Collider Cooling Scheme

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- Philosophy
- Scheme
- Recent advances
  - Matching out of a 50 T solenoid
  - Fernow's new cooling lattices
- Conclusion

Luminosity Dependence

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

$$\mathcal{L} \ \propto \ B_{\text{ring}} \, P_{\text{beam}} \ \ \Delta\nu \, \frac{1}{\beta^*}$$

- Higher $\mathcal{L}/P_{\text{beam}}$ requires lower $\beta_\perp$ or correction of $\Delta\nu$
- Lower emittances do not directly improve Luminosity/Power

- Why do we want "Low Transverse Emittance ?
  1. To lower N_μ to ease space charge etc. $N_\mu \ \propto \ \Delta_\nu \ \epsilon_\perp$
  2. To reduce aberrations in Ring IP to allow lower β^*
- Why do we want "Low Longitudinal Emittance ?
  1. To reduce dp/p & chromatic aberrations in Ring IP to allow lower $\beta_\perp$
  2. To keep $\sigma_z \ < \ \beta_\perp$ as β^* is reduced

How do we get Low Emittance

For LiH, equal "partition functions" $J_{\perp,z} = 2/3$, and p$\approx$ 200 MeV/c

$$\text{Equilibrium } \epsilon_\perp \;=\; \frac{\beta_\perp \; C_{\text{mat}}}{\beta_v \; J_\perp} \;\approx\; 0.01\;\beta_\perp$$

$$\text{Equilibrium } \sigma_\theta \;=\; \sqrt{\frac{C_{\text{mat}}}{J_\perp \beta_v^2 \gamma}} \;\approx 50 mrad$$

$$\text{Equilibrium } dp/p \;\approx 3\%$$

For fast 6D cooling we need:

- Low $\beta_\perp$
- Large transverse angular acceptance $\Delta\theta \;\approx 6\;\sigma_\theta \;\approx\; 300 \quad (\text{mrad})$
- Large momentum acceptance $\frac{\Delta p}{p} \;\approx\; 6\;\frac{\sigma p}{p} \;\approx\; 20\%$

These are tough requirements at any $\beta_\perp$

How do we get low $\beta_\perp$, large $\Delta\theta$ and large Δp

1. Continuous or long cells with adiabatic or designer matching No resonances
   - 50 T Solenoids + adiabatic, Balbakov, Li Lenses, old Alternating solenoids
   - Helical cooling alternating with separate mini-linacs
2. Periodic focus in short un-chromatically corrected cells
   Cells short so that Δp between resonances gives momentum acceptance
   - SFOFO, RFOFO,Super-Fernow, Helical + gaps for rf, Garren/Kirk rings
3. Periodic focus in longer chromatically corrected cells
   Resonances avoided by correcting phase advance vs. momentum
   complicated by transverse aberrations at large θs
   - PIC, Rees rings
   - Wedge Reverse emittance Exchange (REMEX)
     distinguished from Emittance Exchange in absorbers at low momenta

