Ionization Cooling Beamline for a Muon Collider

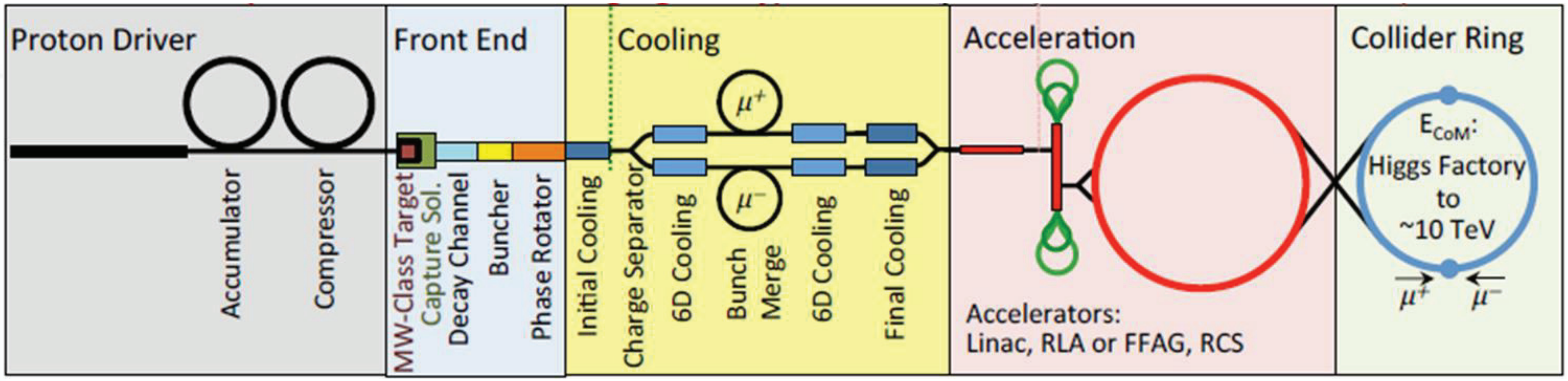
Diktys Stratakis
Fermi National Accelerator Laboratory

COOL 21 Workshop (online only)
November 4, 2021

Outline

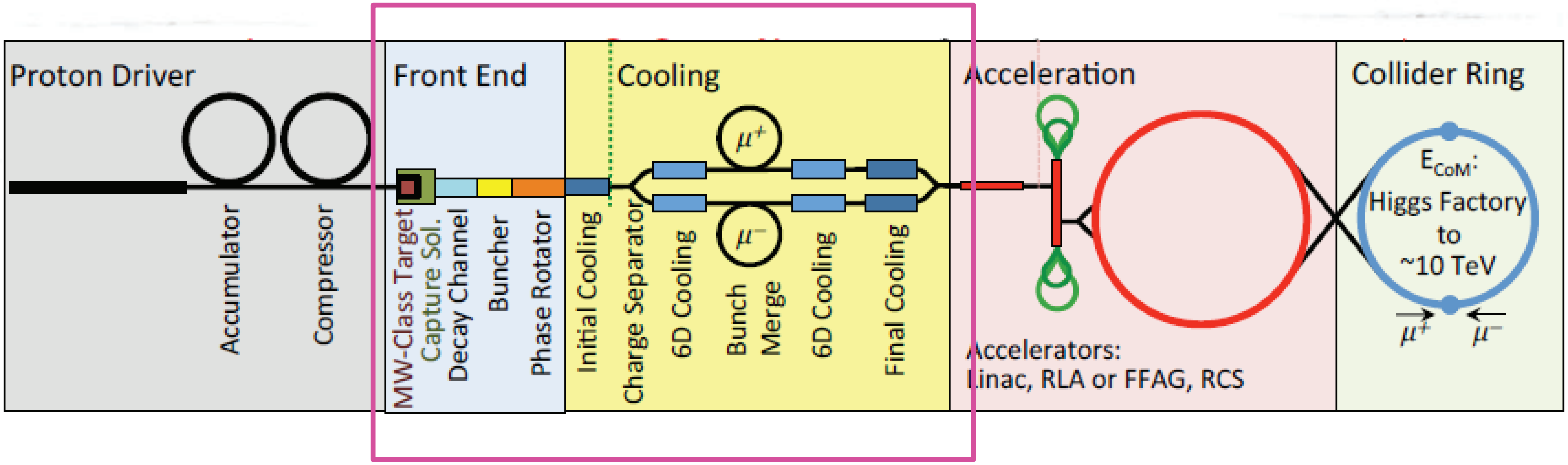
- Overview of a Muon Collider
- Concept of ionization cooling
- Ionization cooling schemes considered for a Muon Collider
  - Early stages: 6D Cooling schemes
  - Late stages: 4D cooling schemes
- Current status
- Future work

Muon Collider as viewed by MAP



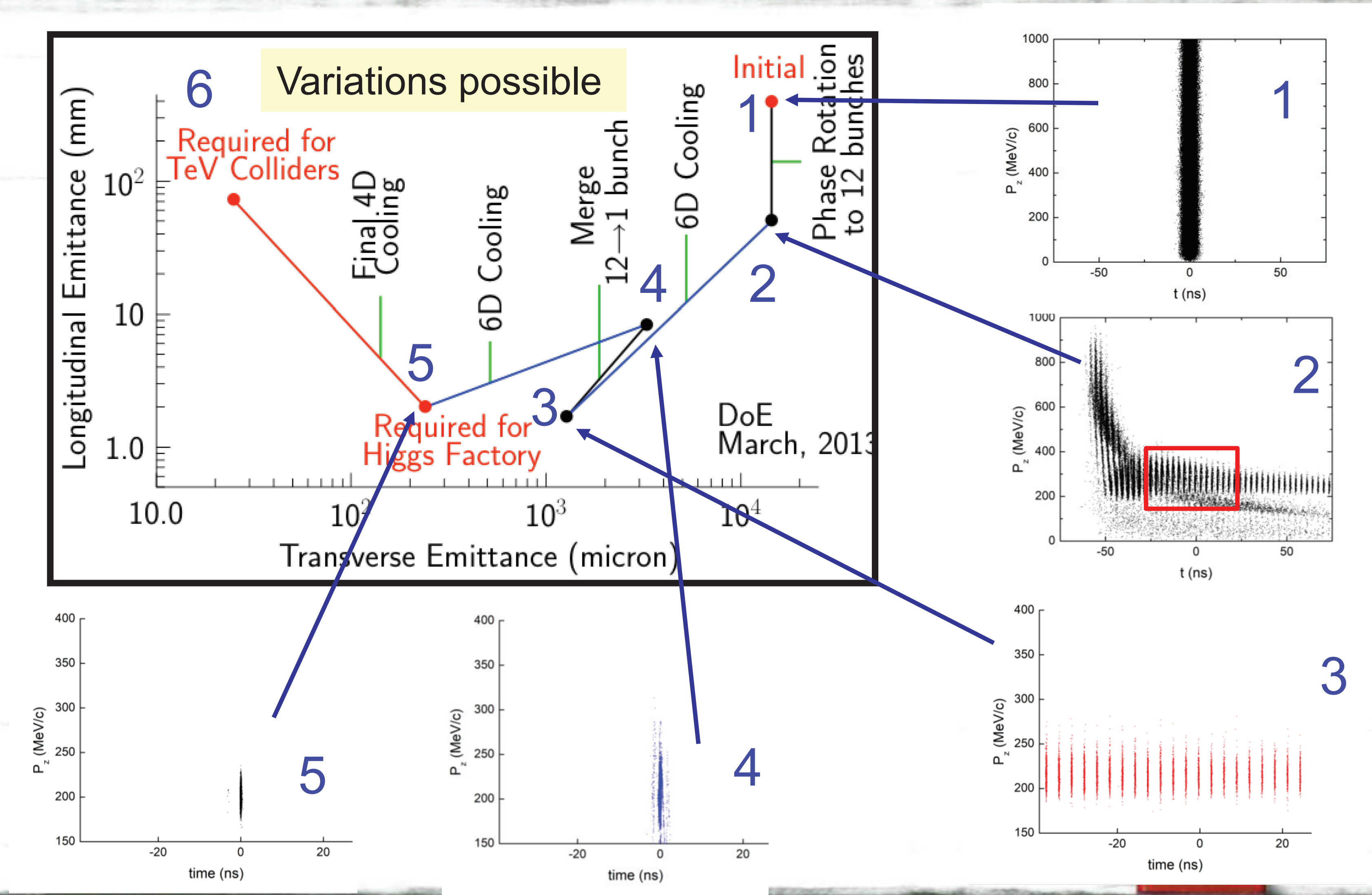
- Muon Accelerator Program (MAP) considered a proton driven machine
- The desired 6D beam emittance for a Muon Collider (MC) is ~6 orders of magnitude less from the one at the target
- Significant “muon cooling” is required!

