A COMPLETE SCHEME OF IONIZATION COOLING FOR A MUON COLLIDER

Robert B. Palmer, J. Scott Berg, Richard C. Fernow, Juan C. Gallardo (BNL)
Yuri Alexahin, David Neuffer (FNAL)
D. Summers (Mississippi University)
Stephen A. Kahn (Muons Inc.)

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History

1969	Concept discussed	Budker
1981	Ionization Cooling	Skrinsky, Pmarkhomchuk
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 paper

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	-	135	540	m
Efficiency $N_\mu/N_{\mu o}$	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

- Transverse emittance requirement same for all examples

Proton Driver

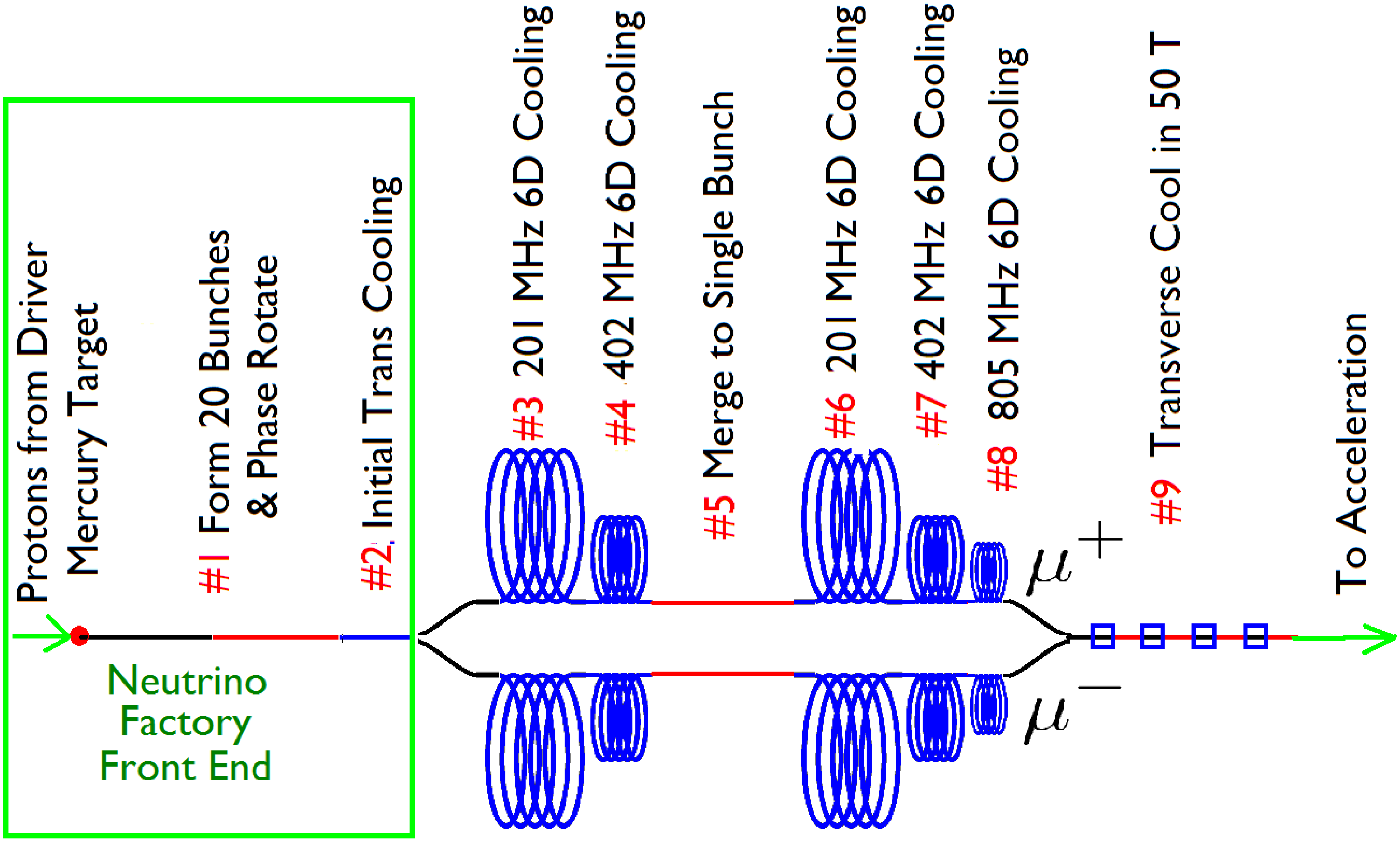
- Average proton power of 4 MW
- Protons per bunch $8\ 10^{13}$ at 24 GeV
- Extracted bunches must have $\sigma_t\ \leq\ 3$ (nsec)

