# 6-D Cooling

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Muon Accelerator Program Review
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# Outline

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- How Ionization Cooling Works
- Simulation Programs
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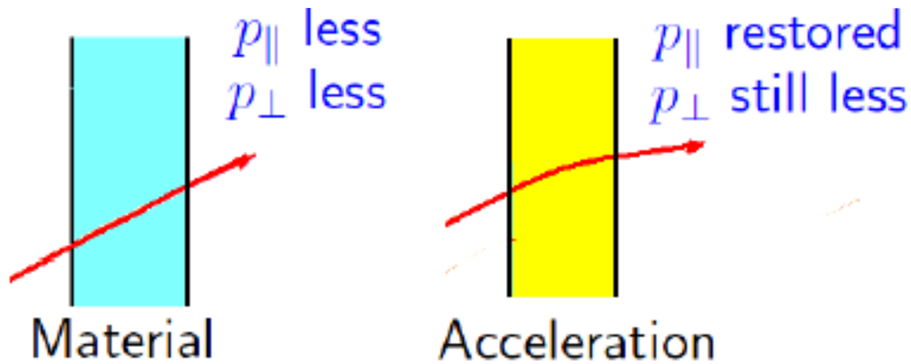
# Why Cooling is Needed

- The muon beam is a tertiary beam generated by the decays of secondary pions.
- The initial muon beam is huge: enormous transverse emittances and a very large momentum spread.
- It is infeasible to accelerate such a large beam to TeV.
- To obtain adequate luminosity, the normalized 6-D emittance must be reduced by roughly $10^6$.
- We call this reduction in emittance “cooling”; it is directly analogous to thermodynamic cooling.

# How Ionization Cooling Works Basics

- By alternating absorbers with acceleration, the $p_\perp$ of each particle can be reduced:




- This is inherently a 2-D process in {x',y'} (={dx/dz,dy/dz}); it operates in the 4-D transverse phase space.

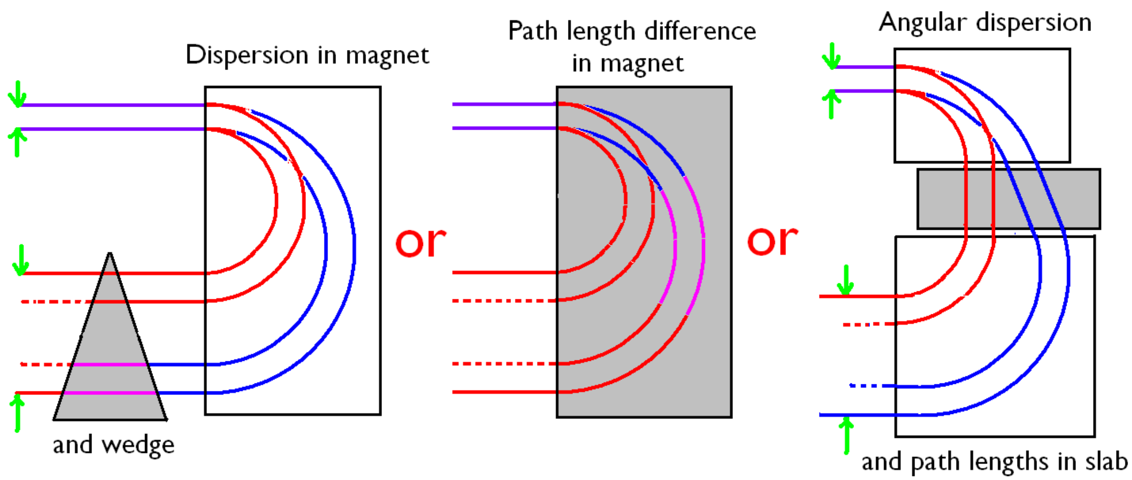
- Energy loss with re-acceleration cools the beam, multiple scattering heats it – need low-Z absorber ($H_2$, LiH, …).

# How Ionization Cooling Works Basics

- Liouville's theorem is not violated: the electrons in the absorber are heated (but they aren't part of the beam).
- It takes many cooling cells to achieve the $10^6$ emittance reduction required.
- The channel must be designed to partition the emittance reduction into all 6 dimensions {x,x',y,y',dt,dp/p}.

# How Ionization Cooling Works
# Partitioning the Cooling

- Re-partitioning the cooling in the transverse dimensions merely requires a change in focusing of the beam.
- Partitioning cooling to the longitudinal dimension requires emittance exchange:




Reduced Longitudinal emittance, increased transverse emittance.

