International MUON Collider Collaboration

Rectilinear cooling channel

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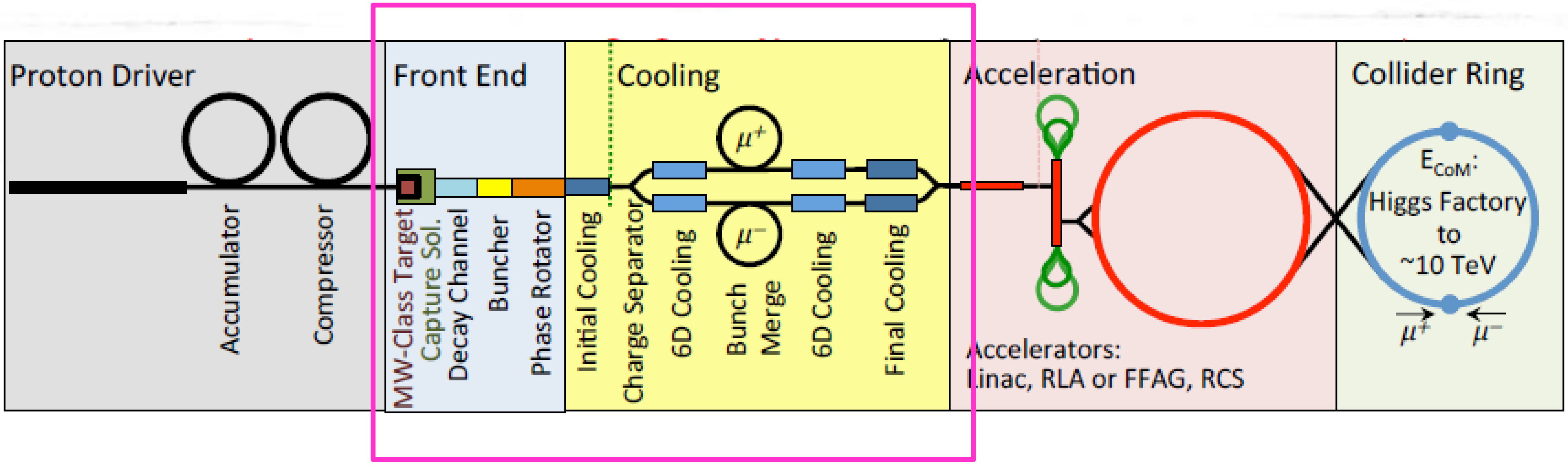
1st Muon Community Meeting (online only)
May 20, 2021

Outline

- Rectilinear cooling channel overview
- Lattice design
- Performance
- Future work

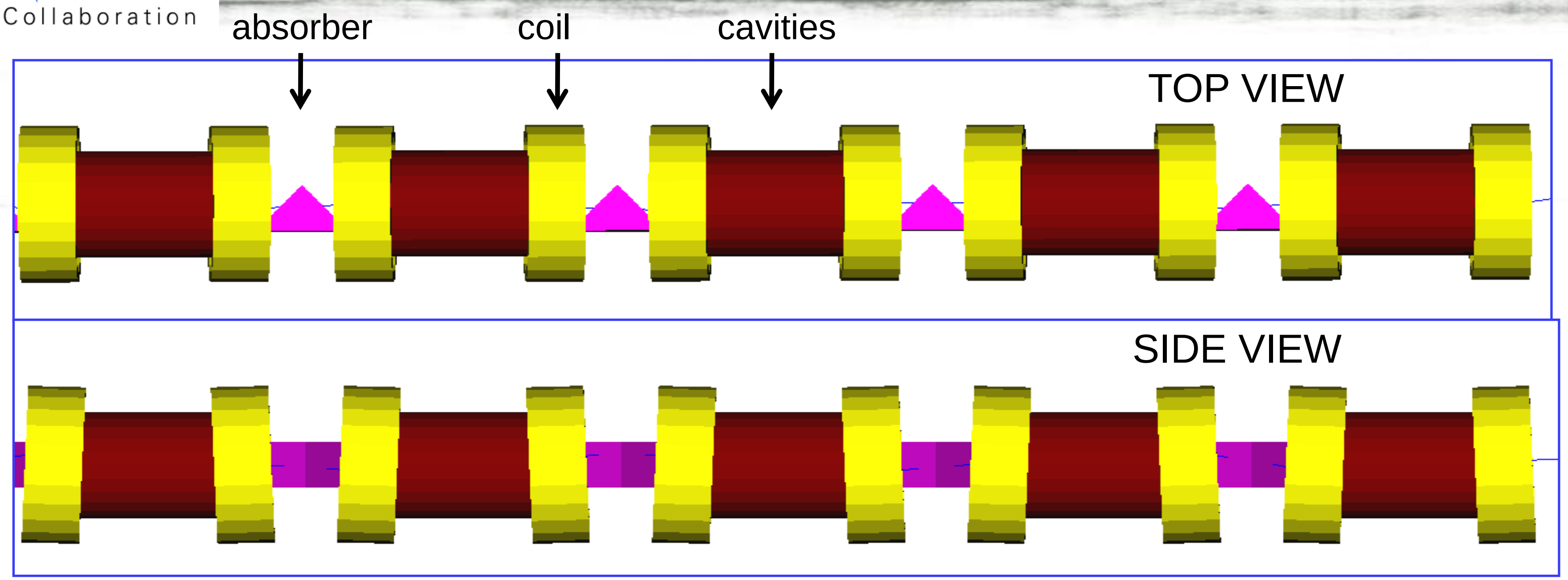
Cooling for a Muon Collider



- 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 (if necessary)

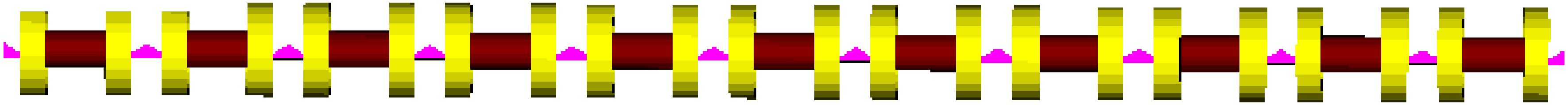
Focus of this talk

Rectilinear channel concept

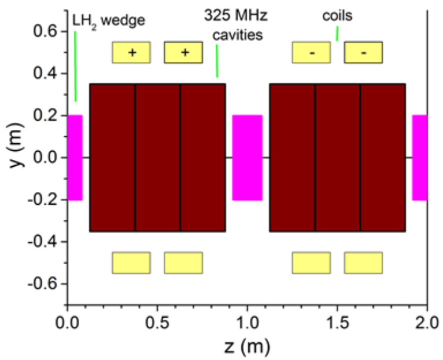


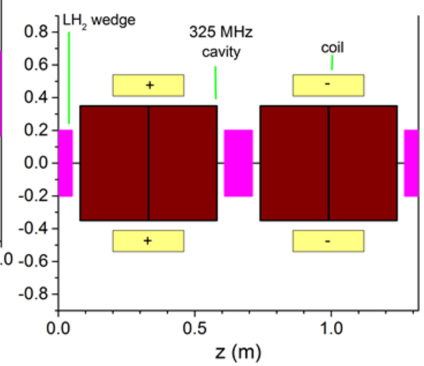
- Straight geometry simplifies construction and relaxes several technological challenges
- Multiple stages with different cell lengths, focusing fields, rf frequencies to ensure fast cooling
- Its performance will be discussed later today

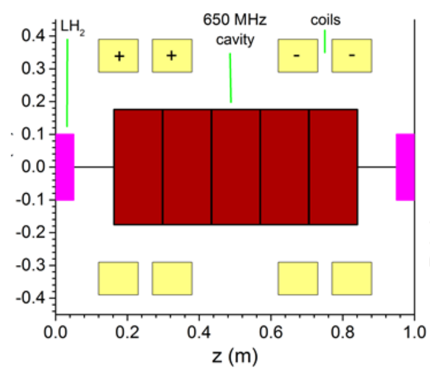
Cooling before merge (4 stages)

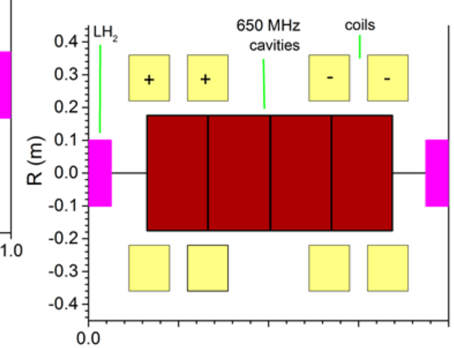


STAGE 1	STAGE 2	STAGE 3	STAGE 4
132 m (66 cells)	171.6 m (130 cells)	107 m (107 cells)	70.4 m (88 cells)







