Bright muon sources

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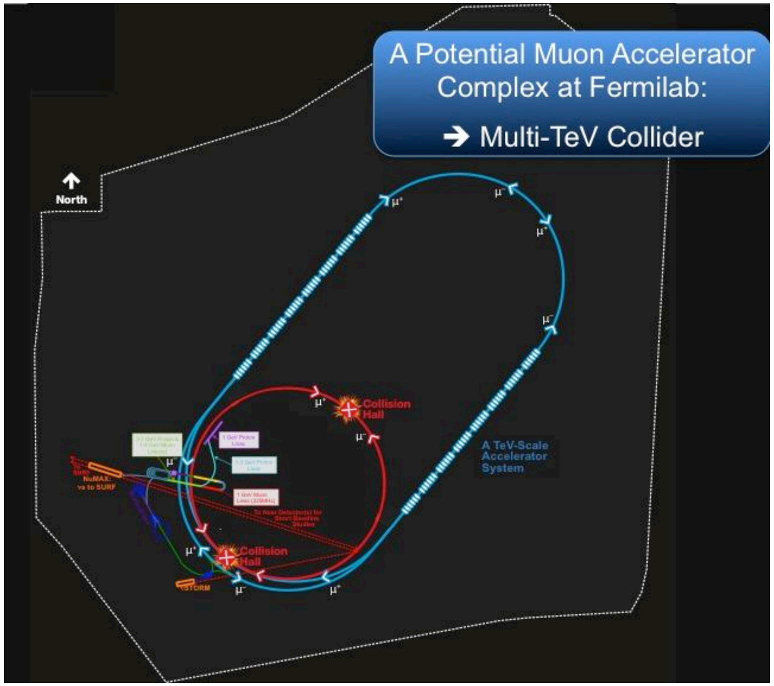
August 29, 2014

Outline

- Motivation
- Ionization cooling
- Six-dimensional (6D) cooling
- Cooling stages and options
- Issues and mitigation
- Summary

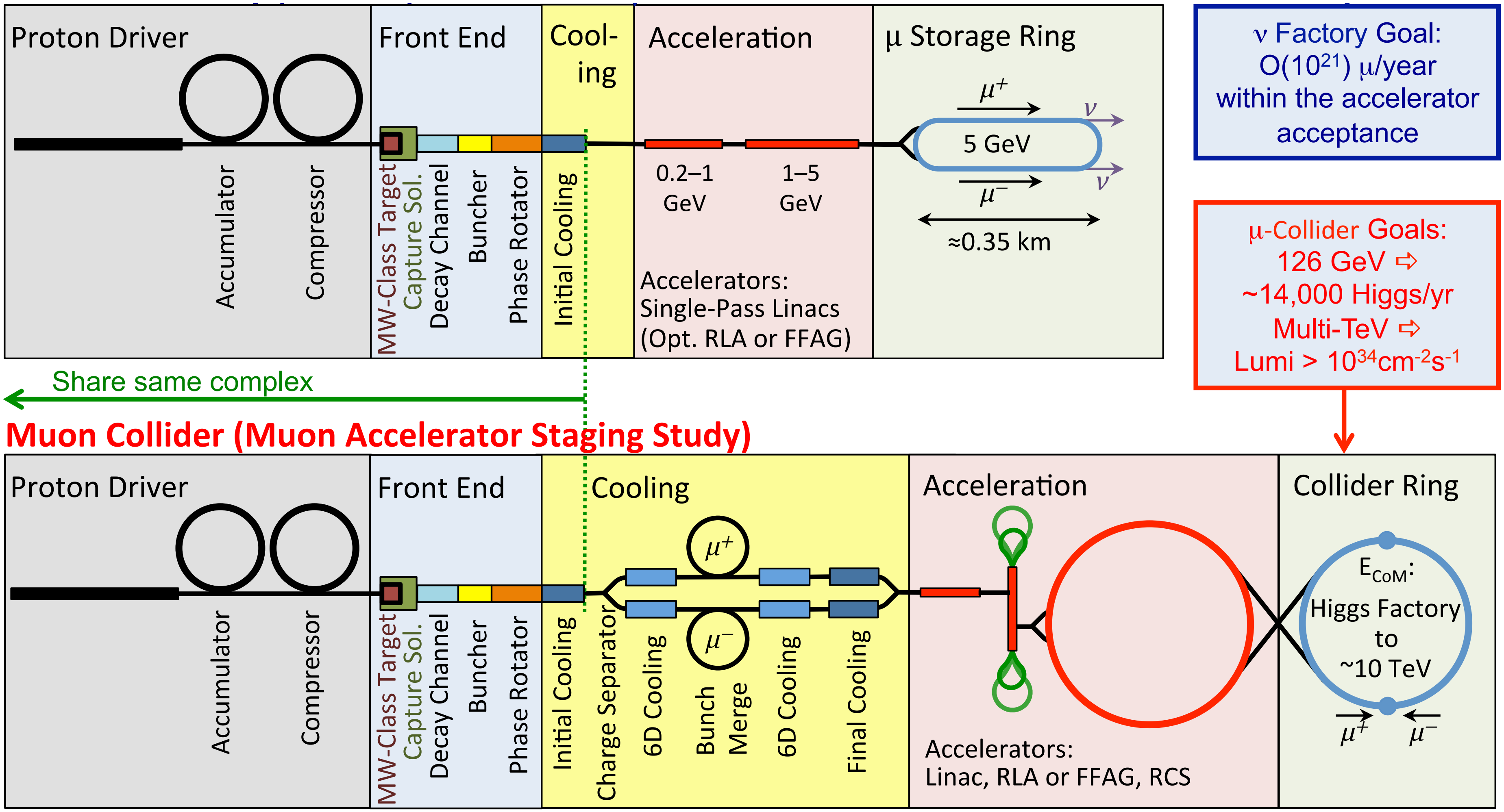
Muon advantages and challenges


A Potential Muon Accelerator Complex at Fermilab:
→ Multi-TeV Collider

- (+) Muons are elementary particles, clean collisions at full energy. Advantage over protons where only fraction of the energy goes into quark-quark collisions.
- (+) Muons are much heavier than electrons, no bremsstrahlung issue. Compact footprint.

(-) Muons decay (τ=2.2 μs at rest), need to be focused and accelerated fast.
(-) Tertiary production results in large phase space volume, need beam size reduction (=cooling).

Introduction: NF & MC



ν Factory Goal:
O(10^{21}) μ/year
within the accelerator
acceptance

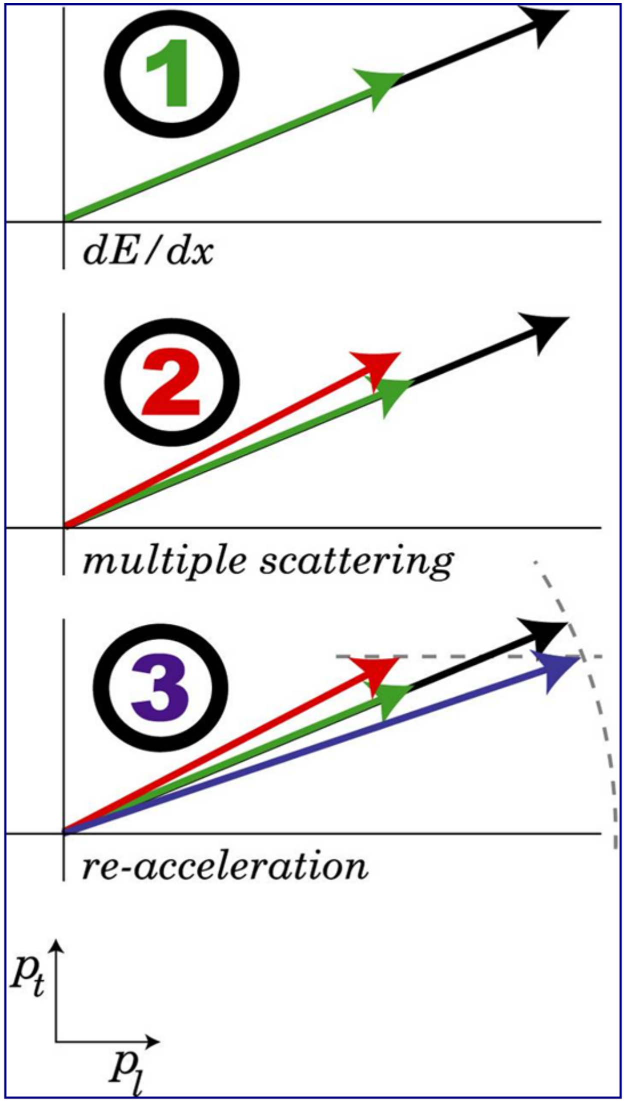
μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