Cooling as viewed by MAP

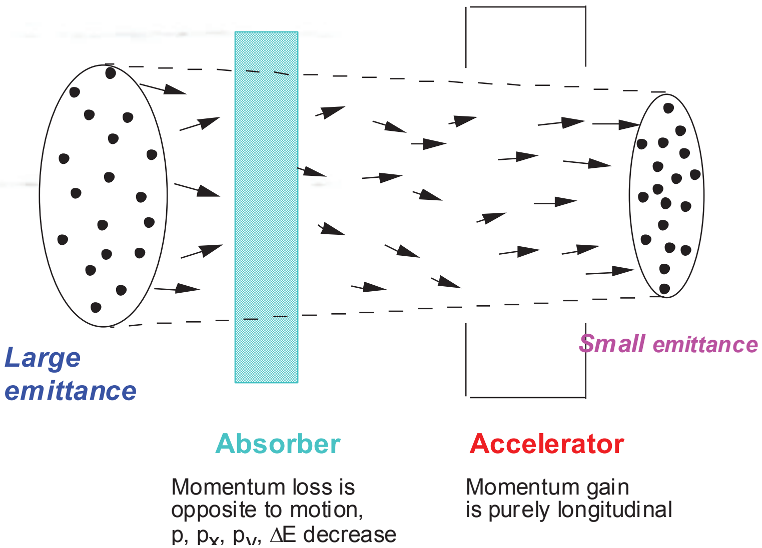


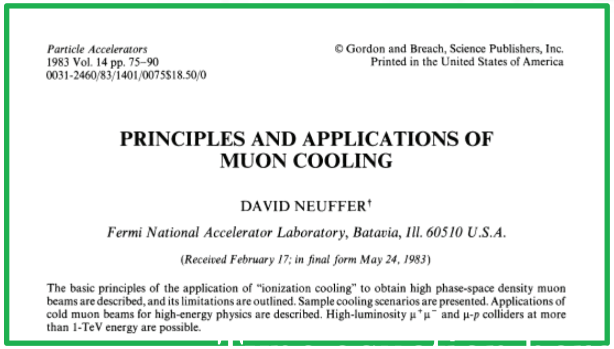
- Front-end produces 21 well aligned muon bunches
- Two sets of 6D cooling schemes
  - One before recombination (trans ε≈1.5 mm)
  - One after recombination (trans ε≈ 0.30 mm or less)
- Final cooling to shrink trans ε by an order of magnitude more

Cooling baseline



Ionization cooling formalism (1)





Particle Accelerators
1983 Vol. 14 pp. 75–90
0031-2460/83/1401/0075$18.50/0

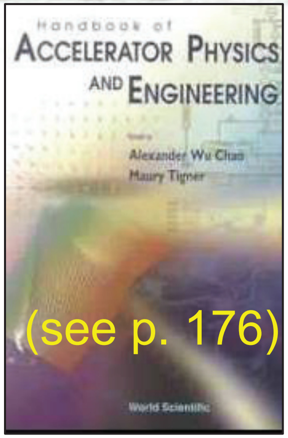
PRINCIPLES AND APPLICATIONS OF MUON COOLING

DAVID NEUFFER†

Fermi National Accelerator Laboratory, Batavia, Ill. 60510 U.S.A.

(*Received February 17; in final form May 24, 1983*)

The basic principles of the application of "ionization cooling" to obtain high phase-space density muon beams are described, and its limitations are outlined. Sample cooling scenarios are presented. Applications of cold muon beams for high-energy physics are described. High-luminosity $\mu^+\mu^-$ and μ-p colliders at more than 1-TeV energy are possible.



Energy loss term

Multiple scattering term

- Transverse cooling:

$$\frac{d\varepsilon_T}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_T + \frac{\beta\gamma\beta_T}{2}\frac{d\theta_0^2}{ds}$$

- Minimum emittance:

$$\varepsilon_T^{\mathrm{eq}} = \left(\frac{dE}{ds}\right)^{-1}\frac{\beta_T(13.6\ \mathrm{MeV})^2}{2\beta m_\mu c^2 L_R}$$

L_R: Radiation length

E: Muon energy

β_T: Transverse beta function

$\frac{dE}{ds}$: Energy loss

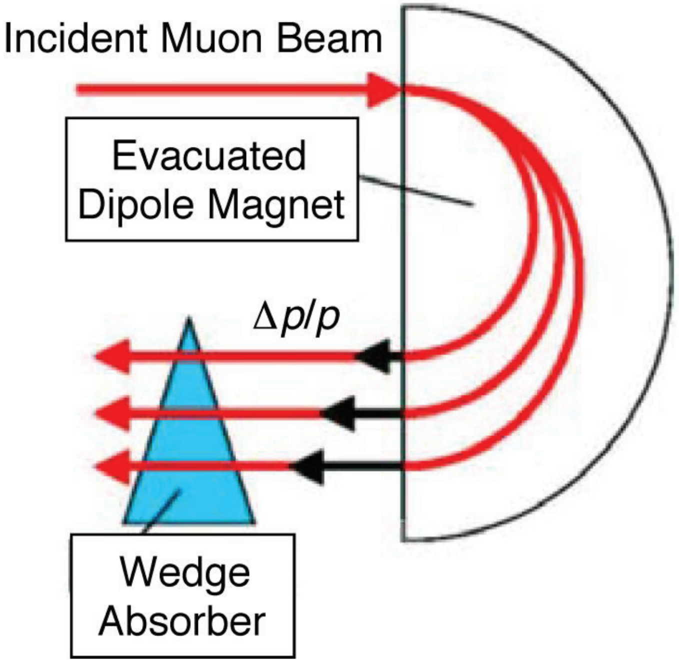
- Cooling can be controlled by material and magnetic focusing properties

