Collider Scheme with Bunch Merging

R. B. Palmer, J. S. Berg, R. Fernow, J. Gallardo (BNL)
S. Kahn (Muons Inc)

FNAL

July 2006

- New Collider Parameters
- Current Scheme
  - Pre-Merging RFOFO Cooling
  - Merging
  - Post-merging RFOFO Cooling
  - HTS Solenoid Cooling
  - Acceleration with ILC Linacs
- Potential problem
- Alternative technologies
  - Gas filled Helix
  - PIC and similar lattices for low $\epsilon_\perp$
  - Lithium Lenses
  - Wedge inverse emittance exchange
- Conclusion

Luminosity Dependence

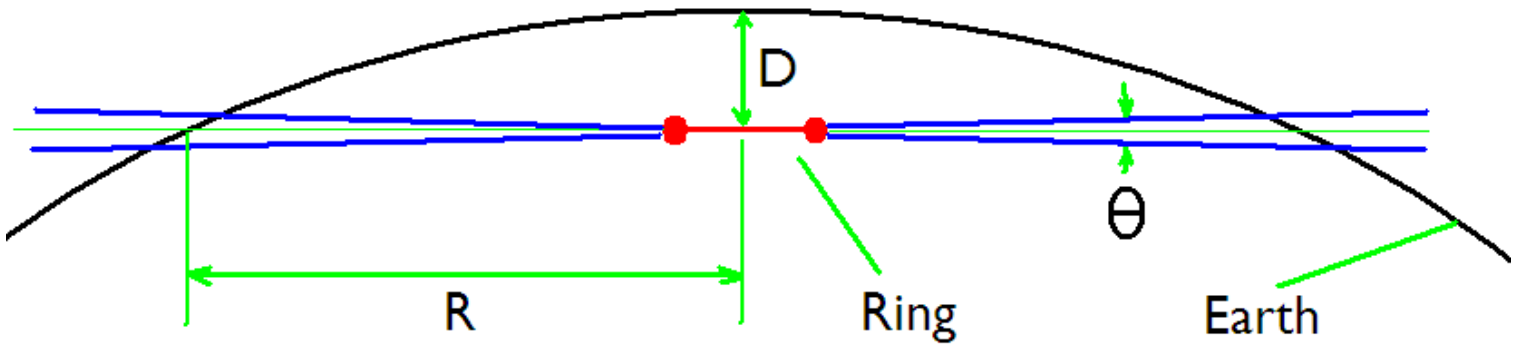
- Luminosity limited independent of emittance:

$$\mathcal{L} \;\propto\; n_{\rm turns}\, f_{\rm bunch}\, \frac{N_\mu^2}{\sigma_\perp^2} \qquad\qquad \Delta\nu \propto \frac{N_\mu}{\epsilon_\perp}$$

$$\mathcal{L} \;\propto\; B_{\rm ring}\, P_{\rm beam}\;\; \Delta\nu\, \frac{1}{\beta_\perp}$$

- Higher $\mathcal{L}/P_{\rm beam}$ requires lower $\beta_\perp$ or correction of $\Delta\nu$
- But lower emittance helps by lowering muons per bunch

Neutrino Radiation Constraint King



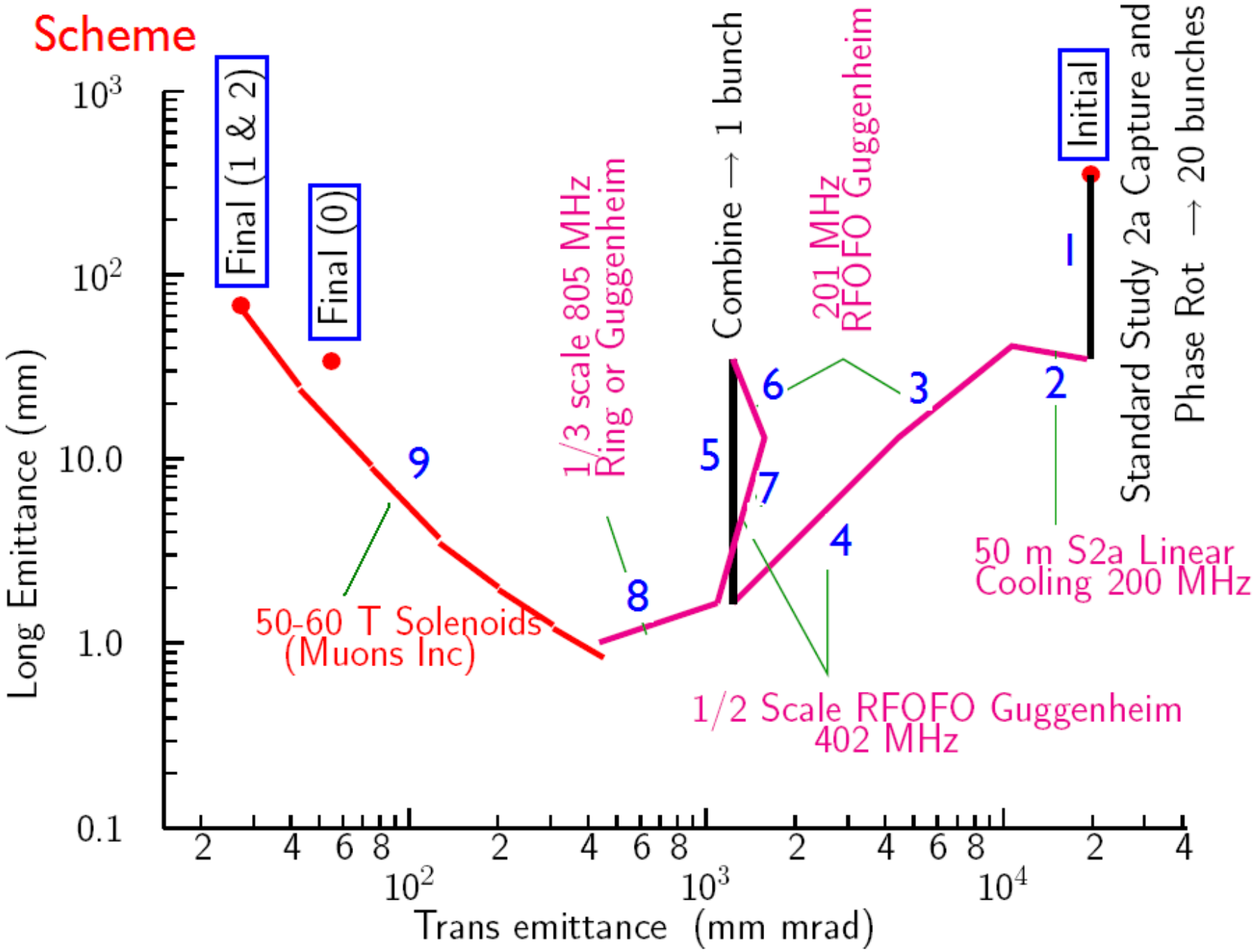
$$\text{Radiation} \;\propto\; \frac{I_\mu\,\sigma_\nu}{\theta\;R^2}\,\gamma \;\propto\; \frac{I_\mu\,\gamma^3}{D} \;\propto\; \frac{\mathcal{L}\;\beta_\perp}{\Delta\nu\;\;<\mathrm{B}>}\;\frac{\gamma^2}{D}$$

For fixed $\Delta\nu$, $\beta_\perp$ and $< B >$; and $\mathcal{L} \propto \gamma^2$:

$$\text{Radiation} \;\propto\; \frac{\beta_\perp}{\Delta\nu\;\;< B >\;\;D}\,\gamma^4$$

Use: 1/10 Federal limit = 10 Mr/year

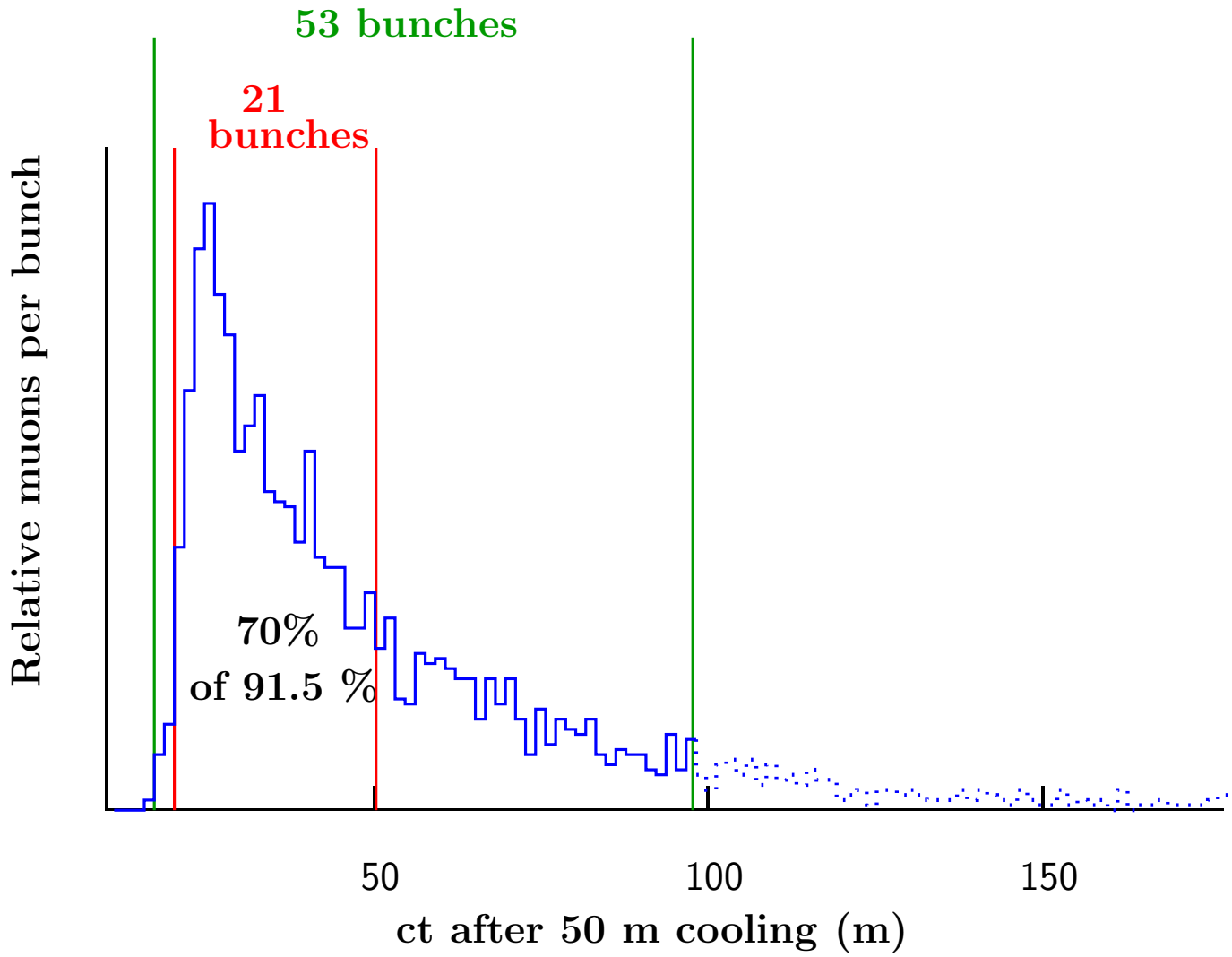
	Phase 0	Phase 1	Phase 2	cf 97	
C of m Energy	2	4	8	3	TeV
Luminosity	1	4	8	7	10^{34} cm^{2}sec^{-1}
Tune Shift	.05	0.1	.1	.05	
Bunches	$1+1$	$1+1$	$1+1$	$2+2$	
Muons/bunch	2	2	2	2	10^{12}
Ring <bending field>	5.18	5.18	10.36	5.18	T
Ring circumference	4.1	8.1	8.1	6.1	km
Trans Emittance	50	25	25	50	pi mm mrad
rms momentum spread	.12	0.12	0.06	0.16	%
Beta at intersection	3	3	3	3	mm
Beam sigma at IP	5.6	2.8	2.0	3.2	μm
Long Emittance	36	72	72	72	pi mm rad
Repetition Rate	6	6	3	15	Hz
Muon Beam Power	4.5	9	9	37	MW
Required depth for ν rad	32	135 (ILC)	540	300	m
Proton Driver power	≈ 1.5	≈ 1.8	≈ 0.8	4	MW


Scheme
Final (1 & 2)
Final (0)
Initial
Combine → 1 bunch
1/3 scale 805 MHz
Ring or Guggenheim
201 MHz
RFOFO Guggenheim
Standard Study 2a Capture and
Phase Rot → 20 bunches
50-60 T Solenoids
(Muons Inc)
1/2 Scale RFOFO Guggenheim
402 MHz
50 m S2a Linear
Cooling 200 MHz
1
2
3
4
5
6
7
8
9
Long Emittance (mm)
Trans emittance (mm mrad)
10^3
10^2
10.0
1.0
0.1
2
4
6
8
10^2
10^3
10^4