- Schematics of the neutrino factory (top) and muon collider (bottom)
- Initial collection and cooling are the same in both machines

Ionization cooling

- NF/MC are tertiary beam machines (p ➔ π ➔ μ). Emittances coming out of the target are very large.
- Need intense μ beam ➔ need to capture as much as possible of the initial large emittance.
- Large aperture acceleration systems are expensive ➔ for cost-efficiency need to cool the beam prior to accelerating.
- NF requires a modest amount of initial 6D cooling.
- MC designs assume significant, O(10^6) six-dimensional cooling.
- Need to act fast since muons are unstable. The only feasible option is ionization cooling.

Ionization cooling

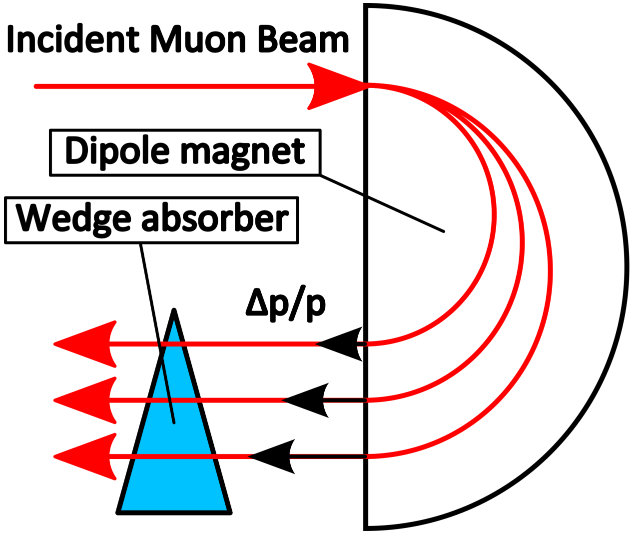


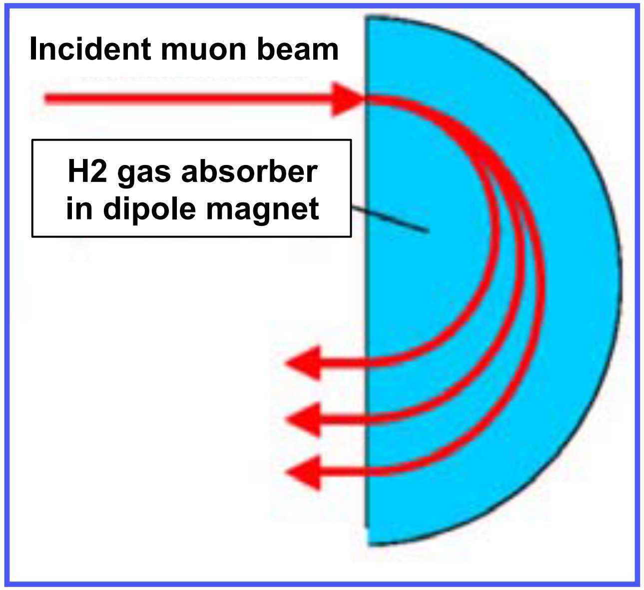
$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp(0.014GeV)^2}{2\beta^3 E_\mu m_\mu X_0}$$

- $d\varepsilon_n/ds$ is the rate of normalized emittance change within the absorber; βc, E_μ, and m_μ are the muon velocity, energy, and mass; $\beta_\perp$ is the lattice betatron function at the absorber; and X_0 the radiation length of the absorber material. Need low $\beta_\perp$, large X_0.

1. Energy loss in material (all three components of the particle's momentum are affected).
2. Unavoidable multiple scattering (can be minimized by choosing the material with large X_0, hence, low Z.
3. Re-accelerate to restore energy lost in material. Only the longitudinal component of momentum is affected.

6D cooling via emittance exchange

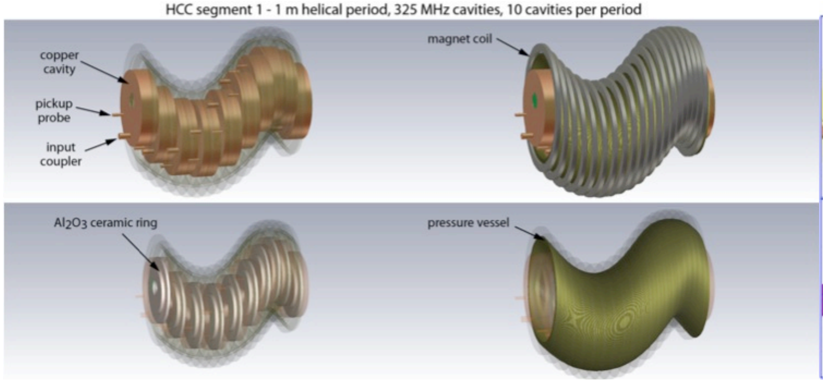


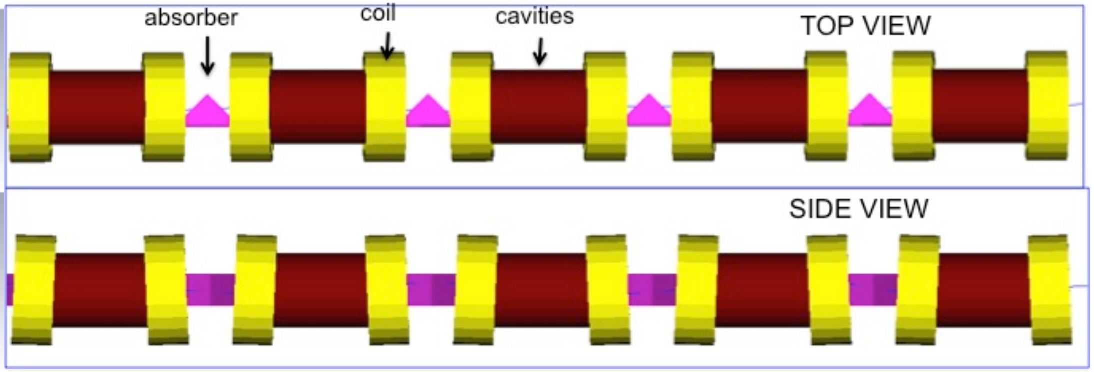


- Emittance exchange principle: instead of letting the beam with zero dispersion through a flat absorber, introduce dispersion and let the particles with higher momentum pass through more material, thus reducing the beam spread in the longitudinal direction.
- Another option would be to control particle trajectory length in a continuous absorber (gas-filled channel).

