Bright Muon Sources

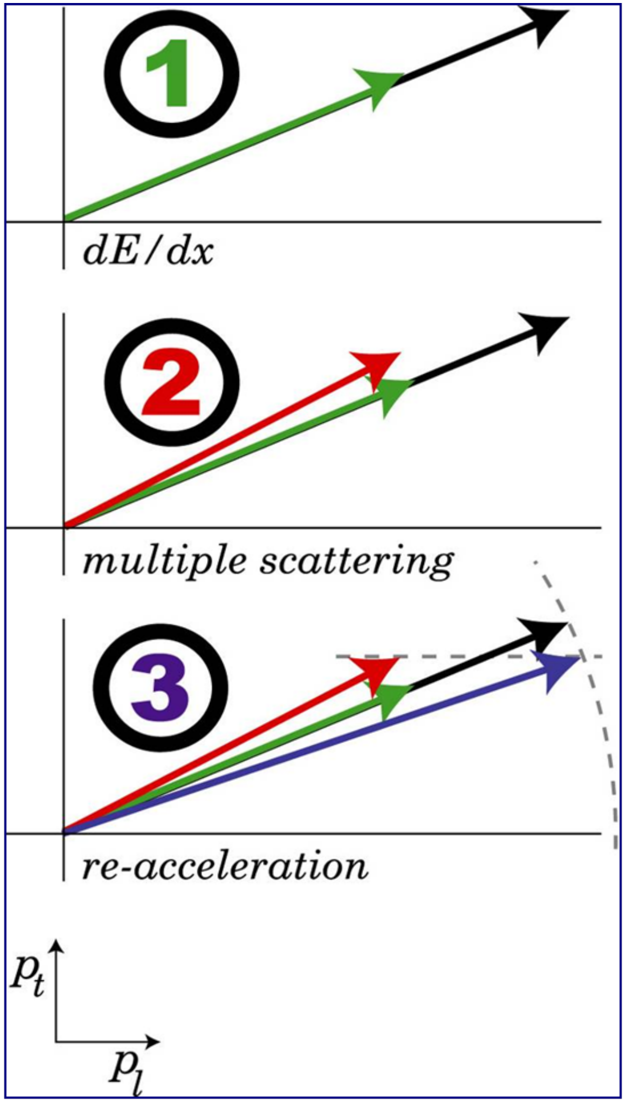
Pavel Snopok
Illinois Institute of Technology and Fermilab

August 12, 2015

Outline

- Introduction
- High-intensity muon beams
  - Target
  - Front end
- High-brightness muon beams
  - Initial cooling
  - 6D cooling (VCC and HCC)
  - Final cooling
- Summary

Ionization cooling

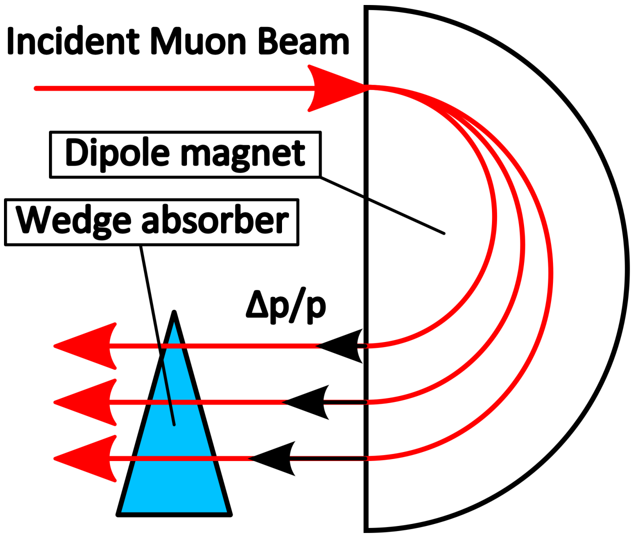


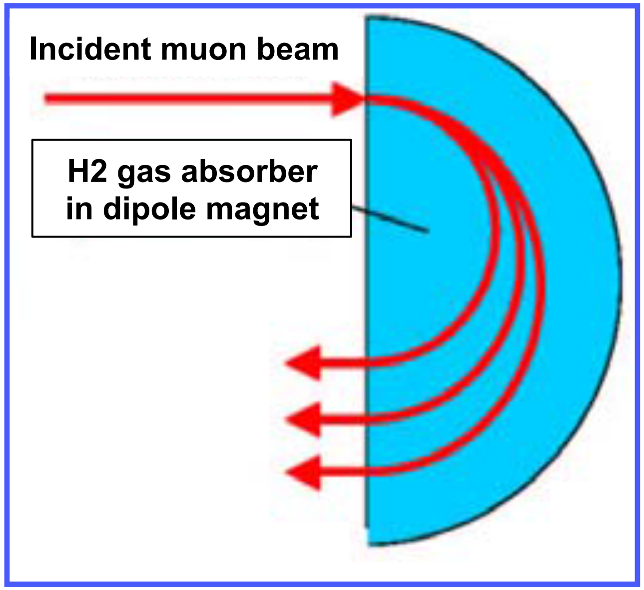
$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014 GeV)^2}{2\beta^3 E_\mu m_\mu X_0}$$

- $d\varepsilon_n/ds$ 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.

