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RECENT PROGRESSES REGARDING ENCLOSED RF CAVITIES FOR FUTURE MUON COLLIDER COOLING CHANNEL

D. Merenich, X. Lu[1,*], Northern Illinois University, Dekalb, IL, USA
T. Luo[†], Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[1]also at Argonne National Laboratory, Lemont, IL, USA

Abstract

The muon collider (MuC) holds strong potential for reaching the 10 TeV energy frontier while introduces several technical challenges. Ionization cooling is essential to reduce beam emittance and achieve required luminosities. In this cooling process, as muons lose energy in absorbers, normal-conducting RF cavities restore it. However, strong magnetic fields—needed for beam focusing—increase the risk of RF cavity breakdowns. Thin beam windows are used to reduce breakdown probability and improve shunt impedance. In this paper, we present some recent studies on these cavities, including: 1) evaluating emittance growth due to particle scattering in the beam windows made of Be and Al by GEANT4, 2) calculating the beam loading effect in the presence of the beam windows with CST wakeifeld solver and Particle-In-Cell solver, 3) deriving the breakdown thresholds for different cavity materials in strong B fields based on a thermal-mechanical model.

INTRODUCTION

Collisions at a parton center-of-mass energy of 10 TeV promise both profound insights into the fundamental constituents of matter and technological advances, as highlighted by the Particle Physics Project Prioritization Panel [1]. To reach this energy, several colliders have been proposed, such as linear e^+e^- machines using wakefield techniques, or large-scale circular proton–proton colliders. A circular muon collider presents unique advantages. The muon's greater mass dramatically reduces synchrotron radiative losses compared to electrons, and—being an elementary particle—its collisions directly utilize the full center-of-mass energy compared to proton.

Although a muon collider's promise is high, it comes with its own set of technical challenges. Muons are created as offspring particles from a proton beam incident upon a target material, resulting in a large initial phase space that is not conducive to a high-luminosity collider. An ionization cooling method is adopted to reduce the muon beam emittance by 10^6 order with in the short muon lifetime. In this cooling process, RF cavities are needed to recover the longitudinal momentum lost in the absorbers. The surrounding large external magnetic fields have been shown to increase breakdown rates [2–4], which is a major challenge for such cavities. A thin, low-Z window is used to enclose the cavity to increase the shunt impedance and relieve the breakdown rates. These windows also cause scattering to the incident beam. In this work, the emittance dilution caused by scattering for Aluminum (Al) and Beryllium (Be) windows is presented. The effect of beam loading, which is crucial for the large bunch charge of the muon beam, is also investigated for the closed-window geometry. Lastly, the effects of breakdown enhanced by large magnetic fields are discussed for various window materials.

* xylu@niu.edu
† tluo@lbl.gov

EMITTANCE DILUTION DUE TO THIN BEAM WINDOWS

The thin, low-Z windows minimize muon loss and scattering but must be thick enough to resist thermo-mechanical deformation. Previous studies considered Be windows; however, handling and machinability issues have motivated exploring alternative materials. One possible choice is Al due to conductive properties similar to Be. Our GEANT4 simulations compared Al and Be windows [5], utilizing the FTFP_BERT package and Gaussian particle distributions. The window configurations are based on the latest 6D rectilinear cooling lattice design [6], which includes 4 pre-merging stages (A1-A4) and 10 post-merging stages (B1-B10). Space charge and external field effects, unrelated to scattering mechanisms, were neglected. Figure 1 shows relative normalized emittance changes for the first (A1) and last (B10) stages. Emittance dilution increases with thickness, remaining negligible until stage B6 due to large initial emittance. At later stages with significant cooling, dilution grows substantially. While single-window changes are small, cumulative effects across hundreds of multi-cell cavities could

