Cooling in 50T solenoids

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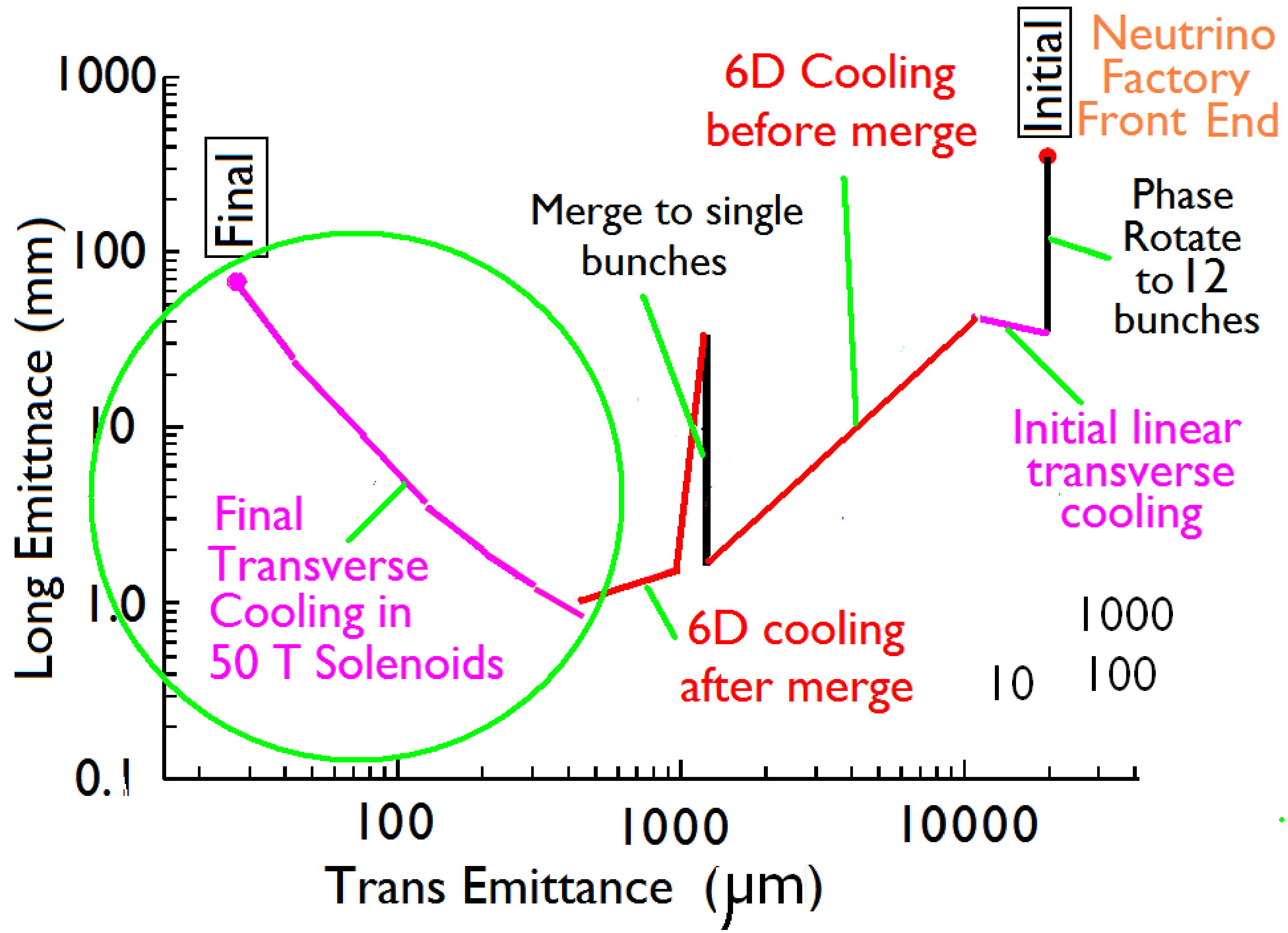
1) Requirements

Current Parameters (Not official)

C of m Energy	1.5	3	TeV
Luminosity	1	4	10^{34} cm^{2}sec^{-1}
Beam-beam Tune Shift	0.087	0.087	
Muons/bunch	2	2	10^{12}
Total muon Power	9	15	MW
Ring <bending field>	6	8.4	T
Ring circumference	2.6	4.5	km
β^* at IP $= \sigma_z$	10	5	mm
rms momentum spread	0.1 (0.25)	0.1	%
Muon per 8 GeV p	0.008	0.007	
Repetition Rate	15	12	Hz
Proton Driver power	3.5-4.8	3-4.3	MW
Muon Trans Emittance	25	25	μm
Muon Long Emittance	72 (175)	72	mm

- Lower power estimate based on MARS15 vs. MARS14
- Parenthesized numbers are for New 1.5 TeV collider design

Emittances vs. Stage



- Initial 400 (μm) transverse and 1 (mm) longitudinal
- Final 25 (μm) transverse and 72 (175) (mm) longitudinal

(Parenthesized number for New 1.5 TeV collider design)

Muon Survival (still a 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	$\boxed{.7}$	0.1
Acceleration to 0.75 TeV	0.7	0.07

For required Muons per bunch	2 10^{12}
Muons per bunch after merge	8 10^{12}
Initial Muons per bunch	2.8 10^{13}

For initial muons per 24 GeV proton	0.4
Initial 24 GeV protons	70 10^{12}
Initial 8 GeV protons	200 10^{12}

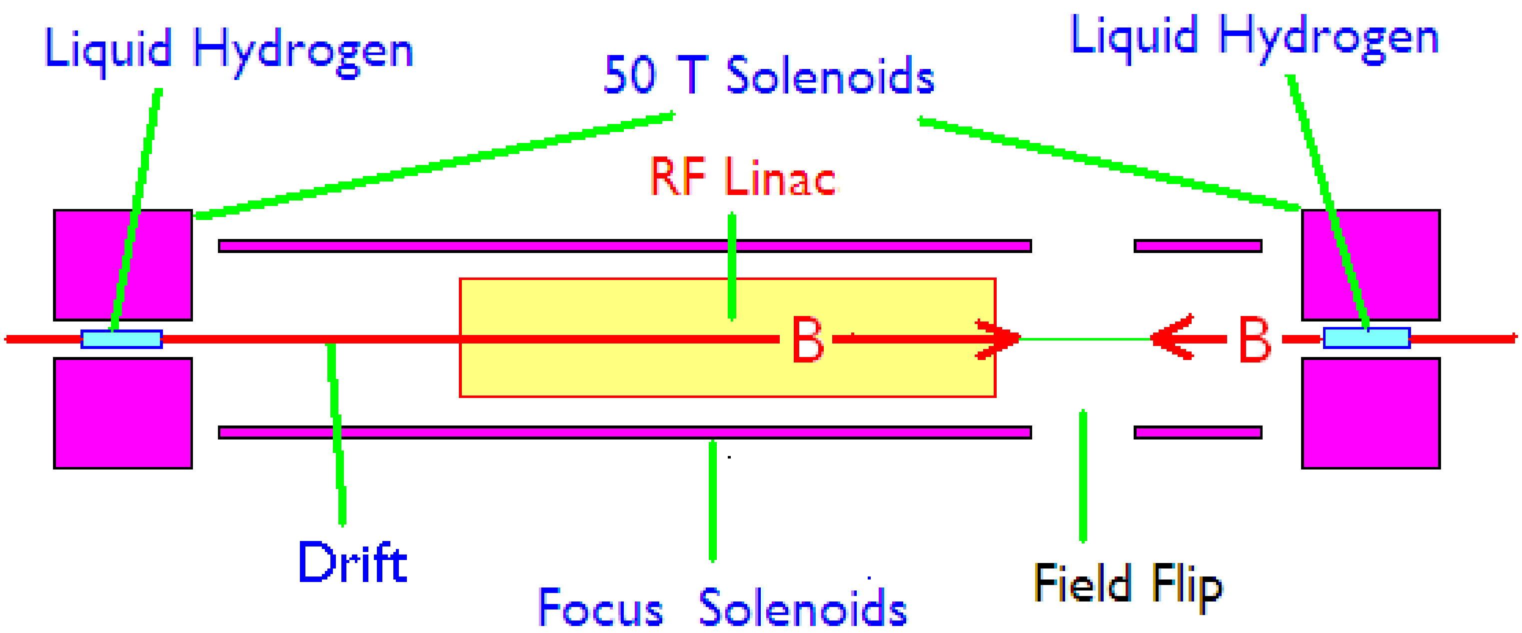
- These are large numbers: pushing the designs of proton buncher, target, space charge in cooling, and wake fields in acceleration
- Cooling to transverse emittance < 25 (μm) would ease potential problems

Requirements for final cooling

Initial transverse emittance	μm	400	
Initial longitudinal emittance	mm	1	
Final transverse emittance	μm	25	Lower if possible
Final longitudinal emittance	mm	72 (175)	
Transmission	%	70	

Numbers in parenthesis for the new collider ring design

2) Introduction



- Drift and rf to match longitudinal emittances
- Adiabatic field changes match transverse emittances
- Field flips to stop accumulating Canonical angular momentum

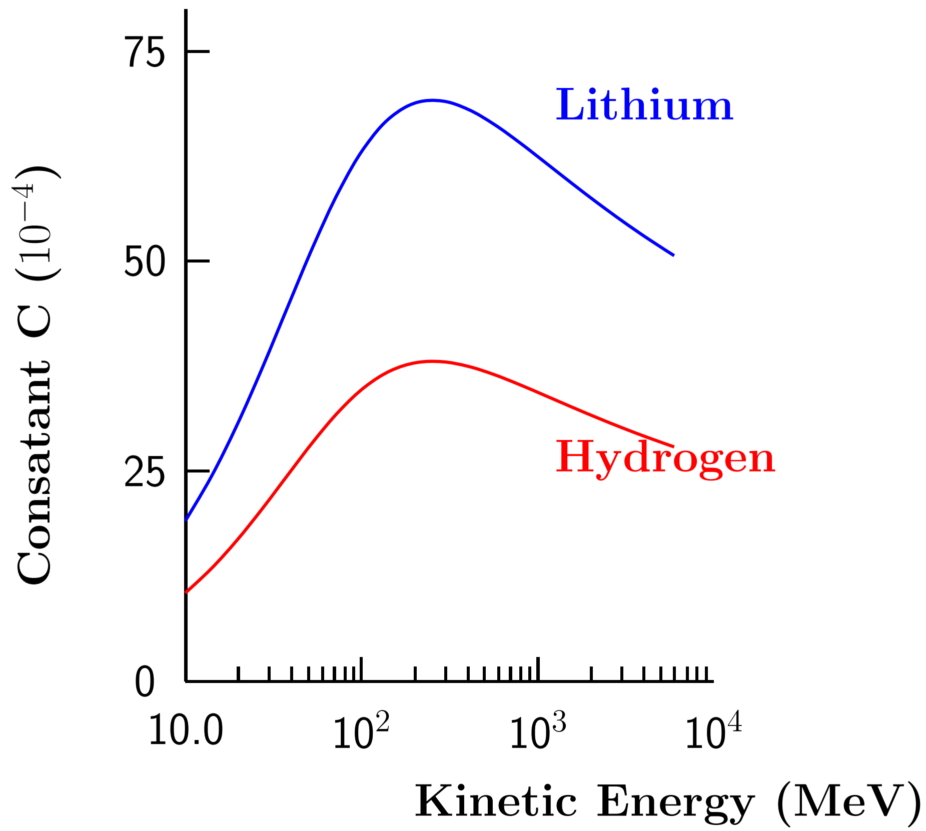
- 50 T solenoids now possible with hybrid Resistive and Low Temp Super-conducting technology, but power consumption very large
- HTS materials should allow all super-conducting magnets
- R&D discussed in appendix

3) Theory

a) Equilibrium emittance

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

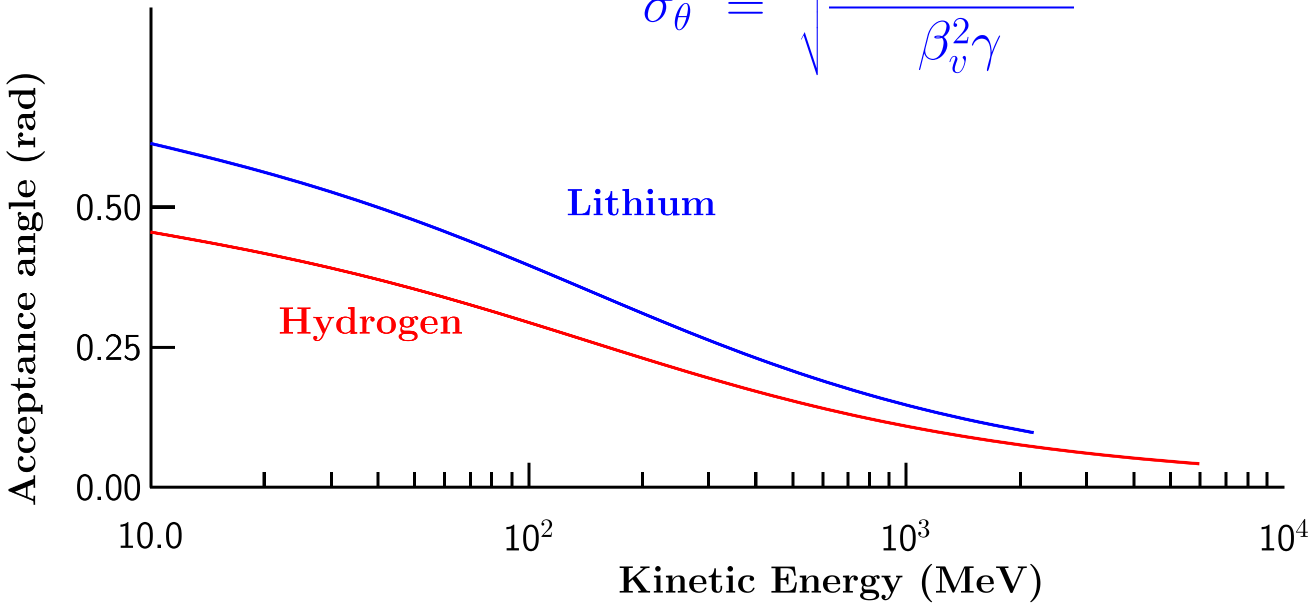
As a function of energy:

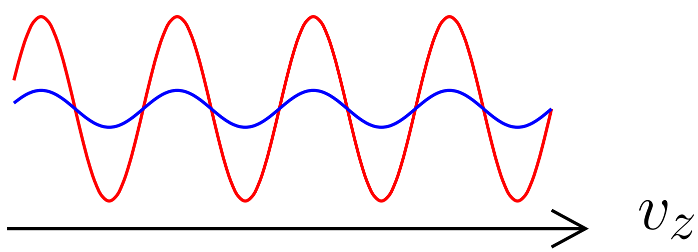


$C(mat, E)$ is a factor of 3 less at 10 Mev vs. 200 MeV

b) Beam Divergence Angles

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

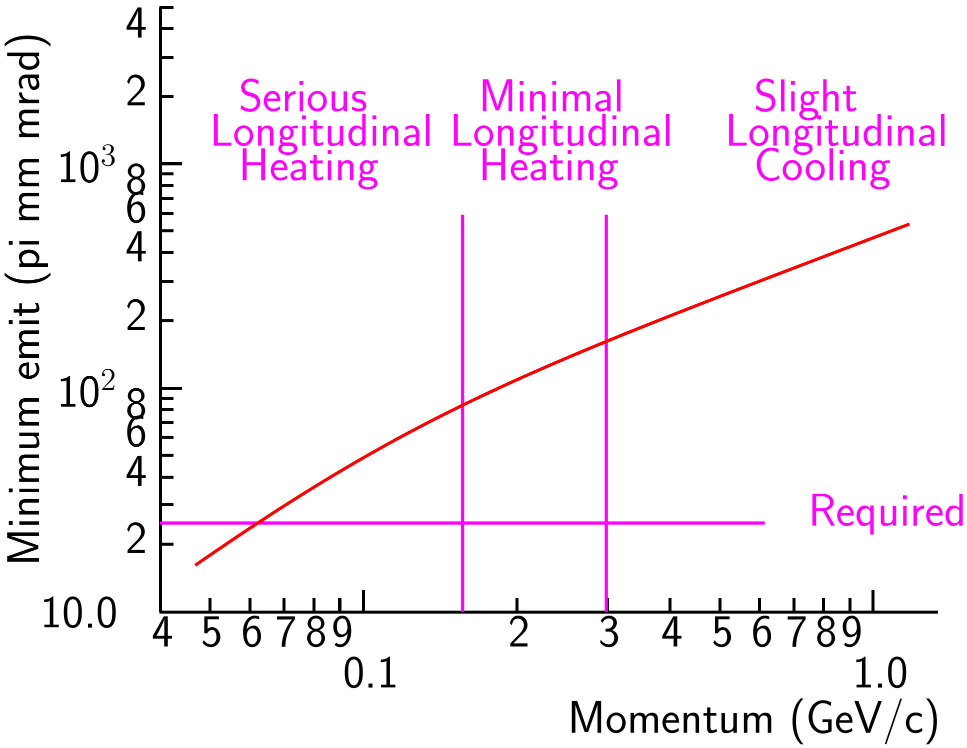


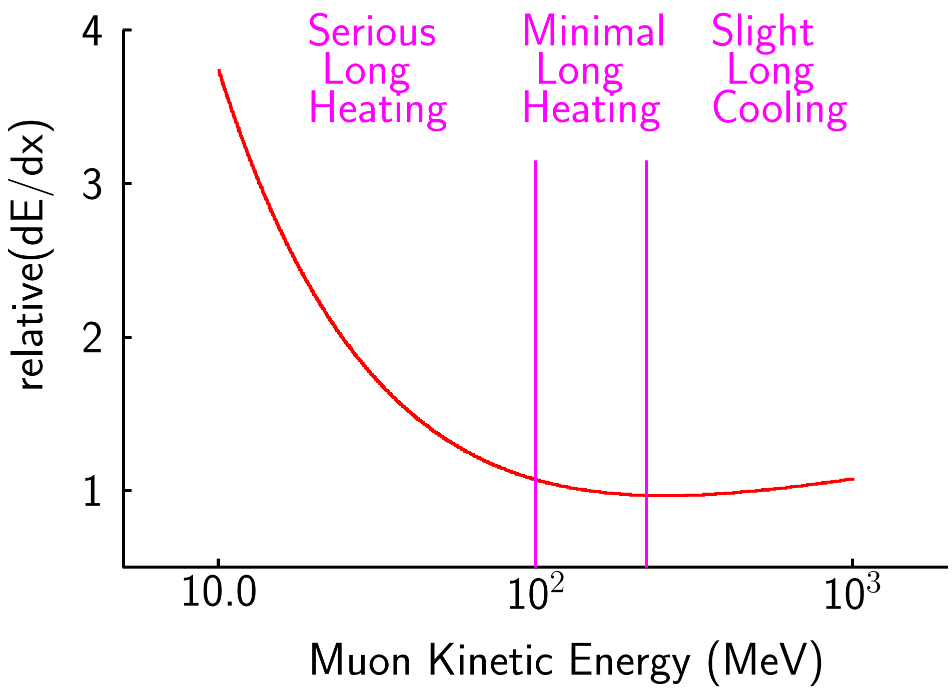


- Large angles at low momenta cause significant velocity vs. amplitude effects
- Large amplitudes have further to go $\rightarrow$ lower v_z

c) Minimum emittance in solenoids vs. momentum

$$\beta_\perp = \frac{2\,[pc/e]}{c\,B_{sol}} \qquad \epsilon_{x,y}(min) = C(mat,E)\,\frac{2\,\gamma\,[mc^2/e]_\mu}{B_{sol}\,c}$$





