Bright Muon Sources

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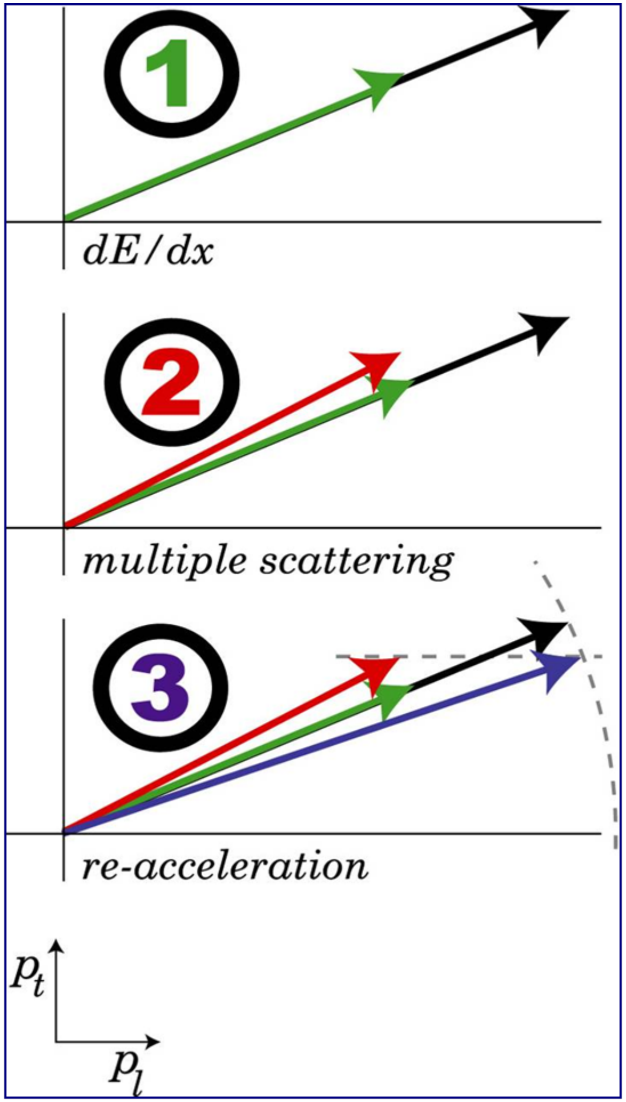
Outline

- Introduction
- Key progress
  - Initial cooling
  - 6D cooling (VCC and HCC)
  - Final cooling
- Current and future activities
  - Bright muon sources
  - MICE data integration
- Session agenda

Ionization cooling

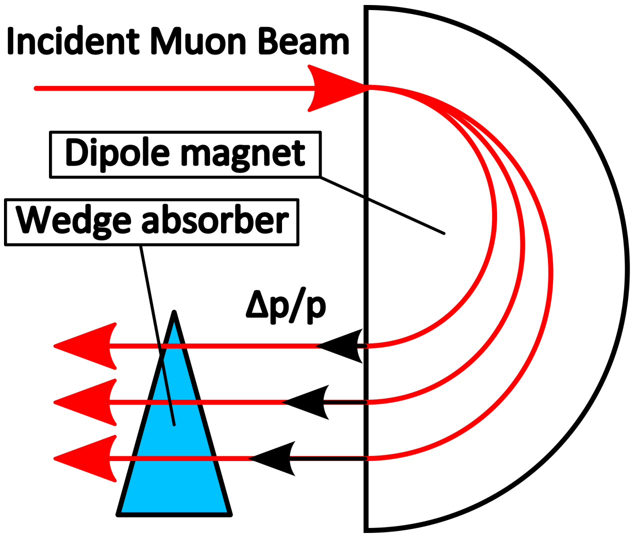


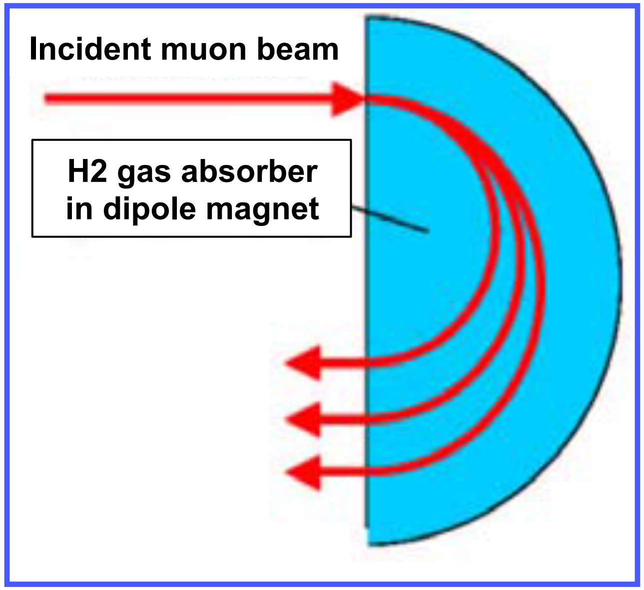
$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014 GeV)^2}{2\beta^3 E_\mu m_\mu X_0}$$

- $d\varepsilon_n/ds$ 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.

