Ionization Cooling

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US Muon Collider Community Meeting

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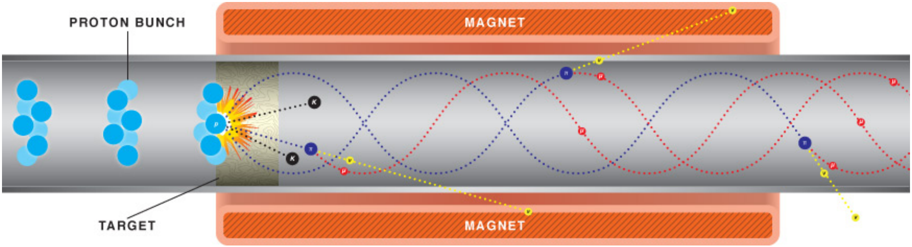
Deja Vu: 2004 NFMCC meeting at Riverside, CA

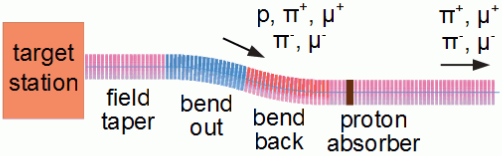
Front End

Decay channel

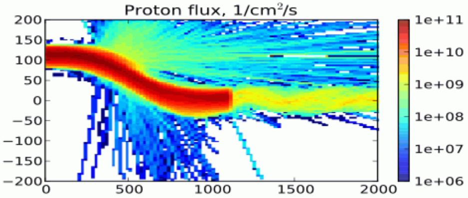


- Above: simplified artistic representation of the decay channel.
- Issues:
  - Need to get rid of high-energy protons.
  - Need to get rid of low-energy protons.
  - Need to keep heat/radiation load on coils at bay (we are in 2-2.5 T solenoidal field that focuses our particles).