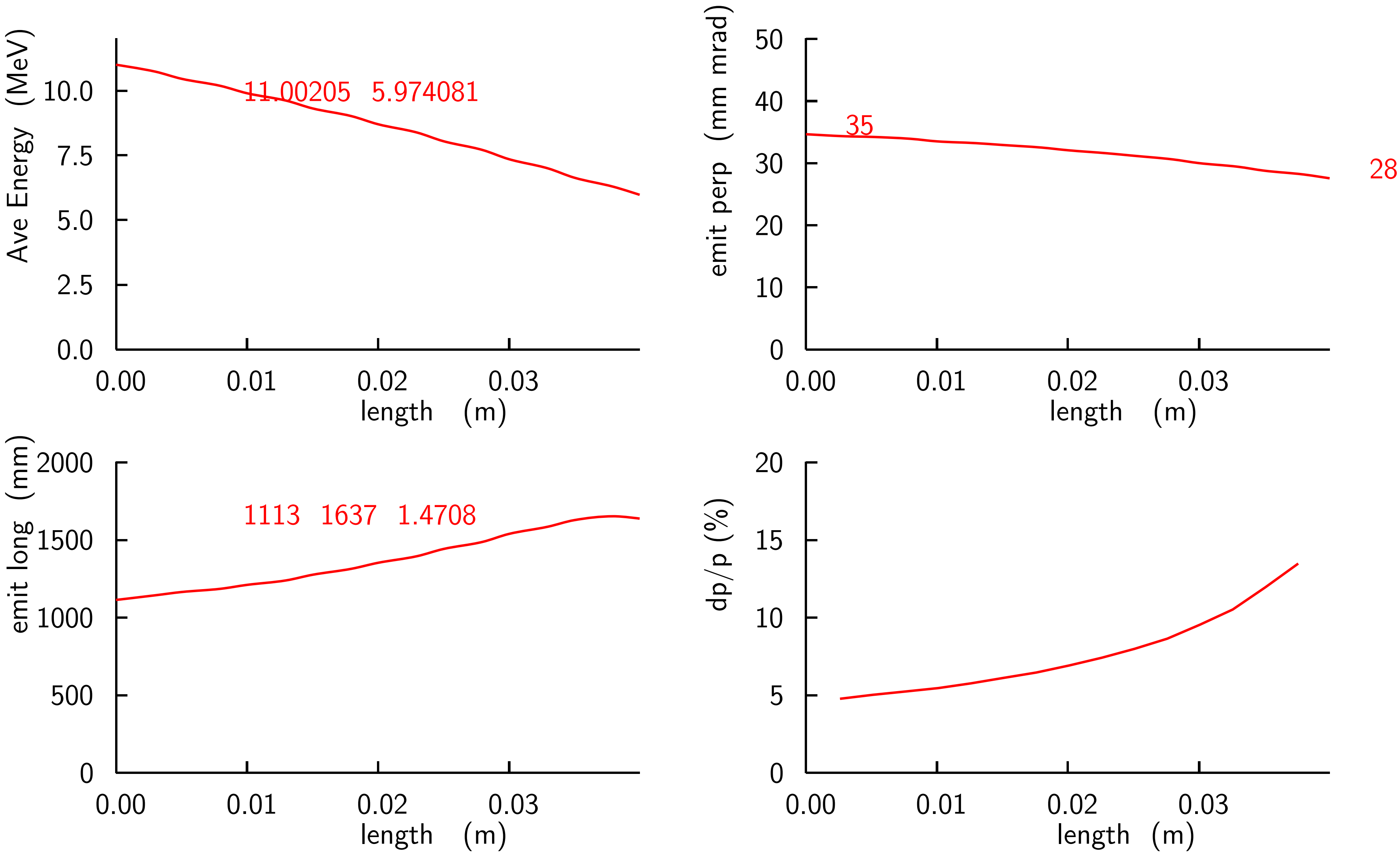
At momenta where longitudinal emittance is not blown up ($\approx$ 200 MeV/c) even with 50 T the minimum emittance is $\approx$ 100 μm $>>$ required 25 μm

But if longitudinal heating allowed & momenta $<$62 MeV/c (17 MeV) then muon collider requirements met

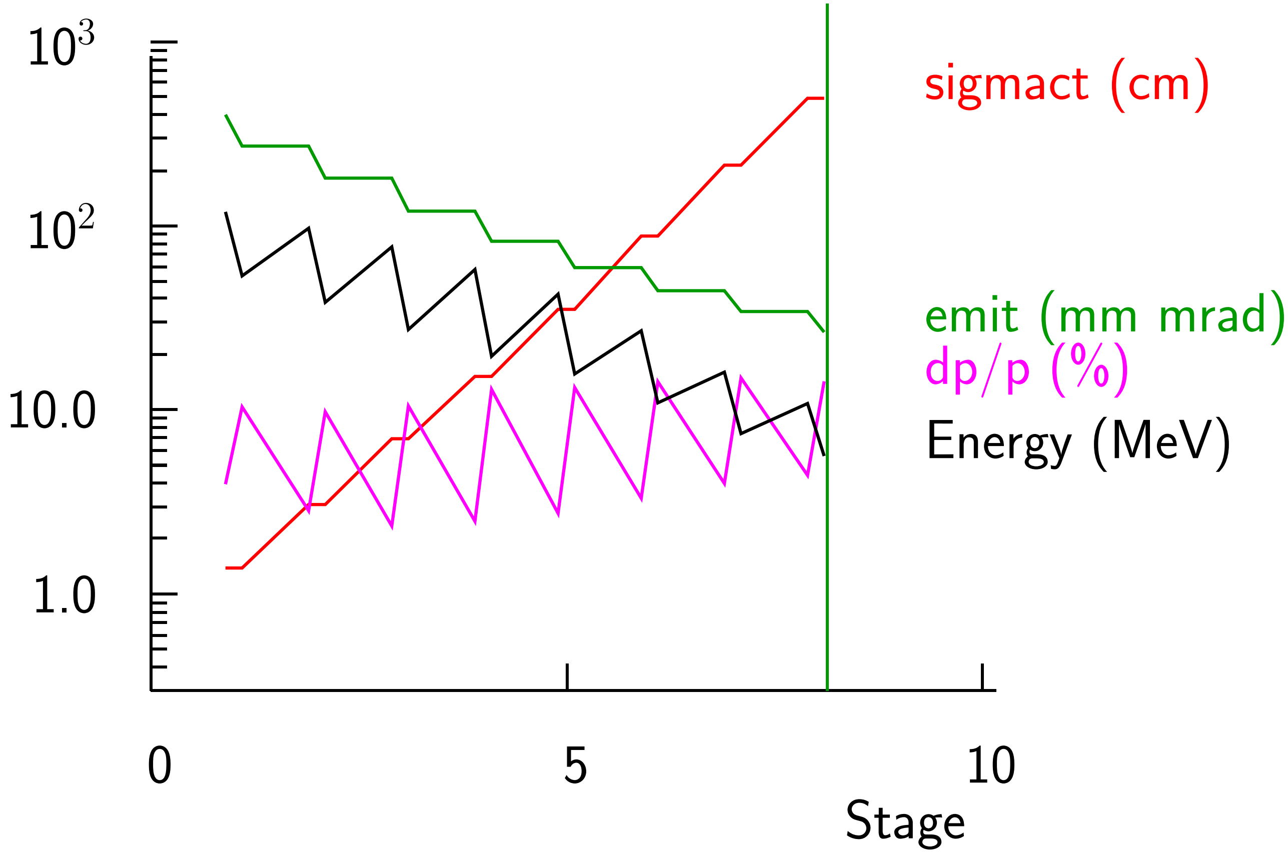
4) Initial design and ICOOL simulations

8 stages, simulated with constant fields and no matching

Example stage



Parameters of many stages

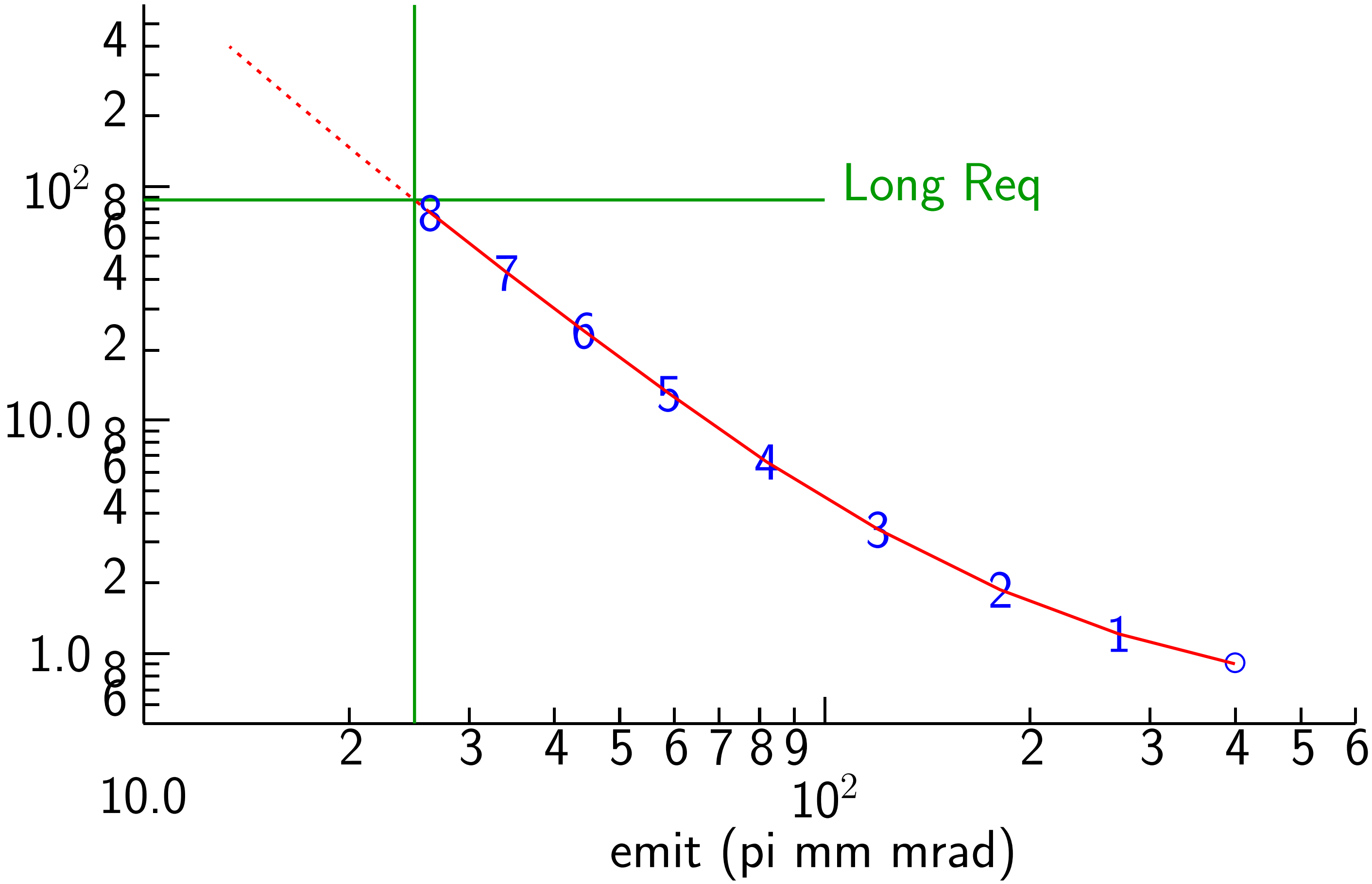


- Between stages:
  - Energy increased
  - dp/p reduced
  - sigma ct increased

so each stage has lower frequency rf

- Note long bunch length at end (500 cm)

Longitudinal vs transverse emittances

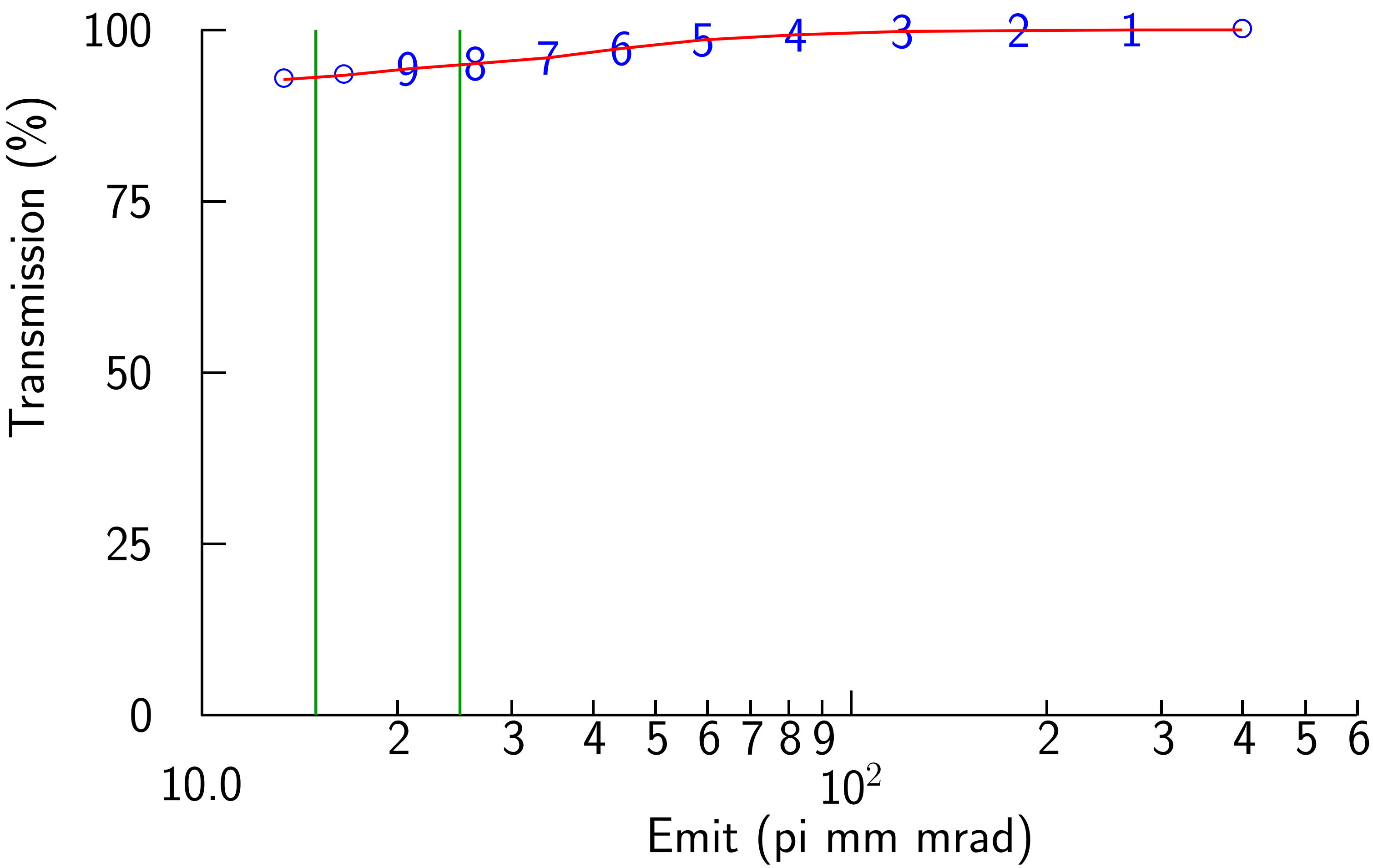


- Approximately 25 μm transverse for 72 mm longitudinal
- Approximately 20 μm transverse for 175 mm longitudinal

