6D Cooling Lattices including a Planar Snake

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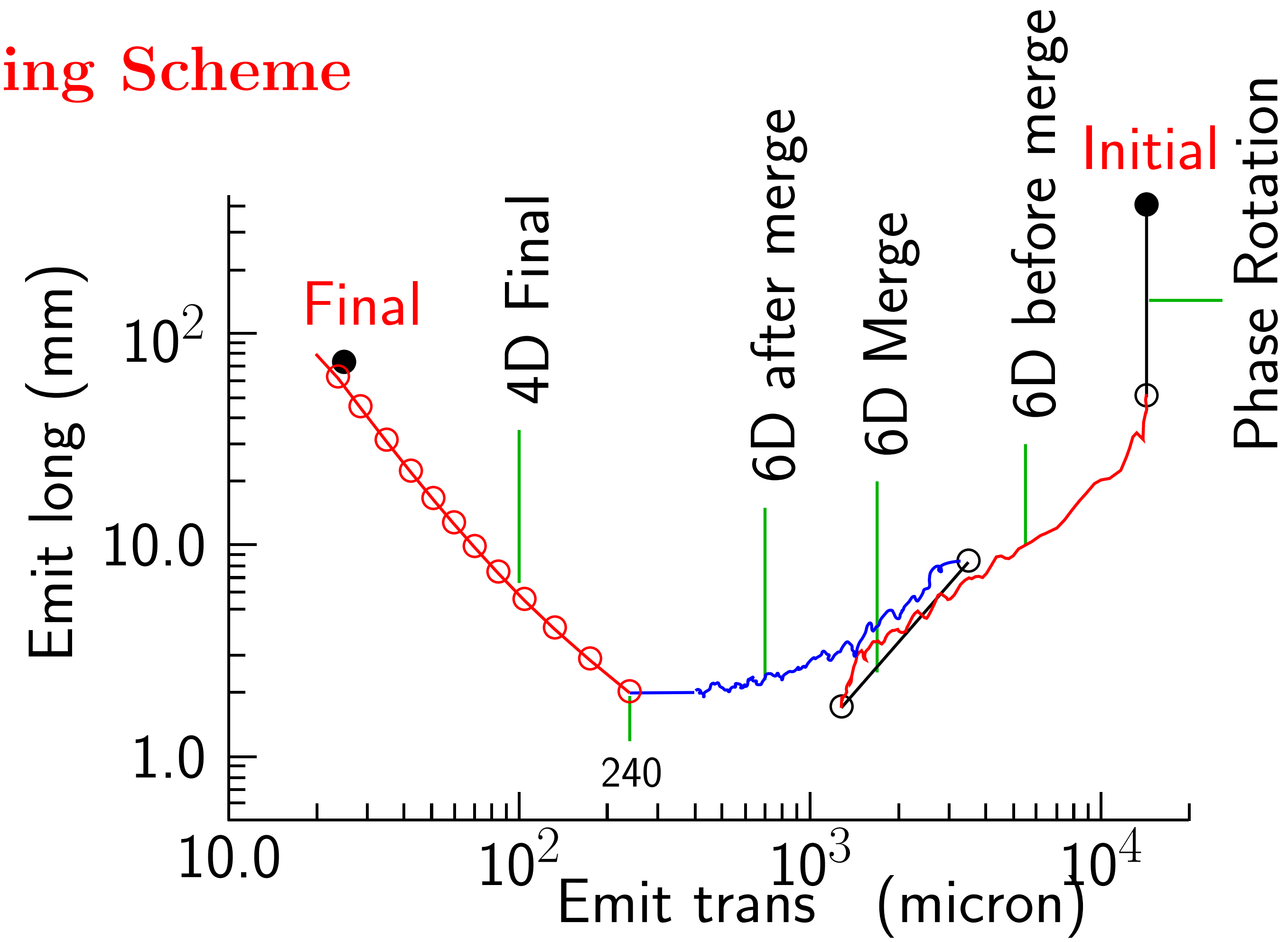
- Introduction to Lattices
- Helical Cooling Channel (HCC)
- Guggenheim & other RFOFO Lattices
- Helical FOFO Snake
- Planar RFOFO Snake
- Current densities
- Conclusion

Cooling Scheme



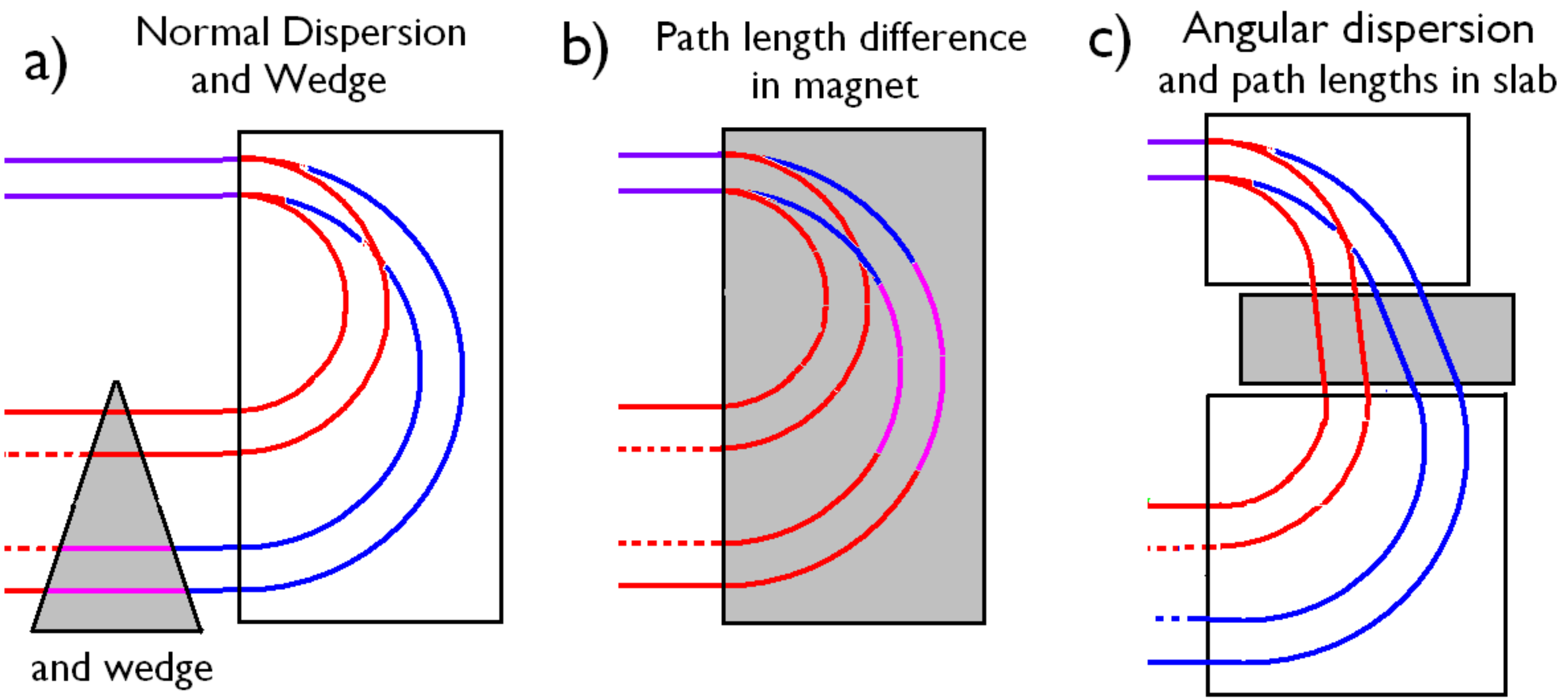
- Goal: $\epsilon_\perp = 0.240$ mm, $\epsilon_\parallel = 2$ mm
- Guggenheim designs have met these requirements on paper
- Current densities high & forces challenging
- Motivating search for alternative lattices

Transverse Cooling

$$\epsilon_{\perp} \propto \beta_{\perp} \propto \frac{1}{B}$$

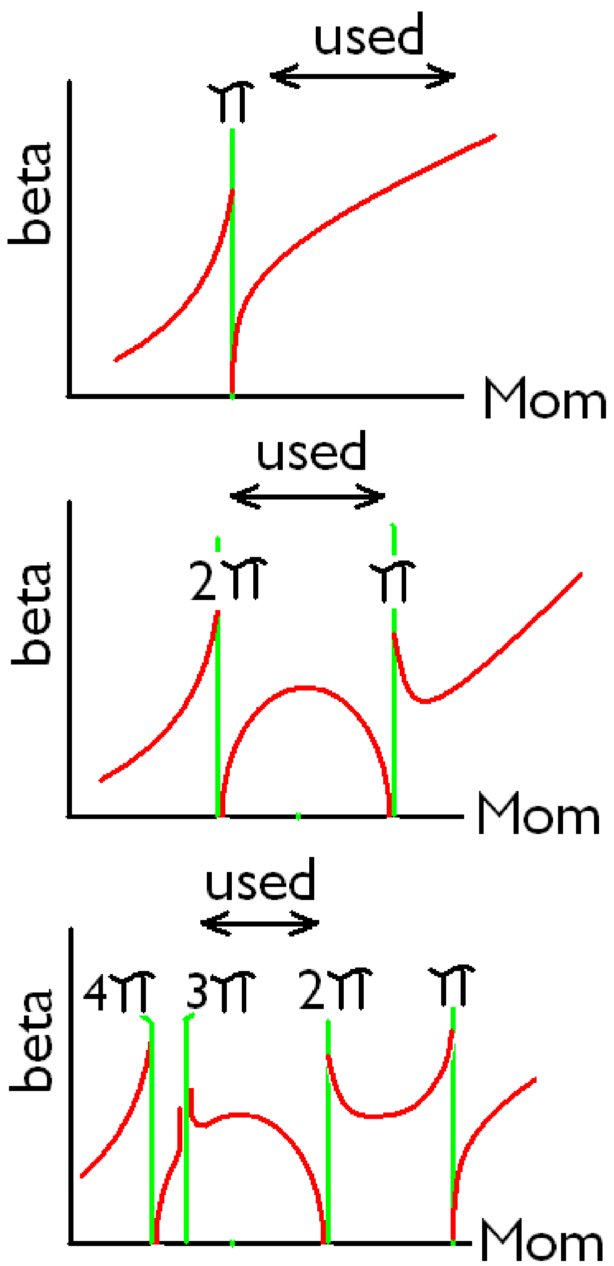
- How to get a low $\beta_{\perp} \times B$?
- Periodic lattices can help

