Tapered 6D ionization cooling channels for Muon Accelerators

Diktys Stratakis

Brookhaven National Laboratory

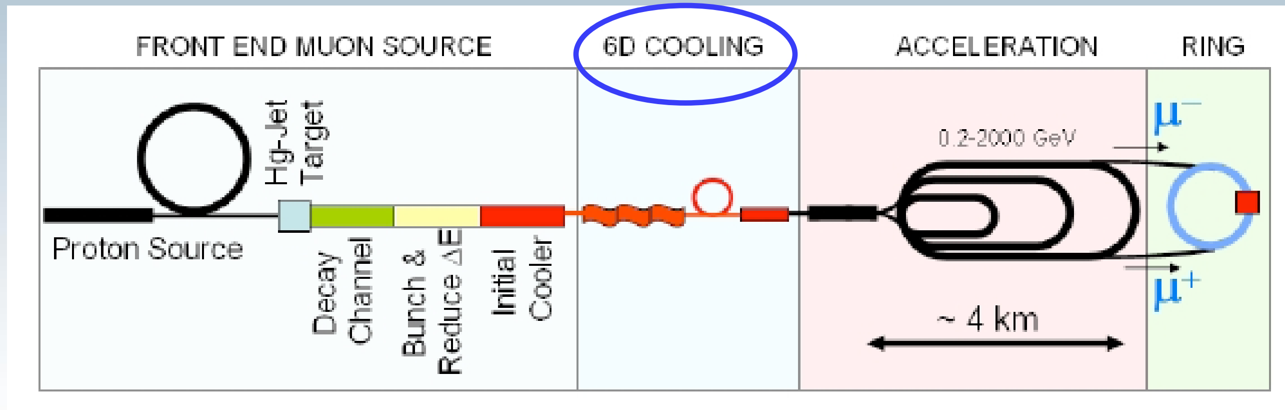
NUFACT Workshop, Beijing, China

August 21, 2013

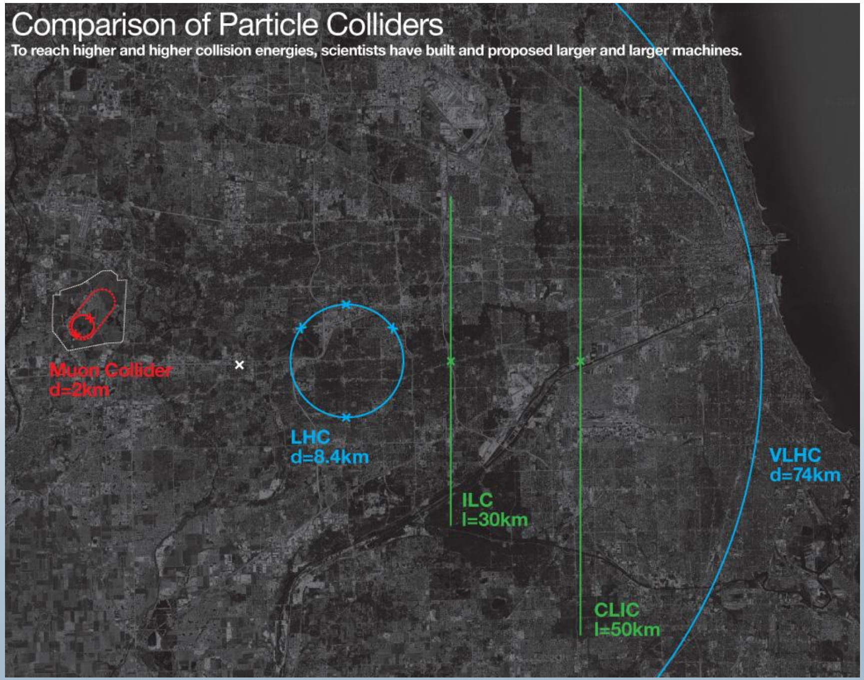
Outline

- Introduction to ionization cooling
- Describe a promising 6D cooling lattice
  - A tapered helical lattice (known as “Guggenheim”)
- Evolution to a straight version of a Guggenheim
  - Transform the Guggenheim to a straight lattice. Yes, it works!
- Review key lattice parameters
  - Identify the required rf freq., voltage, B-field, absorber length
  - Discuss magnet & engineering feasibility
- Evaluate Performance
  - Carry out a full “front-to-end” simulation

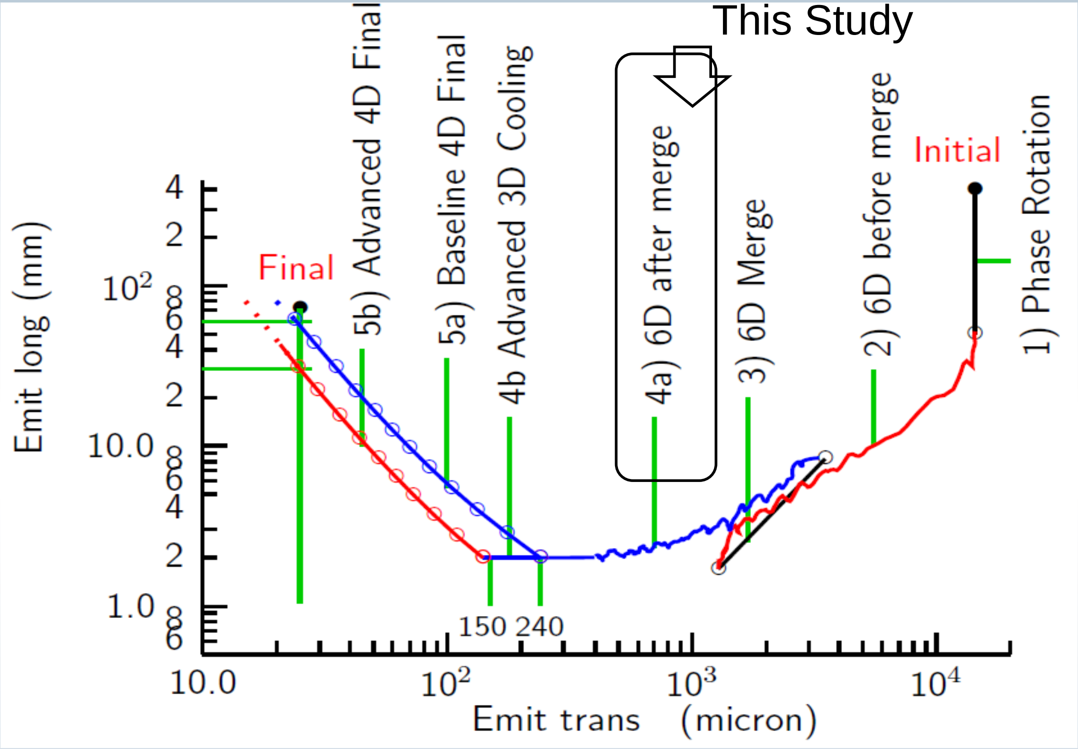
Muon Collider (MC)



- A MC offers high collision energy at a compact size
- 6D Cooling is a essential step for achieving high luminosity on the Collider.

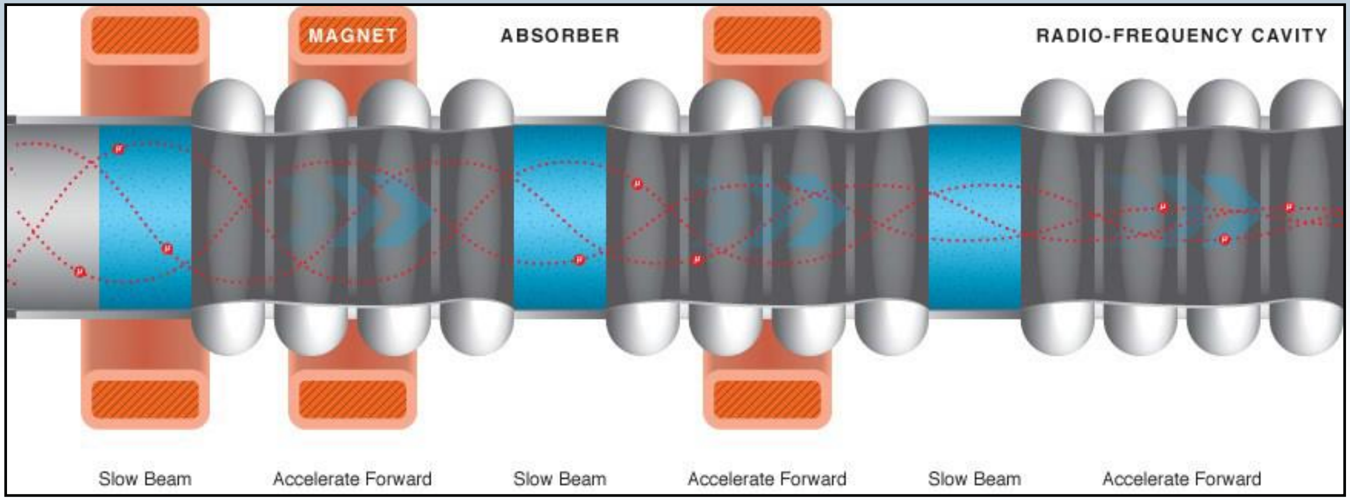


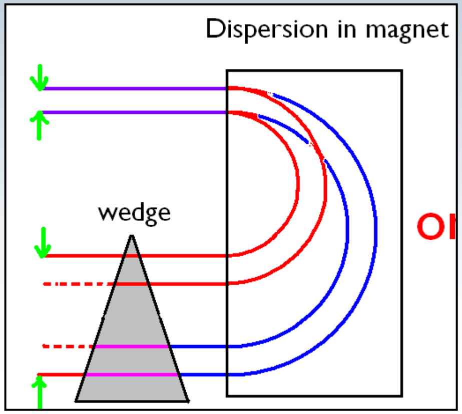
Cooling requirement



- Longitudinal emittance must go down by a factor of 10
- Transverse emittance must go down by a factor 1000
- Must happen before muons decay (at rest 2 μs)