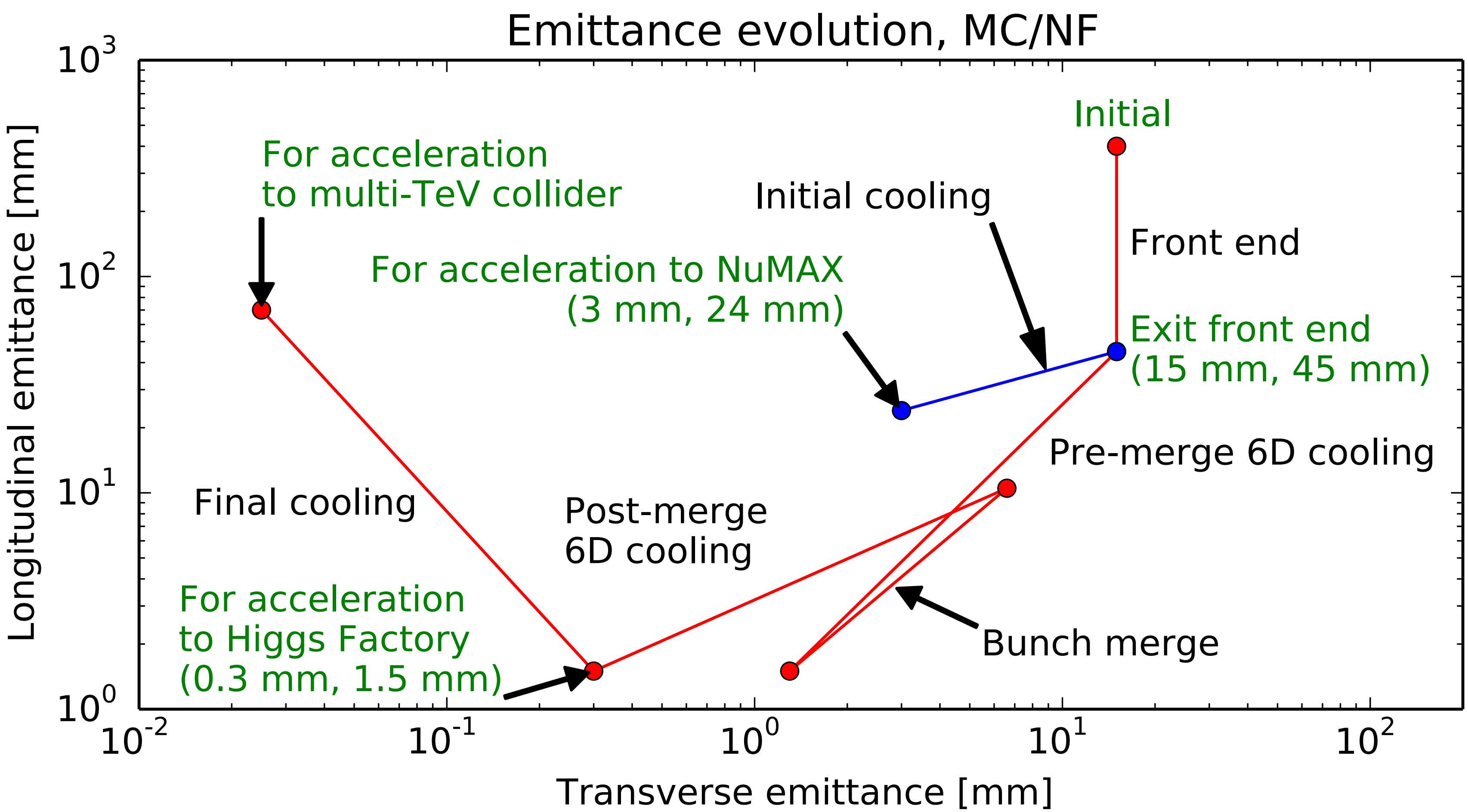
6D cooling via emittance exchange





- 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).

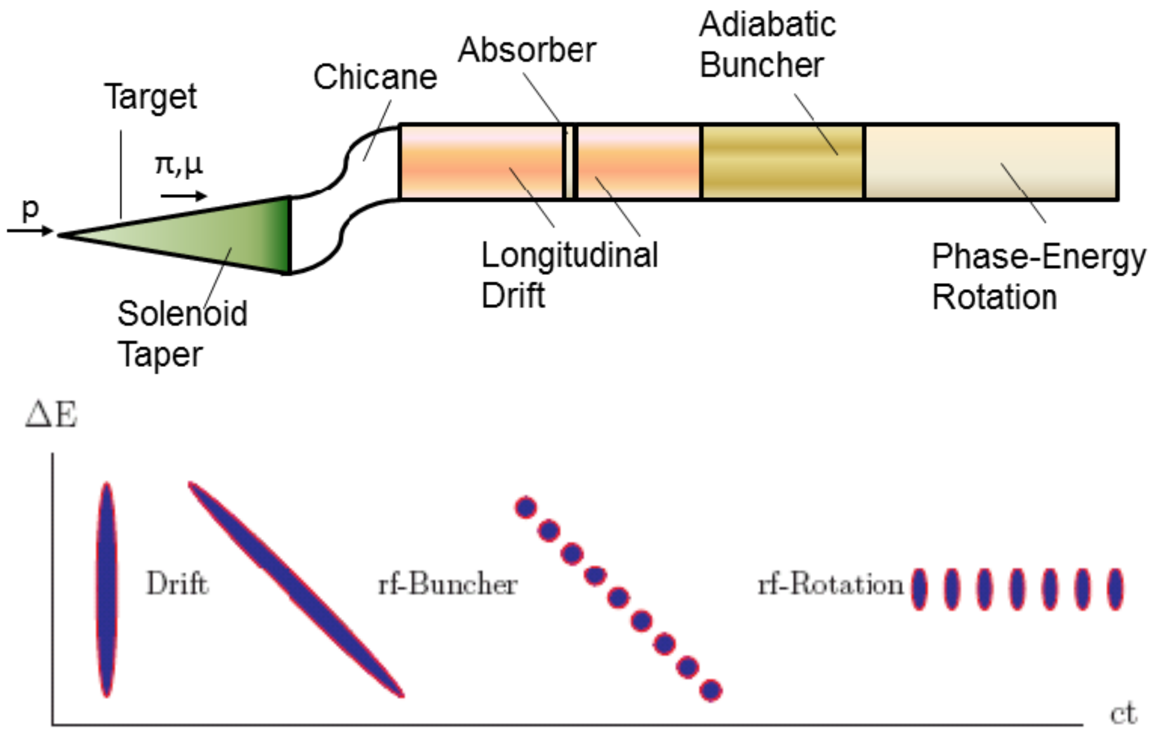
Emittance evolution diagram



Target and Front End

High-intensity muon source

- Captures muons that result from the decay of pions that are produced by a high intensity proton beam impacting a target
- Performs initial phase space manipulation of these muons to make them well-suited to subsequent accelerator systems

