Cooling in 50T solenoids

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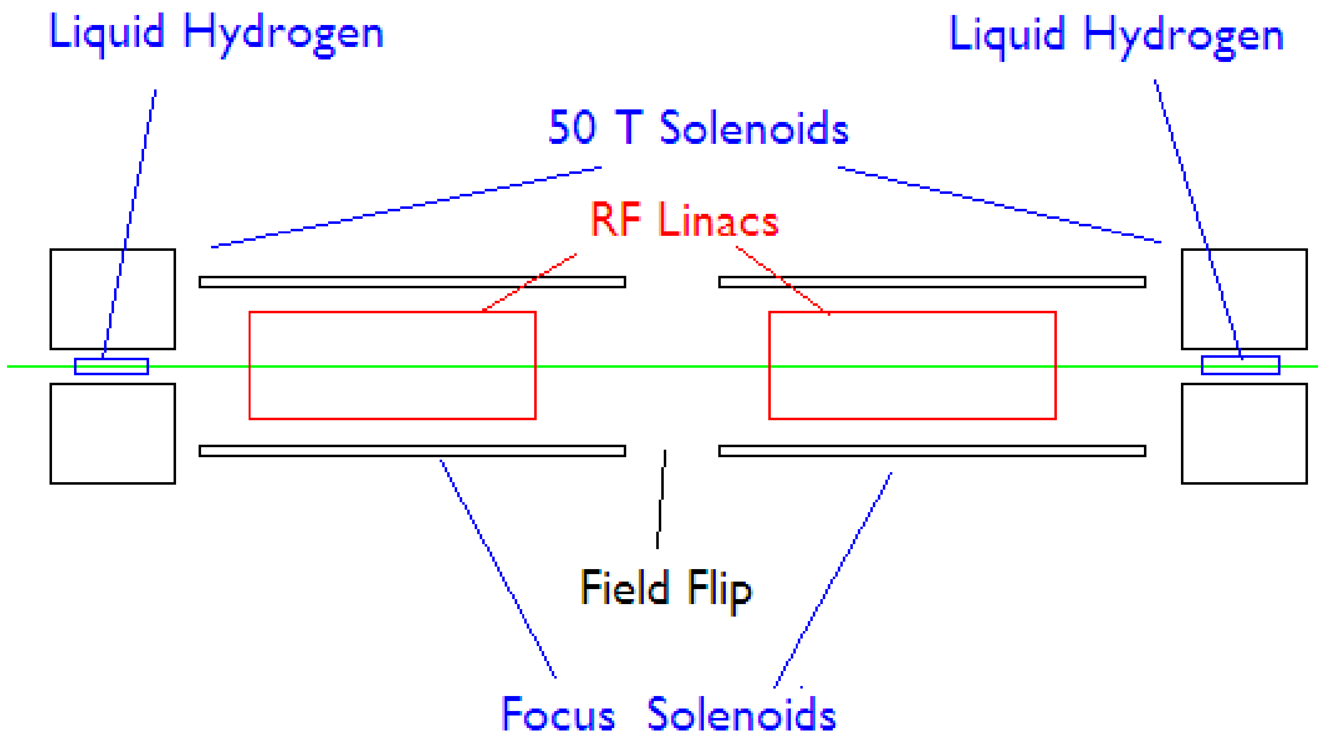
- Introduction
- Parameters of many stages
- Decay losses during re-acceleration
- Decay losses in matching
- Amplitude effects in early stages
- Improvement if Landau tails removed ?
- Merging after acceleration
- Moderate use of Super Fernow
- Space charge tune shifts
- Conclusion

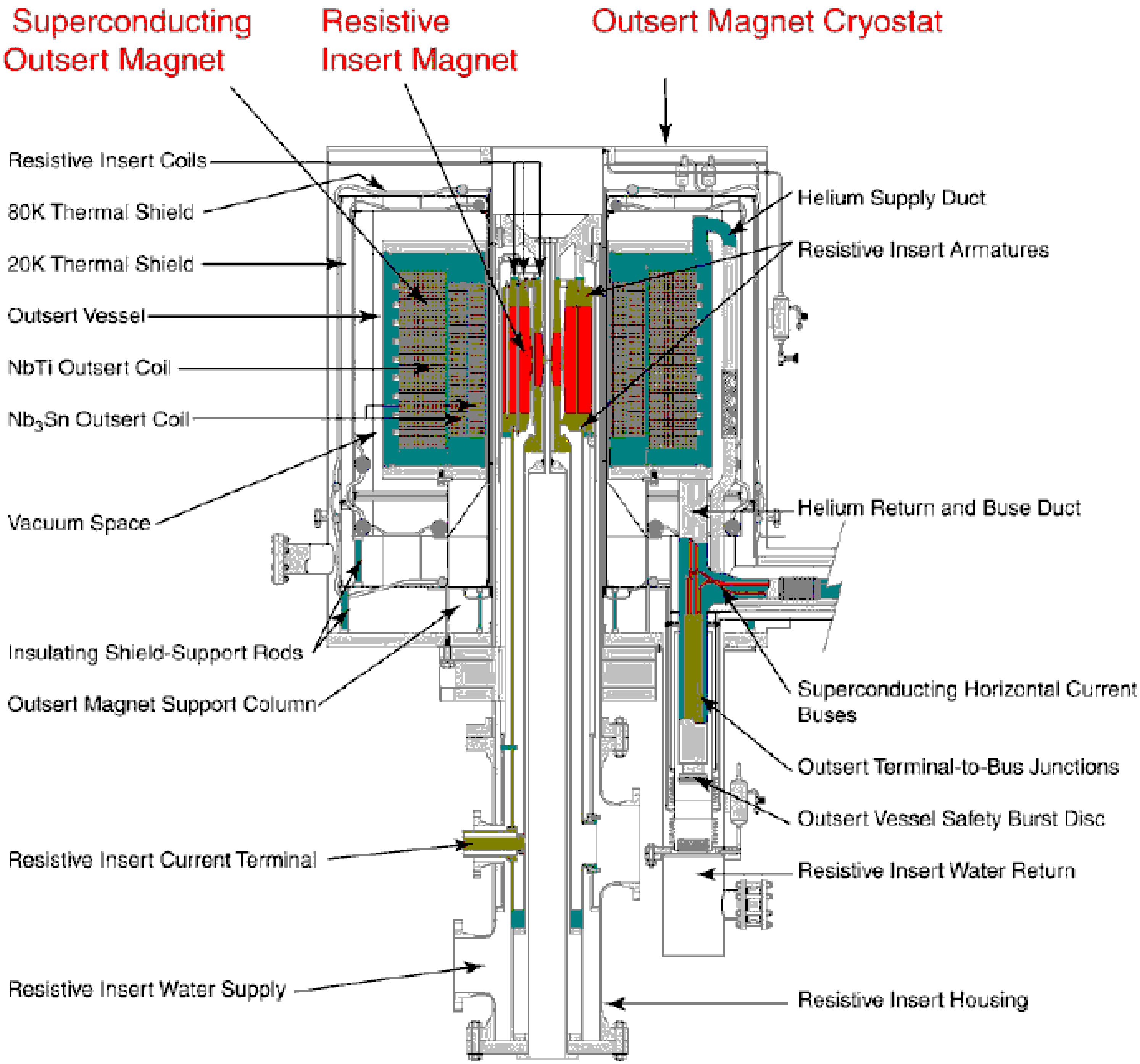
Transverse Cooling in Very High Field Solenoids

- Lower momenta allow strong transverse cooling, but long emittance rises:
- Effectively reverse emittance exchange

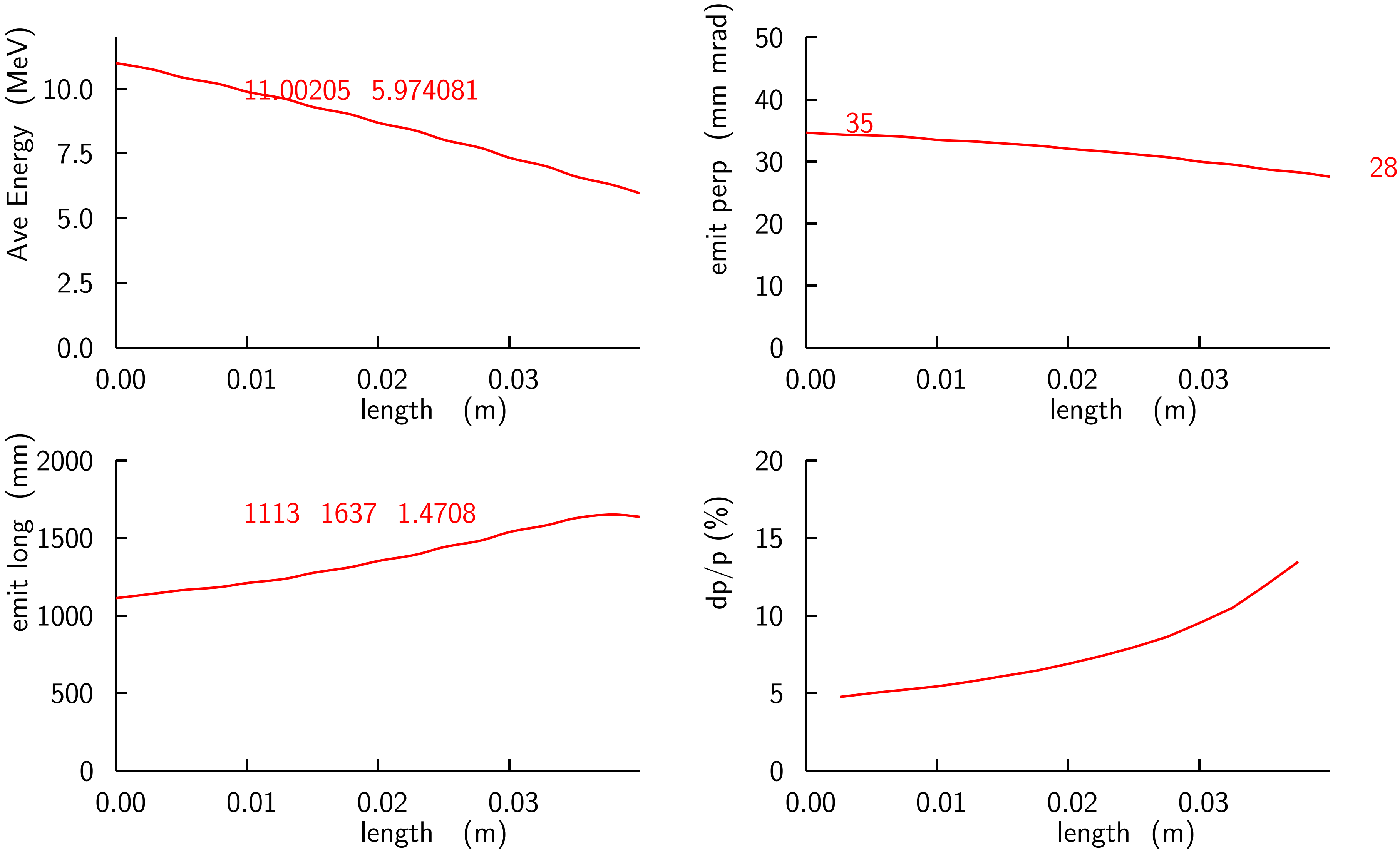


- 50 T HTS Solenoids
  - Current and ss support varied with radius to keep strain constant
  - Design using existing HTS tape at 4.2 deg. gave 50 T with rad=57 cm
  - 45 T hybrid with Cu exists at NHFML, but uses 30 MW
  - 30 T all HTS under construction