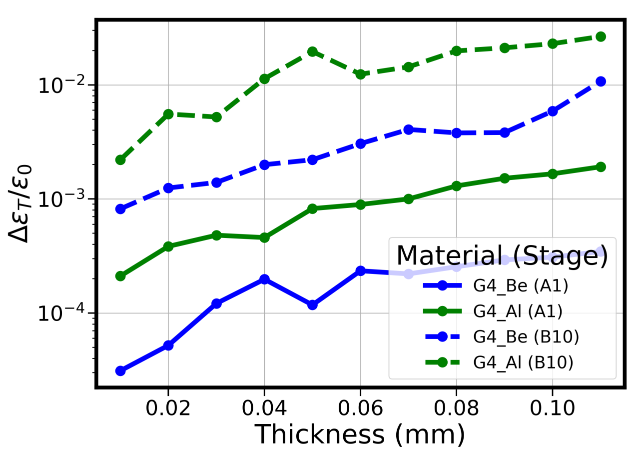

Figure 1: Relative emittance changes for Stages A1 and B10 in the muon collider cooling lattice.

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be significant. Achieving comparable dilution requires Al window thicknesses *1/4* those of Be.

BEAM LOADING IN AN ENCLOSED PILLBOX CAVITY

A charged particle beam traversing an accelerating structure excites fields of its own that can interact back on the beam. The wake potential of a beam,

$$W_z = \frac{1}{q_{source}} \int_{-\infty}^{\infty} dz [E_Z(\mathbf{r}, z, t)]_{t=(s+z)/\beta c}, \quad (1)$$

is used to describe the average voltage seen for a given distance from the center of the bunch. Because of the superposition of source fields, the wake potential can be taken as the sum of structure and space charge wakes, $W_z = W_{sc} + W_{struct}$. For conventional structures with beam pipes, CST Particle Studio's Wakefield Solver [7] can be used to resolve the Wakefield effects of a beam. This solver cannot compile when the beam passes through a conducting material, requiring special attention for the wakefields seen in the muon collider cavities. A small pipe insertion into the closed pillbox geometry is also insufficient, as indicated by Fig. 2, which shows the structure wake using the Wakefield solver. The pipe radius has an impact on the final wakefields, especially in the short-range.

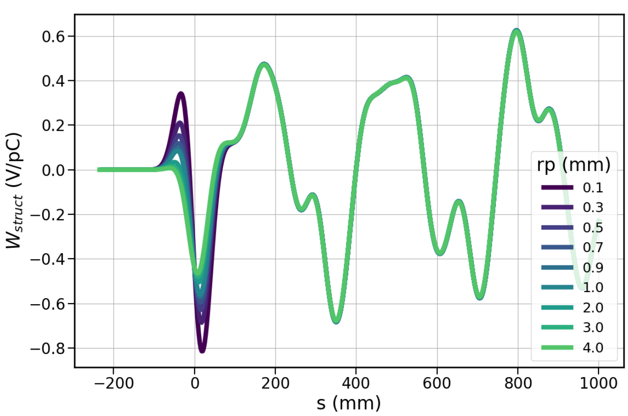

Figure 2: Structure wake potential for a smooth pillbox with varying beam pipe radii r_p.

To overcome these limitations, the CST Particle-in-Cell (PIC) solver was used to resolve the electric fields excited by an incident particle beam and a post-processing method was carried out in Python to resolve the wakefields of the beam. Figure 3 shows the comparison of wakefields for a smooth conducting pipe (i.e., the space charge wake). It is observed that the post-processing method agrees perfectly with CST wakefield solver if the bunch length excitation is below the cutoff of the fundamental pipe mode. Above this mode, reflections from the longitudinal boundaries occur.

To resolve the structure wakefields of the enclosed cavity, a pillbox cavity was placed in a vacuum structure, with a smooth pipe extension with a fundamental mode outside