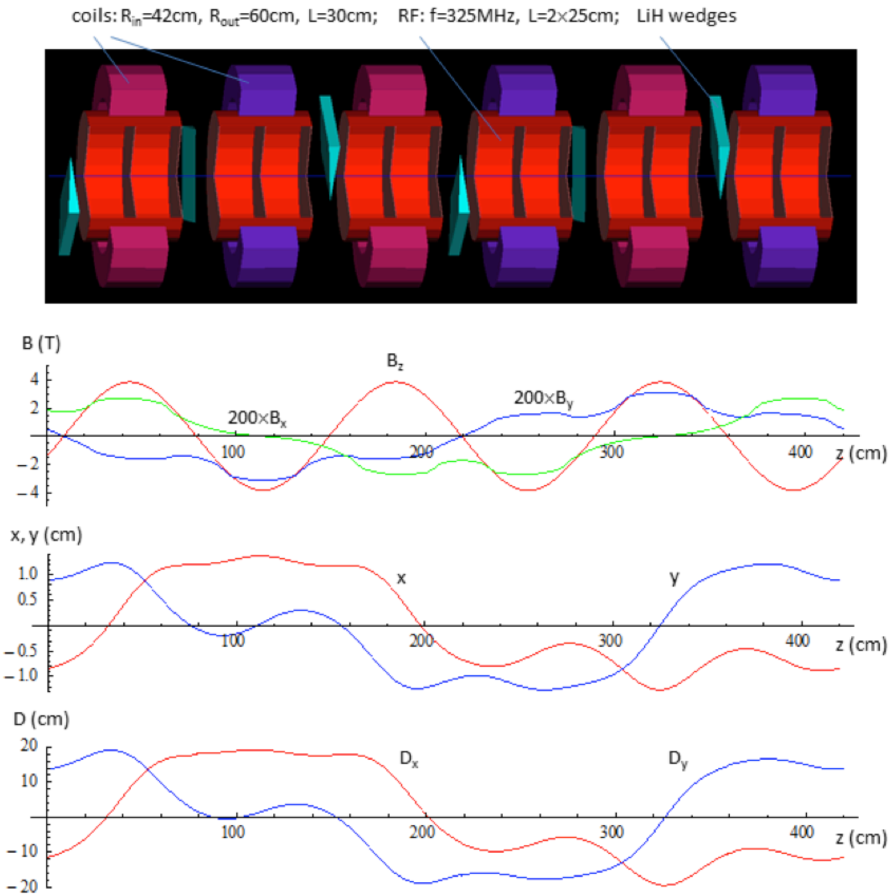


Main components:

- Target (topic of a dedicated talk by Kirk McDonald on Friday at 14:30)
- Chicane (to eliminate high energy protons)
- Drift channel (π to μ decay) with a proton absorber (for low energy protons)
- Buncher and phase rotator for producing a train of bunches

Initial Cooling

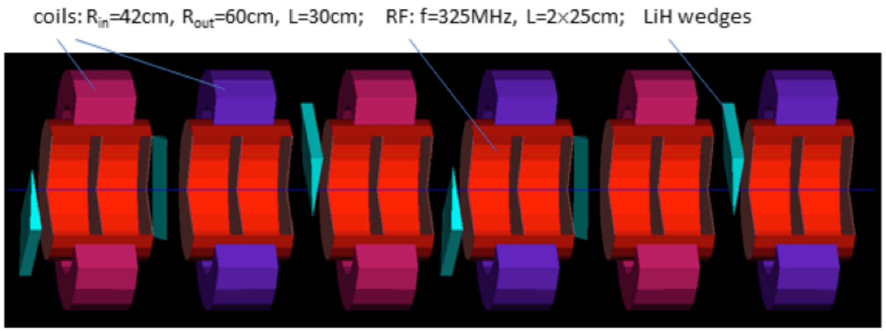
Initial cooling, contd.

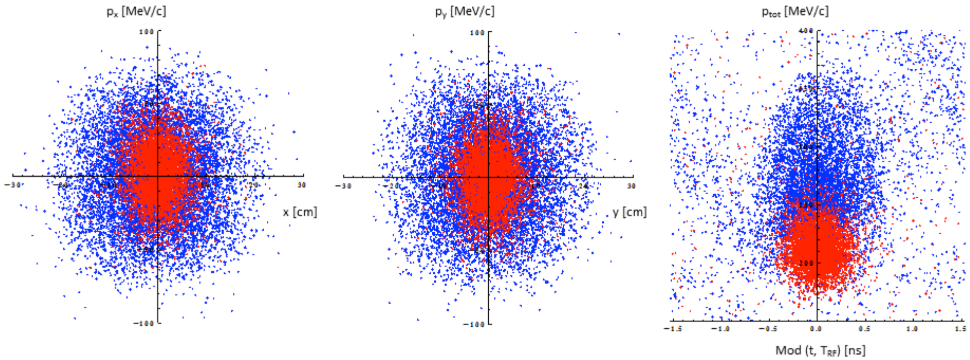


One period of the HFOFO lattice (top), magnetic field for muon momentum 230 MeV/c (second from top), μ^+ equilibrium orbit and dispersion (two bottom plots).

- 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

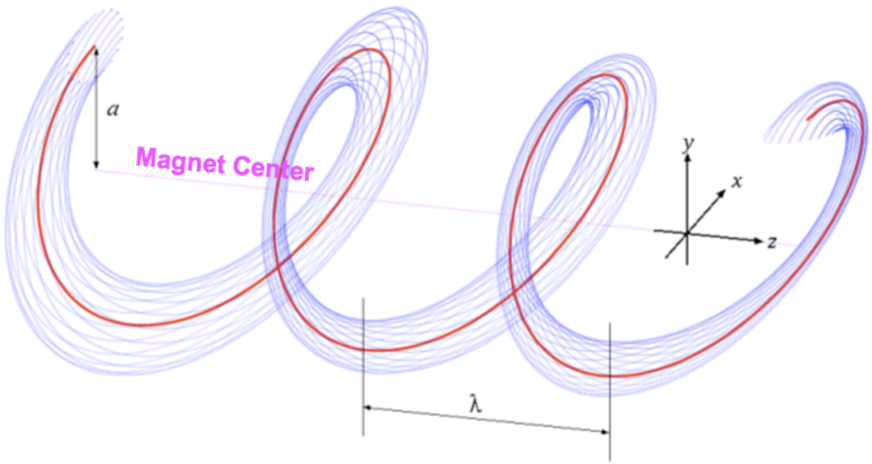


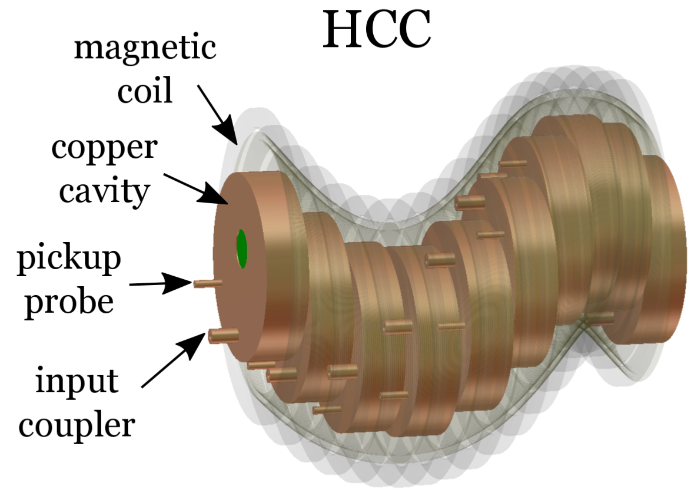


- Initial cooling channel:
  - Get into 6D cooling mode right away.
  - Capable of cooling both charges simultaneously (cost reduction).
  - Preliminary design concepts for both vacuum and gas-filled RF cavities (documented, along with lattice files).
  - Improved matching from Initial Cooling section to Helical Cooling Channel (HCC).

