Overview of muon cooling

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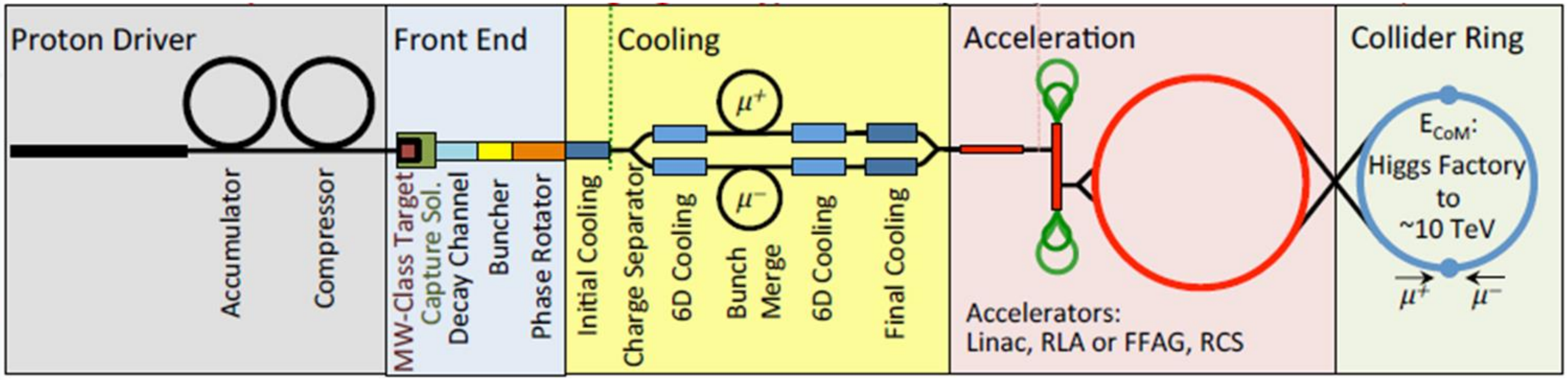
Workshop on a Muon Collider Testing Opportunities (online only)
March 25, 2021

Outline

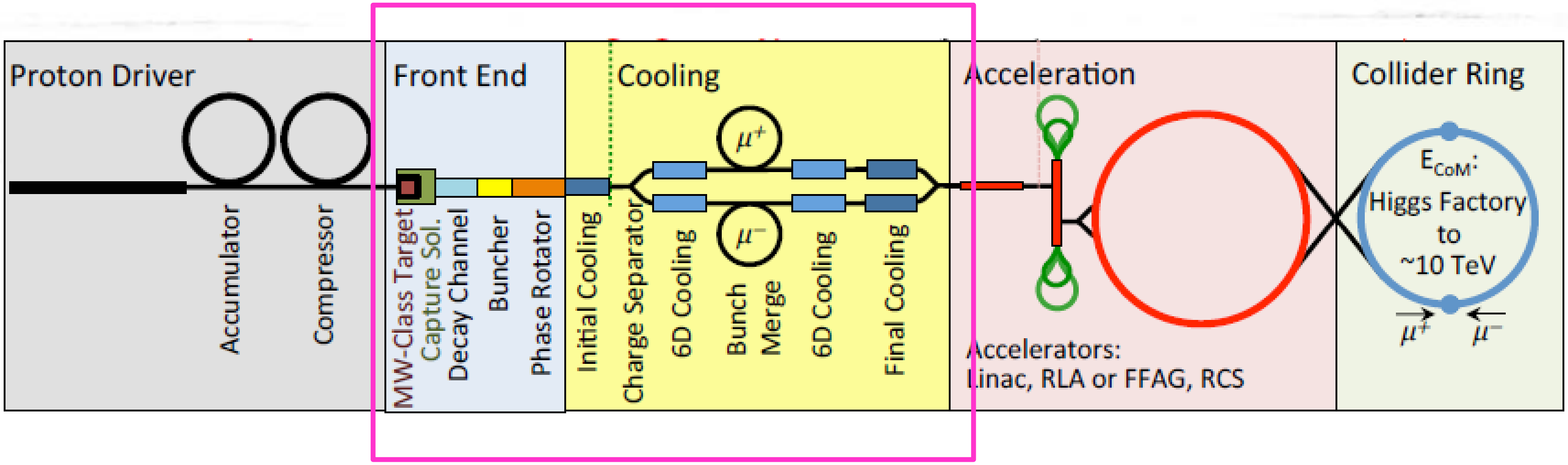
- Overview of a Muon Collider
- Concept of ionization cooling
- Two-class of cooling schemes considered for a Muon Collider
  - Early stages: 6D Cooling schemes
  - Late stages: 4D cooling schemes
- Realistic implementation of a cooling channel

Muon Collider as viewed by MAP



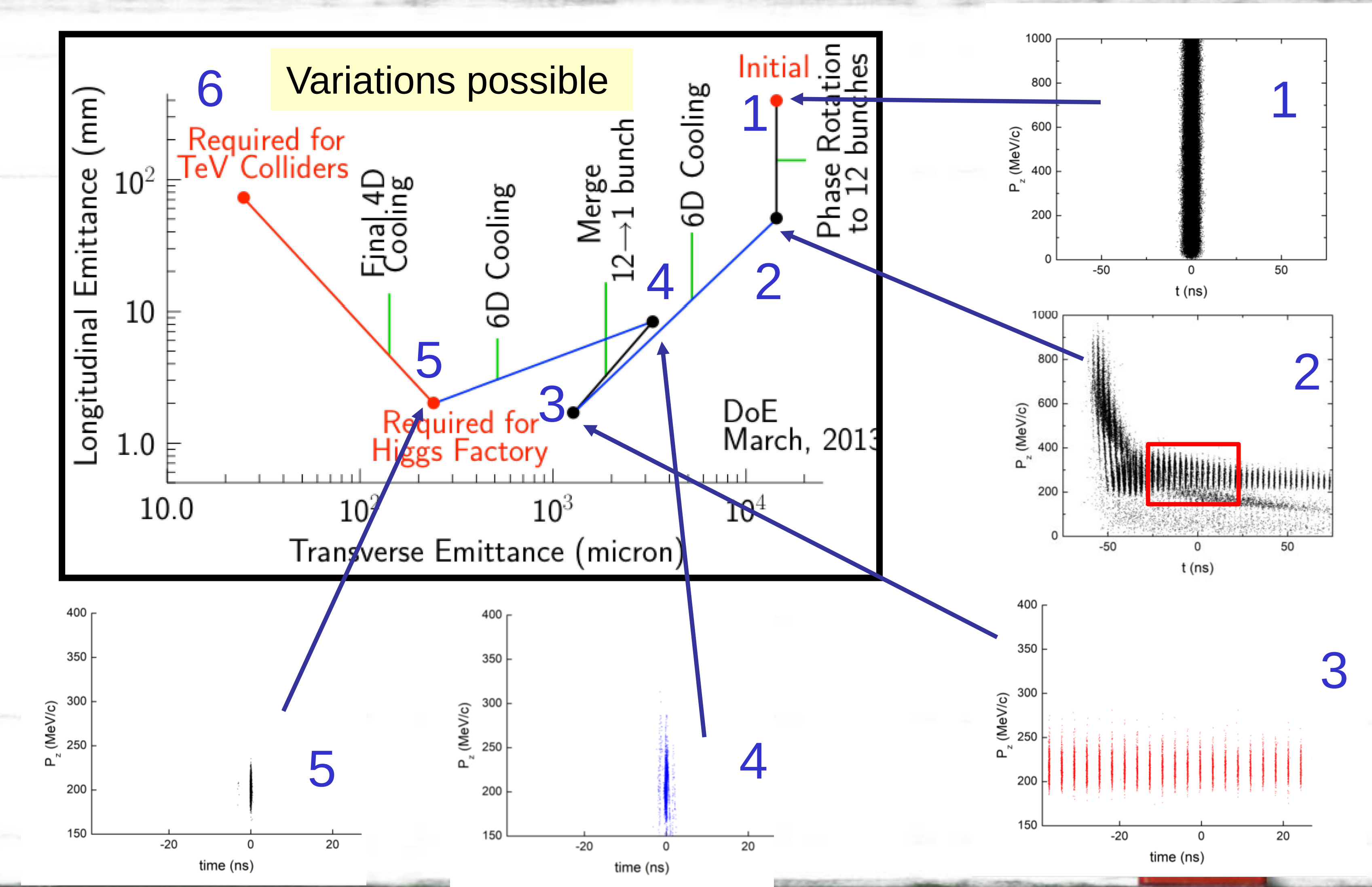
- The desired 6D emittance for a Muon Collider (MC) is 5-6 orders of magnitude less from the emittance of the muon beam at the production target
- As a result, significant "muon cooling" is required.

