6D cooling baseline

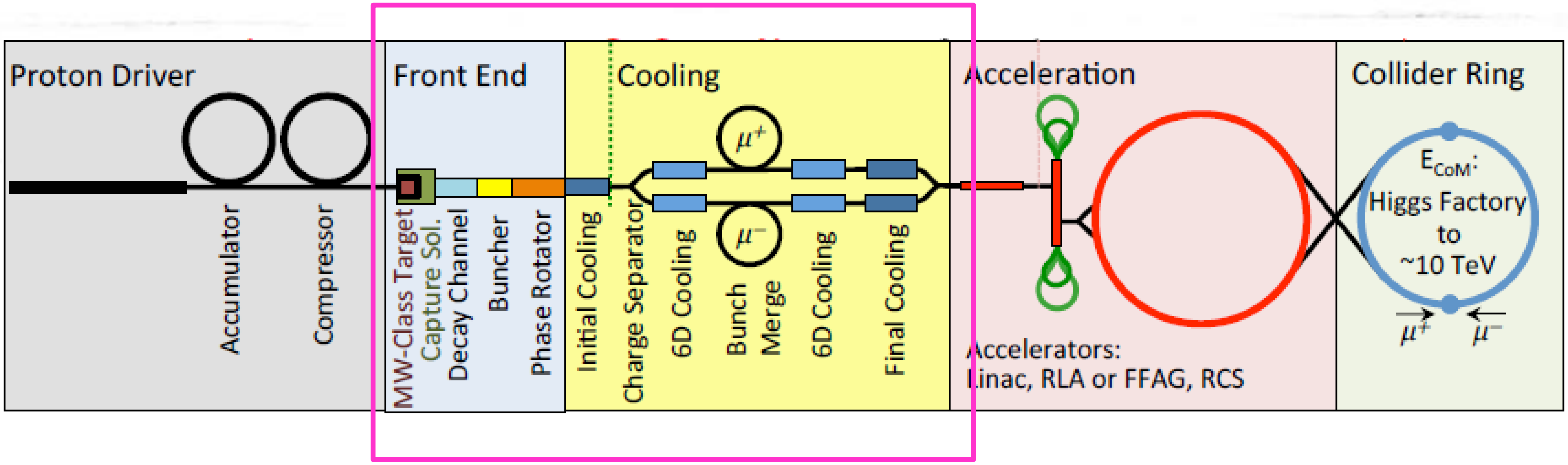
Diktys Stratakis
Fermi National Accelerator Laboratory

2[st] Muon Community Meeting (online only)
July 12, 2021

Outline

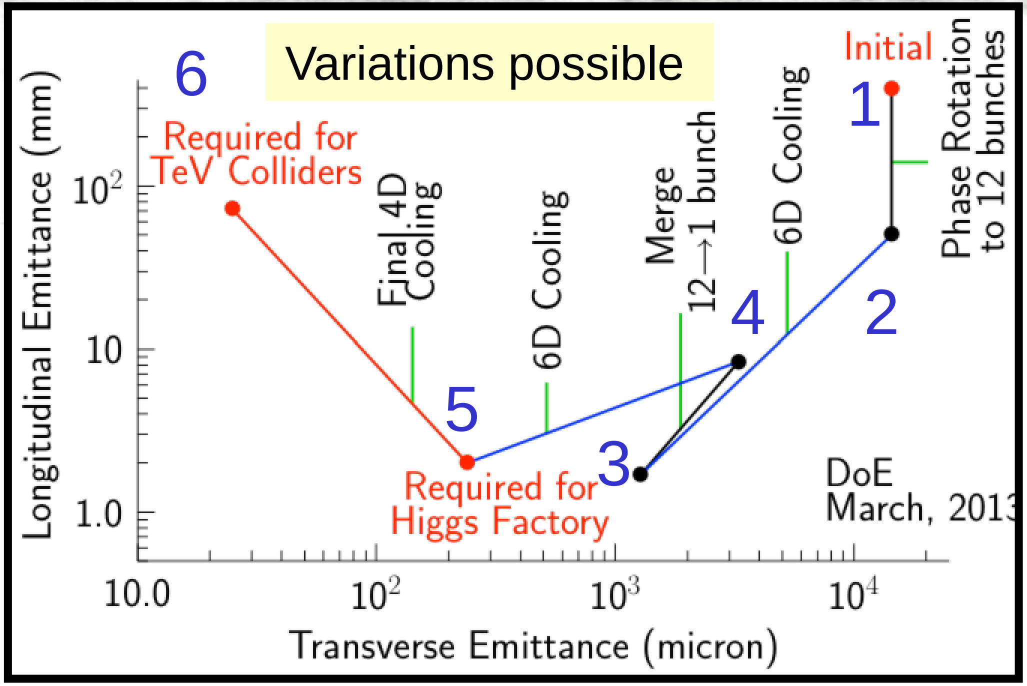
- Muon Collider cooling requirement
- Lattice design and performance (rectilinear)
- Future work on 6D cooling (rectilinear)
  - Lattice Design
  - RF cavities and RF windows
  - Absorbers
  - Magnets
  - Instrumentation
  - Variations?

Cooling for a Muon Collider



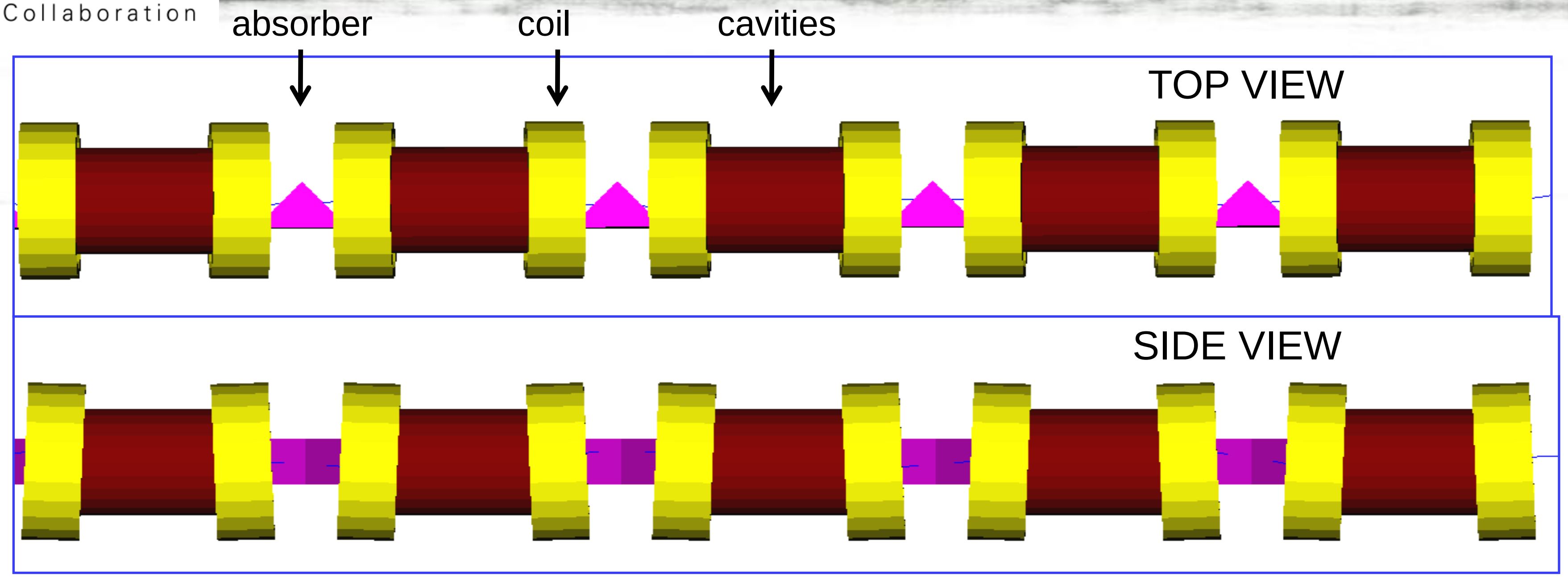
- Front-end produces 21 well aligned muon bunches
- Two sets of 6D cooling schemes
  - One before recombination (trans ε≈1.5 mm)
  - One after recombination (trans ε≈ 0.30 mm or less)
- Final cooling