Emittance Exchange Required for 6D cooling

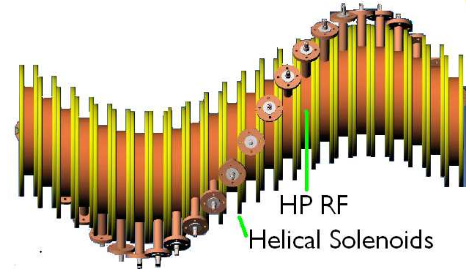


Lattices Types

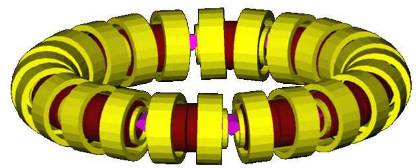
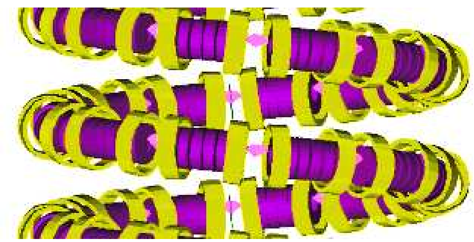
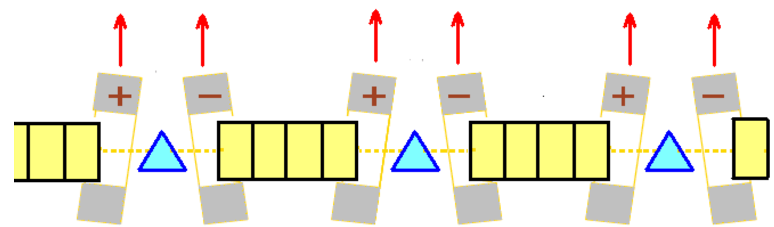
- HCC beta amplitudes non-periodic
- FOFO (Focus-Focus)
  - simply periodic
  - phase advance $\pi > \phi$
  - used in Final 4D cooling
- SFOFO/RFOFO (Super-Focus-Focus)
  - bi-periodic
  - phase advance $2\pi > \phi > \pi$
  - used in Guggenheim
- Higher Tune
  - e.g. Helical FOFO Snake
  - e.g. Planar Snake
  - use phase advance $3\pi > \phi > 2\pi$



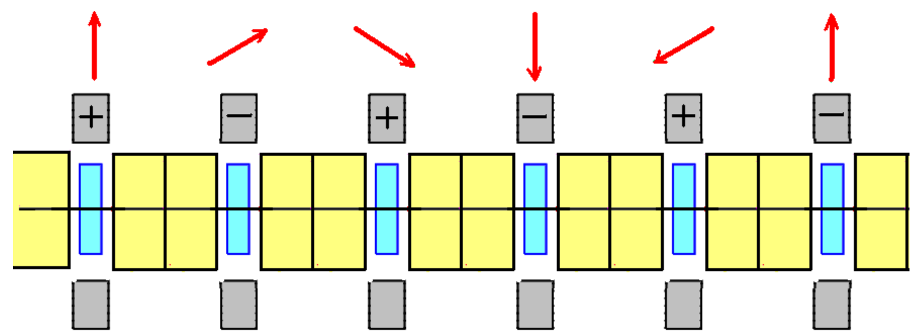
1. HCC (Beta amplitudes non-periodic)
   - Only one sign
   - HP gas containment



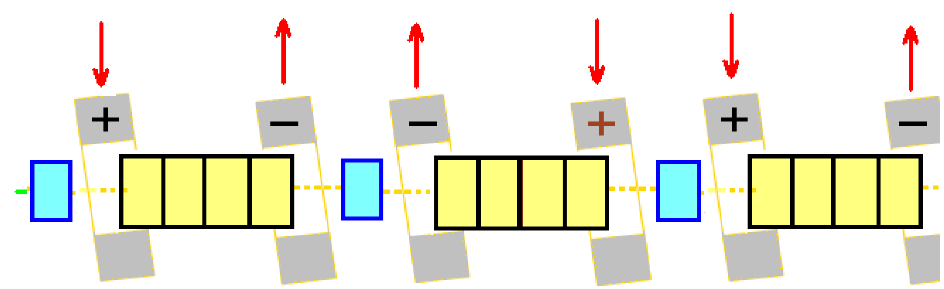
2. RFOFO (bi-periodic)
   (a) Ring
   (b) Guggenheim
   (c) Balbekov Rectilinear RFOFO
      - Only one sign
      - Forces out

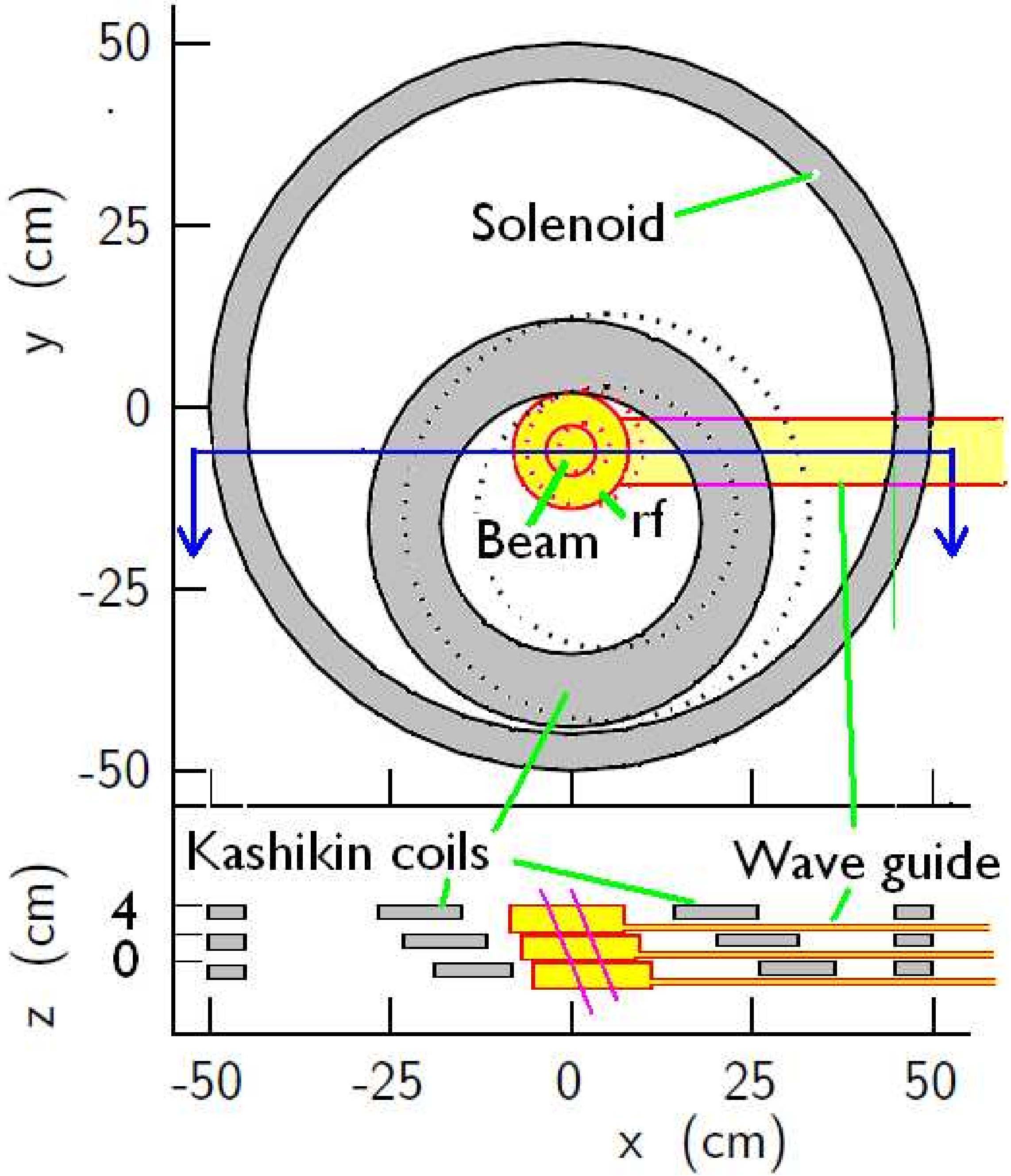
3. Helical FOFO Snake (Alexahin)
   - Axial forces are balanced
   - Cools both signs



4. Planar RFOFO Snake
   - Forces inward
   - Cools both signs



1) Helical Cooling Channel



- Emittance exchange by path length in high pressure hydrogen gas (b)
- Simulations using ideal fields in 7 stages down to $\epsilon_\perp$=0.32 mm, $\epsilon_\parallel$=1 mm
- Coil Designs for these required fields only for Stages 2 and 6
- Longitudinal space for Kashikin (Helix) Coils limited by wave guides
- If waveguides can be relocated, current densities could be less