Cooling as viewed by MAP

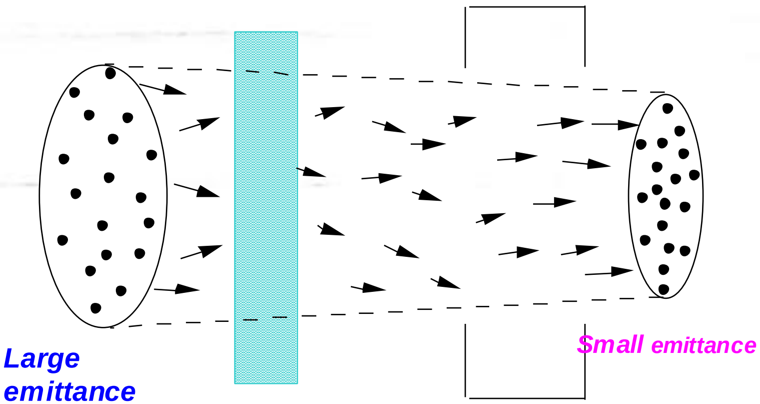


- Front-end produces 21 well aligned muon bunches
- Two sets of 6D cooling schemes
  - One before recombination (trans ε≈1.5 mm)
  - One after recombination (trans ε≈ 0.30 mm or less)
- Final cooling to shrink trans ε by an order of magnitude more

Cooling baseline



Ionization cooling formalism (1)

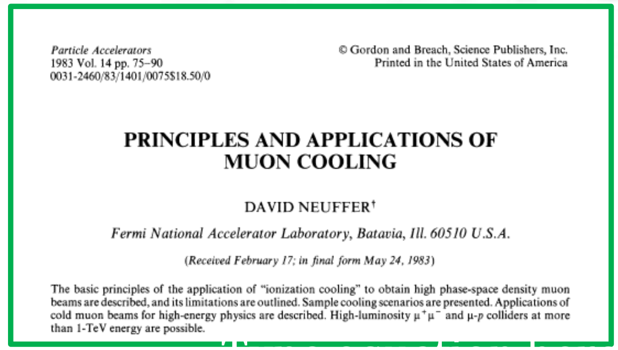


Absorber

Momentum loss is opposite to motion, p, p_x, p_y, ΔE decrease

Accelerator

Momentum gain is purely longitudinal



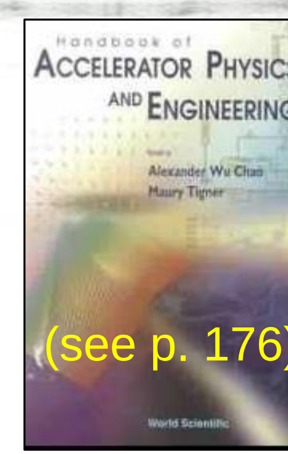
Particle Accelerators
1983 Vol. 14 pp. 75–90
0031-2460/83/1401/0075$18.50/0

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.



(see p. 176)

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

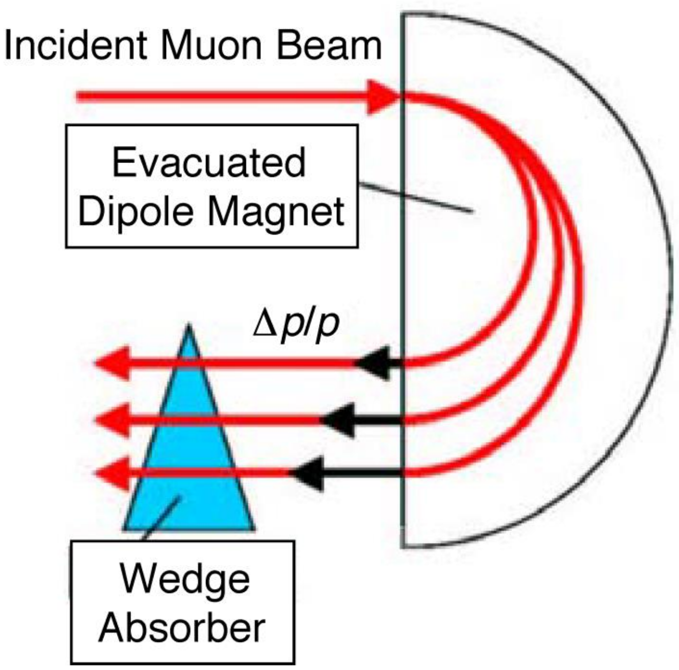
Ionization cooling formalism (2)

- Longitudinal cooling:

Cooling term — Straggling term

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

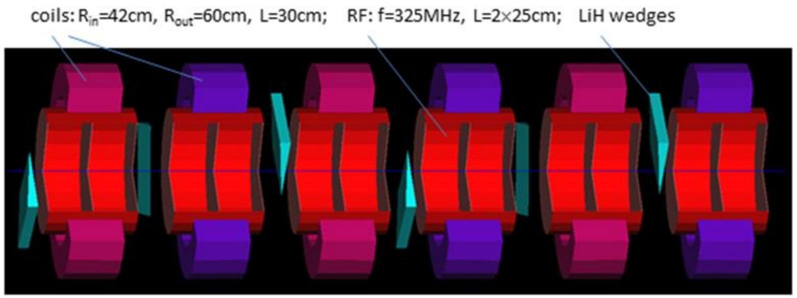
- Cooling occurs only if derivative: $\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E} > 0$
- Ionization loss does not naturally provide adequate longitudinal cooling
- Can be enhanced, if it is arranged that high energy muons lose more energy than low energy ones.

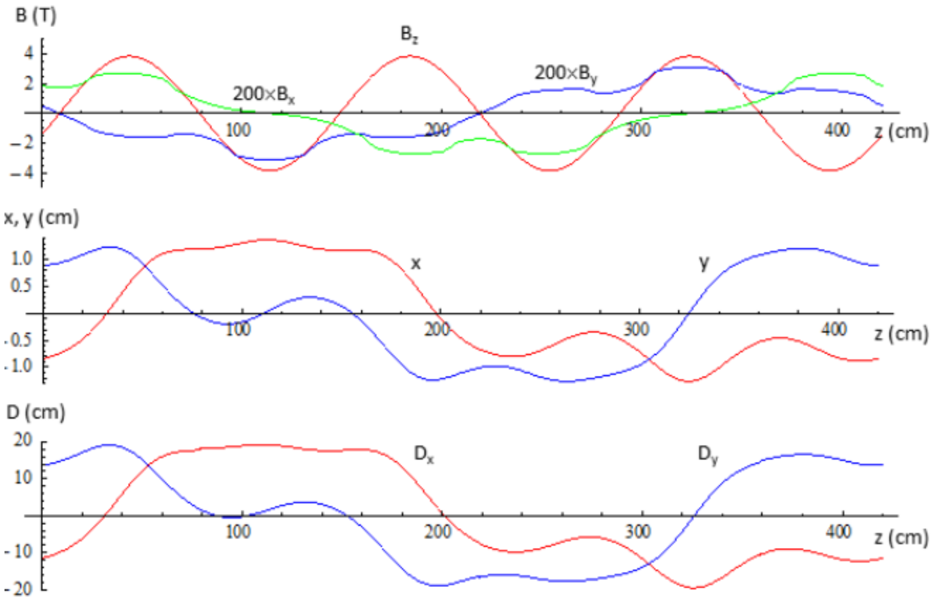


Cooling schemes

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

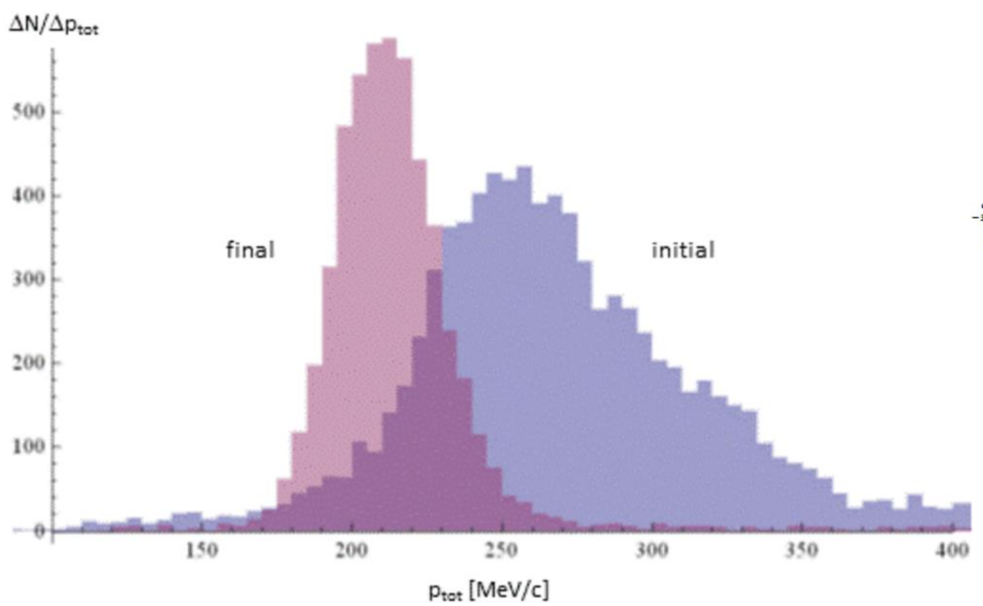
FOFO snake: Design



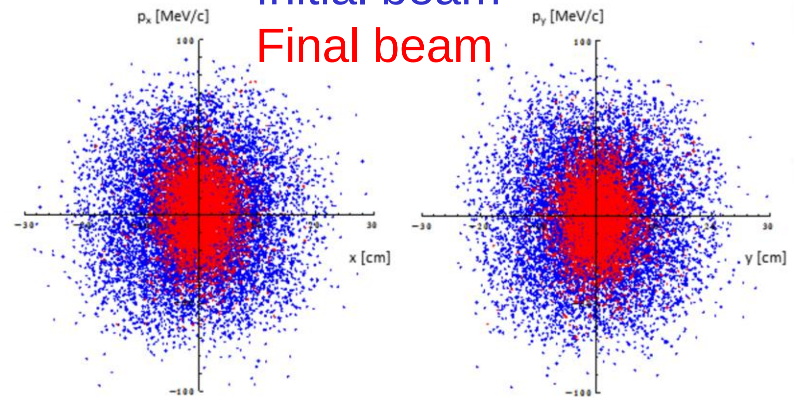


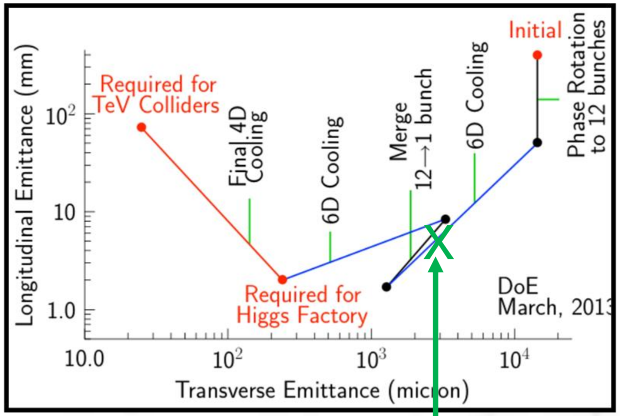
- Transports and cools muons of both signs
- Consists of a set of rotating solenoids that are tilted to provide a small dipole field

