A COMPLETE SCHEME OF COOLING FOR A MUON COLLIDER

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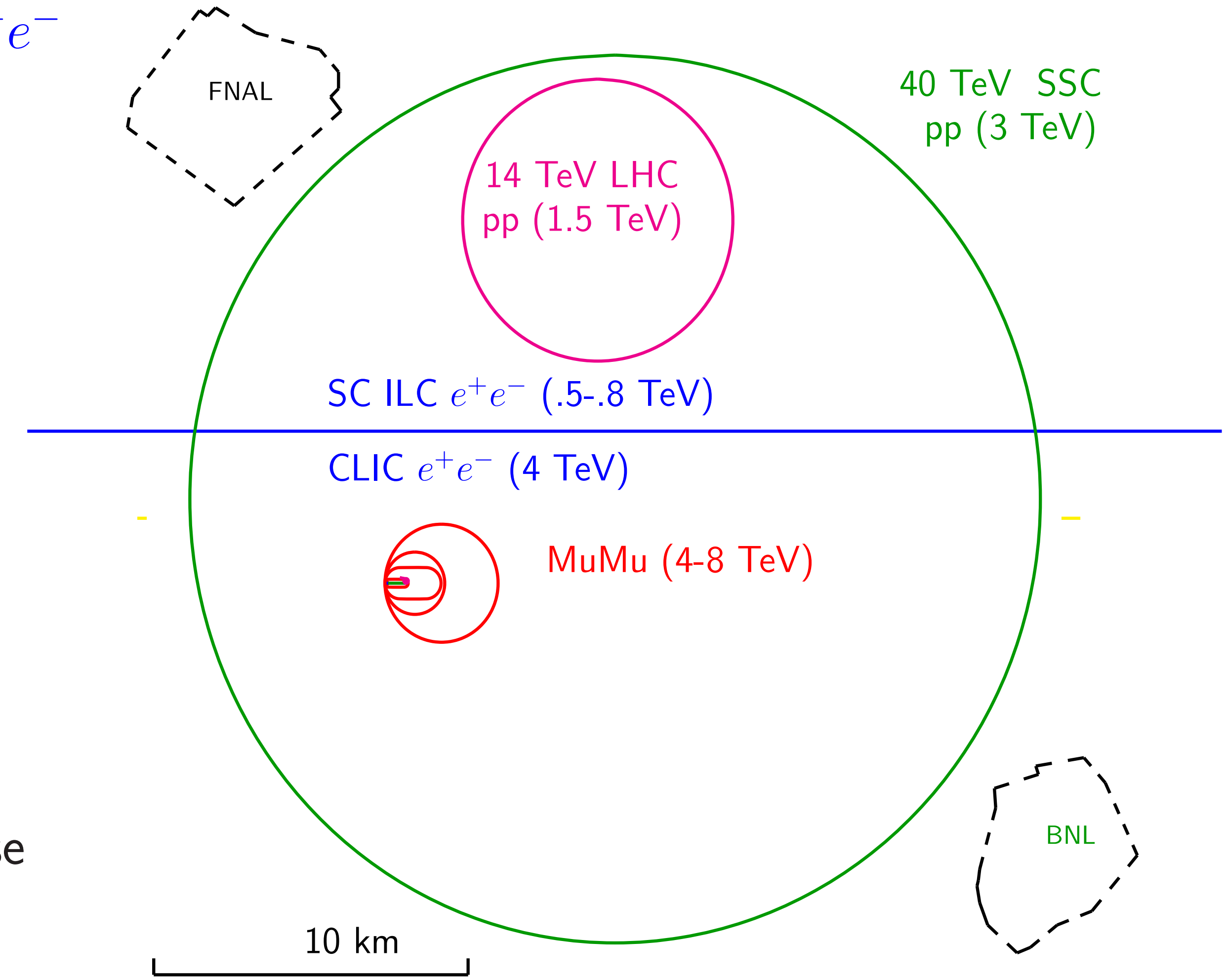
Why a Muon Collider?

- 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

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

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

- Higher $\mathcal{L}/P_{\mathrm{beam}}$ requires lower $\beta_\perp$ or greater $\Delta\nu$
- 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	0.1	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/bunch 10^{13}	16	8	4

- Achieving the 3 nsec bunches at less than 25 GeV would appear hard
- Higher cooling efficiency could ease these requirements

Capture and Cooling Scheme

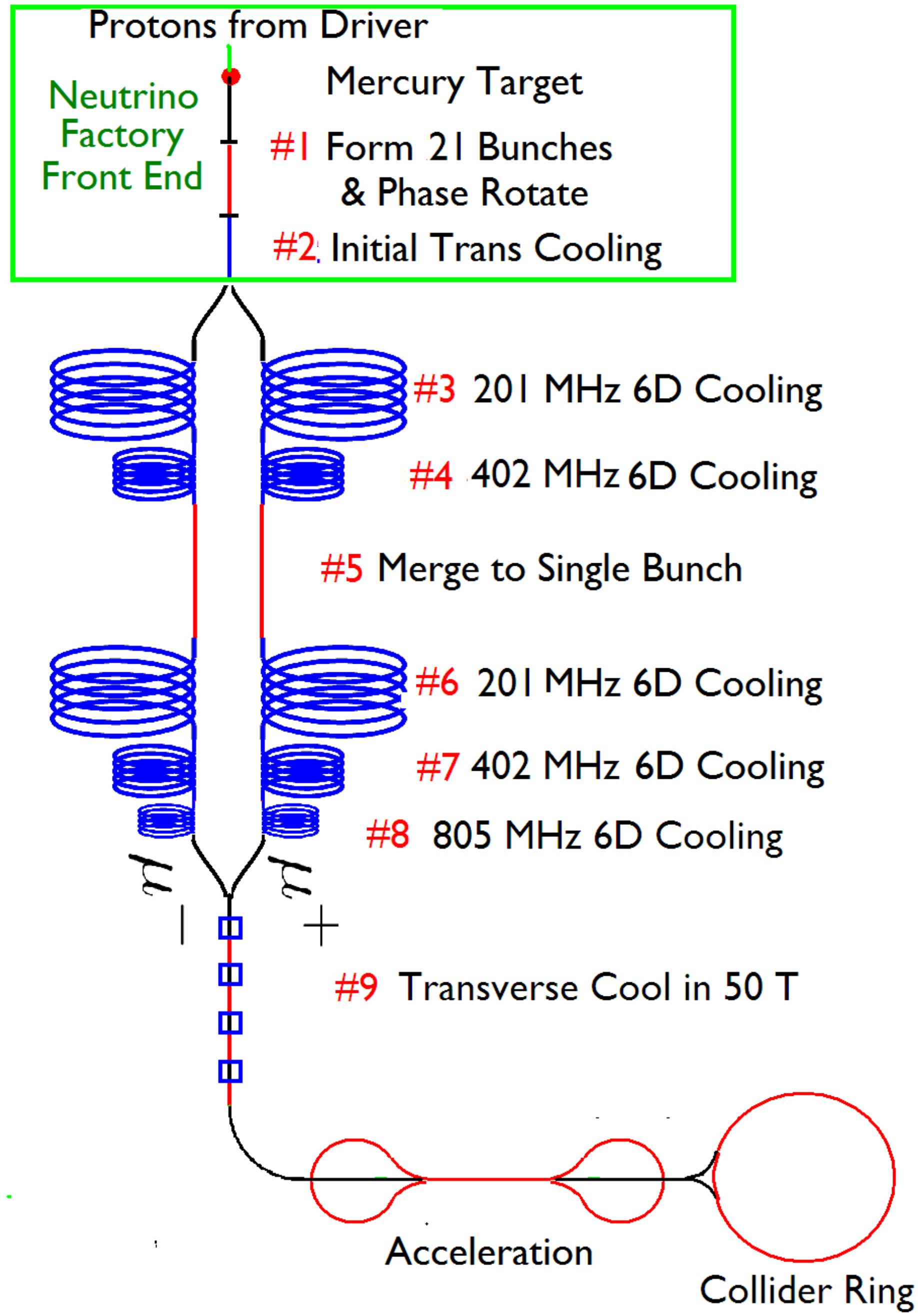
Essential Elements of this Solution:

- 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

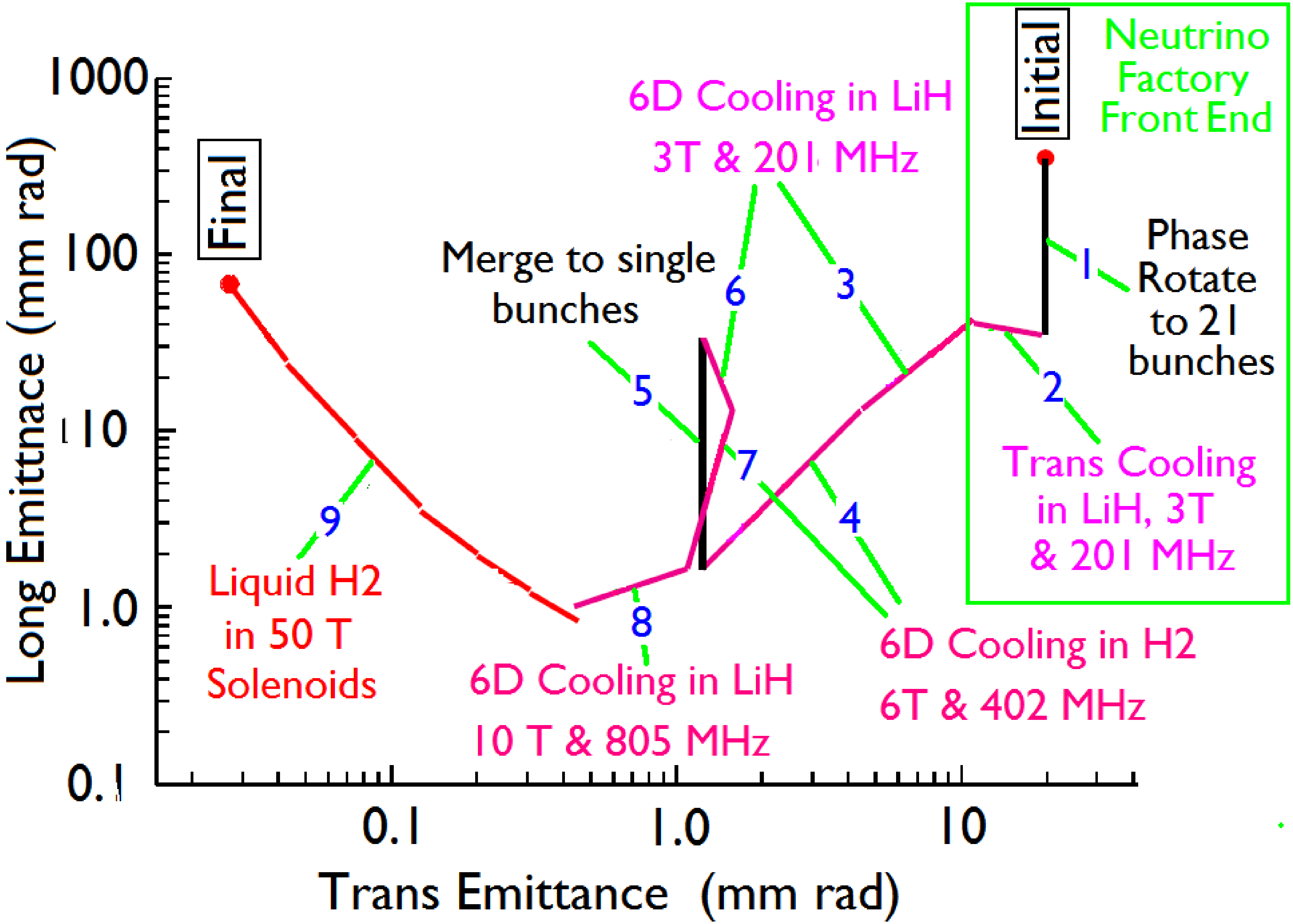
Without any one of these elements, we cannot achieve the requirements

Capture & Cooling Schematic

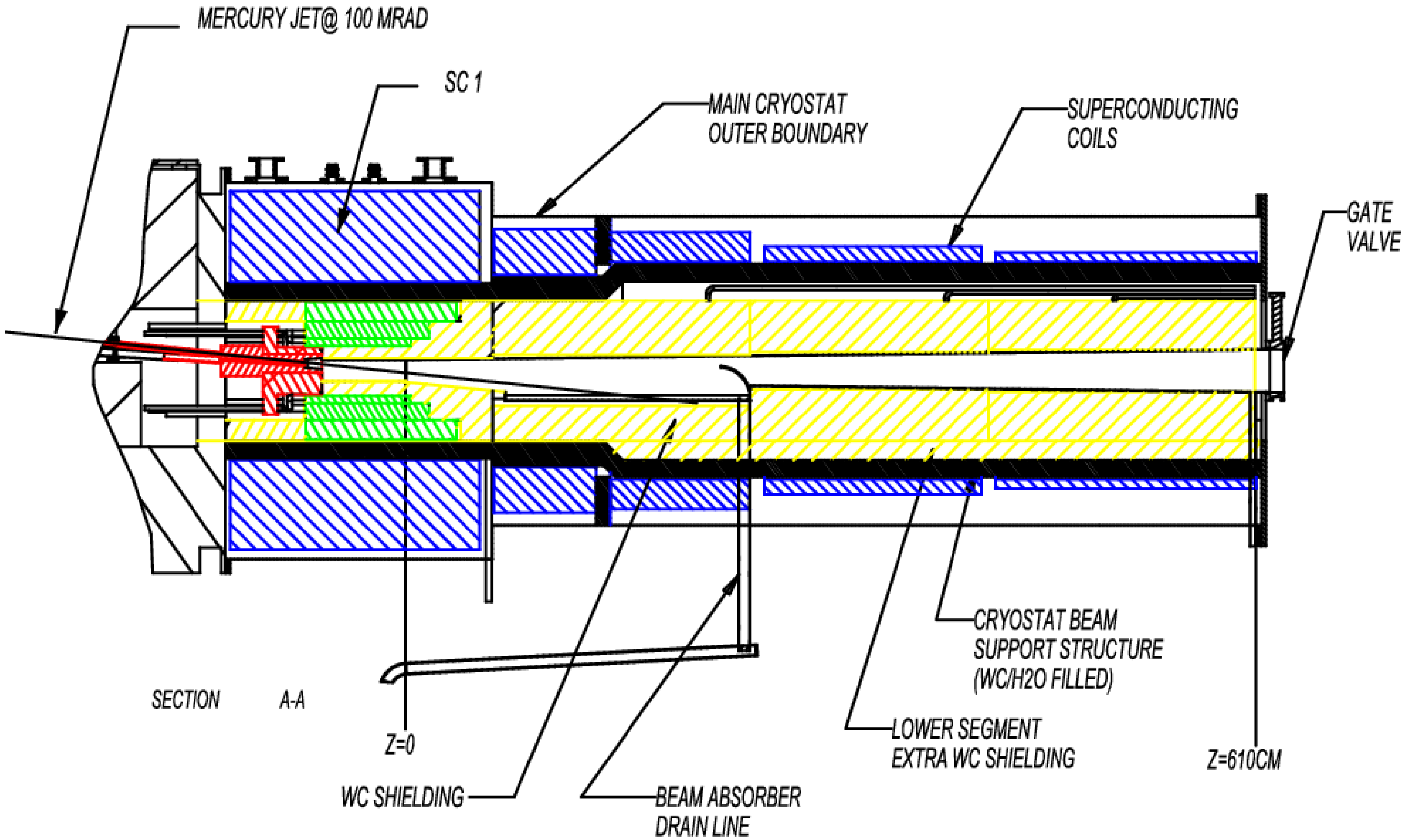
- Not to scale overall length of order 1 km
- We will look at each numbered component later