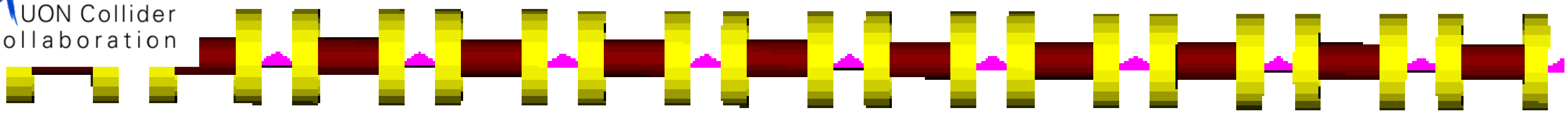


Absorber TOP VIEW

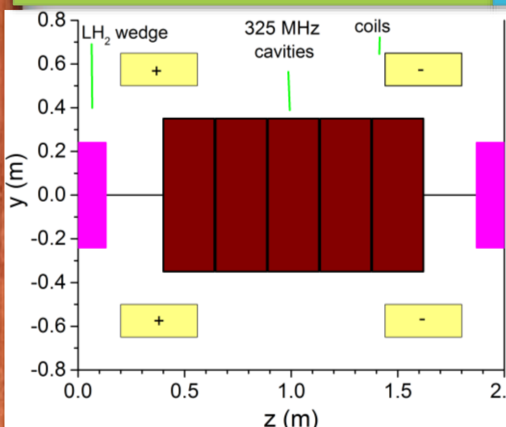
2.3 T (4.2 T) | 3.5 T (8.4 T) | 4.8 T (9.5 T) | 6.1 T (11.8 T)

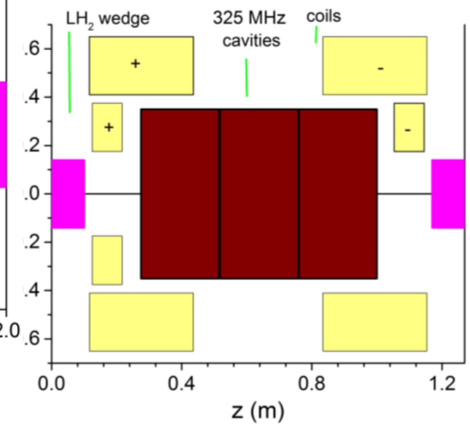
Peak B-field on axis (coil)

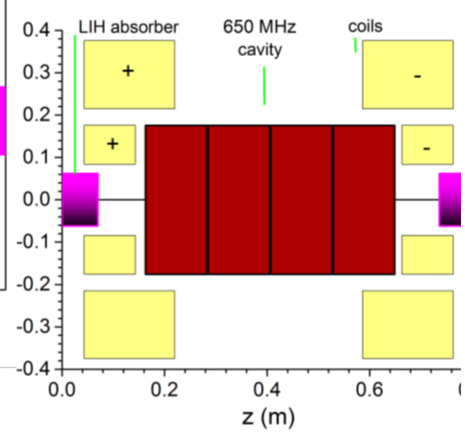
oling after the merge (8 stages)

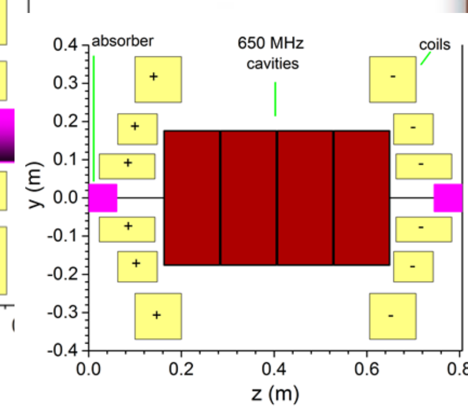


STAGE 2	STAGE 4	STAGE 6	STAGE 8
64 m (32 cells)	62.5 m (50 cells)	62 m (77 cells)	41.1 m (51 cells)





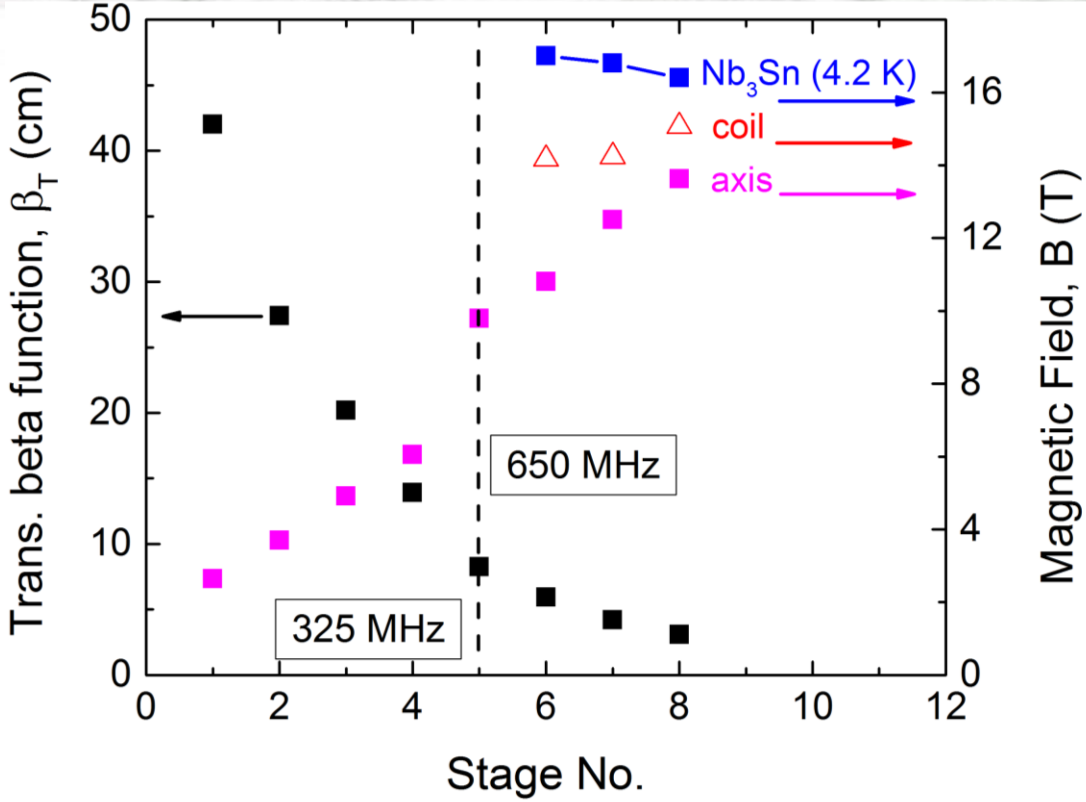




3.7 T (8.4 T) | 6.0 T (9.2 T) | 10.8 T (14.2 T) | 13.6 T (15.0 T)

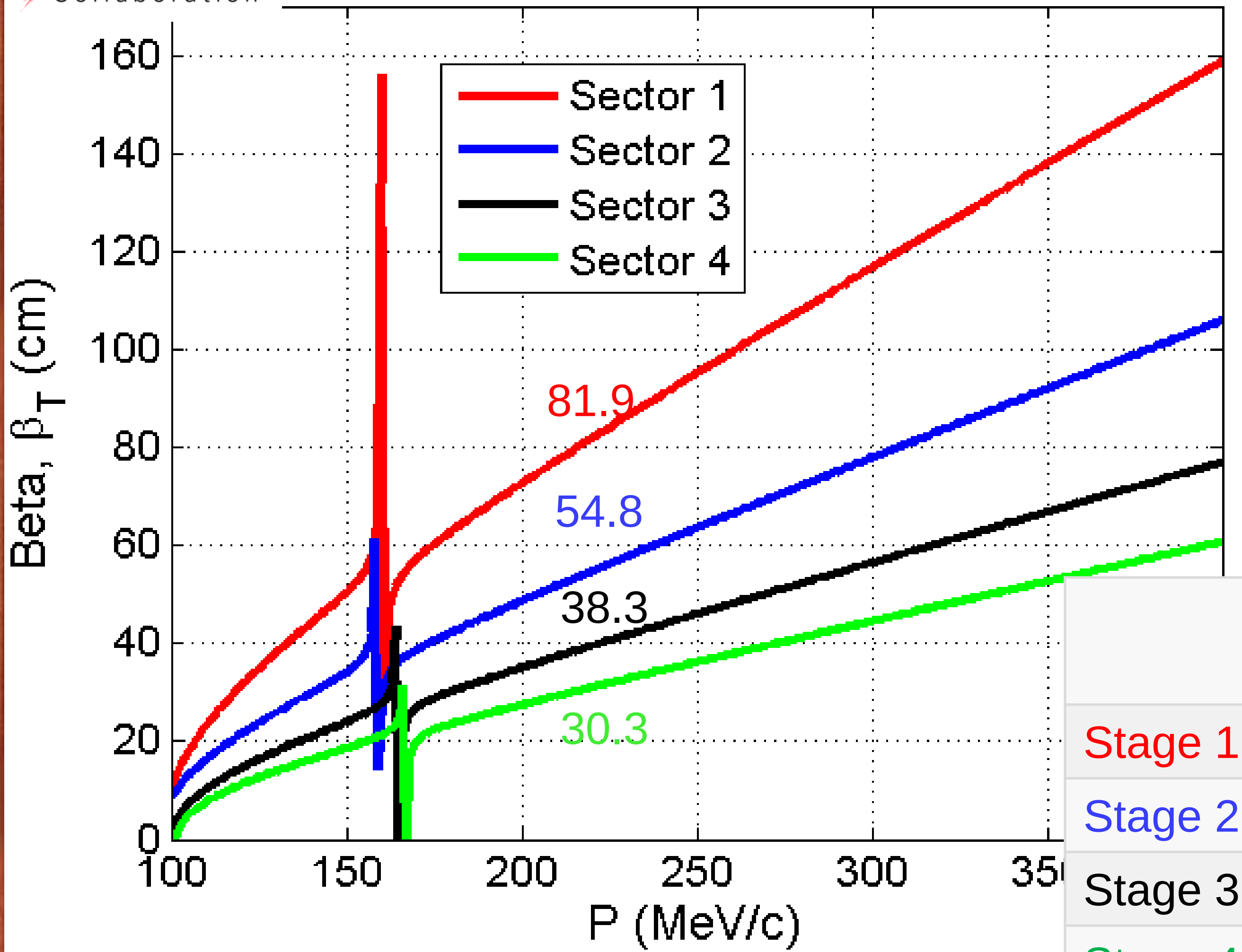
Peak B-field on axis (coil)