FOFO snake: Performance



Initial beam
Final beam

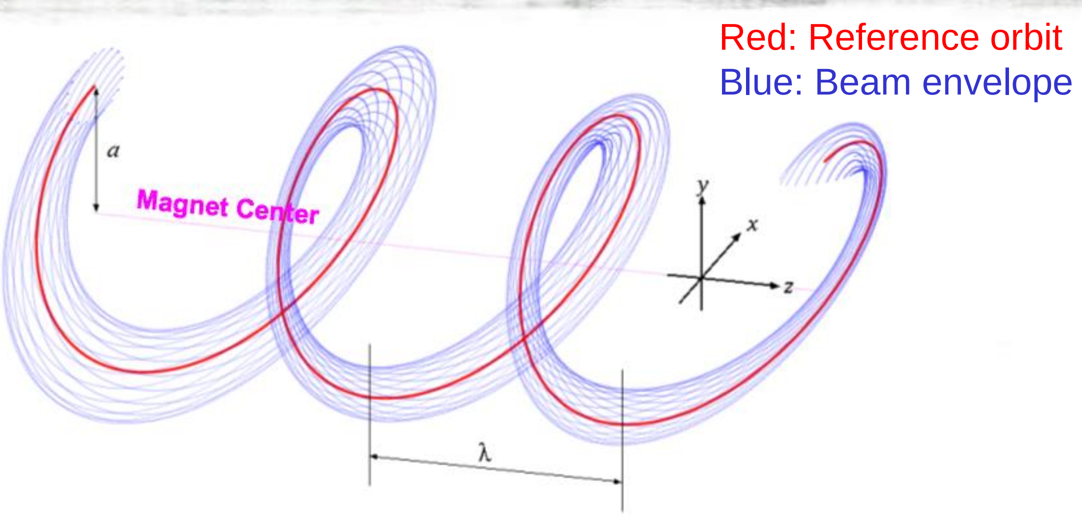


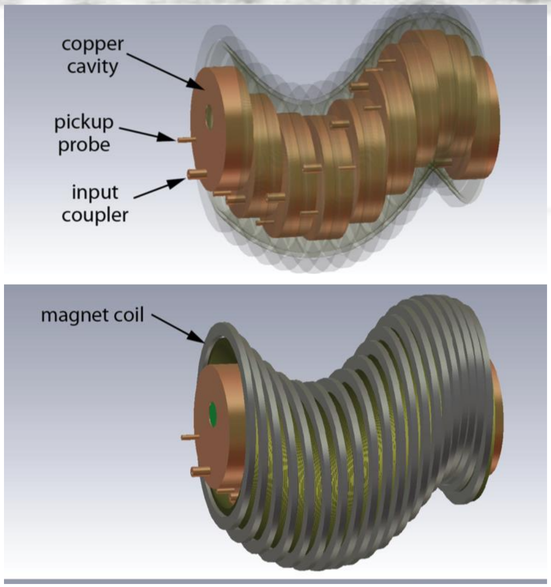


Emittances achieved

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

Helical channel : Design



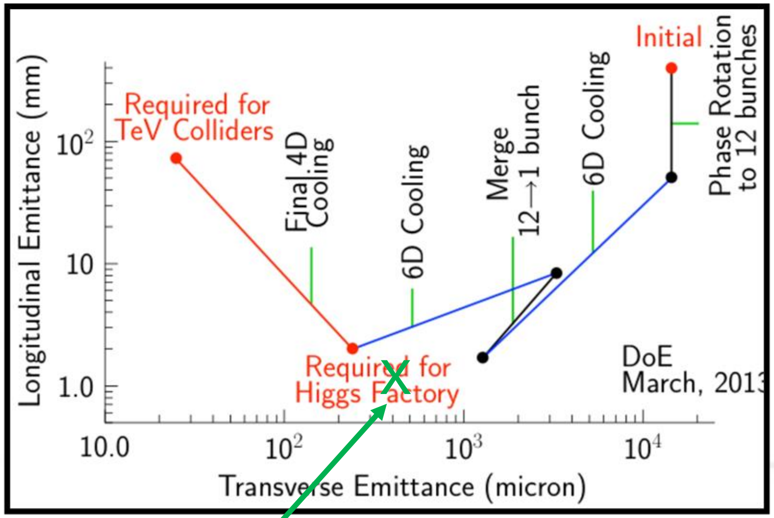


- HCC is filled with hydrogen gas that acts as a continuous absorber
- HCC is composed of a solenoidal field with superimposed helical transverse dipole & quadrupole fields.
- Energy loss, energy regeneration, emittance exchange, and longitudinal and transverse cooling happen simultaneously

Helical channel: Performance

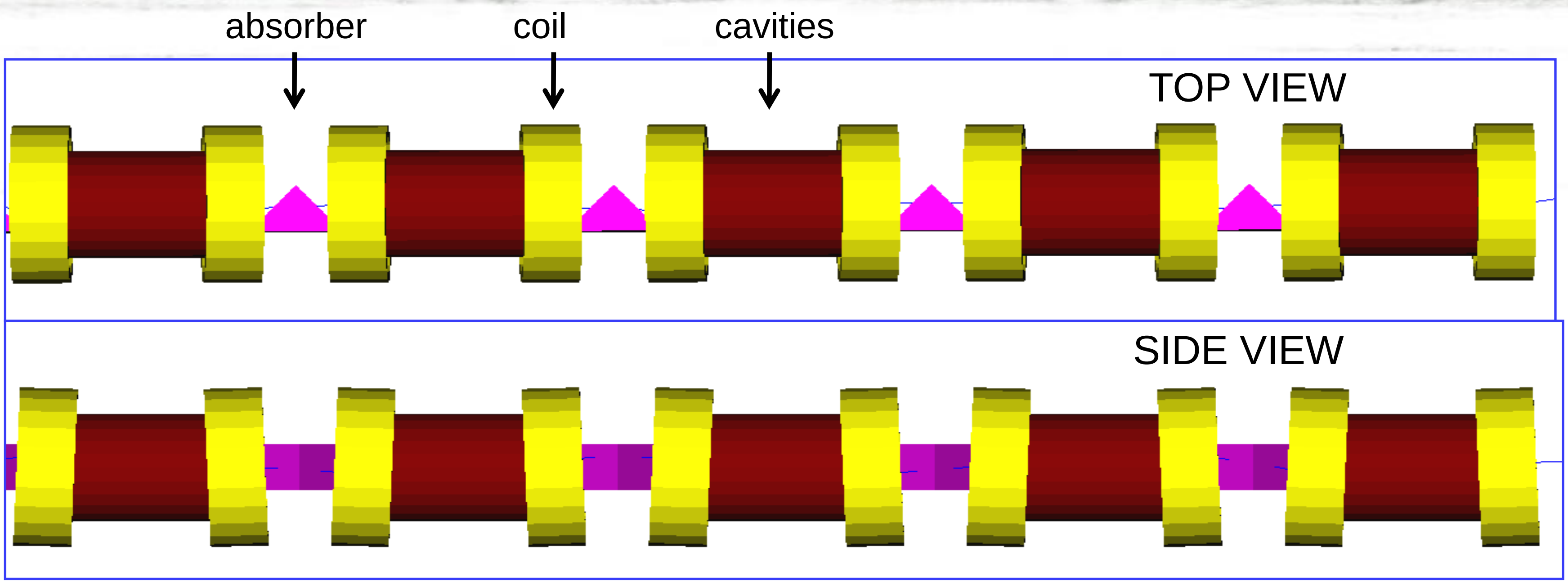
- Demonstrated significant cooling and good transmission
- Gas was opposing cooling to below ~ 0.58 mm on the other hand, HCC can cool to a lower longitudinal emittance since it was not prone to space-charge limitations (see later)

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

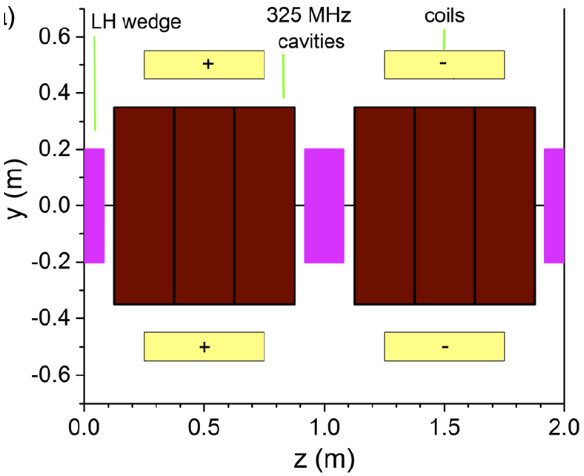
Rectilinear channel: Design (1)

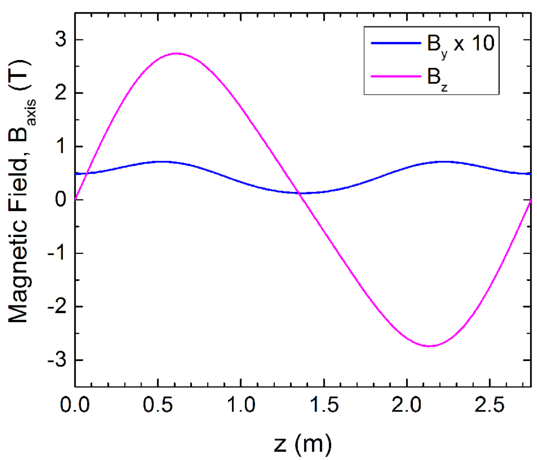


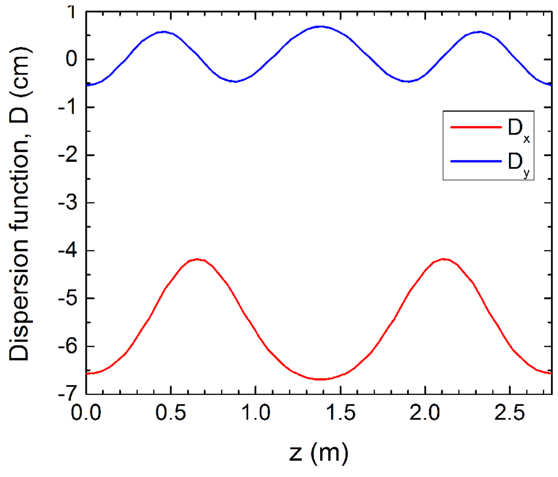
- Straight geometry simplifies construction and relaxes several technological challenges
- Multiple stages with different cell lengths, focusing fields, rf frequencies to ensure fast cooling

