Tapered 6D rectilinear cooling channel with 325/ 650 MHz RF cavities

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6D Vacuum RF Mini-workshop

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6D Cooling paper to appear in PRST-AB

- Selected as an Editors' Suggestion section for 2013

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Tapered channel for six-dimensional muon cooling towards micron-scale emittances

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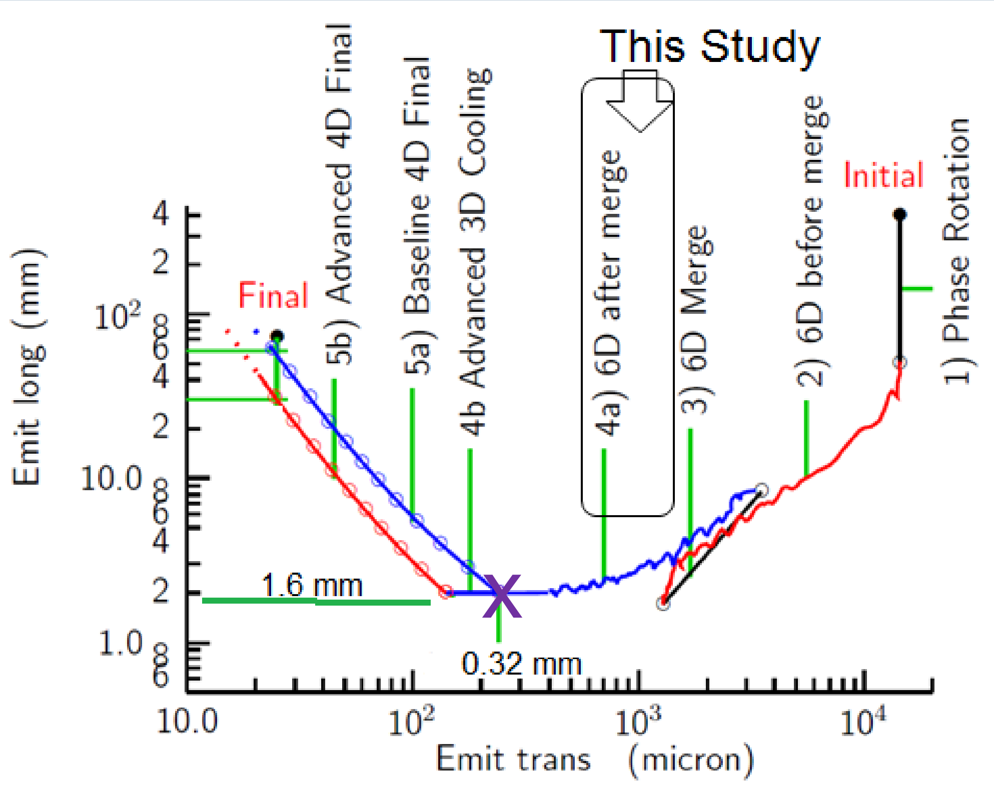
A high-luminosity muon collider requires a significant reduction of the six-dimensional emittance prior to acceleration. Obtaining the desired final emittances requires transporting the muon beam through long sections of a beam channel containing rf cavities, absorbers, and focusing solenoids. Here we propose a new scheme to improve the performance of the channel, consequently increasing the number of transmitted muons and the lattice cooling efficiency. The key idea of our scheme is to tune progressively the main lattice parameters, such as the cell dimensions, rf frequency, and coil strengths, while always keeping the beam emittance significantly above the equilibrium value. We adopt this approach for a new cooling lattice design for a muon collider, and examine its performance numerically. We show that with tapering the cooling rate is not only higher than conventional designs, but also maintains its performance through the channel, resulting in a notable 6D emittance decrease by 3 orders of magnitude. We also review important lattice parameters, such as the required focusing fields, absorber length, cavity frequency, and voltage.

Outline

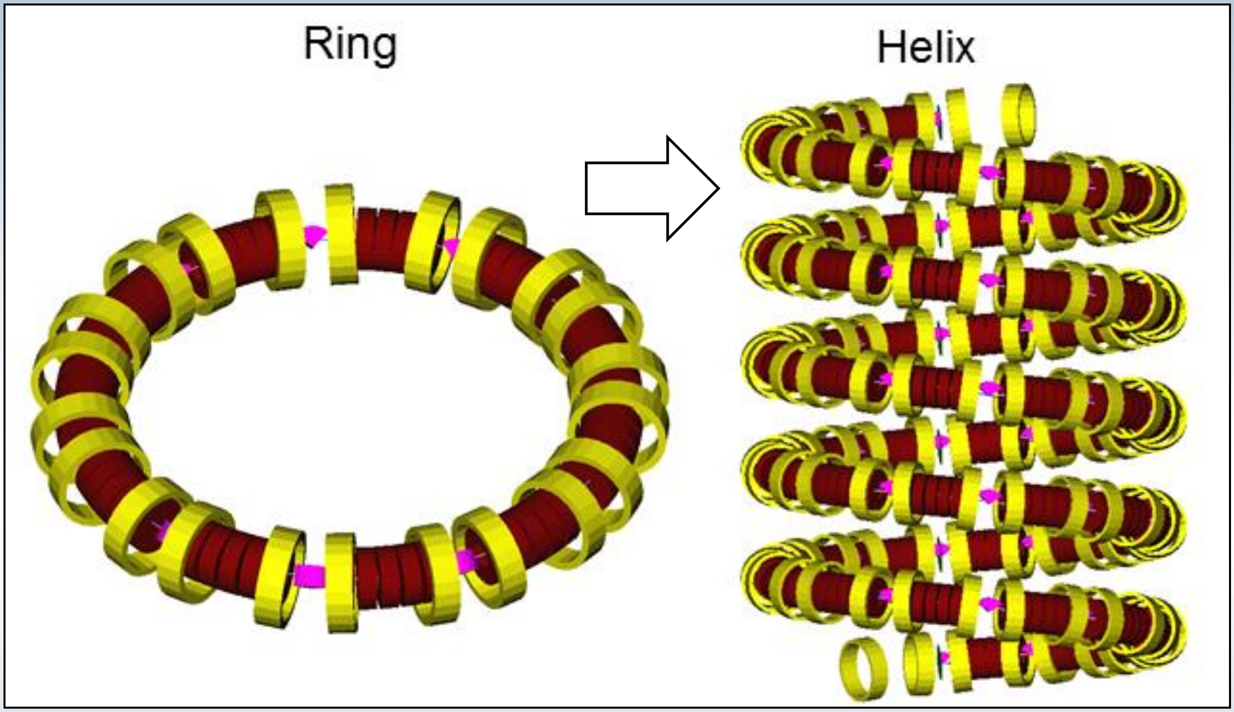
- History
- Describe a promising 6D cooling lattice
  - A tapered rectilinear FOFO snake lattice
- Review key lattice parameters
  - Identify the required rf freq., voltage, B-field, absorber length
  - Discuss magnet & engineering feasibility
  - Discuss space-charge issues
- Evaluate Performance
  - Carry out a full “front-to-end” simulation
  - Compare it with conventional designs (Guggenheim helix)

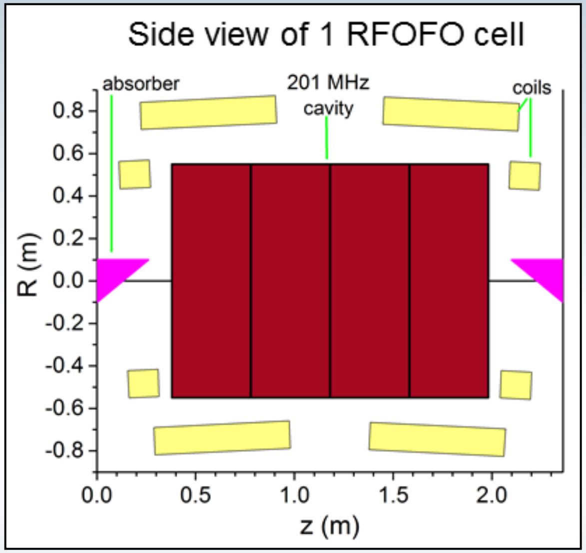
Cooling baseline for a MC



- Desired final parameters after bunch merge:
  - Emittance: ε_L = 1.6 mm, ε_T = 0.32 mm

