Magnets for ionization cooling

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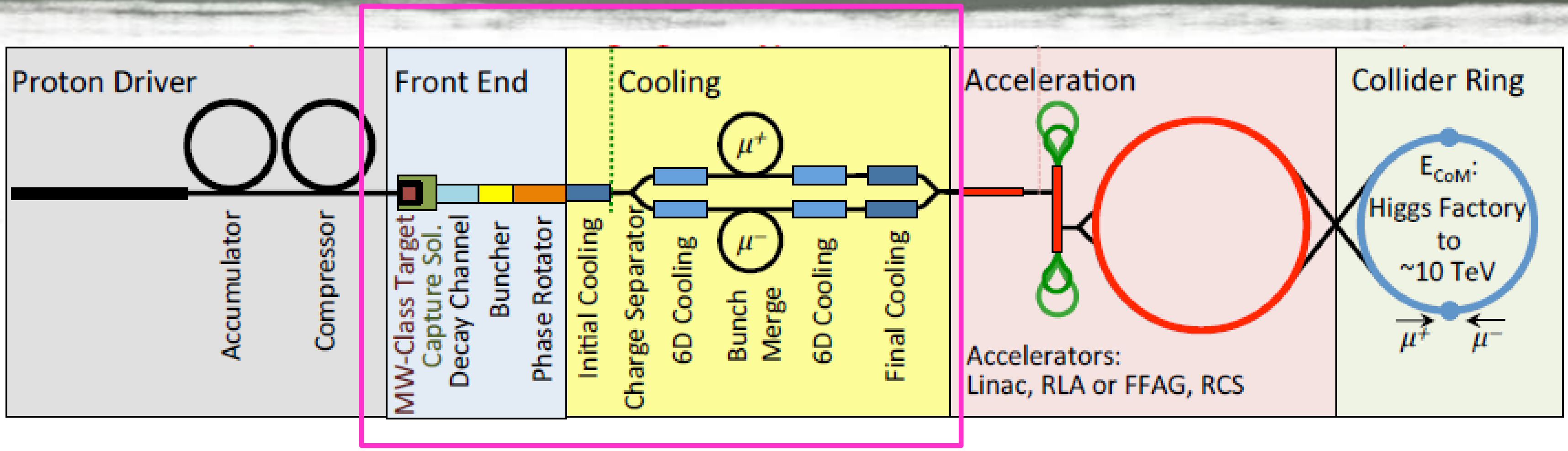
Fermi National Accelerator Laboratory

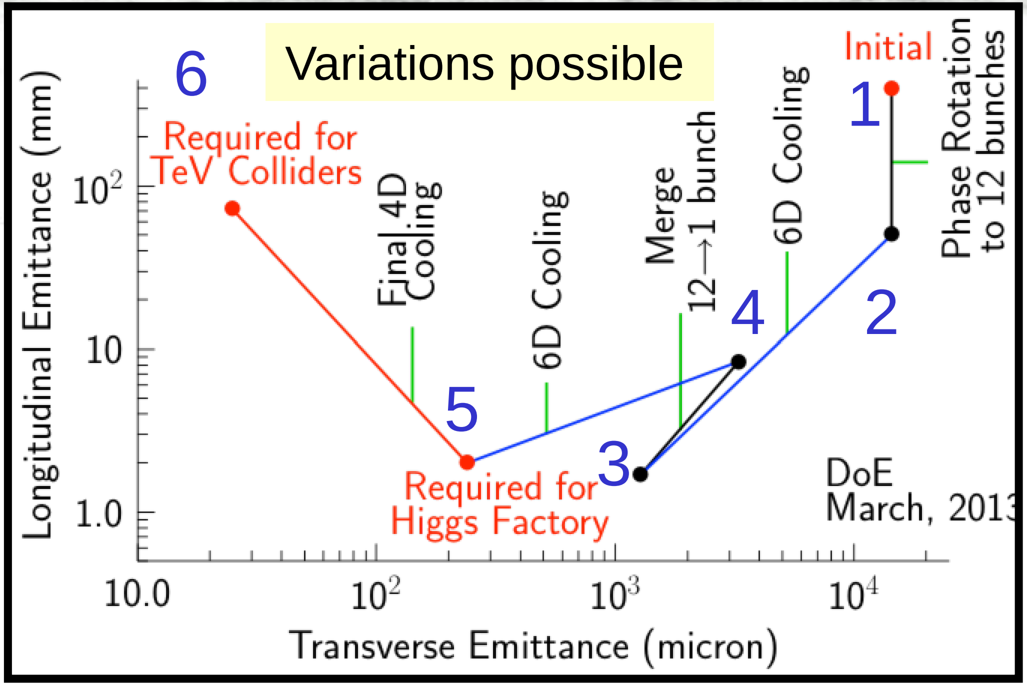
Meeting
March 16, 2023

Cooling for a Muon Collider



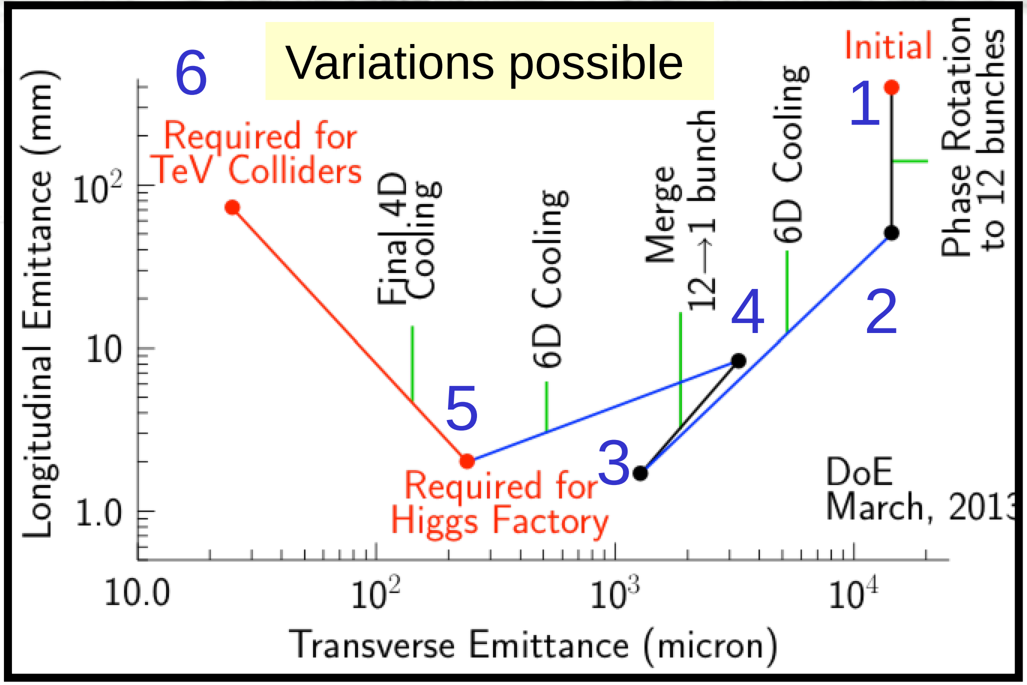
- Front-end produces 21 well aligned muon bunches
- Two sets of 6D cooling schemes
  - One before recombination (trans ε≈1.5 mm)
  - One after recombination (trans ε≈ 300 μm)
- Final cooling
  - Cools only transversely (trans ε≈ 25 μm)

Cooling baseline (1)



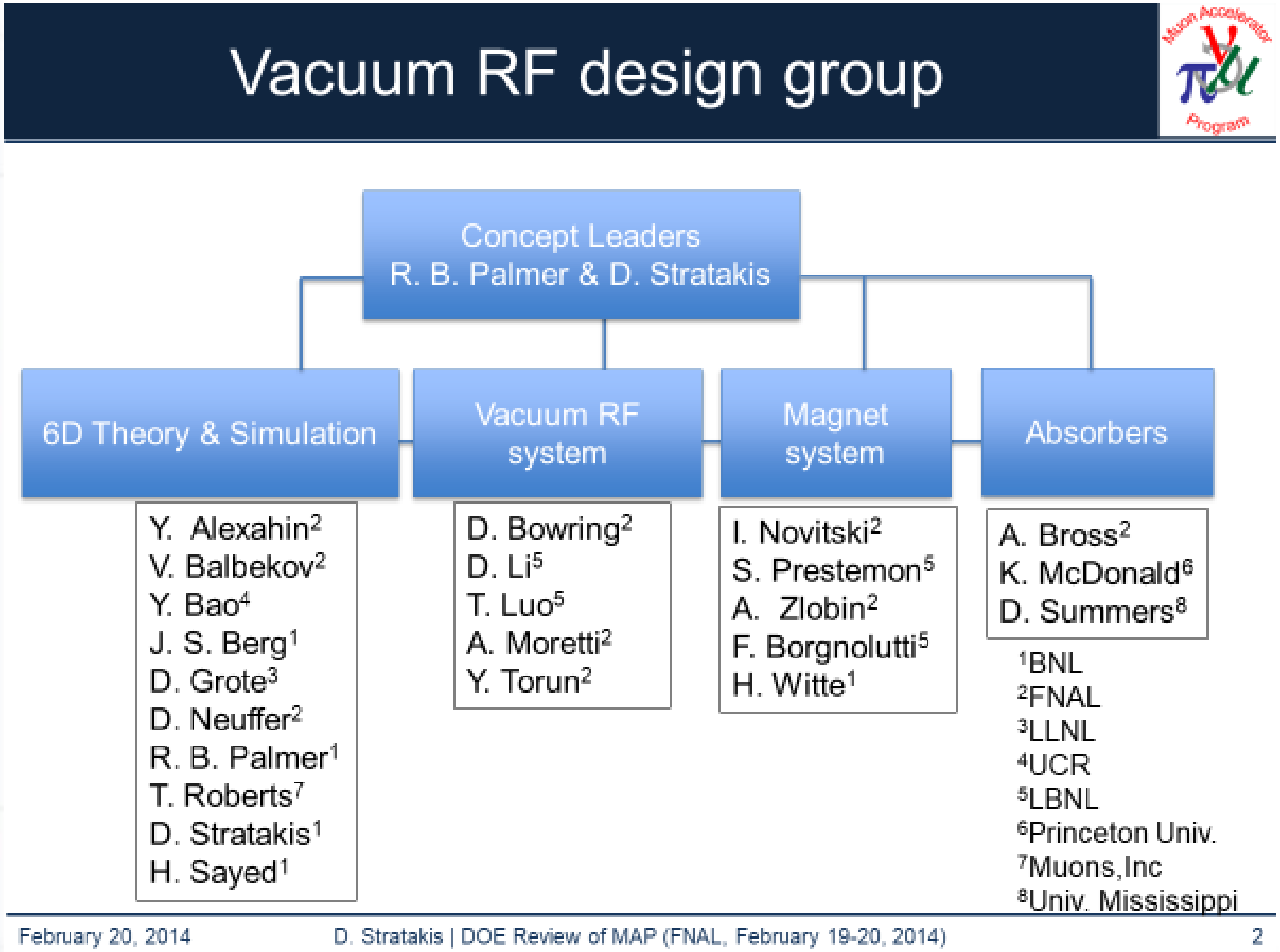
- 6D cooling for step 2 to 3 & step 4 to 5
  - Cool the beam both transversely and longitudinally
- 4D cooling for step 5 to 6
  - Cool the beam transversely and let the longitudinal emittance grow