MAP IBS process

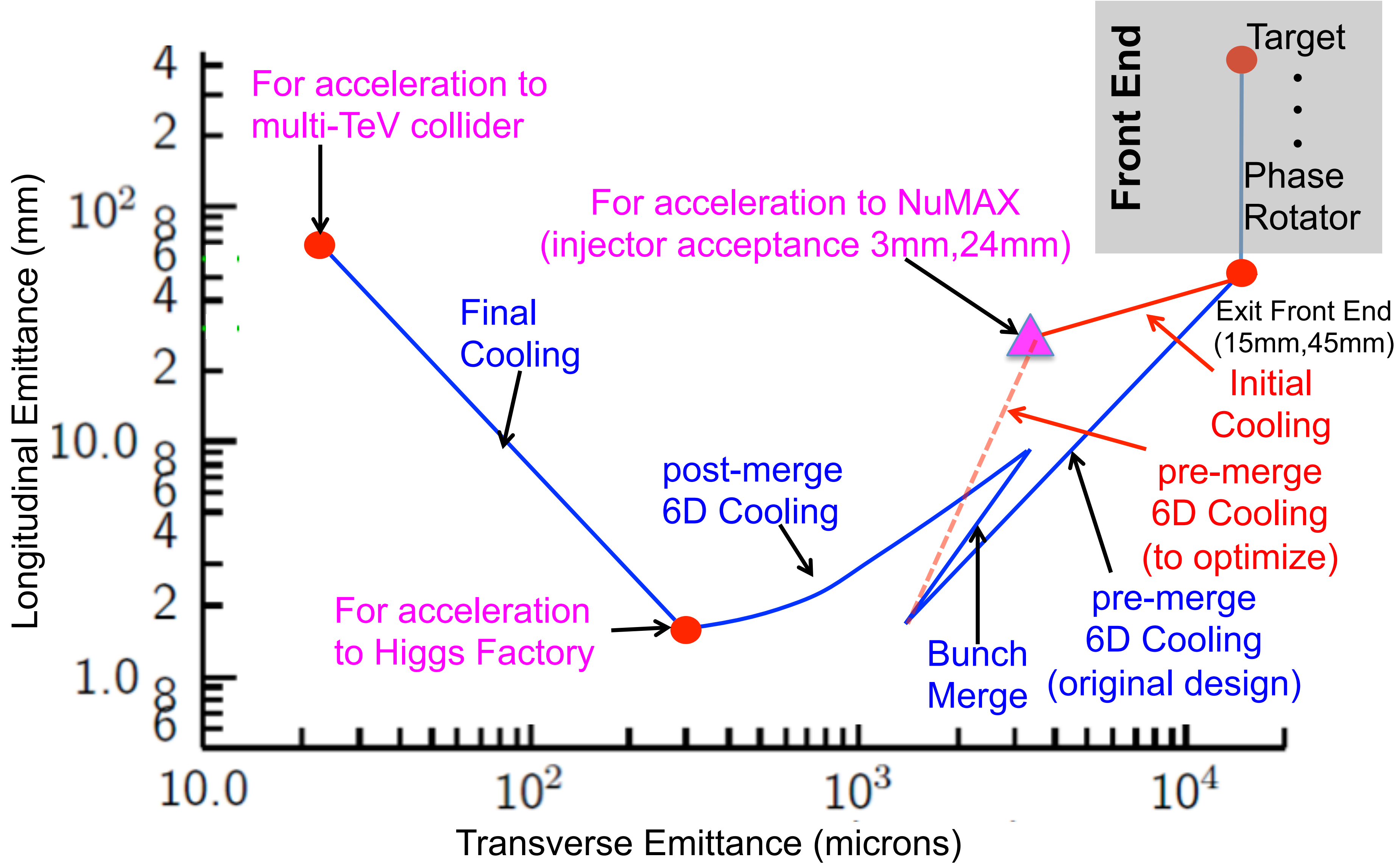
- MAP: Muon Accelerator Program formed in 2010 to unify the DOE supported R&D in the U.S. aimed at developing the concepts and technologies required for muon colliders and neutrino factories.
- IBS: Initial Baseline Selection process aimed at producing initial designs of all key accelerator systems for muon-based neutrino factories and colliders.


HCC segment 1 - 1 m helical period, 325 MHz cavities, 10 cavities per period

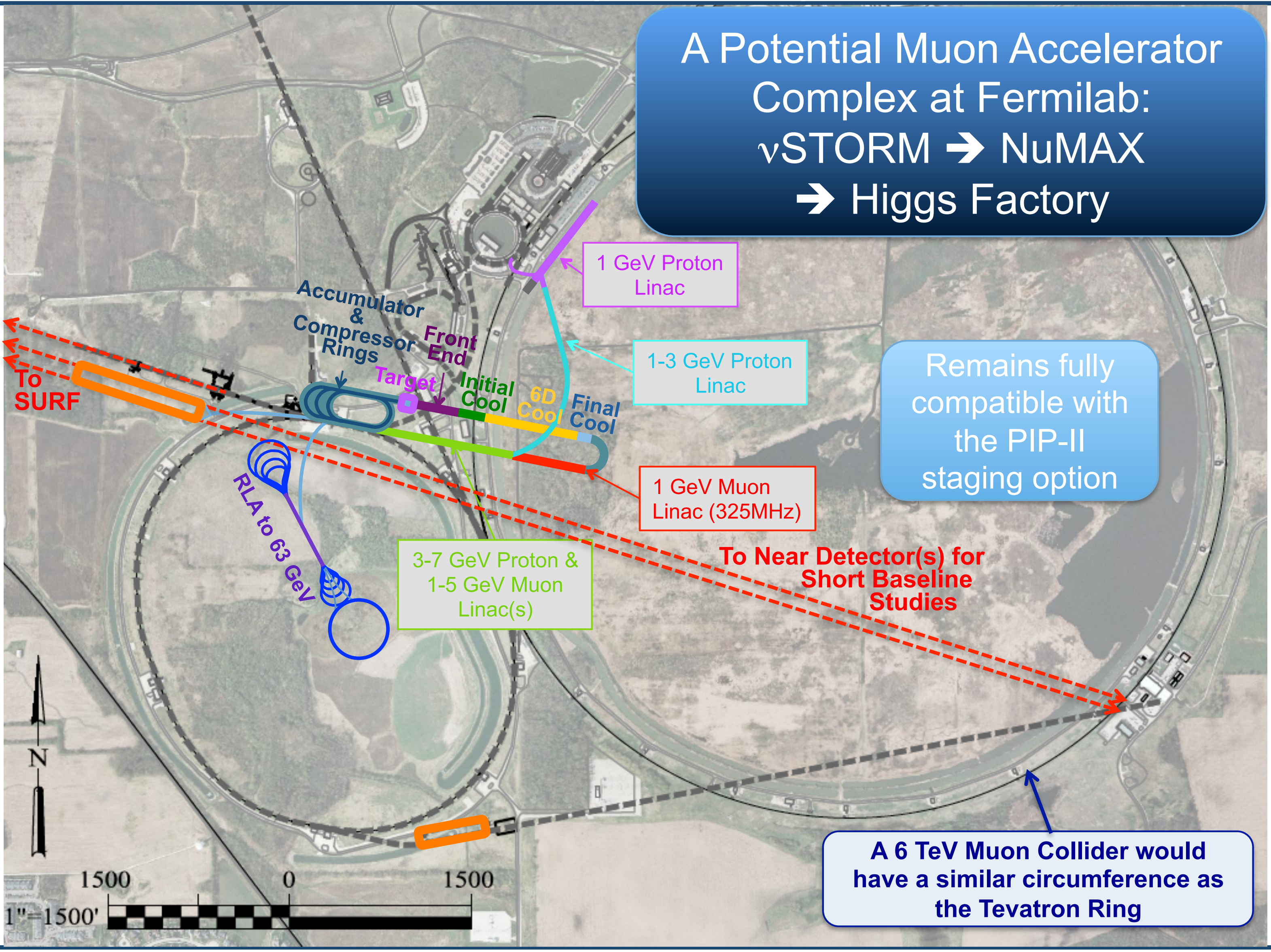


- We have two key alternatives we are pursuing for the 6D cooling channels.
- Left: high-pressure gas-filled RF helical cooling channel (HCC).
- Right: vacuum RF rectilinear cooling channel (VCC).
- IBS encompasses other systems as well: in particular, initial cooling channel, bunch merging, charge separation, and final cooling.