Tapered lattice design: 8 stages



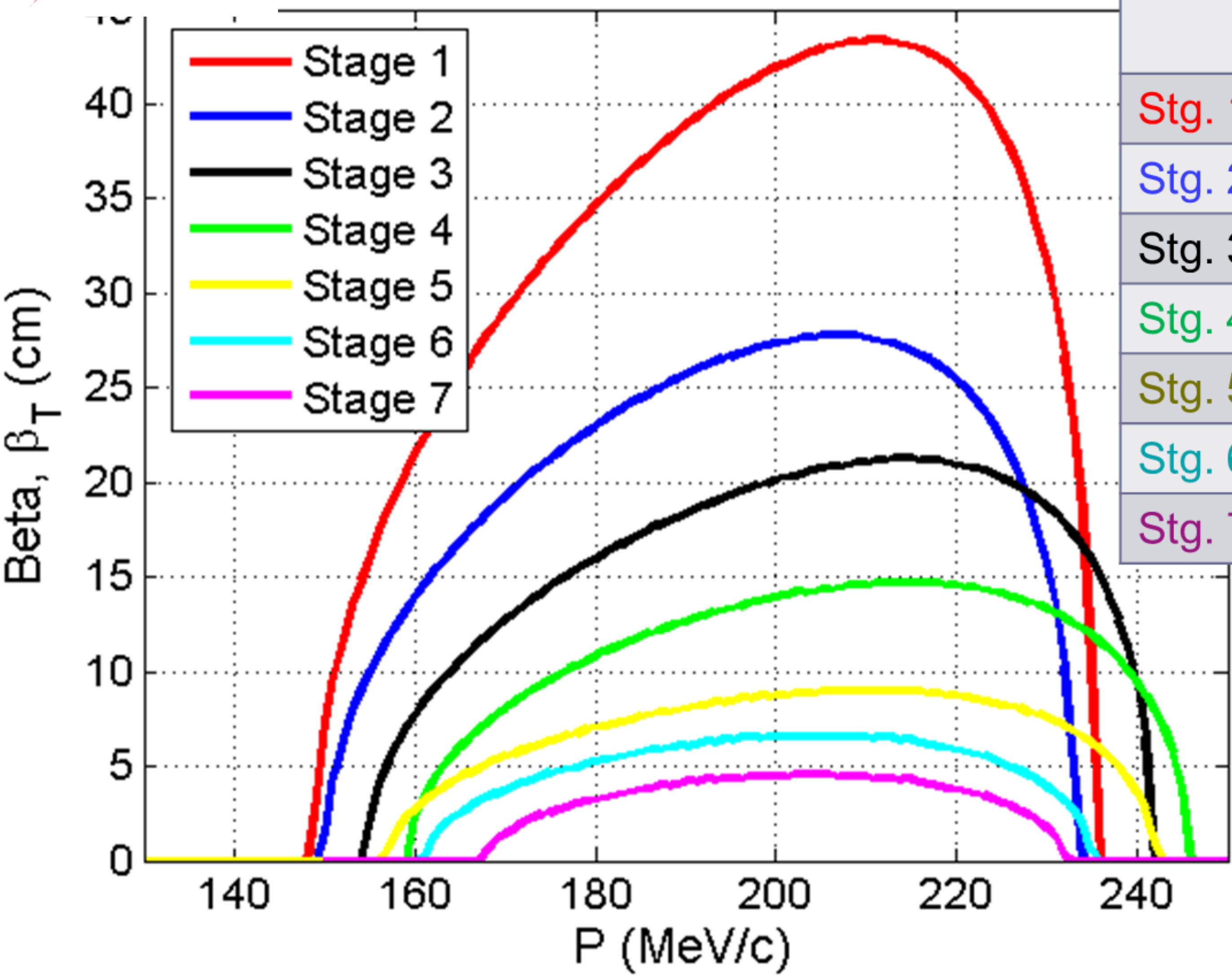
- We set two constrains in our (initial) design:
  - Peak fields on coils don’t exceed Niobium Tin limits
  - Cavities within> 1 T operate at 50% of the achievable gradient at 0 T

Lattice acceptance



	P_z [MeV/c]	σ_{Pz} [MeV/c]
Stage 1	237.8	22.3
Stage 2	228.8	14.4
Stage 3	220.9	12.7
Stage 4	219.4	12.5

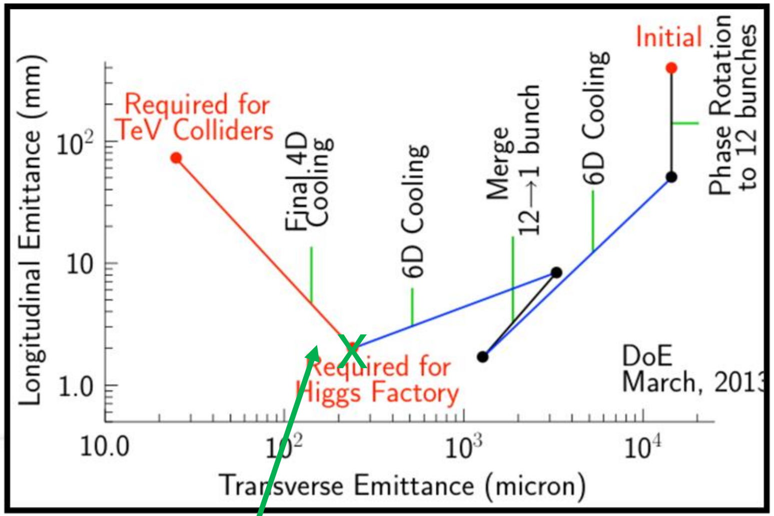
Lattice acceptance



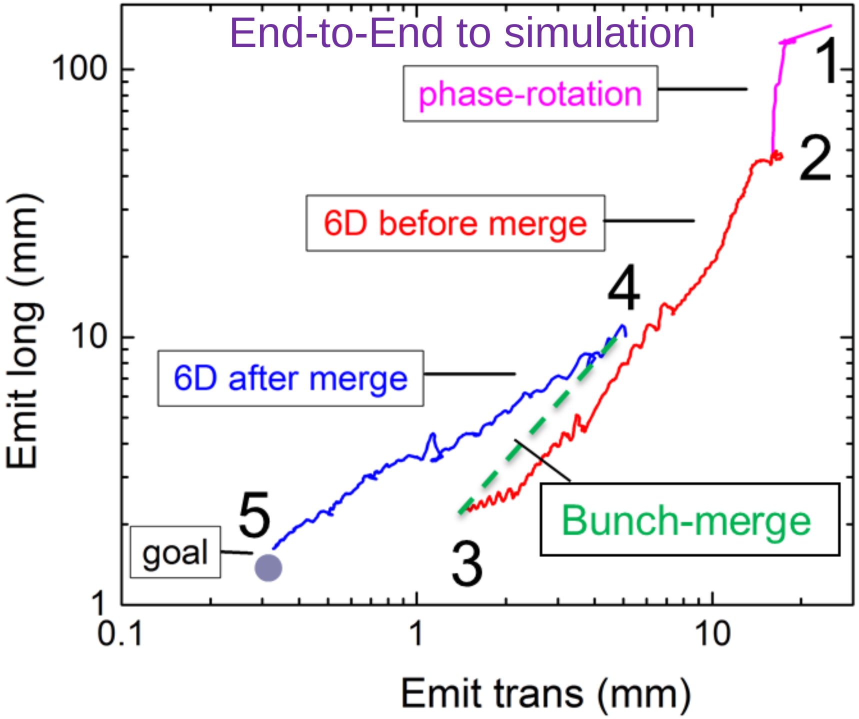
	P_z [MeV/c]	σ_{Pz} [MeV/c]
Stg. 1	219.3	13.9
Stg. 2	212.6	13.9
Stg. 3	216.6	14.3
Stg. 4	214.0	13.1
Stg. 5	211.5	12.6
Stg. 6	207.6	10.8
Stg. 7	207.6	8.6