Cooling baseline (2)



- 6D cooling for step 2 to 3 and step 4 to 5
  - Complete design published. Achieves baseline goal.
- 4D cooling for step 5 to 6
  - Complete design published. A factor of two above baseline goal.

Cooling group (MAP project)



Define Concept

⇓

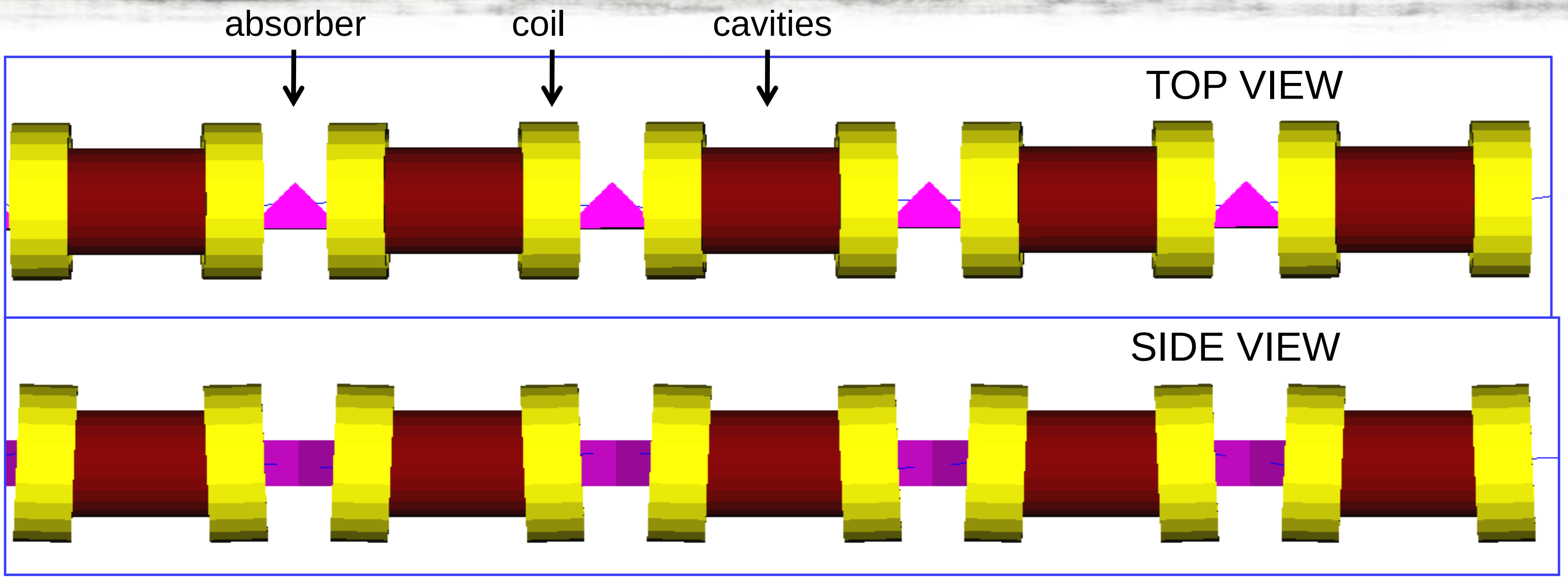
Simulate it

⇓

Realistic implementation

Three dedicated workshops 2014 (2), 2015(1)

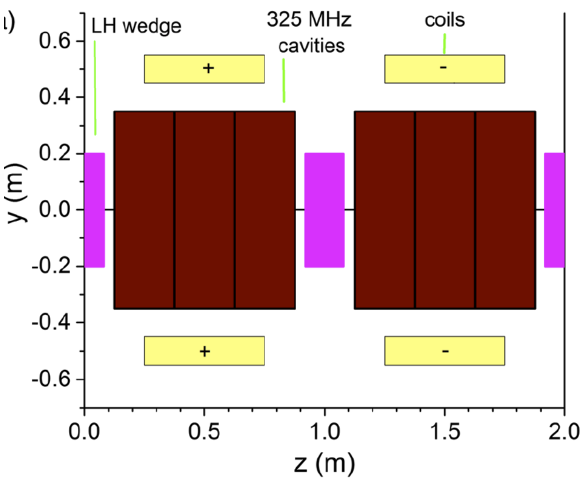
Rectilinear channel for 6D cooling

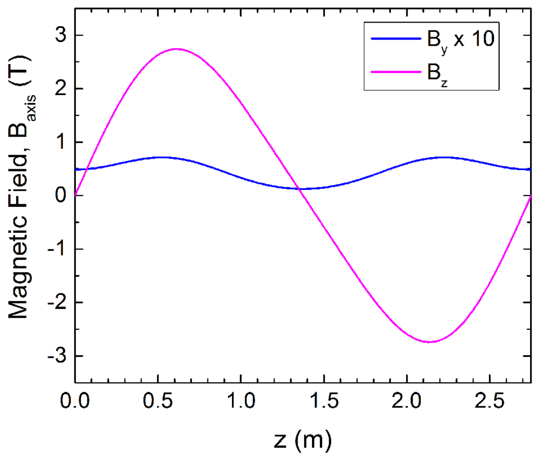


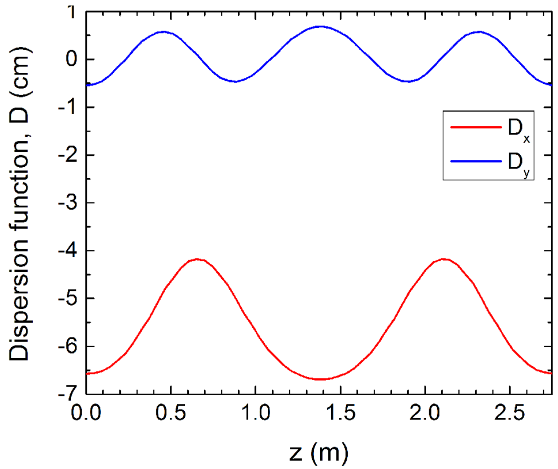
- Straight geometry simplifies construction and relaxes several technological challenges
- Multiple stages with different cell lengths, focusing fields, rf frequencies to ensure fast cooling

