Muon Collider Design

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- Updated collider parameters
- Cooling scheme
- Work since last year
  - Space charge effects
  - Solutions to problem with rf in magnetic fields
  - Fast ramping synchrotrons for muon acceleration
  - Neutrino radiation
- Conclusion

Updated Collider Parameters

C of m Energy	1.5	4	8	TeV
Luminosity	1	4	8	10^{34} cm^{2}sec^{-1}
Beam-beam Tune Shift	0.1	0.1	.1	
Muons/bunch	2	2	2	10^{12}
Ring <bending field>	5.2	5.18	10.36	T
Ring circumference	3	8.1	8.1	km
Beta at IP $= \sigma_z$	10	3	3	mm
rms momentum spread	0.18	0.12	0.06	%
Muon Beam Power	7.5	9	9	MW
Repetition Rate	13	6	3	Hz
Proton Driver power	≈4	≈ 1.8	≈ 0.8	MW
Efficiency $N_\mu/N_{\mu o}$	0.07	0.07	0.07	
Trans Emittance	25	25	25	pi mm mrad
Long Emittance	72,000	72,000	72,000	pi mm mrad

For updated 1.5 TeV example:

- β^* has been increased (3→10 mm), reflecting new lattice studies
- For $\mathcal{L} = 10^{34}$: Rep Rate 6→13 Hz, Proton power 1.6→4 MW

Low vs. High Emittance Collider Parameters

e.g. 2.5 mm mrad vs. 25 mm mrad

- Luminosity, for given beam power and tune shift, independent of emittance

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

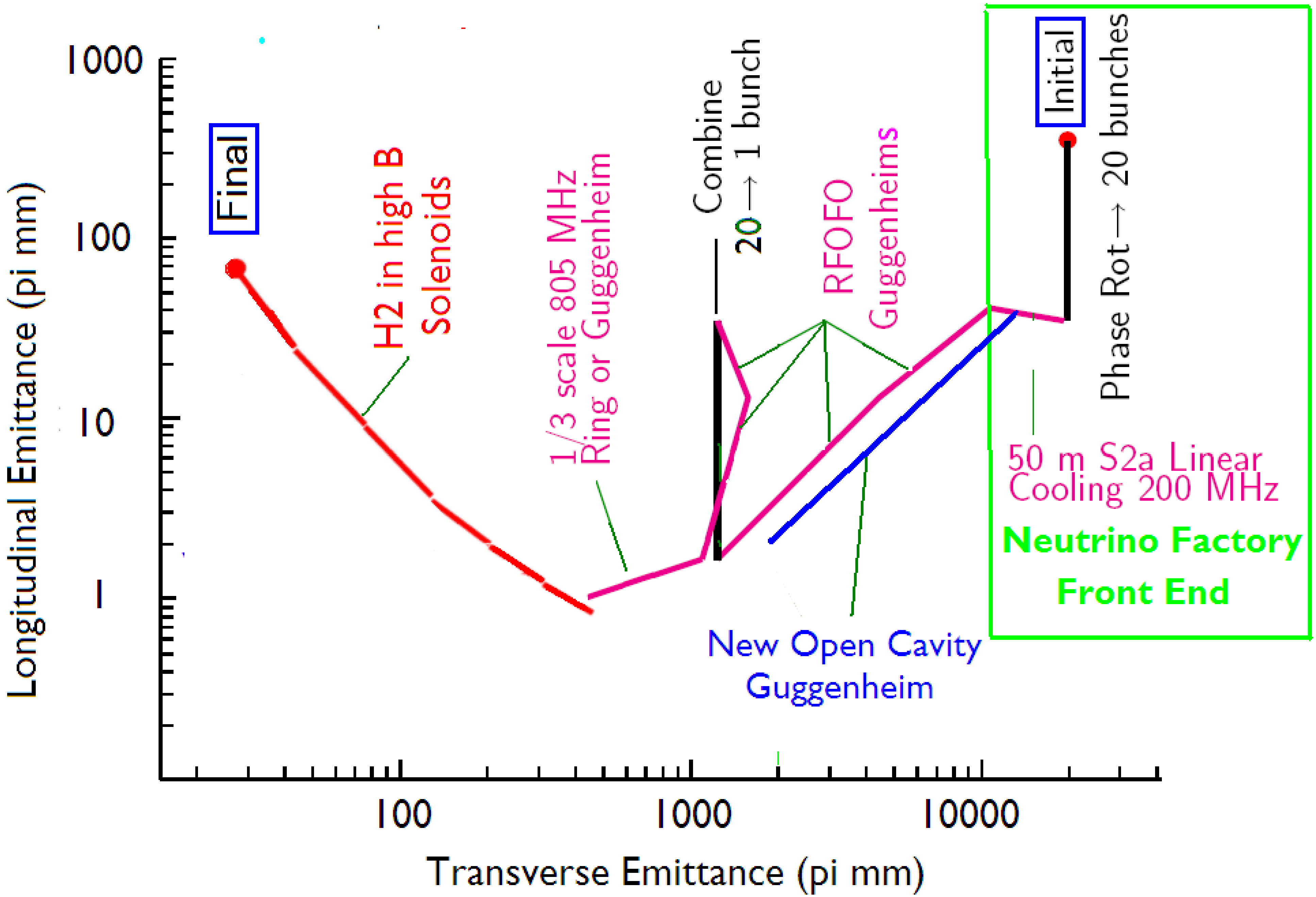
$$\mathcal{L} \propto B_{\mathrm{ring}}\, P_{\mathrm{beam}}\, \Delta\nu\, \frac{1}{\beta^*}$$

- But low emittance improves signal to background per bunch crossing

$$\mathrm{signal} \propto \Delta\nu = \frac{N_\mu}{\epsilon_\perp} \qquad \mathrm{background} \propto N_\mu$$

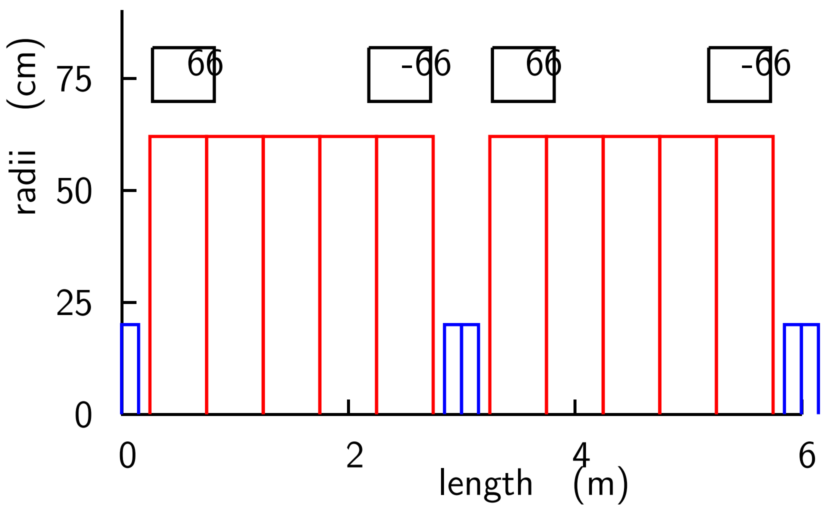
- So lowest practical emittance prefered
- But for this study we restrict ourselves to elements that can now be simulated
- "Low emittance" cooling (PIC and REMEX) do not yet have defined lattices and cannot yet be simulated. They have very challenging requirements.

