Muon Collider Simulation

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MuTac

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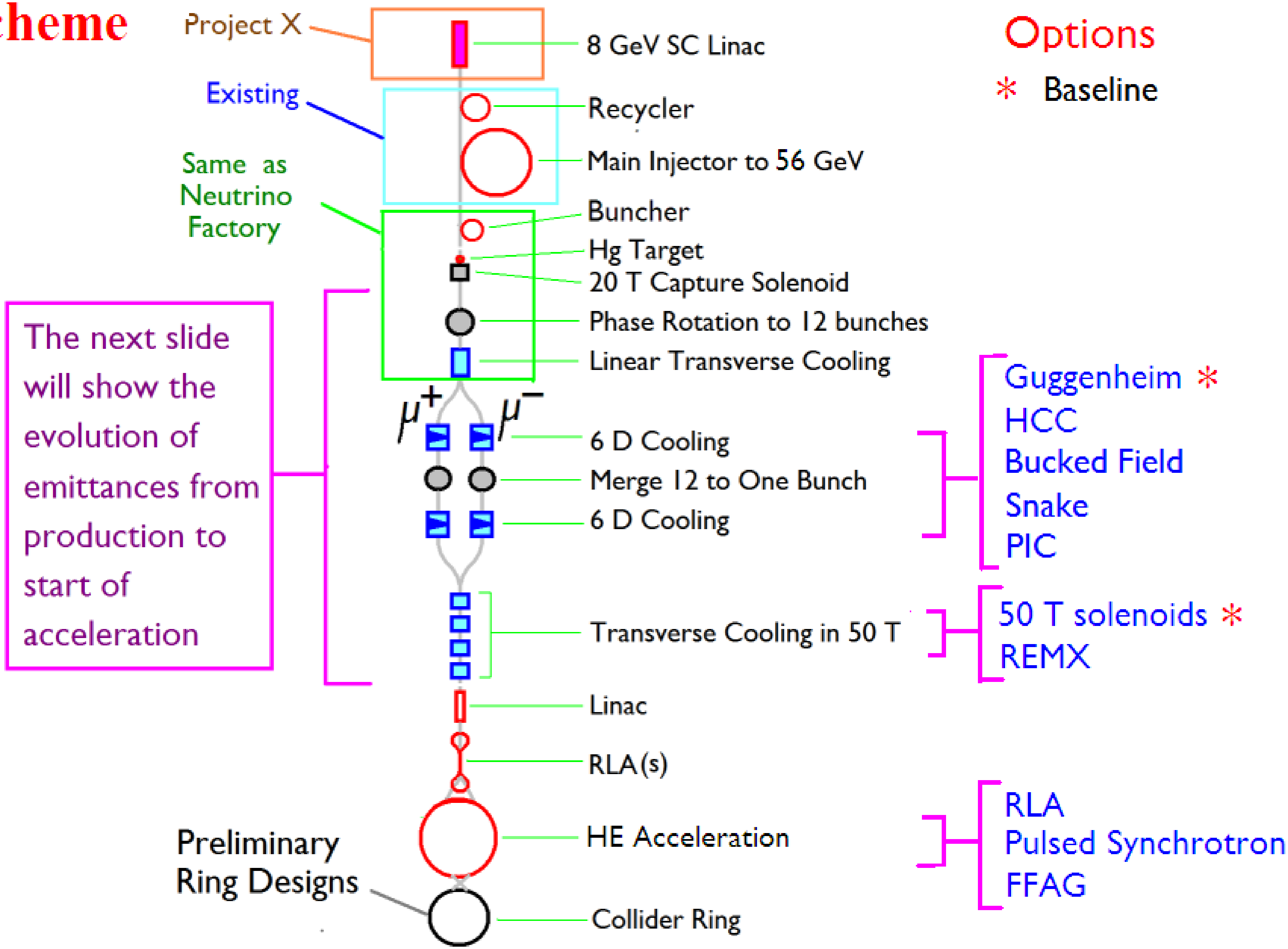
- Introduction and Parameters
- Status of sub-systems simulations
  - Phase Rotation
  - 6D Cooling
  - Final Transverse Cooling (reverse emittance exchange)
  - Acceleration
  - Collider Rings
- A critical issue: vacuum rf in magnetic fields
- Conclusion

Collider Parameters

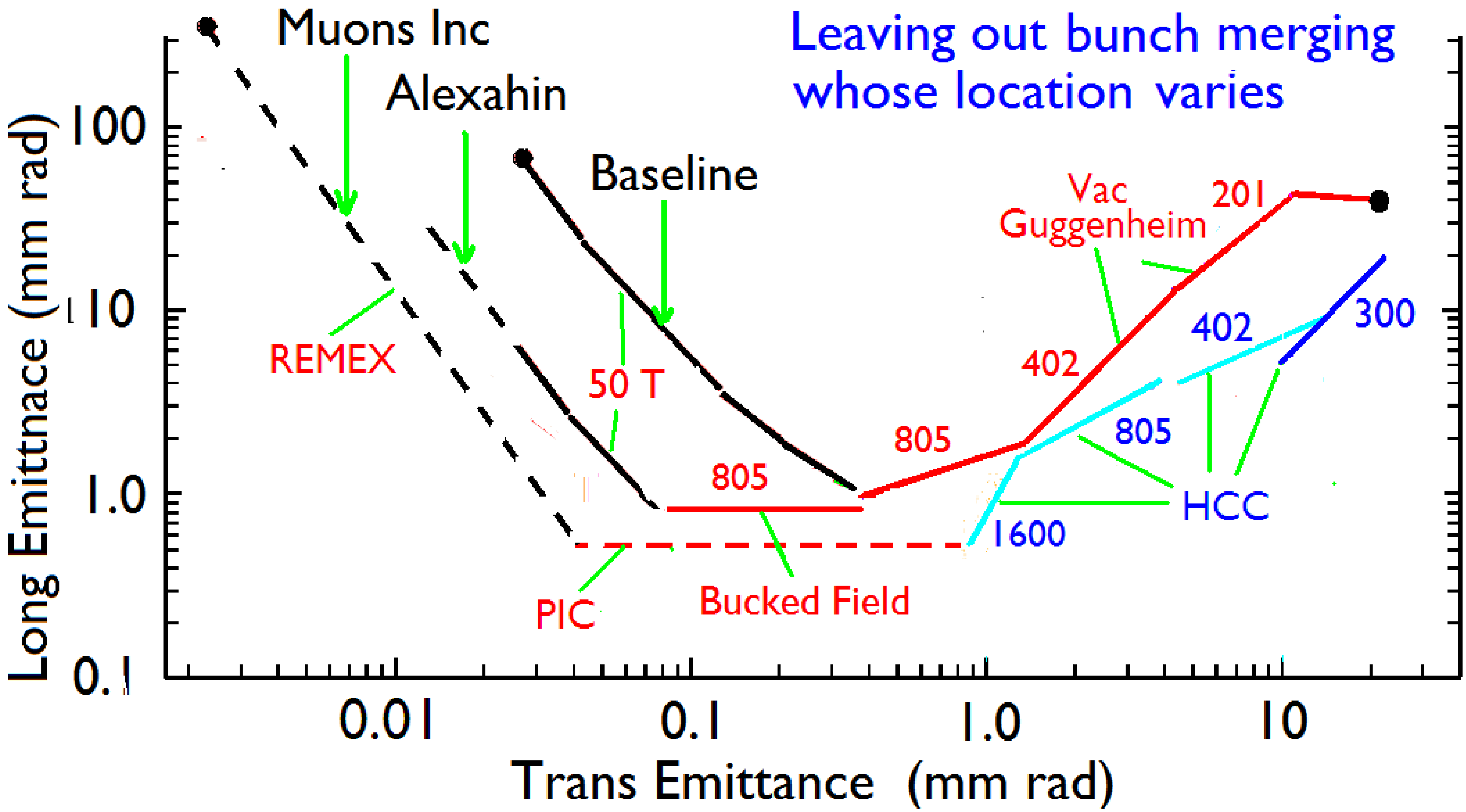
	Low emit	Base	Base	
C of m Energy	1.5	1.5	4	TeV
Luminosity	2.7	1	4	10^{34} cm^{2}sec^{-1}
Muons/bunch	0.1	2	2	10^{12}
Ring circumference	2.3	3	8.1	km
Beta at IP $= \sigma_z$	5	10	3	mm
rms momentum spread	1.0	0.1	0.12	%
Required depth for ν rad	35	13	135	m
Muon survival	0.3	0.07	0.07	
Repetition Rate	65	12	6	Hz
Proton Driver power	3.6	≈4	≈ 1.8	MW
Muon Trans Emittance	2.1	25	25	pi mm mrad
Muon Long Emittance	370,000	72,000	72,000	pi mm mrad

- Luminosities are comparable to CLIC's
- Baselines use real Collider Ring designs, though both have problems
- Baseline emittance and intensity requirement same for two energies
- Lower emittance desirable because allows (but more) smaller bunches
  but required 'Parametric Ionization Cooling' not yet simulated