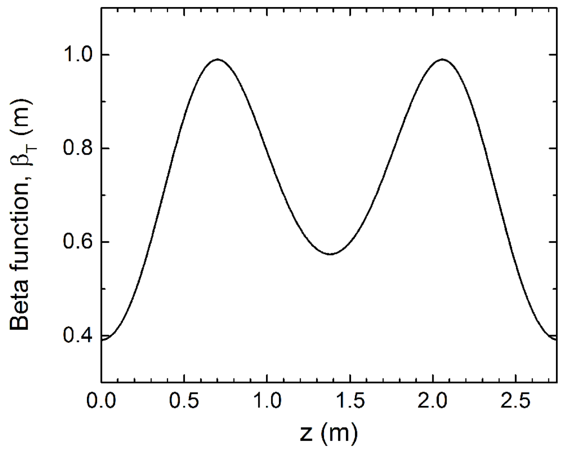
Rectilinear channel: How it works

- 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

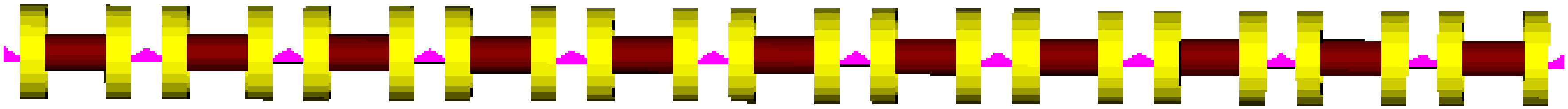




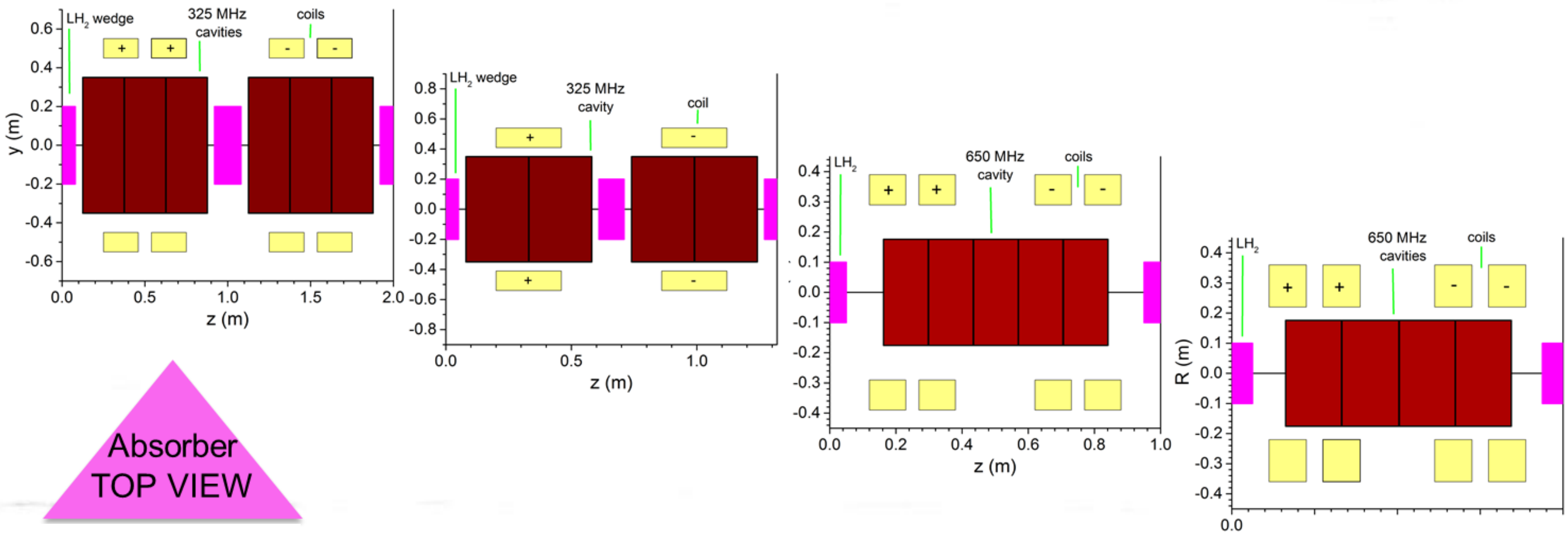




Cooling before merge (4 stages)



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)

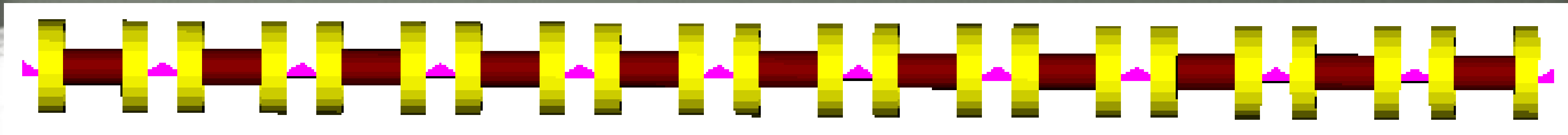
Peak B-field on axis (coil)

Parameters before the merge

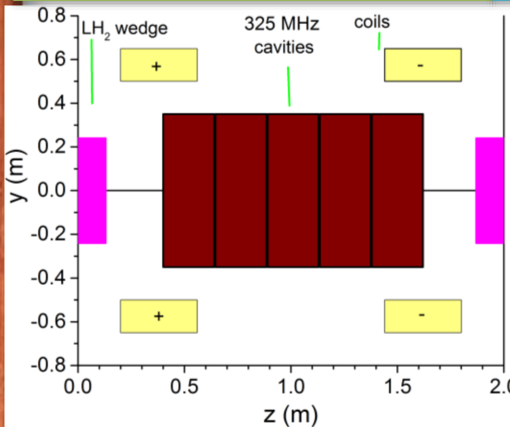
Parameters	Stage 1	Stage 2	Stage 3	Stage 4
Coil tilt (deg.)	3.13	1.80	1.60	0.70
Current density (A/mm^2)	63.25	126.6	165.0	195.0
Max B on coil (T)	4.20	8.47	9.56	11.83
Max B on axis (T)	2.35	3.50	4.82	6.06
Trans. beta (cm)	81.9	54.8	38.3	30.3
Absorber angle (deg.)	40	44	100	110
Absorber type	LH_2	LH_2	LH_2	LH_2
Rf frequency (MHz)	**325**	**325**	650	650
RF gradient (MV/m)	22	22	28	30
Cell length (m)	2.0	1.32	1.0	0.8
Total length (m)	132	171.6	107	70.4

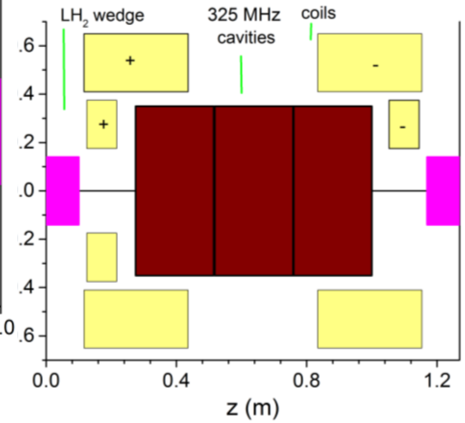
- Lattice parameters have been modified over time

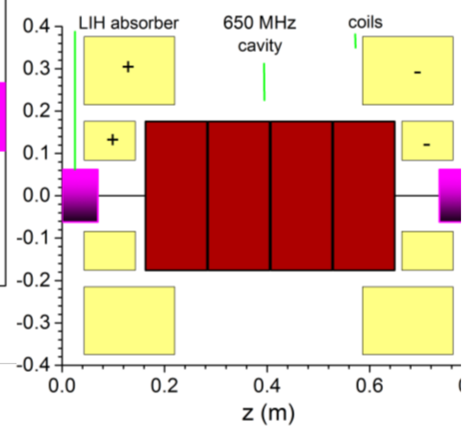
Cooling after the merge (8 stages)

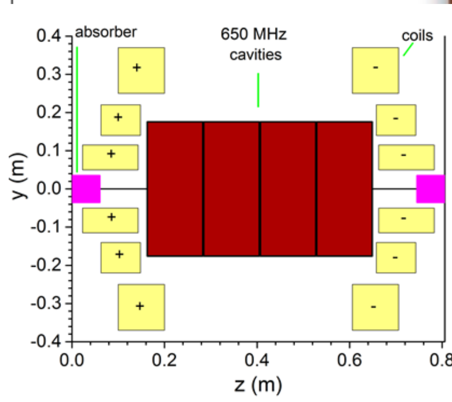


STAGE 2	STAGE 4	STAGE 6	STAGE 8
64 m (32 cells)	62.5 m (50 cells)	62 m (77 cells)	41.1 m (51 cells)









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

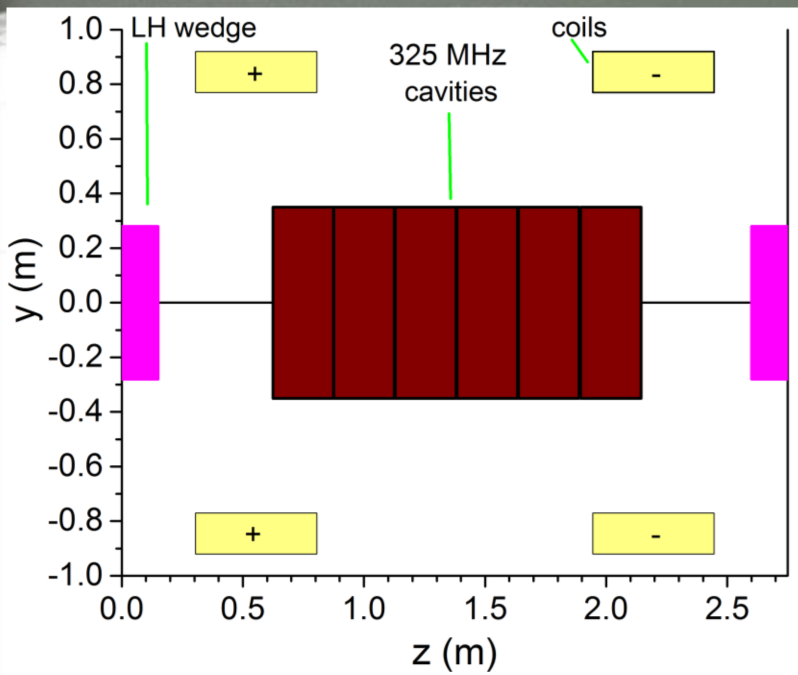
Peak B-field on axis (coil)

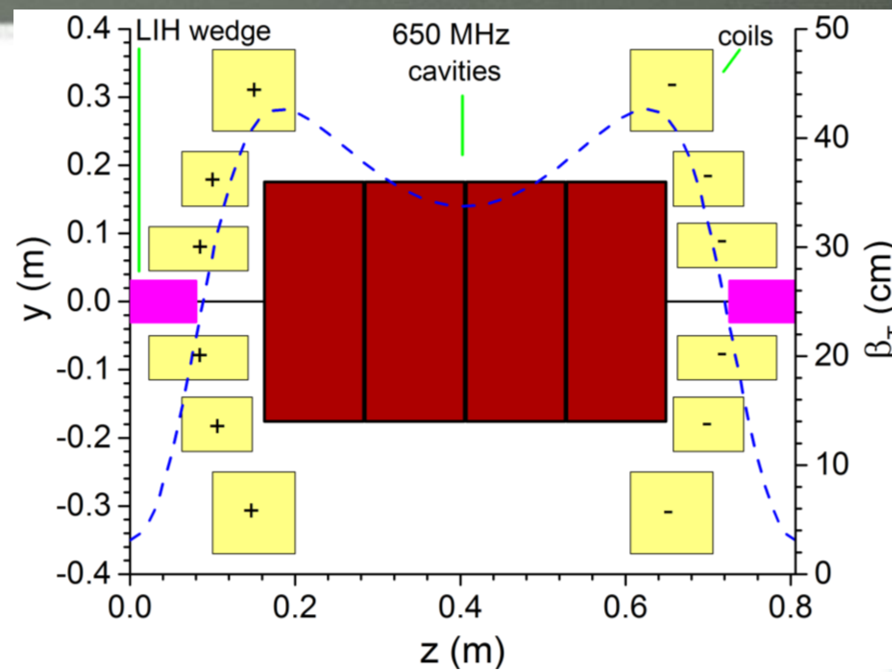
Parameters after the merge

Parameters	St. 1	St. 2	St. 3	St. 4	St. 5	St. 6	St. 7	St. 8
Coil tilt (deg.)	0.9	1.3	1.1	1.1	0.66	0.7	0.8	0.8
Cur. Density (A/mm^2)	69.8	90.0	123.0	94.0	168.1	185.0	198.0	198.
Max B on coil (T)	6.8	8.4	12.2	9.2	14.1	14.2	14.20	14.5
Max B on axis (T)	2.6	3.70	4.9	6.0	9.8	10.8	12.50	12.9
Trans. beta (cm)	42.0	27.4	20.2	14.0	8.1	5.9	4.2	3.7
Wedge ang. (deg.)	120	117	113	124	61	90	90	90
Absorber type	LH_2	LH_2	LH_2	LH_2	LiH	LiH	LiH	LiH
Rf freq. (MHz)	325	325	325	325	650	650	650	650
RF grad. (MV/m)	19.0	19.5	21.0	22.0	27.0	28.5	26.0	26.0
Cell length (m)	2.75	2.00	1.50	1.27	0.806	0.806	0.806	0.806
Total length (m)	55.0	64.0	81.0	63.5	73.3	62.0	40.3	41.1

