

Breakdown Analysis and Wakefield Simulation for RF Cavities in the Muon Collider Ionization Cooling Channel

Dillon Merenich

Northern Illinois University

July 24, 2026

Coauthors and collaborators

- **C. Barbagallo** and **A. Grudiev**
CERN
- **T. Harless**
Northern Illinois University
- **X. Lu**
Northern Illinois University and Argonne
National Laboratory
- **T. Luo**
Lawrence Berkeley National Laboratory

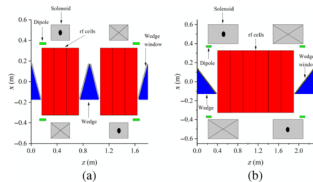
Additional Thanks

- DOE SCGSR program under Contract No. DE-SC0014664
- DOE Contract No. DE-AC02-05CH11231
- DOE Awards No. DE-SC0021928 and No. DE-SC0022010
- International Muon Collider Collaboration for fostering this collaboration
- Thanks to **J. Qiang**, **O. Ramachandran**, **M. Shapiro**, and **G. Rijal** for helpful discussions concerning space-charge effects, particle tracking and code development, and high-field cavity and material-response modeling.

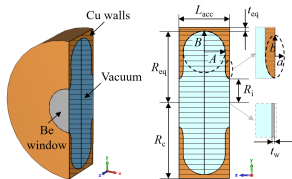
Overview

- 1 Muon Collider Cooling Channel
- 2 Wakefield Simulations of a Bunch with Transverse Extent
- 3 Modeling Breakdown in Strong Magnetic Fields
- 4 Conclusion

Overview of the Proposed Rectilinear Cooling Channel



Staged rectilinear cooling channel



Enclosed, windowed RF cavity

Operating context and simulation challenge

- Normal-conducting RF cavities restore p_z lost in absorbers during ionization cooling.
- The pre- and post-merge stages use cavities operating at **352 or 704 MHz**, with nominal gradients of between **21.2–31.7 MV/m**.
- There are strong, spatially varying solenoidal fields, up to 15 T in a cell.
- Beam size and charge evolve throughout the channel.
- Thin windows close the beam apertures while preserving favorable RF performance.

Cooling-channel parameters adapted from R. Zhu et al., *Phys. Rev. Accel. Beams* 28, 041003 (2025).

Focus of This Talk

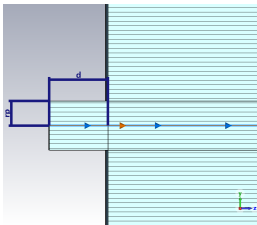
Wakefields

- How can the wake be reconstructed in a windowed, enclosed cavity?
- How does finite transverse bunch size change the balance between cavity modes and direct space charge?

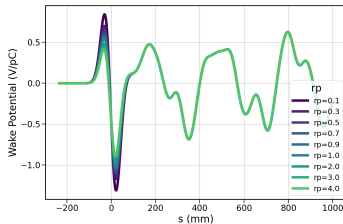
Breakdown

- Do realistic RF and lattice fields preserve localized electron bombardment?
- How do material properties affect the thermomechanical operating limit?

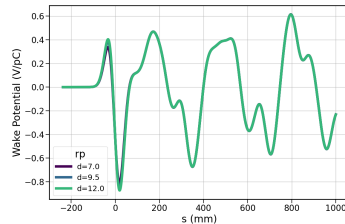
Limitations of the CST Wakefield Solver



Artificial beam-pipe geometry



Pipe-radius sweep



Pipe-extension sweep

Takeaways

- CST requires beam path $\rightarrow$ closing the pipe with a metallic face works only with zero-thickness
- Adding pipe $\rightarrow$ geometry-independent result
- Source is a line-charge $\rightarrow$ misrepresents large beam waist for μCol

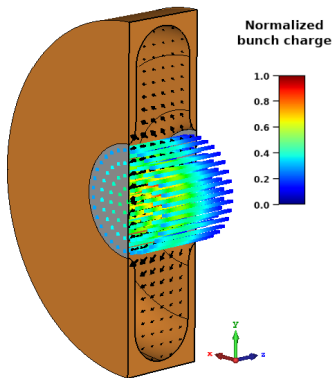
PIC-Based Wake Reconstruction



- The windows remain electromagnetic boundaries but are transparent to the numerical source particles.
- Exported fields are integrated along co-moving test-particle trajectories.