Ionization cooling

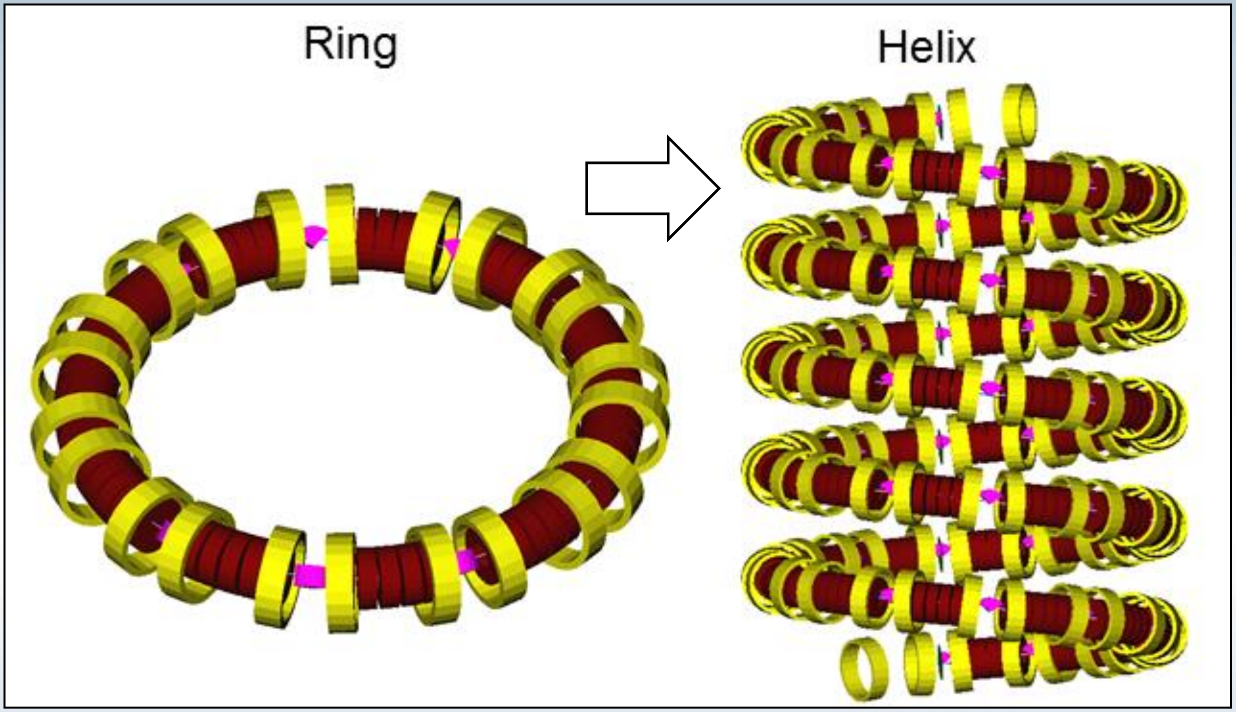


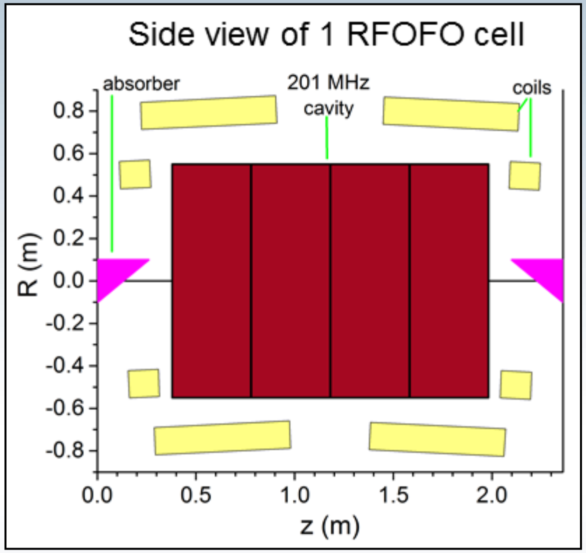


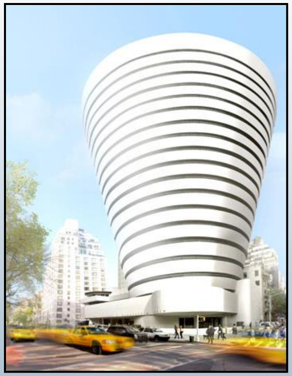
- Ionization cooling is the only feasible option
- Transverse cooling by passing beam via material
- Longitudinal cooling through emittance exchange
- Progressive reduction of the 6D emittance

D. Neuffer, Part. Accel. **14**, p. 75 (1983)

History of 6D cooling lattices



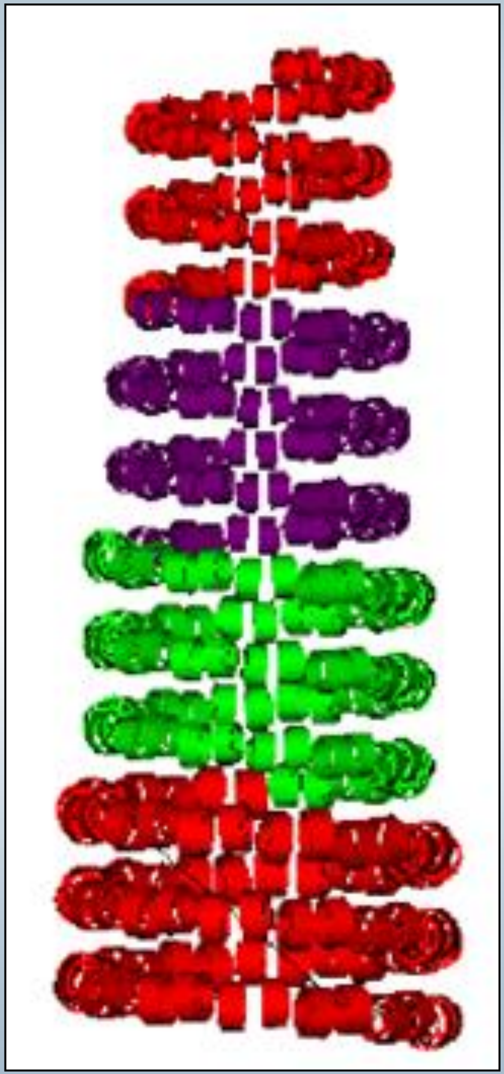




- Tilt coils to generate dispersion
- Emittance exchange on a wedge absorber
- Ring evolved to a helix to avoid injection/extraction issues

Palmer et al., PRST-AB **8**, 021021 (2005); Snopok & Hanson , IJMPA **24**, 987 (2009)

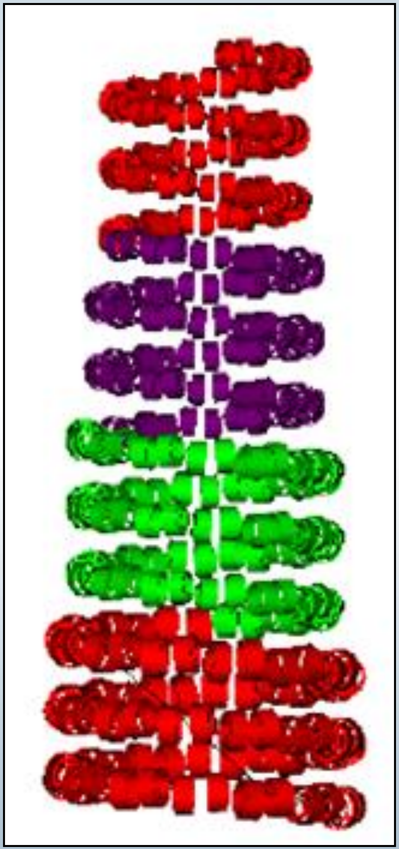
Concept of tapering



- Lattice parameters such as rf freq., cell length, focusing strength, absorber length, change with distance
- Keep emittance above equilibrium
- Tapering pros:
  - More dispersion, faster cooling
  - Impressive constant cooling efficiency
  - Shorter than untapered channels
  - Method is not restricted to a Guggenheim
- Applies to helical and straight lattices

