COOLING FOR MUON COLLIDERS

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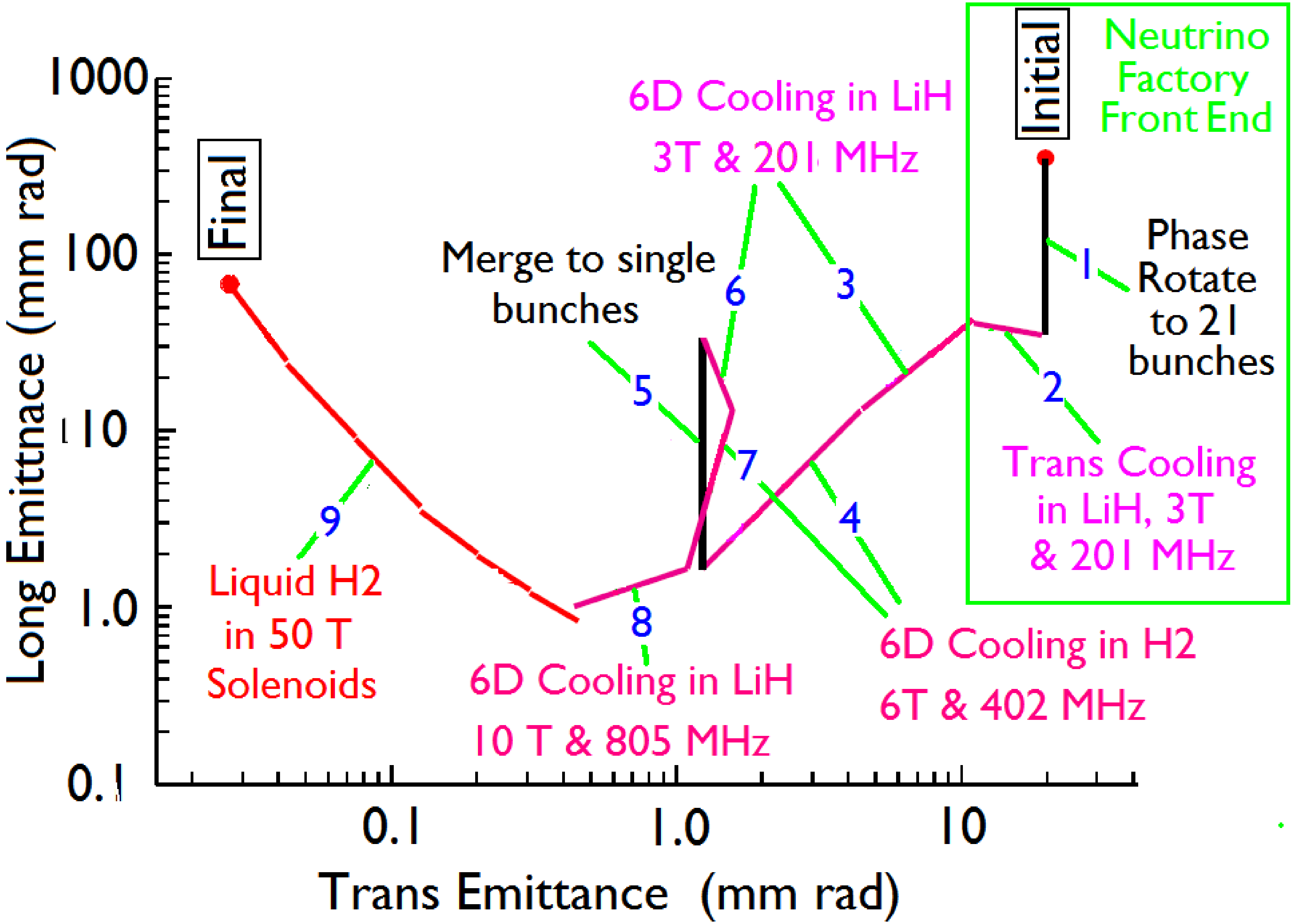
Capture and Cooling Baseline Scheme



Changes to "Baseline" Solution

New optimization of 50T cooling

- Allow dp/p to rise to 0.12%
  - Still ok in 1.5 TeV Ring
- Now cool to 15 pi mm mrad
  - Now 3.3 sigma transverse dynamic aperture was only 2 sigma
  - Protons/bunch at 24 GeV now 4 10^{13} vs 7 10^{13}
  - Repetition Rate now 21 Hz vs 12

Assumptions

$$\mathcal{L} \propto \; < B_{\rm ring} > \; P_\mu \; \frac{\Delta\nu_{\rm beam-beam}}{\beta^*}$$

Assume:

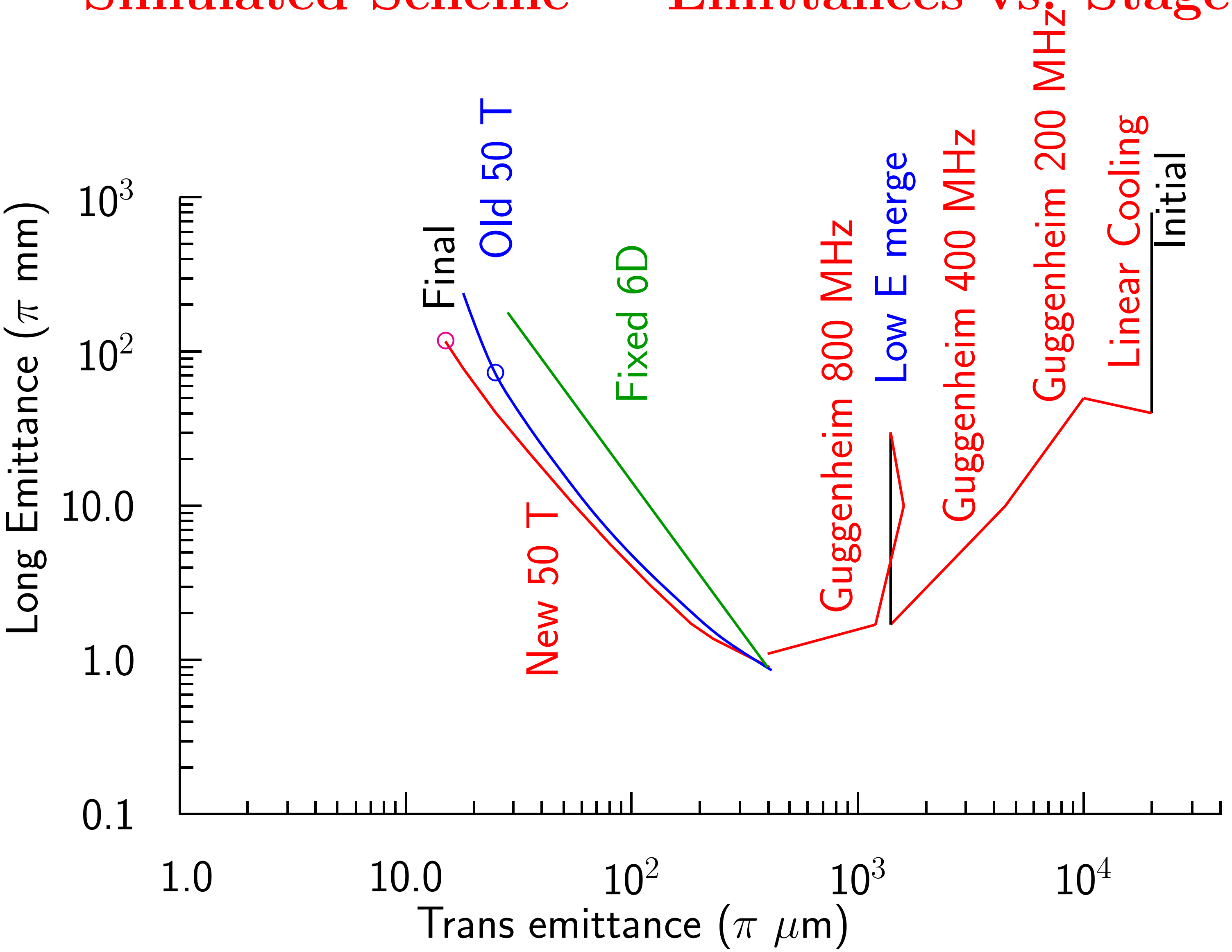
- Front end from ISS Neutrino Factory
- Collider ring from 1.5 TeV MCTF design
- Beam-beam tune shift $= 0.1$
- Total muon survival in cooling & acceleration $=$ 7%
  estimated from simulations
- $< B >$=5.2 T
- p power $=$ 4 MW

Consider 3 options:

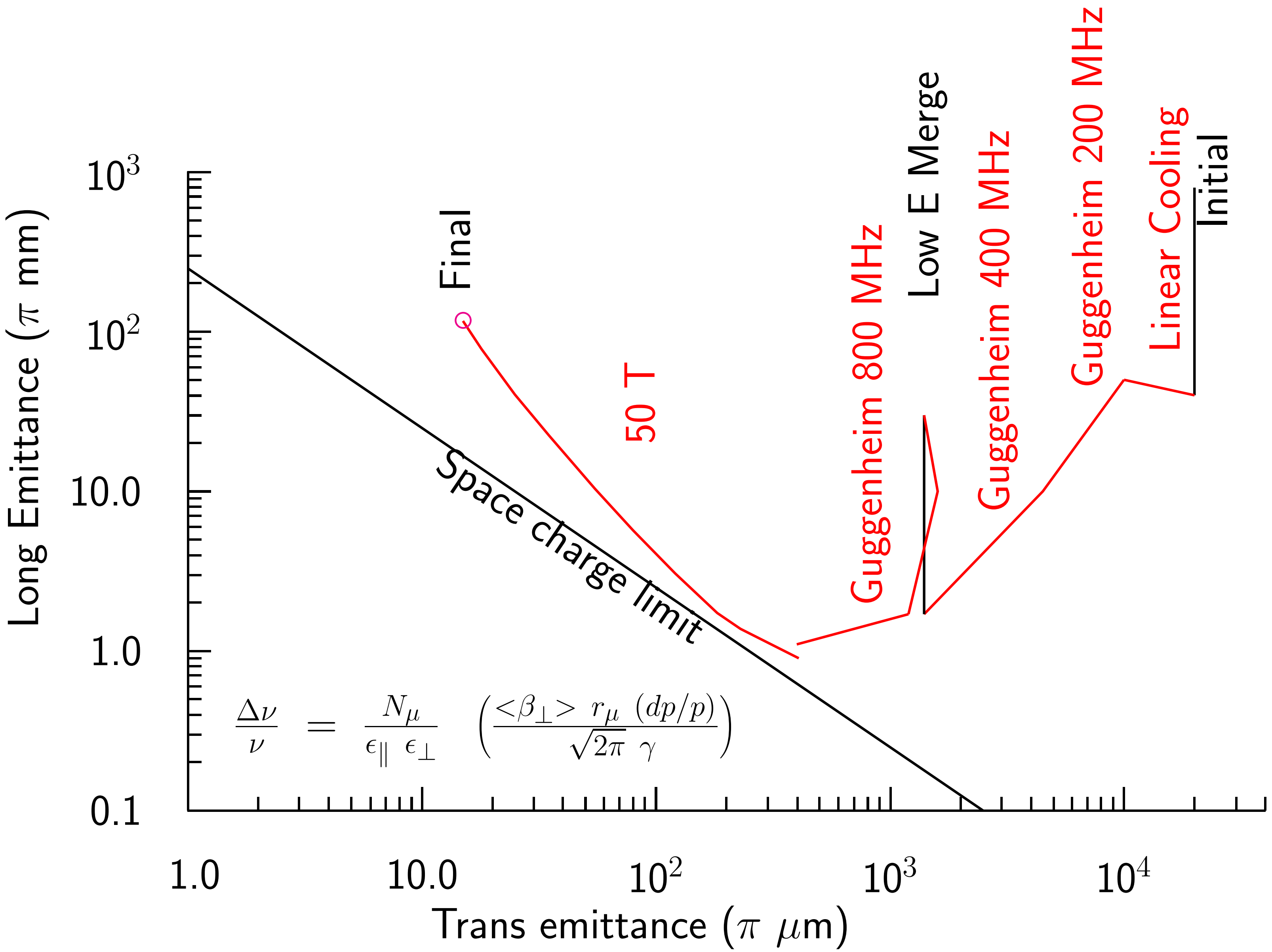
1. Merge bunches at low energy and re-cool afterwards
2. Cool further in longitudinal and merge after some acceleration
3. Cool further in transverse direction and do not merge