Reconstructed wake

$$W_z(s) = -\frac{1}{Q} \int E_z \left(z, t = \frac{z+s}{\beta c} \right) dz$$



Finite Transverse Extent and Wake Decomposition

Finite transverse form factor

$$F_{n,\perp}(\sigma_t) = \int_0^{R_i} 2\pi r_s \rho_r(r_s) \times \sqrt{(R/Q)_n(r_s)} dr_s.$$

Eigenmode wake reconstruction

$$W_{z,\text{eig}}^0(t) = H(t) \sum_n \frac{\omega_n}{2} (R/Q)_n e^{-t/\tau_n} \cos(\omega_n t),$$

with

$$\tau_n = \frac{2Q_{L,n}}{\omega_n}.$$

$$W_{z,\text{eig}}(t, \sigma_t) = \frac{1}{Q_b} \int_{-\infty}^t F_{n,\perp}(\sigma_t) W_{z,\text{eig}}^0(t - t') \lambda(t') dt'.$$

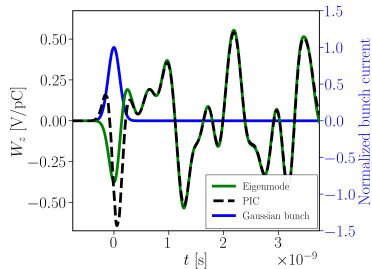
Complete longitudinal wake

$$W_z(t) = \underbrace{W_{z,\text{FM}}(t) + W_{z,\text{HOMs}}(t)}_{W_{z,\text{eig}}(t)} + W_{z,\text{SC}}(t)$$

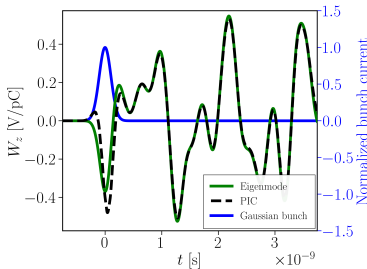
$$W_{z,\text{SC}} = W_{z,\text{ISC}} + W_{z,\text{DSC}}$$

Methods developed at CERN by A. Grudiev and C. Barbagallo

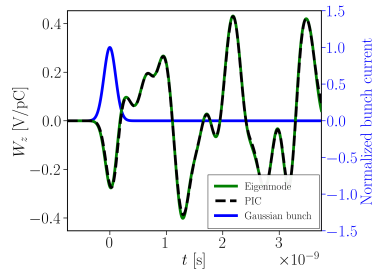
PIC Reconstruction Compared with the Eigenmode Model



Small beam radius
 $\sigma_r = 0.1 \text{ mm}$



Intermediate beam radius
 $\sigma_r = 5.44 \text{ mm}$



Large beam radius
 $\sigma_r = 40 \text{ mm}$

Conclusion

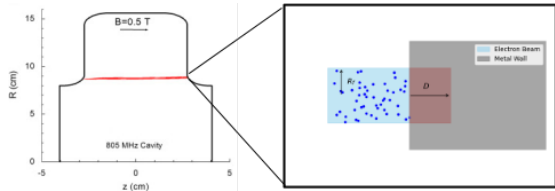
Fixed bunch charge, reducing radius substantially strengthens the space-charge wake $\Rightarrow$ the beam becomes more tightly cooled in the later stages of the channel, space-charge contributions may become non-negligible and should be included, particularly for beams with $\beta \simeq 0.9$.