Red systems used in this example

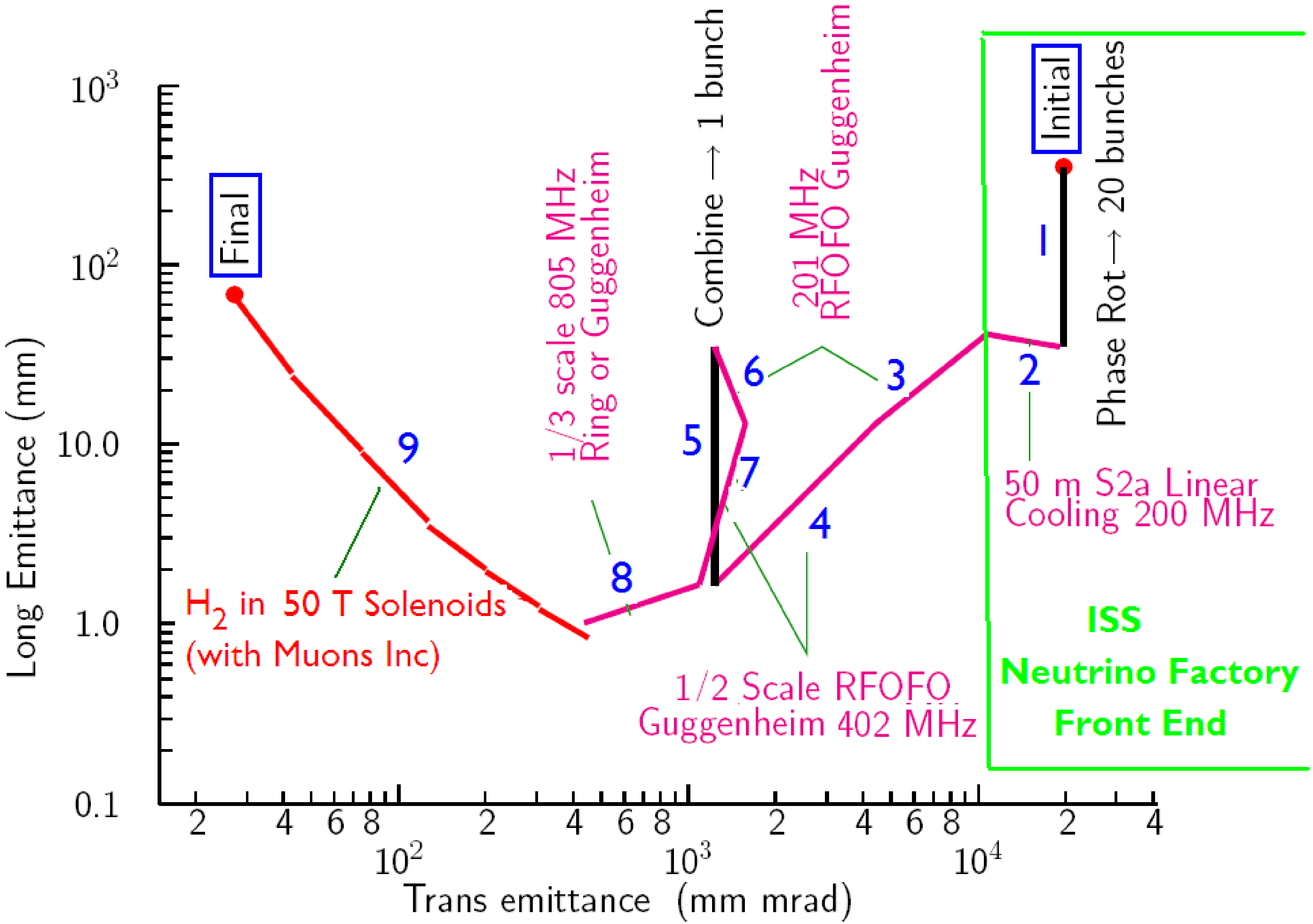
Green systems discussed at end

Example Collider Parameters

4 TeV Collider Ring Parameters from 98 Study, 8 TeV pushed

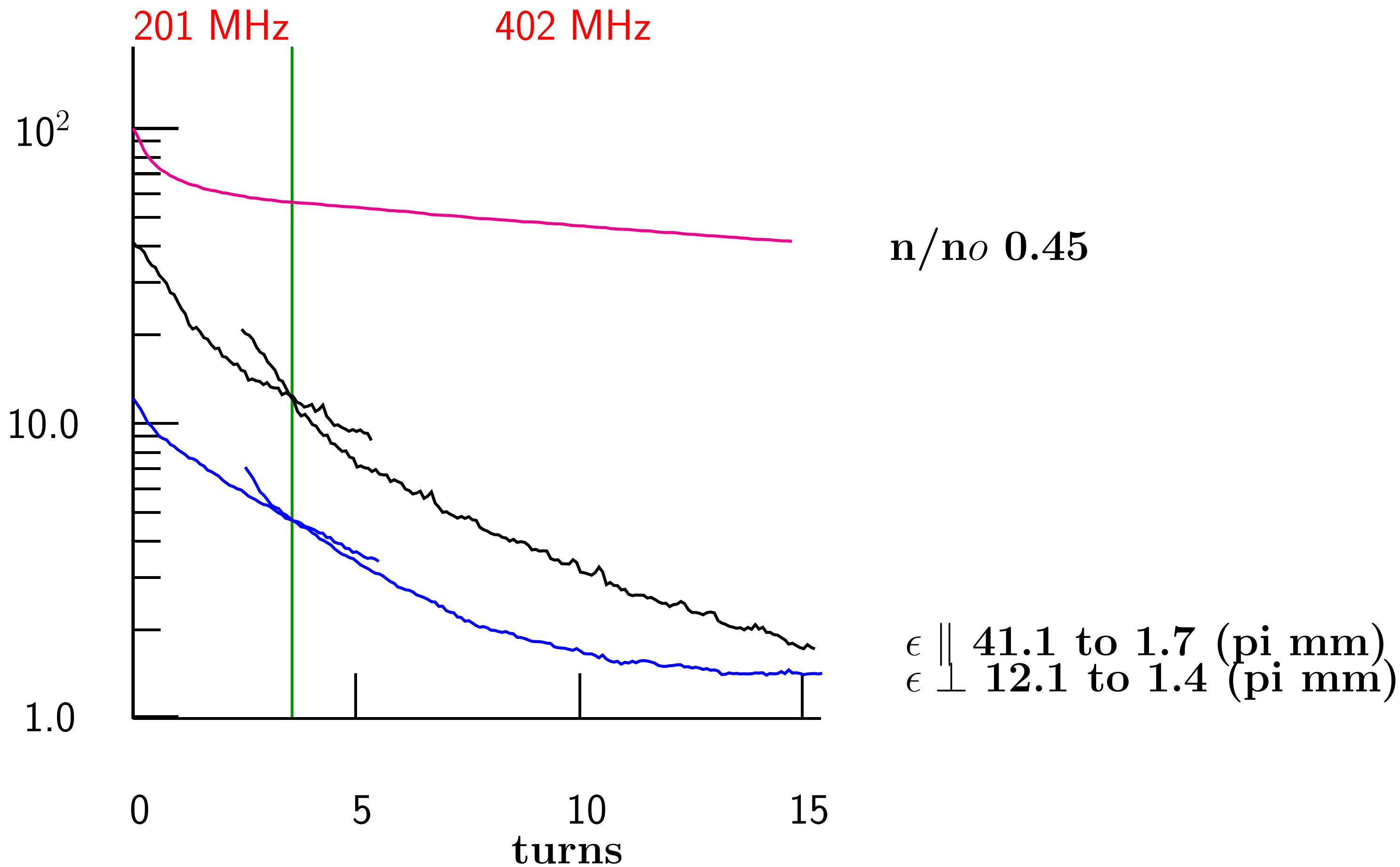
	Phase 1	Phase 2	
C of m Energy	4	8	TeV
Luminosity	4	8	10^{34} cm^{2}sec^{-1}
Tune Shift	0.1	.1	
Muons/bunch	2	2	10^{12}
Ring <bending field>	5.18	10.36	T
Ring circumference	8.1	8.1	km
Beta at intersection	3	3	mm
rms momentum spread	0.12	0.06	%
Muon Beam Power	9	9	MW
Required depth for ν rad	135 (ILC)	540	m
Repetition Rate	6	3	Hz
Proton Driver power	$\approx$ 1.8	$\approx$ 0.8	MW
Trans Emittance	25	25	pi mm mrad
Long Emittance	72,000	72,000	pi mm mrad

Cooling Scheme



3), 4), 6) & 7) 6 D Cooling in Guggenheim helices

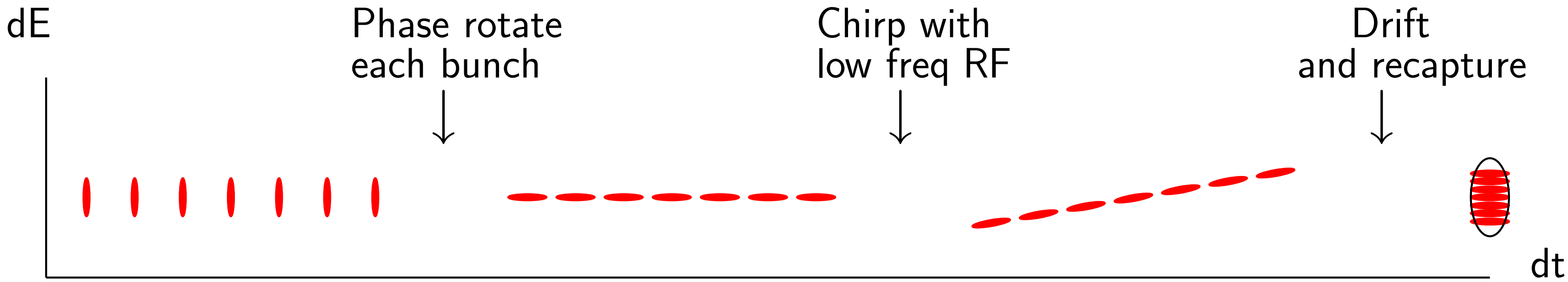
ICOOL Simulations of real fields Balbakov was first



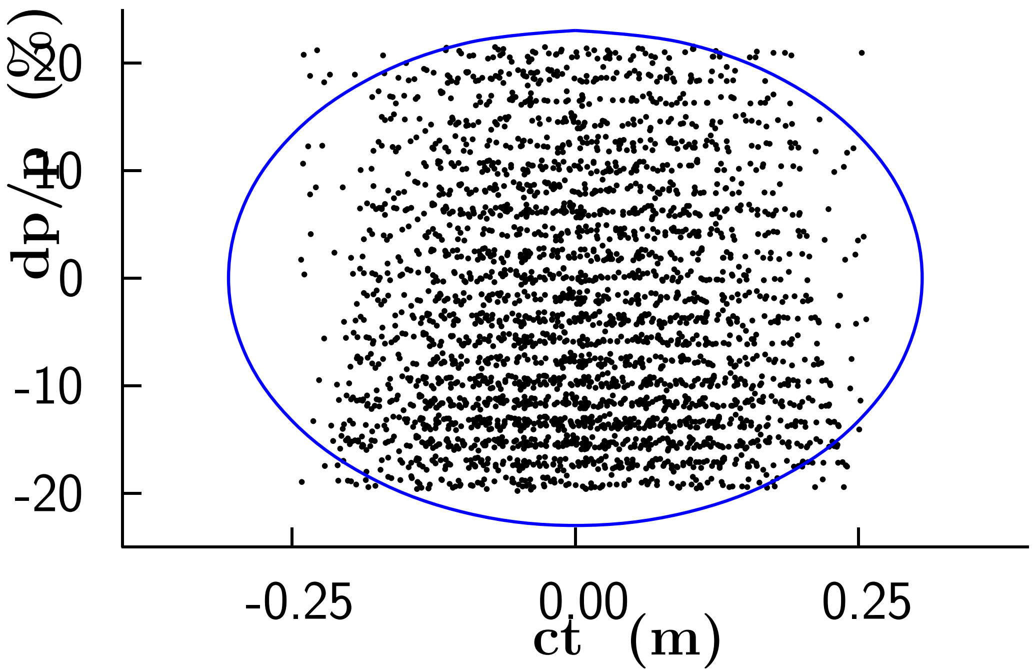
- 201 MHz RFOFO as published, but Guggenheimed (B=3 T)
- 402 MHz RFOFO has all dimensions halved (B=6 T)