1) Bunched Beam Phase Rotation

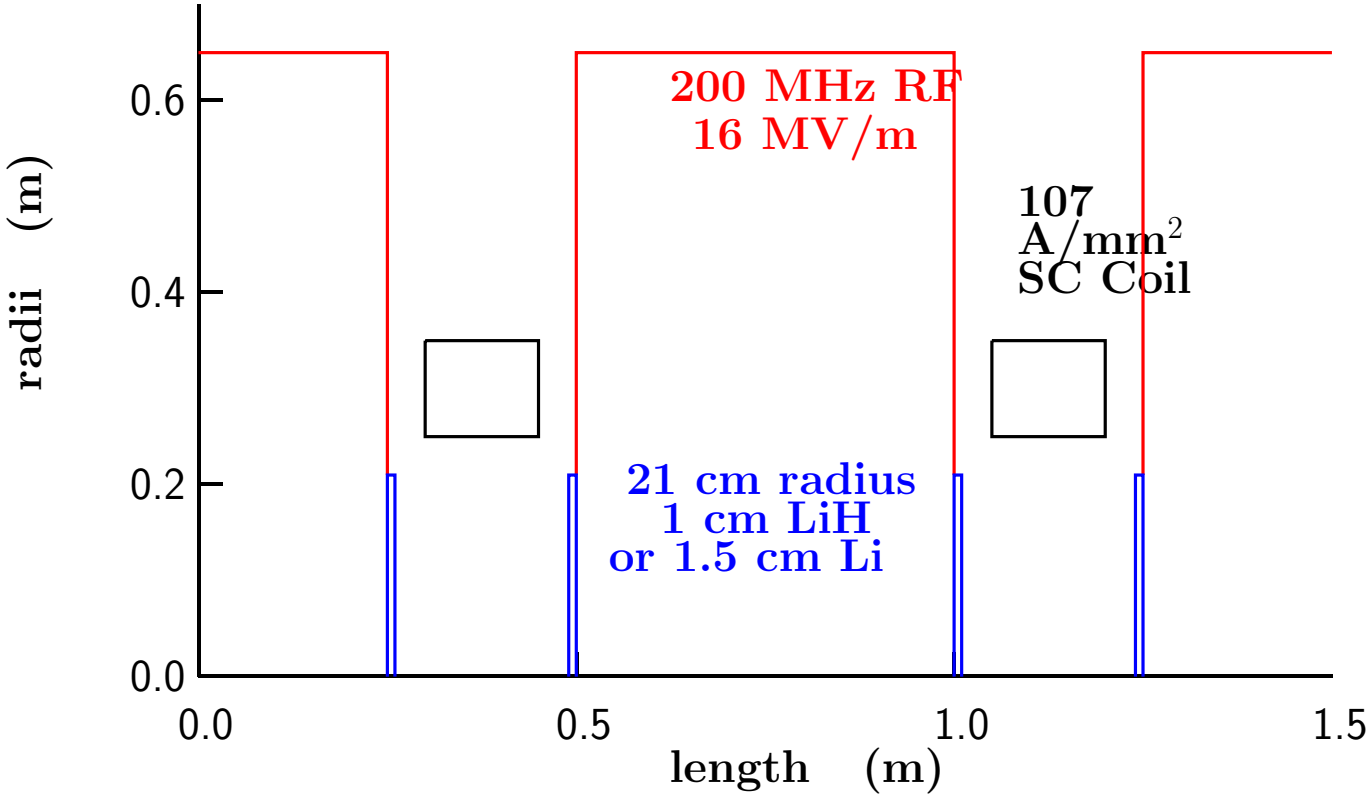
As in Neutrino Factory

Use only 21 of 56 used in Study 2a



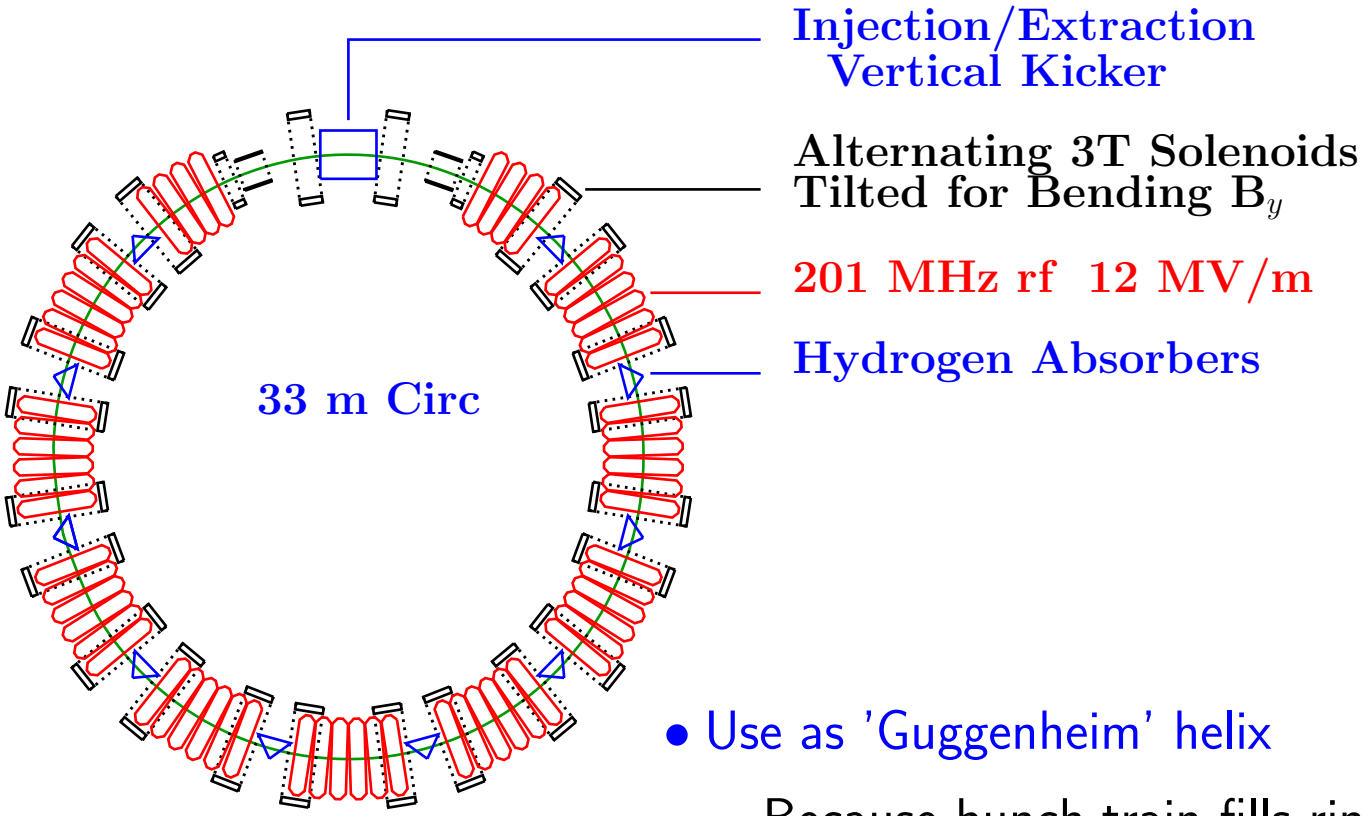
2) 50 m of Study 2a Linear Cooling

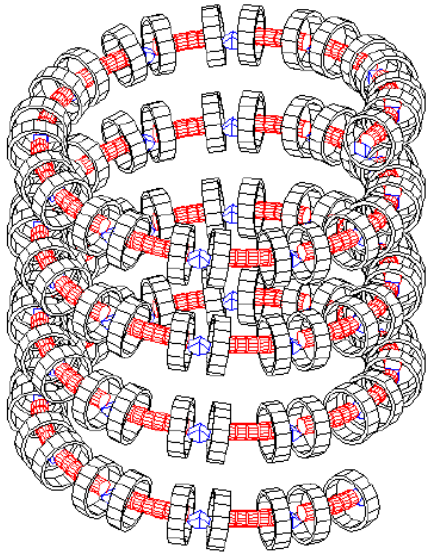
Reduces Transverse emittance from 20 to 10 pi mm
Longitudinal emittance rises from straggling



3) & 4) 6 D cooling in "RFOFO" Rings with Wedges

- Bending gives dispersion
- Wedge absorbers give memittance exchange: Cooling also in longitudinal

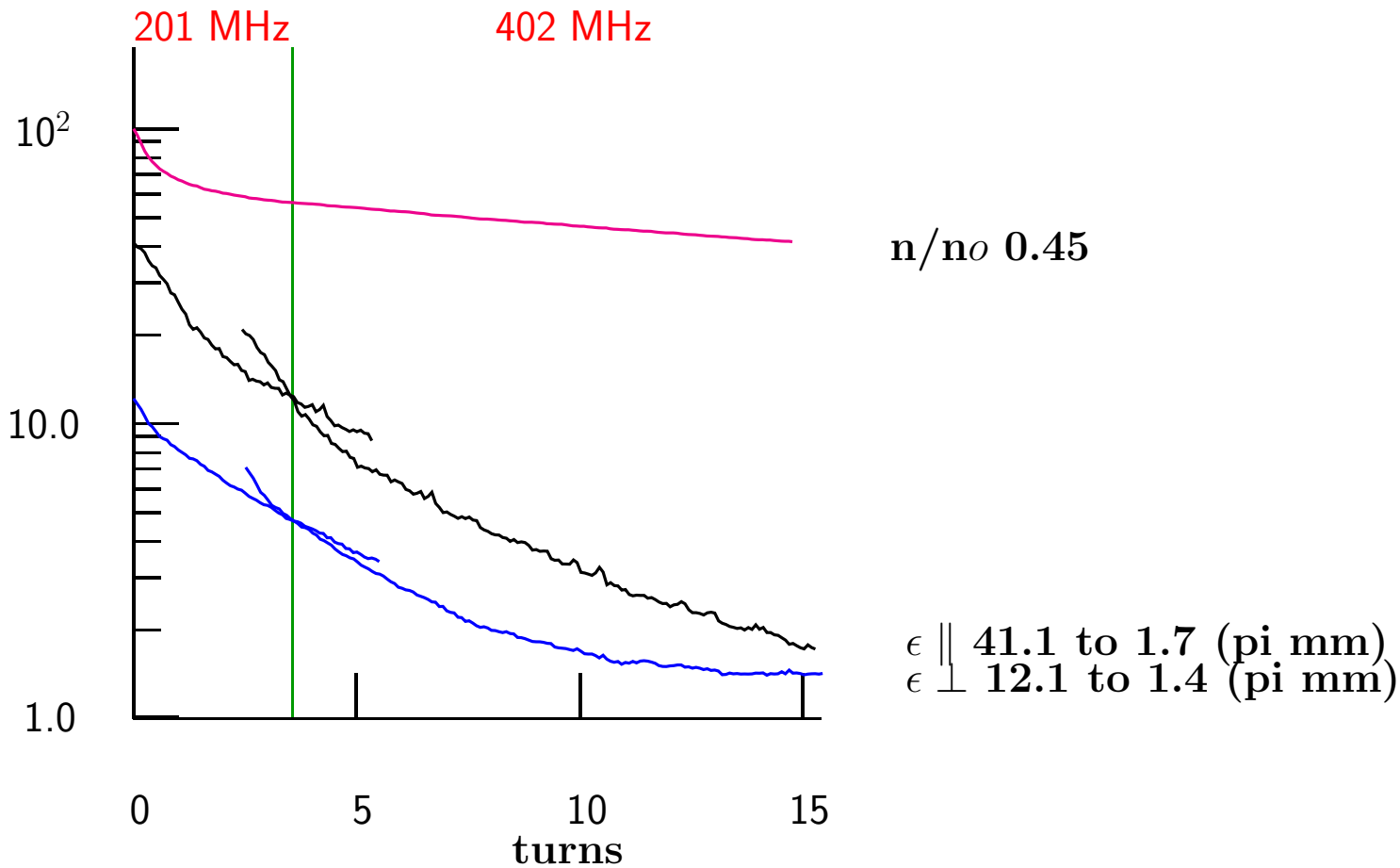




- Use as 'Guggenheim' helix
  - Because bunch train fills ring
  - Avoids difficult kickers
  - Better performance possible by tapering
    Not yet assumed

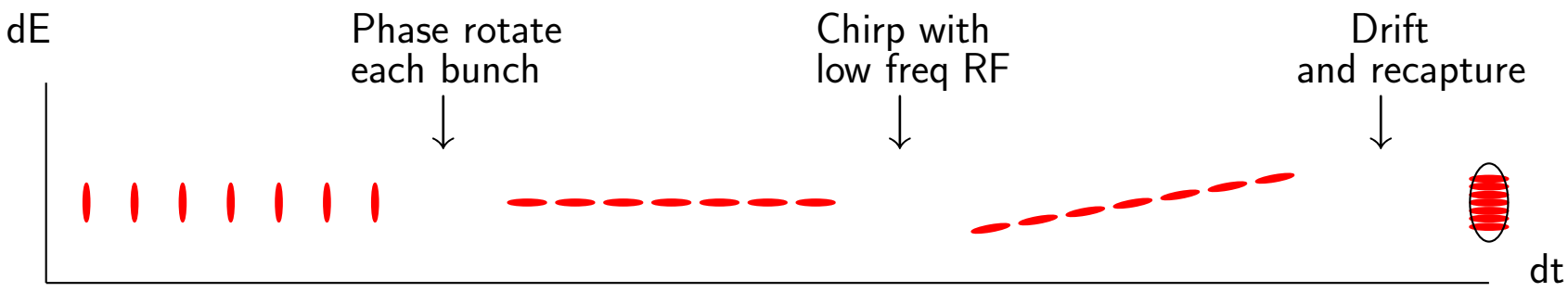
3) with 201 MHz 4) 402 MHz and 1/2 scale

ICOOL Simulations of real fields Balbakov was first

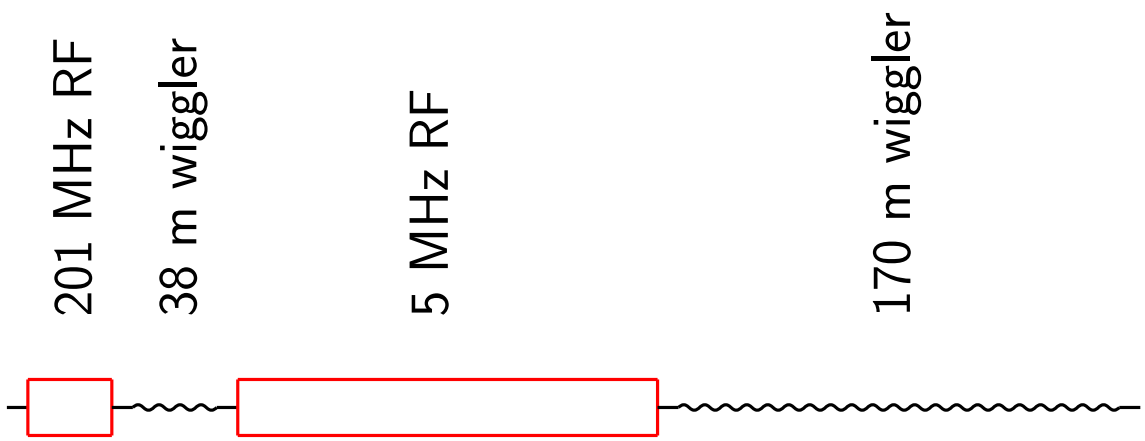


- 201 MHz RFOFO as published, but Guggenheimed (B=3 T)
- 402 MHz RFOFO has all dimensions halved (B=6 T)
- Equilibrium emittances both halved

5) Bunch Merging

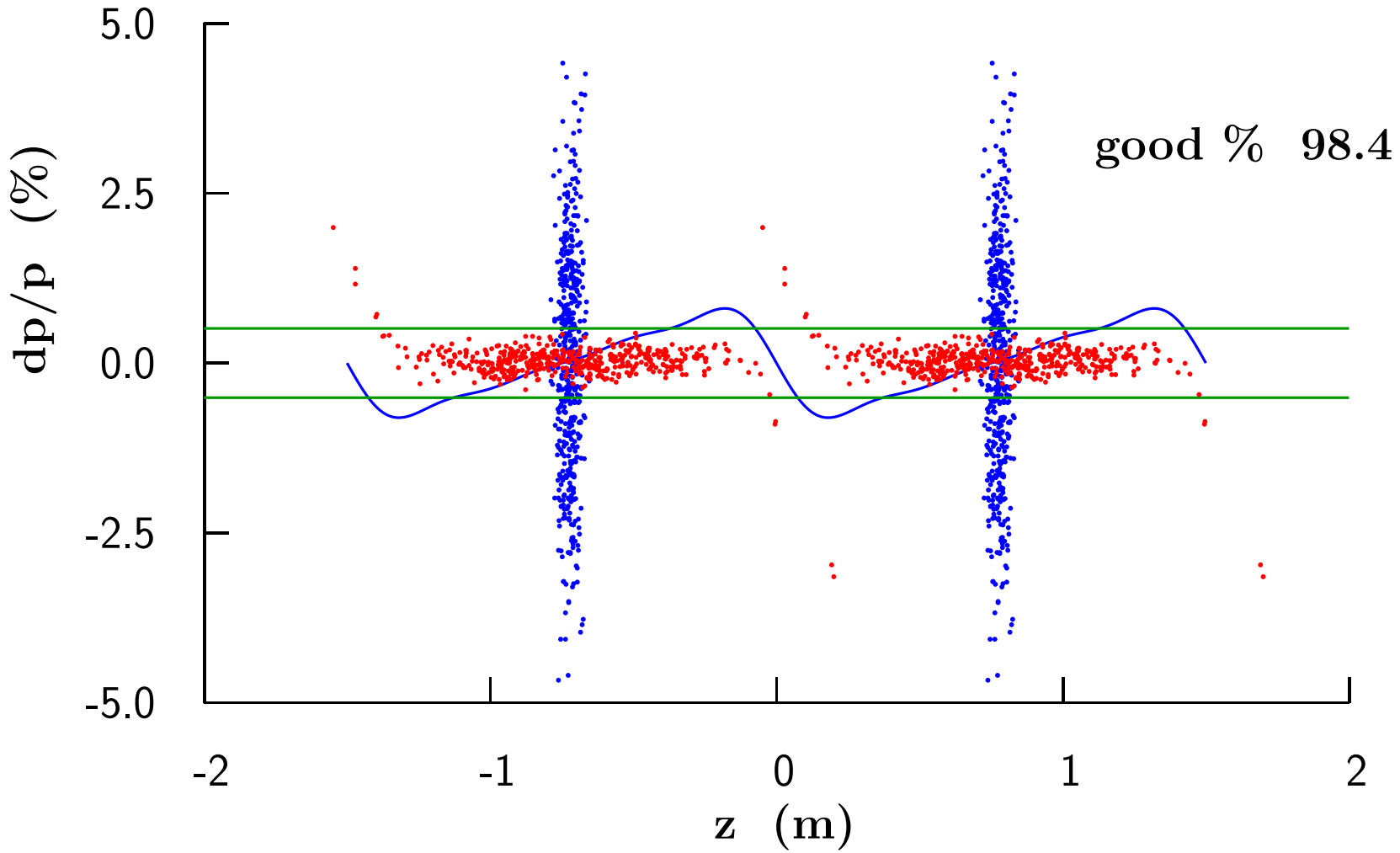


- First rotation with sawtooth RF rotates all bunches individually
- Second rotation with single ramp rotates all bunches
- Merged bunches captured with standard 201 MHz RFOFO RF