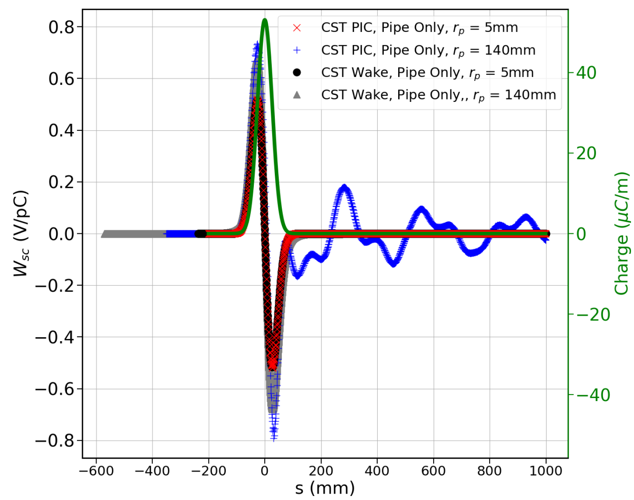

Figure 3: Comparison of CST wakefield solver wakefields to the CST PIC w/ post-processing method for a smooth pipe of different radii.

the bandwidth of the 26.3 mm σ bunch. Three separate simulations are used to simulate the particle as it enters the cavity, exists in the cavity, and exits the cavity, as indicated in Fig. 4. Integration of the wake function excludes the fields in the pipe sections.

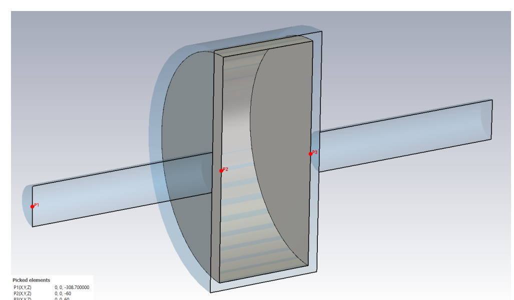

Figure 4: CST PIC solver setup for an enclosed pillbox in a vacuum chamber. The red dots indicate the beginning, entry, and exit points of the particle beam.

Figure 5 presents post-processed wakefields for a rigid 1D beam and a rigid 3D beam with a uniform 25 mm transverse radius, plotted in V/pC. For µC-level muon beams, this corresponds to wake voltages of several MV. Although the finite transverse size slightly suppresses short-range wakes, beamloading effects remain substantial. The corresponding mitigation method and the effects on the beam dynamics will be explored next.

THERMALLY INDUCED RF BREAKDOWN IN LARGE B-FIELDS

Field-emitted electrons can focus onto nearby walls under strong magnetic fields, enhancing local temperature increases [3]:

$$\Delta T = \int_0^{\tau} \int_0^{R_f} \int_0^{D} G_{rz} W(r', z', t') 2\pi r' dr' dz' dt', \quad (2)$$

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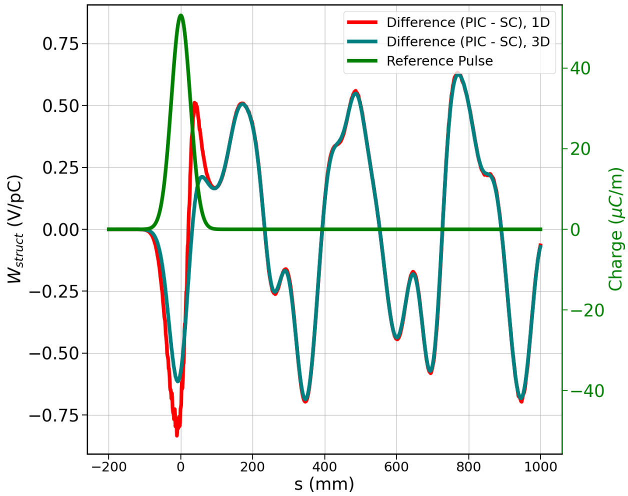

Figure 5: Resulting structure wakefields for a 1D and 3D beam, using the PIC w/ post-processing, for the geometry in Fig. 4.