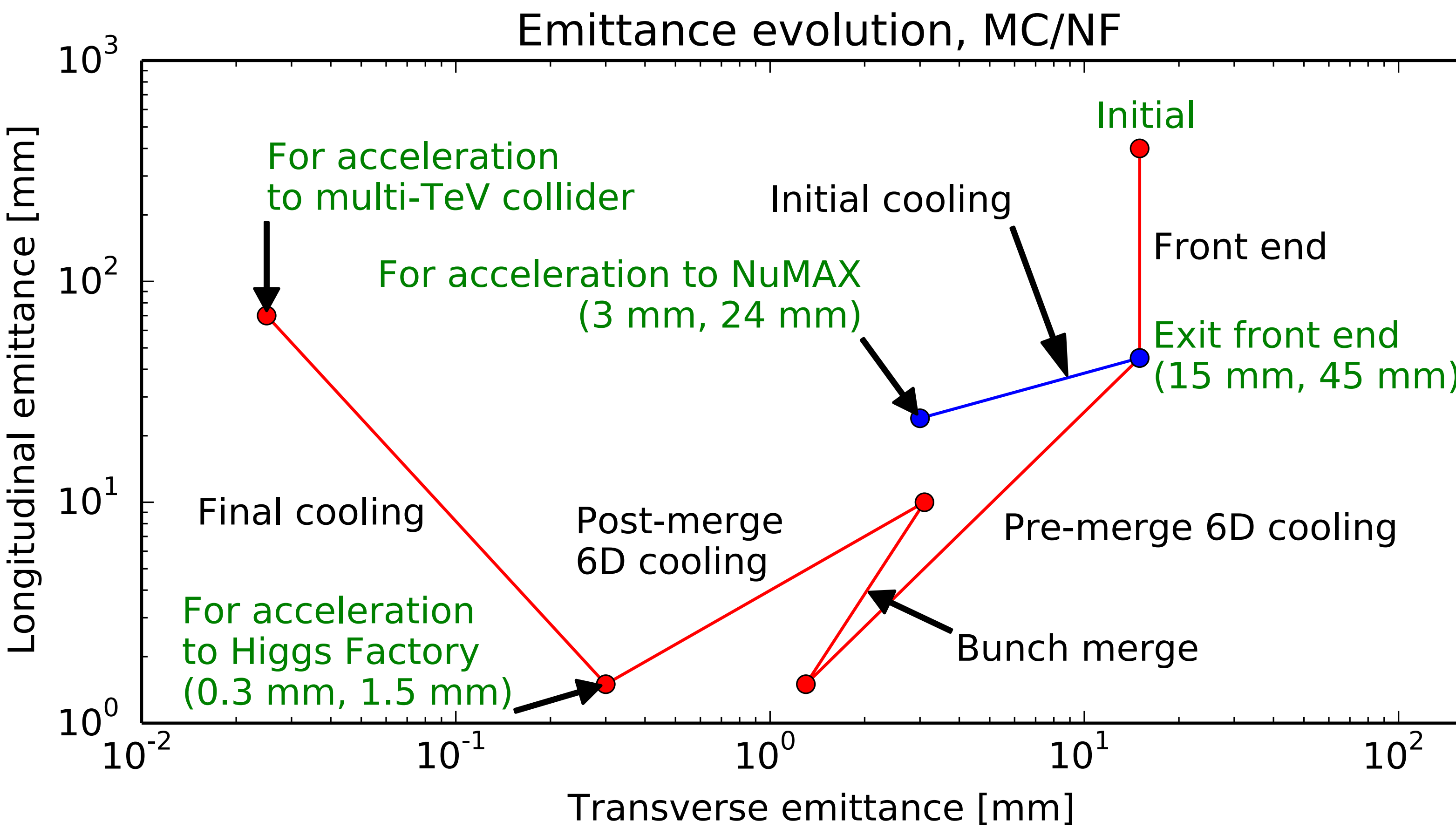
6D cooling via emittance exchange





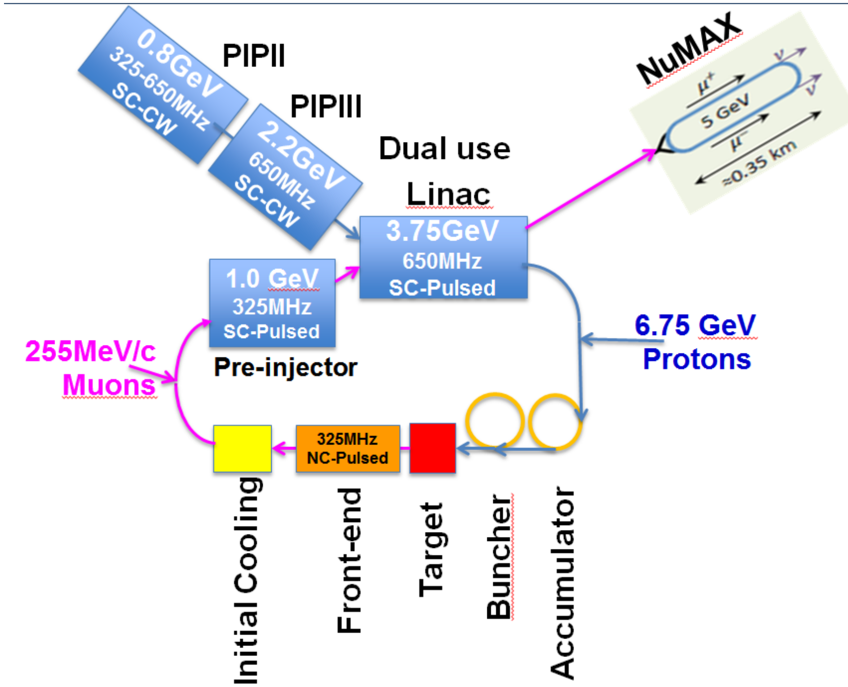
- Emittance exchange principle: instead of letting the beam with zero dispersion through a flat absorber, introduce dispersion and let the particles with higher momentum pass through more material, thus reducing the beam spread in the longitudinal direction.
- Another option would be to control particle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

Emittance evolution diagram



Motivation: MASS recommendations

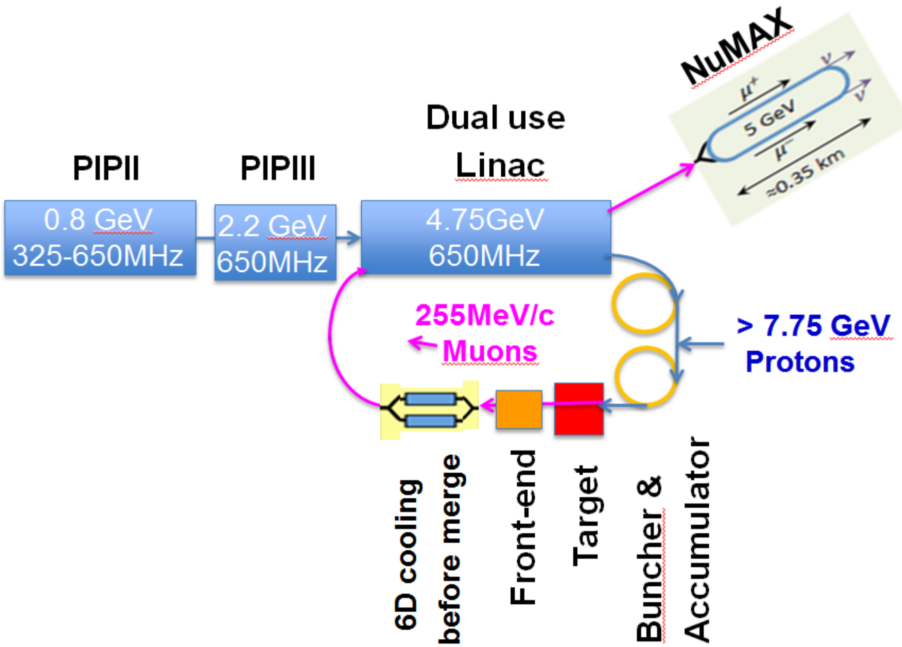
- Even though the P5 report de-emphasizes muon colliders…