History of vacuum RF cooling lattices

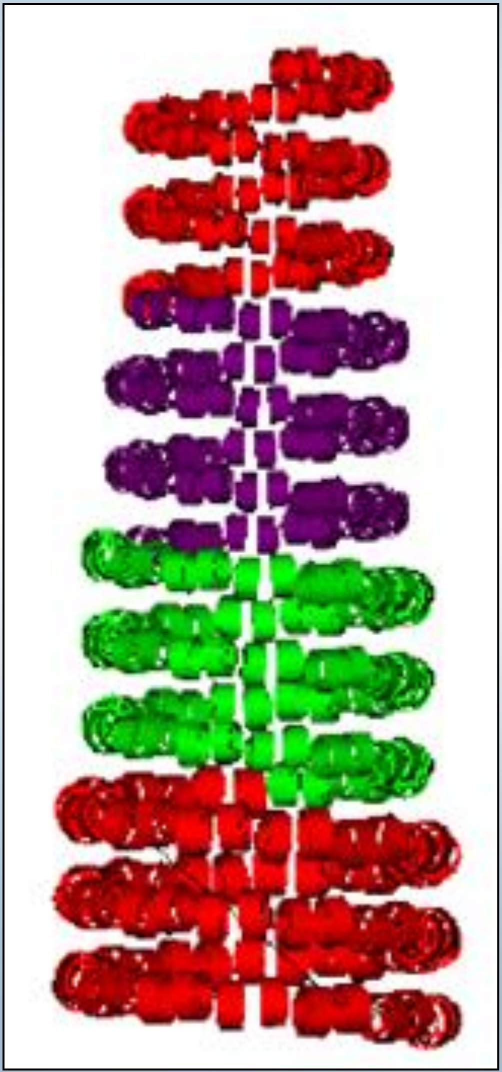




- Tilt coils to generate dispersion
- Emittance exchange on a wedge absorber
- Ring evolved to a helix to avoid injection/extraction issues

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

Concept of tapering

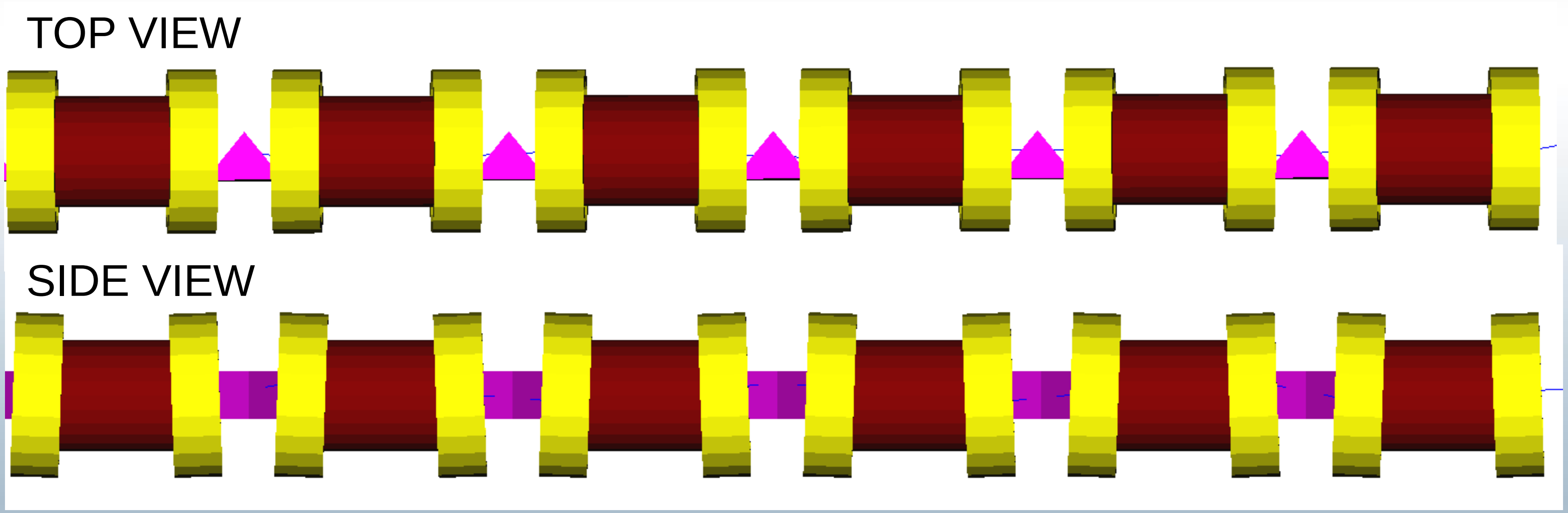


- Lattice parameters such as rf freq., cell length, focusing strength, absorber length, change with distance
- Keep emittance above equilibrium
- Still some problems:
  - Radius of curvature < 1.5 m in last stages
  - Fringe fields
  - Construction challenges
- Apply concept to other designs

D. Stratakis *et al*., Proc. of IPAC 2013, p. 1547

From helical → straight channel

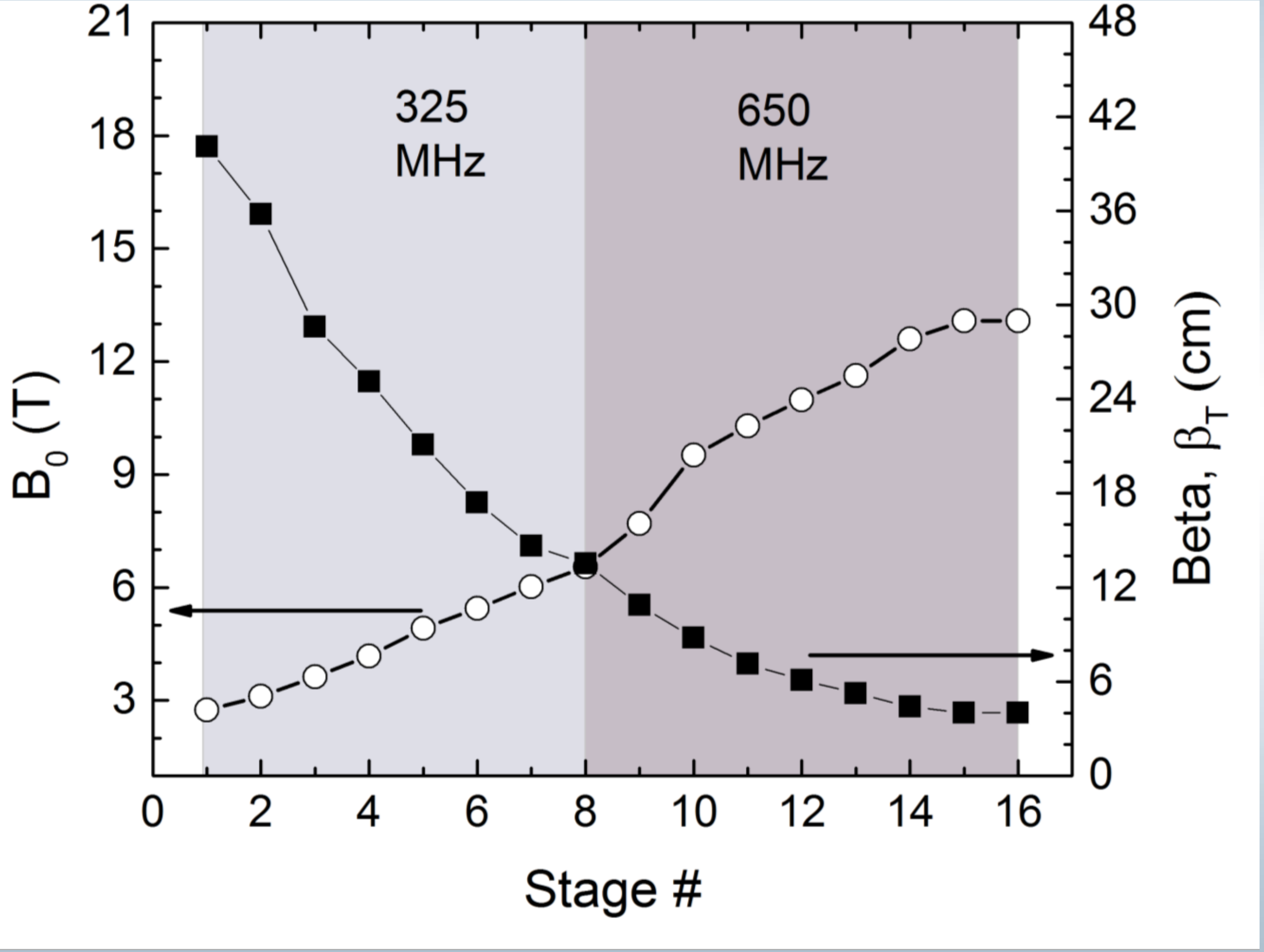
- Rectilinear FOFO snake channel with tilted coils
- Good news: Only minor variations of the Guggenheim lattice parameters are necessary