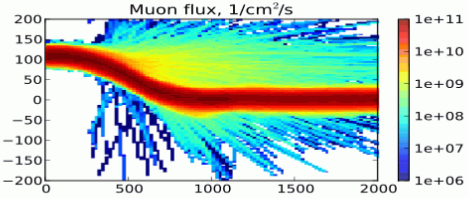
Chicane



Chicane schematics

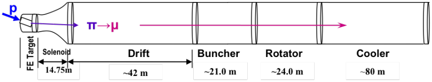


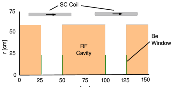
Proton flux, $1/cm^2/s$

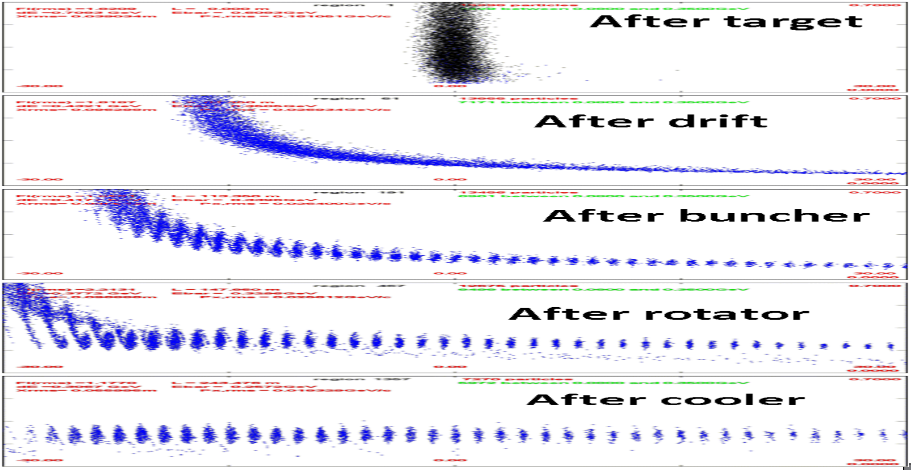


Muon flux, $1/cm^2/s$

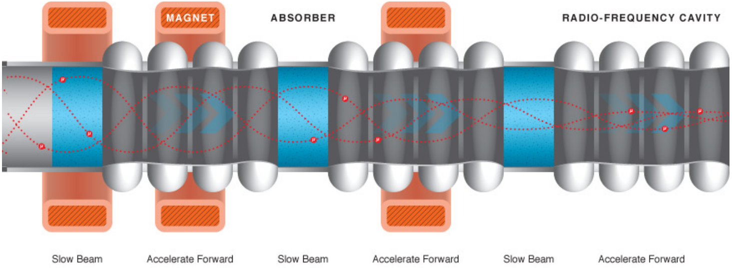
Front end and beam evolution





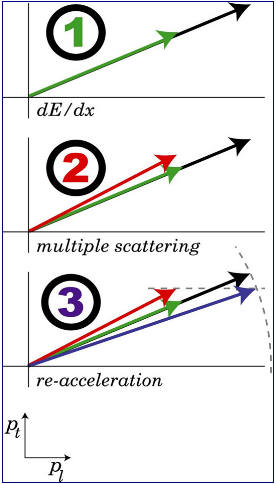


Muon Ionization Cooling: Why Cool?



- MC is a tertiary beam machine (p $\rightarrow \pi \rightarrow \mu$). Beams coming out of the target are very large.
- Need intense μ beam $\Rightarrow$ need to capture as much as possible of the initial large emittance.
- Large aperture acceleration systems are expensive $\Rightarrow$ for cost-efficiency need to reduce emittances prior to accelerating ("cool the beam").
- MC designs assume significant ($O(10^6)$) six-dimensional cooling.
- Need to act fast since muons are unstable. Ionization cooling option fits the bill.

Ionization cooling principle

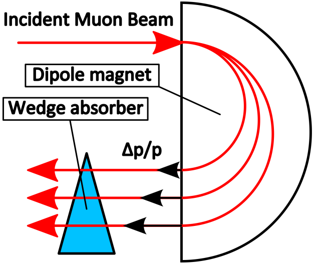


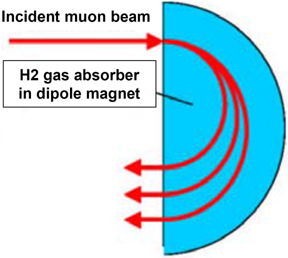
$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (13.6\,MeV/c)^2}{2\beta^3 E_\mu m_\mu X_0},$$

where $d\epsilon_N/ds$ 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-acceleration to restore energy lost in material. Only the longitudinal component of momentum is affected.

Emittance exchange or “How to cool in 6D”





- Emittance exchange principle: instead of letting the beam with zero dispersion through a flat absorber, we introduce dispersion and let the particles with higher momentum pass through more materials, 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).

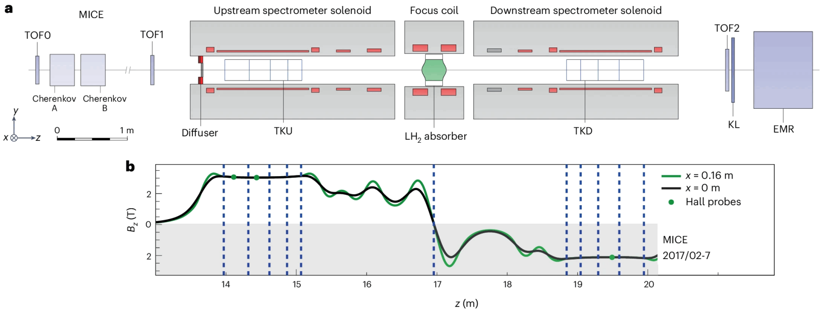
Theoretical vs practical

- Ionization cooling principles were established in the 1970's[1].
- Lots of subtleties ⇒ experiment is essential.
- One of the main aims of the international Muon Ionization Cooling Experiment (MICE) was to demonstrate transverse ionization cooling.
- Publications:
  - Demonstration of cooling signal by observing an increase in the phase-space density in the core of the beam on passage through an absorber:
    MICE collaboration. “Demonstration of cooling by the Muon Ionization Cooling Experiment.” Nature 578, 53–59 (2020).
    `https://doi.org/10.1038/s41586-020-1958-9`
  - Quantification of the ionization cooling signal by measuring the change in normalized transverse emittance:
    MICE Collaboration. “Transverse emittance reduction in muon beams by ionization cooling.” Nat. Phys. (2024).
    `https://doi.org/10.1038/s41567-024-02547-4`

[1] G.I. Budker, in: Proceedings of 15th International Conference on High Energy Physics, Kiev, 1970 A.N. Skrinsky, Intersecting storage rings at Novosibirsk, in: Proceedings of Morges Seminar, 1971 Report CERN/D.PH II/YGC/mng.