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

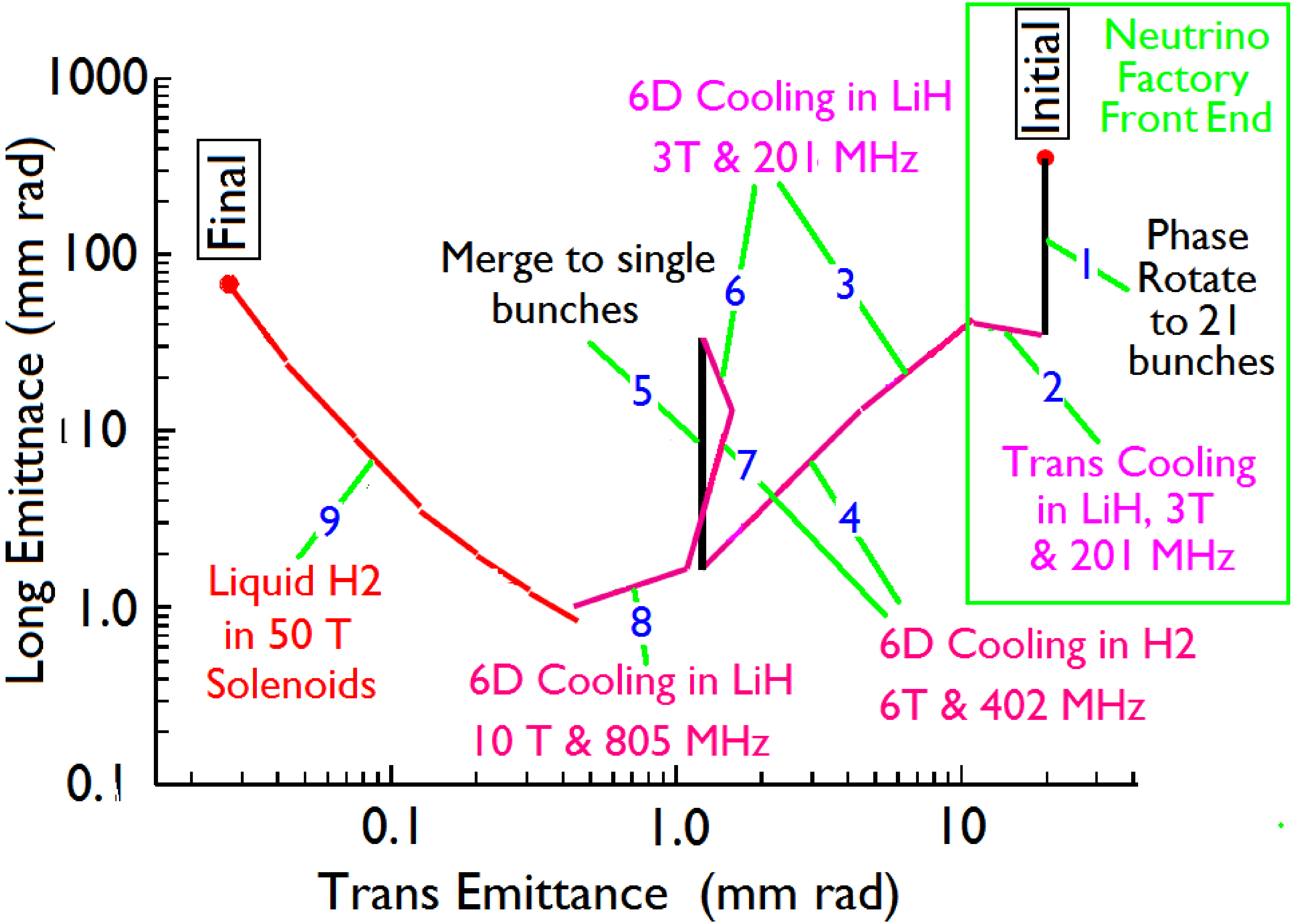
- Achieving the 3 nsec bunches at less than 25 GeV would appear hard
- Higher repetition rate and fewer protons per cycle is an option
- Higher cooling efficiency could ease these requirements
- Needs more study

