A COMPLETE SCHEME OF COOLING FOR A MUON COLLIDER

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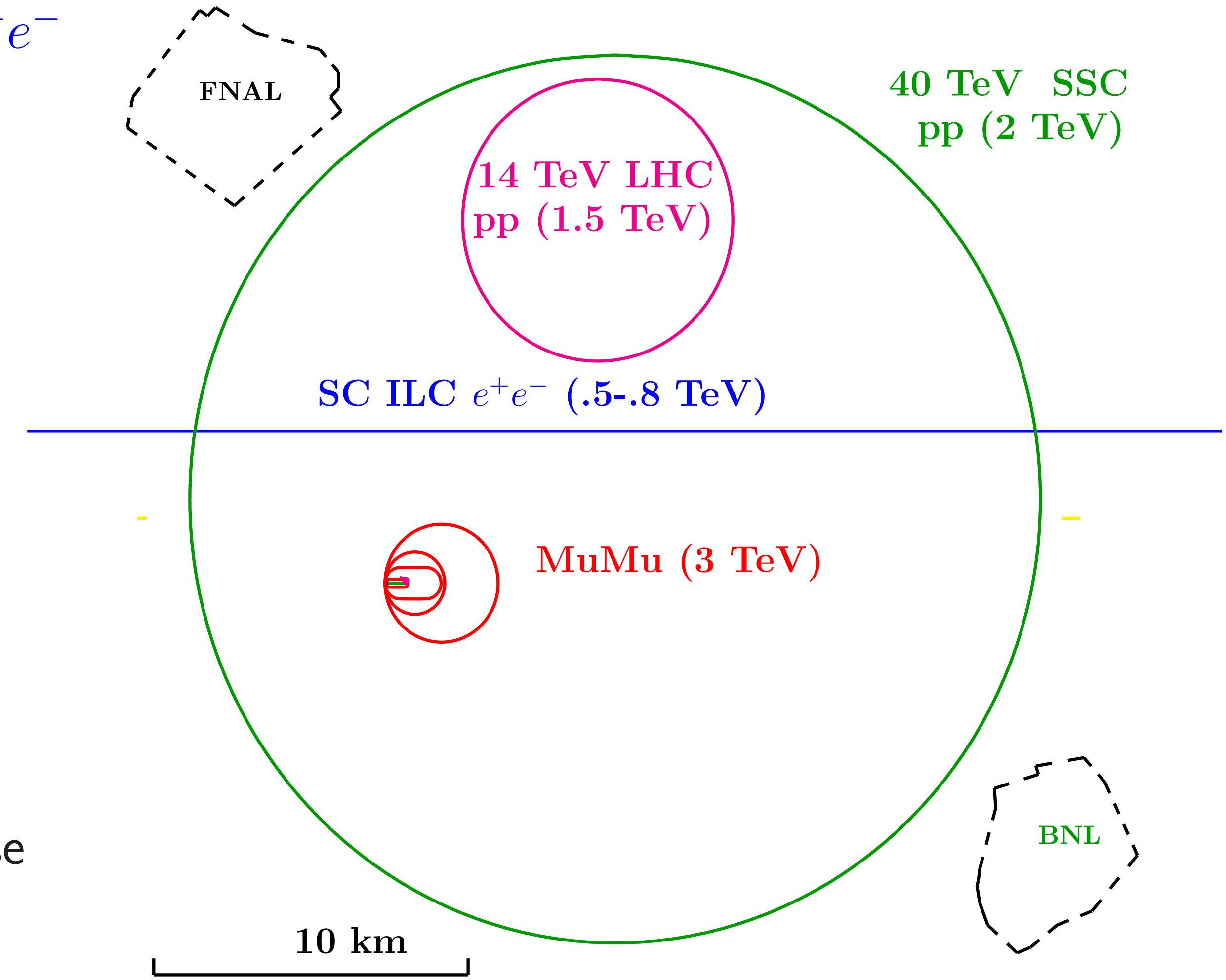
History

1969	Concept discussed	Budker
1981	Muon Ionization Cooling	Skrinsky, Parkhomchuk
1983	First outline	Neuffer
1994	Solenoid capture	Palmer
1996	Snowmass Feasibility Study	
1997	US Collaboration Formed	
1998	DoE organization and funding	
2006	Muon Collider Task Force	FNAL
2007	First Complete Scenario with simulations	This work

Why a Muon Collider?

- Point like interactions as in e^+e^-
- Negligible synchrotron radiation:
  Acceleration in rings vs. linear e^+e^-
  Small footprint
- Collider is a Ring
  $\approx$ 1000 interactions per bunch
  Larger spot for same luminosity
  Easier tolerances
- Negligible Beamstrahlung
  Narrow energy spread
- 40,000 greater S channel Higgs
  Study widths

  BUT
- Muons from pion decay are diffuse
  Need cooling
- Muons decay
  No time for ordinary cooling
  Acceleration must be rapid



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 ?
  - To reduce aberrations in Ring IP to allow lower β^*
- Why do we want "Low Longitudinal Emittance ?
  - To reduce dp/p & chromatic aberrations in Ring IP to allow lower $\beta_\perp$
  - To keep $\sigma_z < \beta_\perp$ as β^* is reduced

Collider Parameters

	This Paper	Snowmass	Extrapolation	
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	0.1	
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	0.09	0.12	0.06	%
Muon Beam Power	7.5	9	9	MW
Required depth for ν rad $(^1)$	13	135	540	m
Muon survival $(^2)$	0.07	0.07	0.07	
Repetition Rate	12	6	3	Hz
Proton Driver power	$\approx$4	$\approx$ 1.8	$\approx$ 0.8	MW
Trans Emittance	25	25	25	pi mm mrad
Long Emittance	72,000	72,000	72,000	pi mm mrad

- Emittance and bunch intensity requirement same for all examples

$(^1)$ With respect to any low lying nearby land. e.g. Fox river at FNAL

$(^2)$ From capture to collider: through cooling, manipulations , and acceleration

Proton Driver

- Average proton power of 4 MW
- Protons per bunch $8\ 10^{13}$ at 24 GeV
- Extracted bunches must have $\sigma_t\ \leq\ 3$ (nsec)

These are tough requirements   Possible parameters might be:

Proton Energy	(GeV)	12	25	50
Protons accelerated	10^{14}	5	5	5
Protons/bunch	10^{14}	1.6	0.8	0.4
Bunches extracted		3	6	12
Repetition rate	(Hz)	4	2	1

- Achieving the 3 nsec bunches at less than 25 GeV would appear hard
- Higher repetition rate and fewer protons per cycle is an option
- Higher cooling efficiency could ease these requirements
- Needs more study

