6D Cooling in Periodic Lattices (Inc. Guggenheim)

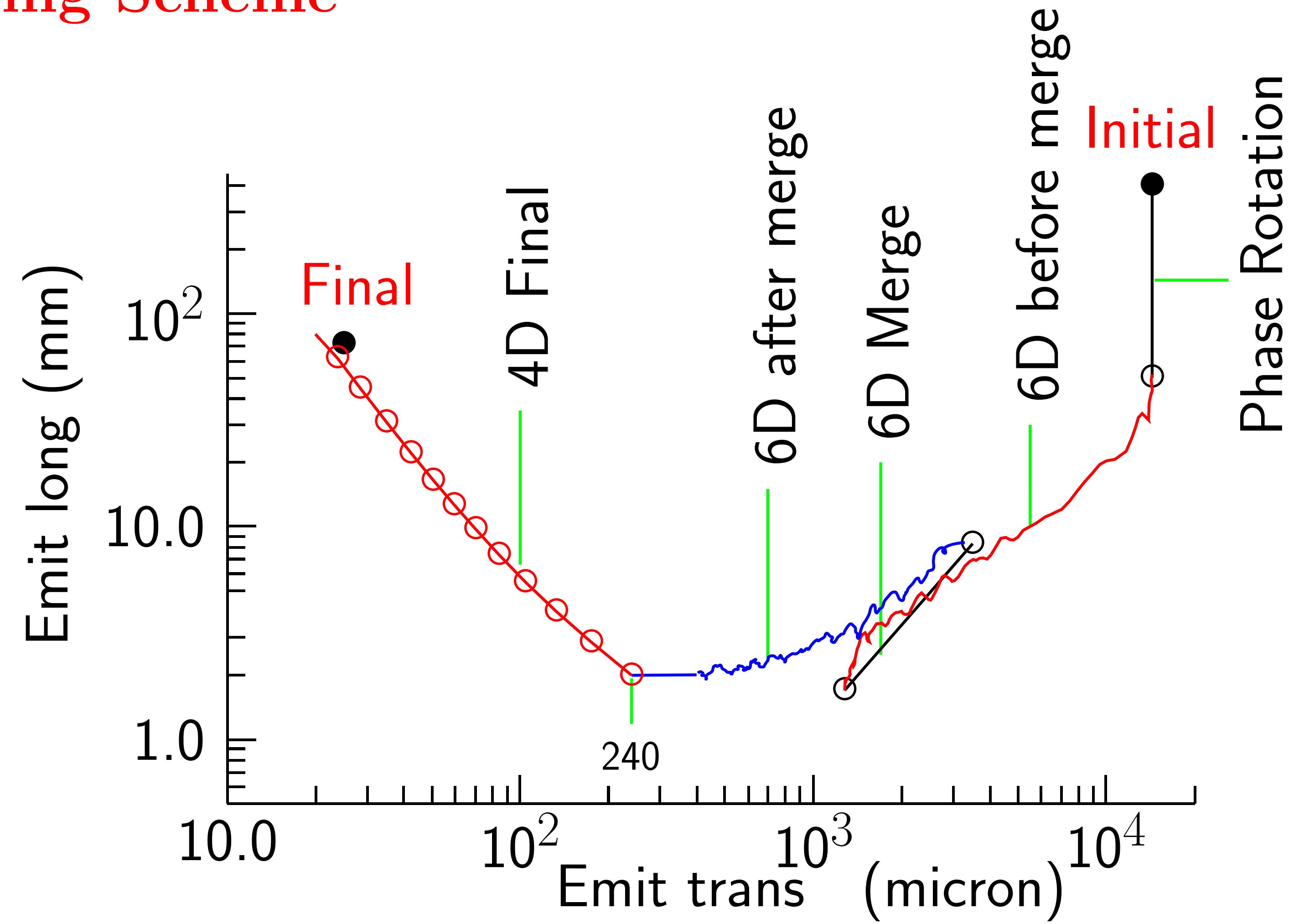
R. B. Palmer, J. S. Berg, R. Fernow, D. Stratakis
(BNL)

COOL13 Muerren

6/10/13

- Introduction
- Design of an early stage lattice
- Parameters vs. length in 2 cells
- Simulation of cooling
- Confirmation using field maps
- Design of late stage lattice
- Conclusion

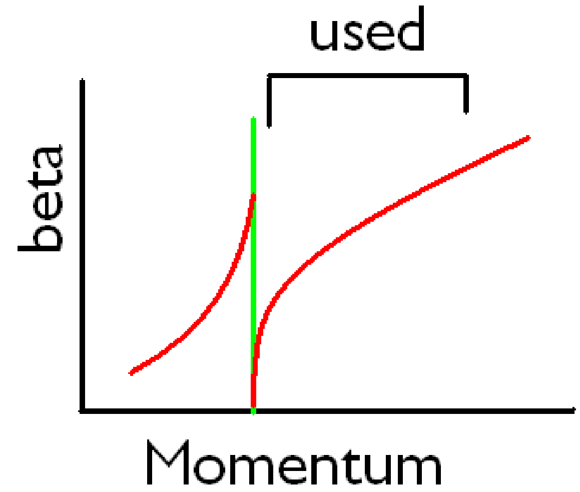
Cooling Scheme



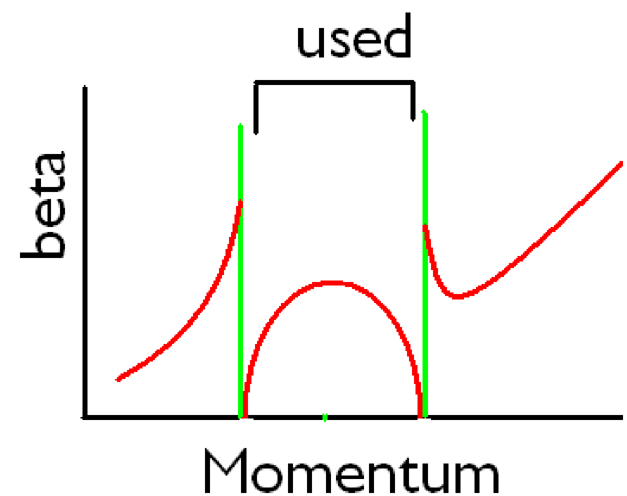
- Guggenheim designs have met these requirements on paper
- Current densities high & forces challenging (may not be possible)
- Motivating search for alternative lattices

Basic Lattices

- FOFO (Focus-Focus)
  - simply periodic
  - phase advance $\pi > \phi$
  - used in Neutrino Factory 4D cooling

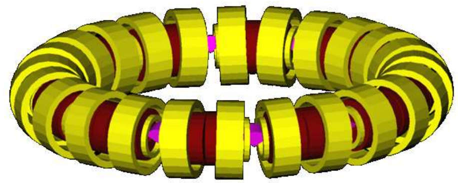


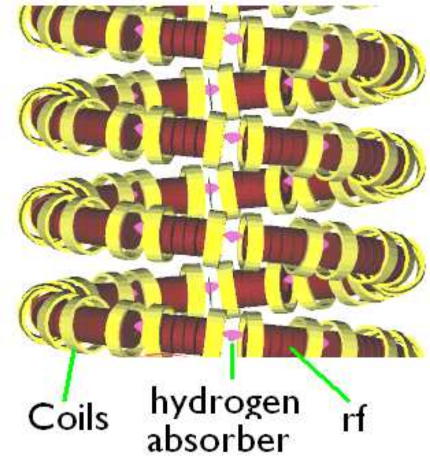
- SFOFO (Super-Focus-Focus)
  - bi-periodic
  - phase advance $2\pi > \phi > \pi$
  - used in Guggenheim



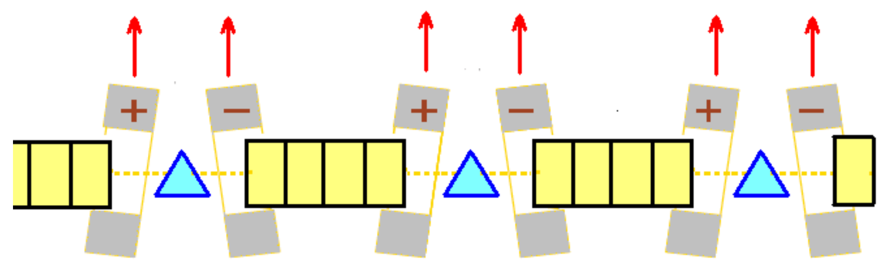
- Higher Tune
  - e.g. FOFO with transverse kicks (Helical FOFO Snake)
  - e.g. RFOFO with transverse kicks (Planar Snake)
  - both use phase advance $3\pi > \phi > 2\pi$

Geometries

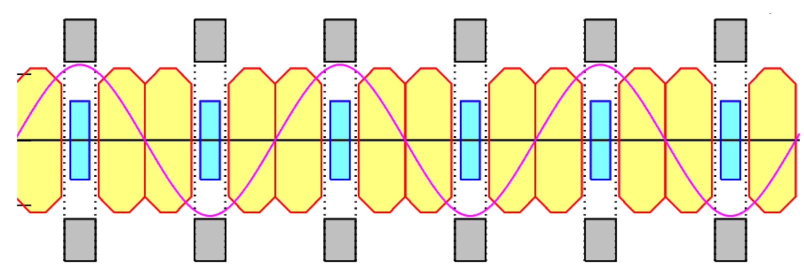




1. Ring
   - Injection hard
2. Guggenheim
   - magnetic shielding hard
3. Balbekov Rectilinear RFOFO
   - Forces outward & hard
   - Only one charge