Total 6D cooling same in all cases

'Simulated Scheme' Emittances vs. Stage

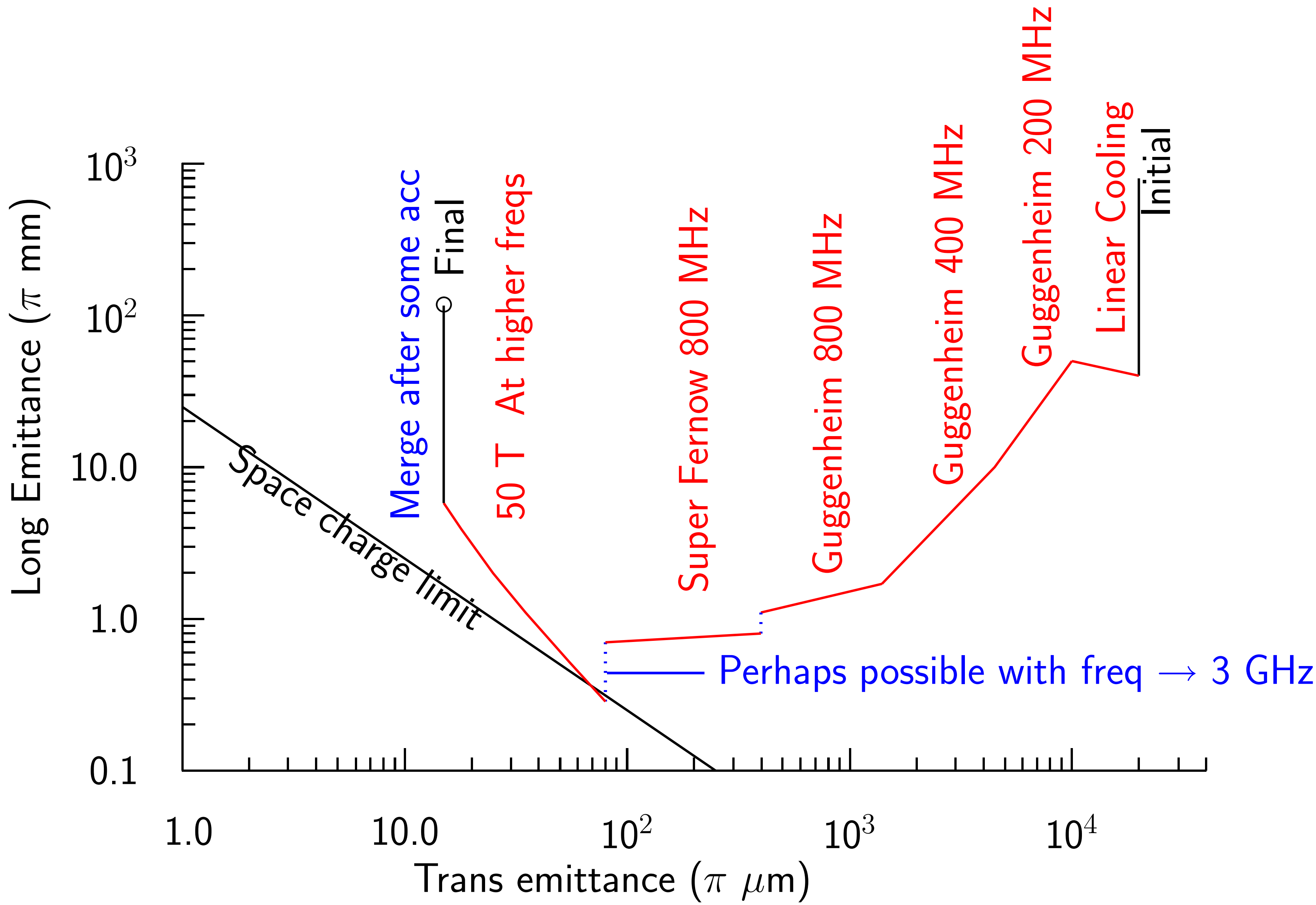


'Simulated Scheme' Emittances vs. Stage



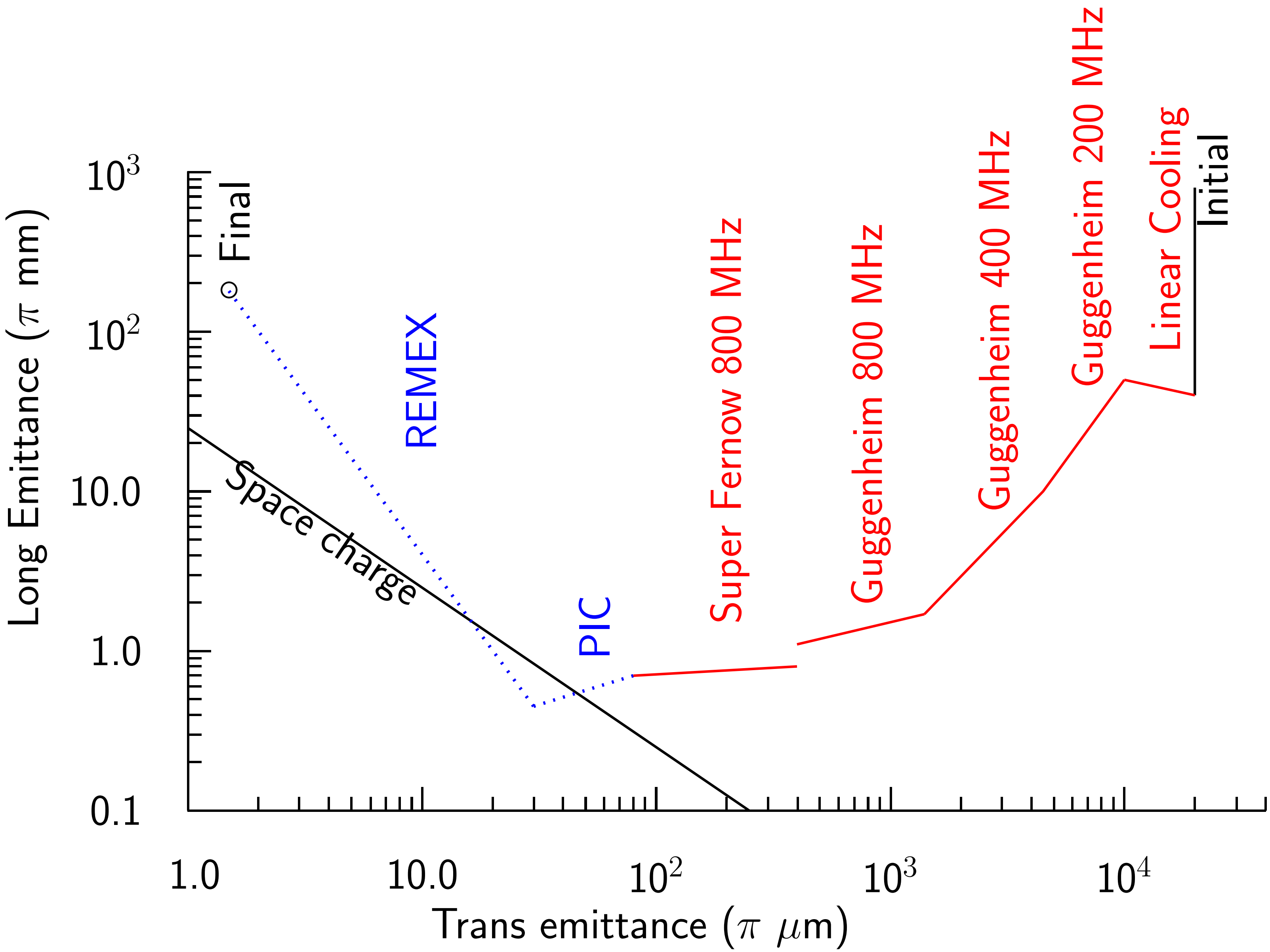
- Transverse space charge $\propto N_\mu/(\epsilon_\perp \ \epsilon_\parallel)$ ok
- Longitudinal space charge and loading not checked yet Problem ??

Alternative with merging after acceleration



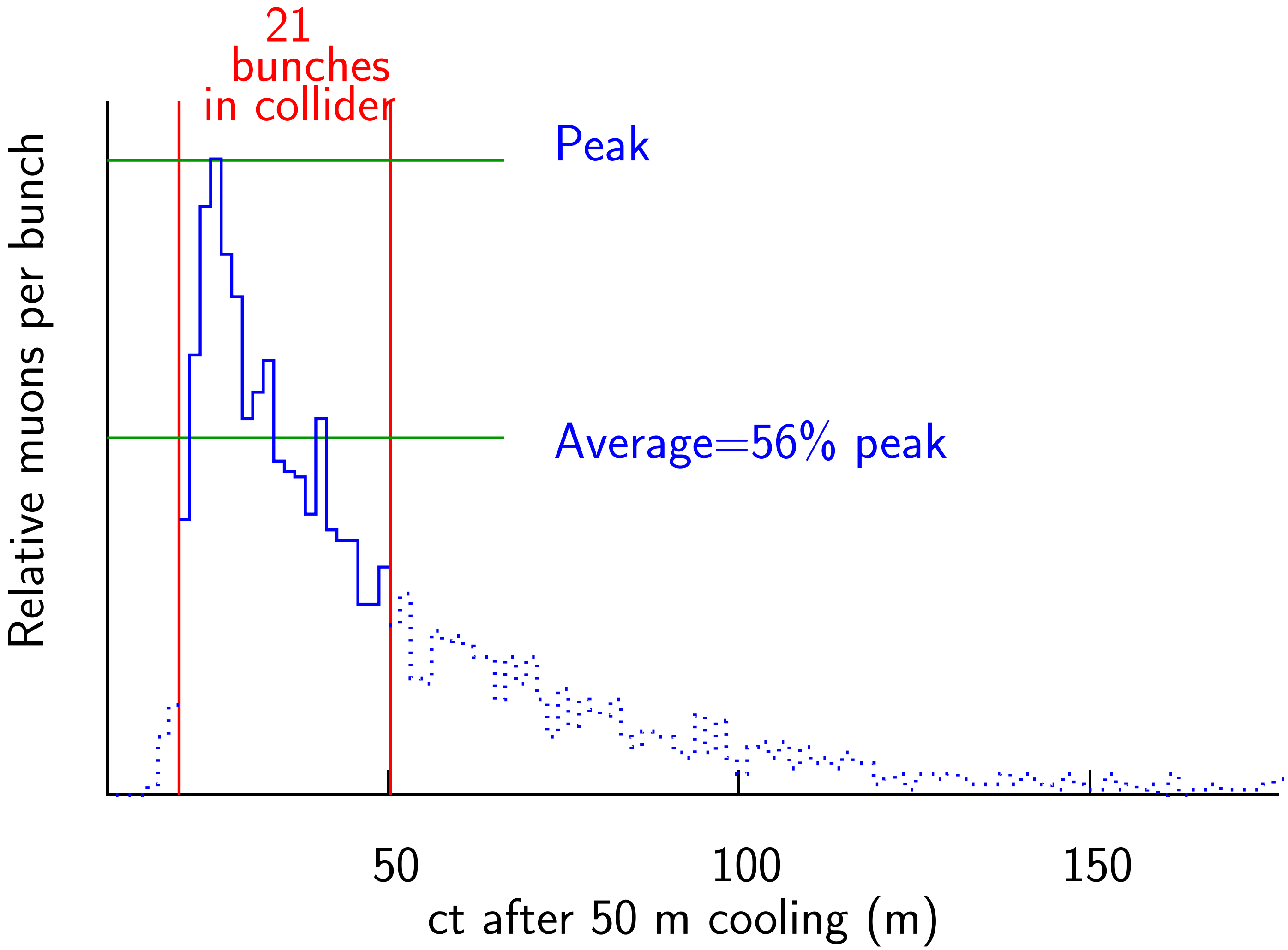
- Transverse space charge limit less, because N_μ less, but still tight
- Longitudinal space charge and loading probably better

Low Emittance Alternative without merging



- But lattices with required acceptance do not exist (yet?)
- Space charge simulation, with ideal PIC lattice, failed with these parameters

Charge per bunch after phase rotation



- Beam beam tune shift limited be largest $N_{\rm bunch}$
- but $\mathcal{E} \;\propto\; \Delta\nu_{\rm average}$