Scheme


Project X
8 GeV SC Linac
Existing
Recycler
Main Injector to 56 GeV
Same as
Neutrino
Factory
Buncher
Hg Target
20 T Capture Solenoid
Phase Rotation to 12 bunches
Linear Transverse Cooling
μ^+
μ^-
6 D Cooling
Merge 12 to One Bunch
6 D Cooling
Transverse Cooling in 50 T
Linac
RLA(s)
HE Acceleration
Collider Ring
Preliminary
Ring Designs
The next slide
will show the
evolution of
emittances from
production to
start of
acceleration
Options
* Baseline
Guggenheim *
HCC
Bucked Field
Snake
PIC
50 T solenoids *
REMX
RLA
Pulsed Synchrotron
FFAG

Emittances vs. Stage



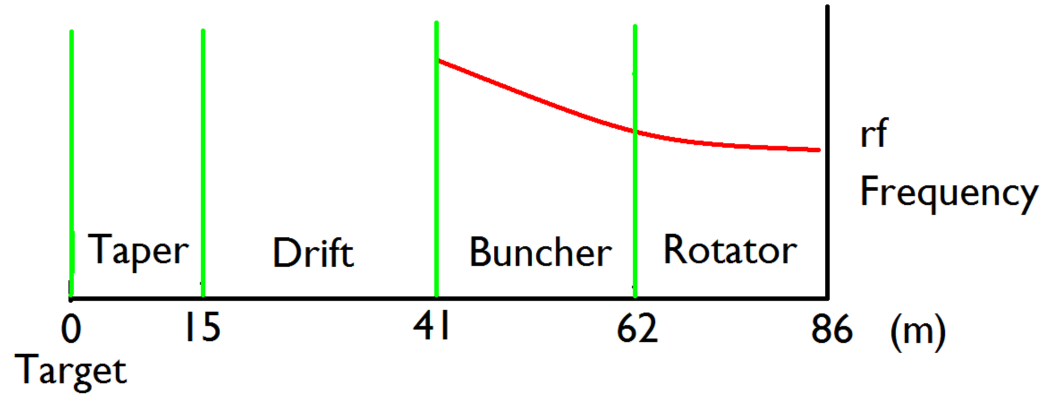
Muon survival shown in appendix 1

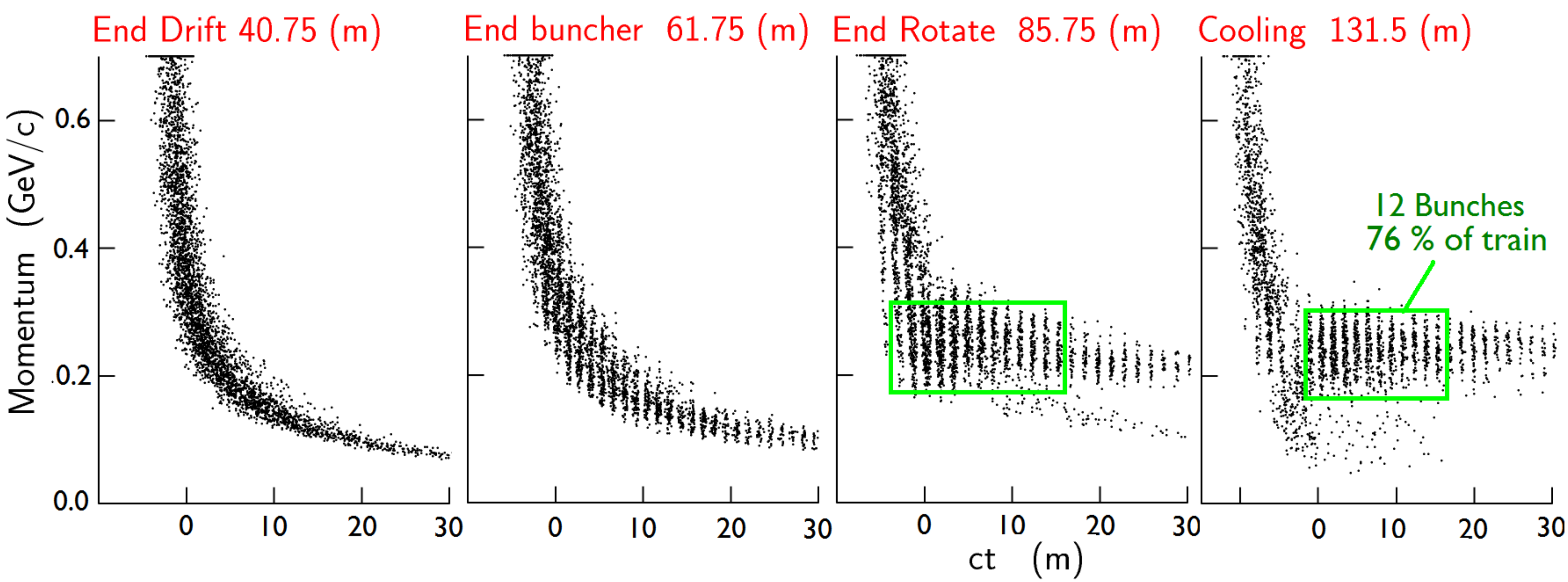
- Every stage of 'Baseline' simulated at some level, but with many caveats
- Dashed lines have not been simulated

Proton Driver (discussed in appendix 2)

Phase Rotate and Bunch (New version Neuffer)

After drift, rf is introduced to bunch the beam and then phase rotate it into approximately 12 (vs 21) good, nearly mono-energetic, bunches.



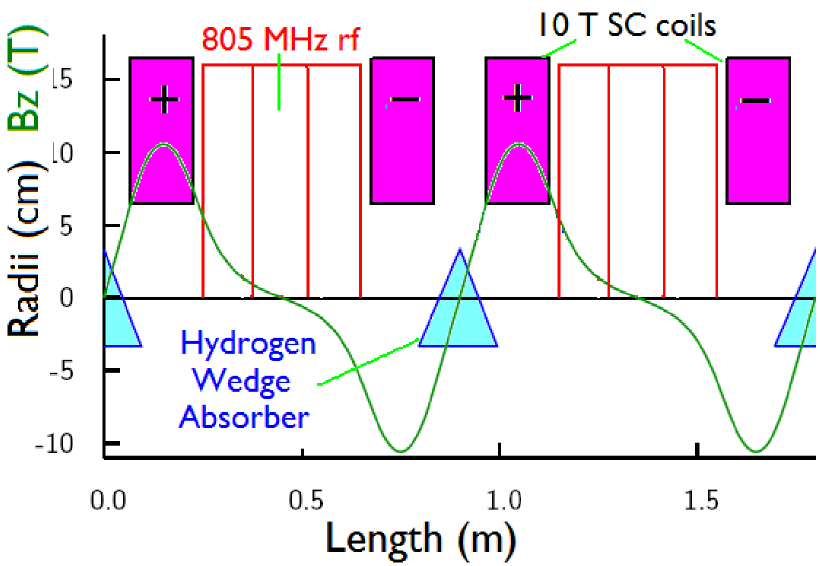


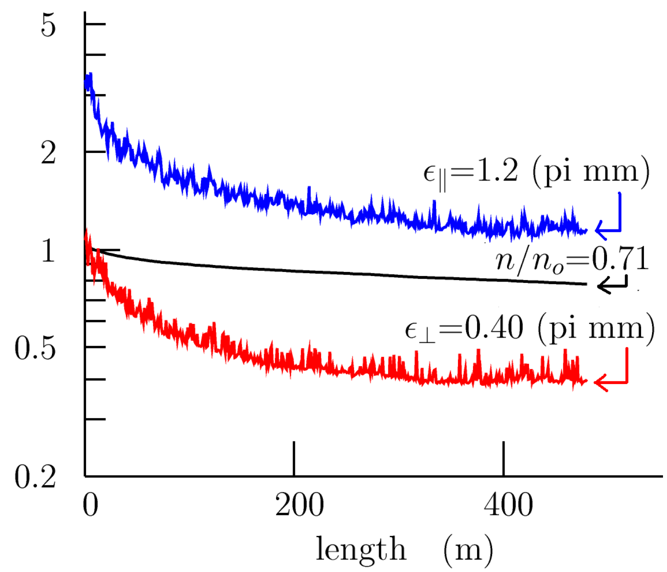
6D Cooling Several schemes under study

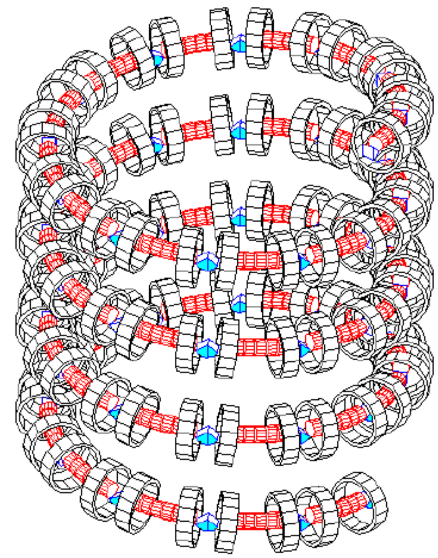
a) "Guggenheim" RFOFO Lattice (Palmer et al)