HCC Current densities

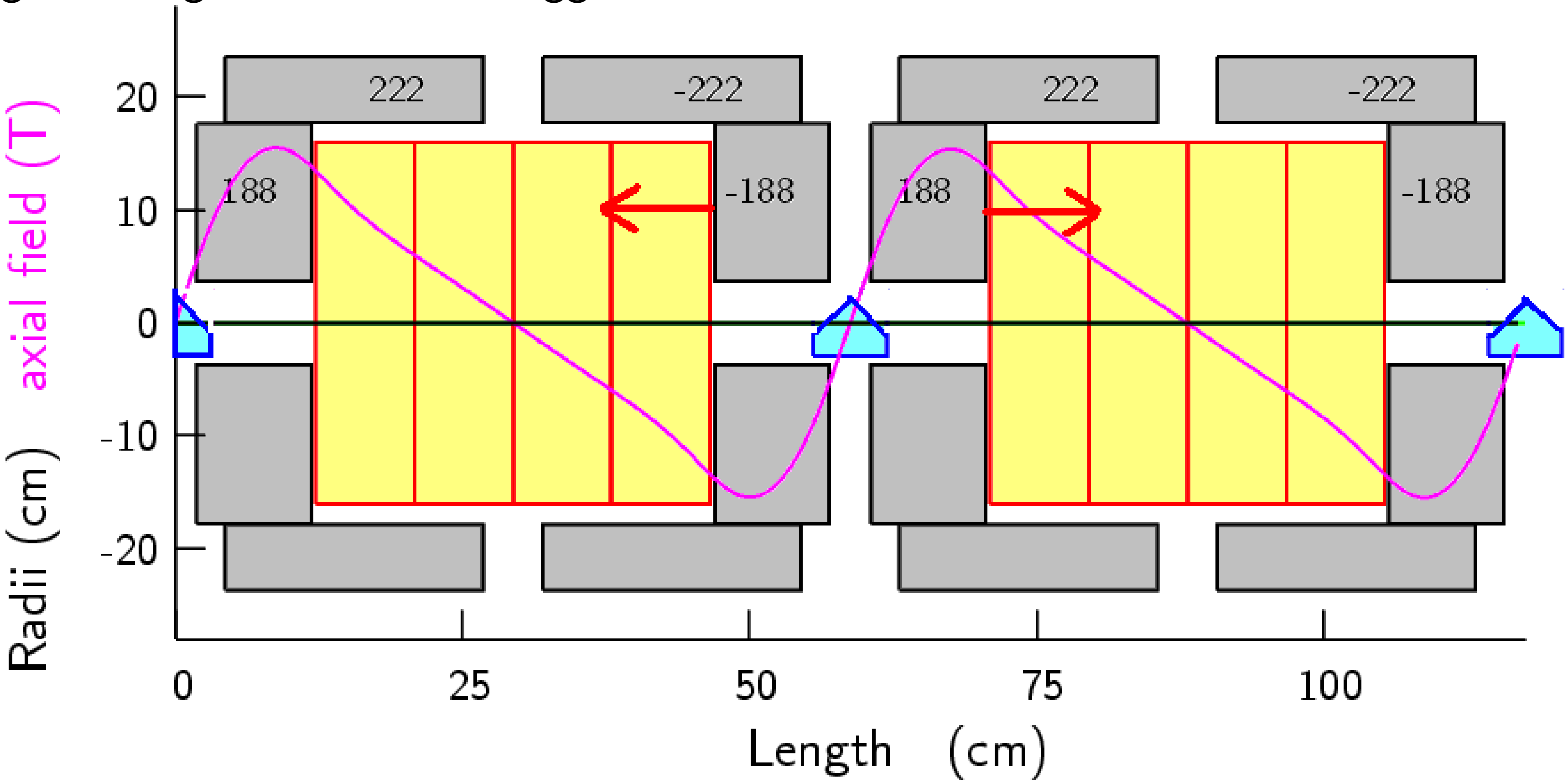
- Since no coil design is published for stage 7, I have scaled them from stage 6
- $\epsilon_\perp \propto L \quad B \propto 1/L \quad j \propto 1/L^2$

stage	R_c	λ	Bz	R1	R2	n	Lc	Bmax	j	$\epsilon_\parallel$	$\epsilon_\perp$
	m	m	T	m	m	m		T	A/mm^2	mm	mm
6	.16	.4	6.73	.18	.28	20	.01	17.26	332.9	1.3	0.42
7	.12	.3	8.8	.14	.21	20	.076	22.6	574	1.0	0.32

HCC vs, RFOFO (Guggenheim) Comparison in Appendix

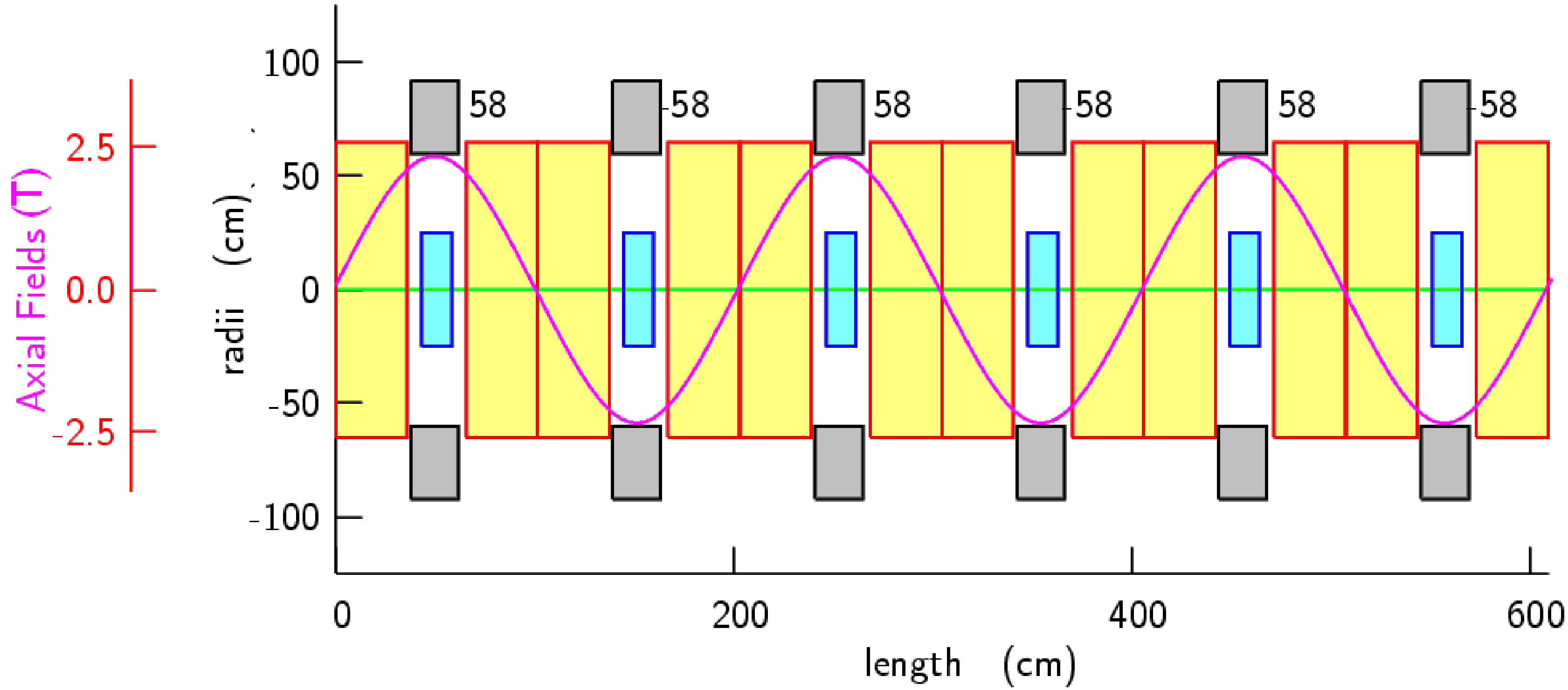
2) RFOFO Lattices: a)Ring b)Guggenheim c)Balbekov

eg last stage of Stratakis Guggenheim



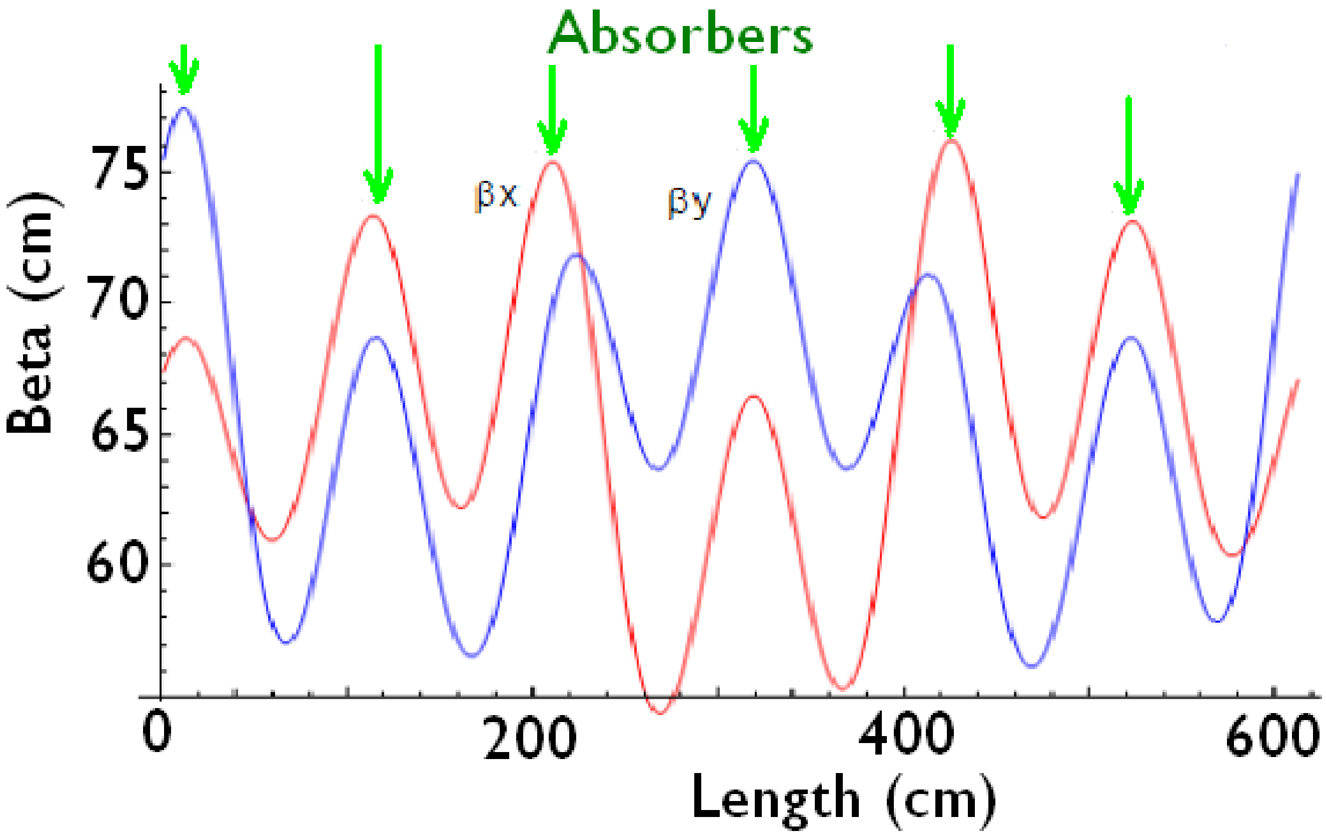
- Emittance exchange by dispersion and wedge (a)
- Cools to $\epsilon_\perp$=0.27 mm & $\epsilon_\parallel$=2 mm (close to 0.24 specification)
- Forces are outward & no space for supports
- Designing Liquid hydrogen wedge non-trivial