- Lattice parameters have been modified over time

Two extremes: First & last stage





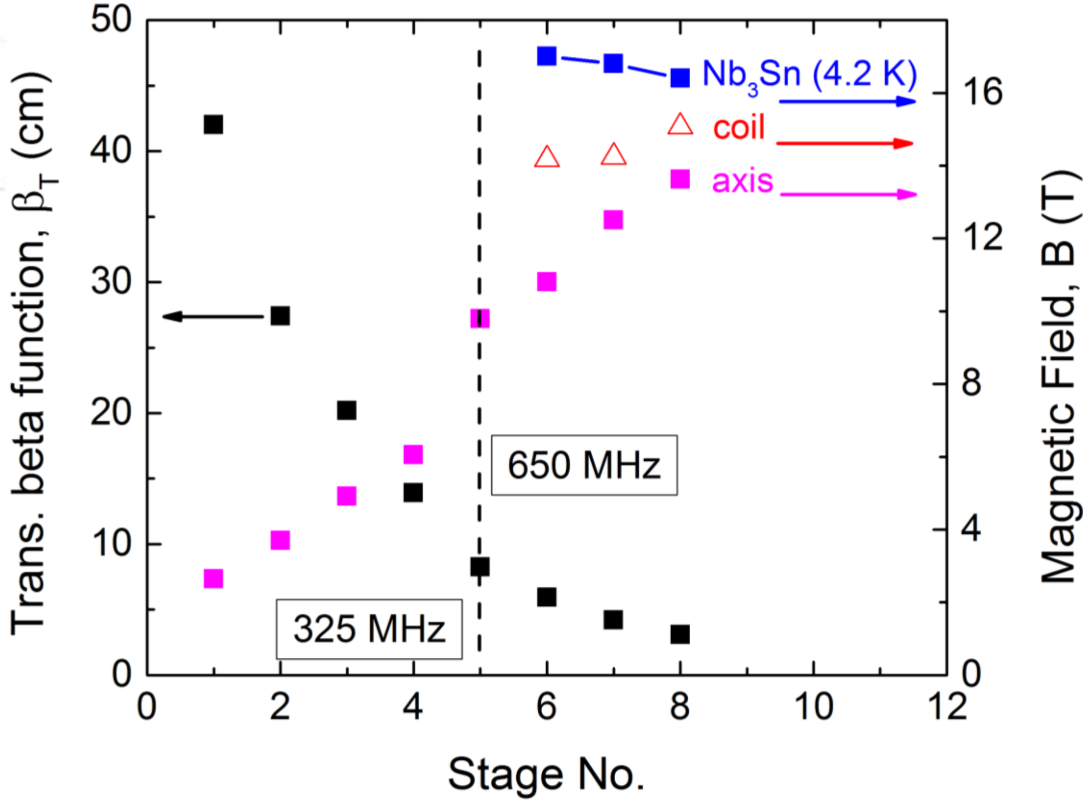
EARLY STAGE OF COOLING

- 275 cm long
- Coils far
- 325 MHz
- Axial B ~ 3 T
- Beta ~ 40 cm

LATE STAGE OF COOLING

- 80 cm long
- Coils near axis
- 650 MHz
- Axial B ~ 12 T
- Beta ~ 3 cm

Constrains during MAP studies



- We set two constrains in our design:
  - Number 1: Peak fields on coils don't exceed Nb_3Sn limits

Constrains during MAP studies

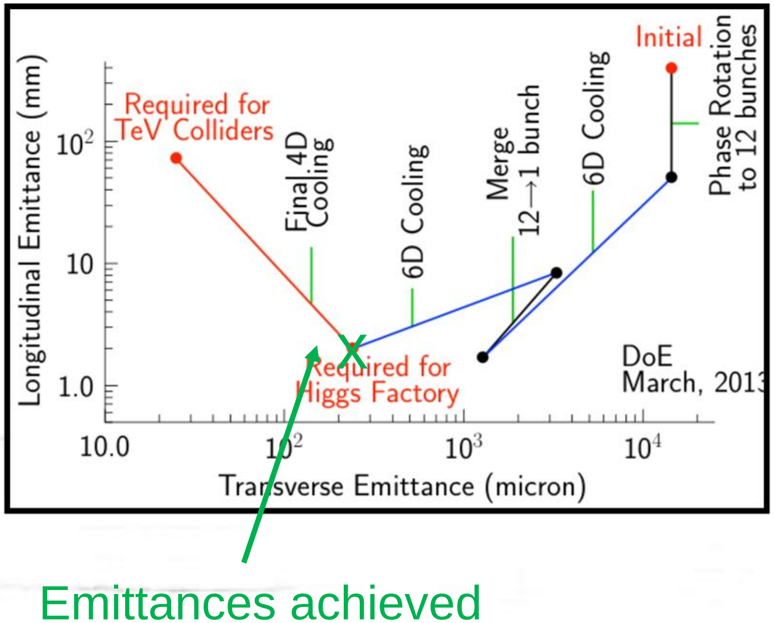
- Need consistent value for comparison
- Cavity lengths also matter
- Propose consistent values
  - consistent with 17 MV/m at 201.25 MHz

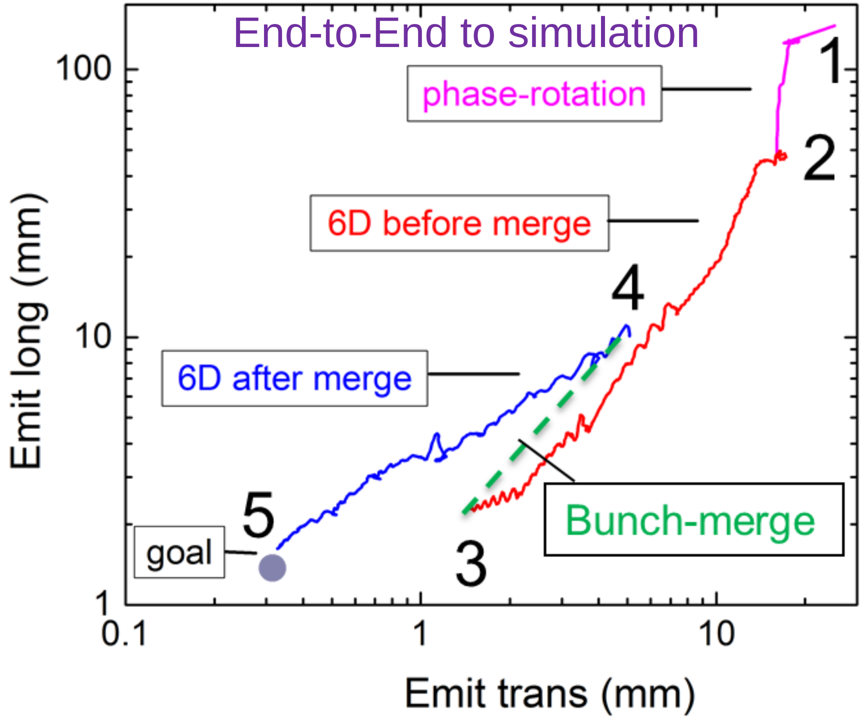
Freq. MHz	Length cm	Grad MV/m	ΔE $v = c$ MeV	ΔE 200 MeV/c MeV
325	30	22	5.51	5.23
650	15	31	3.88	3.68
975	10	38	3.17	3.01

- We set two constrains in our design:
  - Number 2: Cavities within> 1 T operate ~ 50% of the achievable gradient at 0 T