Transmission

These are losses only from decay and stopping in the hydrogen

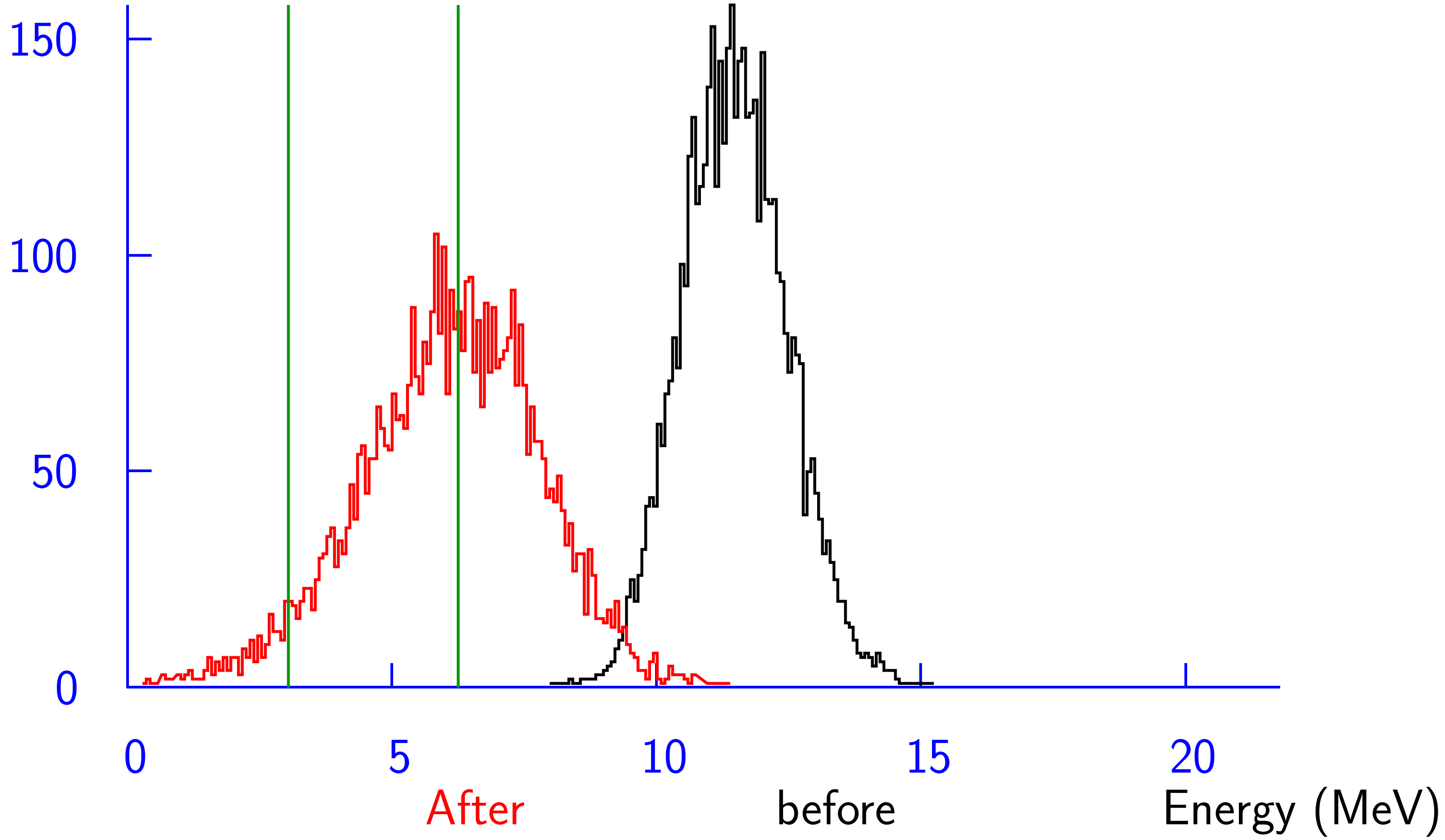
No losses in matching or re-acceleration



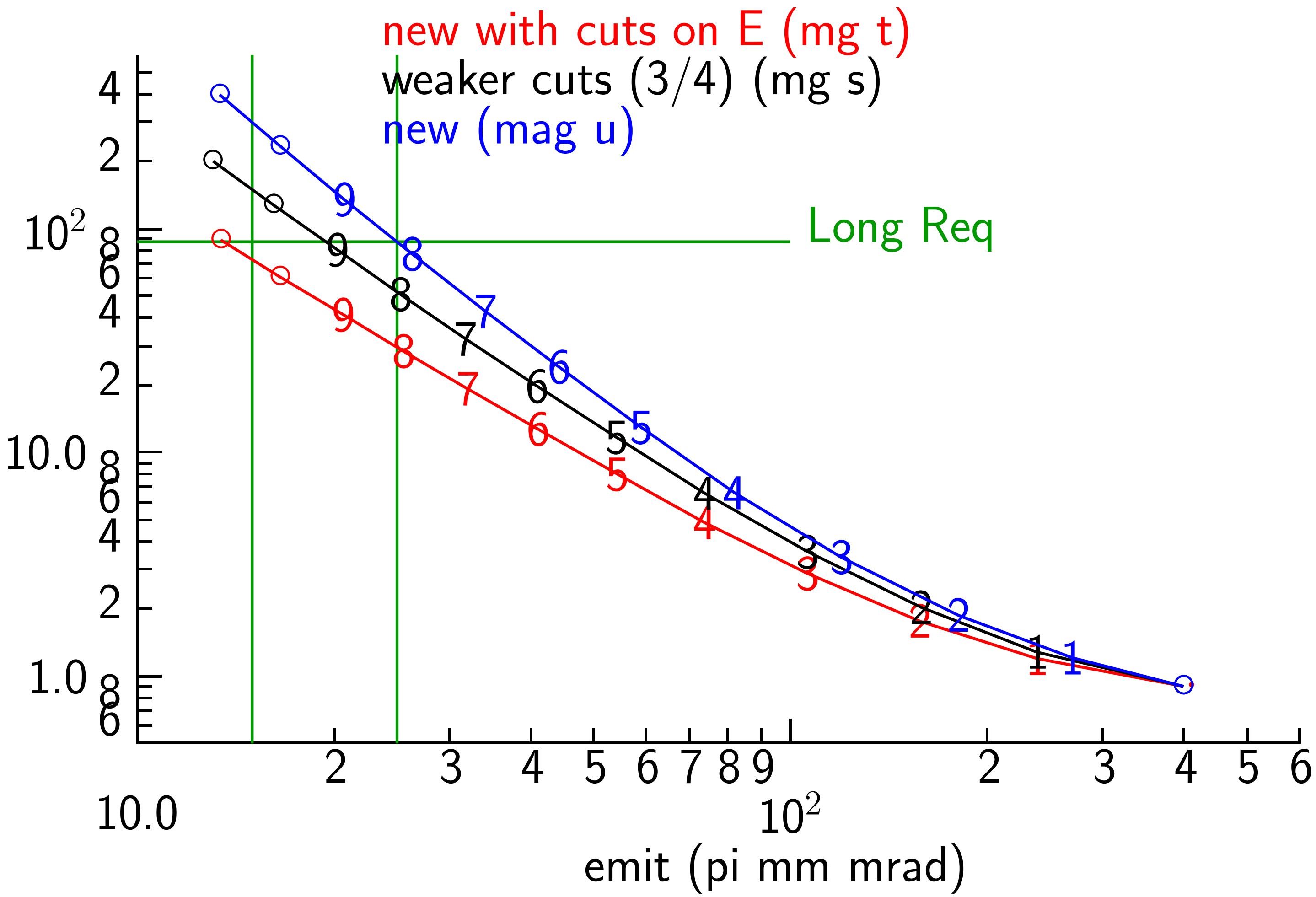
5) Can we do better by cutting the Landau tails ?

Landau tail on energy loss increases longitudinal emittance

what if we though them away?

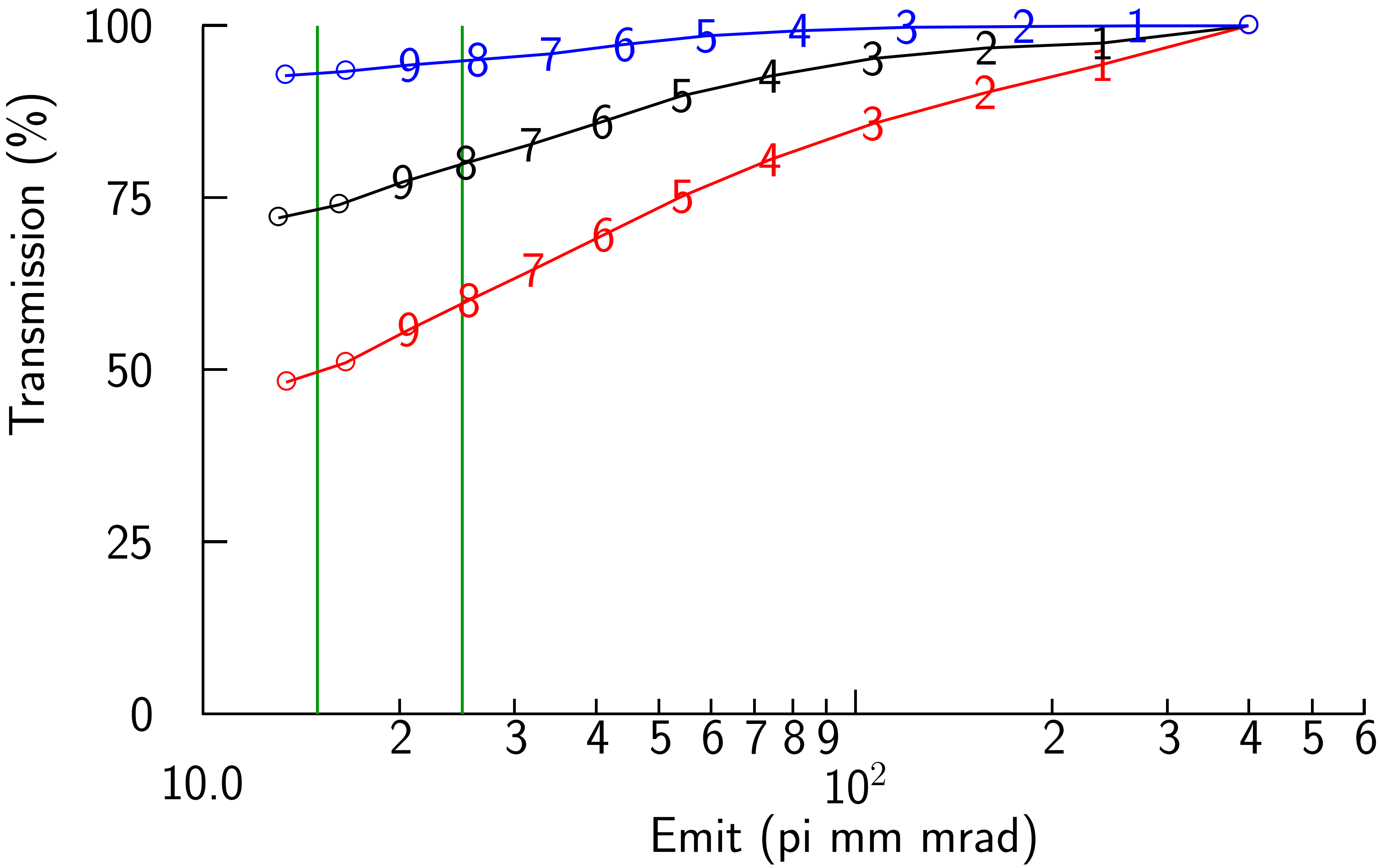


long vs trans



Looks good

But accumulated losses are serious



6) Estimated decay losses

a) In needed drift for phase rotation to longer bunches

$$d(ct) \;=\; \sqrt{\sigma^2_{ct}(\text{after drift}) \;-\; \sigma^2_{\rm ct}(\text{before drift})}$$

$$d(ct) \;=\; \left(\frac{L_{\rm drift}}{\beta_v^2}\right)\; d(\beta)$$

$$=\; \left(\frac{L_{\rm drift}}{\beta_v^3}\right)\frac{1}{\gamma^2}\;\left(\frac{dE}{E}\right)$$