- Whether rf can operate in these magnetic fields questionable

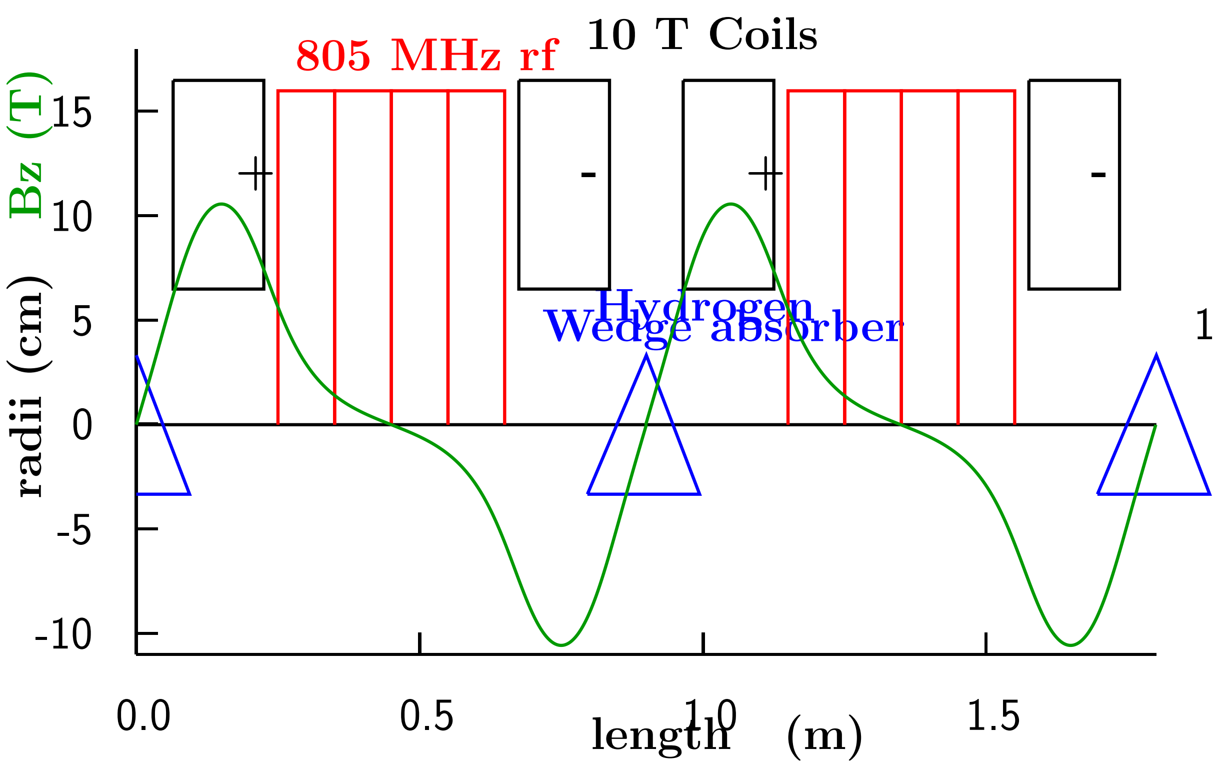
5) Bunch Merging

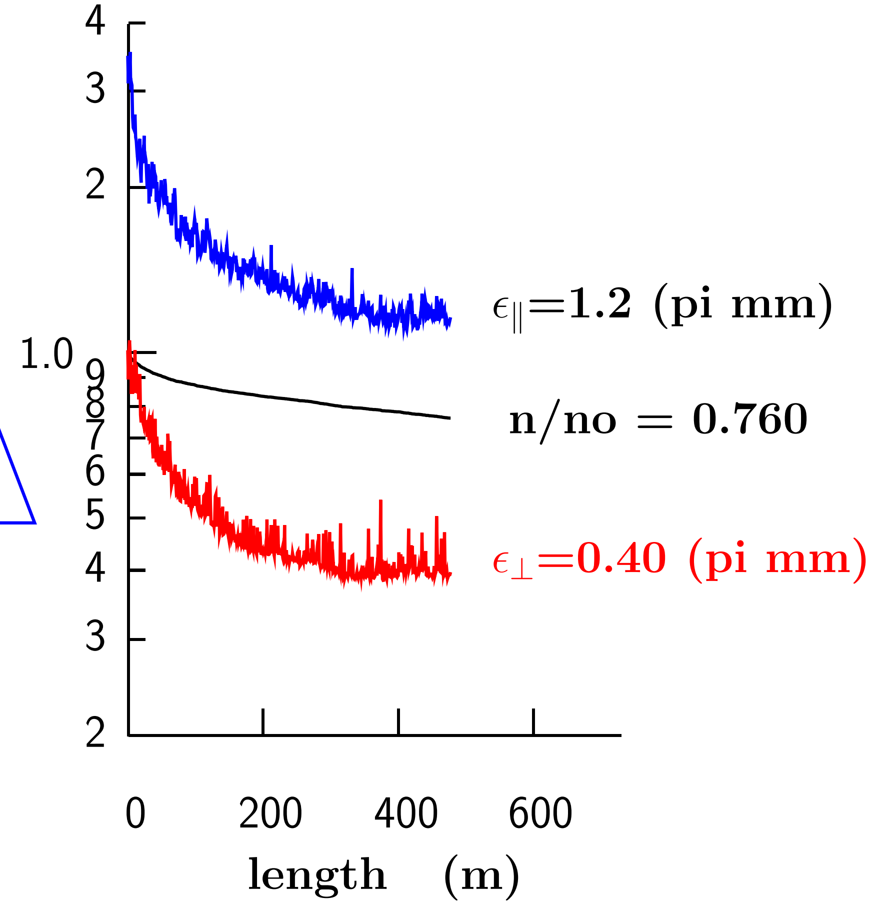


- Drifts in 1 T wigglers, simulated in ICOOL vs amp and mom
- rf 1) at 200 + 23 harmonics 2) at 5 MHz + 2 harmonics
  Simulated off line with parameters from ICOOL



8)New low beta 805 MHz RFOFO Ring

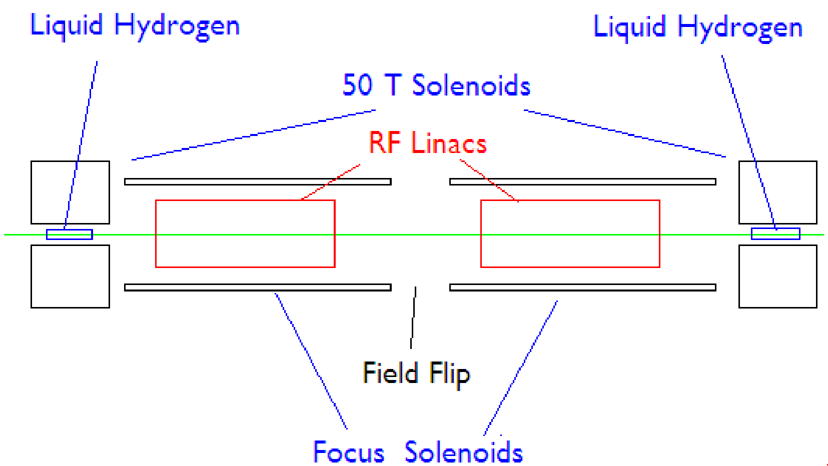


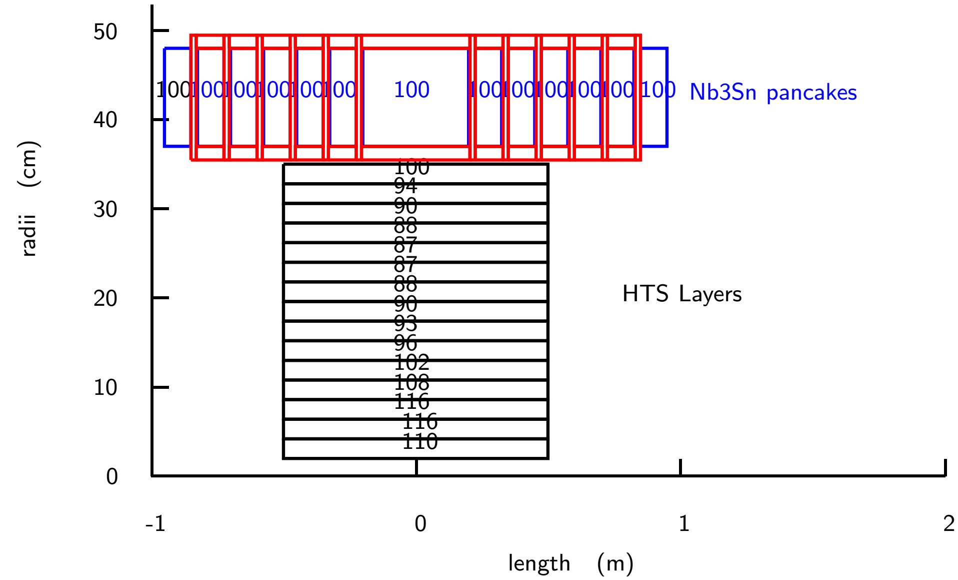


- Uses 10 T high current density (150 A/mm^2) solenoids
- rf operation in fields is questionable

9) Cooling in linear sequence of 50 T solenoids

With Muons Inc.





