Planar Snake 6D Cooling Periodic Lattice

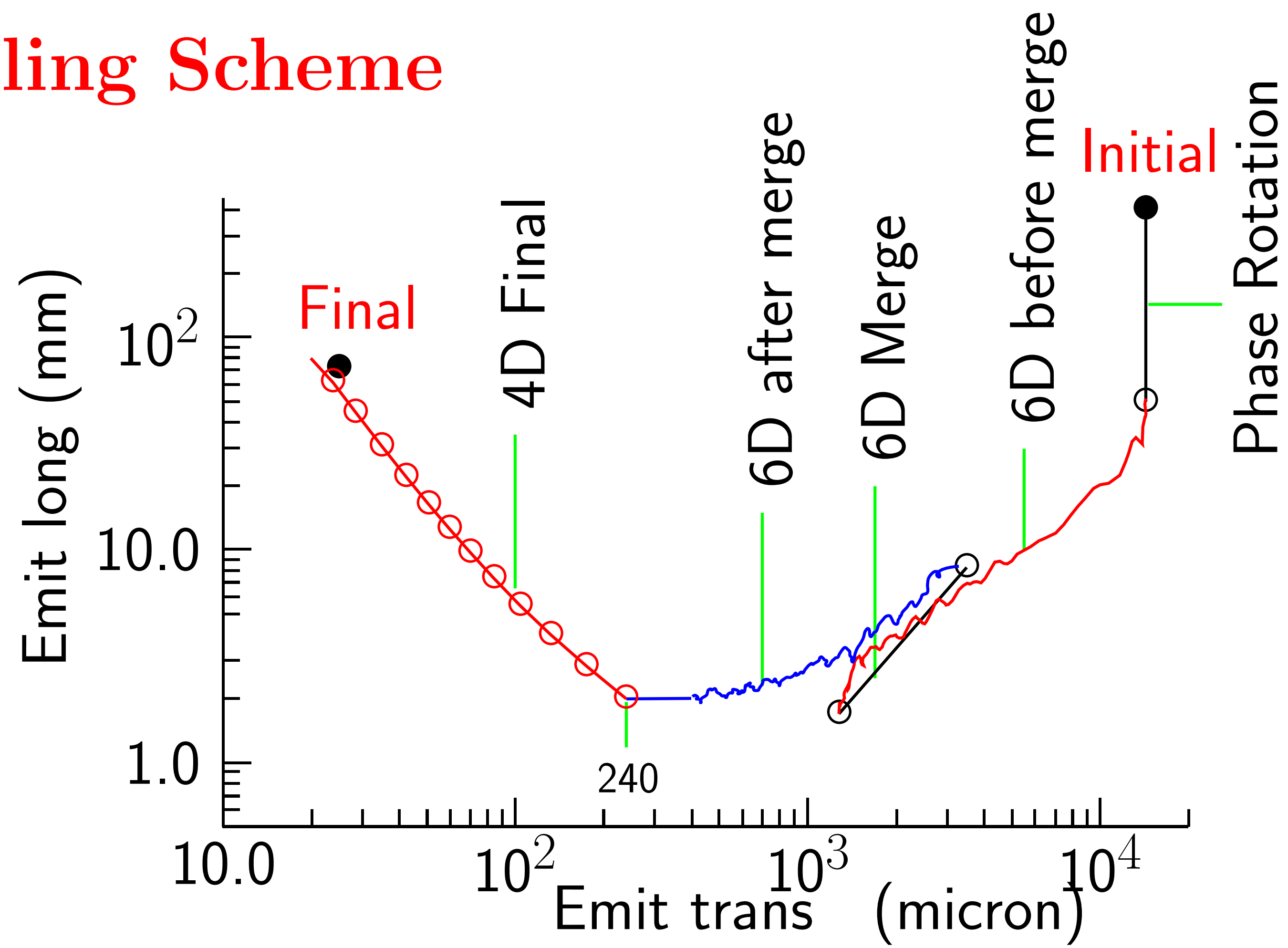
R. B. Palmer, J. S. Berg, D. Stratakis
(BNL)

NUFACT 13

8/22/13

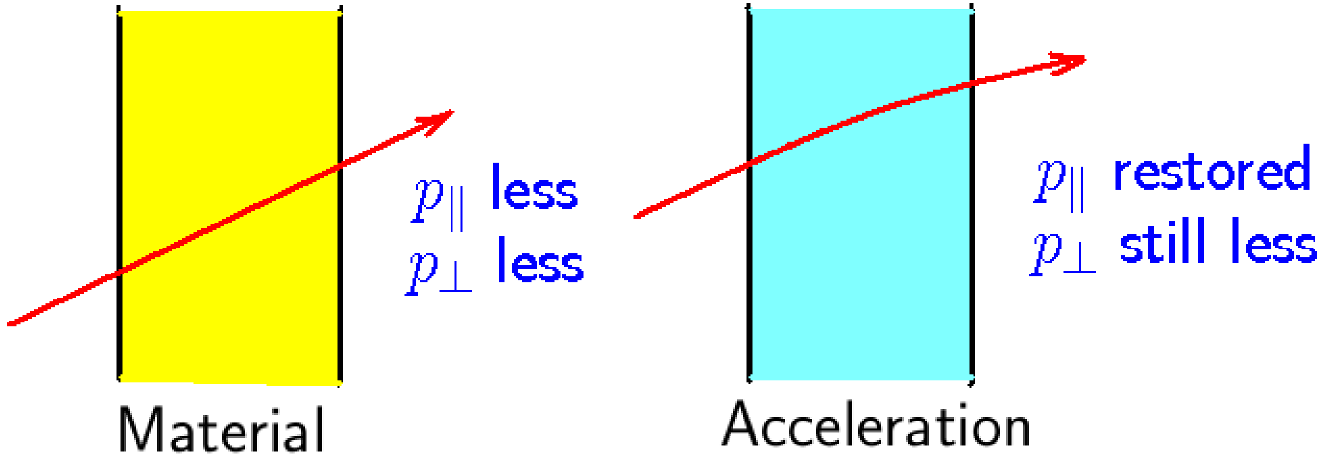
- Introduction
- Guggenheim & other RFOFO Lattices
- Helical FOFO Snake
- Early stage Planar Snake
- Late stage Planar Snake
- Conclusion

Cooling Scheme



- Goal: $\epsilon_\perp = 0.240$ mm, $\epsilon_\parallel = 2$ mm
- Guggenheim/Balbekov designs have met this requirement on paper
- Current densities high & forces challenging
- Motivating search for alternative lattices