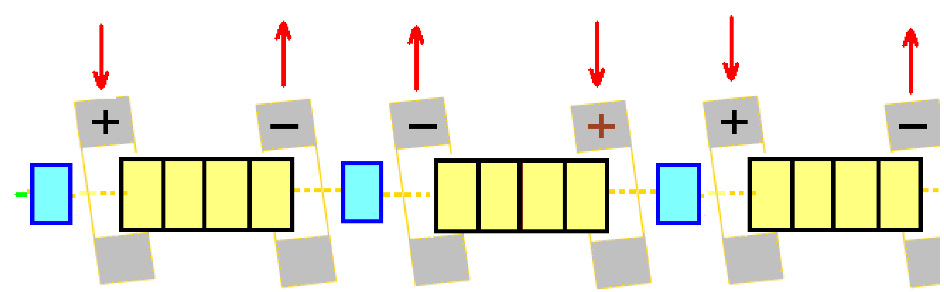


4. Helical FOFO Snake (Alexahin)
   - Axial forces are balanced
   - Cools both signs



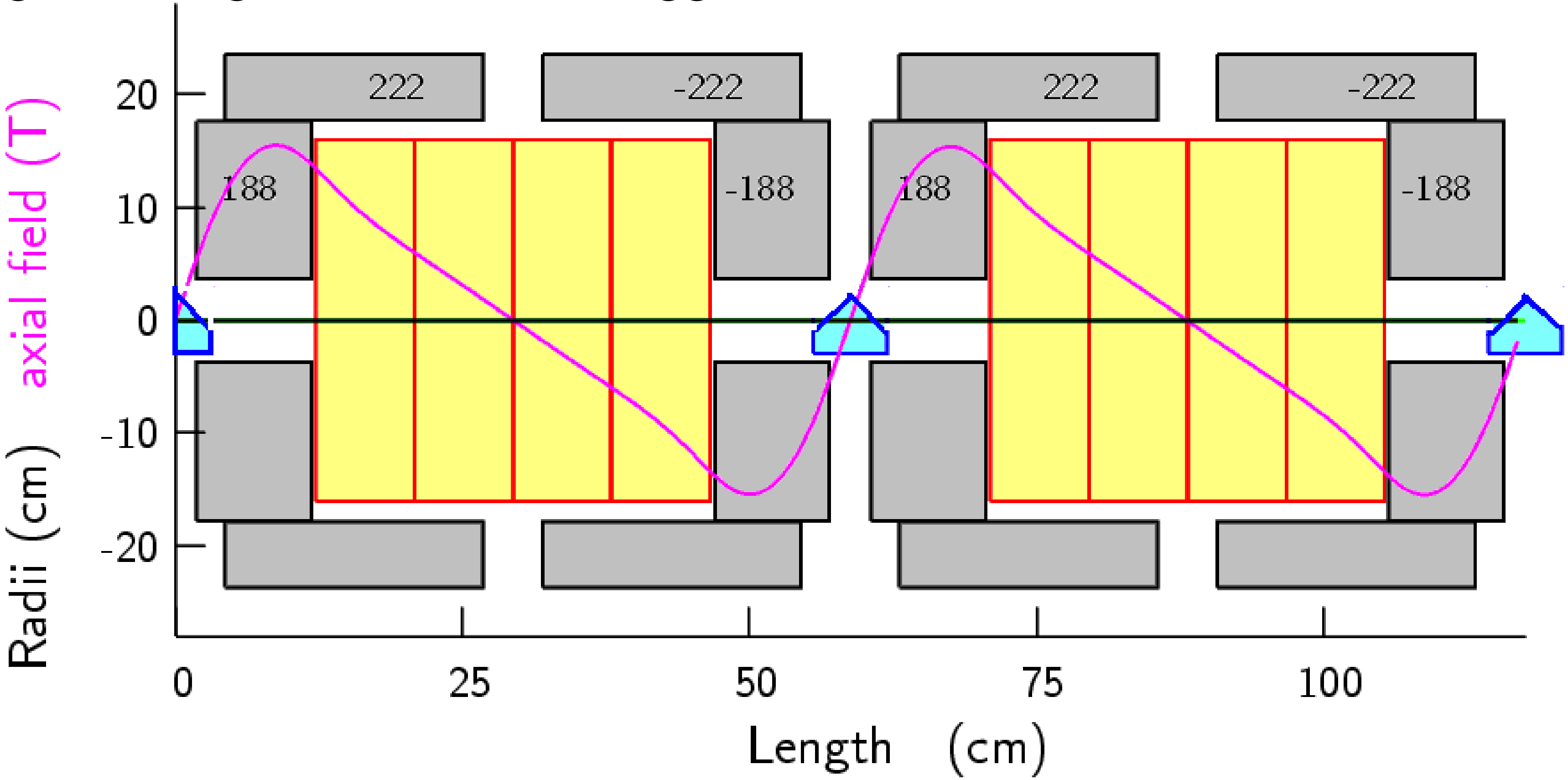
new

5. Planar SFOFO Snake
   - Forces inward
   - Cools both signs



For late stage of #1, #2, or #3

eg last stage of Stratakis Guggenheim

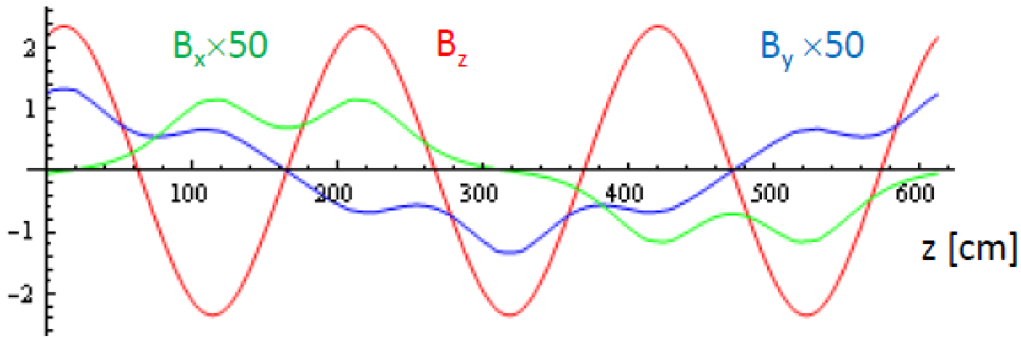


- Coils on either side of absorber are bucking
- Current densities (222 A/mm^2) at limit of HTS conductors
- Forces are outward & no space for supports
- Cools only one sign and requires wedge absorbers

Discus

- Whether ring, guggenheim, or Rectilinear RFOFO
  These options have the same problems:
  1. they require high current densities
  2. the coil-coil forces are outward and hard to support
  3. they can cool only one sign, requiring a complete duplication of channels
  4. they require wedge absorbers that we do not know how to make

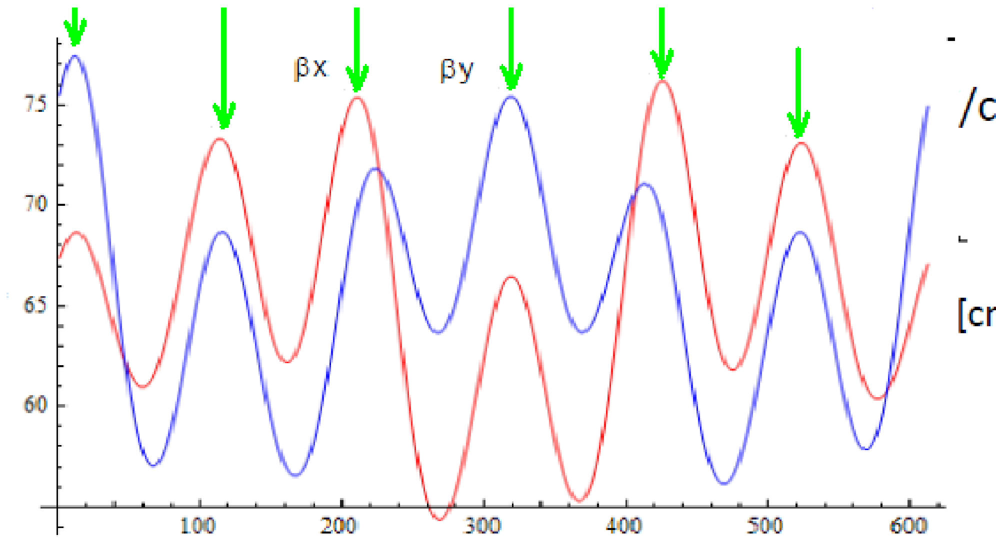
#4 Helical FOFO Snake (Alexahin)