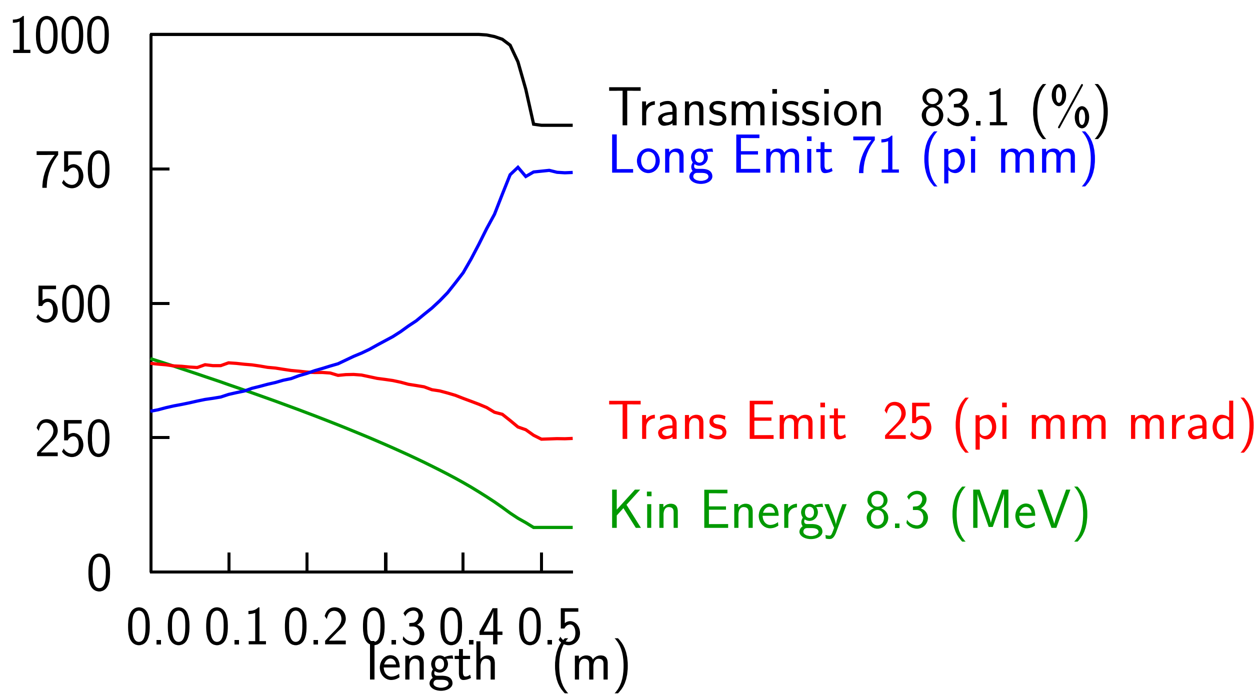
- Layer wound allowing current to vary with radius
- Vary ss support with radius to keep strain constant
- e.g. use existing American superconductor HTS tape

- Much work needed, but 50 T seems practical

ICOOL Simulations (without matching & accel.)

- 6 Solenoids with hydrogen absorbers inside
- Matching only done for last stage

e.g. Simulation of Final Solenoid Cooling



- Lengths up to 1 m in earlier stages

- Need to simulated all matches and re-accelerations

Muon Survival (a first guess)

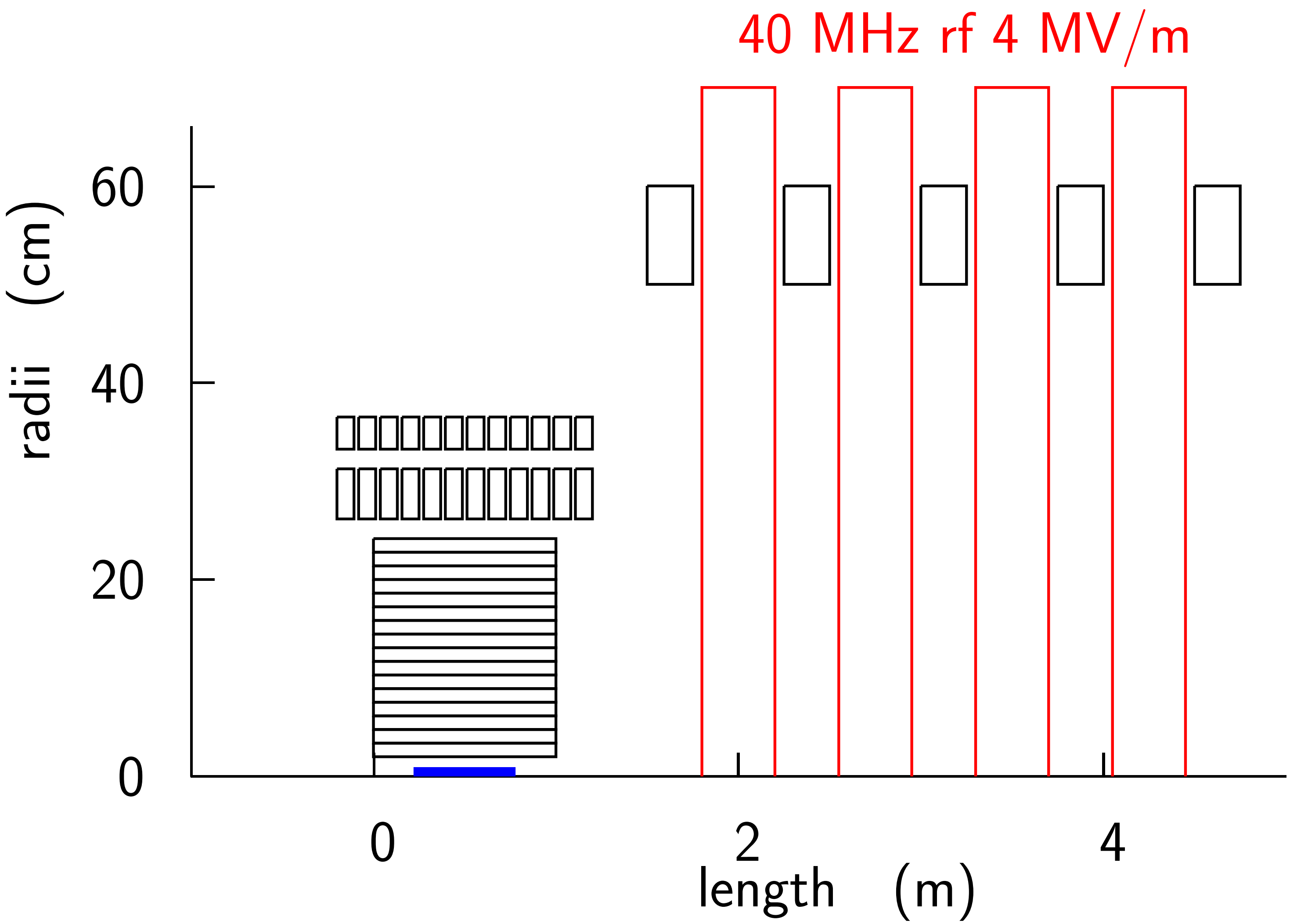
	Transmission	Cumulative
21 vs 54 bunches	.7	.7
Pre-merge RFOFO cooling	$\approx$ .5	.35
Merging	0.8	0.28
Post-merge RFOFO cooling	$\approx$ 0.5	0.14
Final 50 T solenoid cooling	.7	0.1
Acceleration to 2 TeV	0.7	0.07

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**

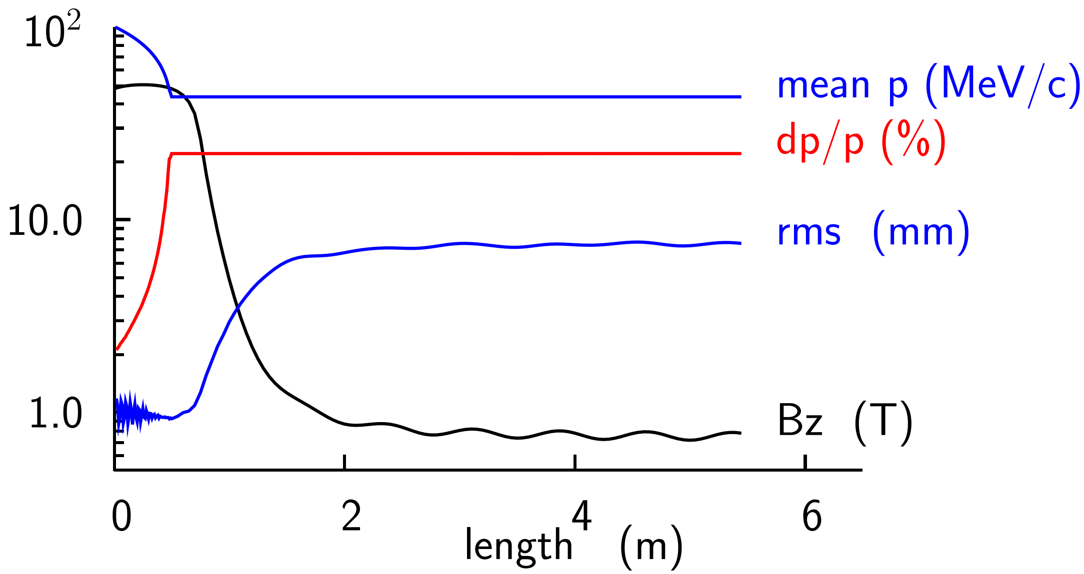
- Proton power $<$ ISS Neutrino Factory
- But lower rep rate $\rightarrow$ more charge/bunch
  Need E$>$ 8 GeV to get 1-3 ns proton bunch of 7 10^{13}
- Loading with 8 10^{12} muons per bunch needs study