Temperature-Dependent Breakdown Model in a Magnetic Field

- Local enhancement of the accelerating gradient G produces a surface field $\beta_{FE} G$.
- The magnetic field focuses the emitted current into electron beamlets.
- During the RF pulse, a beamlet of radius R_f deposits energy over a penetration depth D .
- This work: models real field distributions and performs a material property trade study**

Fowler–Nordheim current density

$$j_{FN} = 6.0 \times 10^{-12} \frac{(\beta_{FE} G)^{2.5}}{\phi^{1.75}} 10^{4.52\phi^{-0.5}} \exp \left[-\frac{6.53 \times 10^9 \phi^{1.5}}{\beta_{FE} G} \right]$$



Heat conduction

$$\left(\nabla^2 - \frac{1}{\alpha_d} \frac{\partial}{\partial t} \right) T + \frac{W}{\kappa} = 0$$

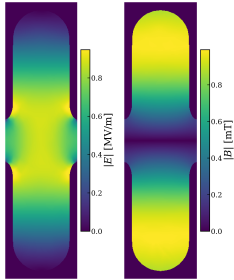
Temperature rise

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

Damage threshold

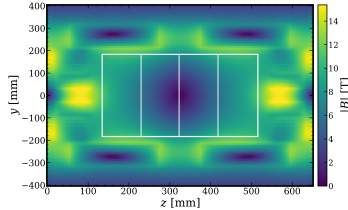
$$\Delta T_s = \frac{(1 - \nu)\sigma_t}{E\alpha_{th}}$$

Dark Current Tracking Simulations with RF-Track



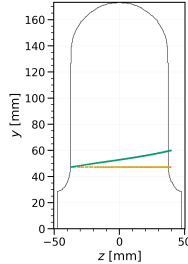
Stage-B8 cavity fields

Electric- and magnetic-field magnitudes



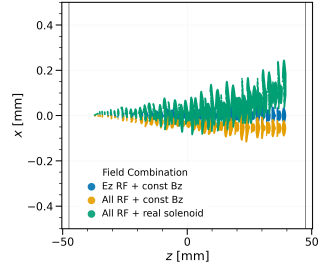
Lattice magnetic field

Maximum longitudinal field: ~ 15.8 T



Electron trajectory comparison

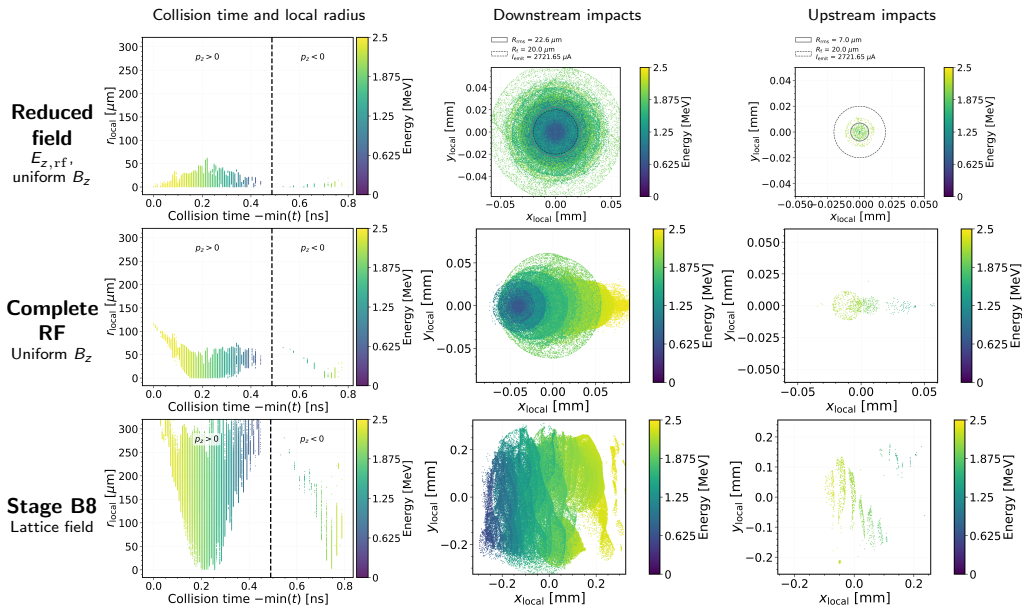
Reduced fields, complete RF fields, and realistic lattice fields