- Lattice arranged as 'Guggenheim' upward or downward helix
- Bending gives dispersion Higher momenta pass through longer paths in wedge absorbers giving momentum cooling (emittance exchange)
- Starting at 201 MHz and 3 T, ending at 805 MHz and 10 T
- Many simulations for ring Work in progress for true Guggenheim Snopok

e.g. 805 MHz 10 T cooling to 400 mm mrad



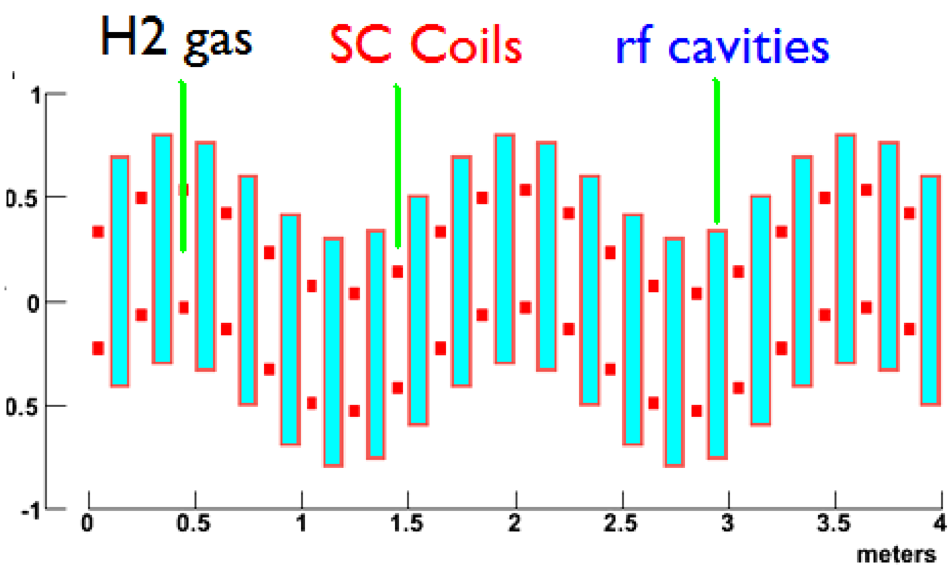


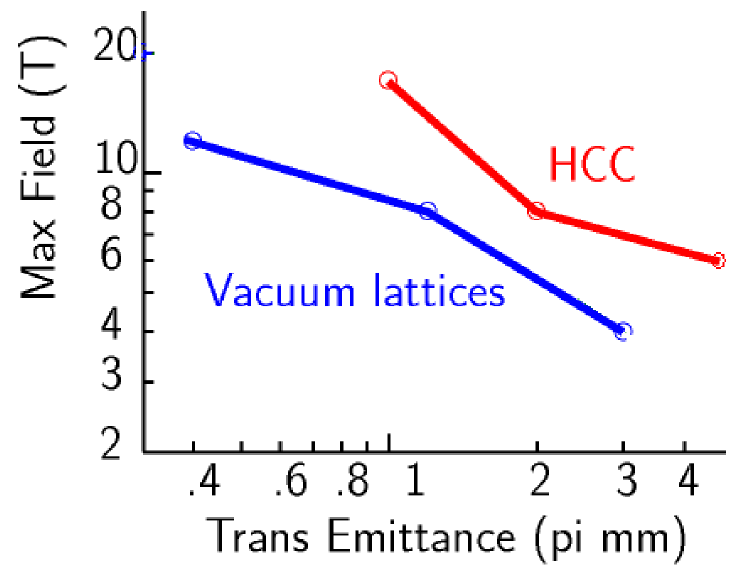


Possible/probable problem of rf breakdown in magnetic fields, as simulated

b) Helical Cooling Channel (HCC) (Derbenev et al)

- Muons move in helical paths in high pressure hydrogen gas
- Higher momentum tracks have longer trajectories giving momentum cooling





- Simulations (Balbekov) favor $\frac{\lambda_{\rm rf}}{\rm pitch} \approx 1.5 \quad \longrightarrow \quad \frac{r_{\rm cav}}{r_{\rm coil}} \approx 1.8$
- But studies (Kahn) indicate fewer coils per period may be ok
- Magnetic fields are higher than in vacuum lattices that can have low β foci

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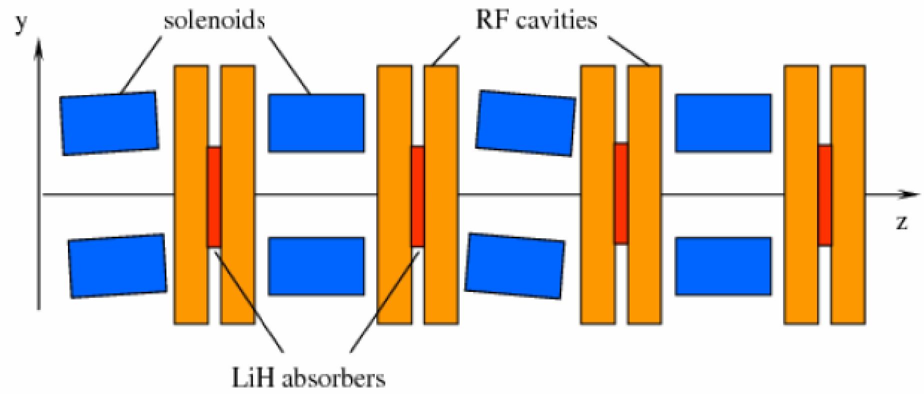
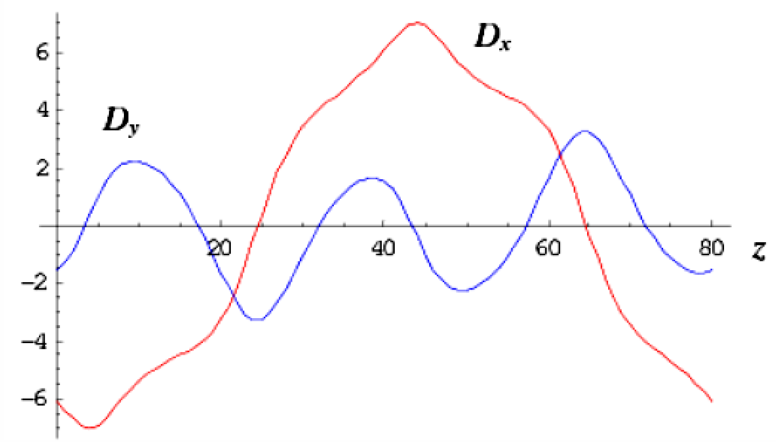
Engineering integration of rf not well defined
Possible problem of rf breakdown with intense muon beam transit

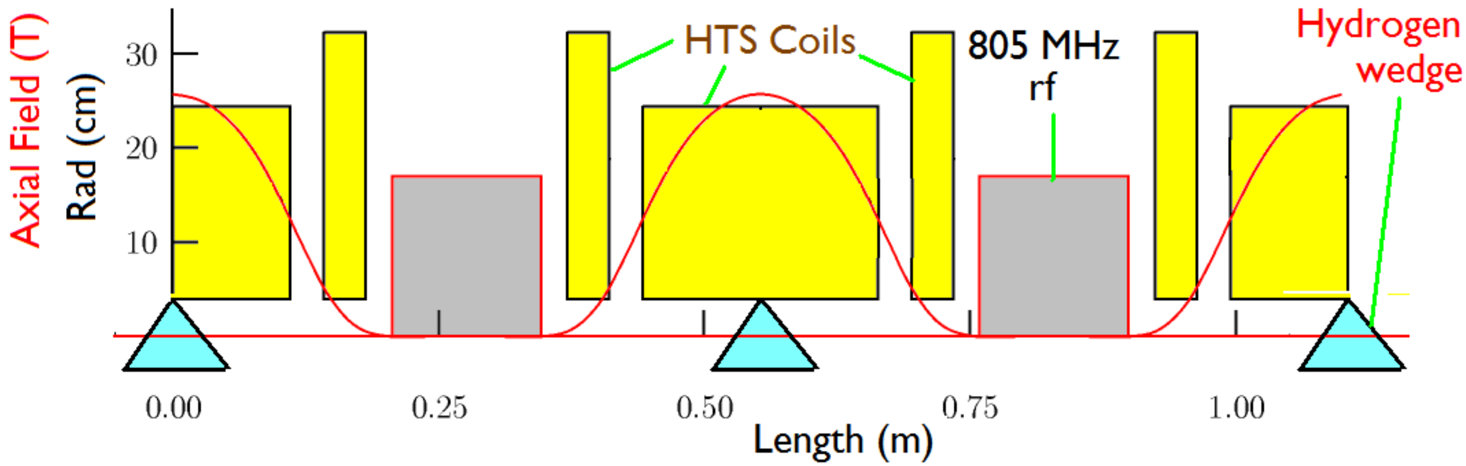
c) FOFO Snake Lattice (Alexahin)