Dispersion is arranged so higher momentum particles have a longer path in the absorber.

- Straggling and the variation of dE/dx with energy contribute to longitudinal heating of the beam.

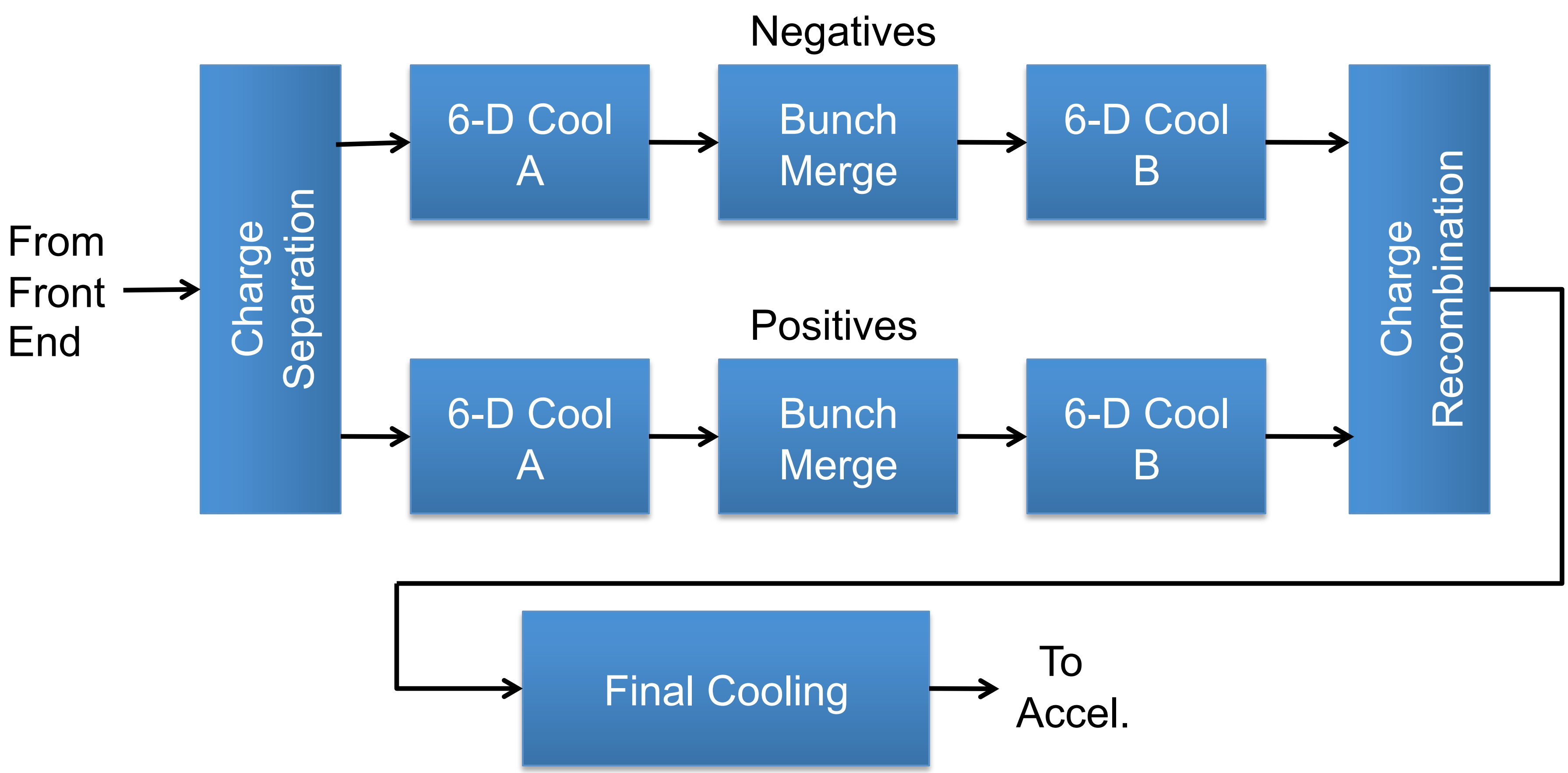
# How Ionization Cooling Works
# Summary

- The 6-D cooling channels below differ in how they arrange the dispersion, absorbers, and focusing to re-partition the cooling among the 6 dimensions.
- All use a helical path, as that is the best way to maintain transverse focusing and to provide the dispersion necessary for the emittance exchange.