Capture and Cooling Scheme

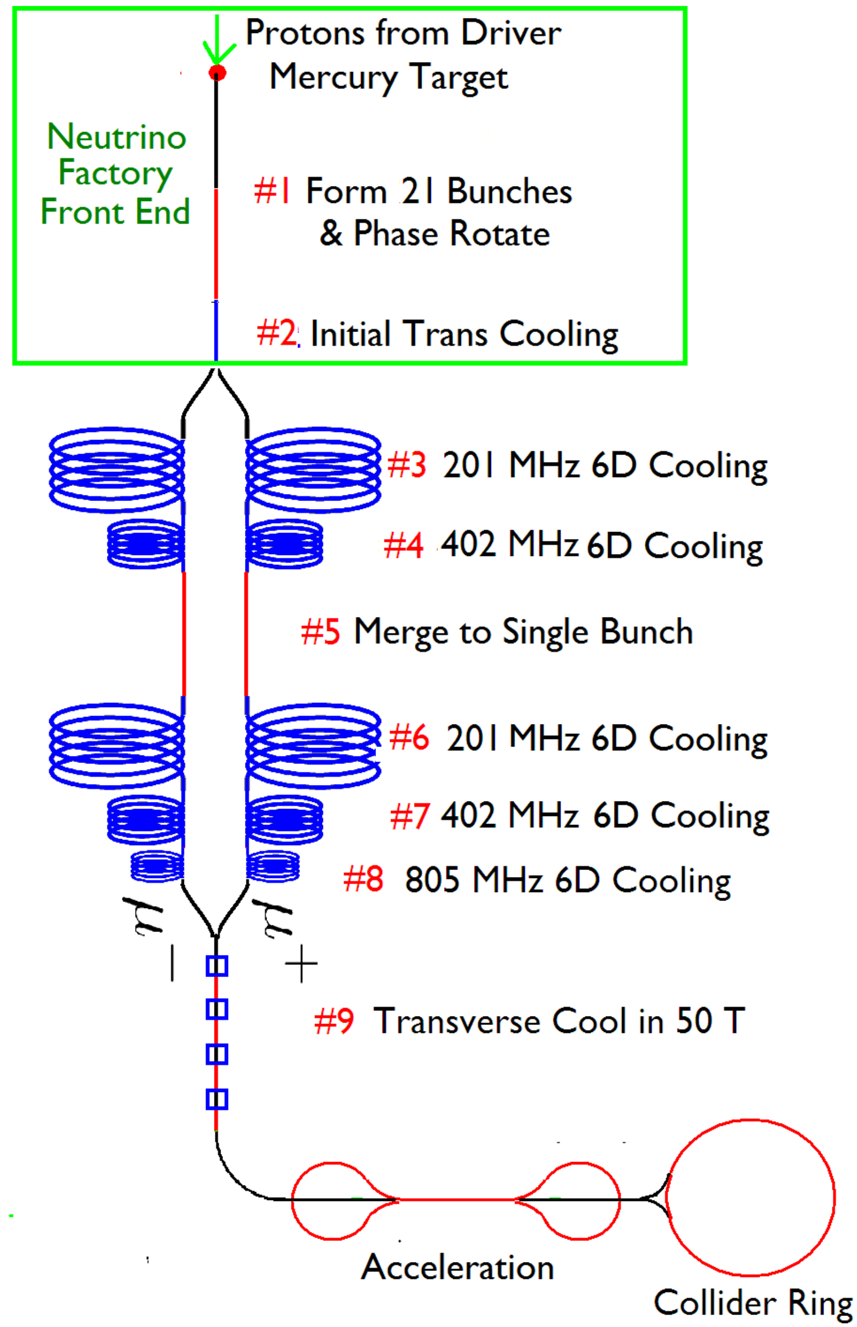
Essential Elements of this Solution:

- Target an intense short proton bunch on a liquid metal target
  Any other target would break
- Capture pions with high field solenoid ($\approx$ 20 T)
  Collects 50% of all useful pions of both signs
- Phase rotation into multiple bunches at moderate frequency (201 MHZ)
- Ionization cooling to cool rapidly in transverse directions
- Emittance Exchange using dispersion and wedges to cool longitudinally
- Bunch merging after initial 6D cooling
  To get single intense bunches
- Re-cooling after merge
  to get single intense cold bunches

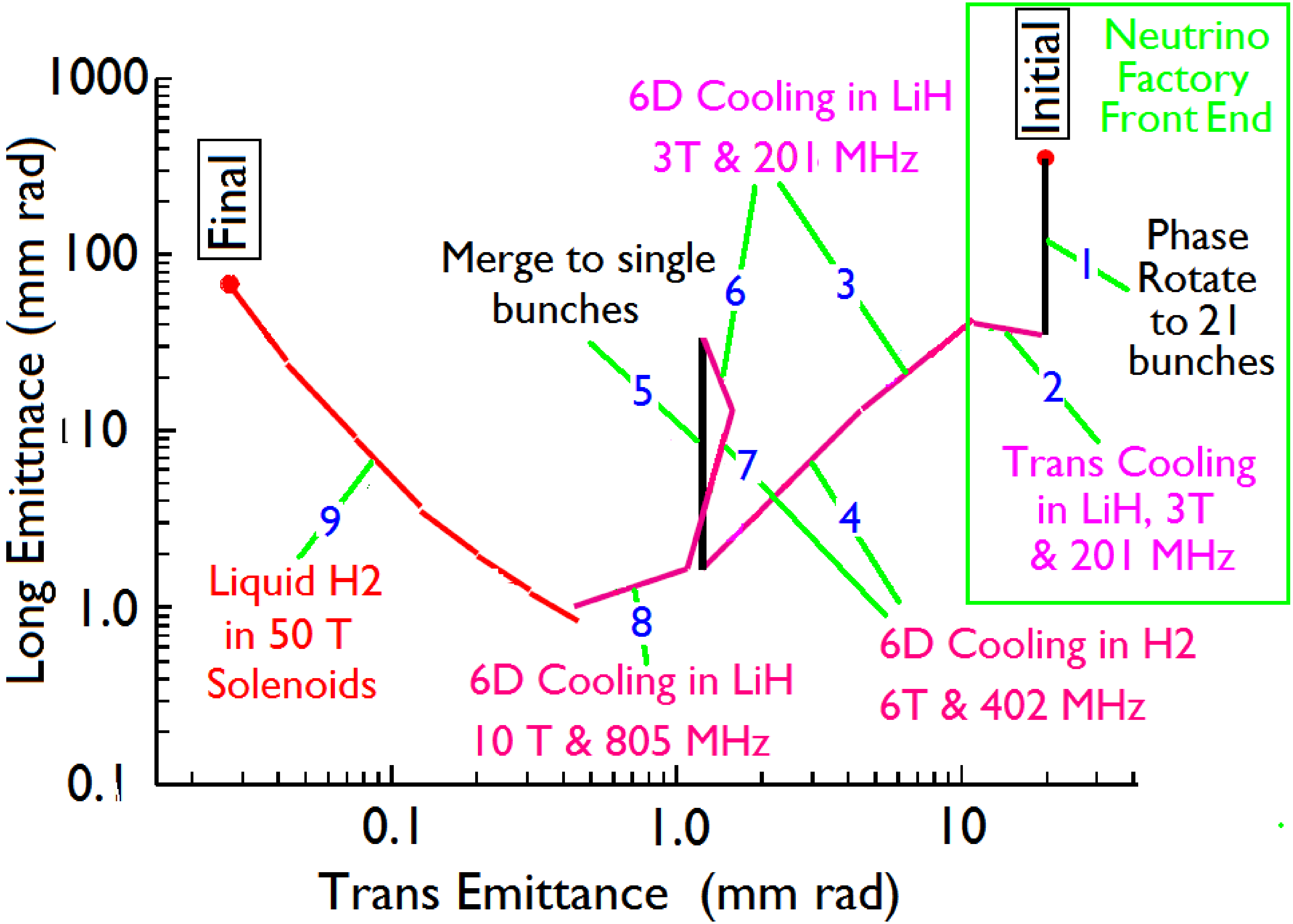
Without any one of these elements, we cannot achieve the requirements

Capture & Cooling Schematic

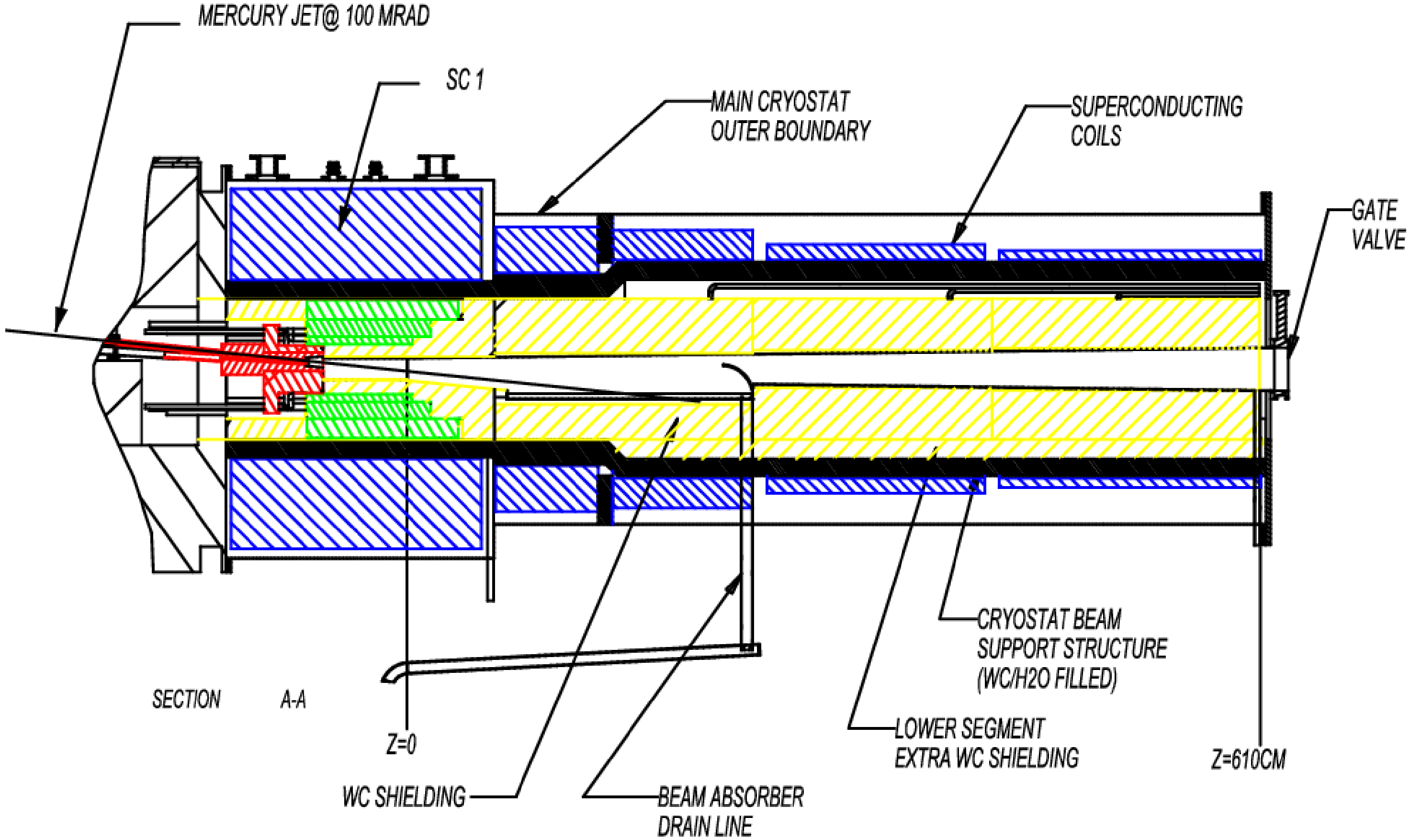
- Not to scale overall length of order 1 km
- We will look at each numbered component later