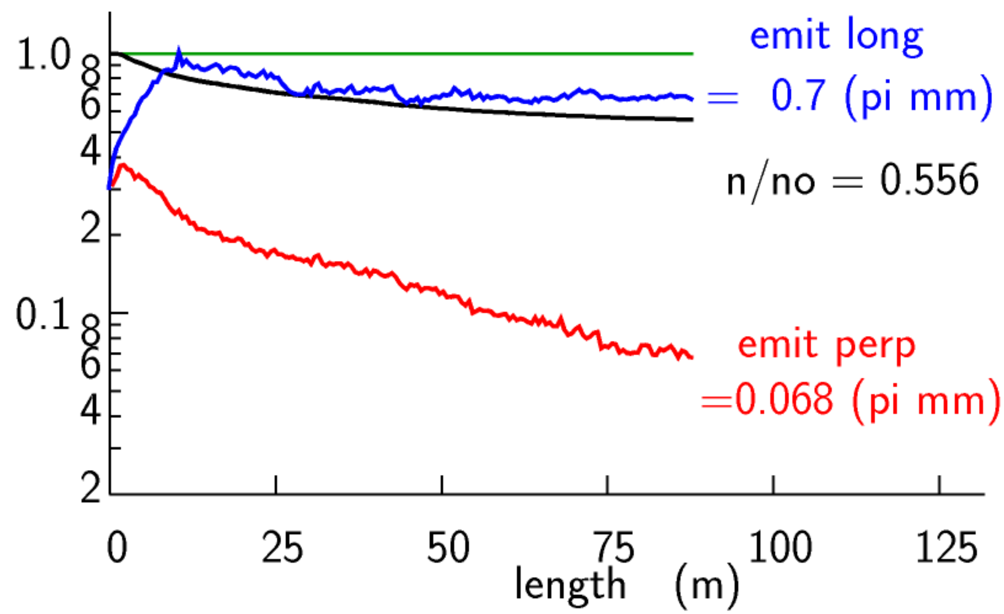


- With large enough aperture this could cool both muon signs simultaneously
- Has been discussed as high pressure gas filled plus LiH wedges but also viable with liquid hydrogen wedges
- Not yet simulated

d) "Bucked Field" non flip lattice (Fernow, Alexahin)

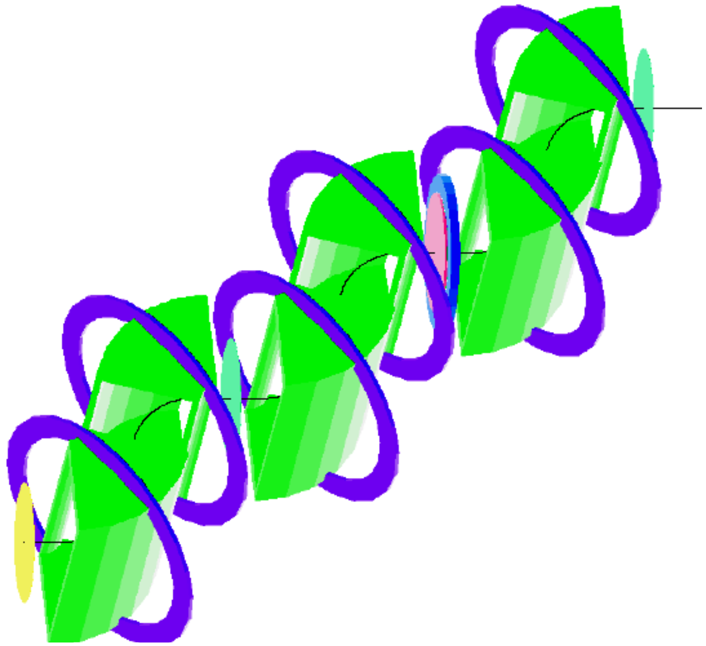


- $\Delta p/p$= 9.6 % ok for final cooling
- Bucking coils remove the field on RF
- 0.125 T By: 33 m circumference
- Transverse $\rightarrow$ 68 (mm-mrad)
  cf final = 25 (mm mrad)
- $\epsilon_{\|}$ = 0.7 π mm (dp/p=2.5%)

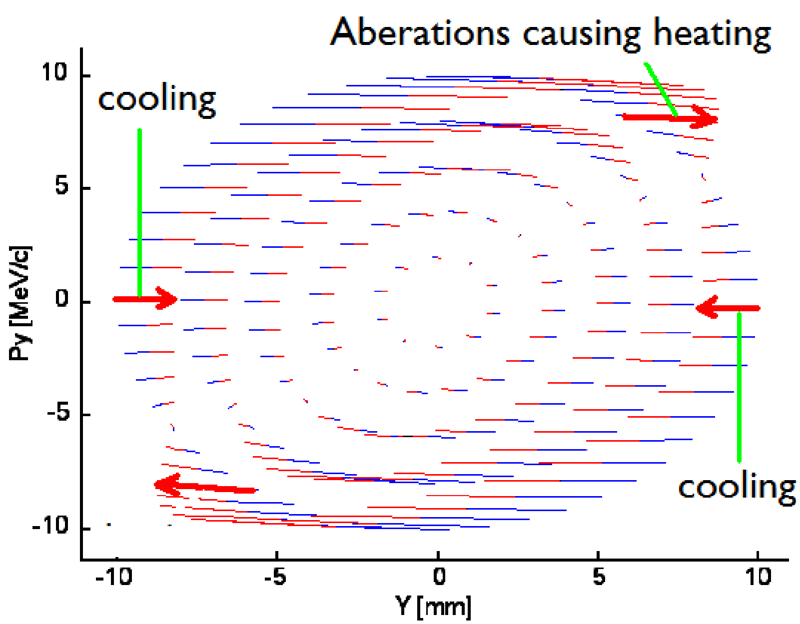


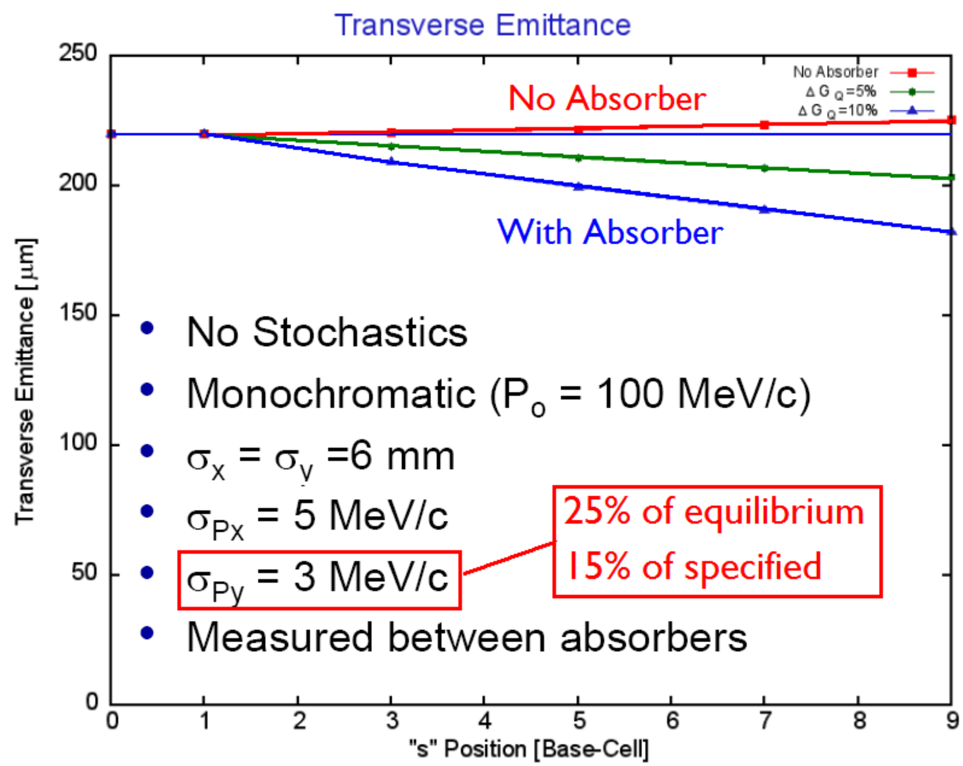
Loss rate greater than other systems - not fully understood

e) Parametric Resonance Cooling (PIC) (Derbenev, Newsham)



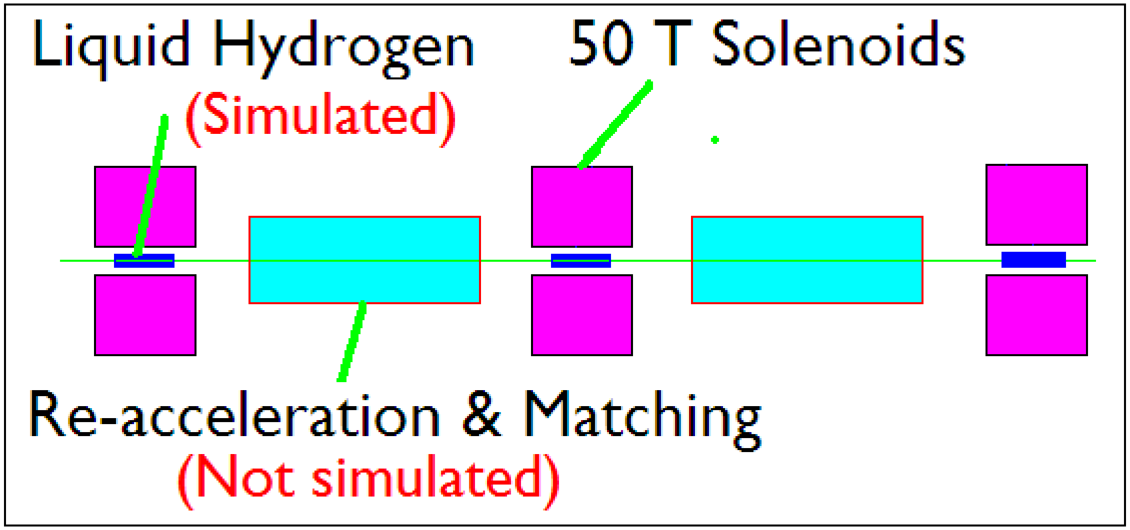
- Designed to be on 1/2 integer resonance
- Without material $\sigma_{x,y}$ shrinks & $\sigma_{px,py}$ grows
- With material and acceleration $\sigma_{x,y}$ shrinks & $\sigma_{px,py}$ are stable
- Demonstration lattice ok, but cools only without stochastic effects