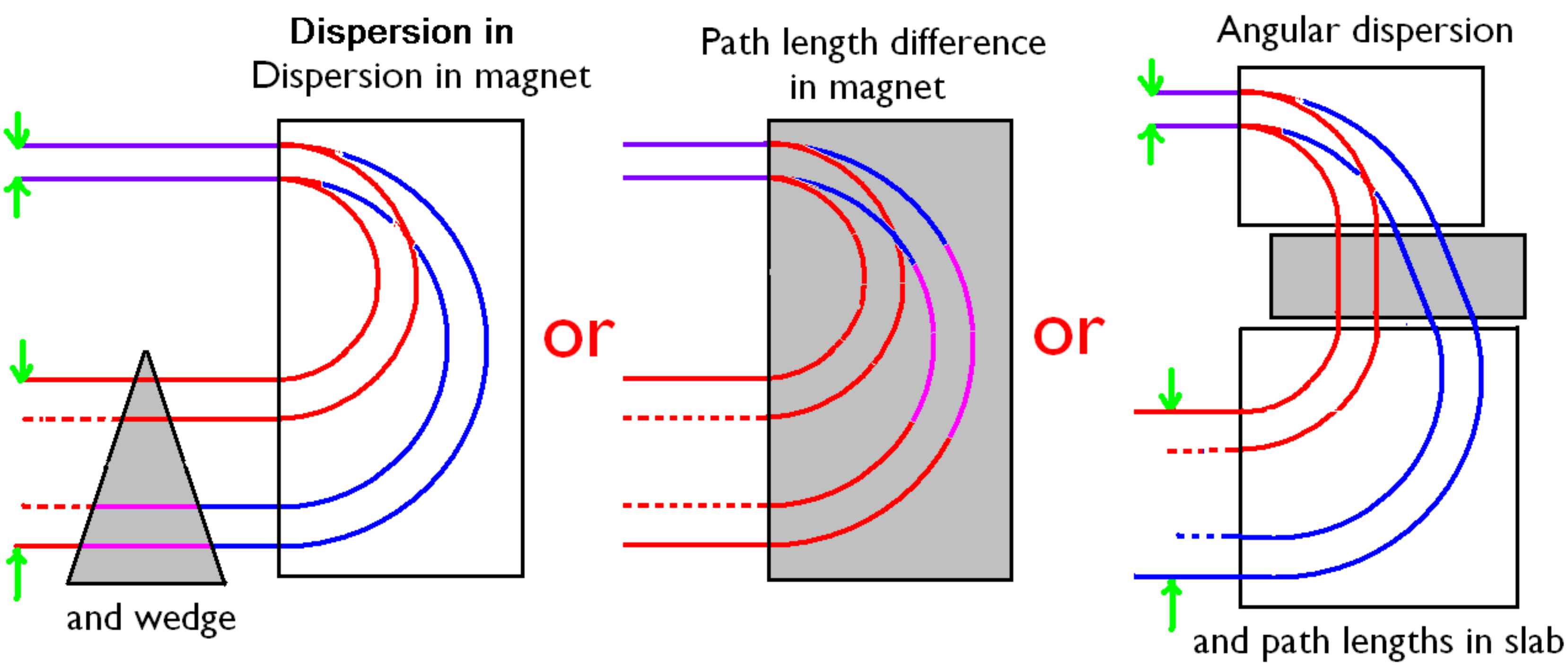
Transverse Cooling



$$\epsilon_{\perp} \propto \beta_{\perp} = \frac{k}{B}$$

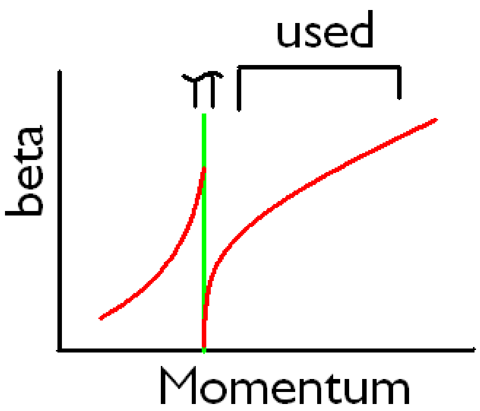
How to get a low k

Emittance Exchange

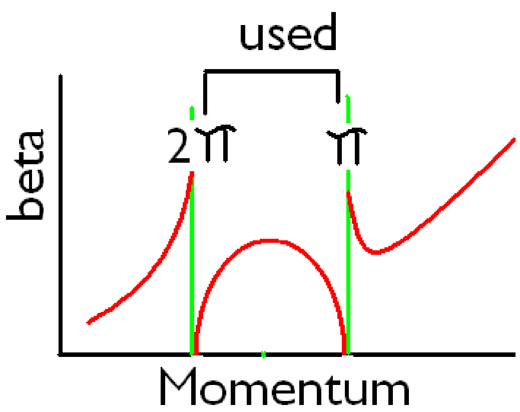


Periodic Lattices Types

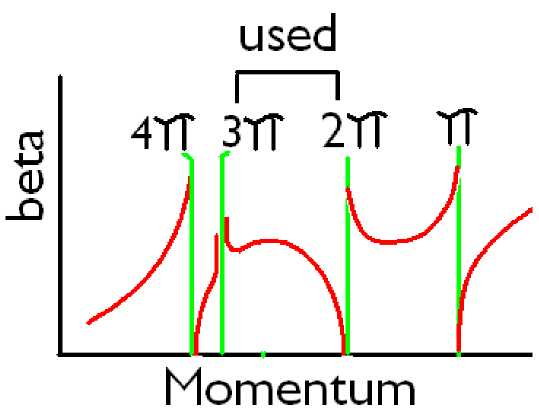
- FOFO (Focus-Focus)
  - simply periodic
  - phase advance $\pi > \phi$
  - used in Final 4D cooling



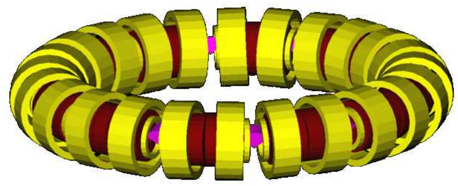
- SFOFO/RFOFO (Super-Focus-Focus)
  - bi-periodic
  - phase advance $2\pi > \phi > \pi$
  - used in Guggenheim



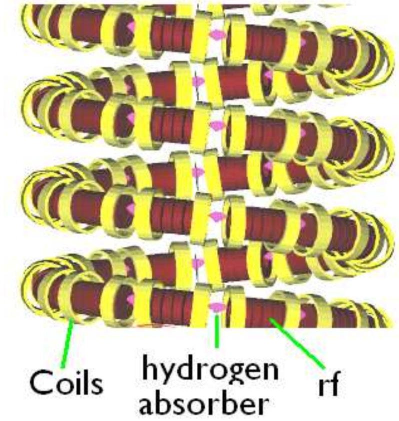
- Higher Tune
  - e.g. Helical FOFO Snake
  - e.g. Planar Snake
  - use phase advance $3\pi > \phi > 2\pi$



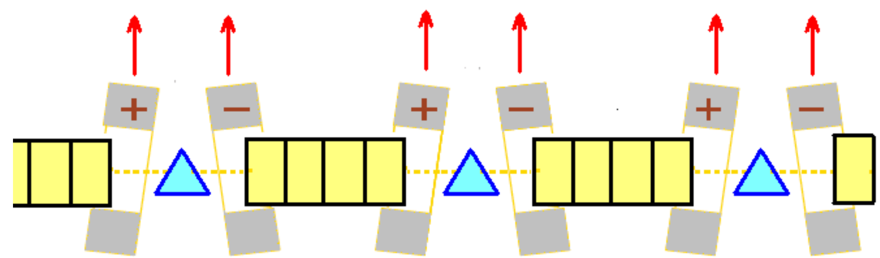
Geometries



1. RFOFO: Ring
   - Injection hard
2. RFOFO: Guggenheim



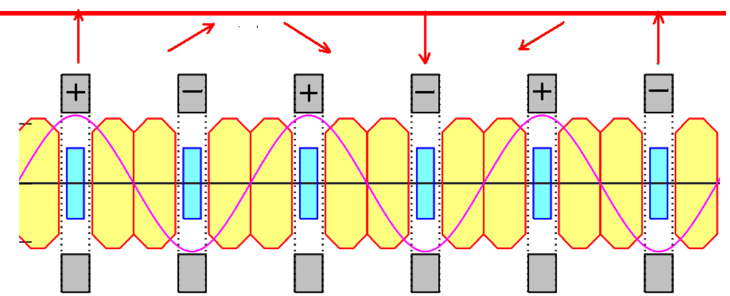
   - Simulation and magnetic shielding hard
3. RFOFO: Balbekov Rectilinear



   - Forces outward & hard
   - Only one charge

---

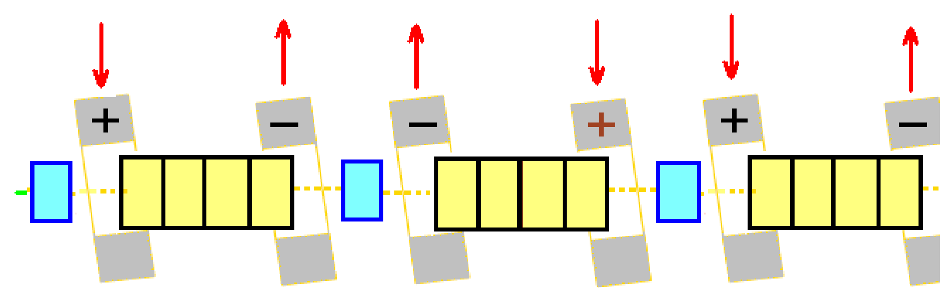
4. Helical FOFO Snake (Alexahin)



   - Axial forces are balanced
   - Cools both signs

---

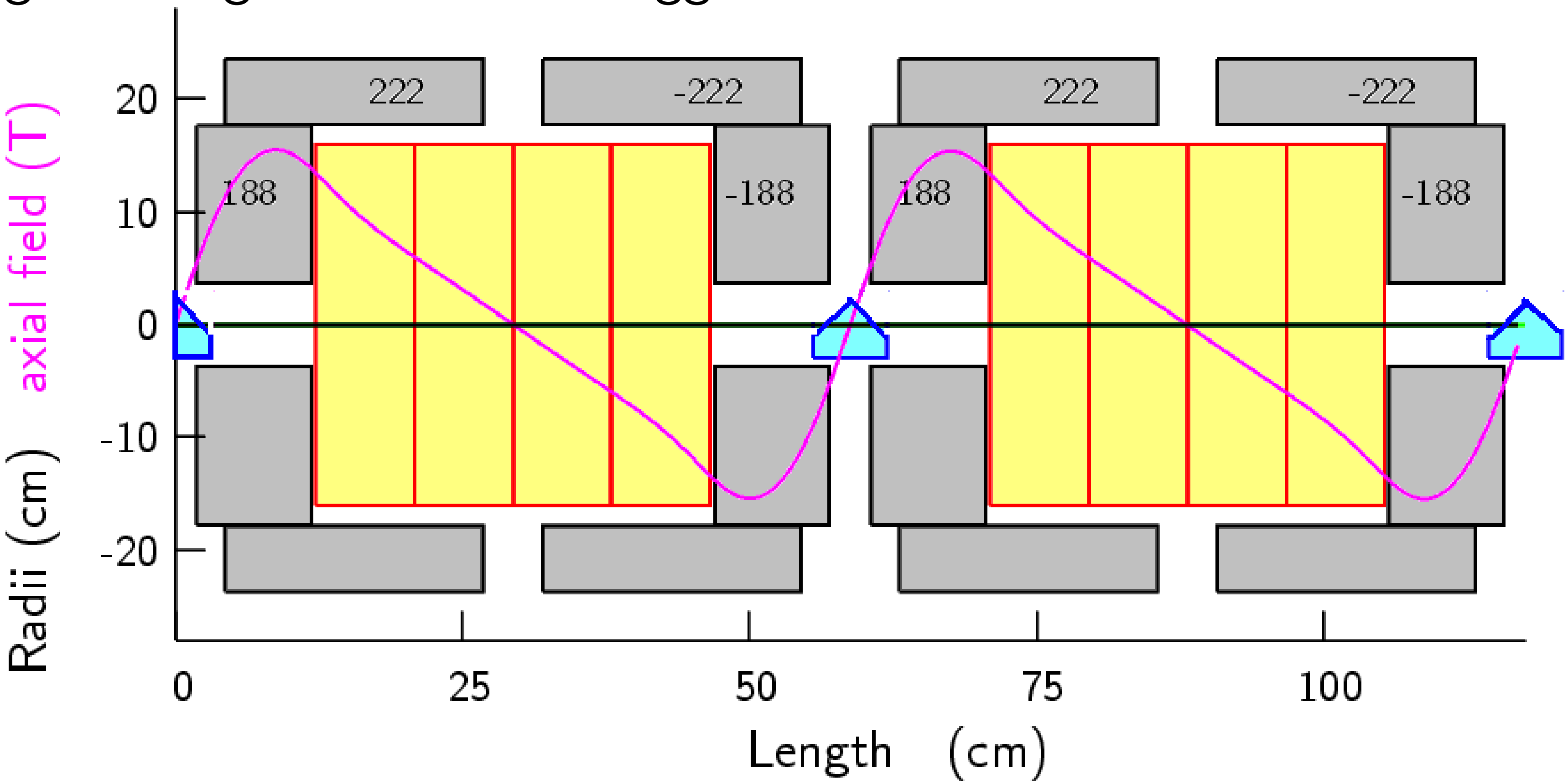
5. Planar RFOFO Snake



   - Forces inward
   - Cools both signs

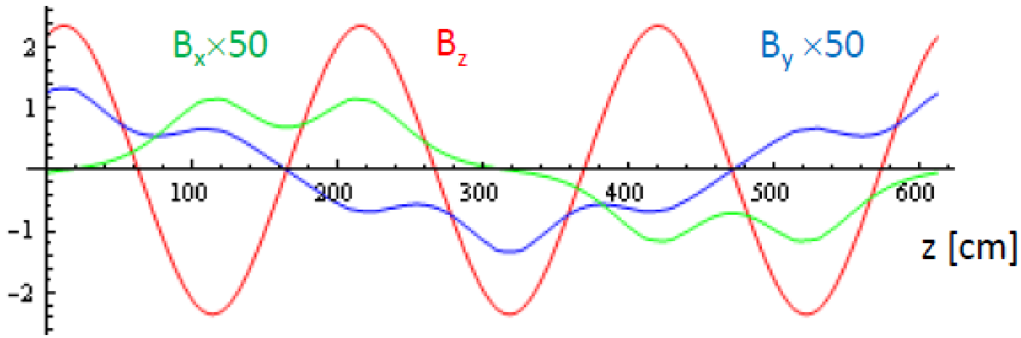
RFOFO Lattices (#1, #2, #3)

eg last stage of Stratakis Guggenheim



- Coils on either side of absorber are bucking
- Current densities high (222 A/mm^2) for β=3.4 cm
- Forces are outward & no space for supports
- Cools only one sign and requires wedge absorbers