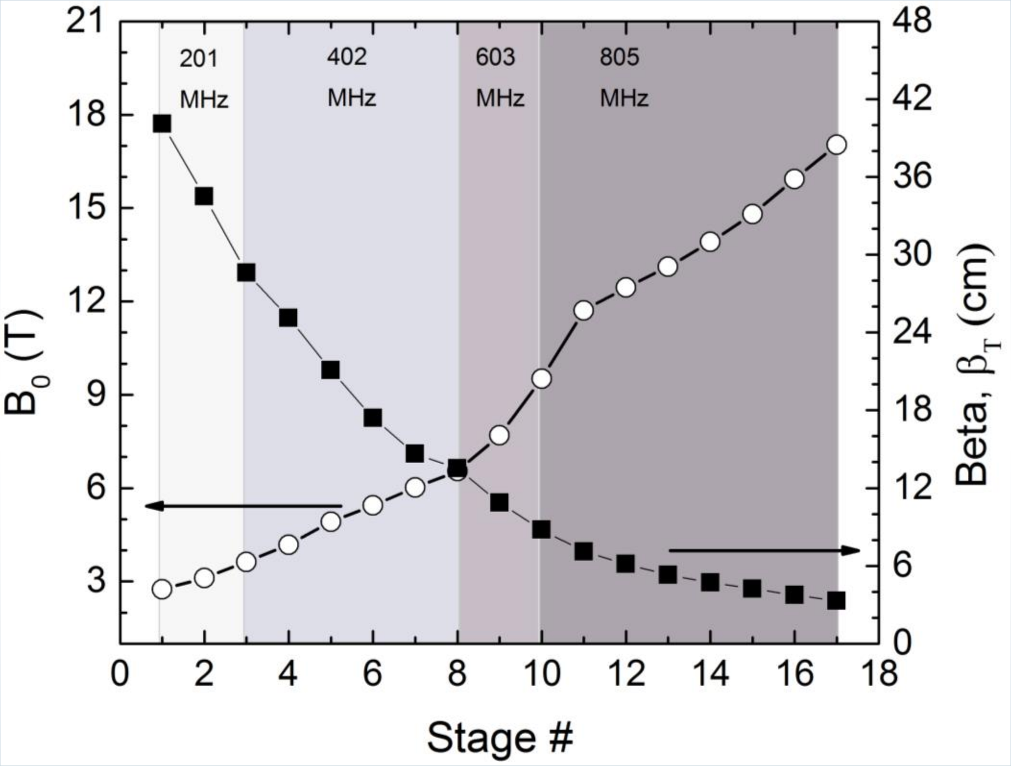
R. C. Fernow *et al*., Proc. of PAC 2001, p. 3861

Lattice parameters



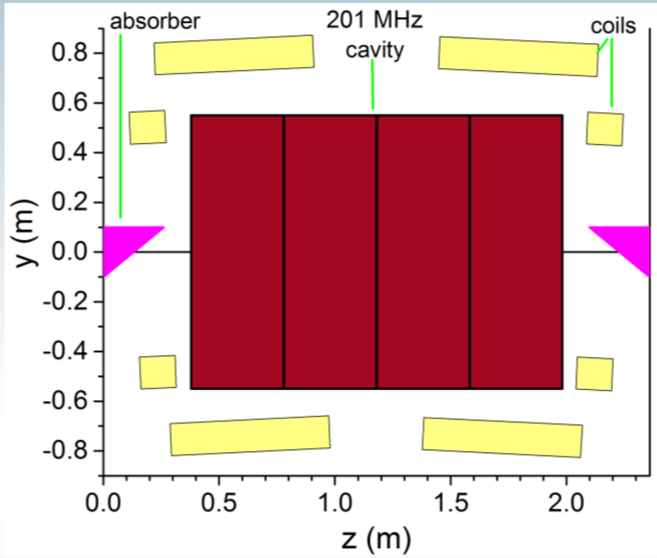
Stage	Cell length [m]	No. of cells	RF freq. [MHz]	RF grad. [MV/m]	RF No.	RF length [cm]	Coil Tilt [deg.]	Wedge angle [deg.]
1	2.75	11	201	16.5	5	37.6	3.25	110
2	2.36	16	201	16.5	4	40.0	2.59	110
3	2.02	16	201	16.5	4	34.3	2.03	110
4	1.73	15	402	16.5	6	19.6	3.90	99
5	1.49	18	402	16.5	5	20.1	2.62	104
6	1.38	26	402	16.5	5	18.64	2.62	111.3
7	1.27	24	402	16.5	6	14.38	1.91	118
8	1.15	19	402	16.5	5	15.65	1.93	120
9	0.995	29	603	19.5	5	13.49	2.46	120
10	0.806	46	603	20.5	5	9.67	2.46	110
11	0.688	42	805	23.6	4	8.59	2.79	120
12	0.688	54	805	23.6	4	8.59	2.95	120
13	0.688	46	805	23.6	4	8.59	3.28	120
14	0.628	43	805	23.6	4	8.59	2.87	120
15	0.608	39	805	23.6	4	8.59	2.89	120
16	0.588	28	805	23.6	4	8.59	2.97	120
17	0.588	20	805	23.4	4	8.59	2.81	116

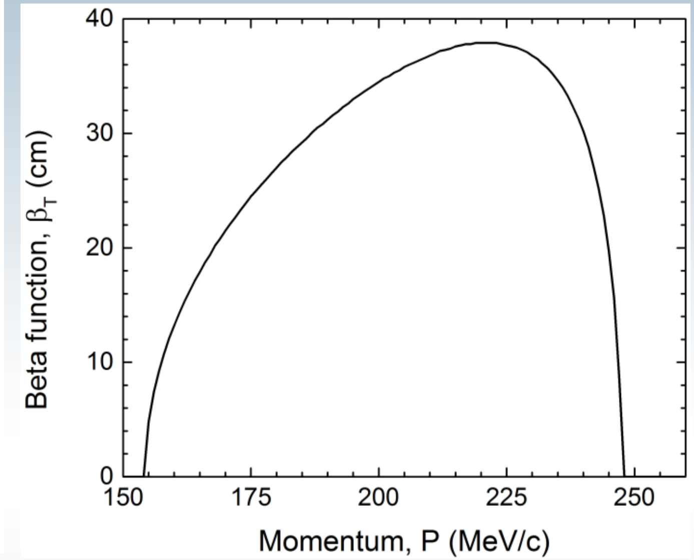
B-Field & beta function requirements

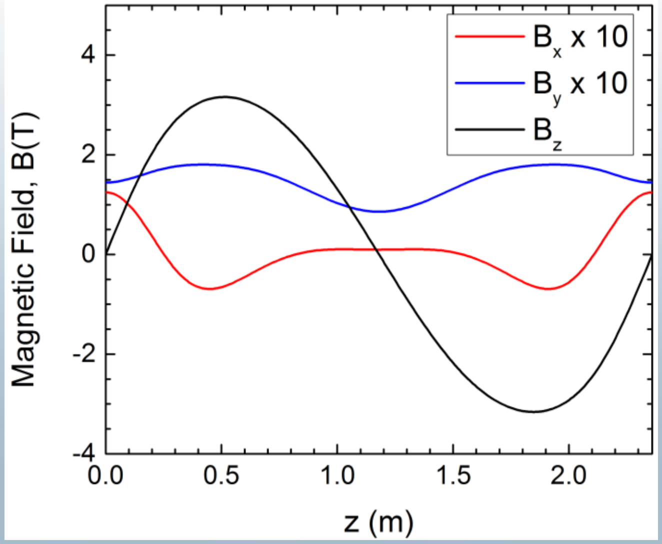


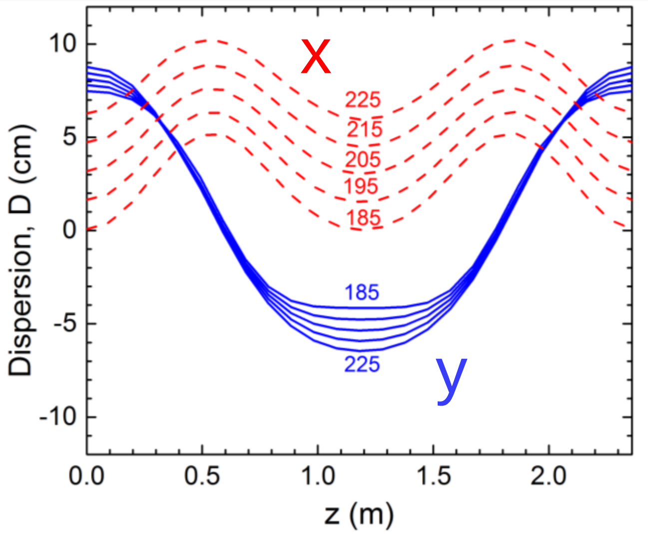
- Early stage: β=40 cm, Late stage: β=3.3 cm
- Highest B is ~17 T, highest grad.~23 MV/m for 805 MHz

Example of a early stage (Stg. 2)