- NuMAX with a limited amount of 6D cooling affords a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeams.
- Cost savings allowing maximum use of higher RF frequency linacs:
  - Moderate cooling of the beam emittances (5x in transverse and 2x in longitudinal) allows a 1 GeV pre-injector linac with 325 MHz RF frequency and a 3.75 GeV dual use linac with 650 MHz RF frequency…



Motivation: MASS recommendations

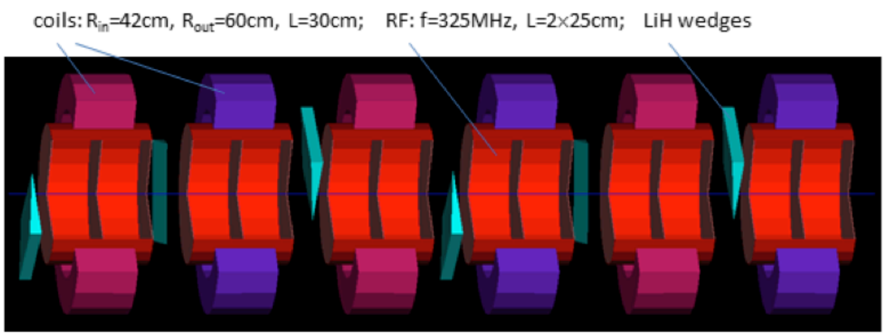
– …more aggressive cooling allows additional savings by eliminating the (expensive) 325 MHz pre-injector and extending the 650 MHz dual use linac to 4.75 GeV. The proton beam energy on target would then be increased to 7.75 GeV, close to optimum muon production.