Ionization cooling formalism (2)

Cooling term — Straggling term

- Longitudinal cooling: $$\frac{d\sigma_E^2}{ds} = -2\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E}\sigma_E^2 + \frac{d < \Delta E_{rms}^2 >}{ds}$$

- Cooling occurs only if derivative: $\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E} > 0$
- Ionization loss does not naturally provide adequate longitudinal cooling
- Can be enhanced, if it is arranged that high energy muons lose more energy than low energy ones.

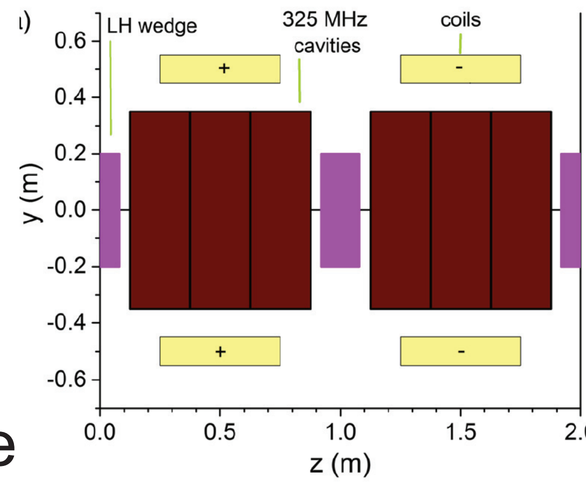


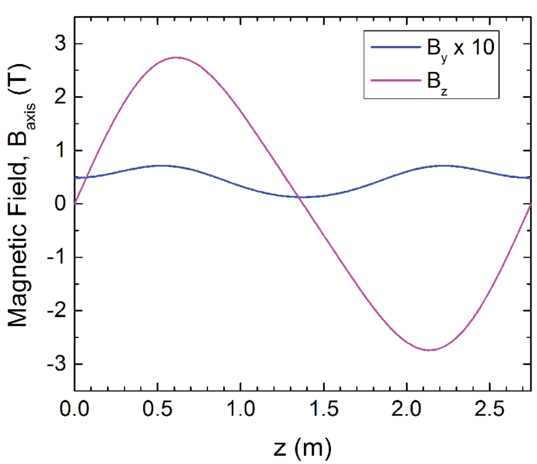
Cooling schemes

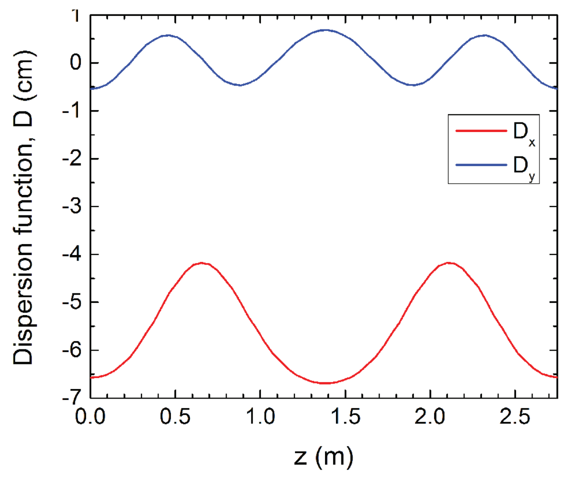
- Historically many schemes have been explored. This talk will focus in a few – mostly the recent ones (last decade)
- 6D Cooling
  - Rectilinear vacuum cooling channel
  - Helical cooling channel
  - Helical FOFO snake channel
- Final cooling
  - A high field solenoidal channel ~ 30 T
  - A parametric resonance ionization cooling (PIC) scheme

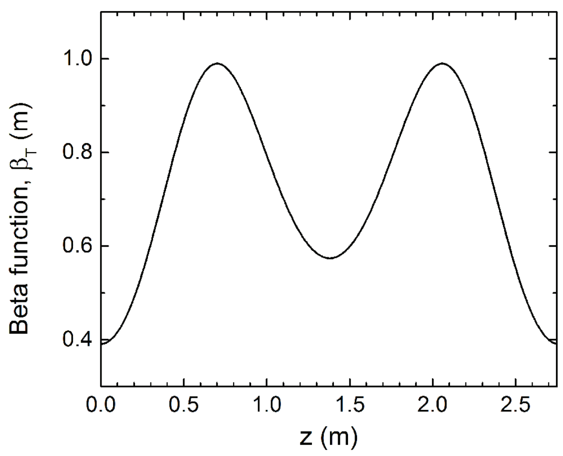
Rectilinear channel: Design (1)

- Coils are slightly tilted to generate a B_y component
- This leads to dispersion, primarily in x.
- 6D cooling on wedge absorber
- Better, if beta is minimum at the absorbe