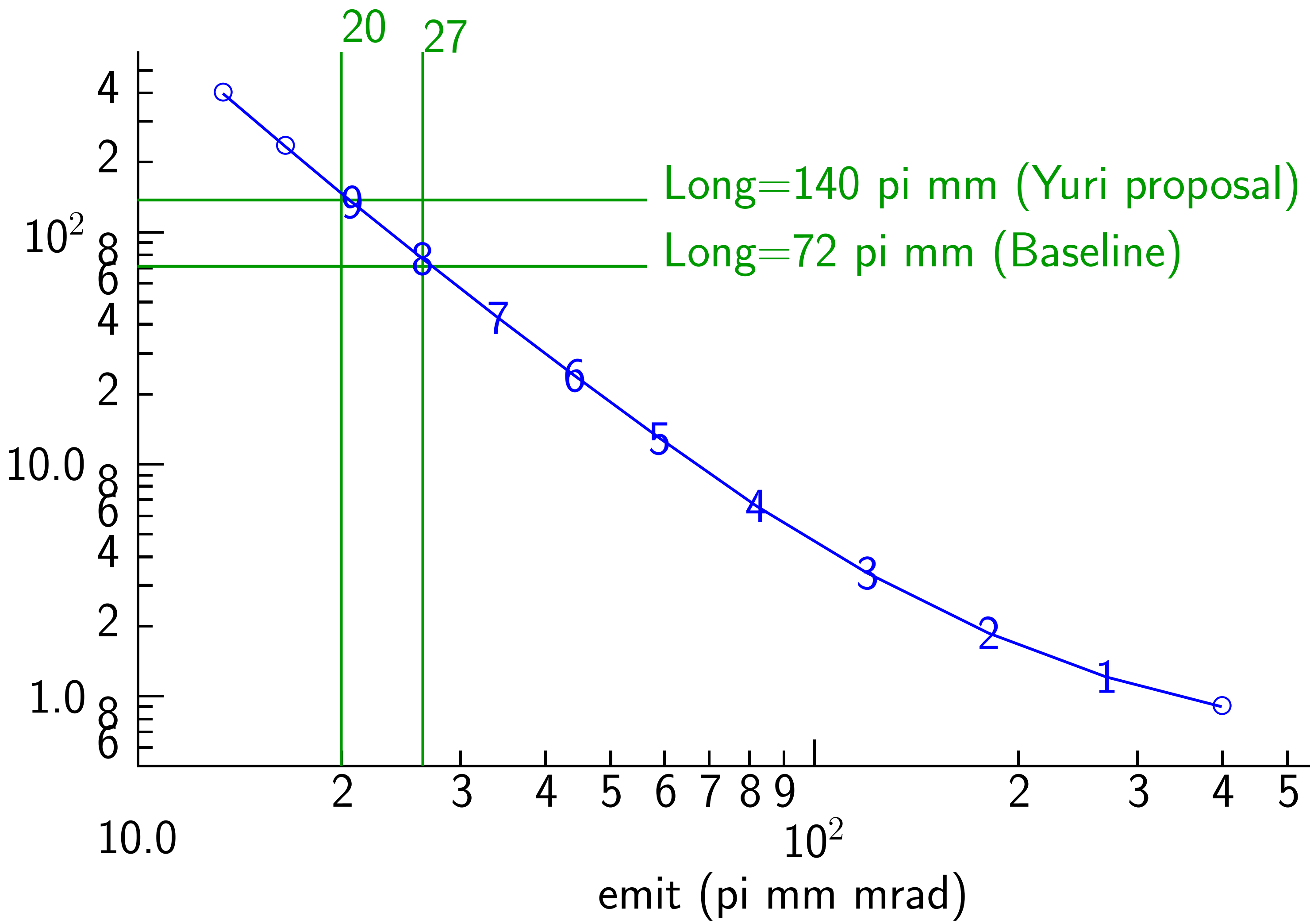
NHFML 45T Solenoid



Example stage

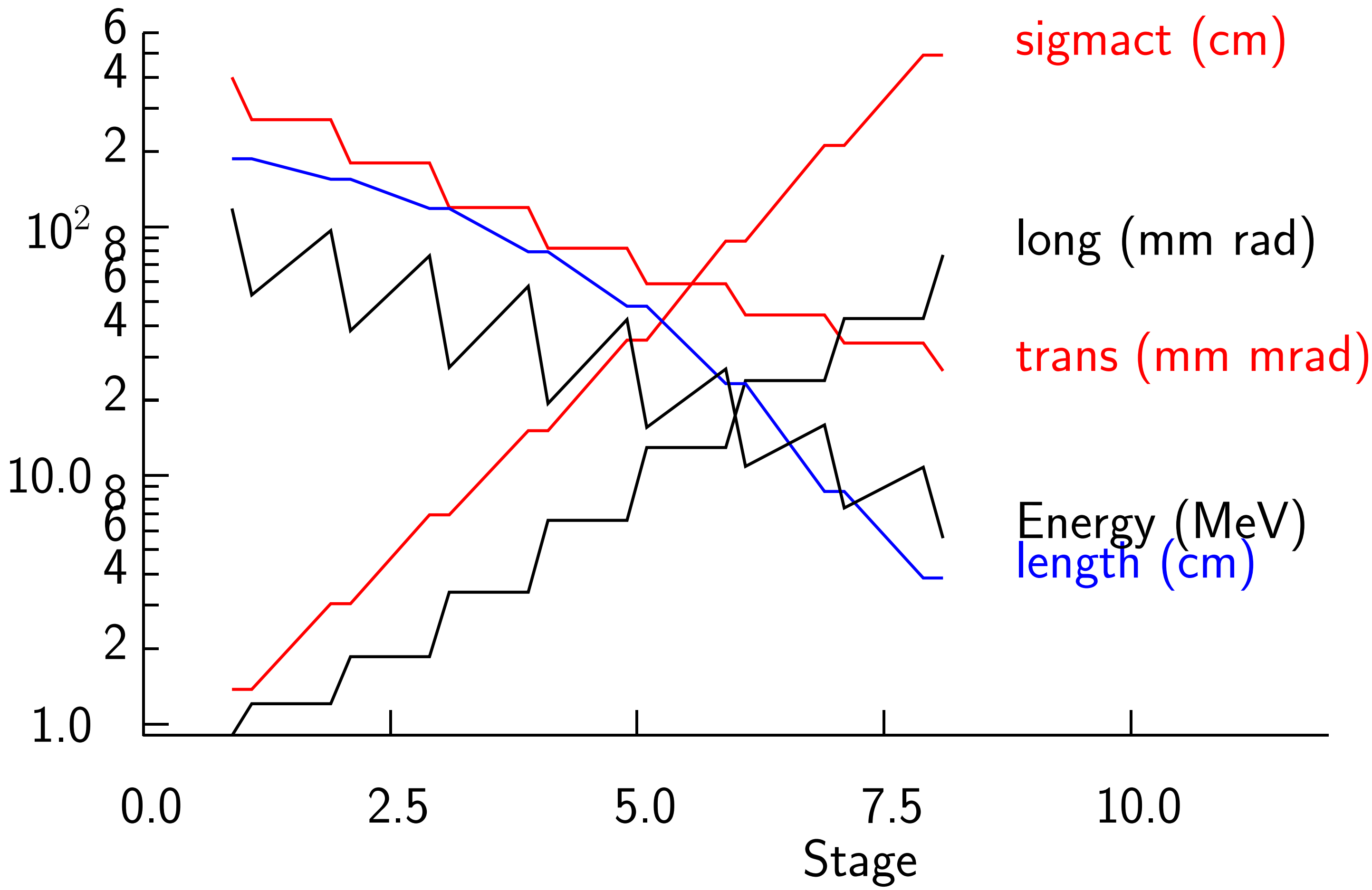


Long vs Trans emittances for many stages



- Initial conditions as from end of 10 T RFOFO 6D cooling
- 27 pi mm mrad near spec (25) at baseleine long emit (72 pi mm rad)
- 20 pi mm mrad below spec at Yuri's increased long emit (140 pi mm rad)