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

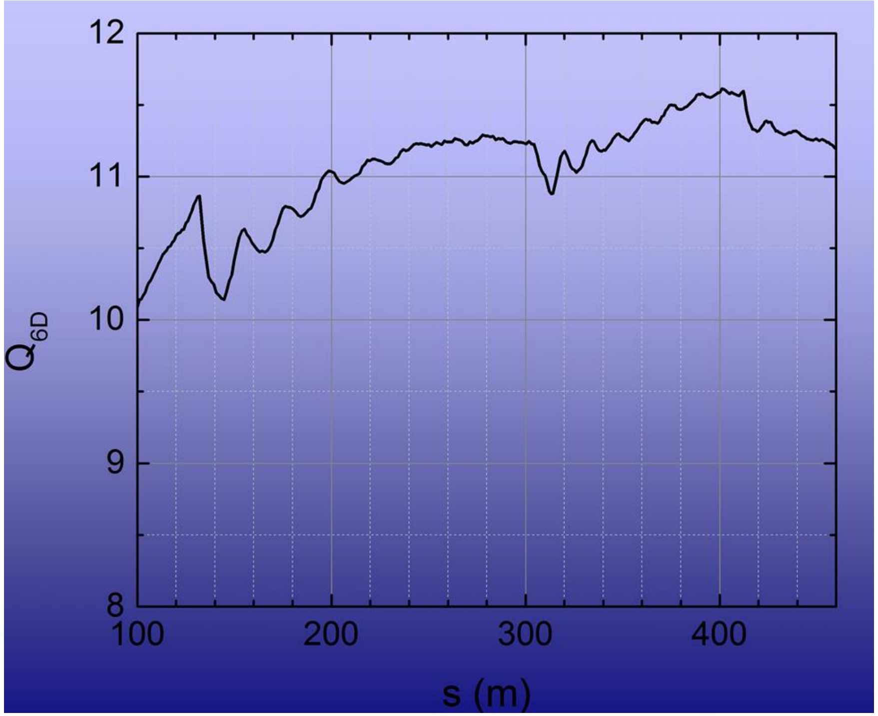


Emittances achieved



Quality Factor

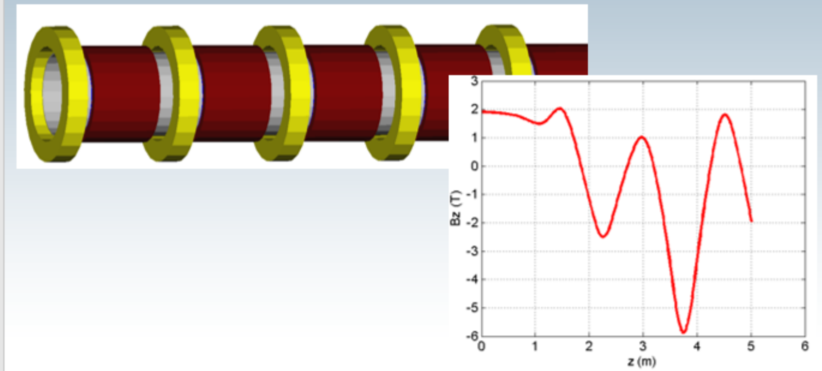
- Quality factor appears relatively stable but worth to recheck again

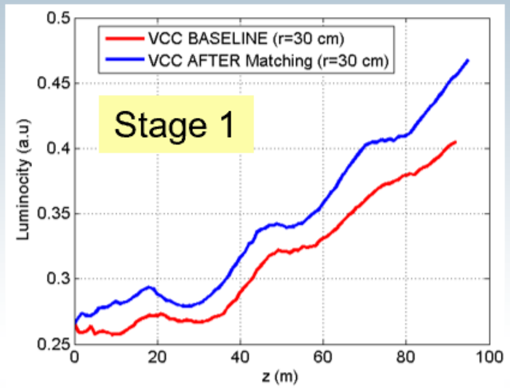


$$Q_6(z) = \frac{d\epsilon_6/\epsilon_6}{dN/N}$$

Future: Improve matching

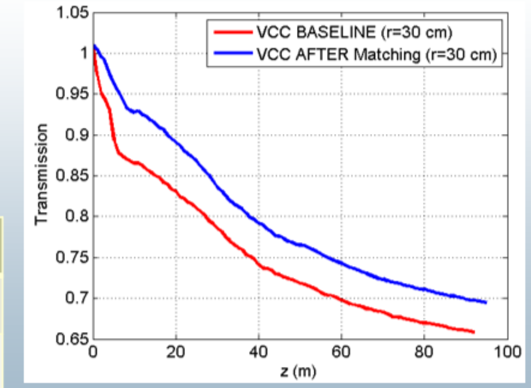
Matching to 6D VCC from Phase-Rotator



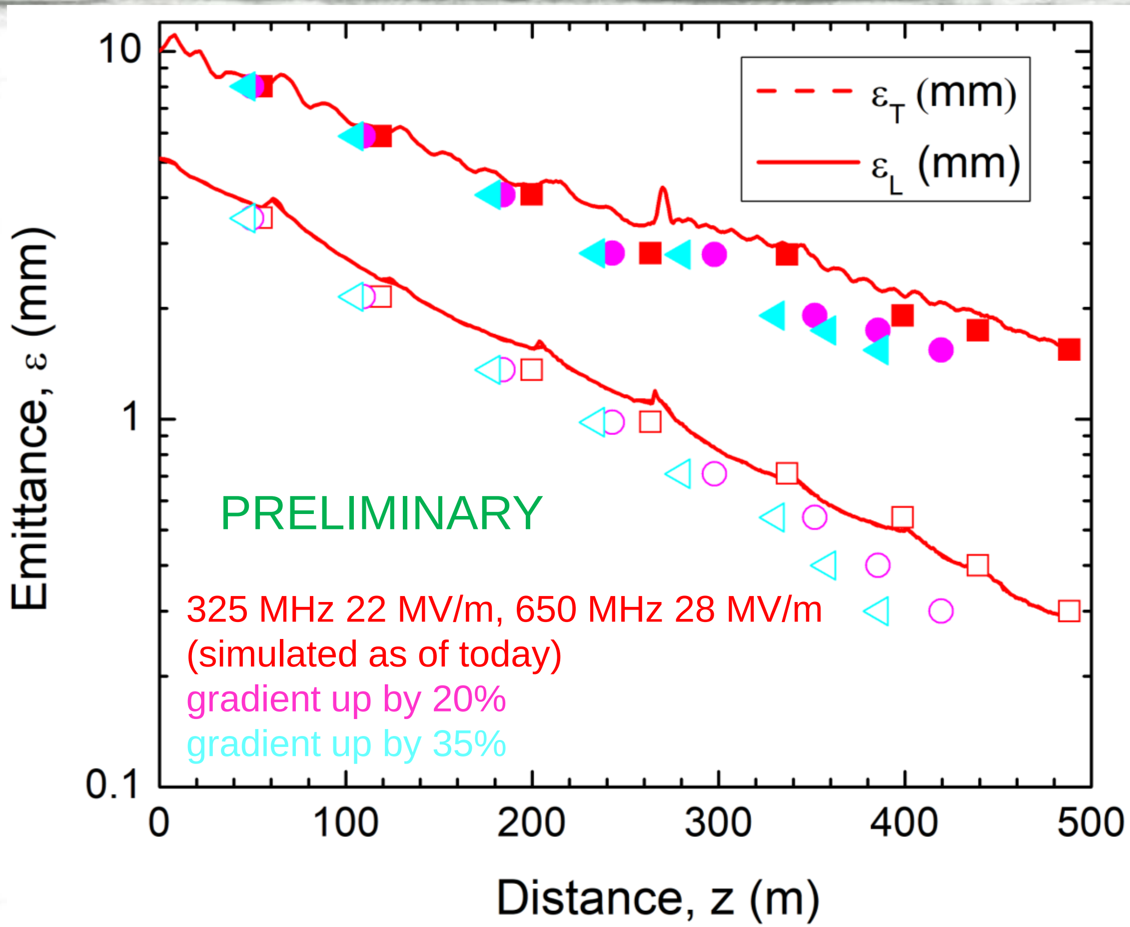


- Matching with 9 solenoidal coils
- ~4% gain in performance
- Allows reducing aperture 35 → 30 cm