Helical Cooling Channel (HCC)

Helical Cooling Channel (HCC)

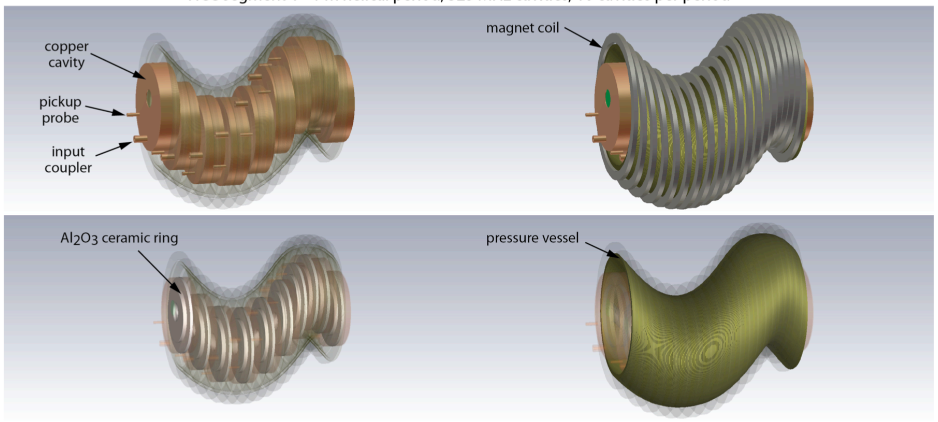


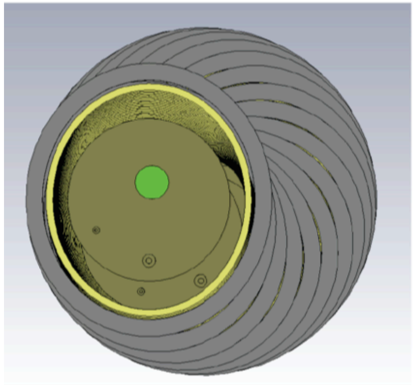


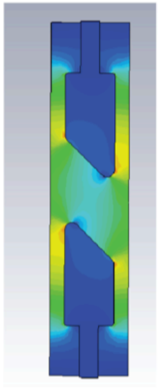
- Dense hydrogen gas distributed homogeneously in a continuous dispersion lattice (no periodic lattice)
- Particle tracking in HCC:
  - red: reference particle
  - particle motions (blue) are periodic by coupling in xyz planes
    - Complete linear dynamics: Ya.S. Derbenev & R.P. Johnson, PRSTAB 8 041002 (2005)

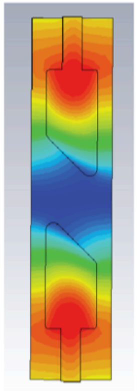
- Innovate helical beam line element:
  - Hydrogen gas-filled RF cavity
    - GH2 is the best cooling material
    - GH2 suppresses RF breakdown
  - Helical solenoid coil
  - Magnetron (great energy efficiency)

HCC, contd.





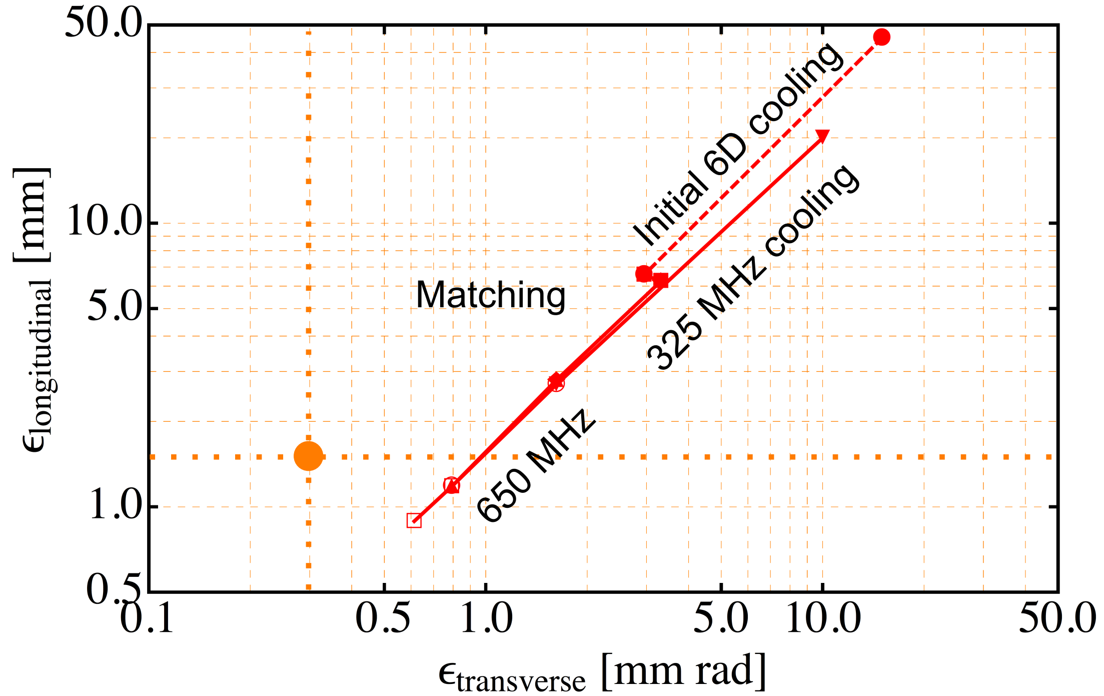




- High-pressure RF helical cooling channel (HCC):
  - Lattices + start-to-end simulations.
  - Lattice is optimized to increase transmission efficiency.
  - Studies of gas-plasma interactions and plasma chemistry are ongoing.
  - Dielectric loaded HPRF test, helical Nb_3Sn coil test, and RF window study were carried out.

HCC, contd.