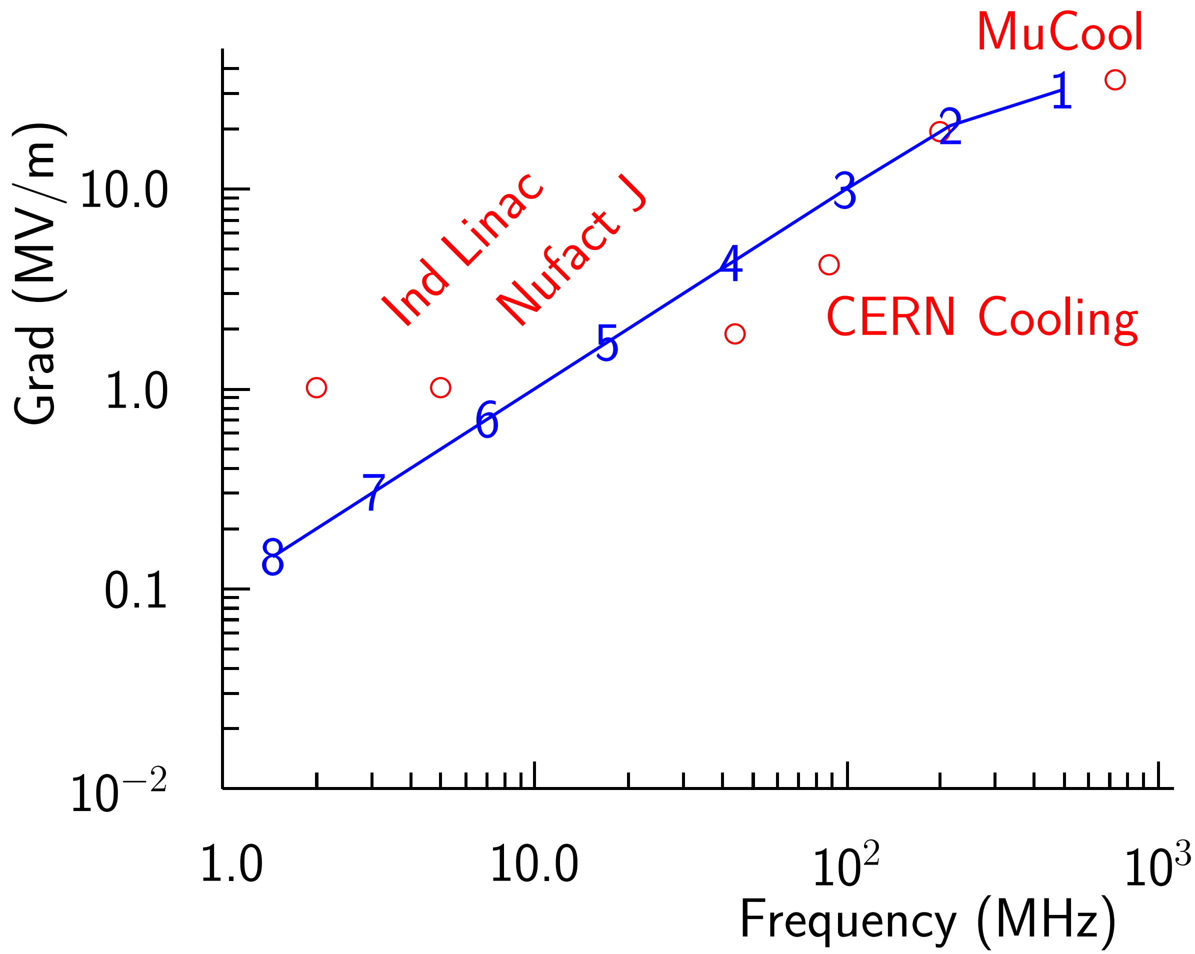
Parameters



- 25 pi mm mrad transverse emit reached when longitudinal emit = 90 (pi mm)
- Between stages: matching and re-acceleration
- Bunch length rises to 5 m requiring very low rf frequency ($\approx$ 1 MHz)
- Hydrogen length in later stages are short $\rightarrow$ 4 cm

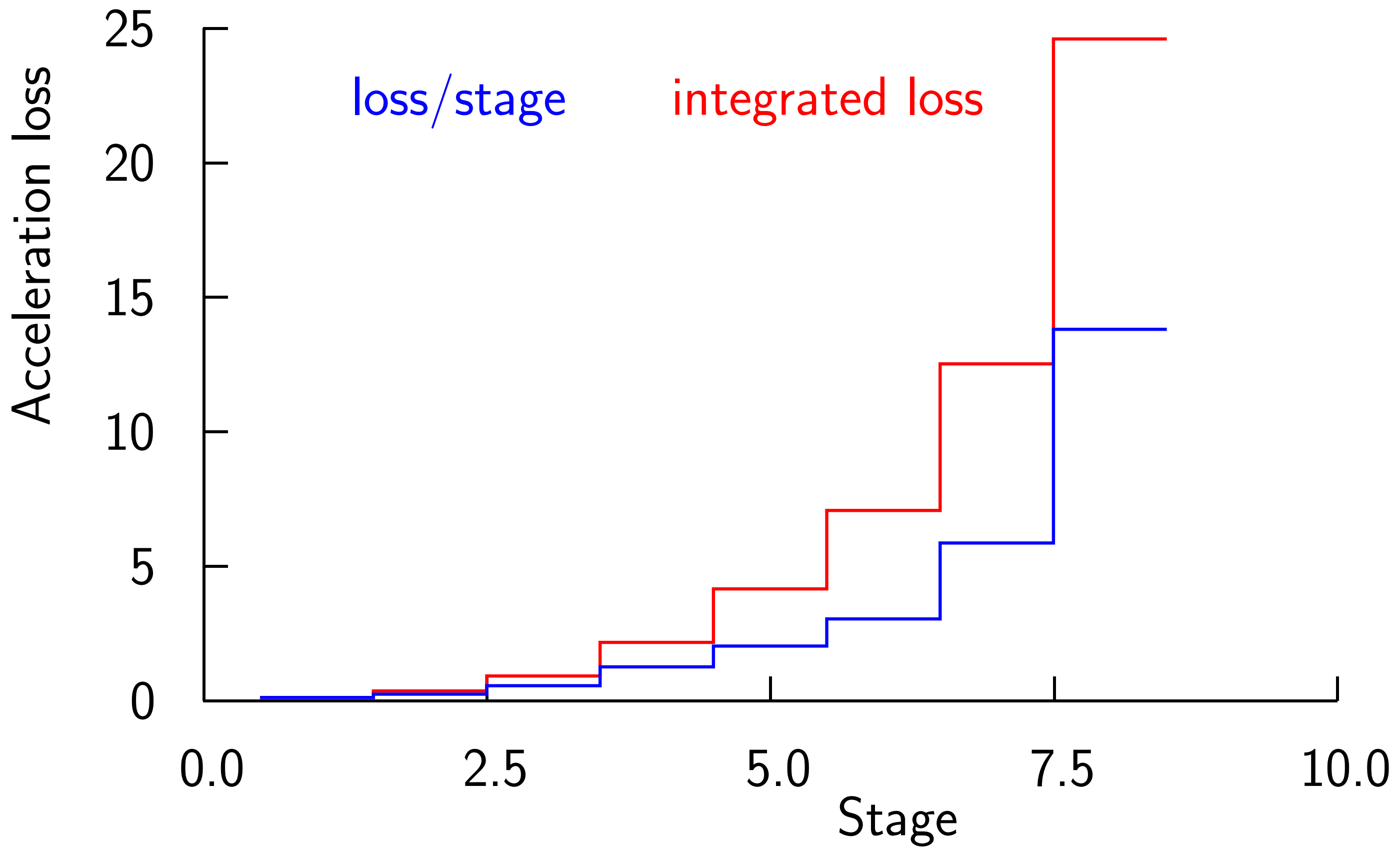
Problem 1: decay losses during Re-accelerations