Cooling Schemes **Work in progress in blue**

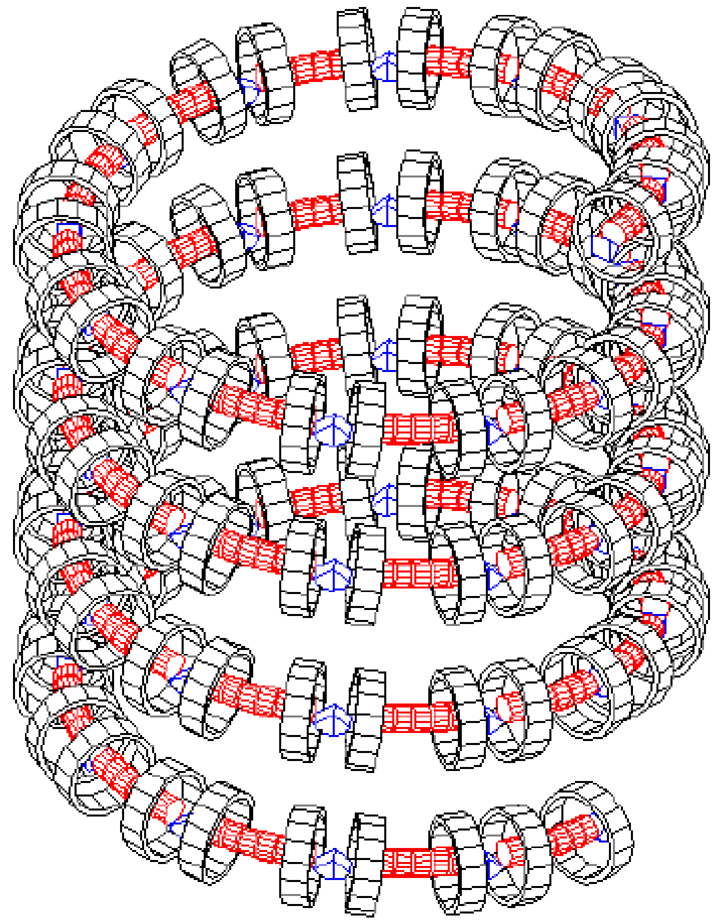


6 D Cooling in Guggenheim helices

- RFOFO lattices
- Bending gives dispersion
- Wedge absorbers give emittance exchange $\rightarrow$ Cooling also in longitudinal
- Use as 'Guggenheim' helix
  - Because bunch train fills ring
  - Avoids difficult kickers
  - Better performance possible by tapering
    Not yet assumed

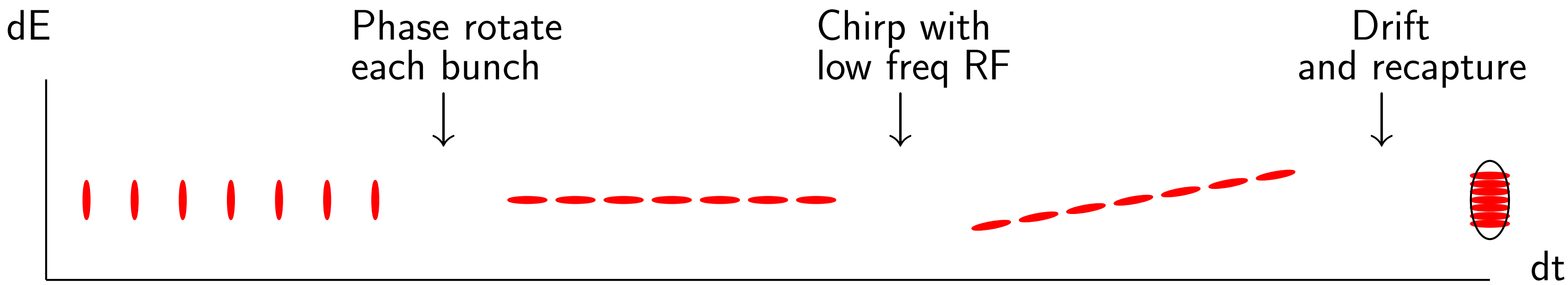


RFOFO Lattice

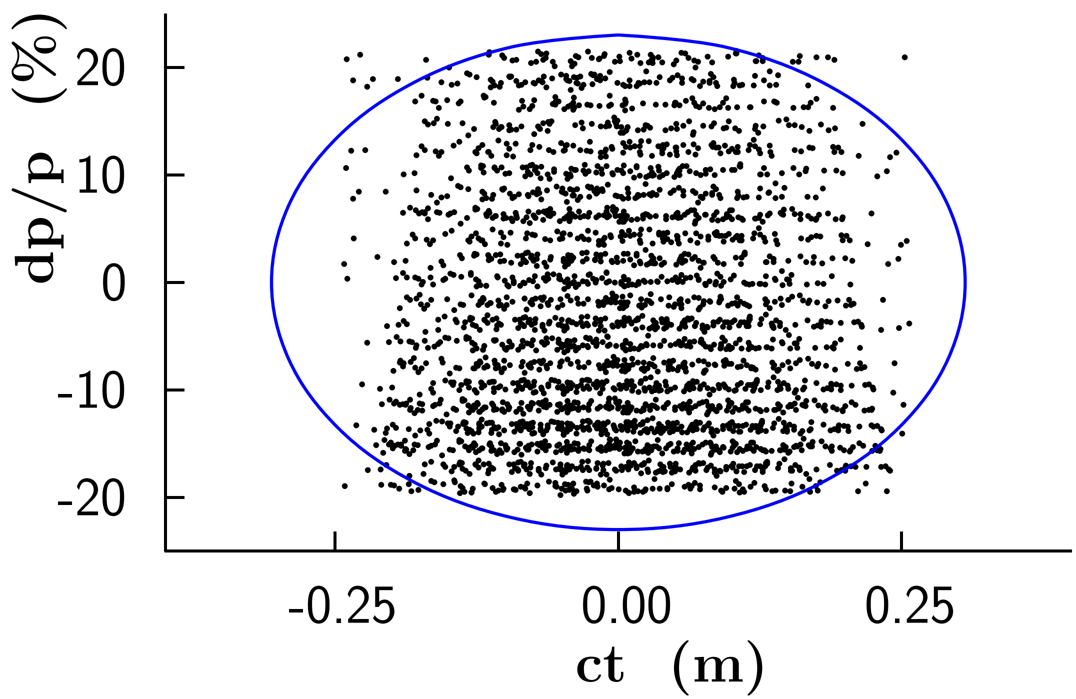


'Guggenheim'