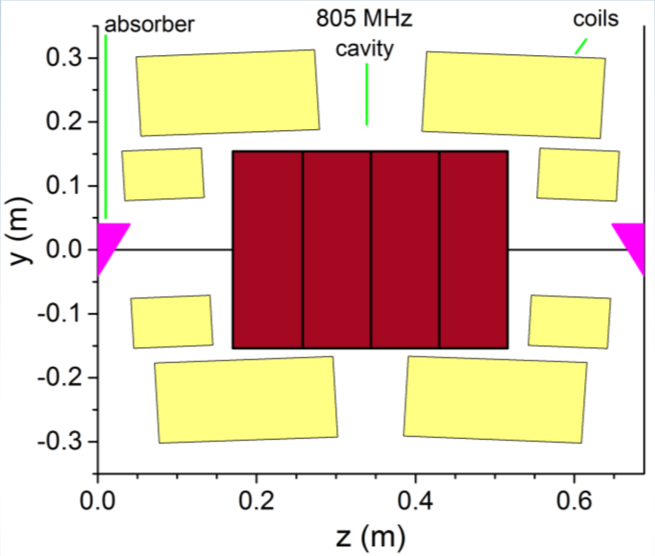


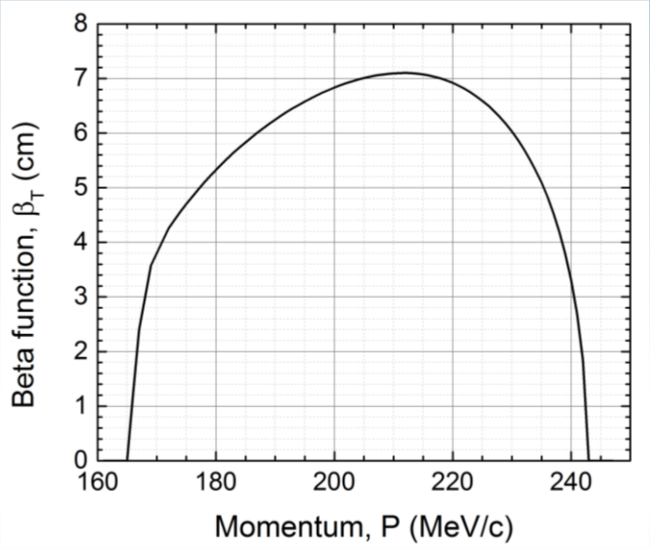


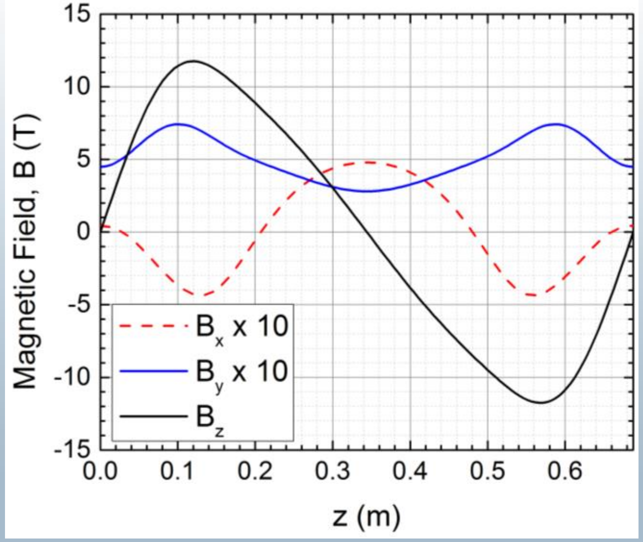


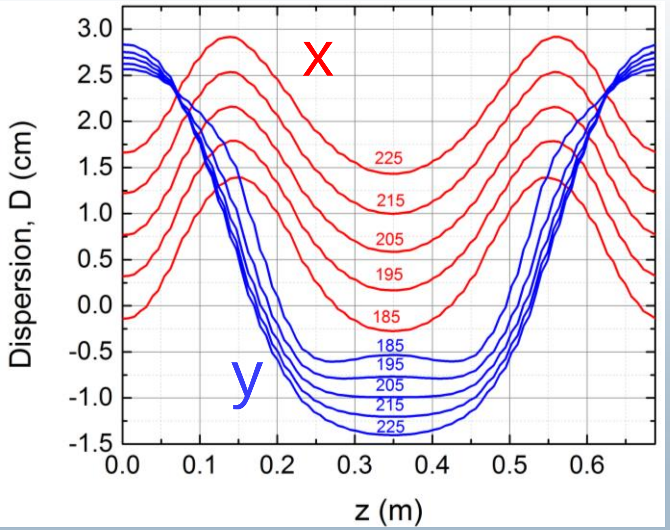


Example of a late stage (Stg. 11)





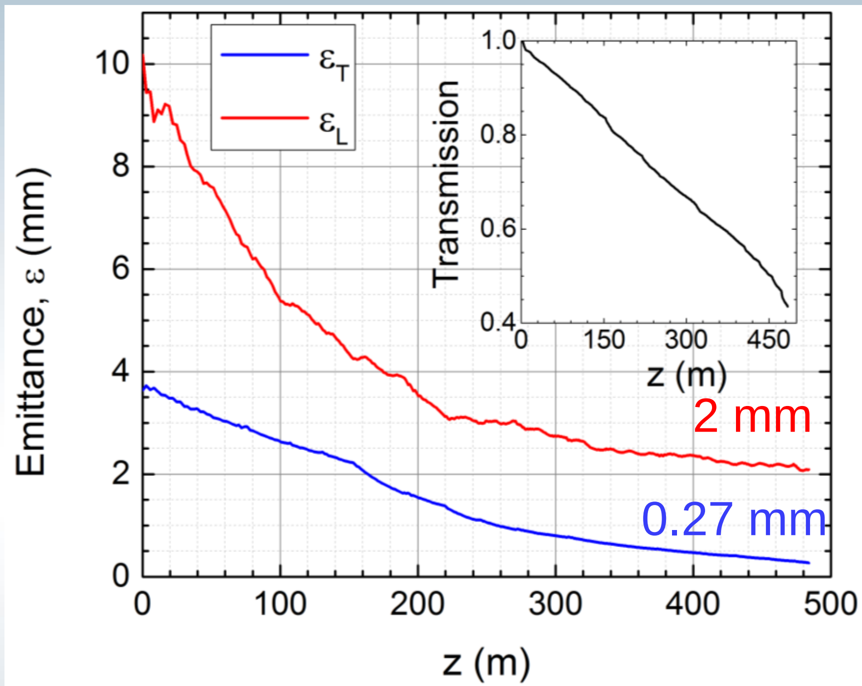


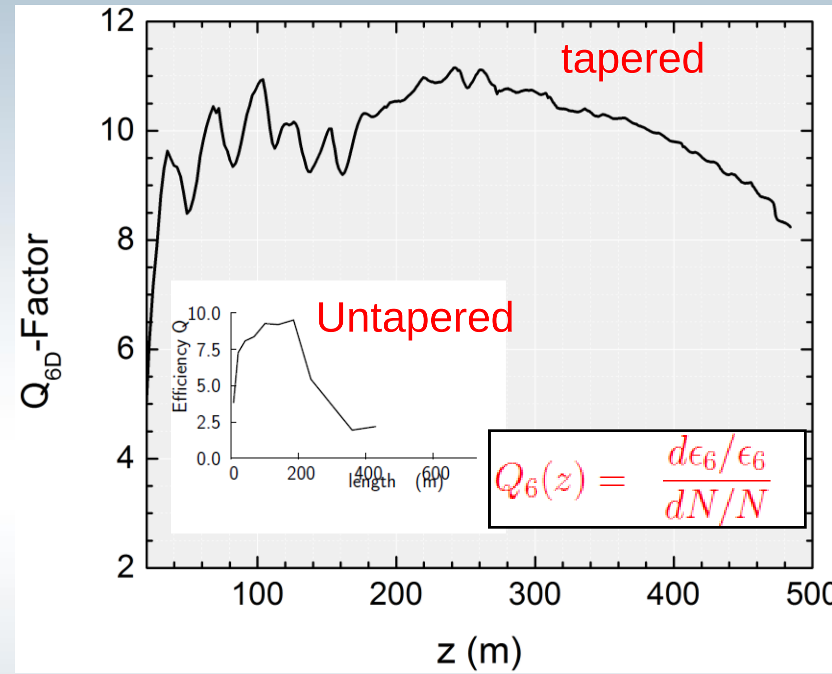


Particle tracking

- Lattice simulated with ICOOL v. 3.30
- Start with a real distribution from the post-merger
- Track 100,000 particles
- Liquid Hydrogen wedge absorber for cooling. Absorber windows included.
- Four frequencies: 201, 402, 603, 805 MHz. RF windows included.

Cooling efficiency



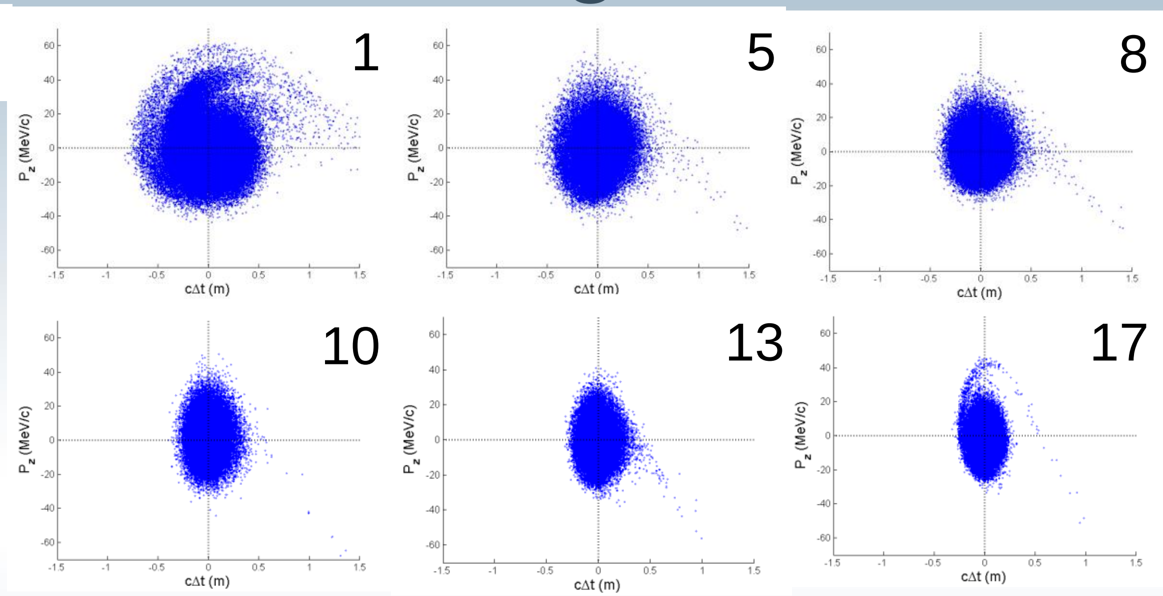


- Cools to MC baseline parameters.
- Q is flat all the way (importance of tapering)
- Transmission ~45% with decays, windows, stochastics.