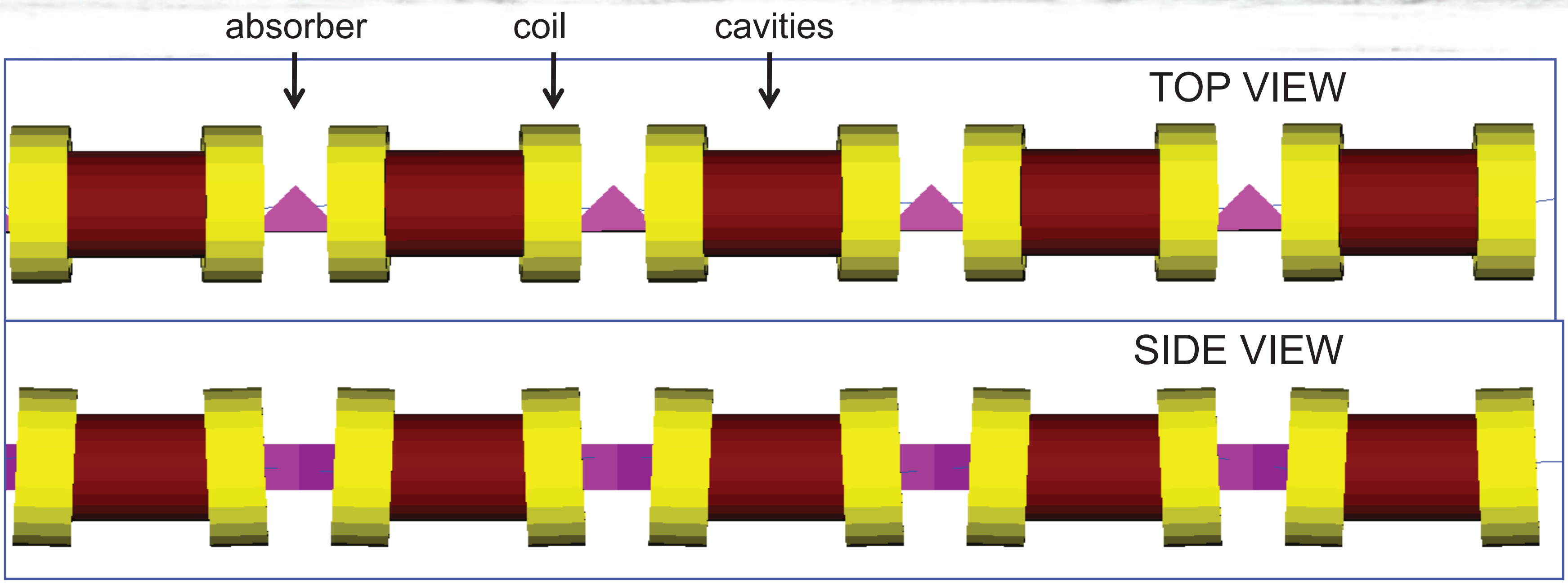






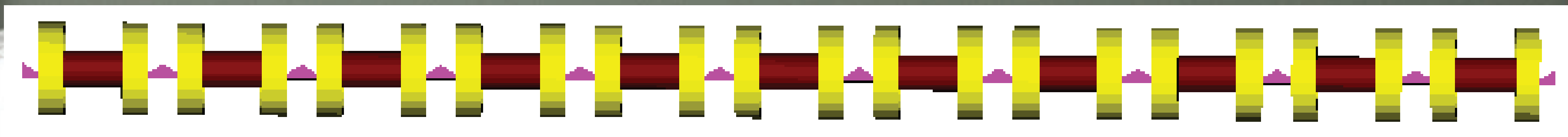


Rectilinear channel: Design (2)

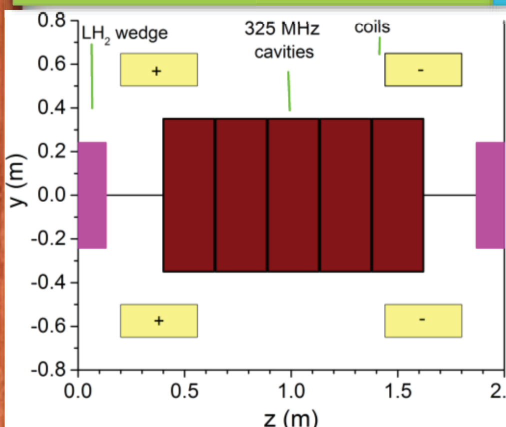


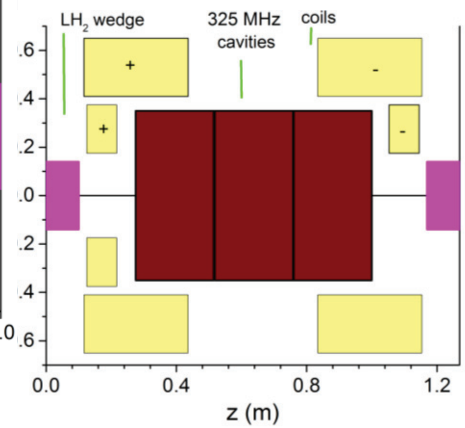
- Straight geometry simplifies construction and relaxes several technological challenges
- Multiple stages with different cell lengths, focusing fields, rf frequencies to ensure fast cooling

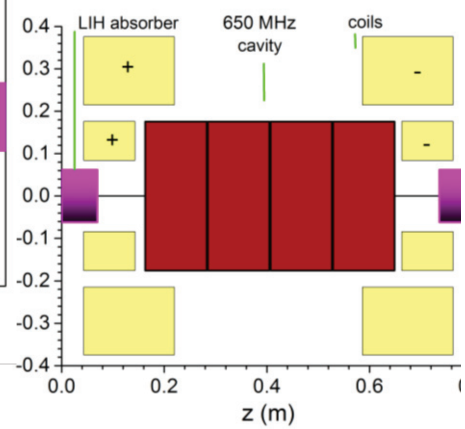
Rectilinear channel: Design (3)

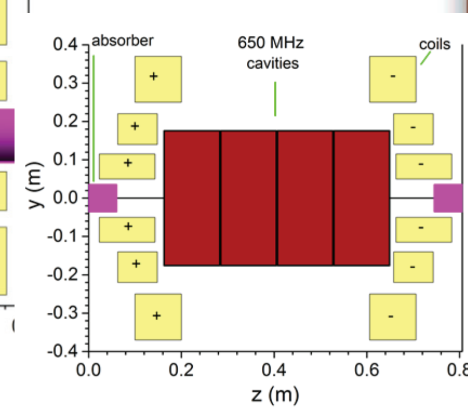


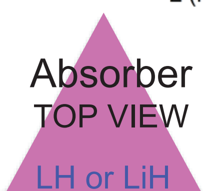
STAGE 2	STAGE 4	STAGE 6	STAGE 8
64 m (32 cells)	62.5 m (50 cells)	62 m (77 cells)	41.1 m (51 cells)