Bunch Merging

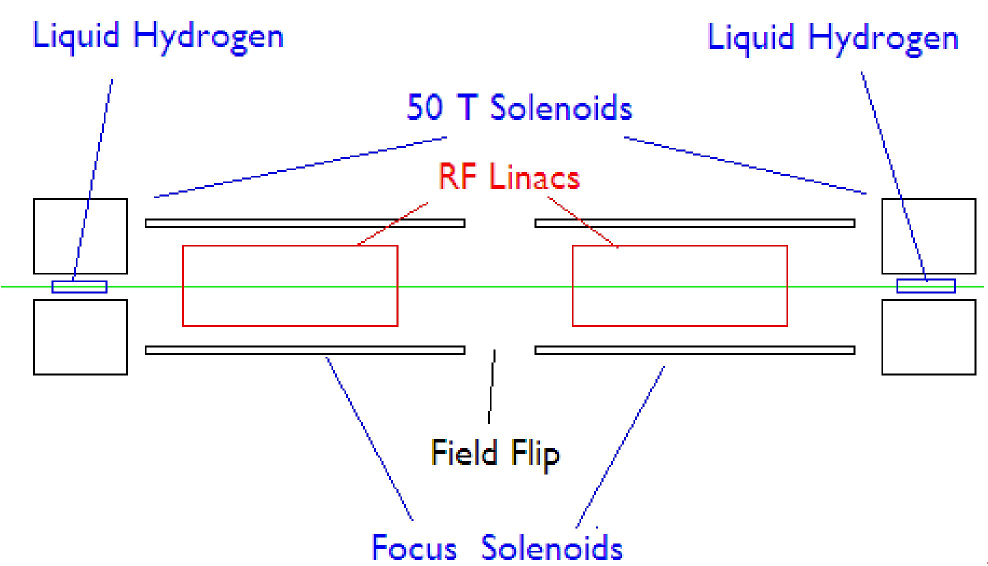


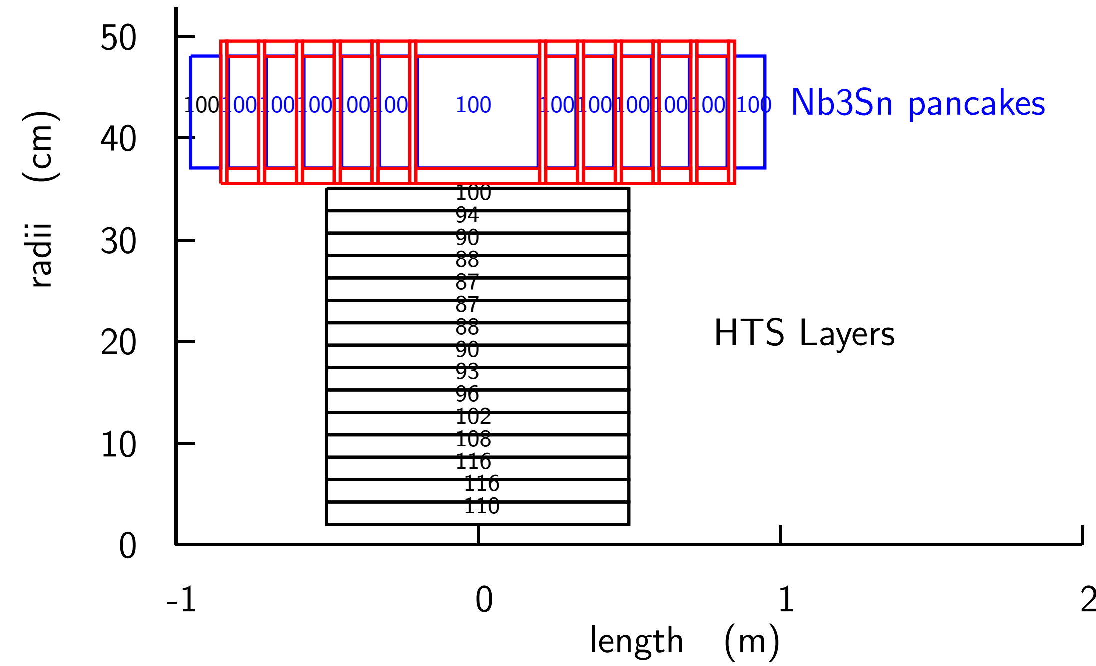
- Drifts in 1 T wigglers, simulated in ICOOL vs amp and mom
- rf: 1) at 200 MHz + 2 harmonics 2) at 5 MHz + 2 harmonics
  Simulated off line with parameters from ICOOL



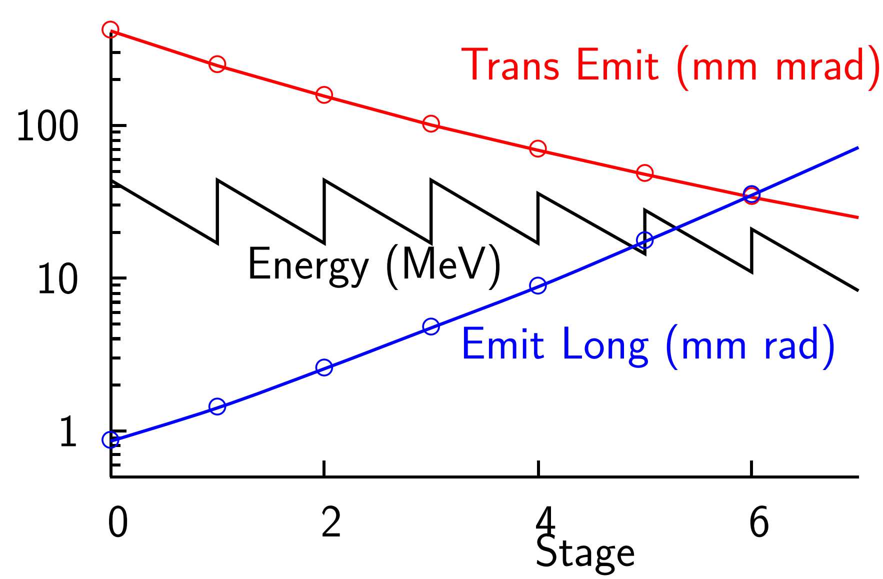
Cooling in linear sequence of very high field solenoids

With Muons Inc.

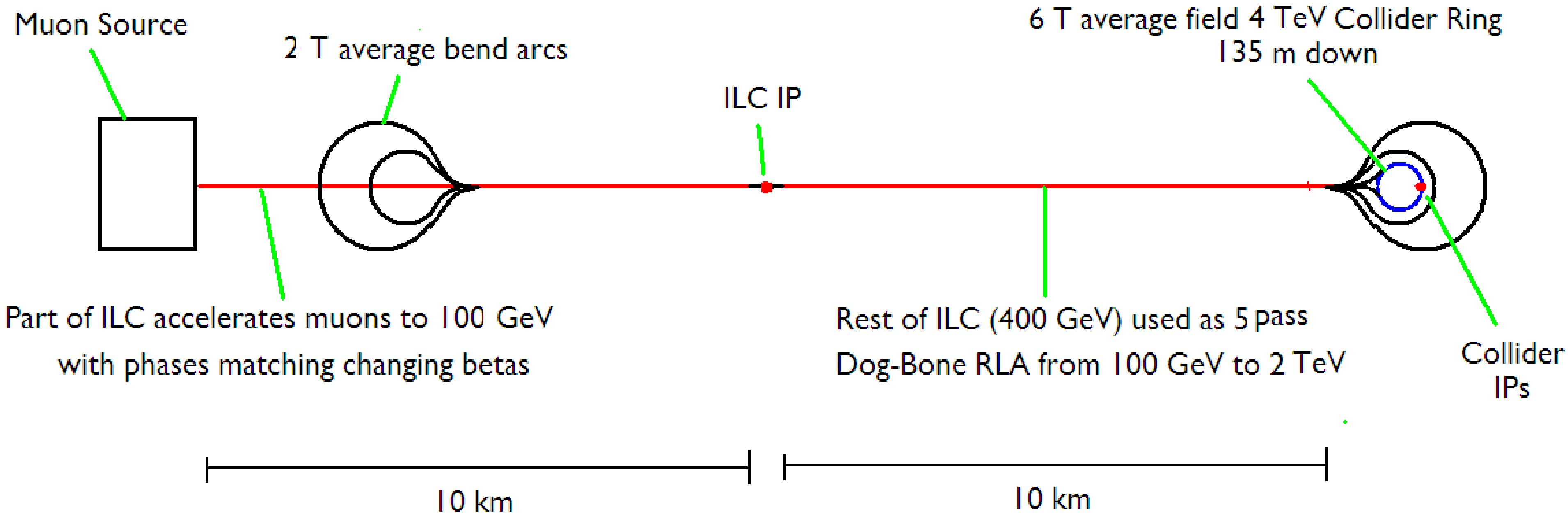




- Existing BSCCO HTS tape gave 50 T
  35 T would yield 1.5 $\times \epsilon_\perp$, 70% of $\mathcal{L}$
- 7 solenoids with liquid hydrogen
- Adiabatic matching to rf
- ICOOL Simulation
  - Ideal Matching and reacceleration
  - Transmission 97%