Cooling baseline



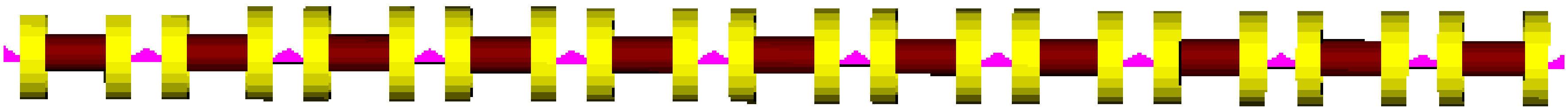
- 6D cooling for step 2 to 3 (bunch merge) and step 4 to 5
  - Rectilinear scheme has shown to achieve the baseline goal
  - Helical FOFO can partly do step 2 to 3. Attractive: cools both signs
- 4D cooling for step 5 to 6

Rectilinear channel concept

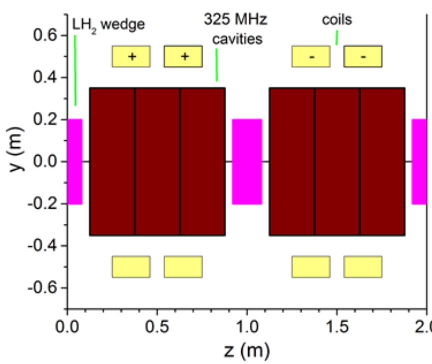


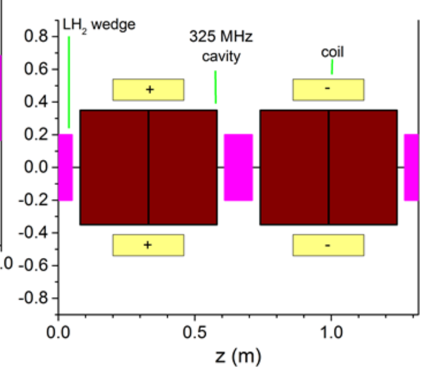
- Straight geometry simplifies construction and relaxes several technological challenges
- Multiple stages with different cell lengths, focusing fields, rf frequencies to ensure fast cooling

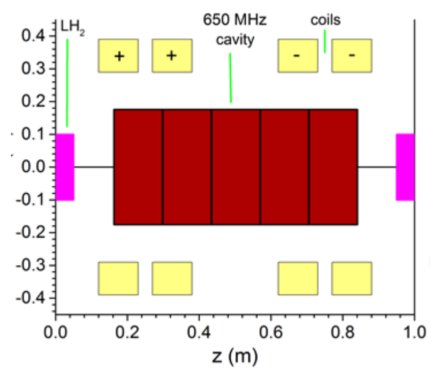
Cooling before merge (4 stages)

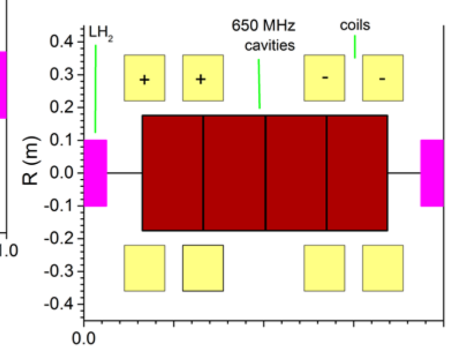


STAGE 1	STAGE 2	STAGE 3	STAGE 4
132 m (66 cells)	171.6 m (130 cells)	107 m (107 cells)	70.4 m (88 cells)









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

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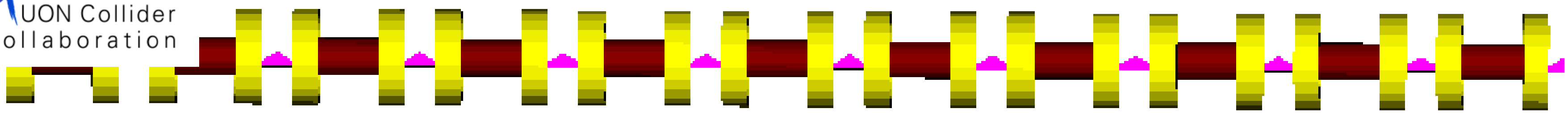
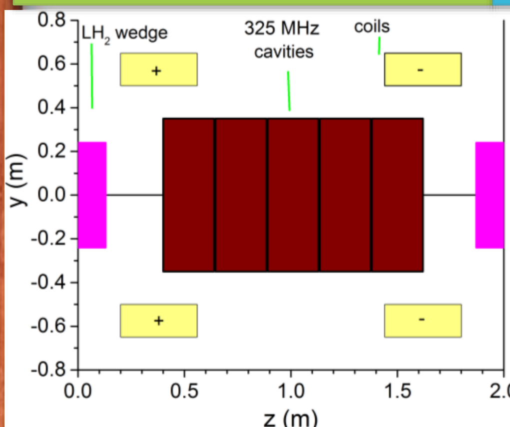
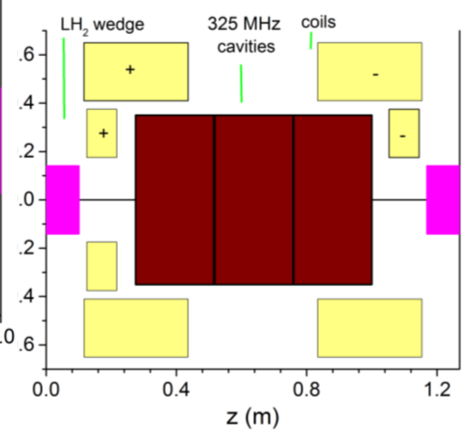
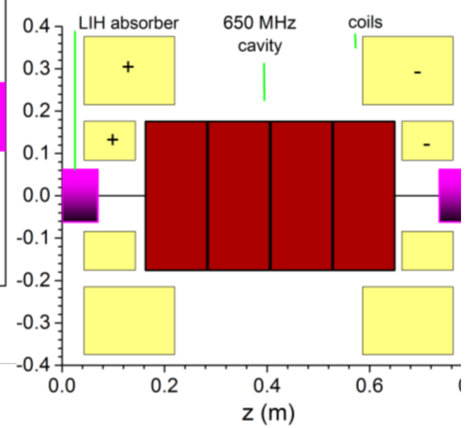
oling after the merge (8 stages)