Emittances vs. Stage



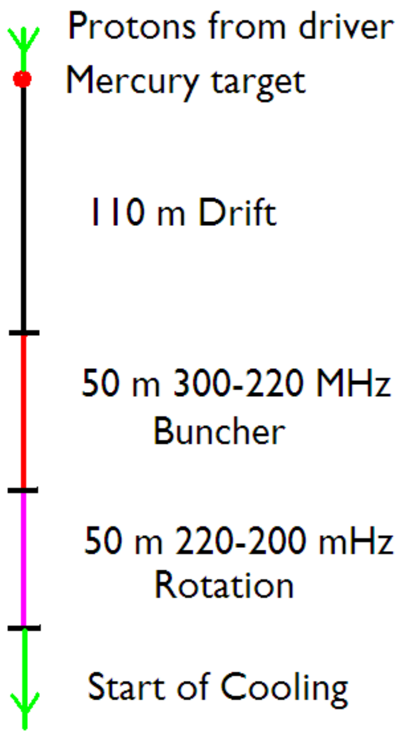
#1 Target and Capture and Phase Rotate



- 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 has tested this concept

Phase Rotation

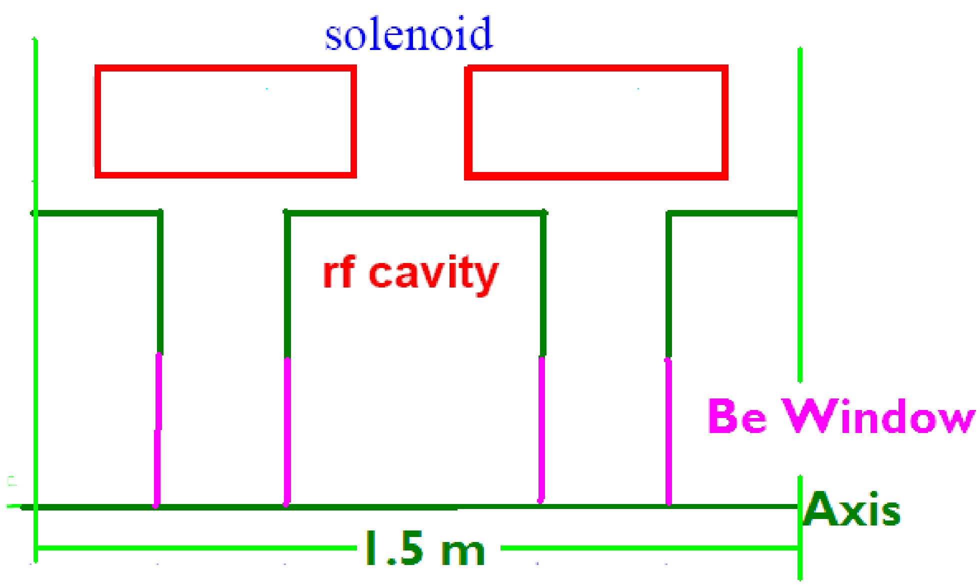
capture into multi-bunches to reduce momentum spread

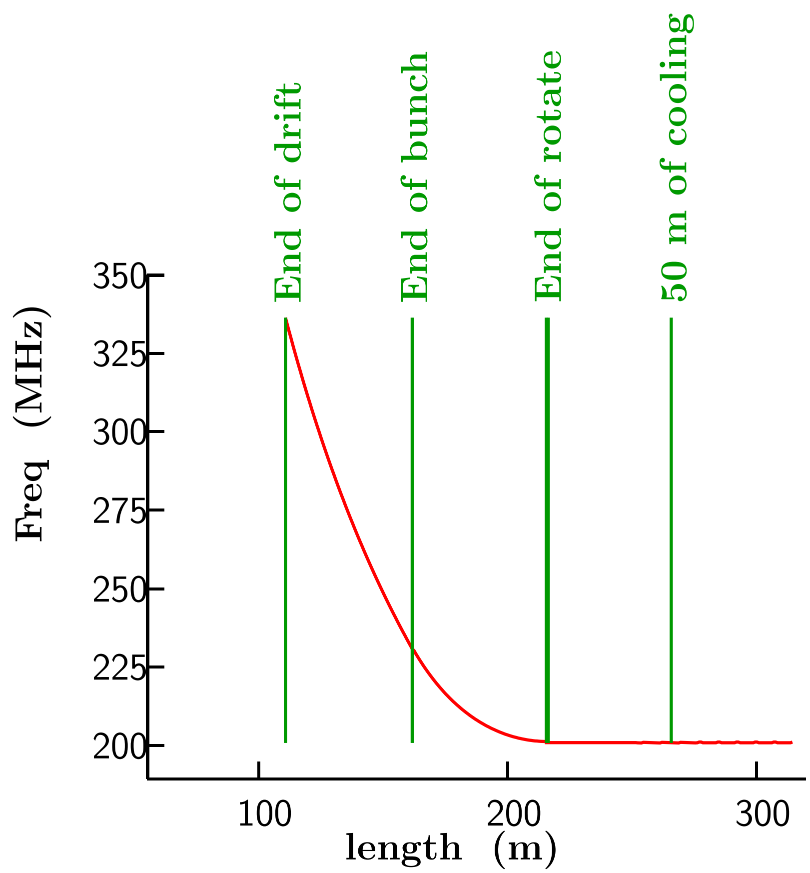


- Drifts and rf in approximately uniform 2 T axial field
- rf using has gradients rising from 0 to 12 MV/m in buncher and 12 MV/m in rotator
- Wavelength in buncher follows increasing extension of bunches
- Frequency then adiabatically approaches fixed 201 MHz