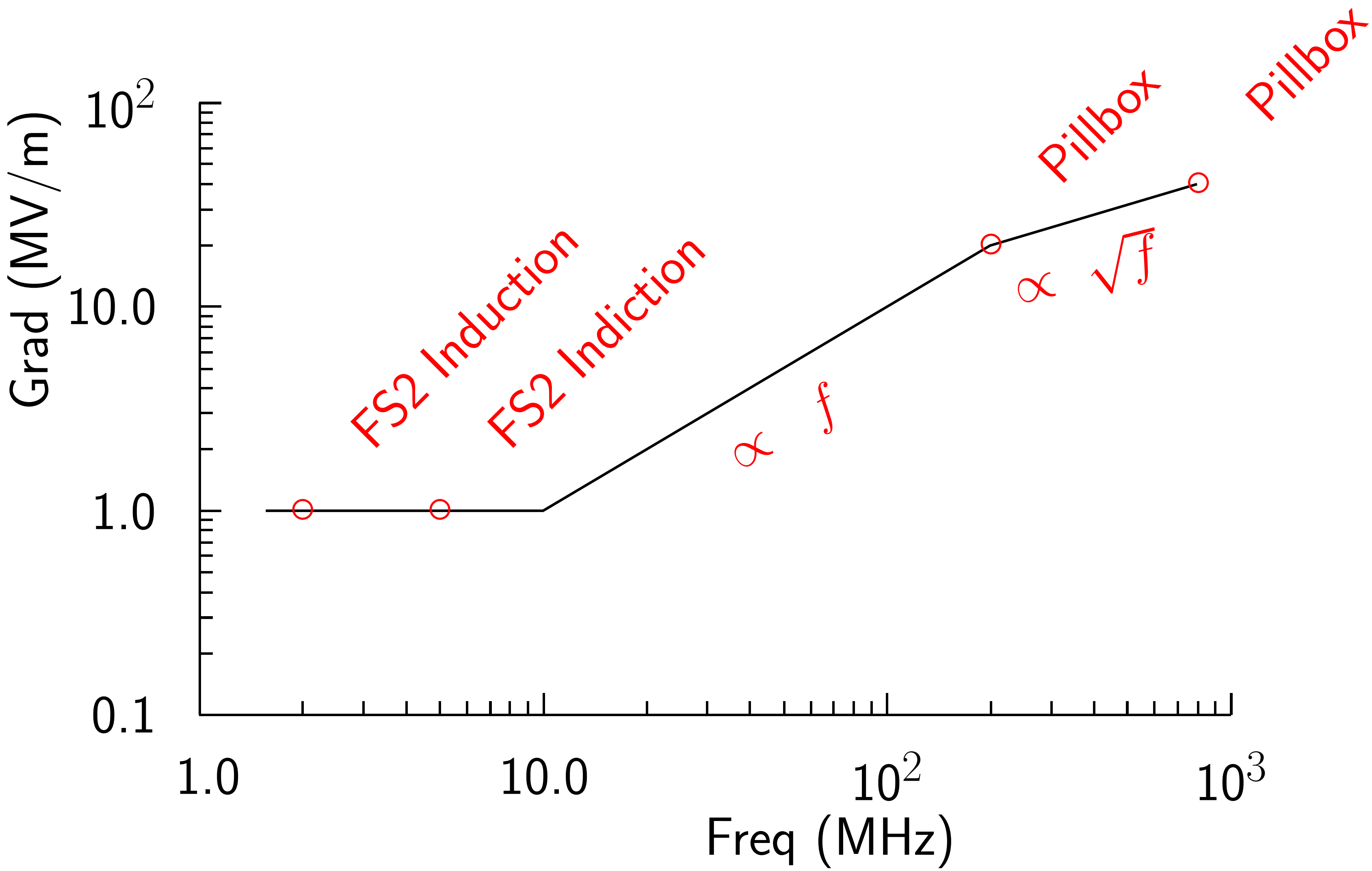
so

$$L_{\rm drift} \;=\; d(ct)\;\frac{\gamma^2\beta_v^3}{dE/E}$$

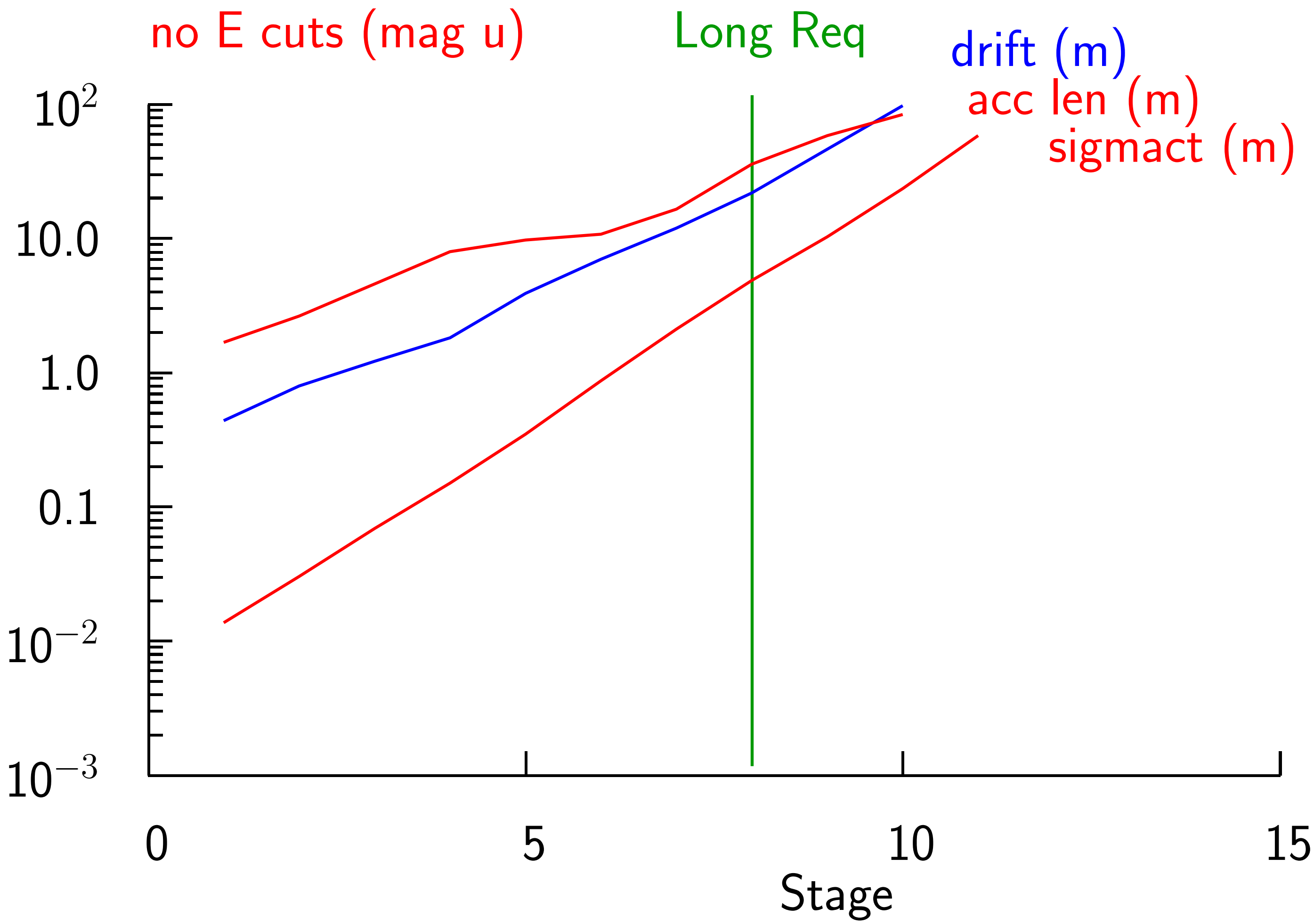
Confirmed in simulation in section 11

b) In Acceleration

Assumed Acceleration Gradient

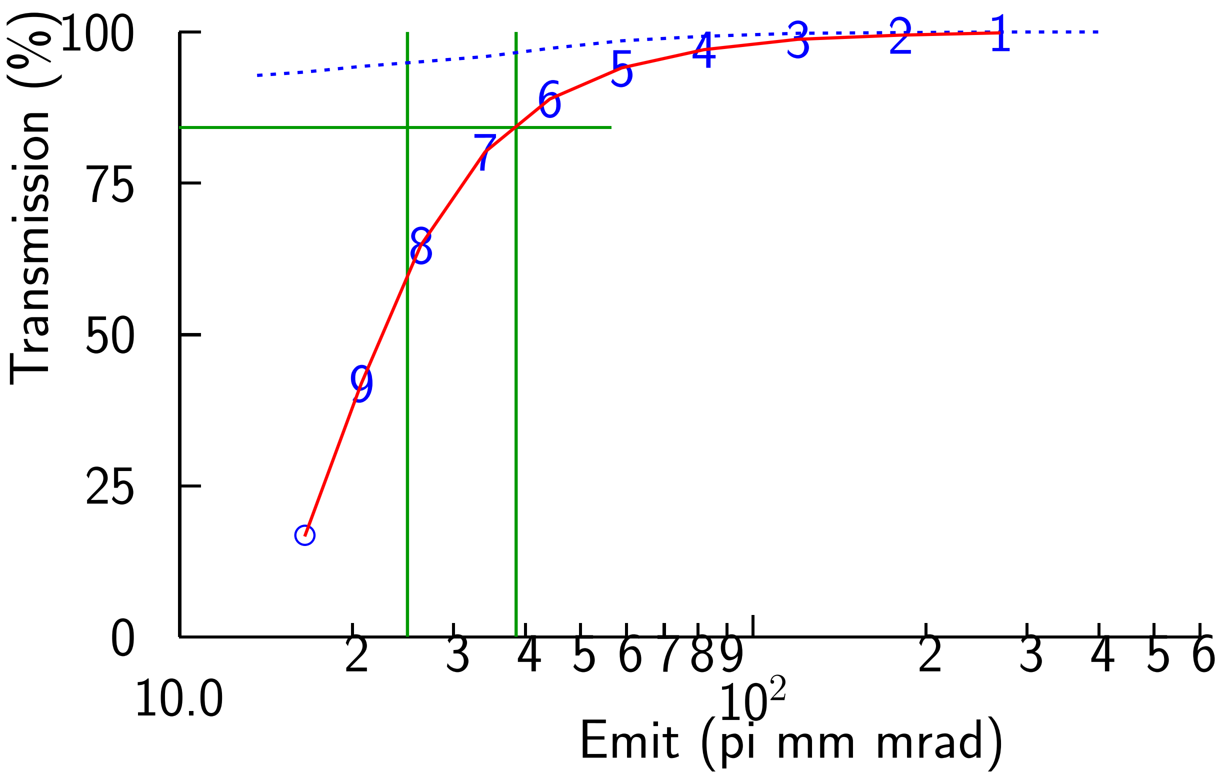


Decay parameters



- Sigma ct becomes very long at end
- Drift and acc lengths similar and large at end
- Assumed here that the lengths add - this is conservative

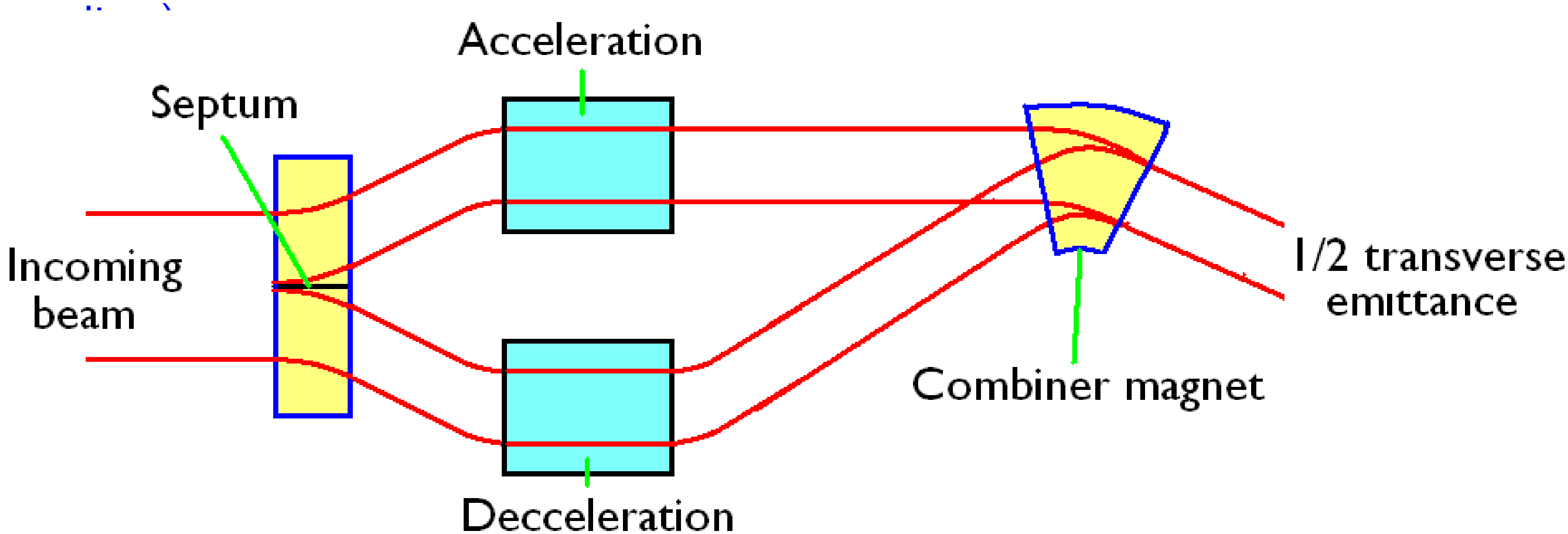
Losses from stopping and decay



- The losses are $\approx$ 60% at $\epsilon_\perp$=25 (μm) cf 70% required)
- For 85% transmission (leaving room for other losses): $\epsilon_\parallel \approx$ 30 (mm)
- i.e. $\approx 1/3$ collider specification (72 mm)
- At that long emittance: Transverse emittances $\approx$ 40 (mm)
- Final emittance exchange then with Septa ?

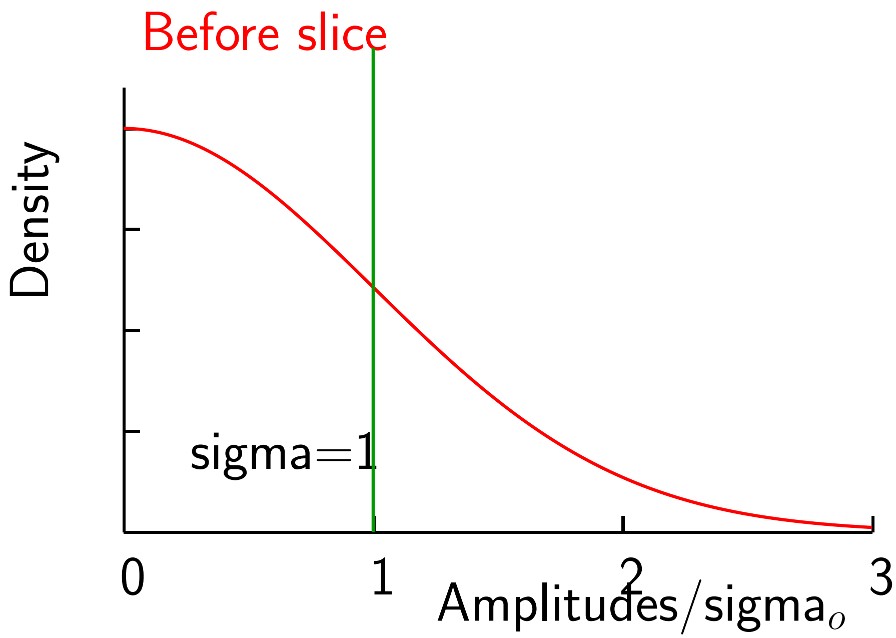
7) Use of Septum emittance exchange (Potato Slicer)

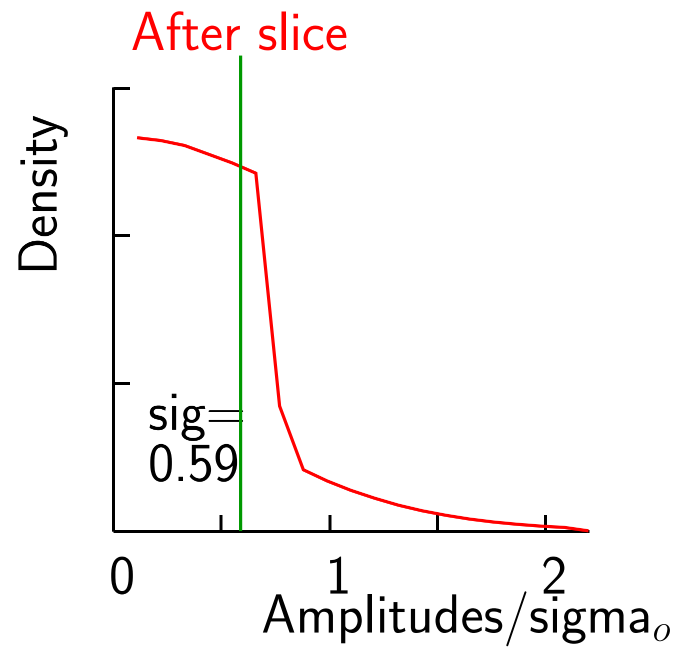
- The last stage (rejected for its decay losses) would have had a slope > 1, meaning the 6D emittance is growing
- This suggests at least one final stage of septum emittance exchange (potato

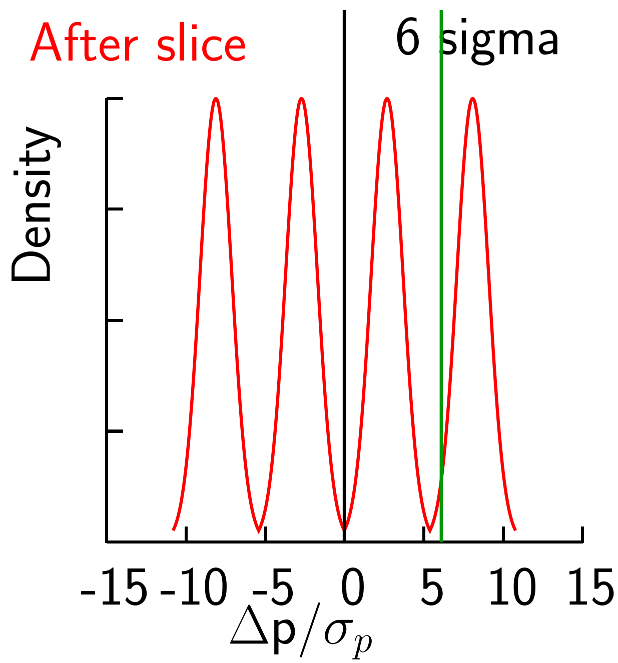


- There would be 2 septums (in x then y) and 4 beams comined: reducing both trans emittances by 40% (see bleow) from 40 to $\boxed{\approx 25\ (\mu m)}$
- Increasing long emittance by ≈ 6 (see below): from 30 to $\boxed{180\ (mm)}$: ok for new lattice with dp/p=0.25%
- This would meet requirements if new 1.5 TeV ring lattice used

Transverse distributions before & after exchange



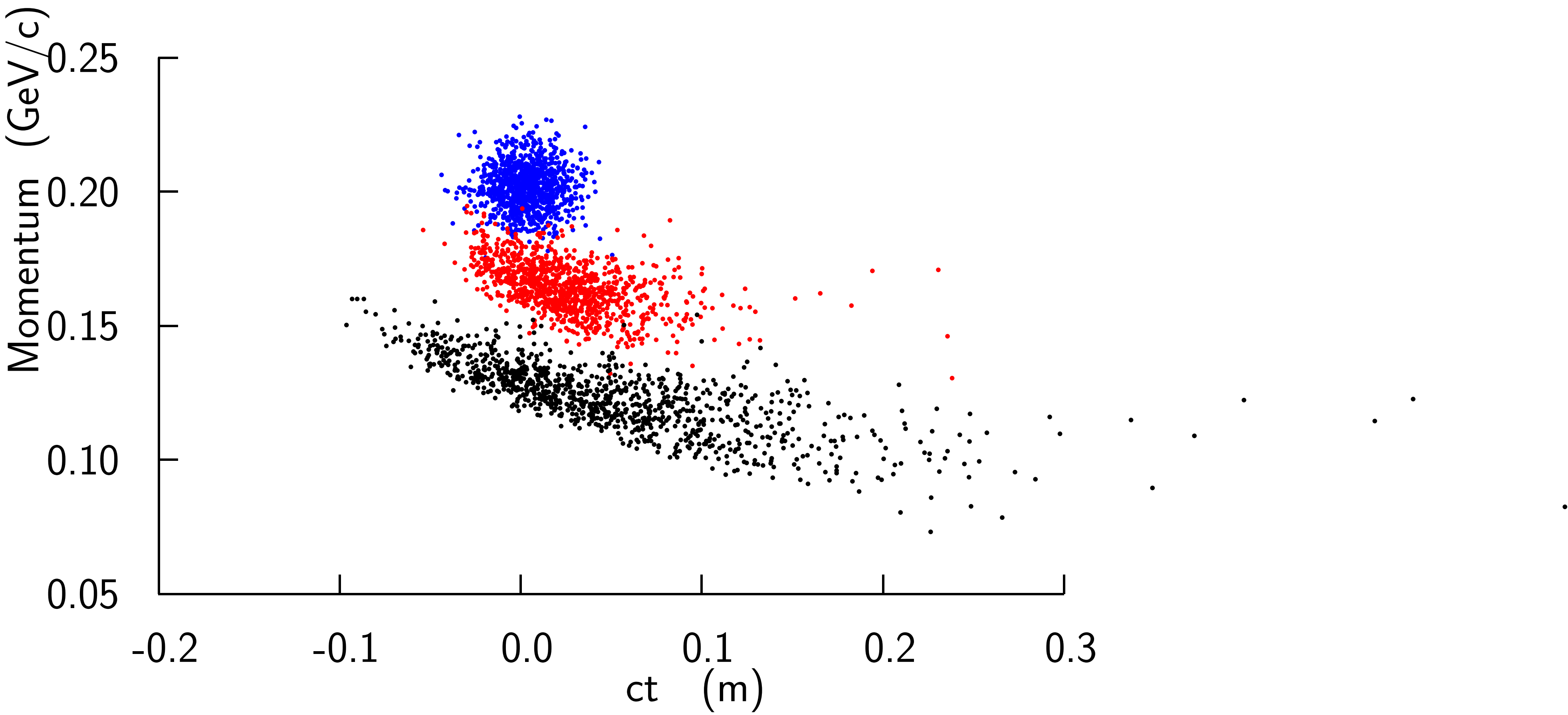




- Transverse distributions $\approx 0.6\times$ original
- Longitudinal distribution (if momenta cut at 2.5 sigma) $\approx 6\times$ original
- These estimated ignore losses from finite septum phase space