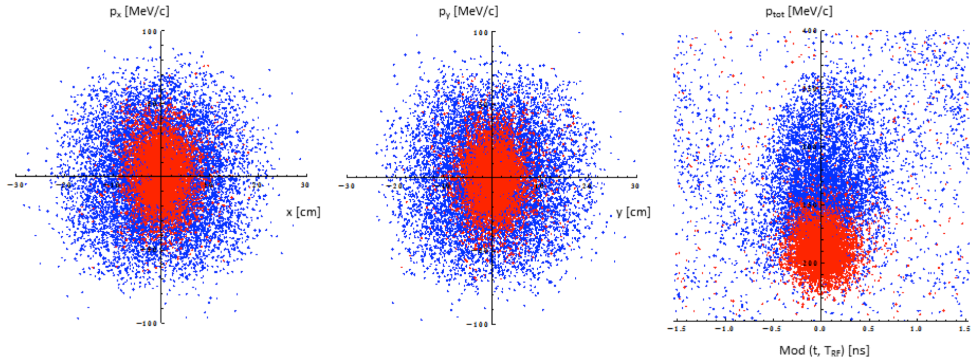
- Cooling specification to be optimized as the best trade-off between linac and cooling cost.



Key progress within MAP

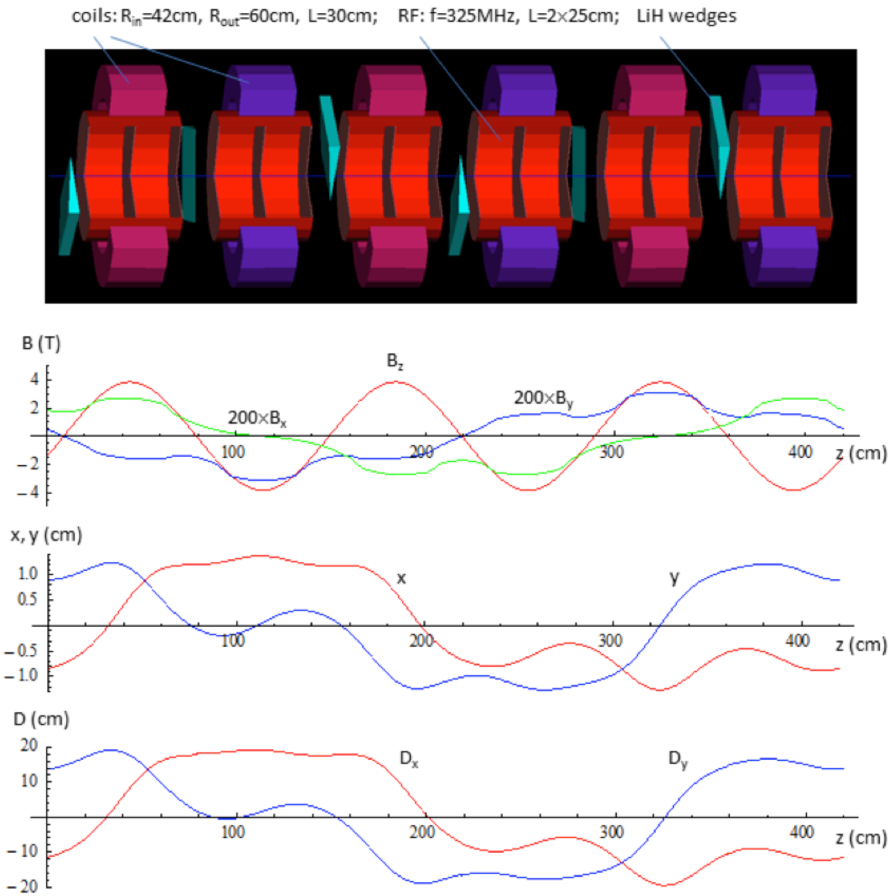
Initial cooling





- 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, contd.