New result 1)
Match out of final 50 T Solenoid

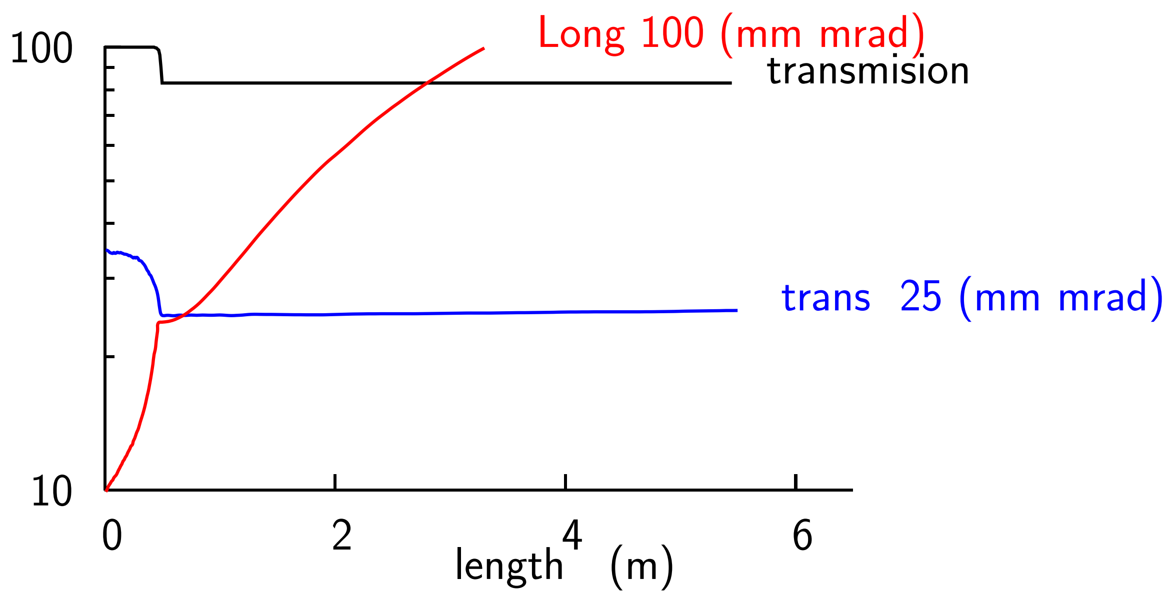
If this works, matching between earlier solenoids probably ok



ICOOL Simulation



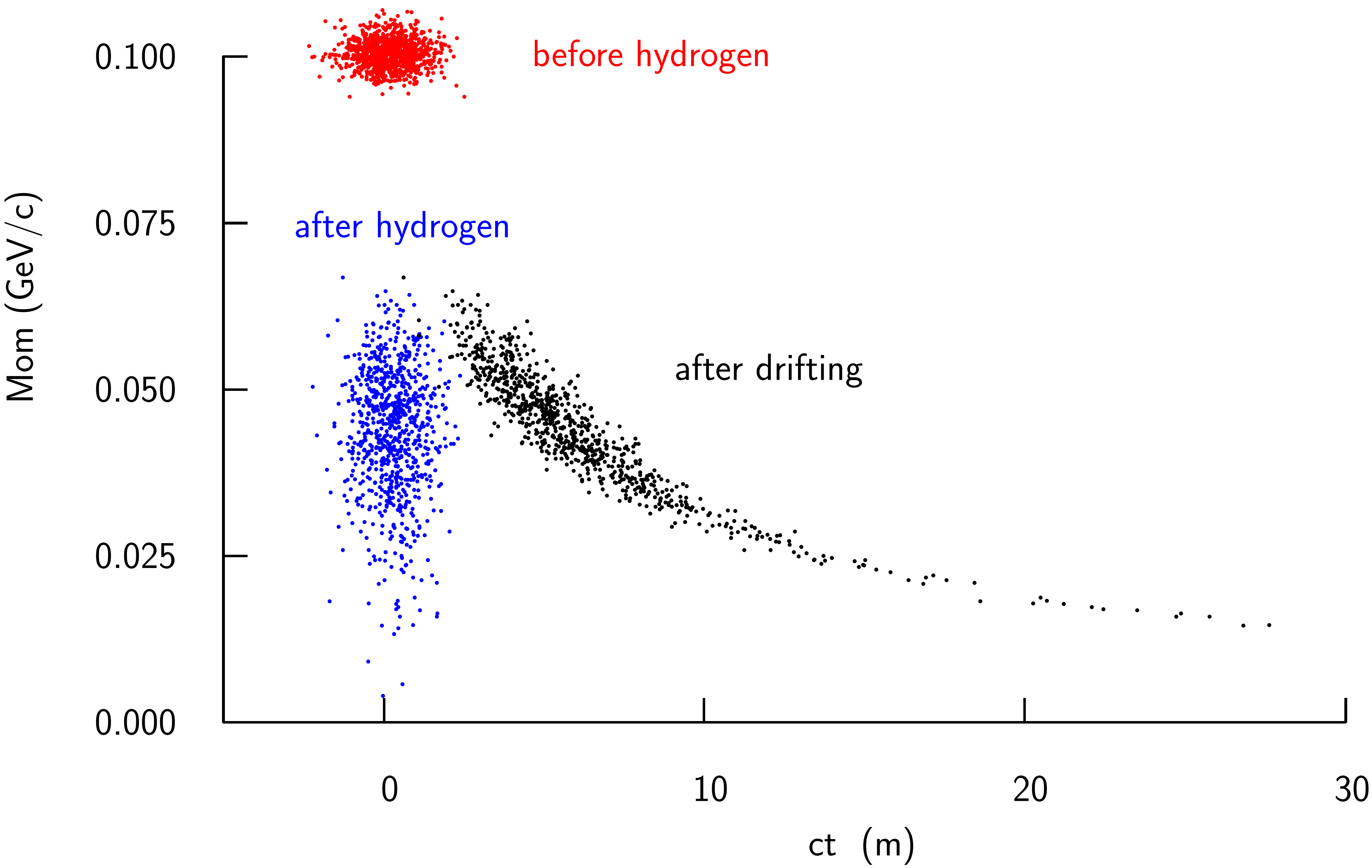
Adiabatic field match to periodic lattice



Trans emittance flat in match

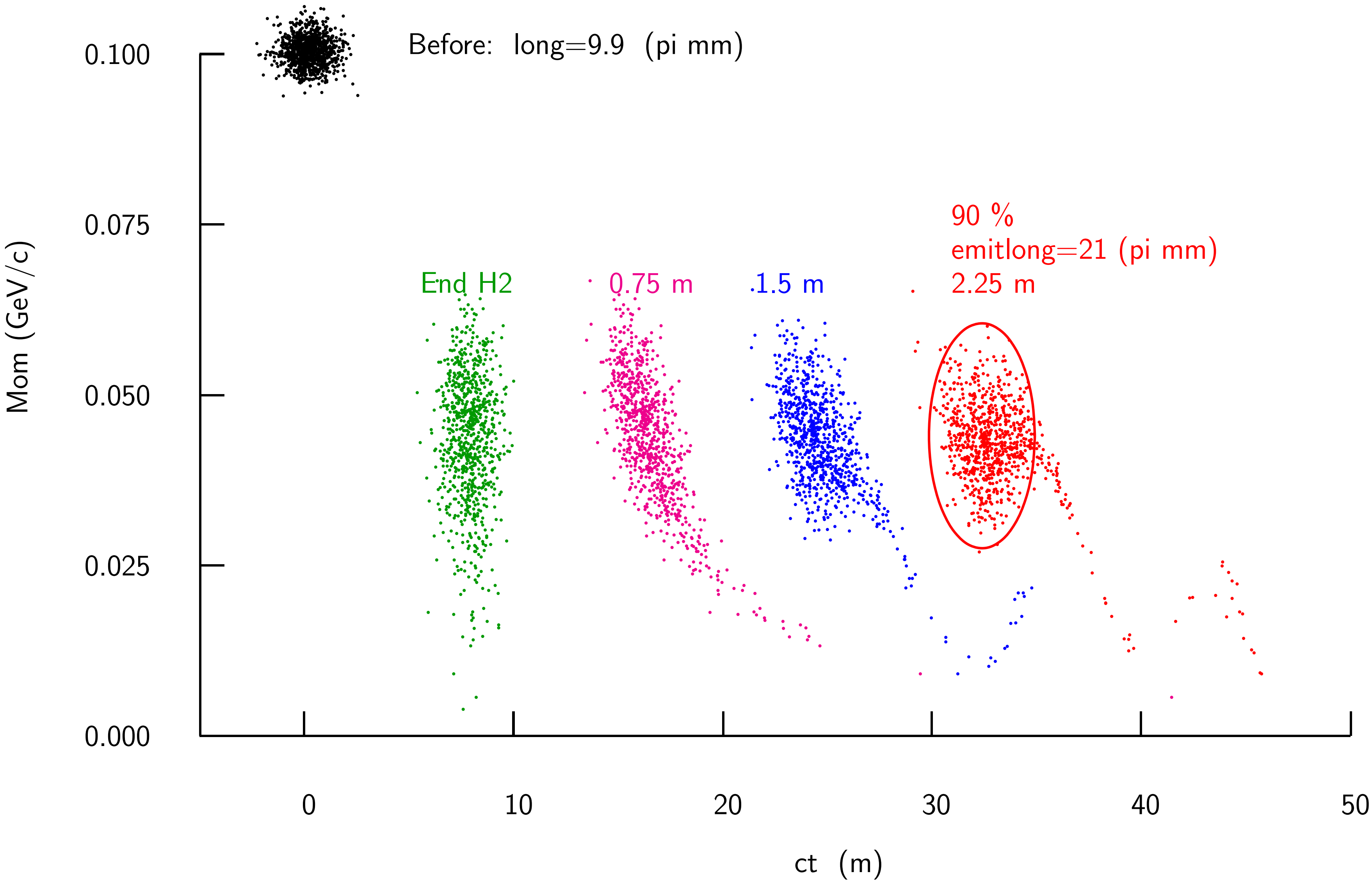
Why is long emittance rising ?