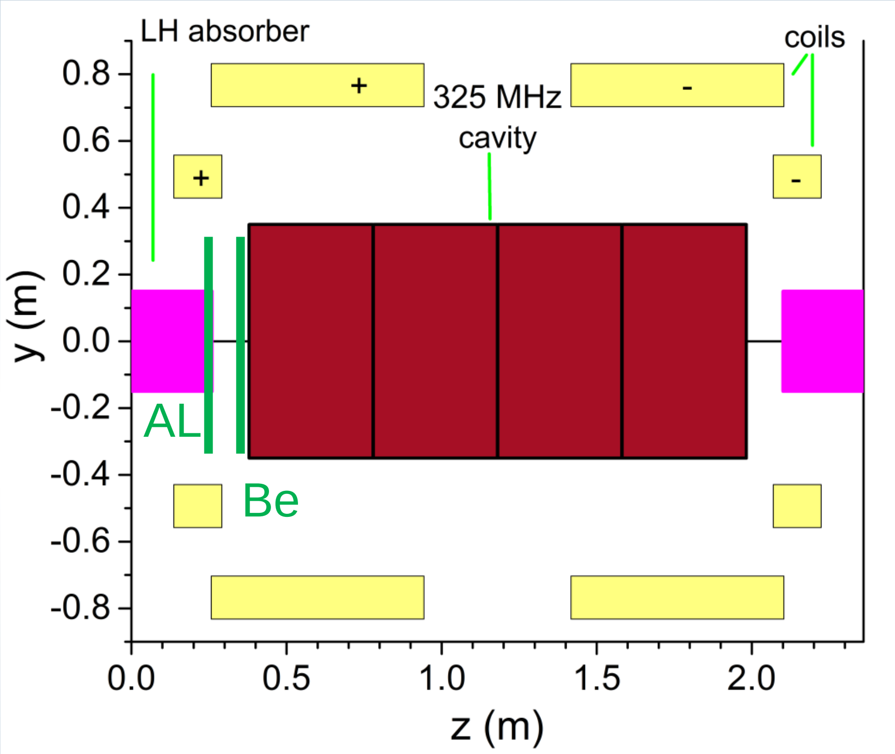
Tapered rectilinear FOFO snake

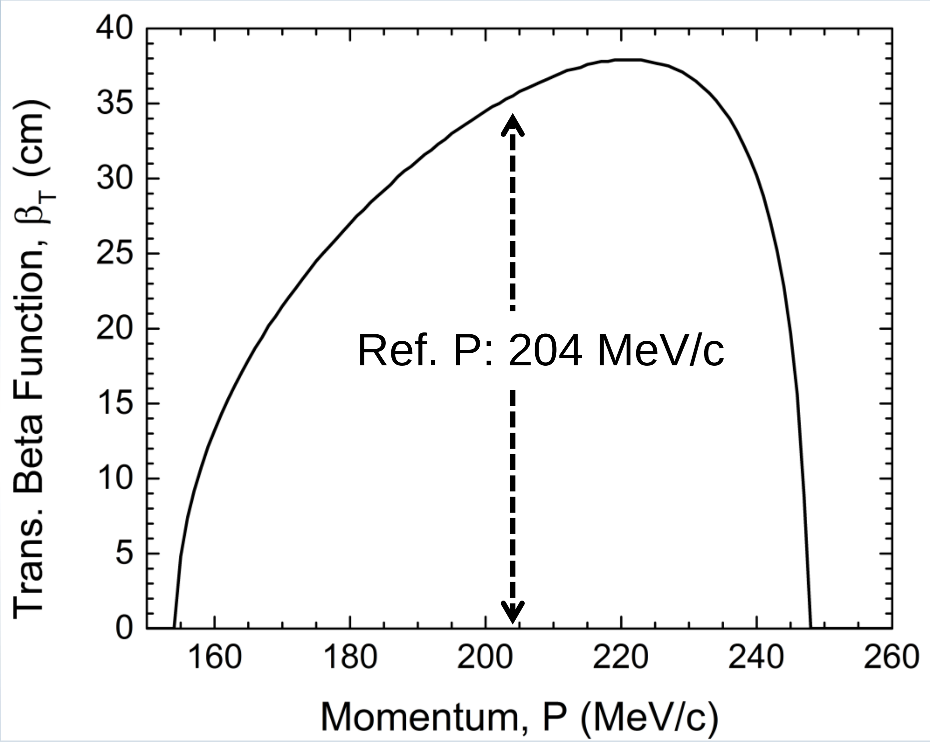
Stg. No.	Cell length [cm]	Stg. Length [m]	RF freq. [MHz]	RF voltage [MV/m]	Tran. Beta [cm]	B_0 axis [T]	B_{max} coil [T]	Coil tilt [deg.]	Disp. [cm]	Abs. length [cm]
1	275	27.5	325	17.5	40.0	2.7	7.1	1.1	6.6	29.79
2	236	33.04	325	17.5	35.8	3.1	5.5	1.1	6.8	23.84
3	202	36.36	325	18.5	28.6	3.6	7.8	1.1	7.5	25.03
4	173	27.68	325	17.5	25.1	4.1	5.6	1.2	3.4	19.31
5	149	35.76	325	19.5	21.1	4.9	7.9	1.3	5.0	15.49
6	138	48.3	325	18.0	17.4	5.4	8.5	1.1	3.8	15.73
7	127	30.96	325	20.5	14.6	6.0	9.4	1.2	5.4	22.85
8	115	28.75	325	20.5	13.5	6.5	10.2	1.1	4.4	21.98
9	99.5	23.88	650	24.0	10.8	7.7	10.4	1.1	2.9	17.14
10	80.6	83.02	650	27.0	8.7	9.5	12.9	1.1	2.3	12.85
11	80.6	47.55	650	26.0	7.1	10.3	12.7	1.1	1.8	11.43
12	80.6	45.13	650	27.0	6.1	11.0	13.0	1.1	1.7	10.00
13	80.6	28.21	650	27.0	5.2	11.6	13.5	1.1	1.6	9.14
14	80.6	23.37	650	26.0	4.3	12.6	14.1	1.1	1.4	9.42
15	80.6	16.92	650	26.0	4.0	13.1	14.2	0.5	0.6	8.48
16	80.6	20.15	650	26.0	4.0	13.1	14.2	0.5	0.6	2.20

Lattice details



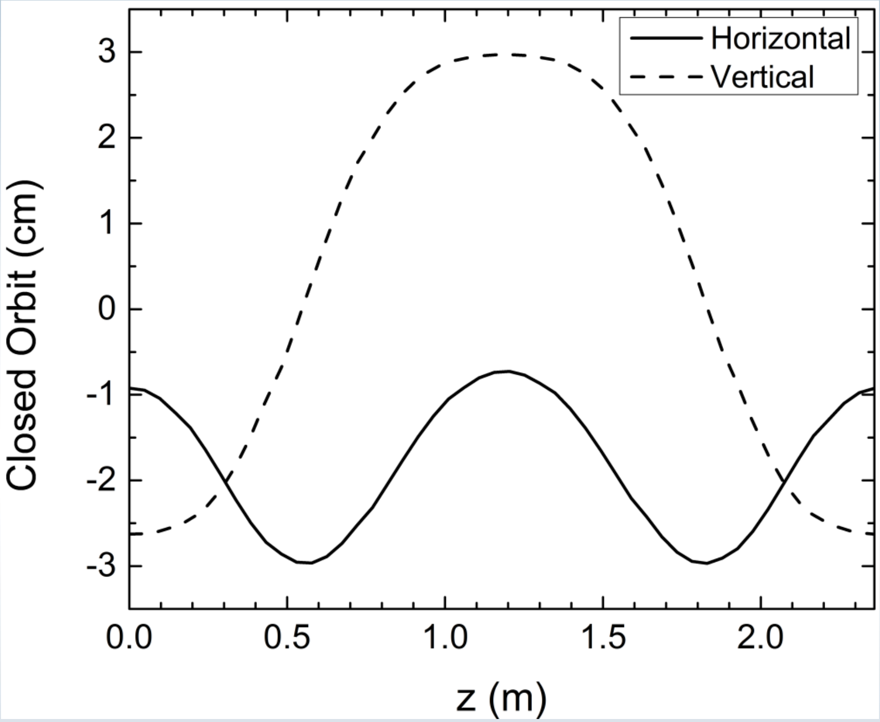
Lattice configuration (Early stages)

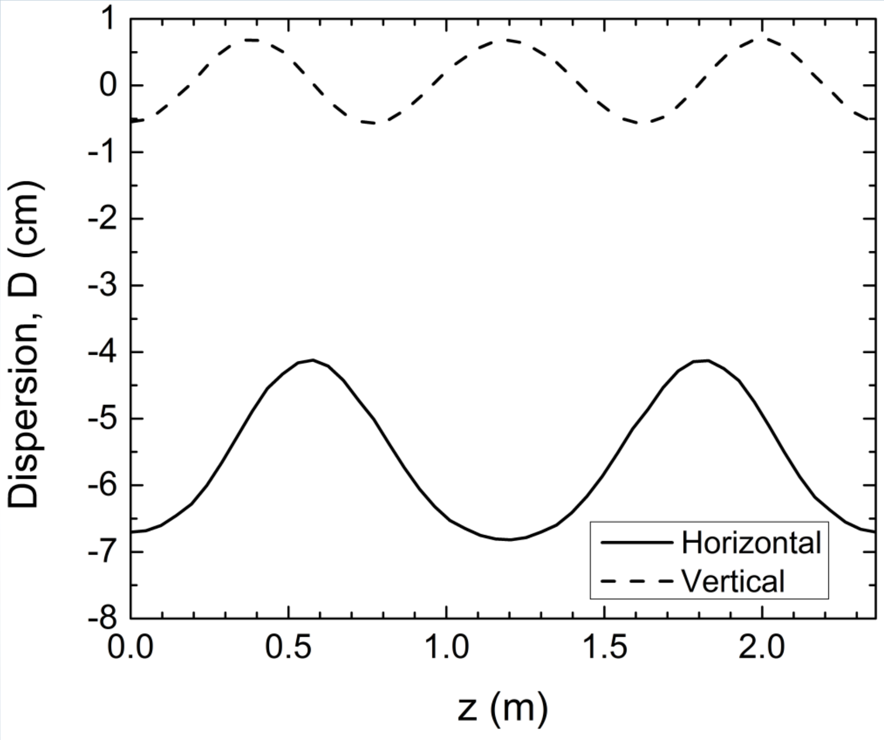




- Coils are tilted by ~ 1.1 deg. (not shown)
- Planar AL absorber windows, BE RF windows, LH wedge
- 325 MHz @ 17-20 MV/m