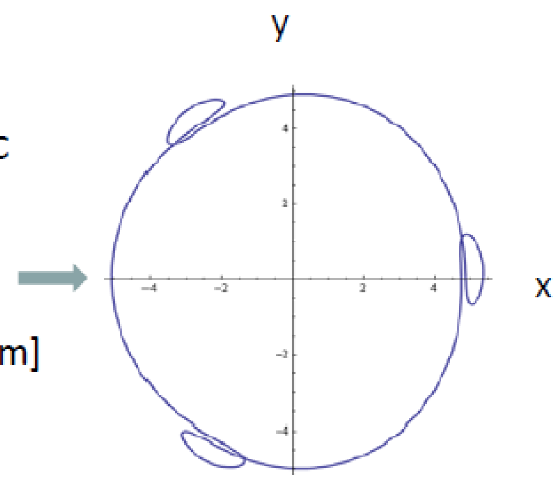


B=2.3 T

L=600 cm

Dx (max)=5 cm

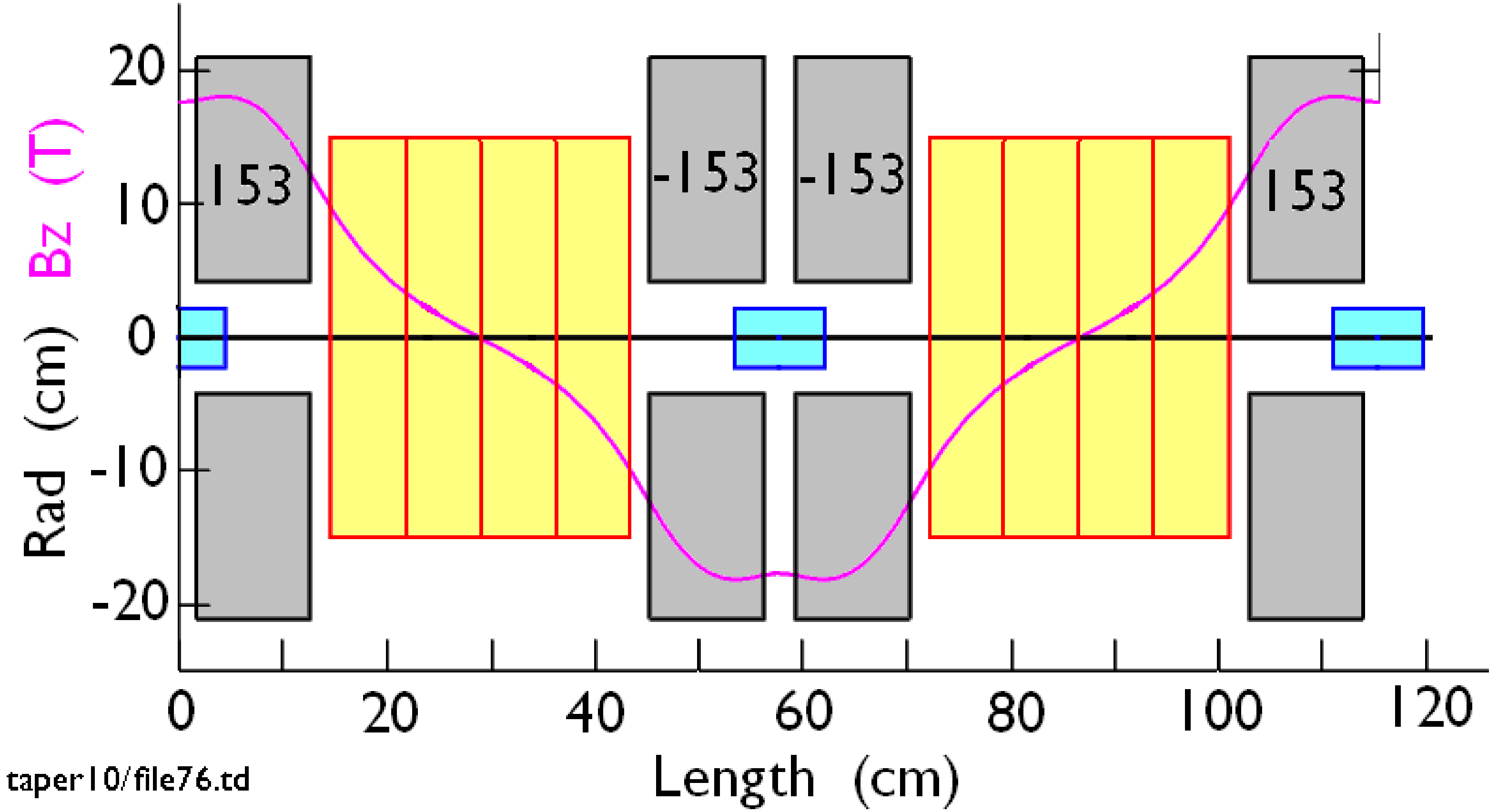




- Because absorbers are at beta maxima ($\approx$ 70 cm)
- Scaling to needed final beta of 2.4 requires

$$B \;=\; \frac{70}{2.4} \times 2.3 \;=\; 67(\mathrm{T})$$

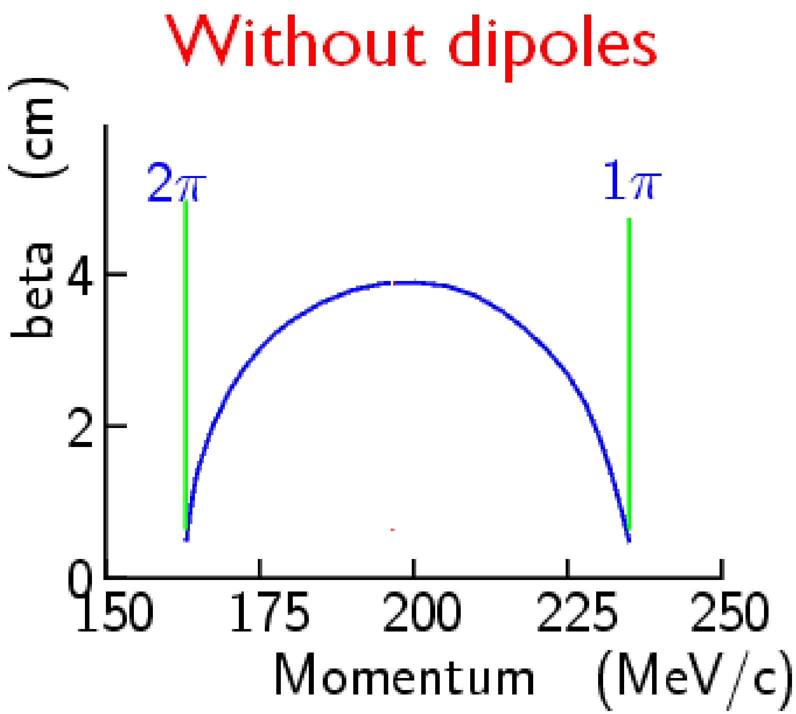
Concept of late stage without bucking

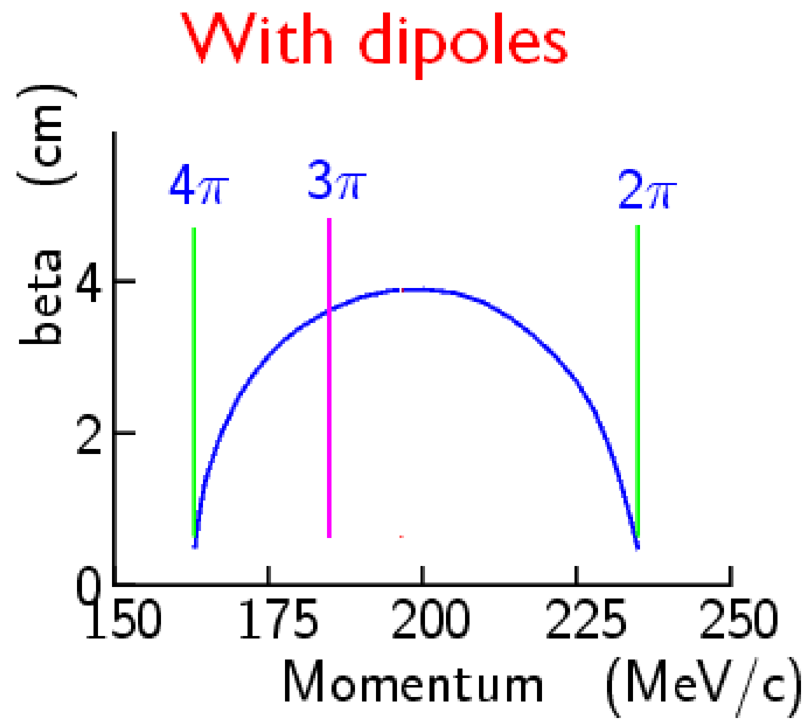


- Coils on either side of absorber are not bucking
- Lower current densities (153 A/mm^2) for a smaller beta (2.1 cm)
- Forces inward and easy to support
- Without tilts for dipole fields this lattice works well
- But we must add the dipoles to achieve emittance exchange

The difficulty with Planar Snake

- Without bending all cells have identical focusing ($\propto \ B^2$)
- With bending (required for dispersion) the symmetry is broken and a resonance exists in the center of the pass band
- We use the wider space 2pi to 3 pi: giving less momentum acceptance, but seems ok





Simulation method used for study

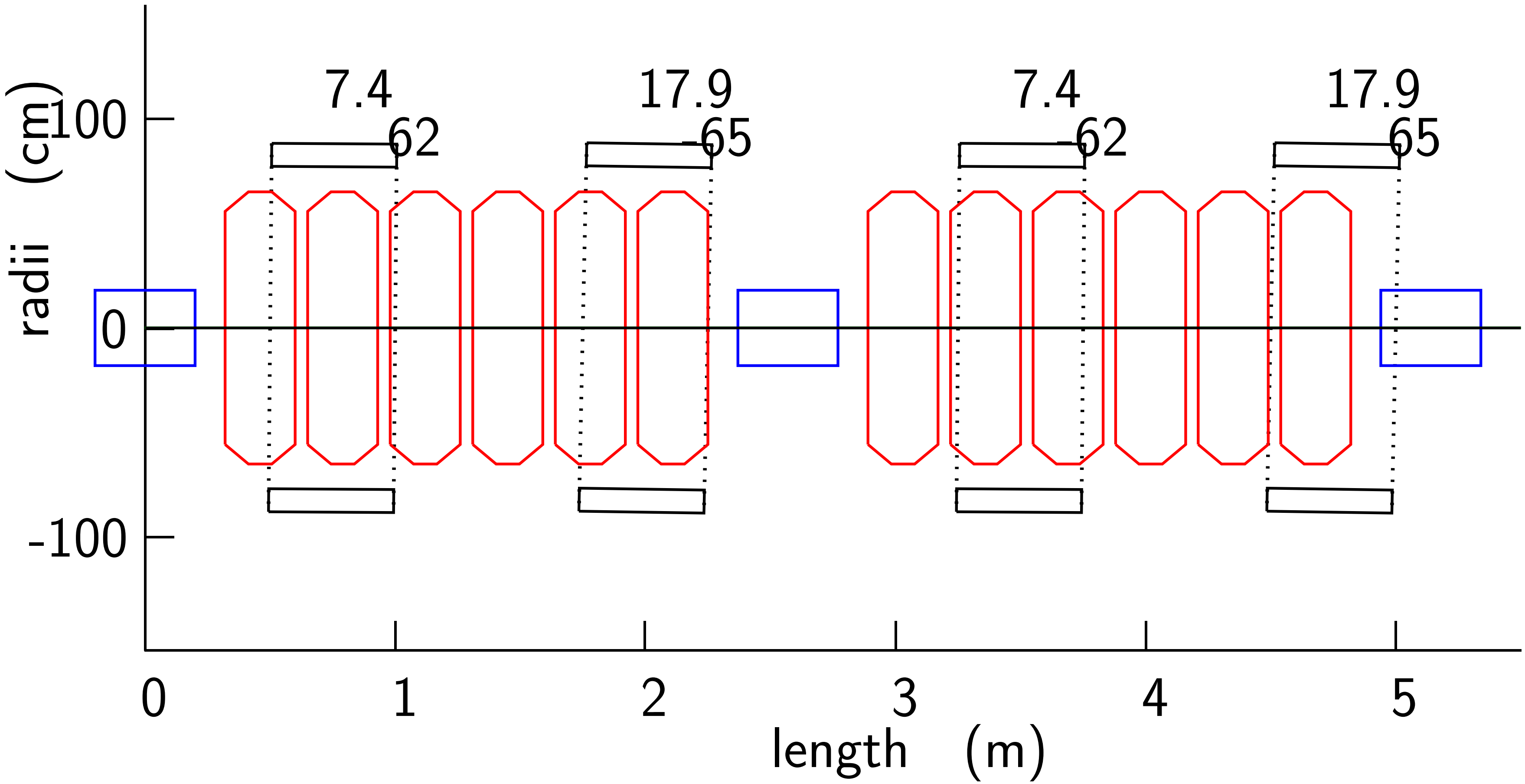
In order to rapidly explore multiple options:

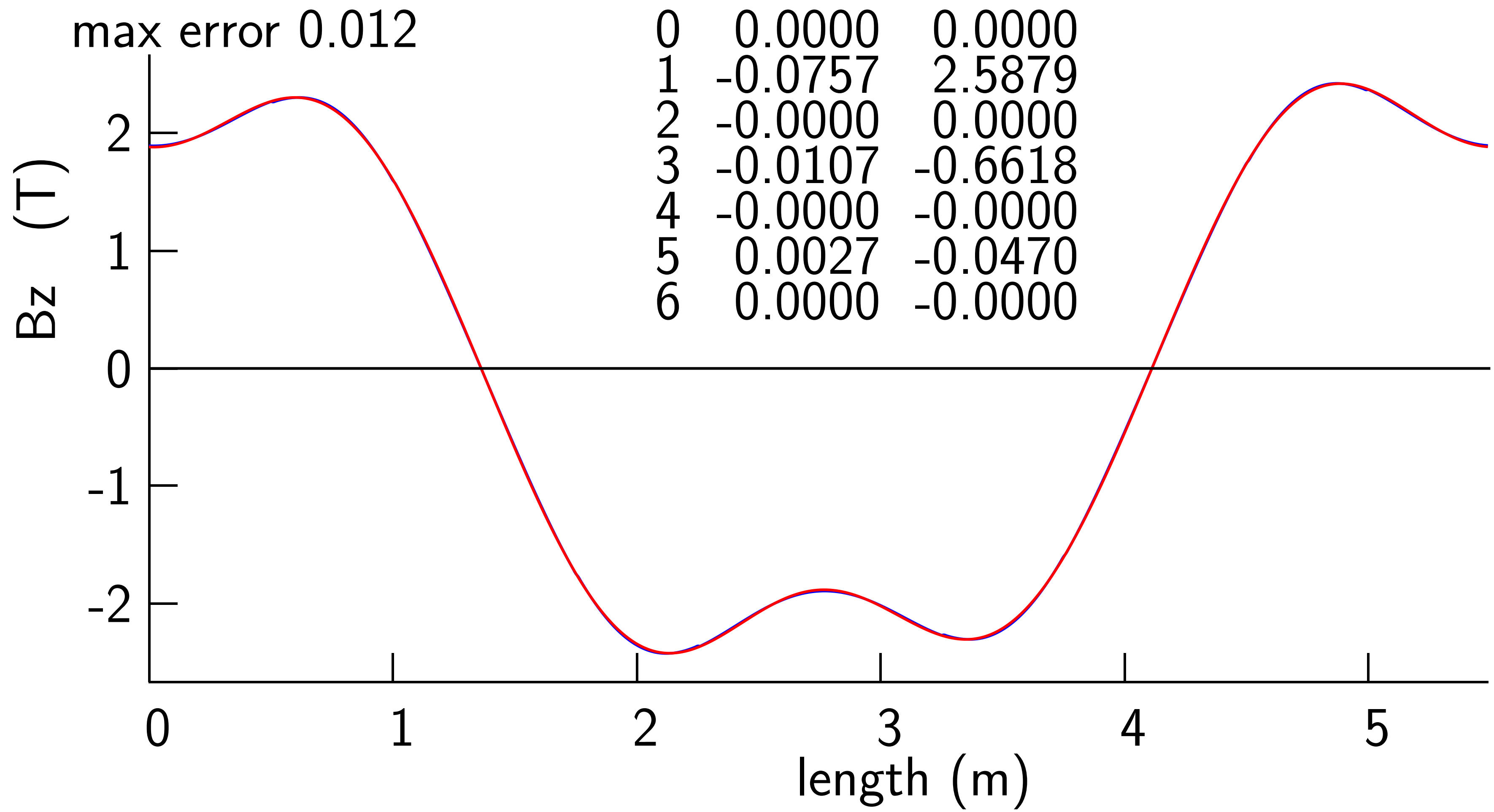
1. Used 3D fields derived by ICOOL from given fields on the axis (straight or curved)
2. Assumed solenoid fields on that axis to be the same as coils on the axis of a straight lattice without dipoles, or tilts
3. Assumed dipole fields (obtained by tilting the solenoids) to be the same as the dipole fields multiplied by the small tilt angle
4. In both cases (solenoid and dipole) the fields on the axis are assumed to be described by Fourier sums

Note that subsequent simmulations with real field maps has confirmed this to be a good approximation

Study of early stage Half Flip Planar Snake

An early stage using 201 MHz





Dipole fields obtained by tilting all coils by 18 mrad

Parameters

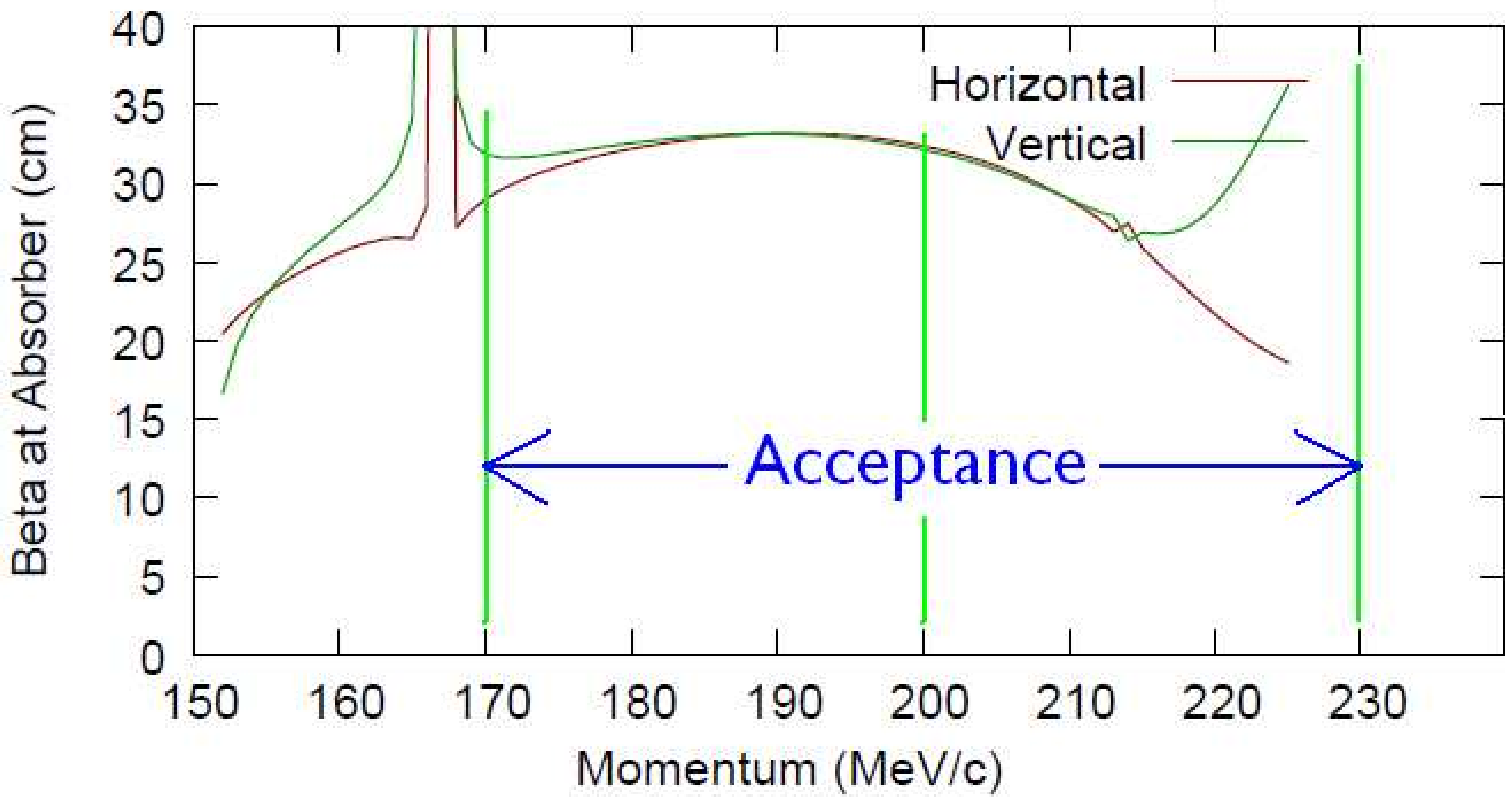
gap	start	dl	rad	dr	tilt	I/A
m	m	m	m	m	rad	A/mm^2
0.500	0.500	0.500	0.770	0.110	0.007	62.22
0.750	1.750	0.500	0.770	0.110	0.018	-65.45
0.500	3.250	0.500	0.770	0.110	0.007	-62.22
0.750	4.500	0.500	0.770	0.110	0.018	65.45