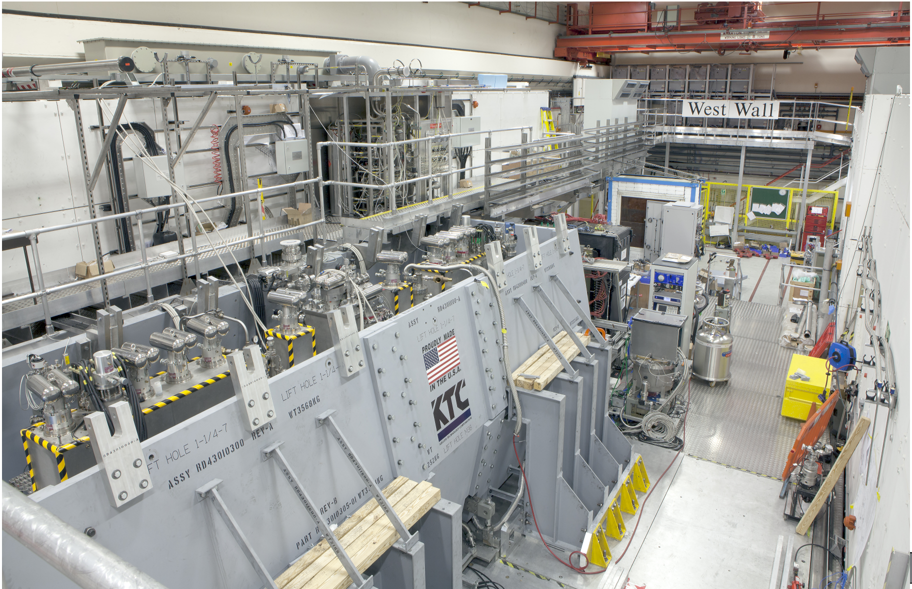
MICE: Muon Ionization Cooling Experiment

MICE and its objectives

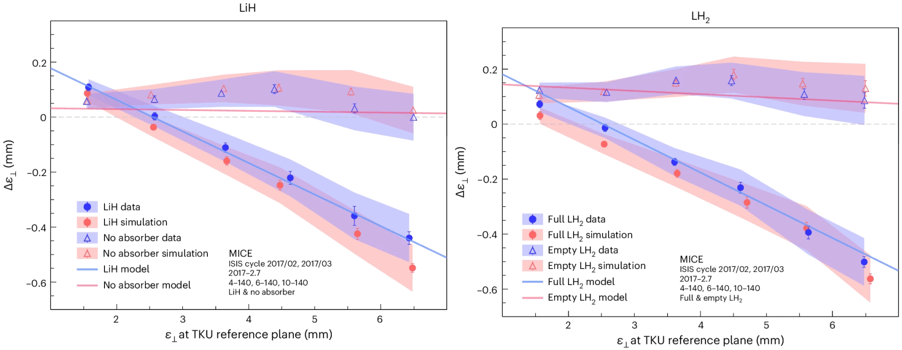


- Design, engineer and fabricate a section of cooling channel.
- Place the cooling apparatus in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of ionization cooling.
- Measure a reduction in transverse beam size with a precision of 1%.
- Develop and thoroughly test simulation and data analysis software.
- Demonstrate transverse emittance reduction.