Long phase plots before & after



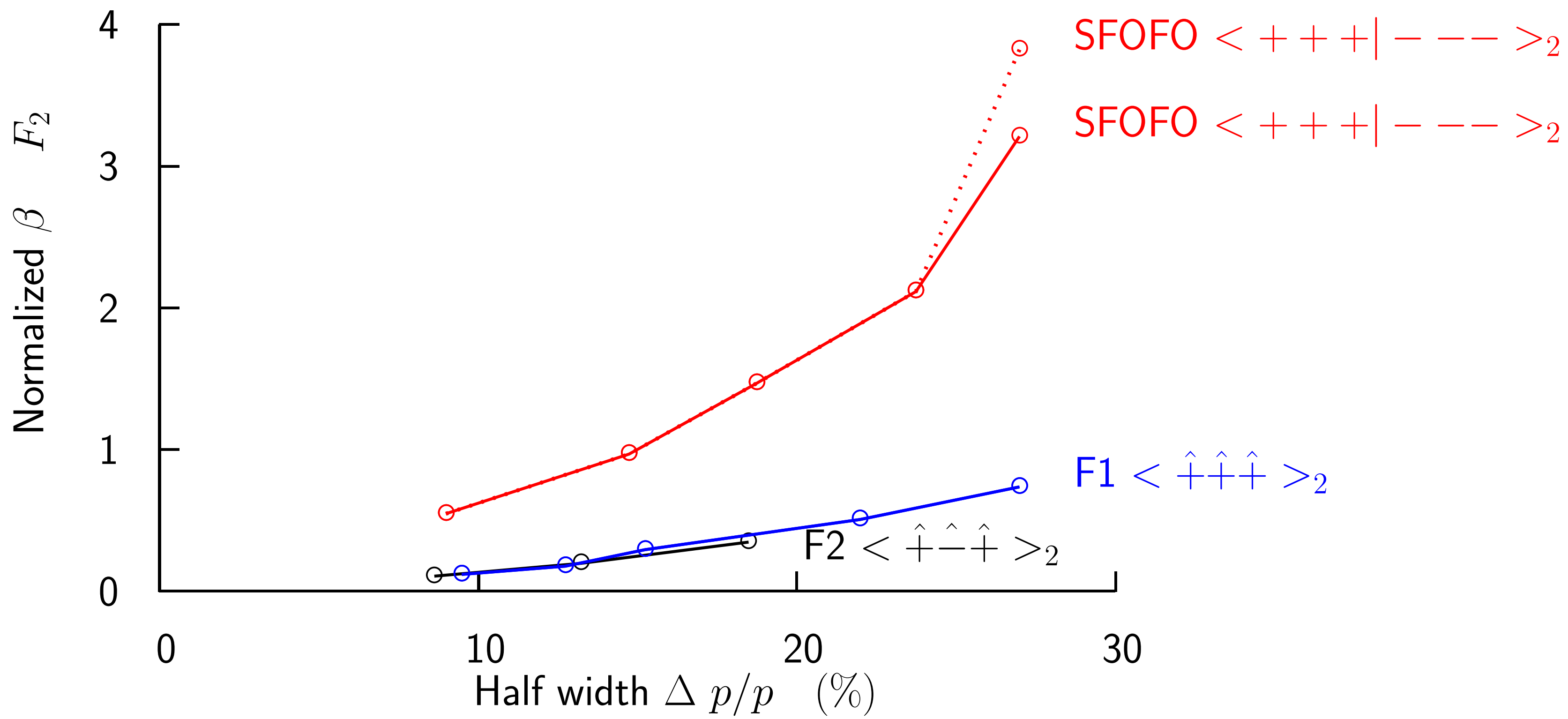
Because drift is non-linear

Use 40 MHz rf to capture bunch

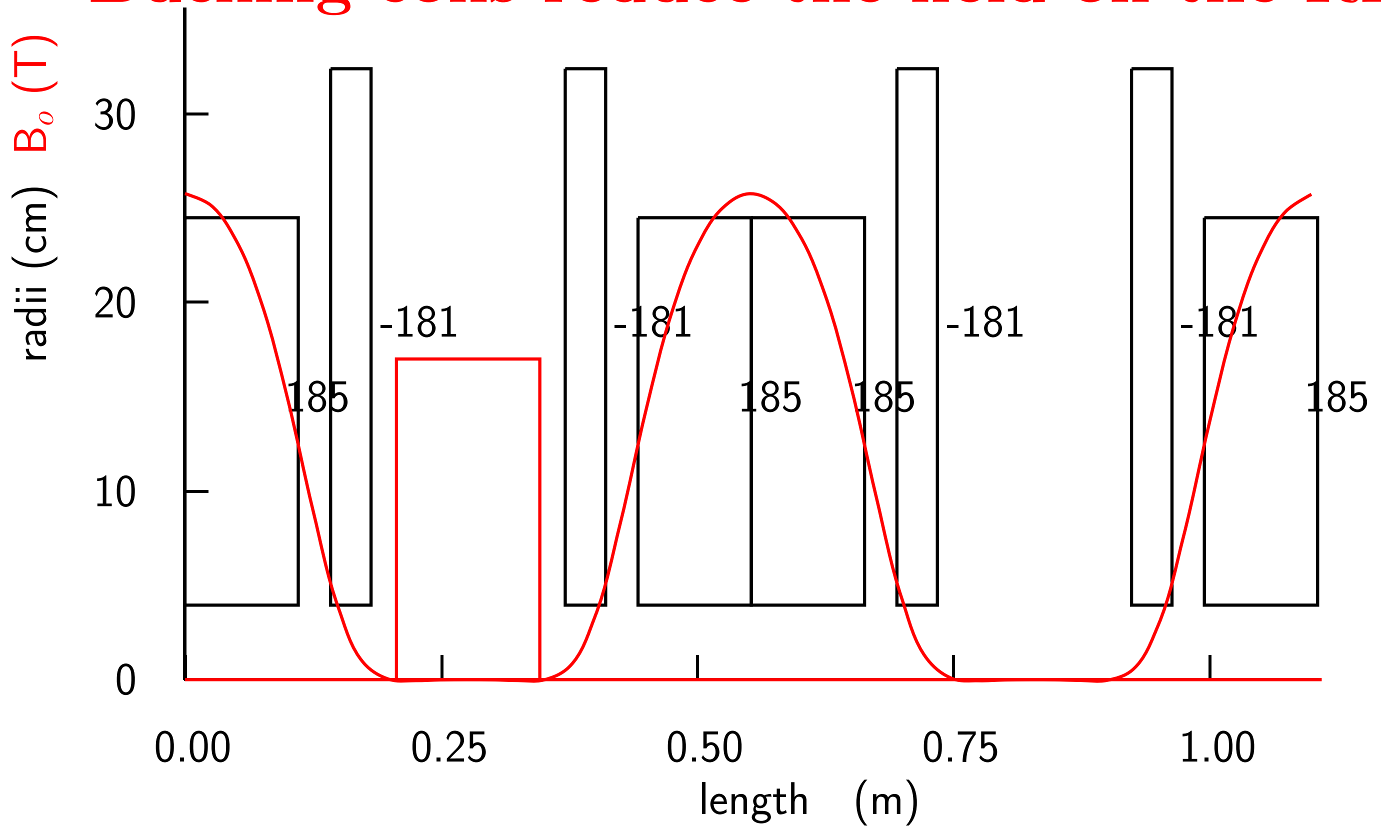


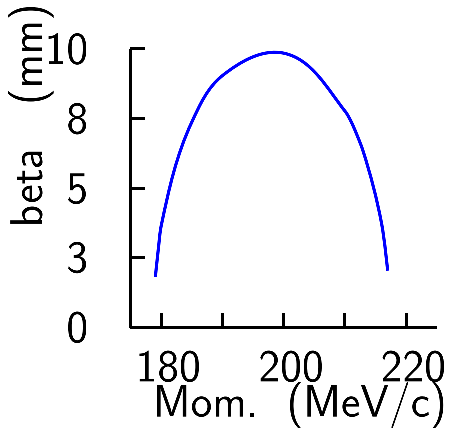
New Reslut 2)
Fernow's Non flip Lattices