Hydrogen absorber 42.6 cm long, radius 18 cm

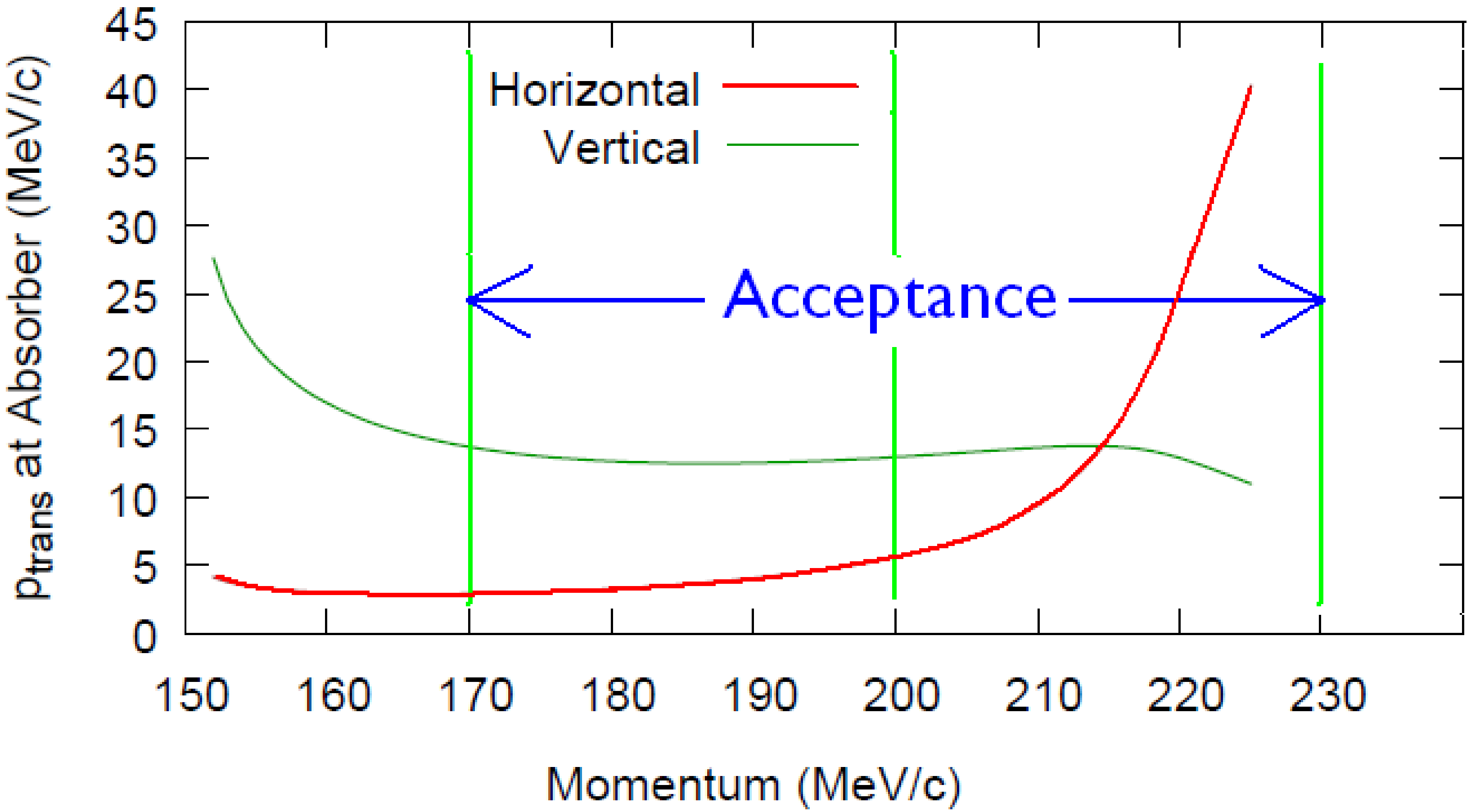
Hydrogen window of 0.5 mm aluminum

rf: 6 pillbox cavities, 33 cm long, 201.25 MHz, 17 MV/m, Initial phase 30 degrees (no rf windows)

Betas vs. momentum (Scott)



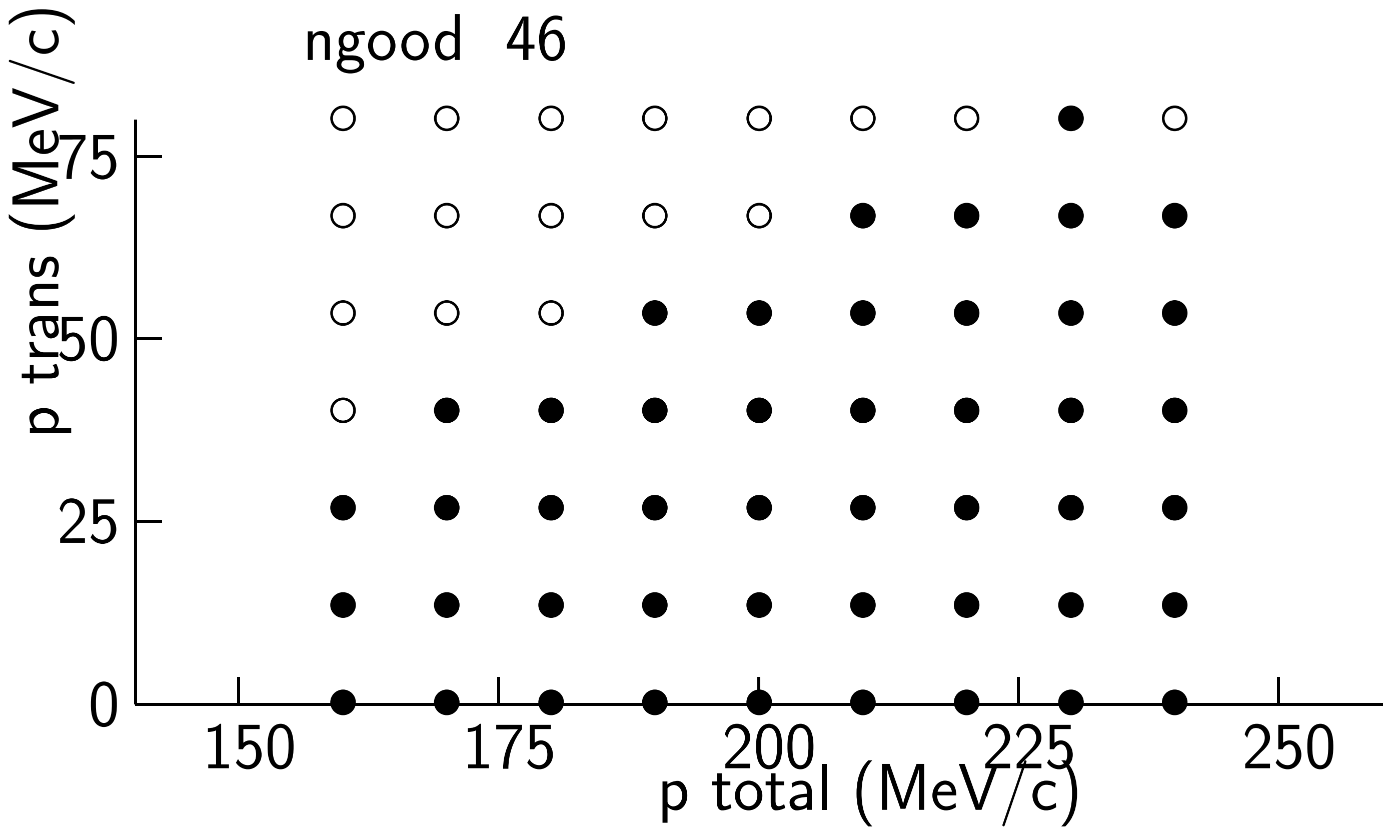
Dispersion vs.momentum (Scott)



Acceptance with tilts

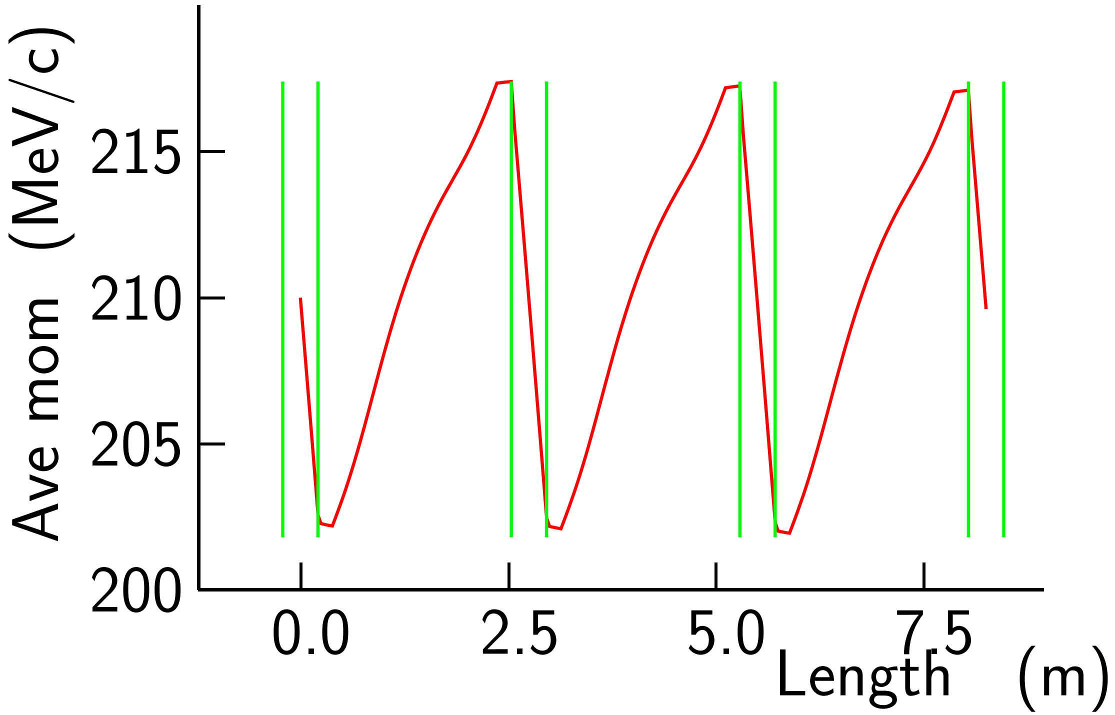
With no absorbers or rf, use ICOOL to propagate through 550 m

