

DAMPING HIGHER ORDER MODES FOR THE COOL COPPER COLLIDER

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Abstract

For next generation particle collider designs, such as the Cool Copper Collider, small beam sizes, short bunch spacing, and beam stability are required to reach the luminosities desired to search for new physics. One challenge to overcome is suppressing the long-range wakefields from higher order modes inside accelerating cavities. Multiple bunches are required to meet the target luminosity, but these wakefields deflect neighboring bunches and lead to emittance growth, hence they must be suppressed to preserve the beam quality. The solution is the addition of damping slots on the accelerator cavities that can couple to these higher order modes and suppress them in the central part of the cavity that the beam passes through to reduce the kick factor of the mode. Additionally, these damping slots can lower the Q value for these modes, causing the excitation to die out between bunches because the mode cannot resonate in the cavity for as long. In this study, we optimize the damping slot geometry to remove higher order modes from the accelerating cavity while preserving the fundamental accelerating mode.

INTRODUCTION

Accelerating cavities can be represented as microwave resonators, which have infinite eigenvalue solutions. The fundamental mode, TM_{010} , acts as the accelerating mode, with an axially symmetric longitudinal electric field along the beam axis and azimuthal magnetic field around the axis. The higher order modes (HOMs) can interact with the beam and have accelerating modes off axis as shown in Fig. 1 that deflect the beam non-uniformly, leading to an increase in beam emittance.

To optimize the radiofrequency (RF) accelerating cavity design for the Cool Copper Collider (C3) [1], careful attention must be paid to retaining the accelerating mode and suppressing the HOMs that spoil beam emittance. The figures of merit for this optimization are the kick factor and Q, which must be minimized for each HOM.

The kick factor is a measure of how much deflecting field the beam experiences for a given small offset from the beam axis along the length of the cavity, normalized to the beam charge. In other words, how much will the beam be deflected or ‘kicked’ in the cavity?

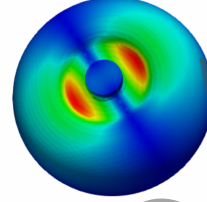


Figure 1: The accelerating cavity without slots as created in Cubit and rendered in Paraview. The second order/dipole mode is shown. Note that the mesh does not need to be very fine for this geometry because there are not any small features and the geometry is simple.

This transverse kick factor (K_n) can be calculated for the n^{th} mode, where $\omega_n/2\pi$ is the frequency of the mode,

$$K_n = \frac{\left| \int_L E_z \exp(j\omega_n s/c) dz \right|^2}{4 \frac{\omega_n a_n^2}{c} U_n L \left(1 - \frac{v_{gn}}{c}\right)}. \quad (1)$$

Here a_n is the radius of the iris, L the cavity length, E_z is the on-axis electric field, and U_n is the energy stored in the cavity [2]. There is also a dependence on group velocity v_{gn} to correct for the temporal overlap between the mode and the beam, but for cells with π phase advance, as is the case here, this correction can be neglected.

Alternatively, the kick factor can be thought of as the overlap between the wakefield in the cavity W and the bunch distribution $\lambda(s)$ integrated over the length of the cavity

$$k_{\perp} = \langle W \rangle = \int_L W(s) \lambda(s) ds \quad (2)$$

for each mode [3].

The other important factor is the quality factor (Q), which determines how long the mode is excited in the cavity. If the mode has a small Q and resonates for a short time, it will be gone before the next bunch is seen. High Q modes will still be in the cavity by the time of the next bunch crossing. Because the structure is cold copper, the walls have low losses and the cavity has large Q factors.

METHODS

In this work, we optimize over the length and width of the damping slots. The slot width, as shown in Fig. 2, is varied from 150 μm to 300 μm and tapers down to a width of 100 μm . The slot length is capped at the cavity radius length due to machining and material constraints.

The final design has a taper down to $\sim 100 \mu\text{m}$ (a reduction of 7 μm on each slot wall is considered for the addition of lossy Nickel-Chromium (NiCr) on the damping slot walls).

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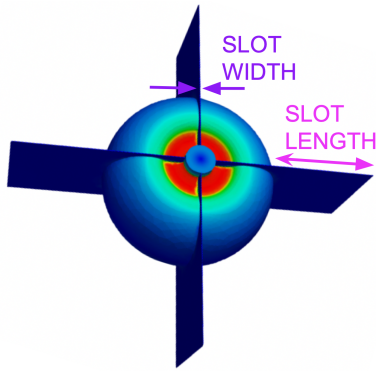


Figure 2: The cavity created in Cubit with damping slots is shown rendered in Paraview with the fundamental mode. This fundamental accelerating mode is preserved for all slot designs presented here. For scale, the radius of the cavity iris is 3.55 mm.