# Simulation Programs

- Muon cooling requires tracking particles through matter, which standard accelerator design codes do not support.
- We have developed two simulation programs that do:
  - ICOOL
    - Primary author: Rick Fernow
    - Fortran, with portions from Geant3
    - https://pubweb.bnl.gov/~fernow/icool/
  - G4beamline
    - Primary author: Tom Roberts
    - C++, based on Geant4
    - http://g4beamline.muonsinc.com
- As muon cooling is new technology, our plans include maintaining both programs and using them to evaluate our designs.
- Other programs may be used as appropriate.

# Overview of the Cooling Subsystem – Current Baseline



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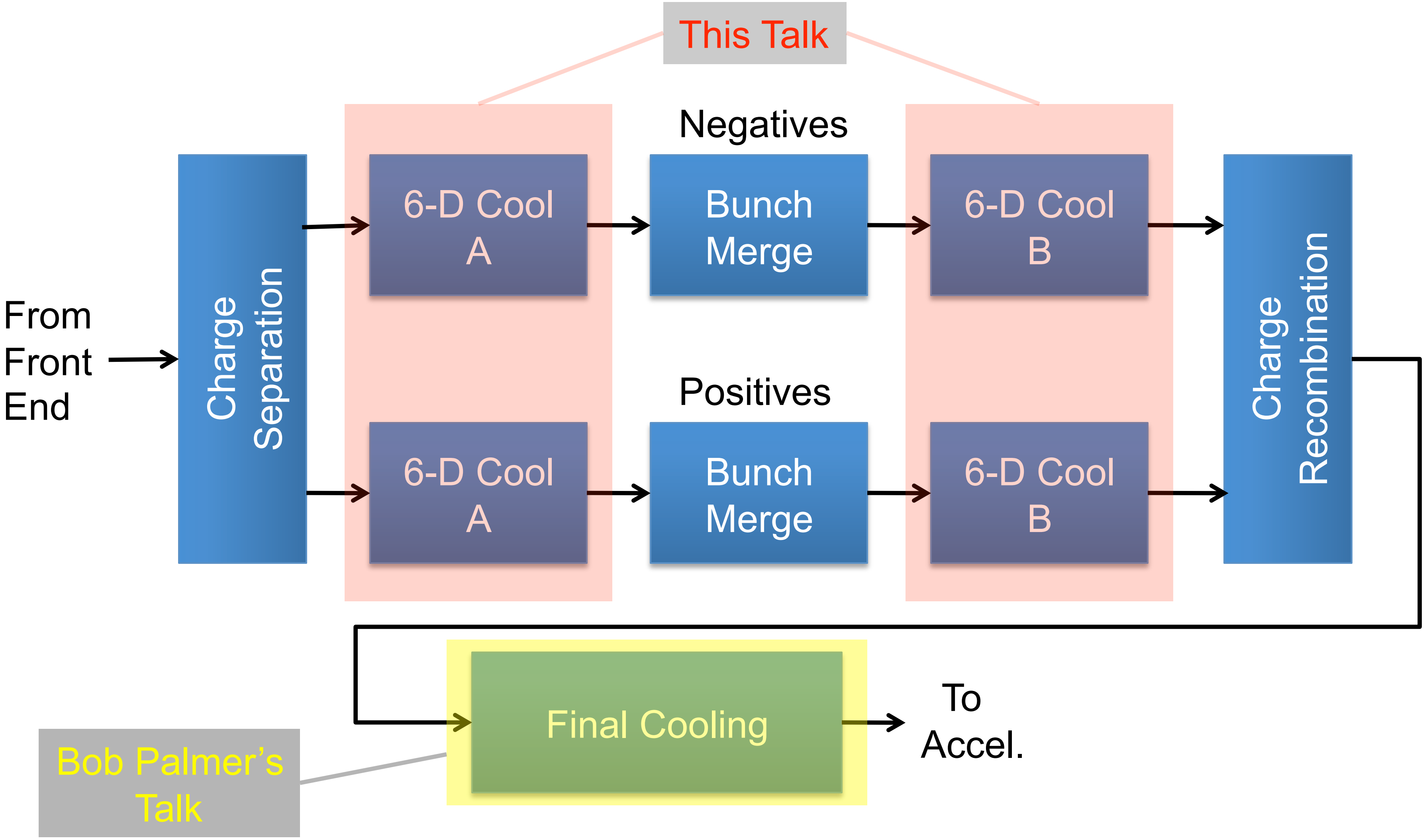