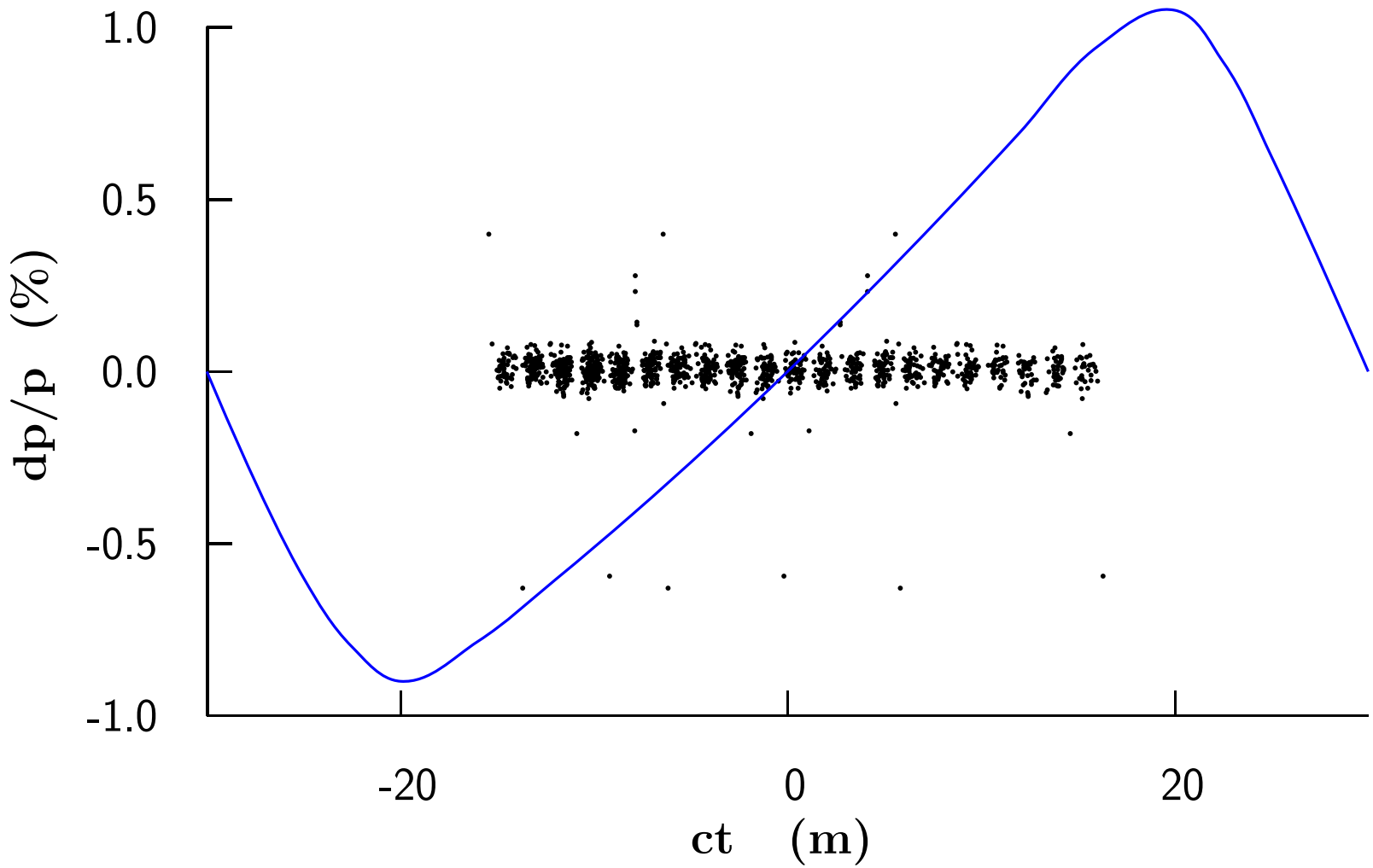


Using ICOOL simulated wigglers to maximize momentum compaction

First Rotation

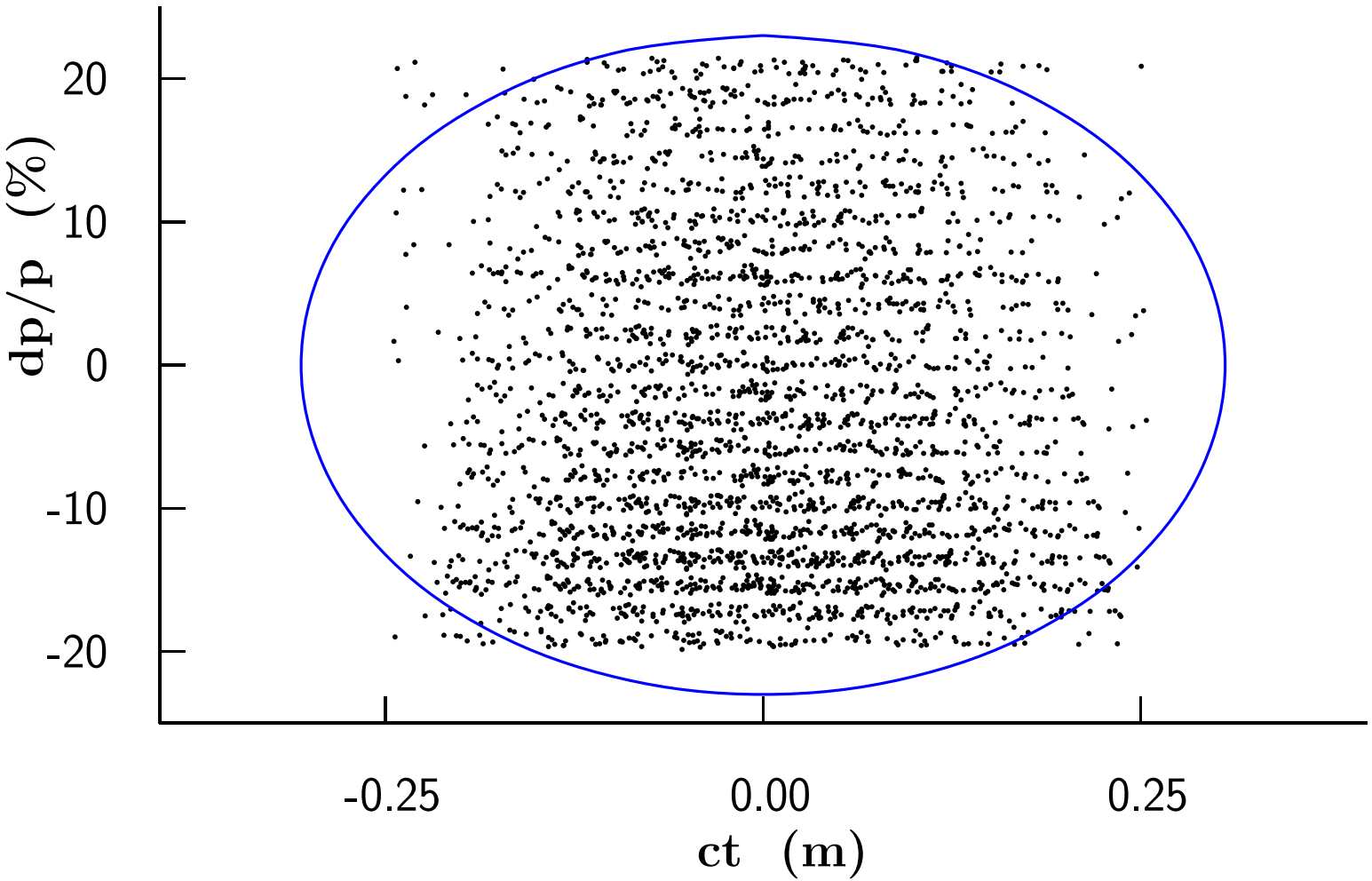


Before Second Rotation



After Both Rotations

not decayed (%) 97.09896 87.72808
in accept (%) 94.57606 eff (%) 80.56277
long acceptance (pi mm) 134.0572
long beta (m) 1.330435 emitlong (mm) 23.18362



6) and 7) 201 MHz and 402 MHz RFOFOs

Cooling in rings now possible because

- Single bunch allows time for kicker rise
- Small transverse emittance assures low kicker energy

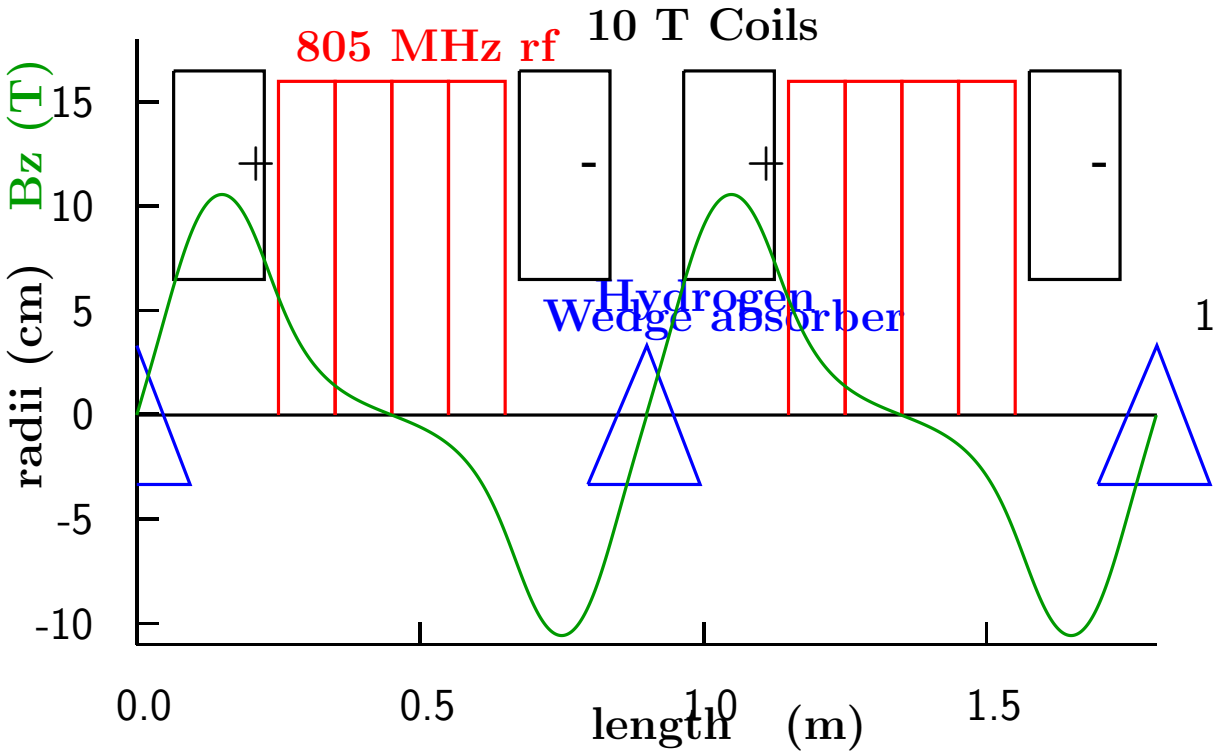
6) Cool longitudinally with 201 MHz RFOFO Ring

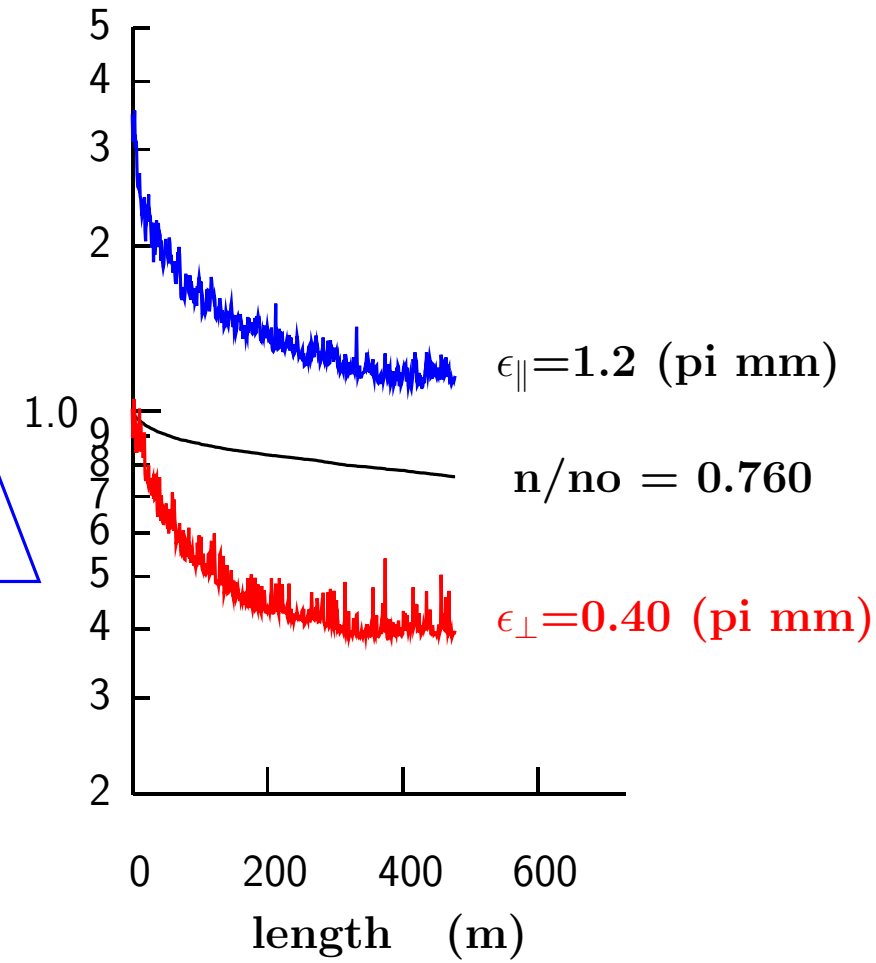
Transverse emittance rises slightly, but longitudinal cools fast

7)Cool further longitudinally with 402 MHz 1/2 scale RFOFO Ring

Slight transverse cooling, strong longitudinal cooling

8)New low beta 805 MHz RFOFO Ring



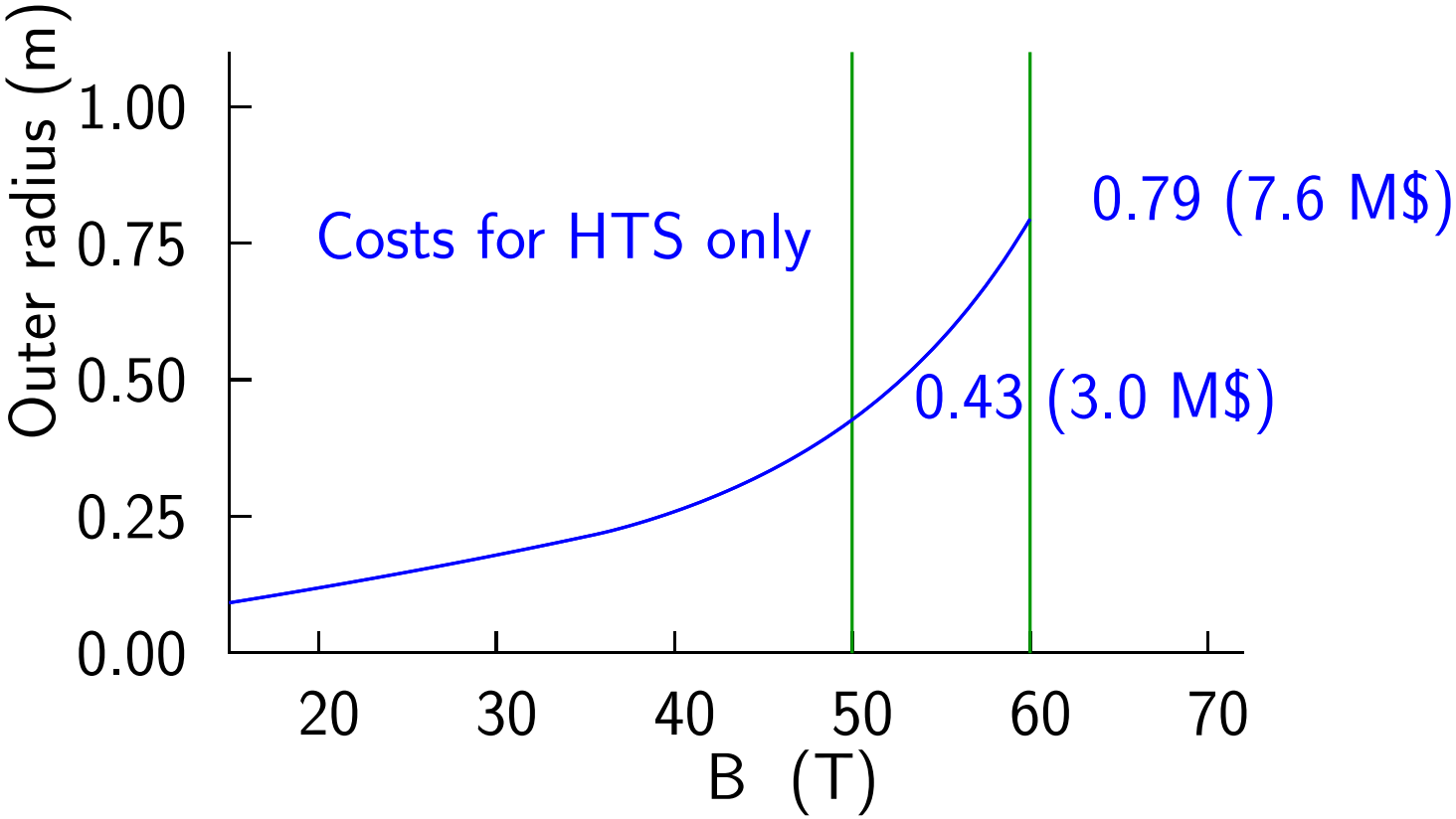


- Uses 10 T high current density solenoids
- Appears the lowest transverse emittance achievable with SFOFO