- HTS materials have very high field limits
- But finite current density limits ($\approx$ 200 A/mm^2)
- Plot beta vs. $\Delta p/p$ for fixed current density



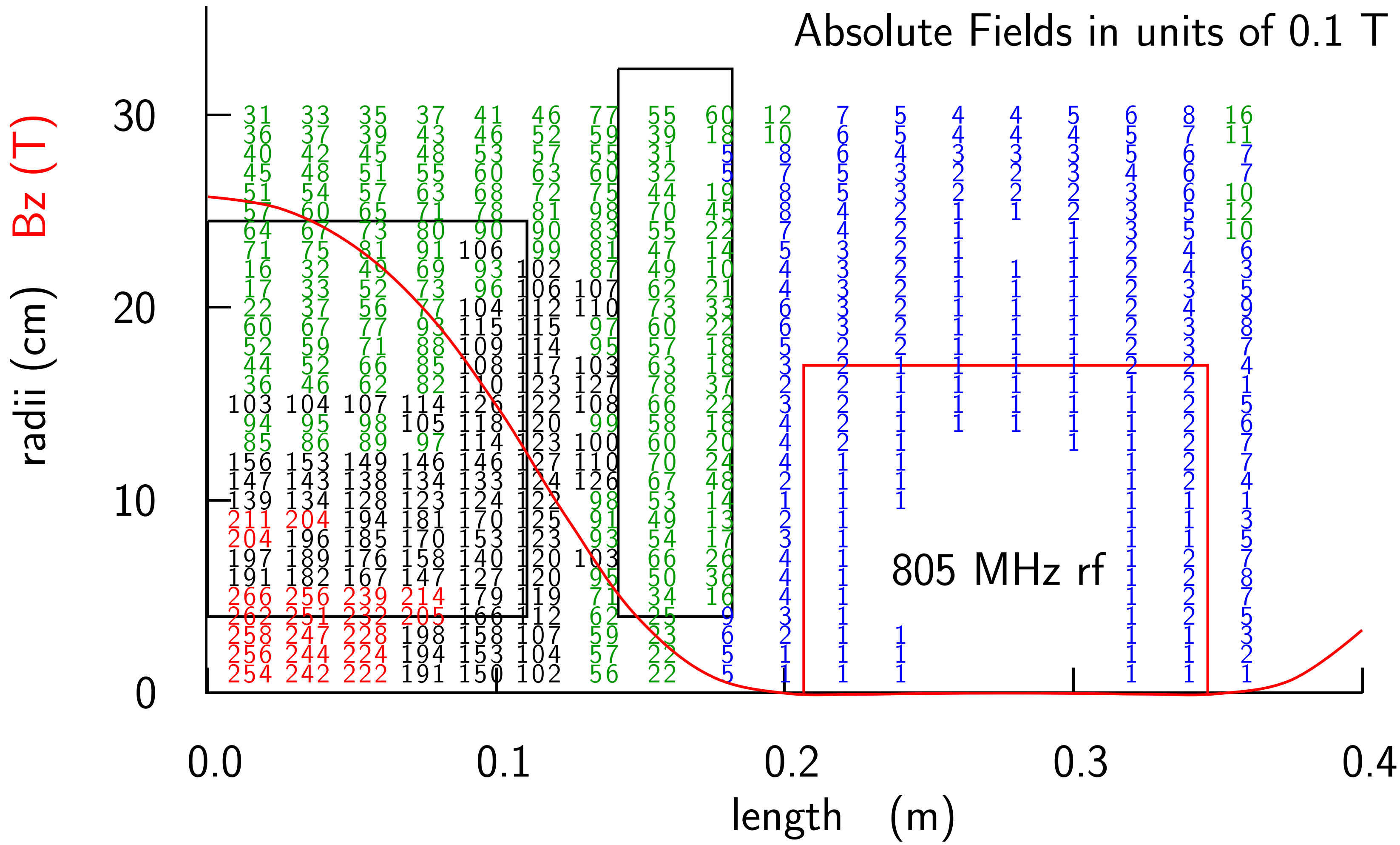
Bucking coils reduce the field on the RF





- The design gave the same 9.6 % $\Delta p/p$ (c.f. 9.5 %)
- With the same current densities ($<$ 200 A/mm^2)
- And, surprisingly, a lower $\beta = 10$ mm (c.f. 12 mm)
- With no field between coils, reversals can be introduced, or left out, without disturbing transverse dynamics

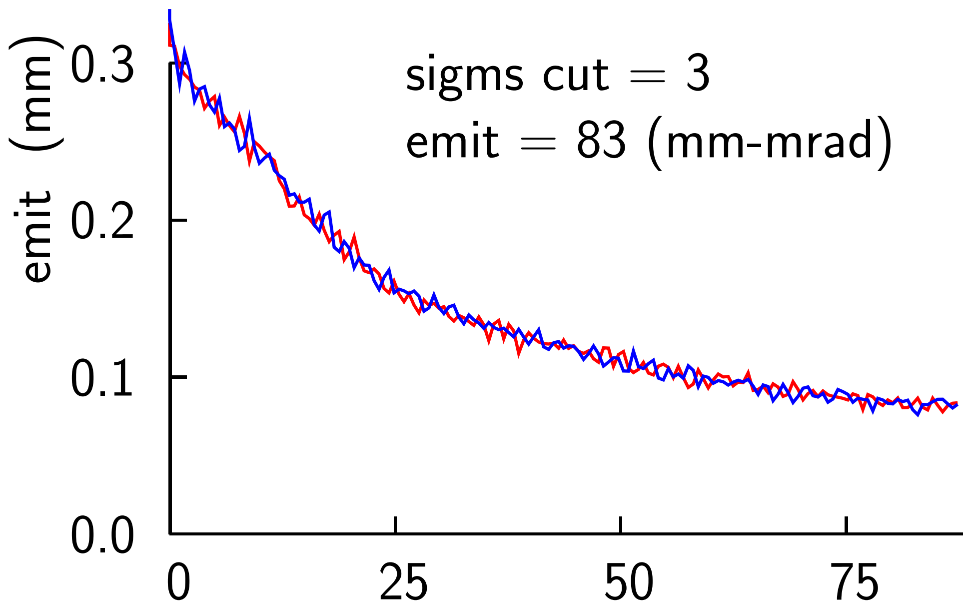
Fields at RF

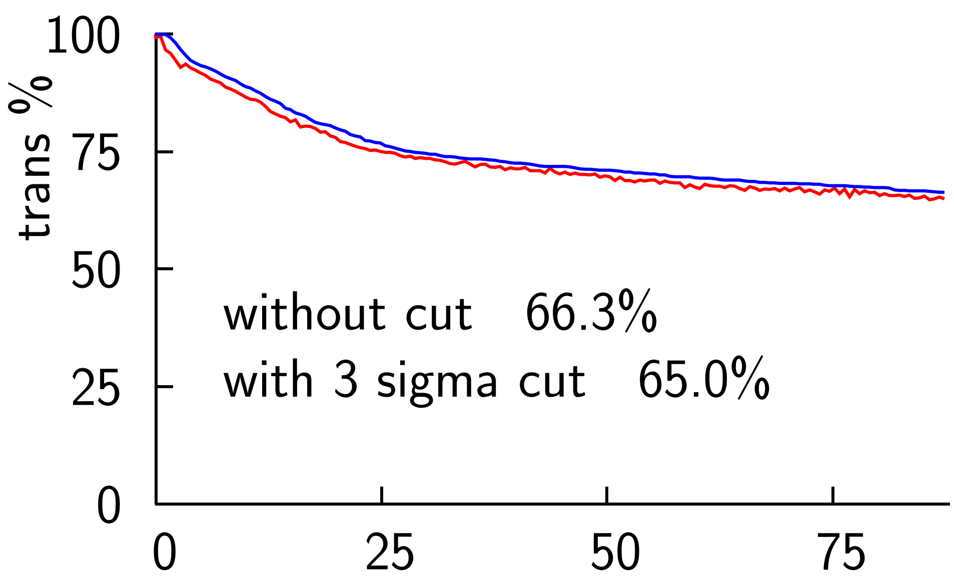


- Field at the rf are less than 0.2 T
- If improved to < 0.1 T, Superconducting cavity could be used