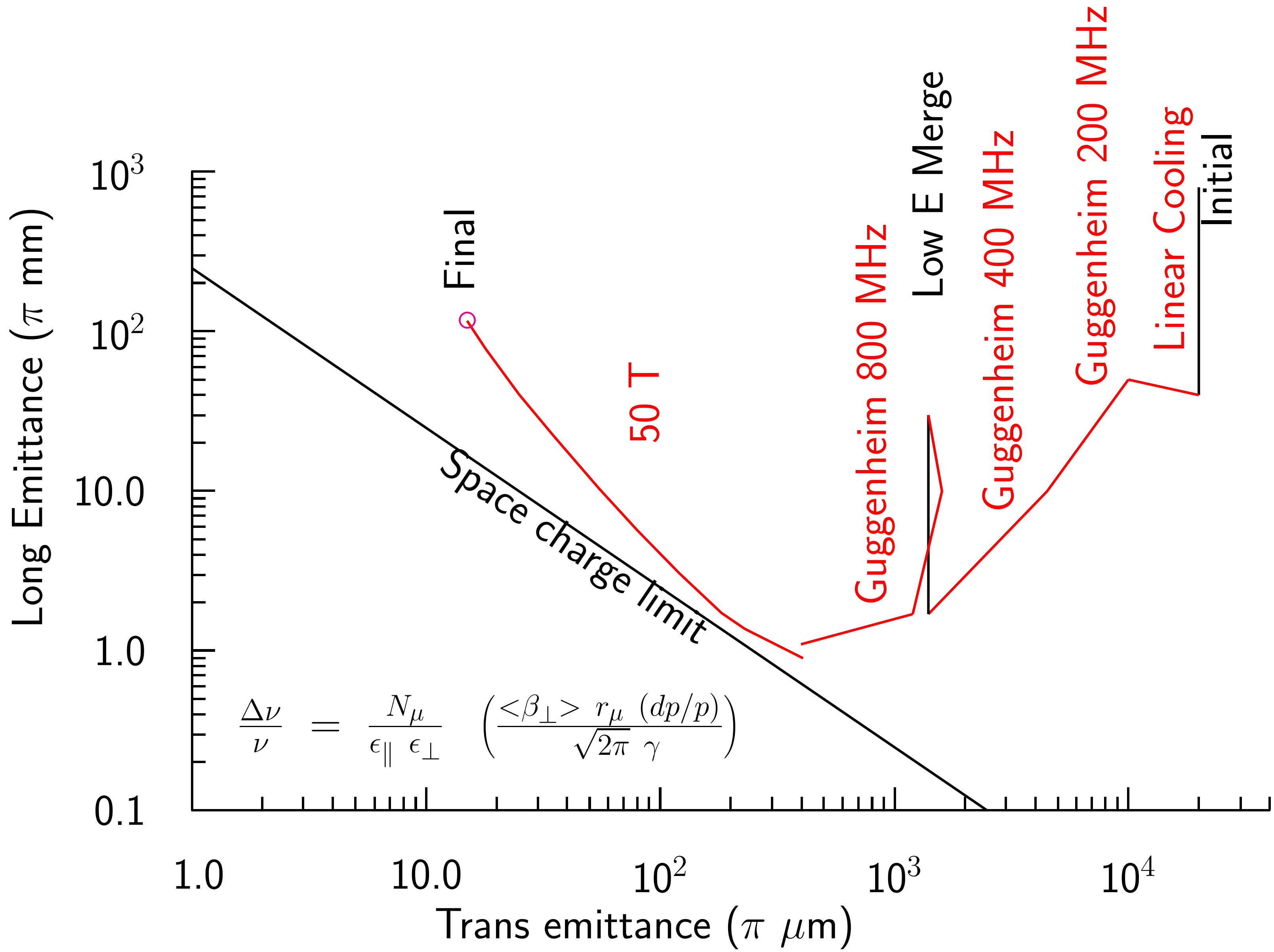
1.5 TeV (c of m) Collider Parameters

	2006	2007	Low emit	
Luminosity	1	1	0.56 [3]	10^{34} cm^{2}sec^{-1}
Beam-beam Tune Shift	0.1	0.1	0.1 (0.056)[2]	
Bunches	1+1	1 + 1	21 + 21	
Muons/bunch	20	12	1.2	10^{11}
Beta at IP $= \sigma_z$	10	10	10	mm
rms momentum spread	.09	0.16	0.16	%
Muon Beam Power	7.5	7.5	7.5	MW
Required depth for ν rad [1]	13	13	13	m
Repetition Rate	12	21	21	Hz
Trans Emittance	25	15	1.5	pi mm mrad
Long Emittance	72,000	116,000	116,000	pi mm mrad

- For comparison, low emittance case has all parameters the same except number of bunches, their intensity, and emittance

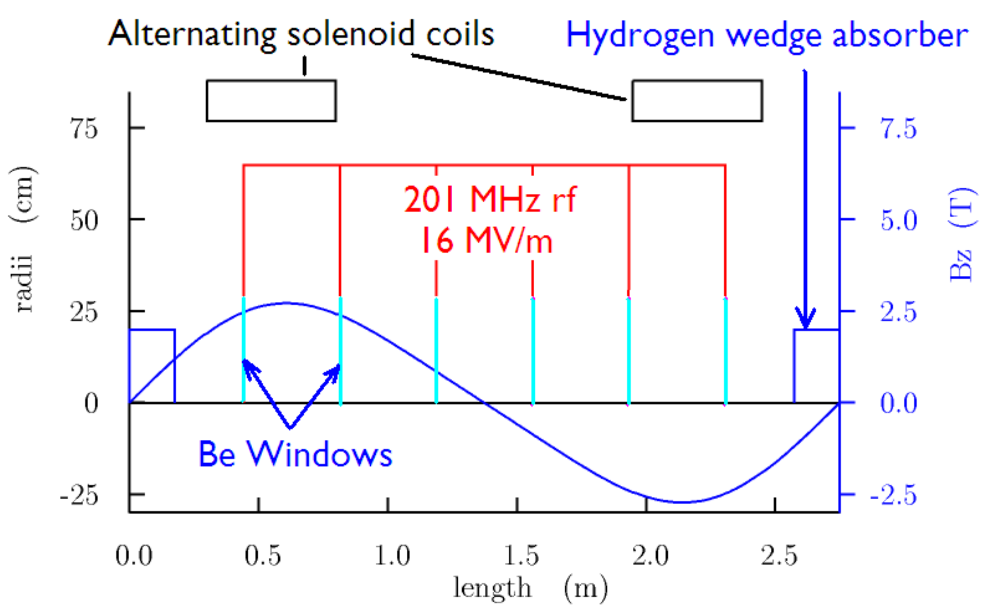
(1) With respect to any low lying nearby land. e.g. Fox river at FNAL
(2) This is the peak number. The average is in ()
(3) For same beam power, luminosity is lower from a lower average tune shift

Back to Baseline with Low Energy merging & re-cooling

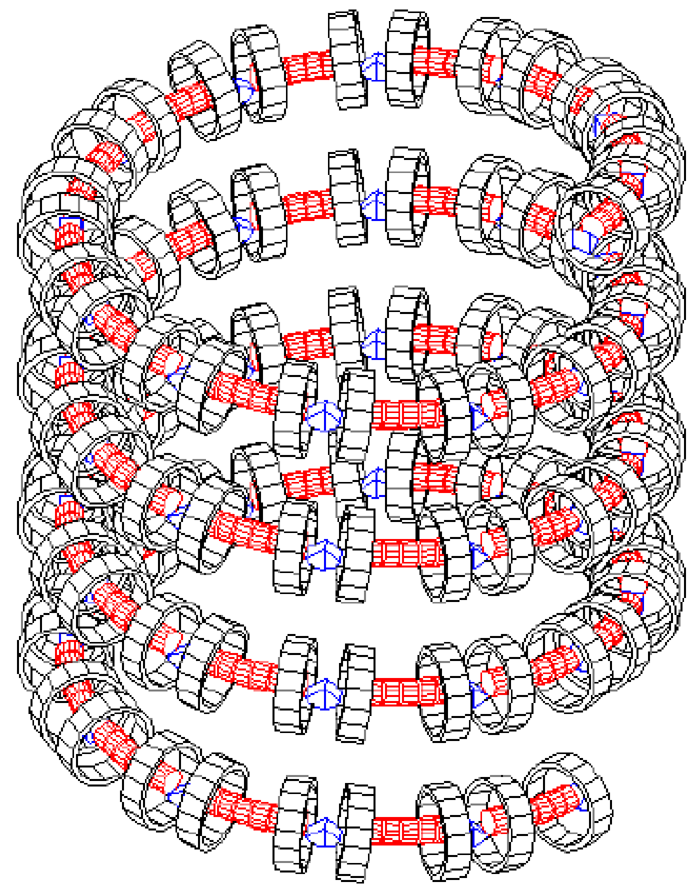


200 and 400 MHz 6D Cooling in Guggenheims

- RFOFO lattices
- Bending gives dispersion
- Wedge absorbers give emittance 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)

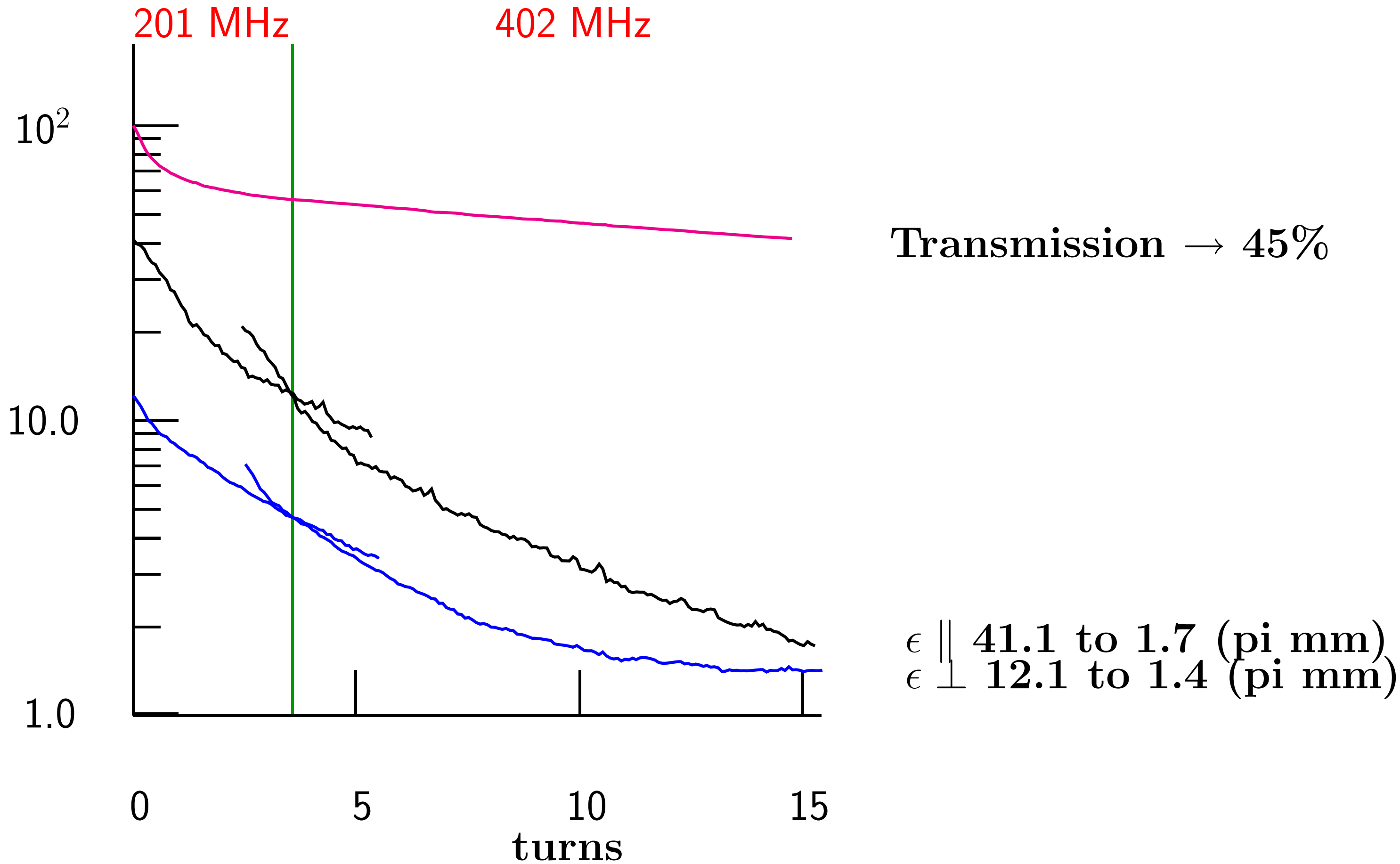


RFOFO Lattice



'Guggenheim'