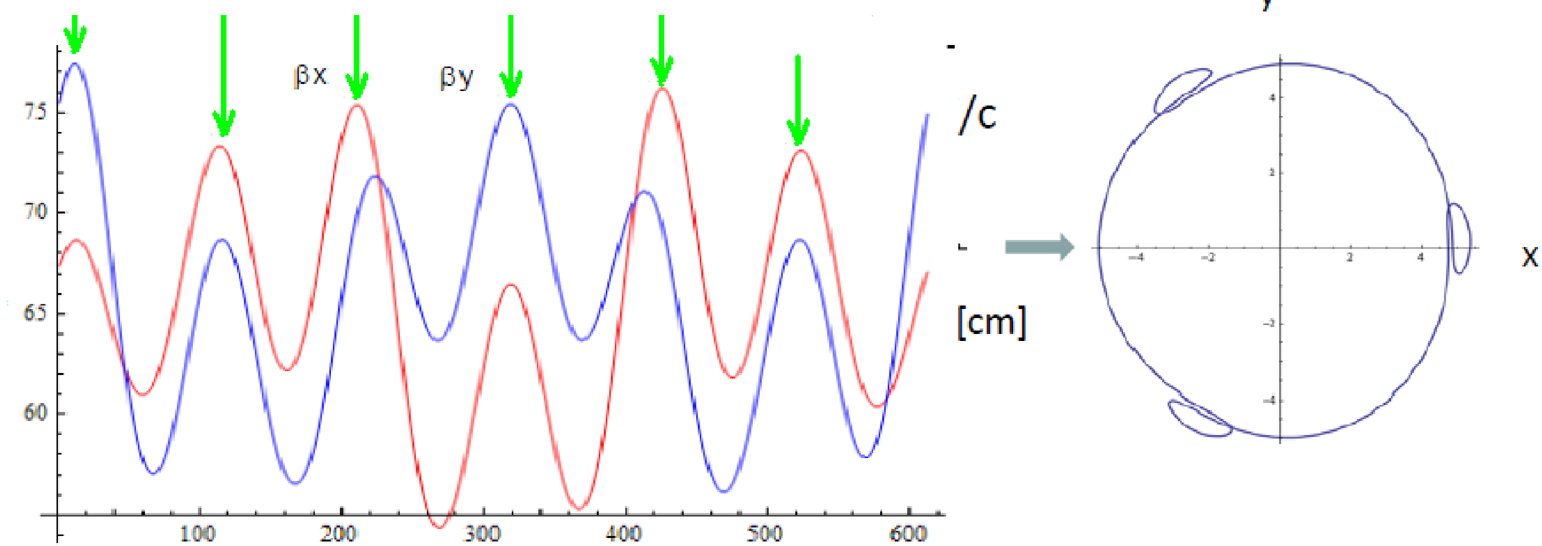
#4 Helical FOFO Snake (Alexahin)



B=2.3 T

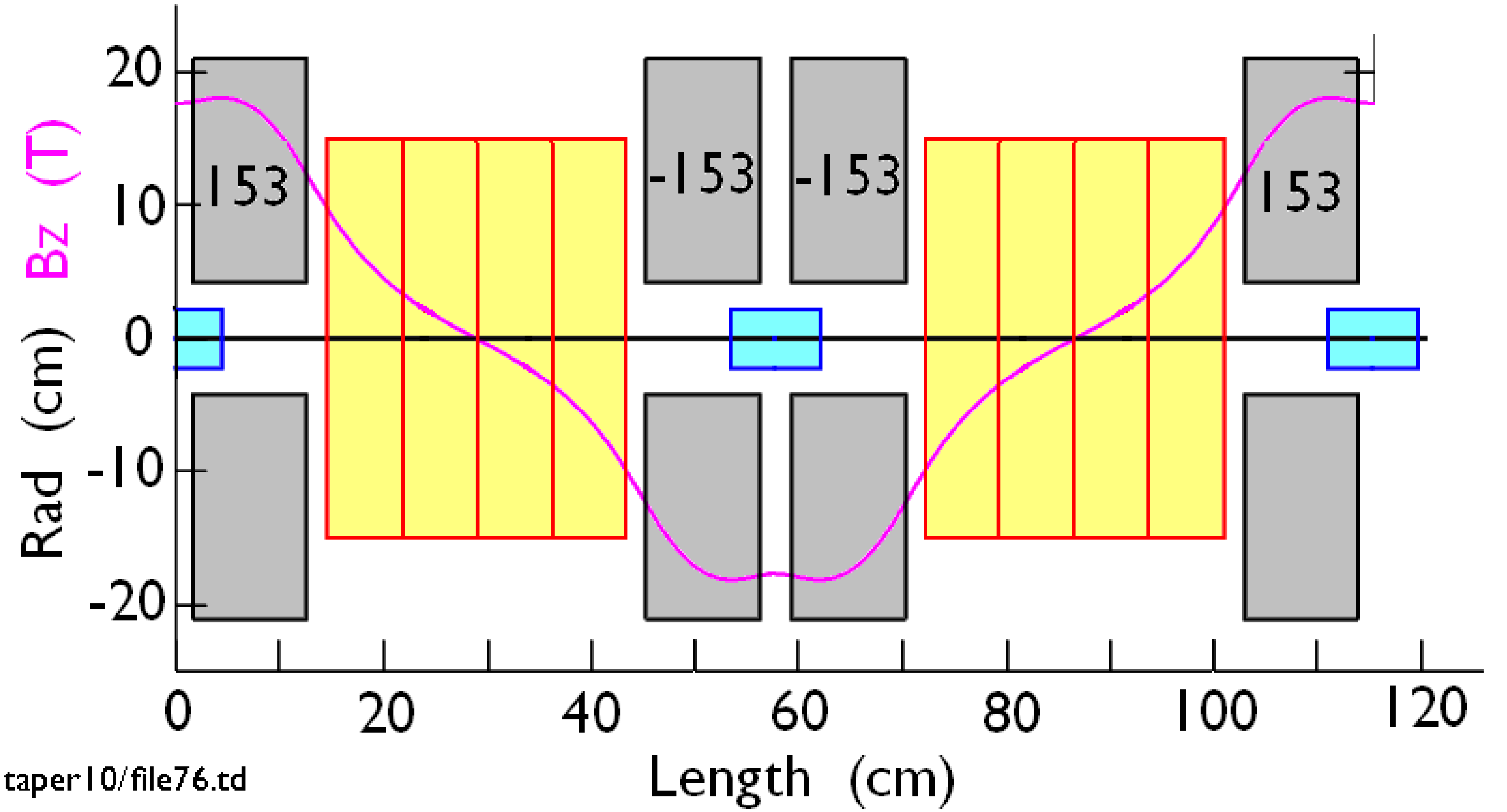
L=600 cm

Dx (max)=5 cm



- Cools both signs with planar absorbers
- But absorbers are at beta maxima (≈ 70 cm)
- Scaling to final beta of 2.4 requires $B = \frac{70}{2.4} \times 2.3 = 67(\text{T})!$
- Good at start of 6D cooling, but not at end

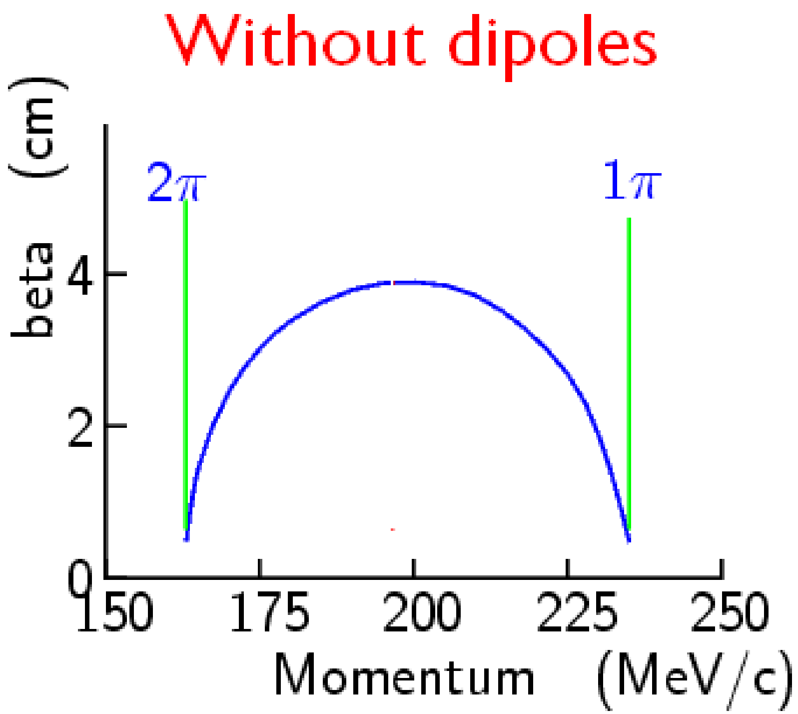
Concept #5: RFOFO Planar Snake

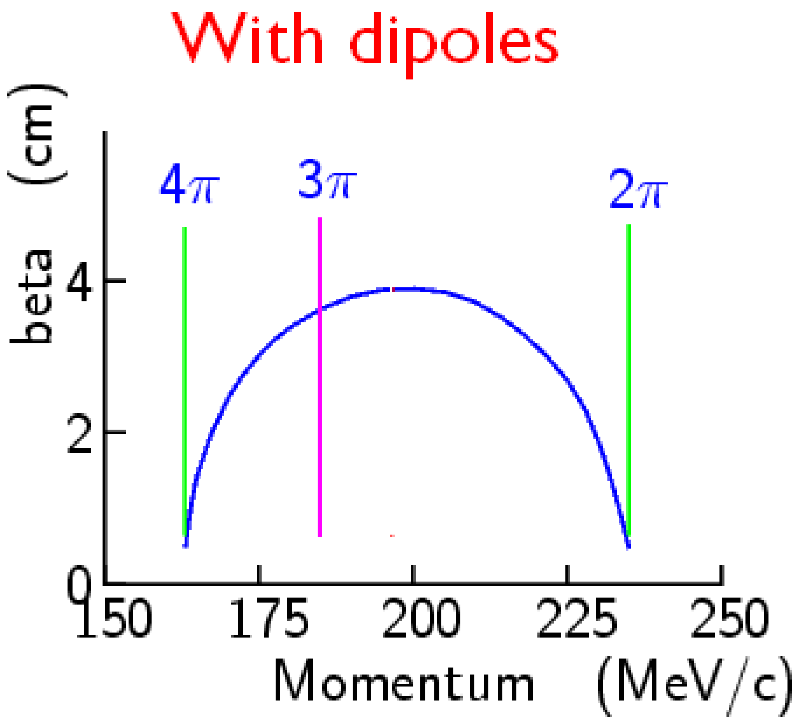


- Coils on either side of absorber are not bucking
- Lower current densities (153 A/mm^2) for a smaller beta $<$ 3 cm
- Forces inward and easy to support
- Without tilts for dipole fields this lattice works well
- But we must add the dipoles to achieve emittance exchange