Parameter	Baseline	With Matching
Cool rate (trans.)	2.13	2.19
Cool rate (long.)	2.76	2.81
Transmission	65.2% (132 m)	68.8% (132 m)

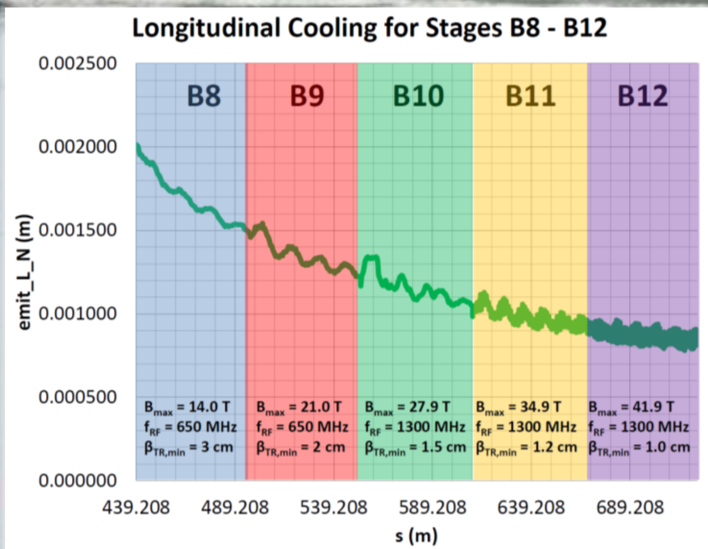


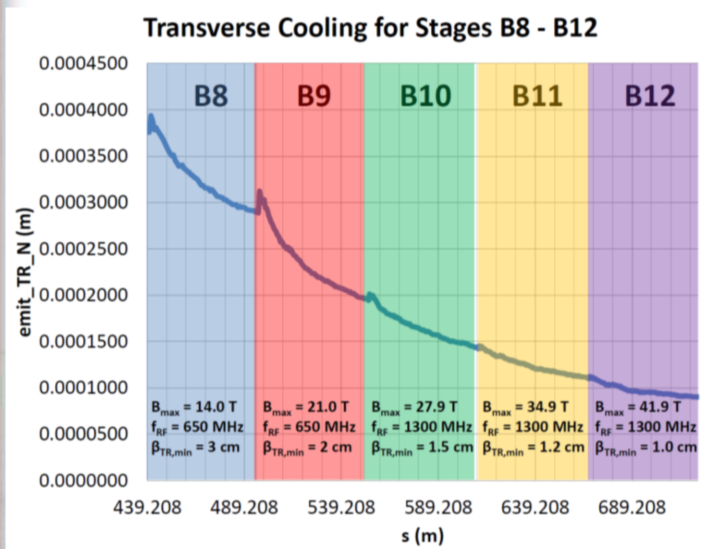
Future: Simulate with higher gradients



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

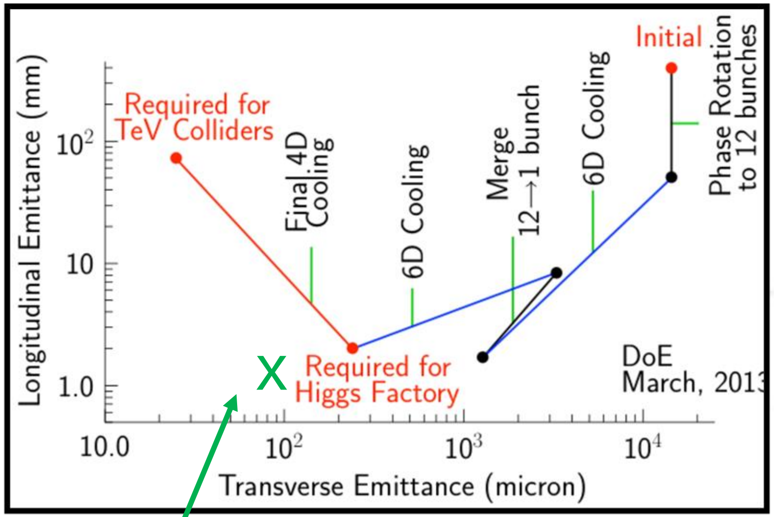
Future: Rectilinear with HTS magnets





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

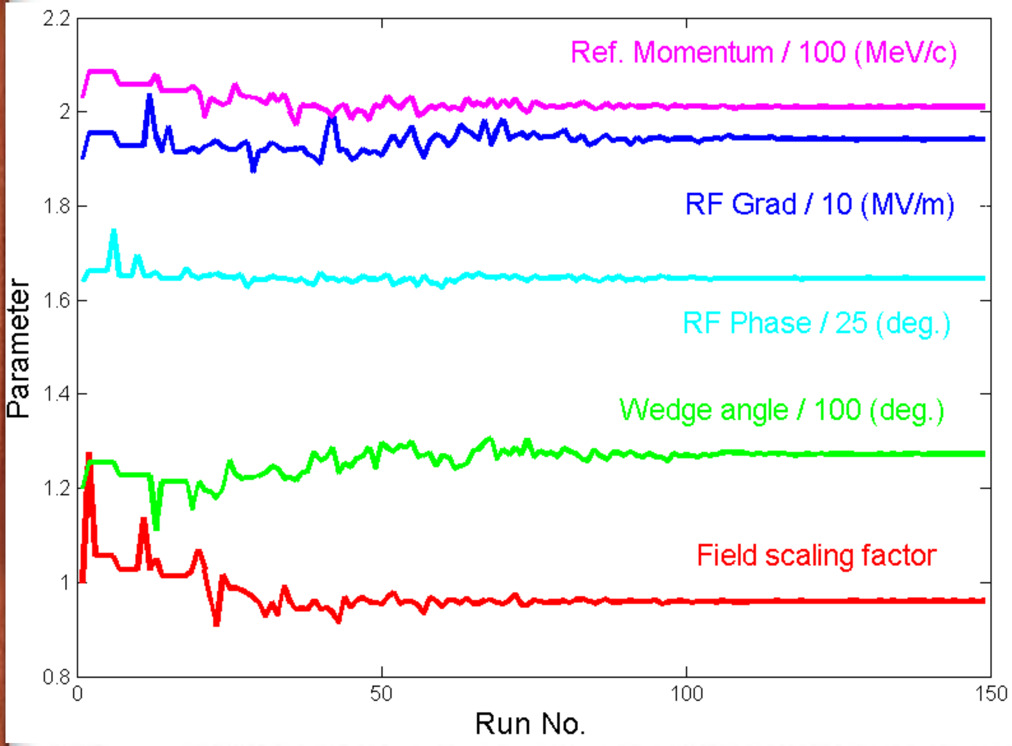
Don Summers,
University of Mississippi

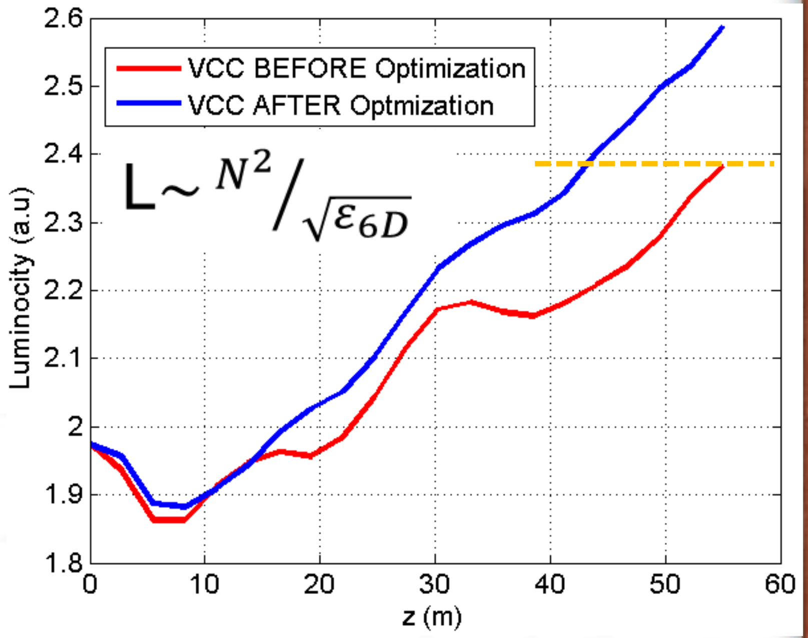


Emittances achieved

Future: Multivariable optimization

- Nelder-Mead algorithm: Objective is to maximize luminosity.
- Applied for VCC optimization: 8 parameters each time
- Promising results for first stage: 25% shorter channel!