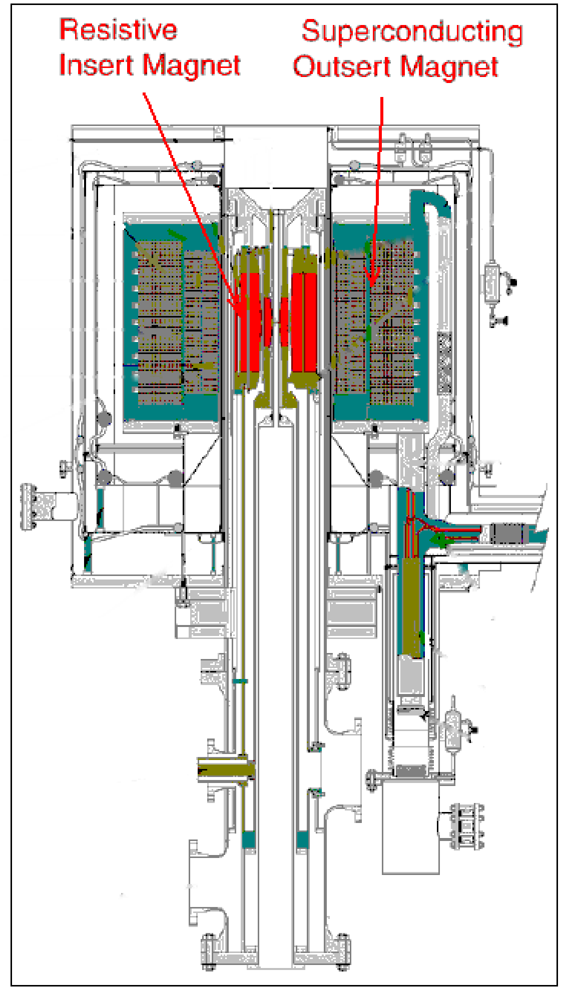




Final Transverse Cooling in High Field Solenoids

- Lower momenta allow transverse cooling to required low transverse emittance, but long emittance rises: Effectively reverse emittance exchange





NHMFL 45 T Hybrid Magnet

- ICOOL Simulation of cooling
  but with ideal matching & re-acceleration
- 45/50 T Solenoids
  - 45 T hybrid at NHMFL, but uses 30 MW
  - 30 T all HTS under construction
  - 50 T Design with HTS tape has rad=57 cm
- Parameters at each stage in appendix 3

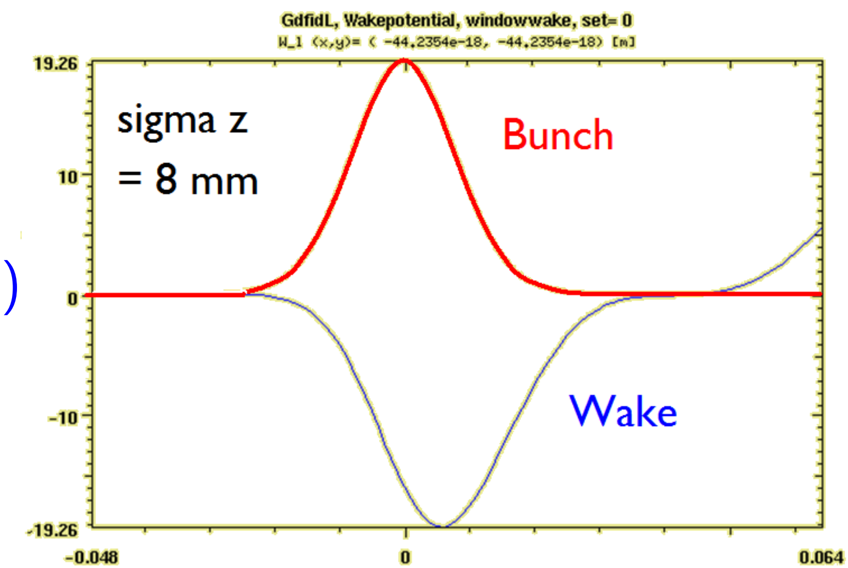
Acceleration

- Sufficiently rapid acceleration is straightforward in Linacs and Recirculating linear accelerators (RLAs)
- Lower cost solution would use Pulsed Synchrotrons (Summers)
  – Pulsed synchrotron 30 to 400 GeV (in Tevatron tunnel)
  – Hybrid SC & pulsed magnet synchrotron 400-900 GeV (in Tevatron tunnel)

Use of 1.3 GHz SCRF for 2×10^{12} muon bunches

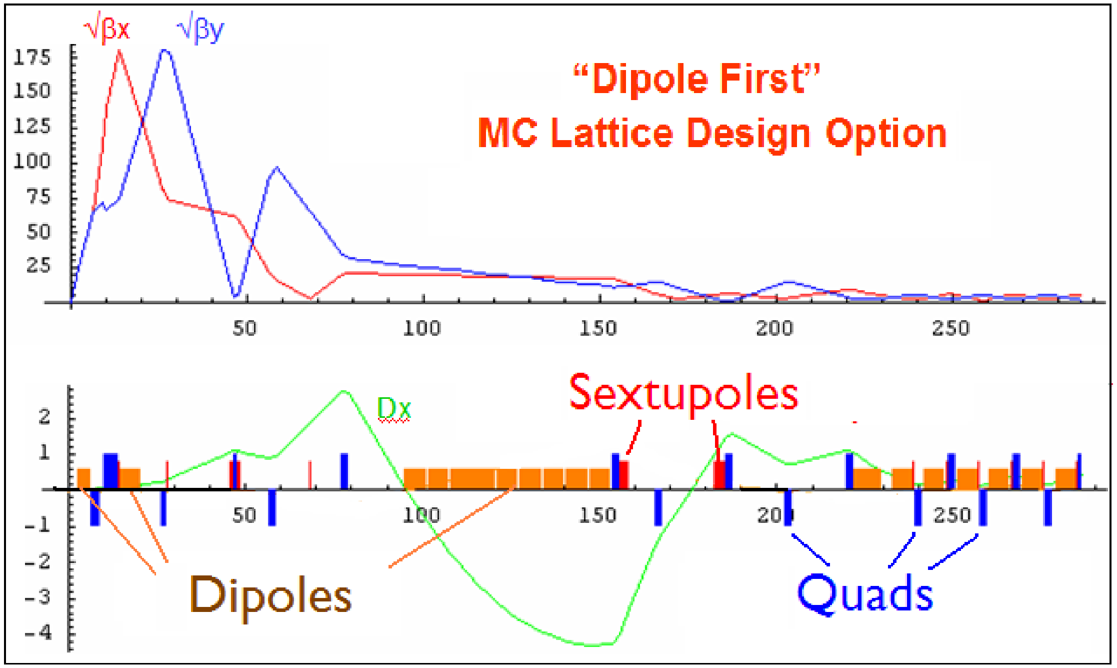
(Yakovlev, Solyak)

- Using standard ILC cavities
  – Bunch must be long e.g. 8 mm
  – Short range long wake=6.2 MV/m
  – Drop of fundamental= 1.3 MV/m
  – Trans wake= 14.4 MV/m^2 (1000× ILC)
- All reduced with 805 MHz vs 1.3 GHz
  – But wall power up by 1.7
  – And no 10 MW rf source



Collider Ring

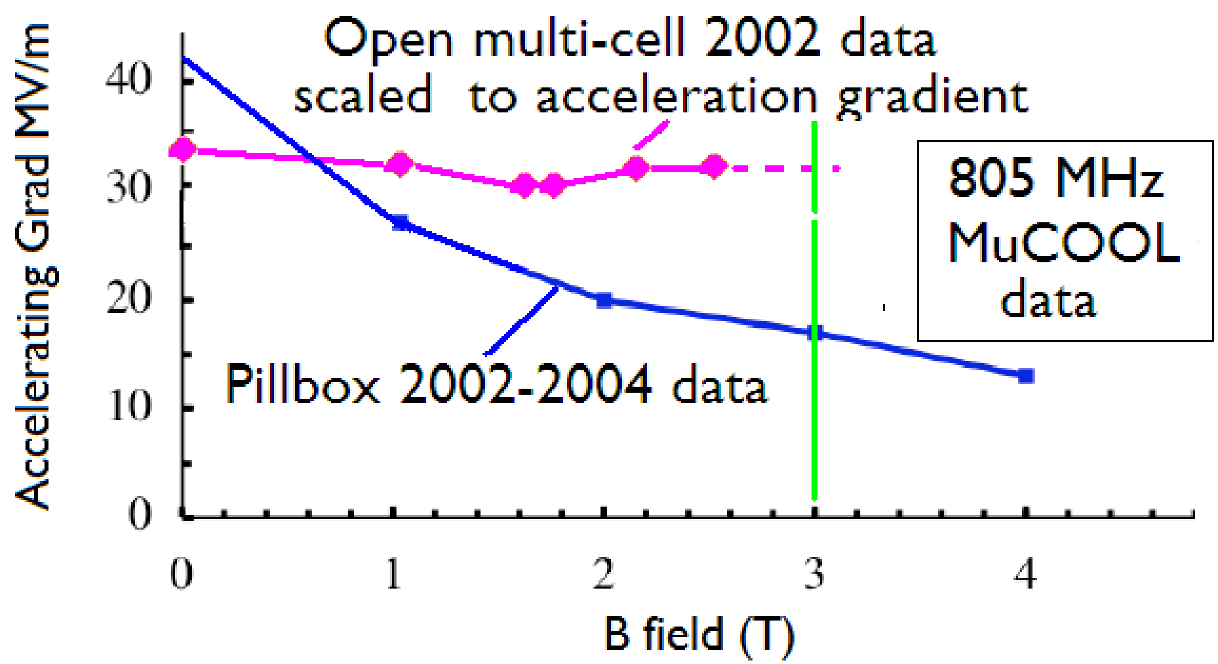
- 1.5 TeV (c of m) Design (Alexahin, Gianfelice-Wendt)