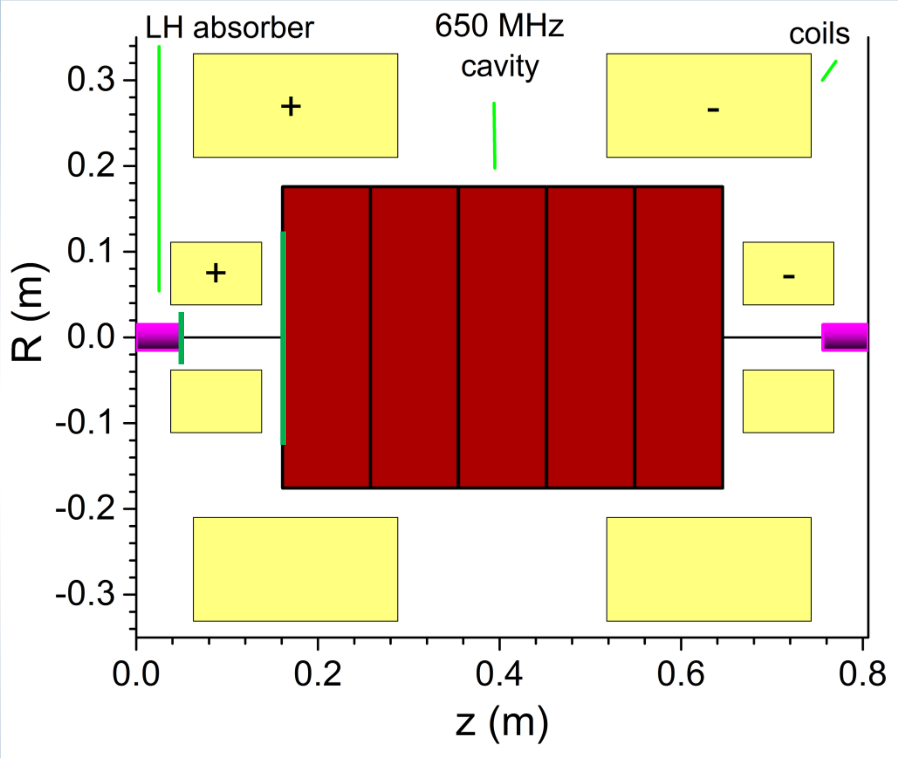
Lattice properties (Early stages)

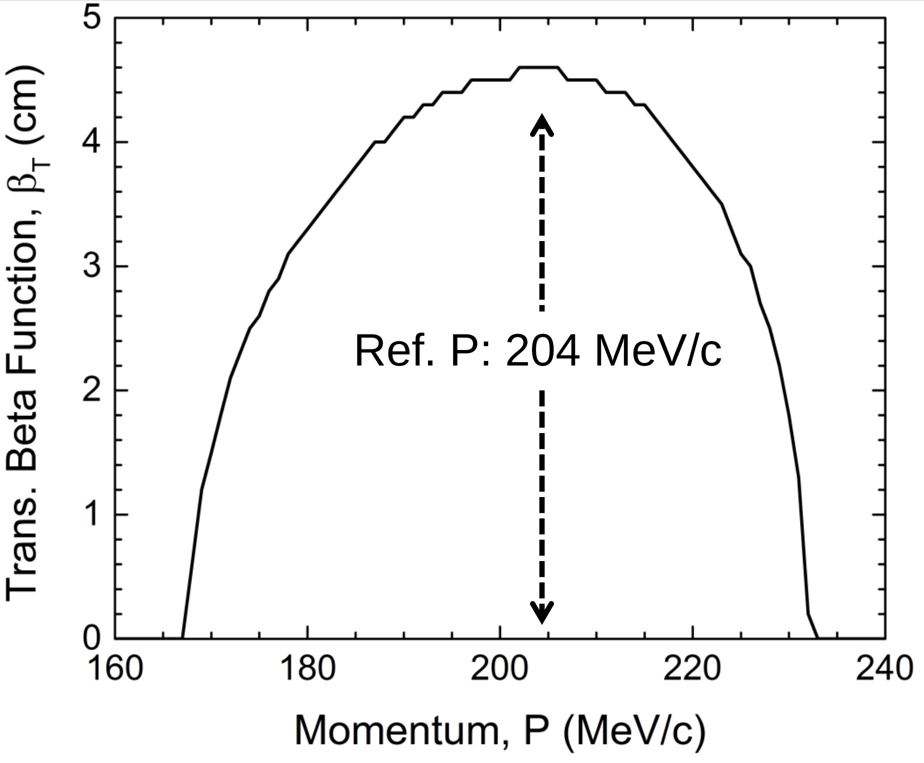




- Closed orbits and dispersion at 204 MeV/c
- Horizontal dispersion, is maximum at the absorber

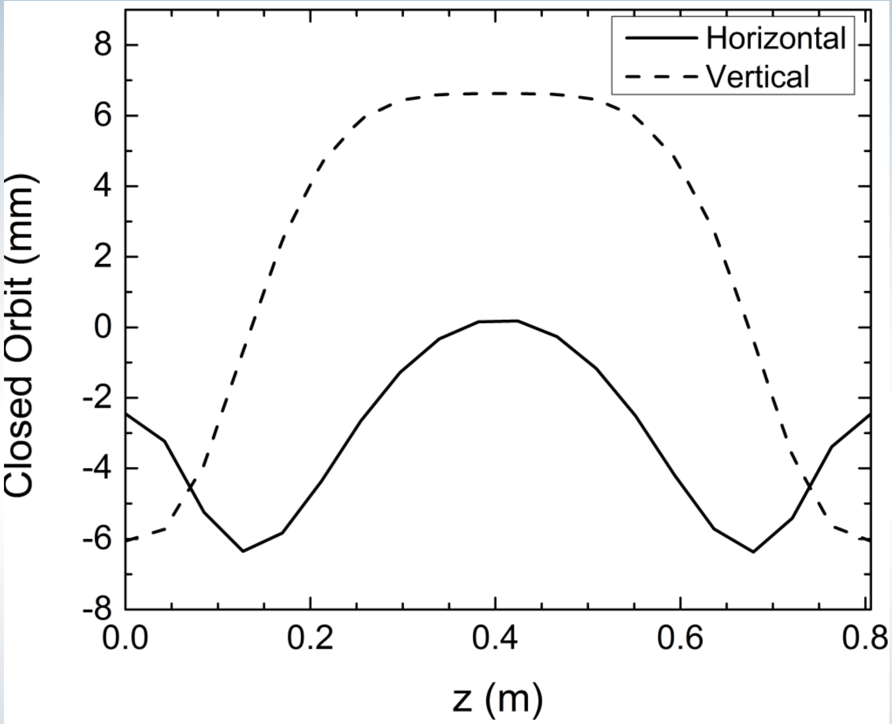
Lattice configuration (Last stages)