Cooling scheme overview



Muon Accelerator Staging Study (MASS)



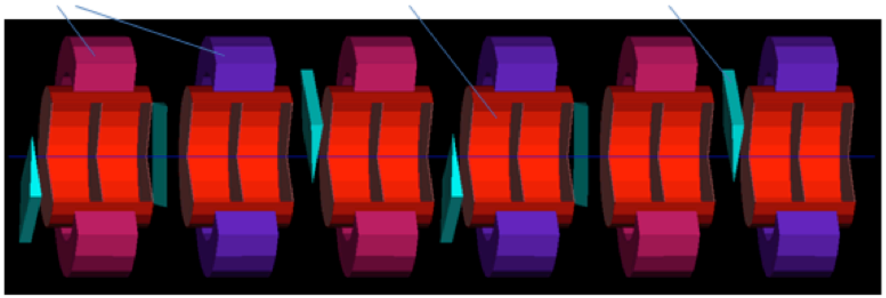
A Potential Muon Accelerator Complex at Fermilab:
νSTORM ➔ NuMAX
➔ Higgs Factory

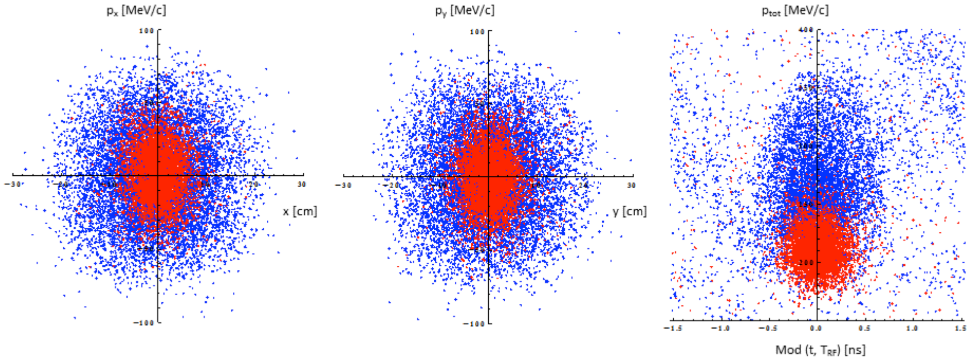
Remains fully compatible with the PIP-II staging option

A 6 TeV Muon Collider would have a similar circumference as the Tevatron Ring

Initial cooling

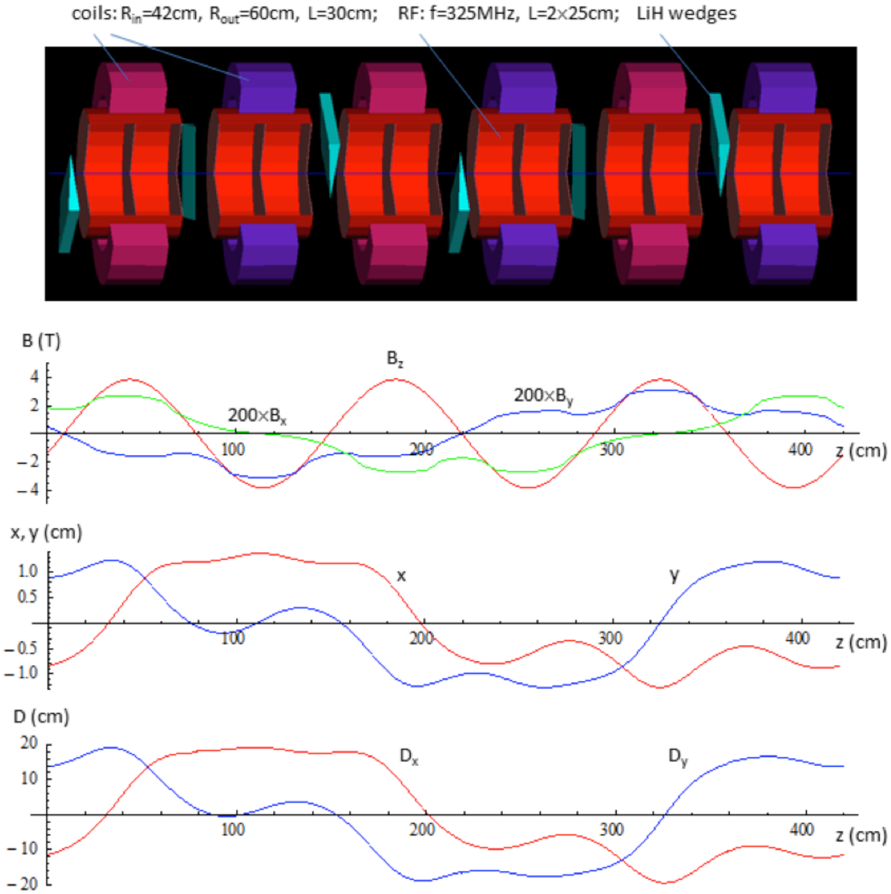
coils: R_{in}=42cm, R_{out}=60cm, L=30cm;   RF: f=325MHz, L=2×25cm;   LiH wedges





- Initial cooling channel:
  - Based on potential identified by MASS for NF cost optimization, began to explore initial 6D cooling.
  - Capable of cooling both charges simultaneously (cost reduction).
  - Preliminary design concepts for both vacuum and gas-filled RF cavities.
    - Completion of Initial Cooling concept specification based on a gas-filled HFOFO channel.
  - Improved matching from Initial Cooling section to Helical Cooling Channel (HCC).