Emittances vs. Stage



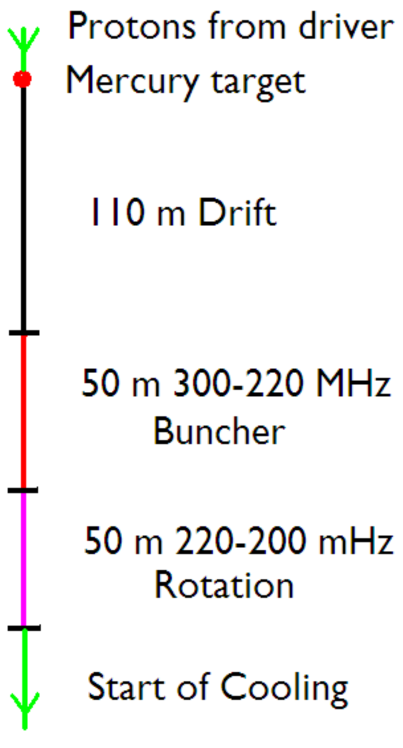
#1 Target and Capture and Phase Rotate



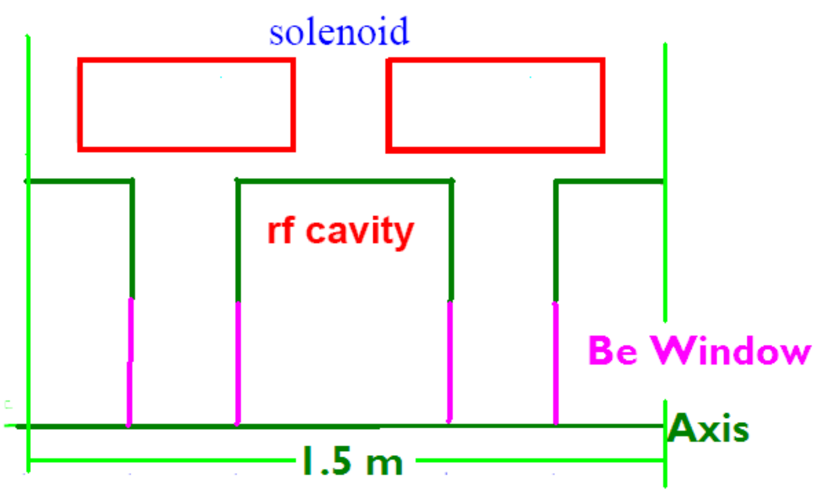
- Liquid mercury Jet 'destroyed' on every pulse
- 20 T Solenoid captures all low momentum pions
- Field subsequently tapers down to approx 2 T
- Target tilted to maximize extraction of pions
- MERIT Experiment at CERN will test this concept