9) Cooling in linear sequence of 50-60 T solenoids

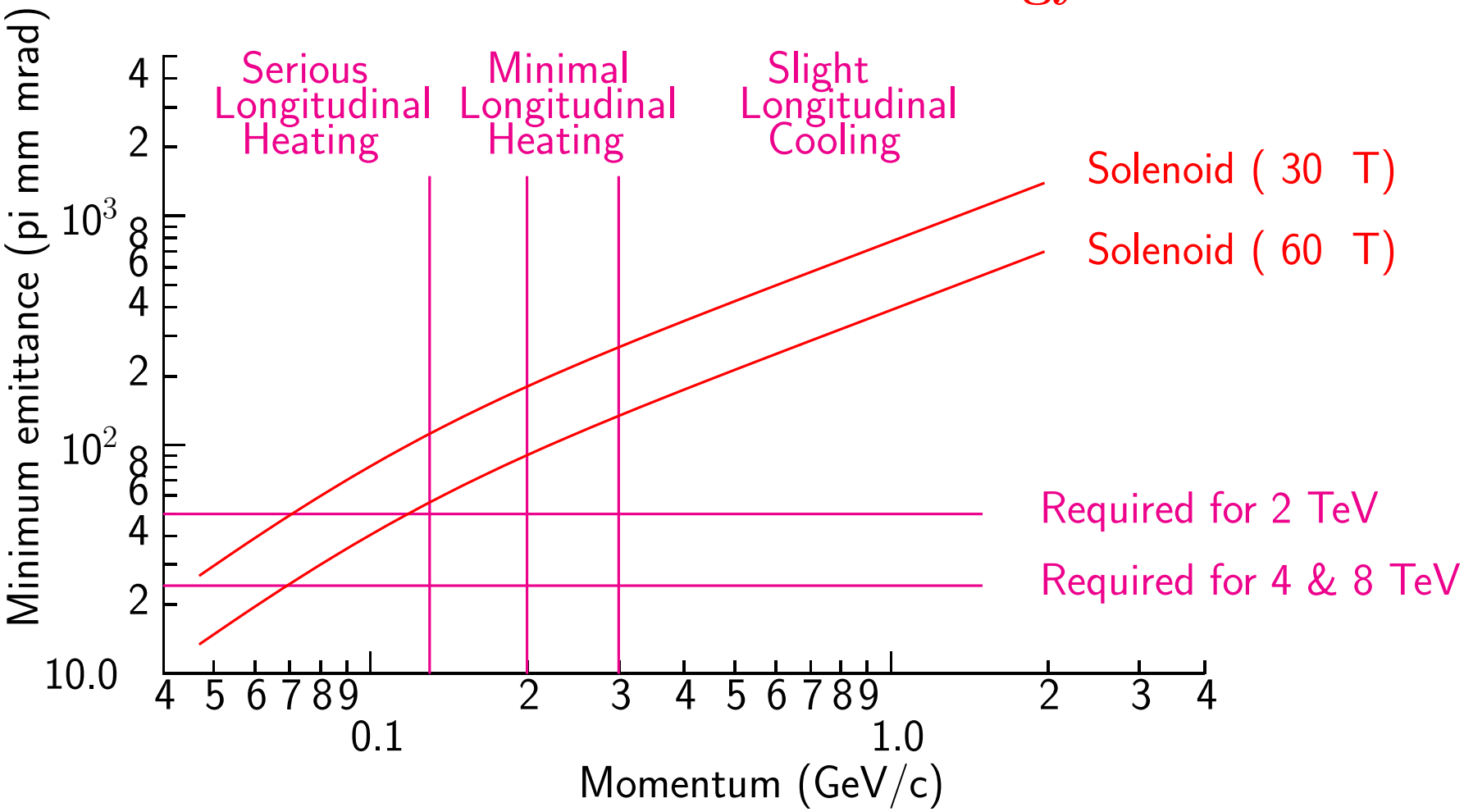
Muons Inc. Proposal

- Layer wound allowing current to vary with radius
- Vary ss support with radius to keep strain constant
- e.g. use existing American superconductor HTS tape



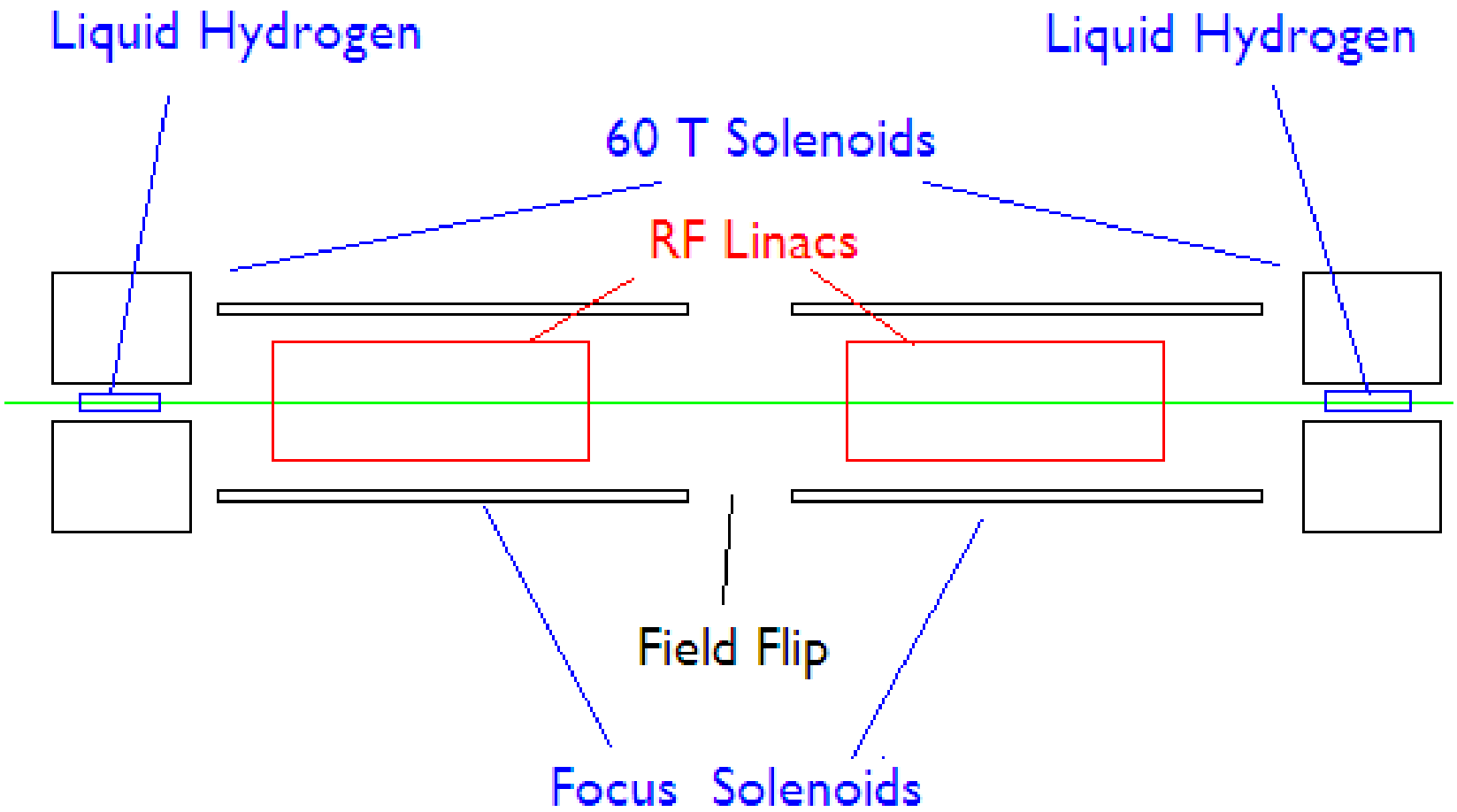
- Much work needed, but 50 T seems practical

Achievable emittances vs muon energy



- 50 π mm achievable without much longitudinal growth
- 25 π mm requires lower momenta and long. growth
- Minimizing number of solenoids requires allowing momentum to fall and longitudinal growth, but this seems acceptable

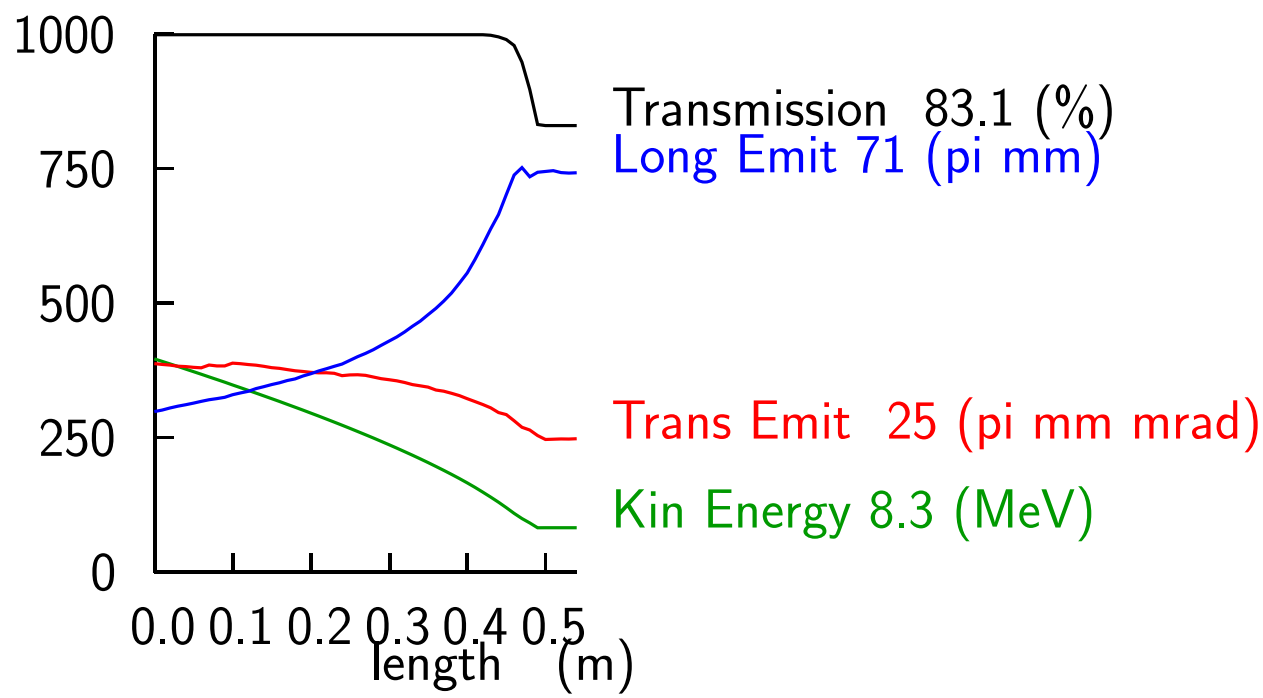
Conceptual Lattices



ICOOL Simulations (without matching & accel.)

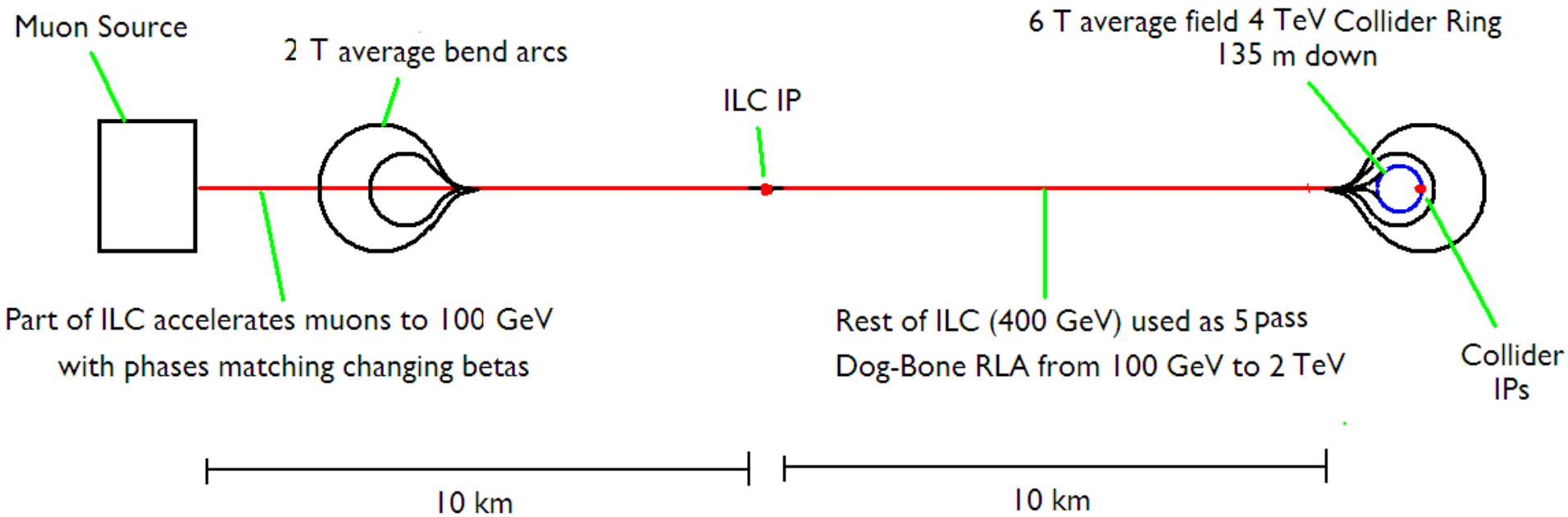
- 6 Solenoids with hydrogen absorbers inside
- Better performance if more than current 6 stages used
- Matching and acceleration not yet done
- But adiabatic solenoid matching should be easy

e.g. Simulation of Final Solenoid Cooling



- Lengths up to 1 m in earlier stages

9) Acceleration using ILC



- 4 TeV design assumes 500 TeV ILC gradients (30 MV/m)
- Decay losses from 1 GeV to 2 TeV only 8 %
- 8 TeV design will depend on nature of 1 TeV ILC upgrade
- If no ILC, then RLA to 1 TeV, then pulsed synchrotron (Summers)

Muon Survival (a first guess)

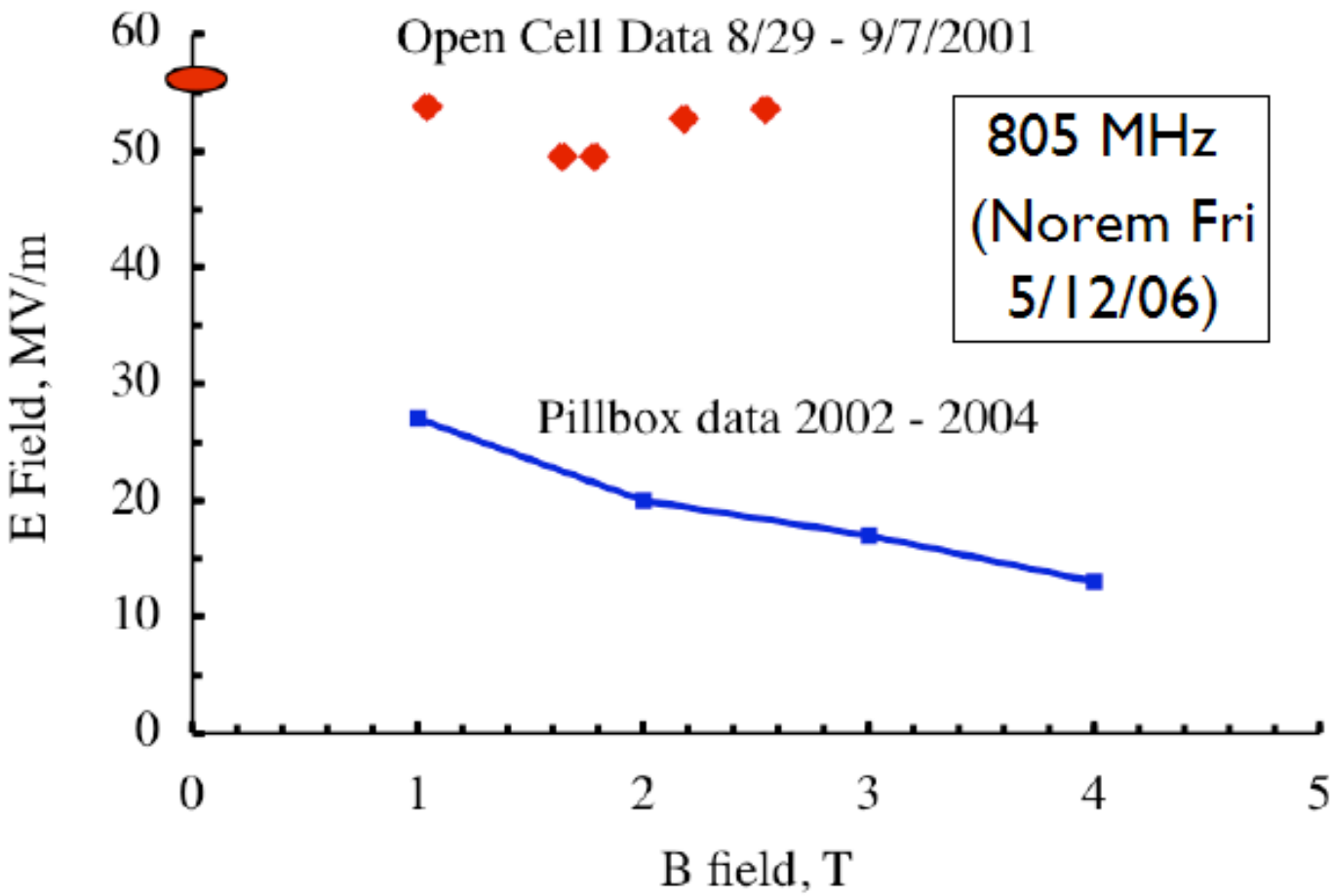
	Transmission	Cumulative
21 vs 54 bunches	.7	.7
Pre-merge RFOFO cooling	$\approx$ .5	.35
Merging	0.8	0.28
Post-merge RFOFO cooling	$\approx$ 0.5	0.14
Final 50 T solenoid cooling	.7	0.1
Acceleration to 2 TeV	0.7	0.07

Required Muons per bunch	2 10^{12}
Muons per bunch after merge	8 10^{12}
Initial Muons per bunch	2.8 10^{13}
Initial muons per 24 GeV proton	0.4
Initial 24 GeV protons	7 10^{13}
Proton power for 4 TeV (MW)	**1.5**
Proton power for 8 TeV (MW)	**0.8**