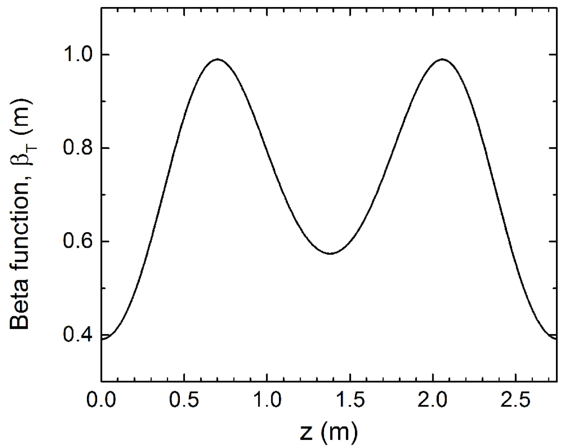
Rectilinear channel: Design (2)

- 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

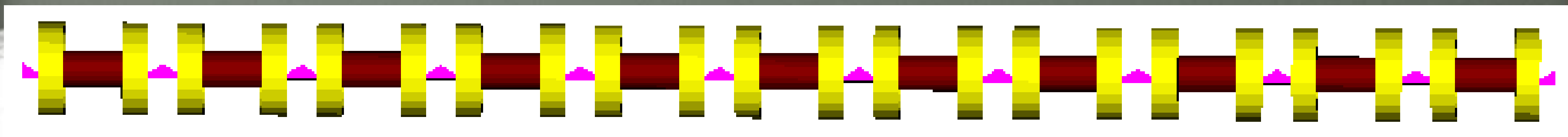




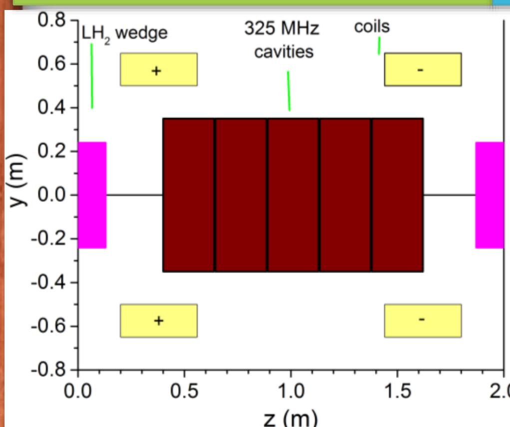


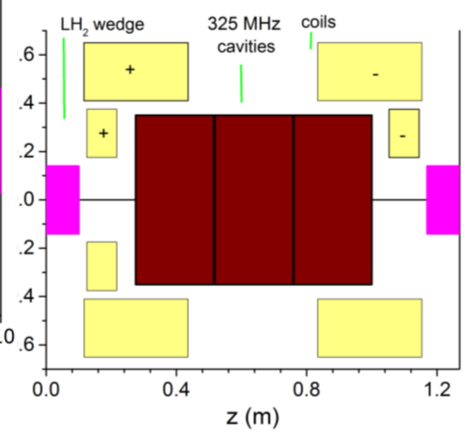


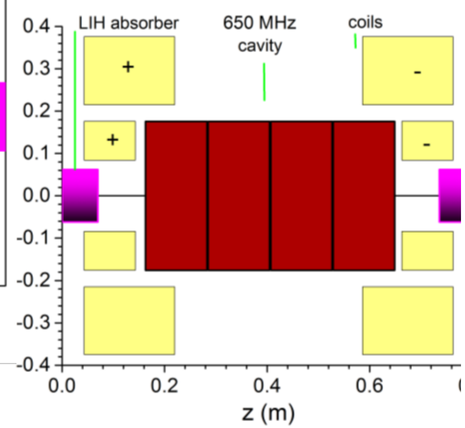
Rectilinear channel: Design (3)

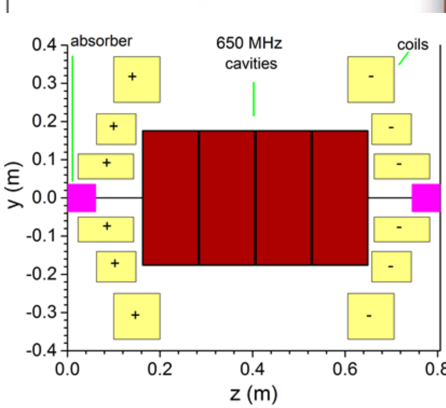


STAGE 2	STAGE 4	STAGE 6	STAGE 8
64 m (32 cells)	62.5 m (50 cells)	62 m (77 cells)	41.1 m (51 cells)







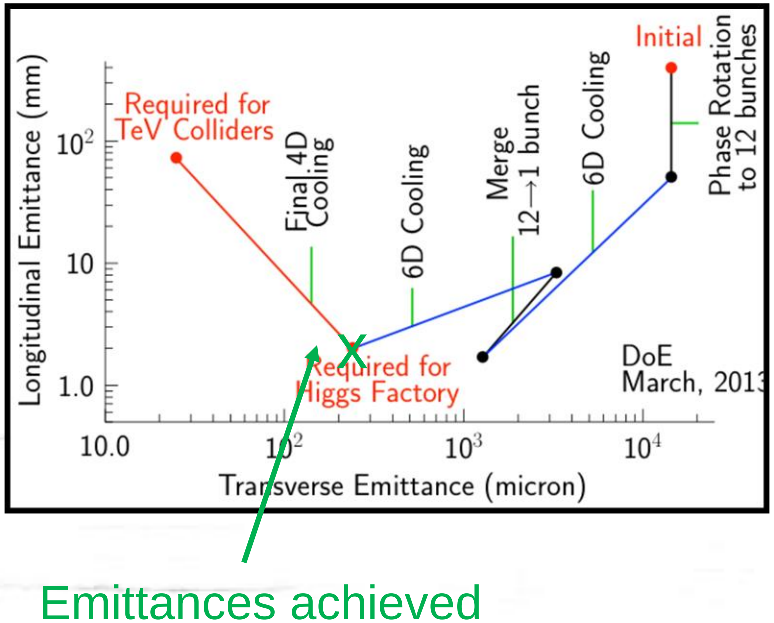


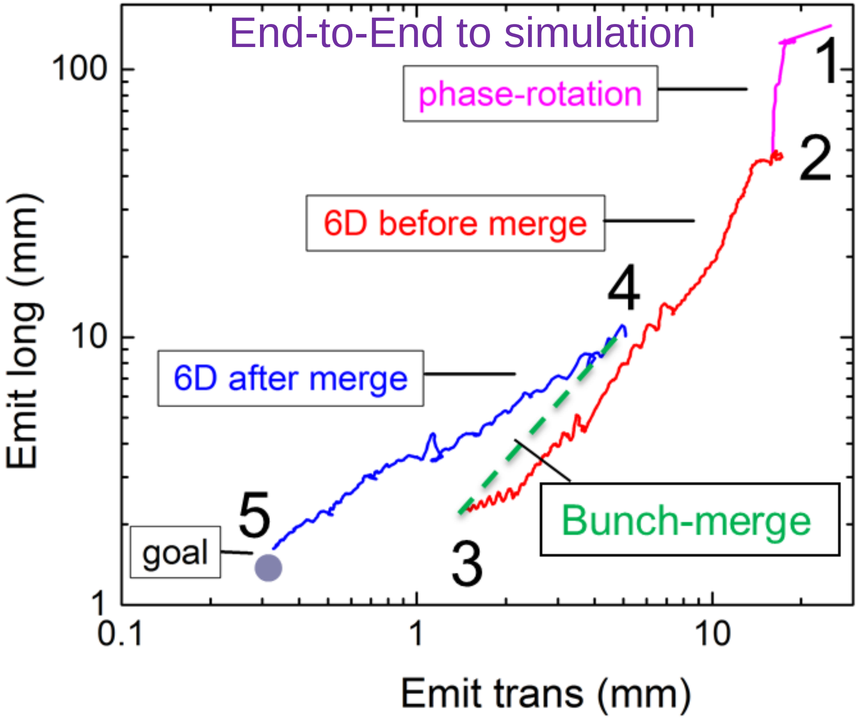
3.7 T (8.4 T) | 6.0 T (9.2 T) | 10.8 T (14.2 T) | 13.6 T (15.0 T)

Peak B-field on axis (coil)