Design and feasibility questions

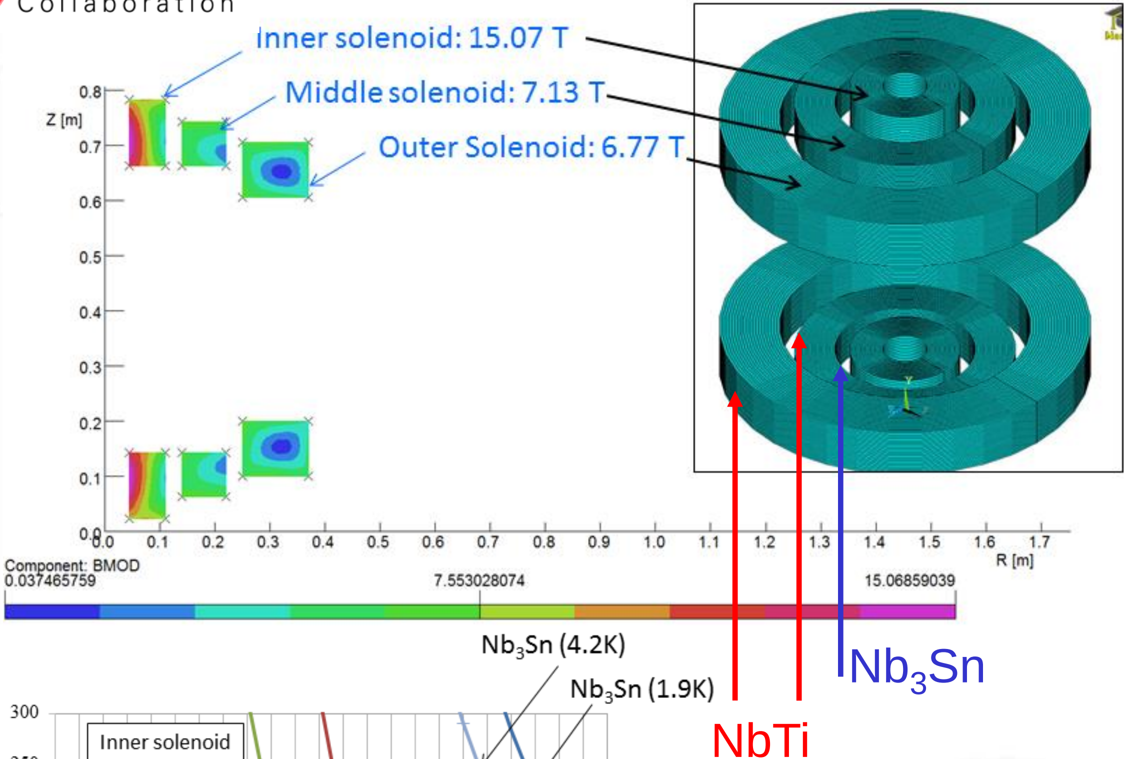
- Lattice Design
  - Cooling of muons of both signs is a bonus. How far can we push the FOFO snake or a similar channel?
  - Would a higher rf gradient make the cooling channel shorter? Would integration of optimization algorithms help? [Details]
  - How far can we push the rectilinear using HTS magnets?
- 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]

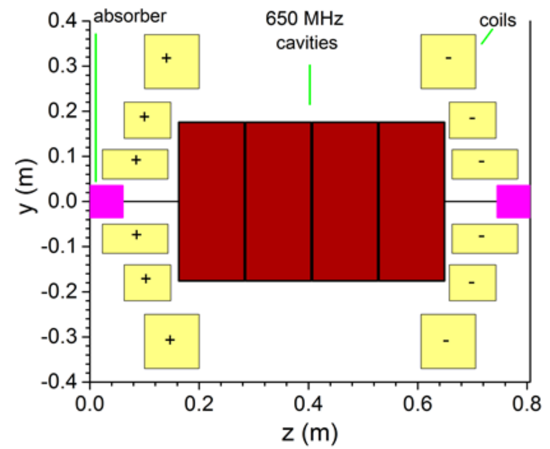
Design and feasibility questions

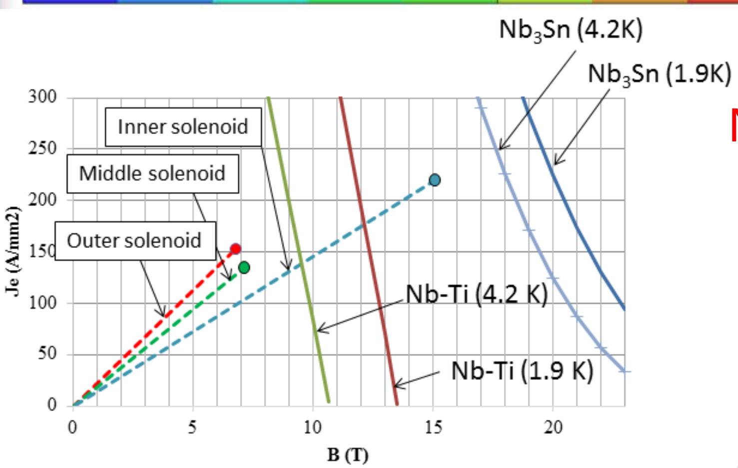
- Magnets [Details]
  - Current densities are near the limits of Nb3Sn. Other magnet technologies?
  - Are forces & stresses in coils acceptable?
  - Tilted coils or dipoles? Holger's proposal?
- Required instrumentation and assembly [Details]
  - Identify required diagnostics & how to operate them under cooling environment
  - Design space for integrating them
  - Space for waveguides – appropriate space between coils and rf - Engineering design

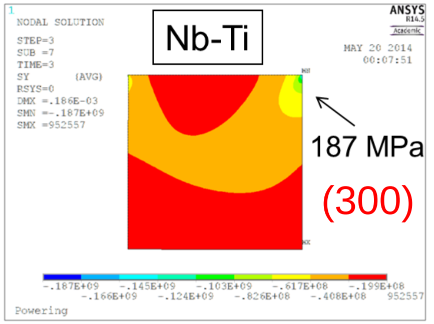
Magnet technology

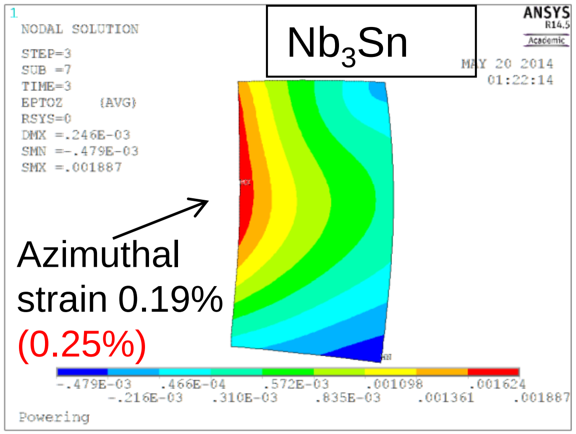
[BACK]







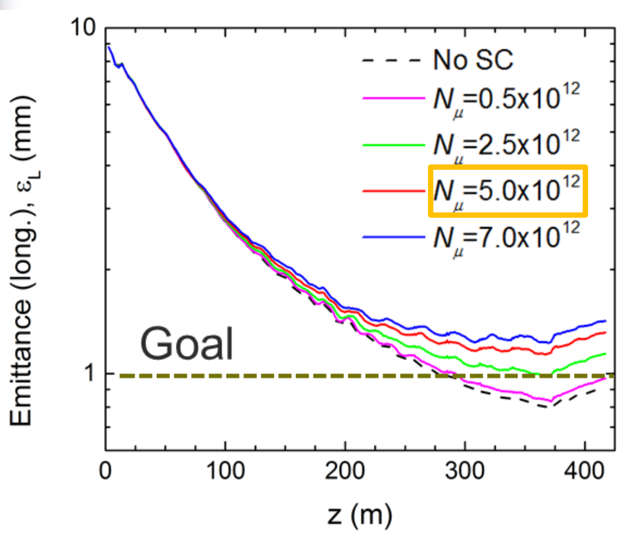


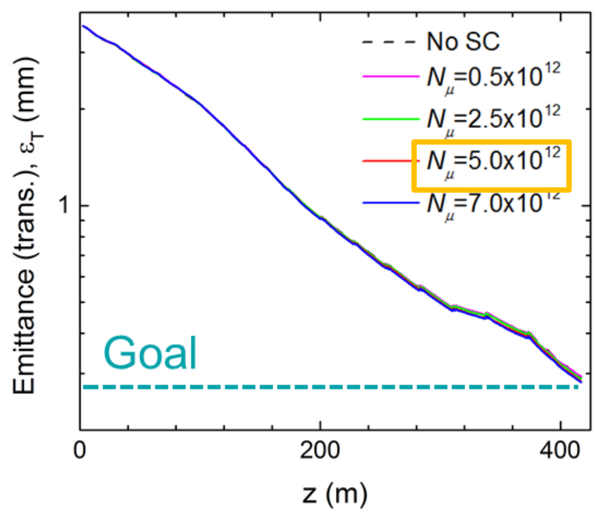


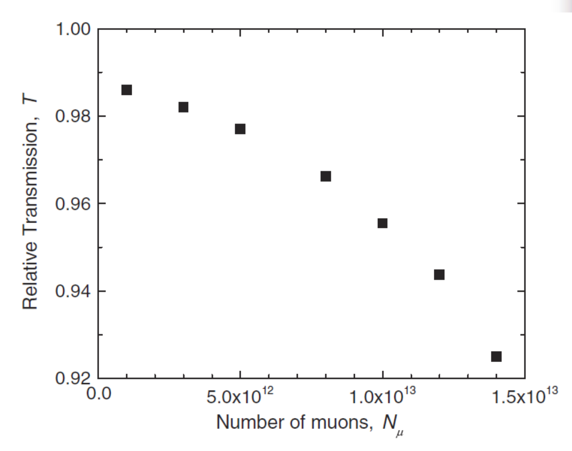
Influence of space-charge

[BACK]