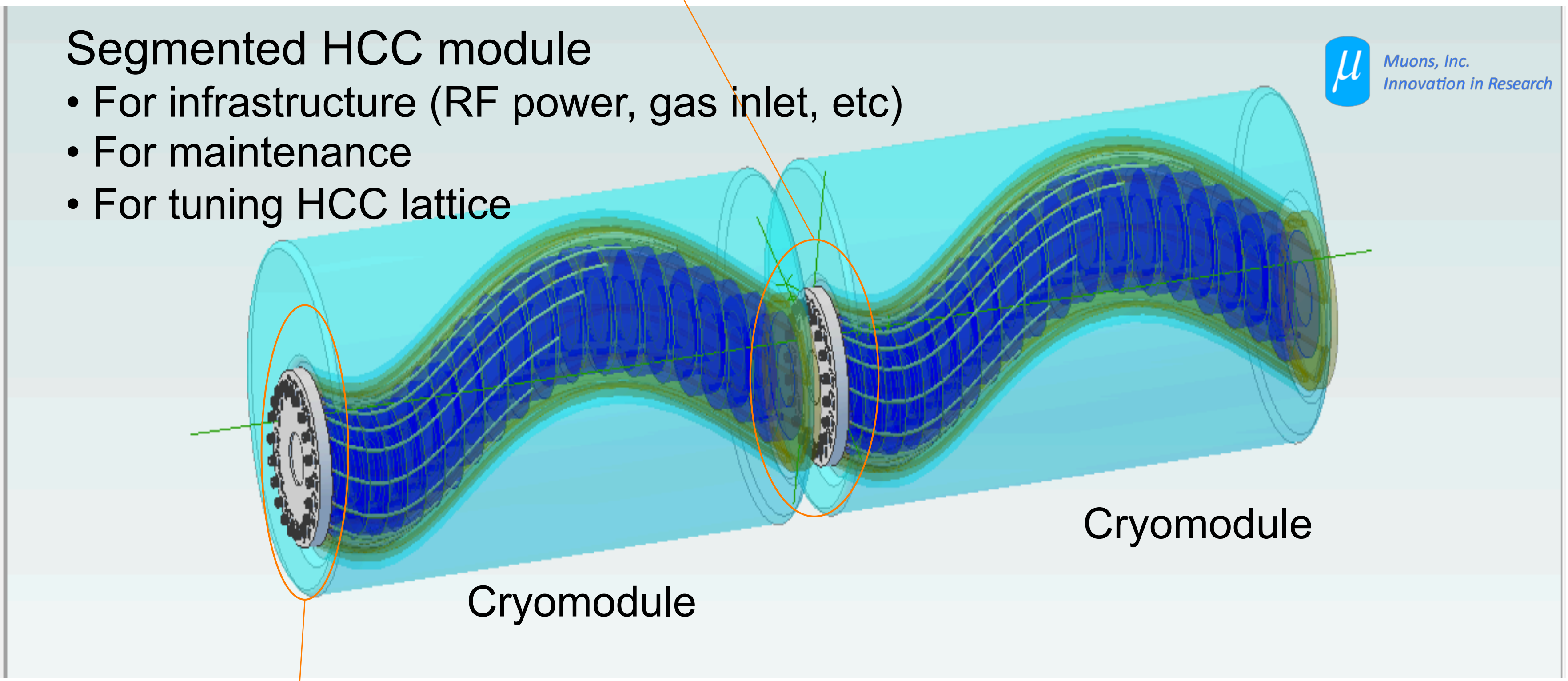
- Matching: transmission improved 56 % → 72%
- 6D HCC:
  - RF parameters:
    - E = 20 MV/m,
    - f = 325 & 650 MHz
  - gas pressure:
    - 160 atm at 300 K,
    - 43 atm at 80 K
  - magnetic fields:
    - B_z = 4-12 T
- Equilibrium emittance
  - e_T = 0.6 mm
    - (goal: 0.3 mm)
  - e_L = 0.9 mm
 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



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

HCC cryomodule

Use the pressure sealing technology to connect adjacent module which has been developed in the gas-filled RF cavity project



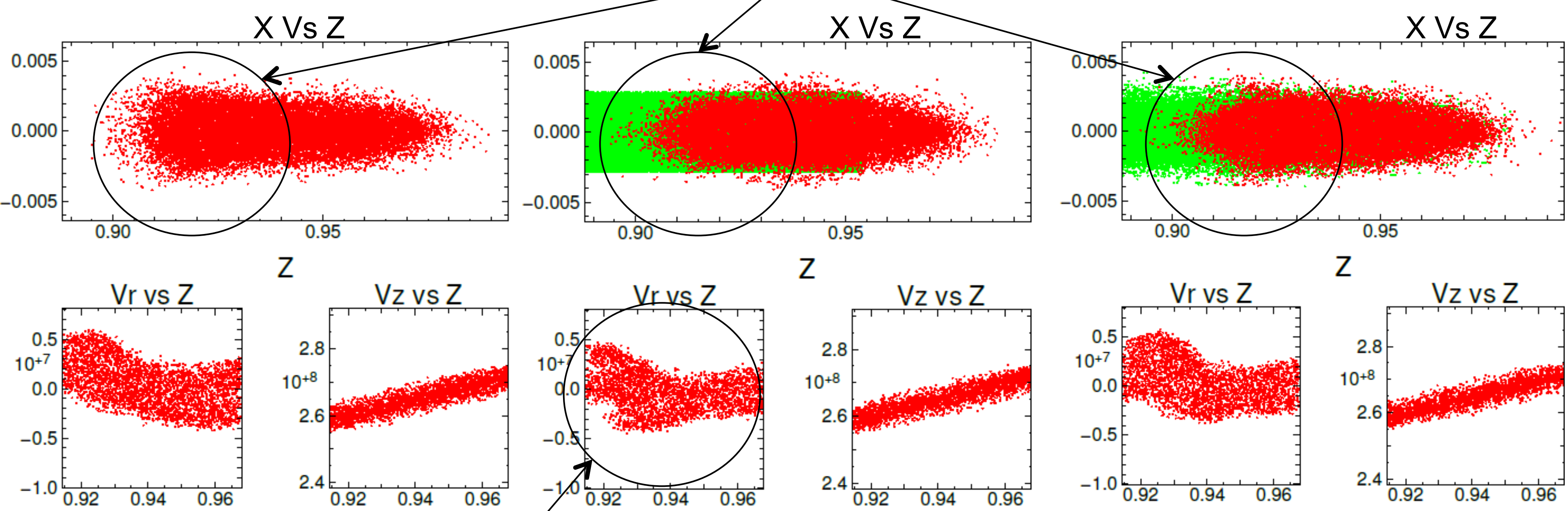
RF power & gas inlet & coolant & current conductor access from each end plate