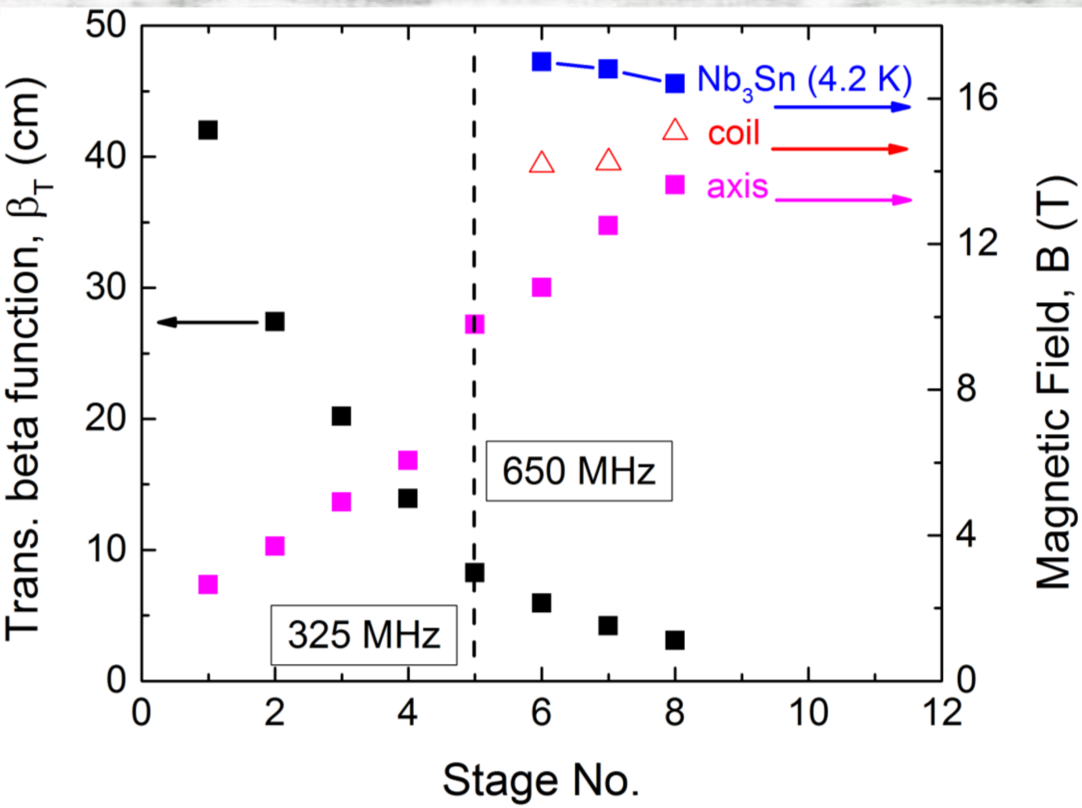
Rectilinear channel: Performance

- 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



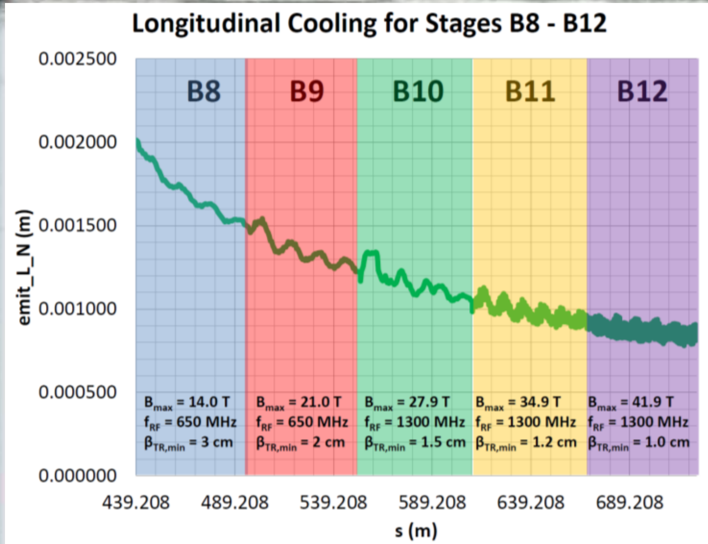


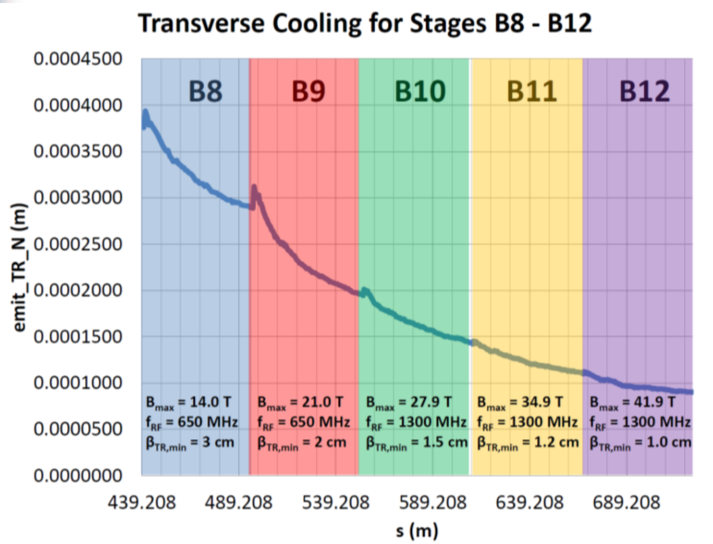
Rectilinear: Magnet technology



- 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

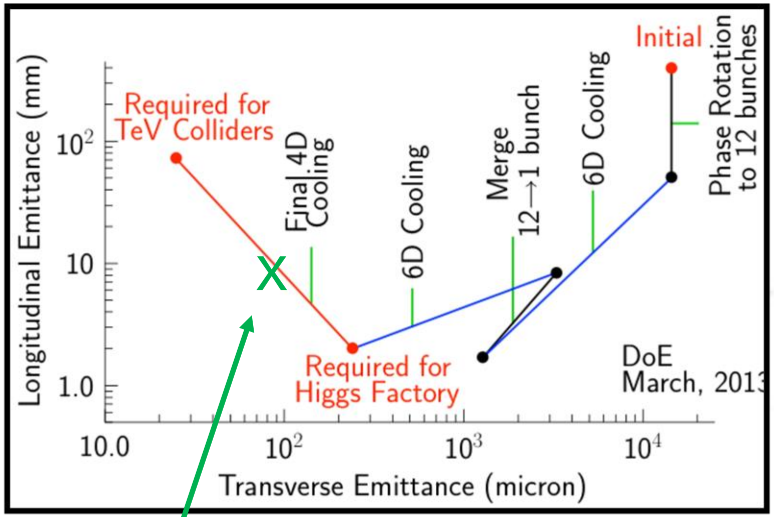
Rectilinear with HTS magnets





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

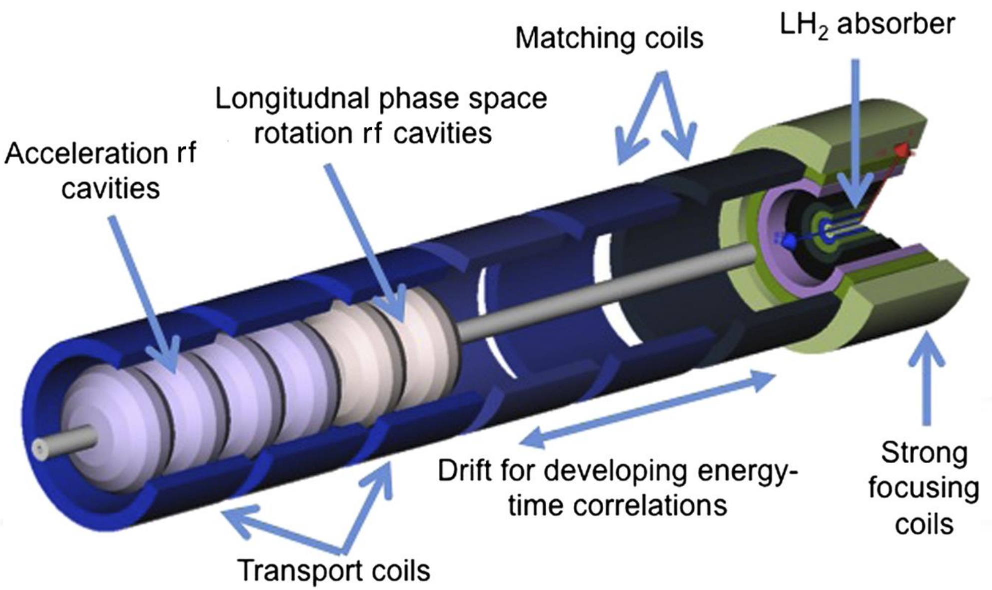
Don Summers,
University of Mississippi

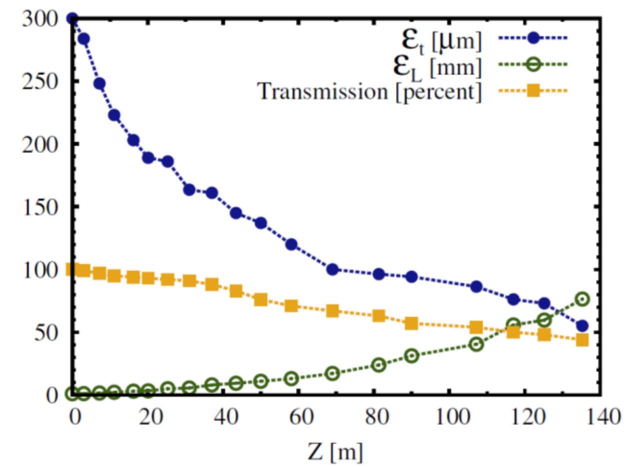


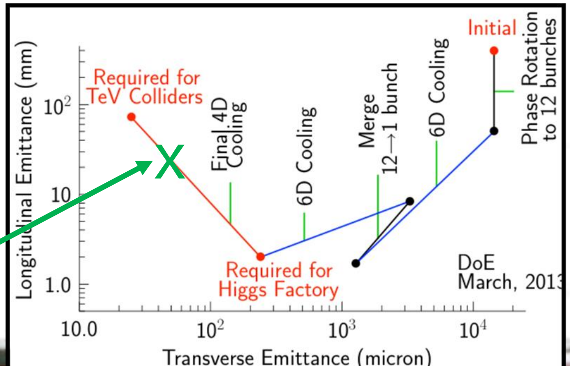
Emittances achieved

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. Transmission ~70% still in the low side