Assumed Acceleration Gradient



Low frequencies imply low accelerating gradient

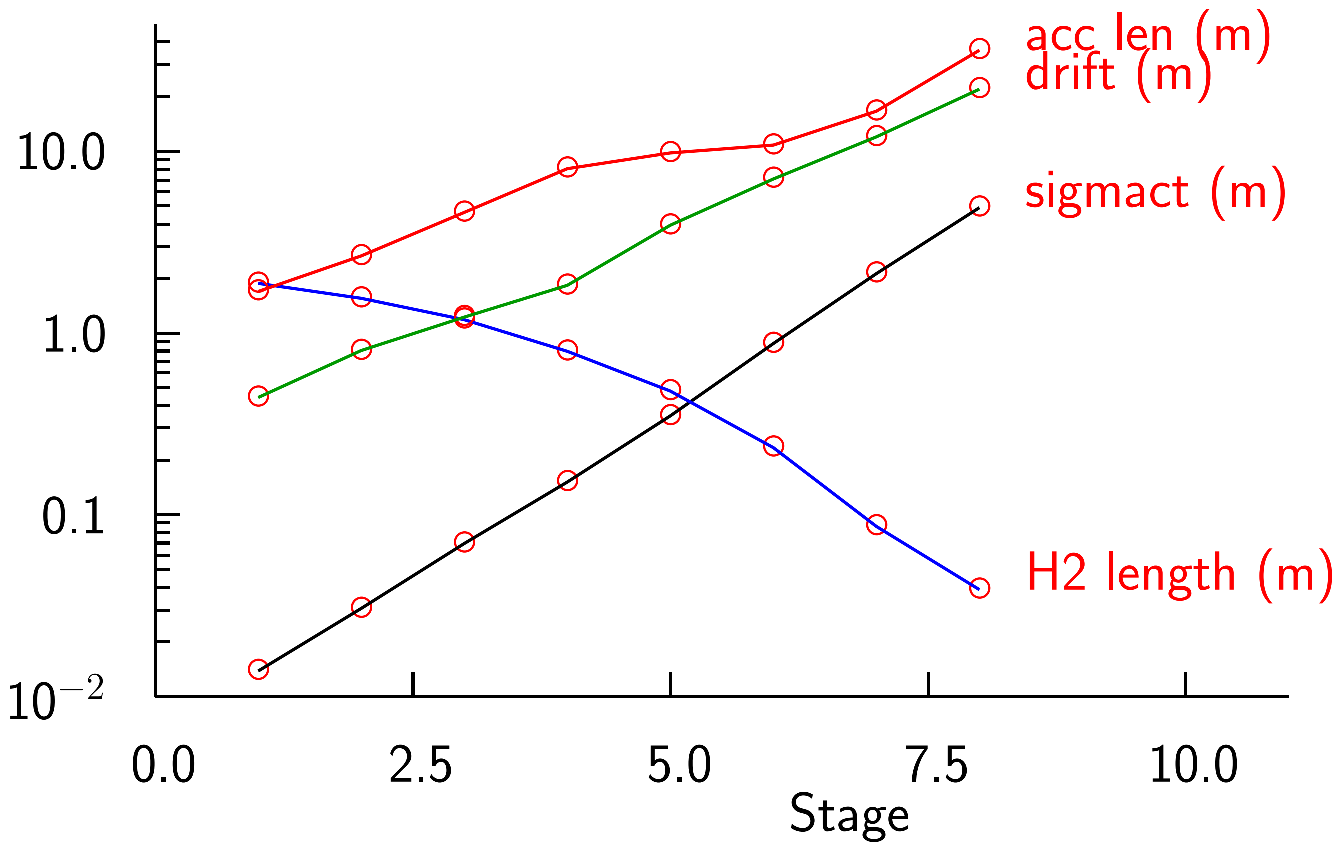
Decay losses in acceleration



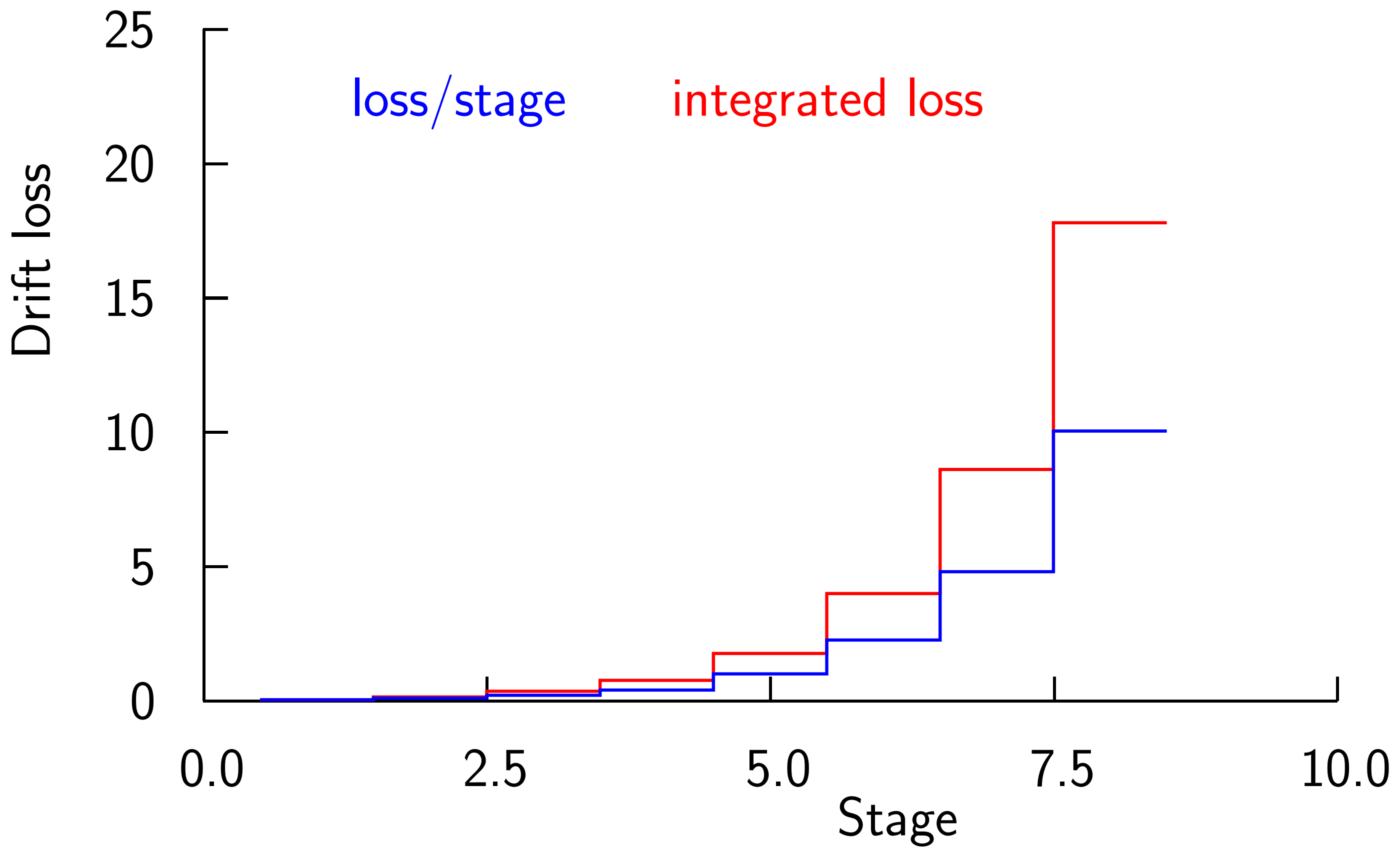
- We need to find out what the real acc gradient limits are
- It may be worth using Induction Linacs in last stages
- Raising the frequency would also help (see the following)

Problem 2: decay loss during Longitudinal matching

- After each stage, the dp/p is large
- Phase rotations required to lower the dp/p→ ≈ 4%
- this requires a drift followed by rf (just as after the target)



- The last drift (after stage 8 before acceleration) is 25 m long at low energy: giving significant decay loss



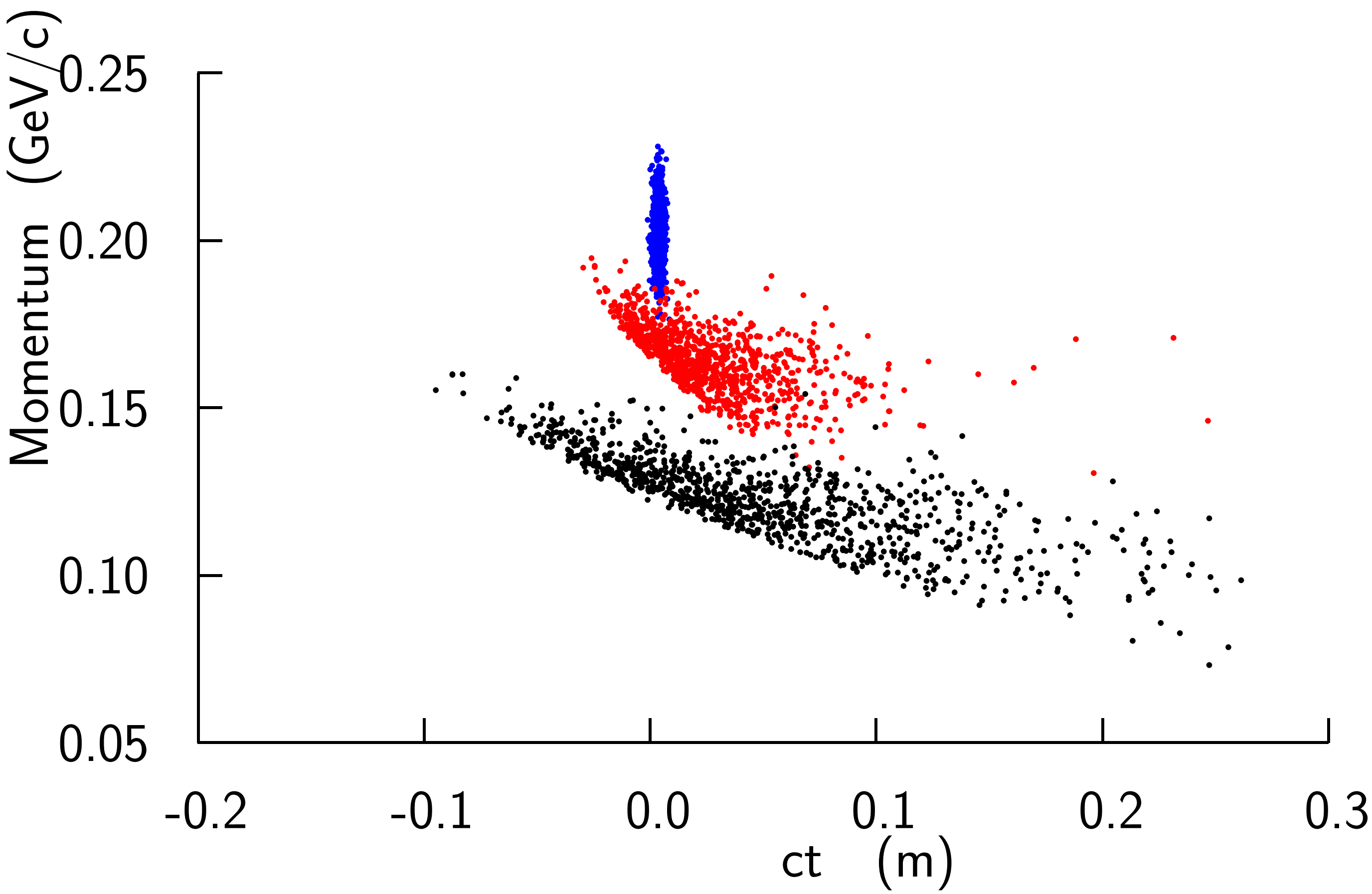
How to fix this

- The required drift lengths can be reduced by increasing the dp/p
- This reduces decay losses
- It also increases the rf frequency reducing acc length and decays

