From Neutrino Factory to Muon Collider

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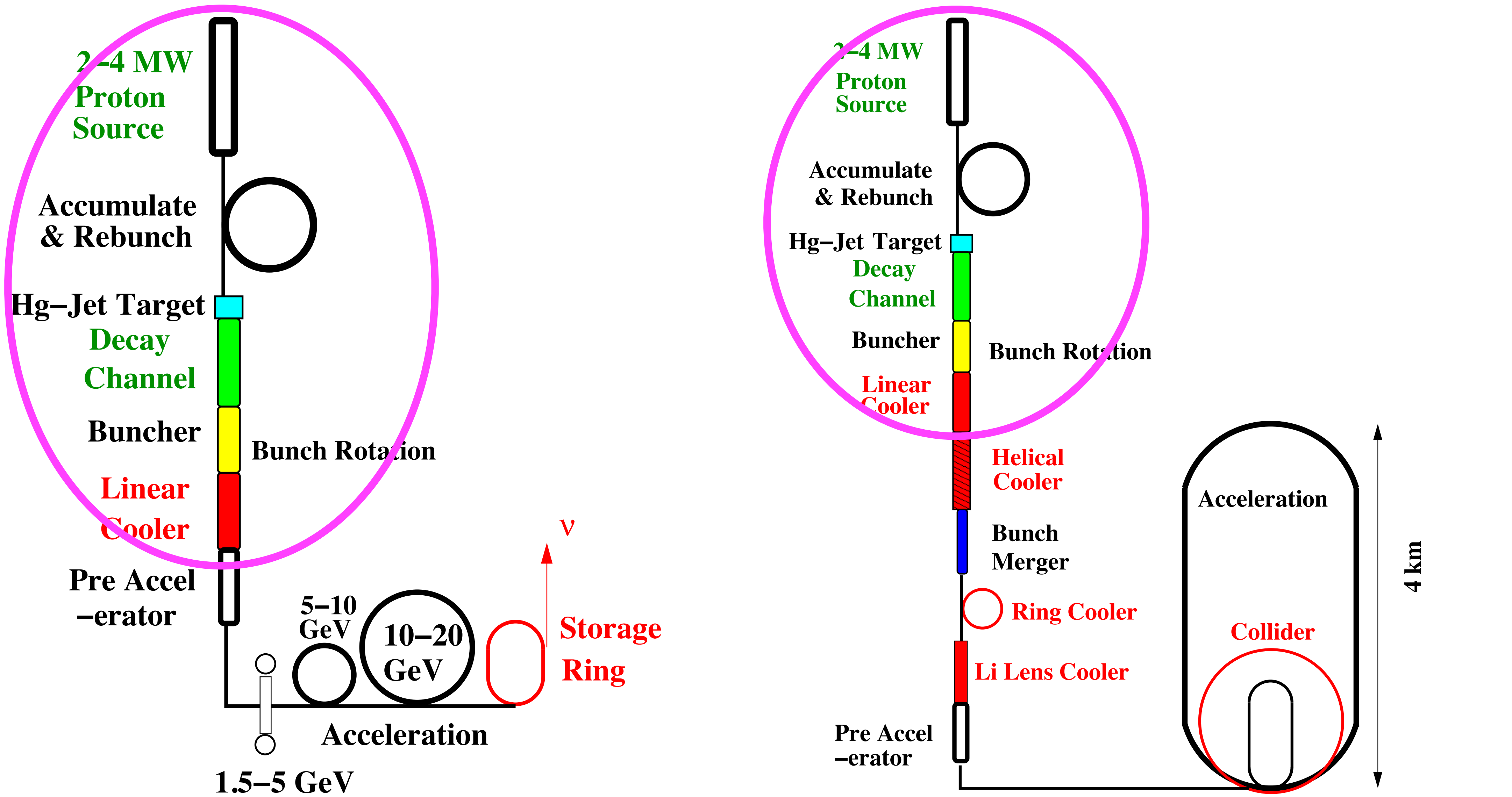
Outline

- Neutrino Factory/Muon Collider Comparison
- Muon cooling for a Neutrino Factory or Muon Collider
- 6D cooling
- Final cooling
- Acceleration
- Storage ring
- Conclusions

μC-νF Comparison



- Front ends similar or identical!

➡ Can μC be built as νF upgrade?

Key μC Parameters

Table 2. Example parameters for a 1.5 TeV (c.m.) muon collider [26].

	LEMC	HEMC
Avg. luminosity (10^{34} cm^{-2} s^{-1})	2.7	1
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β^* (cm)	0.5	1
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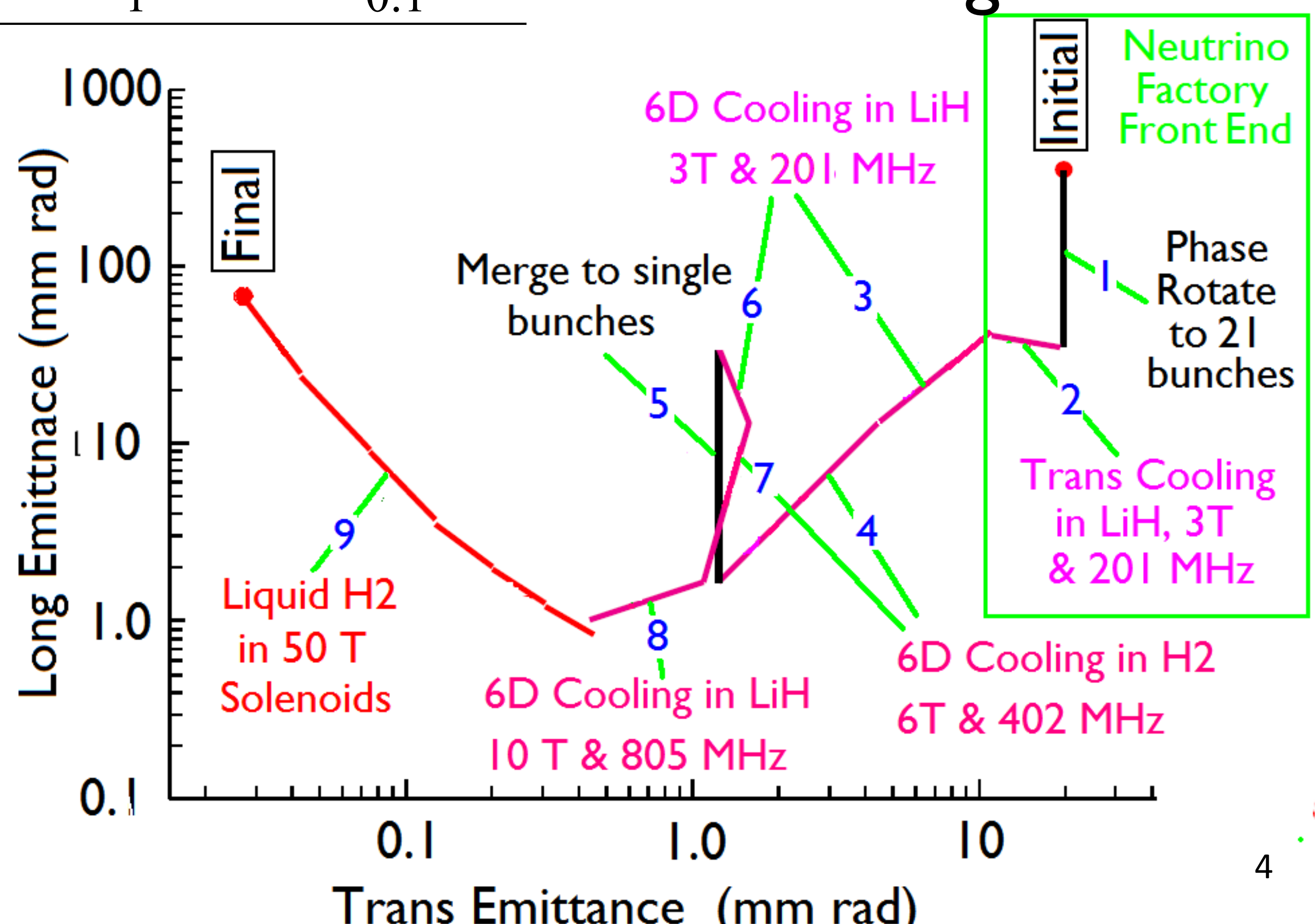
Muon bunches in collider (each sign)	10	1
Norm. Transv. Emittance (μm)	2.1	25
Norm. Long. Emittance (m)	0.35	0.07
Energy spread (%)	1	0.1

