Tolerance Studies for the IMCC Rectilinear 6D Ionization Cooling Channel

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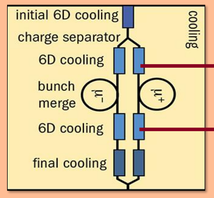
3D MODEL

Making the Case for Tolerance Studies

- Reaching a ~10^{34} cm^{-2} s^{-1} luminosity within the short 2.2 μs μ lifetime requires the reduction of the 6D emittance of the μ beam in a process described as muon cooling.
- The International Muon Collider Collaboration (IMCC) baseline design, the rectilinear channel, utilizes solenoids, dipoles, RF cavities, and Liquid Hydrogen (LH) absorbers to facilitate ionization cooling.
- The optimal parameters for these components in the Rectilinear Channel may not be fabricated exactly when constructing a demonstrator.
- Tolerance Studies: Introduce deviations to the optimal rectilinear channel parameters to probe cooling performance.

IMCC Rectilinear Channel and Tolerance Studies



30 – 65 Cells = 1 Stage

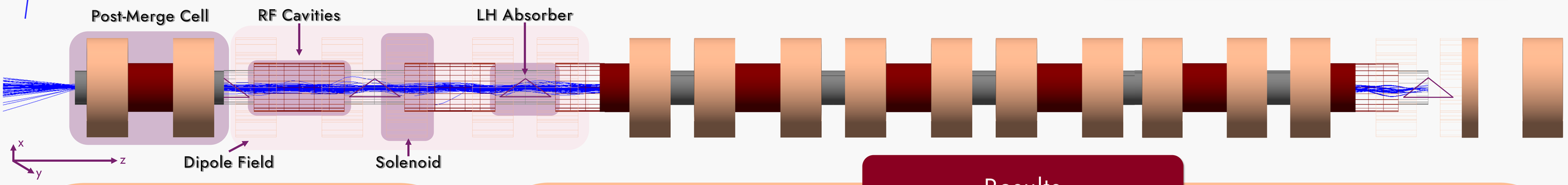
4 Pre-Merge Stages (A1—A4)

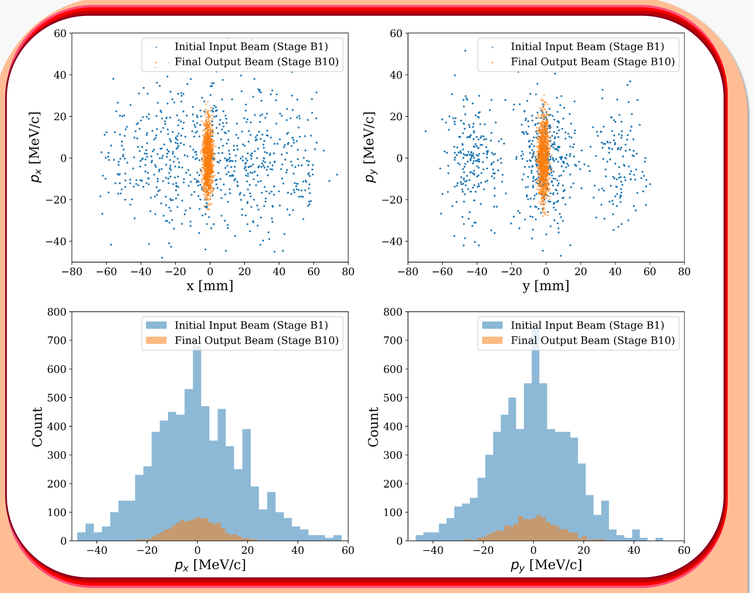
10 Post-Merge Stages (B1—B10)

- Simulation: G4Beamline; Emittance and Transmission calculations: ECALC9f
- Tolerance Studies Method:
  1. Generate random errors from a truncated Gaussian distribution:
     i. Mean = The nominal value of a parameter
     ii. Standard Deviation = Value between 1%–10% of the average mean
  2. Output of a stage → Input of next stage.
  3. Sample 10 times.