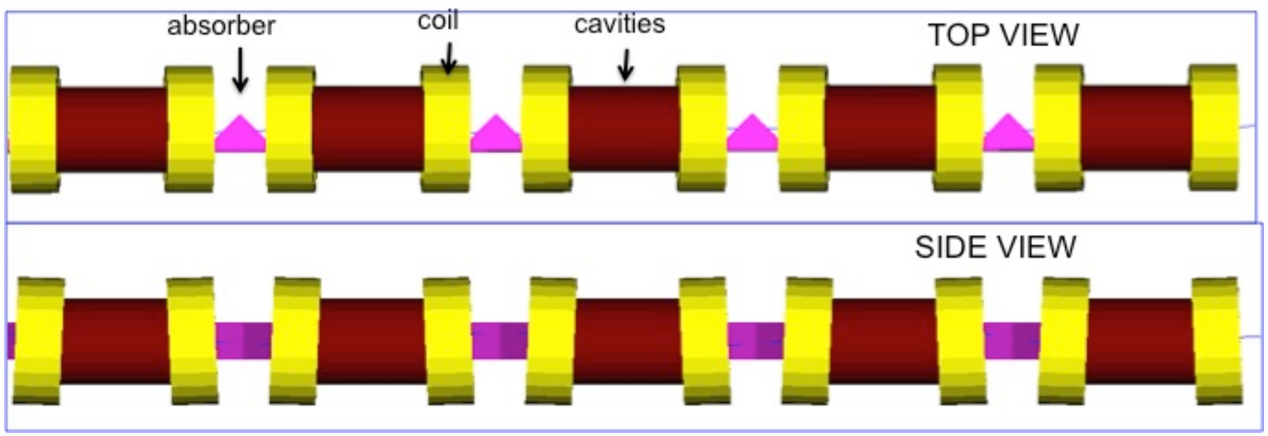
One period of the HFOFO lattice (top), magnetic field for muon momentum 230 MeV/c (second from top), μ^+ equilibrium orbit and dispersion (two bottom plots).

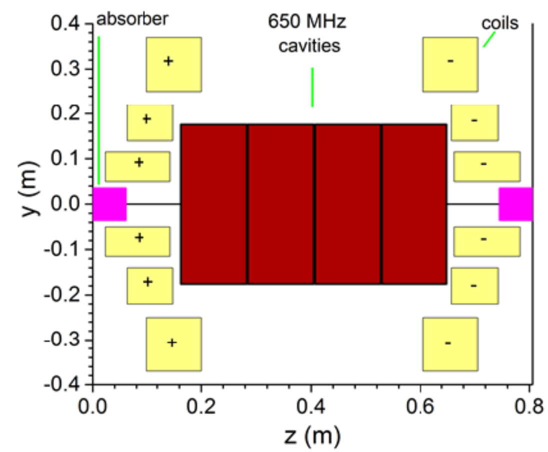
- Focusing field is created by alternating solenoids, inclined in rotating planes (0°, 120°, 240°, etc.)
- μ^- and μ^+ orbits have the same form with longitudinal shift by half period.
- RF: f=325 MHz, E_{max}=25 MV/m.
- LiH wedge absorbers + high-pressure gas-filled RF cavities.
- 6D emittance reduced 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.

Initial cooling, contd.

- There is no dedicated talk at this collaboration meeting; however,
- All the information regarding the channel can be found on DocDB, note 4377: http://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4377
  - Gas-filled HFOFO snake documented
  - Lattice files provided

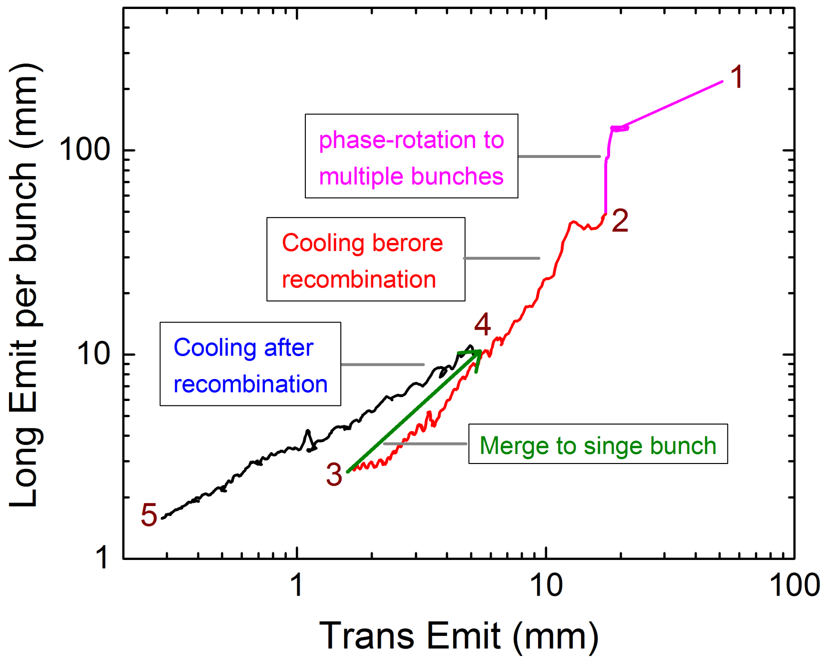
Vacuum RF cooling channel (VCC)