# Overview of the Cooling Subsystem

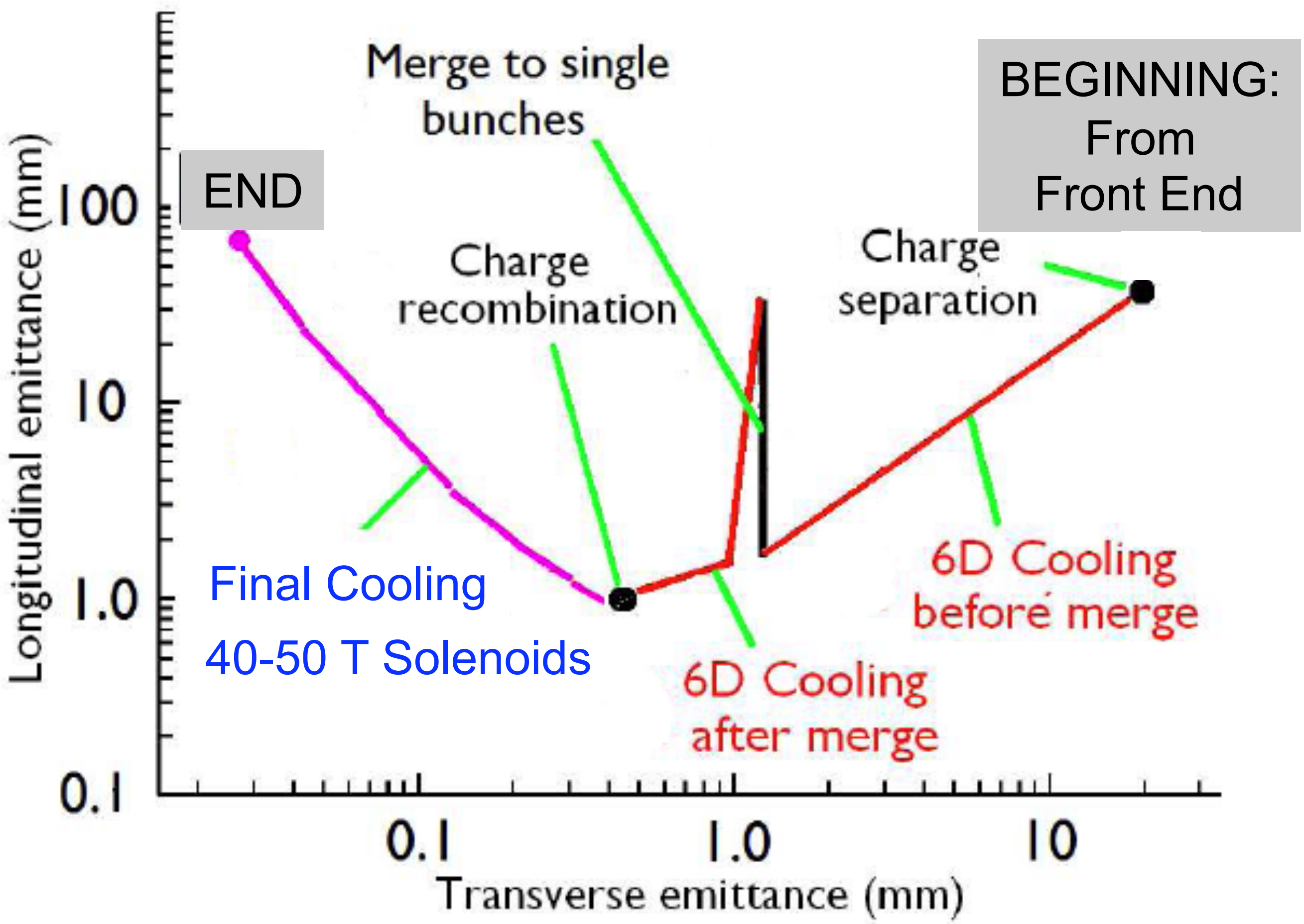
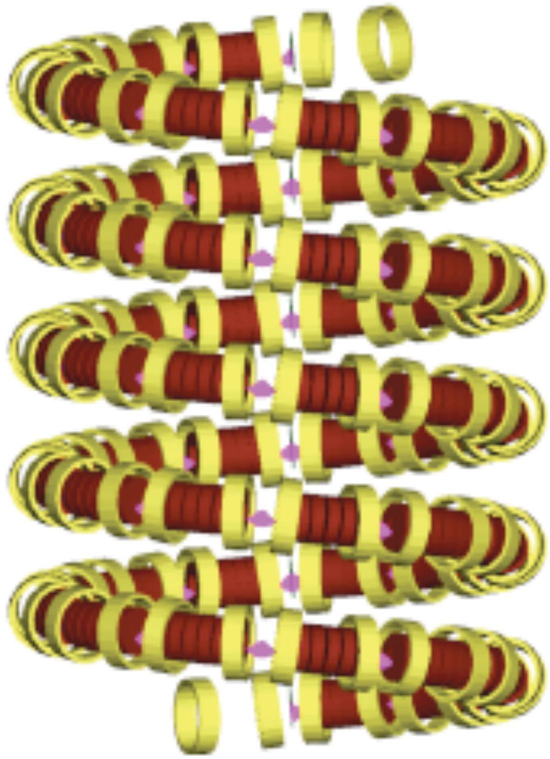