- 2 ways to get 10^{34}
- compare with νF:

7,400 Need ~300X more cooling than νF!

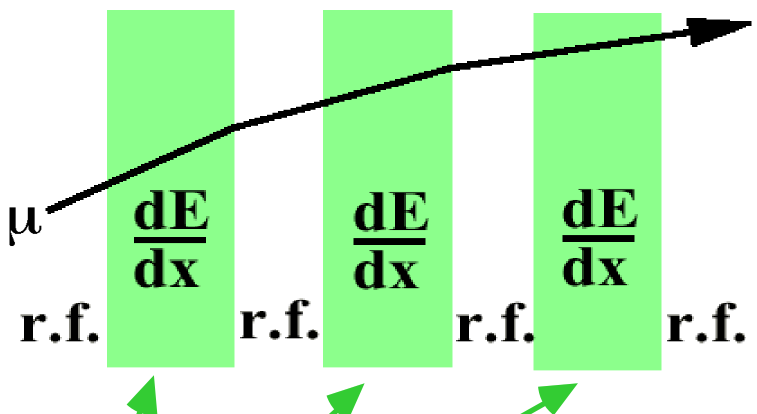
- How to get there: (1 scenario)
- Must cool both transversely and longitudinally

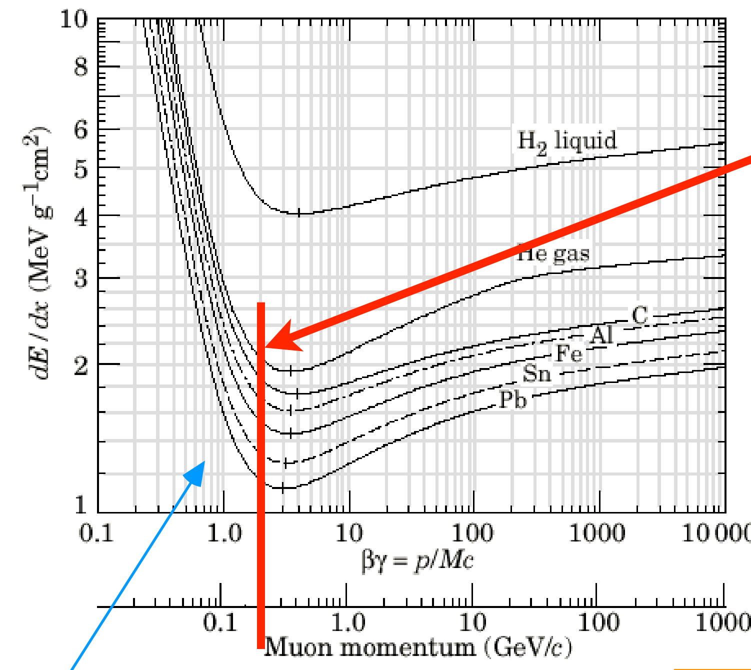


Ionization Cooling

Reminder:

- Muons cool via dE/dx in low-Z medium:





- ionization minimum is ≈ optimal working point

– Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

- 2 competing effects ⇒ equilibrium emittance:

$\varepsilon_0 \propto \beta_\perp / \langle dE/ds \rangle X_0$

– RF cavities between absorbers replace ΔE

– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

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

(emittance change per unit length)

- Only practical way to cool within 2μs μ lifetime

Ionization Cooling

Note:

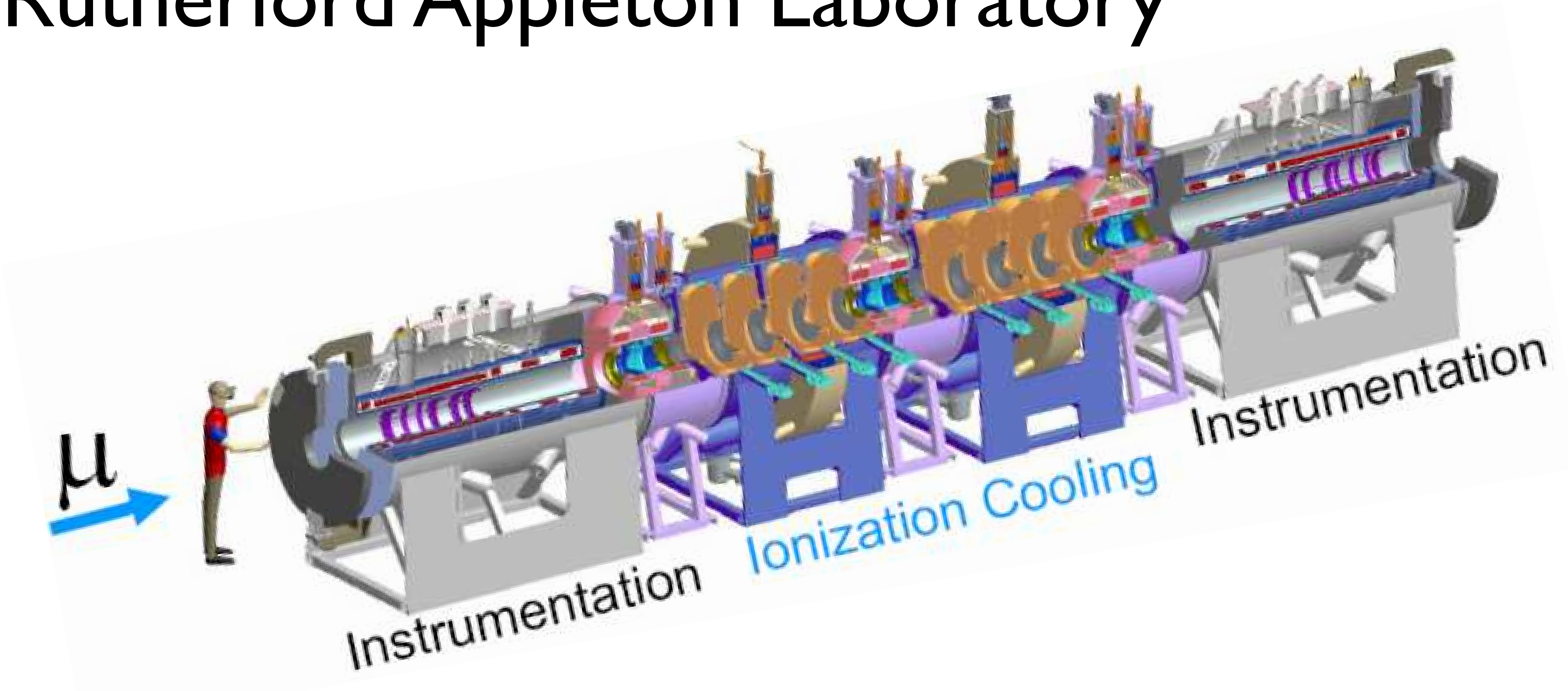
- *dE*/*dx* cooling mechanism inherently transverse
  - reduces p_x, p_y, p_z while acceleration replaces only p_z

    ⇒ cools only beam divergence
  - coupled to beam area by variable focusing

    → 4D transverse cooling
- Demonstration in progress (MICE), 2013 goal...