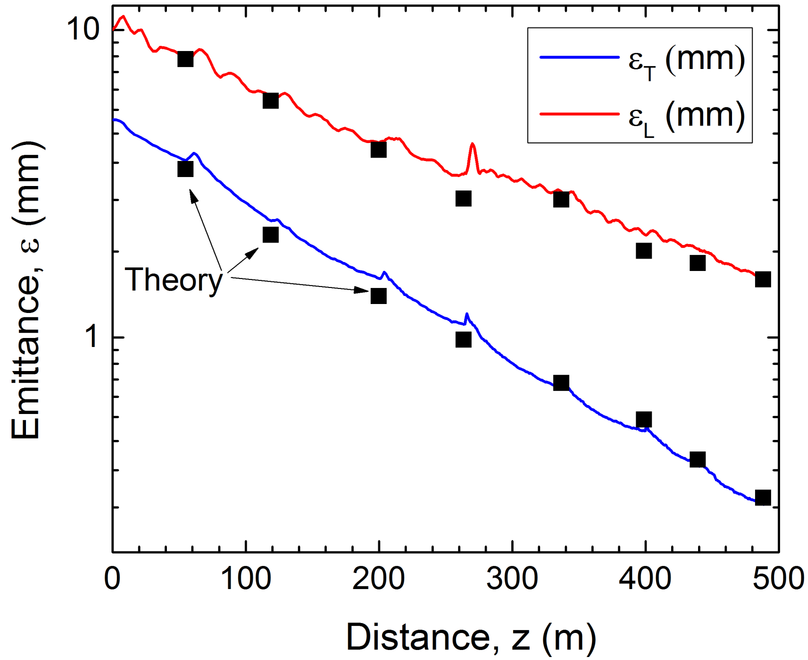




- Vacuum RF cooling channel (VCC):
  - Lattices + start-to-end simulations.
  - Lattices optimized and achieved emittance goals specified by MAP.
  - Progress on bunch merge. See talk by Yu Bao.
  - Investigation of window effects.
  - Thermal & mechanical analysis of RF windows.
  - Magnet design.
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

VCC, contd.





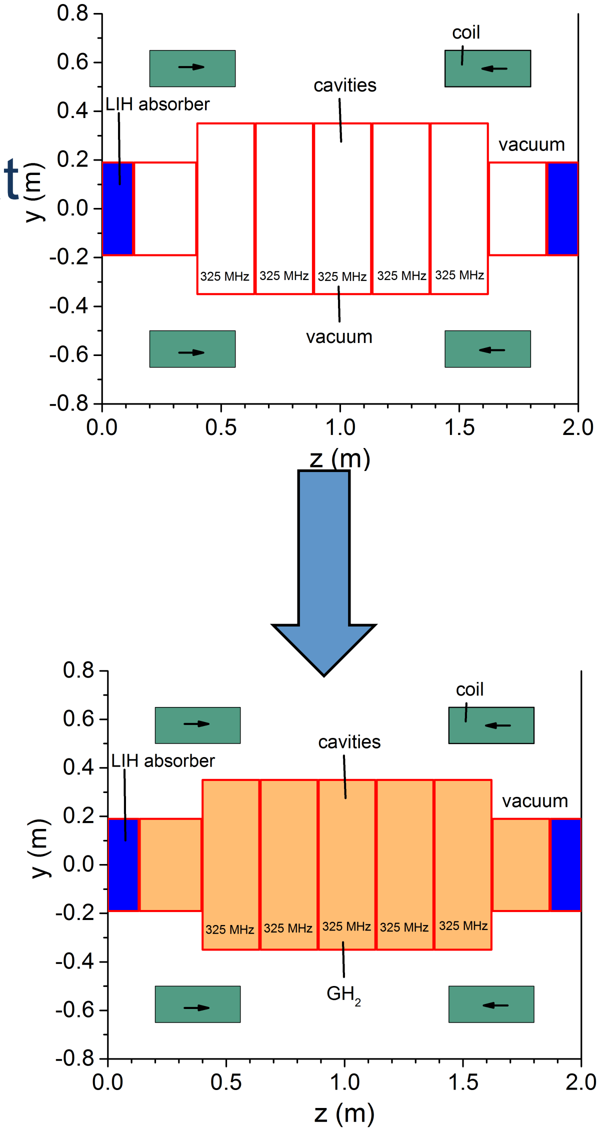
Emittance evolution plot: reaching 0.28 mm in transverse emittance and 1.57 mm in longitudinal emittance

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.