ICOOL using above Fourier description of fields on axis

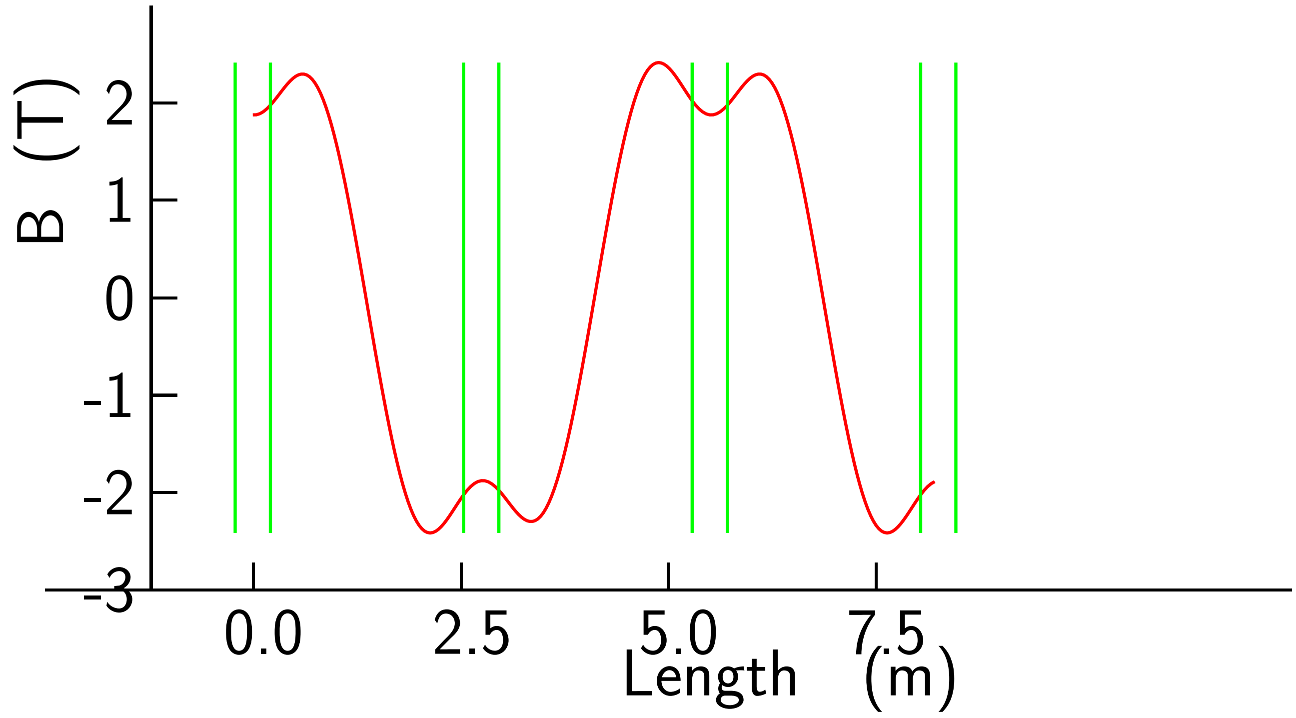


This is better than many Guggenheims

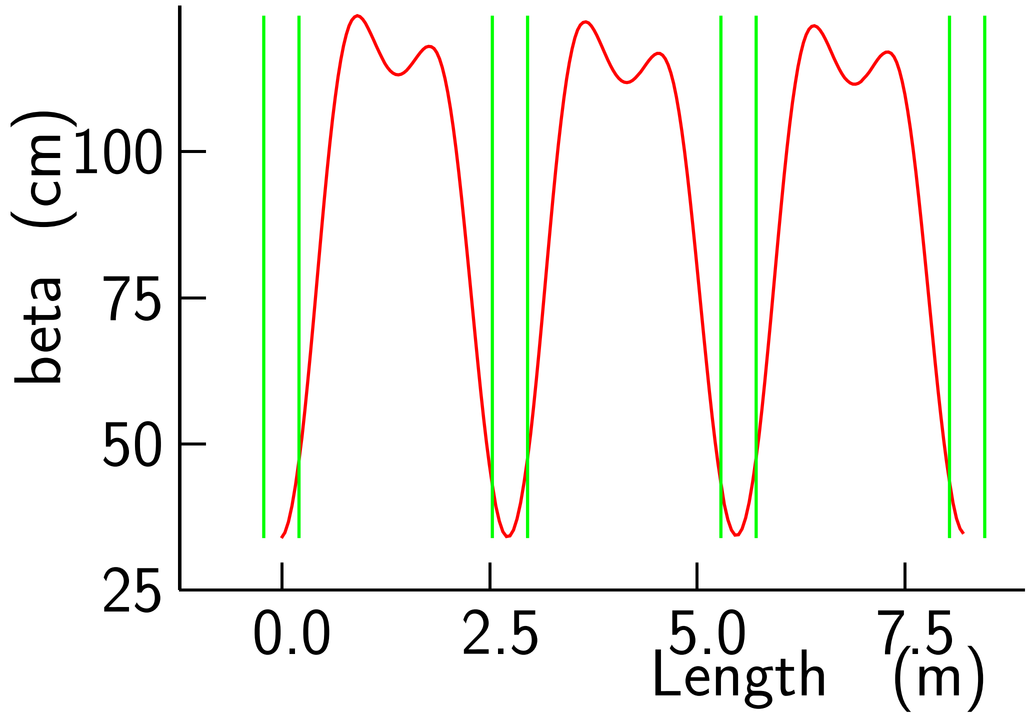
Details vs length



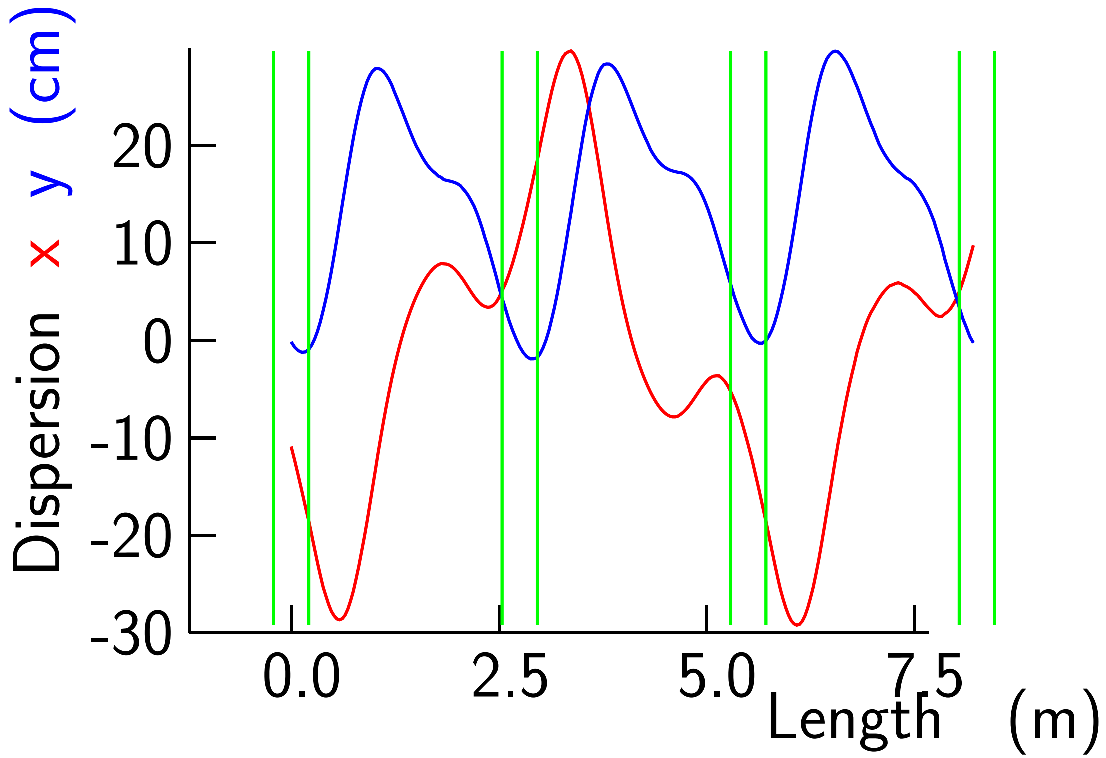
- Momenta drop in absorbers
- And re-accelerated between them in rf



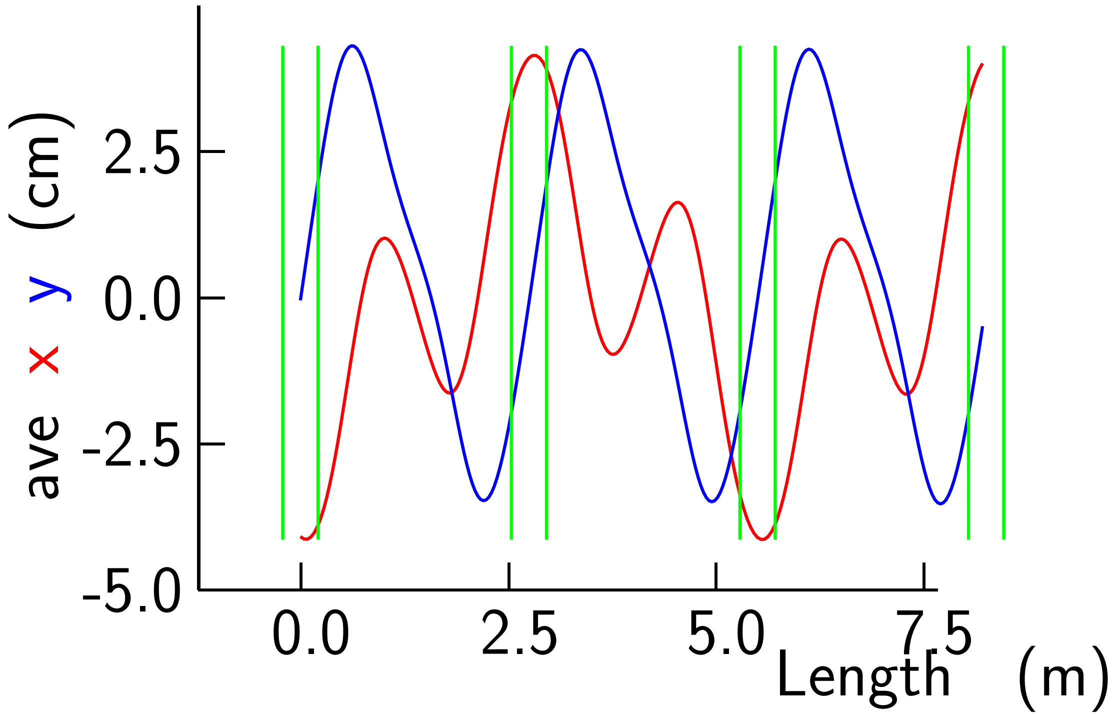
- B fields large at absorbers
- Because solenoids on either side add



- Betas very small at absorbers (2.1 cm)
- But large between them ($\approx$ 120 cm)