Beam-plasma interaction in gas-filled RF cavities

J. Ellison

No plasma | Manually added | WARP added

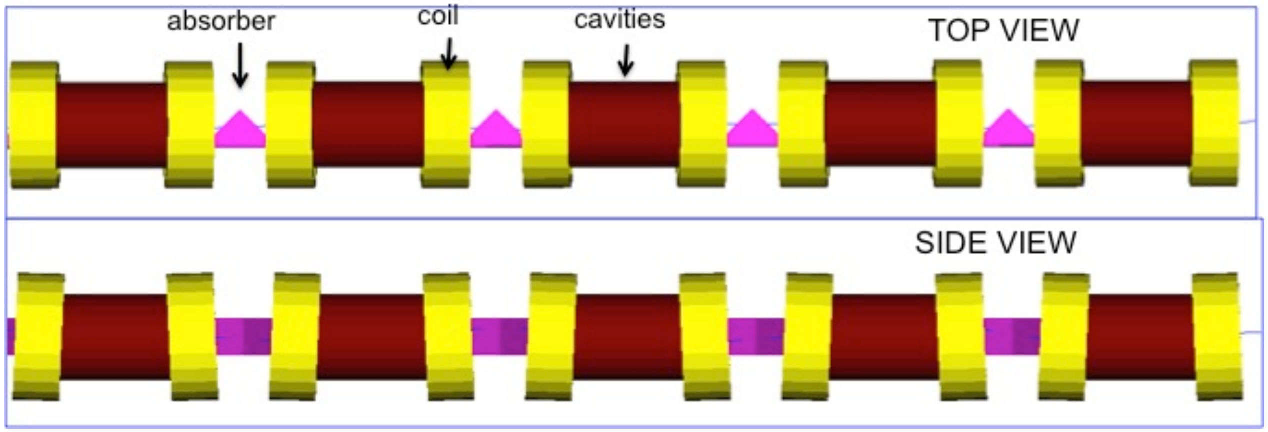
Less spread in bunch tail due to charge neutralization

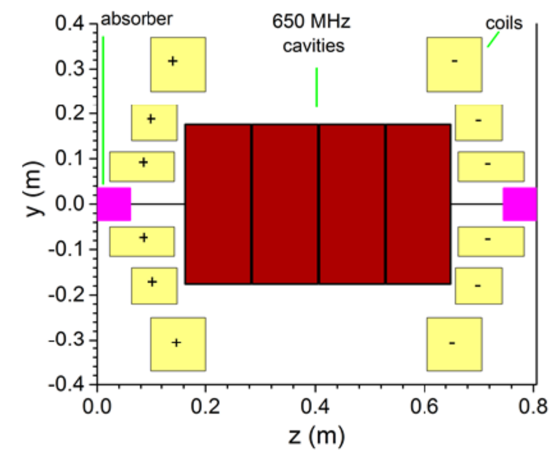


Edge effect from uniform cylinder

Rectilinear Vacuum Cooling Channel (VCC) and Hybrid Cooling Channel

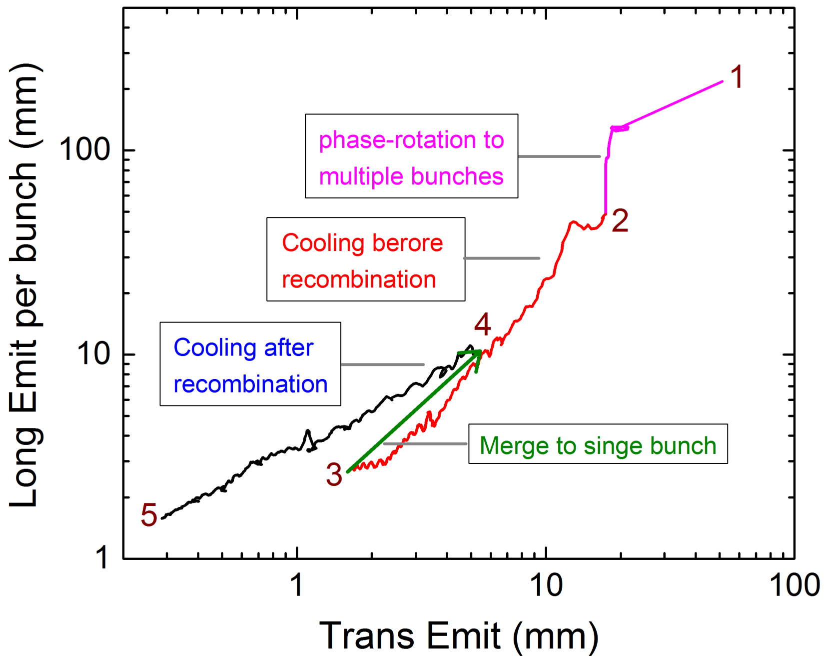
Vacuum RF cooling channel (VCC)

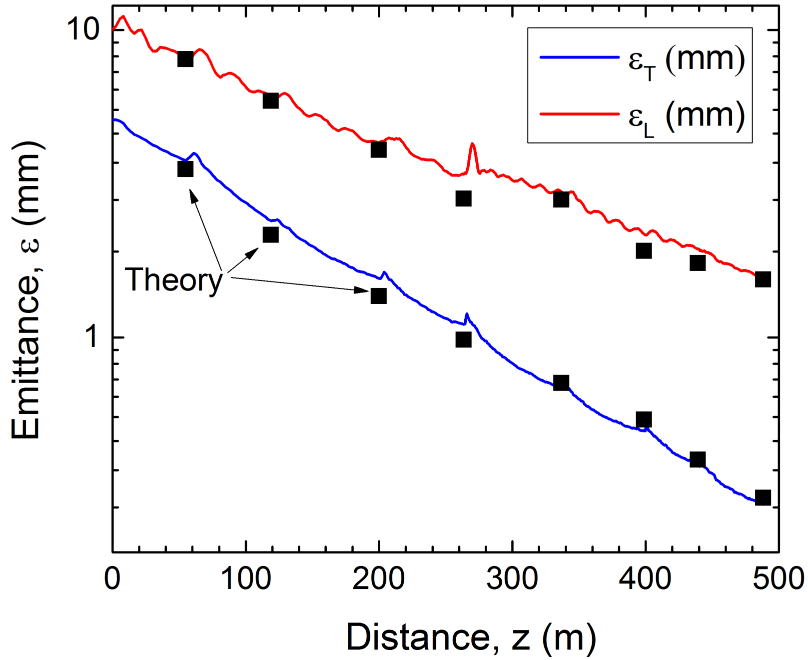




- Vacuum RF cooling channel (VCC):
  - Lattices + start-to-end simulations.
  - Lattices optimized and achieved emittance goals specified by MAP.
  - Progress on bunch merge.
  - Investigation of window effects.
  - Thermal & mechanical analysis of RF windows.
  - Magnet design.
  - Significant improvement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

VCC, contd.