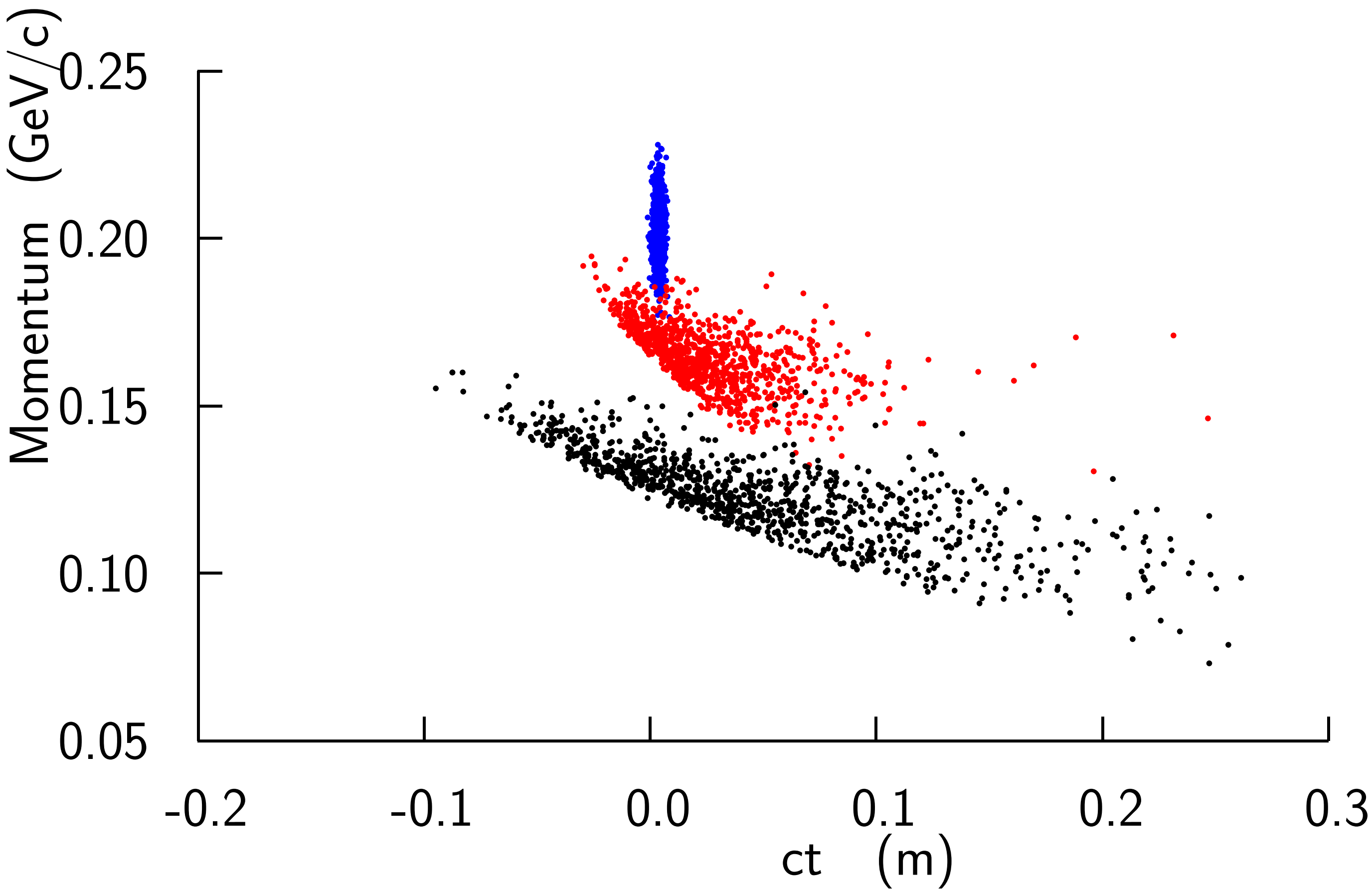
8) Amplitude problem at start

Calculated longitudinal emittance found to rise more than dE increase predicts



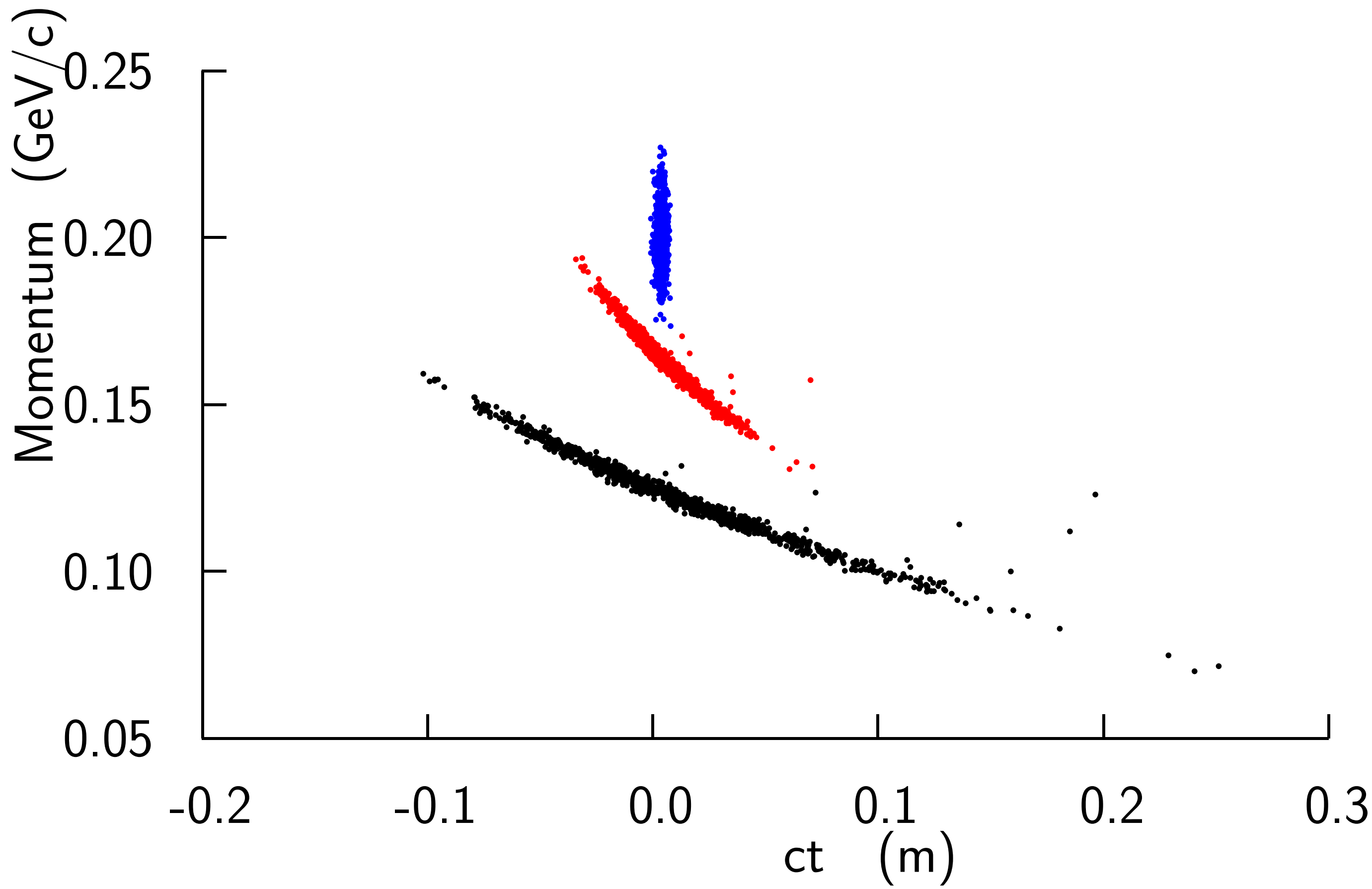
Blue before absorber   Red half way   Black at end

Effect clearer if no initial ct spread



- Is it due to amplitude dependent forward velocity ?

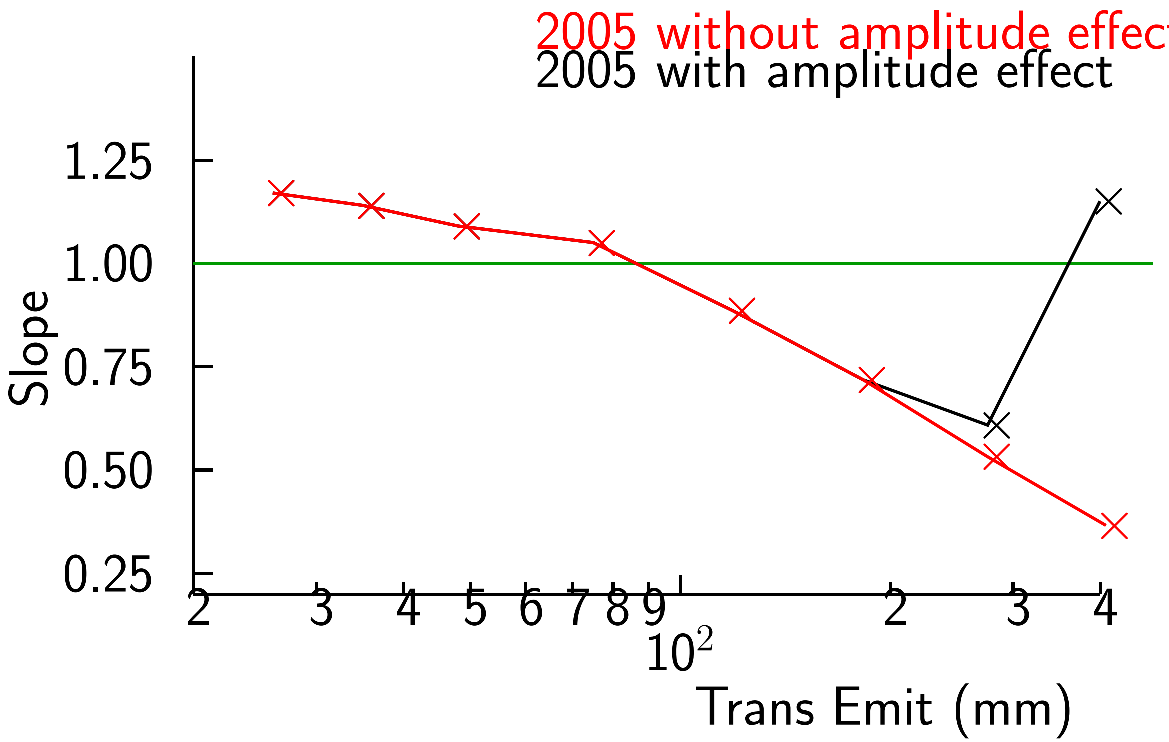
Set amplitudes = 0



- Yes, it is due to amplitude dependent forward velocity

Effect of this on performance

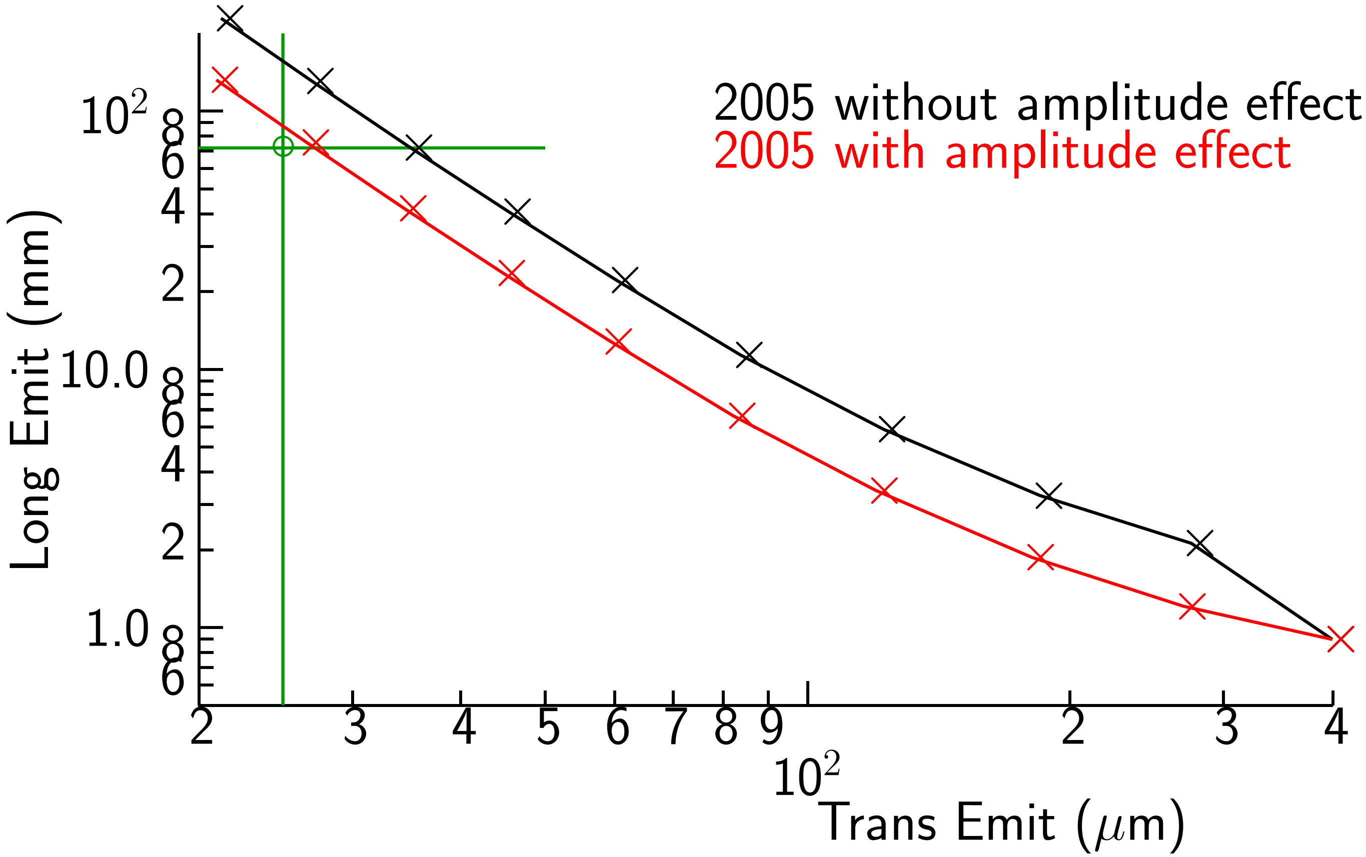
From simulation, find long vs. trans emit slopes for individual stages



- slope $<$ 1 means 6D cooling
- Slope $>$ 1 means 6D heating
- Slope=1 means pure emittance exchange

- Heating in first stage (large emittance) due to amplitude effect
- Heating in late stages (small emittances) due to slope of dE/dx

Long vs. transverse emittances



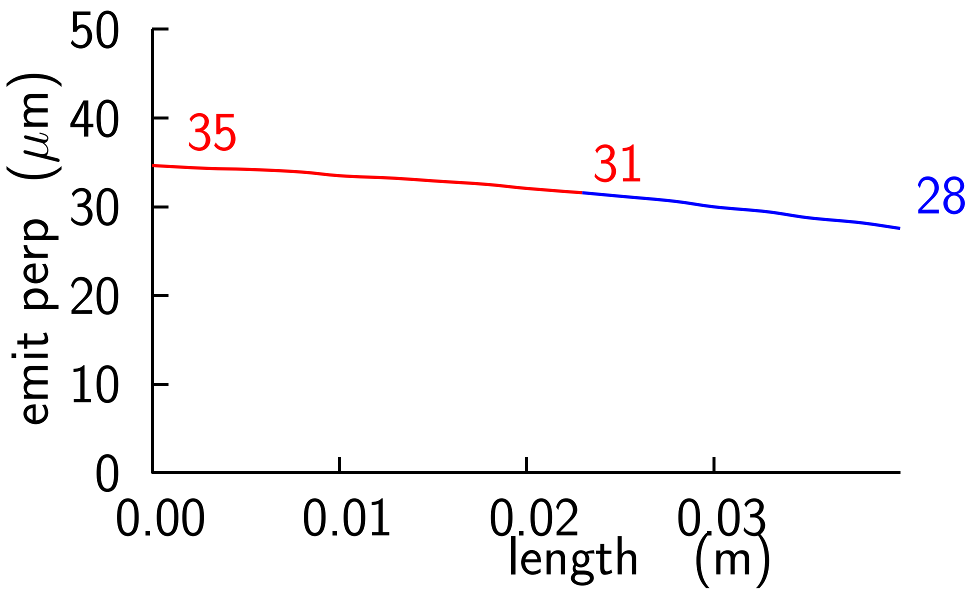
- Momentum vs, amplitude correlation will improve performance
  - Some part of this correlation will occur naturally but we have little control
- So though better than black, unlikely to equal red line (with effect excluded)
- Performance certainly below requirements

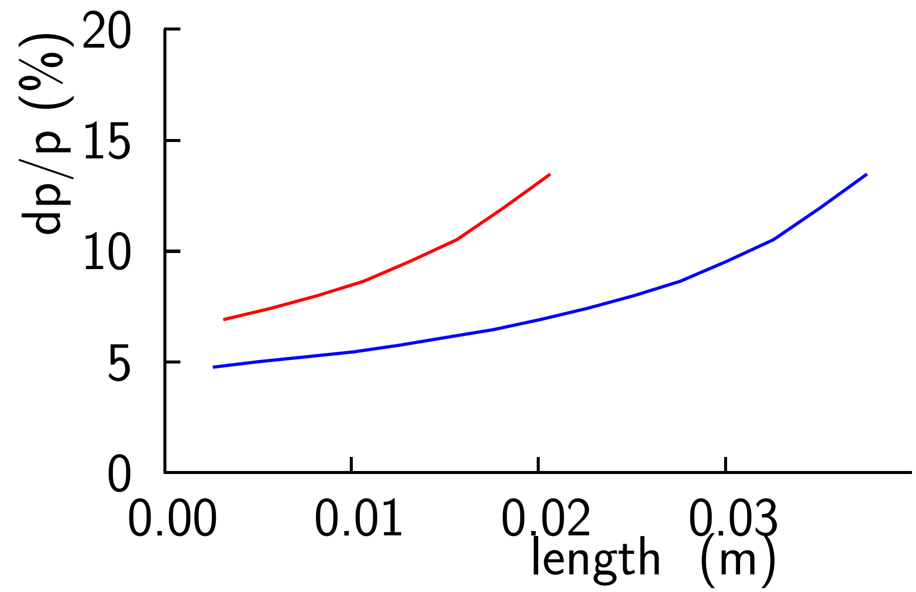
9) Summary conclusions using 2005 designs

- Two problems
  - Unacceptable decay loss in final stages in long drifts and acceleration of very long bunches
  - Probably unacceptable longitudinal emittance loss in first stage from amplitude dependent forward velocities
- Use of septum emittence exchange may solve the first problem, but it remains unlikely thet the specificastions can be met with these designs
- One should re-examine the design of the final 6D cooling to see if the starting parameters can be improved
- Or try re-optimizing the high field stages to improve their performance (next)

10) New optimized designs and ICOOL simulations

- Reduce magnetic field in first stage (50 $\rightarrow$ 35 T)
- Use more shorter stages