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

Last 4 slides shown last year

Since Last Year

1. Check Space Charge Effects
2. Possible solutions to problem with rf in magnetic fields
   (a) Gas filled cavities in helices
   (b) Gas filled cavities RFOFO lattices
   (c) Open vacuum cavities with coils in irises
   (d) HTS lattice with no field on rf
3. Study fast ramping Synchrotrons for muon acceleration
   Cheaper alternative to long RLAs
4. Consideration of neutrino radiation for 1.5 TeV collider

1) Space Charge Tune Shift ($\rightarrow$ spread)

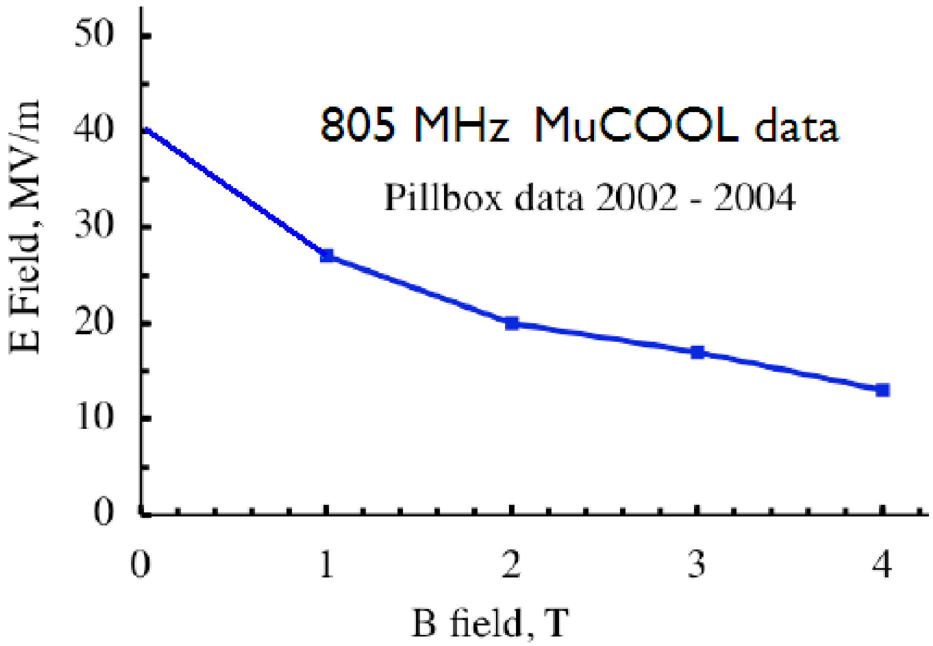
From S Y Lee, where $\epsilon_\perp$ is the normalized transverse emittance:

$$\frac{\Delta\nu}{\nu} = \left(\frac{N_\mu}{\epsilon_\perp}\right) \frac{<\beta_\perp> \; r_\mu}{\sqrt{2\pi}\sigma_z \; \beta_v \gamma^2}$$

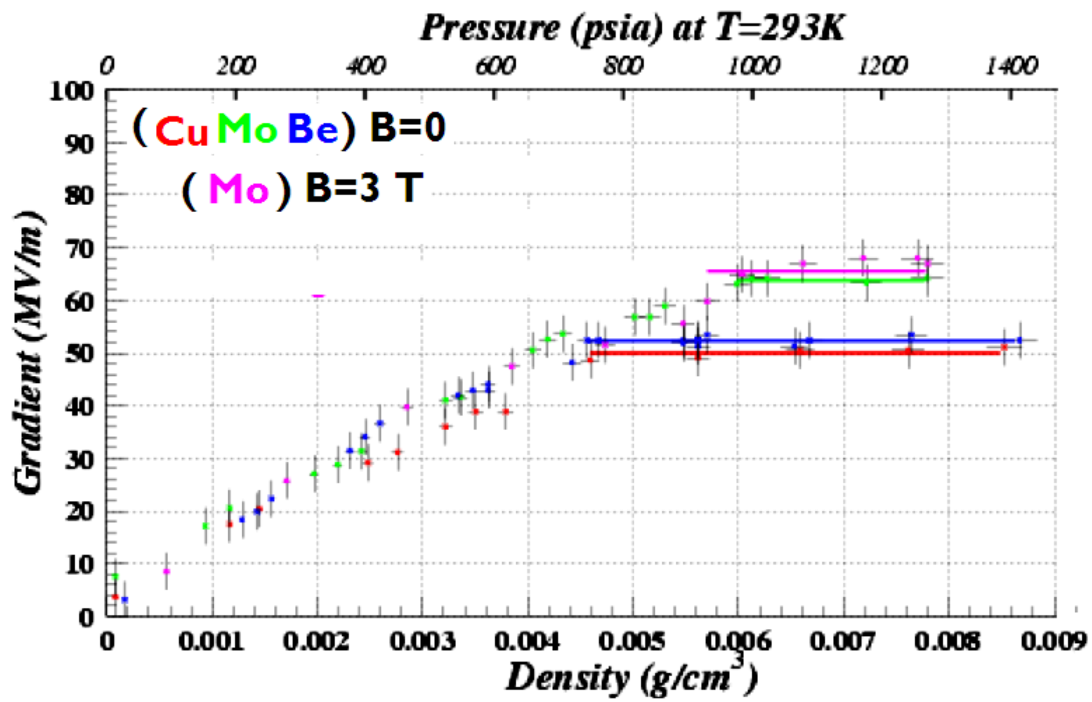
case	N_μ 10^{12}	$<\beta_\perp>$ m	σ_z m	$\epsilon_\perp$ mm mrad	p MeV/c	$\Delta\nu/\nu$
Last 50 T cooling	2.8	0.3	4	25	50	0.1
Last RFOFO Guggenheim	4	0.19	0.025	400	200	0.22
First RFOFO Guggenheim after merge	6	0.6	0.02	2000	200	0.24

- 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 $\Delta\nu/\nu$=0.75 so tune spreads of 0.22 & 0.24 will reduce the momentum acceptance of large amplitudes
  This needs to be included in simulations

2) Gas Breakdown in Magnetic fields



Vacuum



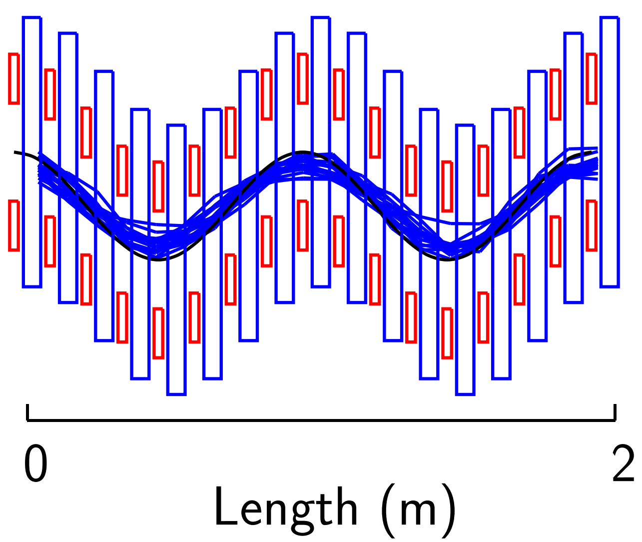
Gas

Possible solutions

- Live with lower gradients
  and suffer greater decay and acceptance losses
- Use gas filled cavities
- Use open cell cavities
- Shield the field from the cavities