Study 2a system
Neuffer has new one
optimized for collider

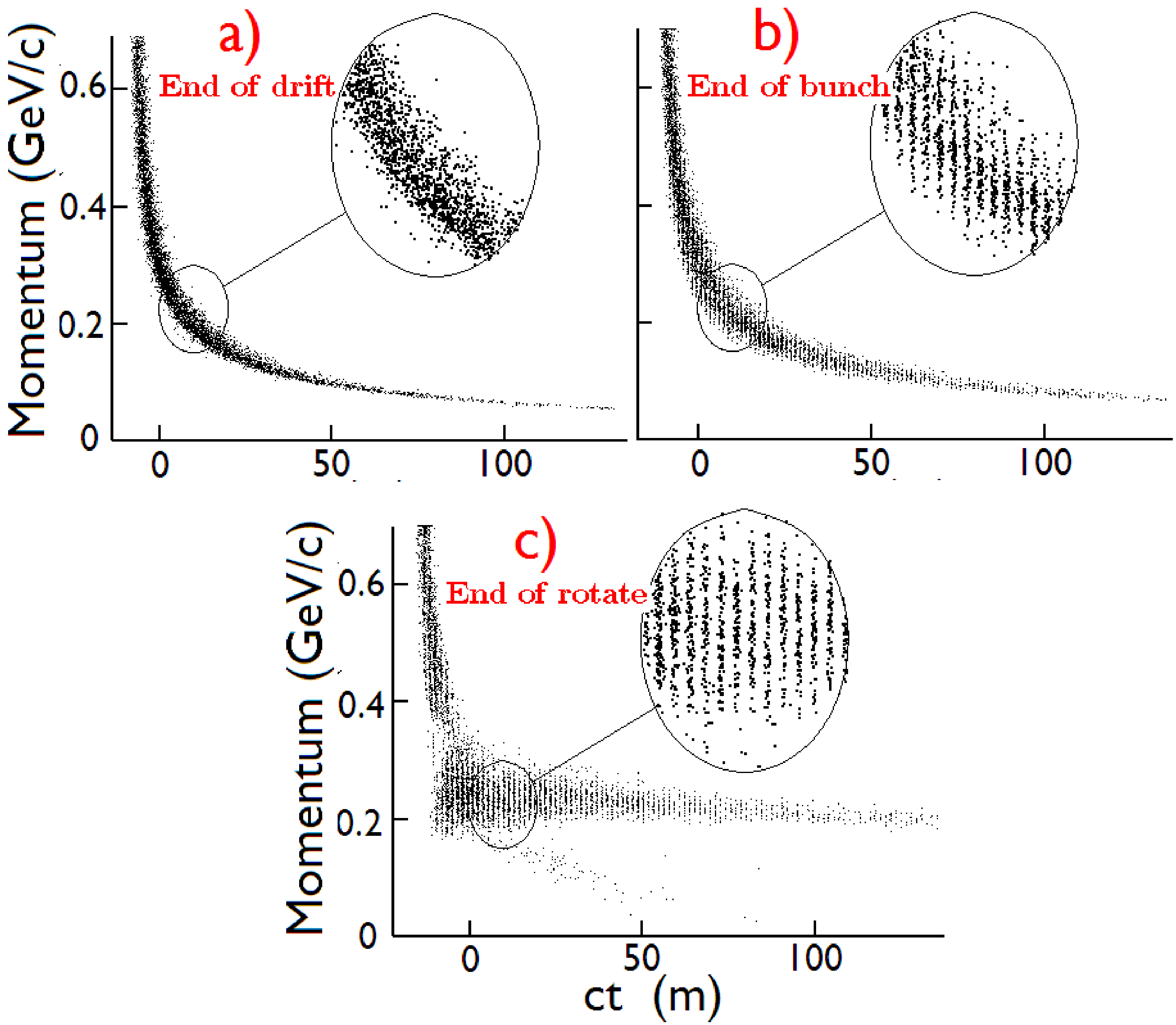
rf systems





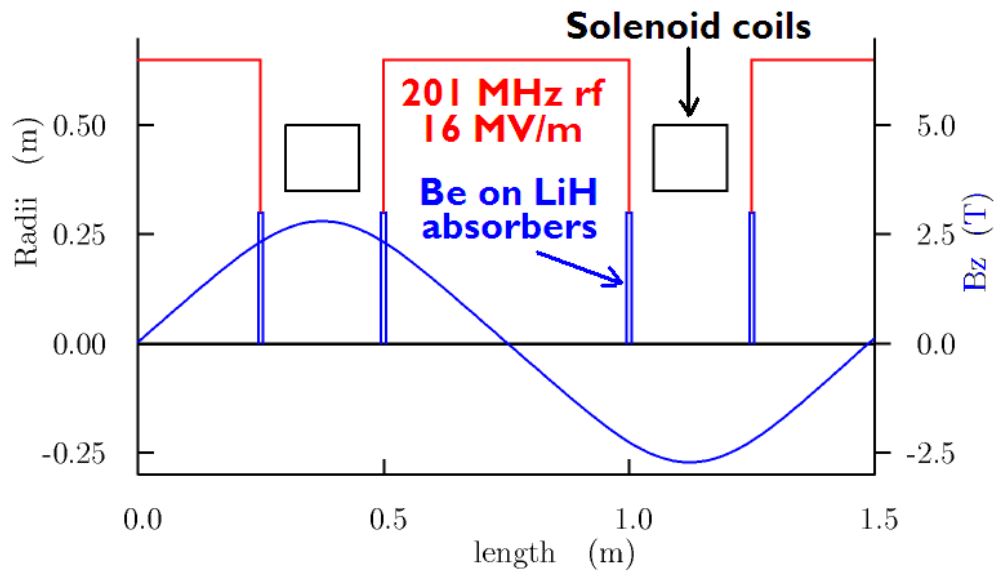
- With solenoids outside rf there may be breakdown problems
- Neuffer has studied systems with gas in the rf
- Open cavities with coils in irises may also be solution

Phase Rotation Simulation

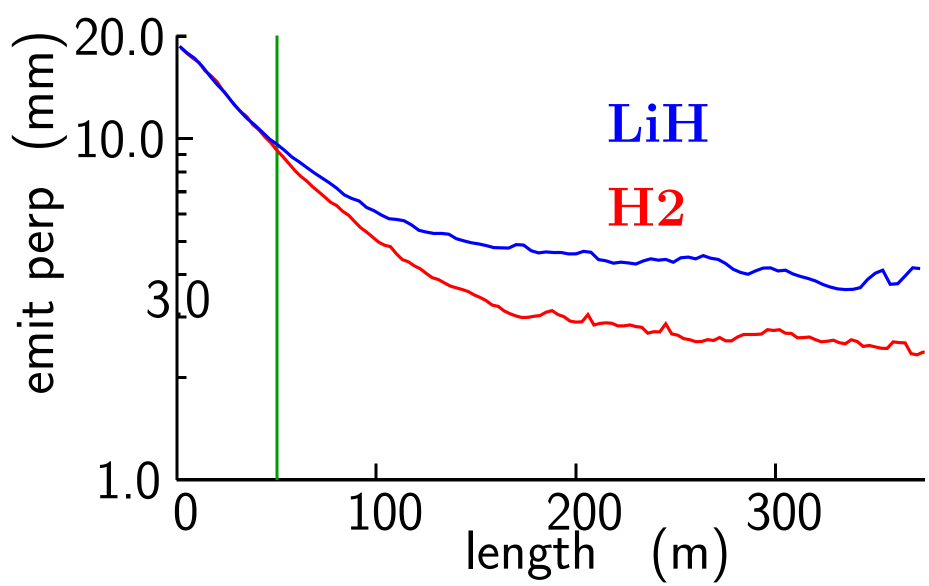


#2 Initial Linear cooling

Reduces transverse beam to fit into 6D cooling



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

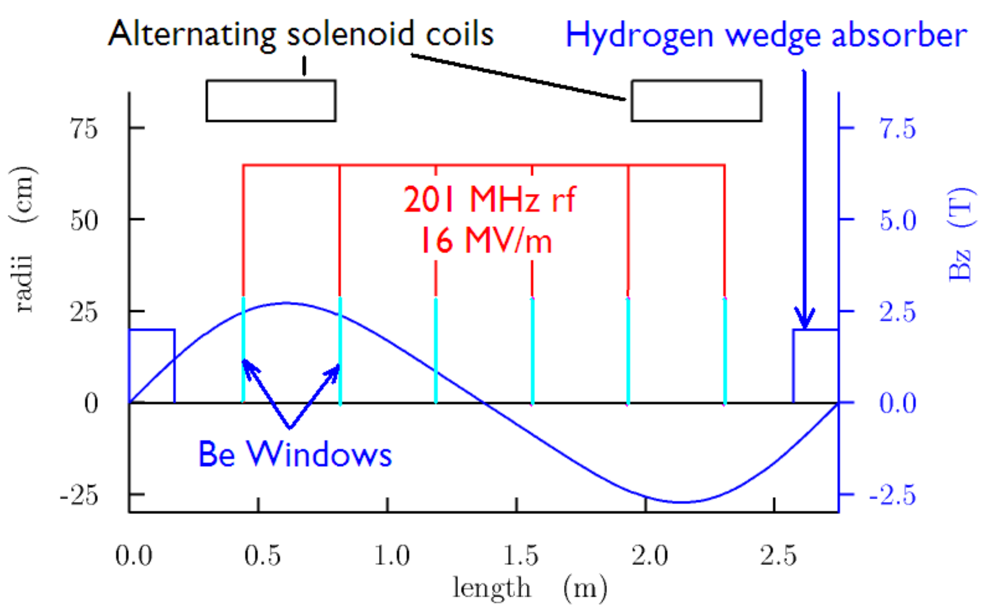


- Negligible difference between LiH and H2 before 50 m

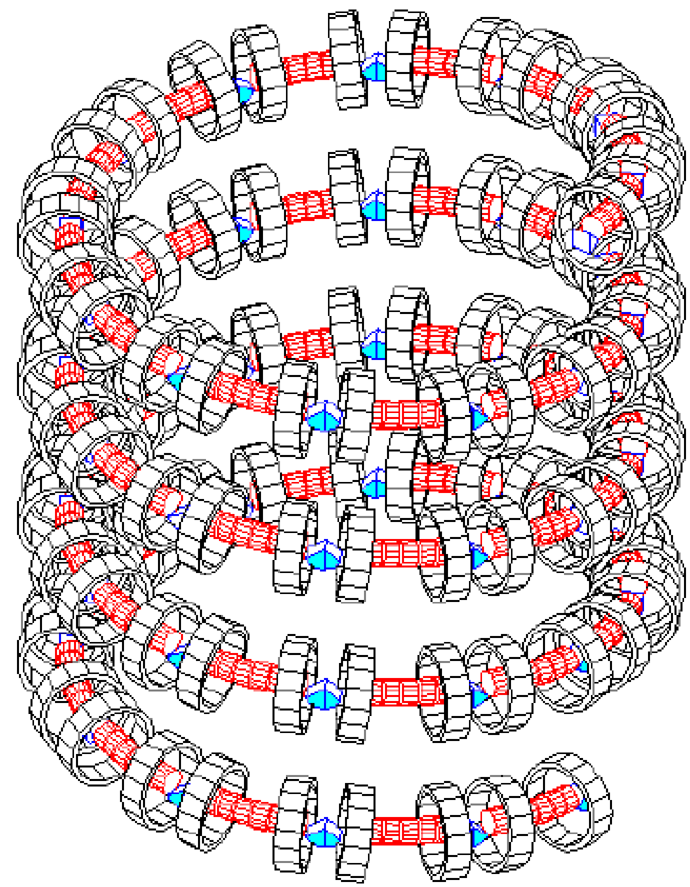
- MICE Experiment at RAL will demonstrate Ionization Cooling