Figure credit: R. Palmer

# 6-D Cooling Guggenheim



A short section of a Guggenheim cooling channel.

- Basically a cooling ring stretched out vertically to simplify extraction and injection; also reduces heating power in absorbers (from multiple turns).

- Lumped liquid hydrogen absorbers (pink), or LiH
- Vacuum RF cavities (dark red)
- Solenoid magnets, inclined to force the beam to follow the helix (yellow)

# 6-D Cooling Guggenheim

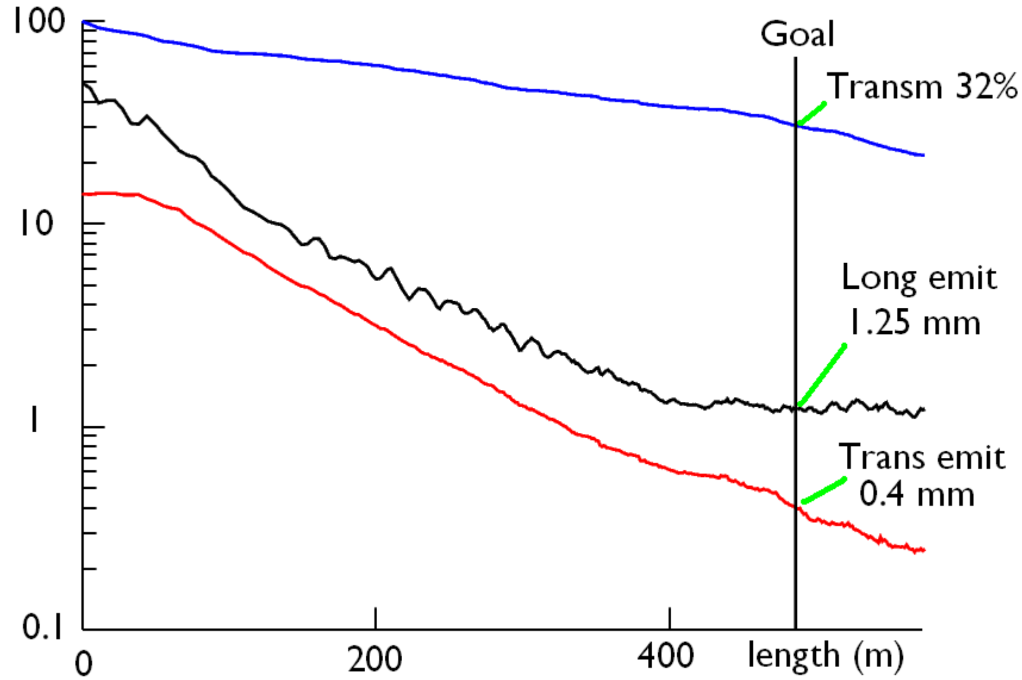
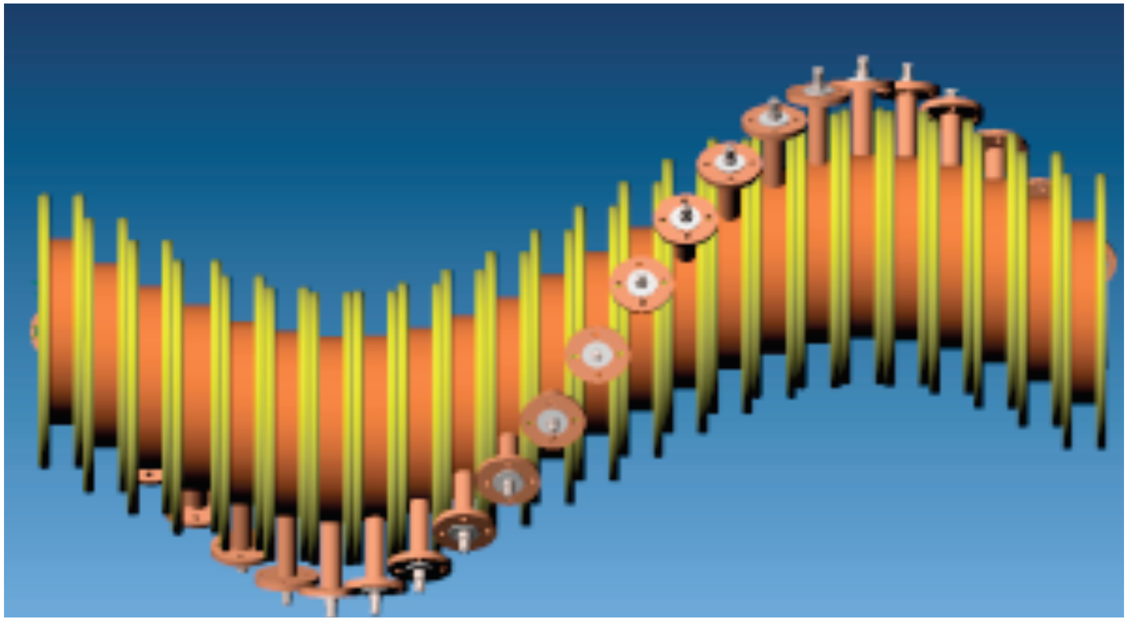