- At the end of cooling, 5×10^{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

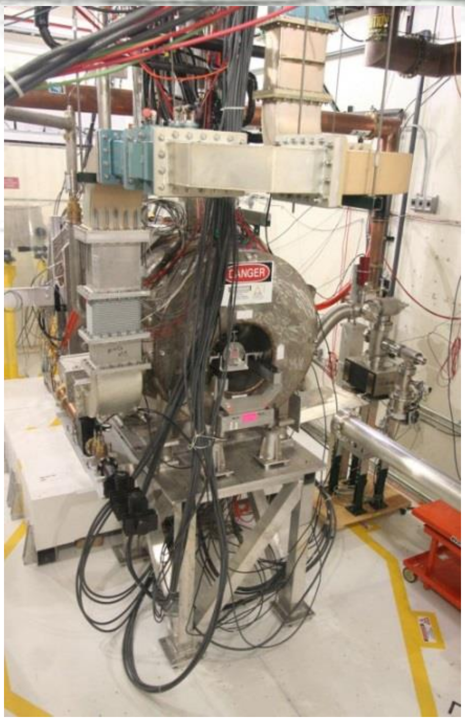


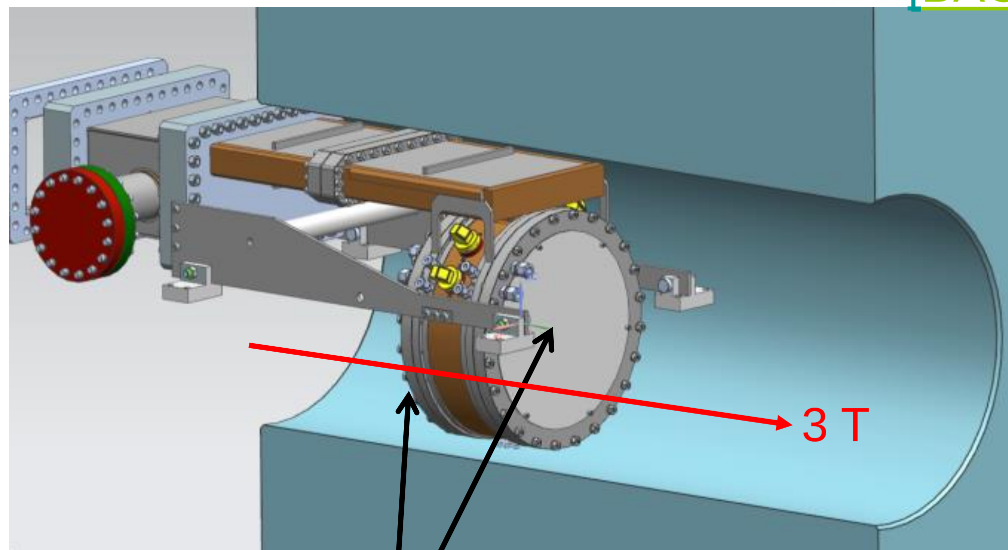




Modular cavity test: A game changer

[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

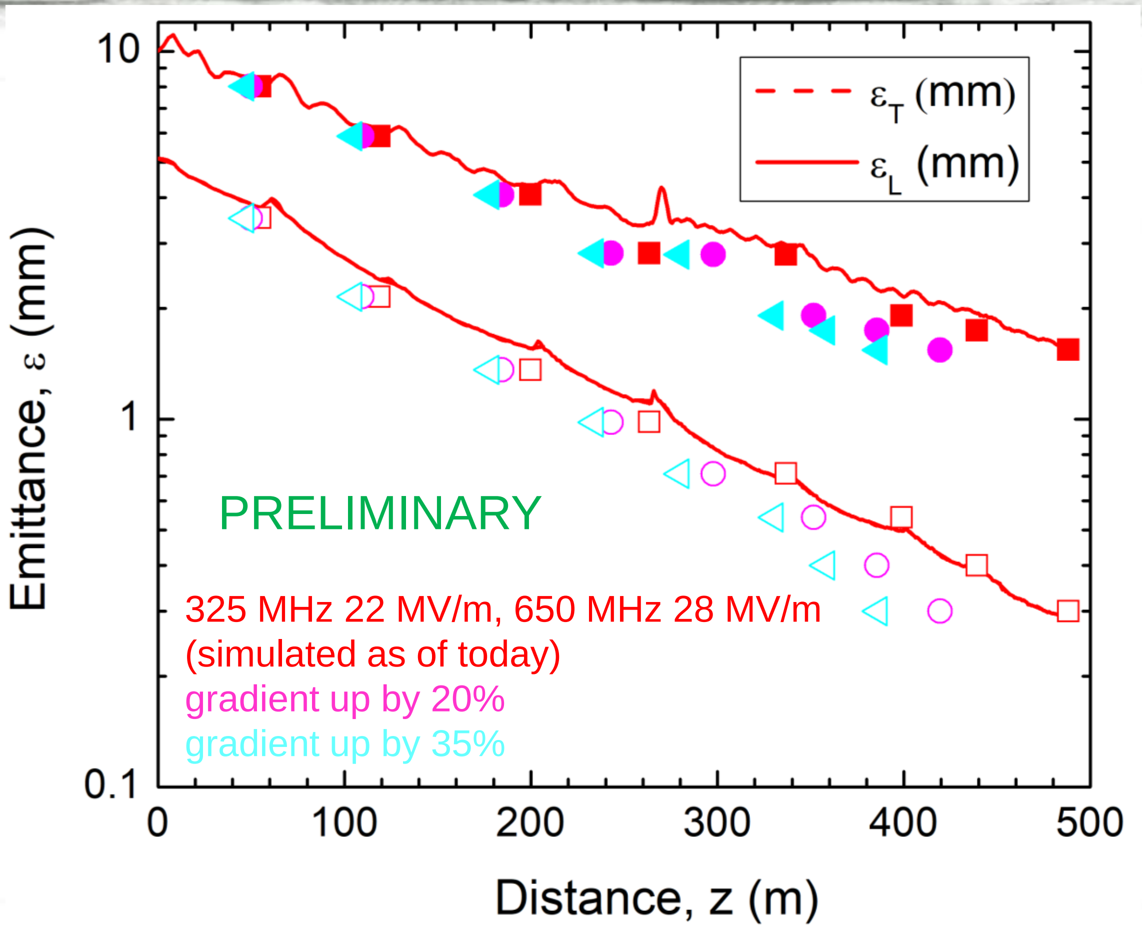
D. Bowring,* A. Bross, P. Lane, M. Leonova, A. Moretti, D. Neuffer, R. Pasquinelli, D. Peterson, M. Popovic, D. Stratakis, and K. Yonehara
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

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

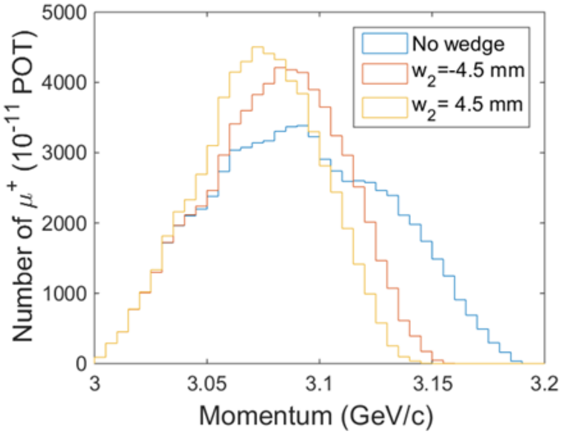
[BACK]