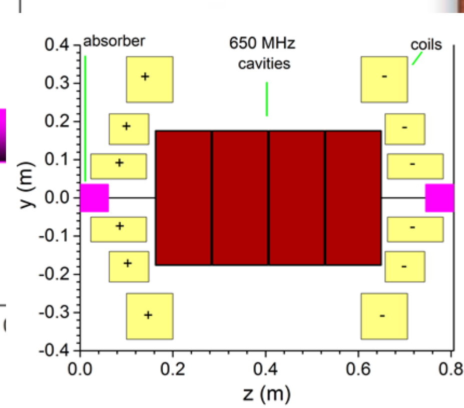


STAGE 2	STAGE 4	STAGE 6	STAGE 8
64 m (32 cells)	62.5 m (50 cells)	62 m (77 cells)	41.1 m (51 cells)









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

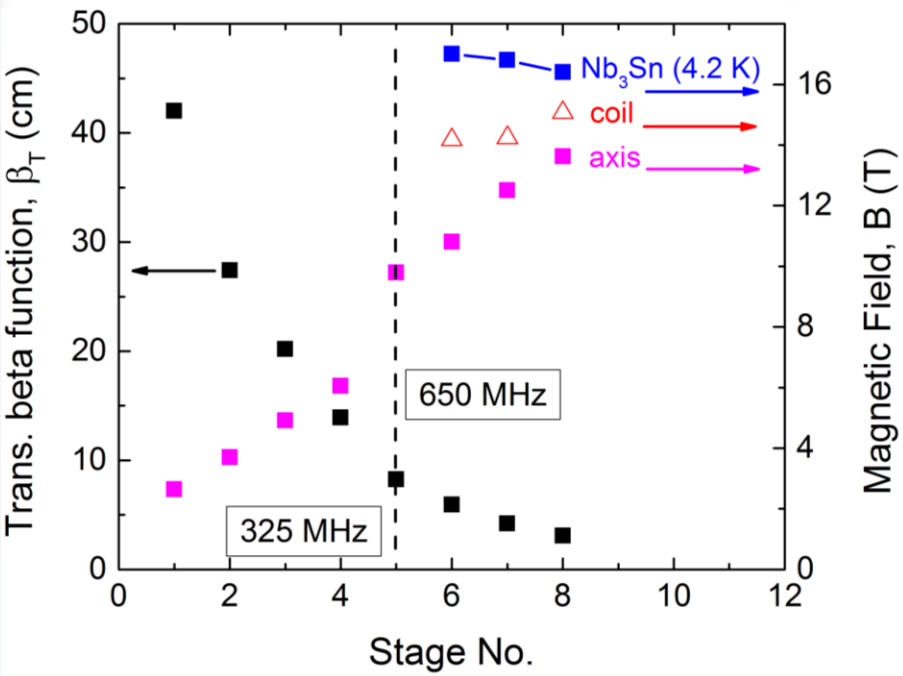
Peak B-field on axis (coil)

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

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

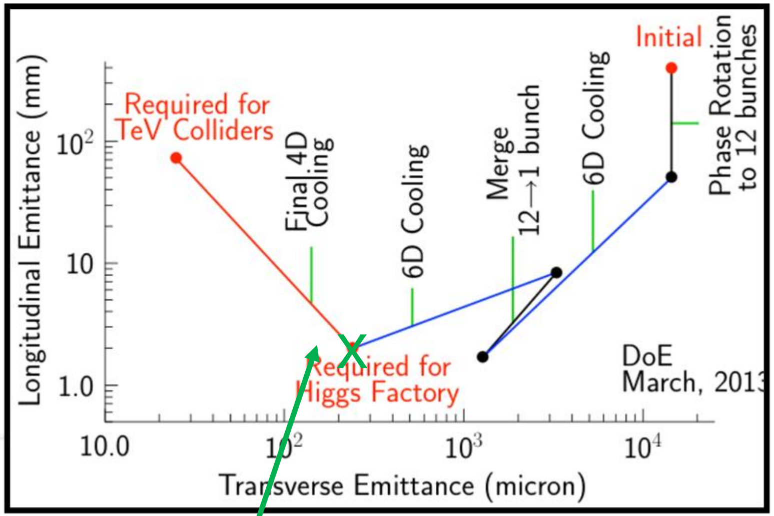
Freq. MHz	Length cm	Grad MV/m	ΔE $v = c$ MeV	ΔE 200 MeV/c MeV
325	30	22	5.51	5.23
650	15	31	3.88	3.68
975	10	38	3.17	3.01

8 October 2013 J. S. Berg | Analysis of Cooling Lattices | Vacuum RF

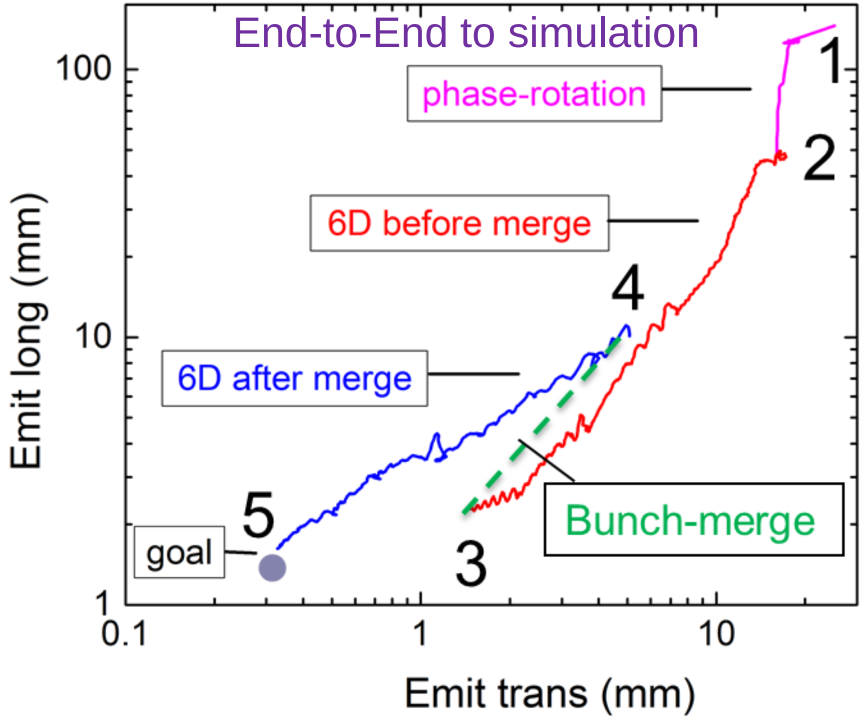
- We set two constrains in our (initial) design:
  - Peak fields on coils don't exceed Niobium Tin limits
  - Cavities within> 1 T operate ~ 50% of the achievable gradient at 0 T