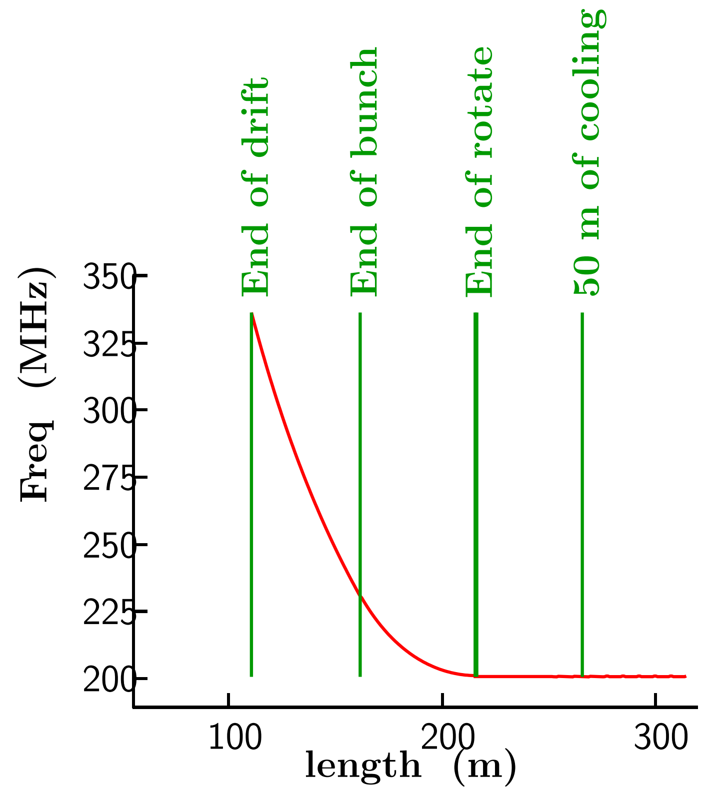
Phase Rotation

capture into multi-bunches to reduce momentum spread

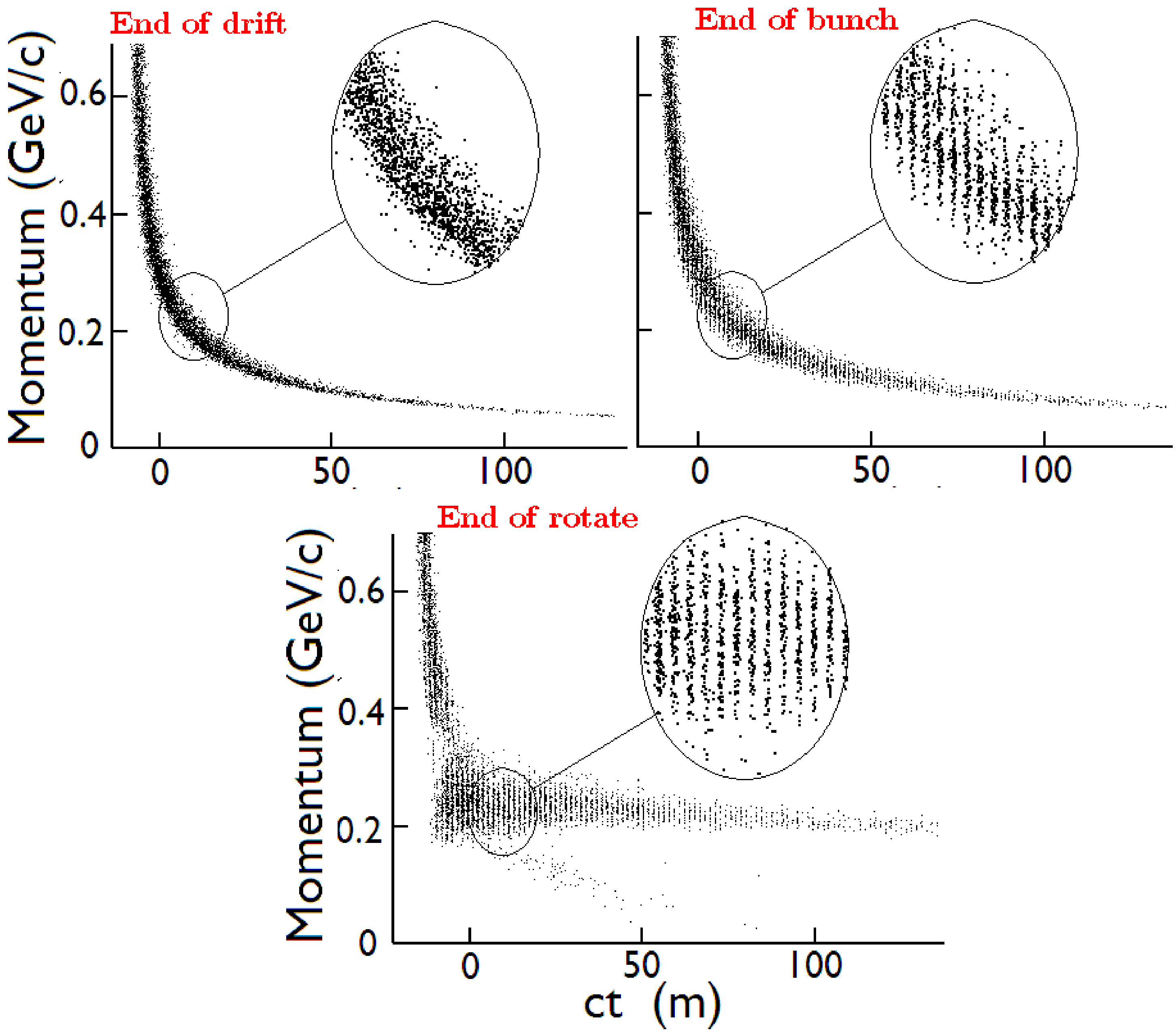


- Drifts and rf in approximately uniform 2 T axial field
- rf using has gradients rising from 0 to 12 MV/m in buncher and 12 MV/m in rotator
- Wavelength in buncher follows increasing extension of bunches
- Frequency then adiabatically approaches fixed 201 MHz



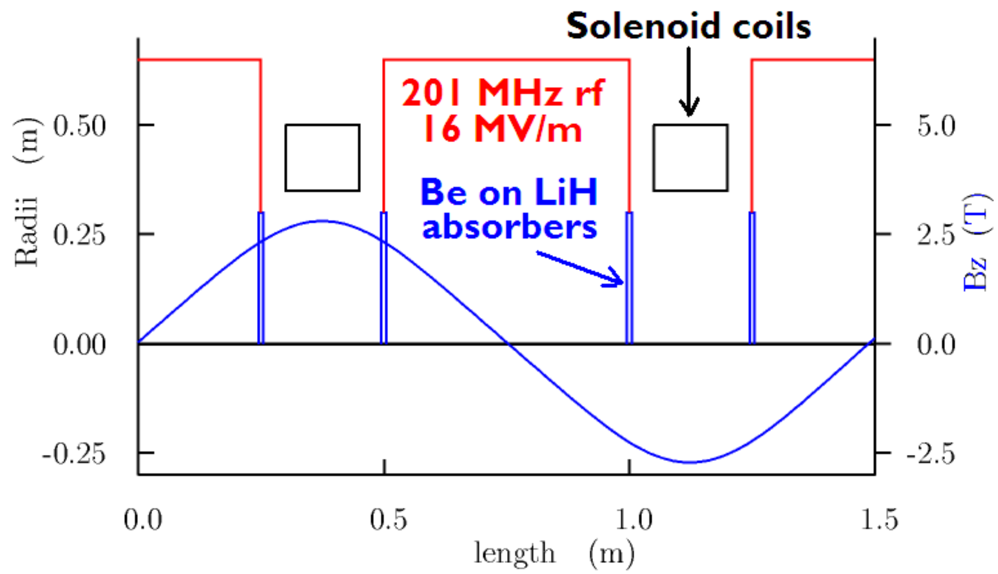


Phase Rotation Simulation

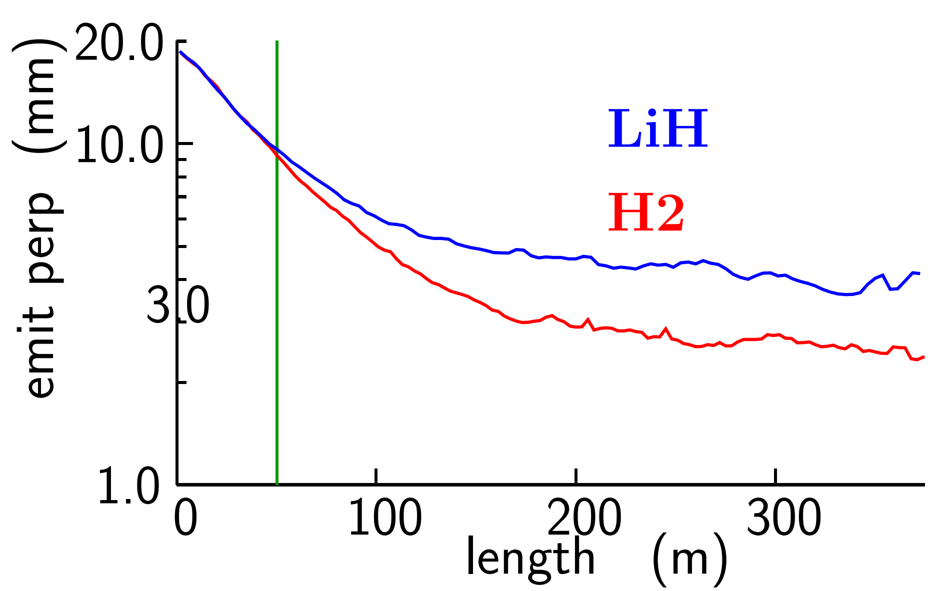


#2 Initial Linear cooling

Only Ionization cooling is fast enough



- Linear channel cools both signs transversely
- Tapering the focus field should improve performance
  (not yet assumed)