Tracking results

- Three field models isolate the effects of transverse RF and lattice fields.
- Transverse RF fields shift the electron trajectories and impact locations.
- The realistic lattice field broadens the distribution, but impacts remain localized.
- Particle source sampled based on β_{FE} from FN

Localized Impacts



Relevance of Thermal Loading

- ① Tracking simulations show that the non-uniform fields create complex bombardment profiles in space and time
- ② The localization of the bombardments indicate that thermal loading from bombardment is still relevant with transverse field components and fringing fields

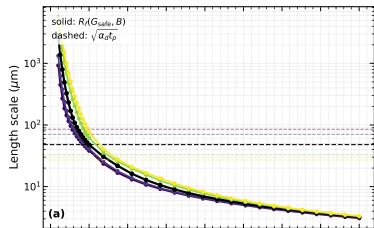
Temperature rise

$$\Delta T(r, z, \tau) = \int_0^\tau \int_0^{R_f} \int_0^D G_{rz} \left(r, z; r', z'; \tau - t'; \alpha_d = \frac{\kappa}{\rho C_p} \right) W(r', z', t') 2\pi r' dz' dr' dt'$$

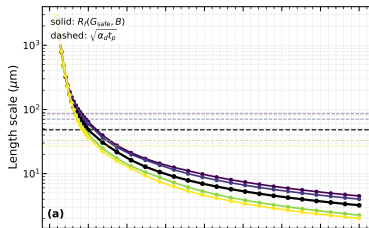
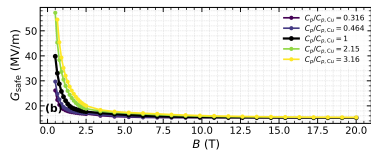
Thermal diffusivity, $\alpha_d = \kappa/(\rho C_p)$, balances spatial spreading of heat and atomic reaction to power density deposit W .

Next we sweep C_p , κ , and ρ to assess what materials could help mitigate bombardment induced damage

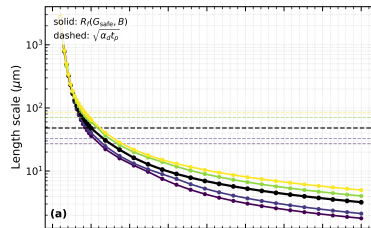
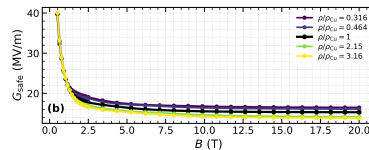
Material-Property Sensitivity



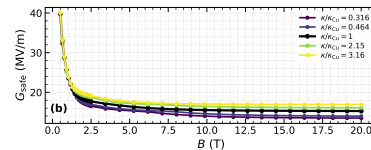
Heat capacity, C_p



Density, ρ



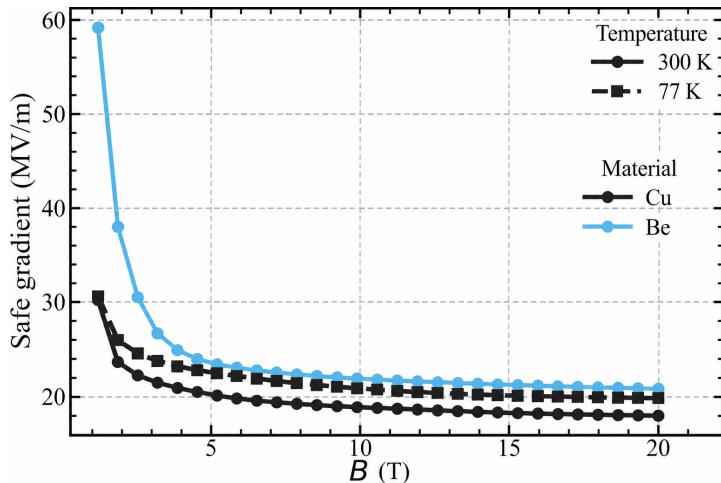
Thermal conductivity, κ



Conclusion

No single property controls the response: ρC_p governs local energy storage, while κ becomes increasingly important as magnetic focusing reduces the impact radius.