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

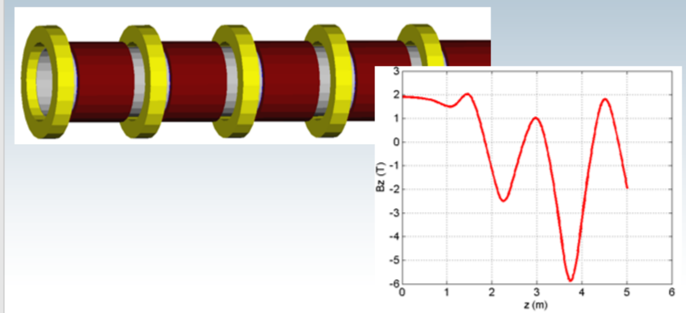


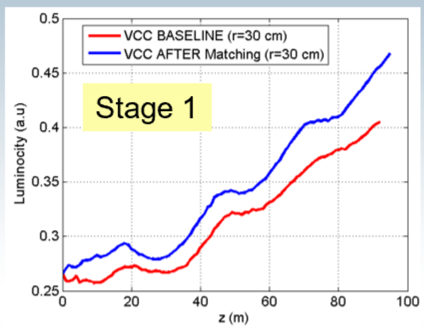
Emittances achieved



Lattice Design: Matching & tolerance

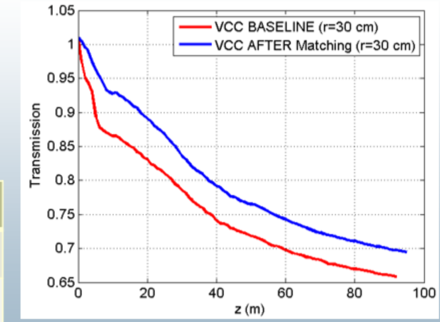
Matching to 6D VCC from Phase-Rotator





- 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)

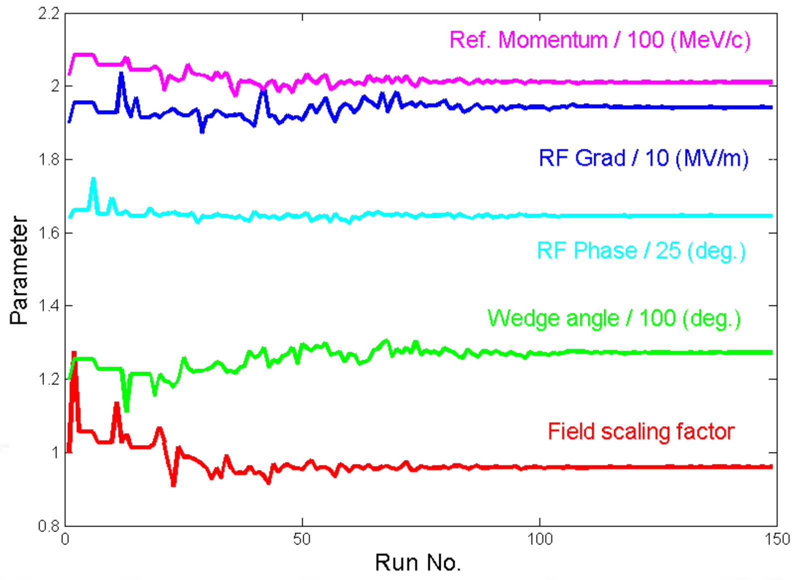


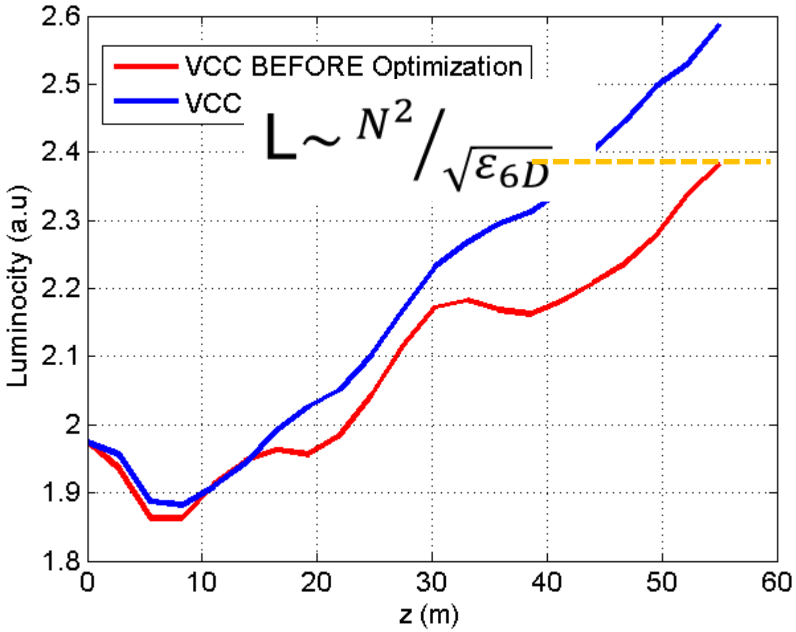
11

- What we need to further study:
  - Proper matching between individual stages
  - Tolerance to errors such as misalignments, quad errors etc

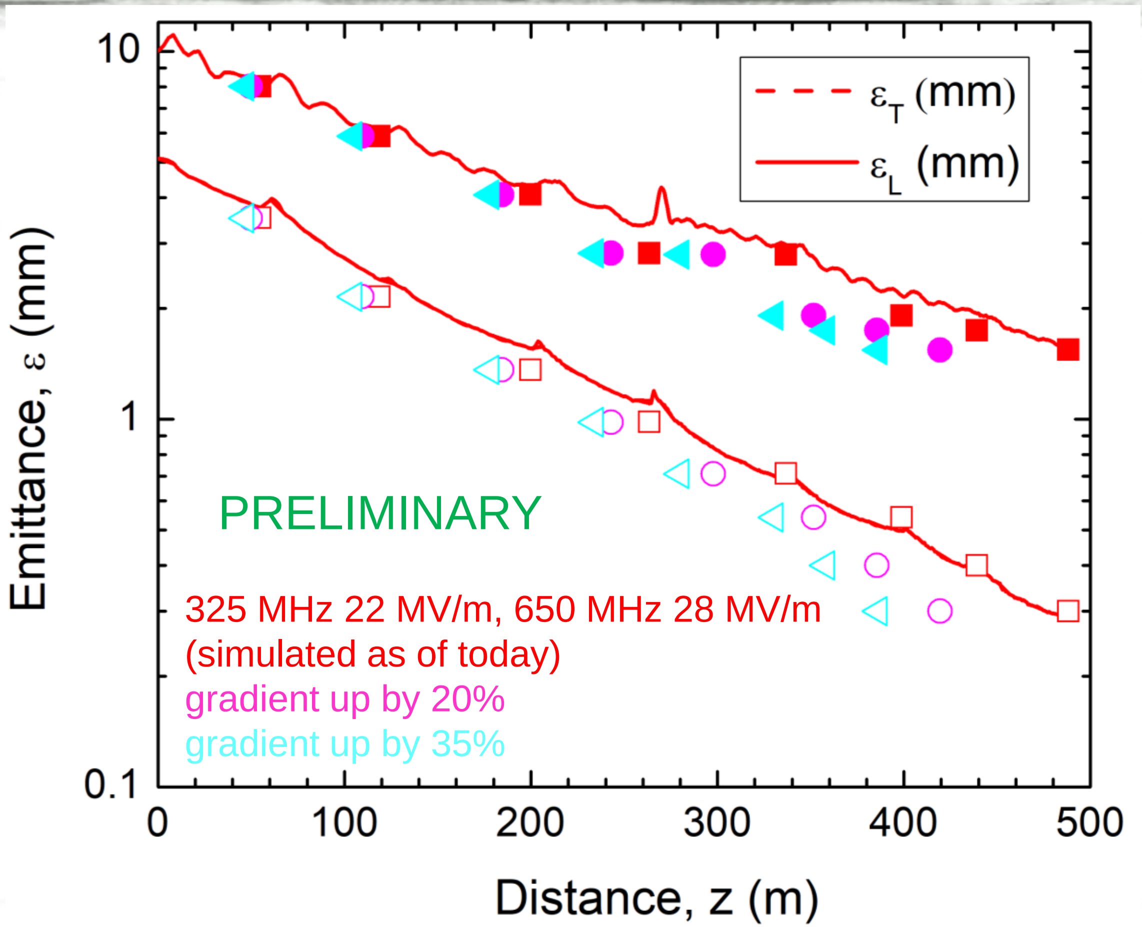
Lattice Design: Variable optimization

- Nelder-Mead algorithm: Objective is to maximize luminosity.
- Promising results for first stage: 25% shorter channel!
- What we need to further study:
  - Multivariable optimization algorithms to maximize performance