  - Nearly meets requirements
  - But early dipole may deflect unacceptable background into detector
- 4 TeV (c of m) 1996 design by Oide
  - Meets requirements in ideal simulation
  - But is too sensitive to errors to be realistic (Alexahin)
- Solutions without dipole first (Johnstone)
- Work also on a Low emittance ring but dp/p 0.3% not 1.0 % (Bogacz)

A Critical issue

- Vacuum acceleration is needed in all schemes (Guggenheims, PIC or other) for low emittance 6D cooling
  - Focusing needed to get low beta
  - Gas, if used, would be present where beta is also large and spoil emittance
- 805 MHz pillbox cavity observed breakdown in mag fields
- Shielding the fields from rf (Bucked Field) gave larger losses
- "Open cavity" did not show gradient degradation, but focused dark current drilled a hole in a window

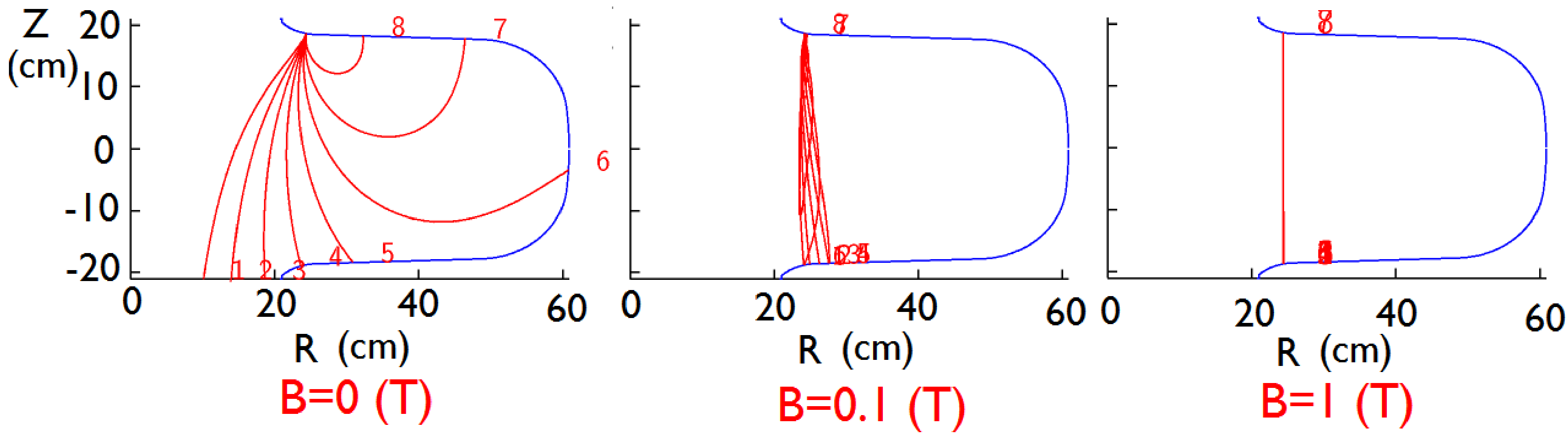


Simulations with new code CAVEL (Fernow)

Earlier study by G Romanov

Tracking, with Fernow's new program CAVEL, electrons from highest field location for differing axial magnetic fields.

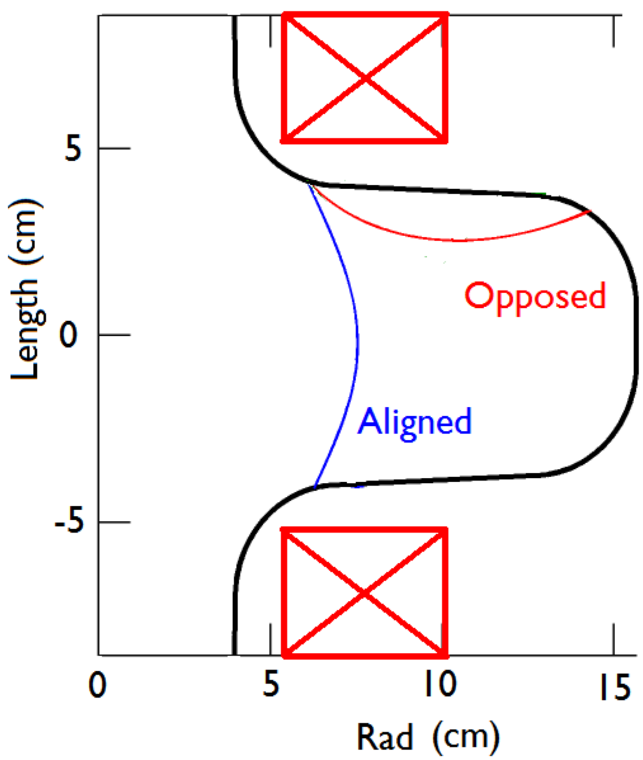
e.g. 201 MHz with 17 MV/m

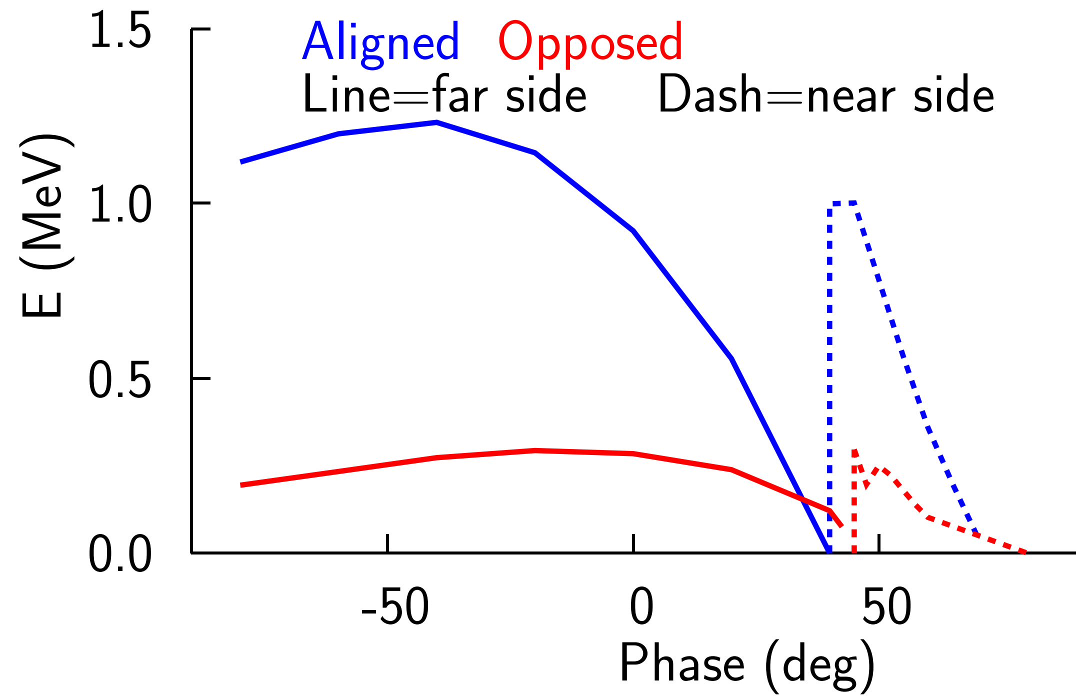


- For for B $\geq$ 1 (T), magnetic field focuses electrons from high field spot on one iris
  - To a high field region on another iris
  - Or back to the initial high field location
- Plausible explanation for loss of gradient & damage in external magnetic fields

Open 805 MHz cavity with coils in the irises

(Palmer, Fernow, Gallardo)