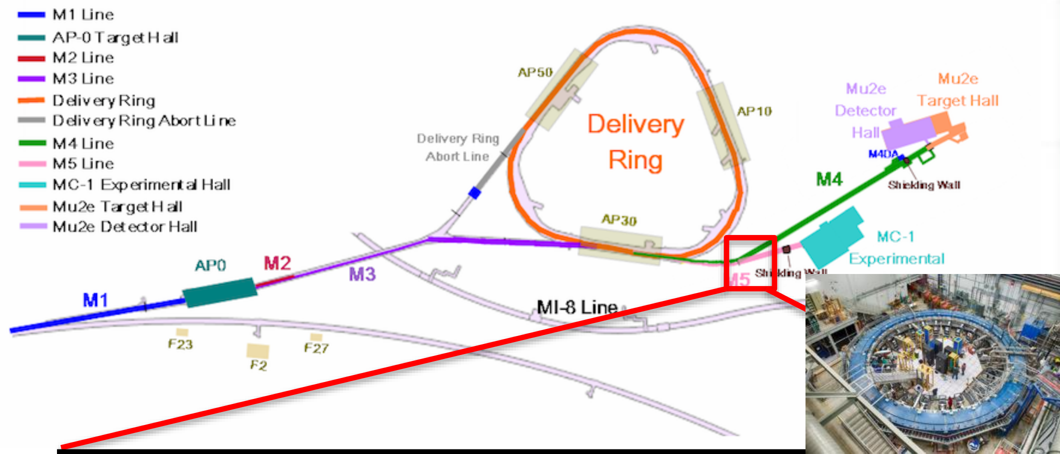


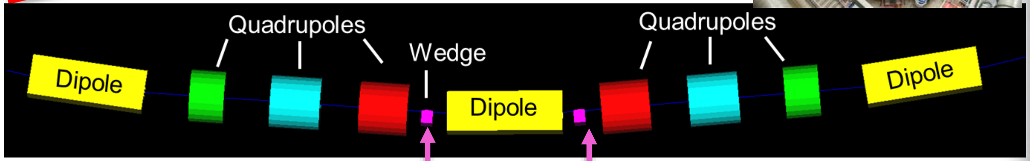
- Increasing the rf gradient can reduce the length of the cooling channel

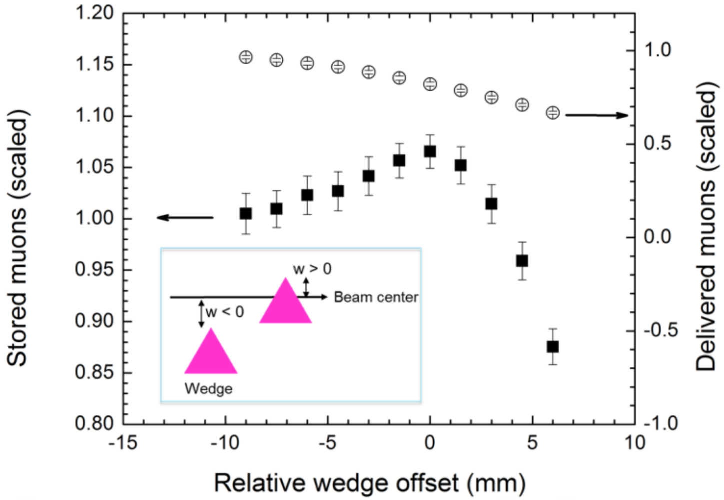
Emittance exchange for the Muon g-2 Experiment

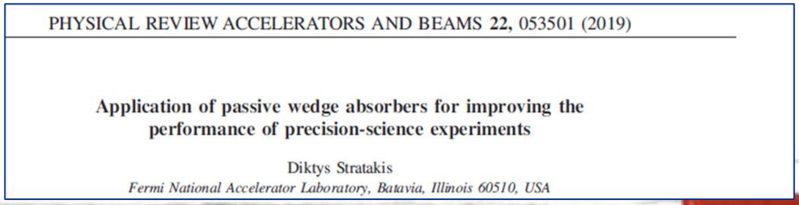
- Proof-of-principle experiment: Demonstrated 8% gain [BACK]











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

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

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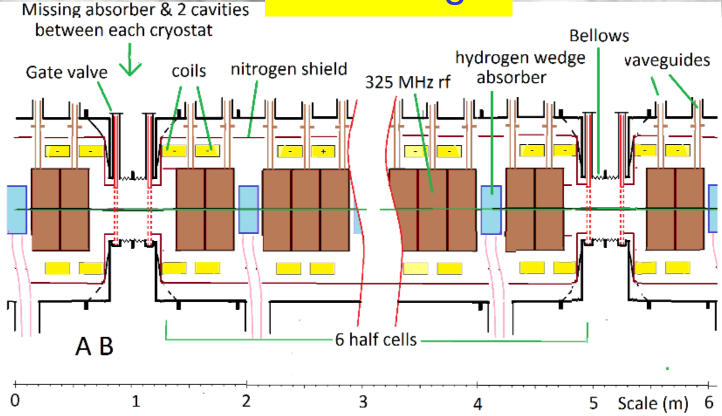
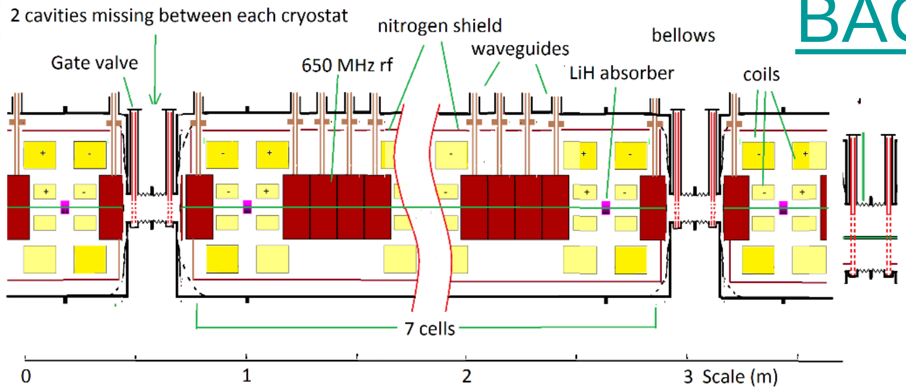
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

Engineering design

First Stage



Last Stage



BACK

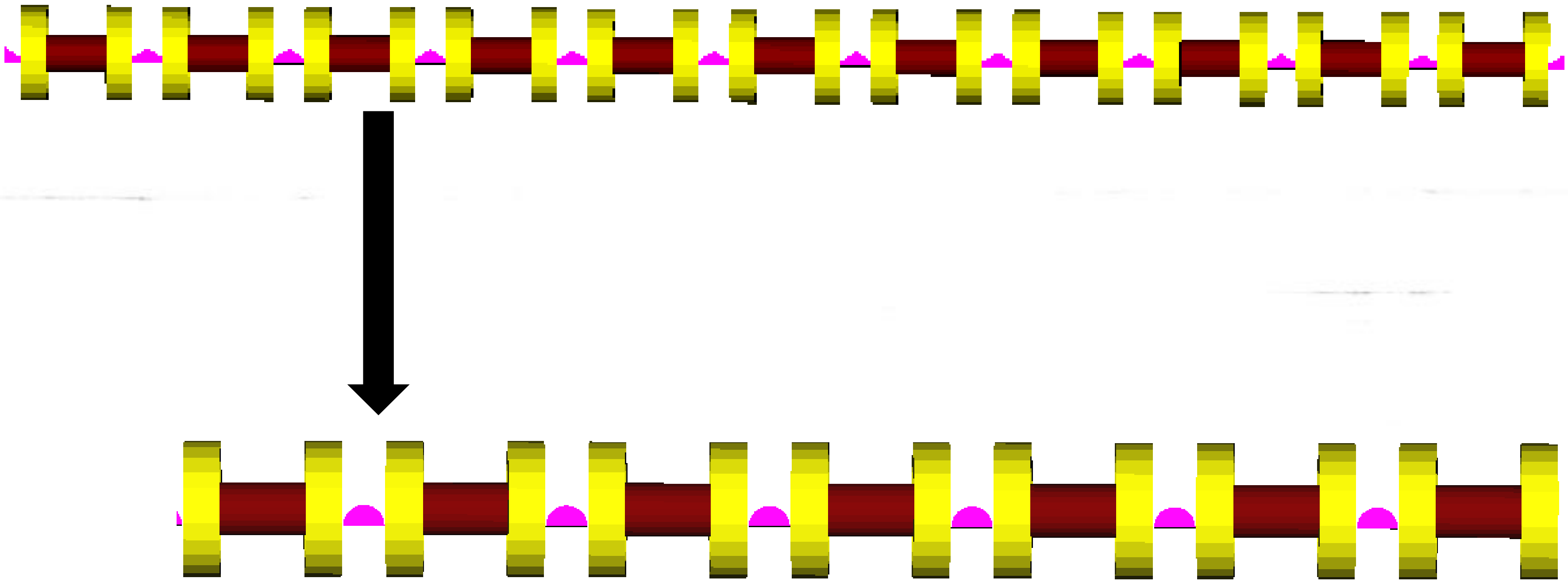
Design of cryostats

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]