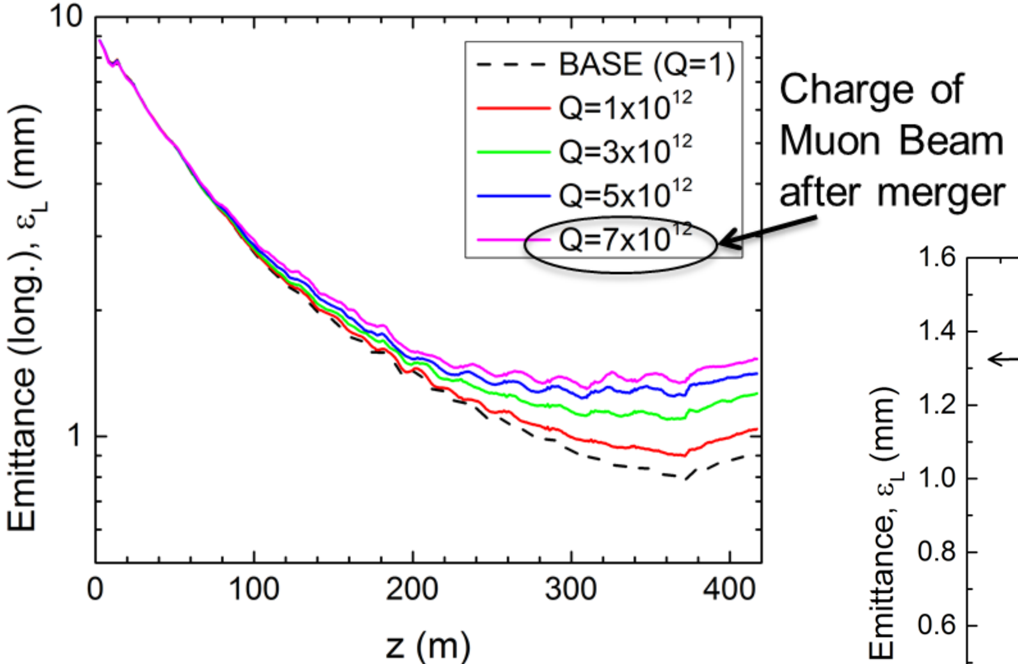
Lattice Design: Higher rf gradients

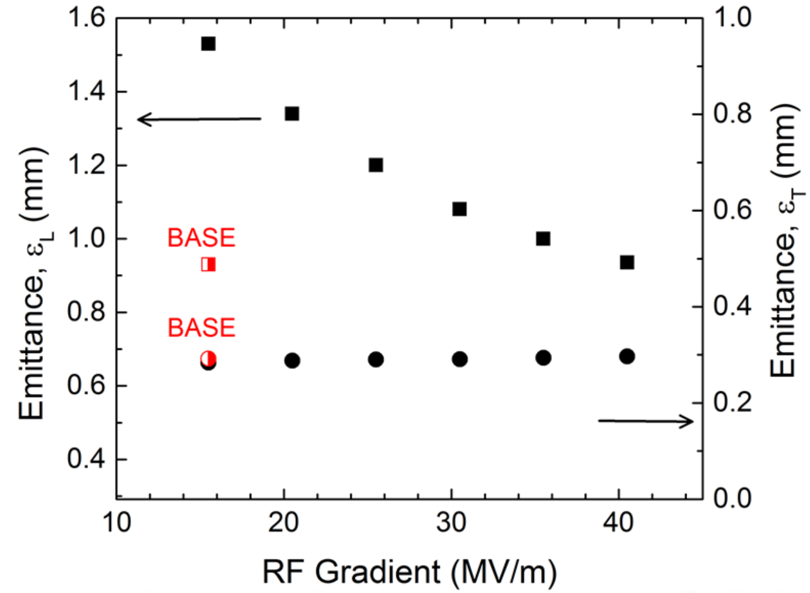


- Increasing the rf gradient can reduce the length of the cooling channel

Bonus: Space charge compensation

- Simulations have shown that space-charge effects can be compensated by increasing rf gradient

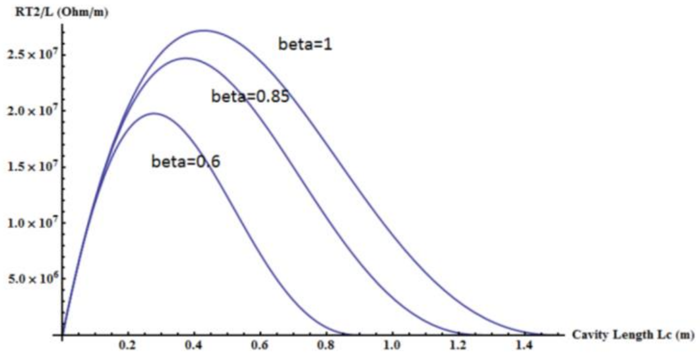


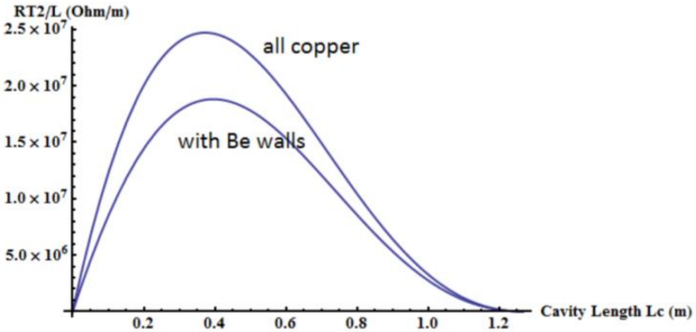


RF: Length for Cu/Be cavities

f_0=325 MHz, R_c=0.353 m			
β	0.6	0.85	1.0
L_c (m)	0.180	0.245	0.282
RT^2/L_c ($M\Omega/m$)	36.8 / 18.6	48.2 / 23.9	54.3 / 26.7
Power (MW)	4.56 / 8.71	4.77 / 9.22	4.89 / 9.52
f_0=650 MHz, R_c=0.177 m			
β	0.6	0.85	1.0
L_c (m)	0.090	0.122	0.141
RT^2/L_c ($M\Omega/m$)	52.0 / 26.3	68.1 / 33.8	76.8 / 37.7
Power (MW)	1.61 / 3.08	1.69 / 3.26	1.73 / 3.37

$$P = \frac{(E \cdot L_c)^2}{(RT^2/L_c)_{max} \cdot L_c}.$$

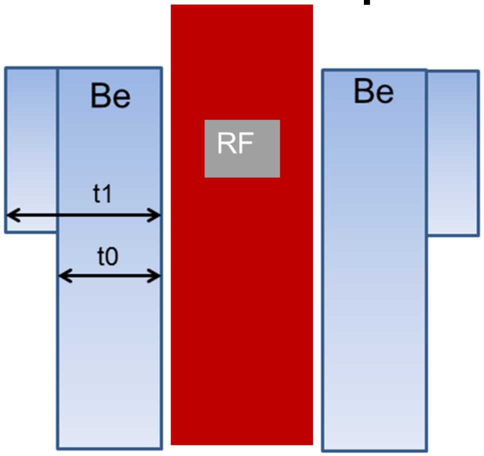




- Performance sensitive to rf length
- The optimum length for a Be made cavity might be different
- This should be taken into account in new designs