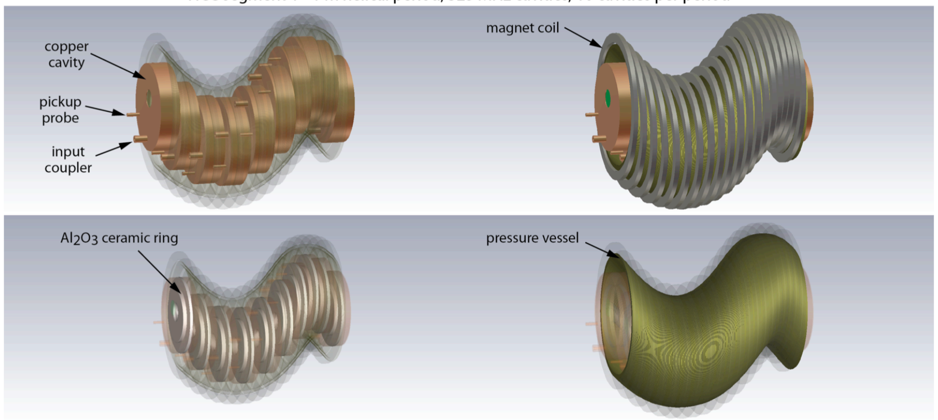
Hybrid cooling channel

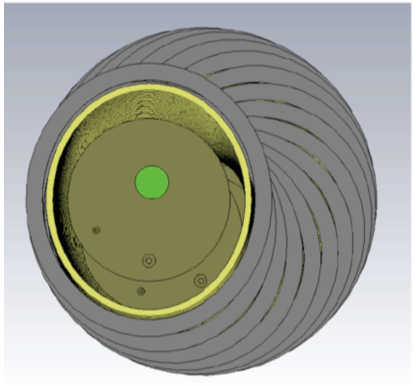
- One area of concern: breakdown of RF cavities in high magnetic fields.
  - Experiments at MTA have demonstrated that using cavities filled with high-pressure gas can prevent breakdown.
- An important recent conceptual development: reconsideration of a hybrid cooling channel
  - rectilinear channel 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.
- See talk by Diktys Stratakis.



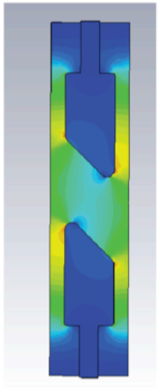
Helical cooling channel (HCC)

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

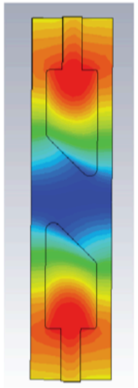




front view



E-field

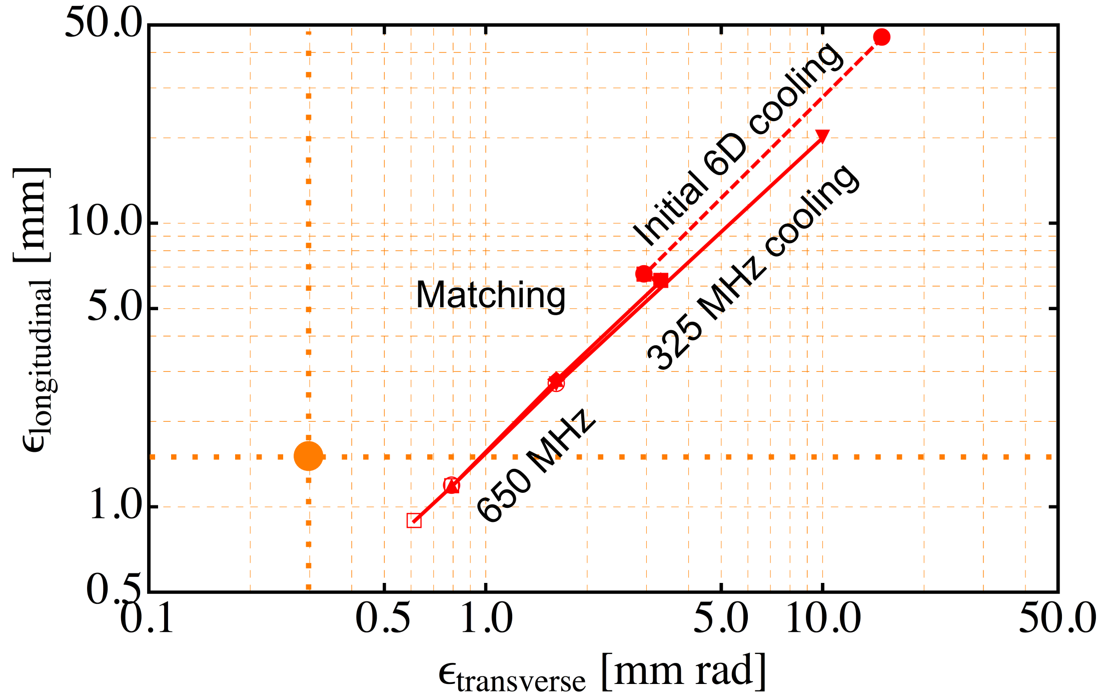


H-field

- 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.
  - Proceeded with dielectric loaded HPRF test, helical Nb_3Sn coil test, and RF window study.
  - Wake field studies with high order modes.