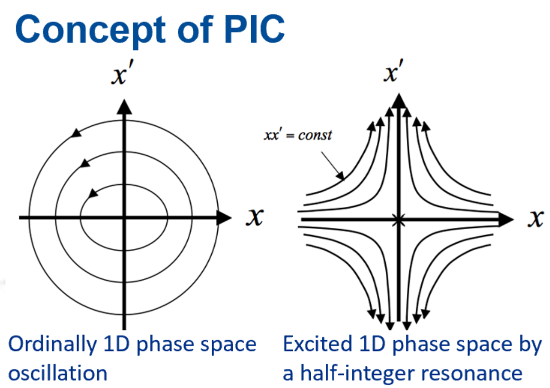


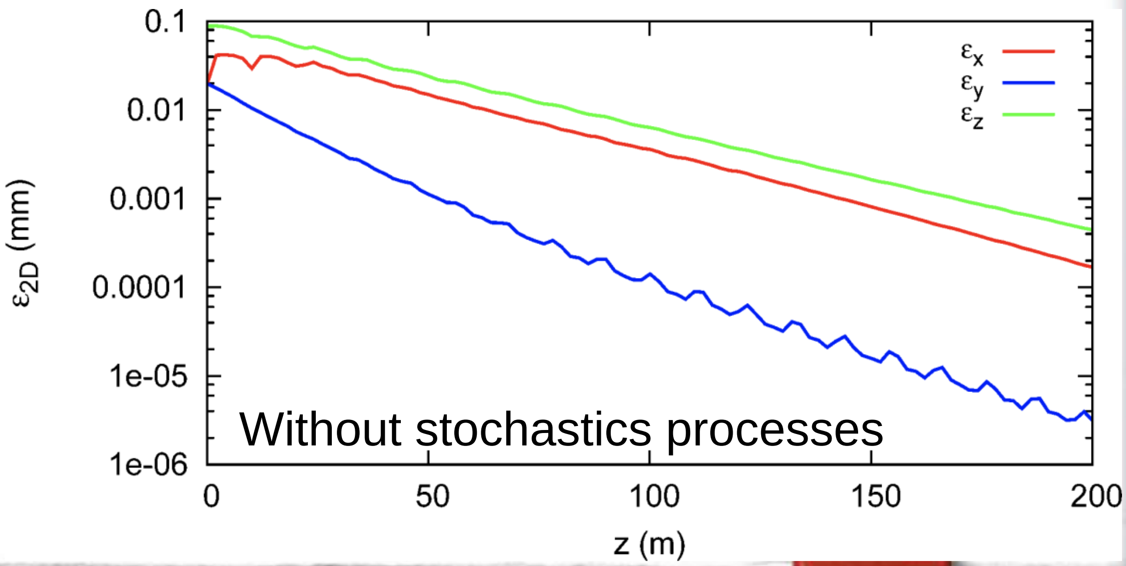


Emittances achieved

Final Cooling: PIC Method

- Parametric resonance ionization cooling (PIC) scheme, a half-integer resonance is applied to excite the phase space in hyperbolic motion (top right picture).
- As a result, the achievable transverse emittance is lower than the conventional cooling channel, and independent from strength of magnetic field





Design and feasibility questions

- Lattice Design
  - Cooling of muons of both signs is a bonus. How far can we push the FOFO snake or a similar channel?
  - Would a higher rf gradient make the cooling channel shorter? Would integration of optimization algorithms help? [Details]
  - How far can we push the rectilinear using HTS magnets?
- RF Cavities
  - Can we operate vacuum rf cavities in magnetic fields? [Details]
  - Is it possible to construct a Be based cavity?
  - What is the appropriate thickness and shape of rf Be windows?
- Absorbers
  - What are realistic shapes of a LH “wedge” absorber? [Details]
  - What is their tolerance on MC beam intensities?
- Beam dynamics
  - Impact of collective effects on beam cooling [Details]

Design and feasibility questions

- Magnets [Details]
  - Current densities are near the limits of Nb3Sn. Other magnet technologies?
  - Are forces & stresses in coils acceptable? What are the coil tilting tolerances?
- Required instrumentation and assembly [Details]
  - Identify required diagnostics & how to operate them under cooling environment
  - Design space for integrating them
  - Space for waveguides – appropriate space between coils and rf - Engineering design
- Further cooling tests [Details]
  - Are there facilities to further explore cooling?

Summary

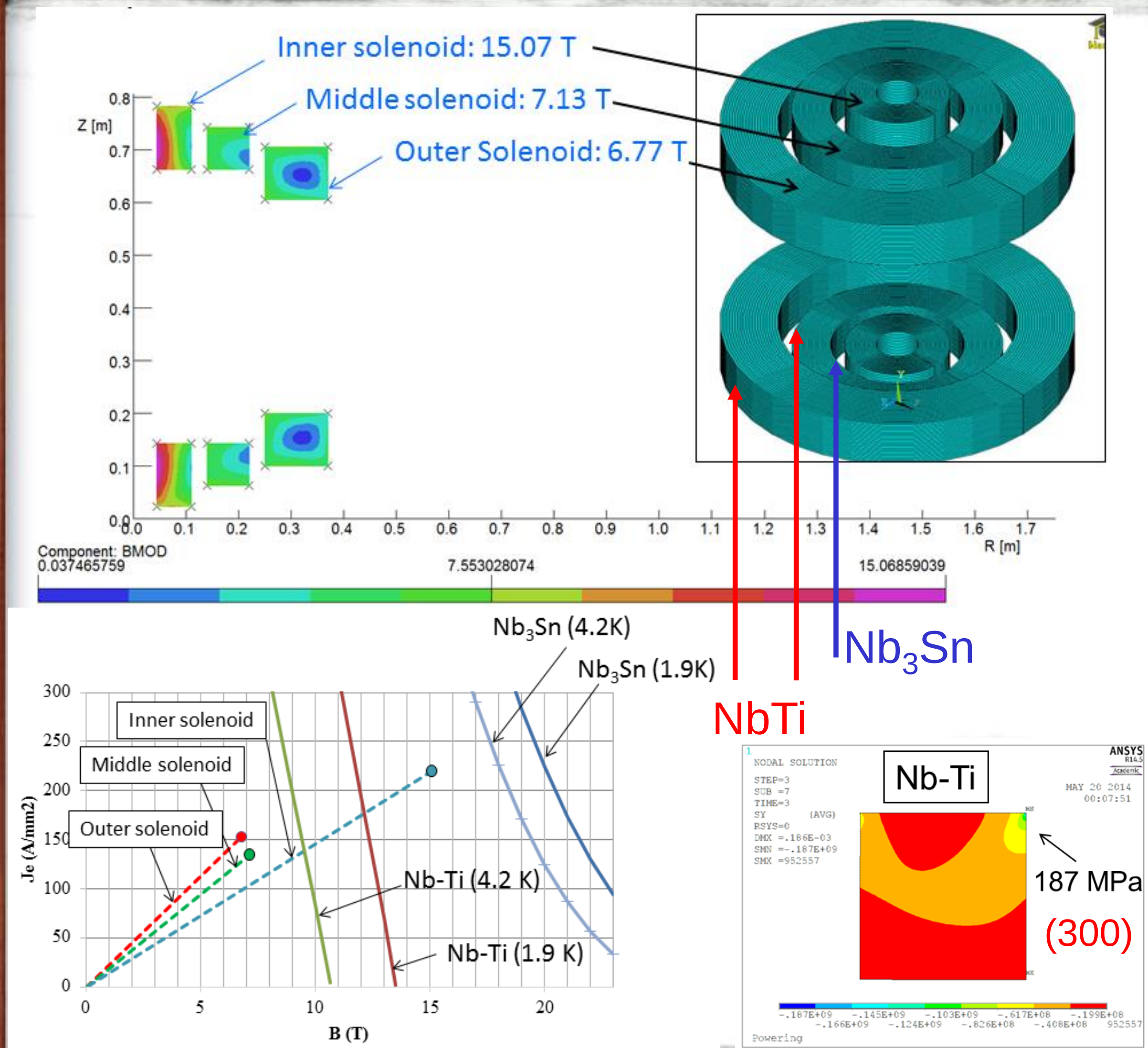
- Several cooling schemes have been designed and simulated with very promising results
- Its important to emphasize that most were paper studies without a detailed engineering study to see if their configurations were feasible.
- Most work on these has stopped ~ 2015. In the meantime several progress 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. Devil is in the detail.

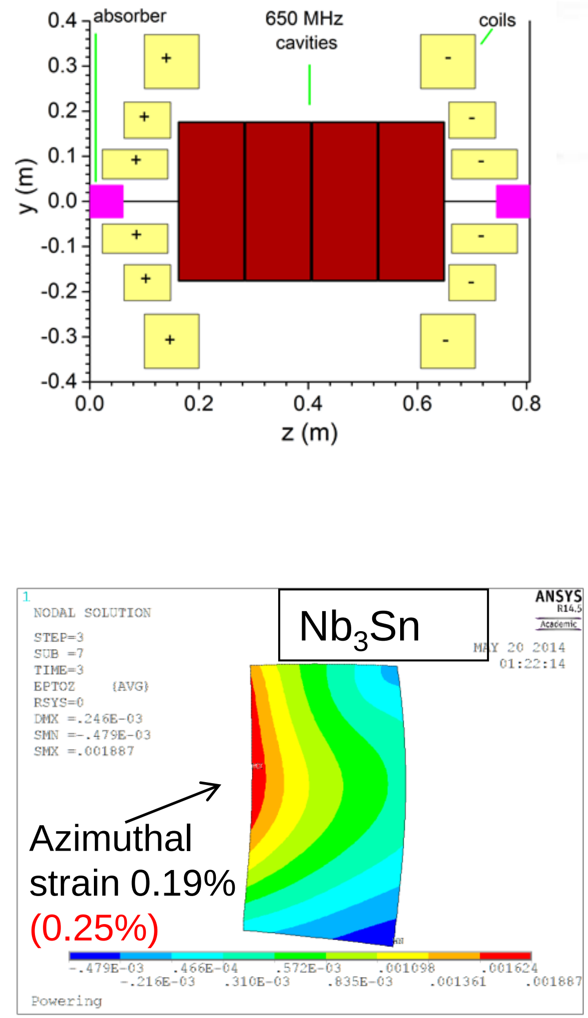
Further related work

- 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)

Magnet technology

[BACK]