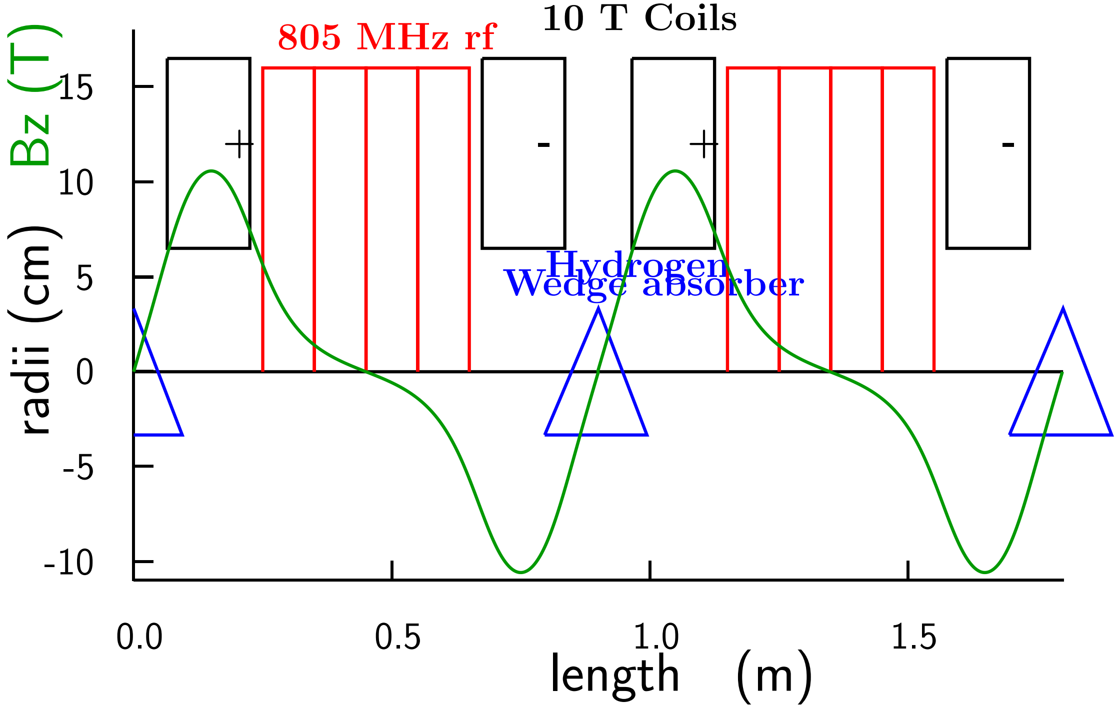
ICOOL Simulations of real fields Balbakov was first

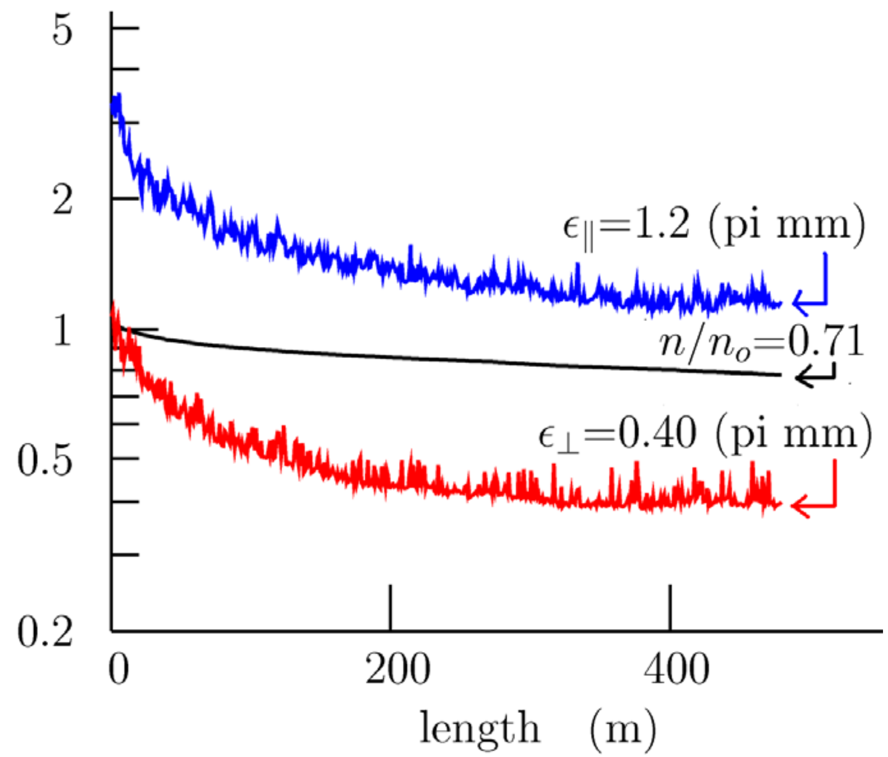


- 201 MHz RFOFO as published, but Guggenheimed (B=3 T)
- 402 MHz RFOFO has all dimensions halved (B=6 T)

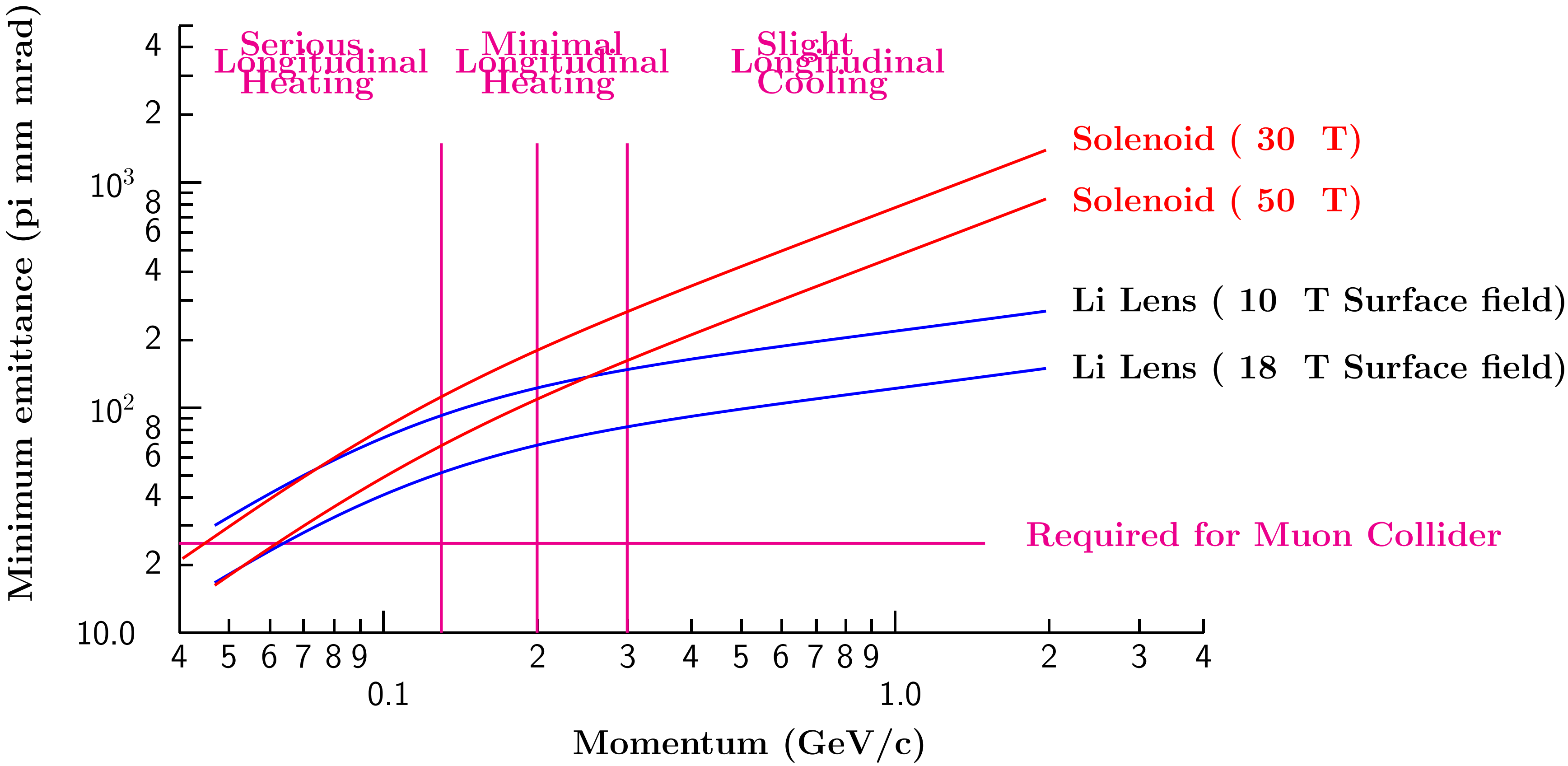
800 MHz 6D cooling in Guggenheim

- Uses 10 T high current density (150 A/mm^2) solenoids





Focusing as a function of the beam momentum

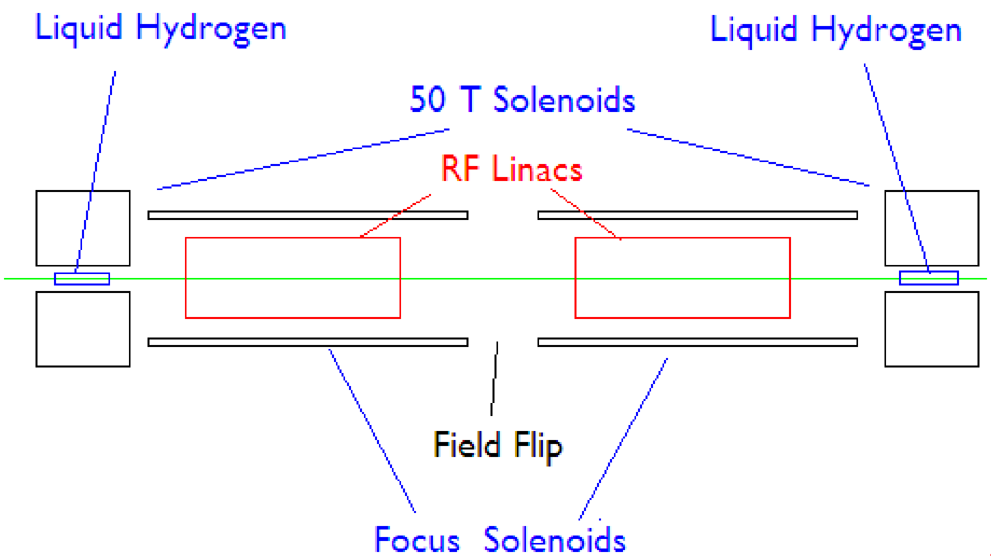


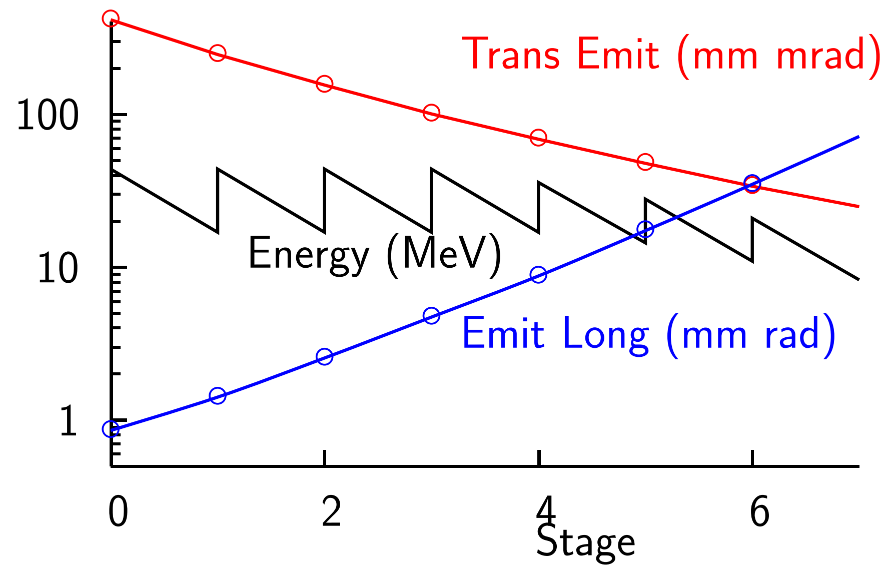
But if we allow longitudinal heating and use very low momenta (45-62 MeV/c or 9-17 MeV):

- Even a 30 T solenoid beats the Li Lens
- A 50 T solenoid is comparable with a 16 T surface field Li Lens that may or may not be build able