#3 #4 6D Cooling in Guggenheim helices

- RFOFO lattices Coils outside rf may give breakdown - open cavity may fix
- 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

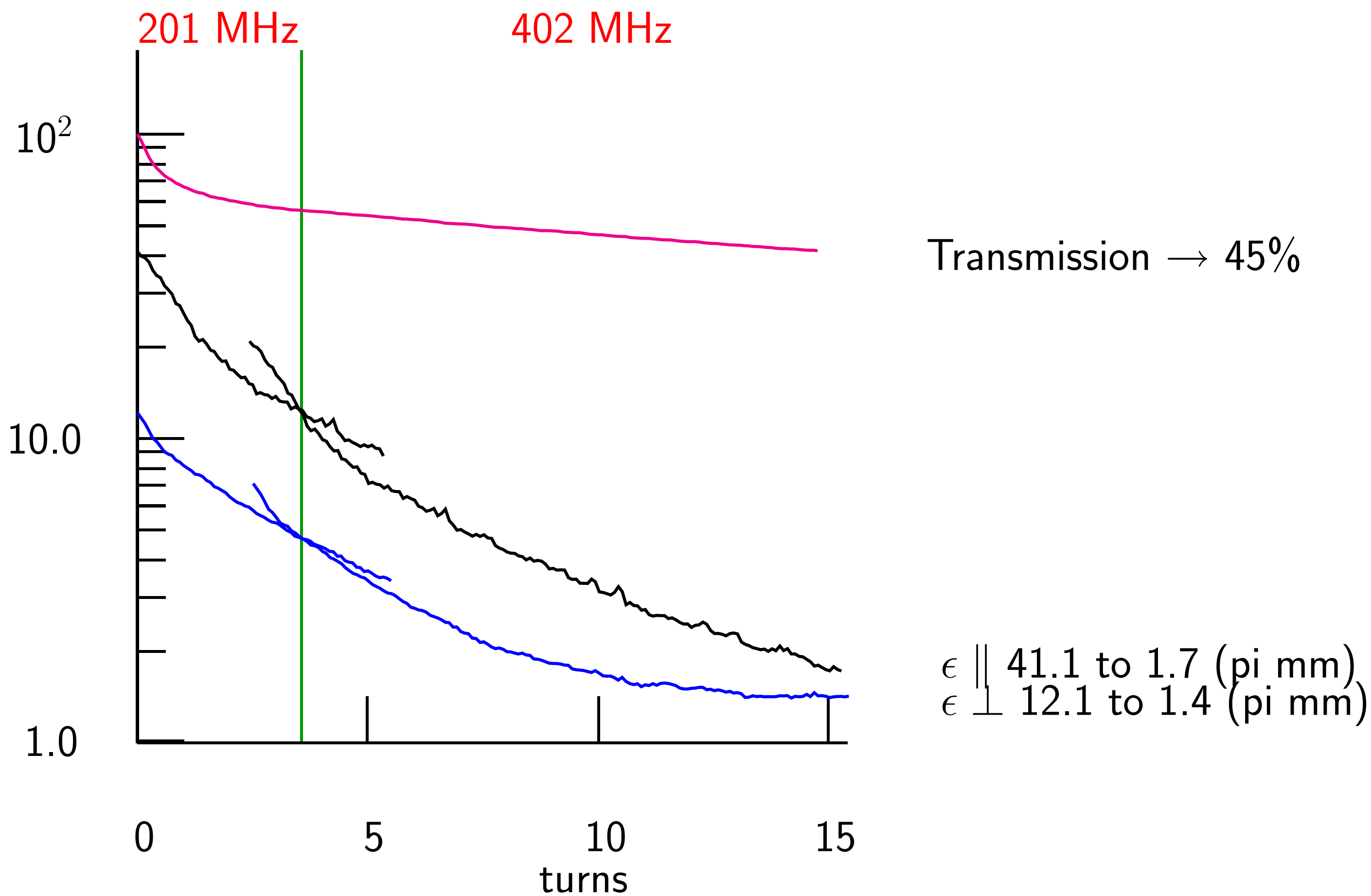


'Guggenheim'

ICOOL Simulations of real fields

Balbakov was first to simulate with real fields

We are assuming that "Guggenheiming" does not change performance

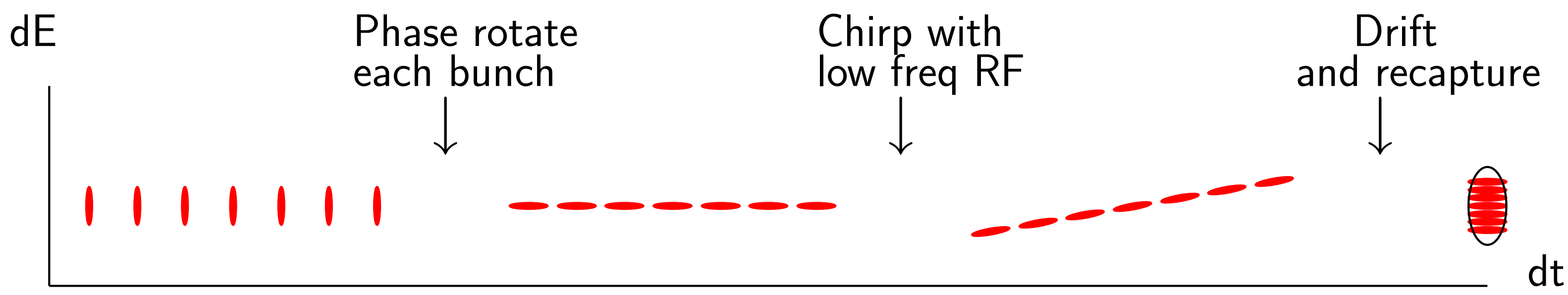


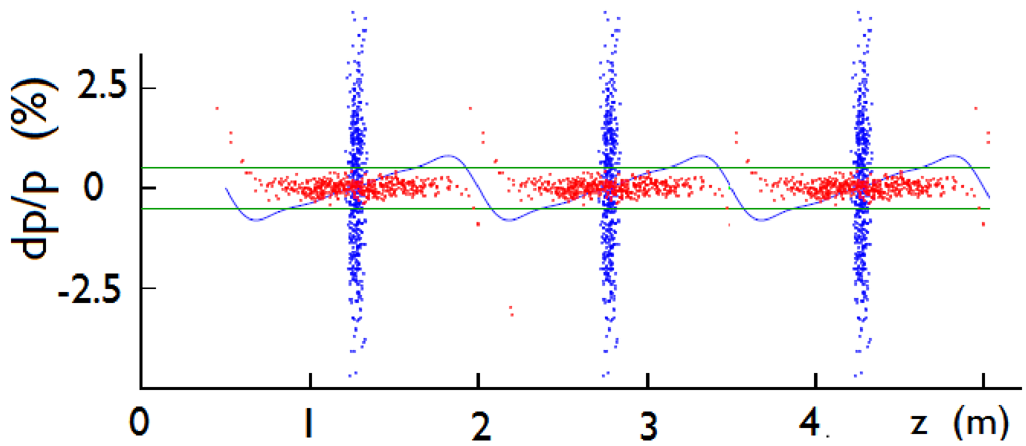
- 201 MHz RFOFO as published, but Guggenheimed (B=3 T)
- 402 MHz RFOFO has all dimensions halved (B=6 T)

#5 Bunch Merging

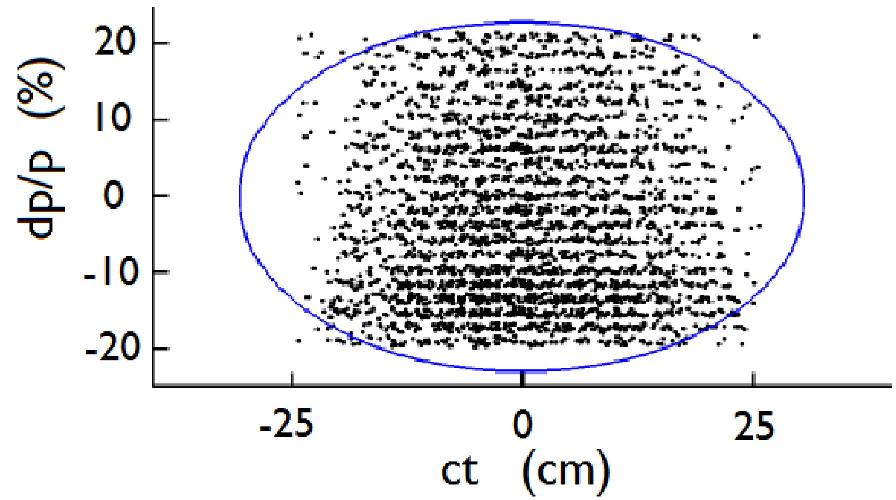
- Luminosity proportional to muons per bunch squared
- Few large bunches required
- Capturing to one large bunch would have required low frequency rf ($\approx$ 30 MHz) with low gradients and inefficiency
- We thus:
  - Capture into multiple bunches at 201 MHz
  - Cool them till small enough to:
  - Merge them and recapture at 201 MHz
  - Re-cool the merged bunches
- Merging after acceleration not possible because 50T cooling ends with bunches much longer than un merged bunch spacing