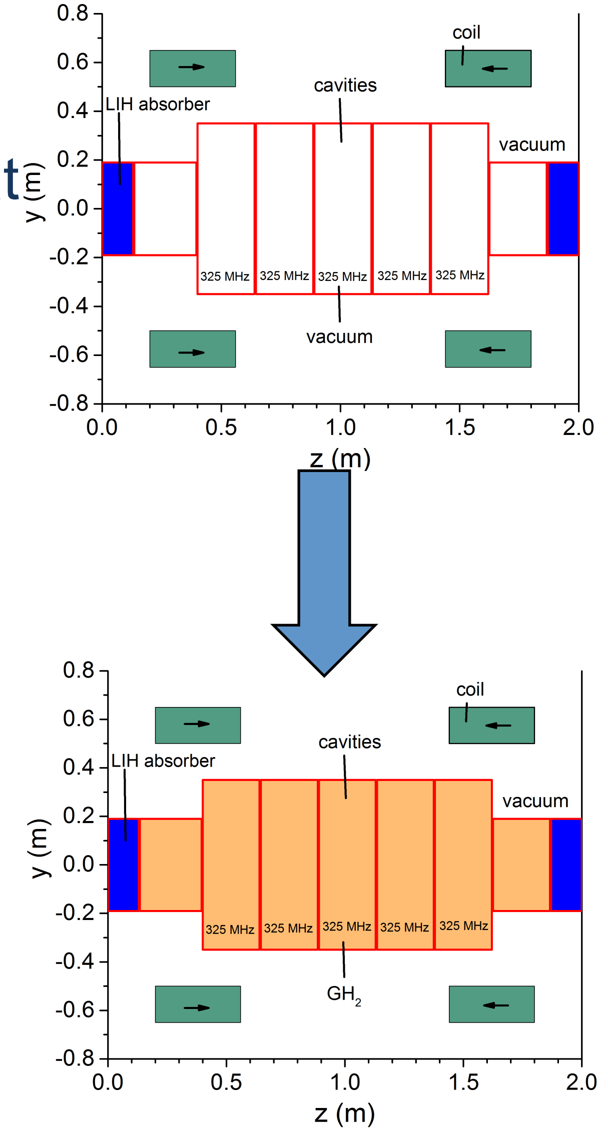
Emittance evolution plot:
reaching 0.28 mm in transverse emittance
and 1.57 mm in longitudinal emittance

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.

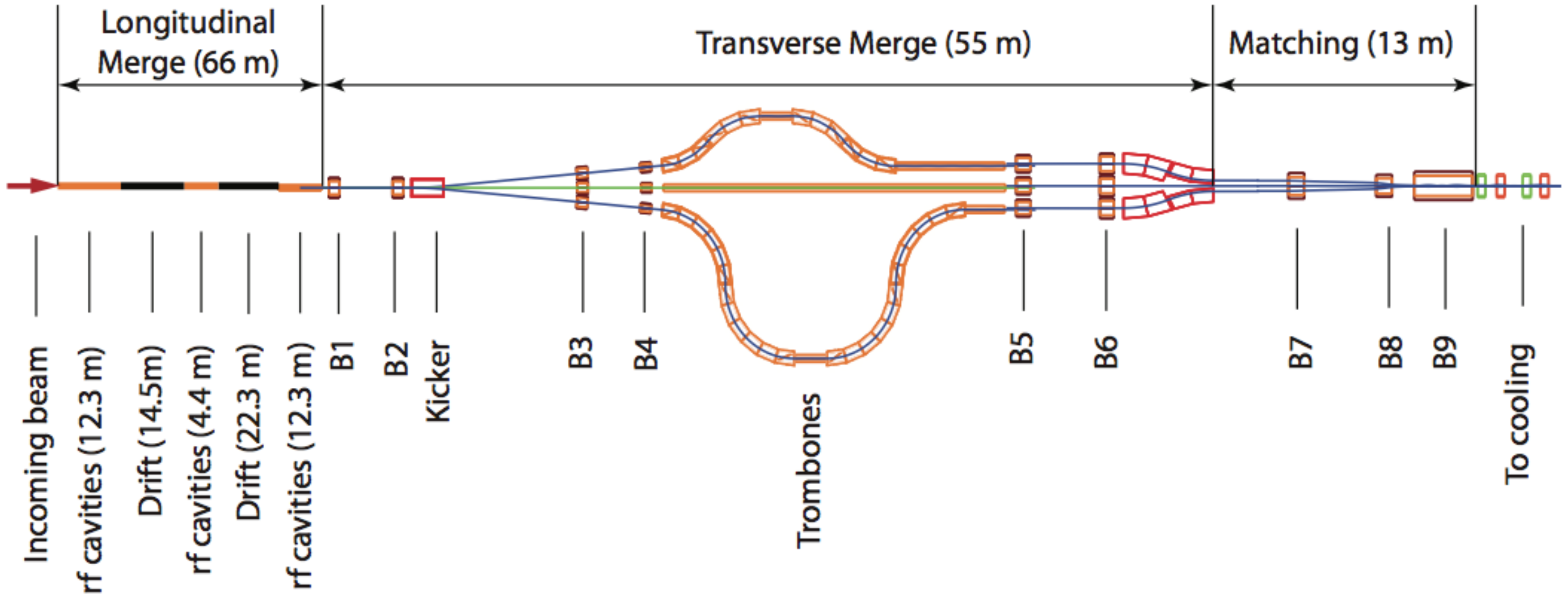
Hybrid cooling channel

- 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 the next talk by Diktys Stratakis.