Problem 3: amplitude effects in early stages

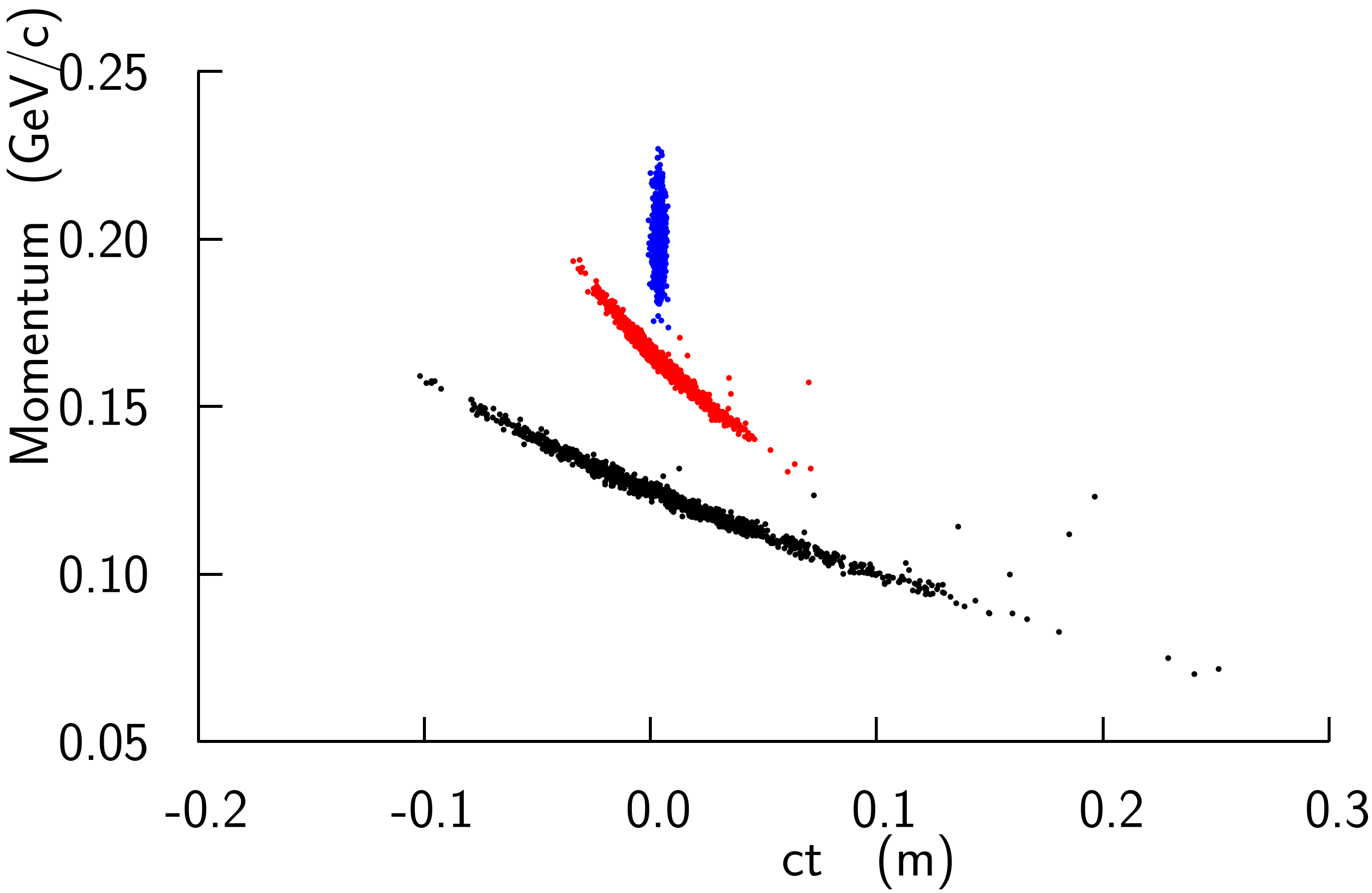
- Calculated longitudinal emittance rises more than dE increase predicts
- Not a problem if bunch is long (as in later stages)
- Effect is due to amplitude dependent forward velocity in the 50 T

- Effect very clear if no initial ct spread



If no transverse amplitude

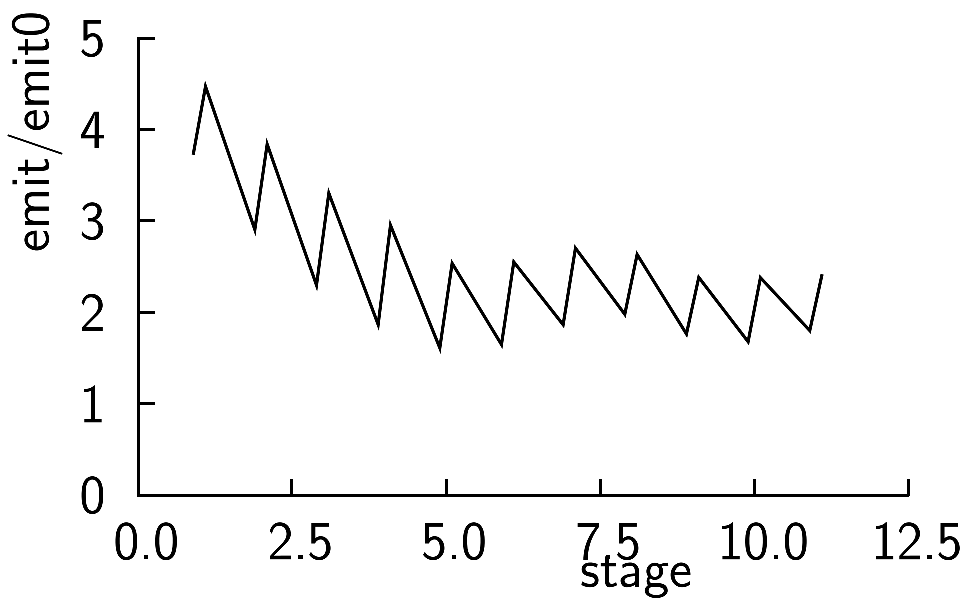
If no transverse amplitude then amplitude dependent forward velocity effect removed



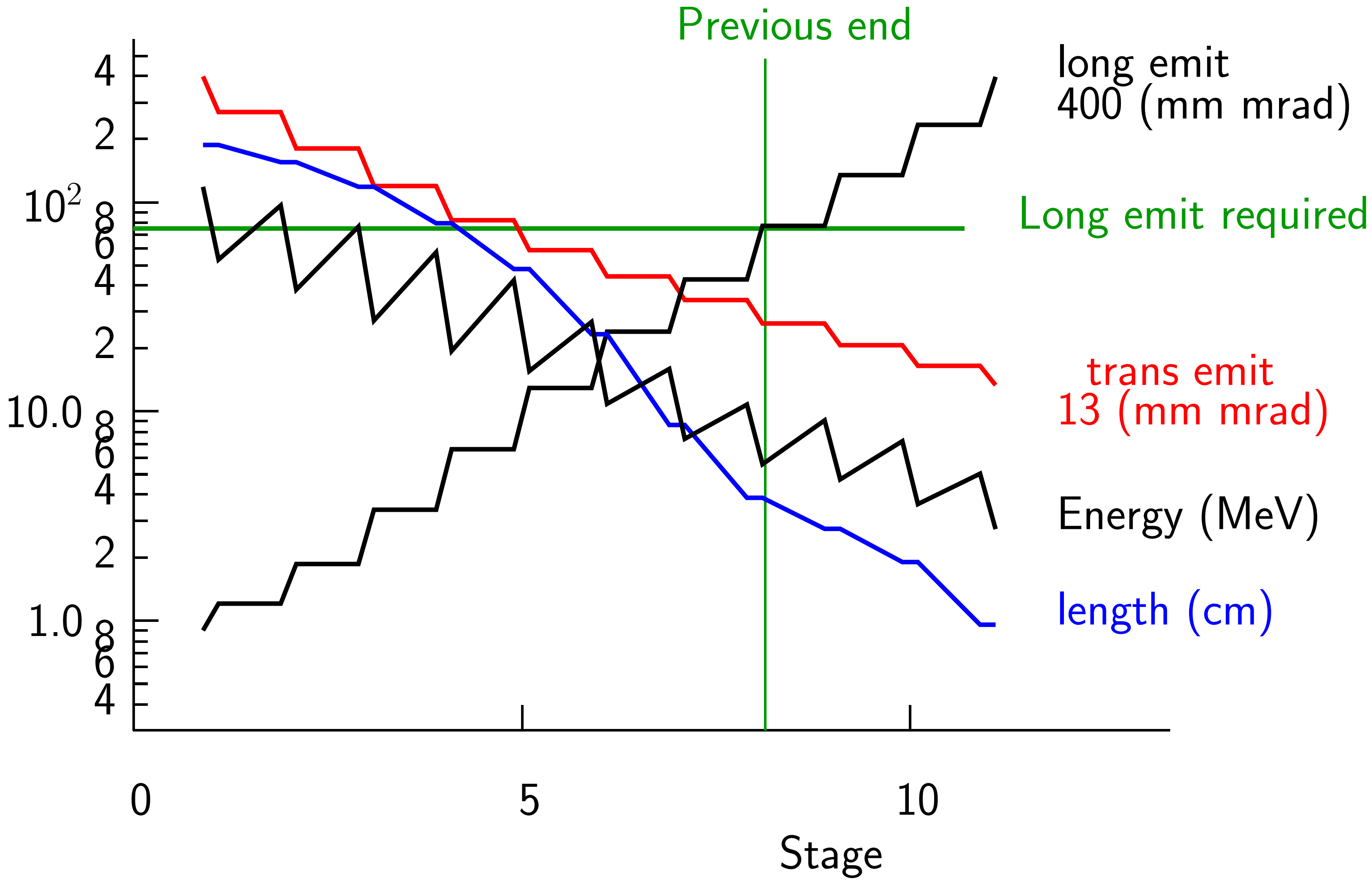
So problem is primarily from amplitude dependent motion in solenoid

How to fix this problem

1. Lengthen bunches
   - decrease initial dp/p
   - lower energy
2. Decrease amplitude effect
   - lower B field
     The current B is generous at start - see plot
   - Include initial amplitude-energy correlation - that will be present after previous 6D cooling
   - go several stages with alternating B - which will maintain this correlation