- Proton power $<$ ISS Neutrino Factory
- But lower rep rate $\rightarrow$ more charge/bunch
  Need E$>$ 8 GeV to get 1-3 ns proton bunch of 7 10^{13}
- Loading with 8 10^{12} muons per bunch needs study

Potentially serious problem in above SFOFO Lattices

- In above RFOFO Guggenheims: RF in high Mag Fields
- Inconsistent data: may/may not be a problem
- If it is a problem, all RFOFOs need redesign to lower fields



Conclusion

- Good Muon Colliders at 2, 4, and 8 TeV defined
  Consistent with Neutrino radiation and Tune shifts
- First complete cooling scheme
  Preliminary simulations of all components

To Do

- Design matching and accel between final solenoid coolings
- Study loading, wake, space charge and impedance problems
- Design lattices with lower fields on RF
- Consider alternative technologies
  - Gas filled Helices vs. RFOFO Rings
  - PIC and Similar lattices vs. High Field Solenoids
  - Lithium Lenses Vs. High Field Solenoids
  - Reverse emittance exchange with wedges vs. High Field Solenoids

Needed experimental work

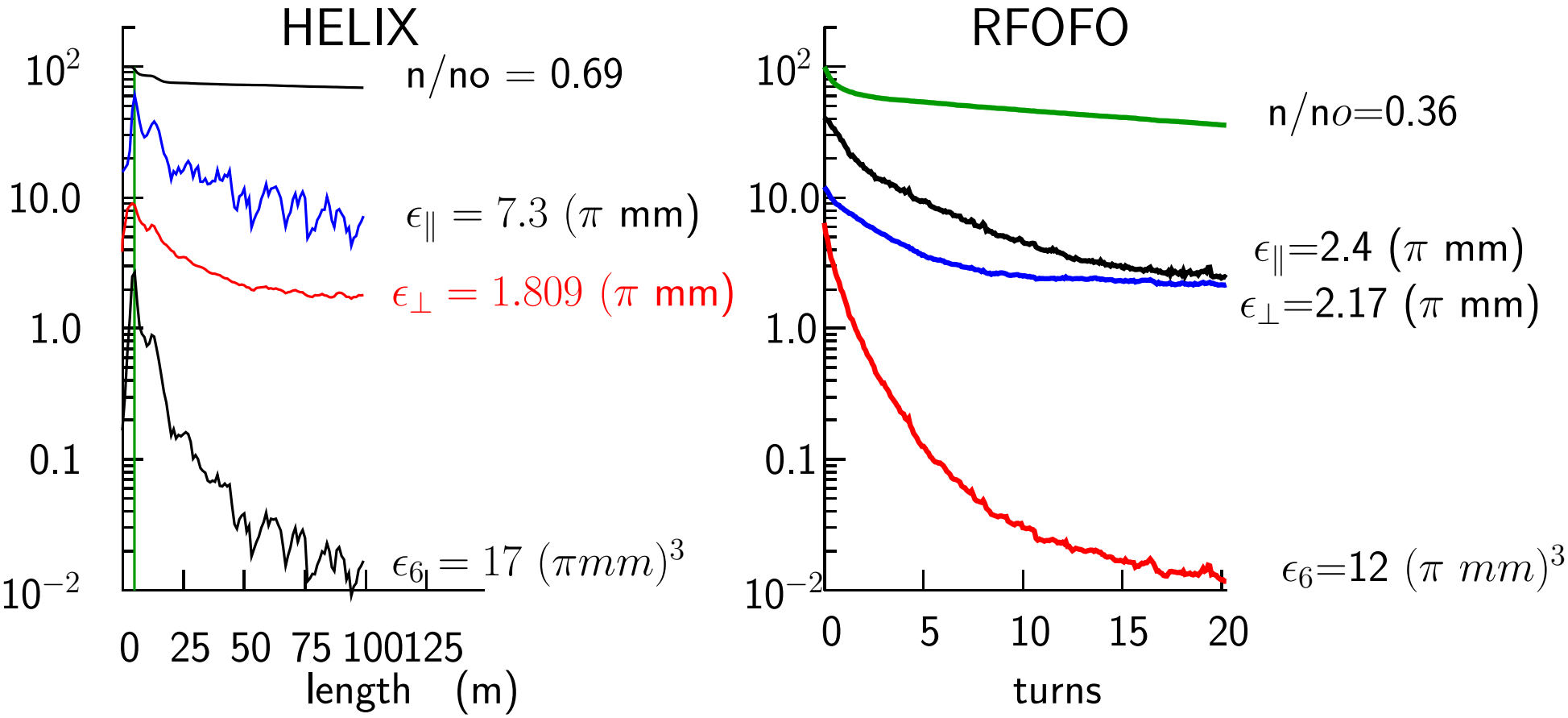
1. Demonstate mercury jet target - MERIT
2. Demonstrate transverse emittance cooling - MICE
3. Demonstrate emittance exchange: wedge and dispersion in MICE
4. R&D on Magnetic fields on RF cavities

5. R&D on high current density small Nb3Sn solenoids
6. R&D on very high field HTS solenoids
7. R&D on high field (open mid plane?) accelerator magnets

- Ongoing work on 1-4
- But no current work on 5-7

1) Helical Gas filled Channels vs. RFOFO Rings

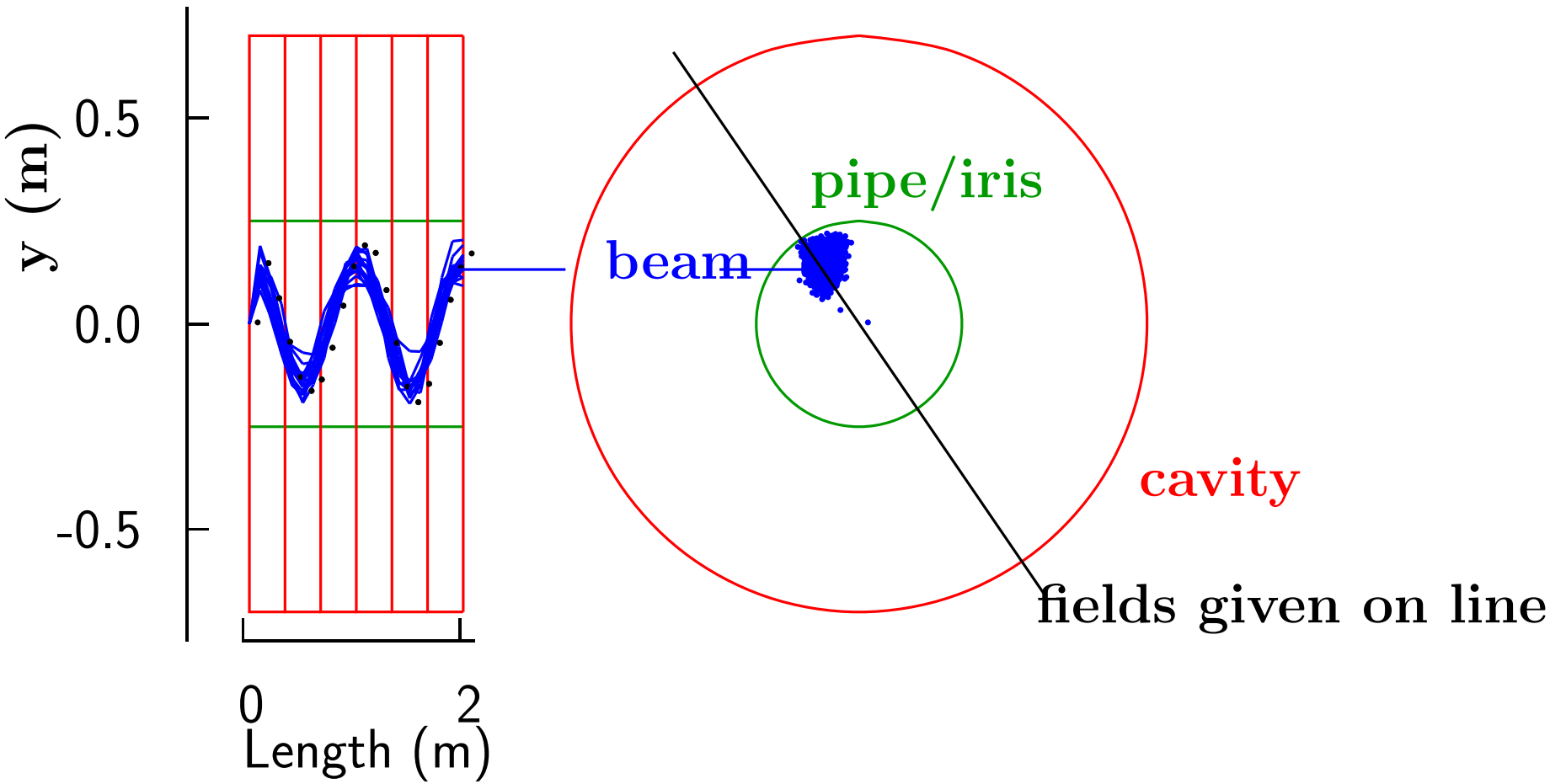
ICOOL Simulations, Helix from Katsuya Yonehara (Muons Inc May 06)



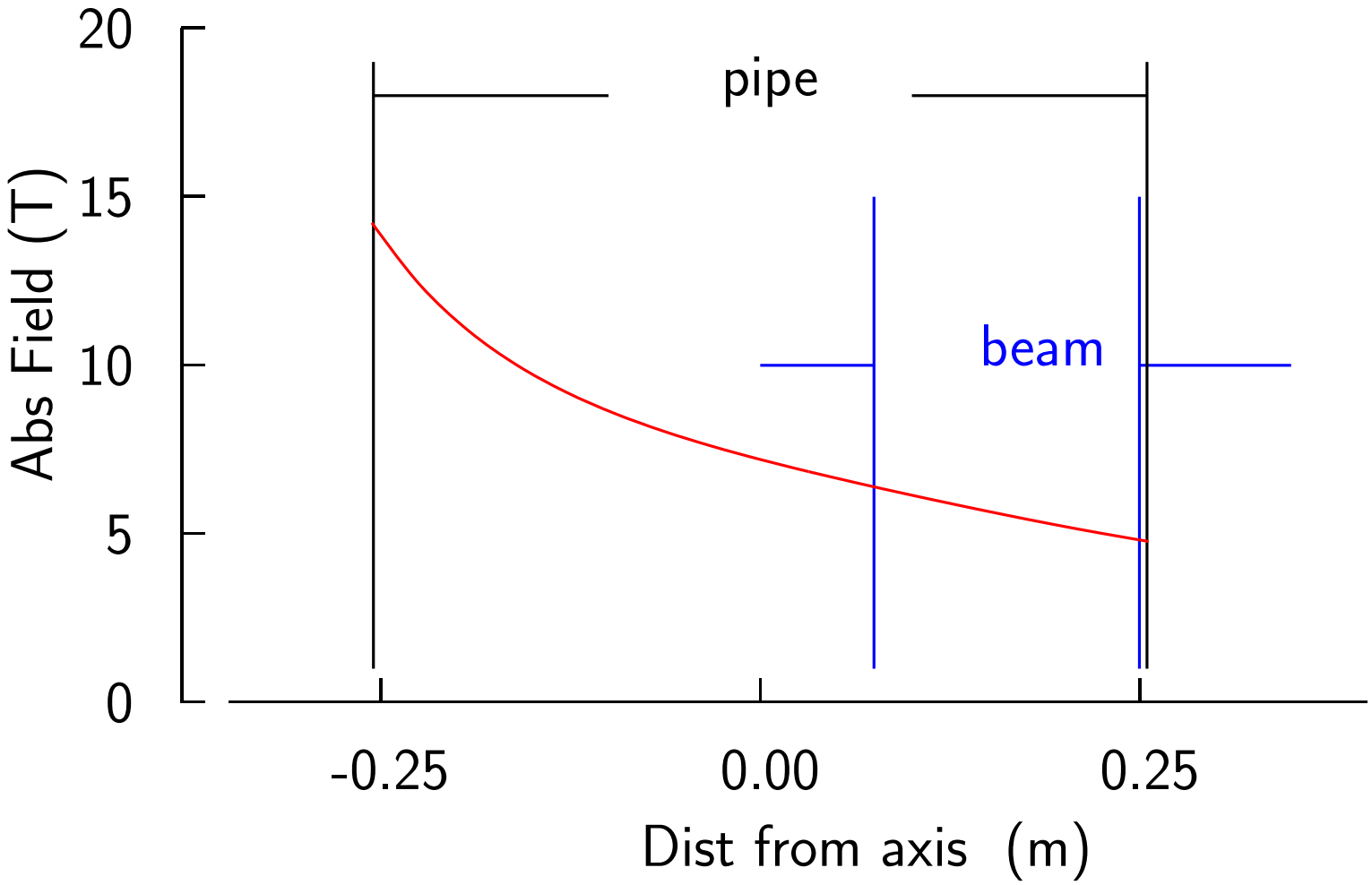
- Helix Merit (from 5 to 100 m) = 166 cf RFOFO 188
- High RF Fields: 31 MV/m cf 15 MV/m RFOFO
- Less longitudinal cooling

Problems

- Simulation used acceleration independent of r
  Merit dropped to 60 when real fields simulated
- High magnetic fields at coils, if outside RF

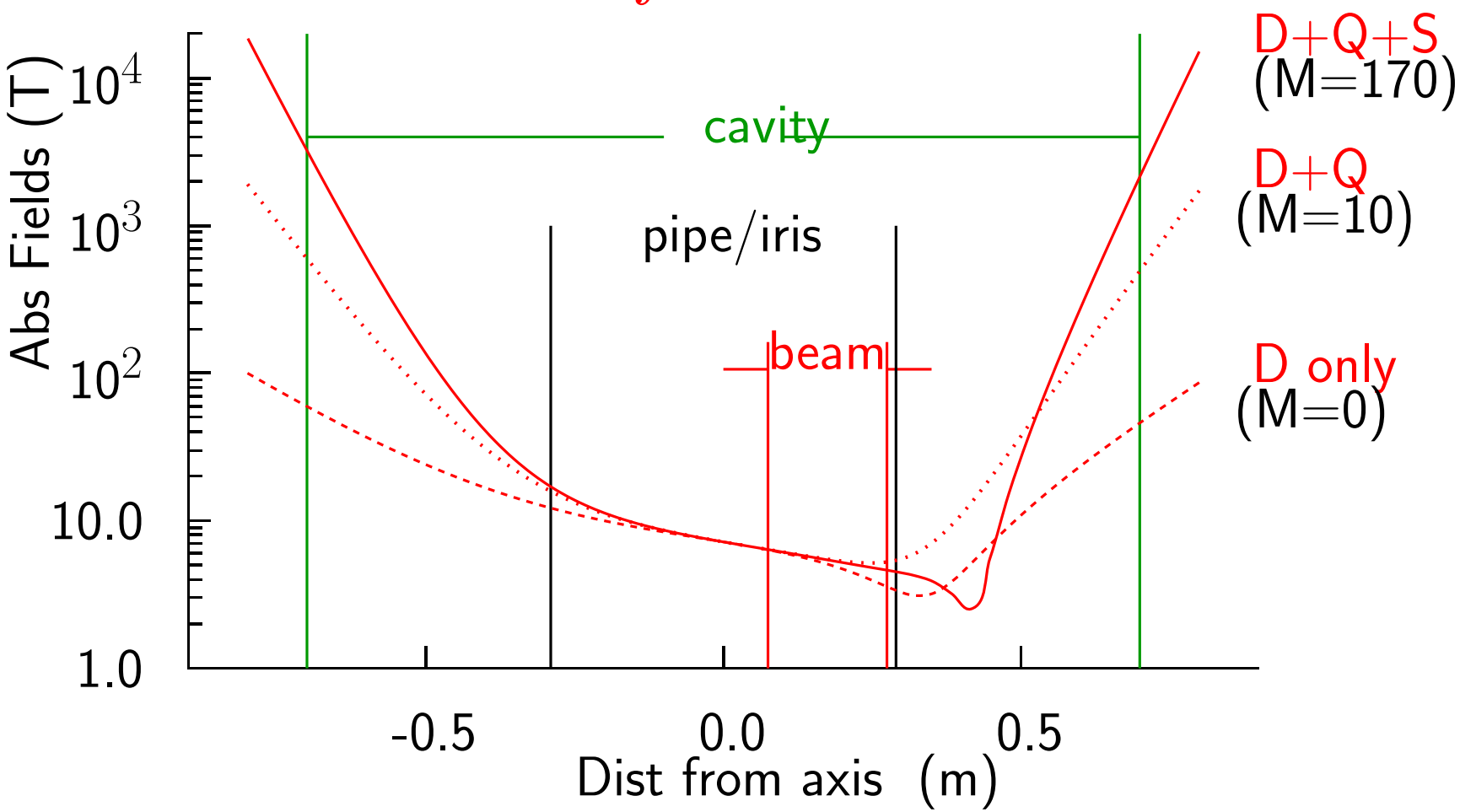


Fields within 'Pipe'



- Max Field 15 T
- Higher than SFOFO ($\approx$ 5T at coils)
- But not impossible