MICE

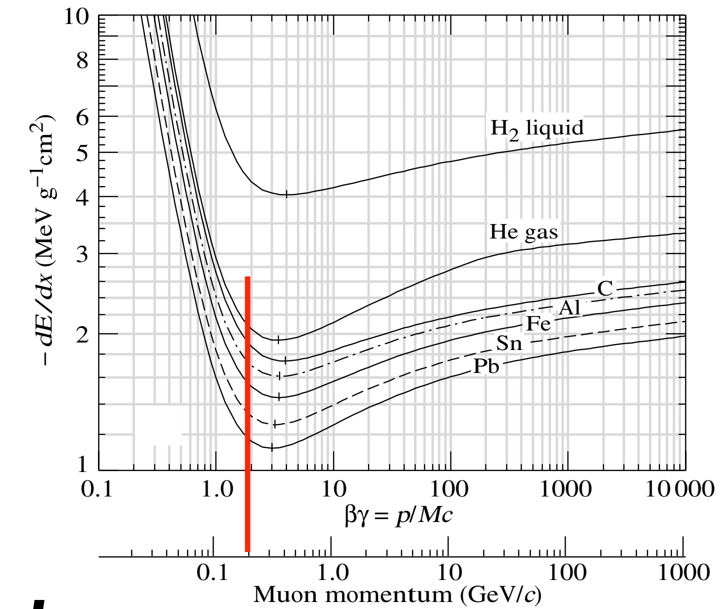
- Muon Ionization Cooling Experiment at UK's Rutherford Appleton Laboratory



- Beamline working, apparatus buildup in progress
  - see WG3 parallel talks by Torun, Apollonio, Rayner

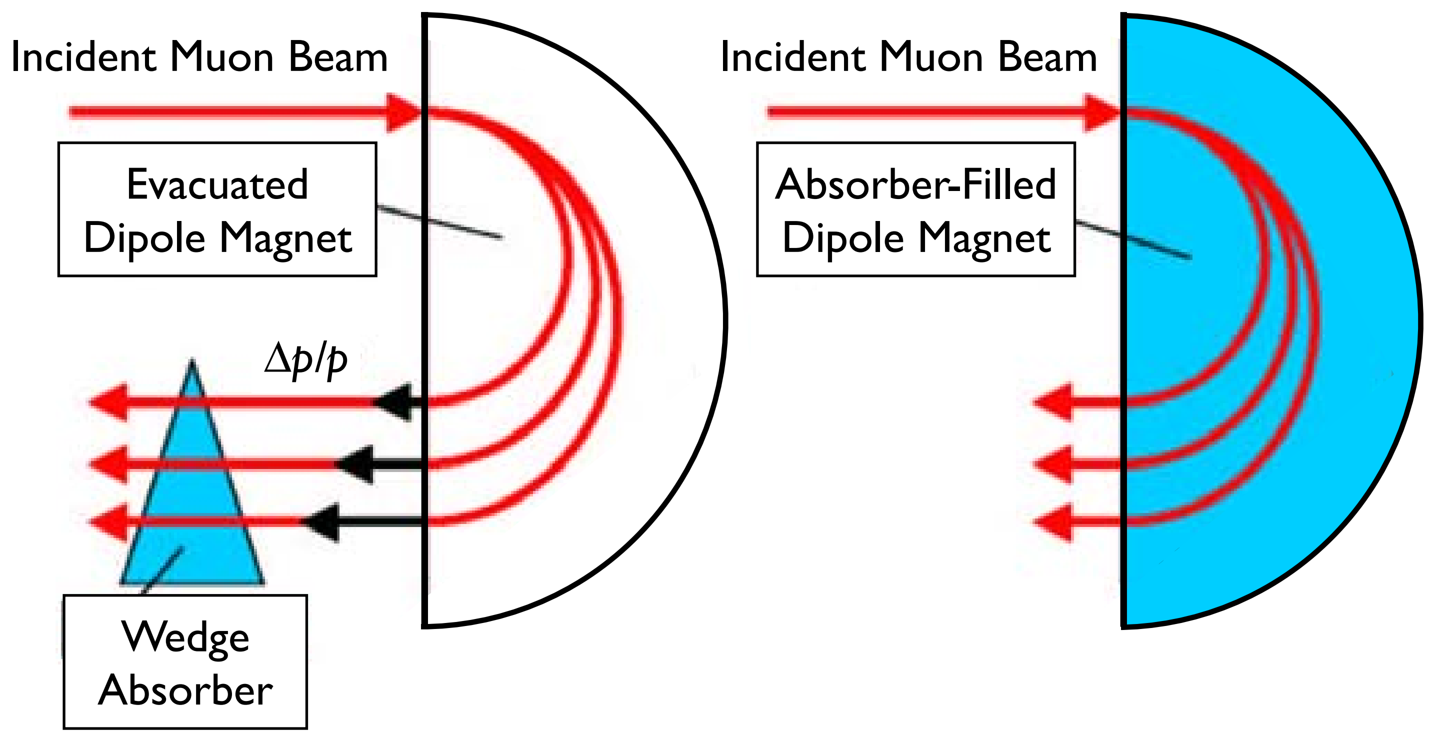
How to cool in 6D?

- Work above ionization minimum to get negative feedback in p_z?



- No – ineffective due to straggling

⇒cool longitudinally via *emittance exchange:*

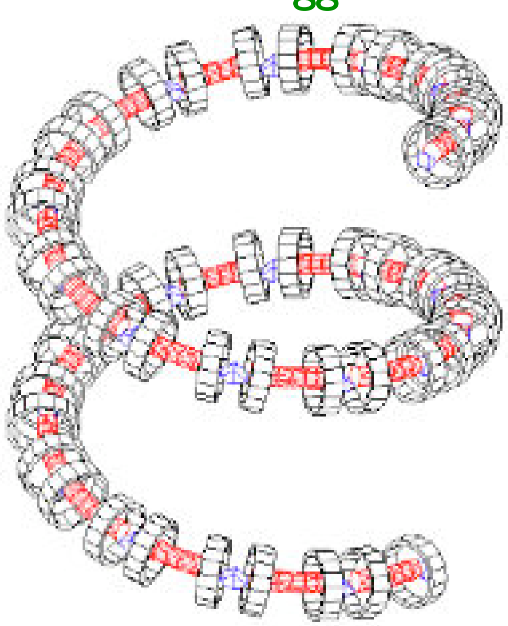


- Cool $\varepsilon_\perp$, exchange $\varepsilon_\perp$ & $\varepsilon_{||}$ → 6D cooling

How to cool in 6D?