Conclusion

- Compared to the current state-of-the-art RF cavities with fractional deviation of at most 0.01% [7], the cooling performance remains tolerant:
  - RF phase errors above 2° reduce the transmission by > 2% and increase the final longitudinal emittance by a ~0.05 mm but they don't significantly impact the transverse emittance. Total of 0.004 mm^3 increase in the 6D emittance.
  - (Fractional) RF gradient errors above 0.05-0.1 reduce the transmission by > 2% and increase the final longitudinal emittance by a ~0.05 mm but they don't significantly impact the transverse emittance. Total of 0.002-0.005 mm^3 increase in the 6D emittance.
- Future work should involve looking at solenoid specifications such as current and position errors as well as looking at various optimization algorithms.

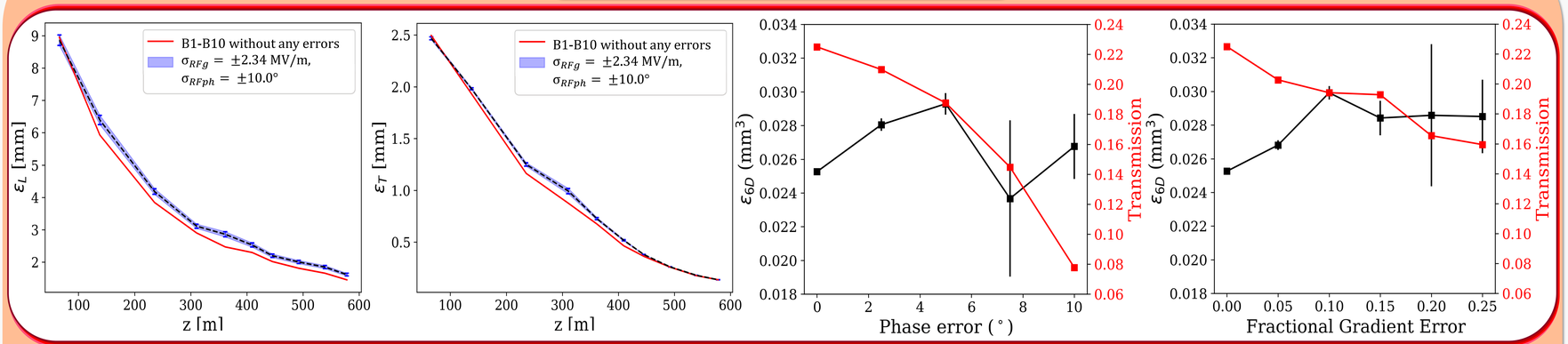




Ionization Cooling: Muon Cooling through ionization of atoms within the low atomic number wedge-shaped absorber material.

Ionization Cooling

Results



Longitudinal Emittance (left) and Transverse Emittance (right) evolution across all 10 post-merge B stages due to 10% RF fractional gradient error, i.e. 2.34 MV/m, and 10° RF phase error.

Variation of normalized 6D emittance and transmission (% survival) across all 10 post-merge B stages due to RF fractional gradient errors (left) and RF phase errors (right). RF gradient is the amplitude of the RF applied electric field and RF phase is the phase of the field.

[1] "Sketching out a Muon Collider." CERN Courier, 8 May 2020, cerncourier.com/a/sketching-out-a-muon-collider/.
[2],[4] Yonehara, Katsuya. "MiniCourse: Accelerator Design for a multi-TeV Muon Collider", March-June 2025.
[3] Batygin, Yuri. "5. Beam Focusing in Axial-Symmetric Field." U.S. Particle Accelerator School, uspas.fnal.gov/materials/19NewMexico/PILA/5.Axial_Symmetric.pdf.
[5] Zhu, Ruihu, et al. "Design method, performance evaluation, and tolerance analysis of the rectilinear cooling channel for a Muon Collider." Physical Review Accelerators and Beams, vol. 28, no. 4, 24
[6] "Buckets and Bunches." Taking a Closer Look at LHC - Buckets and Bunches.
[7] Doolittle, L. "THE LCLS-II LLRF SYSTEM." 6th International Particle Accelerator Conference, accelconf.web.cern.ch/IPAC2015/.

Sources