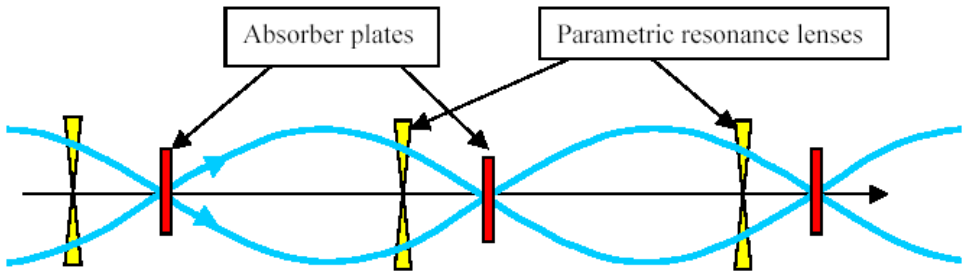
Fields Outside Cavity



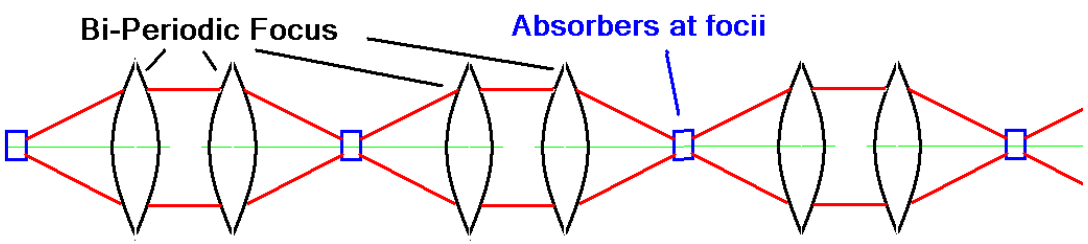
- Only usable without RF, alternating with Accel in linear systems
- To avoid diluting exchange, accel in vacuum, loosing advantage
- Also then hard to maintain bunch structure
- Not a proof, but life is hard

2) PIC and other cooling in thin absorbers at foci

As alternative to Final High Field Solenoids



PIC



SFOFO

- Both require strong focus to the local low beta
- Both require attention to momentum dependence
- Either could suffer from space charge effects
- Both probably limited by solenoid's spherical aberrations

Beam Divergence Angles Required for Cooling

$$\epsilon_{x,y}(min) \;=\; \frac{\beta_\perp}{\beta_v\; J_{x,y}}\; C(mat, E)$$

$$\sigma_\theta \;=\; \sqrt{\frac{\epsilon_\perp}{\beta_\perp\; \beta_v \gamma}}$$

so for a beam in equilibrium

$$\sigma_\theta \;=\; \sqrt{\frac{C(mat, E)}{\beta_v^2 \gamma}}$$ independent of emittance

for 75 % of maximum cooling rate, an aperture at 3 σ, the required angular acceptance A of the system must be

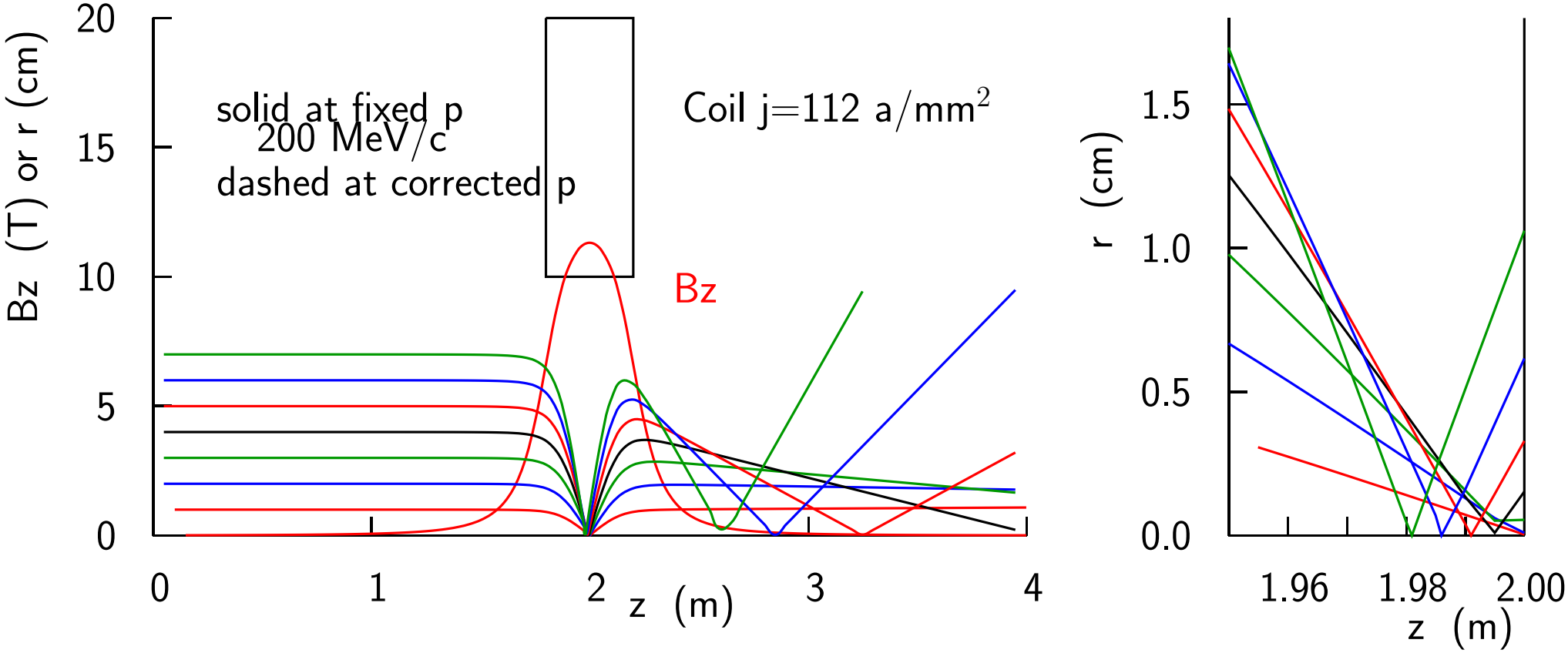
$$A \;=\; 3\sqrt{4}\,\sqrt{\frac{C(mat, E)}{\beta_v^2 \gamma}}$$

For p=200 MeV/c:

Material	H2	Li	Be	C
Ang Acceptance (Rad)	0.28	.38	.43	.58

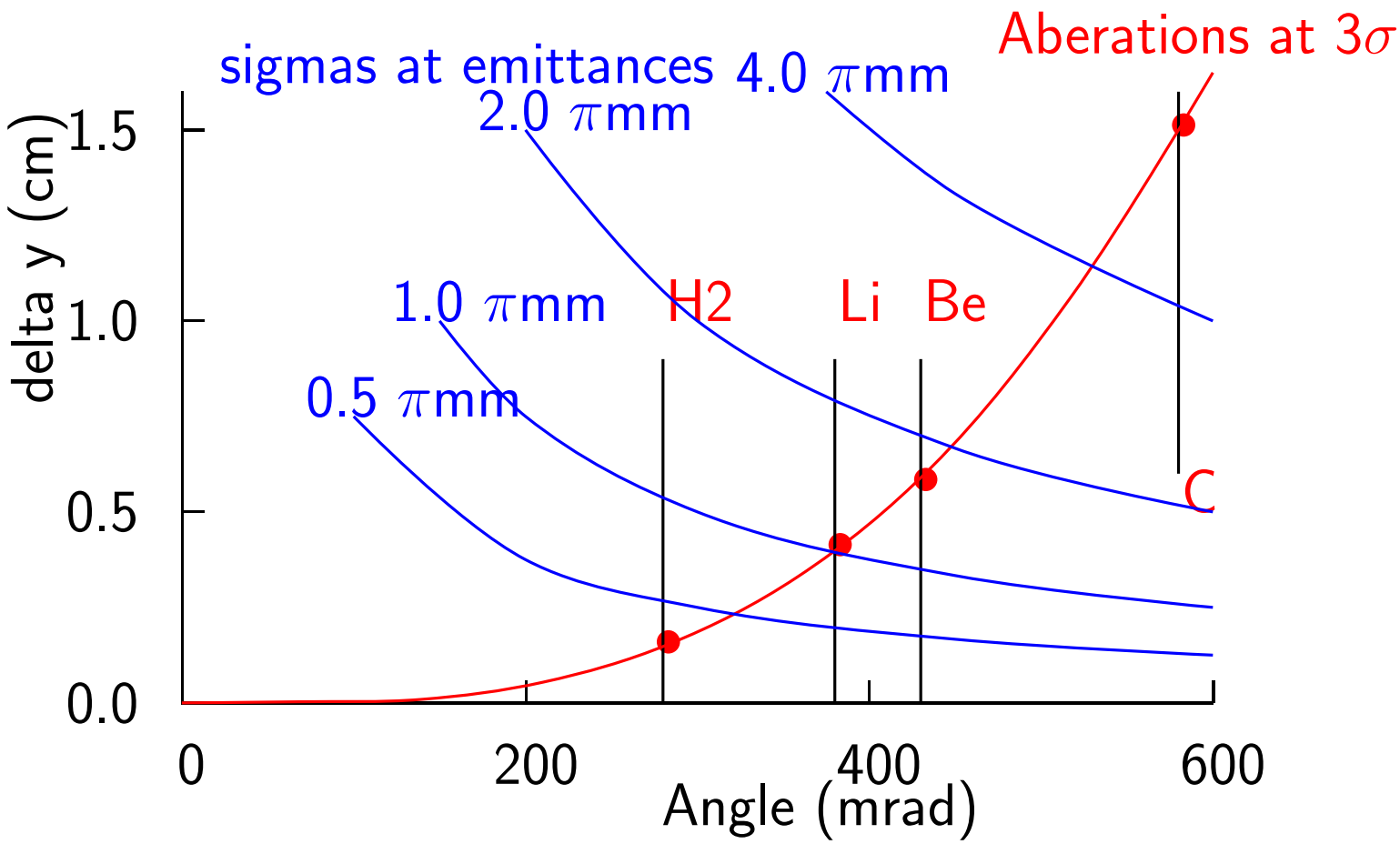
These are very large

Track through low beta focus



- Focus coil used has highest reasonable current density
- Tracks shown have divergencies from 70 to 520 mrad
- Spherical aberrations large (1cm) at such high divergencies

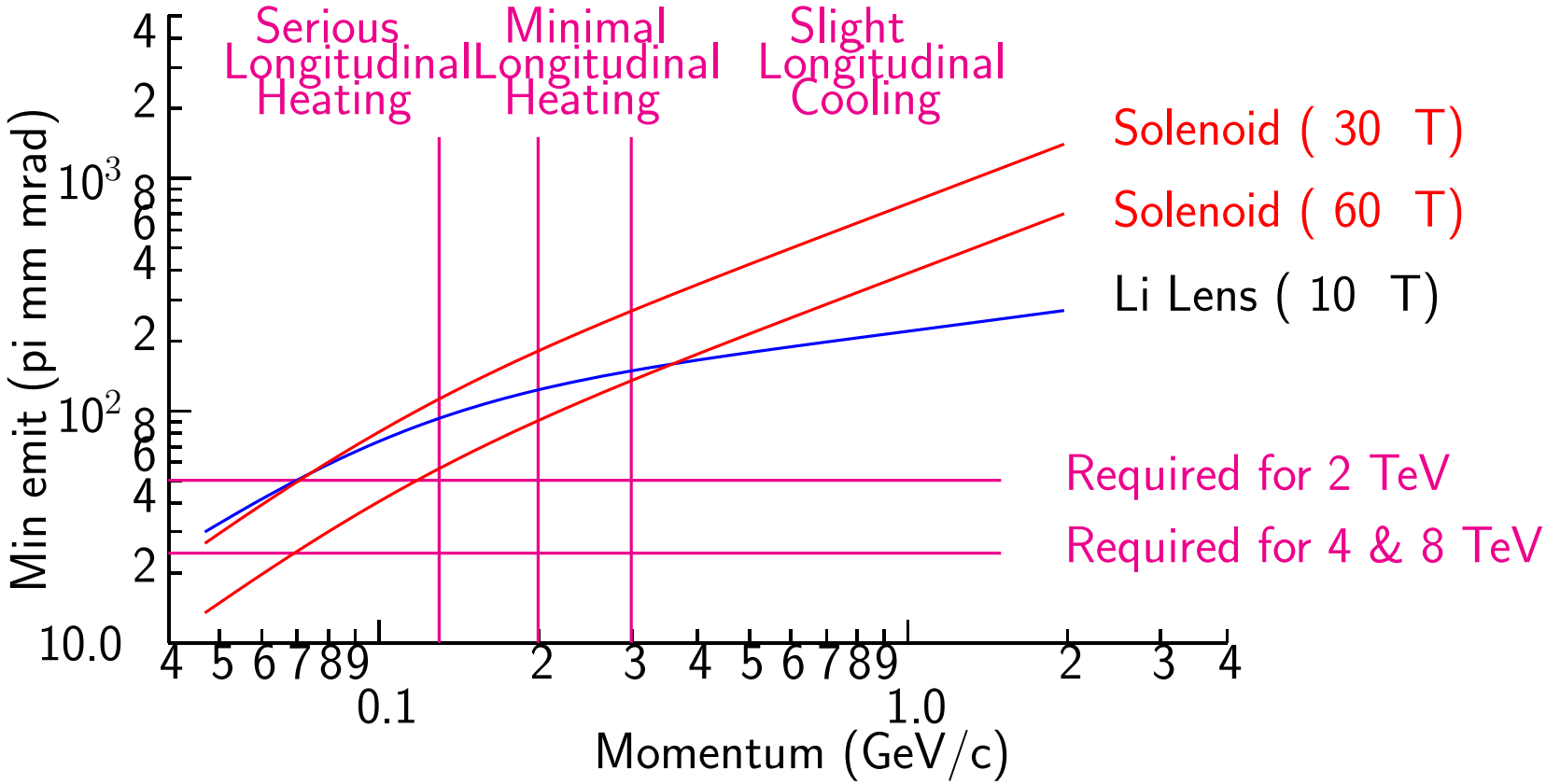
Aberrations compared with sigmas



- Suggests problems with H2 at $\epsilon_\perp < 0.4\ \pi\mathrm{mm}$
- Suggests problems with Li at $\epsilon_\perp < 1.0\ \pi\mathrm{mm}$
- Suggests problems with Be at $\epsilon_\perp < 1.6\ \pi\mathrm{mm}$
- Suggests problems with C at $\epsilon_\perp < 5.0\ \pi\mathrm{mm}$

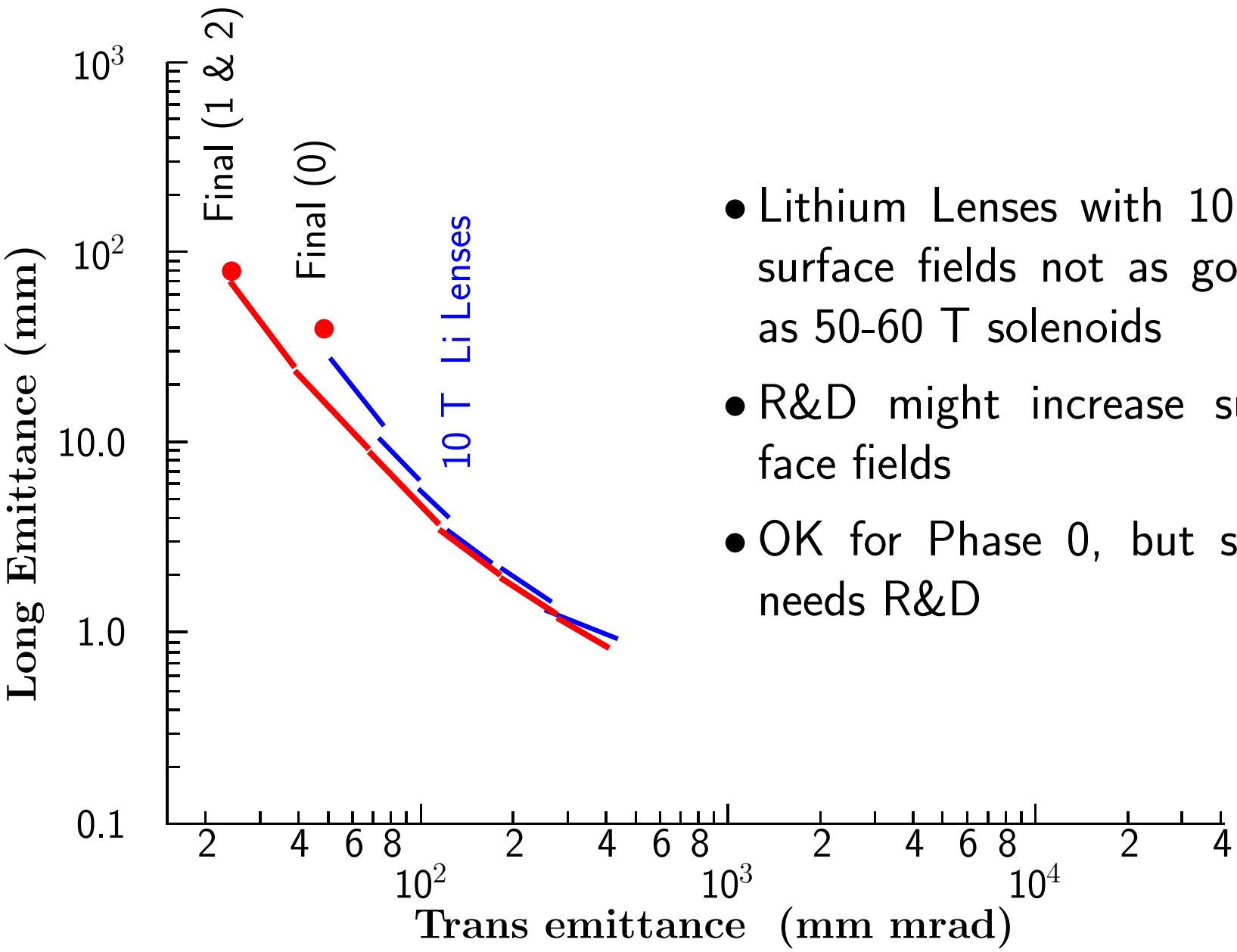
Not a proof
But life is hard

3) Lithium lenses vs. High Field Solenoids



- Li Lens Performance similar to 30 T Solenoid
- Acceptable for 50 π mm for 2 TeV Collider
- But matching in and out is more difficult
- Much R&D Required on Li Lens

ICOOL Simulations (without matching or accel.)