Why more shorter stages helps

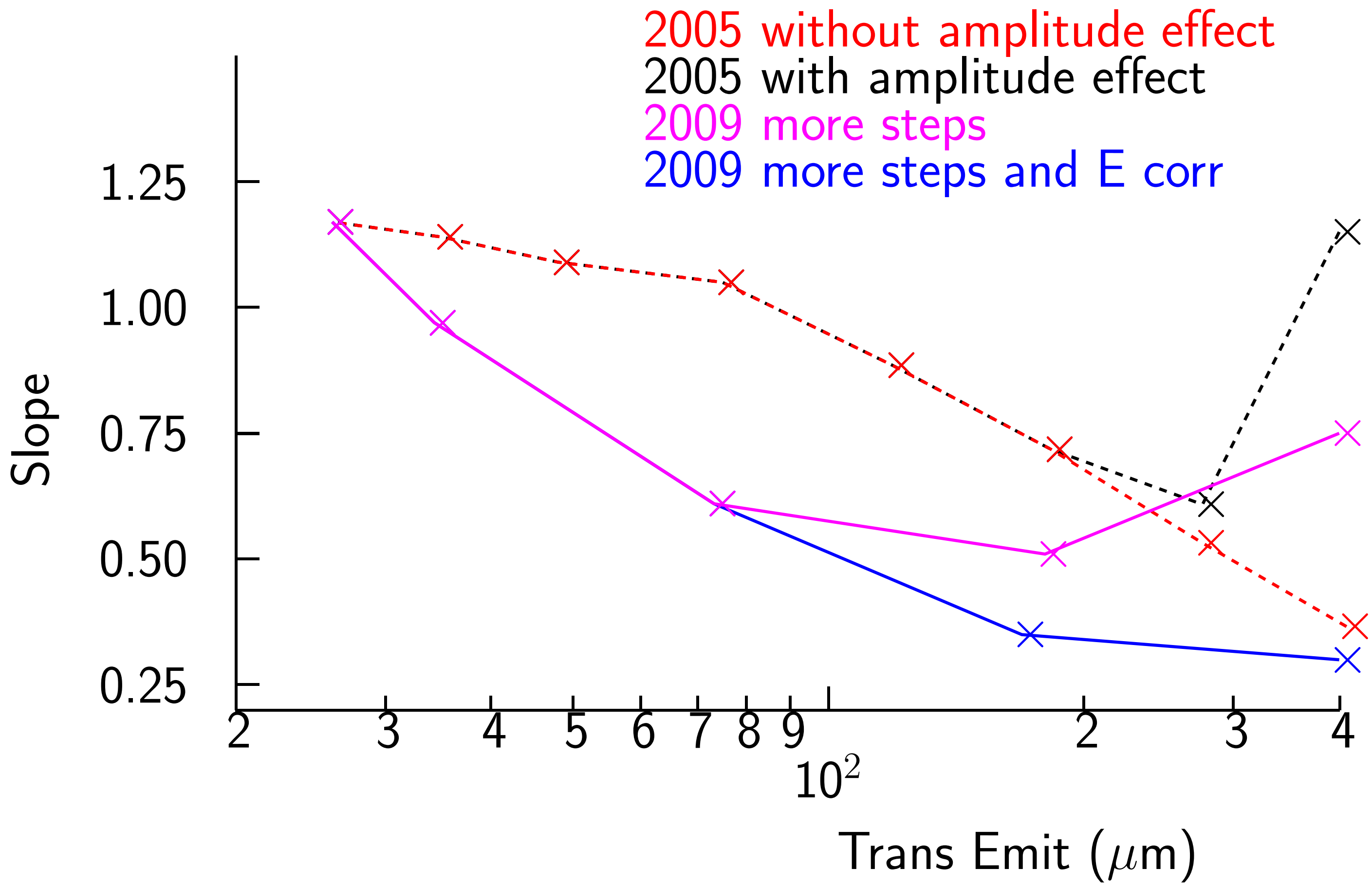
- Straggling has less effect if dp/p is large
- But if dp/p is large initially, some tracks will stop & be lost sooner
  - Requiring a shorter target
  - And thus less transverse cooling/stage
  - But less longitudinal growth

Parameters

	file	L	E1	E2	$\epsilon_{\perp 1}$	$\epsilon_{\perp 2}$	$\epsilon_{\parallel 1}$	$\epsilon_{\parallel 2}$	dE1	dE2	loss	slope
		cm	MeV	MeV	μm	μm	mm	mm	MeV	MeV	%	
A	m1d	100	120	88	400	338	.9	1.1	4.4	5.1	1.17	.75
B	m3ulb	90	120	91	180	161	2.7	3.0	8.9	9.7	0.11	.51
C	m5a	5.5	26.5	23	73	68	7	7.5	8.8	9.5	1.54	.53
D	m7b	3	11	7.3	29	24	21	29	1.7	2.3	1.18	.97
E	mag8u	2.5	8.9	4.7	25	20	40	68	0.85	1.4	0.8	1.2

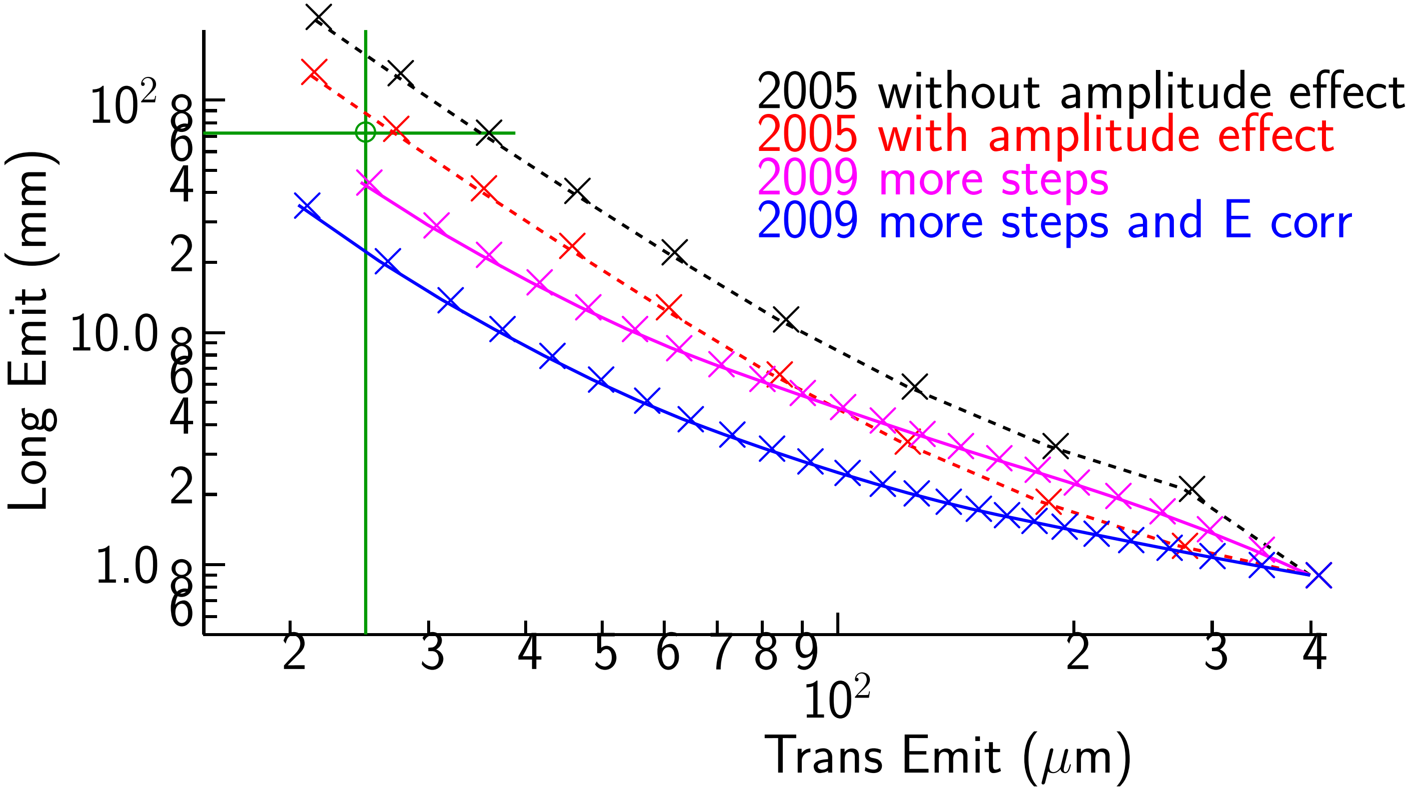
- 5 stages were simulated and performance of others interpolated
- These are preliminary numbers
- More optimization needed
- More stages needed

Slopes with new optimization



- New optimization (magenta) gives lower slopes for all stages
- With ideal momentum-amplitude correlation, even lower slopes (blue)
- Reality will lie soewhere between the two

Performance of new optimization



- 19 stages: 13 at 50 T (cf 8 for 2005) , 6 with fields down to 35 T
- Transverse emittance of 25 (μm) achieved with
  - Long emit of 41 (mm) without amp-momentum correletion
  - Long emit of 22 (mm) with ideal amp-momentum correletion
- Reality somewhere between: assume Long emit of 30 (mm)
- This meets the requirement (72 mm) and avoids excessive decay losses

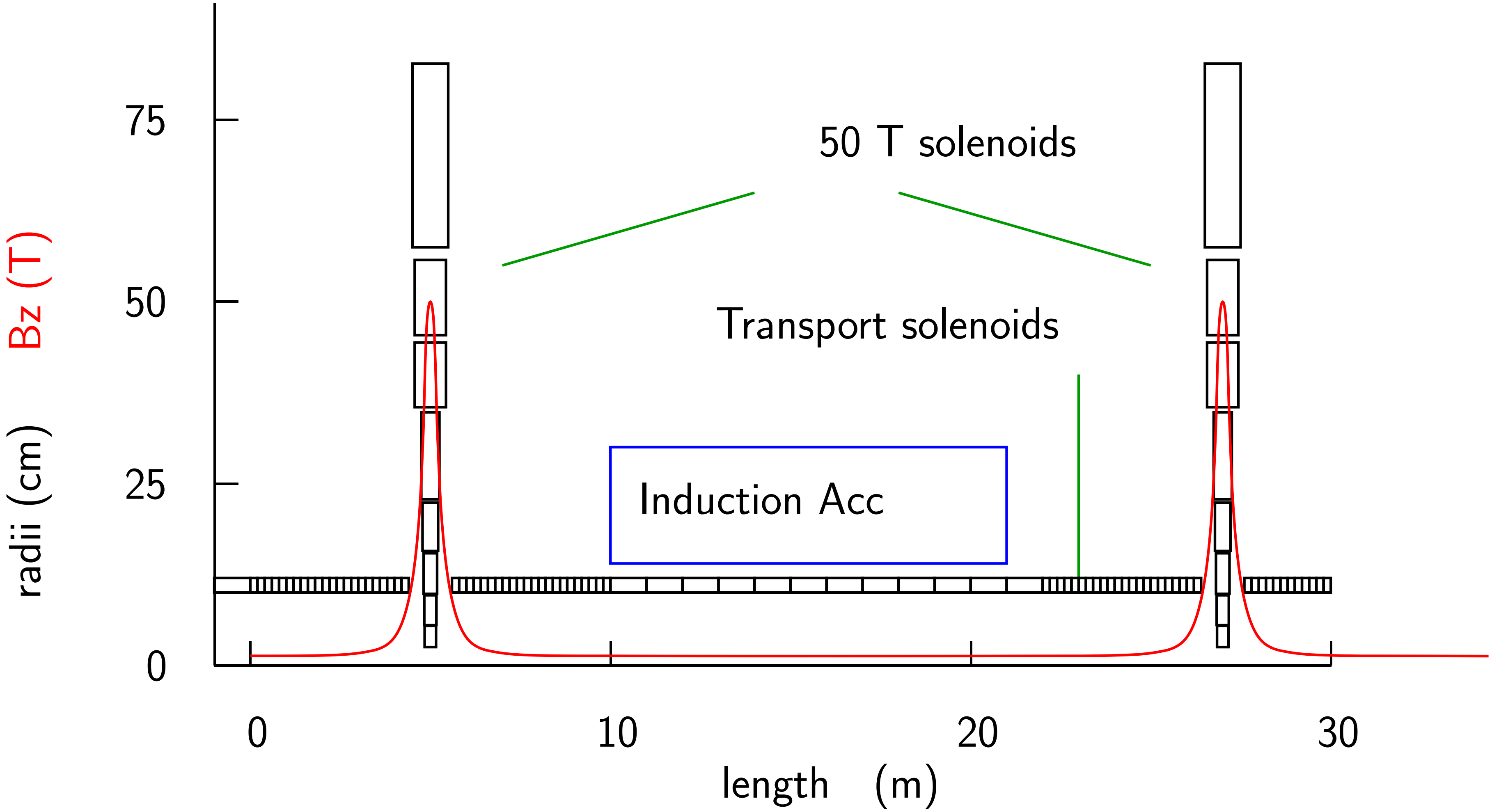
Addition of Septum emittance exchange (Potato Slicer)

- The above meets the transverse emittance requirement of 25 (μm)
- And exceeds the longitudinal requirement: 30 (mm) vs. 72 (or 175 for new ring)
- Further 50T cooling stages would reduce trans emit to below 25 (μm) but with excessive decay losses from the long matching and re-acceleration
- Such further stages would have slopes $>$ 1: the 6D emittance is growing
- Suggesting the use of a stage of septum emittance exchange (potato slicer)

This would:

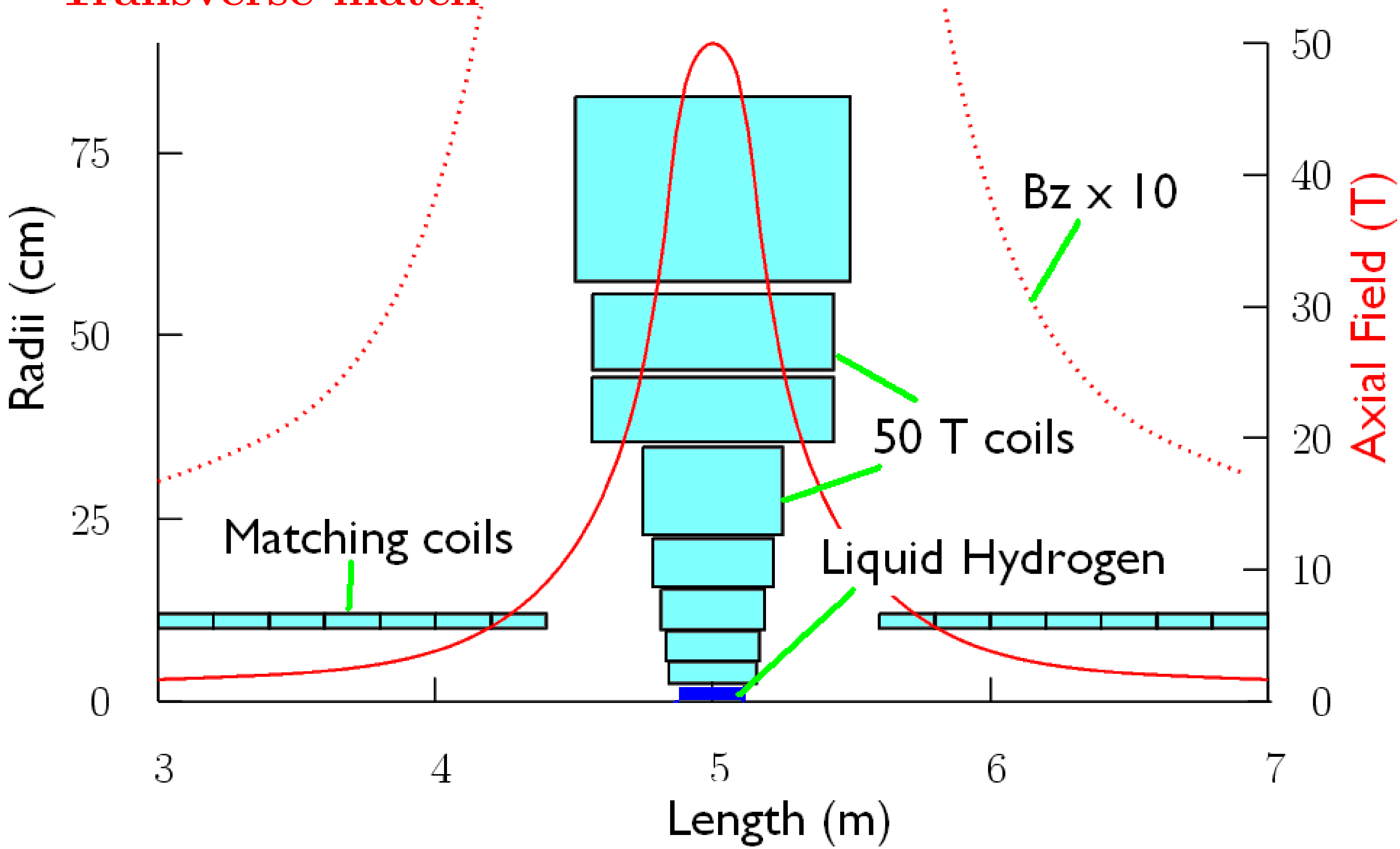
- Increase longitudinal emittance to $6 \times 30 = 180$ (mm) (which is ok for new lattice with dp/p=0.2 %)
- Reduce transverse emittance to $25 \times 0.6 = 15$ (μm)
- Reduce muons/bunch, protons per bunch, and backgrounds by factor 0.6
- Increase repetition rate by factor 1.7