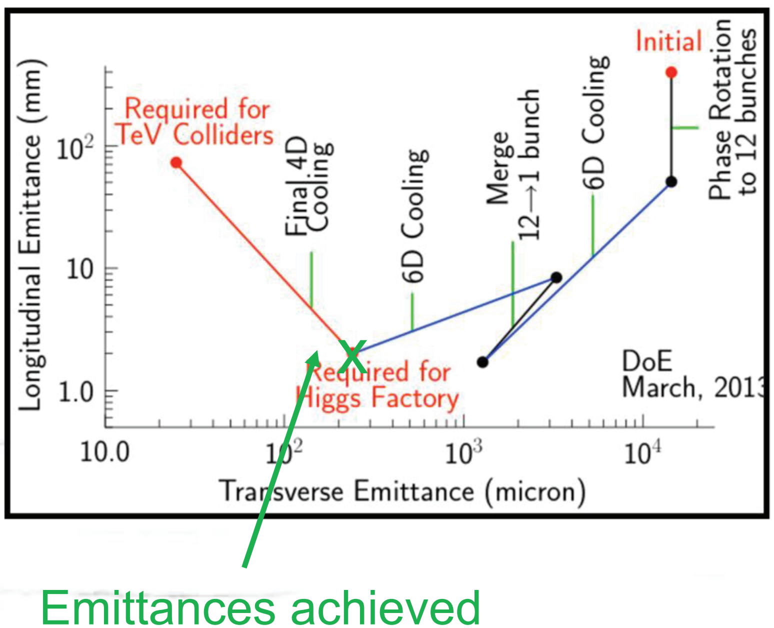


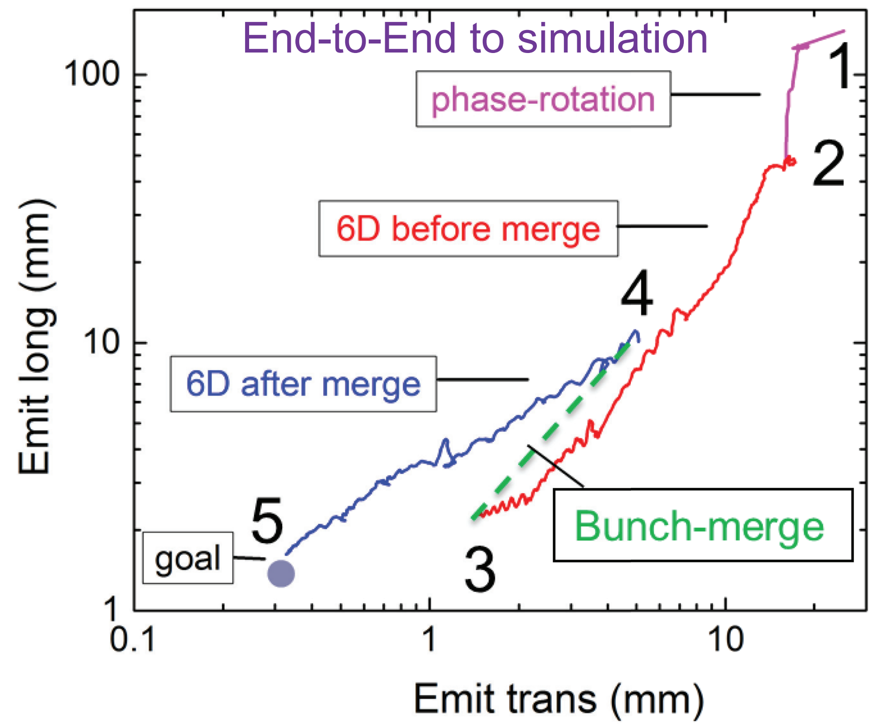
3.7 T (8.4 T) | 6.0 T (9.2 T) | 10.8 T (14.2 T) | 13.6 T (15.0 T)

Peak B-field on axis (coil)

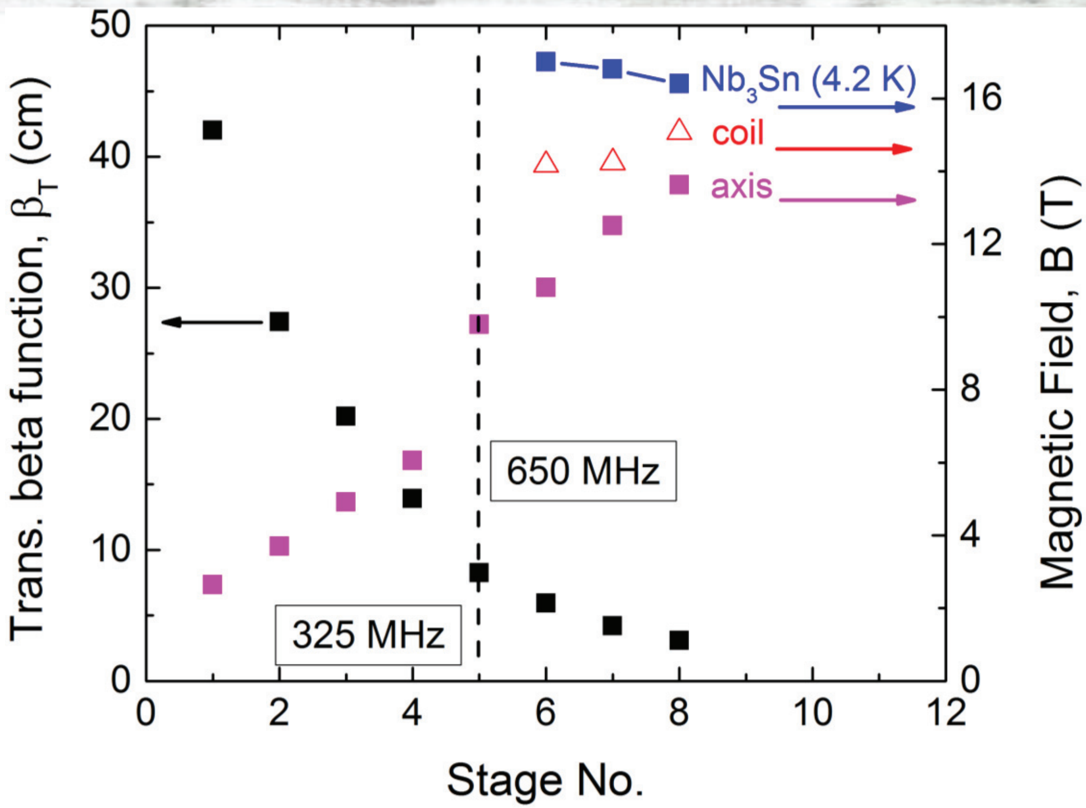
Rectilinear channel: Performance

- Complete end-to-end simulation from the target (point 1)
- 6D emittance reduction by five orders of magnitude (point 5)
- Achieved emittances and transmissions specified by MAP
- Overall distance ~ 900 m



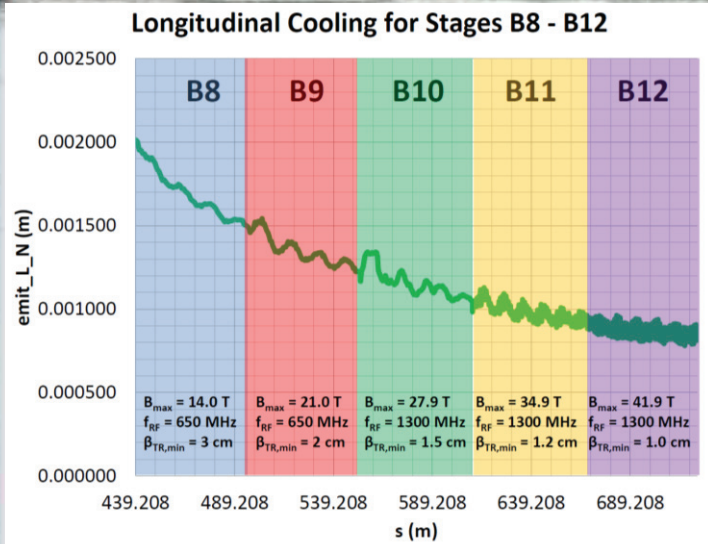


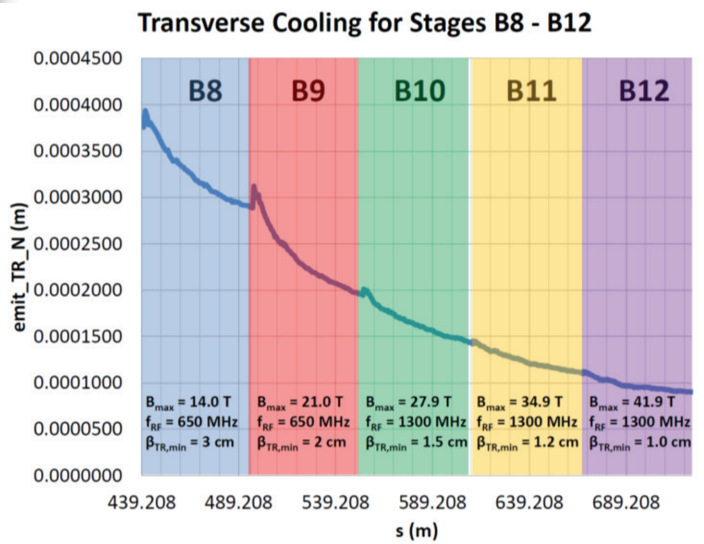
Rectilinear: Magnet technology



- We set two constrains in our (initial) design:
  - Peak fields on coils don't exceed Niobium Tin limits
  - Cavities within> 1 T operate at 50% of the achievable gradient at 0 T