Figure credit: R. Palmer

- ICOOL simulations of a tapered Guggenheim cooling channel.
- Overall transmission is 32%.

# 6-D Cooling
# Helical Cooling Channel



A short section of a Helical Cooling Channel; outer solenoid not shown.

- Continuous high-pressure hydrogen gas absorber
- Short solenoids (green) in “helical solenoid” configuration give solenoid, helical dipole, and helical quadrupole fields
- Integrated high-pressure RF cavities (orange)
- Pressure windows only at beginning and end

# 6-D Cooling
# Helical Cooling Channel

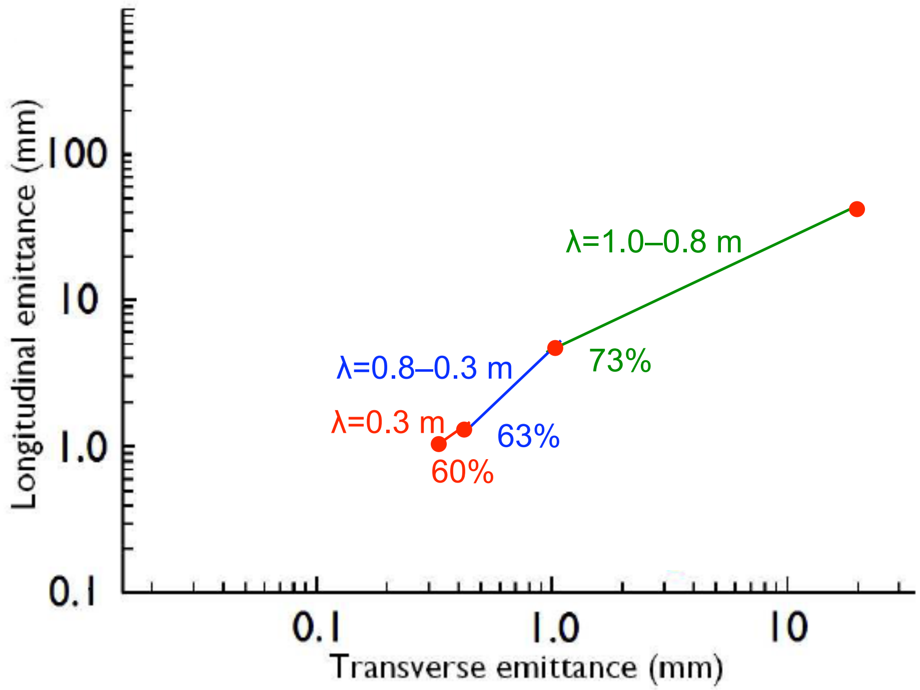



Figure credit: K. Yonehara and T. Roberts

- G4beamline simulation of three tapered helical cooling channels.
- Overall transmission is 60%.