where G_{rz} is the Green's function solution to the heat conduction equation with incident heat per volume, W. Integration limits τ, R_f, and D represent the RF pulse duration, focused electron beamlet radius, and electron penetration depth, respectively. Temperature rises exceeding the plastic deformation threshold can trigger breakdown. Previous studies examined breakdown gradients in magnetic fields for Cu, Al, and Be [2–4, 8]. Recent experiments highlighted improved breakdown resilience for Cu at 77 K (Cold Cu) compared to room temperature copper. Estimated safe-operating-gradients (SOG) for Cu, Al, Be, and Cold Cu as a function of magnetic field are shown in Fig. 6. At lower fields, Al and Be outperform Cold Cu due to higher temperature thresholds. However, stronger fields decrease electron spot size, increasing power density, and the combination of the reduced field-emitted current and increased thermal diffusivity, α_d, enhances its resilience. The plateauing effect of safe operating gradients occurs as the magnetic field increases and space charge limits the decrease of the beam spot size, yielding a similar OG, at higher B-fields.

The effect of pulse length reduction is also assessed and shown in Fig. 7. The diffusion length of the material, $\sqrt{\alpha_d \tau}$, decreases with the pulse length. At higher magnetic fields, the beamlet radius decreases, and as the diffusion length of the material grows beyond the beam spot size, the temperature gradient diffuses more efficiently. Thus, the temperature rise saturates before the end of the pulse length, limiting the SOG.

CONCLUSION

Investigated here are scattering effects, beamloading, and thermally induced breakdown for cavities in the future muon collider cooling channel. It is shown that changing the thin-windows from Be to Al is feasible from a scattering perspective if the Al windows are *1/4* the thickness of the Be. It is also shown that emittance dilution is less significant at early

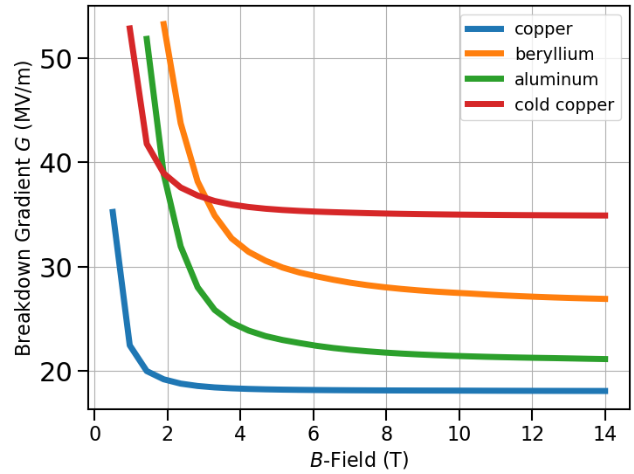

Figure 6: Breakdown gradient as a function of external magnetic fields for various materials.

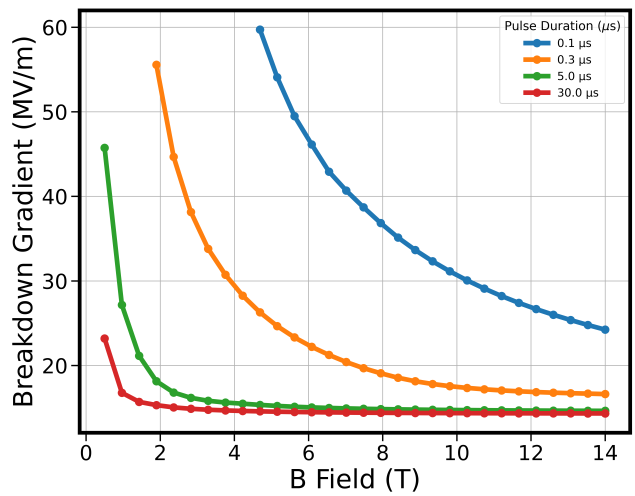

Figure 7: Breakdown gradient as a function of external B-fields for various pulse lengths for room temperature Cu.

stages of the cooling lattice. The effects of beamloading were studied using CST's PIC solver with a post-processing wakefield algorithm. The algorithm was validated, with limitations of bunch length, for simple geometries. The resolved Wake potentials for the muon collider beams indicate wake voltages up to a few MV, which is quite substantial compared to the anticipated gradient requirements. Lastly, we show the enhancements in breakdown resilience when considering copper at 77 K or operation at shorter RF pulse lengths.

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