- Tricky beam dynamics: must handle dispersion, angular momentum, nonlinearity, chromaticity, & non-isochronous beam transport
- After >10 years of work, 3 solutions seem viable:

RFOFO "Guggenheim"



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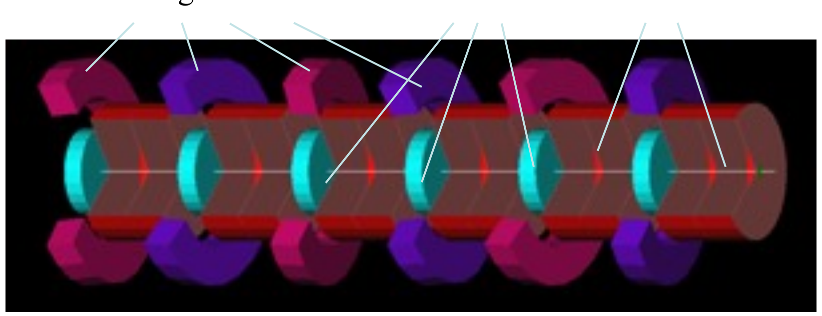
FOFO Snake



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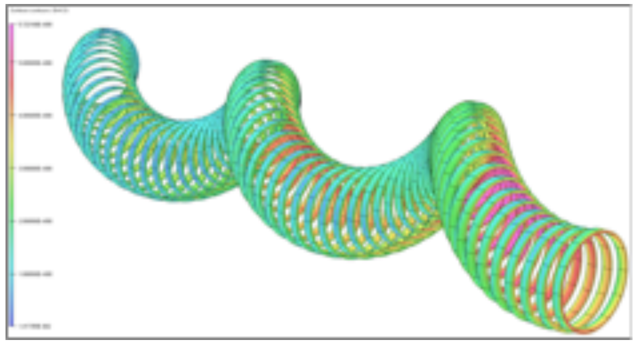
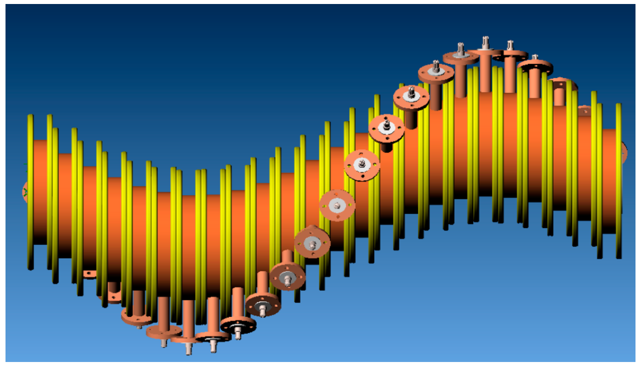
Helical Cooling Channel





Muons, Inc. & FNAL

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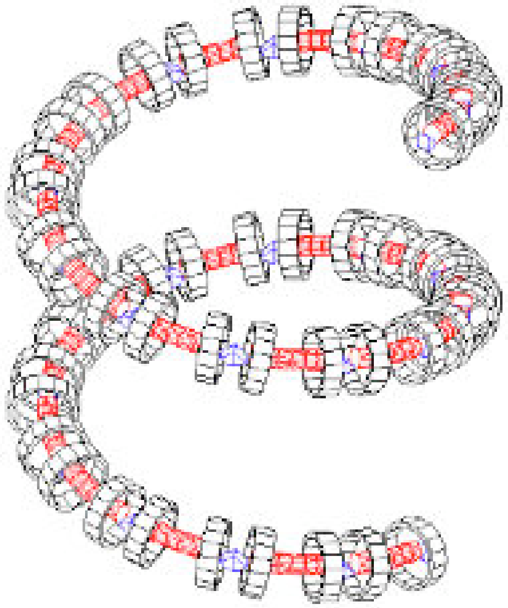

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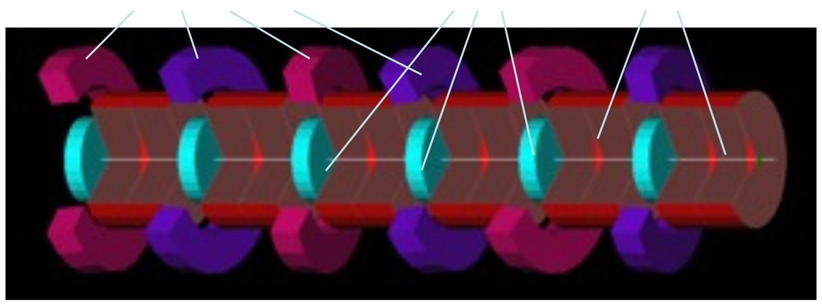

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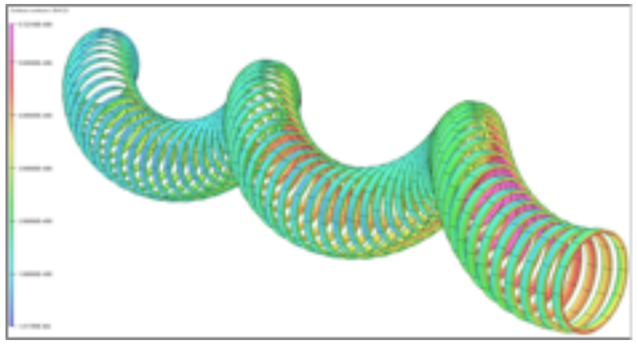
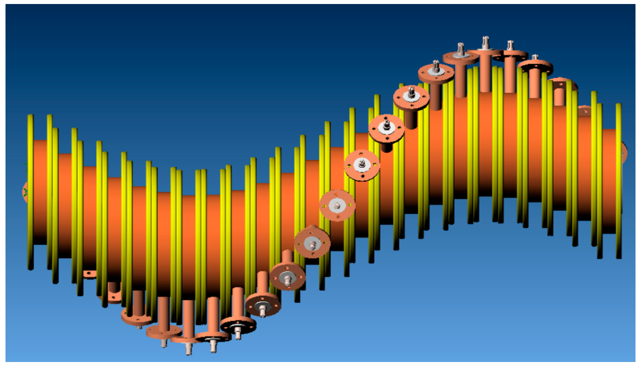