- Lithium Lenses with 10 T surface fields not as good as 50-60 T solenoids
- R&D might increase surface fields
- OK for Phase 0, but still needs R&D

An intriguing possibility

A Helical Li Lens

- Emittance exchange possible at lower emittances than SFOFO
- Should allow substantially lower final 6D emittances
- But still needs 50 T Solenoid for 25 π mm emittance

Reverse emittance exchange with wedges vs. High Field Solenoids

- Requires both low beta and high dispersion
- Worse non linear problems than PIC

Conclusion on Alternatives

- Gas filled Helix with RF does not seem practical
  Only useful if alternated with separate RF
  Loses advantage of gas in RF
  And hard to maintain bunch structure
- PIC or other low beta focus schemes hard for $\epsilon < 500\ \pi mm$
- Lithium Lenses could be alternative to High Field Solenoids
  but difficult matching in and out
  Needs serious R&D
  Only advantage is possibility of helical lens
- Wedge Reverse Emittance Exchange also hard
  But Muons Inc is funded to try

Appendices

- Assumptions
- Bunch Merge Parameters
- High Field solenoids from Summers Fri talk
- Parameters of Final Solenoid Cooling Stages
- Collider ring
- Insertion
- Decay losses
- Shielding
- Detector

- Cooling Beam Divergence vs Mom
- Helix field solutions

Assumptions

- Energy is the physicist's highest priority
  Consider center of mass E of both 4 TeV and 8 TeV
  Add Phase 0 at 2 TeV
- Determine best Luminosities achievable at these energies
- Tune shift ≈ 0.1 probably ok (vs. of 0.044 in Snowmass 96)
  Concensus at Fermilab Low Emittance Workshop Feb 06
- A depth of 135 m "straightforward" for 4 TeV version
  This is the depth proposed for ILC
- Fix Neutrino radiation ≤ 10 mem/year
  1/10 of Federal limit ≤ 100 mem/year
- Use same proton driver and muon cooling for all phases
- Allow higher field magnets, and greater depth for 8 TeV case
  Ave. bending of 10 T vs 5 T, depth of 540 m vs 135 m
- Use same Collider Ring design as in Snowmass 96 Study

Bunch Merge Parameters

First Rotation

Length	38	m
Circumference	45	m
Turns	0.85	
k	-3	
width	$\pm$ 80	cm
RF Freq.	201	MHz
Harmonics	402 603 805	MHz
Average Gradient	0.3	MV/m
Momentum	201	MeV/c
Initial Long Emittance	1.7×21	mm
Decay Loss	3.0	%

Second Rotation

Length	169	m
Circumference	45	m
Turns	3.7	
Kicker rise time	50	nsec
k	-3	
width	$\pm$ 80	cm
RF Freq.	5	MHz
Wave form generator		
Average Gradient	0.3	MV/m
Momentum	201	MeV/c
Decay Loss	12.3	%
Scraping Loss	5.5	%
Final Long Acceptance	134	pi mm
Final Long Emittance	23	pi mm

Wiggler parameters

Overall Fixed Quadrupole	T/m	0.5
Sinusoidal Periodic Dipole	T	.96
Period	m	2.08

Existing HTS Solenoids

from Summers friday Talk

Location	BSCCO	ID/OD/Length	B	IEEE T.A.S.
Florida	Bi-2212	41/165/209mm	20+5=25T	13 (2003) 1396
Karlsruhe	Bi-2223	50/185/177mm	12+5=17T	15 (2005) 1484
MIT	Bi-2223	78/126/402mm	1.7T	15 (2005) 1299
Tohoku	Bi-2223	90/180/250mm	19T goal	15 (2005) 1512
MIT	Bi-2223	40/108/113mm	22.5+1.5=24T	67 (1995) 1923*

Proposed 30T HTS Solenoid

Proposed NHMFL 30 Tesla
NMR Solenoid for Florida

- IEEE Trans. Ap. Supercon. 16 (2006) 1523
- Bi-2223 Oxford Superconductor wire
or Bi-2223 American Superconductor tape
- Dispersed SS reinforcing + Stronger Silver
alloyed with Mg, Sb, Ti, or Nb nanoparticles

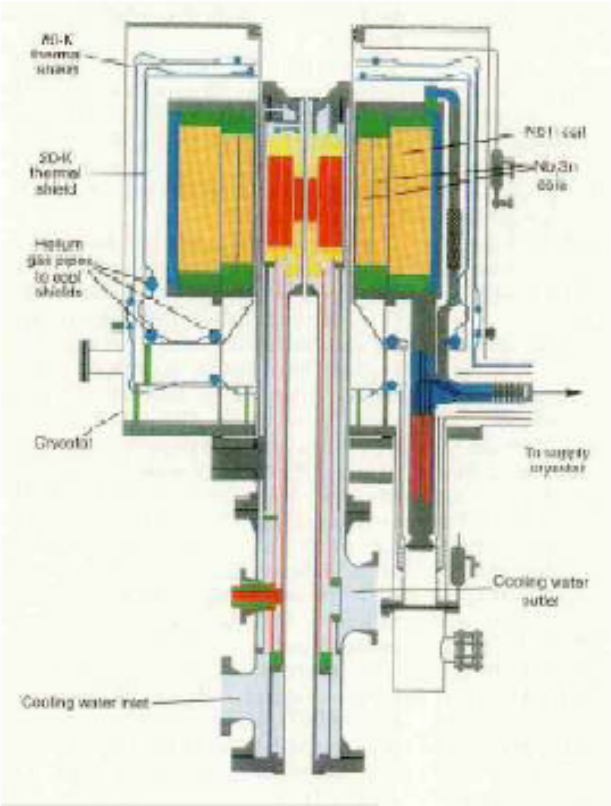
B	Temp	ID	OD	Length	Energy
30 T	4.2 K	100 mm	1100 mm	1750 mm	90 MJ

BSCCO	Strain	J_c	Nb_3Sn	NbTi
304 kg	0.275%	70%	1882 kg	1552 kg

Existing Hybrid 45T Solenoid

Florida 45 Tesla Hybrid Magnet

- Physics Today (Dec 1994) 21
- 32 mm bore, 20 Mwatts, Cu/Nb_3Sn/NbTi



Parameters of Final Solenoid Cooling Stages

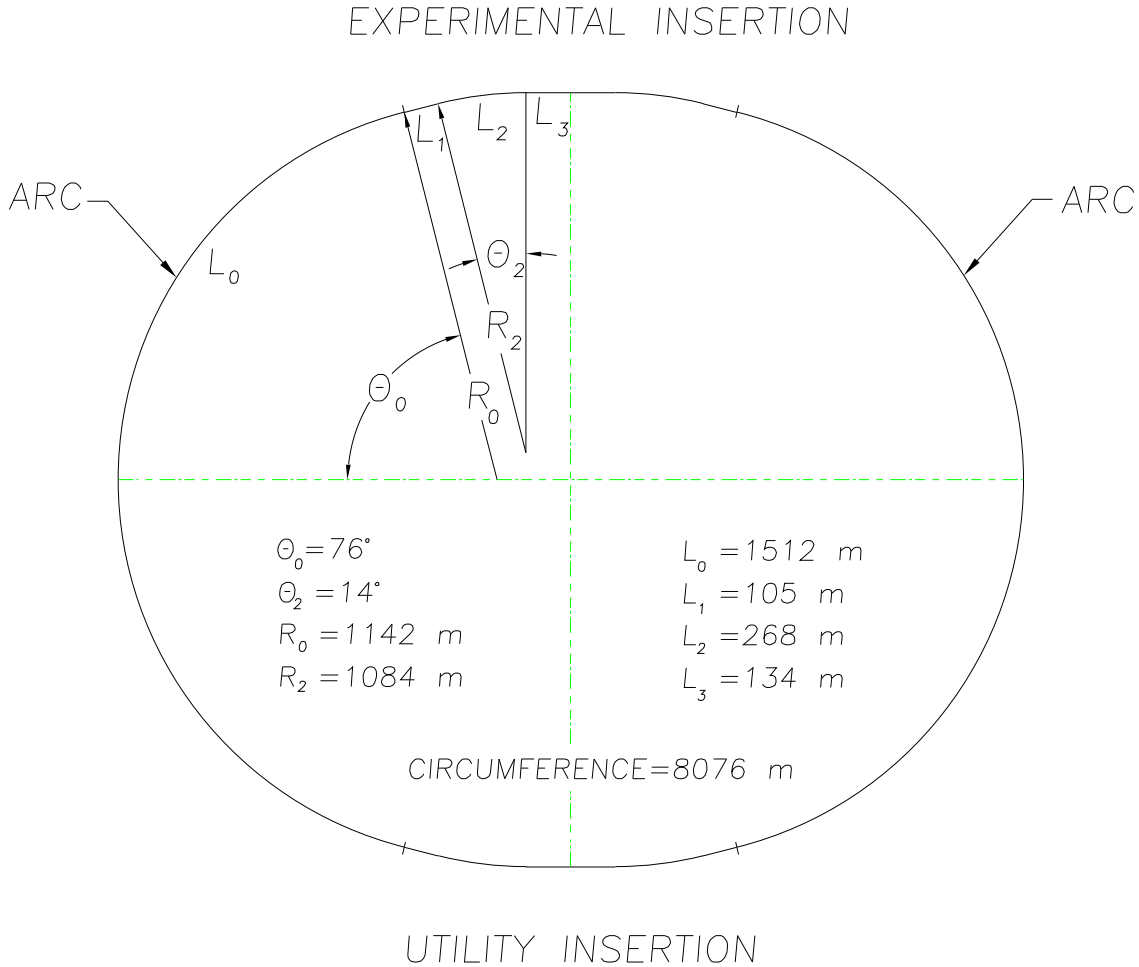
Emittances are at ends of each stage

	emit trans mm mrad	emit long mm	dp/p 1 %	dp/p 2 %	E1 MeV	E2 MeV	dE MeV	sigmaz cm	min freq MHz
1	278	2.5	3.3	8	53	11	42	3.5	800
2	182	4	2.7	8	57	15	41	6.1	400
3	115	7.4	2.5	11	60	22	38	9.4	200
4	68	18.5	2	15	64	28	36	21	100
5	37	50	2	20	68	33	35	50	100

Note

- dp/p increases in each stage
  and must be reduced by phase rotation in linacs
- Bunch lengths are increasing
- Acceleration Frequencies must fall
- But acceleration required is small

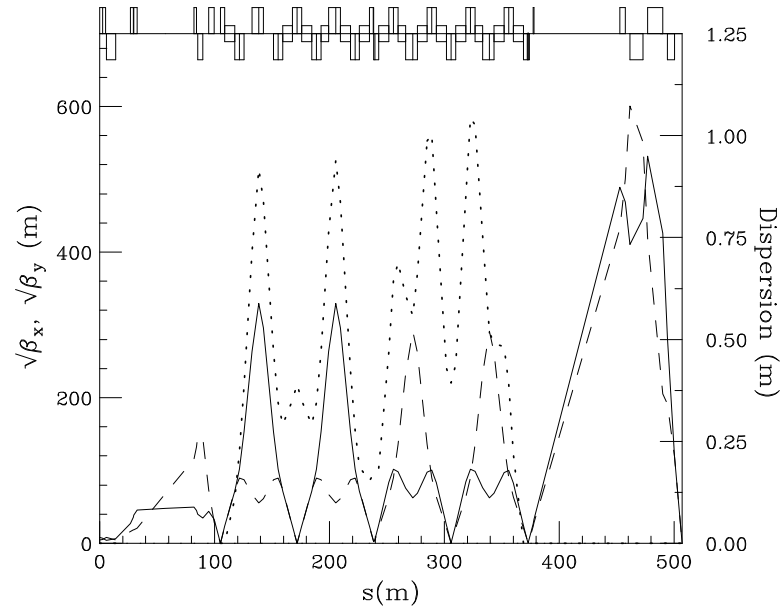
Collider Ring

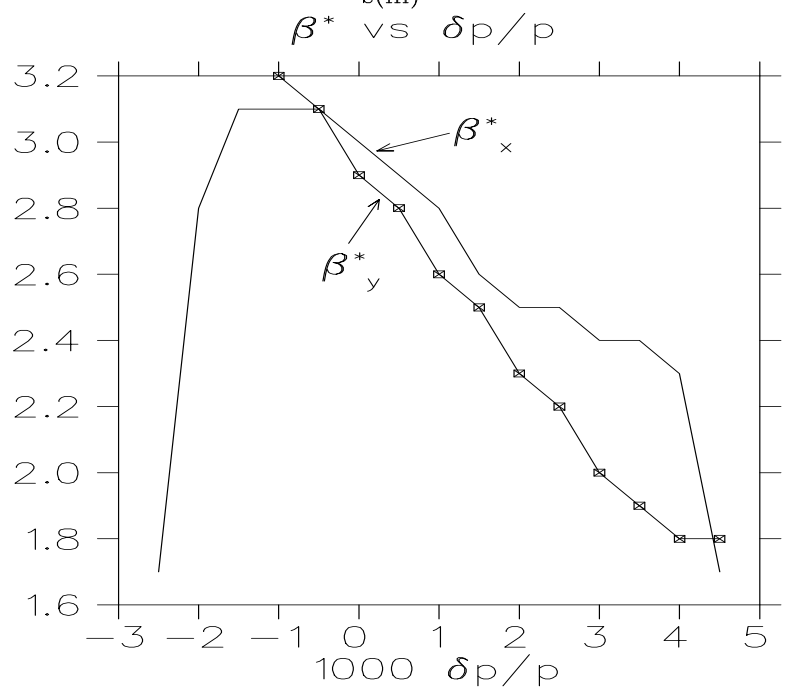


- Much work on ring design
- Requires low beta at intersection (3 mm)
- and goof momentum acceptance ($\pm$ 0.5%)

Low Beta Insertion

- Insertion design follows Linear Collider concepts
- Smaller betas and larger dp/p acceptance would reduce required beam power
- Tune shift correction was studied (Skrinsky)