This 100 μm taper width is required for machining and brazing purposes to prevent the slots from filling with braze material during assembly of the final structure. The slot design with the accelerating mode is shown in Fig. 2.

Because this is a large parameter space, given the range in slot widths and the theoretically infinite number of modes, we limit ourselves to modes that are found to have the most influence on beam dynamics. Previous beam dynamics studies using ELEGANT [4] and 100 Monte Carlo samples with random beam offsets considered different frequency bands at a time and found emittance growth from the modes at 9.27 GHz, 12.35 GHz, 15.78 GHz, 17.47 GHz, 24.11 GHz, and 34 GHz [5]. In particular, the 17.47 GHz and 24.11 GHz frequencies caused the bunch train (133 bunches) to oscillate at sub-harmonics. These are the six frequency bands that we consider in this optimization in order to narrow the parameter space.

In the previous work, a single design of a damping slot was shown to suppress emittance growth from these modes by a factor of 100 [5]. However the exact design of the previous study is no longer optimal because it used a cavity design with lower shunt impedance and included 2 taper sections along the slot and an overall slot length that is no longer feasible due to machining and material constraints. However, this huge improvement signals the importance of slot optimization for beam performance with the new high shunt impedance cavity design. Here we target a combined kick factor $\times Q$ of $\leq 10^4 \text{ V/pC/mm/m}$ for all HOMs.

ANSYS HFSS

ANSYS HFSS (High Frequency Structure Simulator) is a commercial 3D electromagnetic simulation software that uses the finite element method to solve Maxwell's equations for high-frequency electromagnetic problems. The eigenmode solver in HFSS specifically finds the natural resonant modes of electromagnetic cavities and structures by solving an eigenvalue problem derived from Maxwell's equations [6]. Rather than sweeping through frequencies, the solver directly computes the eigenfrequencies (resonant fre-

quencies) and corresponding eigenmodes (electromagnetic field patterns) of the structure. For each mode, it calculates important parameters, including the quality factor (Q) and detailed electric and magnetic field distributions throughout the cavity.

Within HFSS, integrated fields and stored energy can be calculated to compute the kick factor of each mode, following Eq. (1).

Because each mode takes a finite amount of time to solve and there was a large initial parameter space, for most geometries only the eigenmodes in the targeted frequency bands were solved. A bandwidth of 0.8 GHz was analyzed around each bad frequency. For each mode kick factor and Q were computed using HFSS's calculator tool.

Advanced Computational Electromagnetics Code Suite

ACE3P (Advanced Computational Electromagnetics Code Suite) [7] is a set of parallel finite-element codes developed at SLAC for high-accuracy multiphysics modeling of accelerator RF components. The mesh and geometry creation is done using Cubit [8]. In particular, in this work, we take advantage of OMEGA3P, the eigenvalue solver. Post-processing can be done to extract kickfactor and wall-loss Q and visualization is done in Paraview [9].

For ease of optimization, LUME-ACE3P [10] is employed to optimize the kick factor reduction for each mode of interest. Rather than create a new geometry and calculate the kick factor manually for each mode and cavity design, LUME-ACE3P takes the Cubit geometry file, OMEGA3P eigenvalue solver instructions, parameters to sweep over, and postprocessing parameters of interest, and will run the optimization. Optimizing the geometry in both HFSS and ACE3P also provides additional verification of the solution and convergence of the two solvers.

Simulation Parameters

For both the ACE3P and HFSS analysis, a curved slot rather than a linear slot was initially considered, but was considerably harder to mesh and more computationally expensive, so only linearly tapered damping slots were investigated.

In both simulations periodic boundary conditions are applied at the irises and edges of the slots in order to simulate the 40 cell structure that will be fabricated. The cavity walls are cold copper and the slots are coated in NiCr, which is a much lower conductivity to absorb the higher order modes.

RESULTS

In HFSS and ACE3P, the optimal slot design is found to be a 300 μm width and 21 mm length. The reduction in $Q \times \text{kick factor}$ from HFSS is shown in Fig. 3 and ACE3P optimization results are shown in Figs. 4 and 5. A reduction in $Q \times \text{kick factor}$ of ~ 3 orders of magnitude is found in the bands of interest.