Copper and Beryllium Comparison

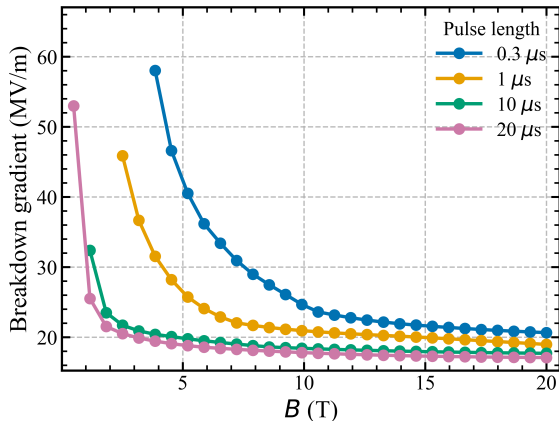


Interpretation

- Cu at 300 K provides the room-temperature reference.
- Be benefits from its high thermomechanical threshold and low energy deposit.
- At high magnetic field, Cu at 77 K benefits from enhanced thermal diffusivity

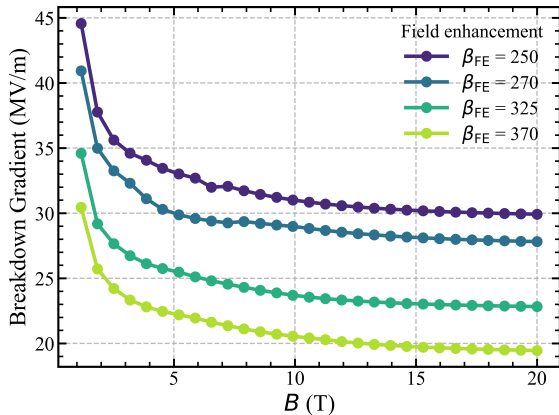
Source: NIST Cryogenic Material Properties Database, Beryllium and OFHC copper data, trc.nist.gov/cryogenics/materials (accessed July 2026).

Sensitivity to RF Pulse and Field Enhancement



RF pulse length

Shorter pulses reduce accumulated heating.



Field-enhancement factor

Lower β_{FE} strongly suppresses field emission. can be associated with cryogenic operation or hardened materials

Conclusions

Wakefield studies

- PIC field exports reconstruct the wake while preserving the closed-window boundaries.
- The projected eigenmode model reproduces the geometric cavity wake.
- At fixed charge, direct space charge grows substantially as the beam radius decreases.
- Later cooling stages therefore require explicit space-charge contributions.

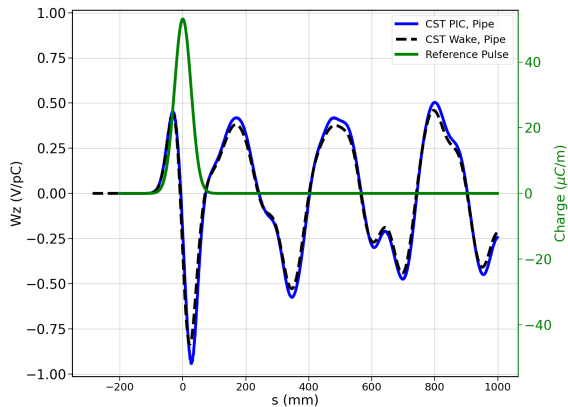
Breakdown studies

- Realistic RF and lattice fields shift and broaden impacts, but bombardment remains localized.
- At high magnetic field, a high diffusivity could be beneficial over strengthened materials.
- Shorter RF pulses reduce heating, although their relative benefit decreases at high field.
- Surface condition through β_{FE} may rival bulk-material effects and requires experimental validation.