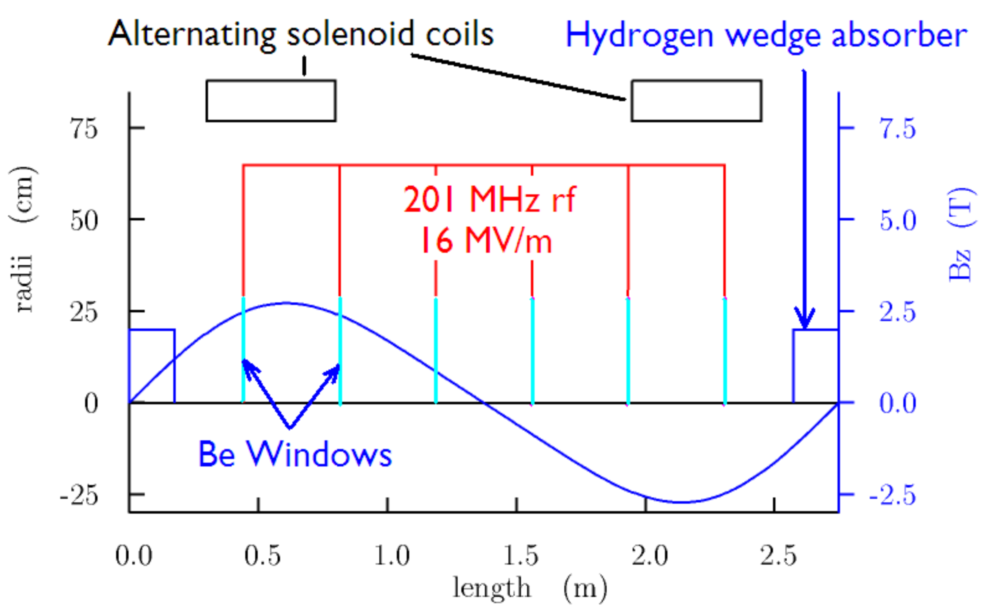


- Negligible difference between LiH and H2 before 50 m

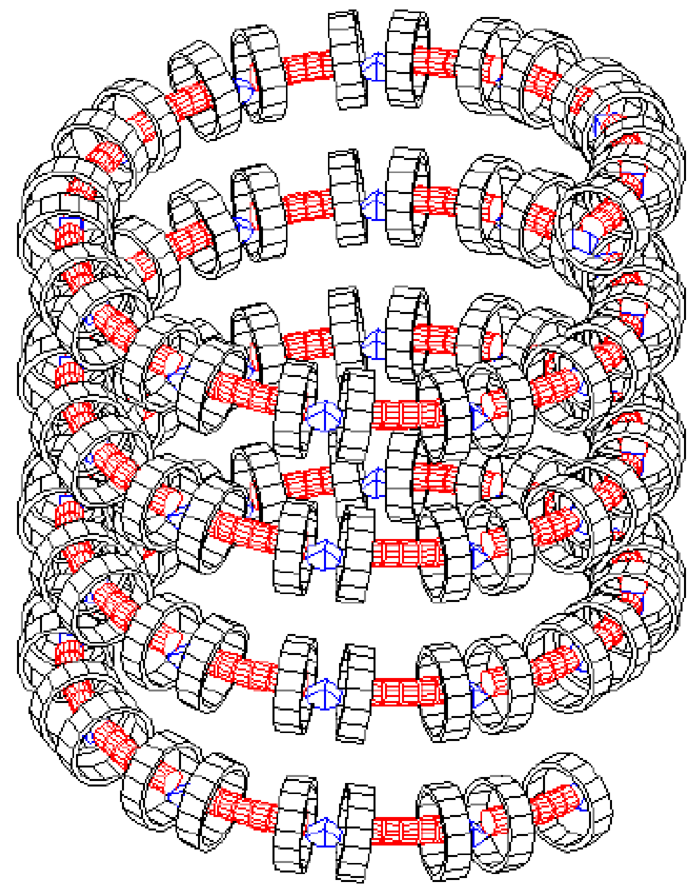
- MICE Experiment at RAL will demonstrate Ionization Cooling

#3 #4 6D Cooling in Guggenheim helices

- 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)

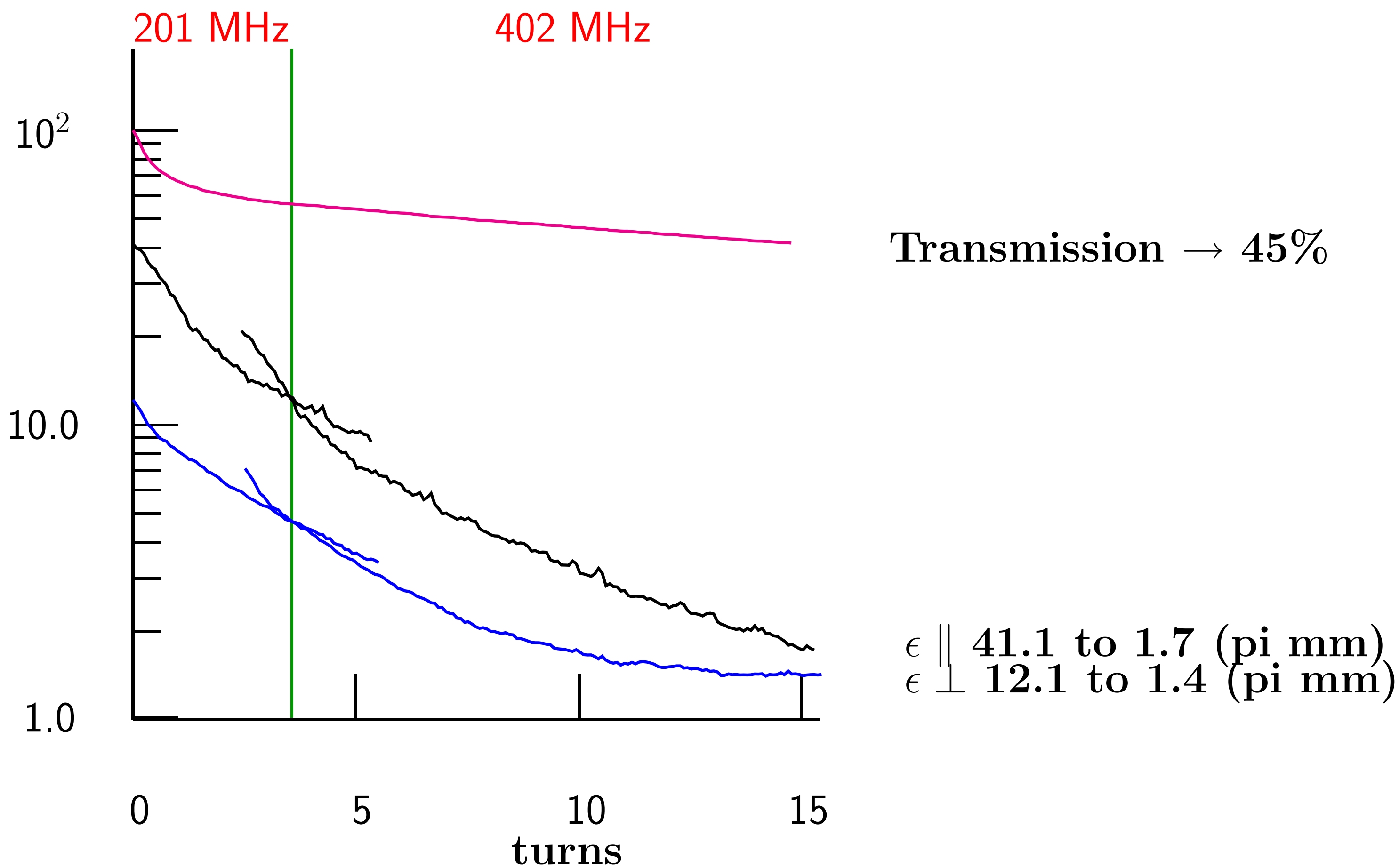


RFOFO Lattice



'Guggenheim'

ICOOL Simulations of real fields Balbakov was first

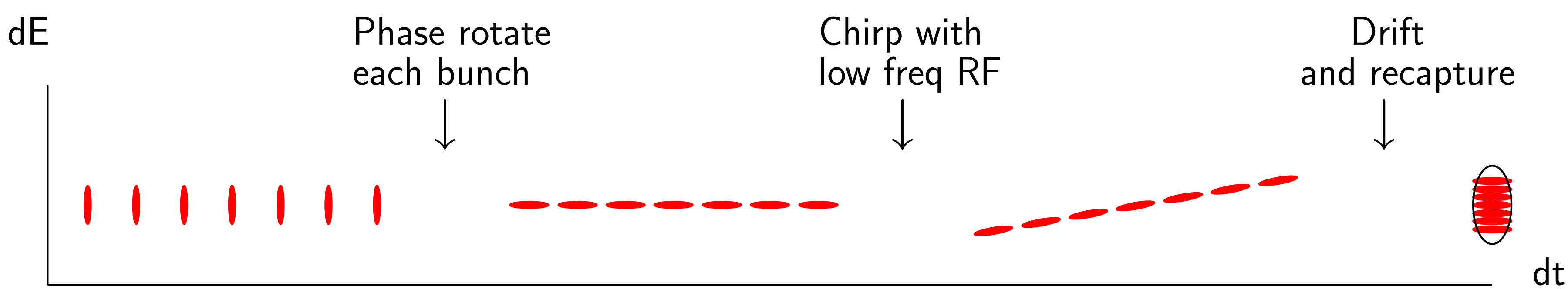


- 201 MHz RFOFO as published, but Guggenheimed (B=3 T)
- 402 MHz RFOFO has all dimensions halved (B=6 T)

#5 Bunch Merging

- Luminosity proportional to muons per bunch squared
- Few large bunches required
- Capturing to one large bunch would have required low frequency rf ($\approx$ 30 MHz) with low gradients and inefficiency
- We thus:
  - Capture into multiple bunches at 201 MHz
  - Cool them till small enough to:
  - Merge them and recapture at 201 MHz
  - Re-cool the merged bunches