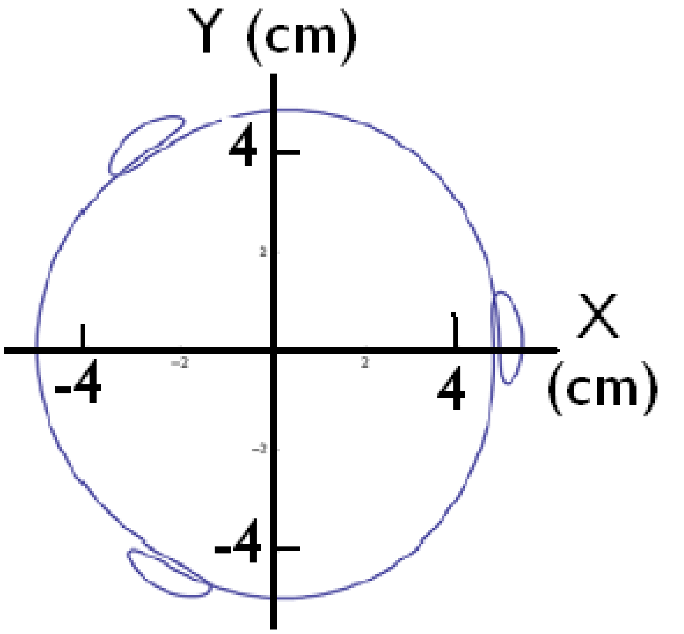
3) Helical FOFO Snake (Alexahin)



- Emittance exchange by angular dispersion and slab absorbers (c)
- Cell=609 cm, Axial Fields 2.35 T
- Operates between 3π and 2π phase advance
- Cools 6D for both signs simultaneously

Betas

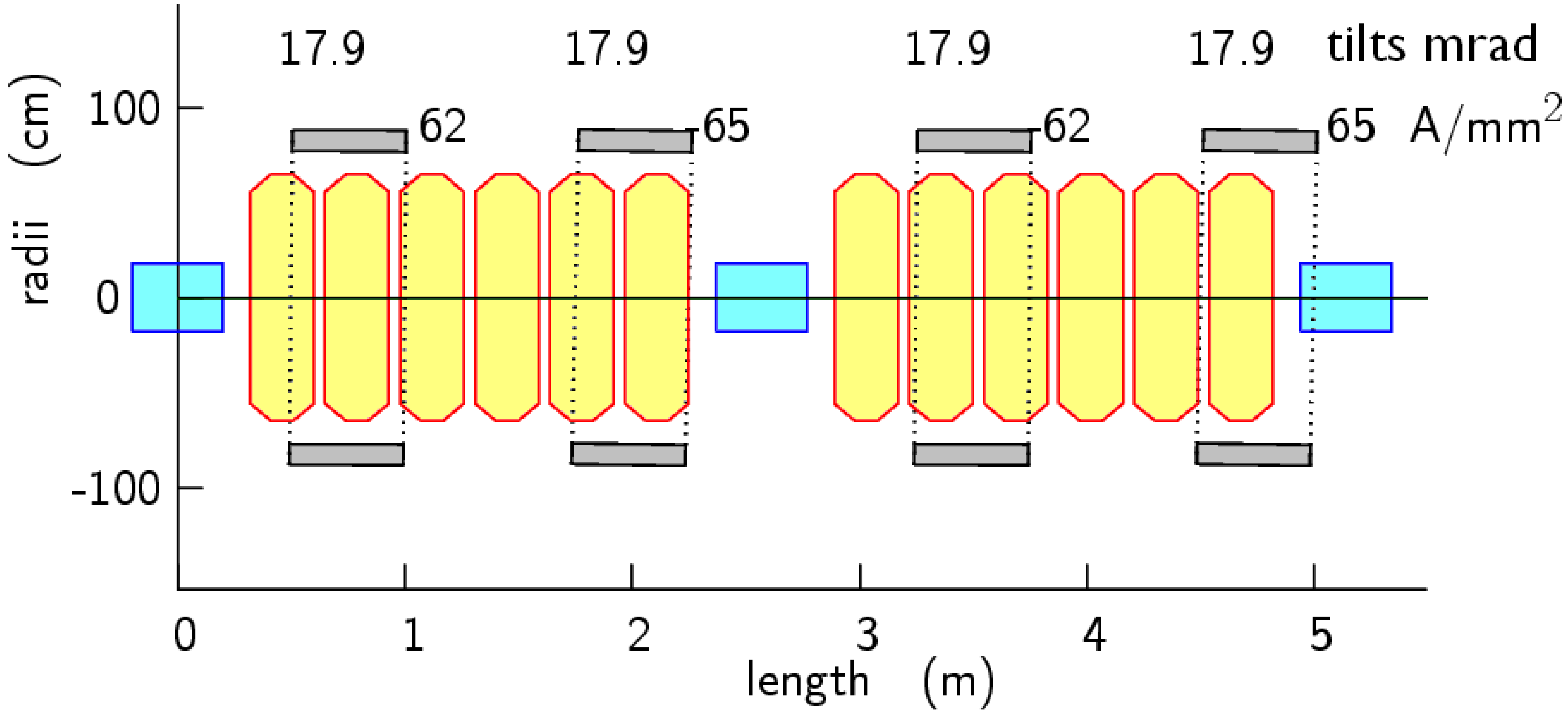




- Absorbers are at beta maxima ($\approx$ 70 cm)
- Scaling to final beta of 2.4 requires $B = \frac{70}{2.4} \times 2.35 = 68.5(\mathrm{T})$!!
- Perhaps good at start of 6D cooling, but not at end

4) Planar RFOFO Snake

An early stage using 201 MHz

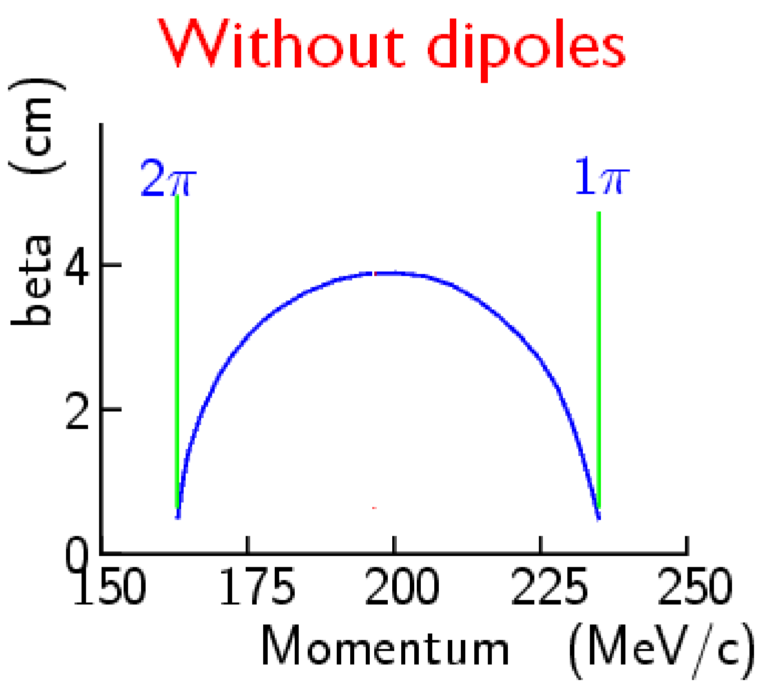


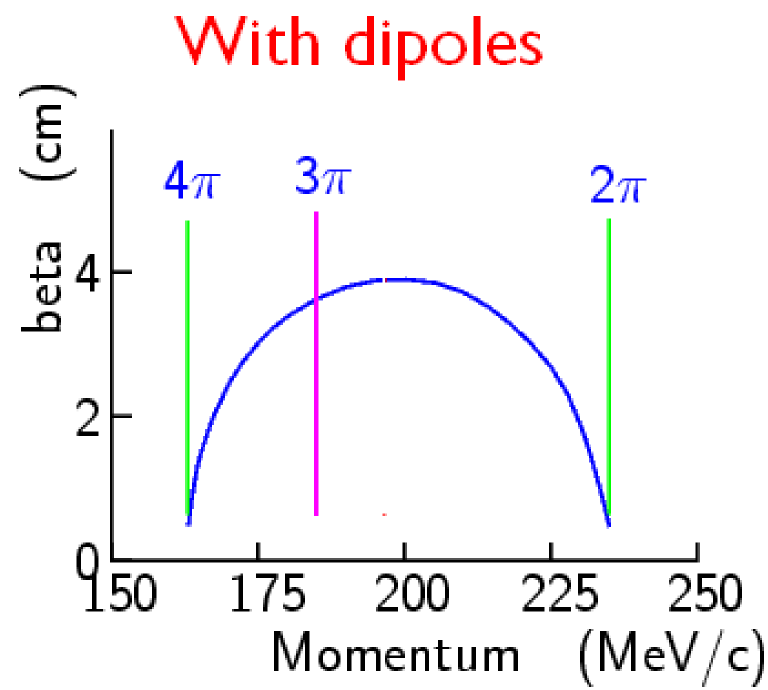
- Exchange, like Helical Snake, by angular dispersion & slabs (c)
- Dipole fields obtained by tilting all coils by 18 mrad
- Cools both signs simultaneously