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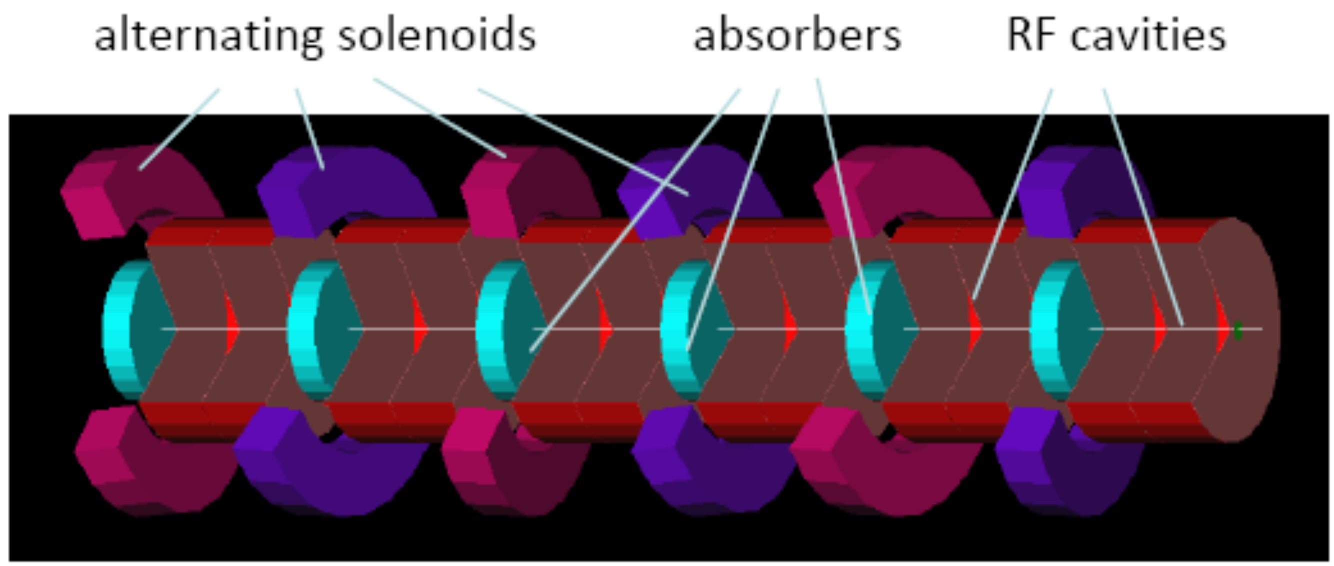
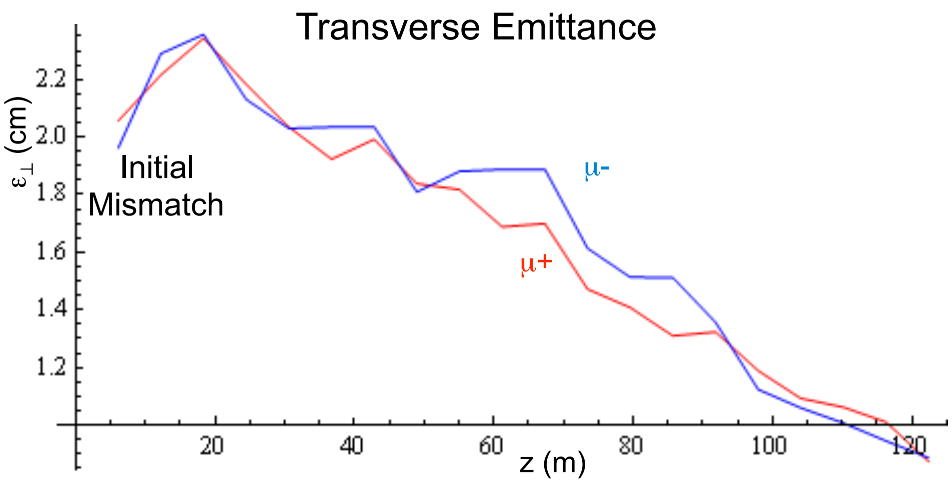
# 6-D Cooling
# Helical FOFO Snake




A short section of a Helical FOFO Snake.

- Basically a linear channel with tilted solenoids to give a shallow helix
- Lumped liquid hydrogen absorbers
- Vacuum RF cavities
- Can cool both positives and negatives