Merging Scheme

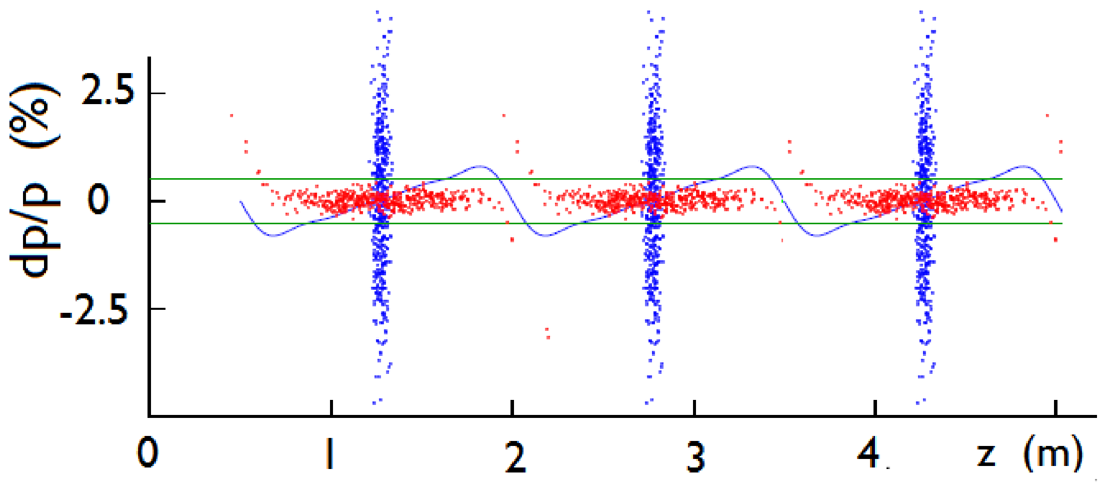


One Dimensional Bunch Merging Simulation

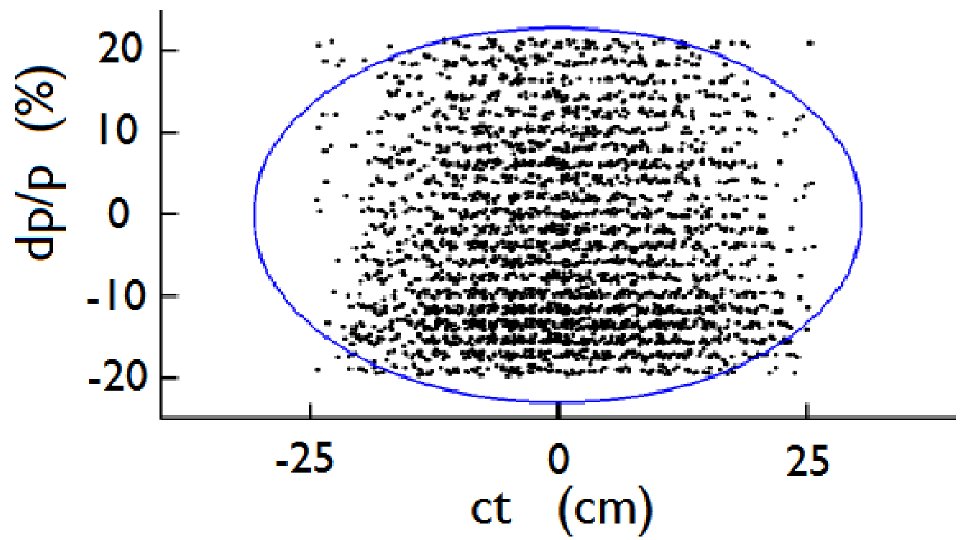
- rf:
  1) at 200 MHz + 2 harmonics
  2) at 5 MHz + 2 harmonics

- Drifts in 1 T wigglers, simulated in ICOOL off line

- Rotations simulated in 1 D using parameters from ICOOL



Stage 1 Rotate individual bunches to reduce dp/p

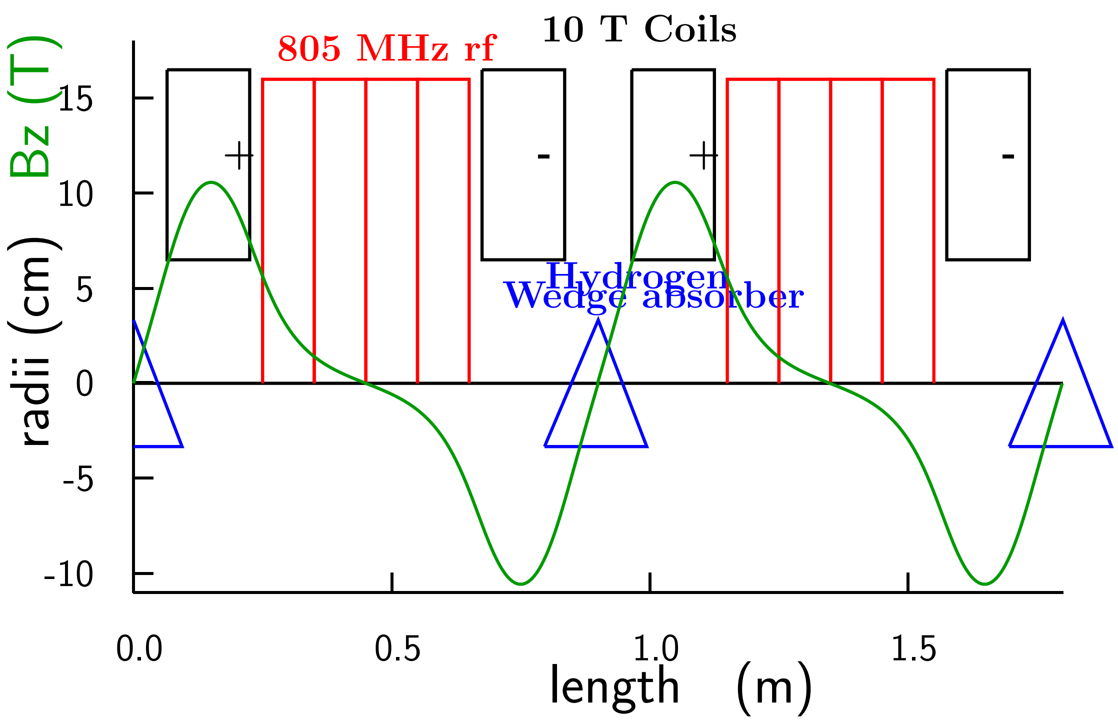


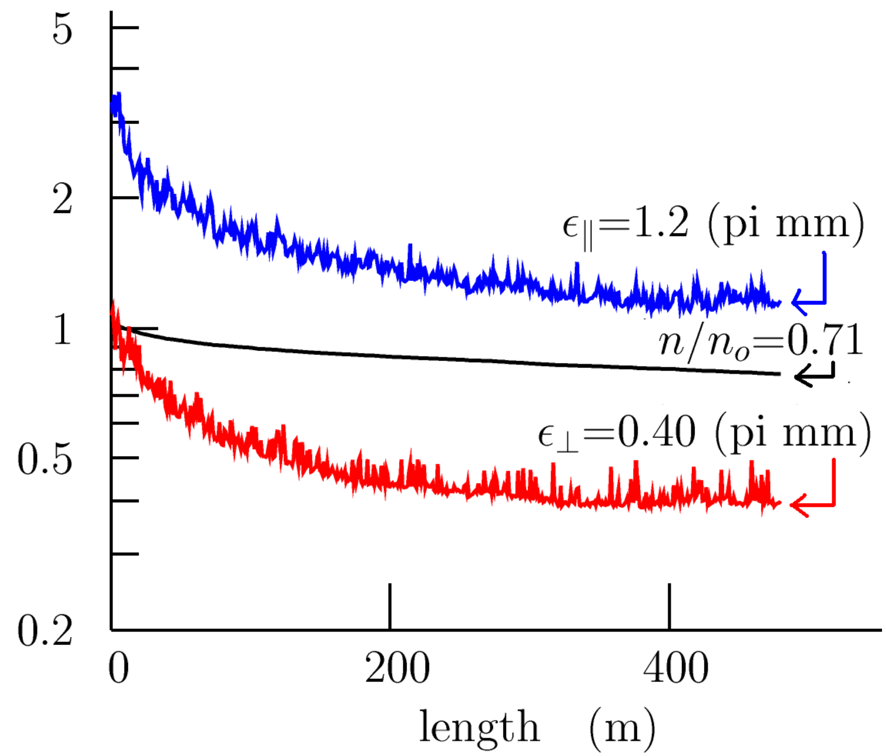
Stage 2 Rotate string of bunches into a stack

Cooling after merge

- #6 #7 Re-cooling in Guggenheim Lattices
  - Essentially identical to #3 and #4
  - Could re-use #3 and #4