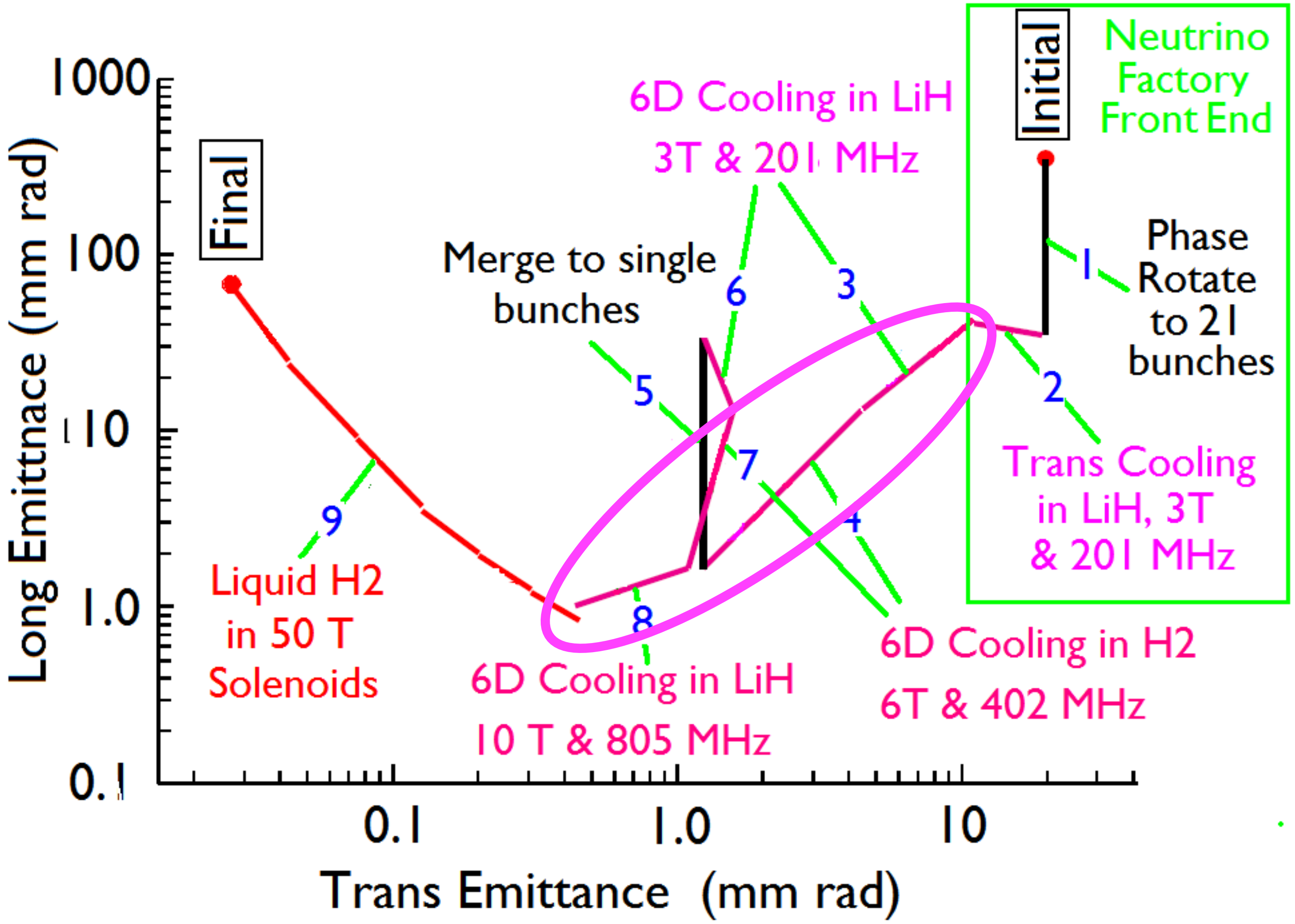


Muons, Inc. & FNAL

  - FOFO Snake can cool both signs at once but may be limited in $\beta_{\perp,min}$ ⇒ may be best for initial 6D cooling
  - HCC may be most compact
  - Not yet clear if all will work in practice, nor which is most cost-effective

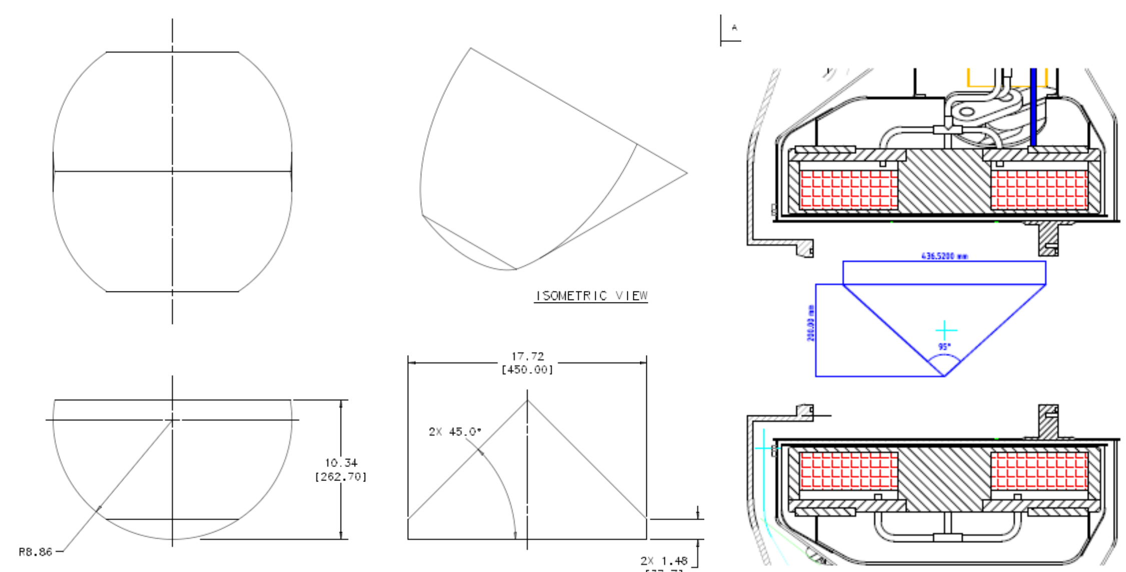
How to cool in 6D?

- Guggenheim simulation results shown here



1st 6D cooling test:

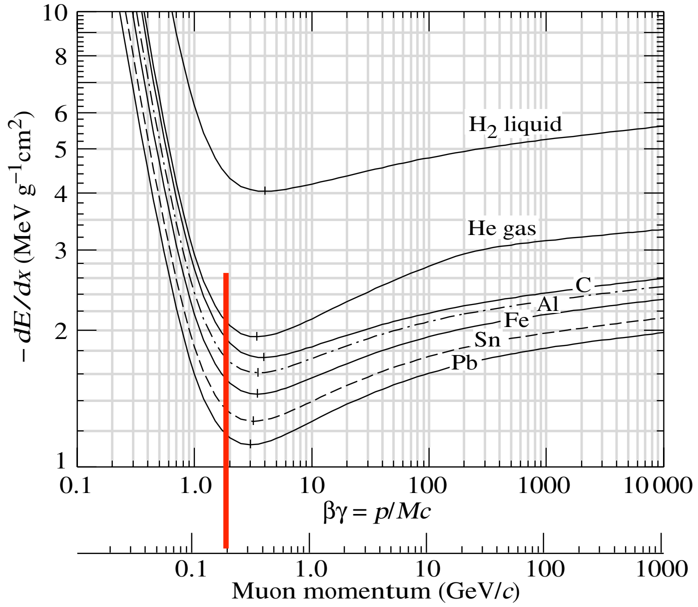
- Some aspects of 6D cooling can be tested by inserting wedges in MICE
- Part of MICE program
  - have ordered LiH wedge:



Beyond 6D Cooling

- To reach ≤25 μm emittance, must go beyond 6D cooling schemes shown above
- One approach (Palmer "Final Cooling"):
  - cool transversely in ~40 T *B* field at low momentum
  - gives lower β & higher *dE*/*dx*:

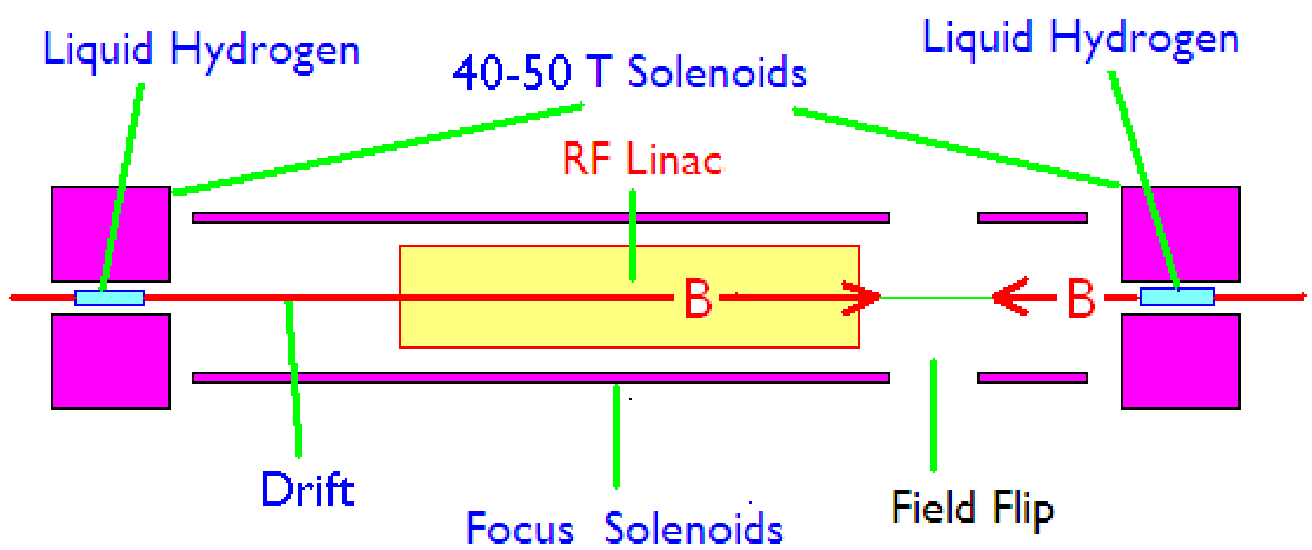
$$\beta_\perp \sim \frac{p}{B}$$



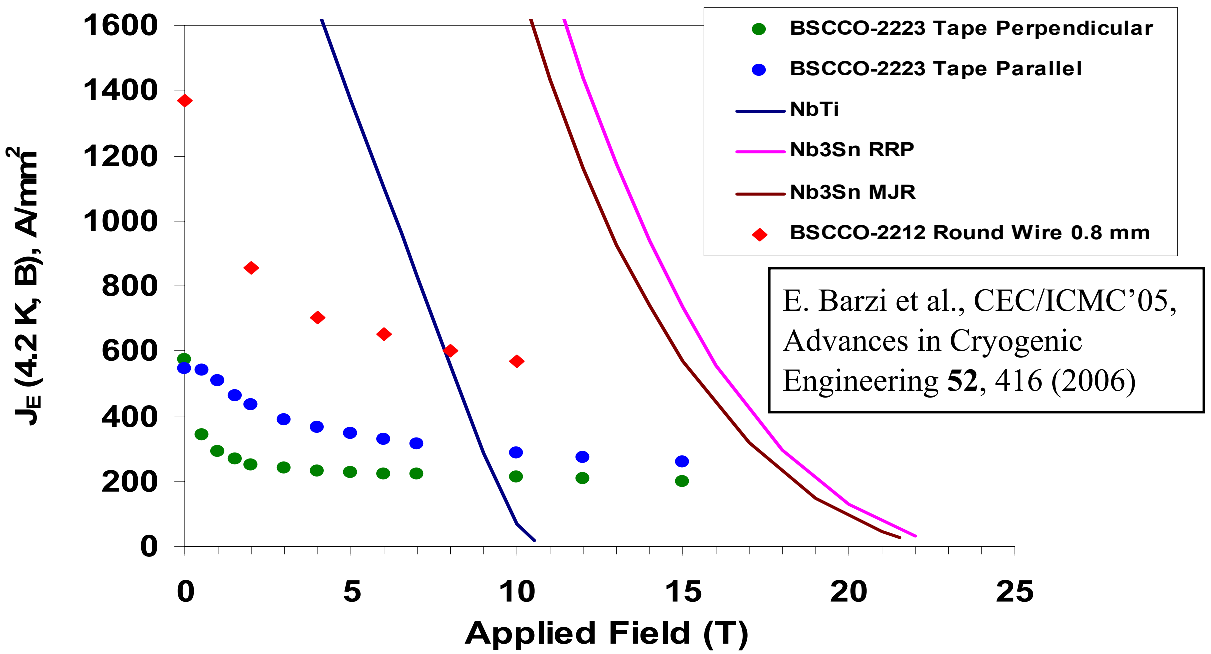
- Lower-*B* options under study as well (Derbenev "PIC/REmEx," lithium lenses)

Final Cooling

- Palmer final-cooling cell:

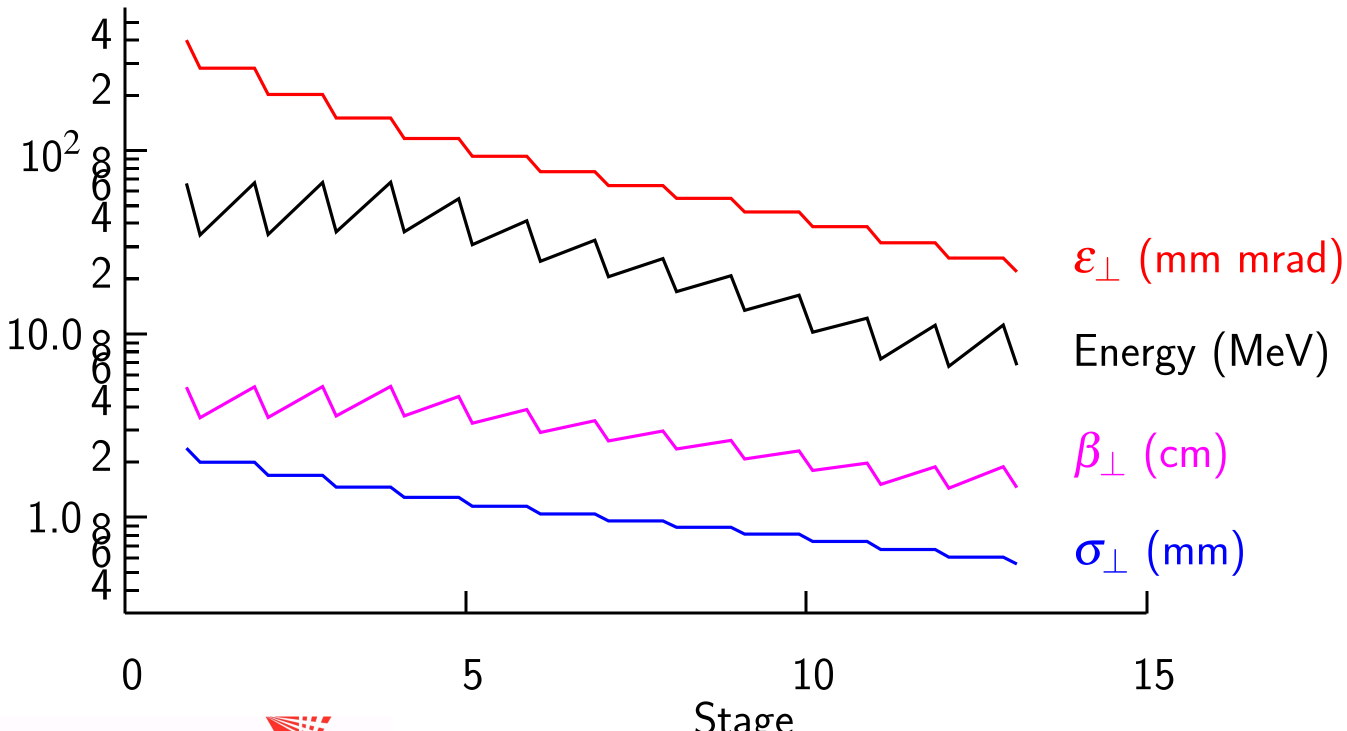


- HTS J_E @ 4.2 K quite flat vs B:



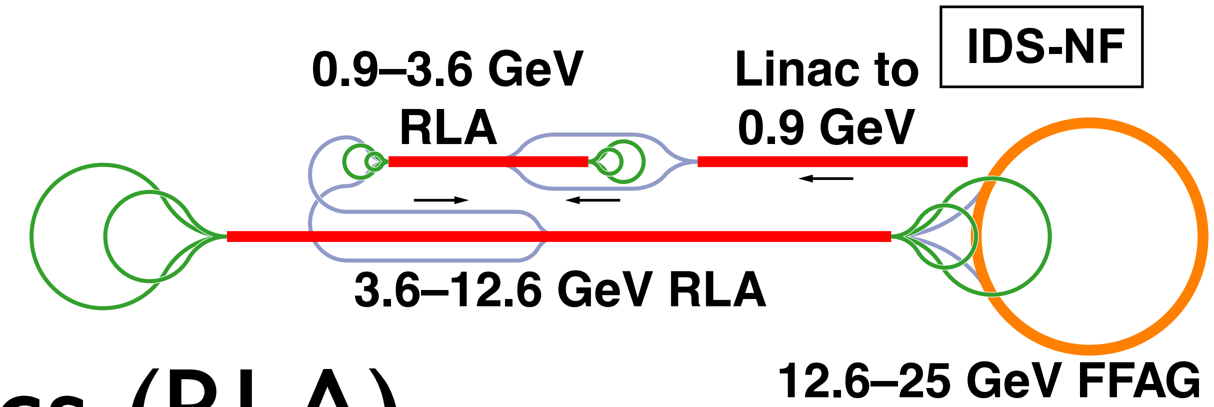
(∃ YBCO 33.8 T hybrid solenoid @ NHMFL)

- Simulation of 13 stages:

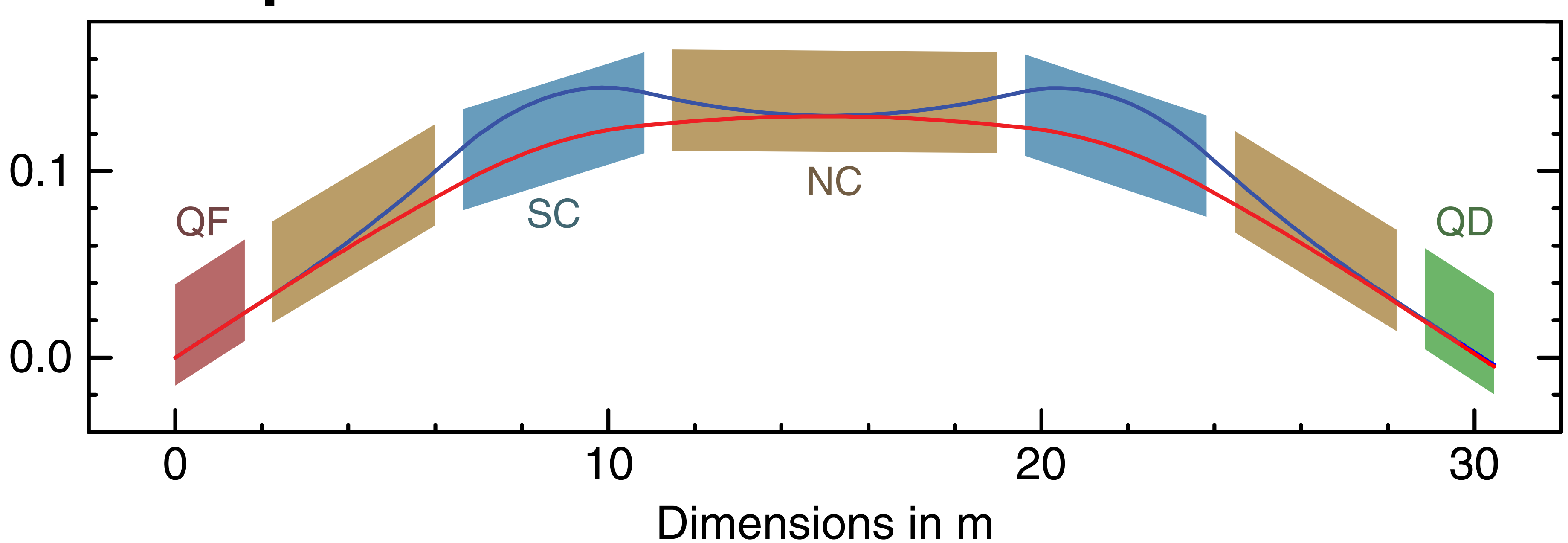


- Beam energy falls from 70 MeV (135 MeV/c) to ≈ 6 MeV
- Bunch length rises from 5 cm to 300 cm rms
- Beam rms radius falls from 2 cm to 6 mm, $\varepsilon_\perp$ to 23 μm
- 65% transmission