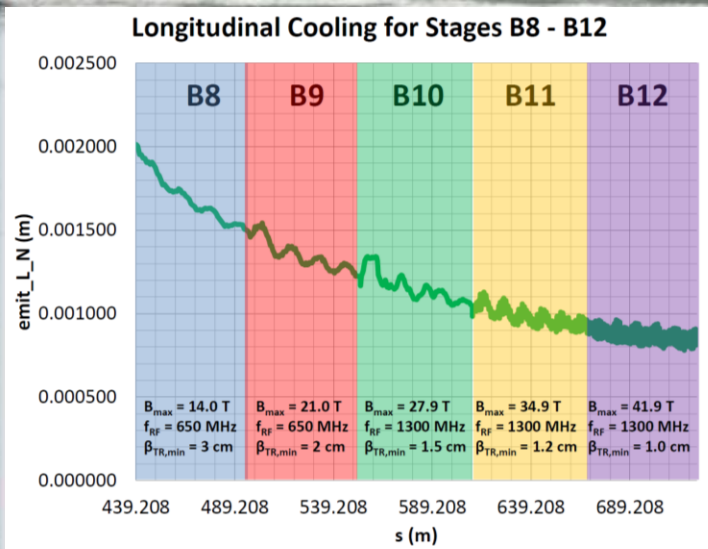
Performance

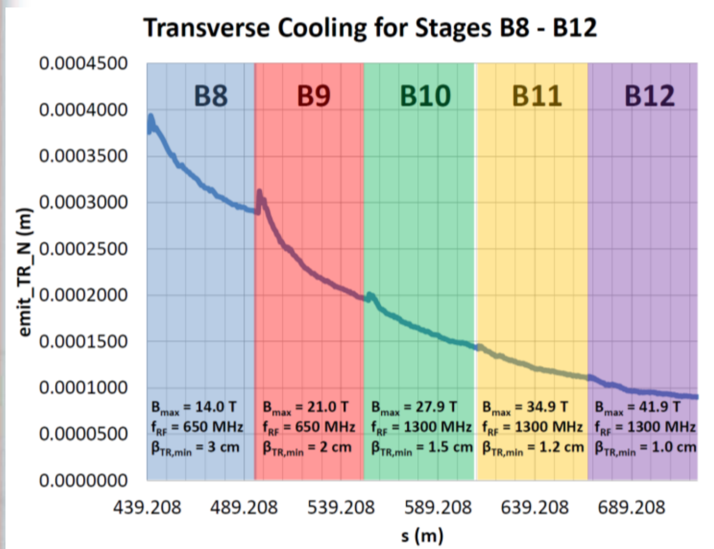
- Complete end-to-end simulation from the target (point 1)
- 6D emittance reduction by five orders of magnitude (point 5)
- Achieved emittances and transmissions specified by MAP
- Overall distance ~ 900 m





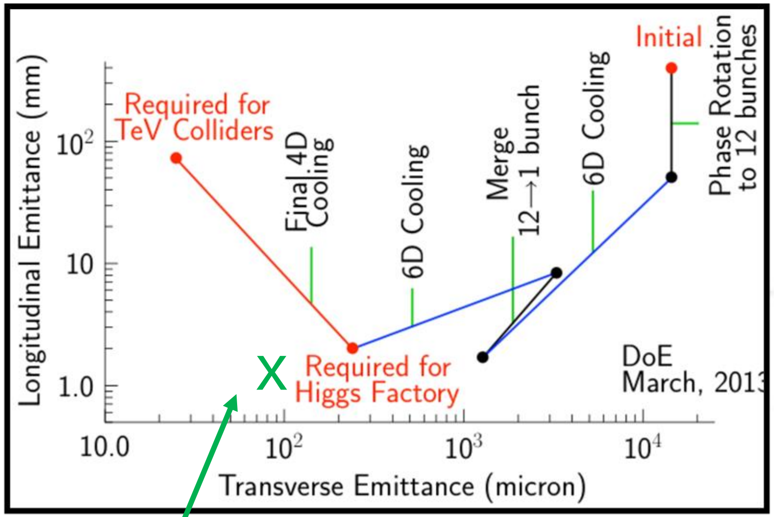
Magnets: Rectilinear with HTS magnets





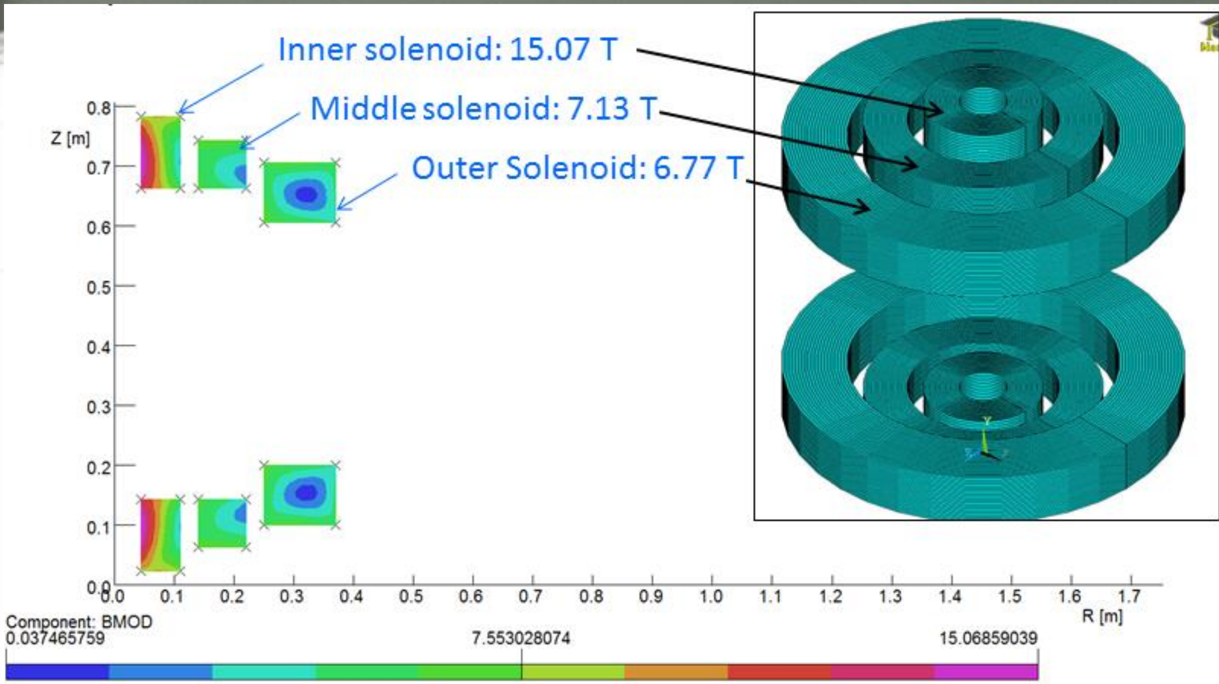
- If HTS magnet technology is considered, rectilinear channel can reduce the 6D emittance even more

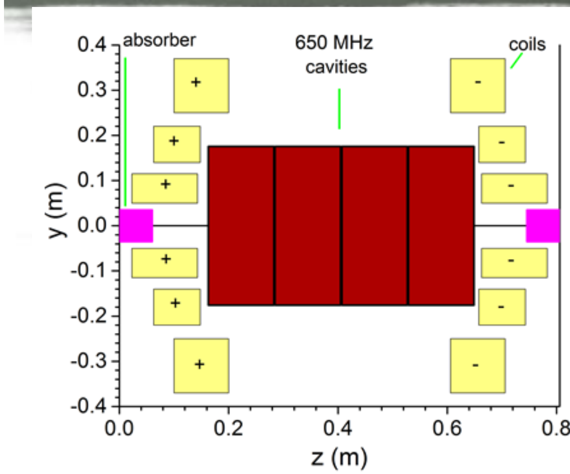
Don Summers,
University of Mississippi



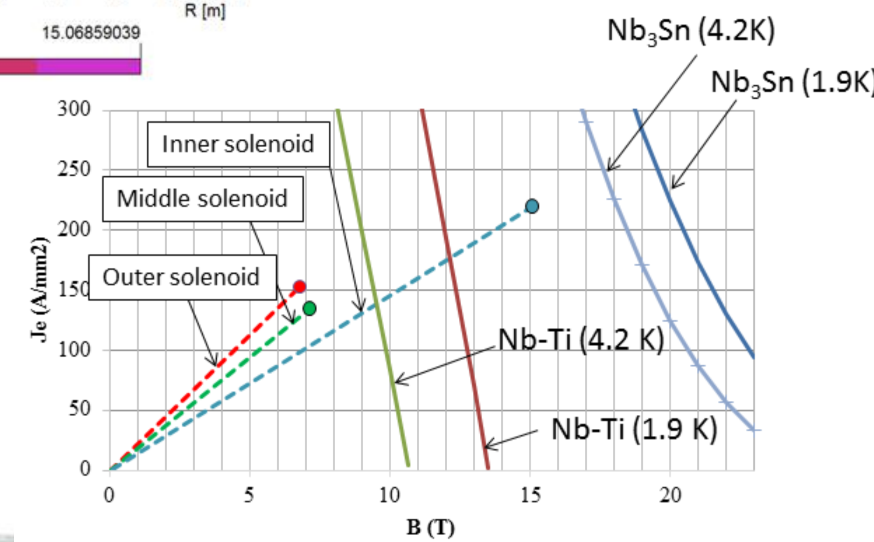
Emittances achieved

Magnet Design (last stage)