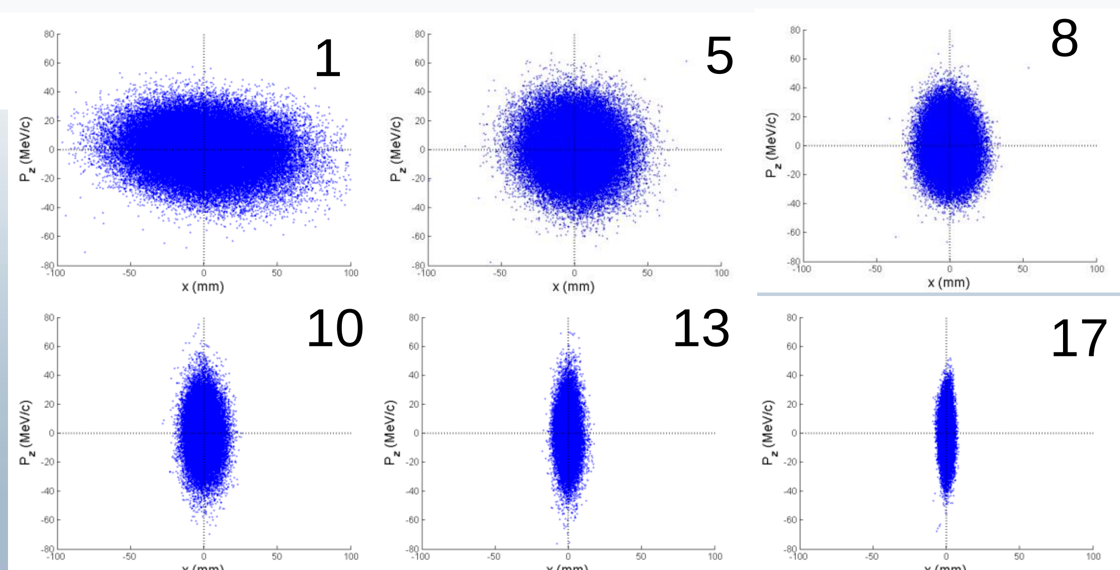
D. Stratakis, R. C. Fernow and R. B. Palmer, Proc. of IPAC 2013, p. 1549

Cooling Performance

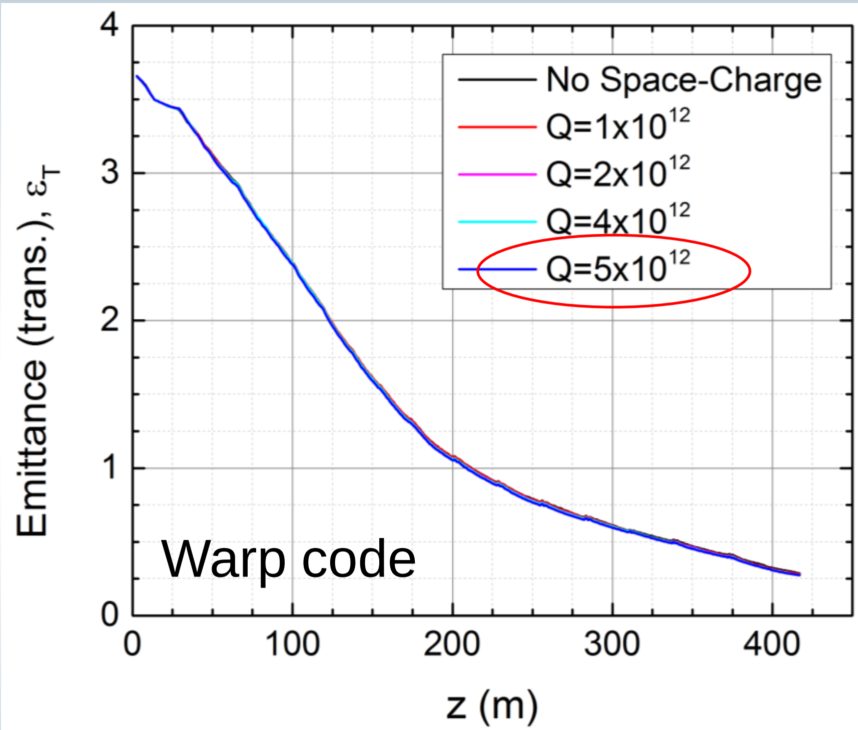
$c\Delta t$-p_z

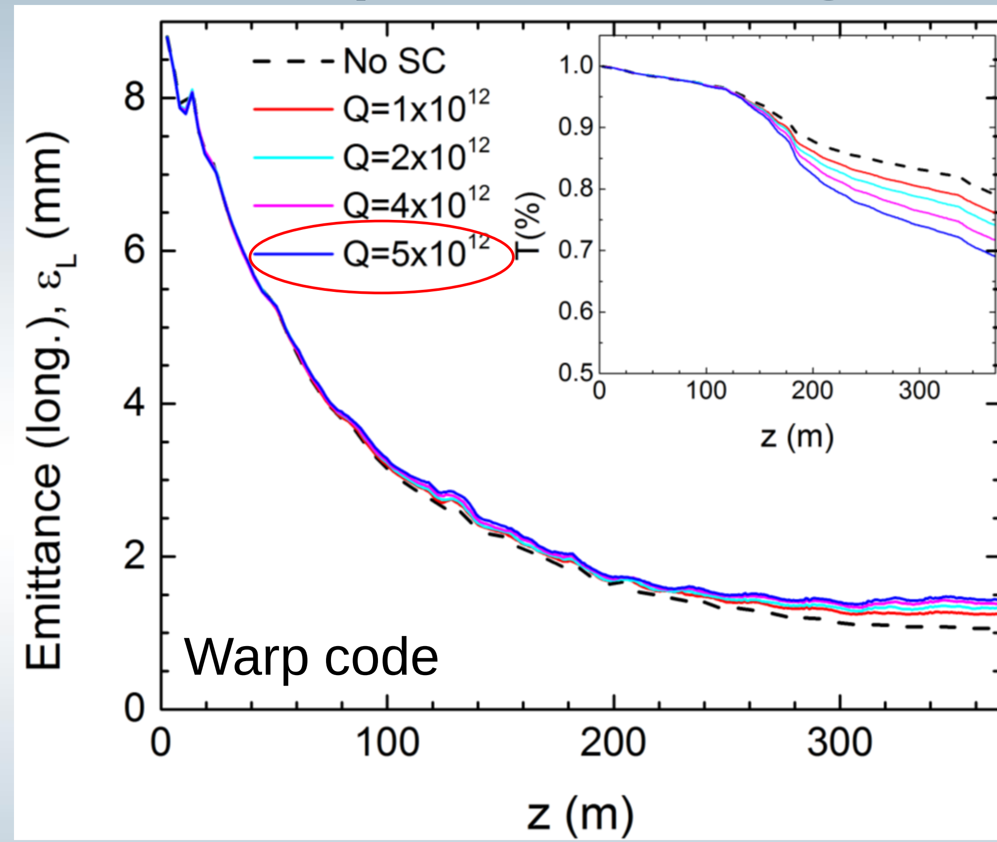


x-p_x



Cooling limitations from space-charge

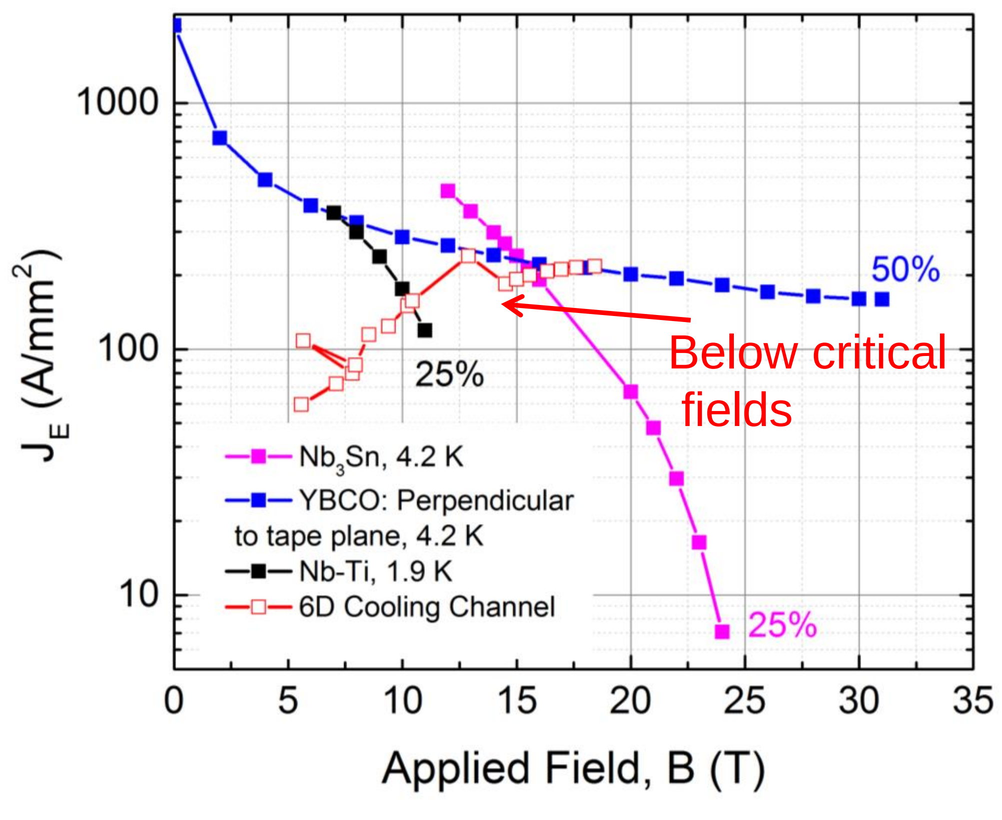




- 20% particle loss after z>200 m due space-charge
- Thus, we avoid cooling longitudinally below 1.5-2.0 mm