The disadvantage of this concept

- 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

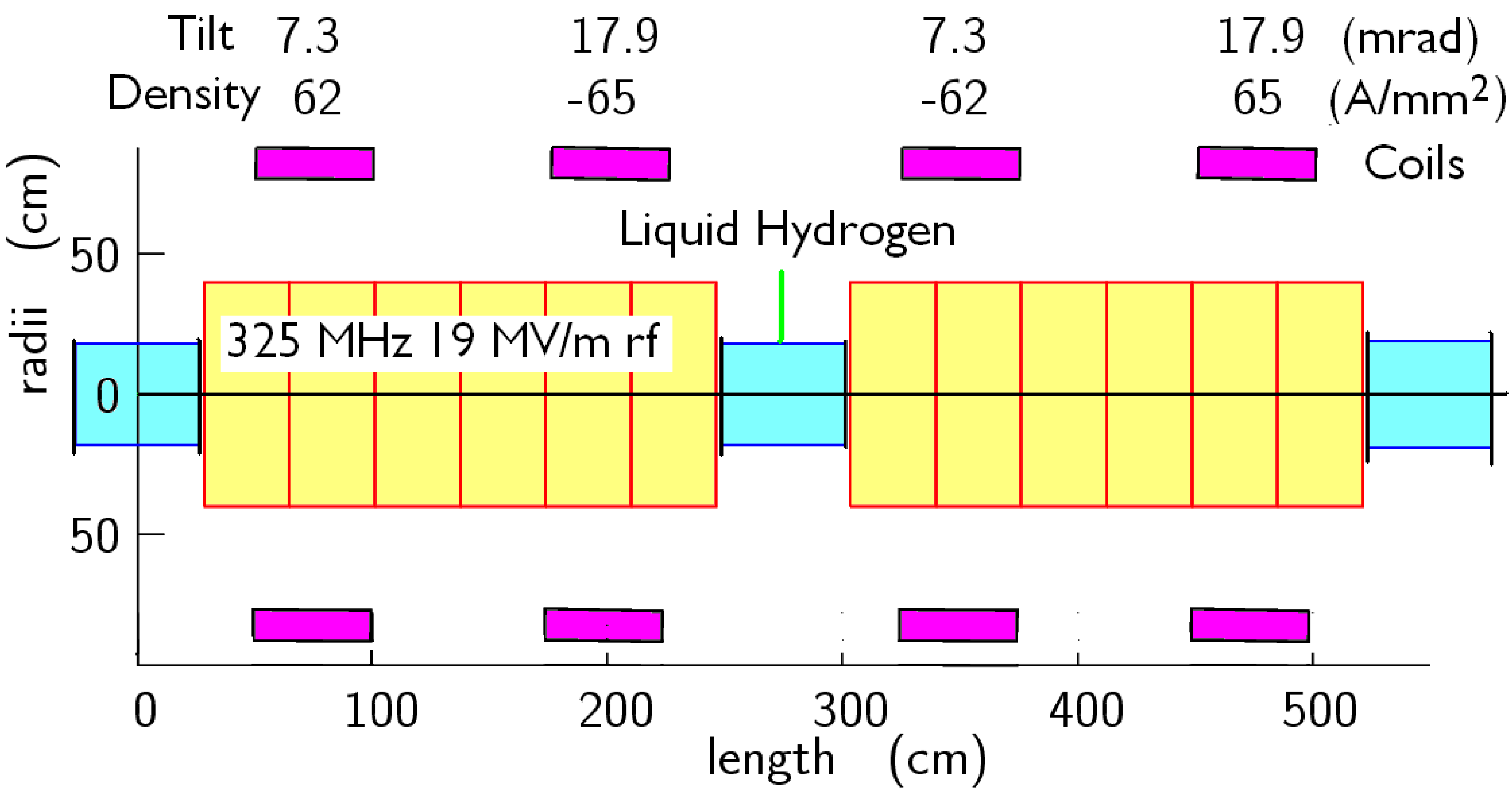
In order to rapidly explore multiple options:

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

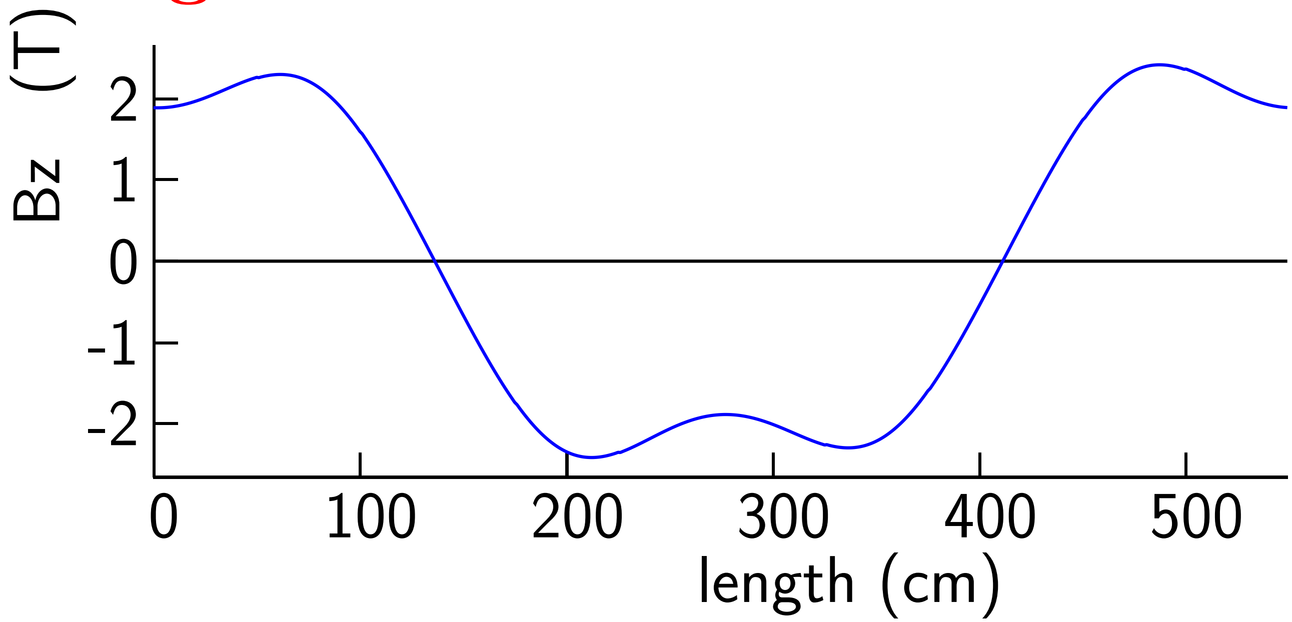
Note that subsequent simmulations with real field maps has confirmed this to be a good approximation