RF windows: Realistic model

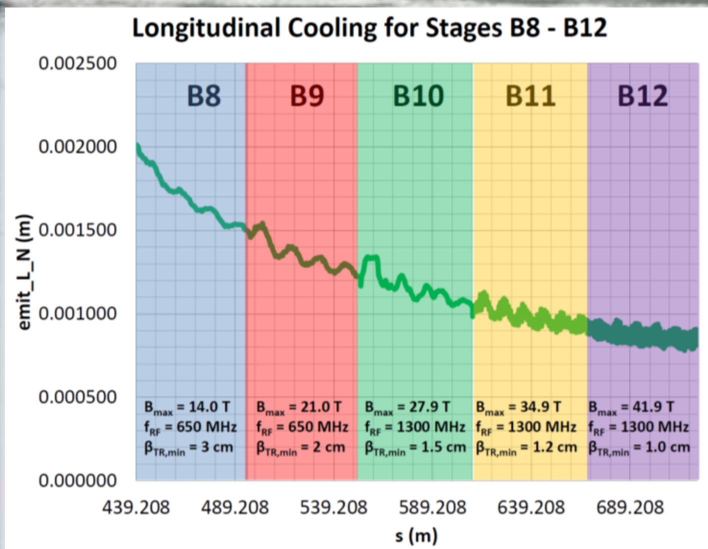
- Be-windows are used in muon cooling to reduce surface gradients and improve shunt impedances
- They are heated by ohmic losses of rf surface currents. With vacuum rf this heat is removed by radial conduction in Be
- With inadequate cooling the central temperature can induce serious stresses and window bowing. This sets minimum window thicknesses requirements.

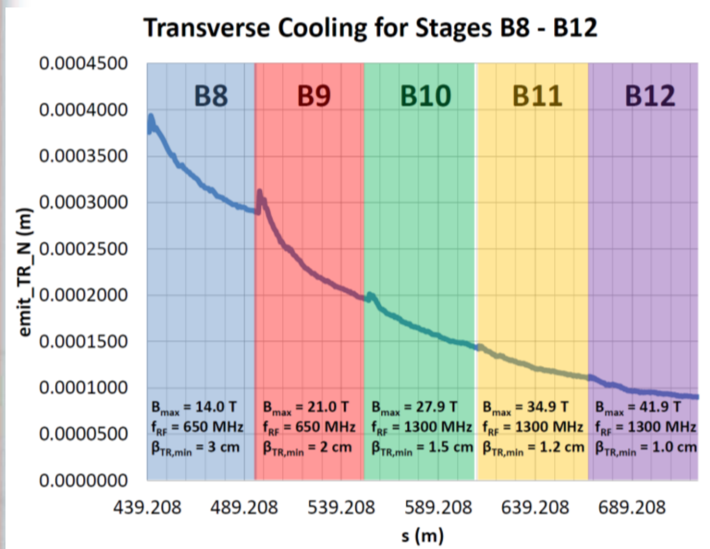


Stage	f (MHz)	rWin (cm)	rStep (cm)	t0 (mm)	t1 (mm)
1	325	30	16	0.3	1.4
2	325	25	15	0.2	0.8
3	650	19	10	0.2	0.6
4	650	13.2	11.4	0.125	0.38

Parameter	Baseline	With Be
Cool rate (trans.)	11.8	10.7
Cool rate (long.)	20.7	18.0
Transmission	49.1%	46.0%

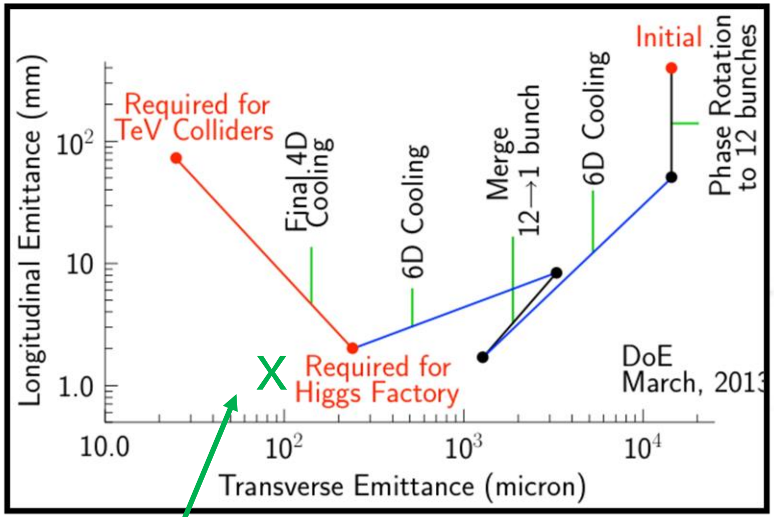
Magnets: Rectilinear with HTS magnets





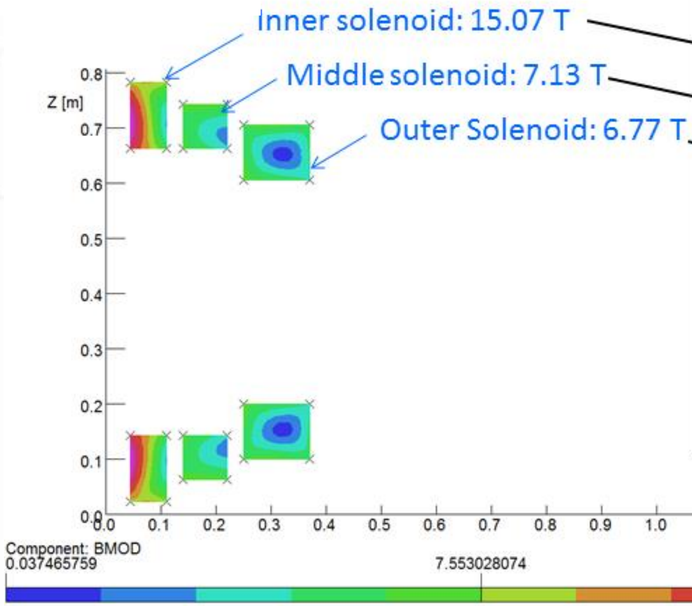
- If HTS magnet technology is considered, rectilinear channel can reduce the 6D emittance even more