Merging Scheme





Stage 1 Rotate individual bunches to reduce dp/p

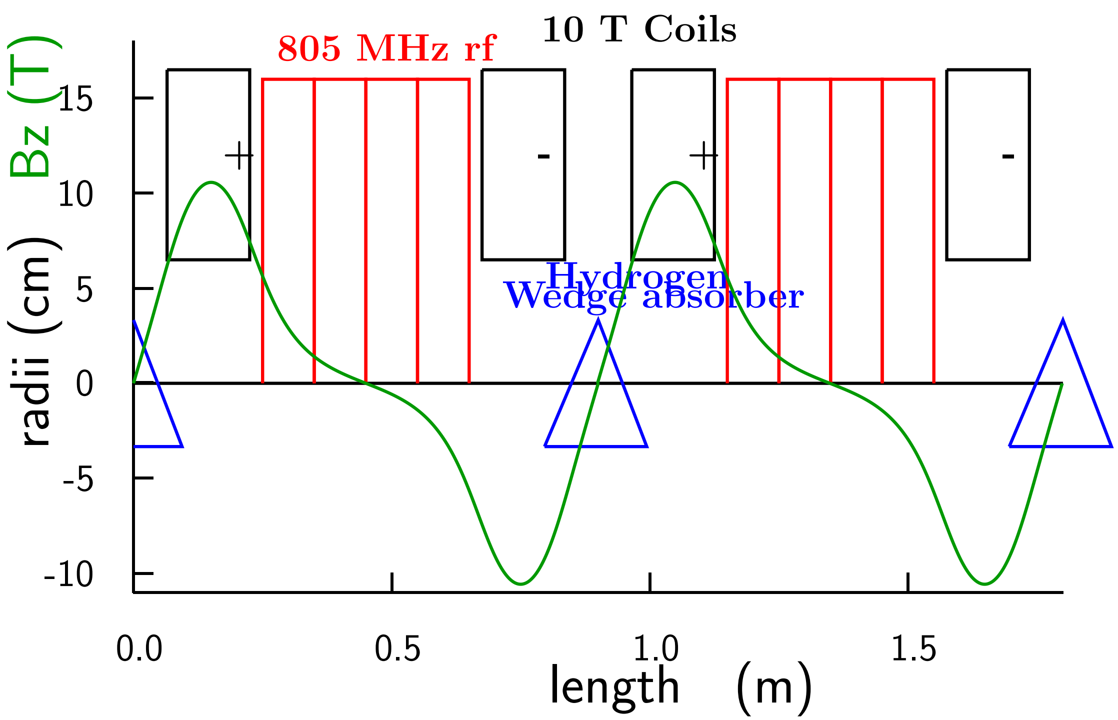


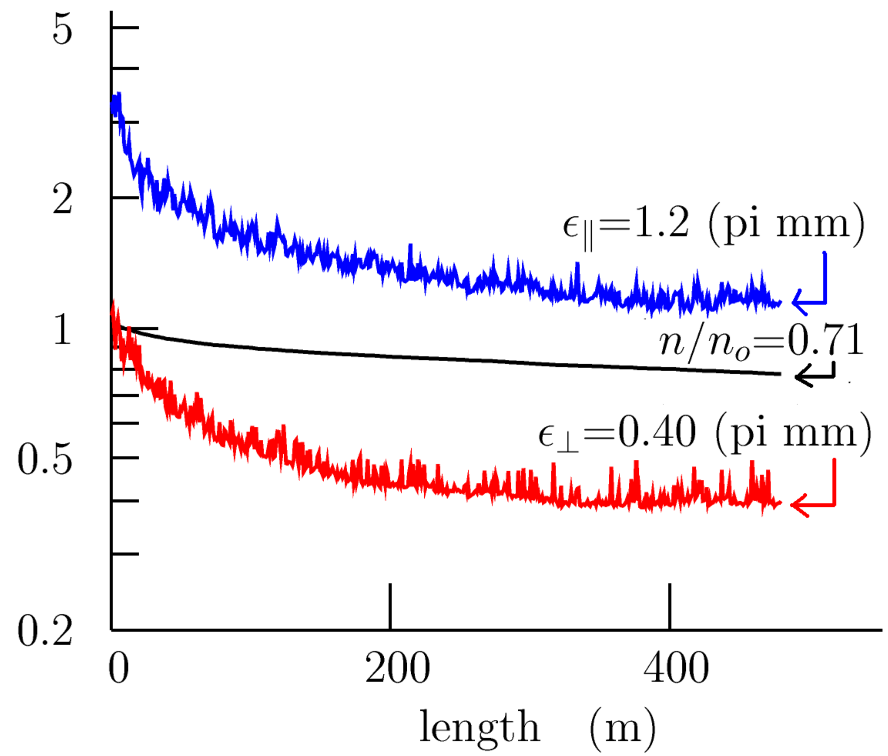
Stage 2 Rotate string of bunches into a stack

- 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
- New Neuffer rotation into 12 (vs 21) bunches should make this easier

Cooling after merge

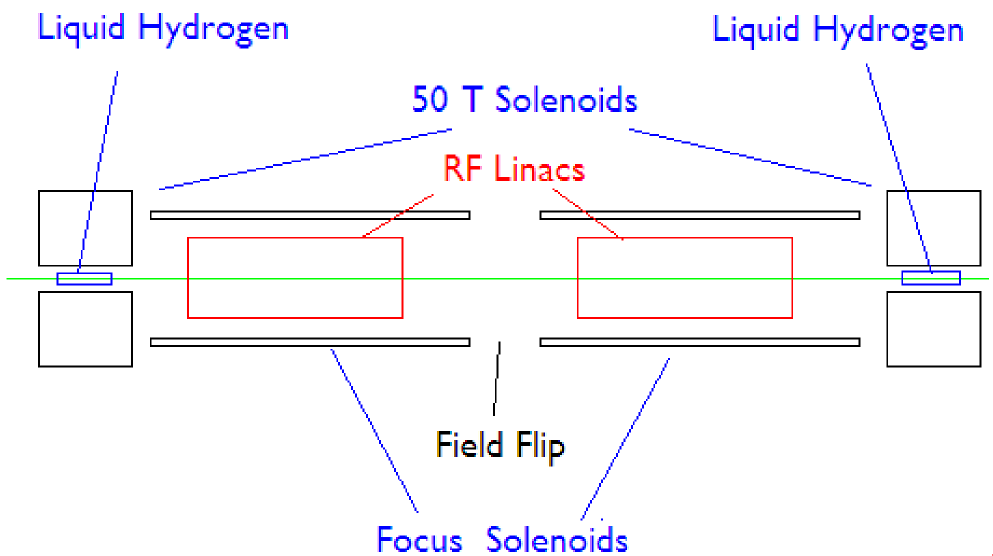
- #6 #7 Re-cooling in Guggenheim Lattices
  - Essentially identical to #3 and #4
  - Could re-use #3 and #4
- #8 Last 6D cooling in higher field lattice
  - Uses 10 T high current density (150 A/mm^2) solenoids
  - rf operation in fields is questionable