2a) Gas filled helical lattices

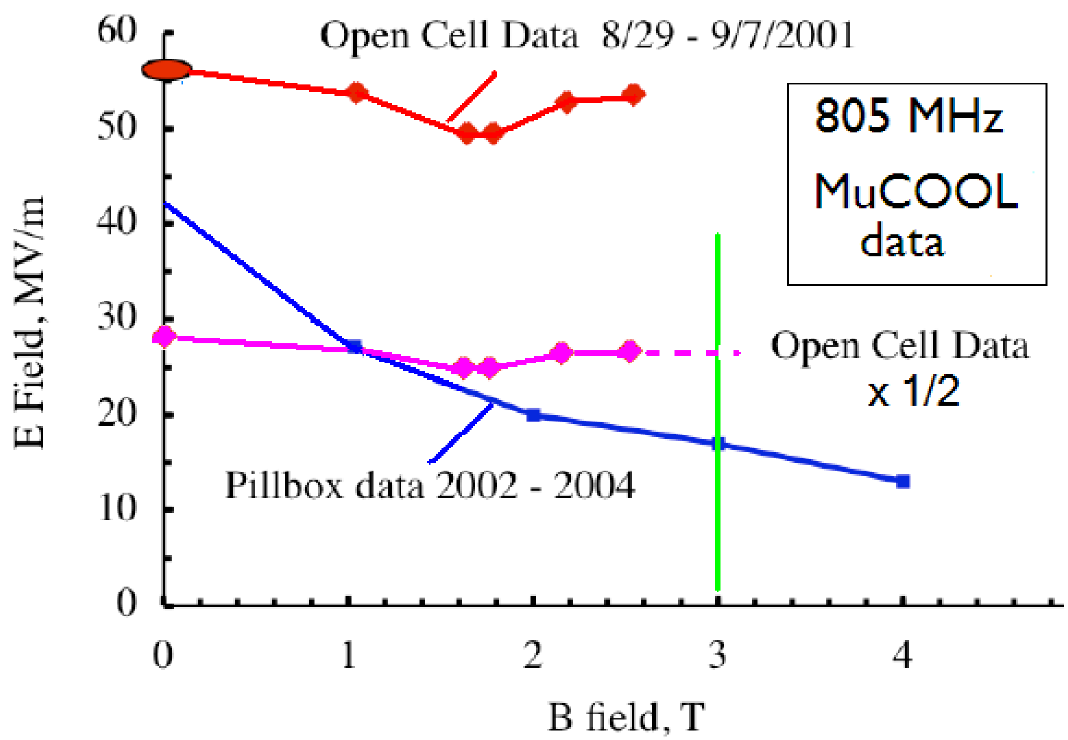
- No reduction observed from magnetic field
- Works well in simulations with ideal continuous fields and no (or magic) rf
  Including solenoid, and helical dipole, quadrupole and sextupole fields
- No simulated solution yet with real coils and rf cavities, and
- Will muon beam cause breakdown ?
  - Ignition source in an inflamable gas
  - Large high pressure volume with thin windows



2b) Adding gas to RFOFO Guggenheims

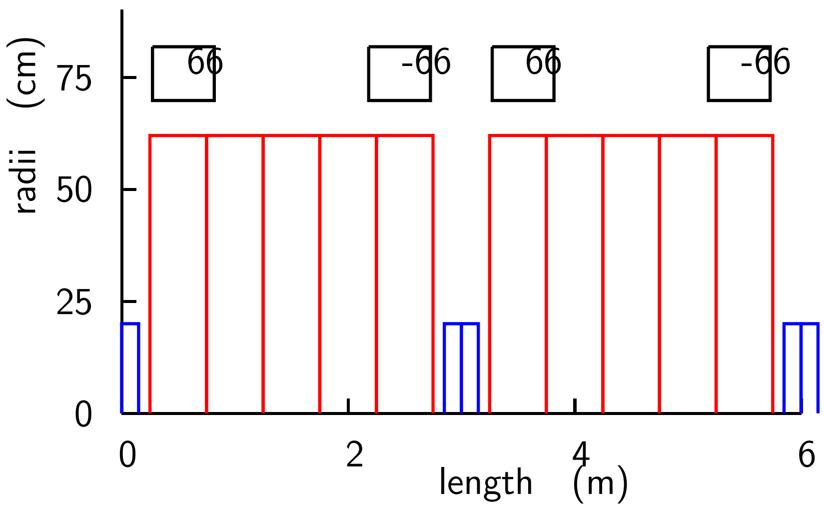
- Assume breakdown $\propto \sqrt{f}$
- Then we can use up to 28 MV/m at 201 MHz
- Simulations of Guggenheim lattices
  - Increased initial cooling rate
  - Higher final emittances
  - Probably viable but needs more study
- But will muon beam cause breakdown ?

2c) Open cell rf with coils in irises

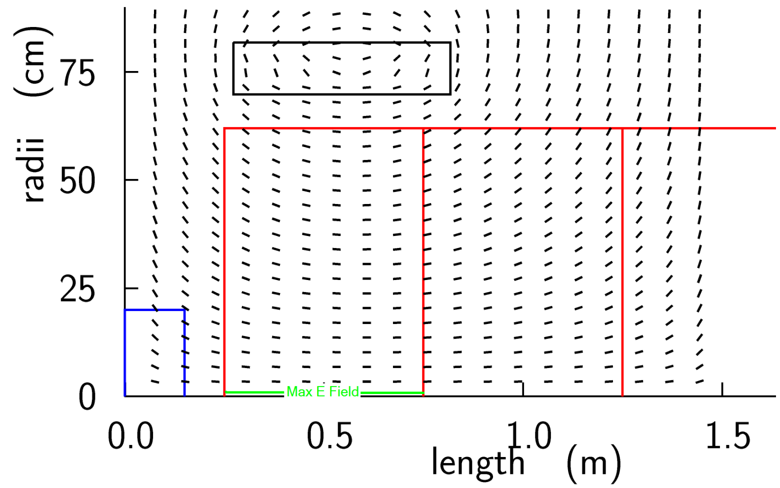


- B field effect on open cavity much less
  average field/surface fields ≈ 1/2
  but open cavity still better at 3 T
- Should be even better if coils in irises