Acceleration



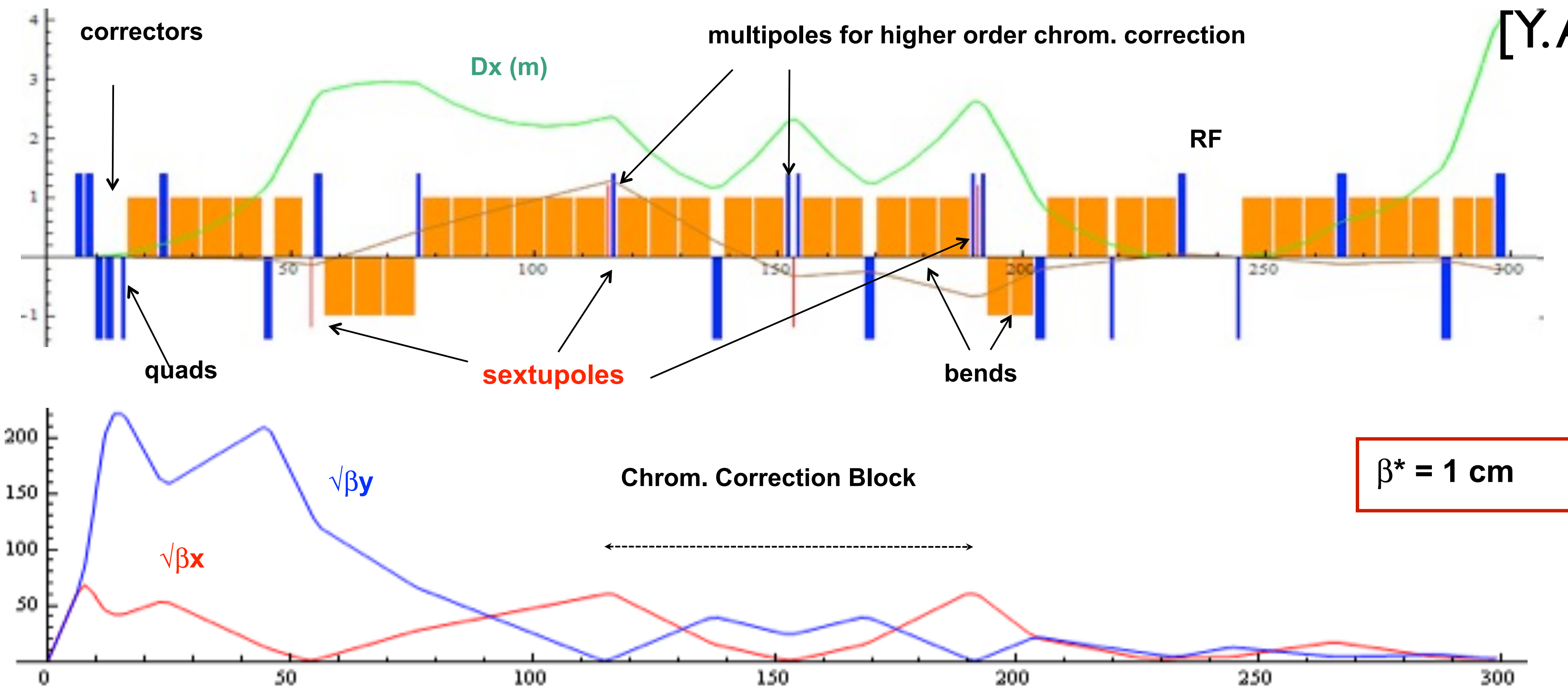
- Initial linac
- Then recirculating linacs (RLA)
- Finally, rapid-cycling synchrotrons (RCS)
- Last RCS uses hybrid 8T SC and –1.8 to +1.8 T pulsed dipoles



Collider Ring

- Example 2.5 km storage ring for $\sqrt{s}$ = 1.5 TeV:

[Y. Alexahin et al., FNAL]



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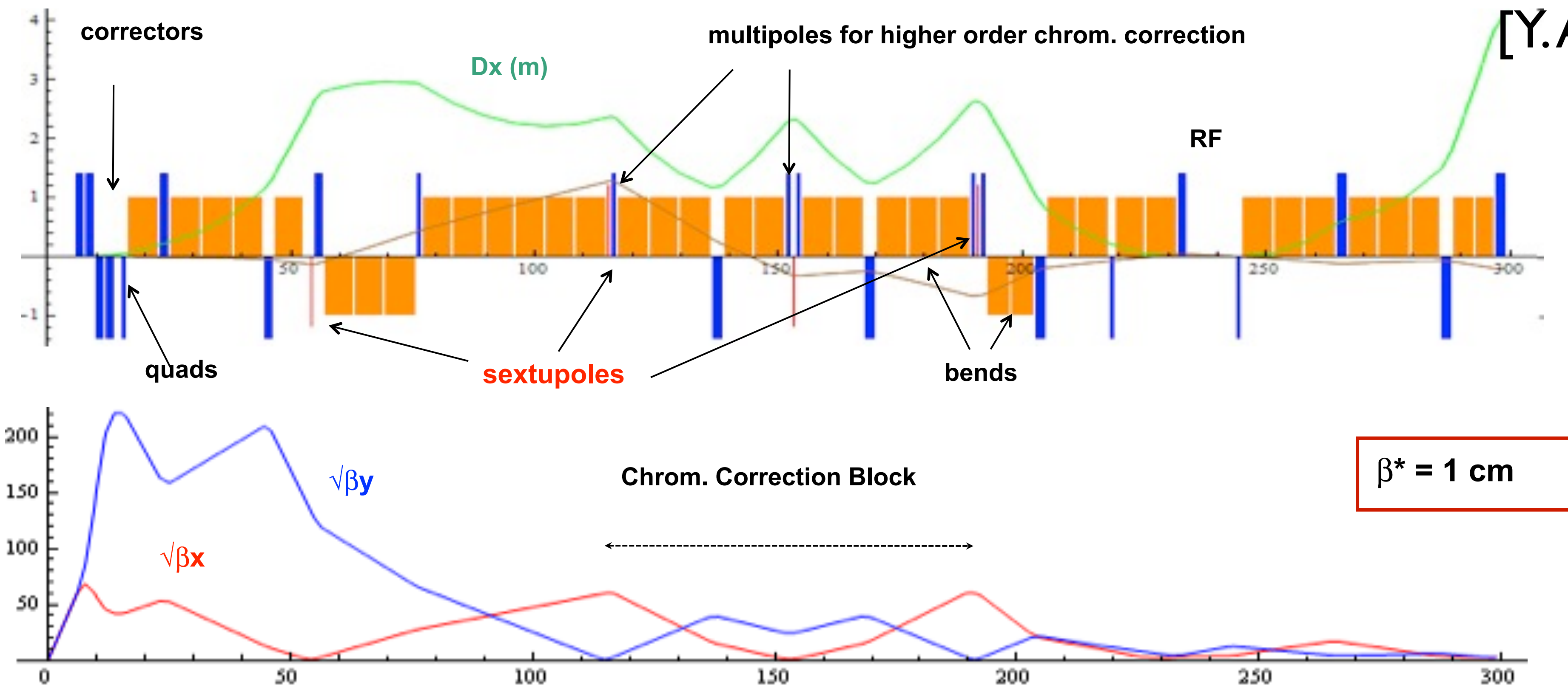
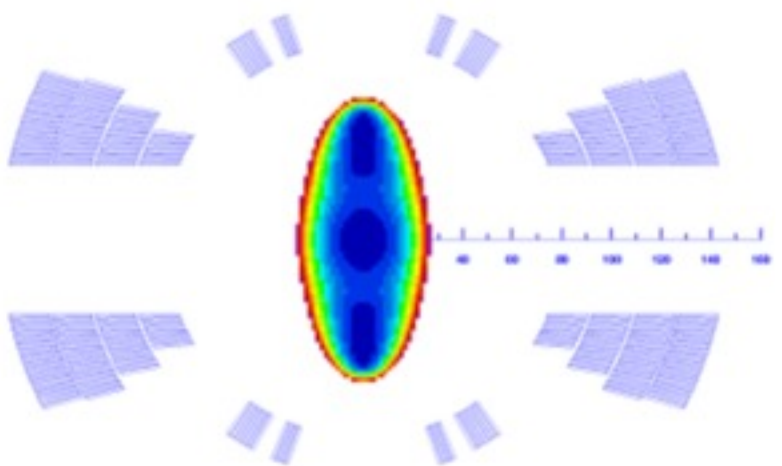


- Employs open-midplane dipoles (8 & 10 T) in order to cope with decay electrons



- Will continue to be refined

Conclusions

- A high-$\mathscr{L}$ Muon Collider is probably feasible, and buildable as a Neutrino Factory upgrade
  - whether things go in this order remains to be seen!
- Requires development of high-field HTS solenoids
- Technology selection, feasibility demonstration, and cost estimation are main goals of MAP 7-year program

Acknowledgments

- My thanks and congratulations to Naba and the organizing committee for an exciting, memorable, and smoothly run workshop!