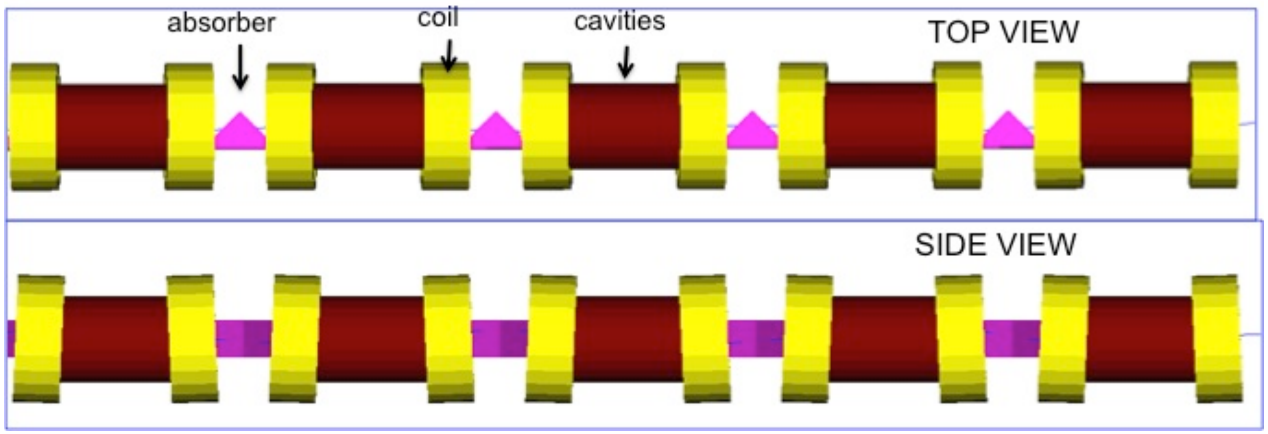
Initial cooling

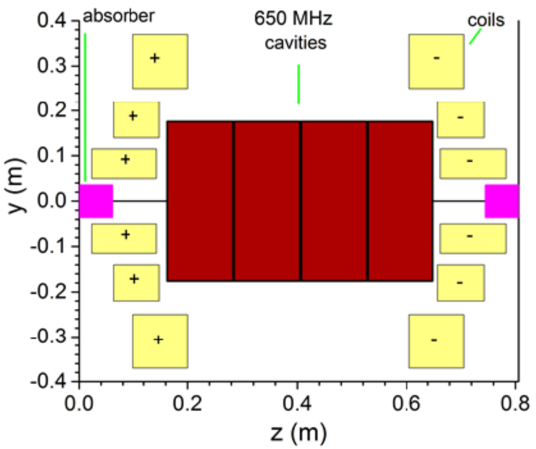


One period of the HFOFO lattice (top), magnetic field for muon momentum 230 MeV/c (second from top), μ^+ equilibrium orbit and dispersion (two bottom plots).

- Focusing field is created by alternating solenoids, inclined in rotating planes (0°, 120°, 240°, etc.)
- μ^- and μ^+ orbits have exactly the same form with longitudinal shift by half period.
- RF: f=325 MHz, E_{max}=25 MV/m.
- LiH wedge absorbers + high-pressure gas-filled RF cavities.
- 6D emittance reduced from 6.2 (μ^+) and 5.6 (μ^-) cm^3 to 51 mm^3.
- Transmission is 68% (μ^+) and 67% (μ^-).
- Channel length, L=125 m.

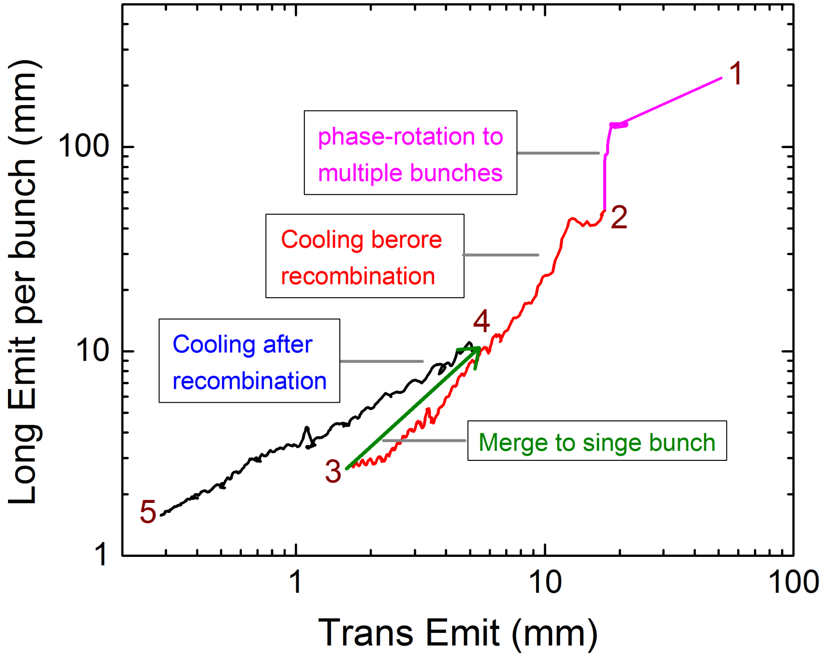
Vacuum RF cooling channel

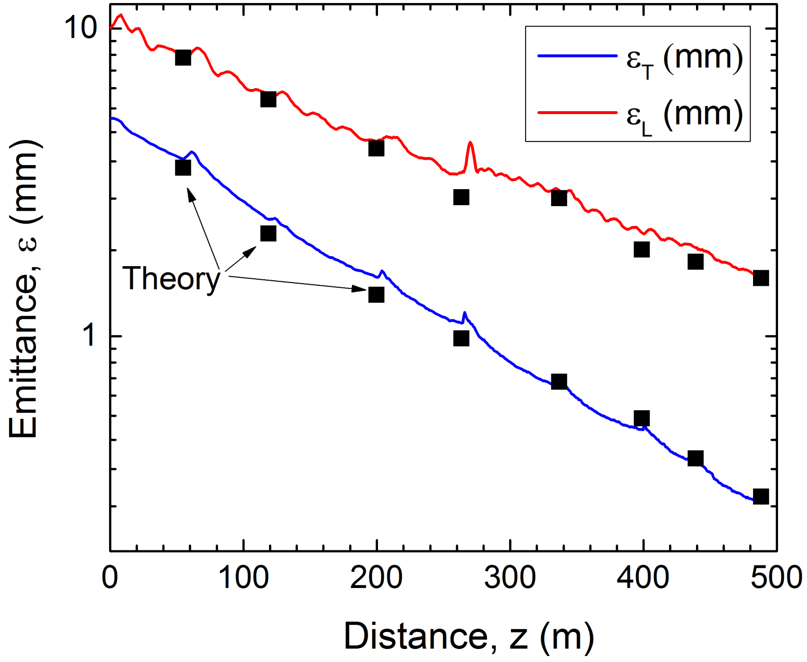




- Vacuum RF cooling channel (VCC):
  - – Lattices + start-to-end simulations.
  - – Lattices optimized and achieved emittance goals specified by MAP.
  - – Progress on bunch merge.
  - – Investigation of window effects.
  - – Thermal & mechanical analysis of RF windows.
  - – Magnet design.
  - – Significant improvement in the final stage of 6D cooling.

Vacuum RF cooling channel





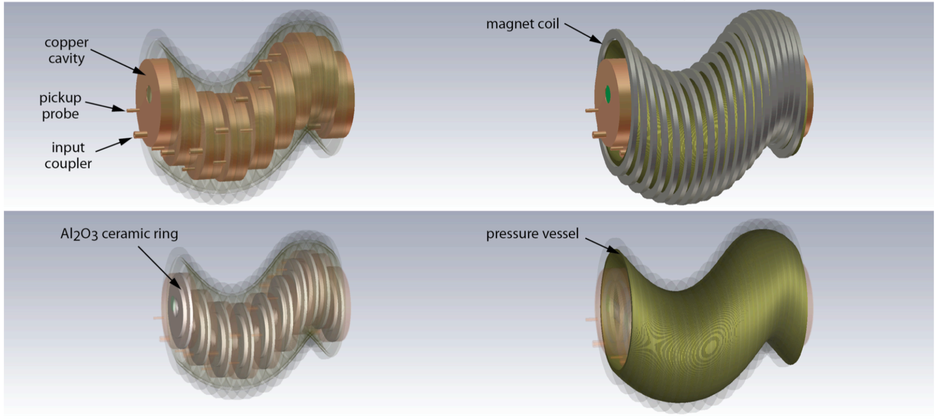
Emittance evolution plot:
reaching 0.28 mm in transverse emittance and 1.57 mm in longitudinal emittance

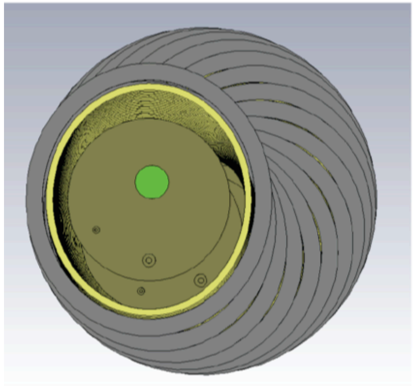
Emittance evolution after bunch recombination: black markers are theoretical predictions

- RF: f=325 & 650 MHz; field: B_z=2.3-13.6 T; cooling section length, L=490 m.
- Transmission: 55% before recombination, 40% after recombination.