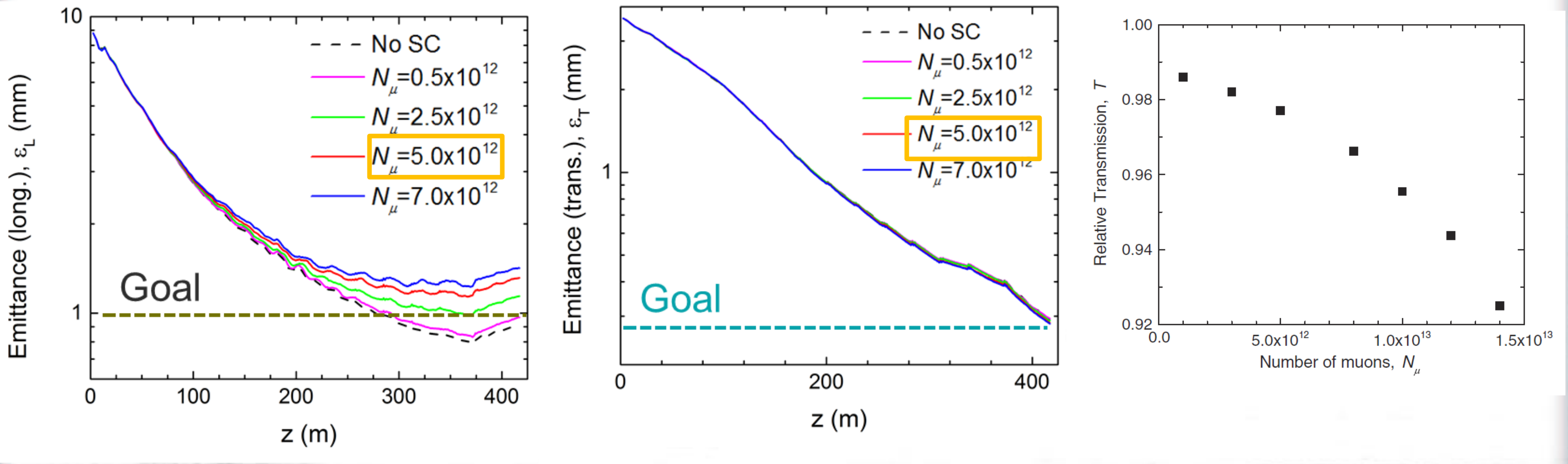




Influence of space-charge

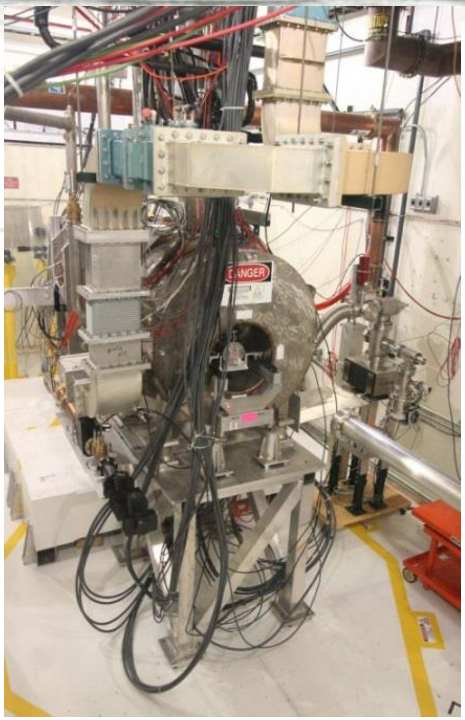
[BACK]

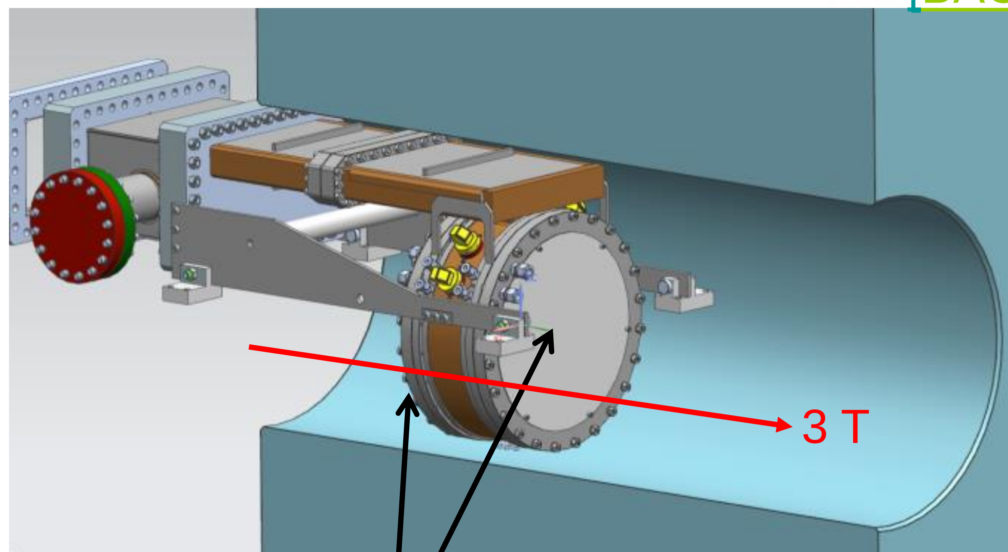
- At the end of cooling, $5x10^{12}$ muons are squeezed within a 2 cm rms bunch. There is a concern for space-charge (SC)
- Simulation revealed that SC causes particle loss & longitudinal emittance growth



Modular cavity test: A game changer

[BACK]





removable plates (Cu, Al, Be)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 072001 (2020)

Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration

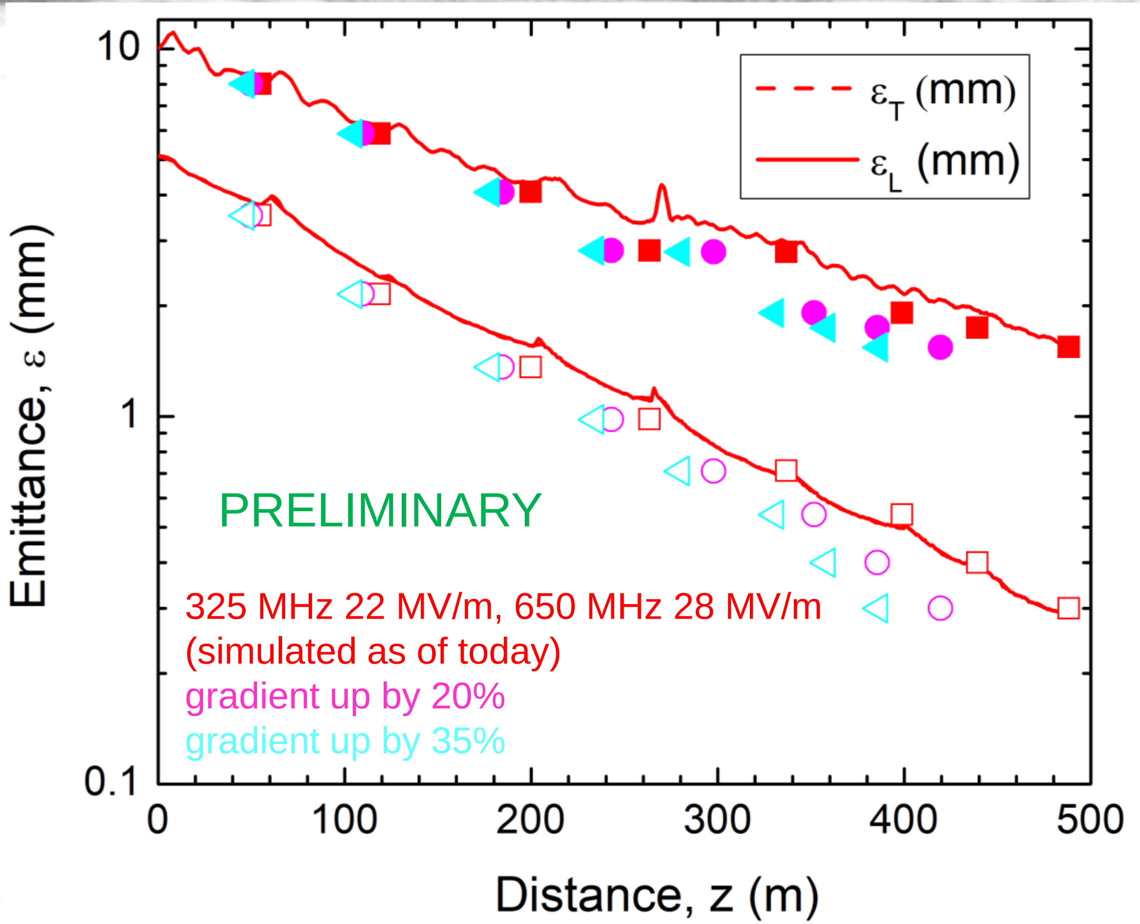
D. Bowring,* A. Bross, P. Lane, M. Leonova, A. Moretti, D. Neuffer, R. Pasquinelli, D. Peterson, M. Popovic, D. Stratakis, and K. Yonehara
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

Material	B-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

- A Beryllium based cavity sustained a high gradient in the presence of multi-tesla B-fields!