Transverse Cooling in 50T Solenoids

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

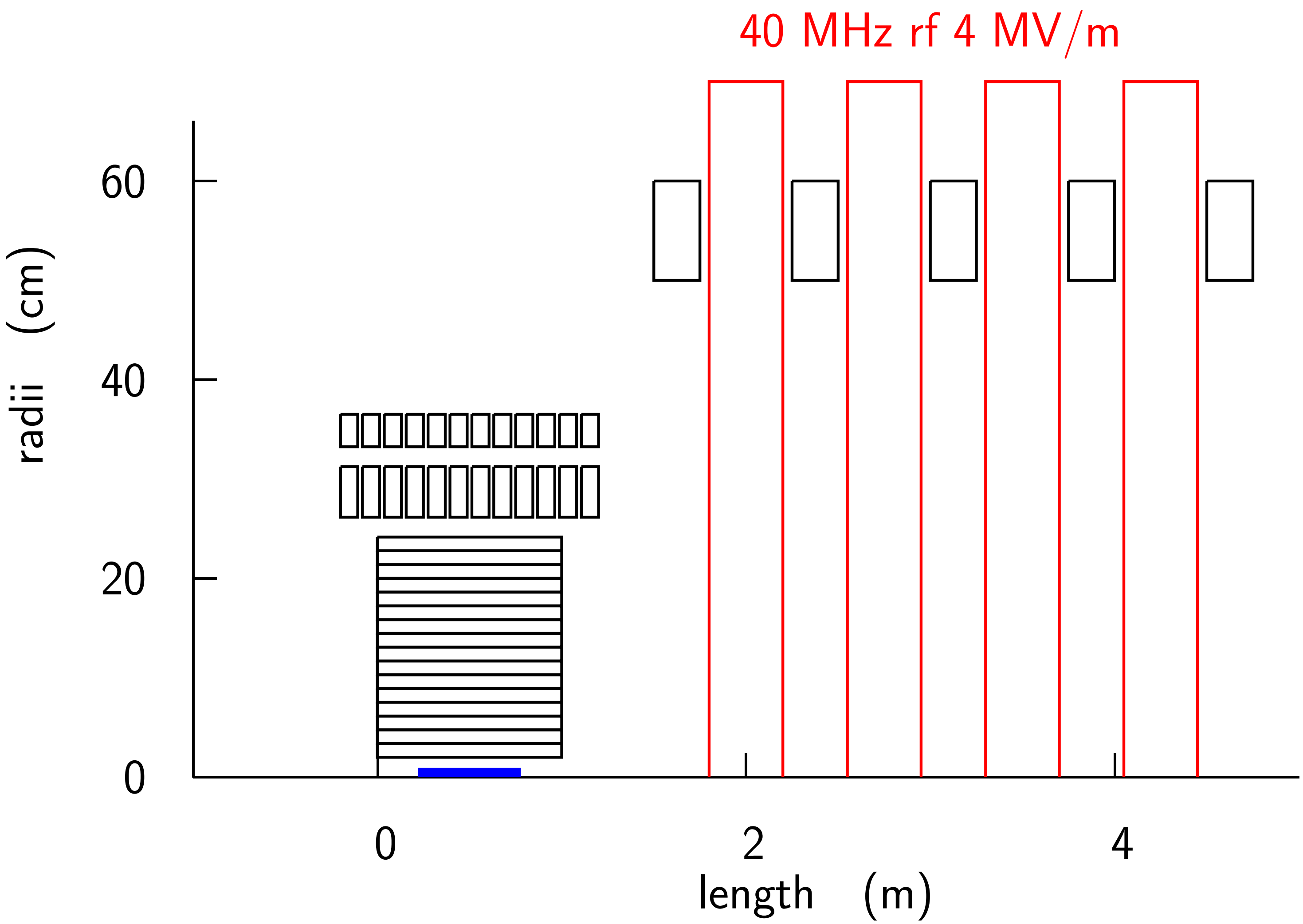




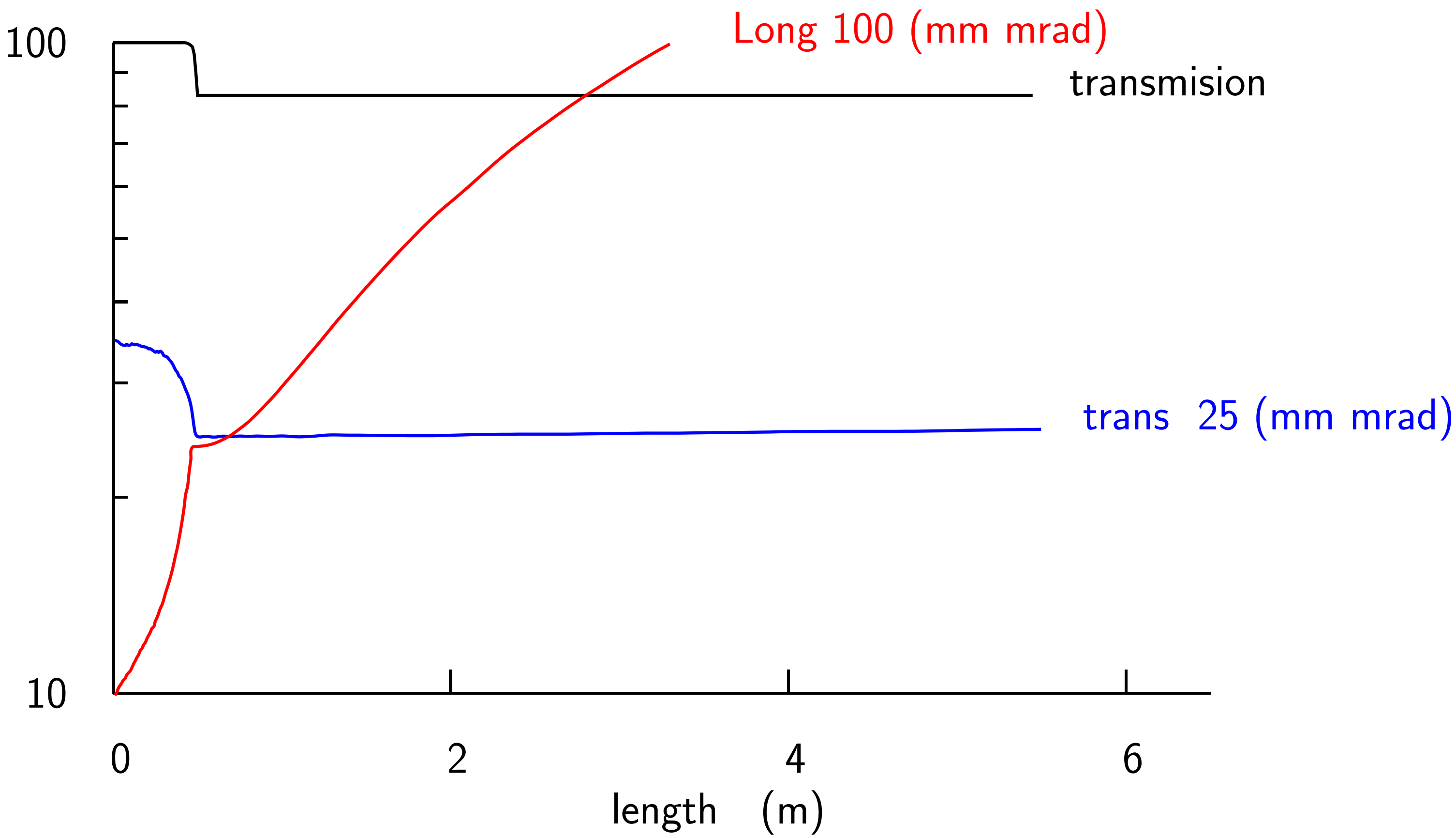
- 50 T HTS Solenoids
  - Current and ss support varied with radius to keep strain constant
  - Design using existing HTS tape at 4.2 deg. gave 50 T with rad=57 cm
  - 45 T hybrid with Cu exists at NHFML, but uses 20 MW
  - 30 T all HTS under construction
- 7 solenoids with liquid hydrogen
- ICOOL Simulation (Ideal Matching and reacceleration, Transmission 97%)