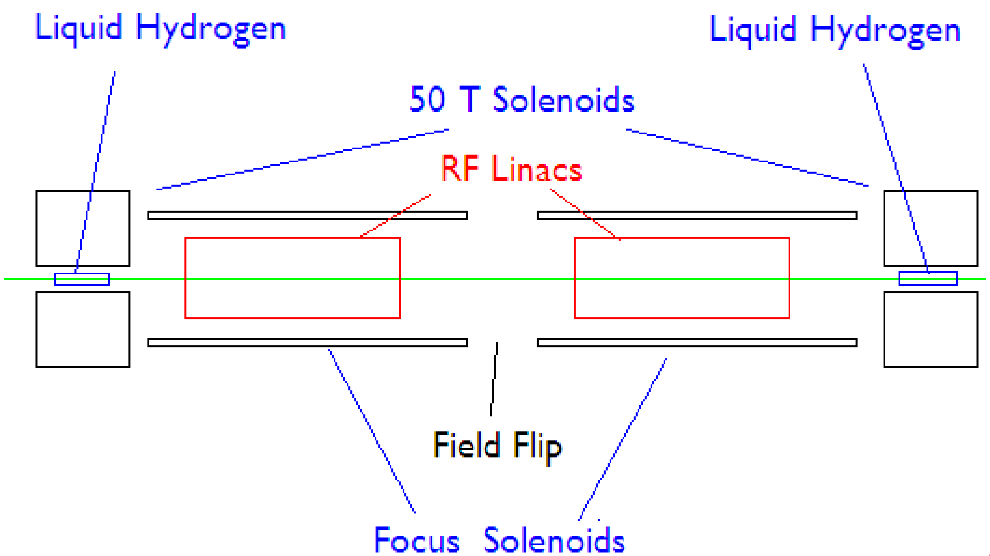
- #8 Last 6D cooling in higher field lattice
  - Uses 10 T high current density (150 A/mm^2) solenoids

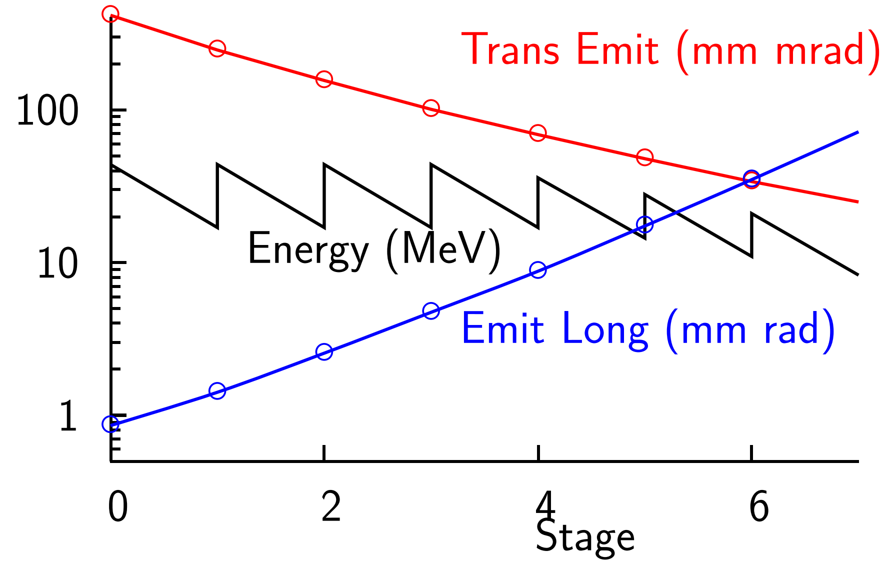




#9 Transverse Cooling in Very High Field Solenoids

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





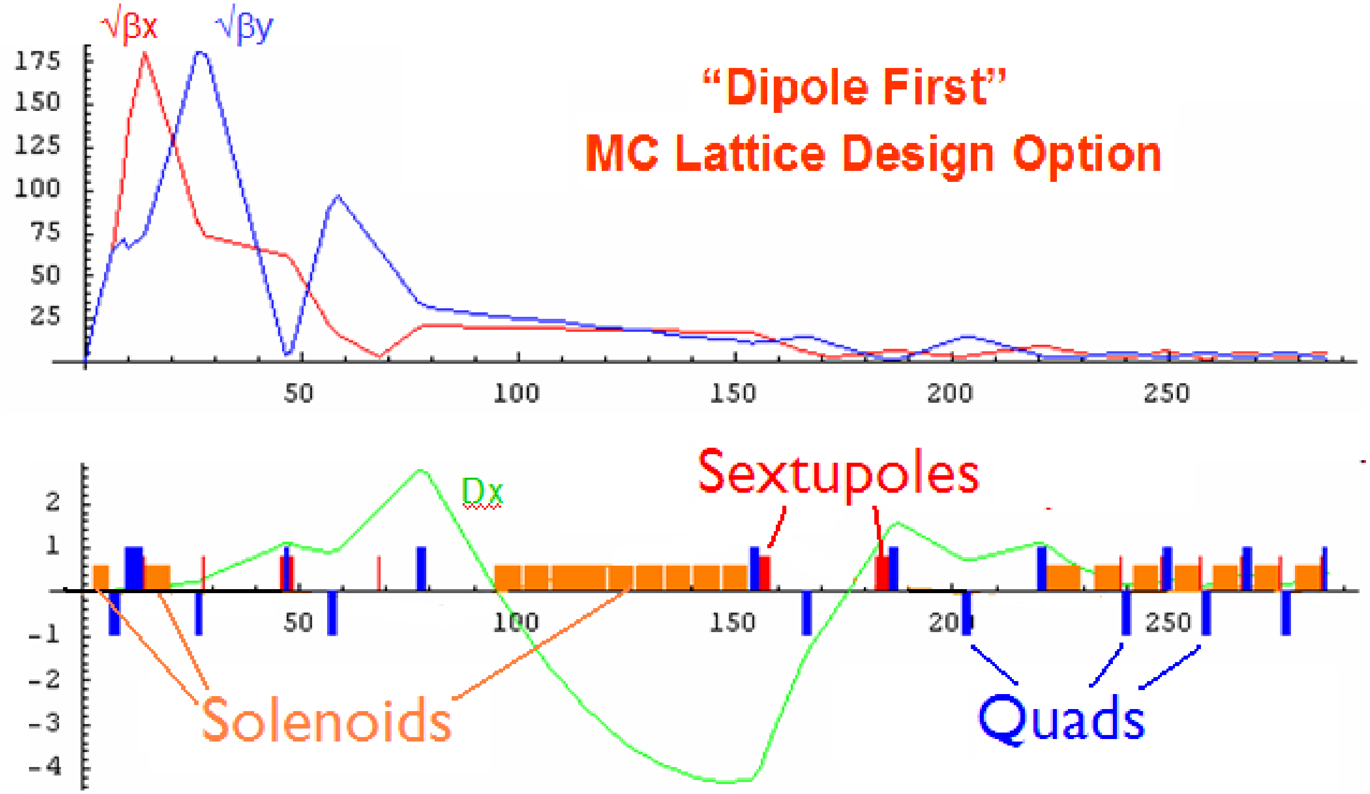
- 50 T HTS Solenoids
  - Current and ss support varied with radius to keep strain constant
  - Design using existing HTS tape at 4.2 deg. gave 50 T with rad=57 cm
  - 45 T hybrid with Cu exists at NHFML, but uses 20 MW
  - 30 T all HTS under construction
- 7 solenoids with liquid hydrogen
- ICOOL Simulation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

Acceleration

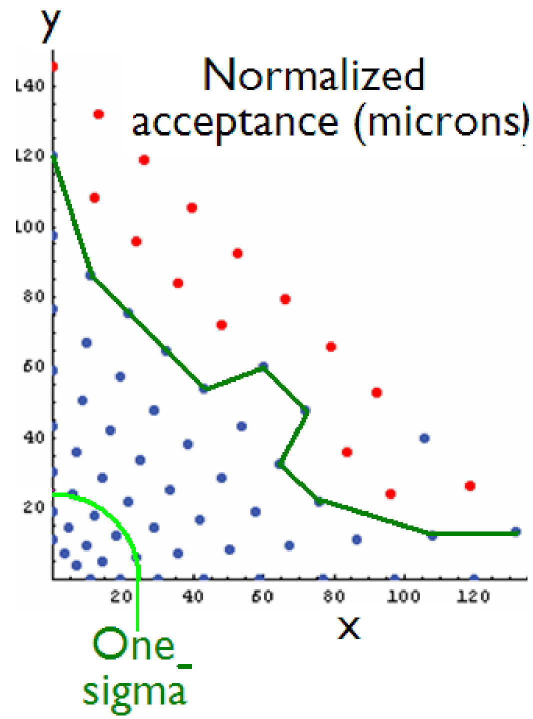
- Sufficiently rapid acceleration is straightforward in Linacs and Recirculating linear accelerators (RLAs)