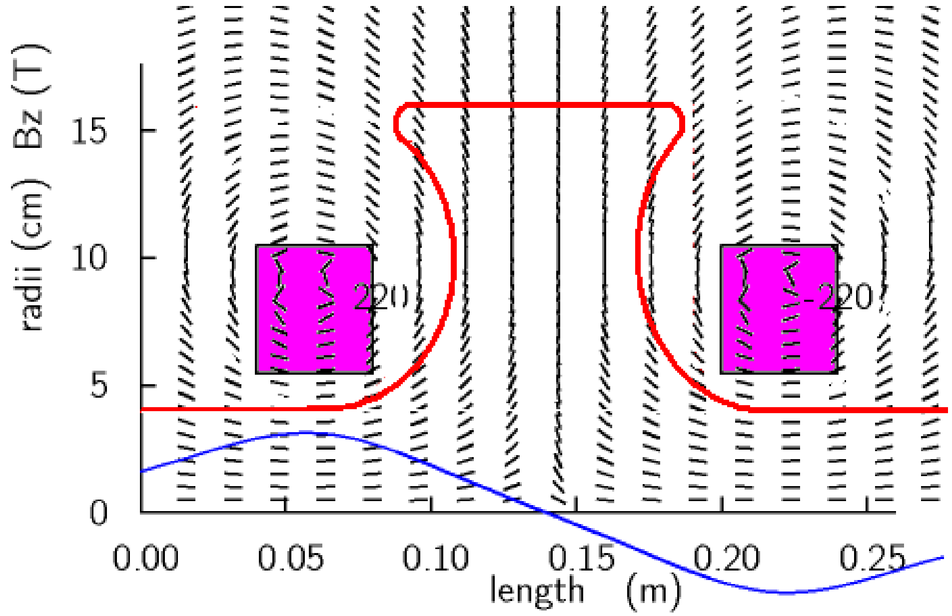


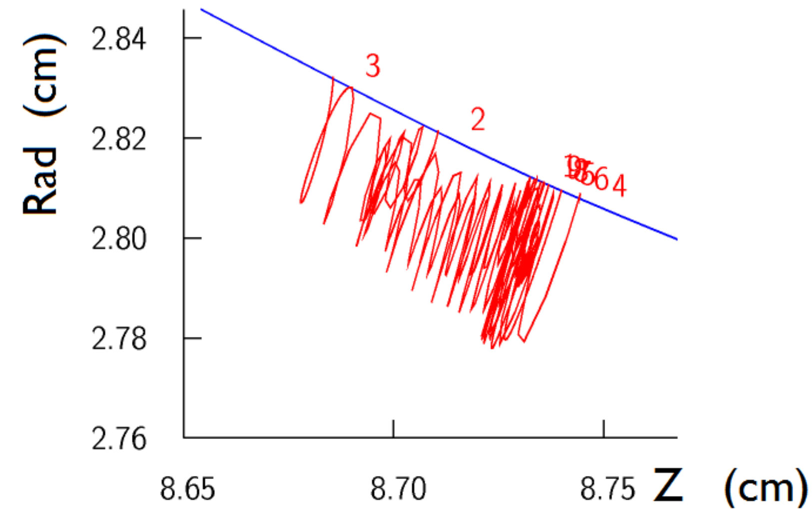


- With coils aligned
  - Much as with axial field
  - Electrons end with significant energy
  - On the high gradient iris opposite
  - Or back at the source

- With coils opposed
  - Electron energies are less
  - They land in low electric field region and are unlikely to cause breakdown or damage
  - But some electrons still return to the initial high gradient iris

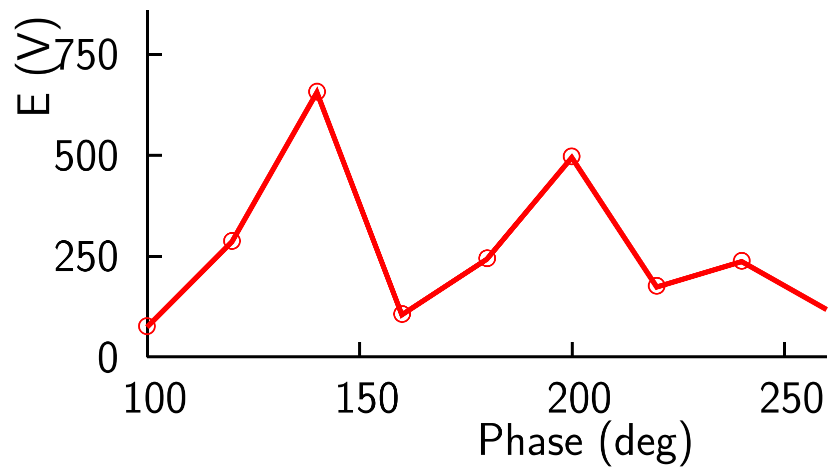
Magnetitically Insulated rf





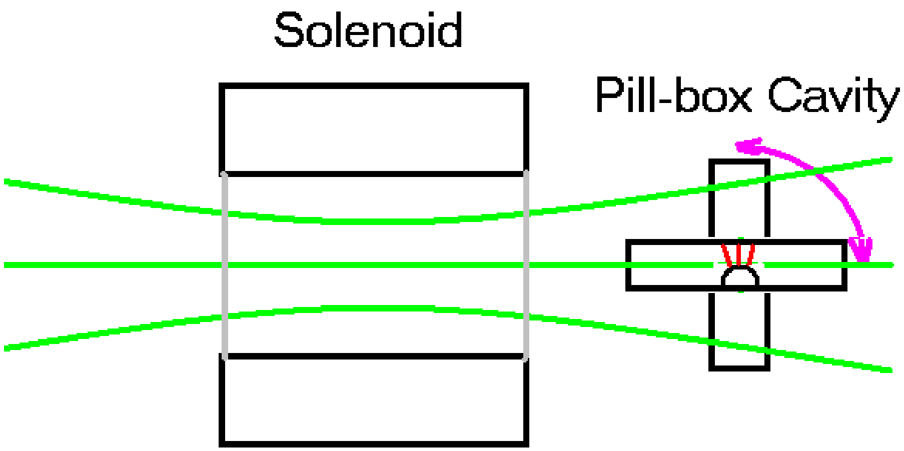
Detail

- All tracks return to the surface
- Energies are very low
- No dark current, No X-Rays !
- No danger of melting surfaces
- But secondary emission now possible
- Could lead to magnetron instability
- Needs experiment