See Appendix for details

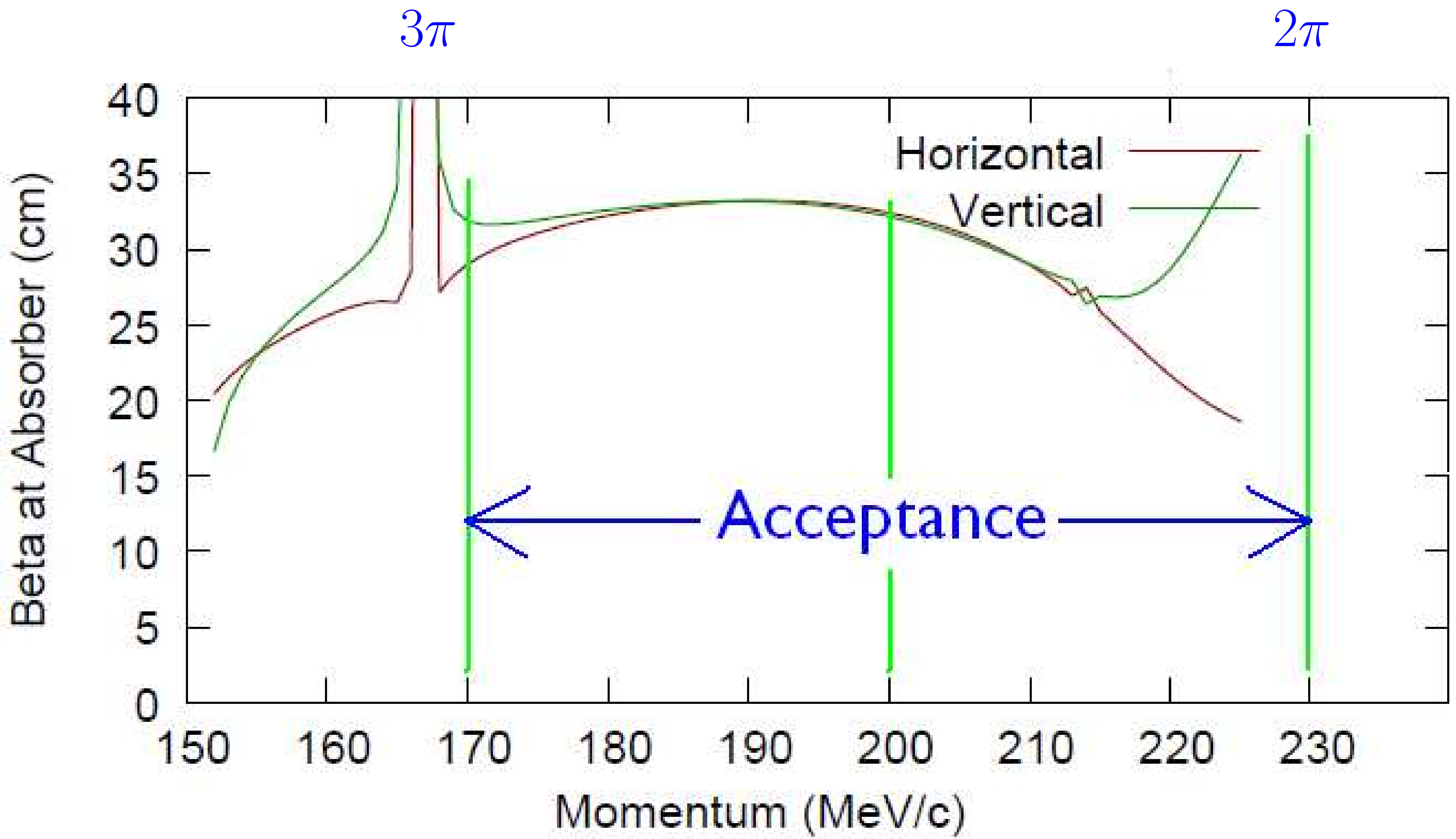
Possible difficulty with this concept

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



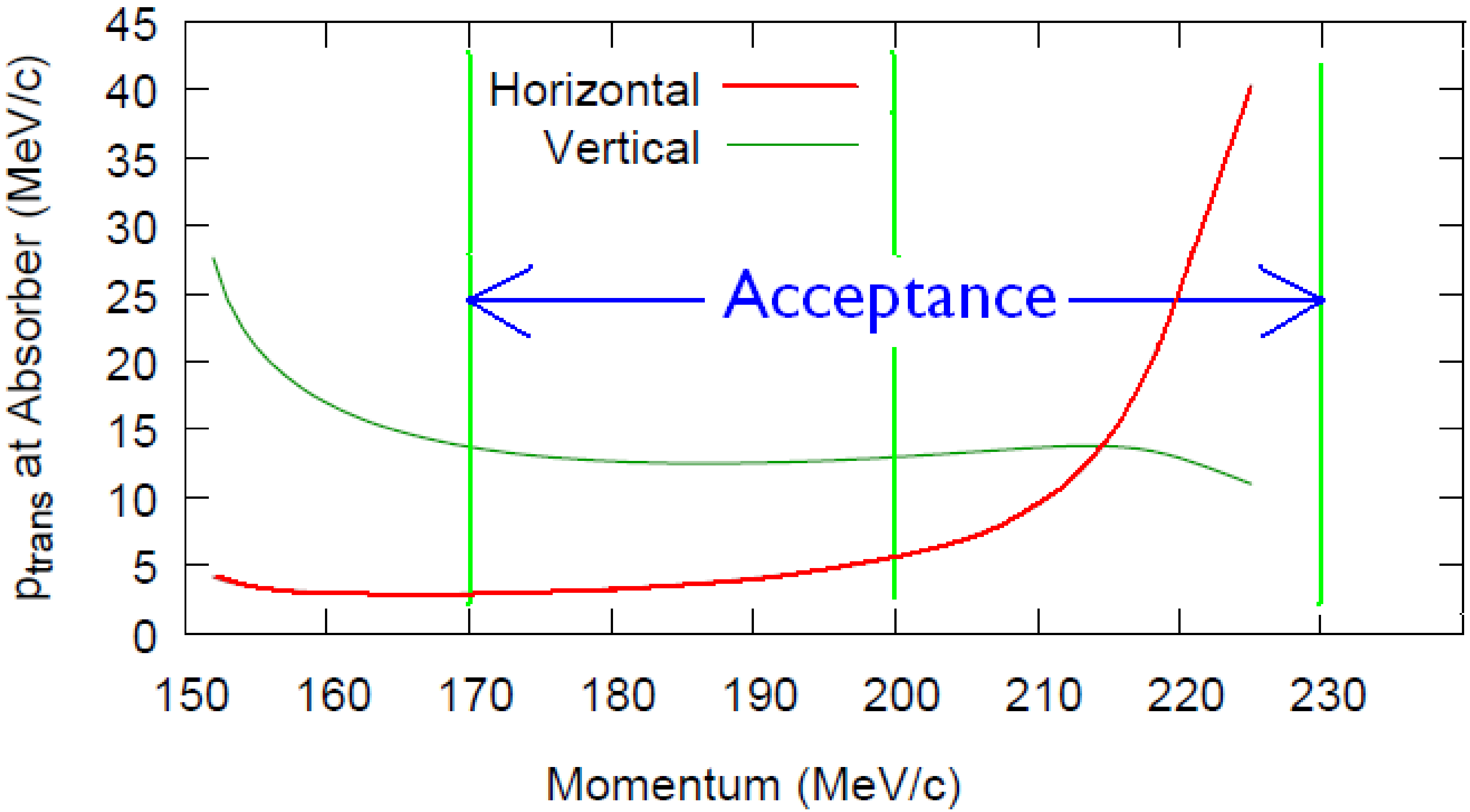


Betas vs. momentum (Berg)



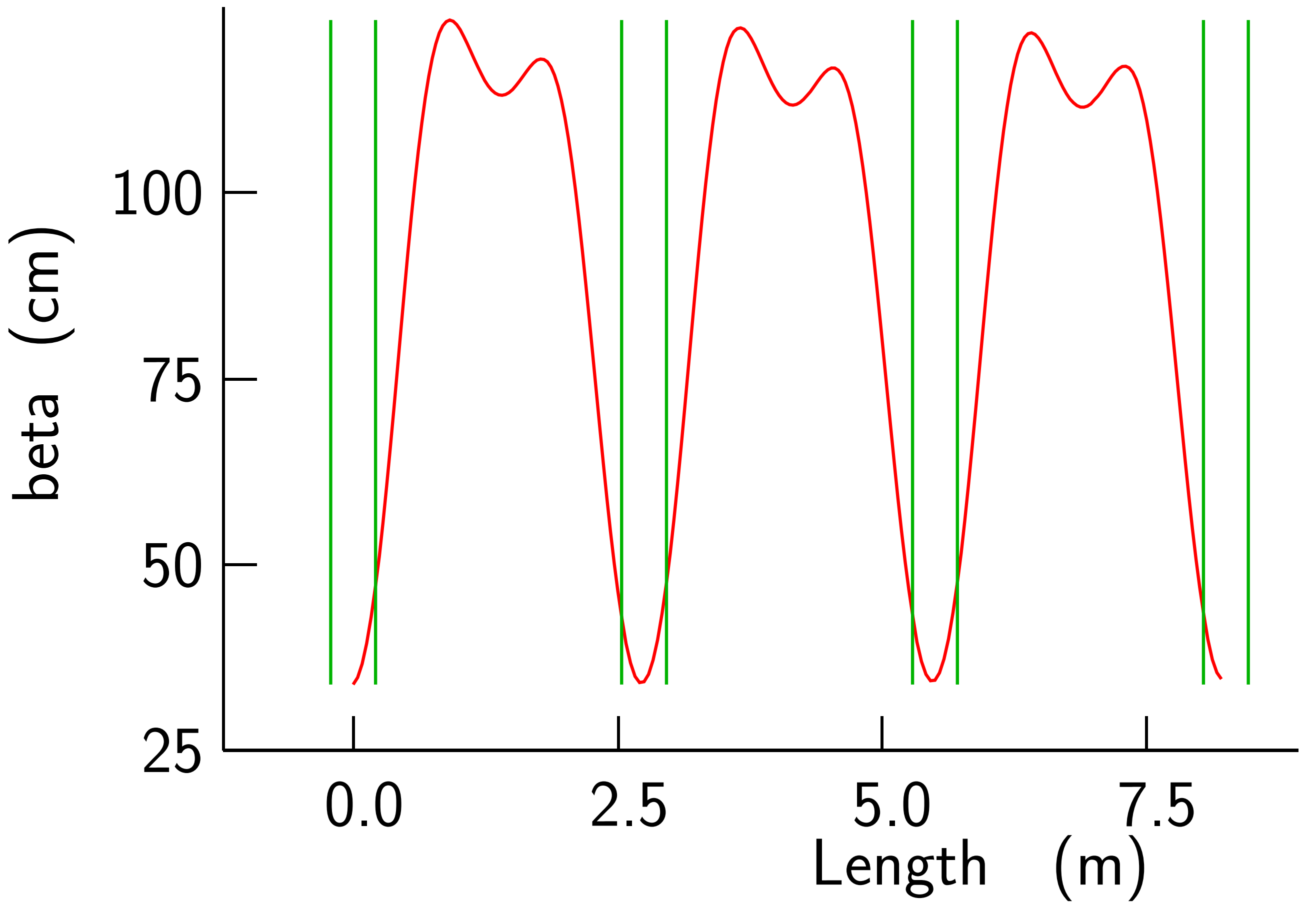
- Acceptance extends far into the 2π resonance at 230 MeV/c
- Acceptance less (60 vs. 80 MeV/c), but not desperately so

Angular dispersion vs.momentum (Berg)



- This is a very non-linear angular dispersion (enhanced by the 2π resonance at 230 MeV/c)
- But works anyway