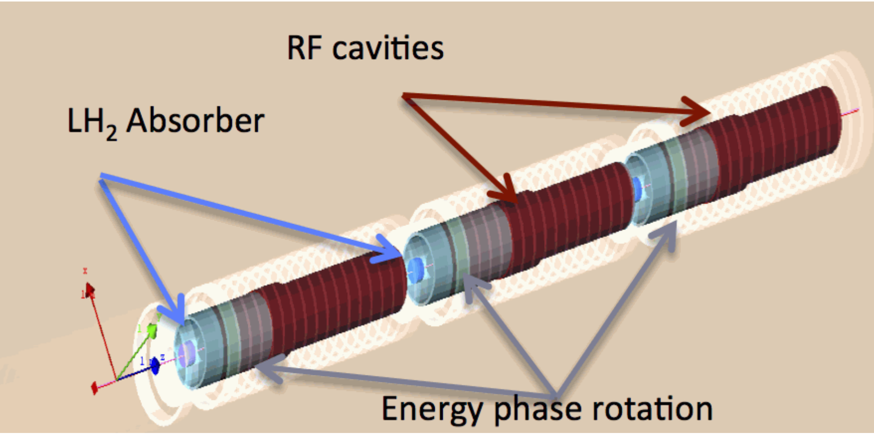
HCC, contd.

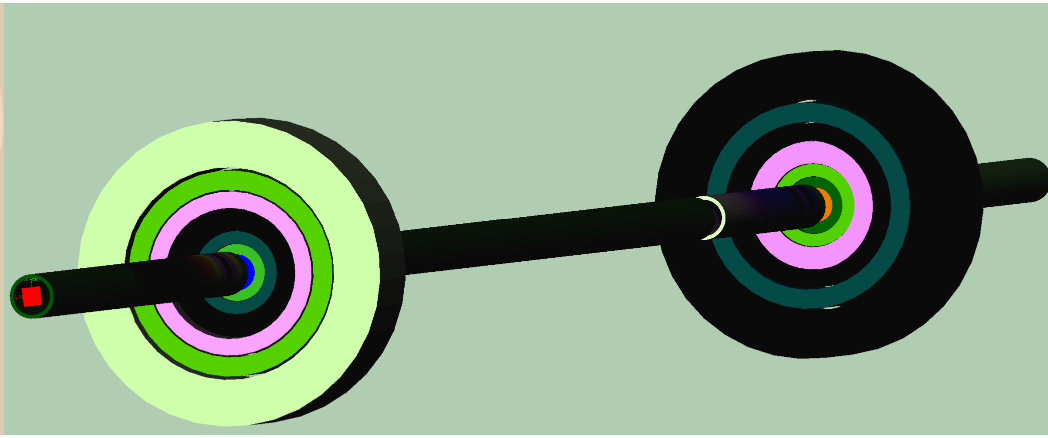
- Matching: transmission improved 56 % → 72%
- 6D HCC:
  - RF parameters:
    - E = 20 MV/m,
    - f = 325 & 650 MHz
  - gas pressure:
    - 160 atm at 300 K,
    - 43 atm at 80 K
  - magnetic fields:
    - B_z = 4-12 T
- Equilibrium emittance
  - e_T = 0.6 mm
    - (goal: 0.3 mm)
  - e_L = 0.9 mm
 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



- Transmission (one cooling section): ~60%
- Channel length (one cooling section): 380 m → 280 m
- See talk by Katsuya Yonehara

Final cooling





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.
- For details, see talk by Hisham Sayed (by phone).

- David Neuffer will present an alternative approach to final cooling.

Current and future activities

Current activities

- The main goals of this portion of the project is to develop 6D cooling concepts to reduce the emittance to produce bright muon beams:
  - understanding their performance limits,
  - making them affordable,
  - enabling a more cost effective downstream accelerator complex.
- We will specify and document the new generation of cooling channel lattices taking into account all recent experimental results.
  - Document current status of all the cooling channel designs
    - complete with the corresponding lattices, ideally, in ICOOL or G4beamline format
  - Prepare technology specification document.

Current activities, contd.

- The key driver is to enable an affordable Intensity Frontier facility after LBNF (i.e., a Neutrino Factory).
- Develop the performance specifications for other applications of cold muon beams.
  - See also talk by Yuri Alexahin.
- Incorporate MICE Step IV cooling results into cooling codes.
  - MICE makes it possible to infer quantitatively the energy loss, scattering, and straggling of muons in materials such as liquid hydrogen and LiH at momentum ~200 MeV/c.
    - Will work with MICE experimentalists and data analysts to determine the beam-material interaction properties of muons, and incorporate these new results into cooling codes.

Session agenda

Session agenda

- 14:00 Hybrid Cooling Channel 20'
- Speaker:Dr. Diktys Stratakis (Brookhaven National Laboratory)

- 14:20 Progress on the Helical Cooling Channel D&S 20'
- Speaker:Katsuya Yonehara (Fermilab)

- 14:40 Ionization Cooling for Muon Experiments 20'
- Speaker:Yuri Alexahin (Fermilab)

- 15:00 Approaches to Final Cooling 20'
- Speaker:Dr. David Neuffer (Fermilab)

- 15:20 Bunch Merge 15'
- Speaker:Dr. Yu Bao (University of California Riverside)

- 15:35 Final Cooling Update 15'
- Speaker:Dr. Hisham Sayed (Brookhaven National Laboratory)

Thank you!