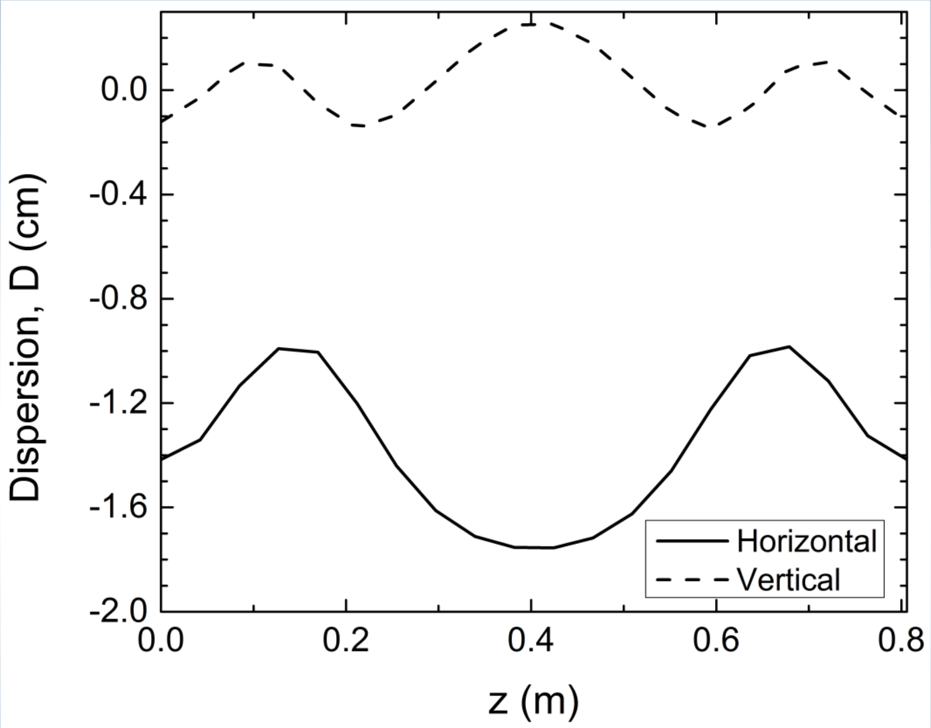




- Coils are tilted by ~ 1.1 deg. (not shown)
- Planar AL absorber windows, BE RF windows, LH wedge
- 650 MHz @ 26 MV/m

Lattice properties (Last stages)



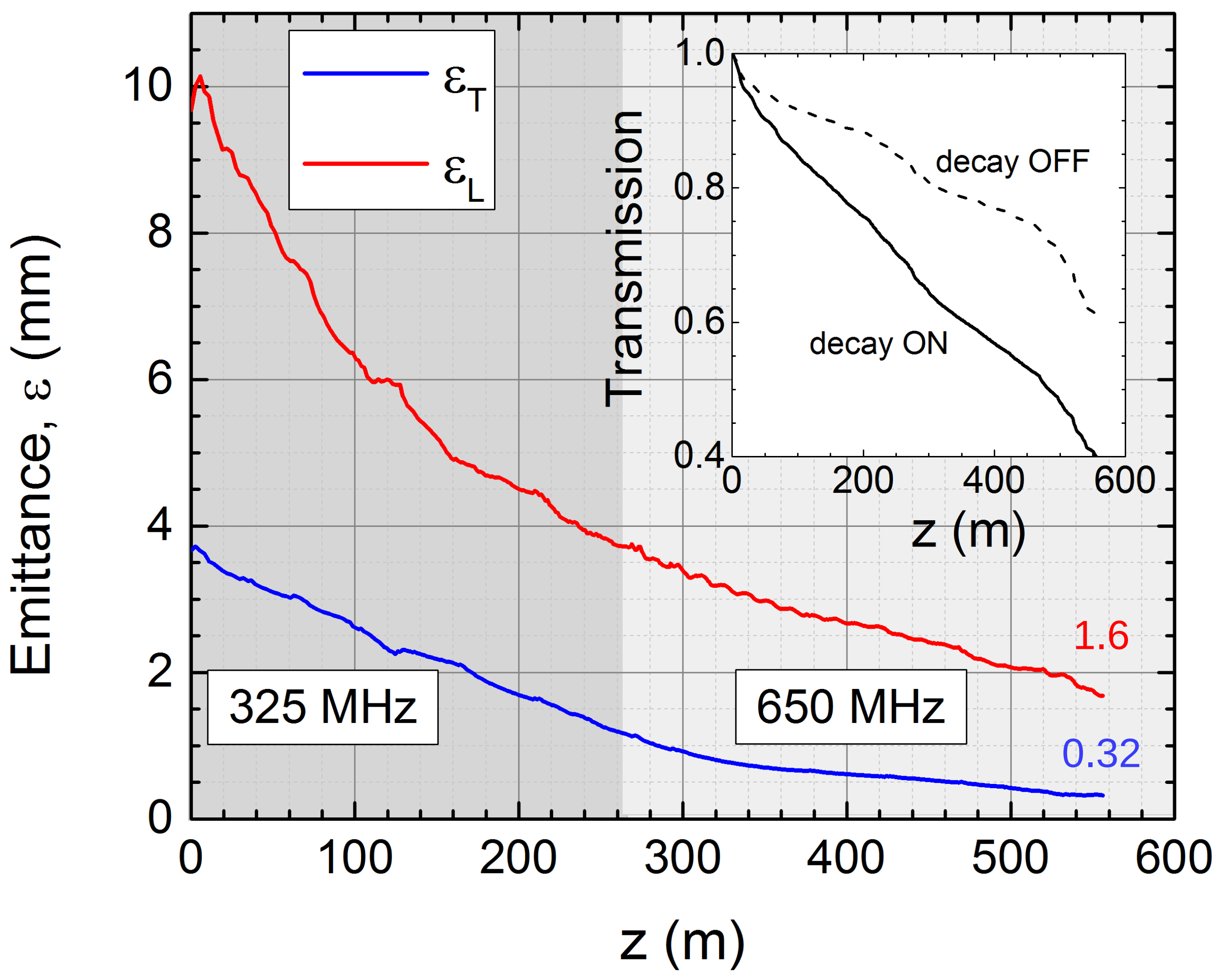


- Closed orbits and dispersion at 204 MeV/c
- Horizontal dispersion, is maximum at the absorber

Simulation details

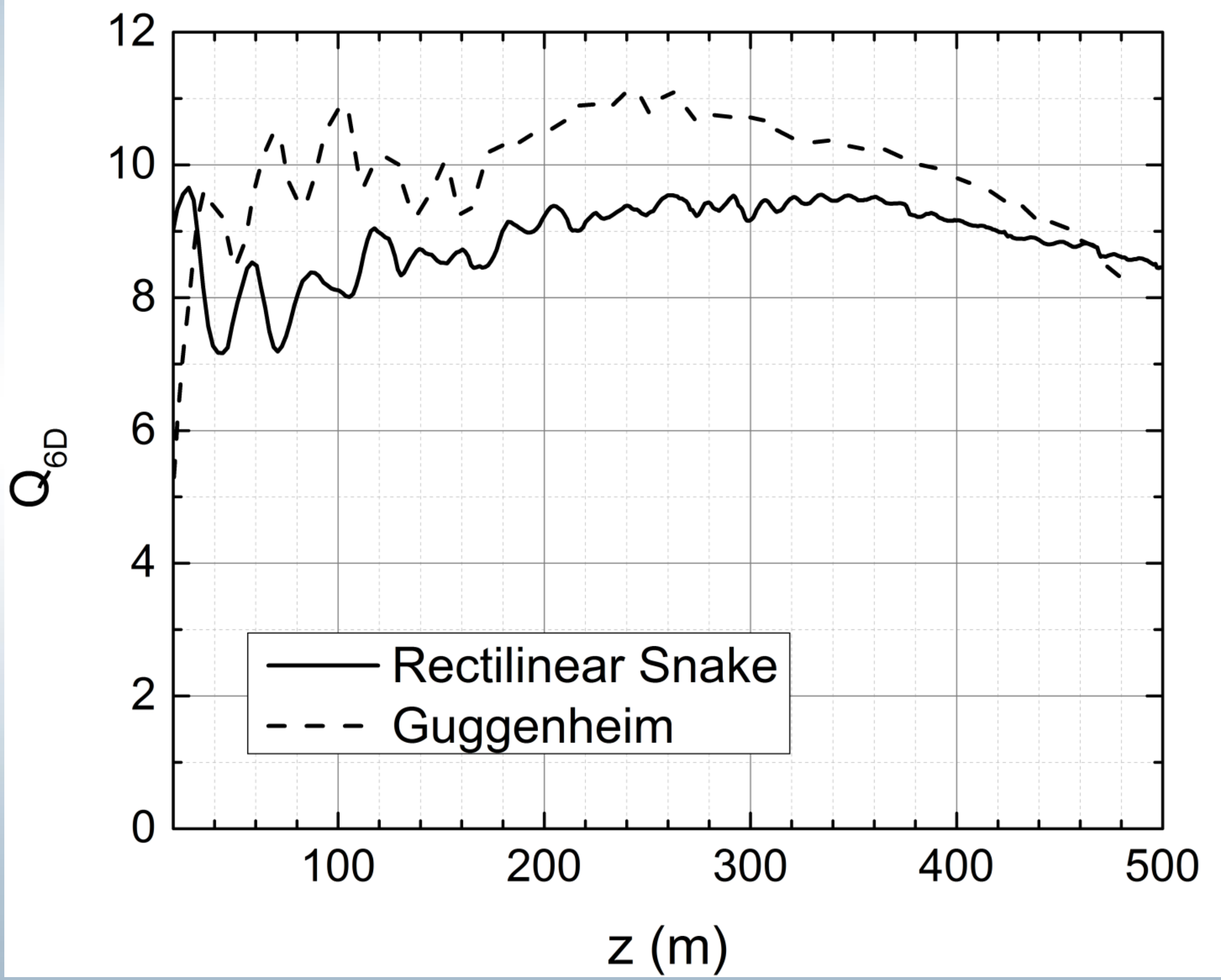
- Lattice simulated with ICOOL
- 16 stages with progressive decrease of beta function
  - Early: β=40 cm, Late: β=4.0 cm
- Coils tilted by 1.1 to 1.3 deg. to generate dispersion
- Liquid Hydrogen wedge for cooling. Absorber and rf windows included.
- Two frequencies: 325 MHz & 650 MHz
- Start with 100,000 particles
- All stages are in a single deck that can be easily adjusted if the input distribution changes