# 6-D Cooling
# Helical FOFO Snake



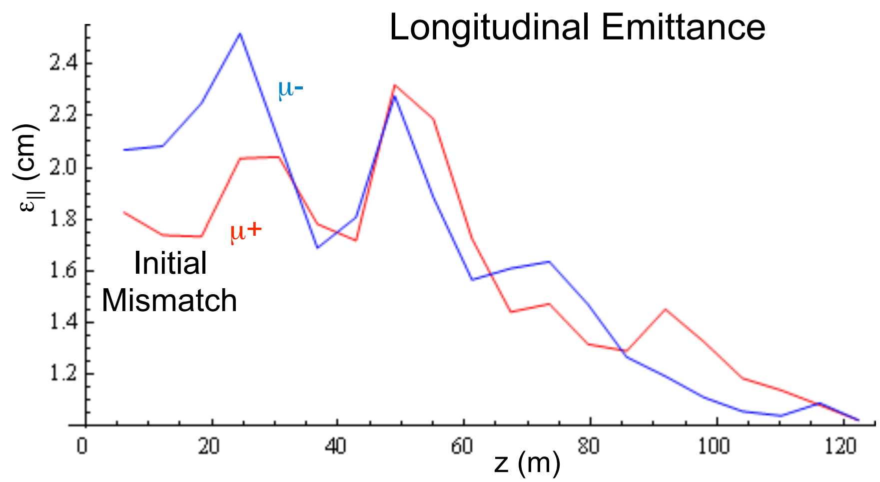




Figure credit: Y. Alexahin

- Simulation results for the helical FOFO snake.
- Transmission after 100 meters is about 60%.

# 6-D Cooling
# Comparison of Techniques

| | Guggenheim | Helical Cooling Channel | Helical FOFO Snake |
|---|---|---|---|
| Absorber | Lumped liquid $H_2$ or LiH wedge | Continuous high-pressure gas $H_2$ | Lumped liquid $H_2$ |
| RF Cavities | Vacuum with Be Windows | High-pressure gas, Be Windows | Vacuum with Be Windows |
| Magnets | Tilted Solenoids | Helical Solenoid | Tilted Solenoids |
| Helix ratio: radius / period | Large, >>1, almost a ring | Moderate, ~0.2 | Small, <<1, almost straight |
| Can achieve low emittance to feed into final cooling | Yes | Yes | No |
| Can cool both charges | No | No | Yes |
| Have initial simulations | Yes | Yes | Yes |

# Down Selection (FY12)

- At present we have three viable 6-D cooling techniques.
- In FY12 we will have enough information to “down-select” and determine the actual cooling subsystem to be used in the Design Feasibility Study Report.
- Our current task is to evaluate the possibilities and collect all necessary information to make an informed choice.
- We expect the selection to be of a complete cooling configuration; multiple techniques may be involved.

# Down Selection (FY12)

- Indeed, even the overall block diagram is subject to selection:
  - At present, it seem likely that a helical FOFO snake will come first, before the charge separation.
  - That may or may not be sufficient to go directly into the bunch merge.
  - The choice for Final Cooling might require the charge recombination to come after final cooling.
- The selection for cooling can be affected by similar down-selections in the Front End and in Technology Development (RF).

# Design and Simulation Level 2 Cooling Tasks

1. Develop approach for comparing, assessing, and selecting cooling techniques
2. 6D Cooling
3. Final Cooling
4. Auxiliary Components (charge separation, bunch merging, charge recombination)
5. Simulation Code Development (ICOOL, G4beamline, ...)
6. Target-to-accelerator simulation of Front End and Cooling
7. RF Systems Simulations
8. DFS Report preparation

# Milestones

| Date | Milestone | Deliverable |
|---|---|---|
| FY12 | specify cooling initial configuration | MAP Review, Design Report |
| FY14 | finish D&S for **Interim MC DFS report**<br>finish D&S for **Final IDS-NF RDR report** | Formal Report<br>Formal Report |
| FY15 | provide specifications & parts count for MC costing | Design Report |
| FY16 | provide description of remaining MC R&D items<br>finish D&S for **Final MC DFS report** | Design Report<br>Formal Report |

# Cooling R&D Issues

- Simulation Issues
  - Match the different sections, with acceptable emittance growth and losses.
  - Evaluate space charge effects (primarily final cooling).
  - Analyze, understand, and evaluate collective effects in the absorbers (primarily final cooling).
    - Plasma effects (ionization electrons)
    - Dielectric polarization effects
    - Effect on space charge, macro-particle interactions, etc.
- Design Issues
  - High RF gradients (See Alan Bross talk)
  - High-field magnets (See Alan Bross talk)
  - High beam heat load in absorbers (needs engineering)
  - High beam loading in RF cavities (needs engineering)

# Why We Believe We Will be Successful

- We already have considerable experience in designing cooling channels:
  - We have multiple techniques for both 6-D and final cooling, and at least one for each of the auxiliary components.
  - We have initial simulations of each technique, indicating they can be put together as shown.
- We have a team of experts already involved.
- The primary developers of the simulation tools we are using are already part of the team.
- **MAP is the culmination of more than 15 years of effort – we are motivated to succeed!**