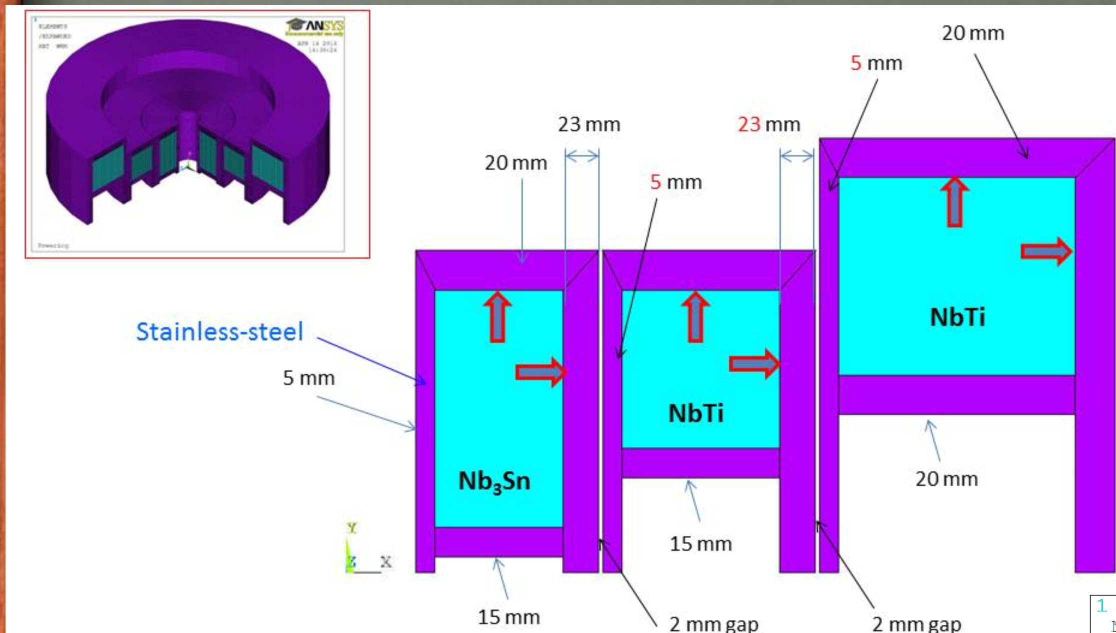


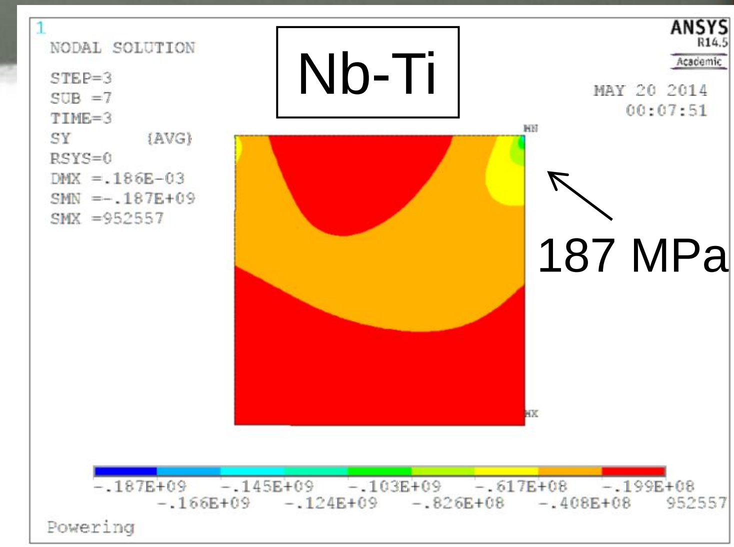


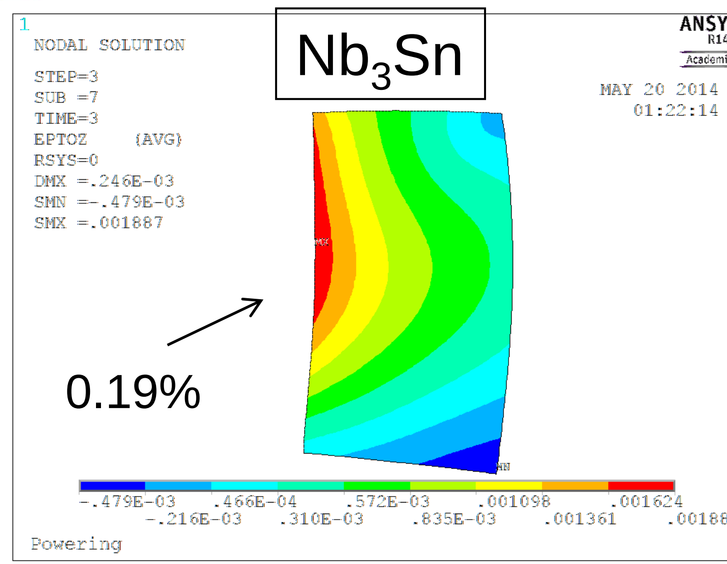
- Inner coil: Nb_3Sn
- Middle, outer: Nb-Ti
- Collaborating effort: Borgnolutti, Prestemon, (LBNL) Witte (BNL)



Mechanical Model



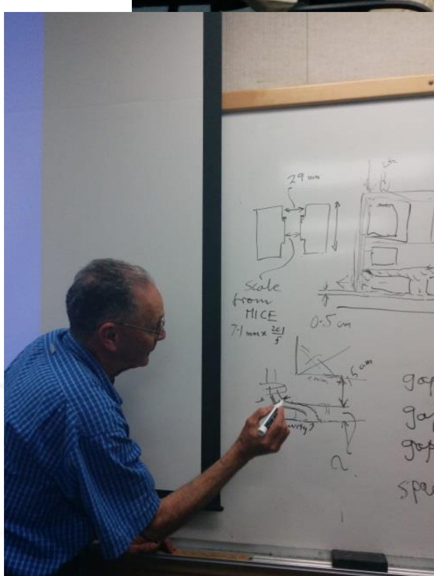


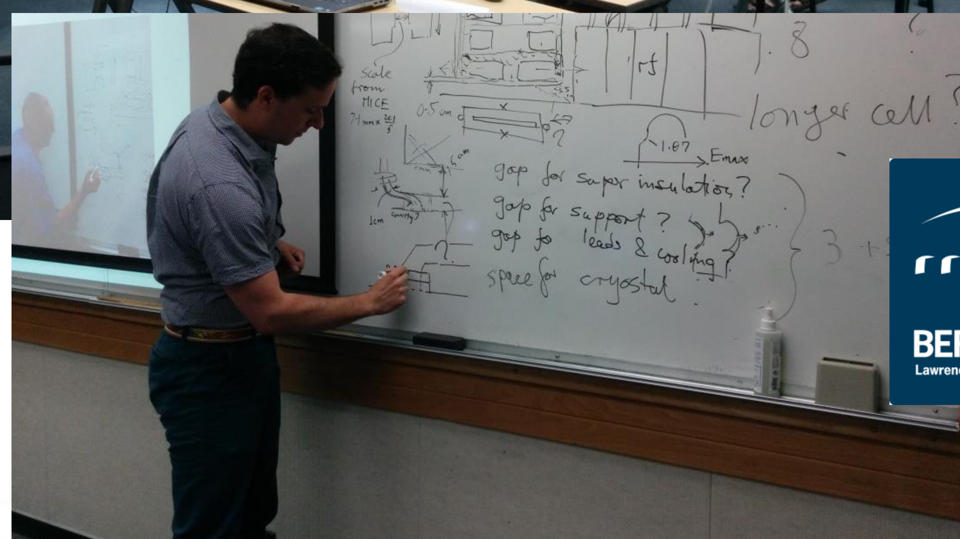


- Azimuthal strain in the inner solenoid (19%) is within Nb_3Sn irreversible limit (25%)
- Stress for Nb-Ti is less than its yield strength (300 Mpa)

What we learned from our workshops

Hosted at LBNL, May 13-14, 2014





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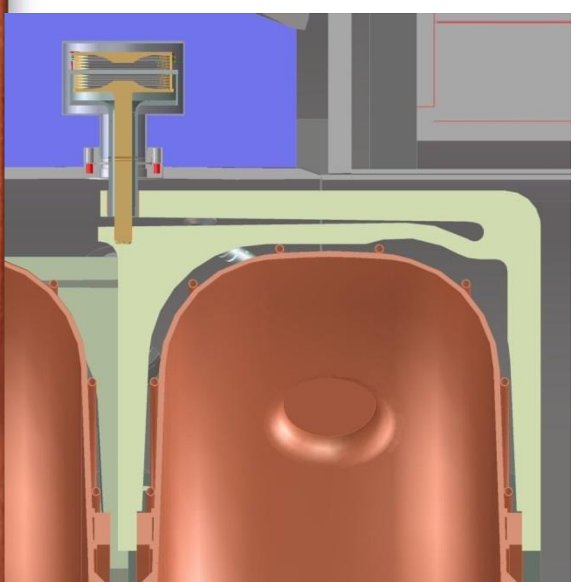
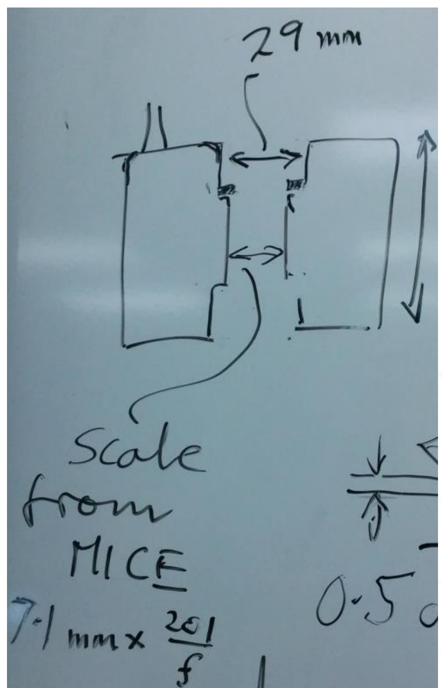
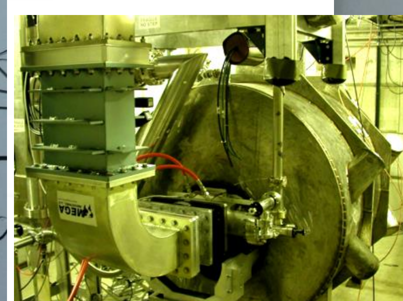
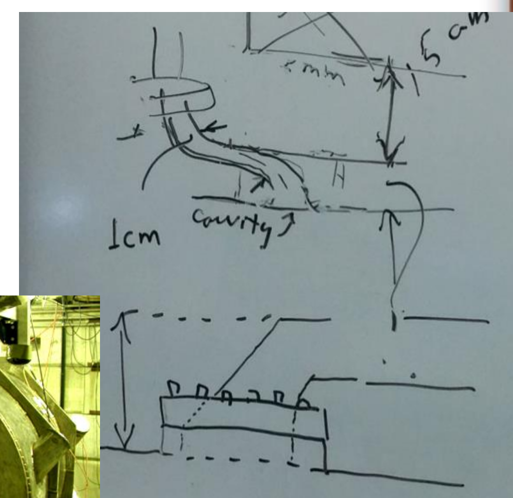
Lessons learned (RF)

- RF Cavity Design:
  - A separation of 5.0 cm (2.5 cm each) needs to be added between cavities for tuners and flanges
  - Cavities can be powered by a curved waveguide-> simplifies the focusing magnet (no need to split the coils).