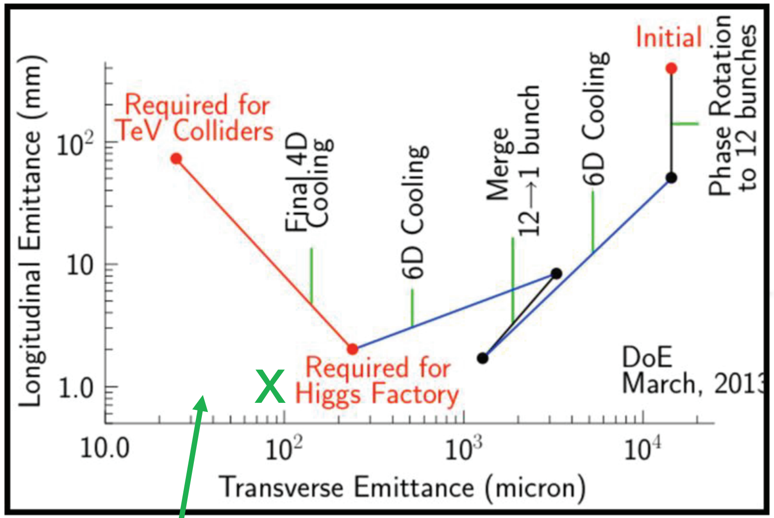
Rectilinear with HTS magnets





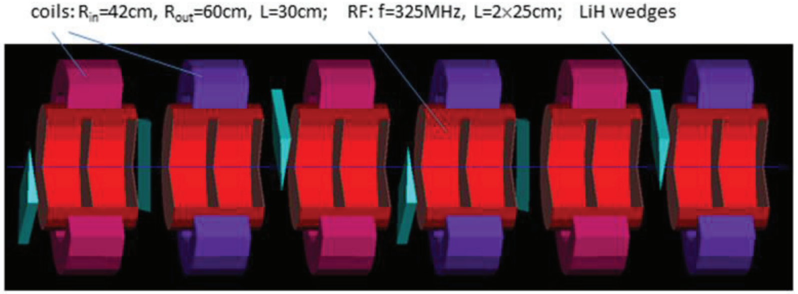
- If HTS magnet technology is considered, rectilinear channel can reduce the 6D emittance even more