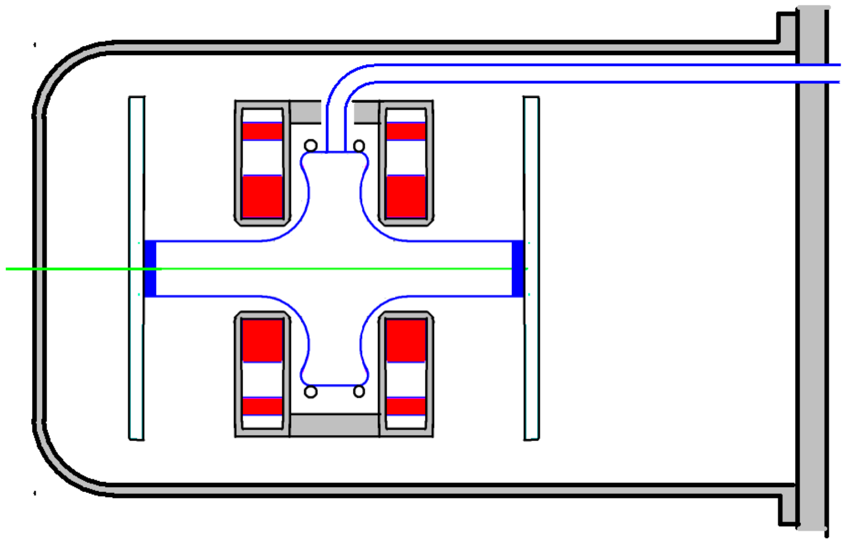


Needed Experiments

First using lab G Magnet and existing cavity at two angles



Then test new Mag Insulated Cavity with coils



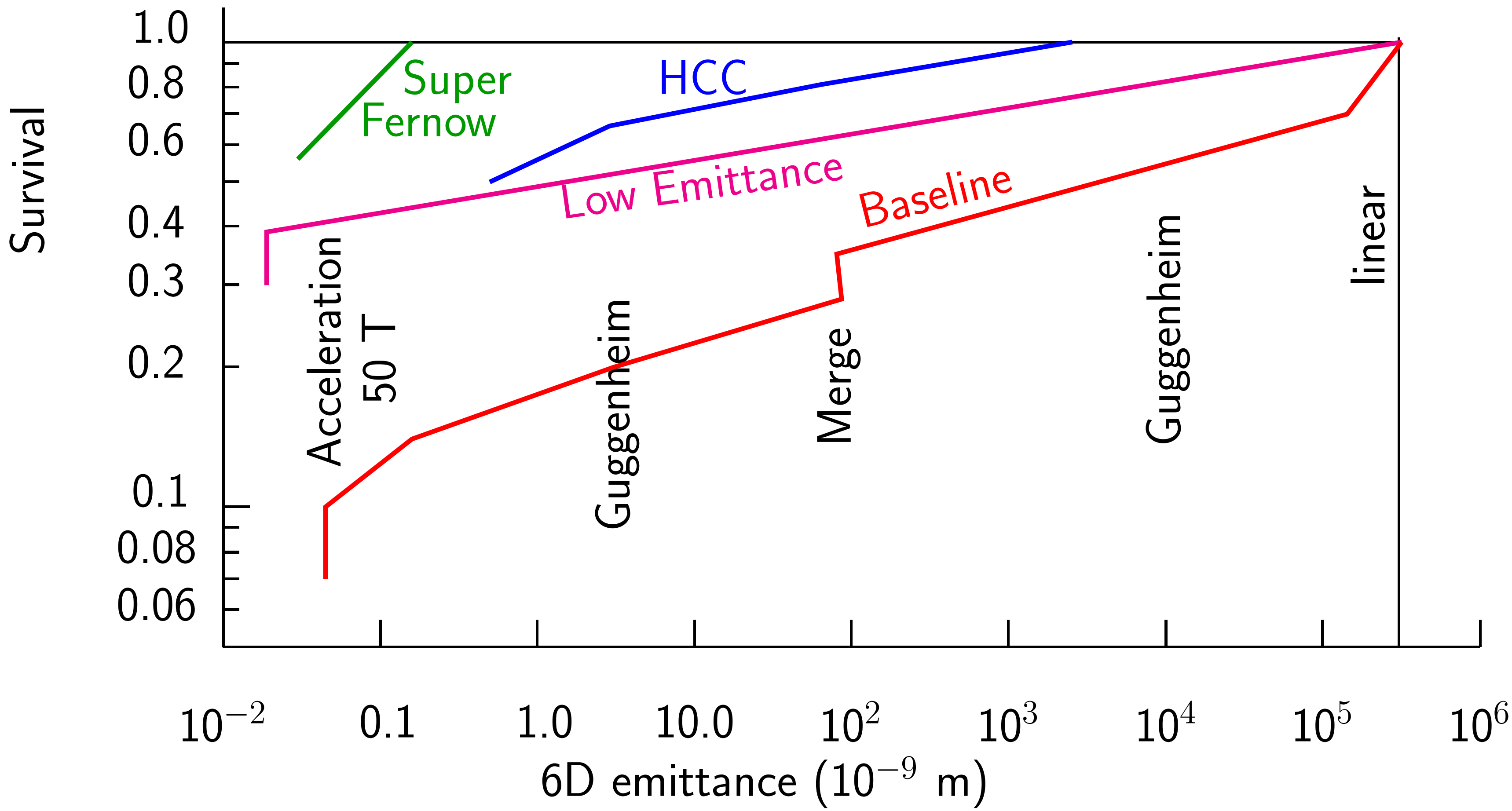
Conclusion

- Baseline remains much the same as last year, but details are improving
  - A new phase rotation gives 12 (vs 21) bunches, making merging easier
  - Working towards simulation of true Guggenheim lattice, but not yet
  - Sequence of 50 T solenoids cooling refined, but no re-acceleration yet
  - Hybrid pulsed magnet synchrotron ok up to 2+2 TeV
  - Wake fields in 1.3 GHz rf have been studied and look manageable
  - rf in magnetic fields remains a probable problem
  - But coils in open cell irises offer possible solutions
- Progress on integrating rf in HCC, but still no engineered solution for rf
- Progress on PIC, but far from realistic acceptance

Plans

- More study of space charge, wakes, and loading
- Integration of 'open cavity' solutions into baseline
- Work towards end-end simulation of baseline with tapering and matches
- Continue searching for viable lower emittance options

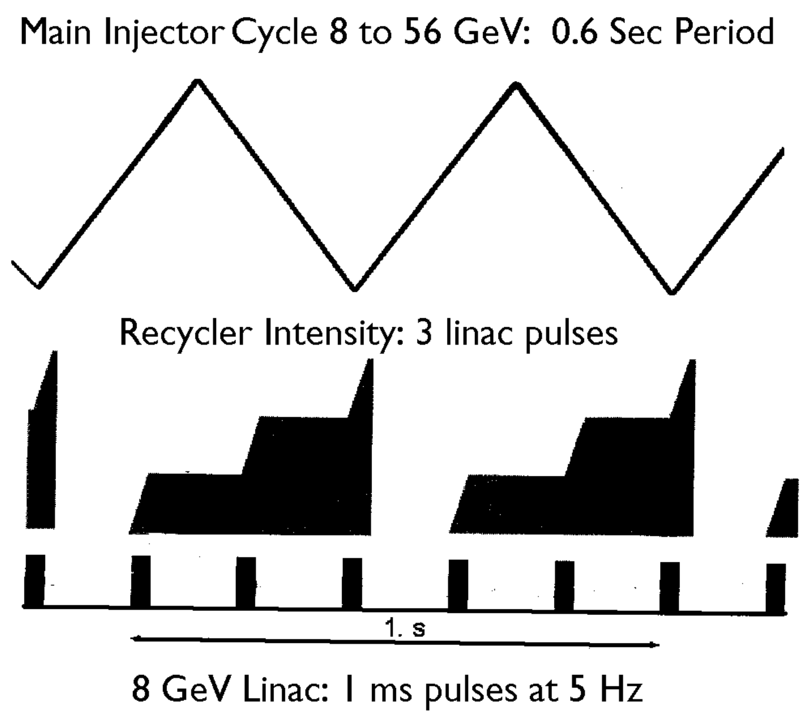
Appendix 1. Estimated losses vs 6D emittance



- The loss estimates for the 'Baseline' are based on the observed slope $\left(\frac{dn/n}{d\epsilon/\epsilon}\right)$ in individual ICOOL simulations, it assumes that with proper tapering and matching these slopes can be maintained over multiple stages
- The HCC simulations using G4Beamline used ideal helical fields
- The Low Emittance estimate included only decay losses

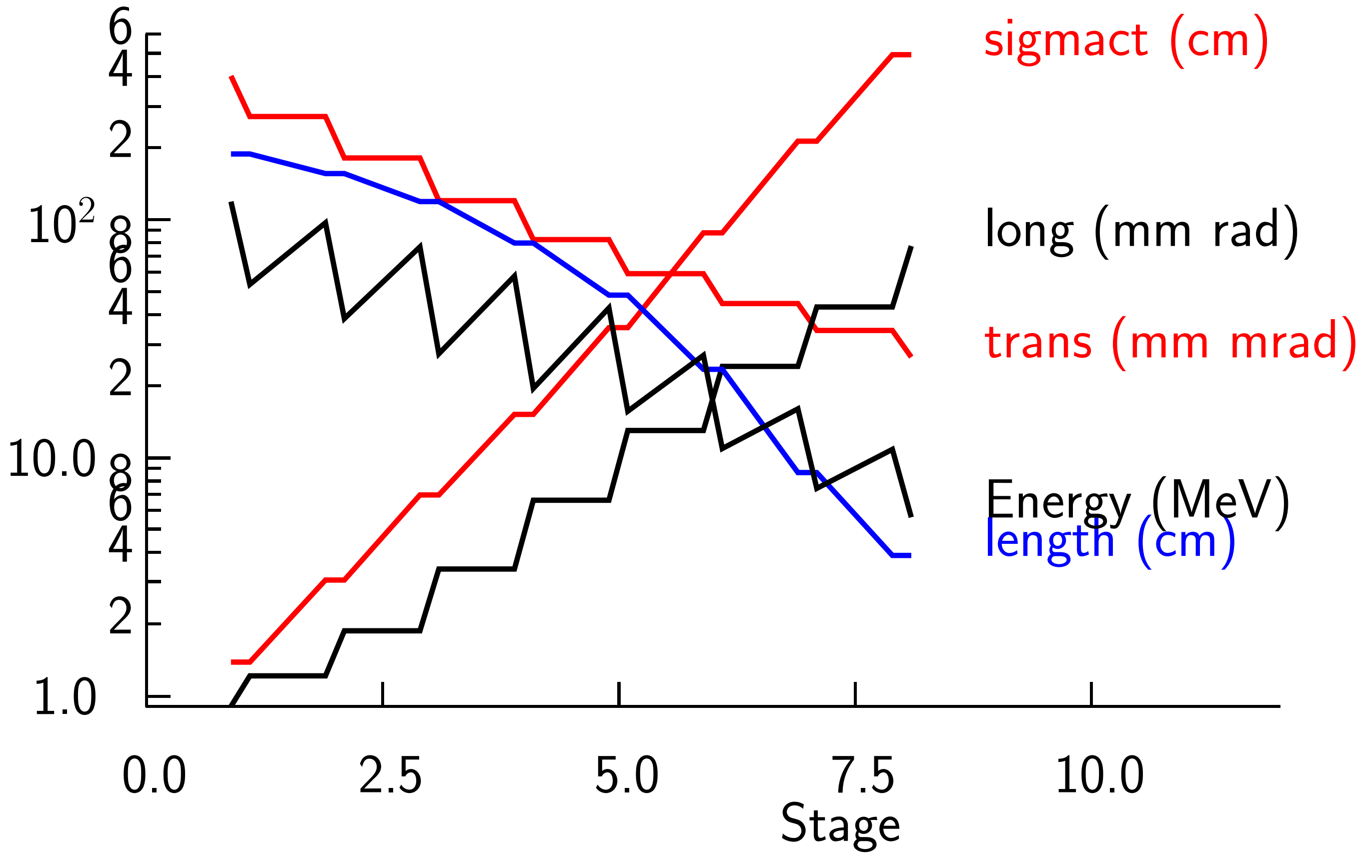
Appendix 2. Proton driver (Neuffer)

- Project X: 8 GeV Linac 9 mA at 5 Hz
- For required power, the pulse length is upgraded 1→2 msec (10^{14} p/p)
- Accumulate 3 trains in Recycler Ring (3 10^{14} p)
- Accelerate to 56 GeV in Main Injector at 1.7 Hz
- → New Buncher Ring*: Re-bunch to 3 ns on h=7 (4 10^{13} each) and extract at 12 Hz
- Average proton power 4 MW



- Production for 'Baseline' at 8 GeV would require bunches 2.8 10^{14} → hard for 3 ns
- Cooling to lower emittances imply more smaller bunches
- A Neutrino Factory could also use many smaller bunches

Appendix 3. Parameters at each 50 T stage (Palmer)



- Note 5 m final bunch length that does not permit trains with 1.5 m separations

- Reverse Emittance Exchange (REMEX) using wedges needs study (Derbenev)