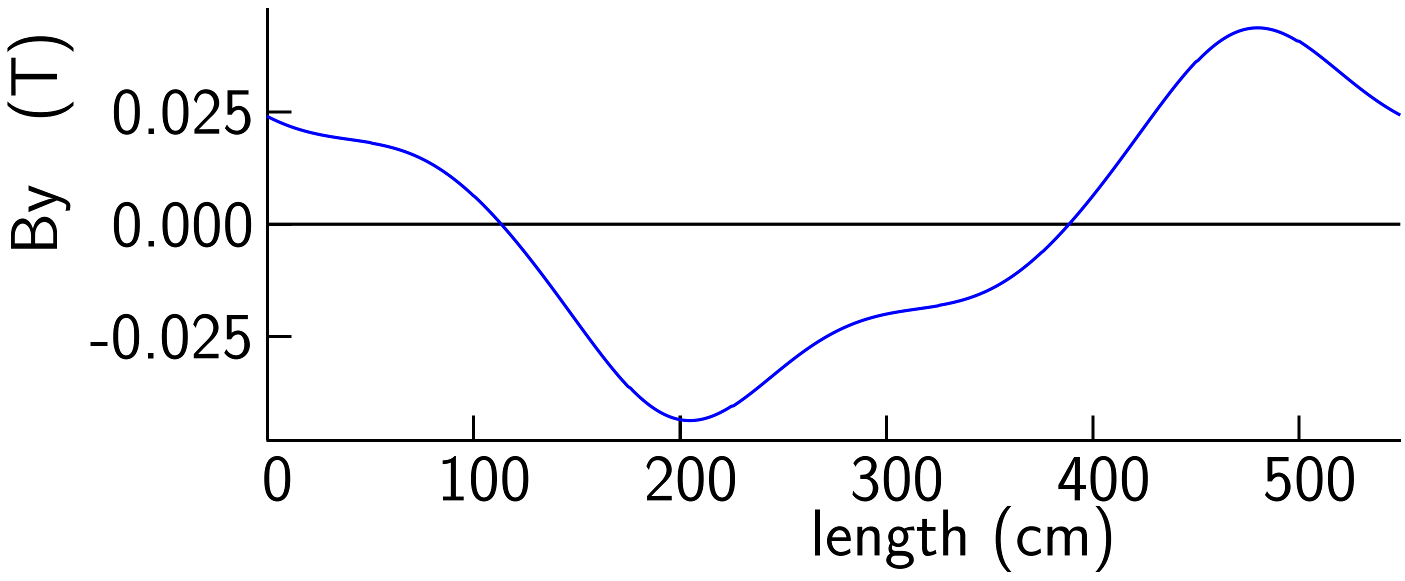
Study of early stage Planar Snake

An early stage using 201 MHz



Magnetic Fields



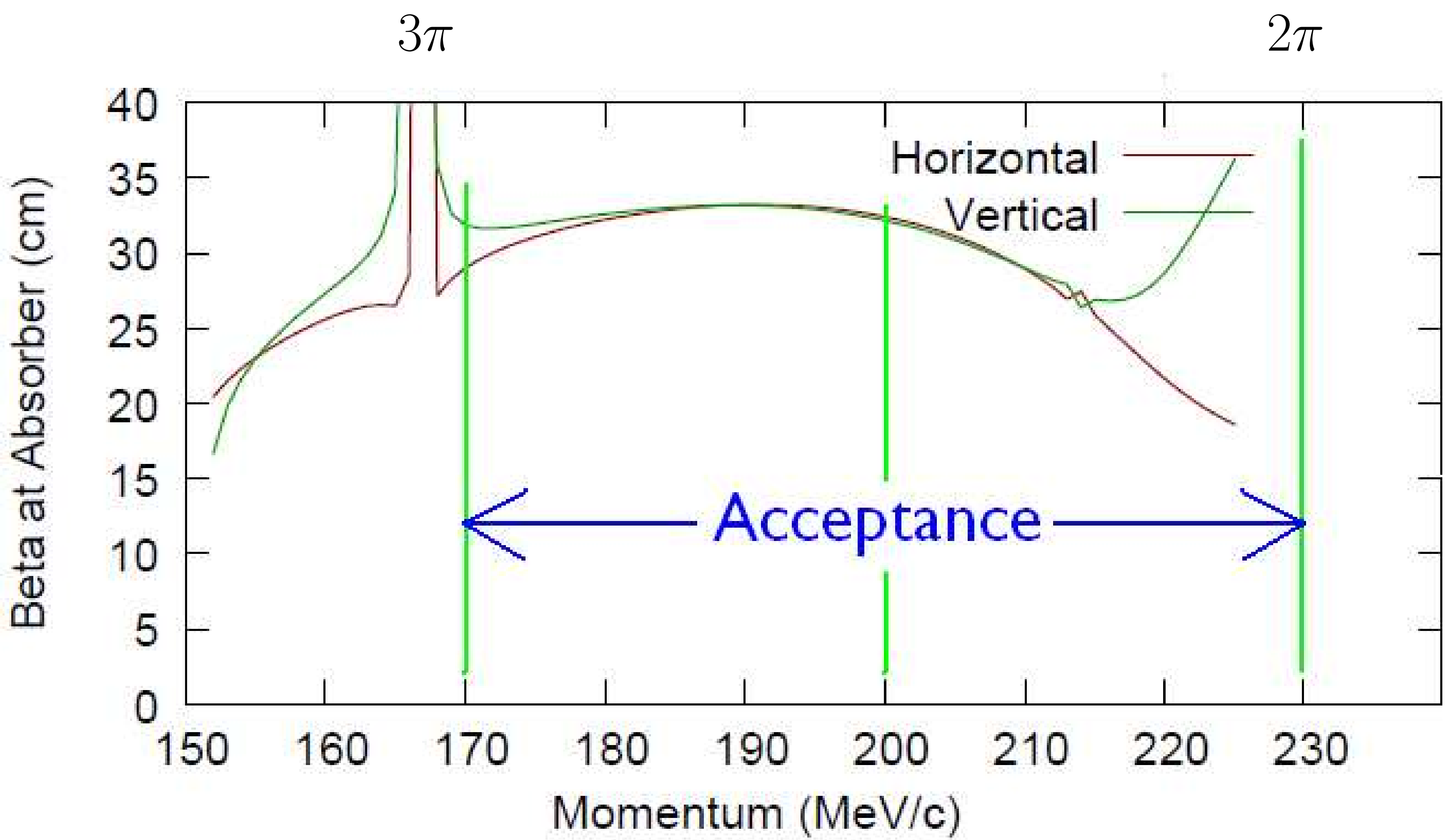


Parameters

gap m	start m	dl m	rad m	dr m	tilt mrad	I/A A/mm^2
0.500	0.500	0.500	0.770	0.110	7.3	62.22
0.750	1.750	0.500	0.770	0.110	17.9	-65.45
0.500	3.250	0.500	0.770	0.110	7.3	-62.22
0.750	4.500	0.500	0.770	0.110	17.9	65.45

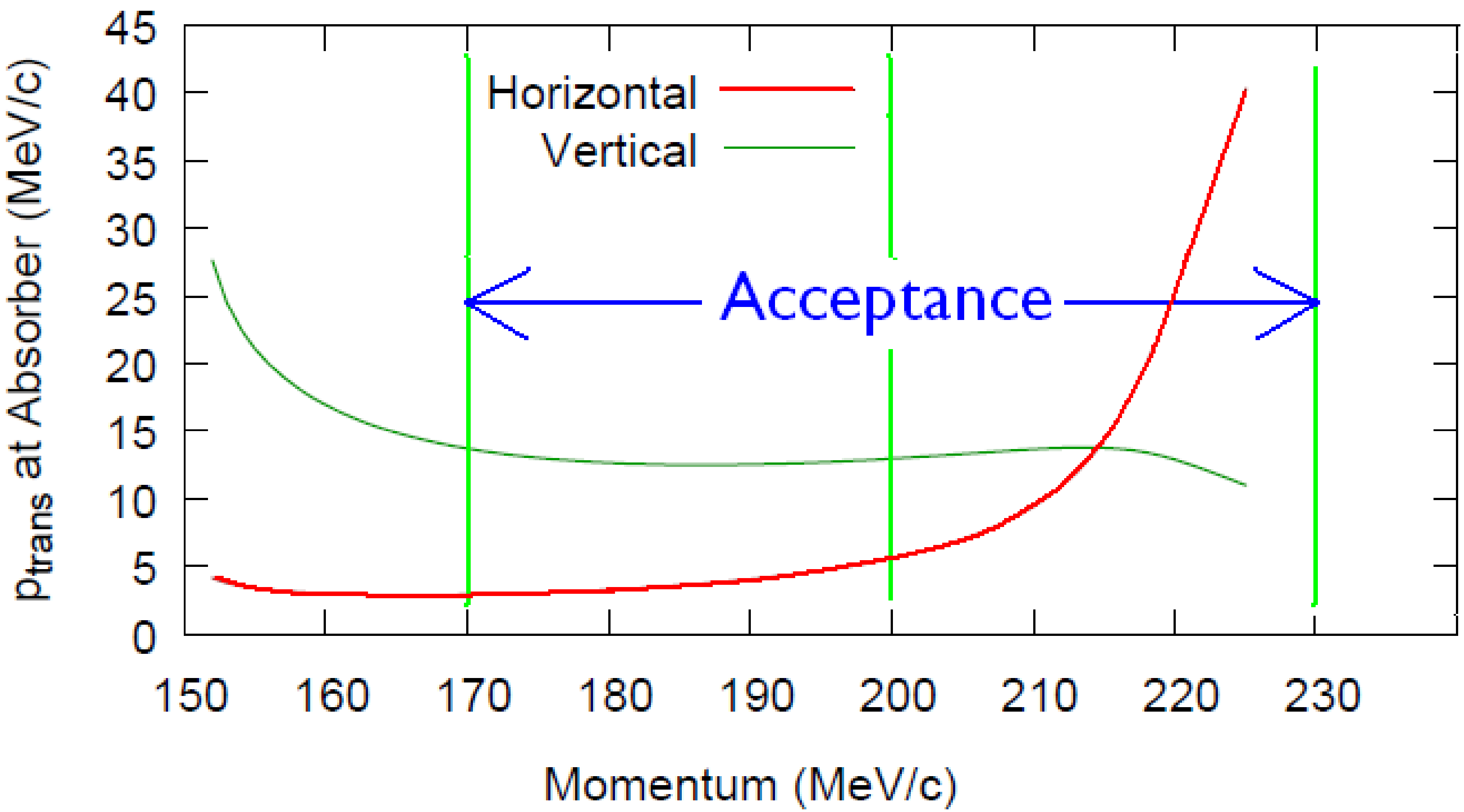
	start cm	dl cm	rad cm	Freq MHz	Grad MV/m	phase deg
H2	-26.30	52.60	18.00			
AL window	26.30	0.050	19.00			
Gap	26.35	2.15				
rf	28.50	36.33	40.00	325	19	30
rf	28.50	36.33	40.00	325	19	30
rf	28.50	36.33	40.00	325	19	30
rf	28.50	36.33	40.00	325	19	30
rf	28.50	36.33	40.00	325	19	30
rf	28.50	36.33	40.00	325	19	30
Gap	246.50	2.15				
AL window	248.65	0.050	19.00			
H2	248.70	52.60	18.00			
AL window	301.30	0.050	19.00			

Betas vs. momentum (Berg)