11) Simulation of match & re-acc between 2 Solenoids



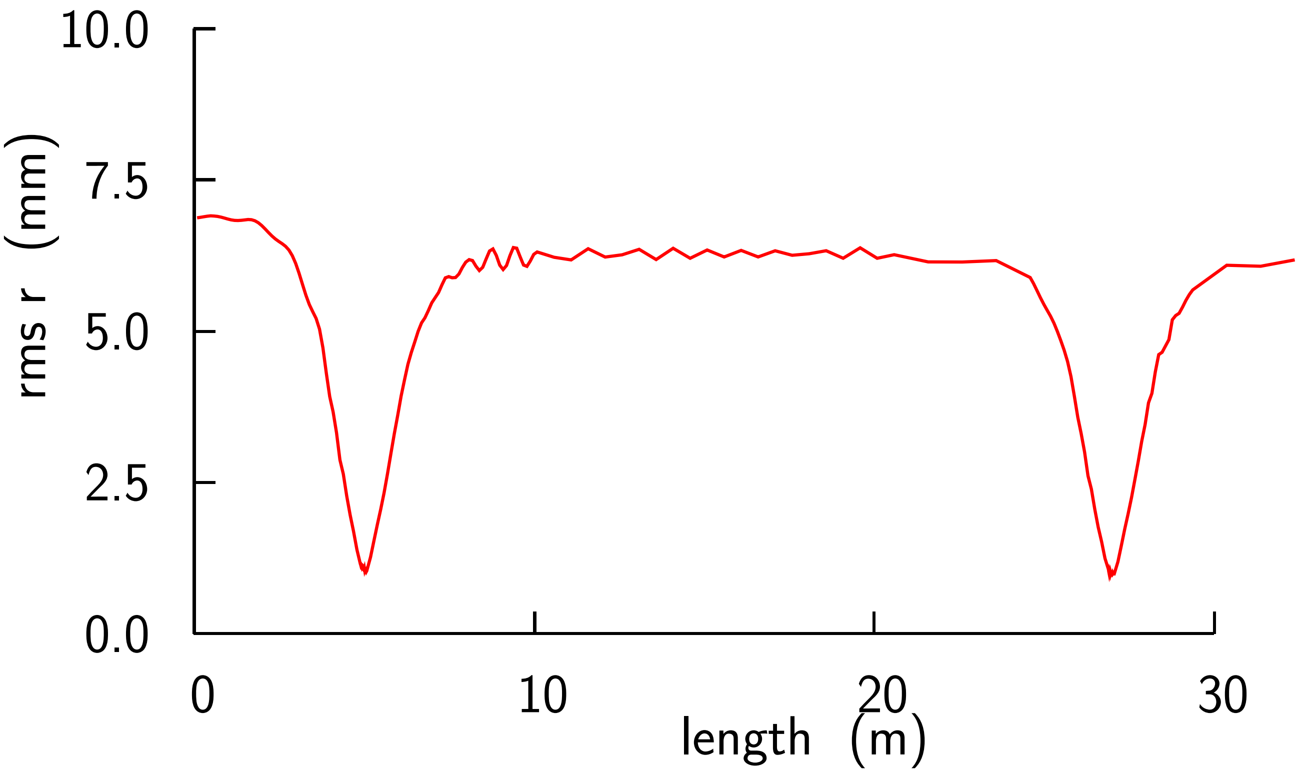
- 50 T design taken from PBL SBIR
- Matching also part of this SBIR

Transverse match



Condition for adiabatic match: $$\frac{d\beta}{dx} \leq 0.25$$

Beam size



- rms 1 mm in magnet 1.2 cm pipe is 6 sigma
- rms 7 cm in induction 10 cm pipe is 7 sigma

Longitudinal Match

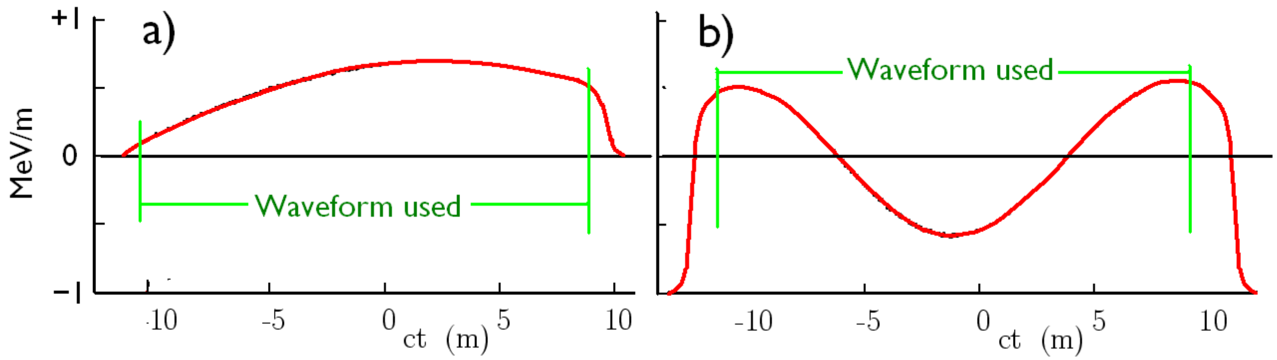
- Attempts using a matrix phase rotation and acceleration gave ≈ 30 % longitudinal emittance growth

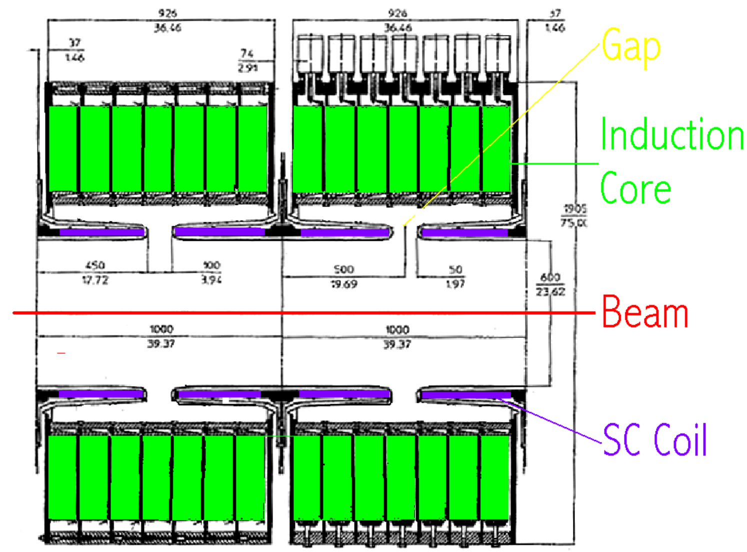
- Then tried real particle simulation with linear induction waveforms
- But particle phase distributions developed banana shapes
- Giving longitudinal emittance growth of the order of 30%

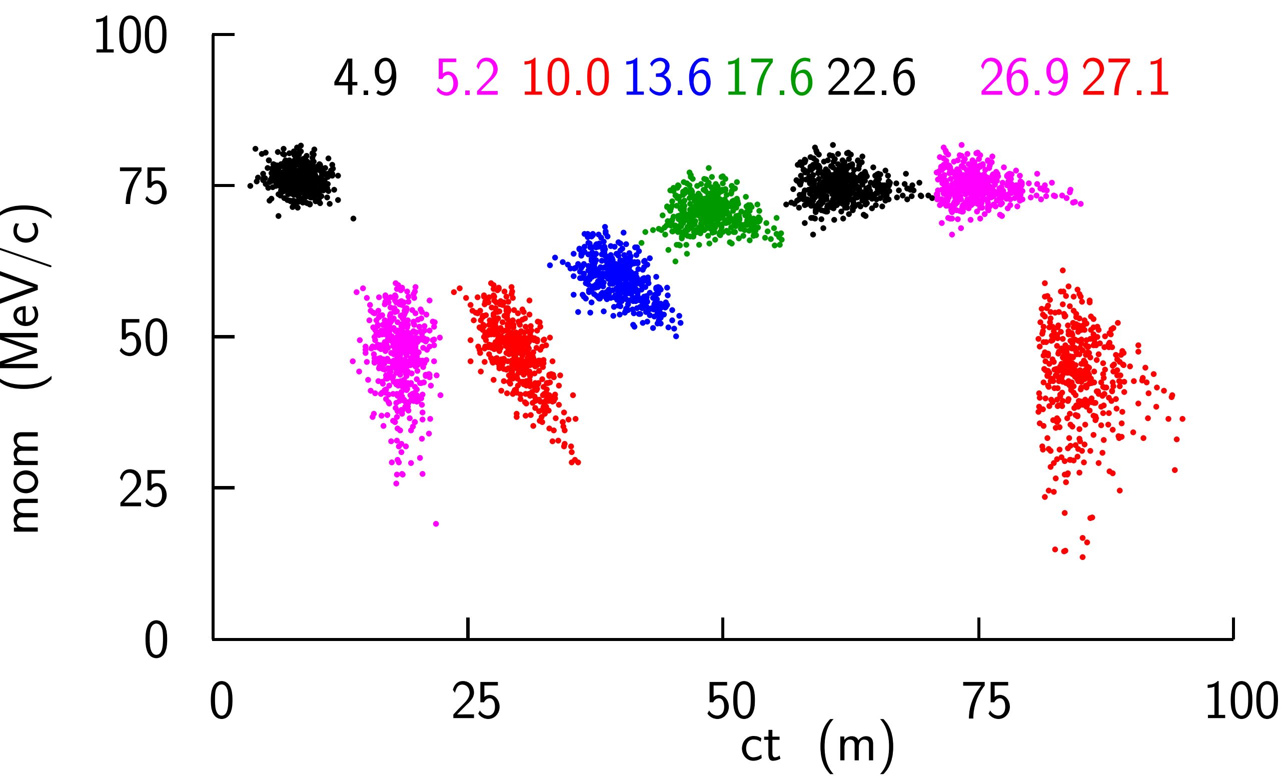
- The problem is intrinsically non-linear

Using sinusoidal waveforms

Uses two Induction Linac Waveforms



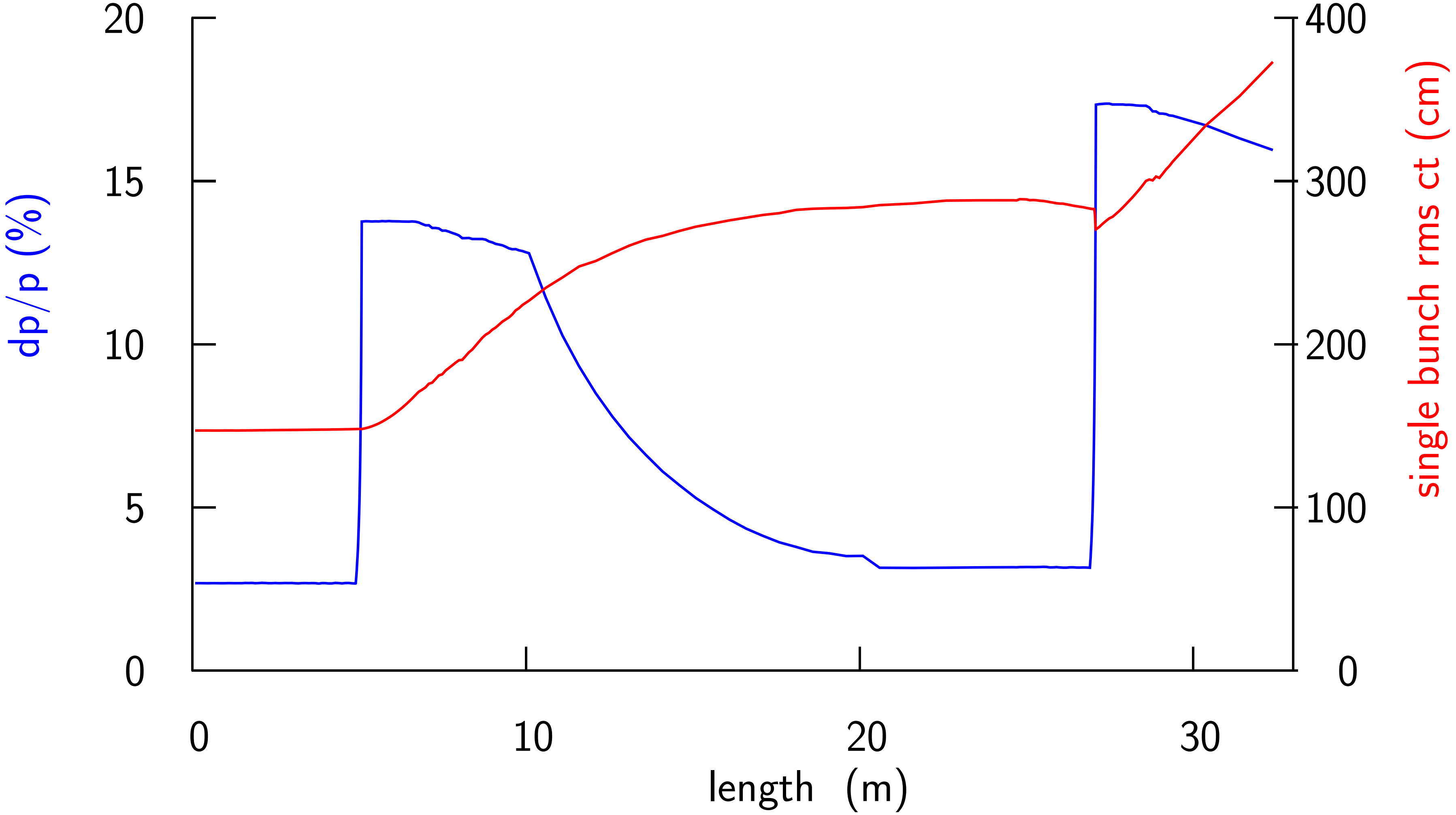




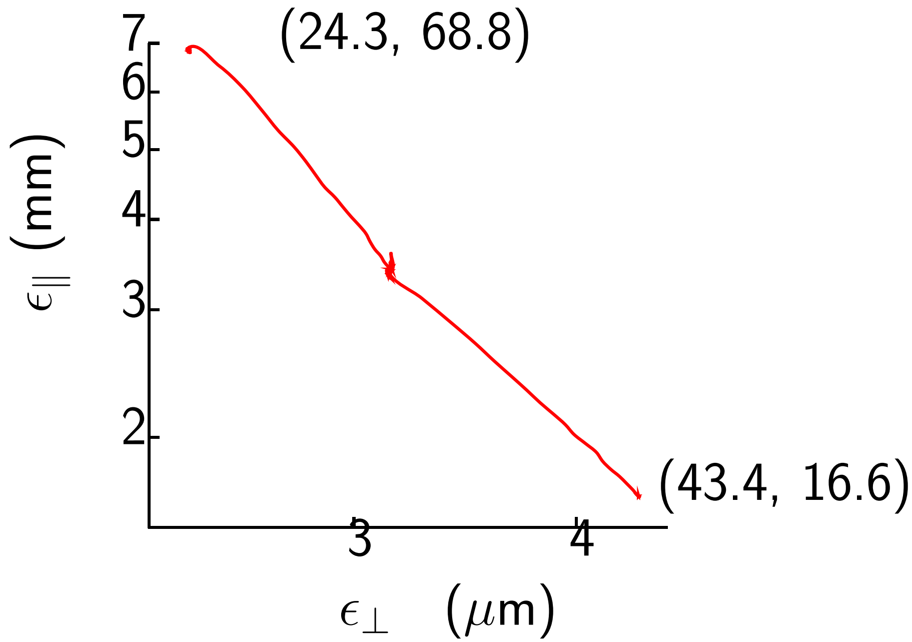
Study II Induction design

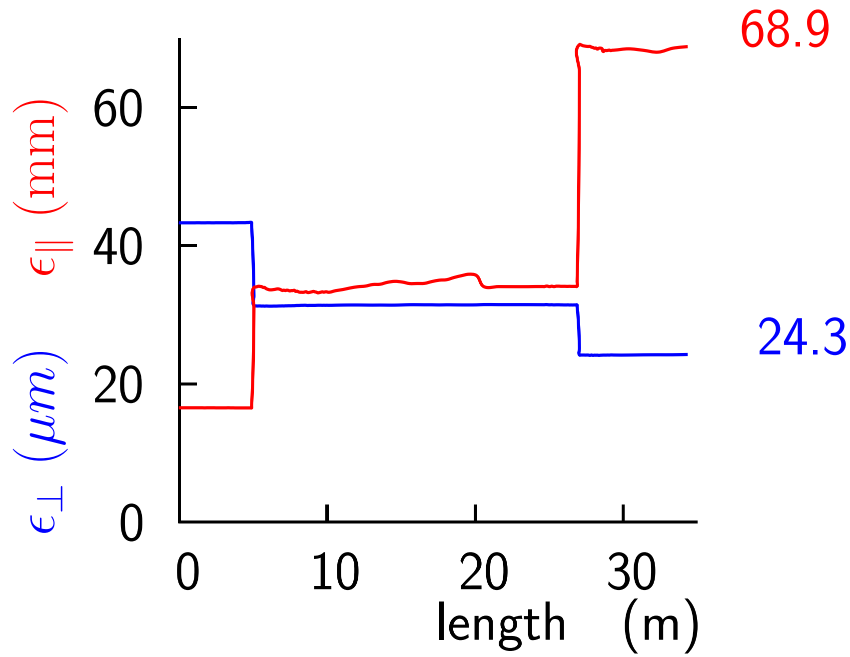
- Good results
- No banana shape

dp/p and sigma z



Emittances

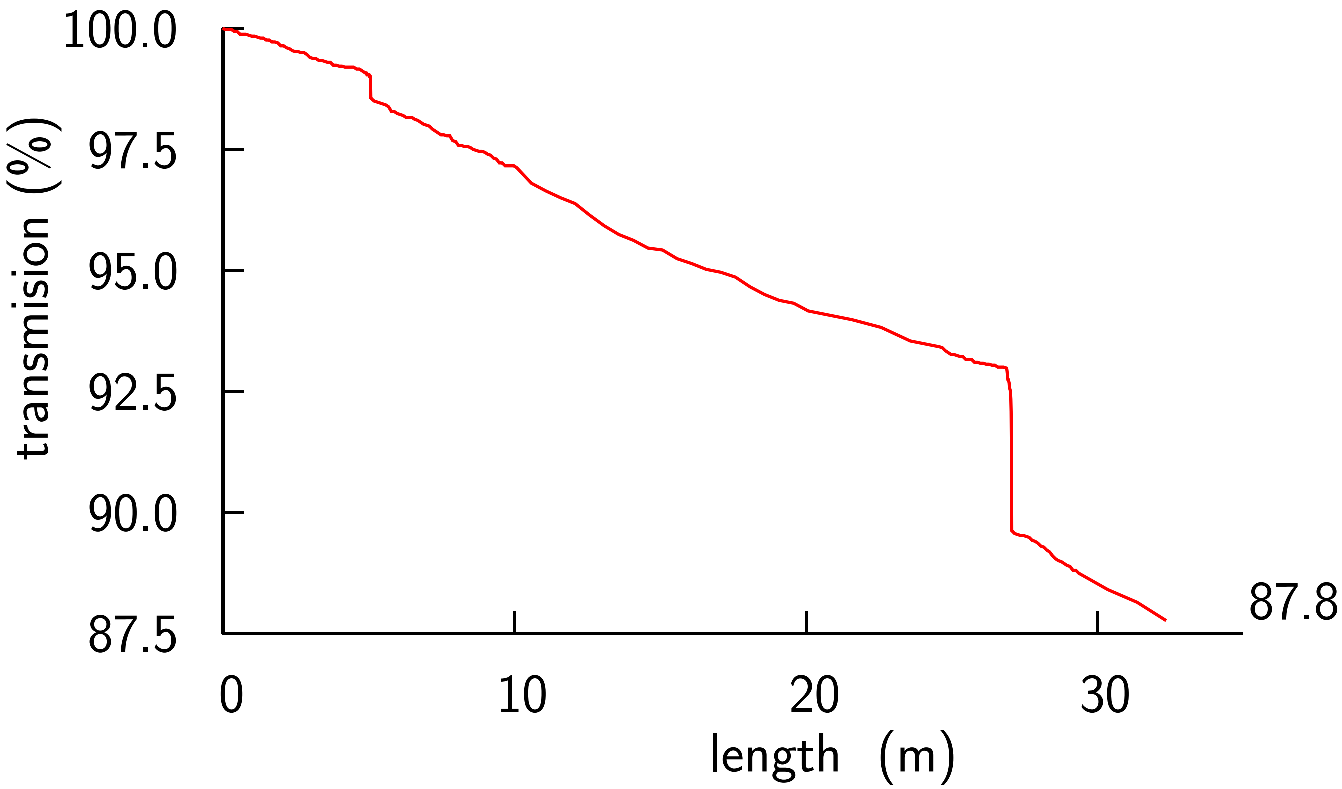




In matching:

- Negligible increase in transverse emittance
- Negligible increase in longitudinal emittance

Transmission

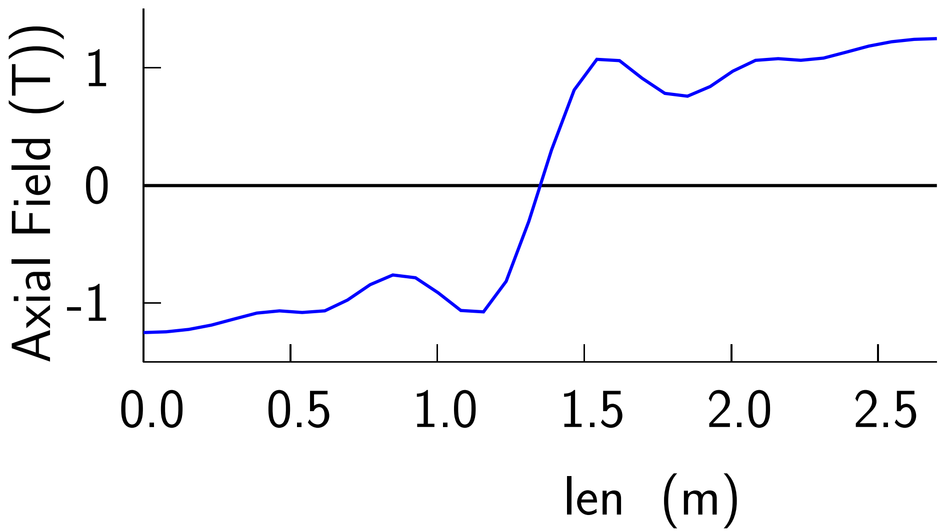


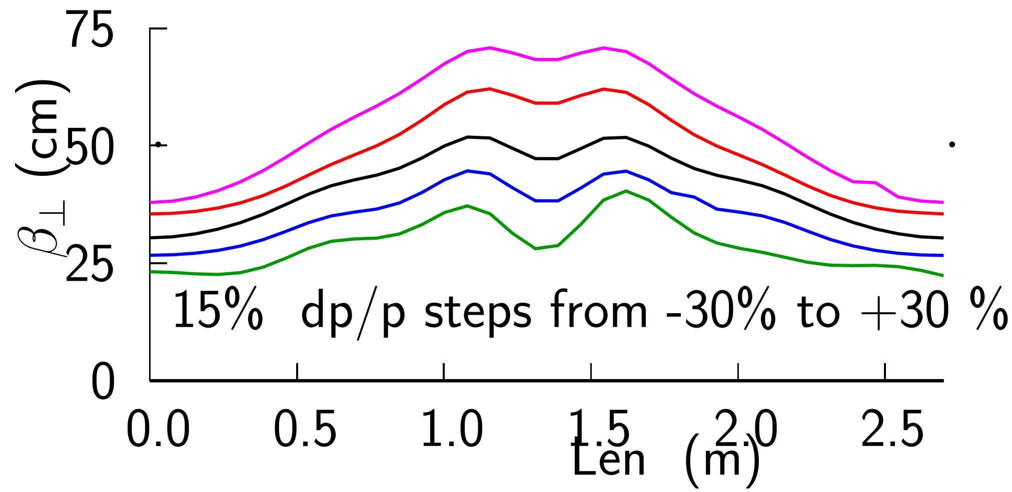
In both cooling stages and match between them:

- 12.5 % loss
- 7.5 % from decay, & 5 % from 4 sig cuts, stopping muons etc
- These losses are too large for total 70% specification
  (as discussed above)

Field flip

- Field flips are needed periodically to stop accumulation of angular momentum
- Not included in the above simulation
- It should be introduced in, or after the re-acceleration (where dp/p is low)



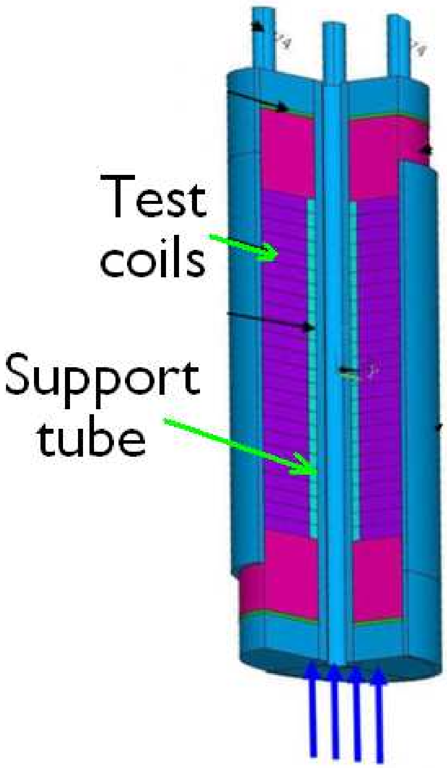


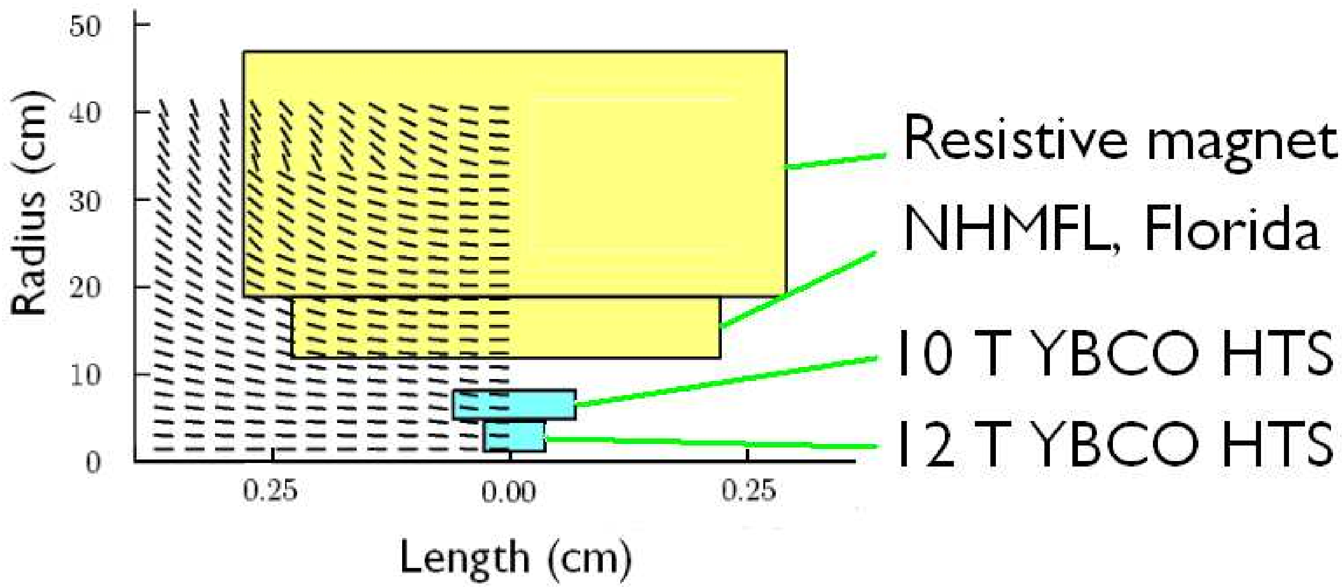
- Good matching is seen at all momenta within 30% of the average
- Such field flips had been used in the Feasibility Study I cooling, and in the Study 2 phase rotation where they introduced negligible emittance growth

11) Conclusion

- Initial design with 8 stages has problems:
  - Losses from decay in long matching & reacceleration of later stages
  - Longitudinal emittance growth from amplitude-velocity effect in 1st stage
- Cutting Landau tails reduces longitudinal emittance, but gives too much loss
- Use of septum emittance exchange may solve loss problem in late stages but amplitude-velocity effect in early stages remains
- A new design using shorter but more stages solves both problems
- It uses 13 50T magnets (vs. 8) plus 6 with fields down to 35T
- Septum emittance exchange might now allow cooling to 15 (μm) giving reductions of muon charge, proton charge, and backgrounds
- A simulation of matching and re-acceleration in one case was ok
- Further optimization of all stages may require fewer than 19
- Simulation then needed of all stages including matching, re-acceleration, & field flips
- Lower emittance final 6D cooling should also be studied

Appendix: HTS R&D towards a 50 T solenoid

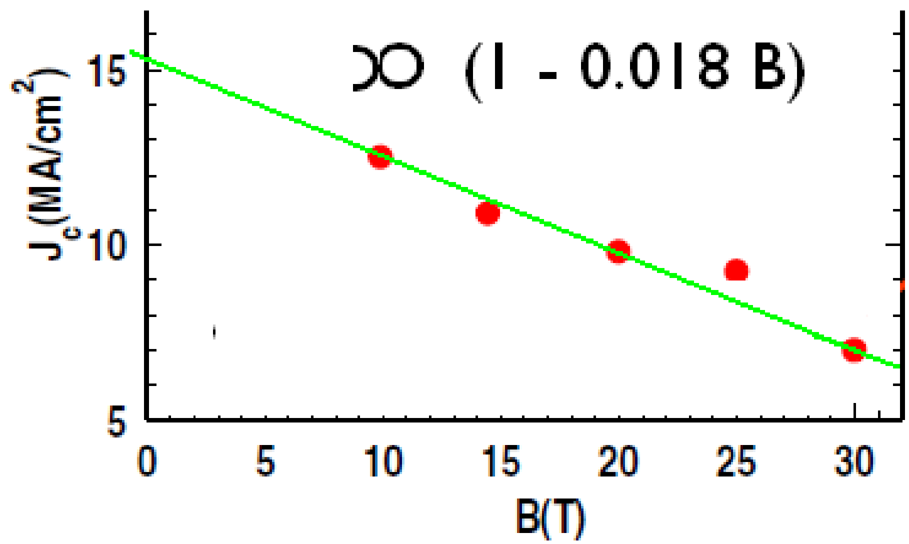




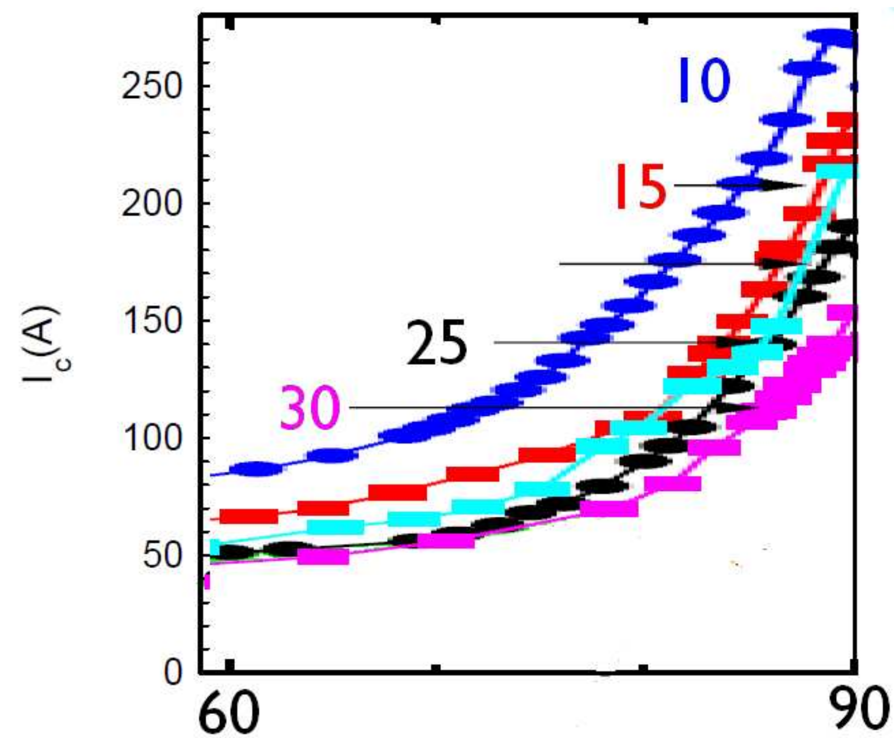
- FNAL program
- Testing multiple small coils in existing 12 T facility
- Fields up to 25 T

- BNL/PBL Program (SBIR)
- Nested YBCO HTS coils under construction
- 12 + 10 T = 22 T stand alone
- Approx 40 T in 19 T NHMFL magnet
- 19 T NbTi + Nb_3Sn design available commercially
- But R&D on higher current density coils proposed

j vs. B and angle for SuperPower YBCO tape



j vs. B (from NHMFL)



j vs angle (from NHMFL)

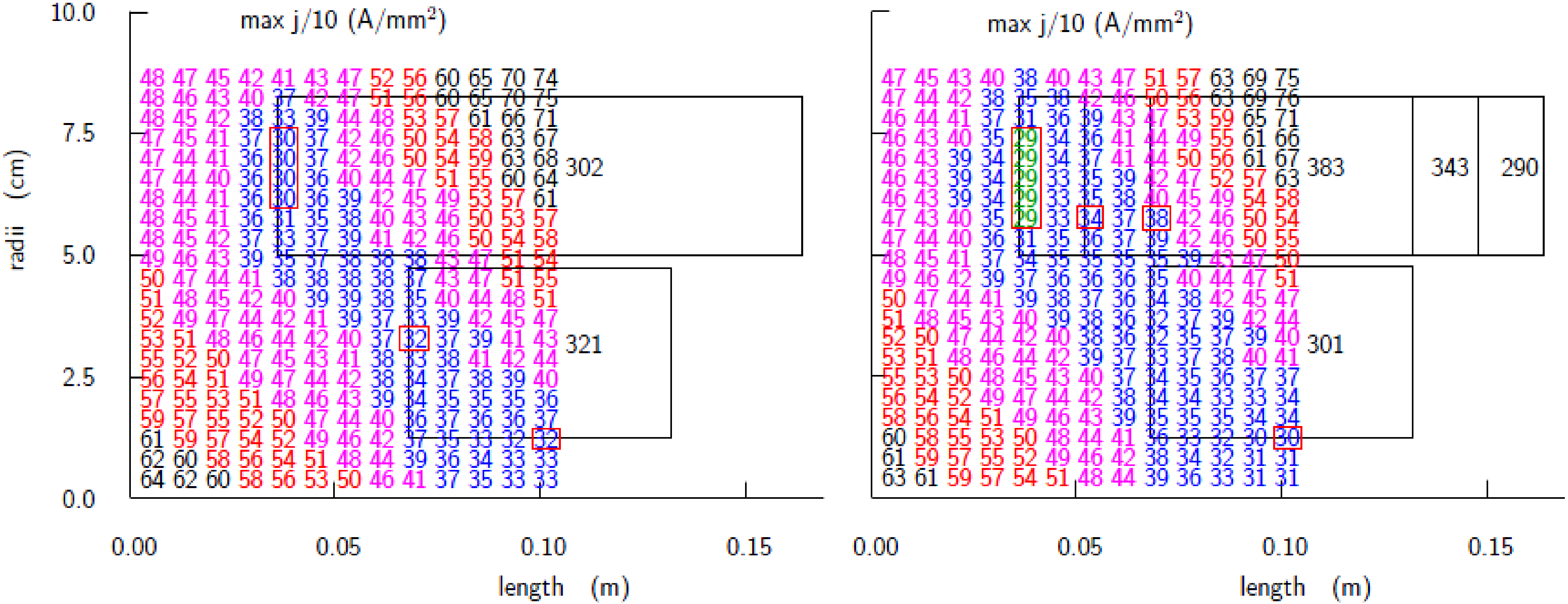
- Absolute normalization from Barsi (FNAL)

$$j(10) = \frac{720}{(4.4 + 0.13)(0.145 + .025)} = 935 A/mm^2$$

- Gives j vs B and angles

$$j = 1140\,(1 - 0.018\,B)\ \exp -(0.057 - .0001(B - 20)^2)\ \theta \qquad (\mathrm{A/mm^2})$$

Match maximum allowed currents including angle



- Lowest maximums are on coil ends
- If all powered with same current Bmax=38.9 T
- Currents lowered on end 4 pancakes: B$\rightarrow$ 39.9 T
- If Bi-2212 coils added: Bmax $\rightarrow$ 40.5 T
- If at 1.8 K Bmax $\rightarrow$ 42 T

Conclusion

- Several designs of 50 T 'all super conducting' magnets have been published
- Yet doubts remain as to whether they are realistic

- This test will apply the Bob Wilson approach: start building

- A 19 T super-conducting coil to replace the NHMFL resistive magnet is commercially available (Alvin) and should be a priority
- The use of high current density Rutherford Cable for these outer coils would reduce their size and cost and an SBIR phase I has been submitted to explore this option

- There is much to be done, but the approach appears reasonable