#9 Transverse Cooling in Very High Field Solenoids

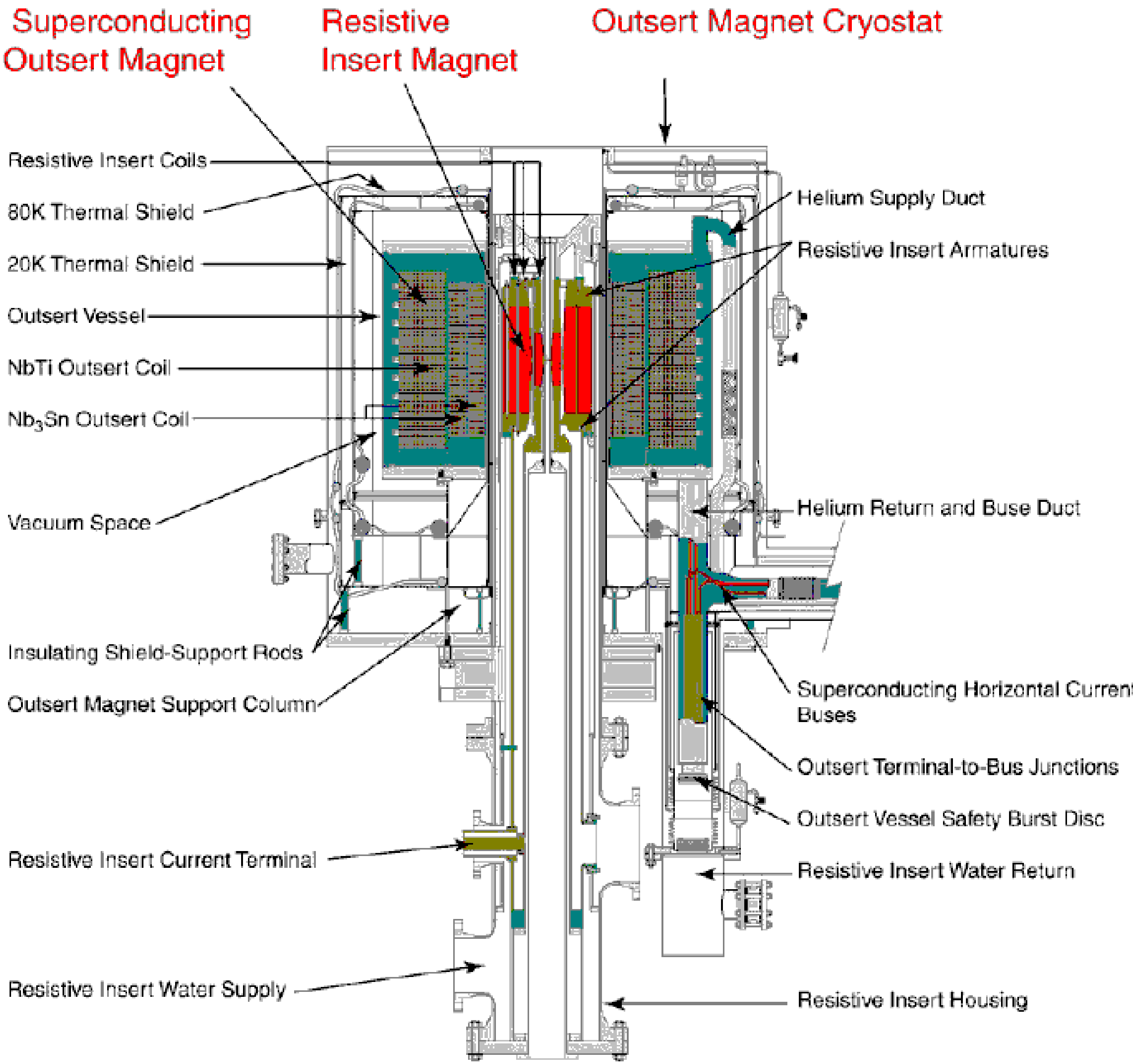
- Lower momenta allow strong transverse cooling, but long emittance rises:
- Effectively reverse emittance exchange



- 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
- 8 solenoids with liquid hydrogen

- ICOOL Simulation (Ideal Matching and re acceleration, Transmission 97%)