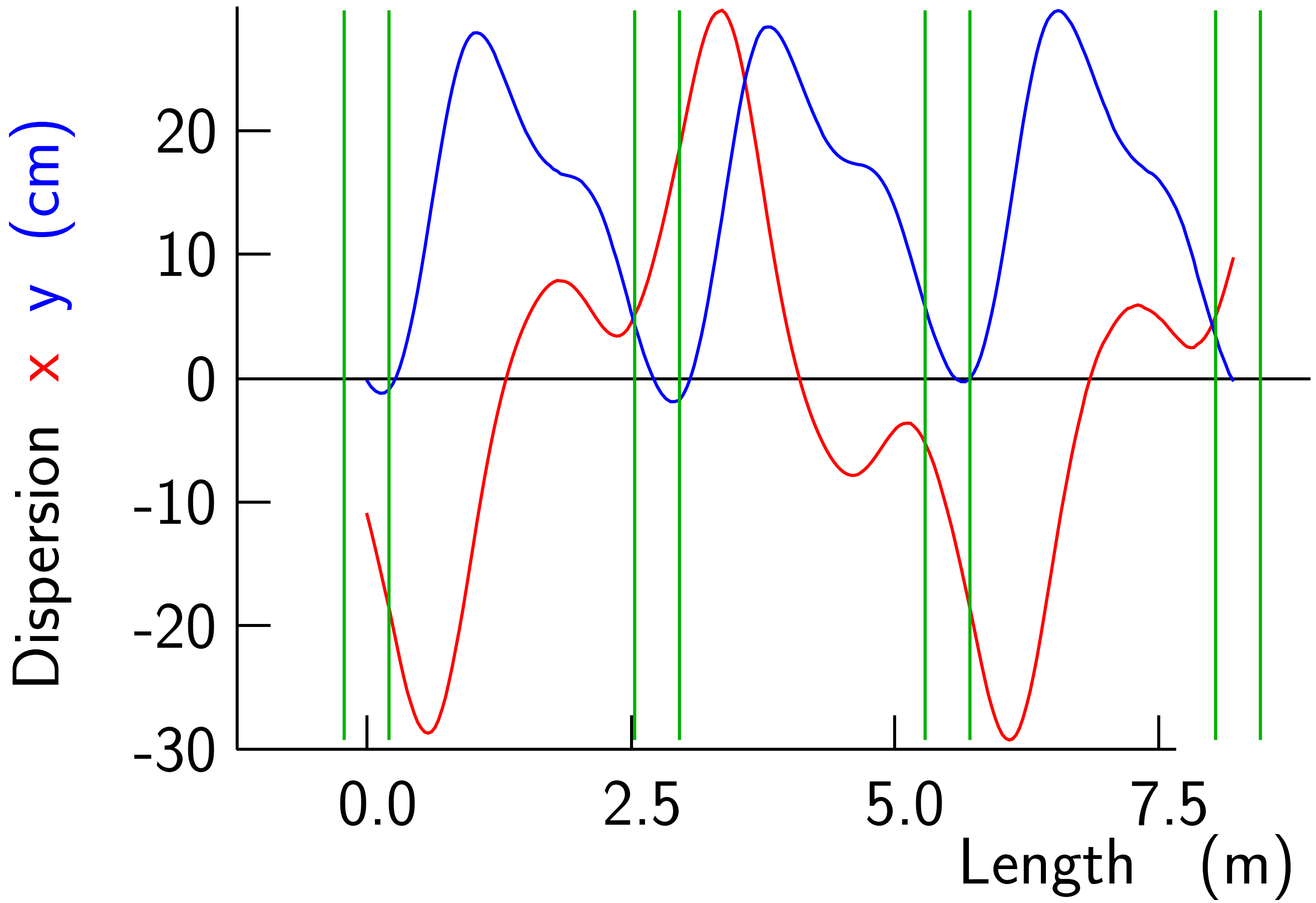
Betas vs length from ICOOL simulation



Absorbers beween green lines

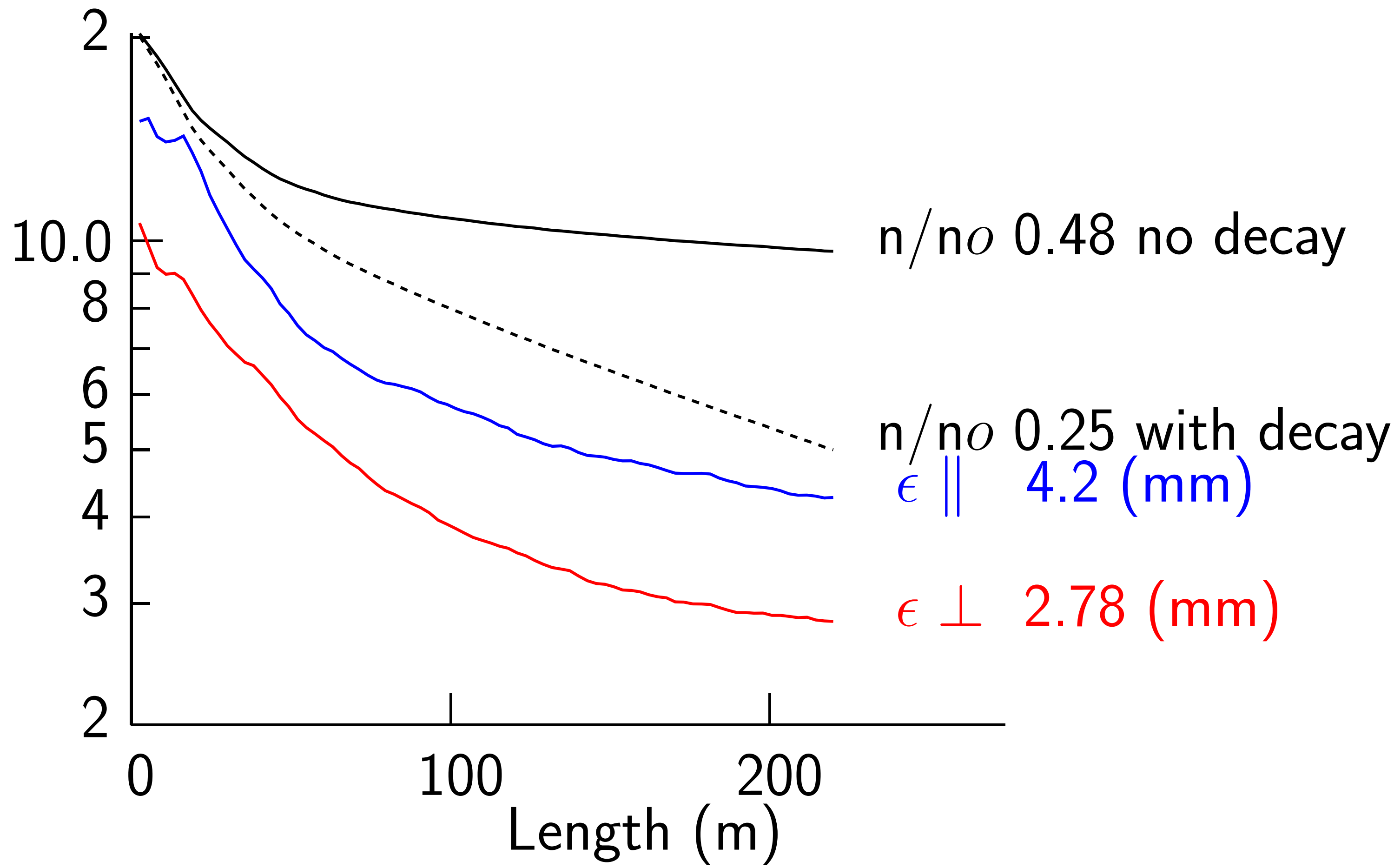
- Betas small at absorbers (30 cm)
- But large between them ($\approx$ 120 cm)

Dispersions vs length



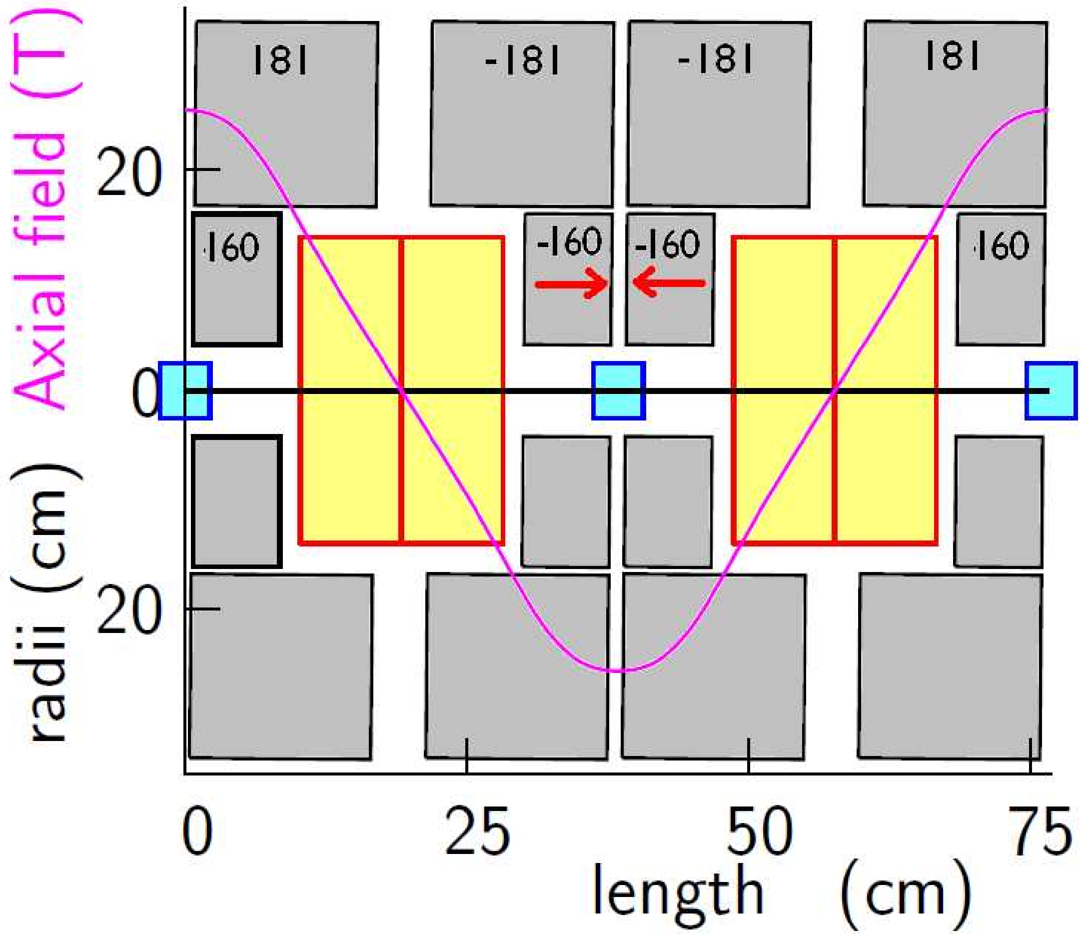
- x and y dispersions are large (30 cm), but small at absorbers
- However, x angular dispersion is large at absorbers and gives emittance exchange with flat absorbers