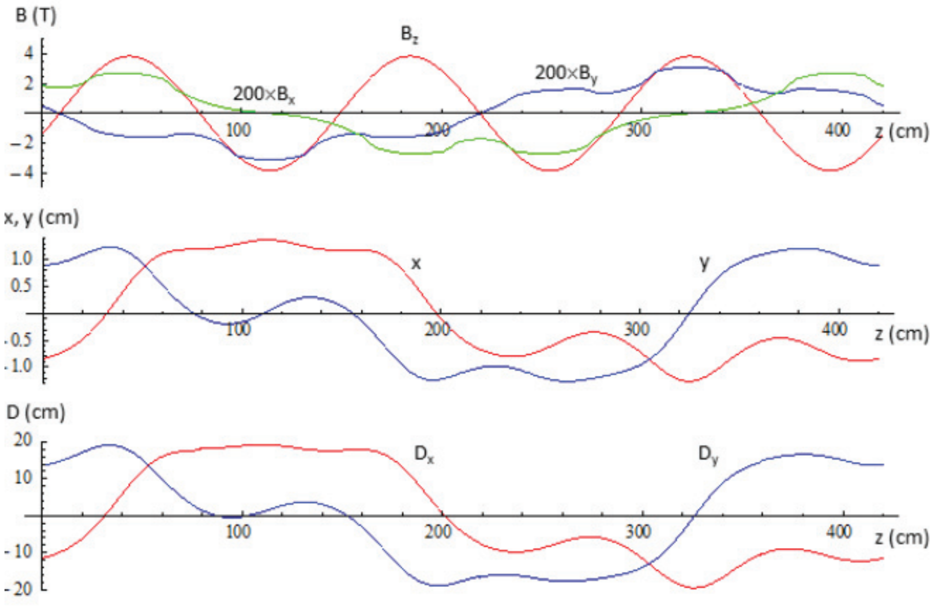
Don Summers,
University of Mississippi



Emittances achieved

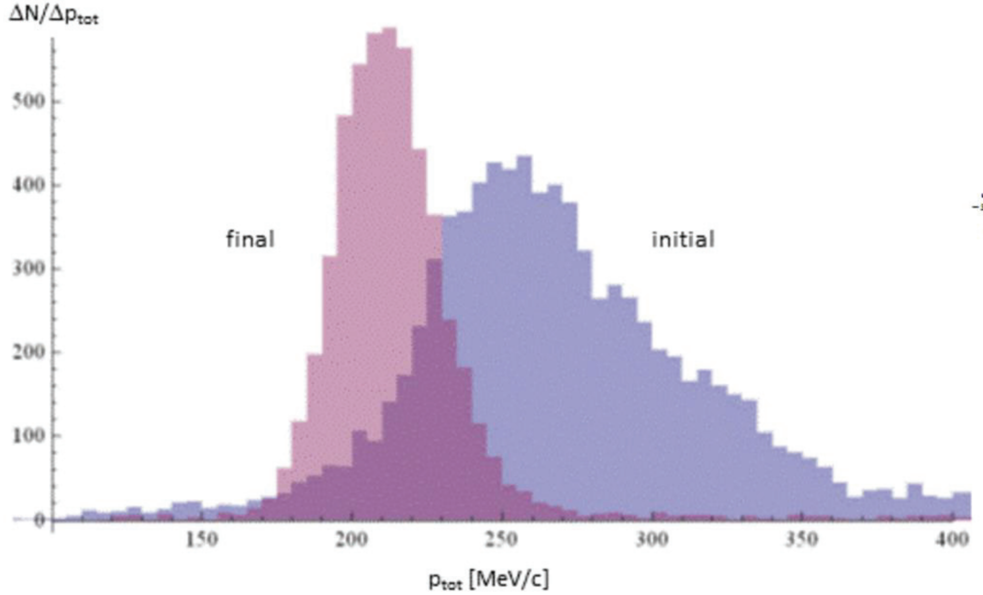
FOFO snake: Design

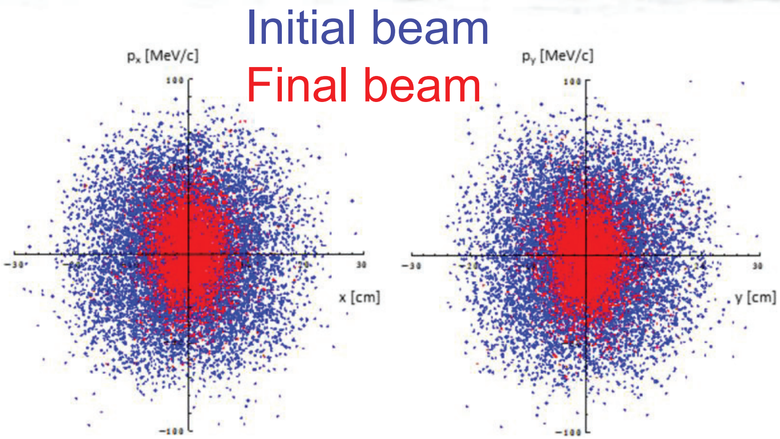


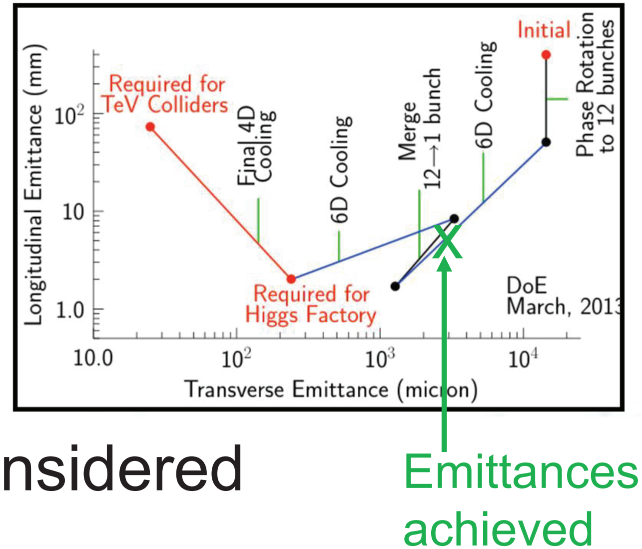


- Transports and cools muons of both signs
- Consists of a set of rotating solenoids that are tilted to provide a small dipole field

FOFO snake: Performance

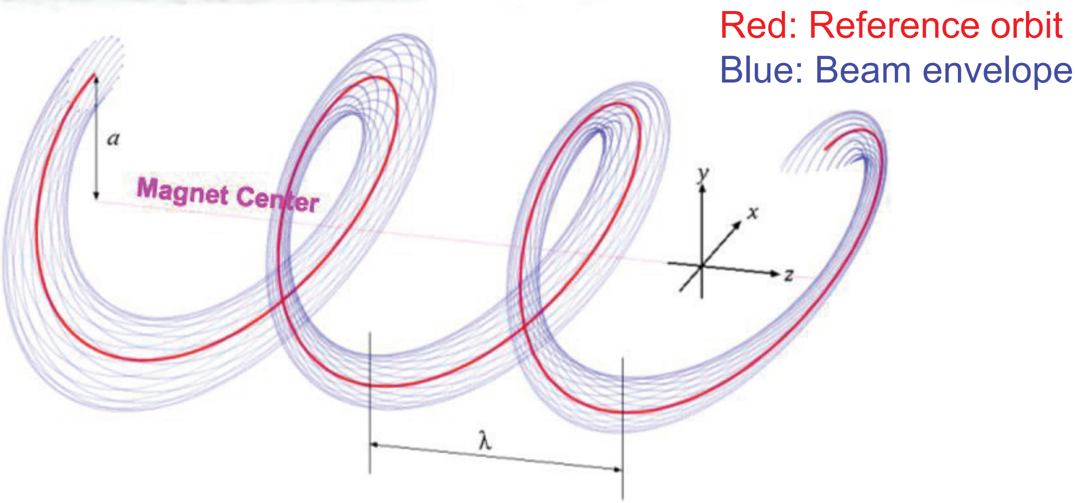


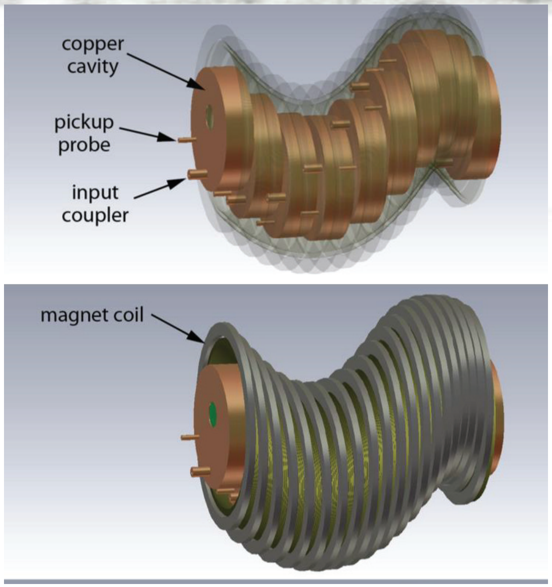




- Good transmission ~70%
- Alternatives schemes need to be considered for lower emittances

Helical channel : Design



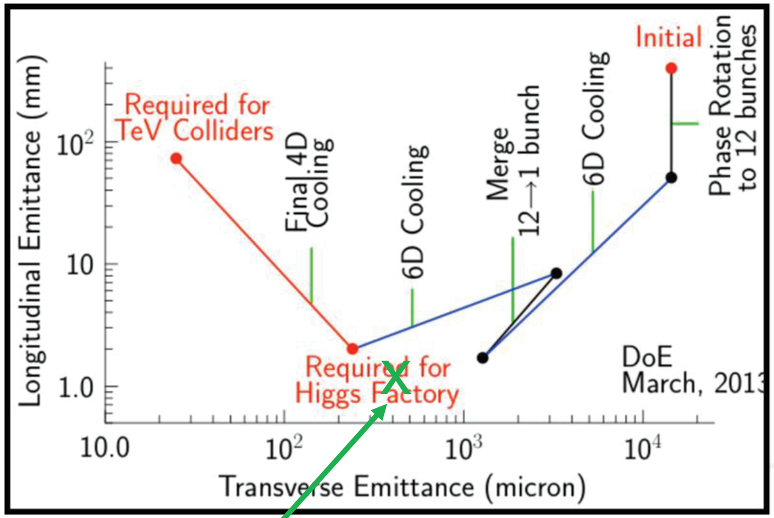


- HCC is filled with hydrogen gas that acts as a continuous absorber
- HCC is composed of a solenoidal field with superimposed helical transverse dipole & quadrupole fields.
- Energy loss, energy regeneration, emittance exchange, and longitudinal and transverse cooling happen simultaneously