MICE Step IV on the floor



MICE: transverse emittance change



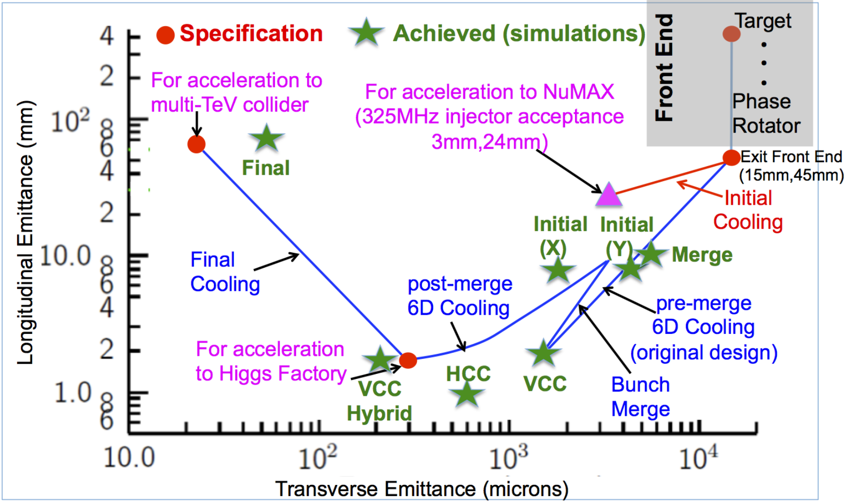
- Emittance change between the upstream and downstream reference planes, $\Delta\varepsilon_\perp$, as a function of emittance at the upstream plane for 140 MeV$/c$ beams crossing the LiH (left) and LH2 (right) MICE absorbers. Results for the empty cases, namely, “No absorber” and “Empty LH2,” are also shown. The measured effect is shown in blue, the simulation – in red.

MICE: summary

- MICE measurement is an important development towards the muon cooling demonstrator, a key intermediary step in the pursuit of a muon collider.
- The demonstration of ionization cooling by the MICE collaboration constitutes a substantial and encouraging breakthrough in the research and development efforts to deliver high-brightness muon beams suitable for high-intensity muon-based facilities.
- MICE measurement demonstrates the viability of this beam cooling technique as a means of producing low-emittance muon beams for a muon collider or a neutrino factory.
- To achieve MC emittance targets, substantial longitudinal and transverse emittance reduction is required, which must be demonstrated.
- The muon beam must traverse multiple cooling cells that produce magnetic fields stronger than those achieved by MICE and which contain high-gradient radio-frequency cavities to restore the beam longitudinal momentum.

Cooling channels

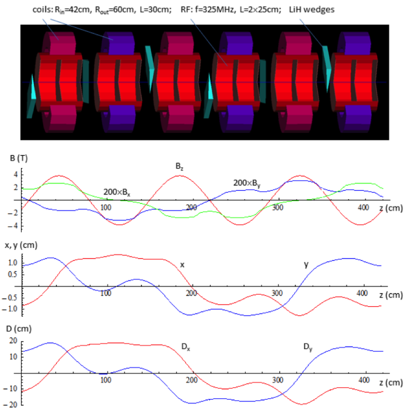
Emittance evolution diagram



Cooling channels for different applications

Initial cooling

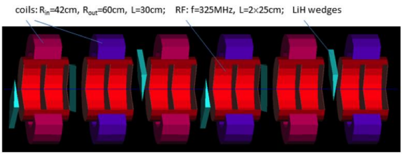
Initial cooling

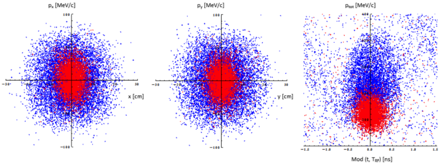


One period of the HFOFO lattice (top), magnetic field for muon momentum 230 MeV/*c* (second from top), μ^+ equilibrium orbit and dispersion (two bottom plots).

- Focusing field is created by alternating solenoids, inclined in rotating planes (0°, 120°, 240°, etc.)
- μ^- and μ^+ orbits have 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

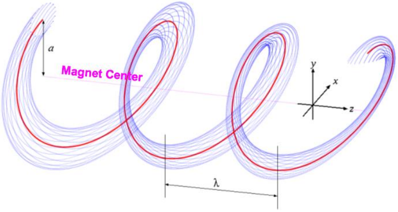


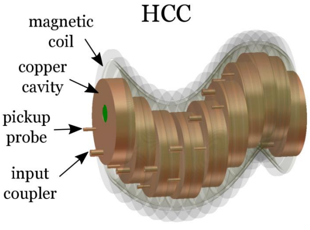


- Initial cooling channel:
  - Get into 6D cooling mode right away.
  - Capable of cooling both charges simultaneously (cost reduction).
  - Preliminary design concepts for both vacuum and gas-filled RF cavities (documented, along with lattice files).
  - Improved matching from Initial Cooling section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

Helical cooling channel

Helical Cooling Channel (HCC)