ICOOL Simulation of early stage cooling



- Good cooling in all 6 dimensions
- Losses dominated by decay

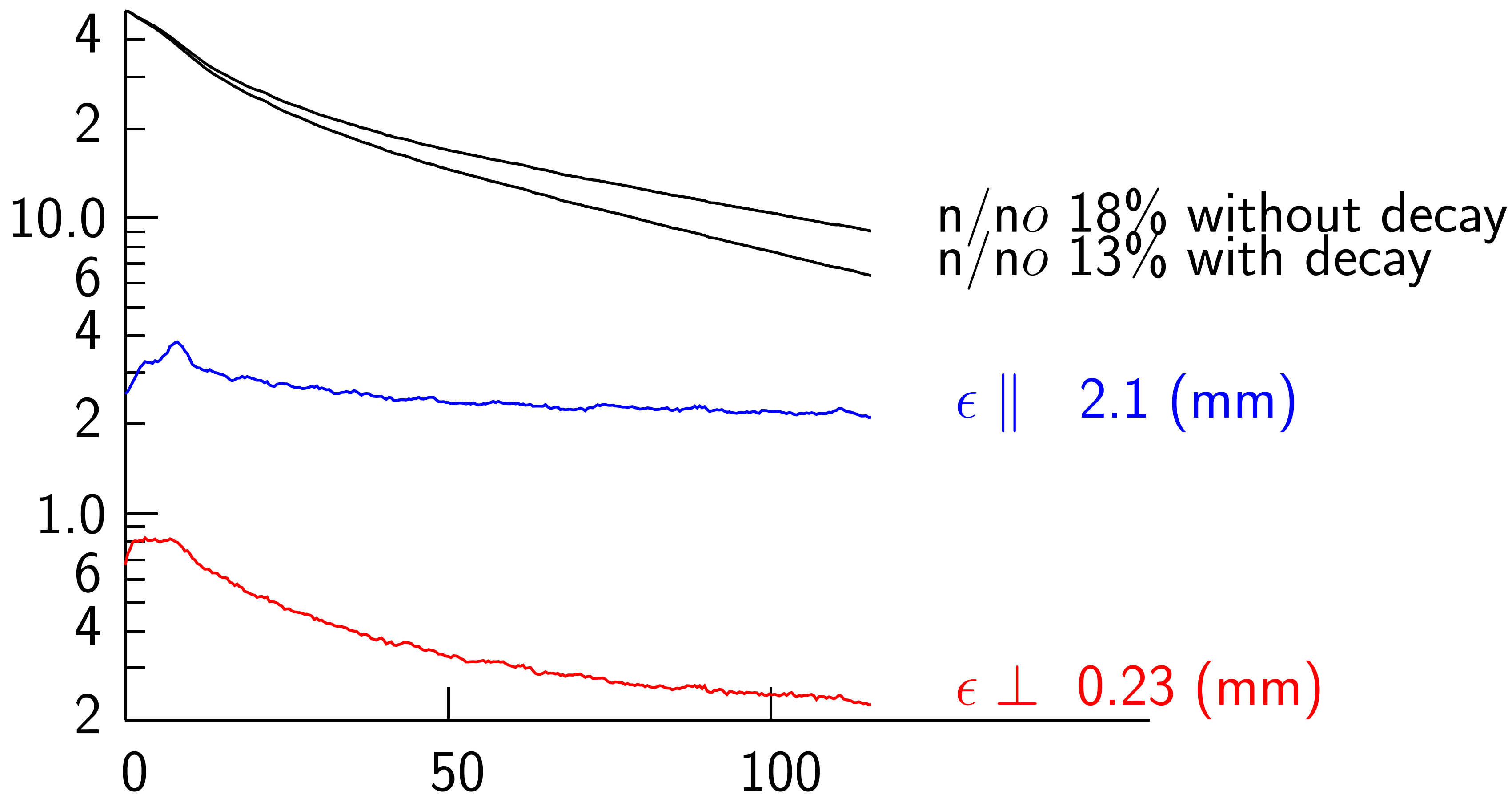
Late stage Planar Lattice



- Coils on either side of absorber are not bucking
- All coils tilted 10.5 mrad (very small)
- Forces now inward

See appendix for details

ICOOL Simulation of late Stage

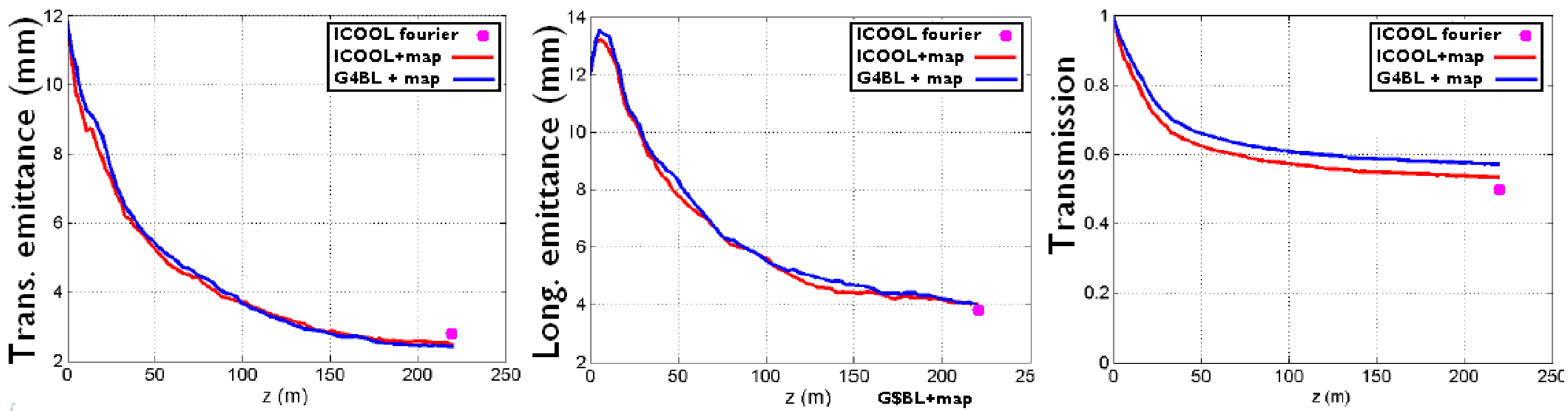


- Beats 0.24 mm emittance requirement
- But losses worrying: we may have to back off

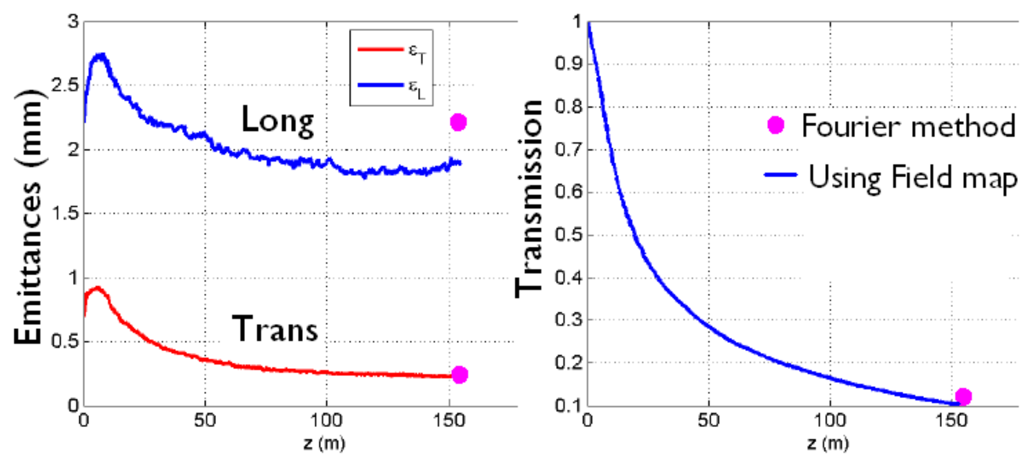
Simulations methods

- Above plots from ICOOL simulation using Fourier method
- Both now confirmed (with slightly better performance) using field maps in both ICOOL and G4BL (Stratakis)

Early Stage



Late Stage



Comparison of fields

System	$\epsilon_\perp$ mm	B_{axial} T	B_{max} T	B_{rf} T
HCC	0.42		17.3	17.3[1]
HCC	0.32		22.6	22.6[1]
RFOFO	0.27	15.6	17.3	13.3
Planar Snake	0.23	25.6	26.3	15.1
HCC	0.27		26.8	26.8[1]
RFOFO	0.27	15.6	17.3	13.3
Planar Snake	0.27	21.8	22.3[2]	12.8[3]

Red: scaled to same emittance

Note 1: Uses HP gas with no dependence on magnetic fields

Note 2: Planar Snake Peak field, for same emittance, higher than Guggenheim, but lower than HCC