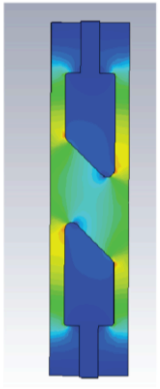
Helical cooling channel

HCC segment 1 - 1 m helical period, 325 MHz cavities, 10 cavities per period

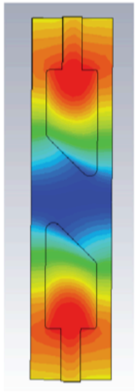




front view



E-field

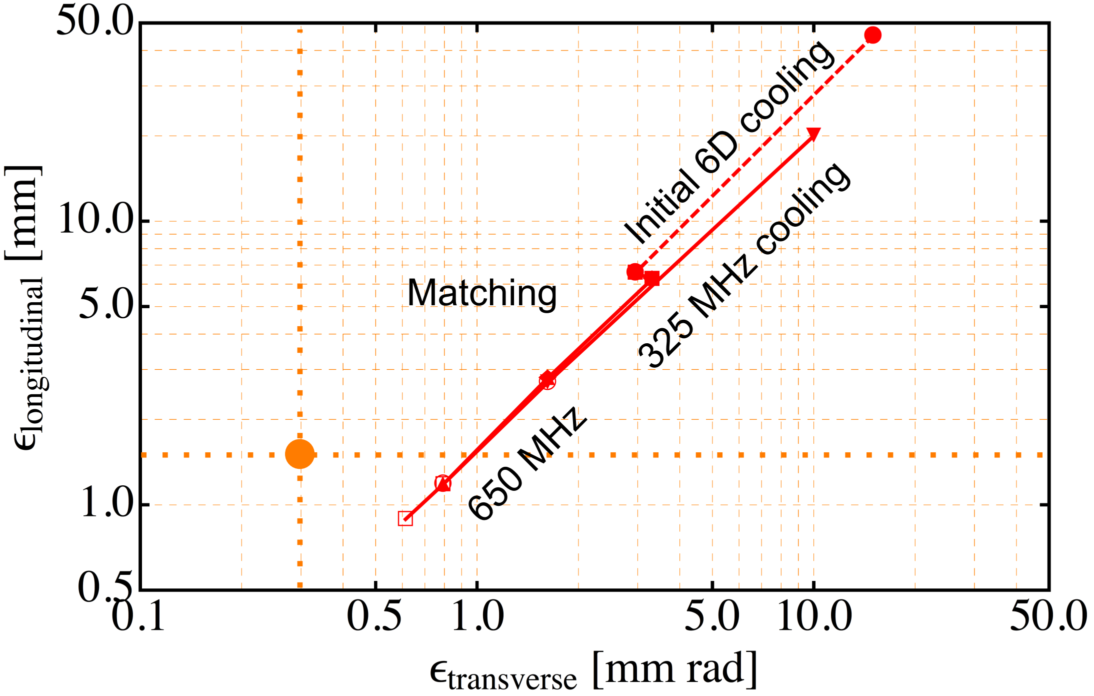


H-field

- High-pressure RF helical cooling channel (HCC):
  - Lattices + start-to-end simulations.
  - Lattice is optimized to increase transmission efficiency.
  - Studies of gas-plasma interactions and plasma chemistry.
  - Evaluation of an accelerating section for helical bunch merge.
  - Dielectric loaded HPRF test, helical Nb_3Sn coil test, and RF window study.
  - Wake field studies.

Helical cooling channel

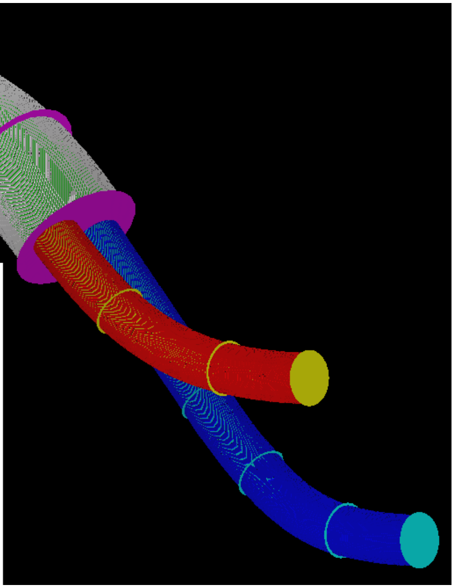
- Matching: transmission improved 56 % → 72%
- 6D HCC:
  - RF parameters:
    - E = 20 MV/m,
    - f = 325 & 650 MHz
  - gas pressure:
    - 160 atm at 300 K,
    - 43 atm at 80 K
  - magnetic fields:
    - B_z = 4-12 T
- Equilibrium emittance
  - e_T = 0.6 mm
    - (goal: 0.3 mm)
  - e_L = 0.9 mm
    - (goal: 1.5 mm)

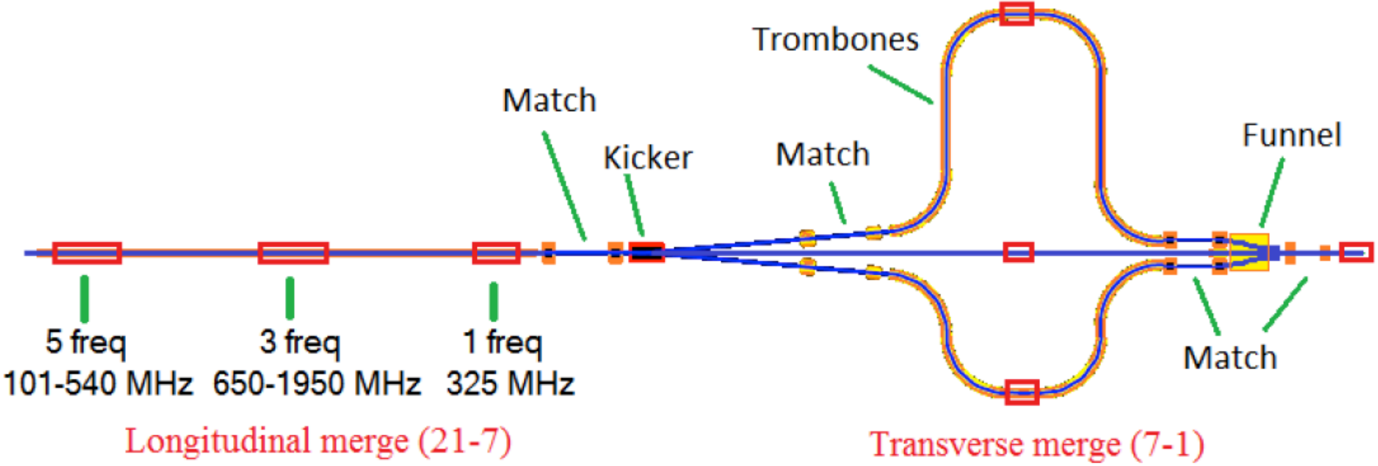


- Transmission (one cooling section): ~60%
- Channel length (one cooling section): 380 m → 280 m