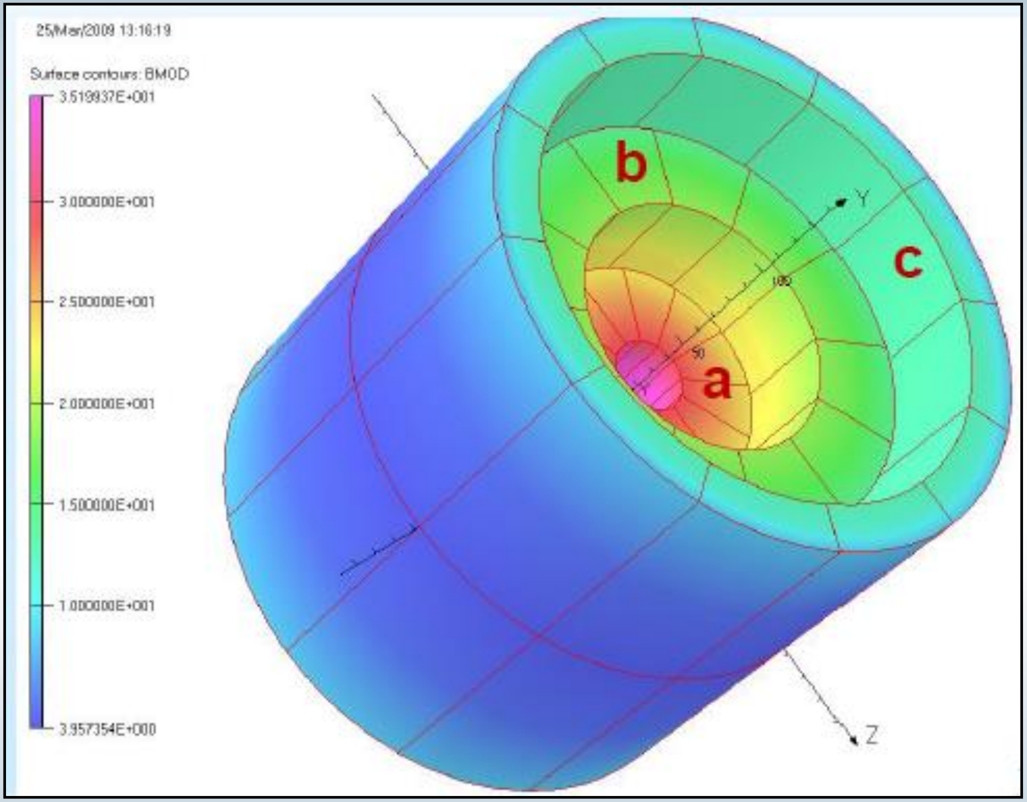
D. Stratakis, R. B. Palmer and D. Grote, Proc. of IPAC 2013, p. 759

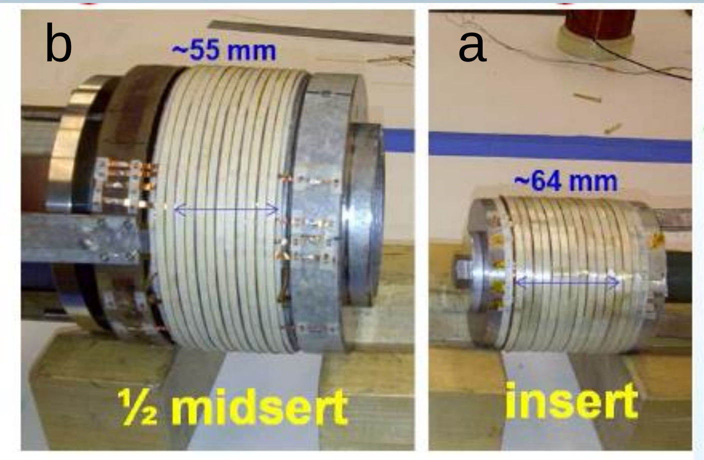
Critical B-Field limits



- Even with modest safety factors our lattice fields are below or close to the critical limits of existing magnet technology
- Results suggest that the last 4 stages require HTS

Recent progress with HTS

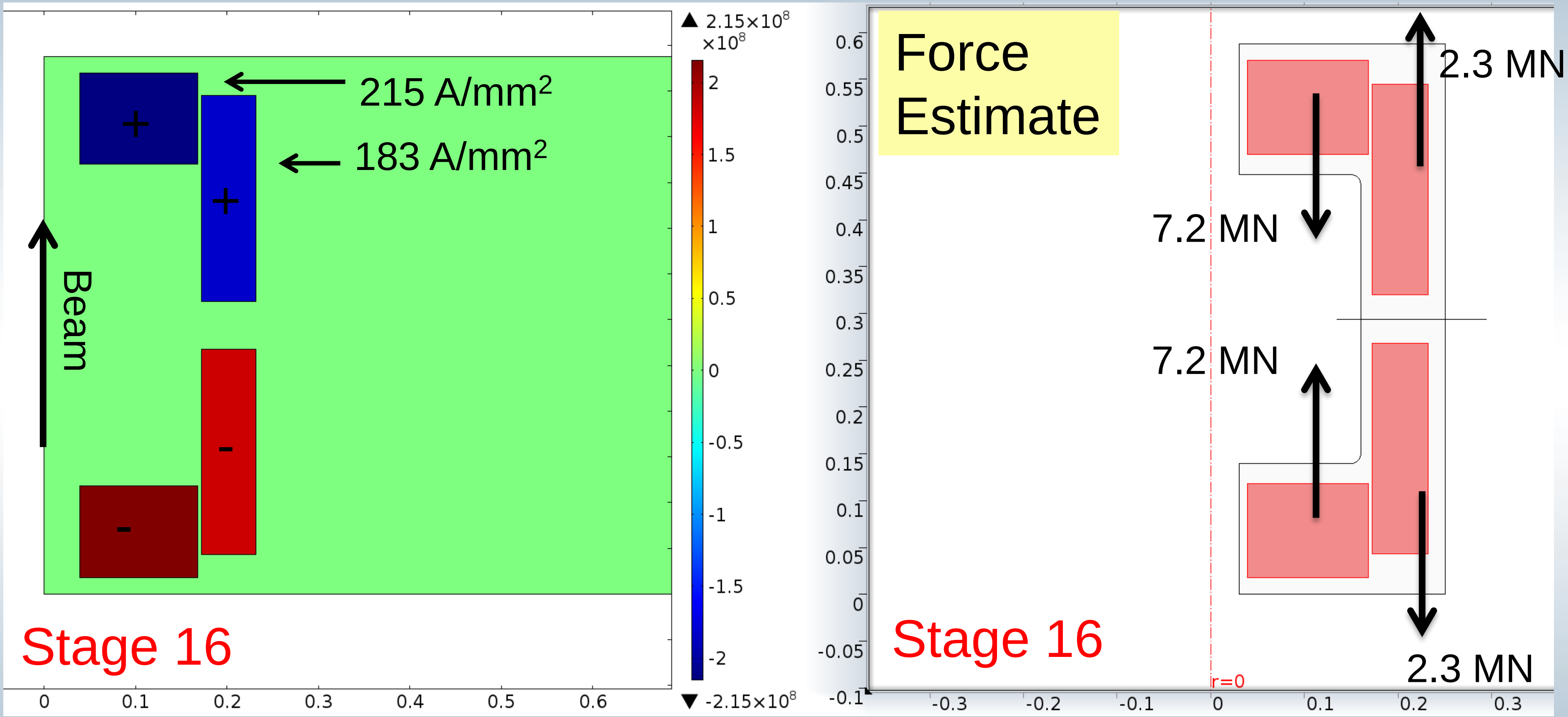




BNL/ PBL Collaboration
(R Gupta et al.)