Future: Simulate with higher gradients

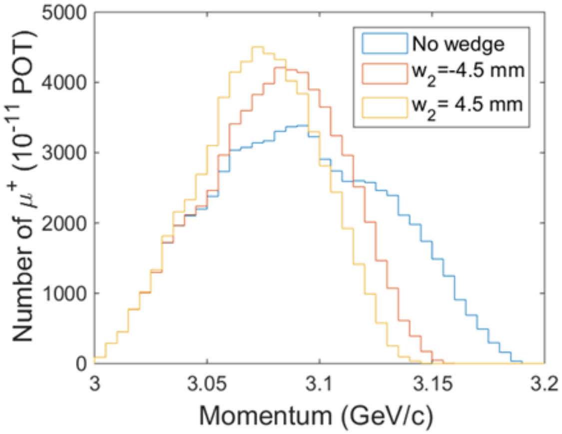
[BACK]

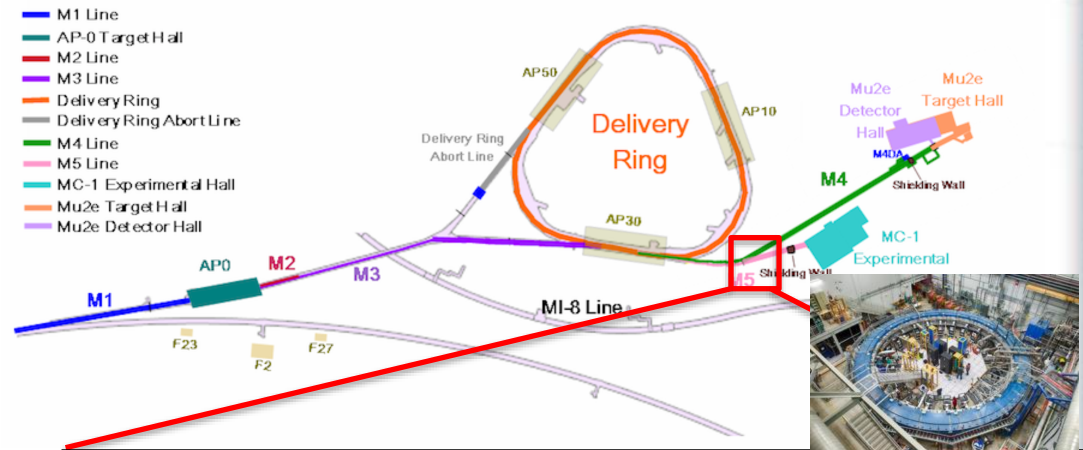


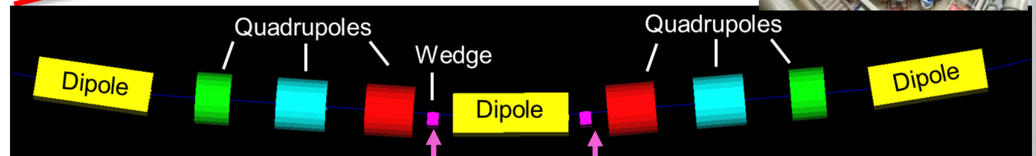
- Increasing the rf gradient can reduce the length of the cooling channel

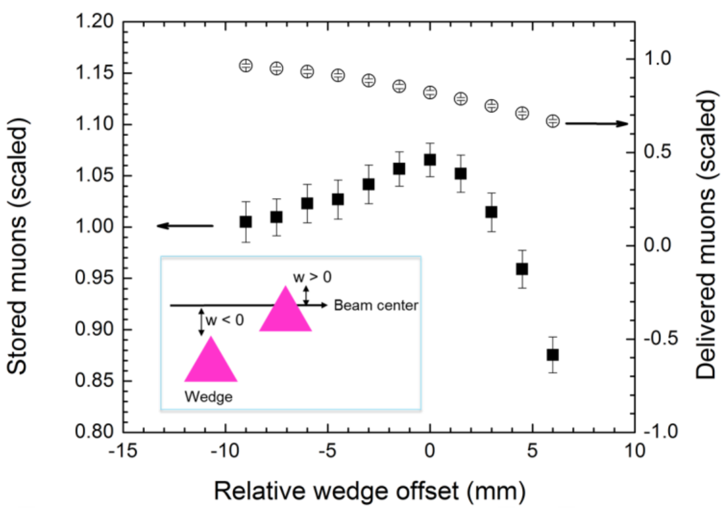
Emittance exchange for the Muon g-2 Experiment

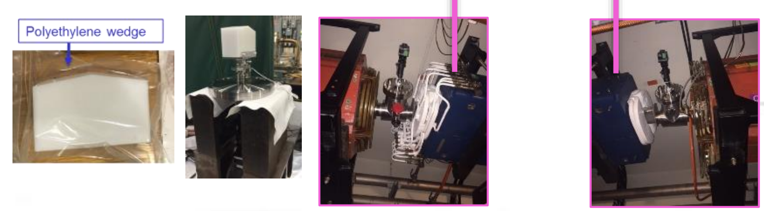
- Proof-of-principle experiment: Demonstrated 8% gain [BACK]











PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 053501 (2019)

Application of passive wedge absorbers for improving the performance of precision-science experiments

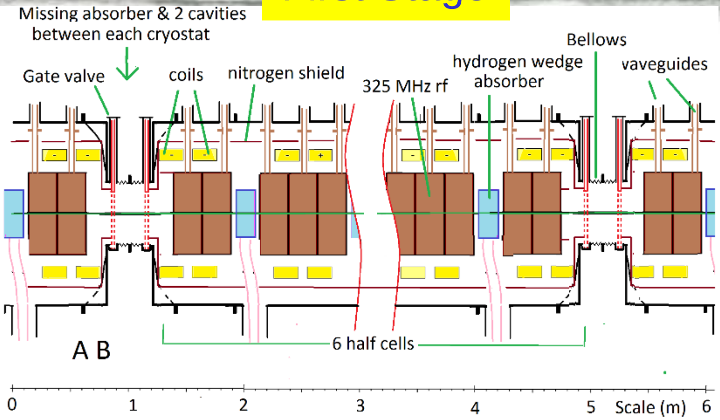
Diktys Stratakis

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

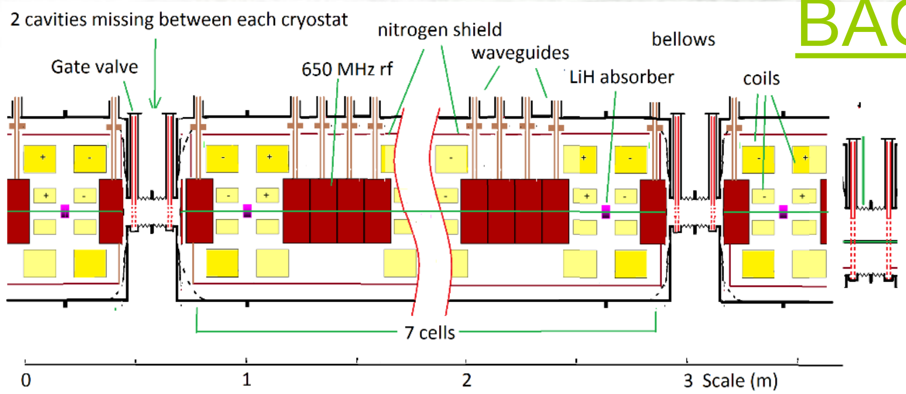
Engineering design

BACK

First Stage



Last Stage



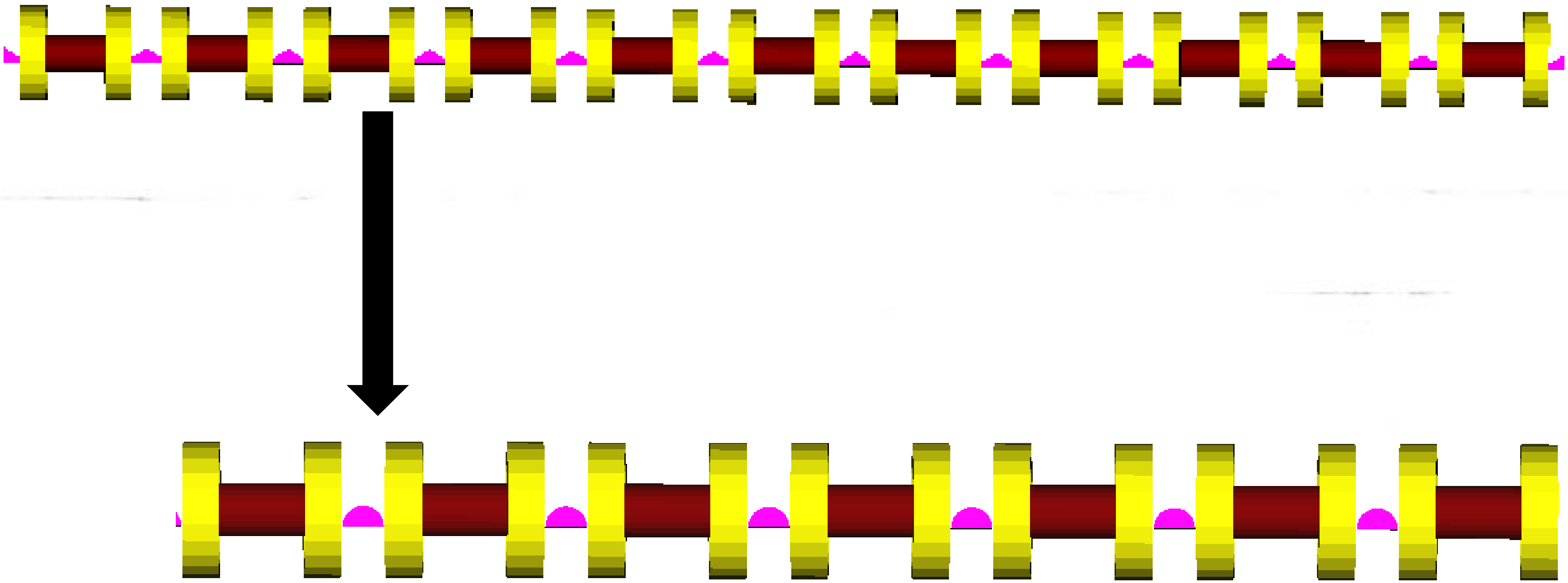
Design of cryostats

1. Approximately 6 cells (or half cells in early stages) are housed in shared cryostats
2. The strict periodicity of focus coils is maintained
3. Space to separate cryostats is made by either
   a) omitting hydrogen absorbers (in early stages) and reducing local rf gradients, or
   b) omitting some of the rf cavities (in a late stage) and shortening, or omitting a hydrogen absorber
4. The space gained can be used for diagnostics and allows installation or removal of a cryostat without disturbing any others.

Dis-assembly for repair or replacement

1. Close gate valves on either side of cryostat
2. Let air into space between near gate valves
3. Open flange between them
4. Pull flanges apart and remove complete cryostat laterally
5. Dis-assemble in clean room if necessary

Wedges vs. Cylinders



- For LH absorber it is easier to construct a cylindrical absorber
- Slightly degrades cooling

[BACK]