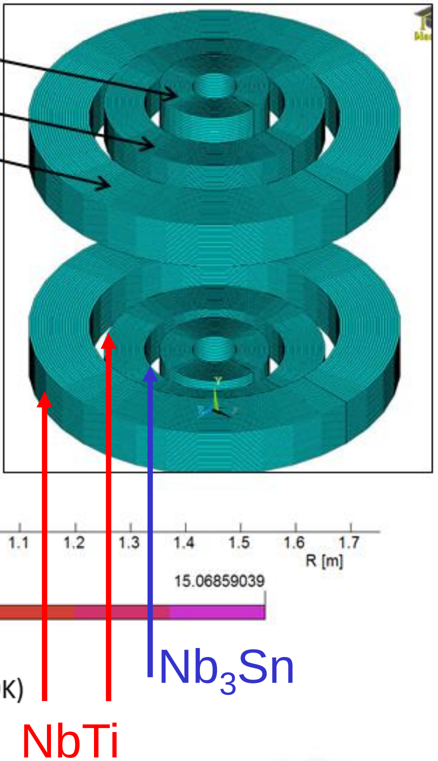
Don Summers,
University of Mississippi

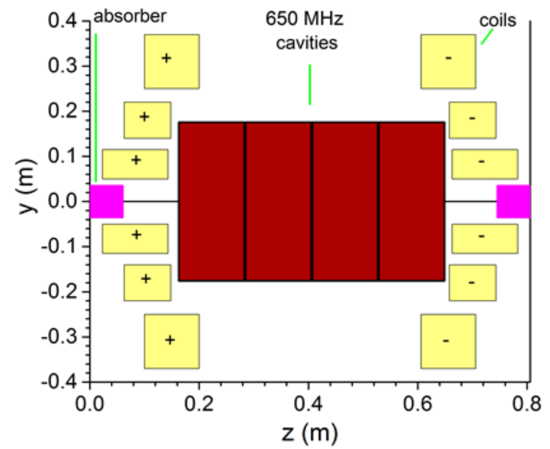


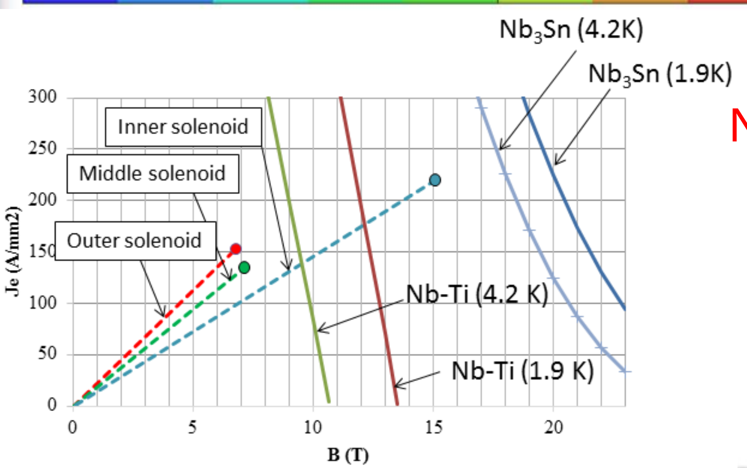
Emittances achieved

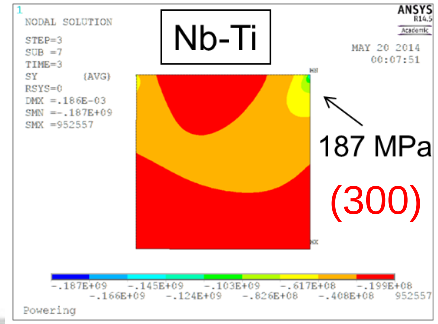
Magnet technology

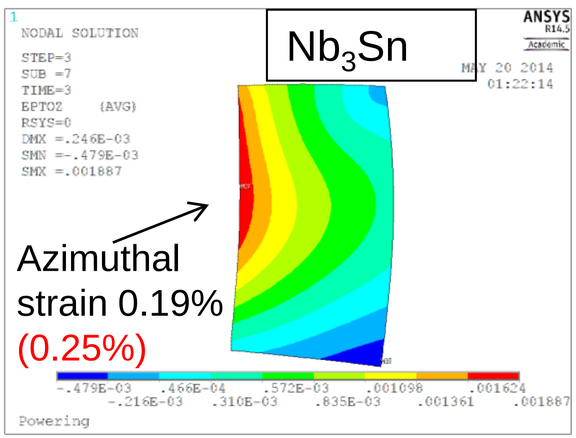






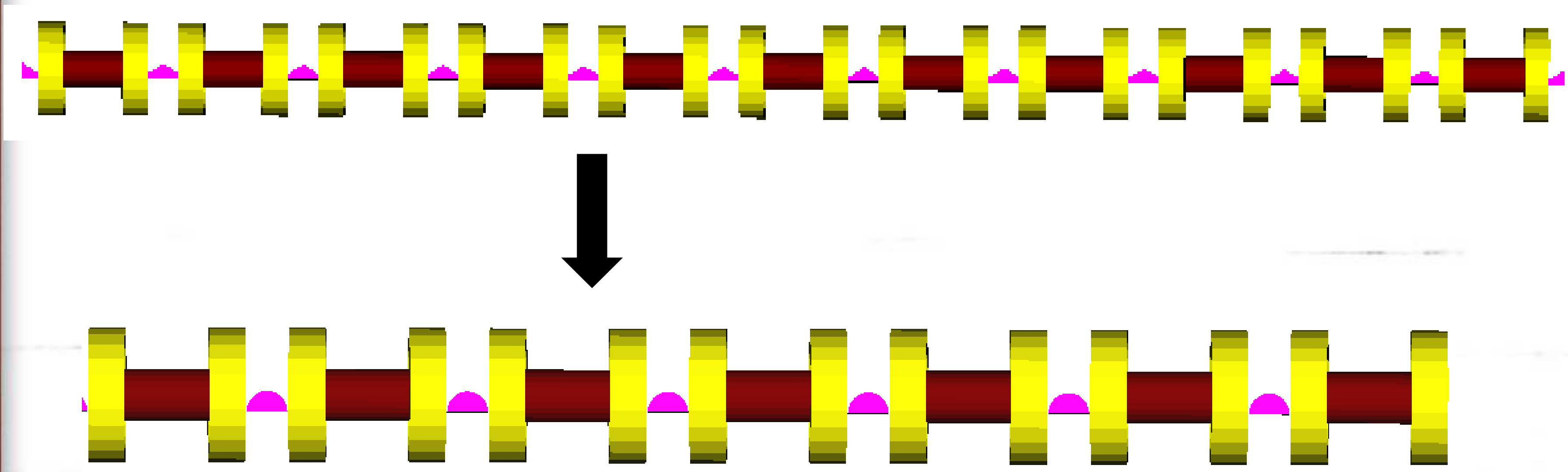






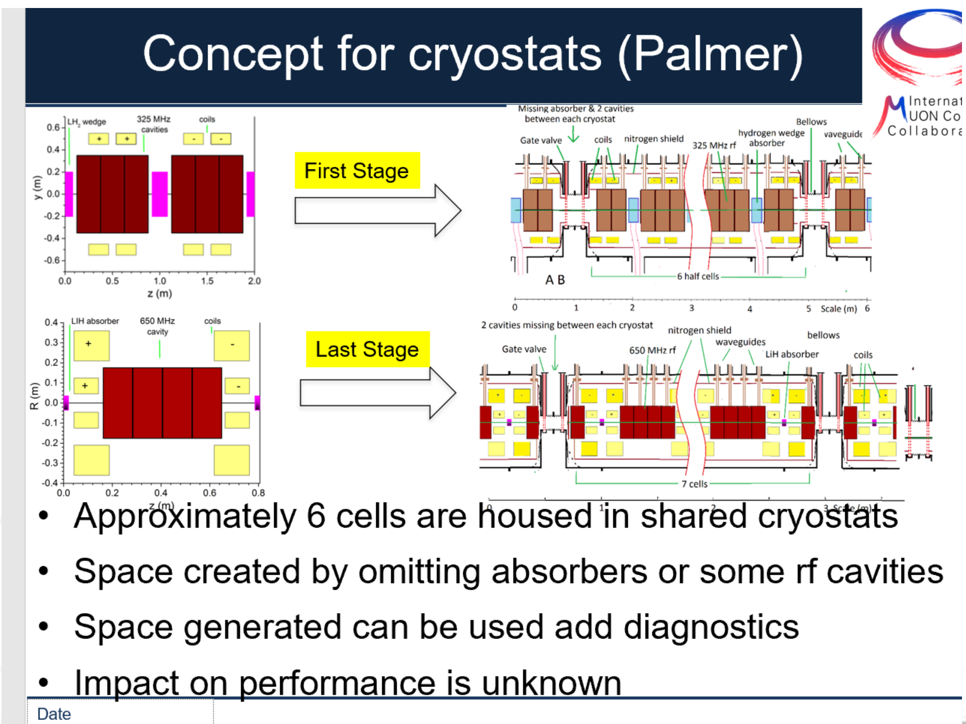
Absorbers

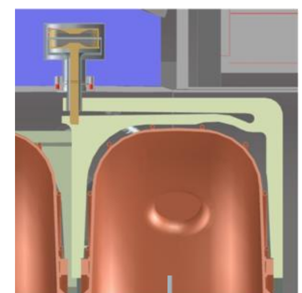
- What we need to further study:
  - What is the tolerance of absorbers in MC intensity regime?
  - What are realistic shapes for a LH absorber? For LH it is easier to construct a cylindrical absorber
  - This slightly degrades cooling and a quantification is needed

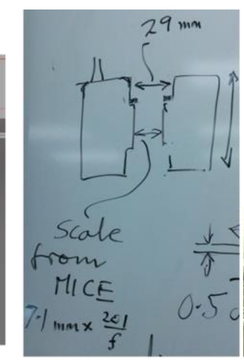


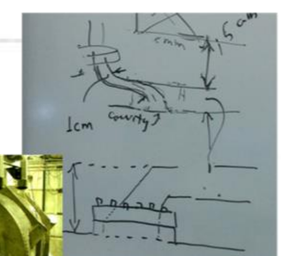
Instrumentation and spacing

- Required instrumentation and assembly
  - 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









20

Instrumentation and spacing

- Required instrumentation and assembly