Match out of final 50 T Solenoid

If this works, matching between earlier solenoids probably ok



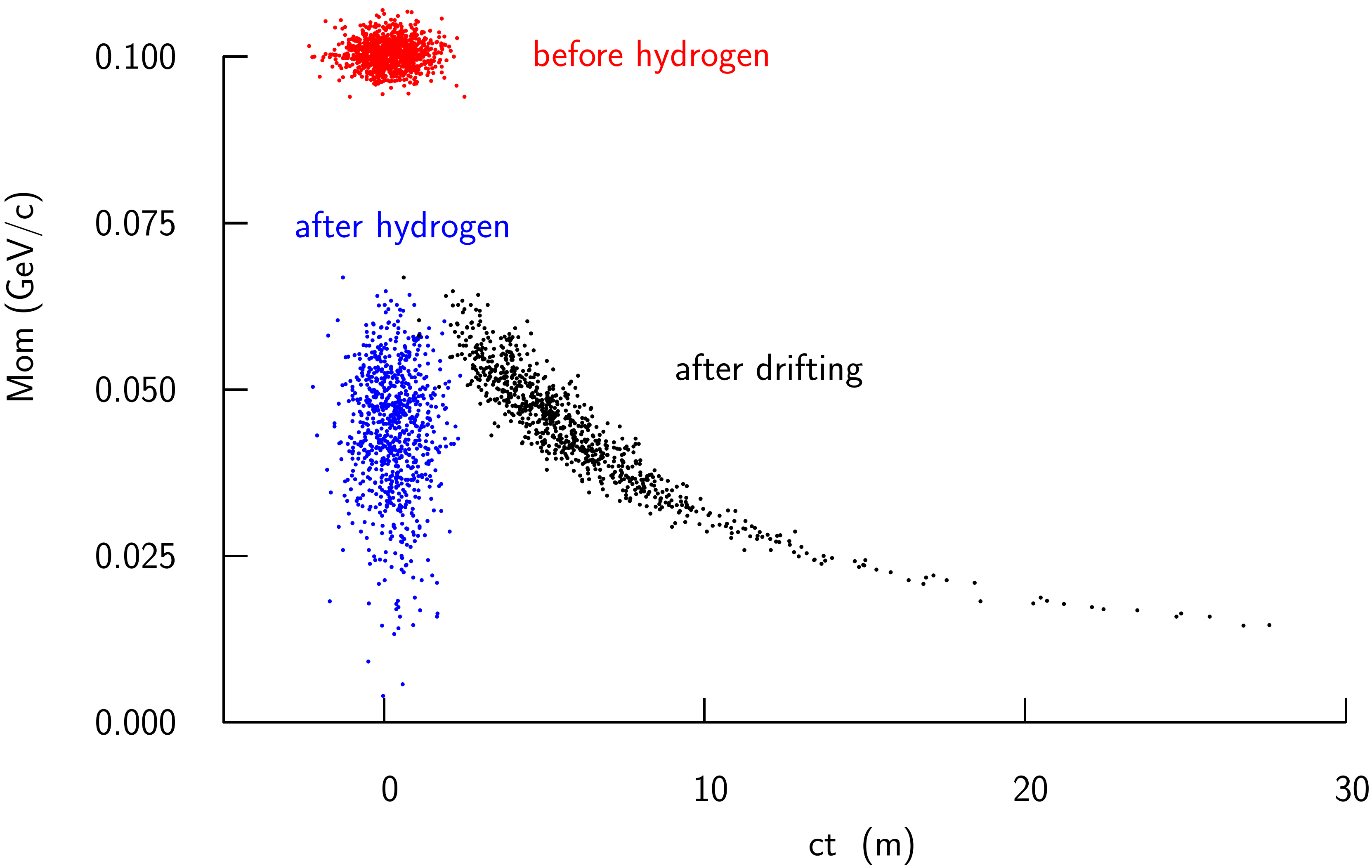
ICOOL Simulation



Trans emittance flat in match

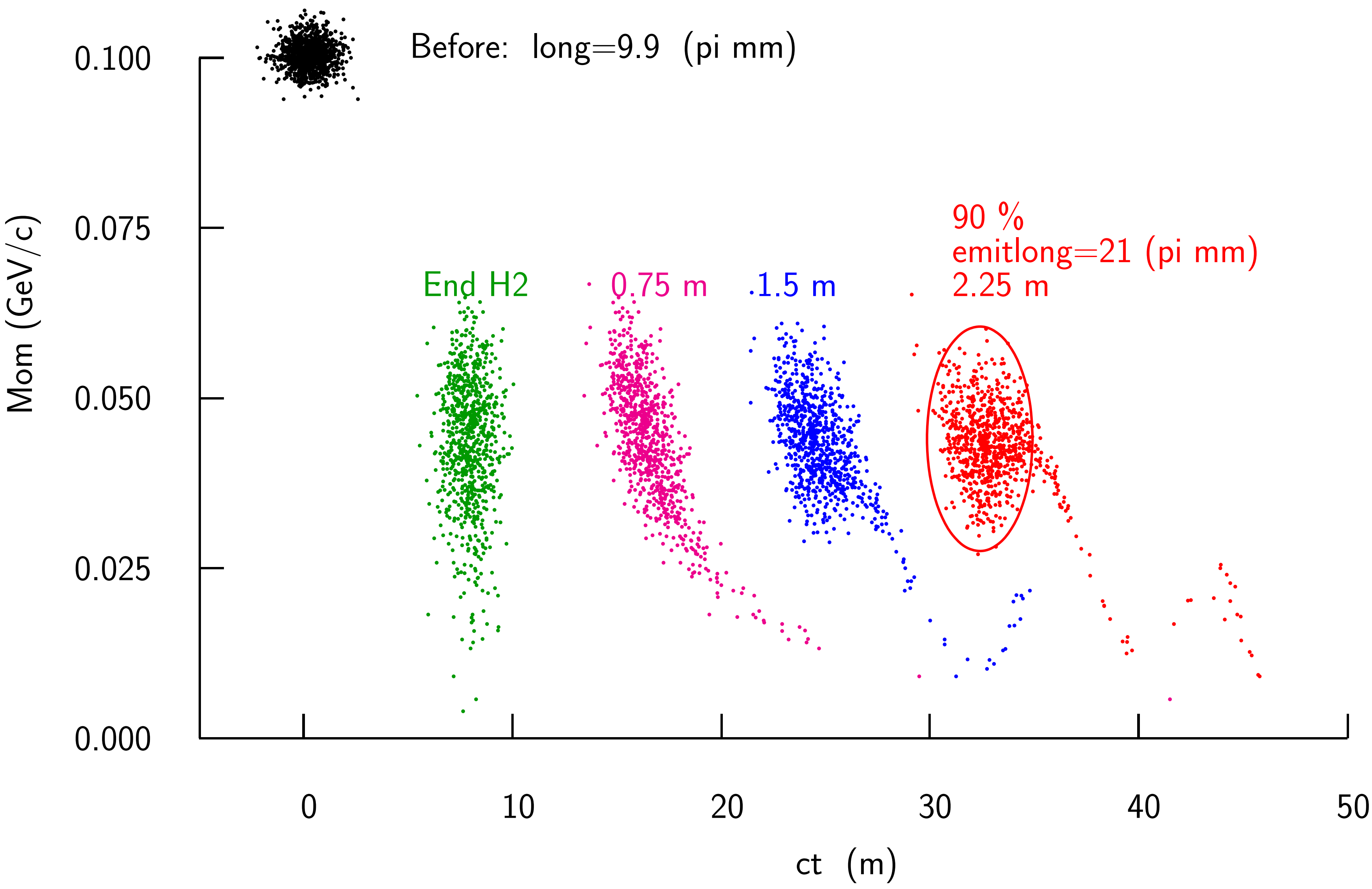
Why is long emittance rising ?