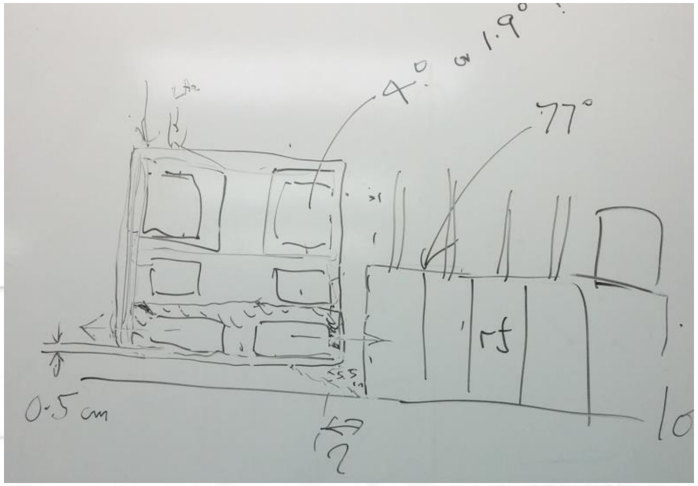


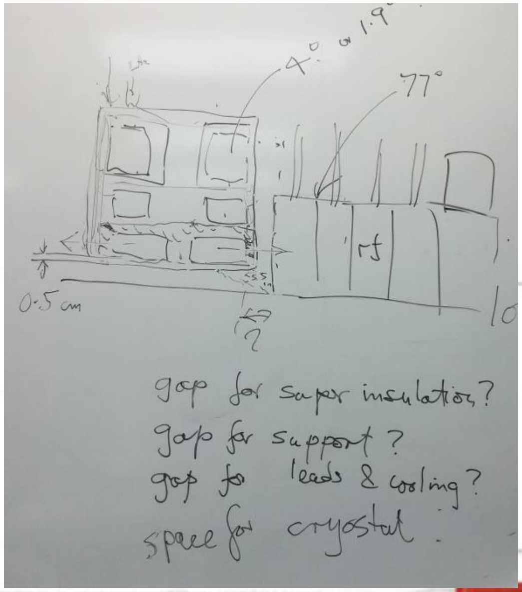




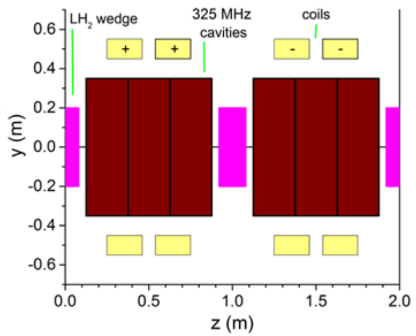
Lessons learned (magnets)

- Magnets:
  - Stage 8 (last stage) looks feasible.
  - Some stages need to be modified. Coils require at least 5 cm extra space in the longitudinal direction to place He bath and coil feeds in/out.
  - Calculation of forces & stresses for earlier stages required
  - Evaluate quench protection



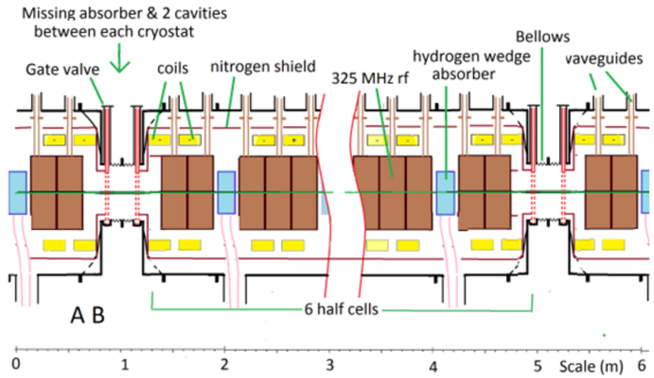


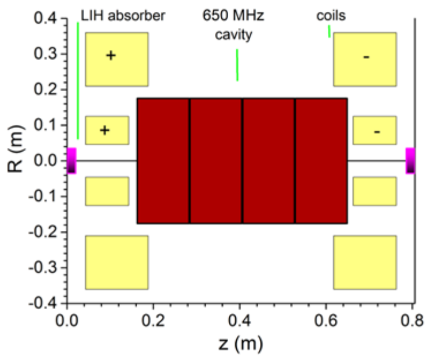
Modifications to consider



[Details](#)

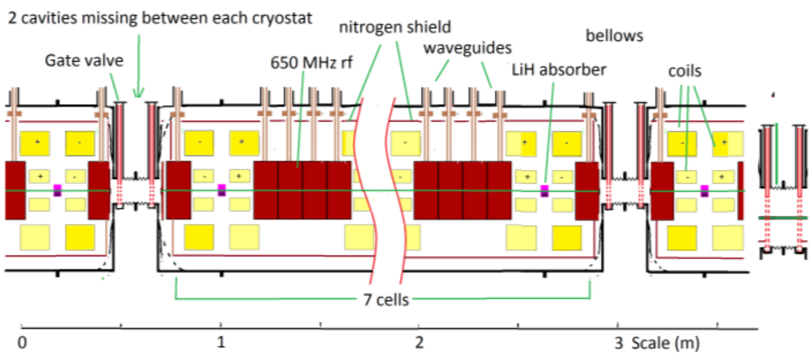
First Stage



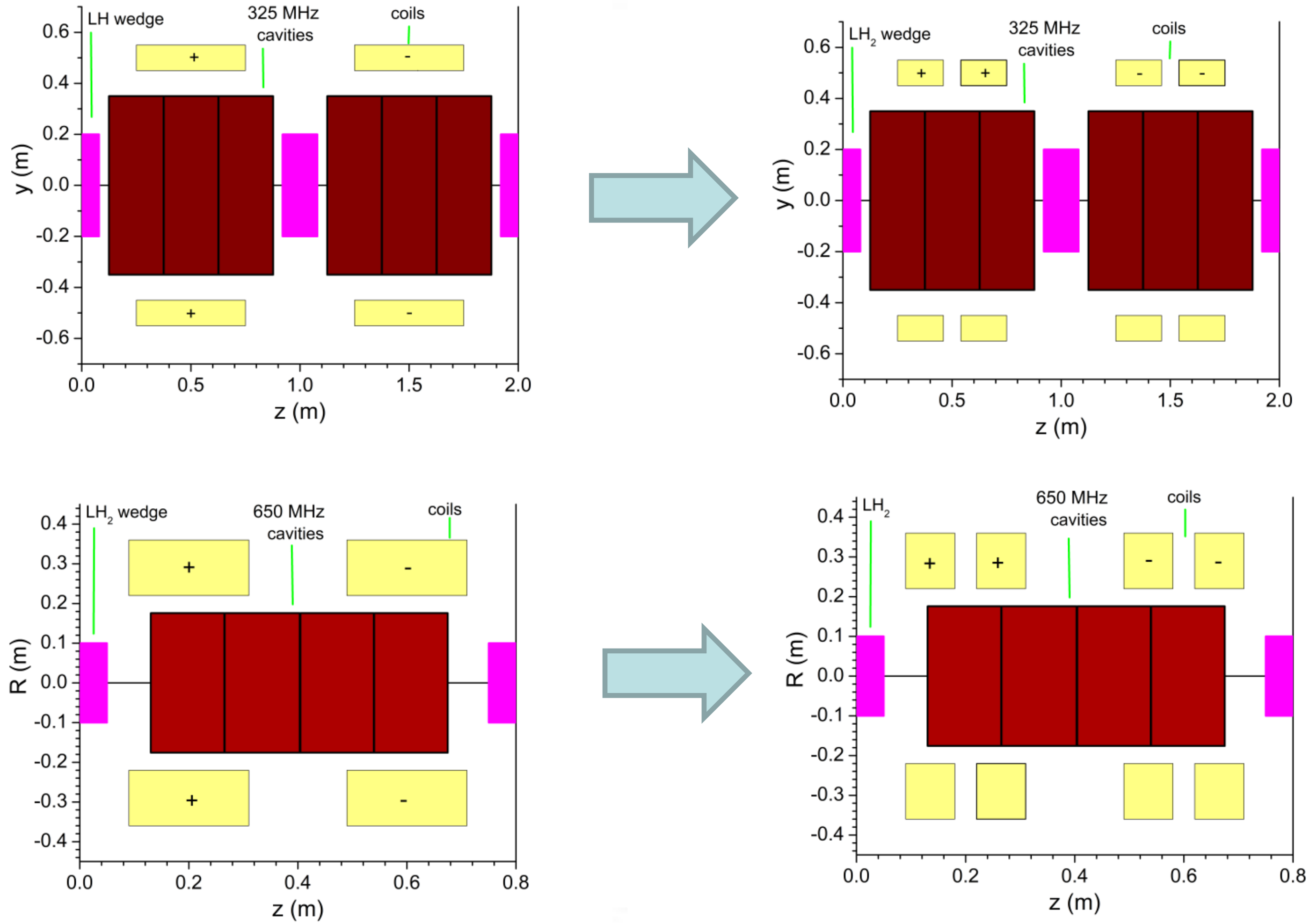


[Details](#)

Last Stage



Modifications to consider



Modifications to consider

- In the original lattice the solenoids are tilted which results in a small dipole field which is required by beam dynamics.
- To generate the dipole field we opt for adding a separate dipole magnet instead, which allows to tune the dipole field.
  - This dipole field can be generated by a saddle coil located on the inside of the solenoids

WEPRI103 Proceedings of IPAC2014, Dresden, Germany

MAGNET DESIGN FOR A SIX-DIMENSIONAL RECTILINEAR COOLING CHANNEL - FEASIBILITY STUDY*

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F. Borgnolutti, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