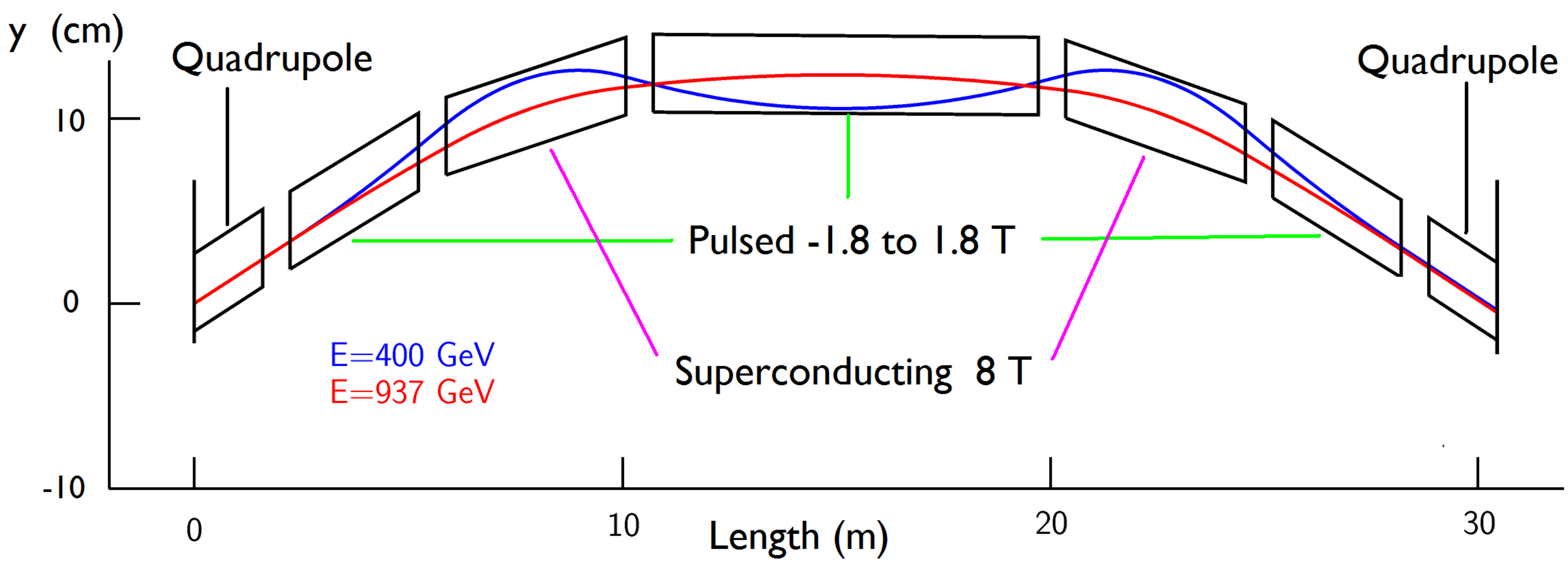
NHFML 45T Solenoid



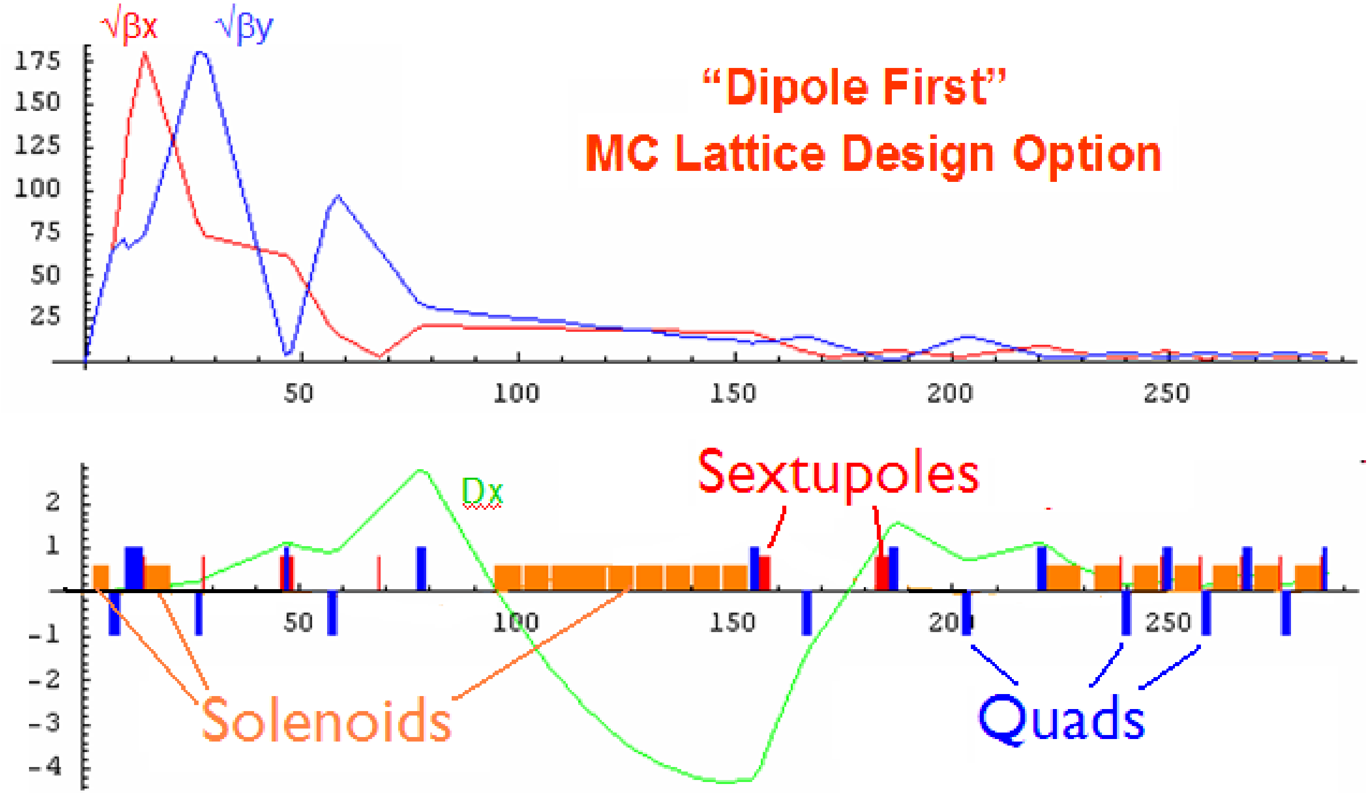
Acceleration

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

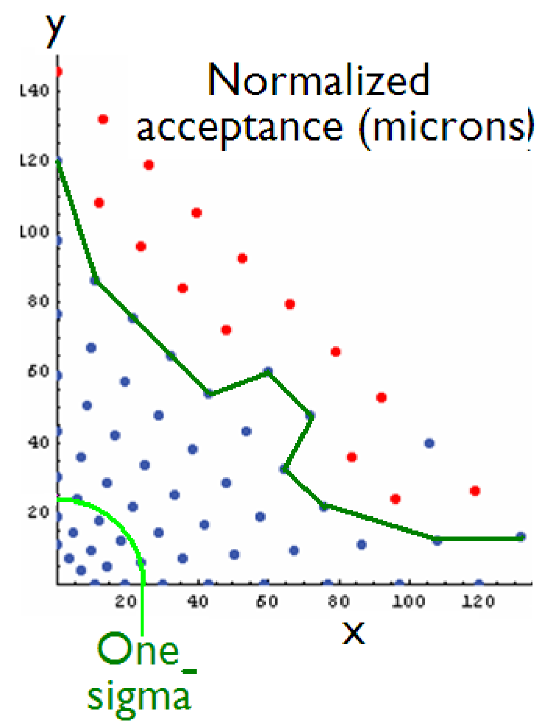
- Lower cost solutions might use:
  - Fixed Field Alternating Gradient (FFAG) accelerators
  - Rapidly pulsed magnet synchrotrons
  - Hybrid SC & pulsed magnet synchrotron 400-930 GeV (in Tevatron tunnel) Hybrid site filler would acc to 2.5 TeV (5 TeV c of m)



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



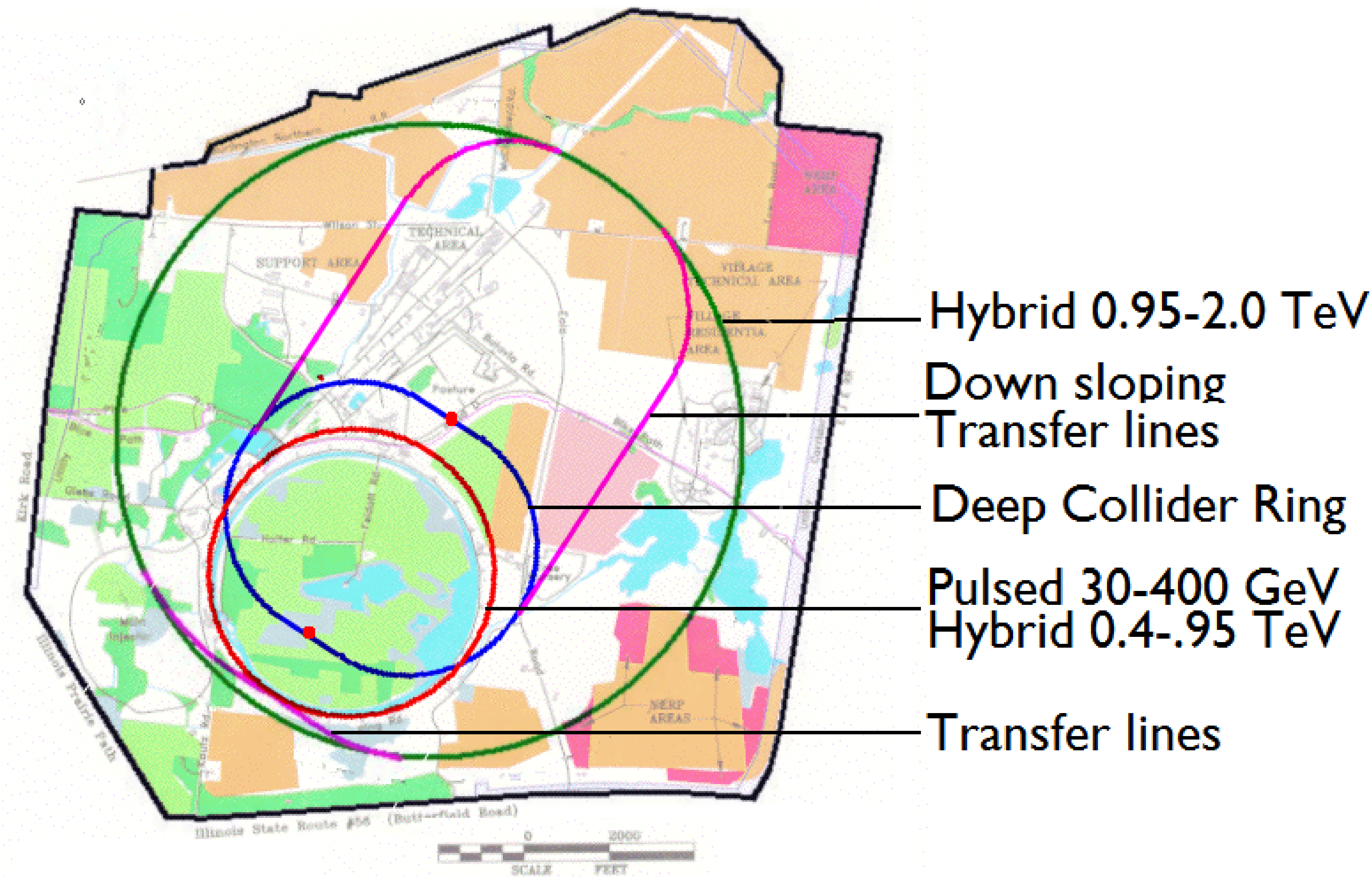
Lattice



Acceptance

- $\beta^* = 1cm \quad \Delta p/p \approx 0.6$ %
  More than adequate for rms dp/p=0.1 %
- $\Delta x, y \approx 2\sigma$ at 25 mm mrad emittance
  Will require scraping of beam (cut at 1.75 sigma loses only 5% of luminosity)
- 18 mm mrad probably possible at dp/p=0.2% ???

Layout of 4 TeV (c of m) on FNAL Site



Ongoing Studies

- Neuffer rotation into 12 instead of 21 bunches
- Possible/probable breakdown of vacuum RF in the specified magnetic fields

  – Possible solution 1) Gas filled cavities
  Works for earlier cooling lattices
  Experiment needed for beam breakdown
  Does not work in later 6D cooling because they require very low betas where there is material

  – Possible solution 2) Open Cavities with coils in irises
  Works in simulation
  Experiments needed for breakdown

- Matching required for all stages
- Tapering of 6D cooling
- Charge separation before 6D Cooling
- OR planar wiggler lattice to replace Guggenheims (cools both muon signs)
- HCC instead of Guggenheim 6D cooling ?

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 ?