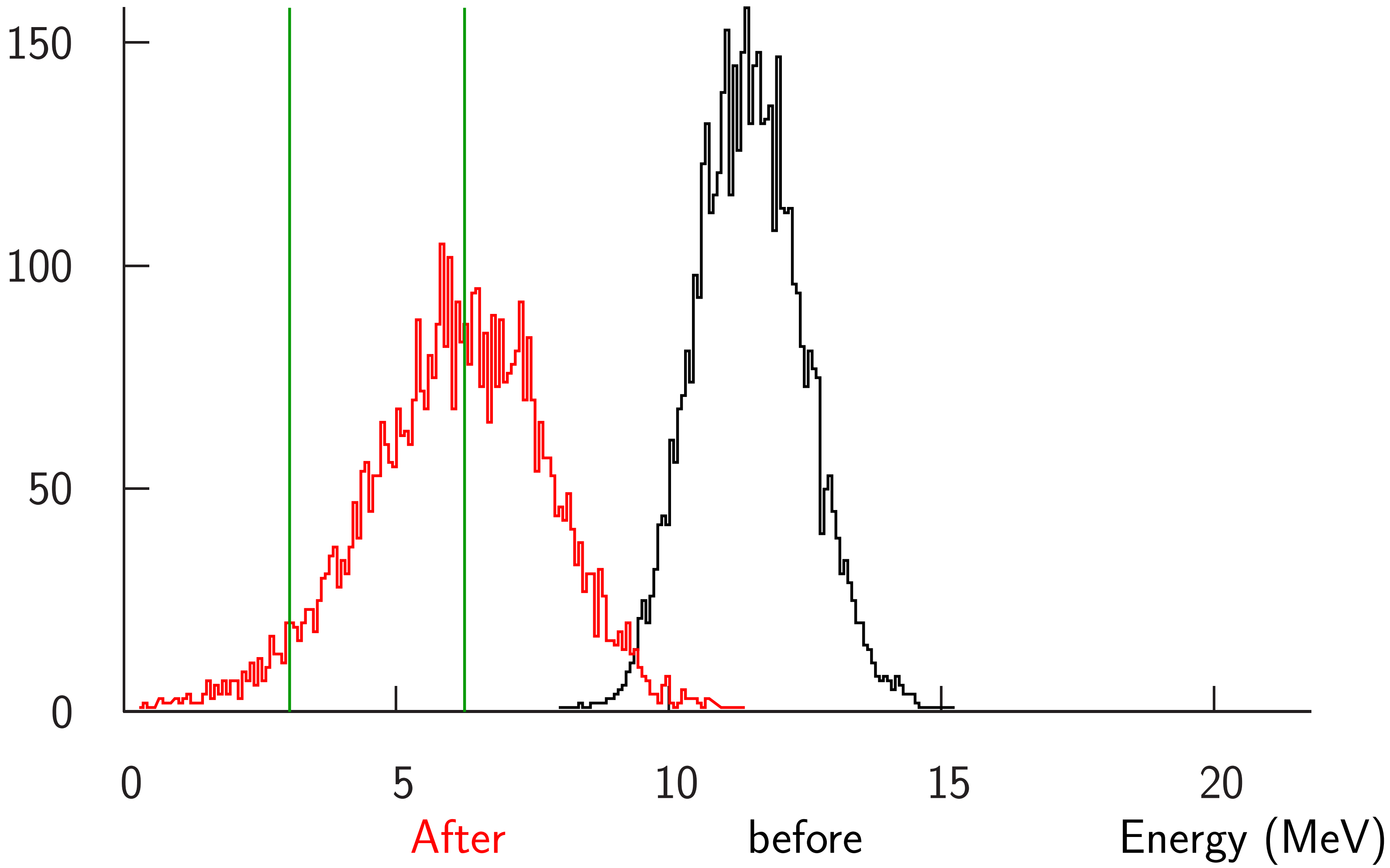
Is lower trans emittance achievable?



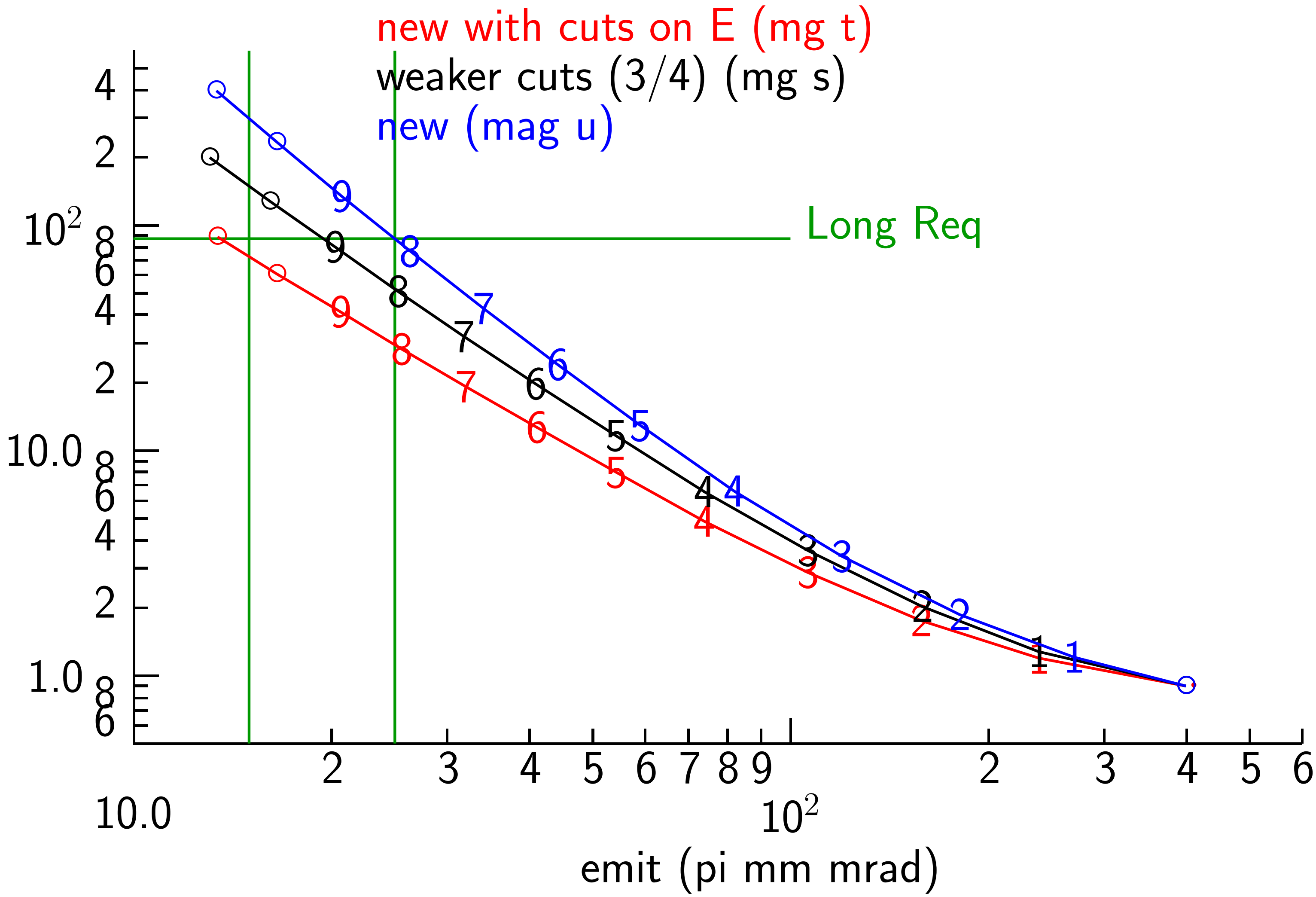
- Transverse emittance down to 13 mm mrad
- But long emittance (400 pi mm) rises far above requirement (72 pi mm)
- Can we restrain longitudinal growth?

e.g. Can we do better if we cut landau tails

- Landau tail on energy loss increases longitudinal emittance
- What if we cut them off?