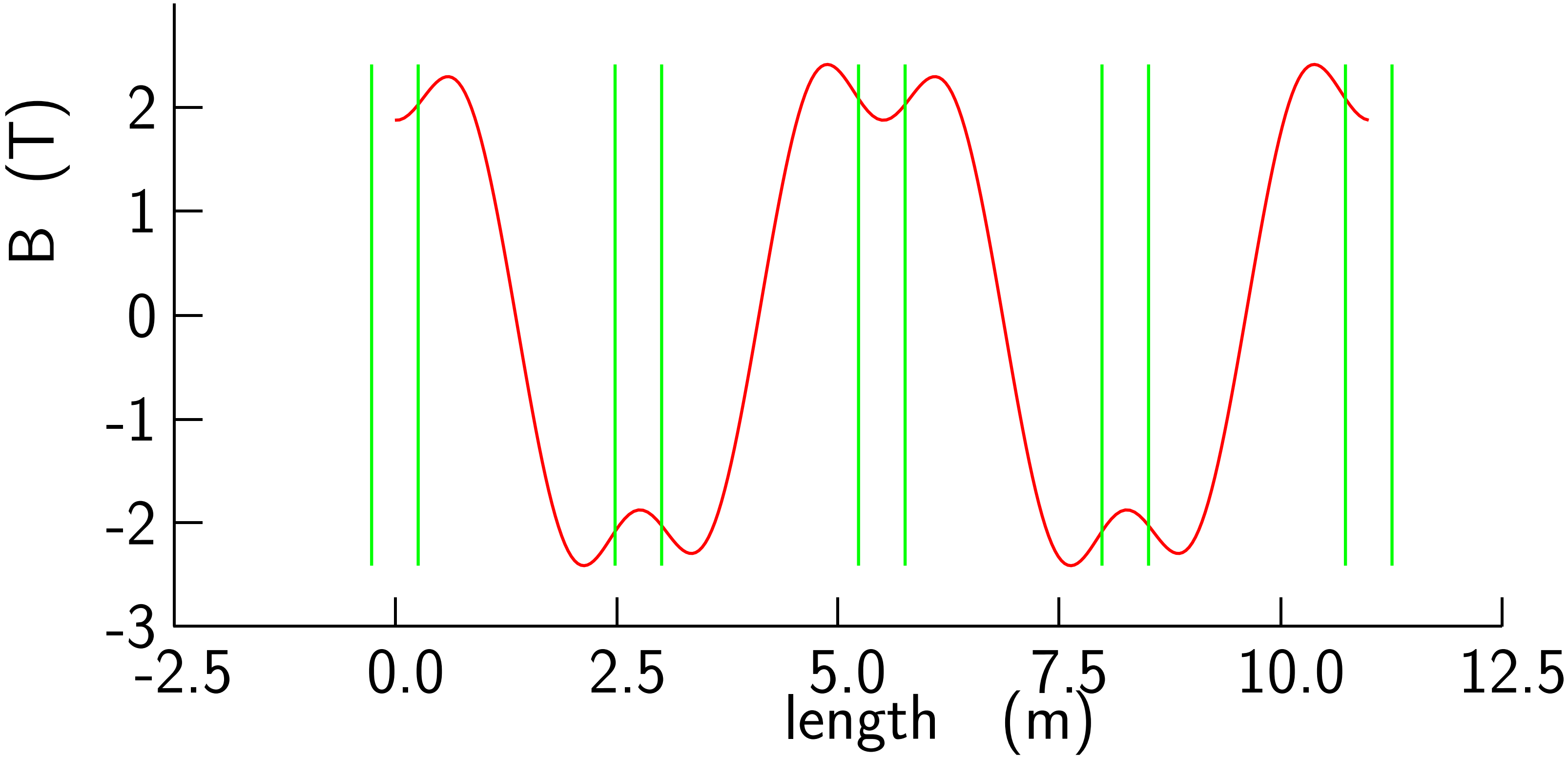
Acceptance extends far into the 2π resonance at 230 MeV/c

Angular dispersion vs.momentum (Berg)

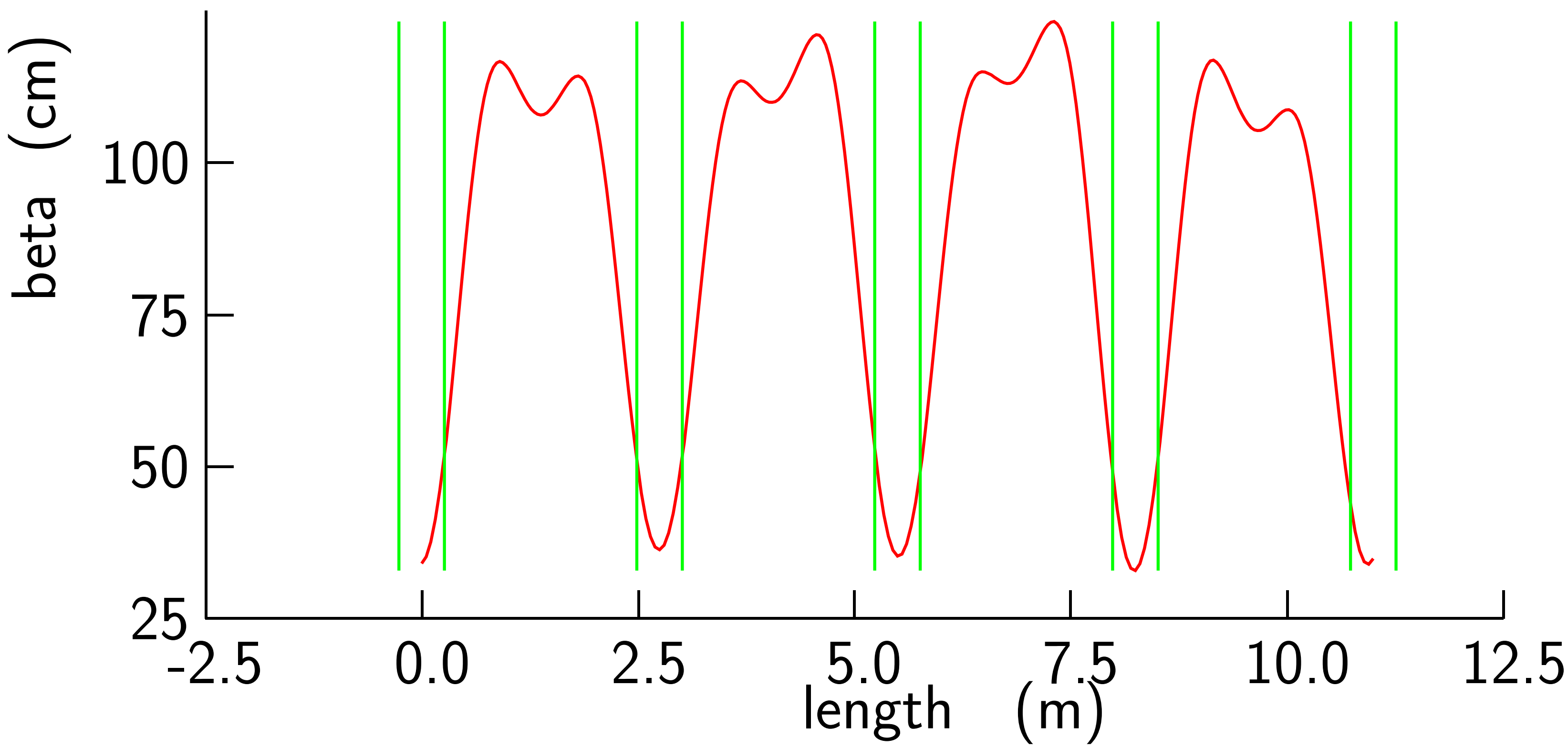


This is a very non-linear angular dispersion enhanced by the 2π resonance at 230 MeV/c but works well