Particle tracking

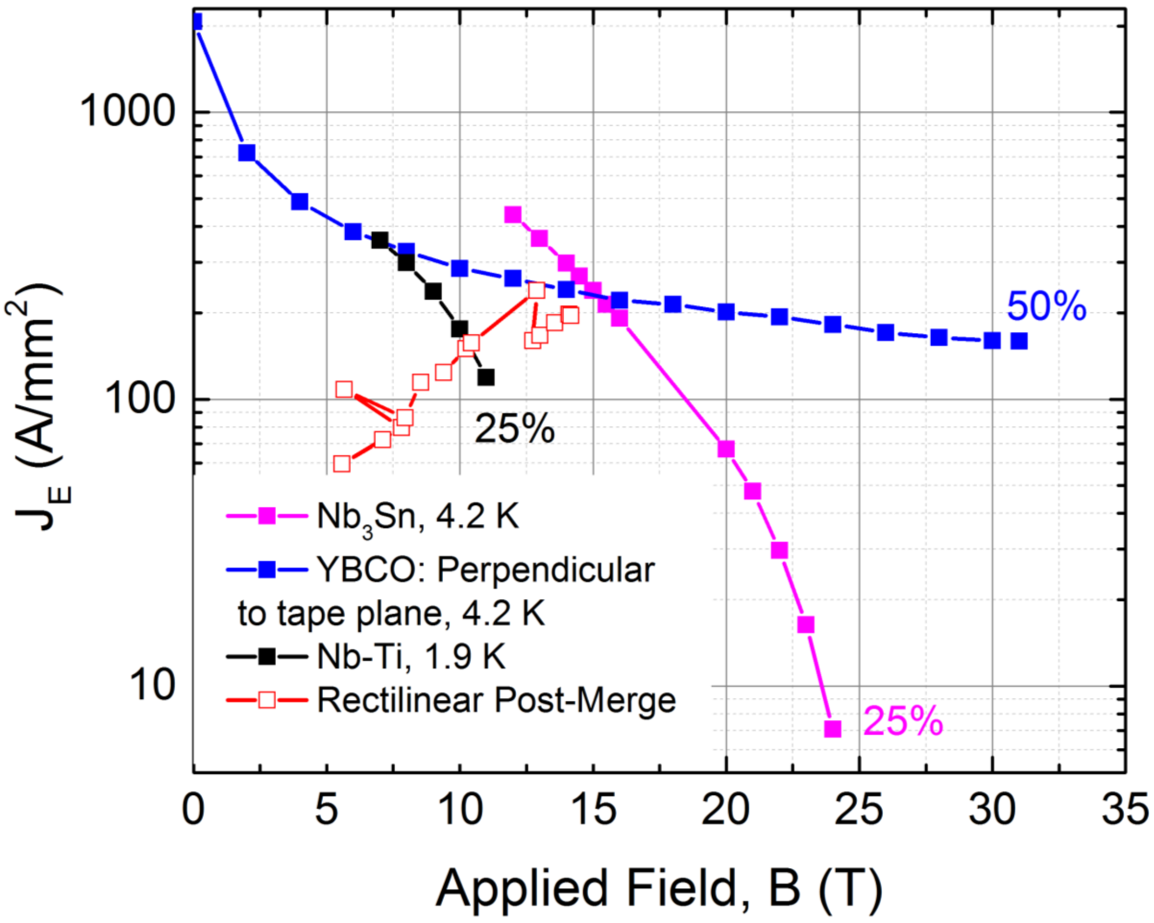


- Comparable (but not so good) as a Guggenheim

Quality factor

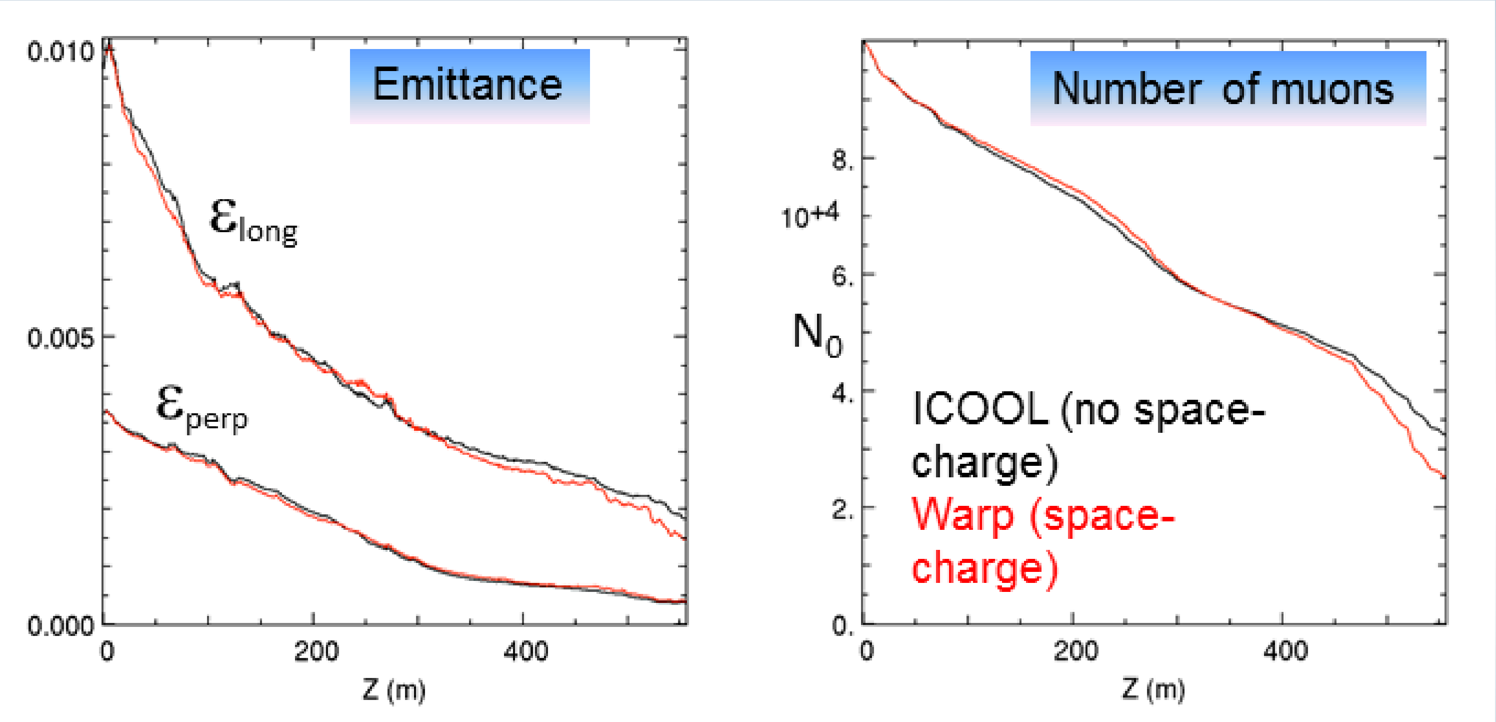


B-Field requirement



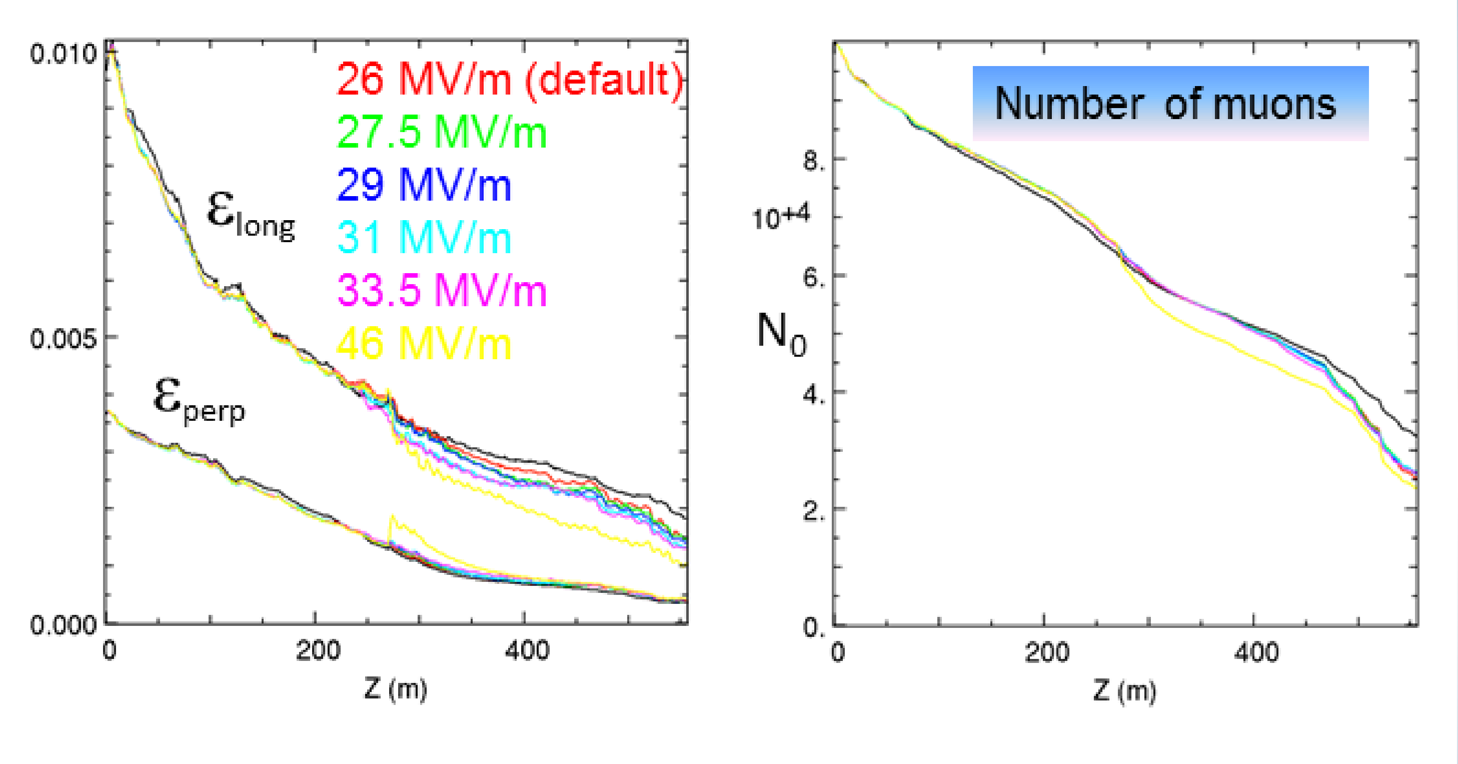
- The maximum peak B-field is 14.5 T with 196 A/mm^2
- Nb_3Sn seems a good candidate.

Space-charge simulation (D. P. Grote)