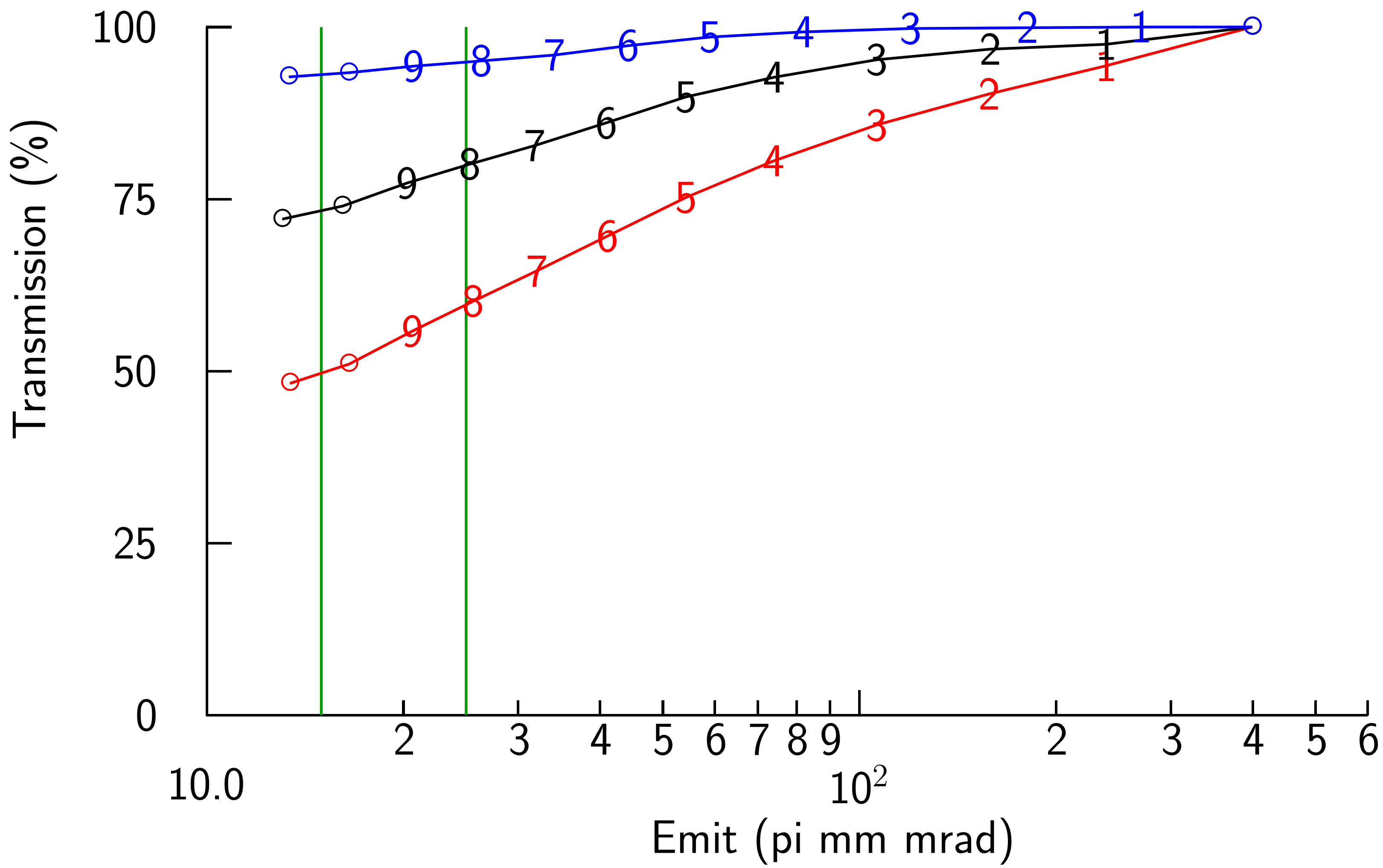


Yes: 15 pi mm mrad achieved



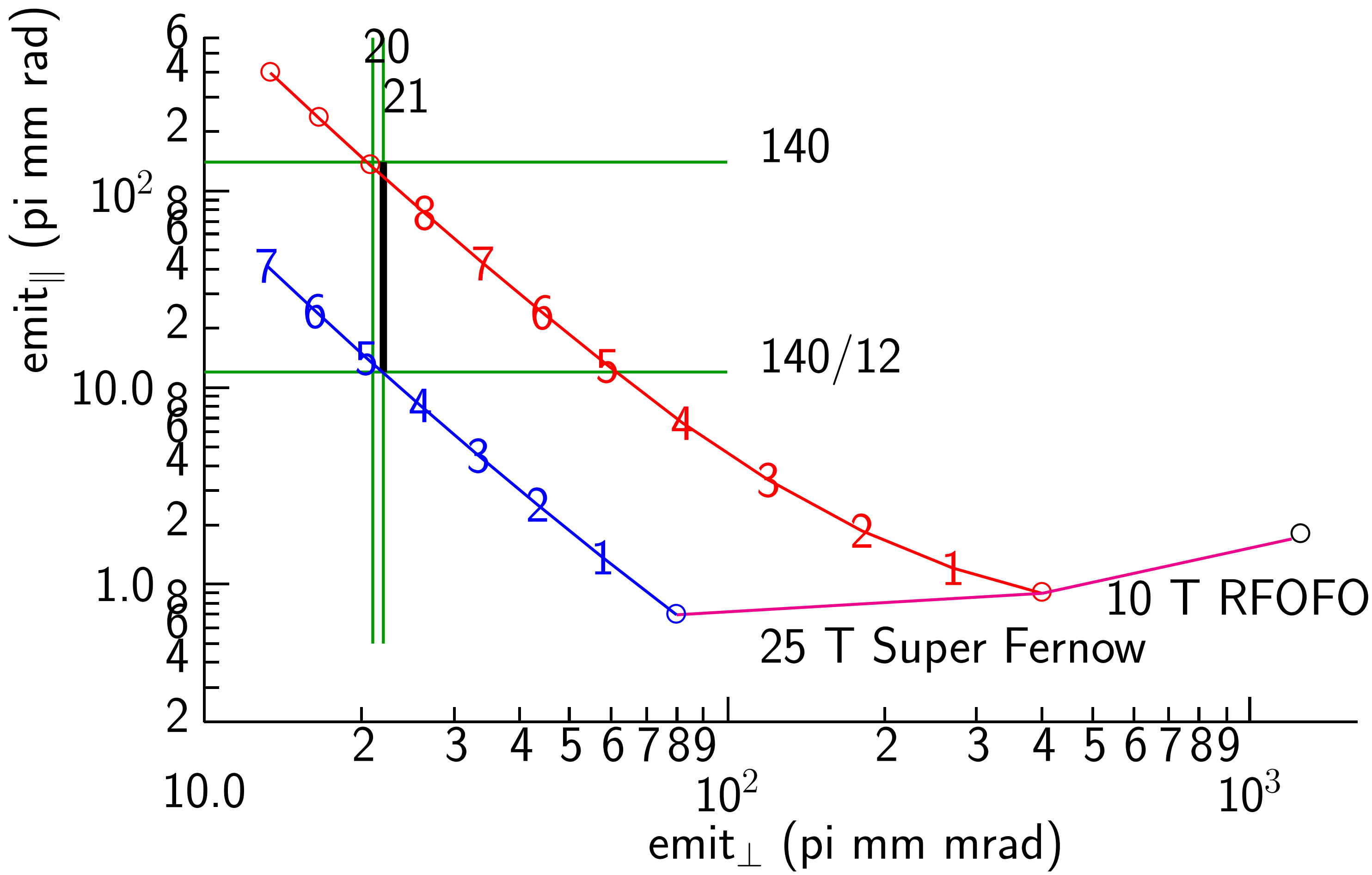
Looks good

But accumulated losses are serious



Merging after acceleration (Yuri's proposal)

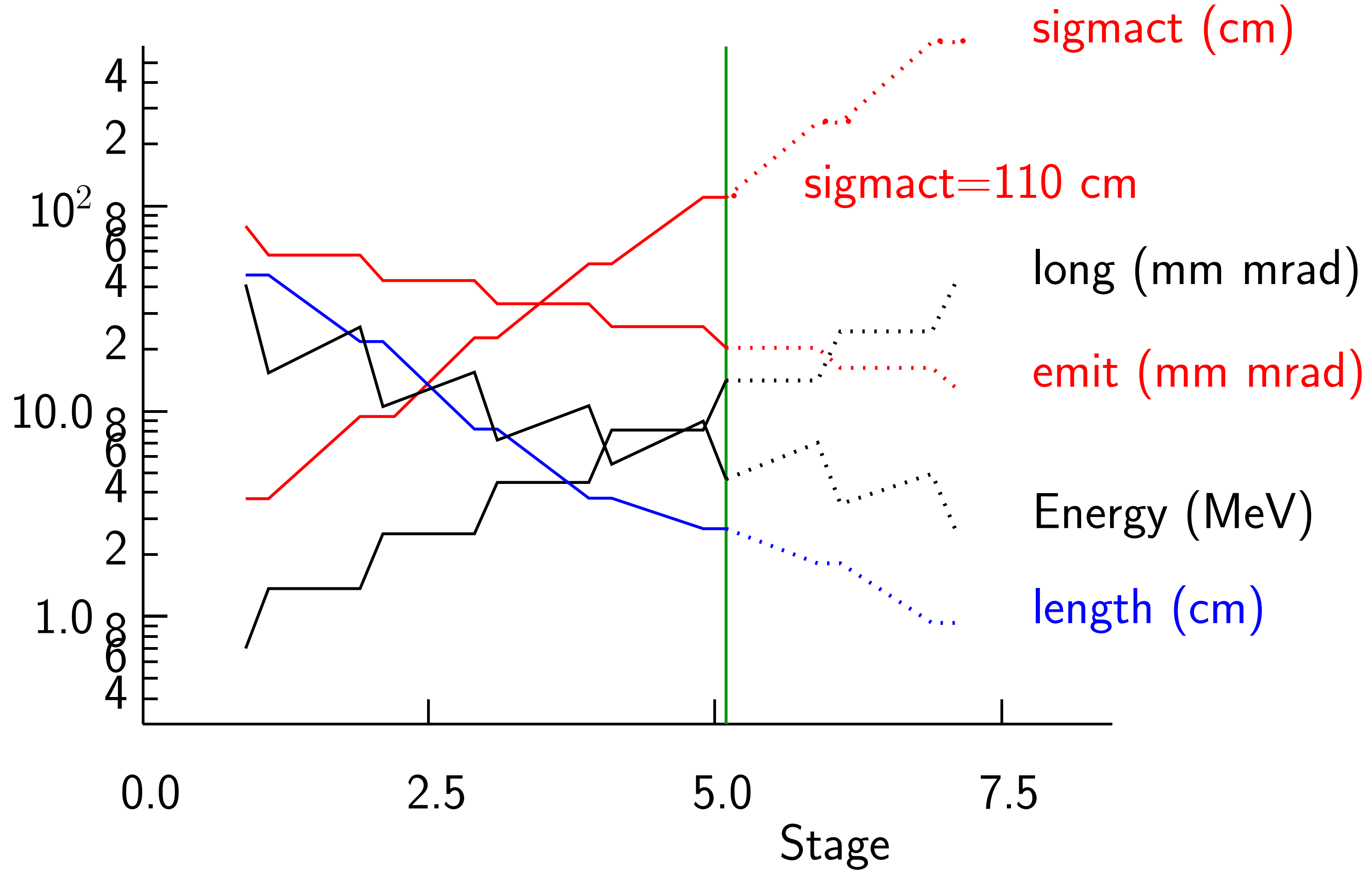
- assume longitudinal emittance 140 pi mm (vs 70 pi mm)
  0.2 % dp/p (vs 0.1%)



- Super Fernow plus merge after acceleration & Conventional merge and re-cool give same final emittance