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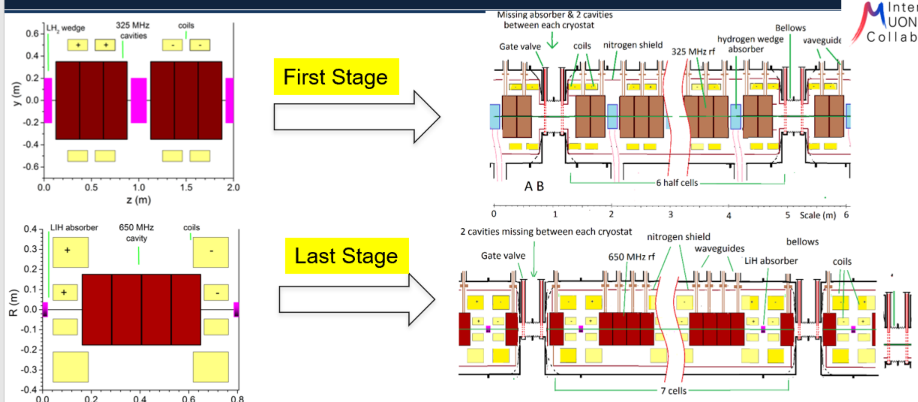
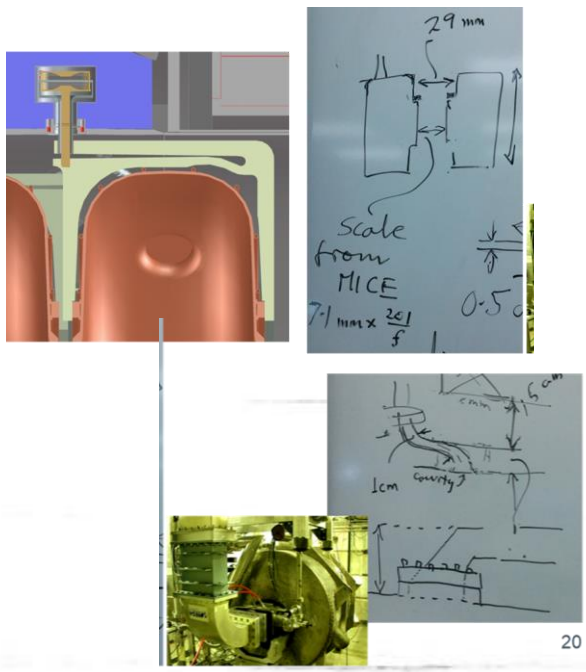
Concept for cryostats (Palmer)



- Approximately 6 cells are housed in shared cryostats
- Space created by omitting absorbers or some rf cavities
- Space generated can be used add diagnostics
- Impact on performance is unknown

Date



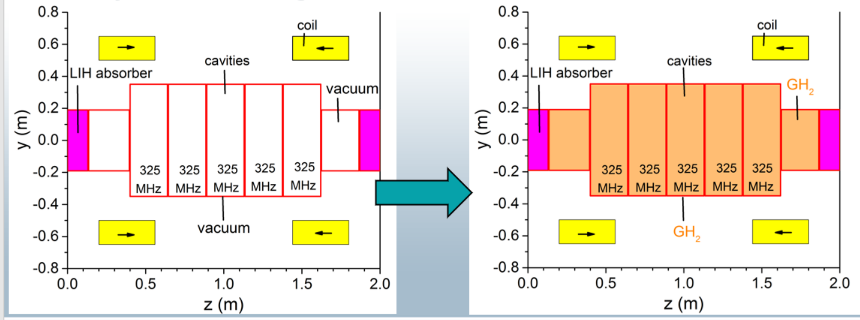
20

Alternative scheme

- In case RF in B-fields becomes an issue…

Hybrid solution

- The gradient of a gas filled cavity showed no magnetic field dependence in a solenoidal field up to 3 T.
- Key Idea: Utilize gas filled cavities in a rectilinear channel. Majority of cooling in LiH and use gas only to protect rf cavity from the high-field.



22

Lattice performance

Essentially, the same performance as an equivalent channel with vacuum cavities

BUT there remains considerable work to do before a hybrid channel can be considered a validated cooling channel option.