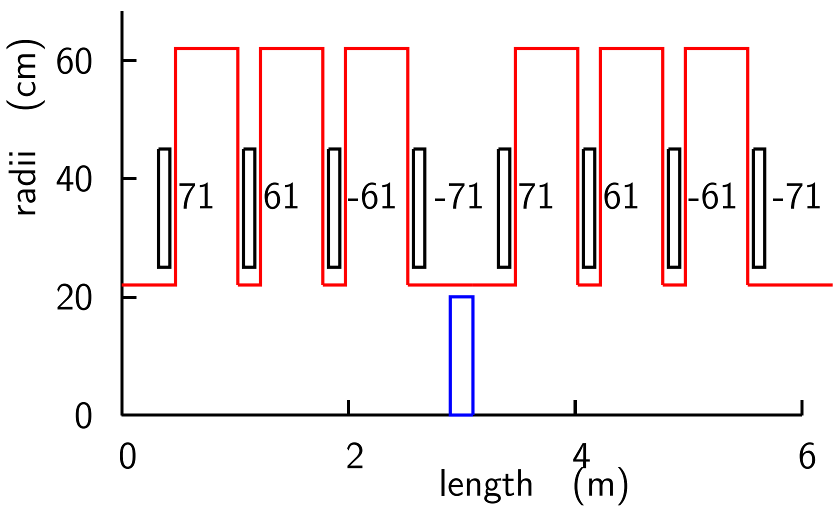
Compare RFOFO Guggenheim lattices



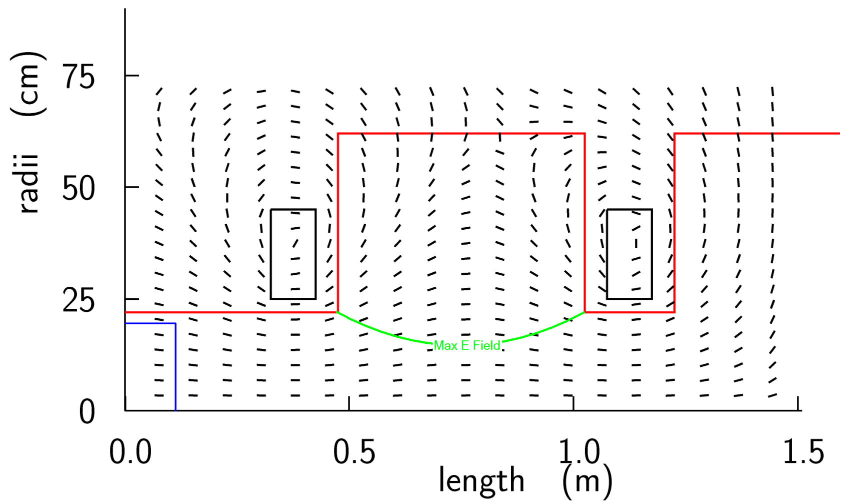
Old RFOFO (Coils outside rf)



Max E field || to B

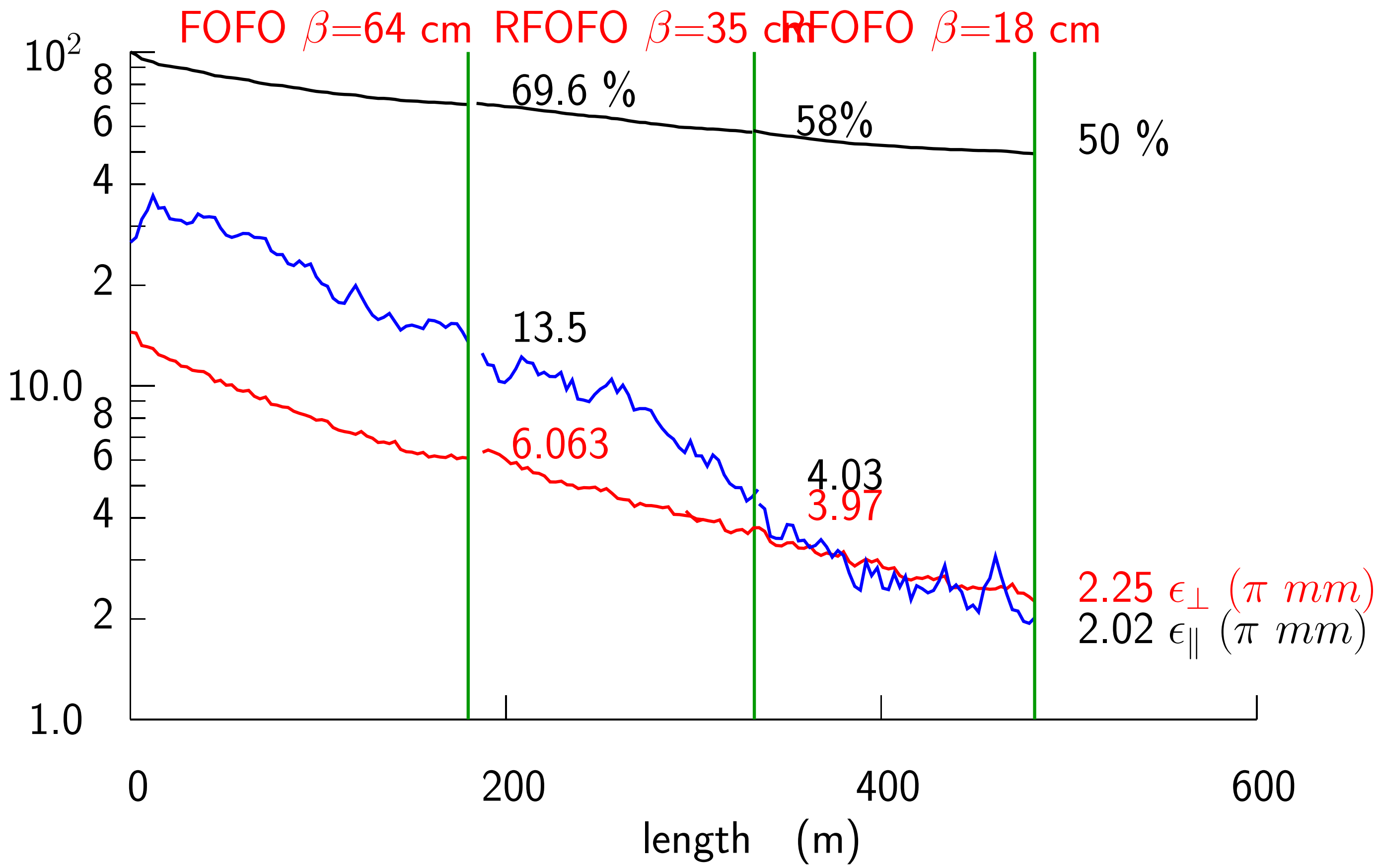


New RFOFO (Coils in irises)