And merge after acceleration does not work

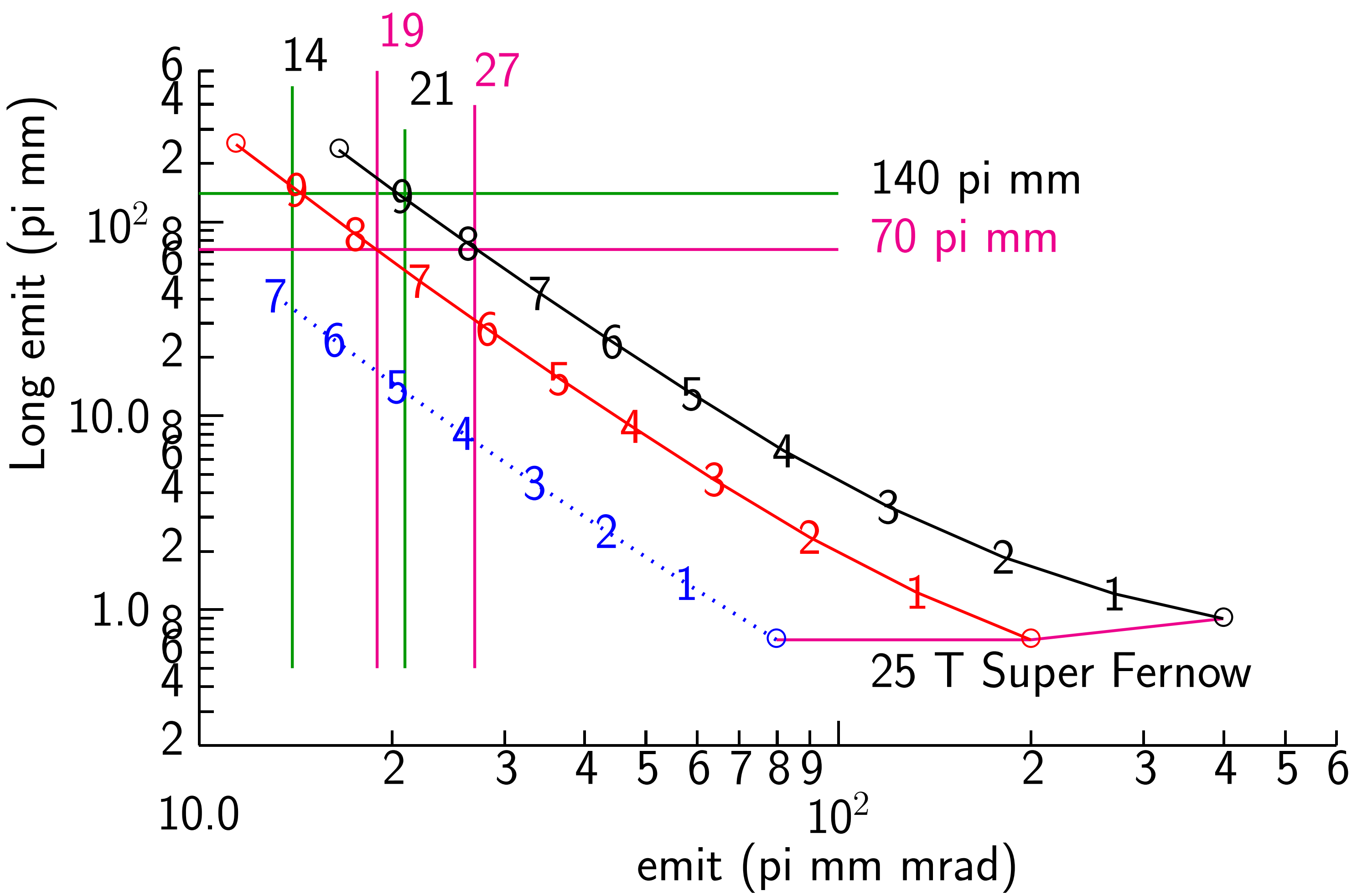
because of bunch length at end of 50 T



- A train of $c\ \sigma_t$ =1.1 bunches cannot have 1.5 m separations in ct

Get lower emittance with moderate Super Fernow

- Keep low energy merge
- Cool till space charge stops one: 200 pi mm mrad $(\Delta\nu/\nu \approx 0.2)$
- Then 50 T sequence till emit long = 140 pi mm



Space Charge Effects

From S Y Lee (p109),for a uniform charge density, where $\epsilon_\perp$ is the normalized transverse emittance:

$$\frac{\Delta\nu_{\rm flat}}{L} = \left(\frac{N_\mu}{\sqrt{2\pi}\ \sigma_z}\right)\ \frac{r_\mu}{2\pi\ \epsilon_\perp\ \beta_v\gamma^2}$$

For a Gaussian distribution:

$$\frac{\Delta\nu_{\rm Gaussian}}{L} = \left(\frac{N_\mu}{2\sqrt{2\pi}\ \sigma_z}\right)\ \frac{r_\mu}{2\pi\ \epsilon_\perp\ \beta_v\gamma^2}$$

This is true INDEPENDENT of $\beta_\perp$

For convenience I define

$$\beta_{\perp\ \rm ave} = \left(\frac{L_{\rm cell}}{2\pi\ \nu_{\rm cell}}\right)$$

Then:

$$\frac{\Delta\nu_{\rm Gaussian}}{\nu_{\rm cell}} = \left(\frac{N_\mu}{\epsilon_\perp}\right)\ \frac{\beta_{\perp\ \rm ave}\ r_\mu}{2\sqrt{2\pi}\sigma_z\ \ \beta_v\gamma^2}$$

where $r_\mu = 1.35\ 10^{-17}$ (mm),

Examples

case	N_μ^1 10^{12}	$<\beta_\perp>$ m	σ_z m	$\epsilon_\perp$ mm mrad	p MeV/c	$\Delta\nu/\nu$
Last 50 T cooling	2.8	0.6^2	6	25	30	0.1
Last RFOFO Guggenheim	4	0.19	0.025	400	200	0.11
First RFOFO Guggenheim after merge	6	0.6	0.02	2000	200	0.12
Super Fernow (after merging)	4	0.12	.01	70	200	0.46
Super Fernow (before merging)	0.5	0.12	.01	70	200	0.06
Moderate Super Fernow (after merging)	4	0.12	.01	200	200	0.2

Note 1: that N_μ is larger at earlier cooling stages to allow for losses
Note 2: This is guess for the betas in the undesigned match and re acceleration

- The accepted $\Delta\nu/\nu$ between the resonaces at $\nu = .5$ and $\nu = 1.0$

$$\frac{\Delta\nu(\text{accepted})}{\nu} \approx \frac{0.5}{0.75} \approx 0.67$$

  - so tune spreads of 0.11 & 0.12 will somewhat reduce momentum acceptance
  - For spread of 0.2 there will be significant effect, but worth trying for emit=14 pi mm mrad

- We have not looked at 'long space charge', 'impedances', or 'wake fields'

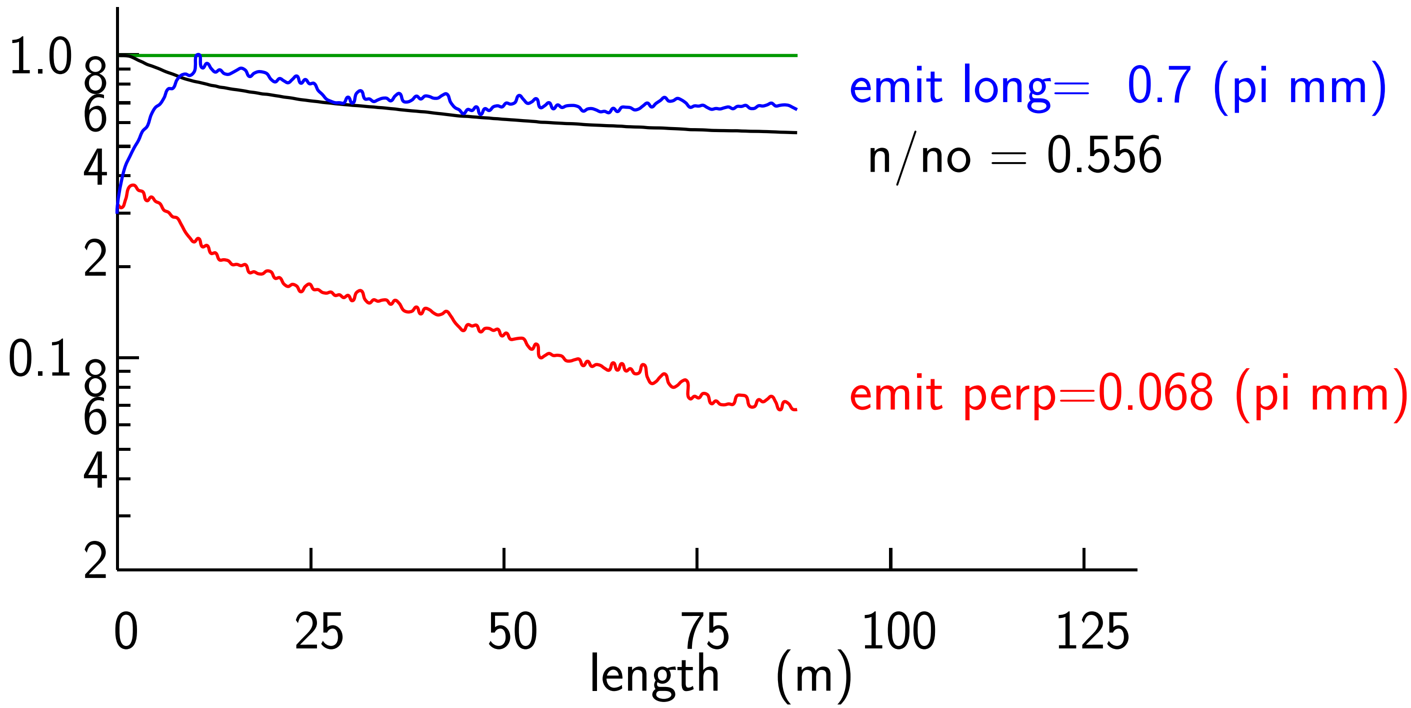
Conclusions

- A set of parameters of 8 stages are simulated without matchings
  - 27 (21) pi mm mrad obtained for long=70 (140) pi mm
  - Decay losses in drift lengths for phase rotation between stages calculated & fix discussed
  - Problem found in early stages due to amplitude dependent forward motion & fixes discussed
  - Cutting Landau tails seemed to allow cooling to 15 pi mm mrad But doing so lowers transmission to 50%
  - SBIR proposal to study more

- Merging after acceleration still does not work
- 14 (9) pi mm mrad may be possible with limited Super Fernow for long=70 (140) pi mm
- Transverse space charge tune shifts seem ok
- No study yet of longitudinal loading/wake/space charge

Super Fernow Lattice

- 33 m circumference
- 14 cm long 805 MHz rf at 42 MV/m and 41 degrees



- Note terrible longitudinal matching in this simulation
- Transverse Cooling to 68 (mm-mrad) cf final required = 25 (mm mrad)
- But ring requires sixty 25 T HTS solenoids or Guggenheim 150 Solenoids !