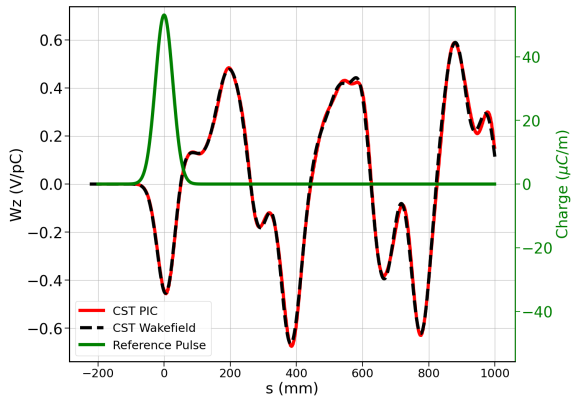
Questions?

Dillon Merenich
Northern Illinois University

Backup: PIC Wake Reconstruction Validation

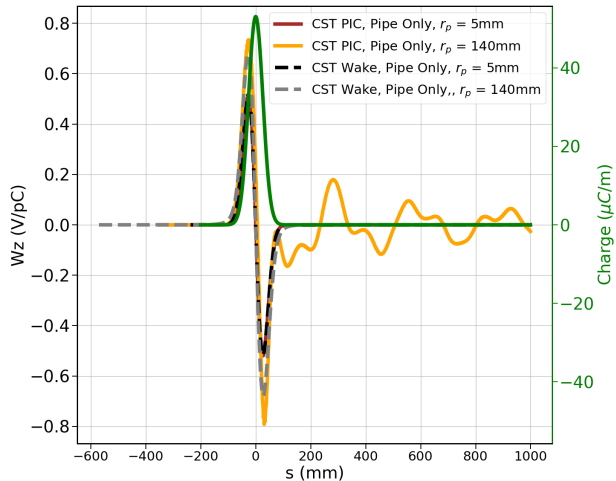


Subrelativistic source: $\beta = 0.9$

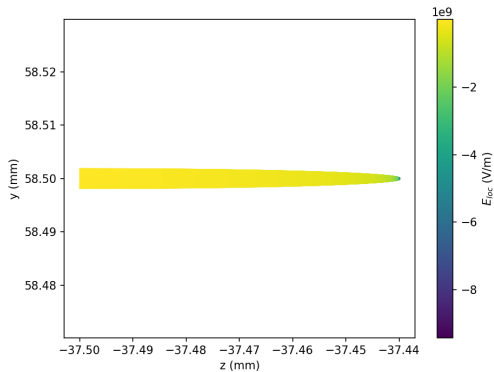


Ultrarelativistic source: $\beta = 1$

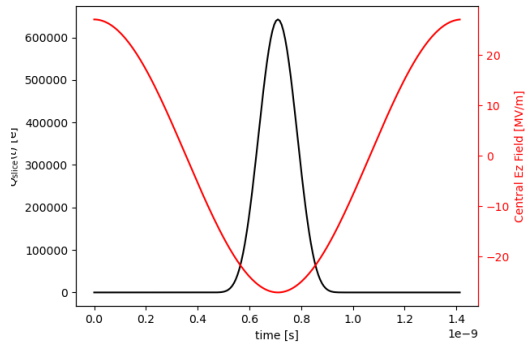
Backup: Independent Direct-Space-Charge Cross-Check



Backup: Field-Emission Source Model

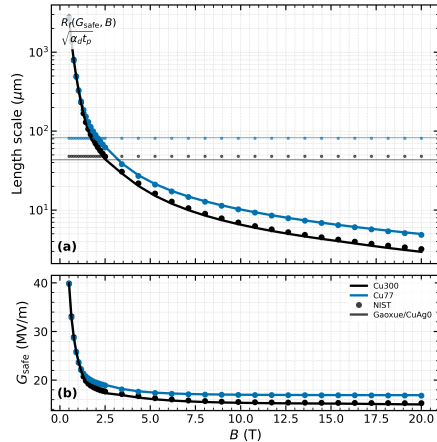


Spatial field enhancement



Time-dependent emission

Backup: Predictions Using DFT Material Models



Source: DFT material-property results provided by Gaoxue Wang and based on G. Wang, E. I. Simakov, and D. Perez, "Ab initio investigation of elastic properties of dilute Cu alloys for high-gradient accelerating structures," *J. Appl. Phys.* **132**, 175112 (2022), doi:10.1063/5.0106880.