Long phase plots before & after

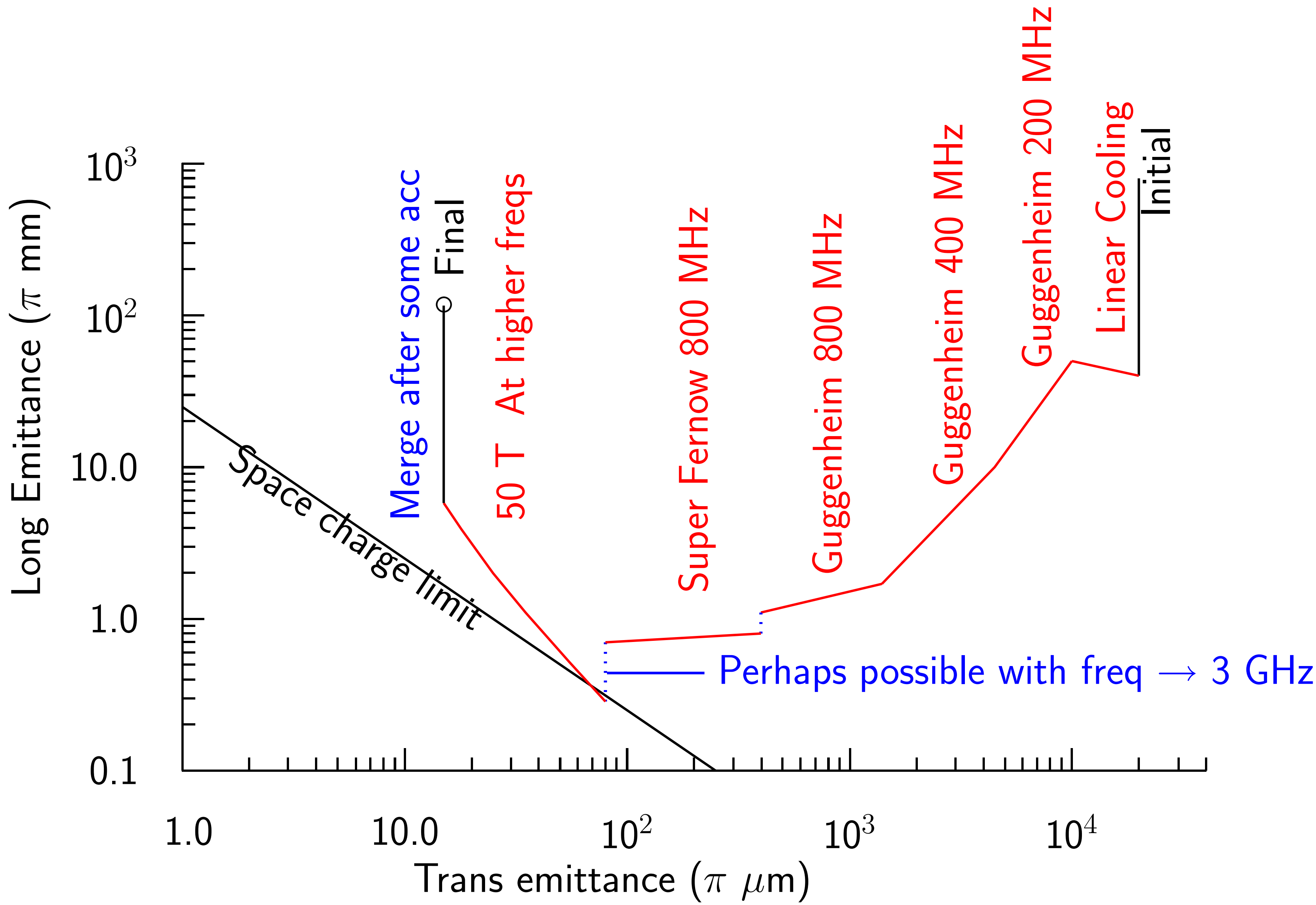


Because drift is non-linear

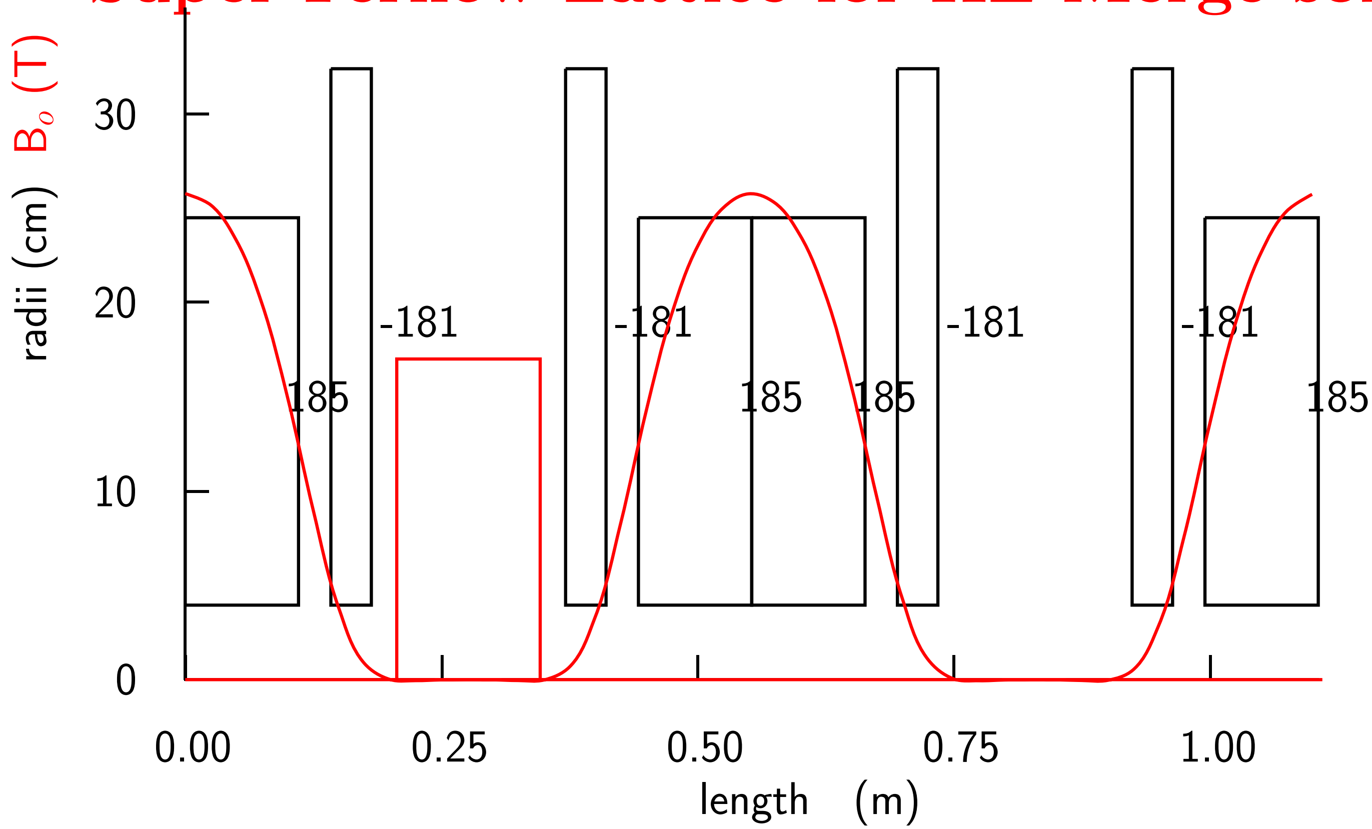
Use 40 MHz rf to capture bunch

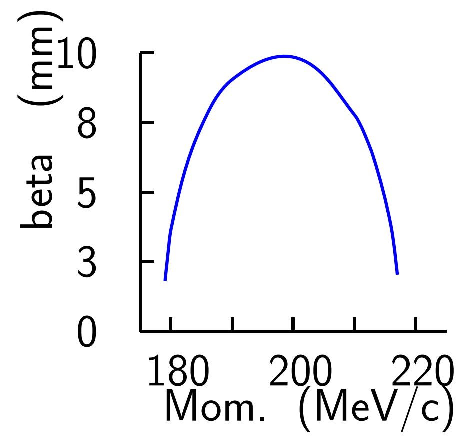


Back to Solution with High Energy merging



Super Fernow Lattice for HE Merge solution

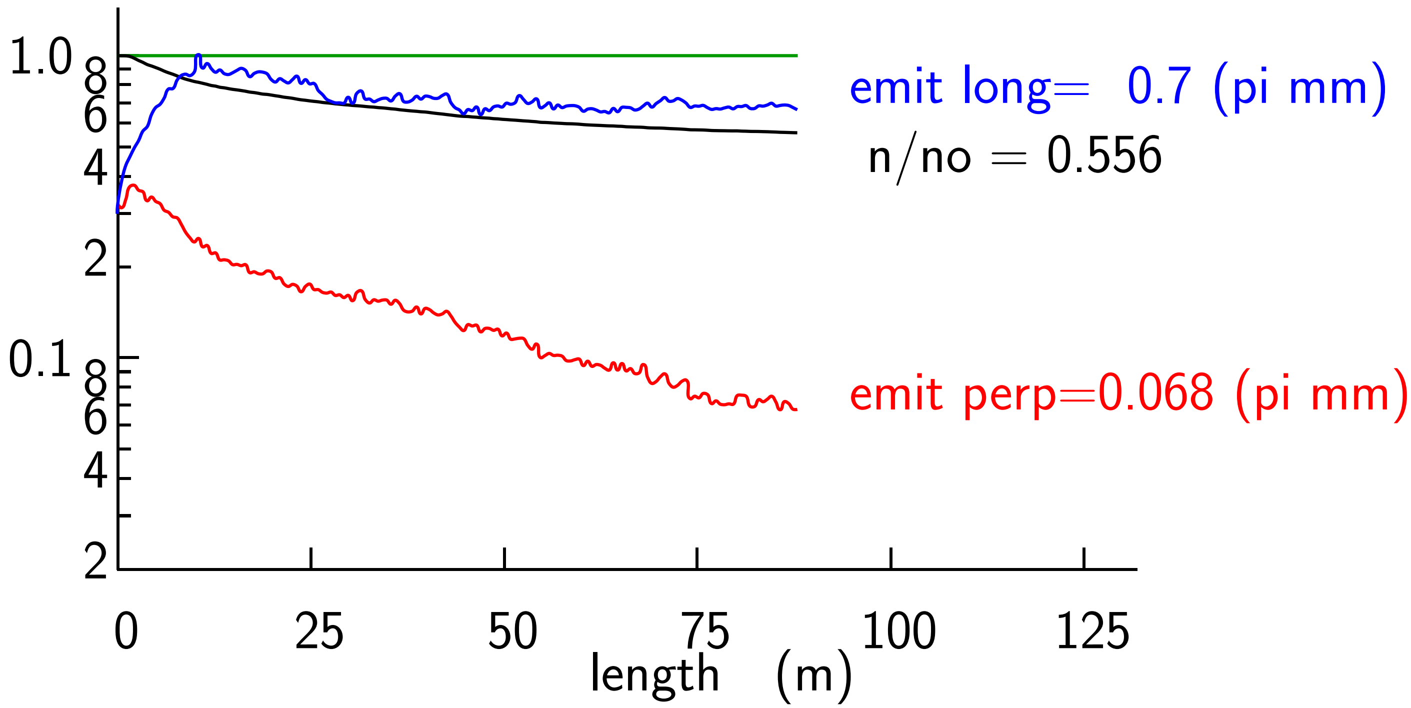




- Current densities $<$ 200 A/mm^2 ok for HTS
- $\Delta p/p$= 9.6 % ok for final cooling
- β = 10 mm
- Bucking coils reduce the field on the RF
- With no field between coils, reversals can be introduced, or left out, without disturbing transverse dynamics

ICOOL simulation of Ring

- 17 mm long LiH absorber
- 0.125 T vertical field: 33 m circumference
- 90 degree apex LiH wedges
- 14 cm long 805 MHz rf at 42 MV/m and 41 degrees



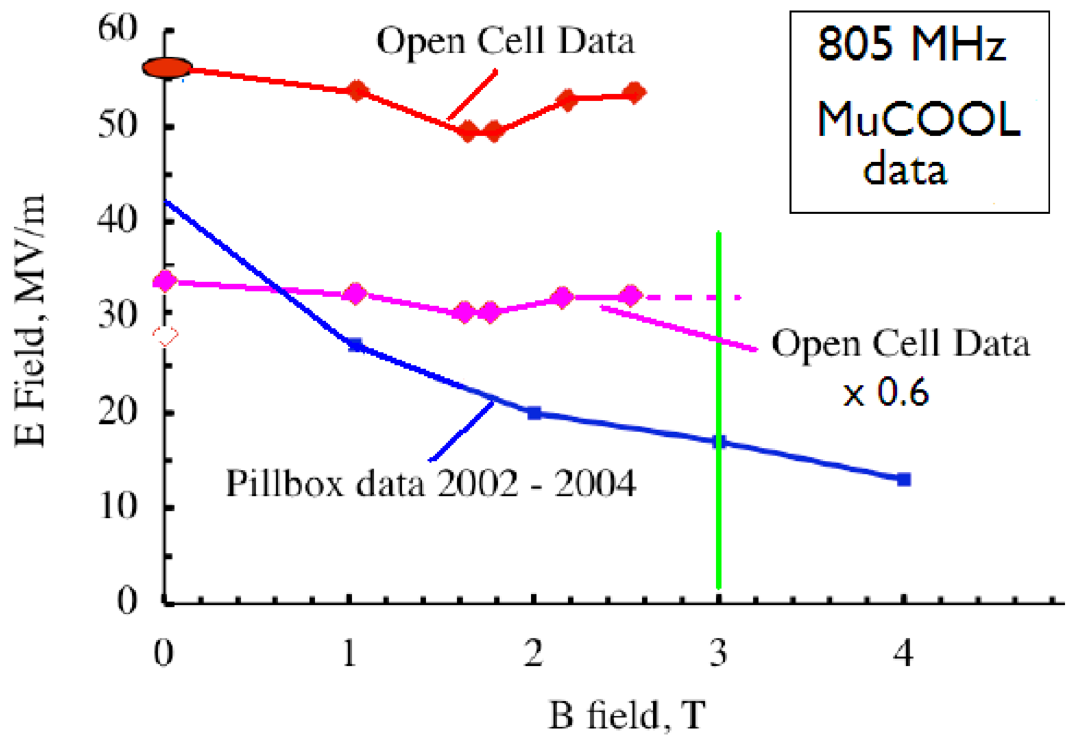
- Transverse Cooling to 68 (mm-mrad)   cf final required = 25 (mm mrad)
- Equilibrium $\epsilon_{\parallel} = 0.7\ \pi$ mm (dp/p=2.5%)

Ongoing Studies

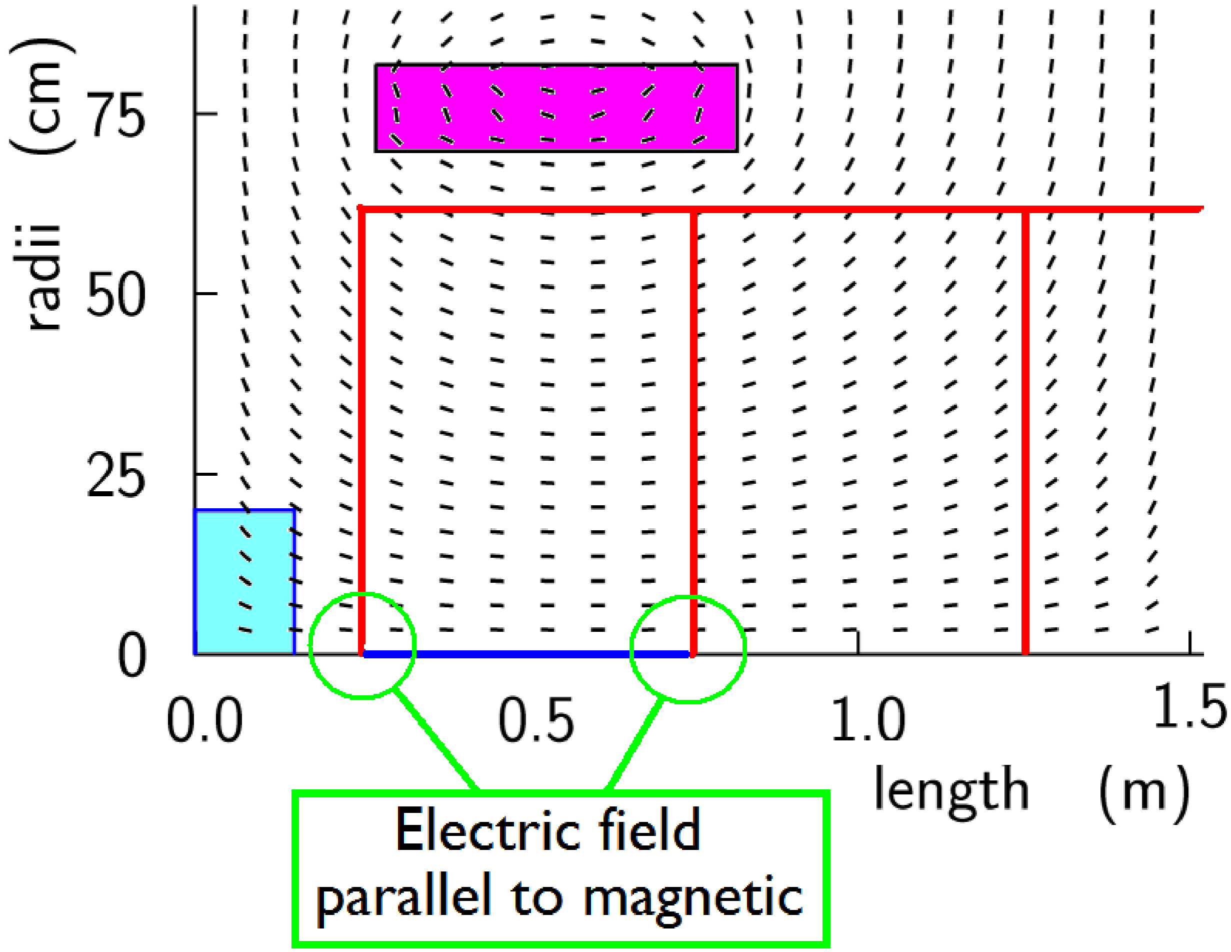
- Fuller simulations
- Longitudinal space charge tune shifts
- Possible/probable breakdown of vacuum RF in the specified magnetic fields
  - Being studied experimentally by MUCOOL Collaboration
  - Possible solution 1) Gas filled cavities
    works for earlier cooling lattices experiment needed for beam breakdown
  - Possible solution 2) Open Cavities with coils in irises (see next)
    works in simulation experiments needed for breakdown
- Planar wiggler lattice to replace Guggenheims (cools both muon signs)
- Fast Helical cooling in hydrogen gas
  Another alternative to RFOFO Guggenheims Rol's talk
  Not intrinsically faster
  Both depend on acc gradient x fraction filled (75% for ours)
- Design of 50 T solenoids

Open cell rf with coils in irises

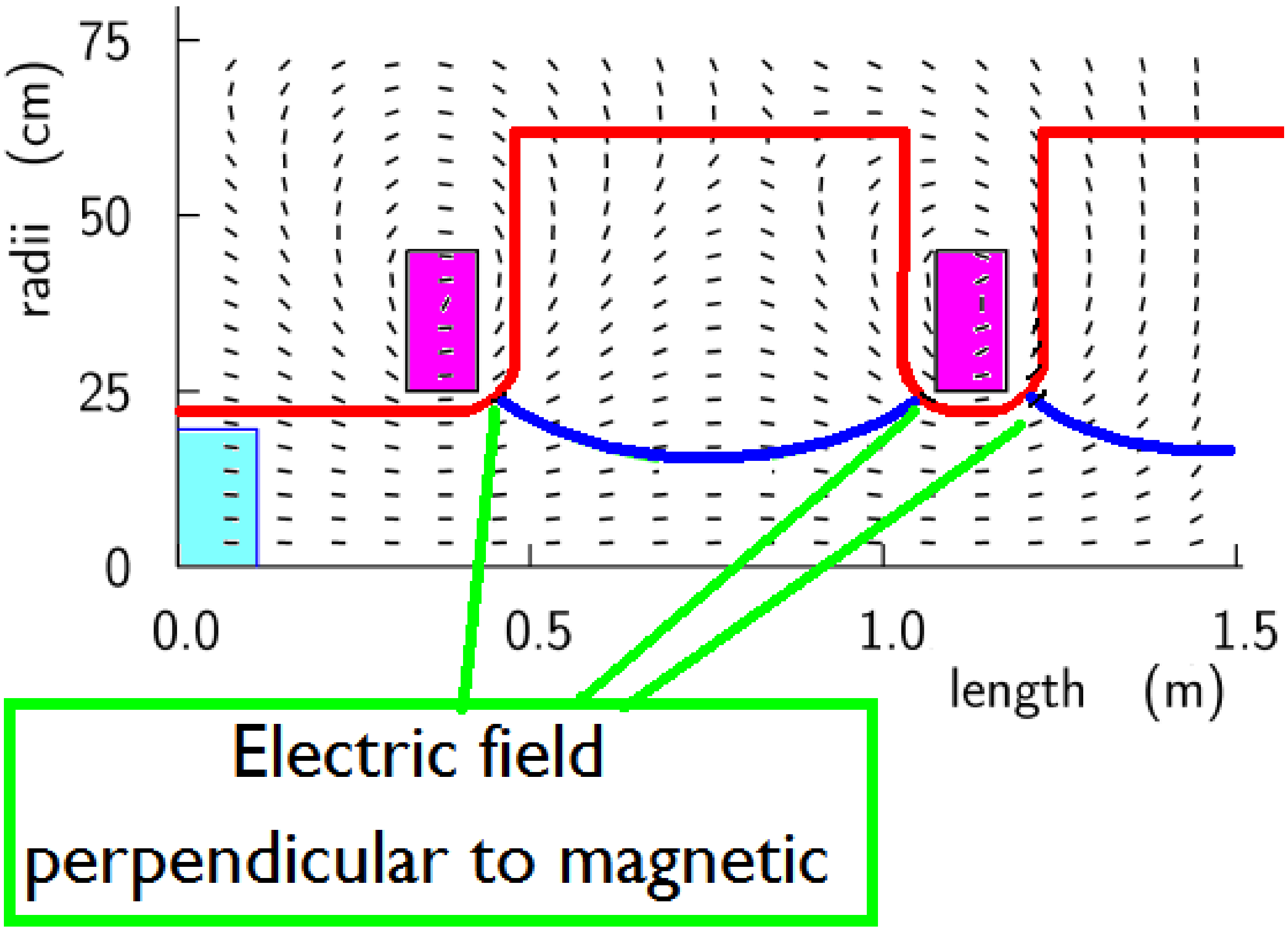
- B field effect on open cavity much less
  average field/surface fields ≈ 1/2
  but open cavity still better at B>1 T
- Should be even better if coils in irises   Max E field ⊥ to B