Max E field ⊥ to B

Start of simulations of open cavity lattice cooling

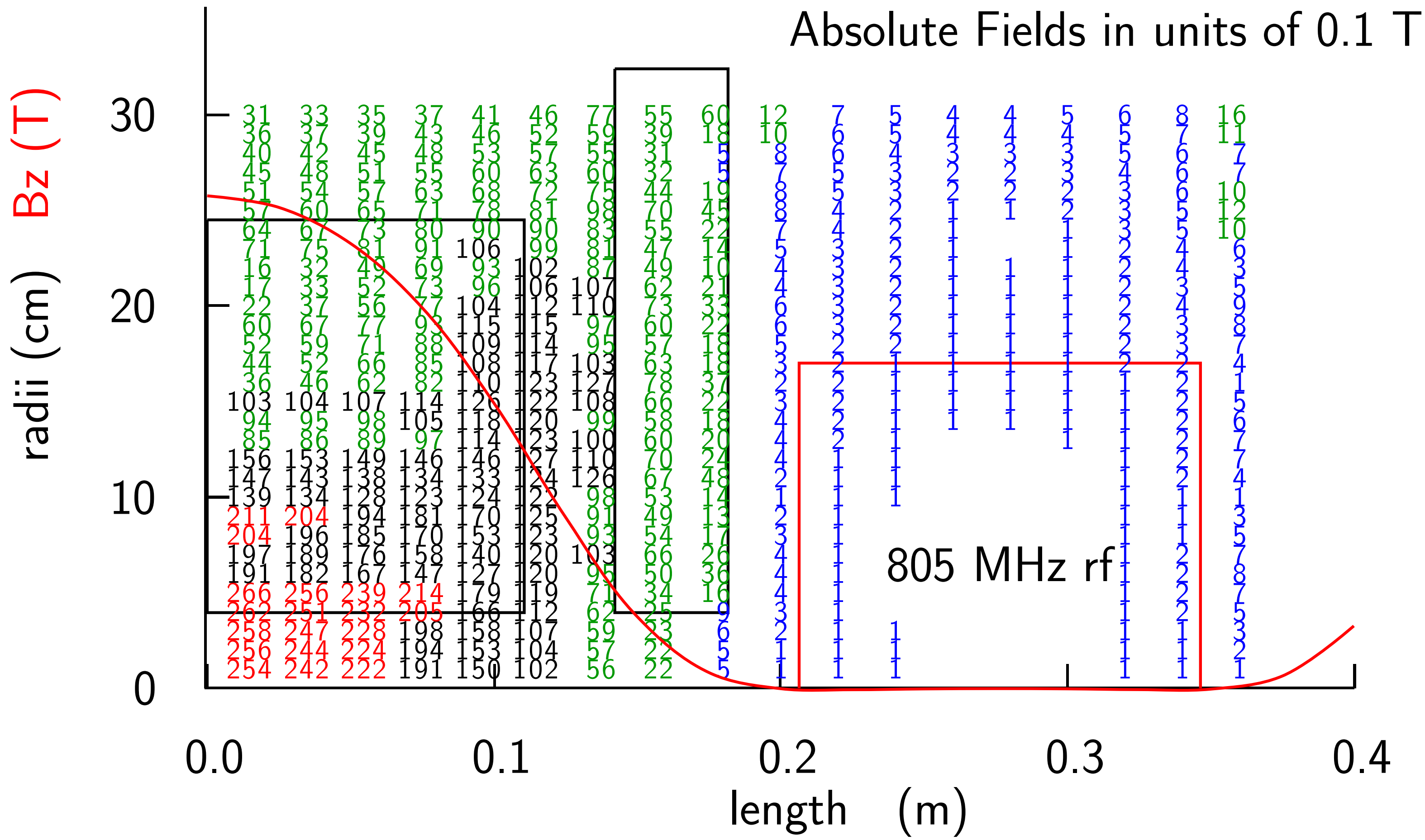


- This simulation gives lower emittances than previous 201 MHz simulations
- But is still work in progress

2d) Lattices with field shielded from Cavities

Only studied so far for a final Guggenheim with already small dp/p

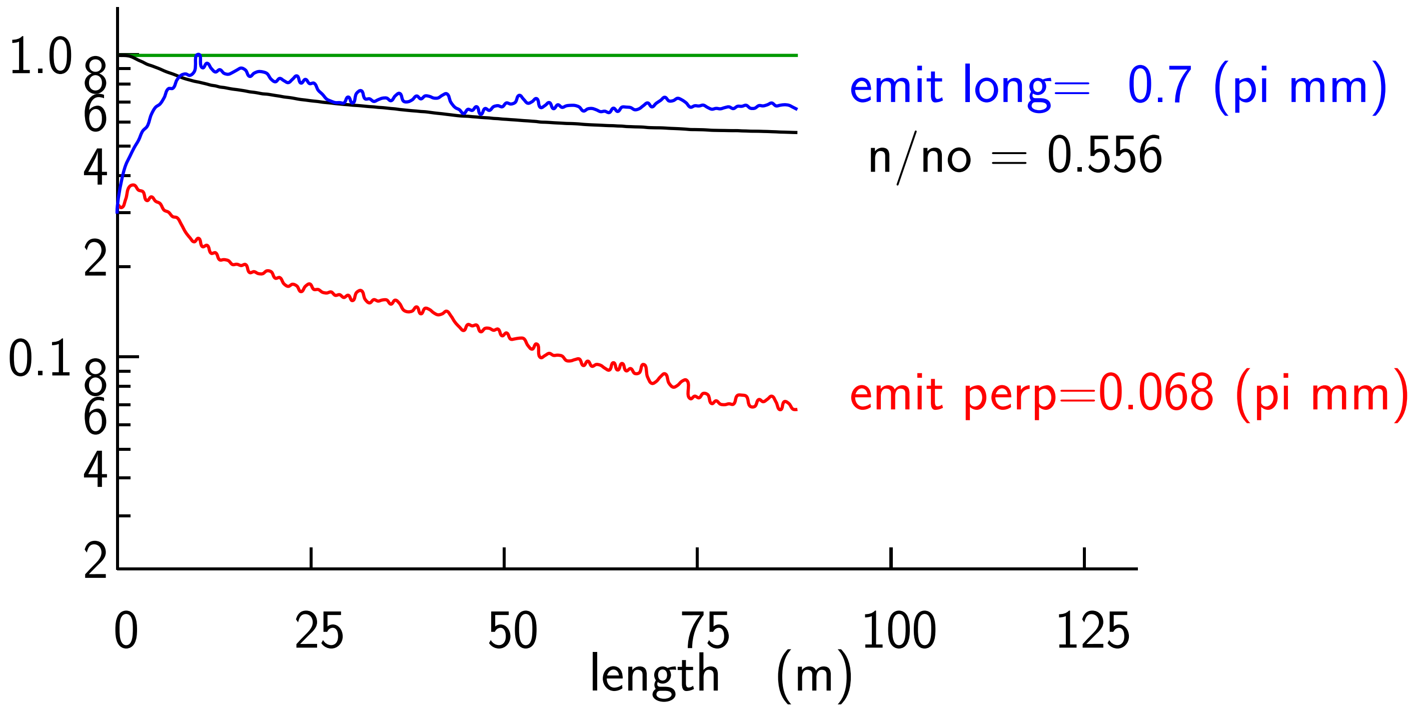
With HTS conductor at 4 deg for minimum beta and field at RF



- Beta is only 1 cm
- Field at the rf is less than 0.2 T
- If improved to < 0.1 T, Superconducting cavity could be used