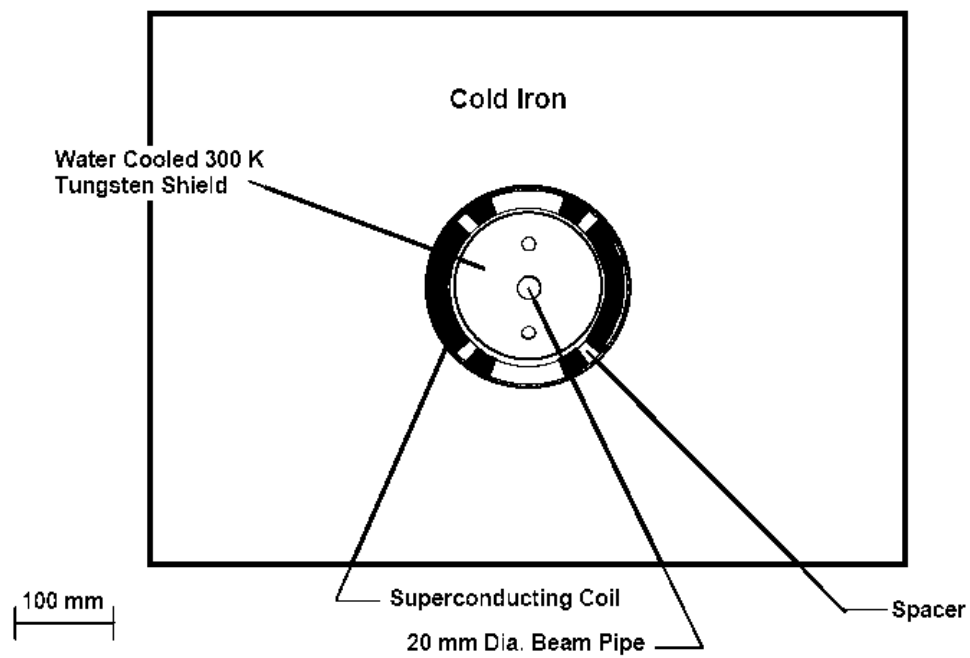


Decay losses

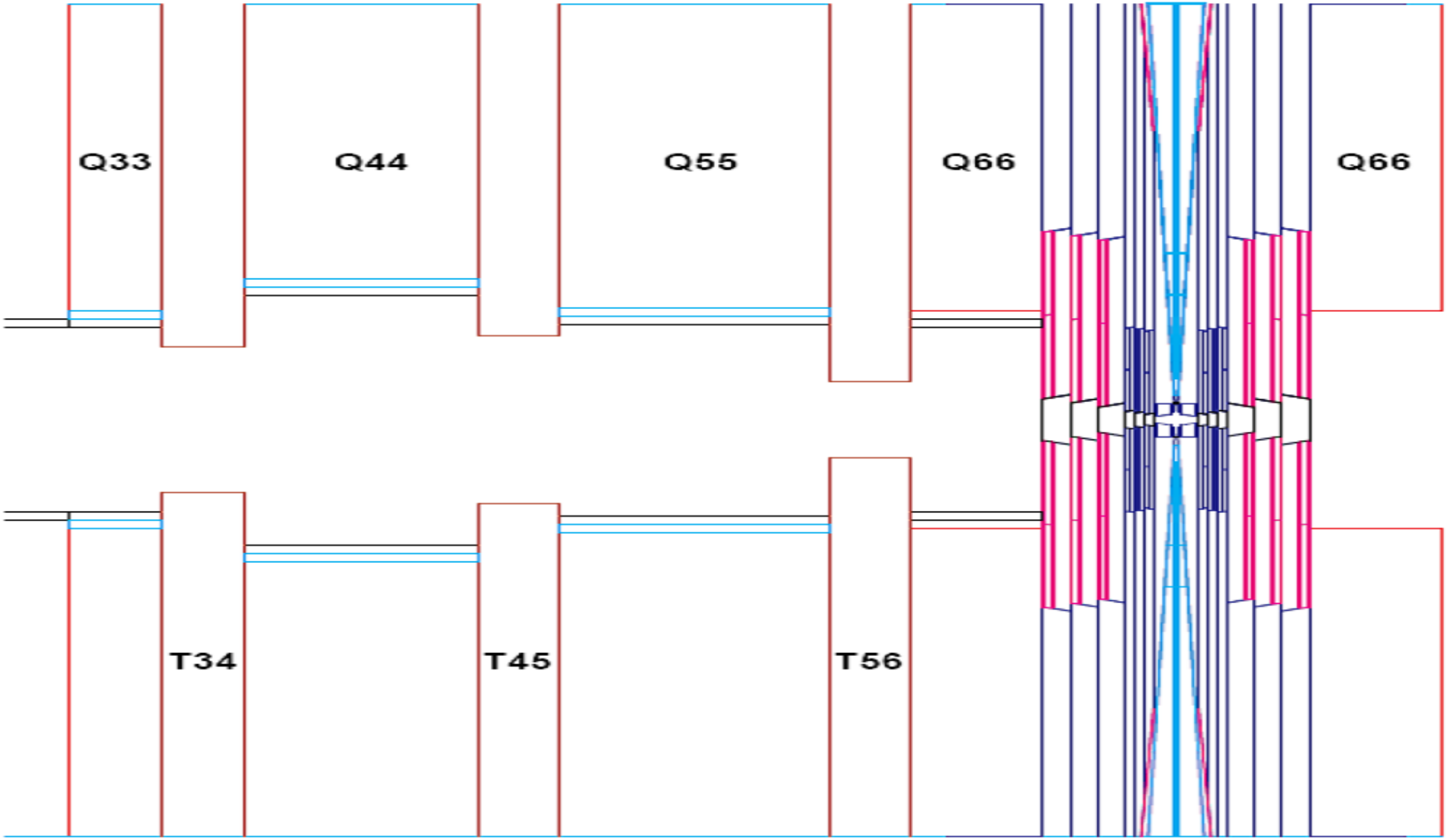
Table 8.2: Muon decay parameters for various parts of a muon collider

Component	Peak Energy (GeV)	Number of Turns	L_T(km)	Total Muon Decay Rate $10^{13} s^{-1}$	Heating Power (kW)	Peak Heat per unit L (Wm^{-1})
Linac	1.0	-NA-	0.12	1.9	0.6	-NA-
First Ring	9.6	9	2.17	1.2	3.6	1.64
Second Ring	79	12	11.3	0.8	19.7	1.75
Third Ring	250	18	29.2	0.4	36.8	1.26
Fourth Ring	2000	18	227	0.6	378	1.66
Collider Ring	2000	1000	7.9	13.1	14600	1840

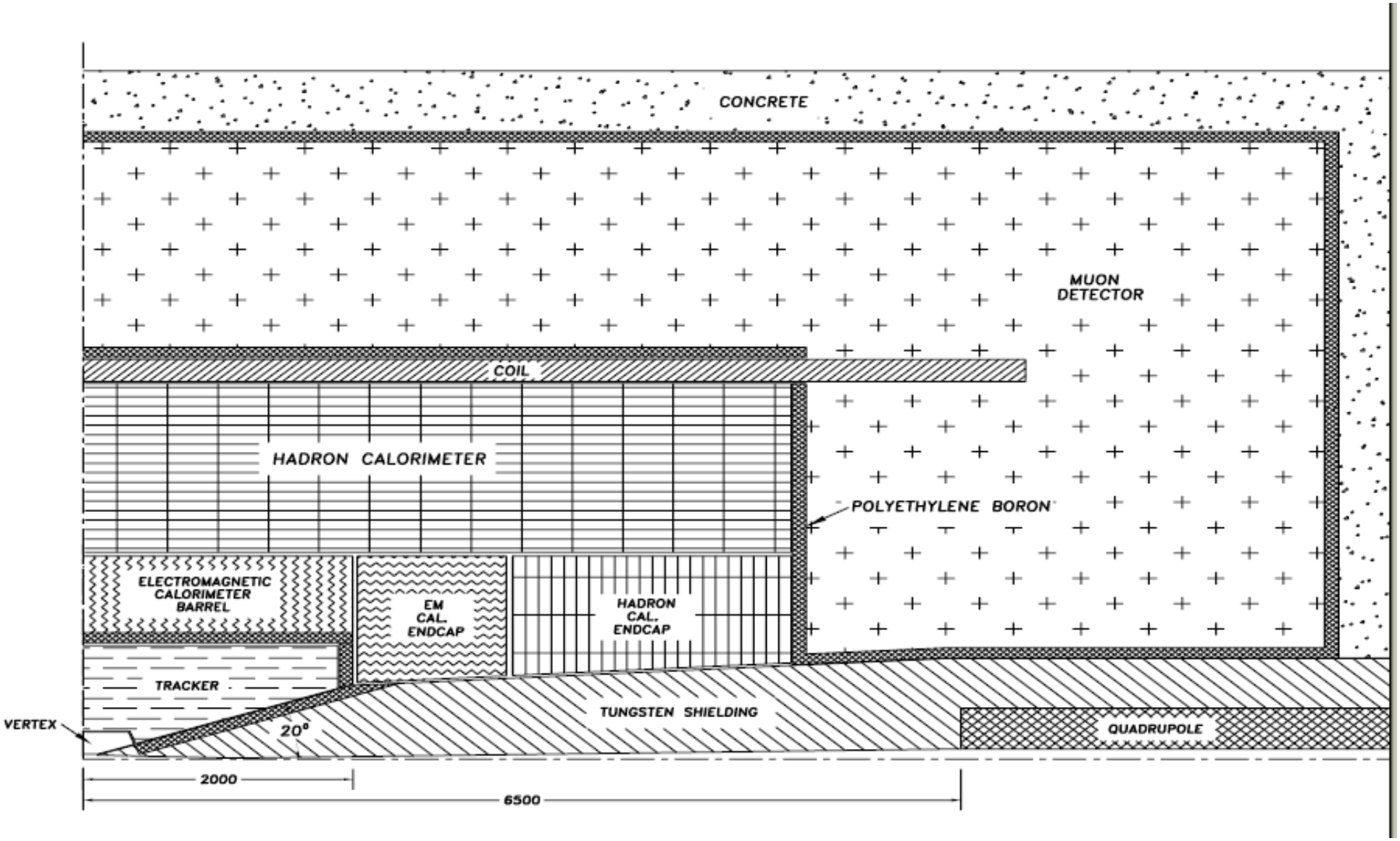
- Heavy shielding only needed for Collider Ring
- 6.5 cm of tungsten appear sufficient
- Must be warm and water cooled



Elaborate Detector Shielding Required (Stumer)



Detector



- Note forward 20 degrees is lost to detector

Parameters of Helix and RFOFO Channels

Look at example from Katsuya Yonehara (May 23 06)

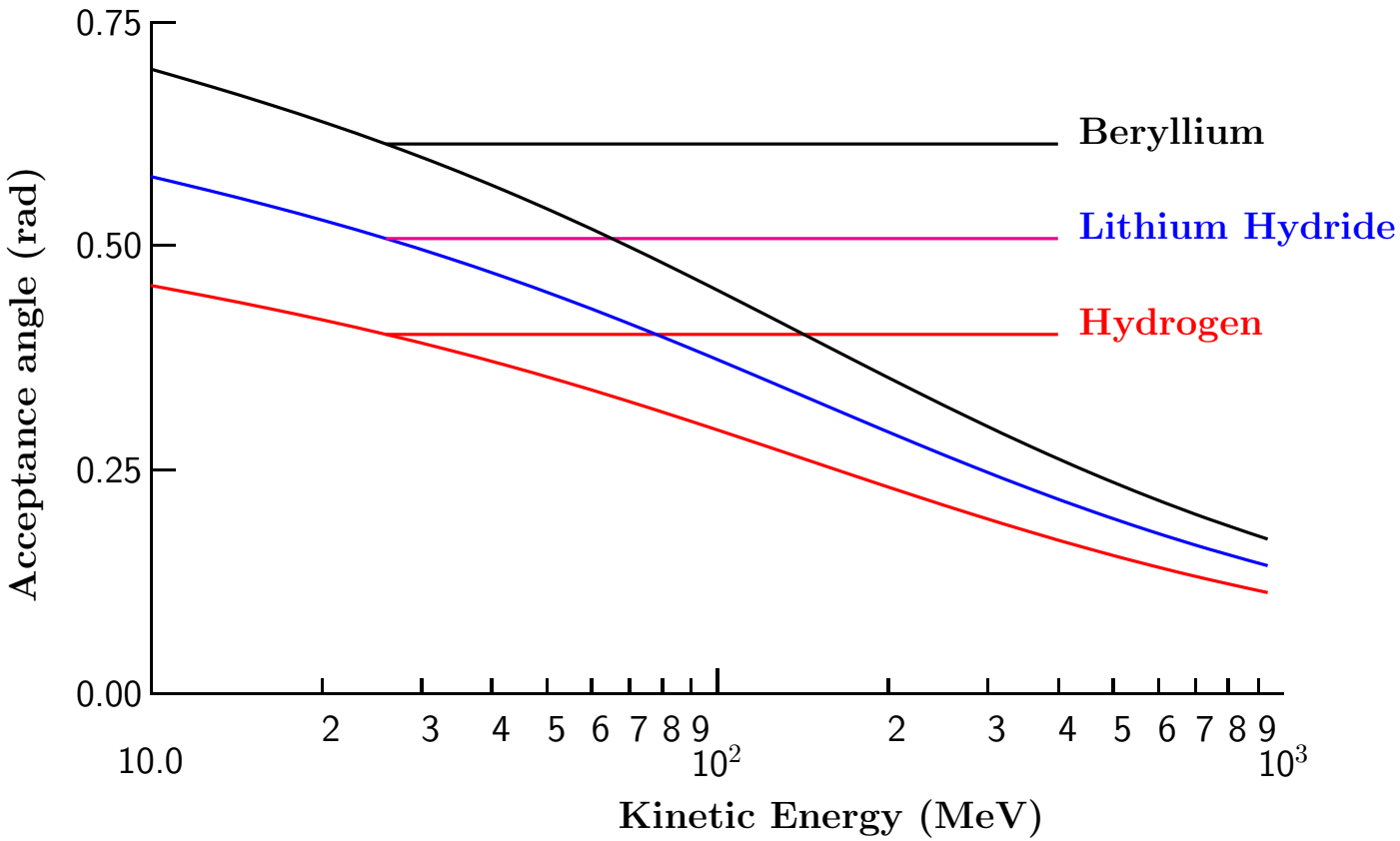
		Helix	RFOFO
Absorber		400 atm H2 gas	H2 liquid
RF frequency	MHz	200	200
RF gradient	MV/m	31.5	18
Max axial B_z	T	7	3
Max axial $B_\perp$	T	1.8	0.5
Min Trans Emittance	π mm	1.8	2.2
Min Long Emittance	π mm	5	2.4
Merit ($\epsilon_2/\epsilon_1\times$ transmission)		166	188

Beam Divergence Angles vs. Momentum

Even if beta could be made arbitrarily small

$$\sigma_\theta \propto \sqrt{\frac{\epsilon_\perp}{\beta_\perp \, \beta_v \gamma}} = \sqrt{\frac{C(mat, E)}{\beta_v^2 \gamma}}$$

For 50 % of maximum cooling rate, an aperture at 3 σ



Helix Fields vs R

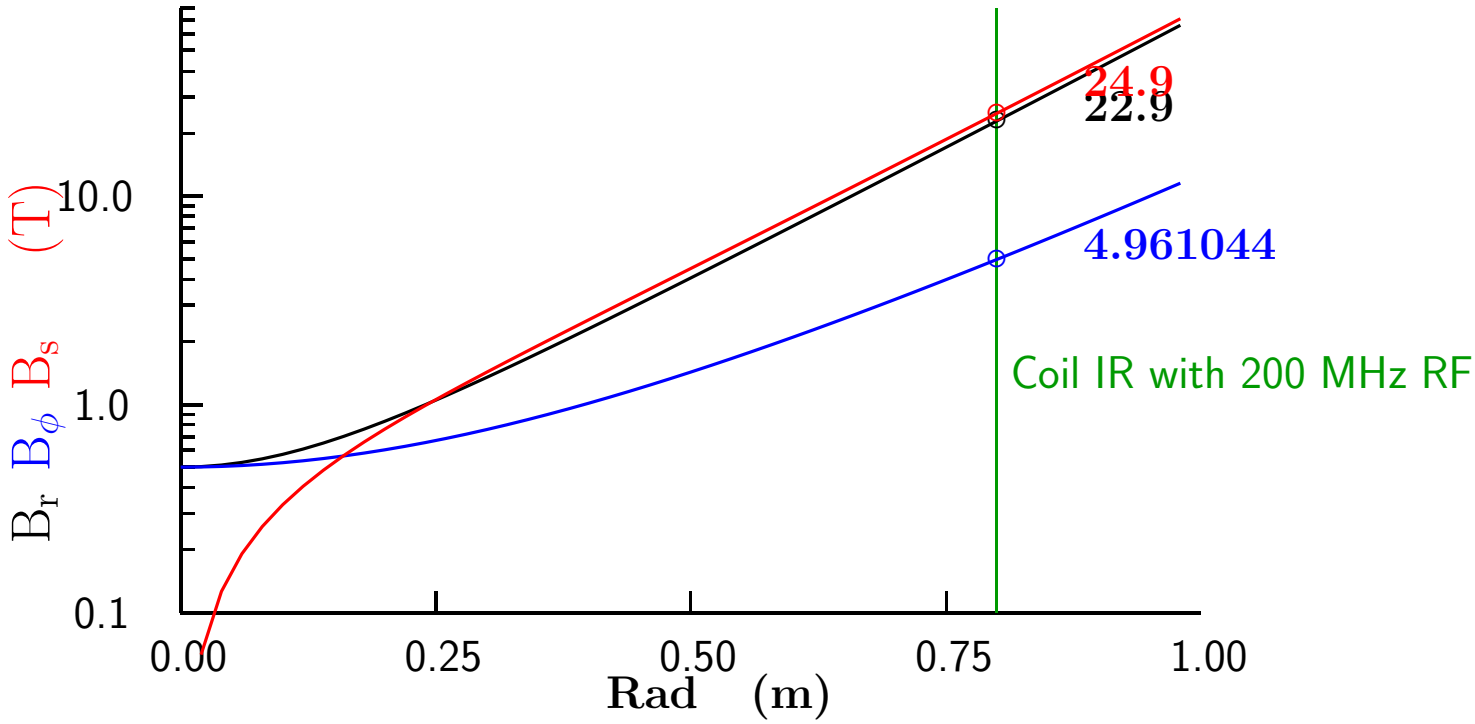
$$B_r = 2B_o\, I_1'(x) \quad \sin(\phi - \alpha s)$$

$$B_\phi = 2B_o\, \frac{I_1(x)}{x} \quad \cos(\phi - \alpha s)$$

$$B_s = 2B_o\, I_1(x) \quad \cos(\phi - \alpha s)$$

For: $\lambda = 1$ m

$B_\perp = 0.5$ T



- Increasing pitch: hurts ds/dp
- Decreasing helix B: hurts ds/dp
- Lowering RF λ $\rightarrow$ lower emit + higher B's
- Exploring emittance exchange before bunching and RF