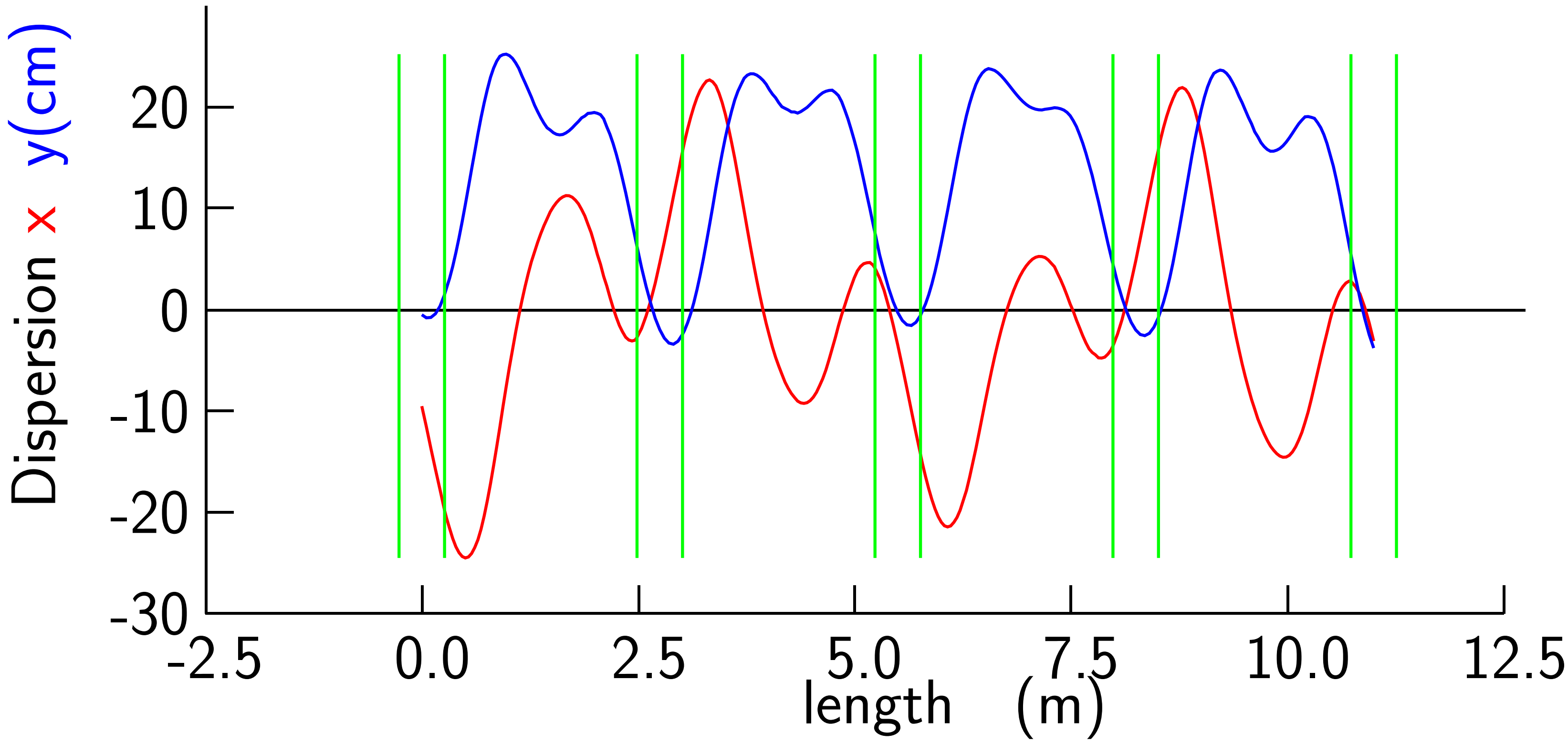
Details vs length



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

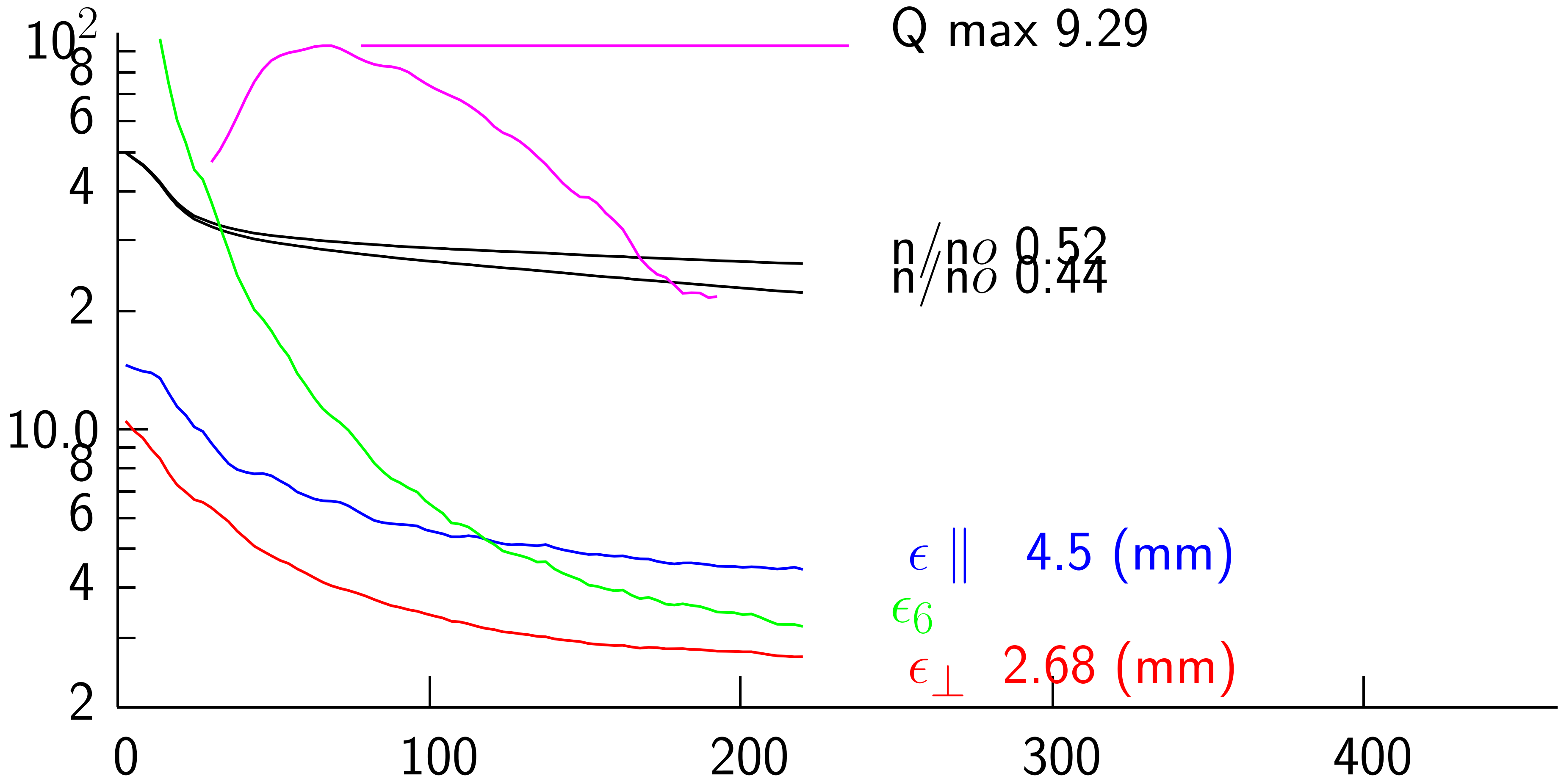


- Betas small at absorbers (30 cm)
- But large between them ($\approx$ 120 cm)



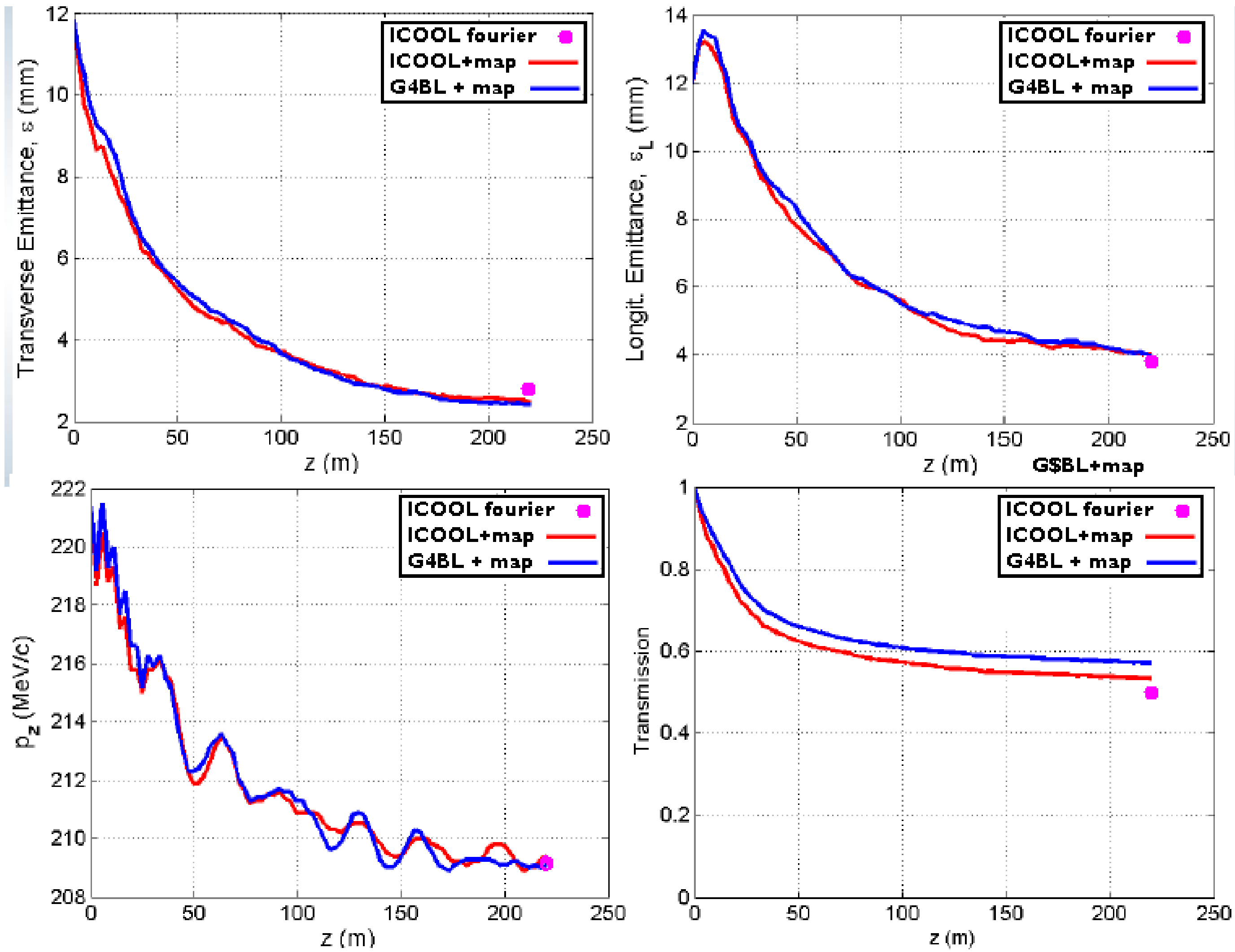
- x and y dispersions are large (30 cm), but small at absorbers
- But x angular dispersion is large at absorbers and gives emittance exchange with flat absorbers

ICOOL Simulation of cooling



- Good cooling in all 6 dimensions
- Q $(d\epsilon_6/\epsilon_6)/(dn/n)$ good or better than RFOFOs

Simulations with real field maps



Fair agreements: ICOOL + Fourier, ICOOL + map, G4BL + map

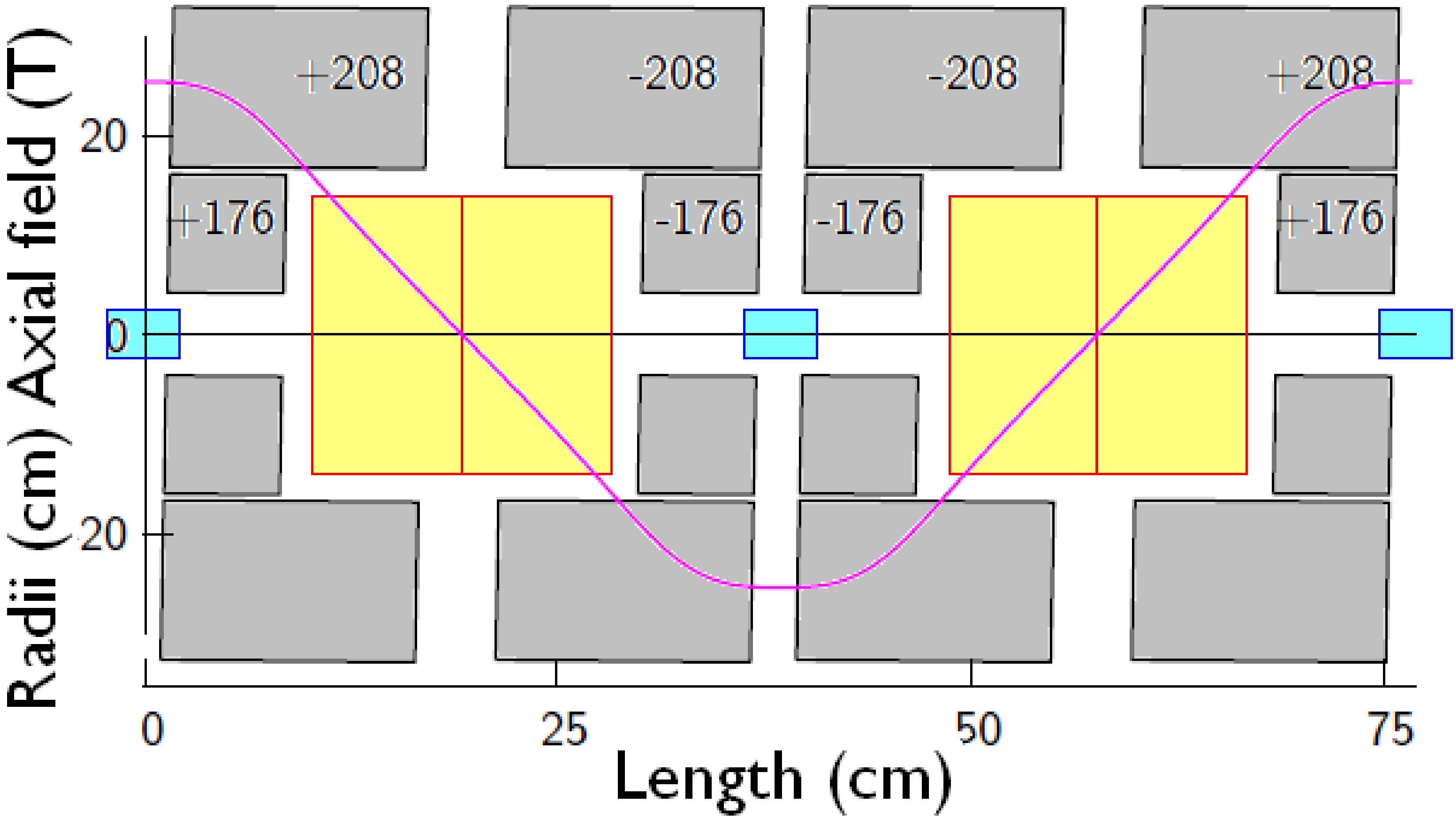
Better transmission & transverse cooling, slightly less longitudinal