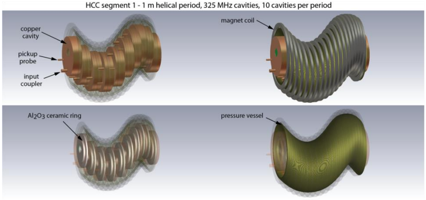


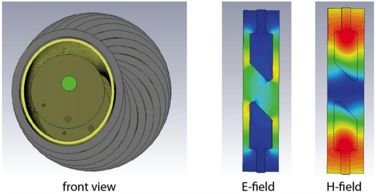


- Dense hydrogen gas distributed homogeneously in a continuous dispersion lattice (no periodic lattice)
- Particle tracking in HCC:
  - red: reference particle
  - particle motions (blue) are periodic by coupling in xyz planes
    - Complete linear dynamics: Ya.S. Derbenev & R.P. Johnson, PRSTAB 8 041002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

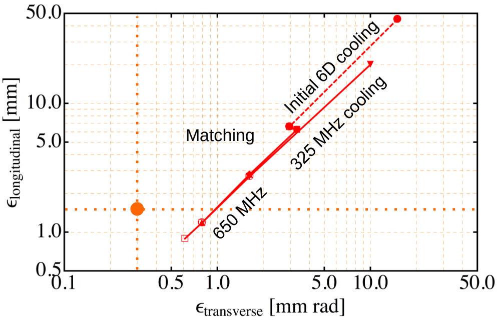




- High-pressure RF helical cooling channel (HCC):
  - Lattices + start-to-end simulations.
  - Lattice is optimized to increase transmission efficiency.
  - Preliminary studies of gas-plasma interactions and plasma chemistry were carried out.
  - Dielectric loaded HPRF test, helical Nb_3Sn coil test,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

HCC, contd.

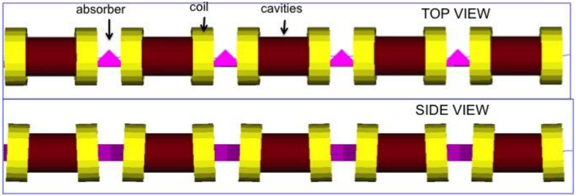
- Matching: transmission improved 56 % → 72%
- 6D HCC:
  - RF parameters:
    - E = 20 MV/m,
    - f = 325 & 650 MHz
  - gas pressure:
    - 160 atm at 300 K,
    - 43 atm at 80 K
  - magnetic fields:
    - B_z = 4-12 T
- Equilibrium emittance
  - e_T = 0.6 mm
    - (goal: 0.3 mm)
  - e_L = 0.9 mm
 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

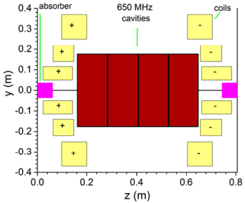


- Transmission (one cooling section): ~60%
- Channel length (one cooling section): 380 m → 280 m

Vacuum/hybrid cooling channel

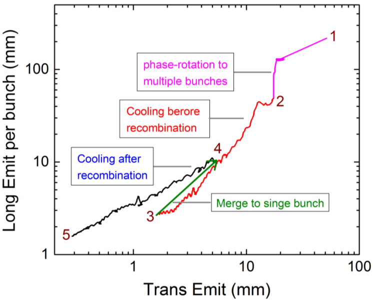
Vacuum RF cooling channel (VCC)

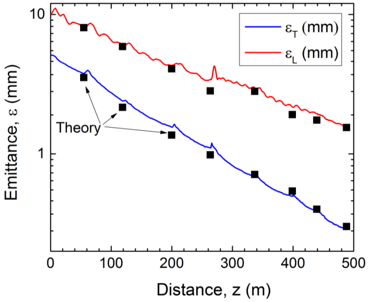




- Vacuum RF cooling channel (VCC):
  - Lattices + start-to-end simulations.
  - Lattices optimized and achieved emittance goals specified by the Muon Accelerator Program.
  - Progress on bunch merge.
  - Investigation of window effects.
  - Thermal & mechanical analysis of RF windows.
  - Magnet design.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

VCC, contd.