ICOOL simulation of straight channel

- 17 mm long LiH absorber
- 14 cm long 805 MHz rf at 42 MV/m and 41 degrees
- Fano method for scattering

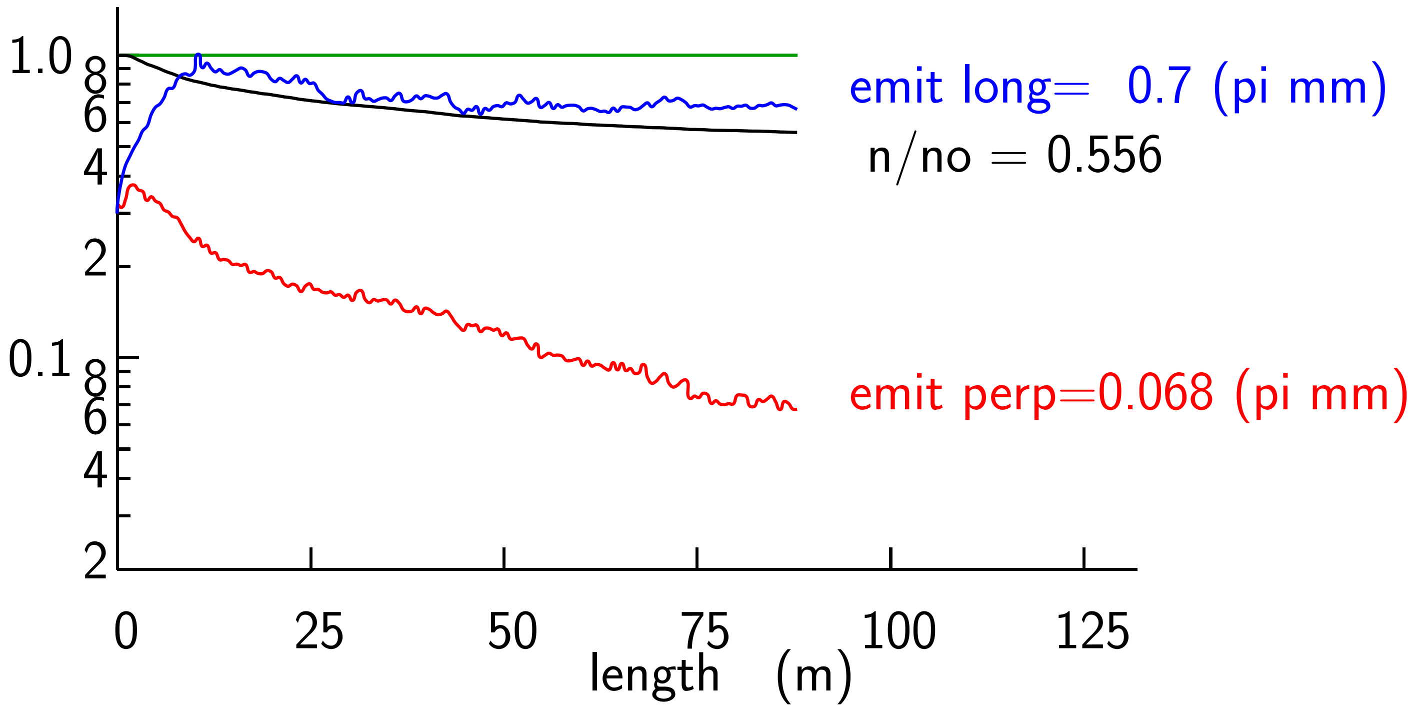




- Cooling to 83 mm-mrad
- But longitudinal emittance rising fast
- We need dispersion and a wedge

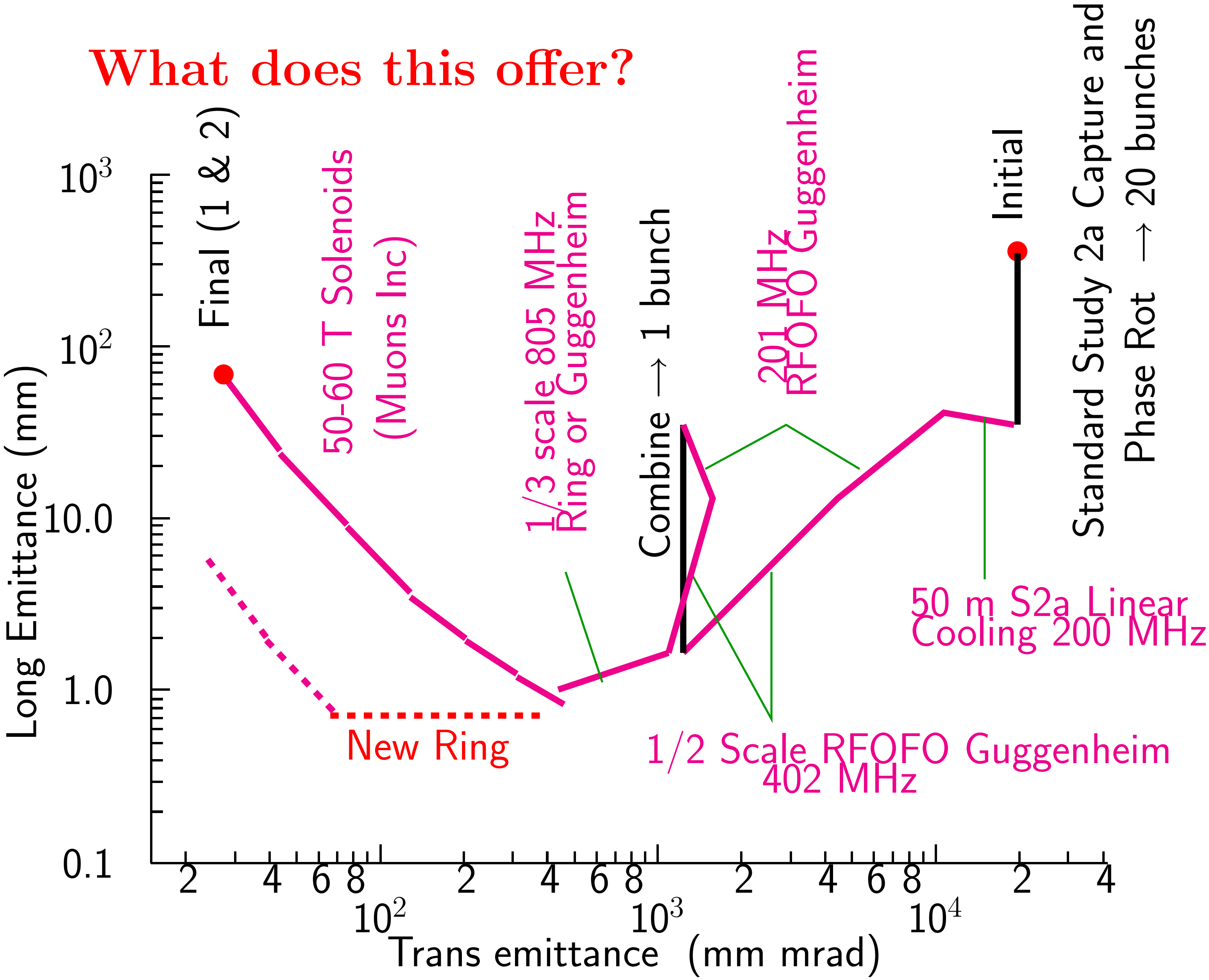
ICOOL simulation of Ring

- 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)
- Poor input matching Equilibrium $\epsilon_{\parallel} = 0.7\ \pi$ mm (dp/p=2.5%)
- But ring requires sixty 25 T HTS solenoids or Guggenheim 150 Solenoids !

What does this offer?



- Much lower final longitudinal emittance
- Less momentum spread in Collider Ring
- Or maybe lower transverse emittance by more emittance exchange (how?)

To Do

- Modify Guggengeim rings to avoid magnetic field on rf
- Look at space charge and loading
- Design matches and re-accelerations between 50 T solenoids
- Simulate bunch merging with actual lattice
- Taper Guggenheims
- Explore use of Super-Fernow lattices to get lower final emittances
- Explore if other systems are better
  (Helical, PIC, REMEX, Rees, Garren ....)

- We do not yet have a "demonstrable solution"
- But we are getting close