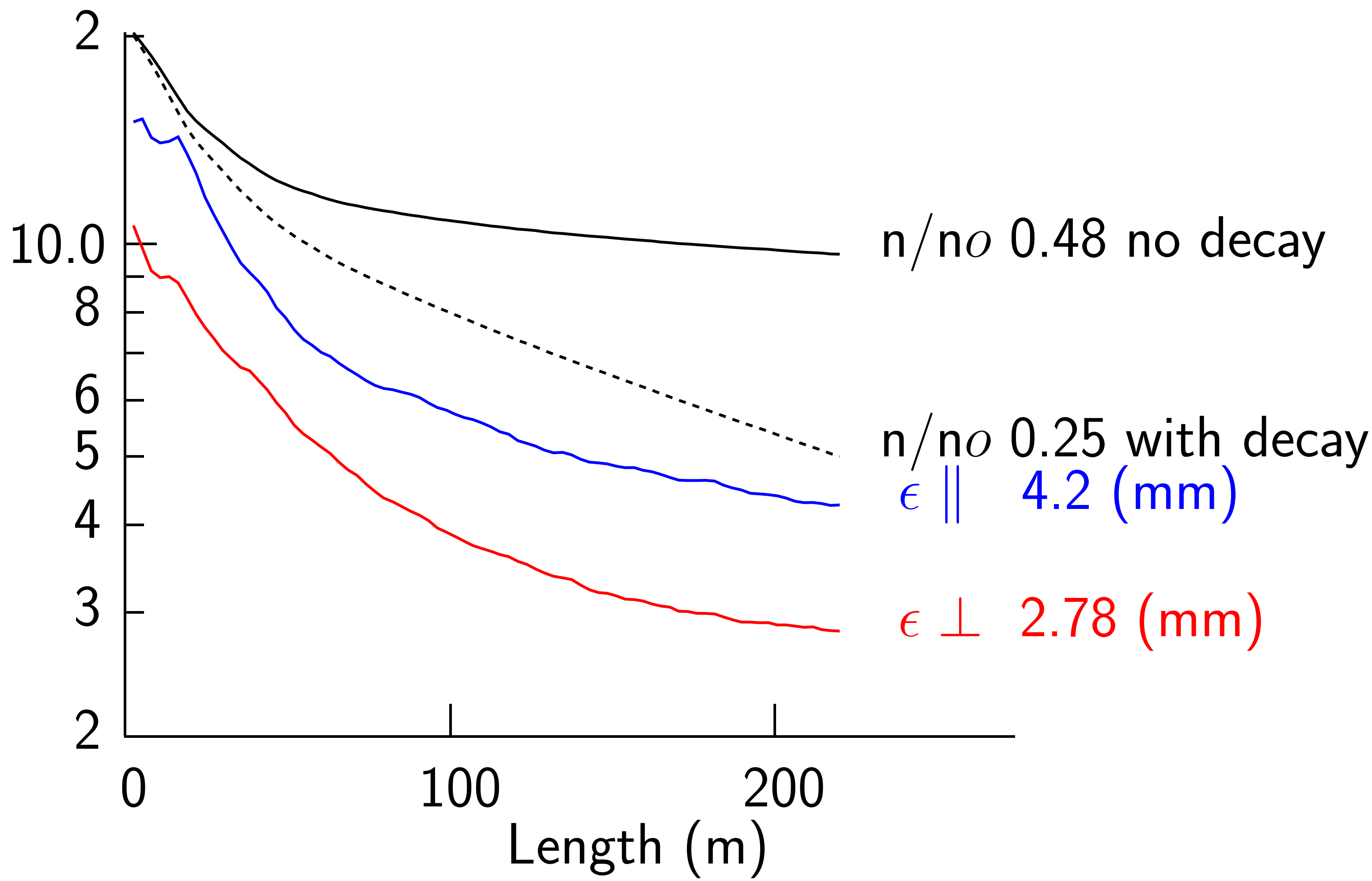


- Dispersions are large (30 cm), but small at absorbers
- However, dispersion prime is large at absorbers

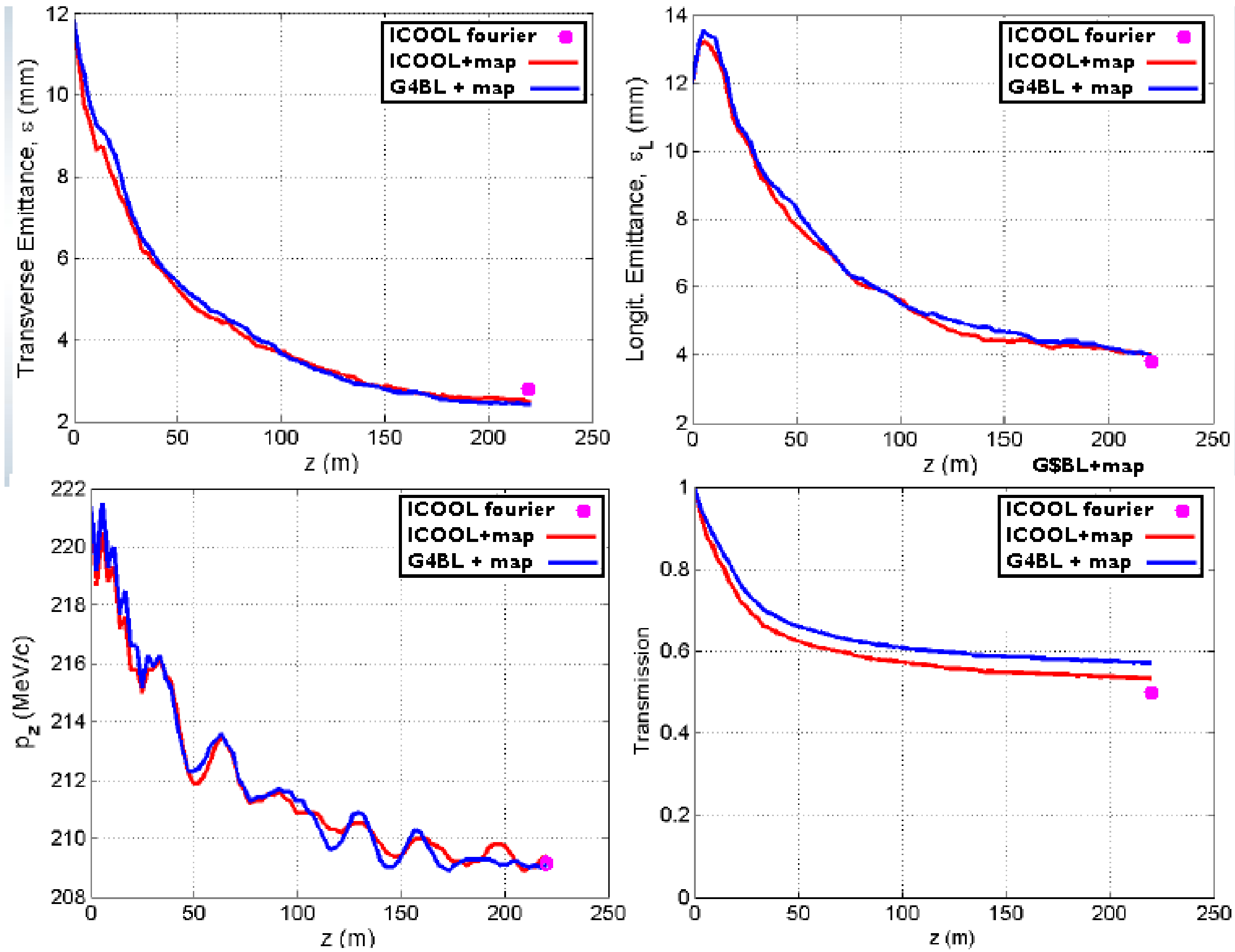


- Beam displacements less than 4 cm (in 18 cm aperture)
- Though bending only in x
  solenoid fields rotate them

ICOOL Simulation of cooling



Simulations with real field maps



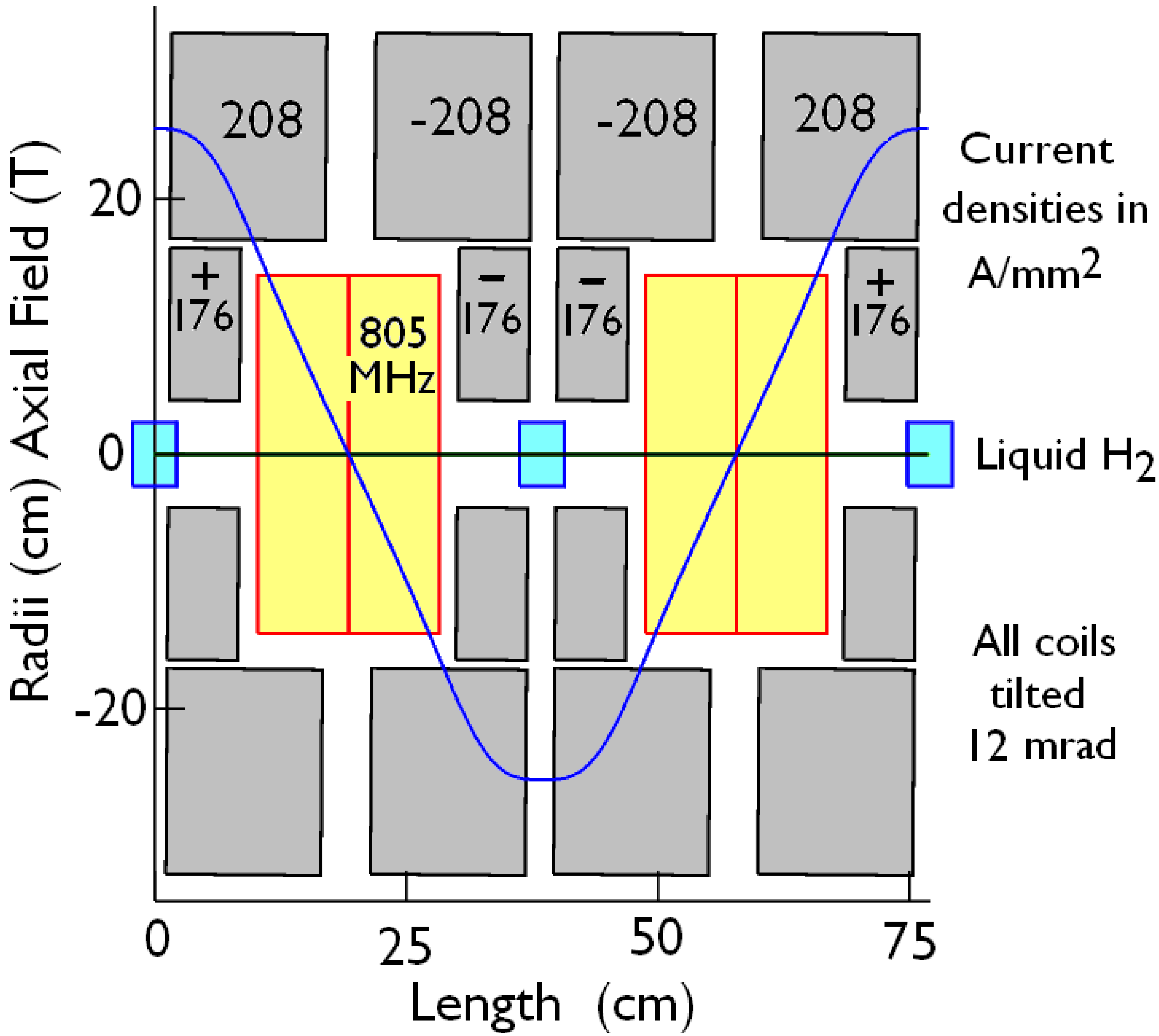
Fair agreements: ICOOL + Fourier, ICOOL + map, G4BL + map
Better transmission & transverse cooling, slightly less longitudinal

Designing a late stage Planar Snake

- Equilibrium emittance $\propto \beta_\perp$ reduced by:
  1. reducing all dimensions while increasing B $\propto 1/L^2$
  2. concentrate bending near absorber, although this reduces mom acceptance

- Reduce cell length: 275 $\longrightarrow$ 38.5 (cm)
- Increase rf frequency: 201 $\longrightarrow$ 805 (MHz)
- Shorten rf while increasing its gradient making space for more coils
- Raise axial field: 2.1 $\longrightarrow$ 24 (T)
- Judiciously concentrate high field near absorbers to decrease beta at the price of reduced momentum acceptance
- Use largest coil blocks to minimize current densities