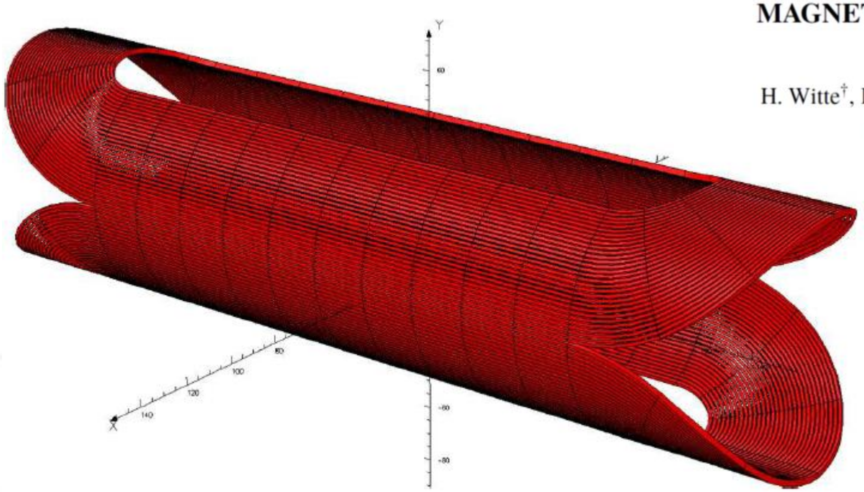


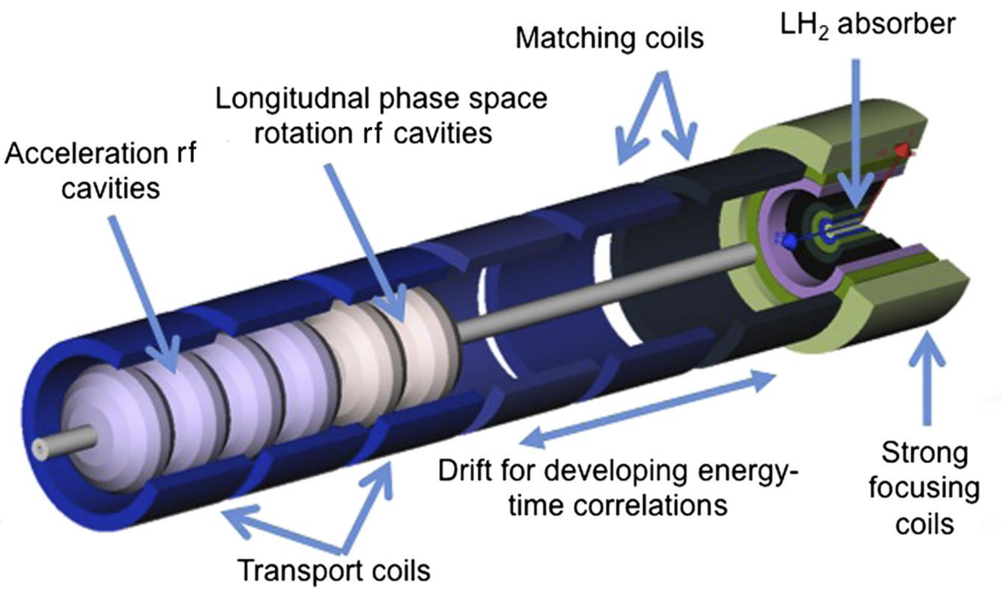
Figure 7: Dipole saddle coil.

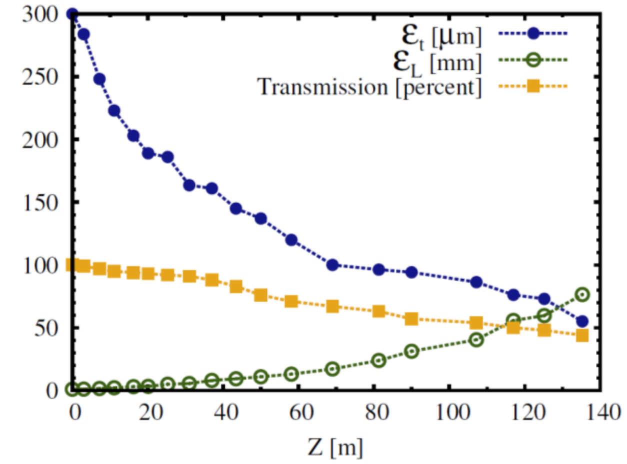
Some additional remarks

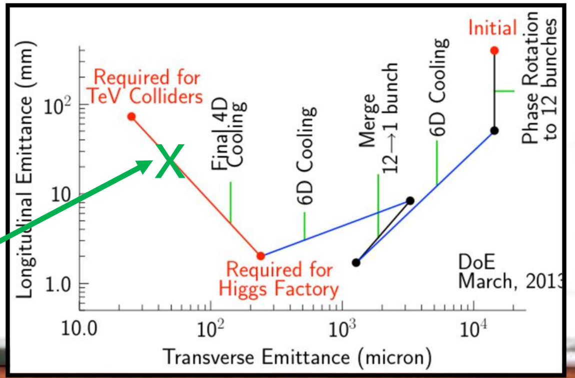
- Coils were simply tilted – is this realistic?
- How sensitive is the performance with various magnet uncertainties (tilt & alignment)
- Matching sections have not been designed for all stages
- If we use HTS how low can push the emittance and is this beneficial?

Final Cooling concept

- A design is in place for final cooling
- Final emittance is a factor of two above the baseline goal.

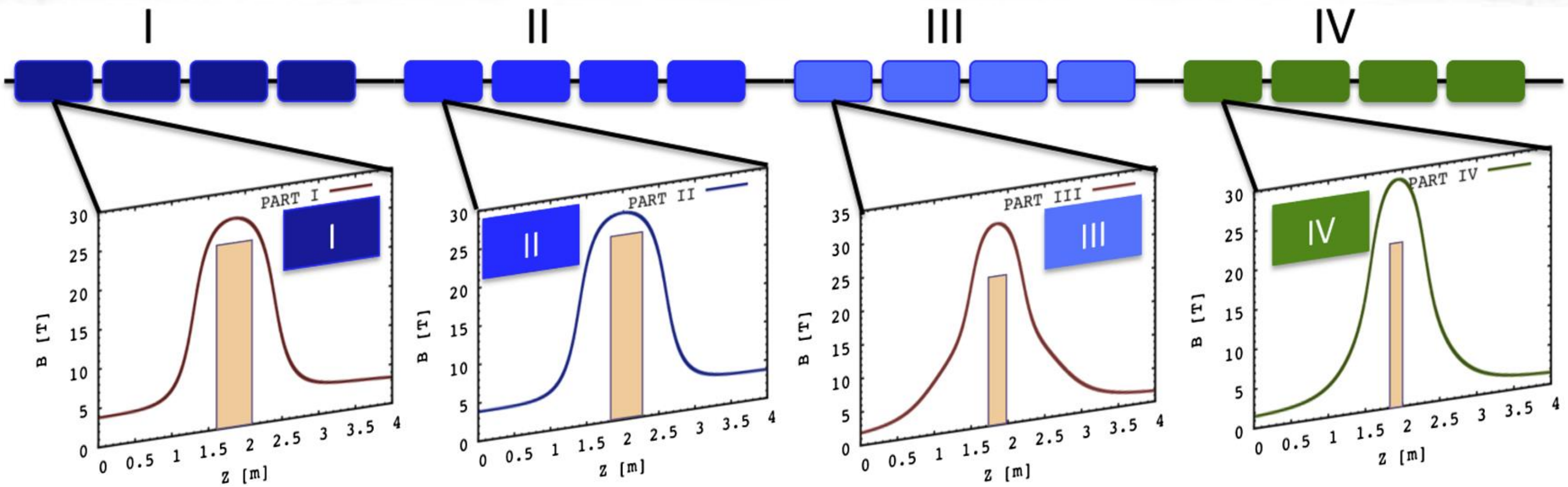


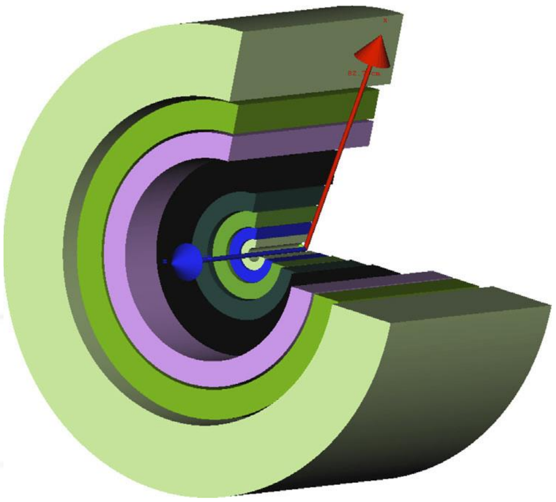


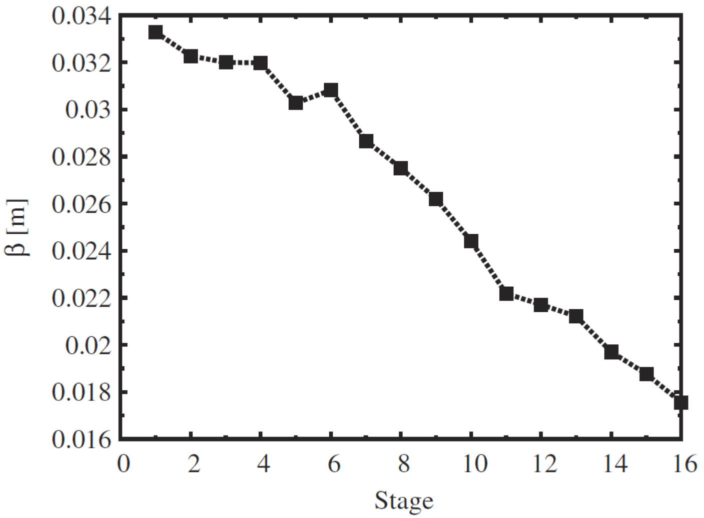


Emittances achieved

Magnet design







Some additional remarks

- Transmission is a issue, especially at the second half of the channel
- Beam is getting long ~ 2-3 m range
- How high should the B-field be in order to reach the emittance goal is a key question
- There is a lot of room for improvement!