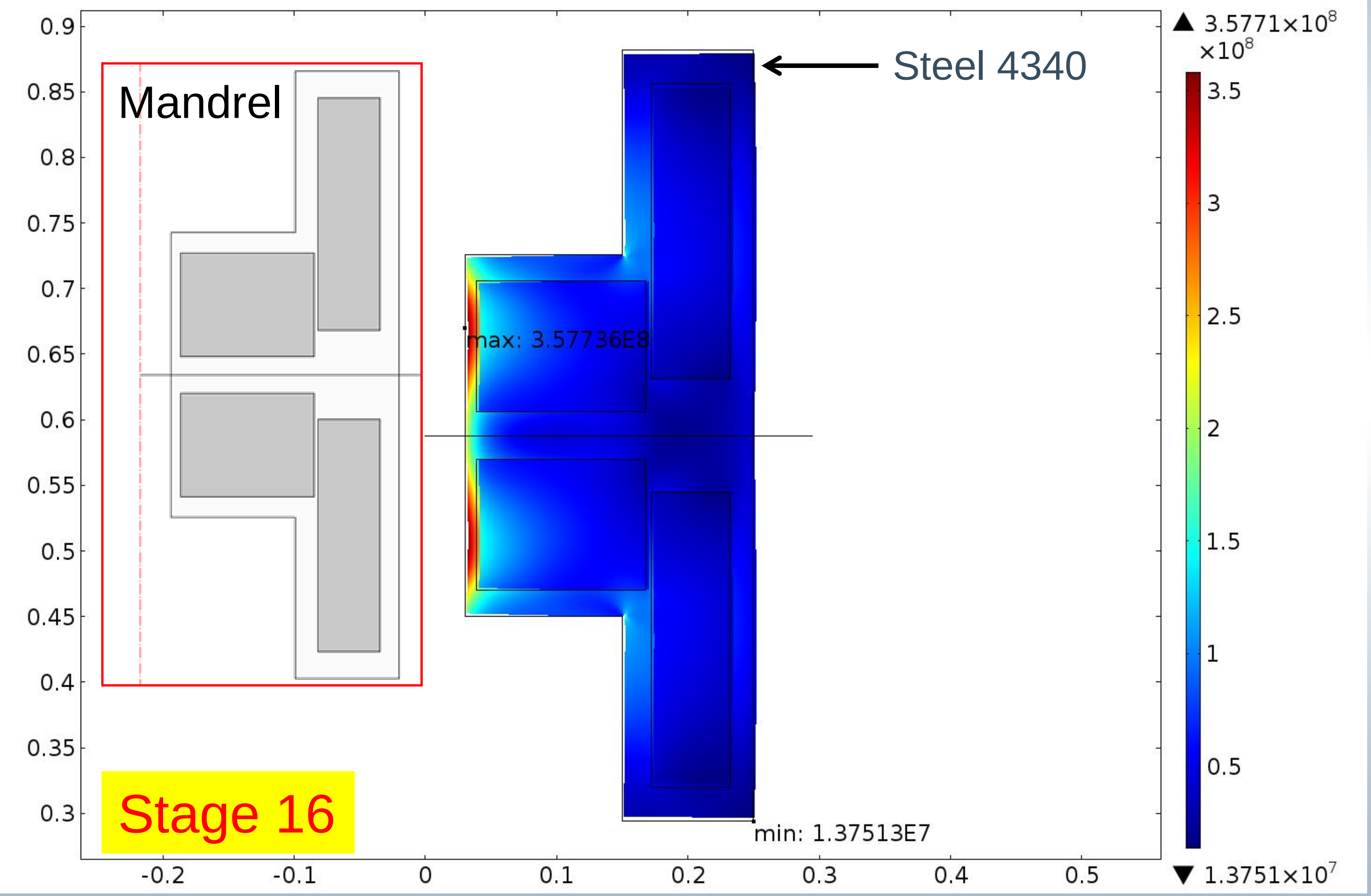
- Tested and build:
  - 25 mm aperture HTS insert generating > 16 T peak field
  - 100 mm aperture HTS midsert generating > 9 T peak field

Engineering studies (H. Witte)



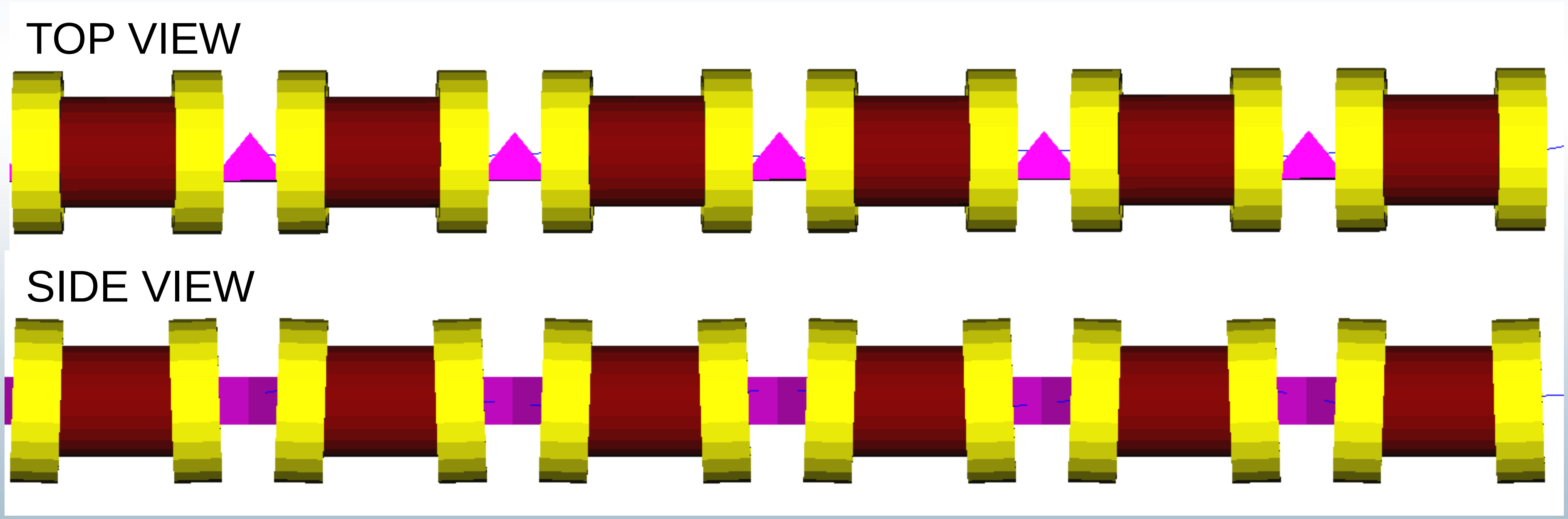
- Preliminary studies with COMSOL

Von-Mises stress (H. Witte)

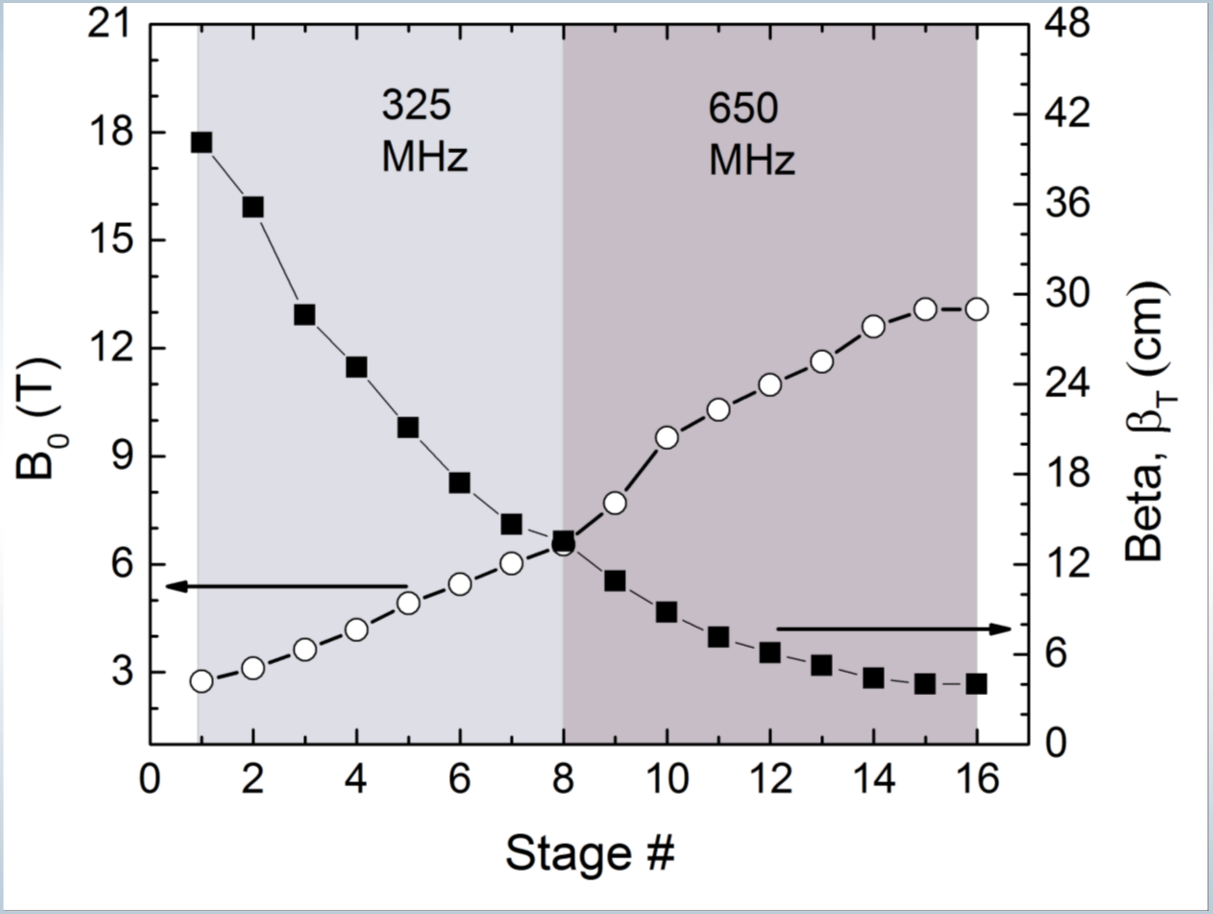


From helical → straight channel

- Good news: Only minor variations of the Guggenheim lattice parameters are necessary