Designing a Late Stage Planar Snake

- Equilibrium emittance $\propto \beta_\perp$ reduced by:
  1. reducing all dimensions while increasing B $\propto 1/L$
  2. 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

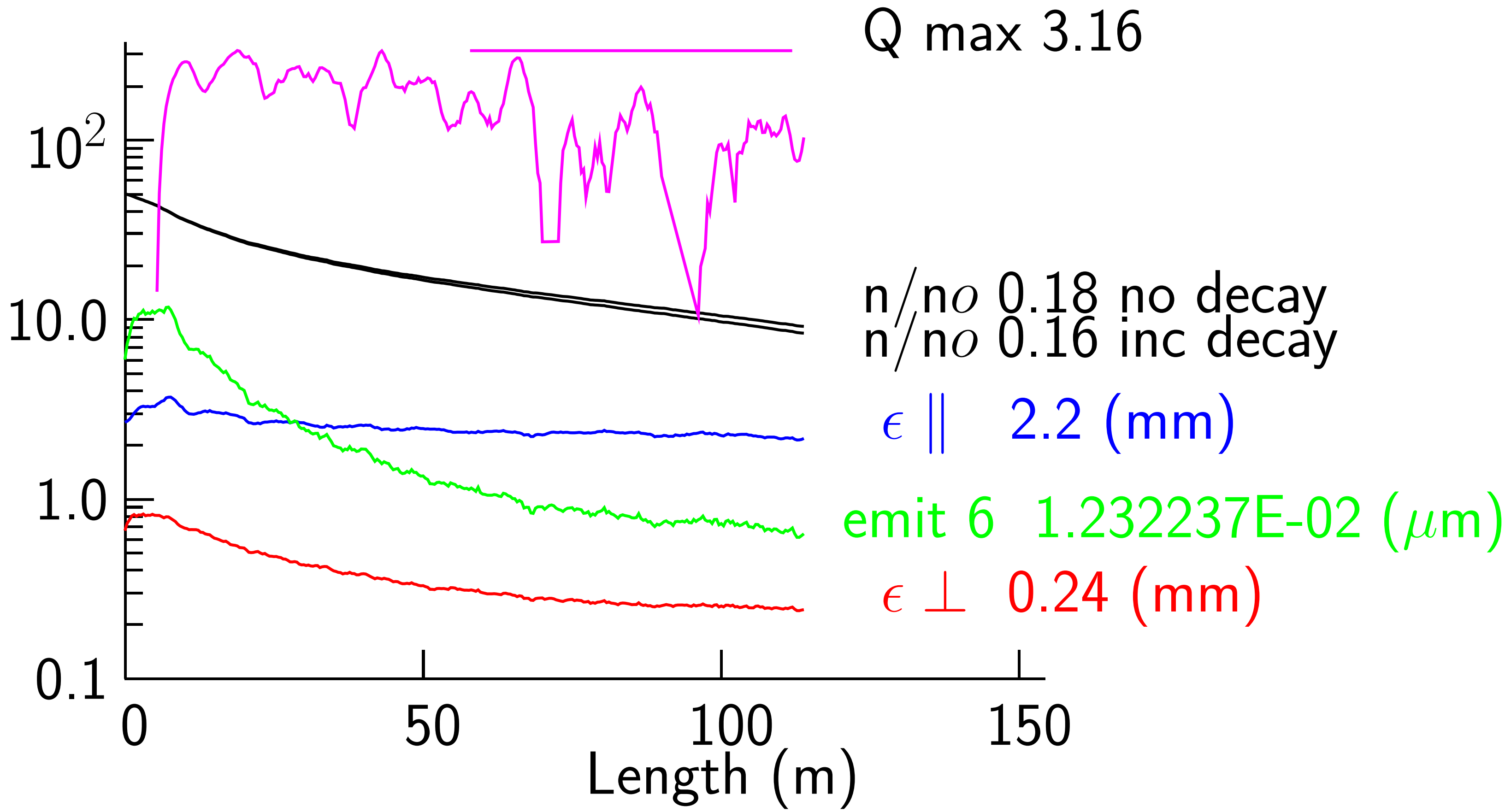


Parameters for late 6D cooling stage

gap	start	dl	rad	dr	tilt	I/A
m	m	m	m	m	mrad	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

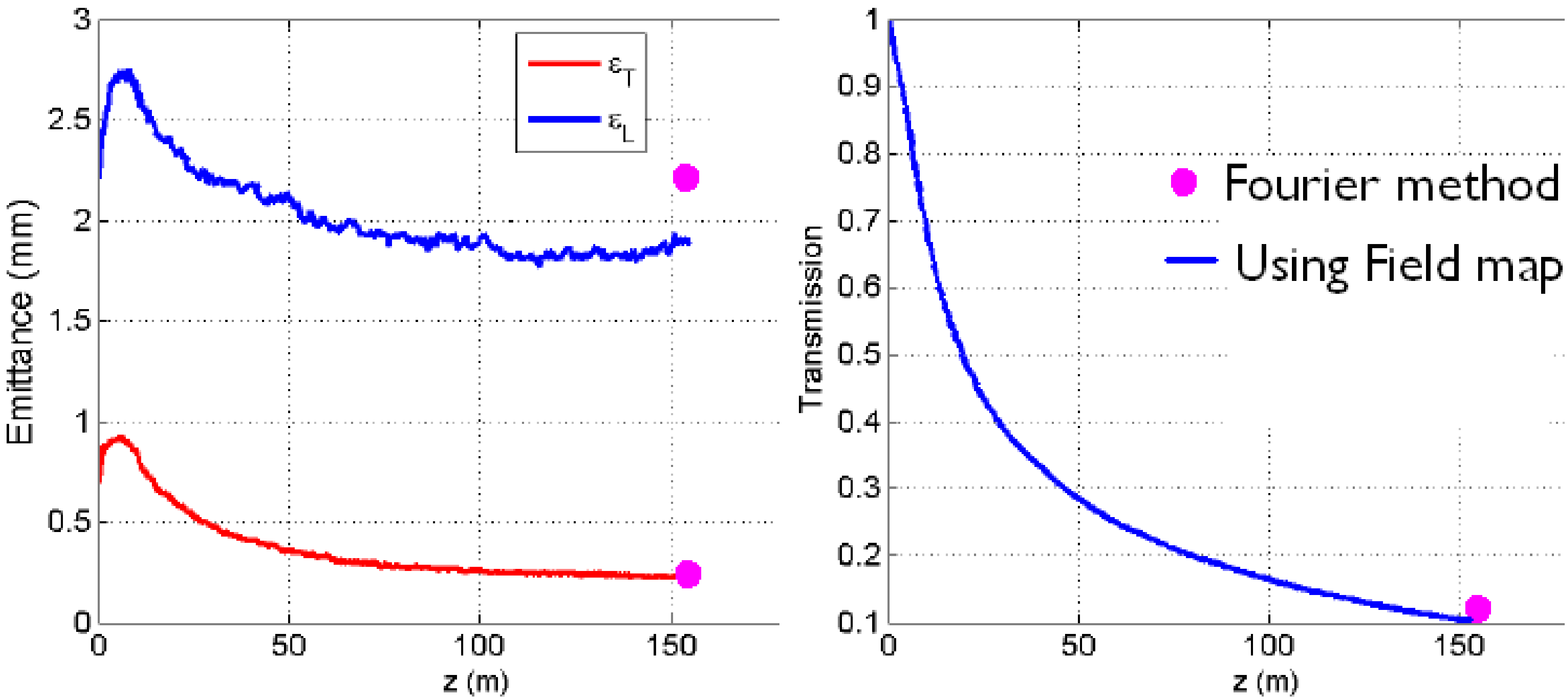
	material	length	radius	freq.	grad	phase
		cm	cm	MHz	MV/m	deg.
Half absorber	Liquid H_2	2.2	2.5			
Absorber window	Aluminum	0.01	2.5			
Gap	Vacuum	8.04	5			
rf cavity	Vacuum	9.0	14	805	35	15
rf cavity	Vacuum	9.0	14	805	35	15
Gap	Vacuum	8.04	5			
Absorber window	Aluminum	0.01	2.5			
Half absorber	Liquid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

ICOOL Simulation (using Fourier method)



- More than meets emittance requirements
- But transmission and Q poor
- Needs more study

ICOOL simulation now with field map



Transverse and transmission in good agreement; longitudinal better

Conclusion

- This lattice was conceived to reduce current densities for late stages, but was tested first in an early 201 MHz stage
- Large angular dispersions with small tilts (0.5 - 1 deg.) from the 2π resonance at the high momentum end
- This gives emittance exchange and 6D cooling of both signs with flat absorbers
- Result has been confirmed using field maps in both ICOOL and G4BeamLine
- This is similar to Yuri Alexahin's Helical FOFO Snake, but is planar and uses an RFOFO lattice with low betas at the absorbers
- A late stage lattice has reached the specified emittances
  With current densities consistent with YBCO HTS conductors
  Forces between coils, being inward, should be manageable
  But Transmission poor
- Needs more work