Probable problem with Pill-box cavities



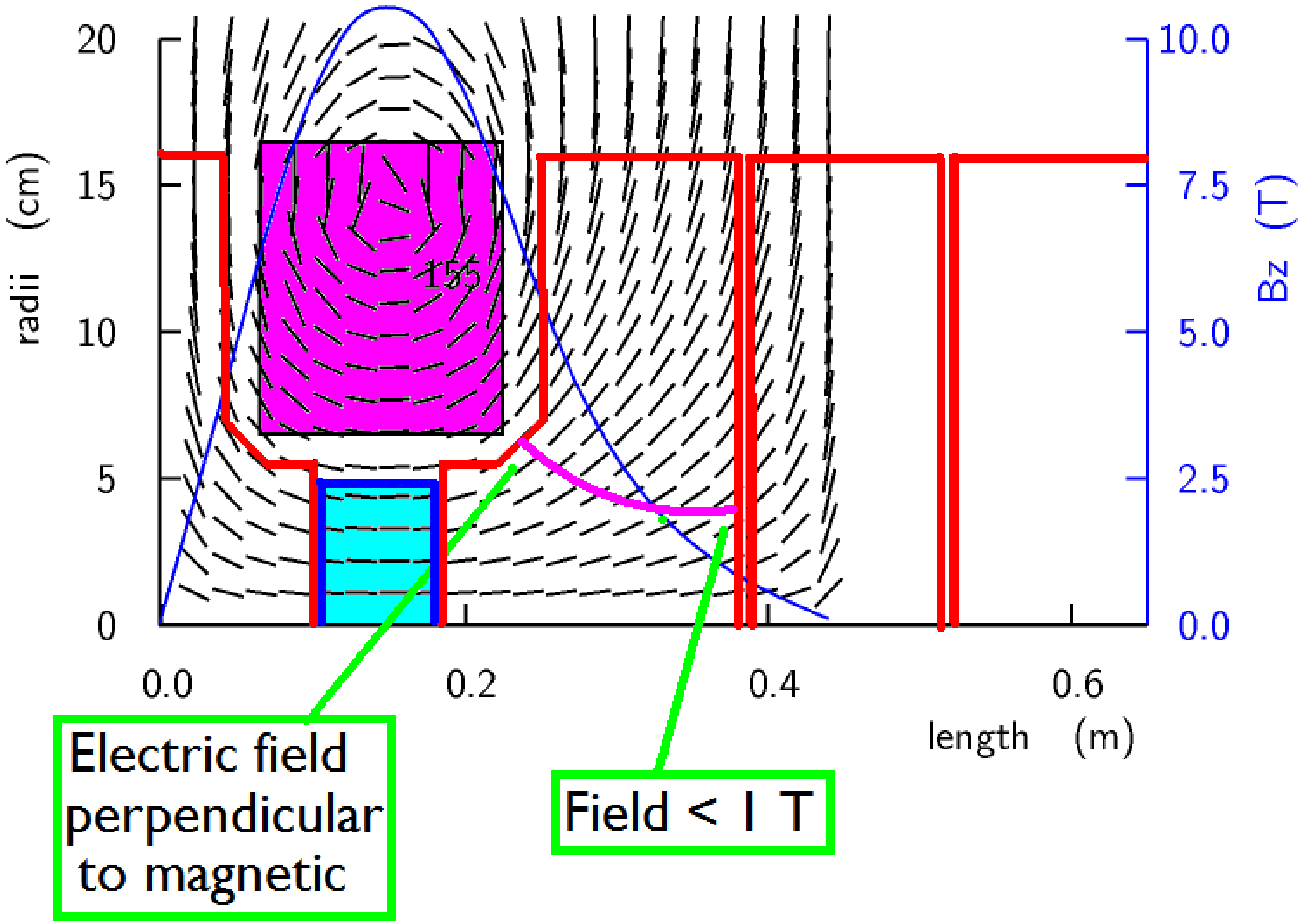
Suggested Solution for early 6 D cooling



- Open cell proposal
- B fields approximately perpendicular to highest E fields

Suggested Solution for 800 MHz cooling

Half open cavity

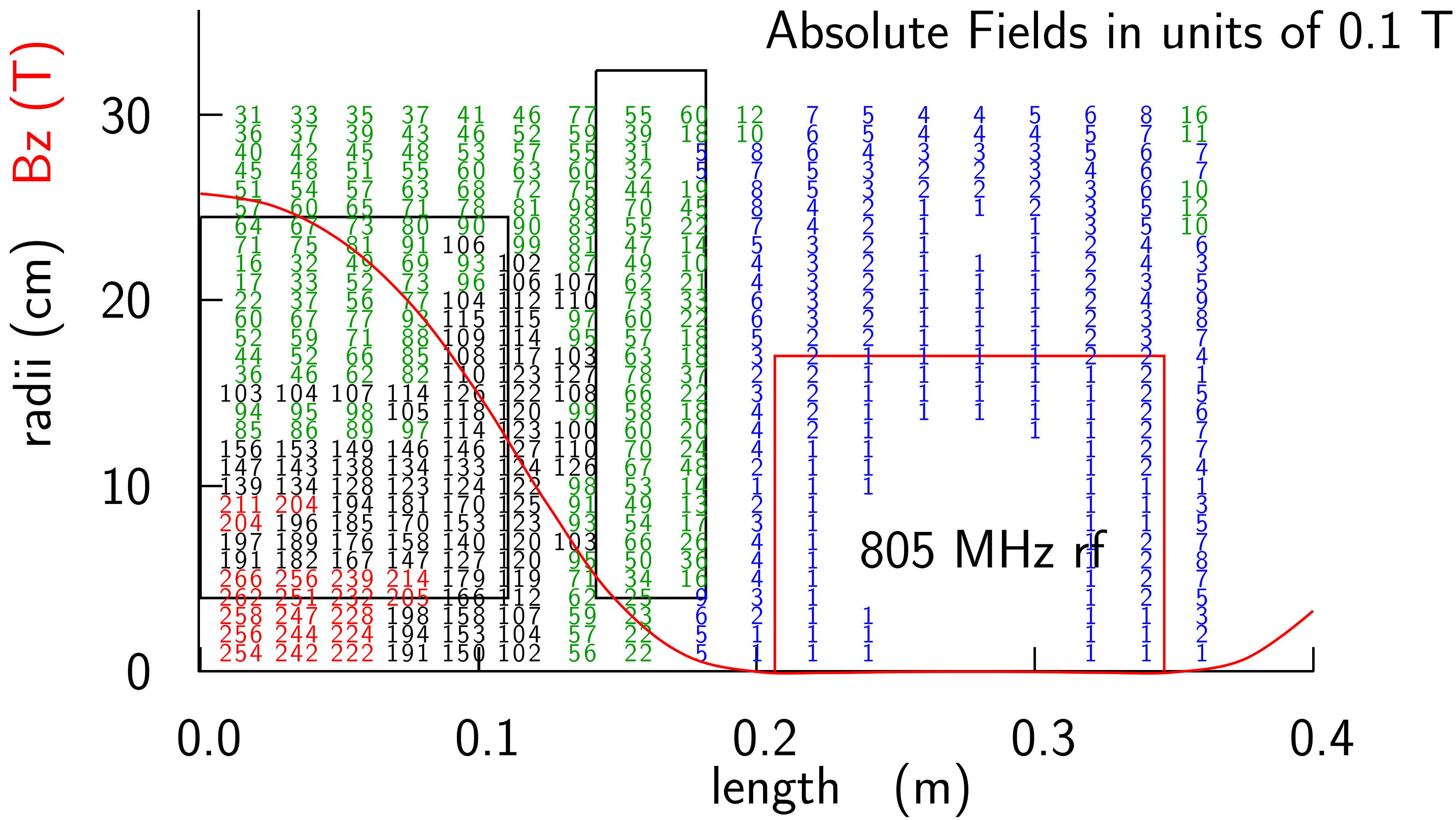


10 T coils are too big to fit in irises, but half open cavity seems doable

Conclusion

- Improved sequence of 50 T stages
  - Emittance now 15 pi mm mrad (vs 25)
  - But dp/p in ring now 0.12% (vs .09%)
- Solution with HE merge not crazy
- Probable solutions to rf in Magnet problem

Fields at RF



- Field at the rf are less than 0.2 T
- If improved to < 0.1 T, Superconducting cavity could be used

Space Charge Effects

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

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

For a Gaussian distribution:

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

This is true INDEPENDENT of $\beta_\perp$

For convenience I define

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

Then:

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

Use many smaller bunches & merge later ?

$$\frac{\Delta\nu}{\nu} = \frac{<\beta_\perp> \ N_\mu \ r_\mu}{\sqrt{2\pi}\ \sigma_z \ L_b \ \epsilon_\perp \ \beta_v \gamma^2} \qquad \text{and} \qquad \sigma_z = \frac{\epsilon_\parallel}{(dp/p)\ \beta_v \gamma}$$

so

$$\frac{\Delta\nu}{\nu} = \frac{N_\mu}{\epsilon_\parallel} \left(\frac{<\beta_\perp> \ r_\mu \ (dp/p)}{\epsilon_\perp \ \sqrt{2\pi}\ \gamma} \right)$$

If we break the N_μ with required $\epsilon_\parallel$ into n_{sb} sub bunches with $\epsilon_\parallel(\text{sub bunch})$

$$\epsilon_\parallel(\text{sub bunch}) = \frac{\epsilon_\parallel}{\mathrm{n_{sb}}} \qquad \mathrm{N}_\mu(\text{sub bunch}) = \frac{\mathrm{N}_\mu}{\mathrm{n_{sb}}}$$

$$\frac{\Delta\nu(\text{sub bunch})}{\nu(\text{sub bunch})} = \frac{N_\mu/n_{sb}}{\epsilon_\parallel/n_{sb}} \left(\frac{<\beta_\perp> \ r_\mu \ (dp/p)}{\epsilon_\perp \ \sqrt{2\pi}\ \gamma} \right) = \text{same as above}$$

What to do

- Only hope is to keep $<\beta_\perp>$ low. This disfavors solutions with local low beta at an absorber (Super Fernow, PIC, Rees etc)
- Favors high field everywhere (50T Solenoids, Helices)

Examples $R_\mu = 1.35\ 10^{-17}$ (m)

Note that N_μ is larger at earlier cooling stages to allow for losses

case	N_μ 10^{12}	$<\beta_\perp>$ m	σ_z m	$\epsilon_\perp$ mm mrad	p MeV/c	$\Delta\nu/\nu$
Last 50 T cooling	2.8	0.3	4	25	50	0.05
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

- Negligible problem in the 50 T solenoids
  They operate in the first pass band & can tolerate large $\Delta\nu/\nu$

- Finite effect in Guggenheim RFOFO lattices
  The accepted $\Delta\nu/\nu$ between the resonaces at $\nu = .5$ and $\nu = 1.0$

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

  so tune spreads of 0.11 & 0.12 will somewhat reduce momentum acceptance
  This needs to be included in simulations

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 train	$2.8\ 10^{13}$
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=24 ($>$8) GeV to get 1-3 ns proton bunch of 7 10^{13}
- Loading with 8 10^{12} muons per bunch needs study