- Lower cost solutions might use:
  - Fixed Field Alternating Gradient (FFAG) accelerators
  - Rapidly pulsed magnet synchrotrons
  - Hybrid SC and pulsed magnet synchrotrons

Collider Ring (Y. Alexahin E. Gianfelice-Wendt)



Lattice

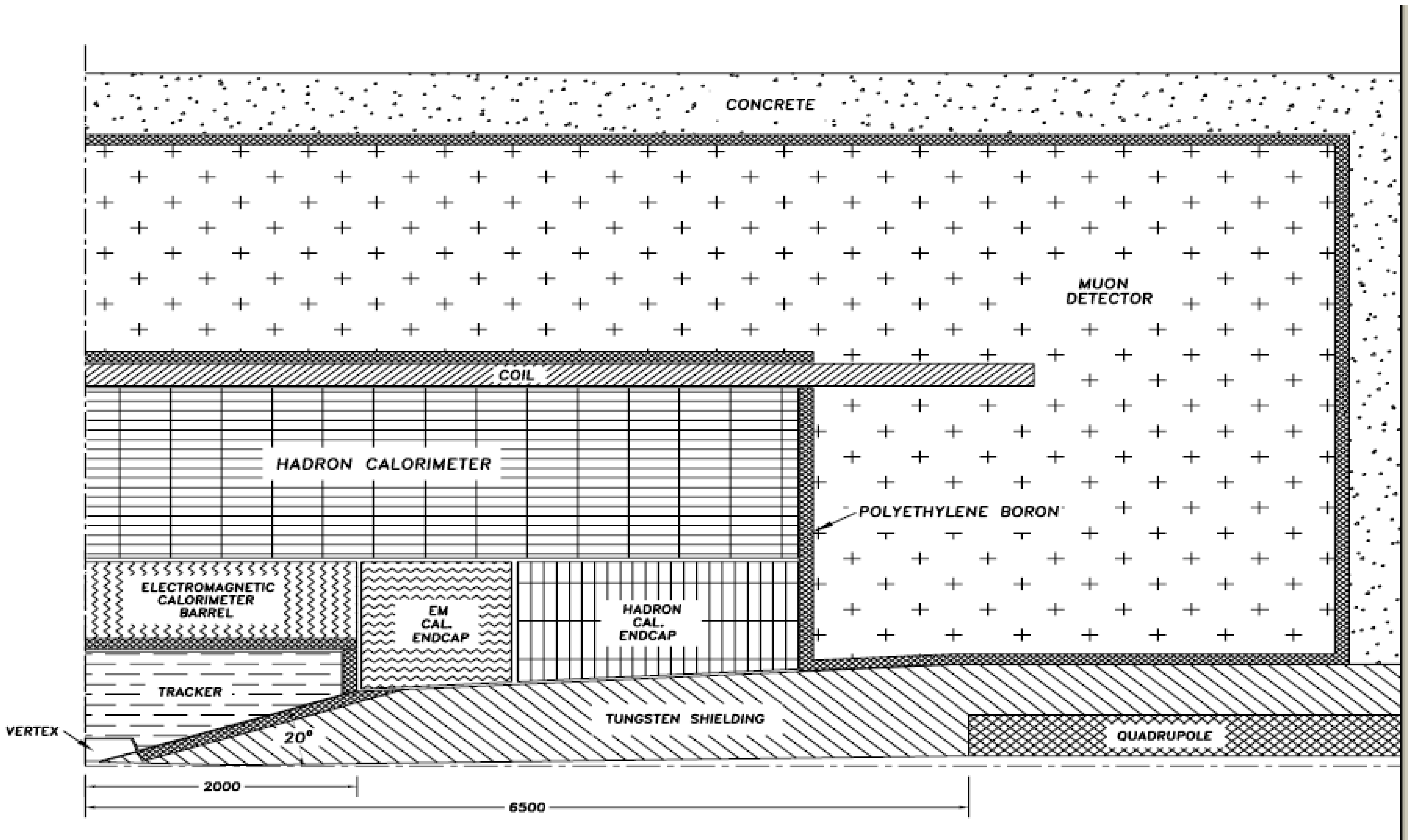


Acceptance

- $\beta^* = 1cm \quad \Delta p/p \approx 0.6$ %
  More than adequate for rms dp/p=0.09 %
- $\Delta x, y \approx 2\sigma$ at 25 mm mrad emittance
  Will require scraping of beam (cut at 1.75 sigma loses only 5% of luminosity)

Detector

- Detector was designed in 96 for 2+2 TeV
- Note forward 20 degrees is lost to detector

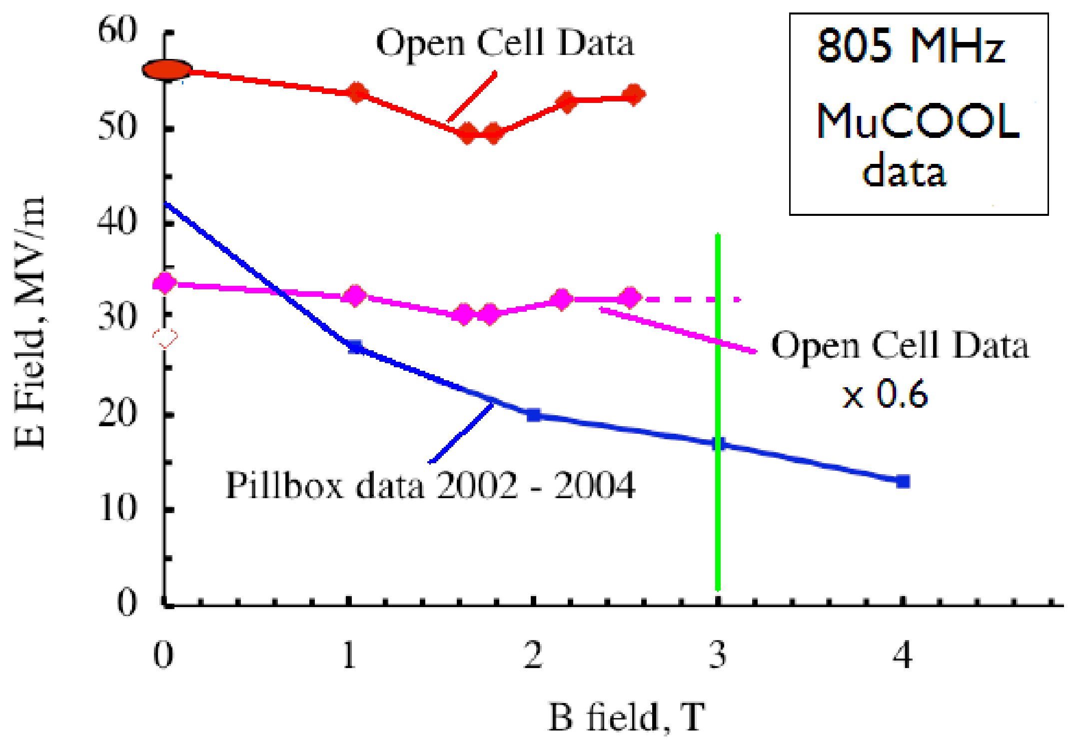


Ongoing Studies

- Fuller simulations
- Space charge tune shifts (moderate, but not in simulations)
- 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 being studied by Muons Inc
  but difficult to introduce required rf
- Design of 50 T solenoids
- Use of more, but lower field (e.g. 35 T) final cooling solenoids
- Design detector shielding

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
- Max E field ⊥ to B



Conclusion

- New 1.5 TeV Collider lattice has more conservative IP parameters
  - Luminosity 1×10^{34} achieved with bunch rep rate ≈12 Hz
  - 1.5 TeV Collider ring must be deep to control neutrino radiation but does not need to be as deep as ILC (135 m)
  - Proton driver (≈ 4 MW) is challenging
- Complete cooling scheme achieves required muon parameters
  - All components simulated (at some level) with realistic parameters
  - But much work remains
- Possible/probable problem with rf breakdown in specified magnetic fields
  - Solutions with gas ?
  - Open cell rf ?