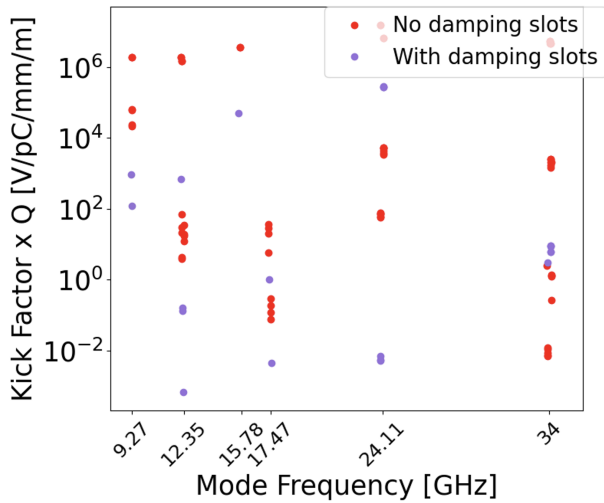


Figure 3: The HFSS design with no damping slots is shown in red and compared to a design with a damping slot width of 300 μm in purple only for the frequencies of interest. The damping slot design shown here is for a 300 μm slot width and 21 mm slot length. Similar plots were made for other slot designs, and the 300 μm slot width and 21 mm slot length had the greatest overall reduction in $Q \times$ kick factor.

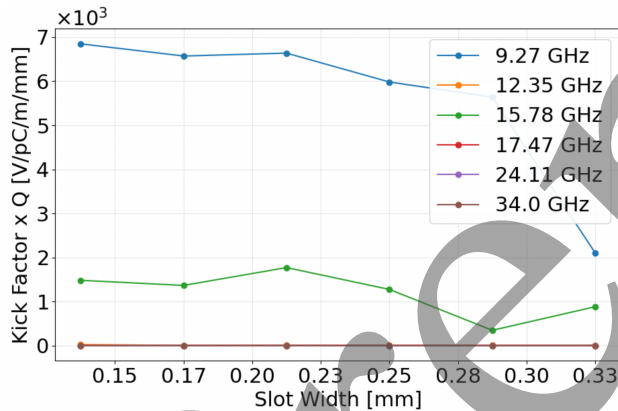


Figure 4: The ACE3P damping slot width was varied using LUME-ACE3P for a variety of frequency modes. $Q \times$ kick factor for each mode is many orders of magnitude below the geometry with no slots ($\sim 10^6$). The optimal design has the widest damping slots of 300 μm .

It is unclear why the kickfactor values are higher in the HFSS solutions compared to the ACE3P solutions. However, both simulations converge on the maximum slot length and width performing best at removing higher order modes. The final design is chosen to be the maximum slot width (300 μm) and length (21 mm), shown in Fig. 6.

CONCLUSION

Higher order modes and their impact on beam performance can be mitigated with the inclusion of damping slots in the accelerating cavity design. Further reduction of wakes

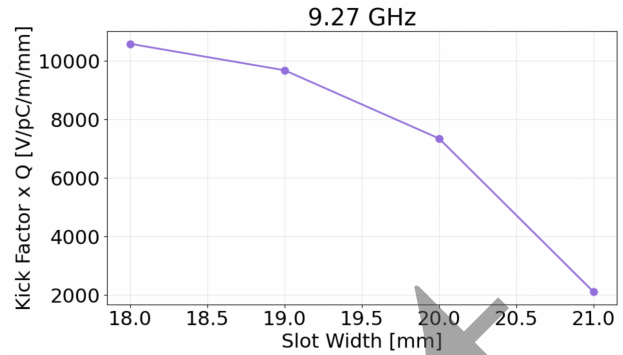


Figure 5: The slot length is varied for the dipole mode using LUME-ACE3P. Longer slots are more effective. The damping is maximized with large slot lengths, so the maximum length of ~ 21 mm is chosen.

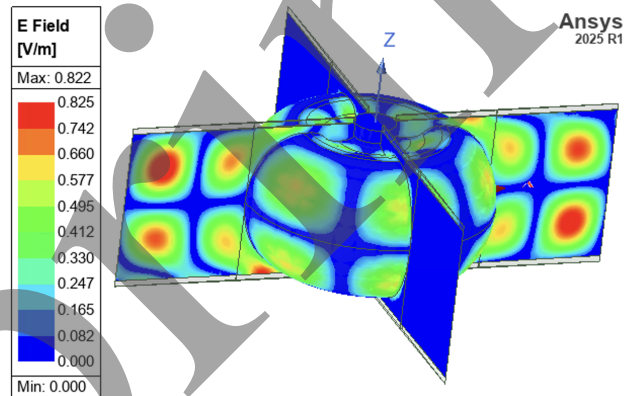


Figure 6: An example of the damping slots absorbing the higher order modes rendered using Ansys HFSS. The peak electric field is in the slots rather than along the beam axis.

can be achieved by detuning. This particular design was optimized using ACE3P and HFSS to have a 300 μm slot width and 21 mm slot length. This cavity design will be used in the proposed Cool Copper Collider and the upcoming European Synchrotron Radiation Facility injector upgrade.

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