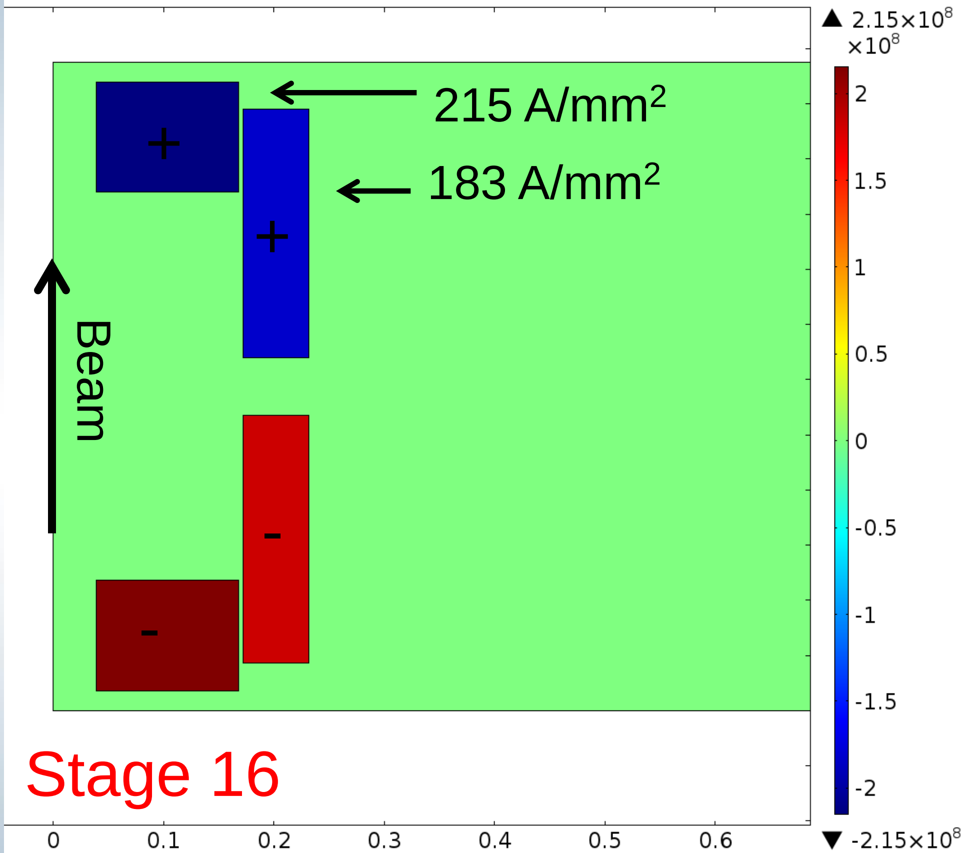
- Simulated in 3D with electrostatic version of WARP
- All lattice element included (wedges, coils, rf)
- Space-Charge causes > 10% particle loss

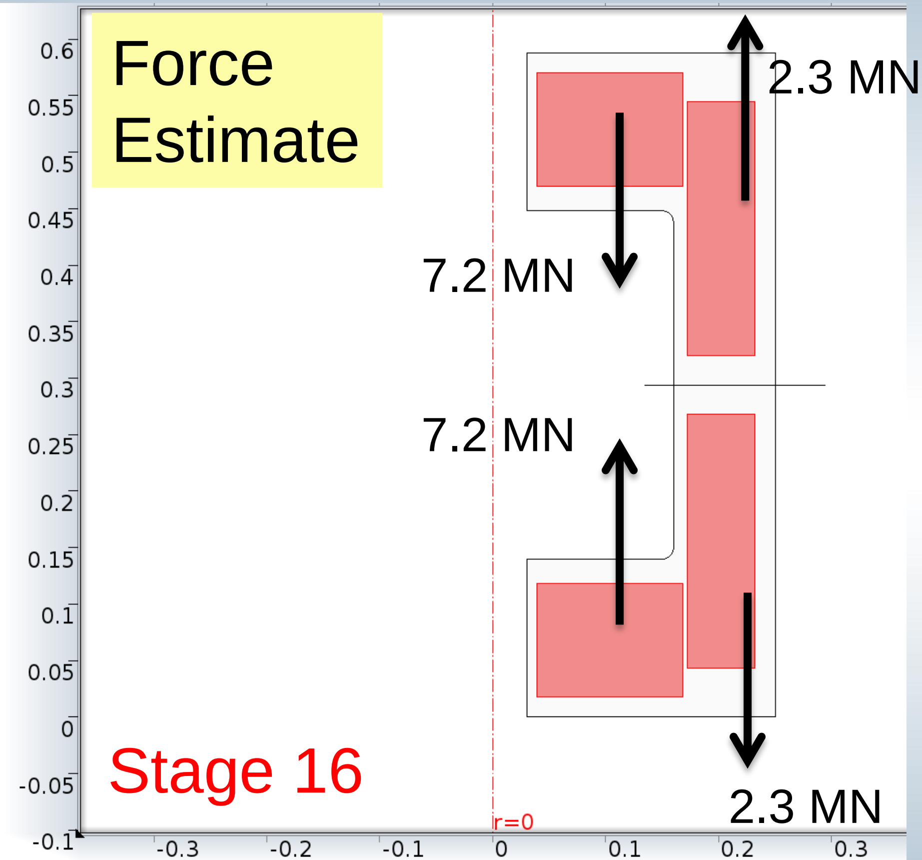
Space-charge mitigation



- Unlike previous studies, it is not clear that increasing the voltage mitigates the particle loss due space-charge.