Late 6D Cooling Cell Design

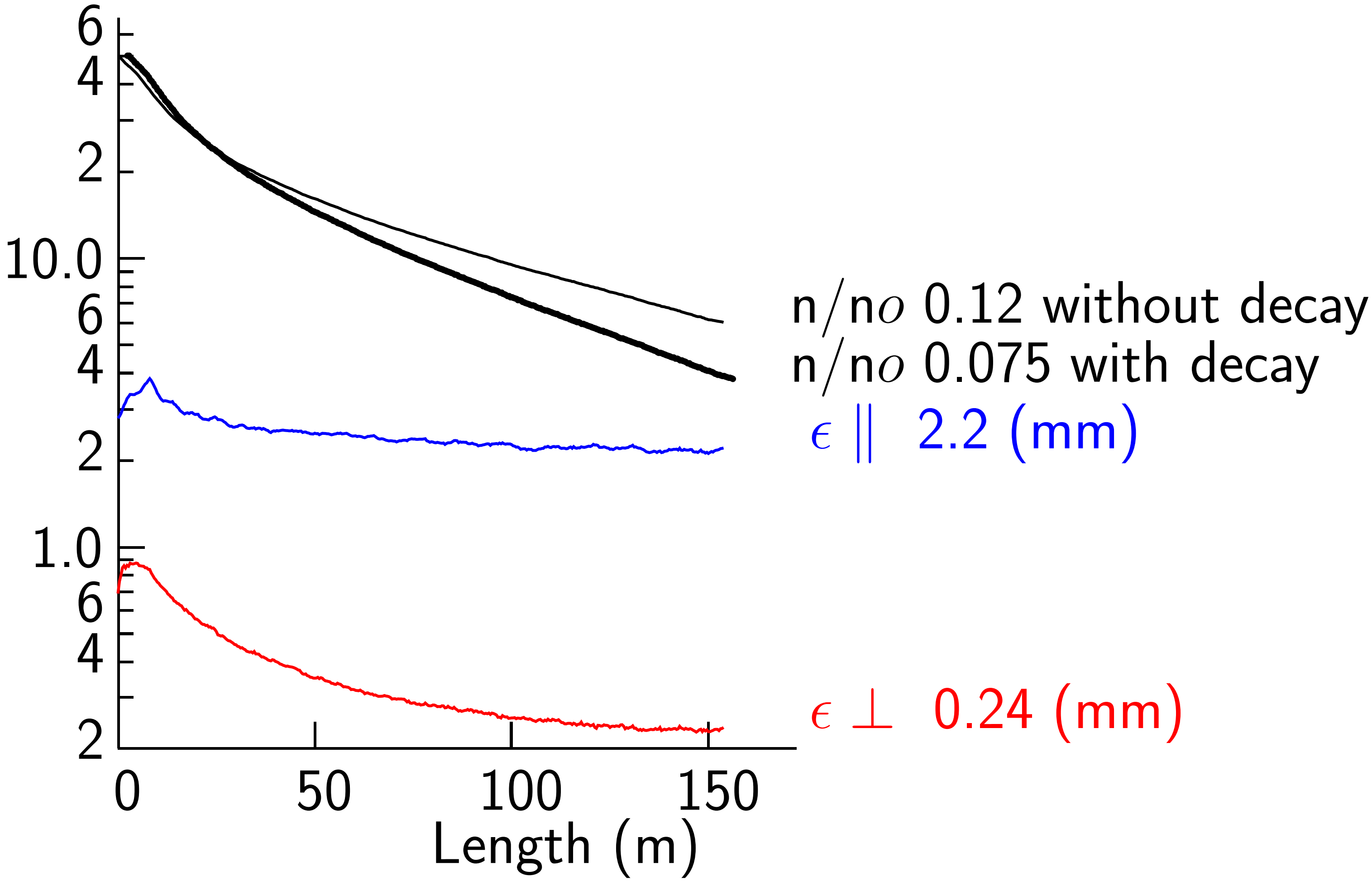


Parameters for late 6D cooling stage

gap m	start m	dl m	rad m	dr m	tilt mrad	I/A A/mm^2
0.014	0.014	0.070	0.042	0.119	12.0	176.47
-0.070	0.014	0.154	0.168	0.161	12.0	208.11
0.049	0.217	0.154	0.168	0.161	12.0	-208.11
-0.070	0.301	0.070	0.042	0.119	12.0	-176.47
0.028	0.399	0.070	0.042	0.119	12.0	-176.47
-0.070	0.399	0.154	0.168	0.161	12.0	-208.11
0.049	0.602	0.154	0.168	0.161	12.0	208.11
-0.070	0.686	0.070	0.042	0.119	12.0	176.47

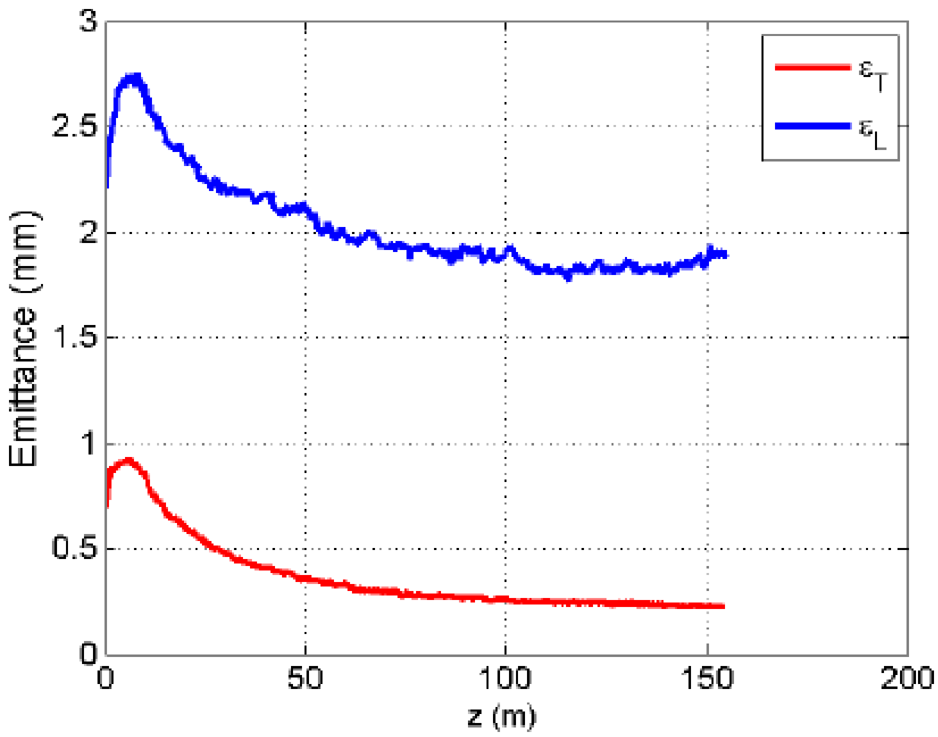
	material	length cm	radius cm	freq. MHz	grad MV/m	phase deg.
Half absorber	Liquid H_2	2.2	2.5			
Absorber window	Aluminum	0.01	2.5			
Gap	Vacuum	8.04	5			
rf cavity	Vacuum	9.0	14	805	35	15
rf cavity	Vacuum	9.0	14	805	35	15
Gap	Vacuum	8.04	5			
Absorber window	Aluminum	0.001	2.5			
Half absorber	Liquid H_2	2.2	2.5			

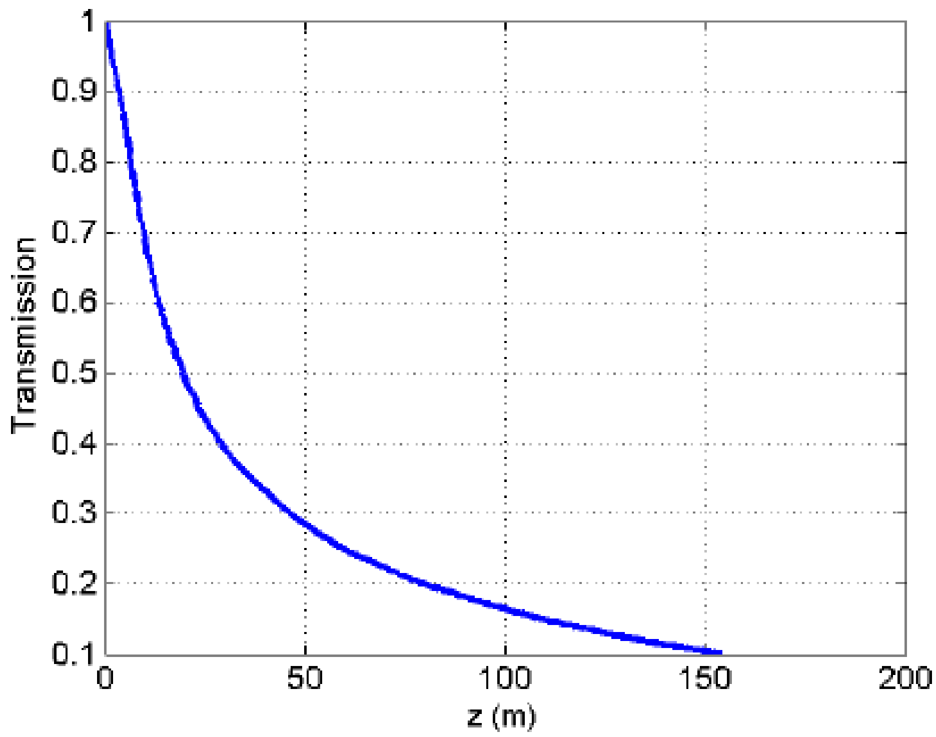
ICOOL Simulation (using Fourier method)



Meets emittance Requirements, but with poor transmission
not yet optimized

ICOOL simulation now with field map





Conclusion

- This lattice was conceived to reduce current densities for late stages, but was tested first in an early 201 MHz stage
- Large dispersions (20-35 cm) are seen with small tilts (0.5 - 1 deg.) from the 2π resonance at the high momentum end
- This arises from the strong angular dispersion at the absorbers combined with significant mean angles
- This is similar to Yuri's Helical FOFO Snake, but is here planar and SFOFO
- This result has been confirmed using field maps in both ICOOL and G4BeamLine
- A design has reached close to the specified emittances
- with current densities ($\approx$ 190 A/mm^2)
- Forces between coils, being inward, are hoped to be acceptable