Charge separation and bunch merge

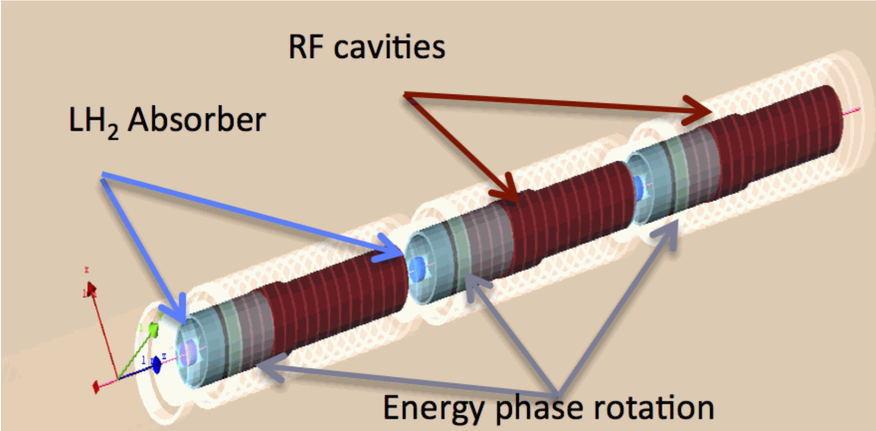
- Charge separation section concept. Separates charges after initial cooling.
- Can be used by HCC or VCC.



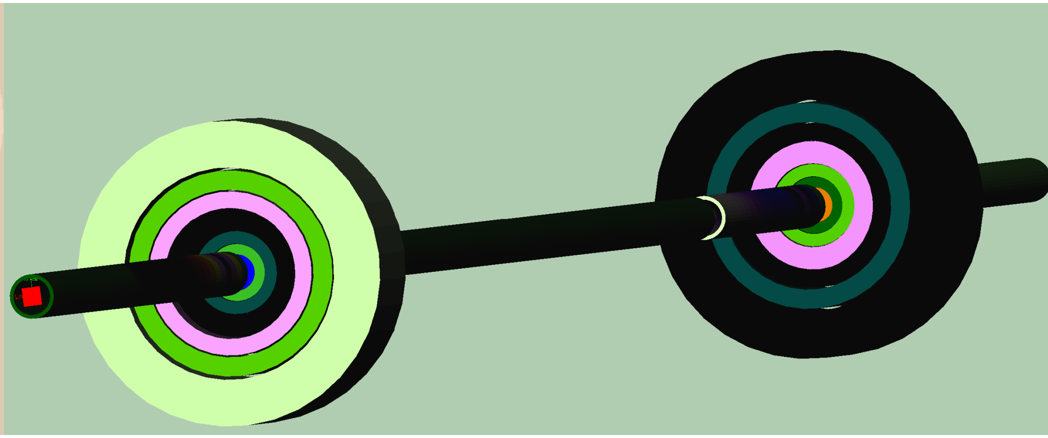


- Bunch merge section concept (VCC). Merges 21 bunches into 7 longitudinally then 7 into one transversely. Combines bunches after some 6D cooling.
- Overall transmission ~78%, emittance grows from 1.6 to 6.8 mm.

Final cooling channel



Early stages: RF inside transport solenoid coils

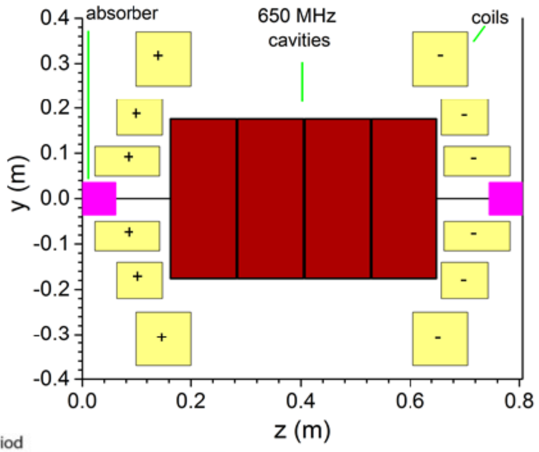


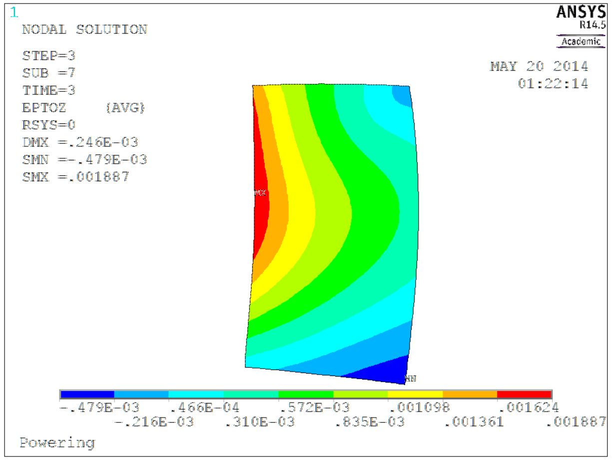
Late stages: transport solenoid coils inside induction linac

- Final cooling channel design with 30-25 T focusing field.
- Preliminary results for a complete design of a high field cooling channel: transverse emittance 55 μm, longitudinal ≈75 mm. (40 T could reach 25 μm.)
- Field flip frequency under study.

Key issues: magnet design, component integration

- VCC: demanding magnet configuration, especially toward the latter stages.
- Azimuthal strain in the inner solenoid (0.19%) is within Nb_3Sn irreversible limit (0.25%).

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1
NODAL SOLUTION

STEP=3
SUB =7
TIME=3
EPTOZ     (AVG)
RSYS=0
DMX =.246E-03
SMN =-.479E-03
SMX =.001887
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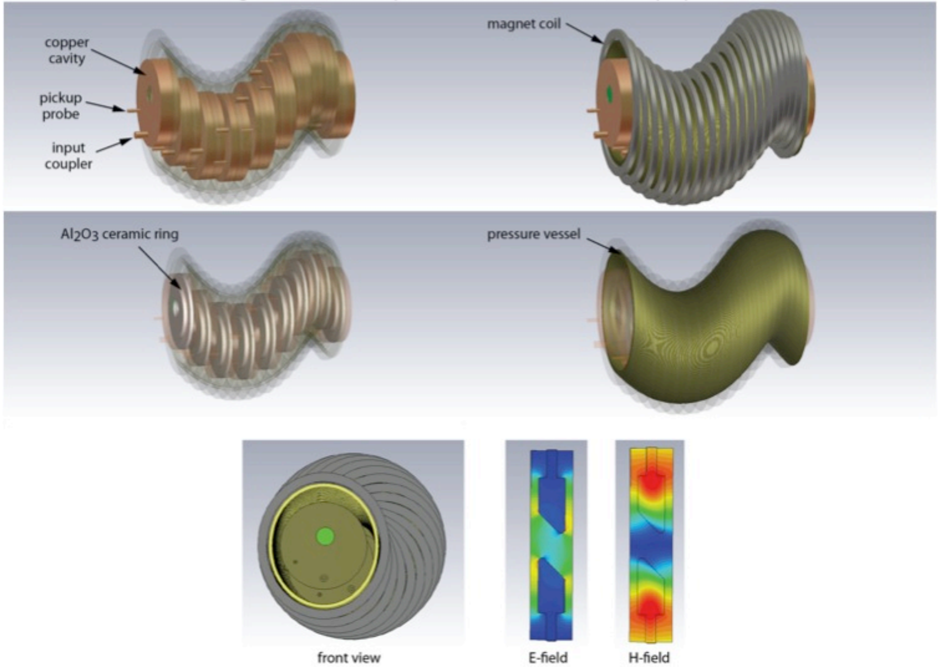
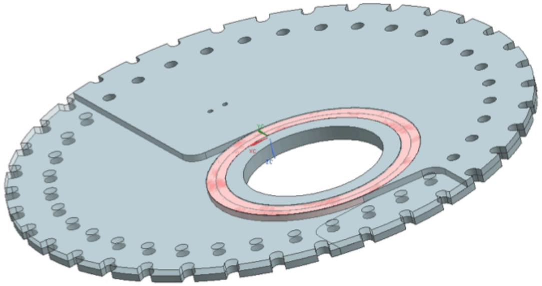
HCC segment 1 - 1 m helical period, 325 MHz cavities, 10 cavities per period