Engineering studies (H. Witte)

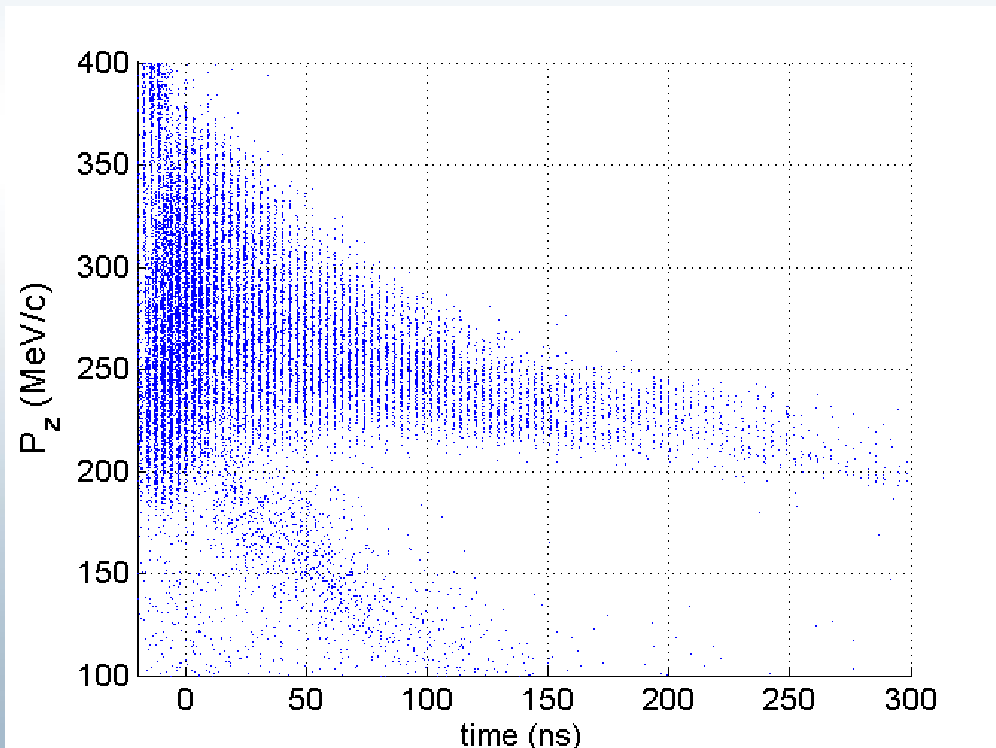


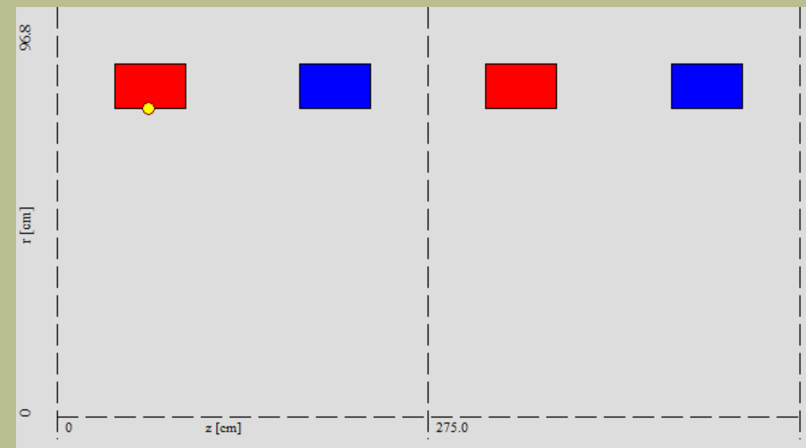


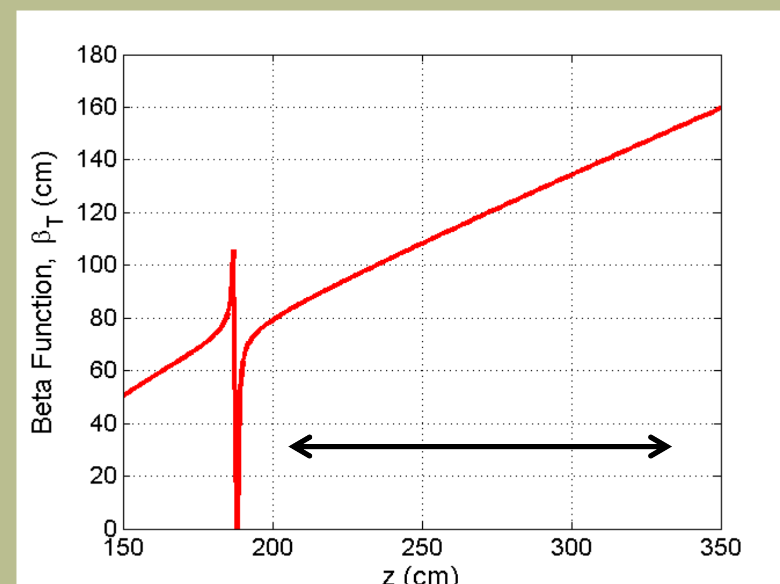
- Preliminary studies with COMSOL

Pre-Merge (Preliminary)

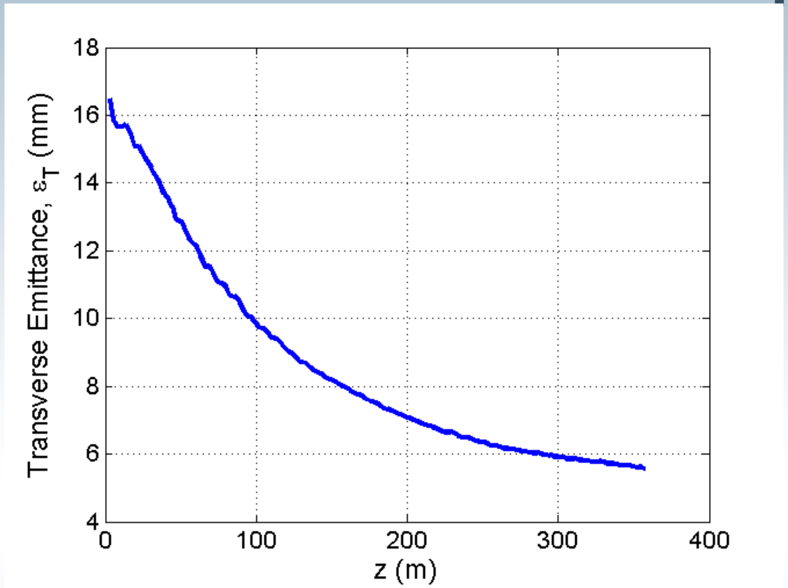
- Beam distribution after the phase-rotator of the 325 MHz front-end:

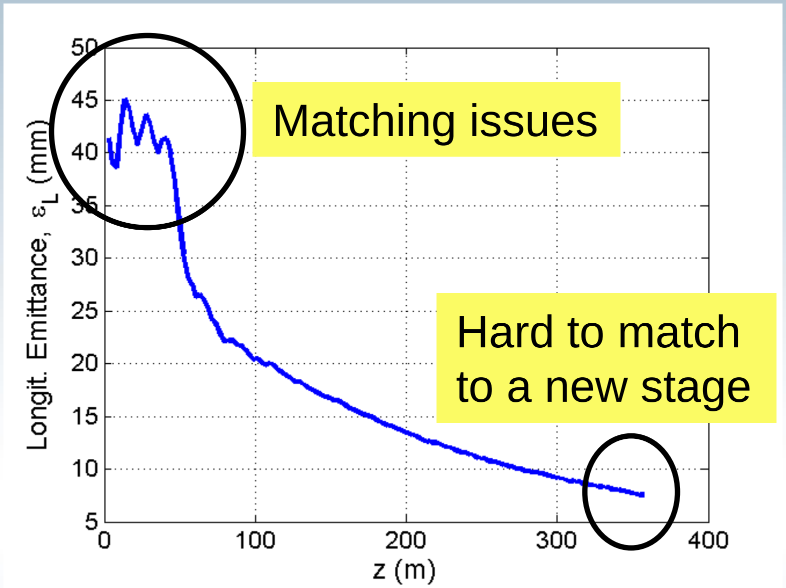


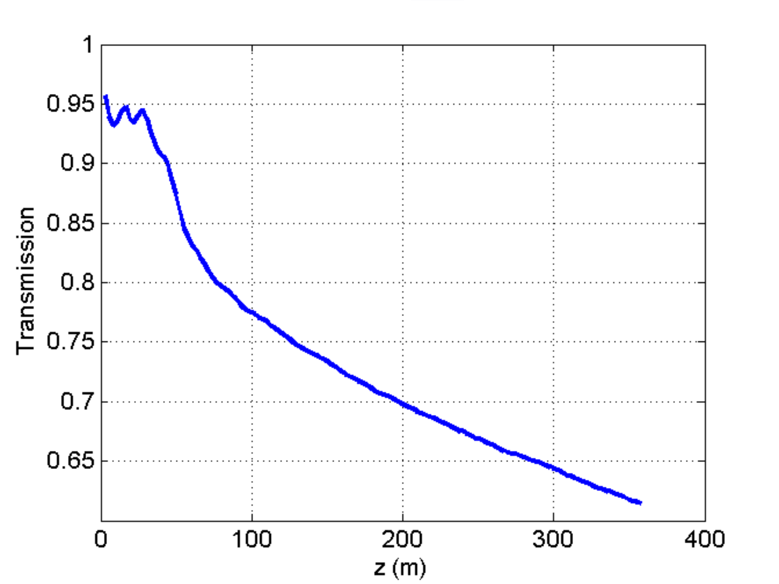




Lattice performance







I need help!

Summary

- I have designed two 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.
- I use 325/650 MHz with modest rf voltages
- With inclusion of modest safety factors, the fields are within the limits of the critical engineering limits.