Bunch Merge

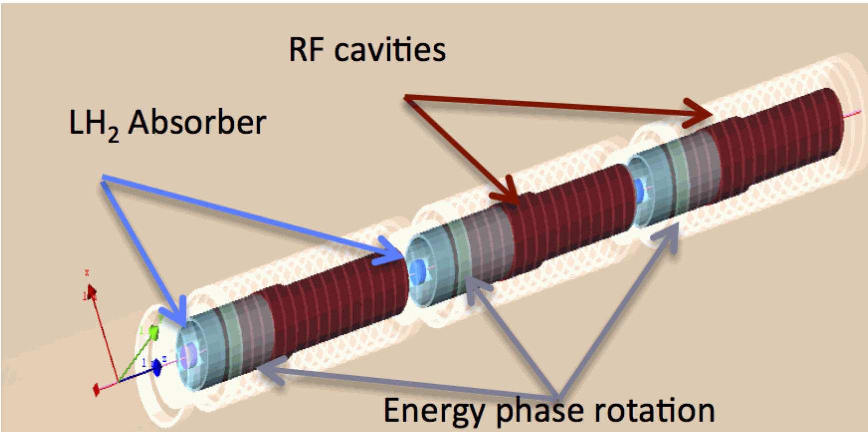
Bunch Merge

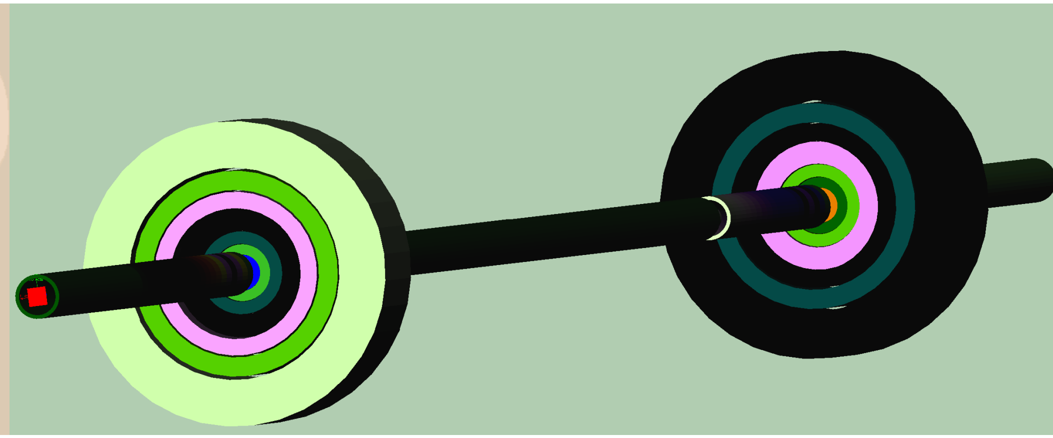


- Longitudinal merge: 21 to 7 bunches
- Transverse merge: 7 bunches to 1
  - kicker magnet sending each bunch one of the…
  - trombones of different length…
  - so that all the bunches arrive at the same time;
  - followed by a funnel and a matching section
- End-to-end simulation by Yu Bao (UC Riverside)

Final Cooling

Final cooling





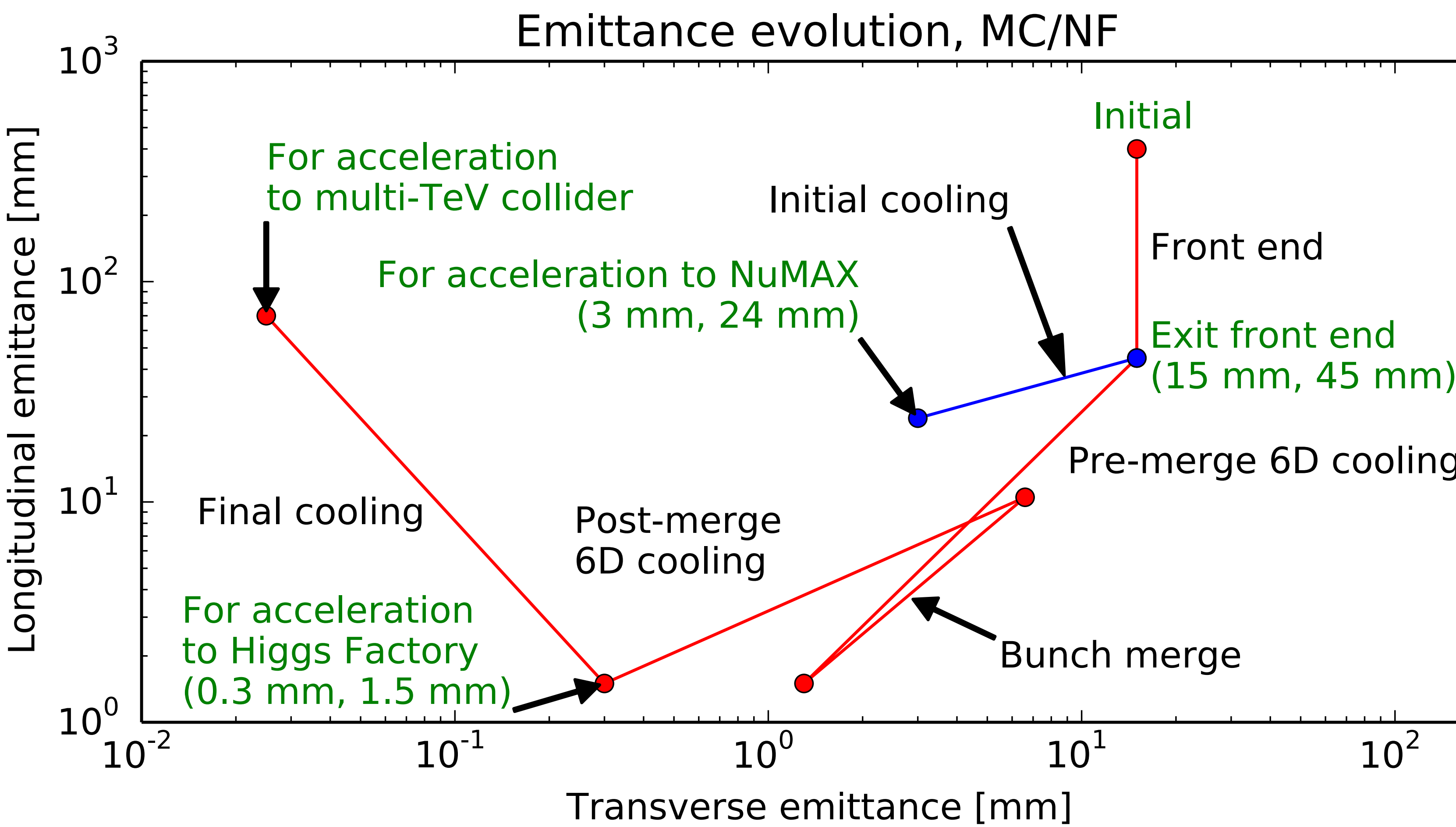
Early stages: RF inside transport solenoid coils

Late stages: transport solenoid coils inside induction linac

- Final cooling channel design with 30-25 T focusing field.
- Complete design of a high field cooling channel: transverse emittance 55 μm (40 T could reach 25 μm), longitudinal ≈75 mm.

- For details and alternative approaches see talk by Mark Palmer later in the session.

Summary



Emittance evolution, MC/NF
Initial
For acceleration
to multi-TeV collider
Initial cooling
Front end
For acceleration to NuMAX
(3 mm, 24 mm)
Exit front end
(15 mm, 45 mm)
Pre-merge 6D cooling
Final cooling
Post-merge
6D cooling
For acceleration
to Higgs Factory
(0.3 mm, 1.5 mm)
Bunch merge
Longitudinal emittance [mm]
Transverse emittance [mm]
10^{3}
10^{2}
10^{1}
10^{0}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

Thank you!