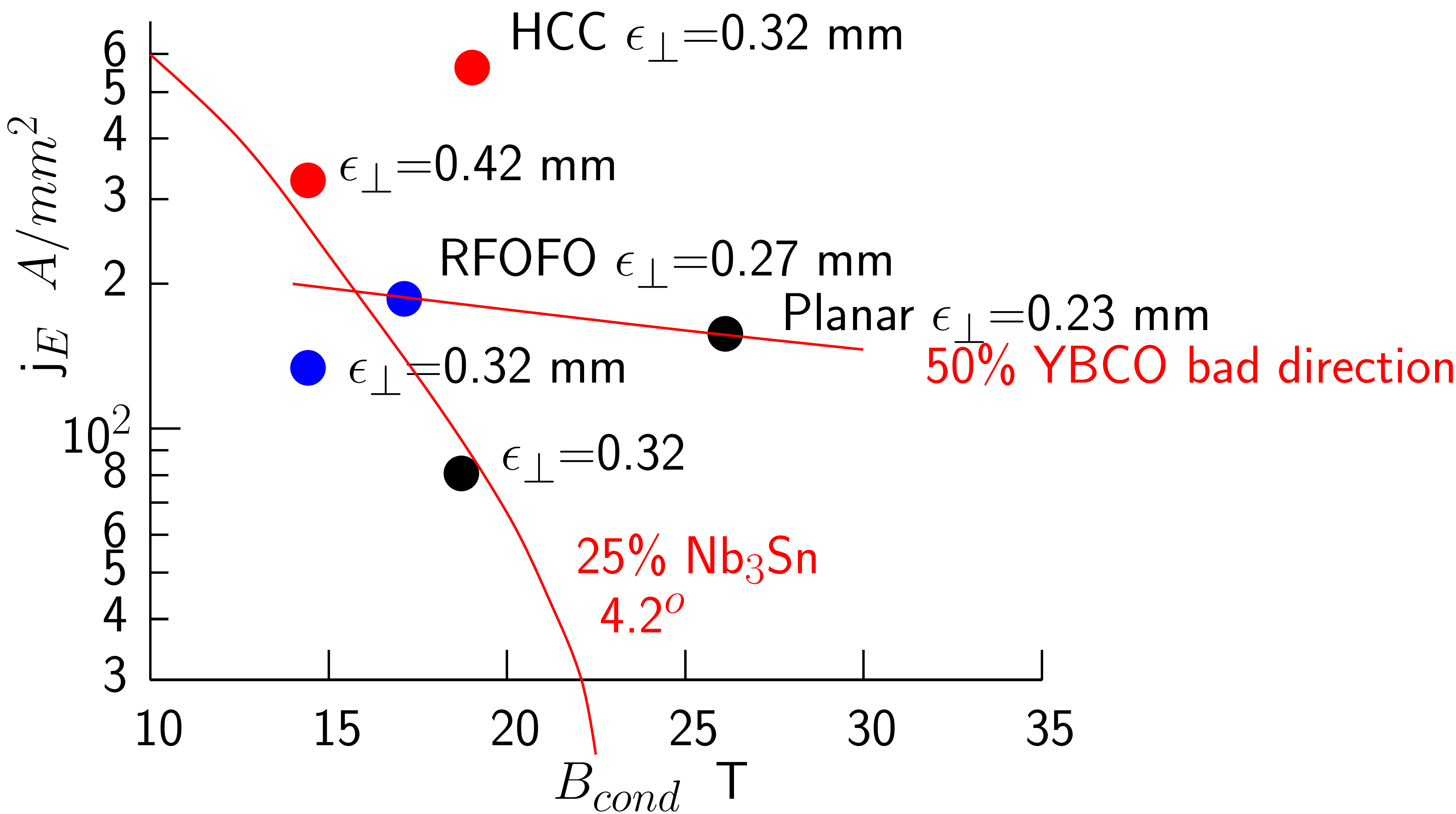
Note 3: For same emittance, Planar Snake 'B on rf' is lower than for RFOFO

Current Densities What are reasonable?

- Start from "engineering" values from NHMFL
- Take 50% for YBCO which itself is strong for stabilization
- Take 25% for Nb_3Sn which is not strong for support and stabilization

Plots of Current Densities of late stage systems

Only the higher field (inner) coils are plotted



See Appendix for numbers

Conclusion on Current densities

- For a given final emittance:
  - HCC needs the highest current densities
  - RFOFO Guggenheim or Balbekov are in the middle
  - Planar RFOFO needs the least
  - An order of magnitude in A/mm^2 from planar to HCC
- Consequences with realistic conductors:
  - The Planar RFOFO achieves transverse emittance of 0.23 mm: below goal of 0.24 mm
  - RFOFO Guggenheim or Balbekov can achieve 0.27 mm: close, but above our goal of 0.24 mm
  - HCC is pushing conductor technology even for 0.42 mm

General Conclusions

- The Planar Snake is the most attractive solution:
  - It cools both signs simultaneously
  - It needs the least aggressive conductor specifications and can cool to the lowest transverse emittances
  - Its coil to coil forces (inward) appear the easiest to constrain
  - Its slab hydrogen absorbers are easier to engineer than wedges
- BUT
  - The planar Snake is the least studied, and least understood
  - Its transmission may be worse than the others
  - Cooling both signs at once has some new challenges: one can only use ODD harmonics: 201, 603, 906, or 325, 975
  - There may be surprises
- If vacuum rf in high magnetic fields unsolved, then HCC or hybrid (not discussed) are only choices

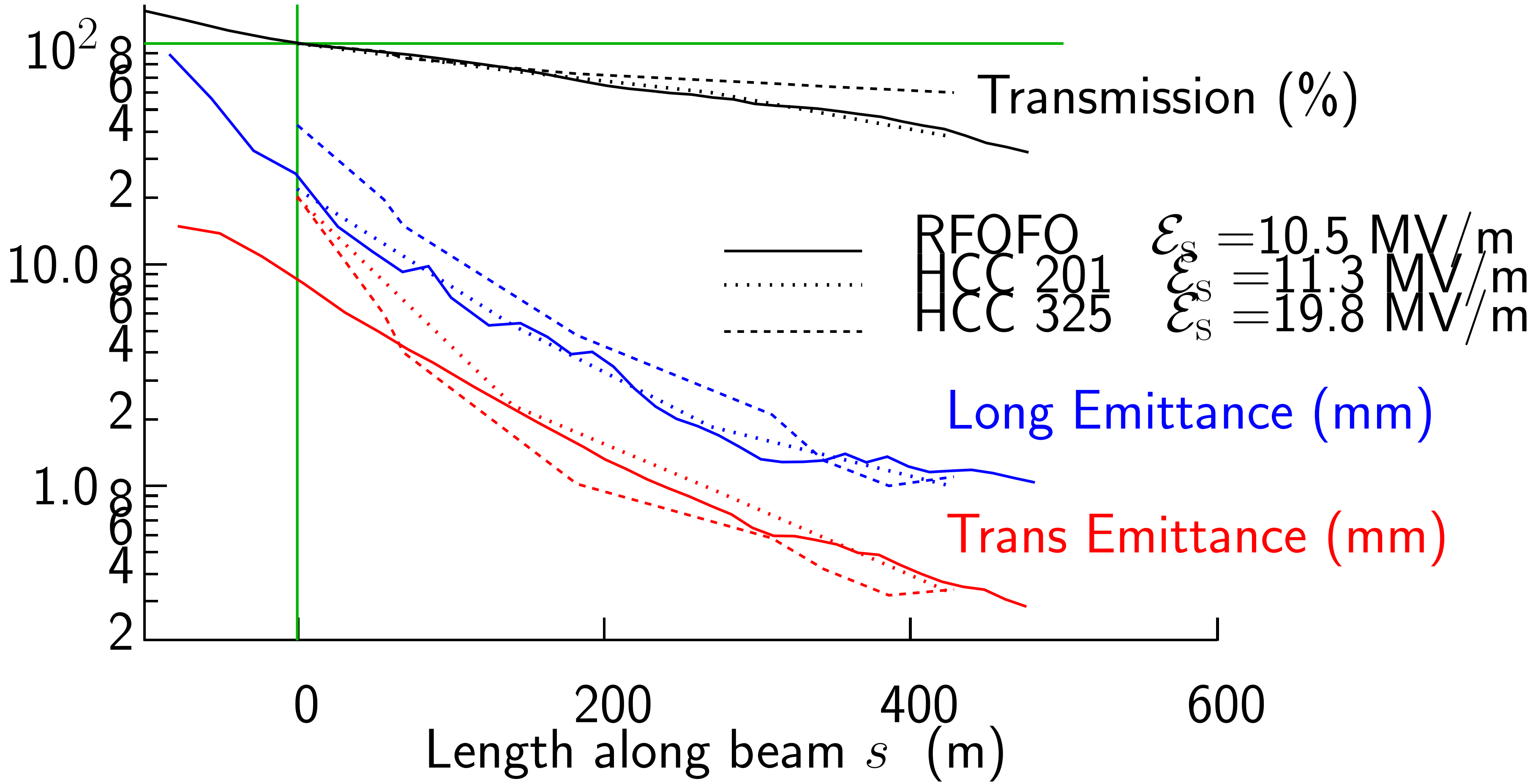
Appendix: RFOFO & HCC Parameters

		RFOFO	HCC	HCC	
Init freq.	f	201	325	201	MHz
Init beqm mag field	B_1	2.4	5	5	T
Final beam mag field	B_n	16	14.7	14.7	T
Ave Hydrogen density	ρ_{H2}	0.011	0.013	0.013	gm/cm^2
rf gradient	$\mathcal{E}$	15.5	32^*	18.5^*	MV/m
Ave beam rf gradient	$\mathcal{E}_s$	10.5	19.8	11.3	MV/m

* Fields increased 15% with indented cavity design

- Average hydrogen densities are similar
- Average rf beam gradients for 201 cases are similar

Appendix: RFOFO & HCC Performances



- Cooling rates similar
  HCC slightly higher as expected from hydrogen density
- Transmissions similar for similar gradients,
  better for HCC with higher rf gradient

Appendix: Parameters of early stage Planar Snake

start	dl	rad	dr	tilt	I/A
m	m	m	m	rad	A/mm^2
0.500	0.500	0.770	0.110	0.017	62.22
1.750	0.500	0.770	0.110	0.017	-65.45
3.250	0.500	0.770	0.110	0.017	-62.22
4.500	0.500	0.770	0.110	0.017	65.45

	material	length	radius
		cm	cm
Half absorber	Liquid H_2	21.3	18
Absorber window	Aluminum	0.05	18
Gap	Vacuum	17.15	50
6 rf cavities	Vacuum	33	64
Gap	Vacuum	17.15	50
Absorber window	Aluminum	0.05	18
Half absorber	Liquid H_2	21.3	18

Appendix: 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	0.01	2.5			
Half absorber	Liquid H_2	2.2	2.5			

Appendix: Late Stage Fields and Current Densities

Case	$\epsilon_{\parallel}$ mm	$\epsilon_{\perp}$ mm	coil	Field T	Density A/mm^2
HCC Stage 6	1.3	0.42	1	14.6	333
HCC Stage 7 (scaled from 6)	1.0	0.32	1	18.2	573
RFOFO (DS stage 17)	2.0	0.27	1	17.3	189
			2	11.3	223
Planar Snake	2.1	0.23	1	26.3	160
			2	19.6	182
Planar snake (scaled)	2.1	0.27	1	22.4	116
			2	16.7	132

The current densities for the outer solenoids in the HCC are not specified and can be appropriately low.

The second (outer) coils for RFOFO and Planar cases are in lower fields and have appropriately higher current densities