ICOOL simulation

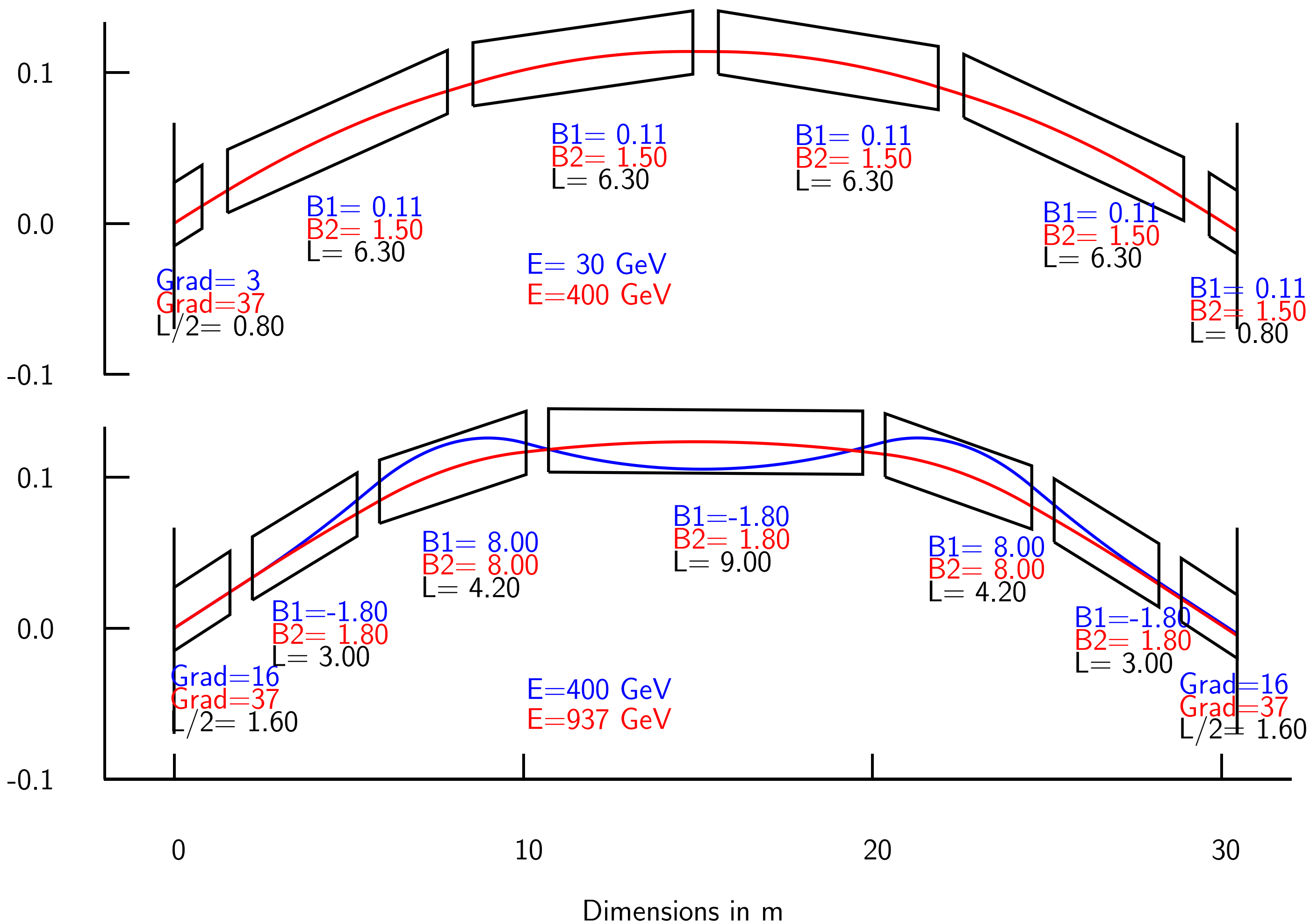
- 33 m circumference, 90 degree apex LiH wedges
- 14 cm long 805 MHz rf at 42 MV/m and 41 degrees



- 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%)
- Space charge tune shift too great ($\Delta\nu/\nu = .54$) & cost too high (60 x 25T)
- Can this concept be used for earlier cooling with lower fields?

3) Ramped Hybrid Pulsed Synchrotron D. Summers

- Linacs and RLAs to 30 GeV
- Pulsed Synchrotron 30-400 GeV (in Tevatron tunnel)
- Hybrid SC and pulsed synchrotron 400-750(930) GeV (also in Tevatron tunnel)



Details

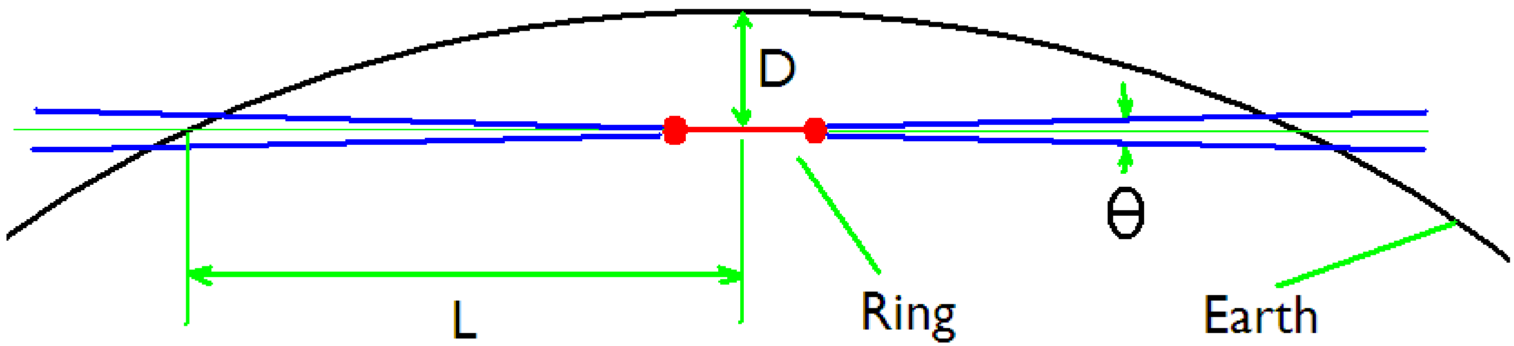
- Both rings have lattices similar to Tevatron
- In the Tevatron tunnel, but
- For 30-400 GeV
  - Ramped quadrupoles 2.2 to 30 T/m in 0.59 msec (400 Hz)
  - Ramped dipoles 0.13 T to 1.8 T in 0.59 msec (400 Hz)
  - 13 GV of superconduction 1.3 GHz rf
  - muon Survival 80%

  For 400-750(937) GeV
  - Longer ramped quads 13 T/m to 30 T/m in 0.92 msec (150 Hz) quads
  - Fixed 8 T dipoles, alternating with
  - Ramped dipoles -1.8 T to 1.8 T in 0.92 msec (550 Hz)
  - Dipoles initalty opposed, then act in unison
  - 8 GV of superconduction 1.3 GHz rf

More Details

- Magnet details
  - Pulsed magnets use .28 mm grain oriented Si steel ok at 1.8 T
  - Cables of multiple insulated 2 mm wires
  - OK single turn Voltage 3100 V
  - Losses in the yoke steel (520+910=1430 kW total at 13 Hz)
- rf details
  - 60 10 MW klystrons
  - 3 cells per coupler to keep cavities full during acceleration
  - Wall power: 22 MW to modulators, 3 MW to cryogenics
  - Loading is 8%: wakefields and HOM need study

Neutrino Radiation D. Summers



$$\text{Radiation} \propto \frac{I_\mu \, \sigma_\nu}{\theta \, L^2}\gamma \propto \frac{I_\mu \, \gamma^3}{D}$$

- Use: 1/10 Federal limit = 10 mR/year
- For D=135 m (ILC depth), and spherical earth: L≈40 Km
- But the Fox river is 29 m below Fermilab,
- So effective depth is 106 m and minimum L=35 Km
- 1.5 TeV, 13 Hz, Radiation from curved parts of ring = 0.13 mrem/year
- Straights, except where σ_θ is large as at IP, must be kept very short to keep maximum radiation $\leq$ 1 mrem/year

Conclusion

- More conservative IP parameters used for collider ring
  - Luminosity 1×10^{34} achieved by increasing rep rate to 13 Hz
  - Collider ring must now be deeper (eg 135 m) to control neutrino radiation
  - Proton driver power now $\approx$ 4 MW
- Probable serious problem with earlier cooling design is magnetic field on rf
  - Solutions with gas in cavities may work
  - Designs with open cell rf promising
  - A lattice for final 6D cooling has negligible field on rf
- Lower cost acceleration using pulsed magnets in synchrotons
  - Rings fit in Tevatron tunnel
  - Second ring uses hybrid of fixed and pulsed magnets
  - Uses grain oriented thin laminations and fine wire cable