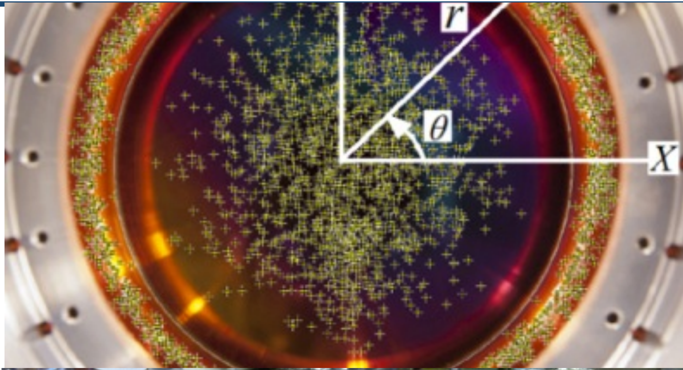


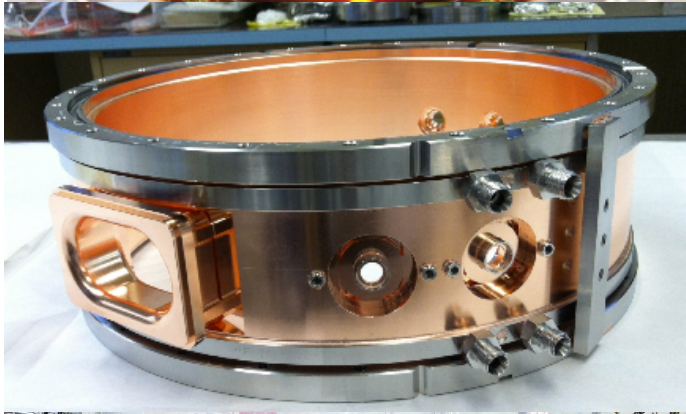
- HCC: integration of RF and helical solenoid.
- Obtaining the right ratio between solenoidal, helical dipole and helical quad components.

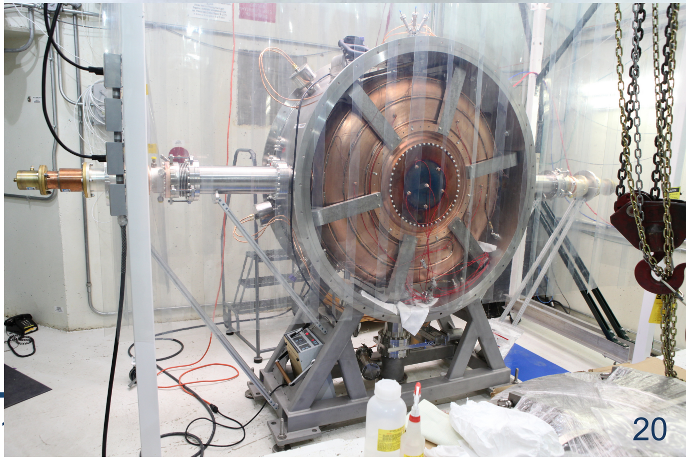


Key issue: RF breakdown

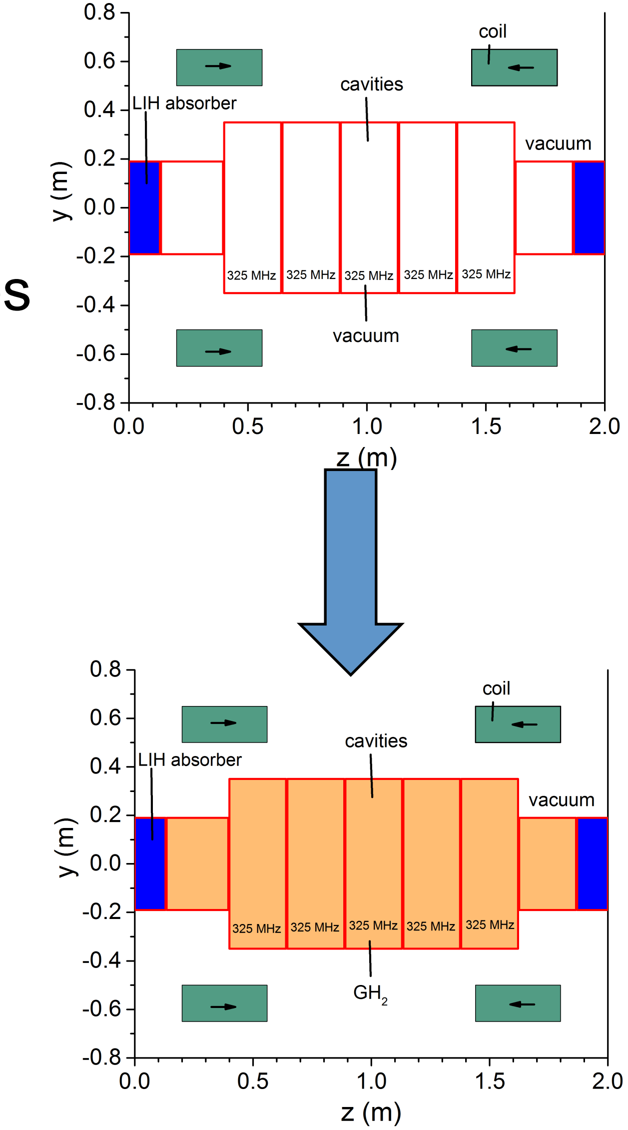
- Muon cooling channels require RF operation in strong magnetic fields.
- Gradients are known to be limited by RF breakdown.
- Extensive experimental program underway at the MuCool Test Area (MTA) at Fermilab.
- Encompasses both vacuum and high-pressure RF.
- Multiple cavities with different surface materials/treatments tested under a variety of conditions.
- Among those being tested is a 201 MHz single-cavity Muon Ionization Cooling Experiment (MICE) module.







Hybrid cooling channel



- The development of 6D cooling concepts is in an advanced state thanks to
  - progress under MAP on the theoretical aspects
  - and experimentally at MTA and at MICE.
- One area of concern: breakdown of RF cavities in high magnetic fields.
  - Experiments at MTA have demonstrated that using cavities filled with high-pressure gas can prevent this breakdown.
- An important recent conceptual development: reconsideration of a hybrid cooling channel
  - rectilinear channel beam line components,
  - external absorbers,
  - cavities filled with medium pressure gas.
- Potential: control RF breakdown in high magnetic fields while maintaining the relative simplicity of rectilinear channel designs.
- Detailed study is underway.

Summary

- Systematic study of six-dimensional cooling and the corresponding D&S effort are underway:
  - End-to-end simulations indicate that the desired emittances are achievable in all cases of interest.
  - D&S group works in constant contact with other groups (magnets, RF) to ensure the designs are realistic.
- RF breakdown issue is being studied, mitigation strategies are being developed (MTA).
  - Hybrid cooling channel is being studied allowing to control RF breakdown in high magnetic fields while maintaining the relative simplicity of rectilinear channel designs.
- Key activities are being reassessed for transfer to GARD.

Thank you!