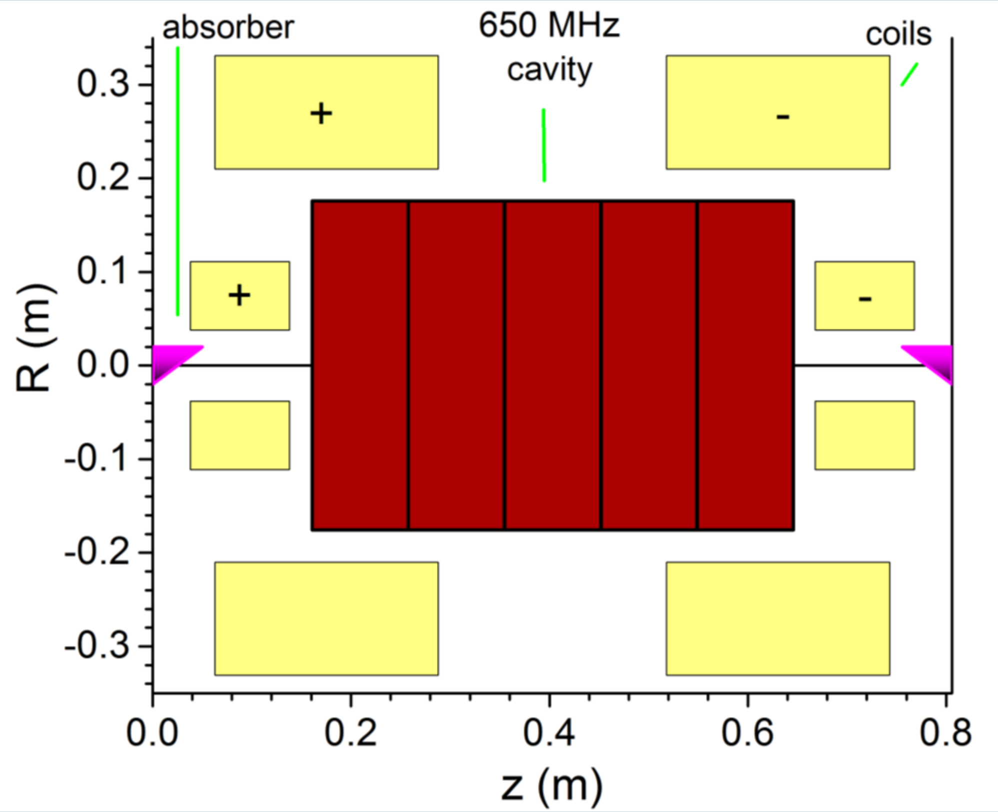


Lattice details



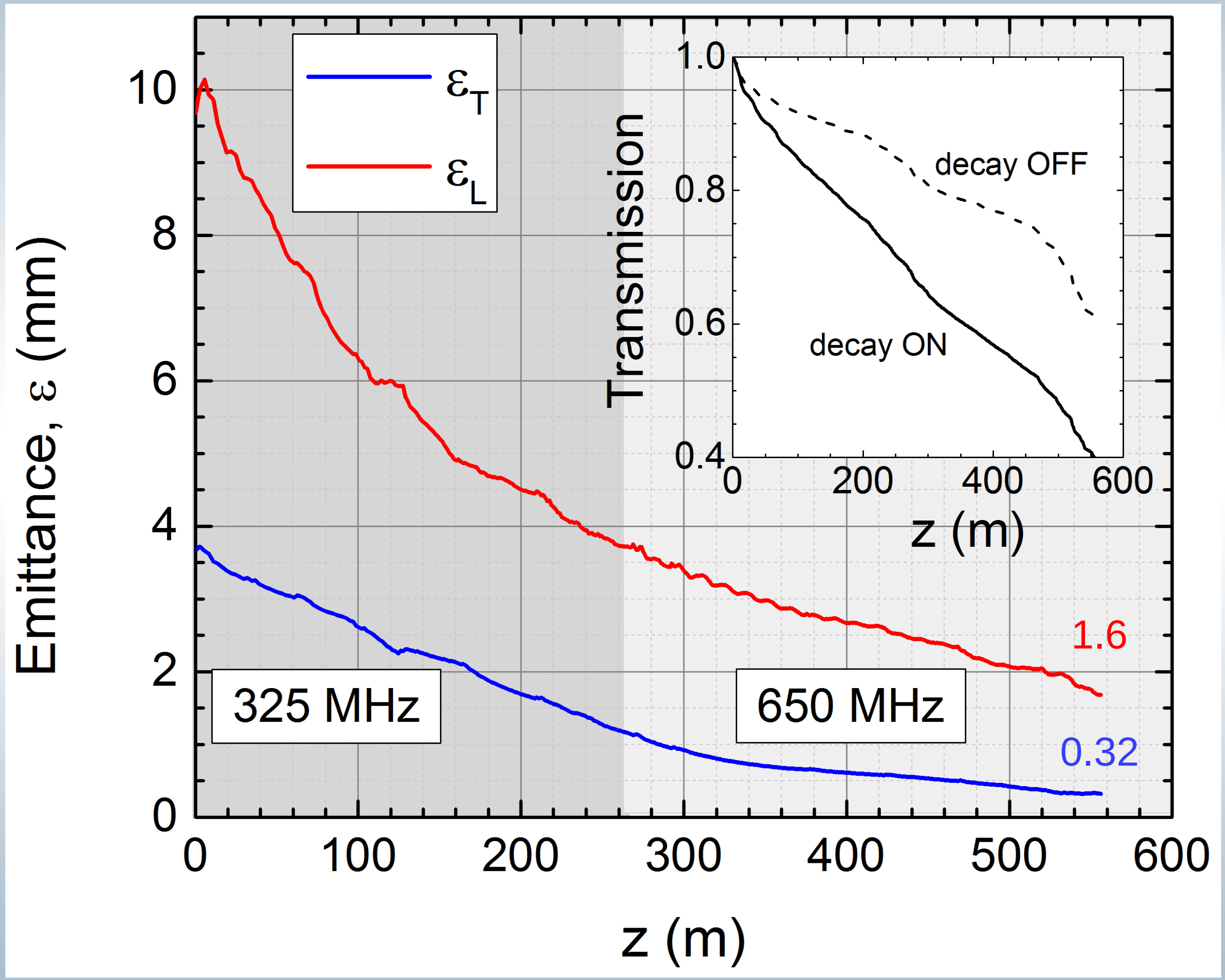
- Replace 201 MHz → 325 MHz. In order to match with Project X initial linac.

Lattice visualization (Last stages)



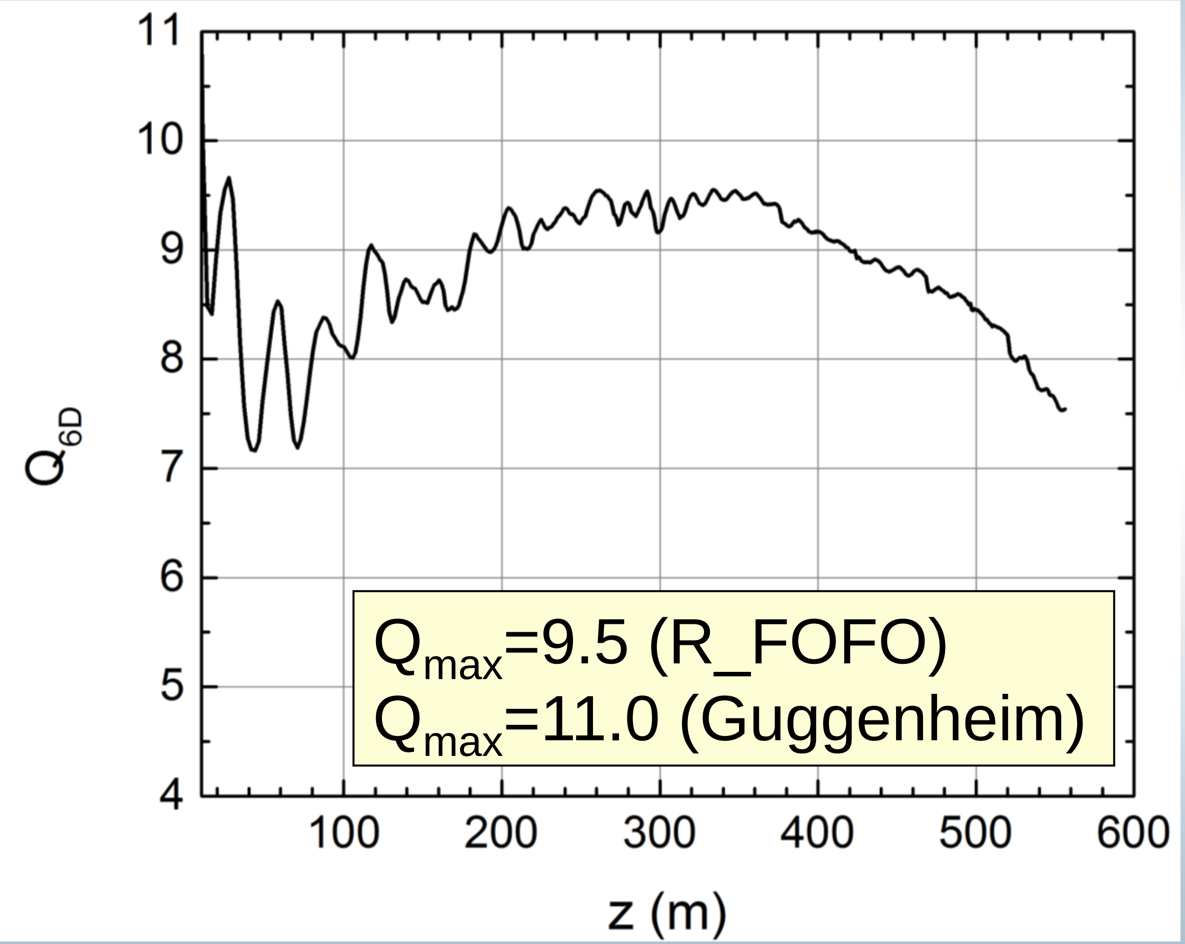
- Last 7 stages have the same configuration
- Coils are tilted by 1.1 deg. (not shown)

Particle tracking



- Performance is comparable to the helical Guggenheim

Quality factor



Summary

- We have presented two alternative cooling schemes for 6D cooling (one helical and one straight).
- With tapering, they offer a notable high performance and both deliver the cooling requirements for a Muon Collider
- While the helical channel delivers the highest performance, the straight lattice offers (hopefully) a simpler engineering design.
- With inclusion of modest safety factors, the fields are within the limits of the critical engineering limits.
- Preliminary study on magnet forces shows encouraging results, although more work is needed.