Helical channel: Performance

- Demonstrated significant cooling and good transmission
- Gas was opposing cooling to below ~ 0.58 mm on the other hand, HCC can cool to a lower longitudinal emittance since it was not prone to space-charge limitations (see later)

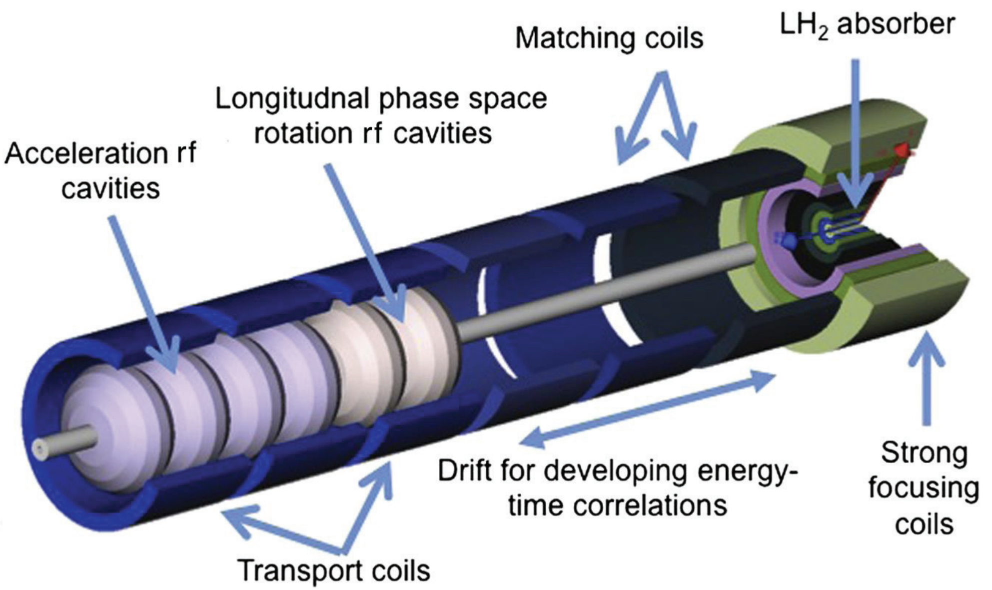
Seg.	λ	L	ν	B_z	b	b'	$\varepsilon_{T,\mathrm{eq}}$	$\varepsilon_{L,\mathrm{eq}}$	$\varepsilon_{\mathrm{tr}}$
unit	m	m	MHz	T	T	T/m	mm rad	mm	
0							5.03	8.82	
1	1.0	50	325	4.41	1.32	−0.32	3.44	6.82	0.94
2	0.8	70.4	325	5.52	1.65	−0.50	1.62	2.41	0.90
3	0.5	120	650	8.83	2.63	−1.28	0.79	1.18	0.81
4	0.4	77.2	650	11.04	3.29	−2.01	0.61	0.89	0.85
		317.6							0.58

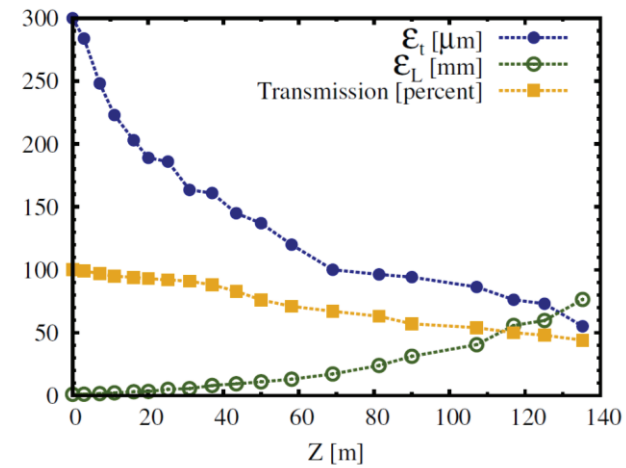


Emittances achieved

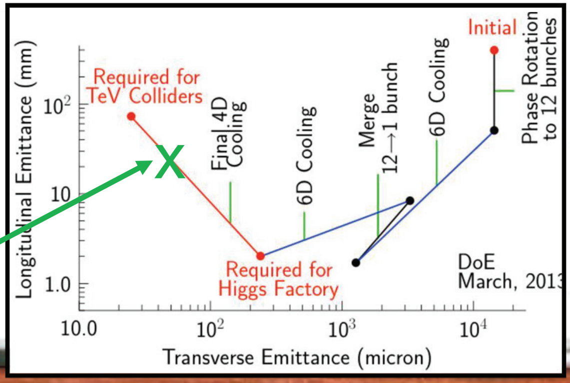
Final Cooling: High field magnets

- Simulated the distribution coming out of the rectilinear channel
- Showed that using 30 T magnets the emittance can be reduced near the regime needed for a MC.





Emittances achieved



Areas of further research

- Magnet technology: High-field, multi-Tesla SC magnets for muon transport and cooling.
  - HTS has seen huge advances recently which is very encouraging.
- RF technology: High gradient, robust normal conducting rf cavities for cooling in multi-Tesla magnetic fields.
  - Beryllium cavity test showed promising results at 3 T
- Lattice designs: Shorter cooling channel designs, capabilities to cool muons of both signs ideal, integration of smart optimization algorithms
- Beam Dynamics: Impact of collective effects on cooling

Current status

- MAP was terminated in 2016; most related work paused
- Meantime, increasingly growing interest in muon colliders from particle physics community, especially in Europe. Formation of International Muon Collaboration on the works.
- In Europe, CERN Council has charged the Laboratory Directors Group to develop the Accelerator R&D Roadmap for the next decade. Muon Colliders are considered.
  - Three community meetings organized with the goal to define the needed muon R&D with deliverables and demonstrators
- From the US side, a Muon Collider forum has been formed that meets monthly
  - AF is actively involved in the upcoming Snowmass process with the particle physics community to define the needed muon collider R&D.

Summary

- Several cooling schemes have been designed and simulated with very promising results
- Its important to emphasize that most were paper studies without a detailed engineering study to see if their configurations were feasible.
- Most work on these has stopped ~ 2015. In the meantime several progress has been made in rf and magnet technology as well as in the development of "smart" algorithms for lattice tuning
- One step forward is to revisit the old designs and see if we can make them better with the new conditions by taking into account engineering considerations.

Further related work

- Neutrino factory cooling
  - D. Stratakis and D. Neuffer, Journal of Physics G: Nuclear and Particle Physics 41,
- Helical cooling channel
  - K. Yonehara, JINST 13, P09003 (2018)
- Final cooling
  - H. Sayed, Phys.Rev.ST Accel.Beams 18, 091001 (2015)
- Bunch merger
  - Y. Bao, Phys. Rev. Accel. Beams 19, 031001 (2016)
- Helical FOFO Snake
  - Y. Alexahin, JINST 13, P08013 (2018)