gradient performance.

The radiofrequency (RF) simulation results showed that the accelerator cavity operates with critical coupling at 5.712 GHz in a π-mode, with equal field magnitudes established in the two separate cells. The simulations predict minimal additional RF loss caused by the NiCr coatings when the accelerator operates in the fundamental mode, and the pulsed heating in NiCr was also minimized.

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[6] CST Studio Suite, `http://www.3ds.com/products/simulia/cst-studio-suite`