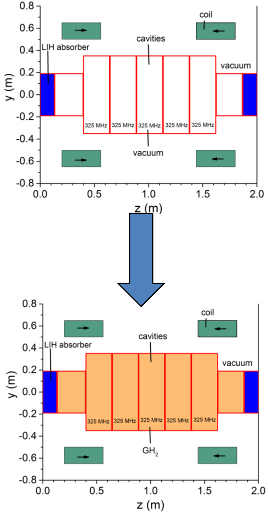
Emittance evolution plot:
reaching 0.28 mm in transverse emittance and 1.57 mm in longitudinal emittance

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.

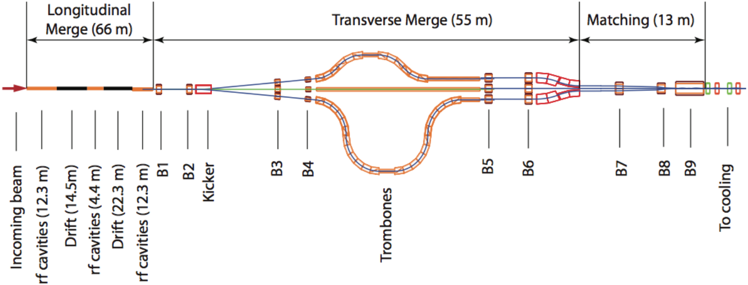
Hybrid cooling channel

- One area of concern: breakdown of RF cavities in high magnetic fields.
  - Experiments at MuCool Test Area have demonstrated that using cavities filled with high-pressure gas can prevent breakdown.
- An important conceptual development: a 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.



Bunch merge

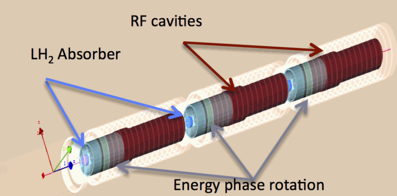
Bunch Merge



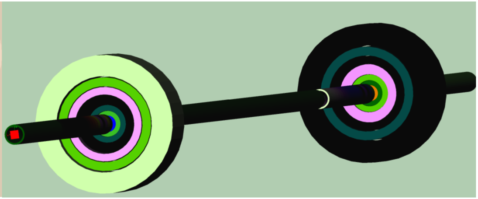
- Longitudinal merge: 21 to 7 bunches
- Transverse merge: 7 bunches to 1
  - kicker magnet sending each bunch one of the…
  - trombones of different length…
  - so that all the bunches arrive at the same time;
  - followed by a funnel and a matching section
- End-to-end simulation by Yu Bao (UC Riverside)

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.
- While the baseline was established and detailed studies carried out, there were multiple alternative proposals
  - For details, see T.L. Hart *et al.* JINST 15 P0300 (2020)

Cooling R&D Plan

Over the next few years the following R&D aspects should be addressed:

- More realistic 6D and final cooling channel simulations using updated physics models (e.g., the most recent version of G4beamline).
- Find the limits of 6D cooling channels by considering improved magnet configurations, and using newer, demonstrated technologies for solenoids and RF:
  - HTS magnet conductors, higher demonstrated RF gradients, liquid nitrogen cooling.
- Consult with engineers (for magnets in particular) to ensure feasibility and cost-effectiveness of cooling channel designs.
- Include collective effects in calculations, devise techniques to compensate for them, and determine performance limits they create.
- Re-optimize the full channel using theoretical and technology improvements, and limitations from engineering.
- Produce a simulation reaching the desired transverse emittances for a collider ring (“final cooling”).
- Optimize cooling channel performance using machine learning.
- Design study of the demonstrator (next slide).

Cooling Demonstrator

- Principles of ionization cooling are understood, but challenges associated with cooling technology/integration exist:
  - operation of NC cavities near SC magnets may compromise the cryogenic performance;
  - installation of absorbers (particularly liquid hydrogen) may be challenging in compact assemblies;
  - mitigation approaches to manage the forces within and between the magnet coils need to be developed.
- A facility that contains a sequence of ionization cooling cells that closely resemble a realistic ionization cooling channel is required
  - allows the integrated performance of the systems to be tested;
  - provides input/knowledge/experience to design a cooling channel for MC.
- For more details, see
  - C. Rogers, “A Demonstrator for Muon Ionisation Cooling,” Phys. Sci. Forum 2023, 8(1), 37; `https://doi.org/10.3390/psf2023008037`
  - and a talk later in this workshop.
- Fermilab’s expertise and facilities make it a natural host for such a demonstrator.

Thank you!