Capture and Cooling Scheme

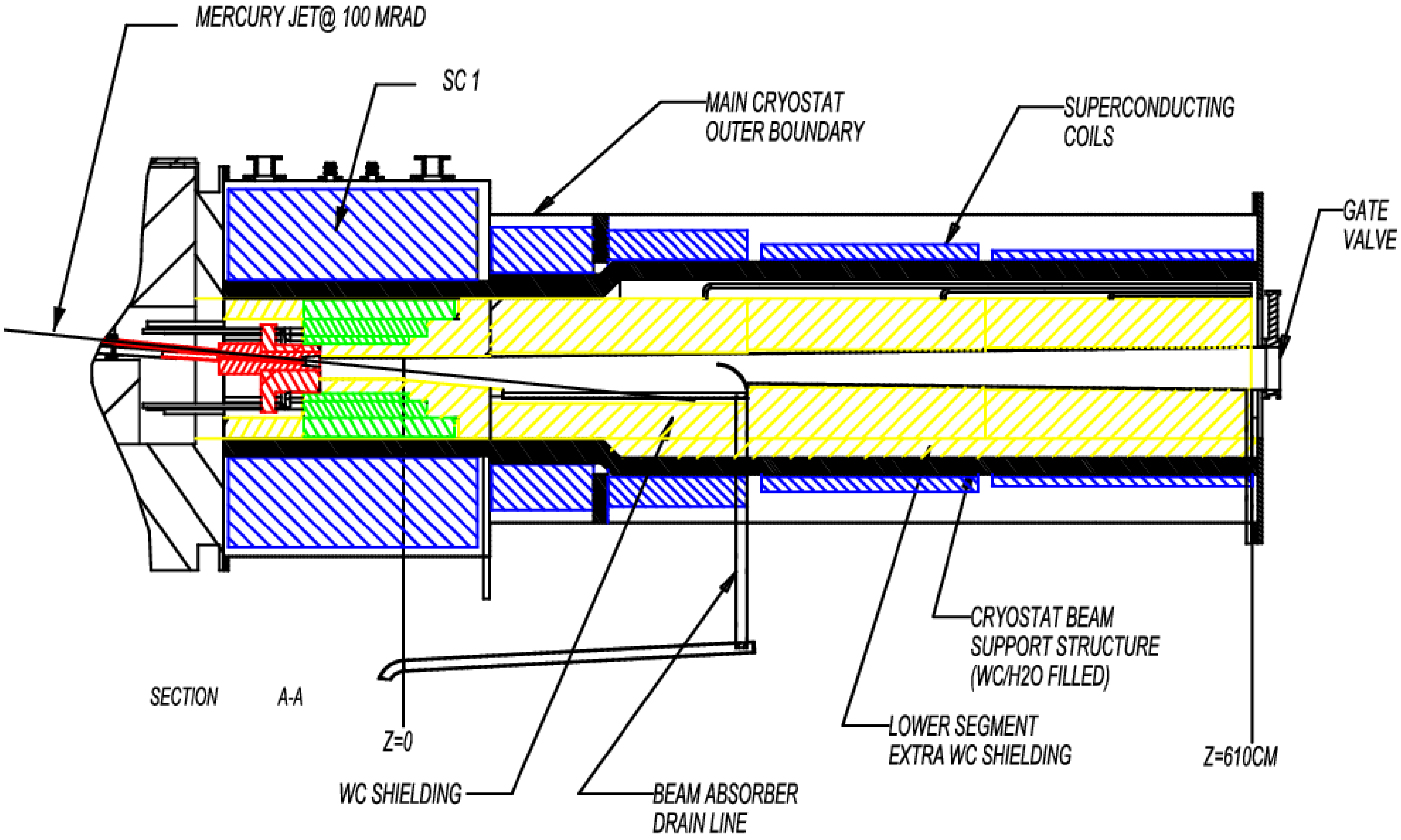


Not to scale overall length of order 1 km

Emittances vs. Stage



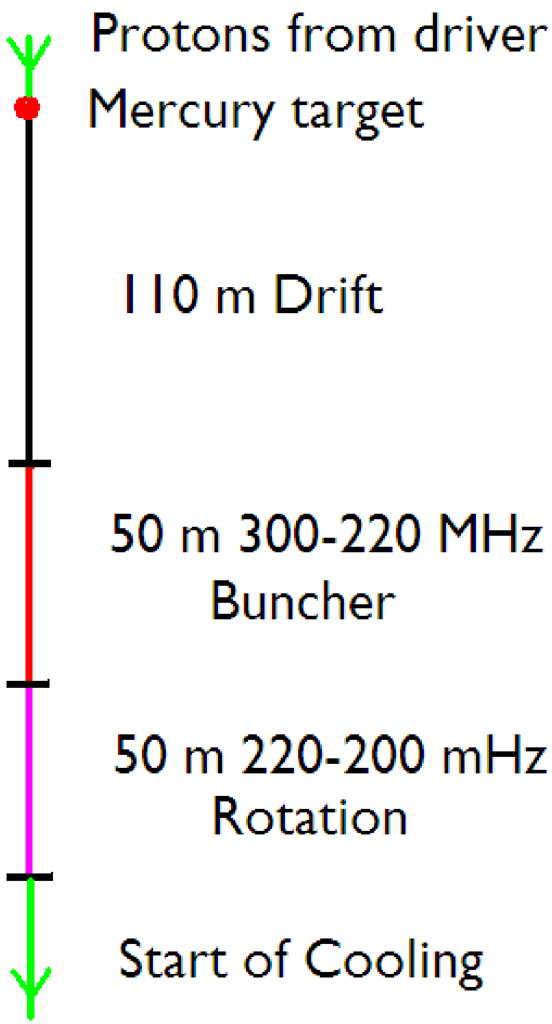
#1 Target and Capture and Phase Rotate



- 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 Simulation

capture into multi-bunches to reduce momentum spread



Protons from driver

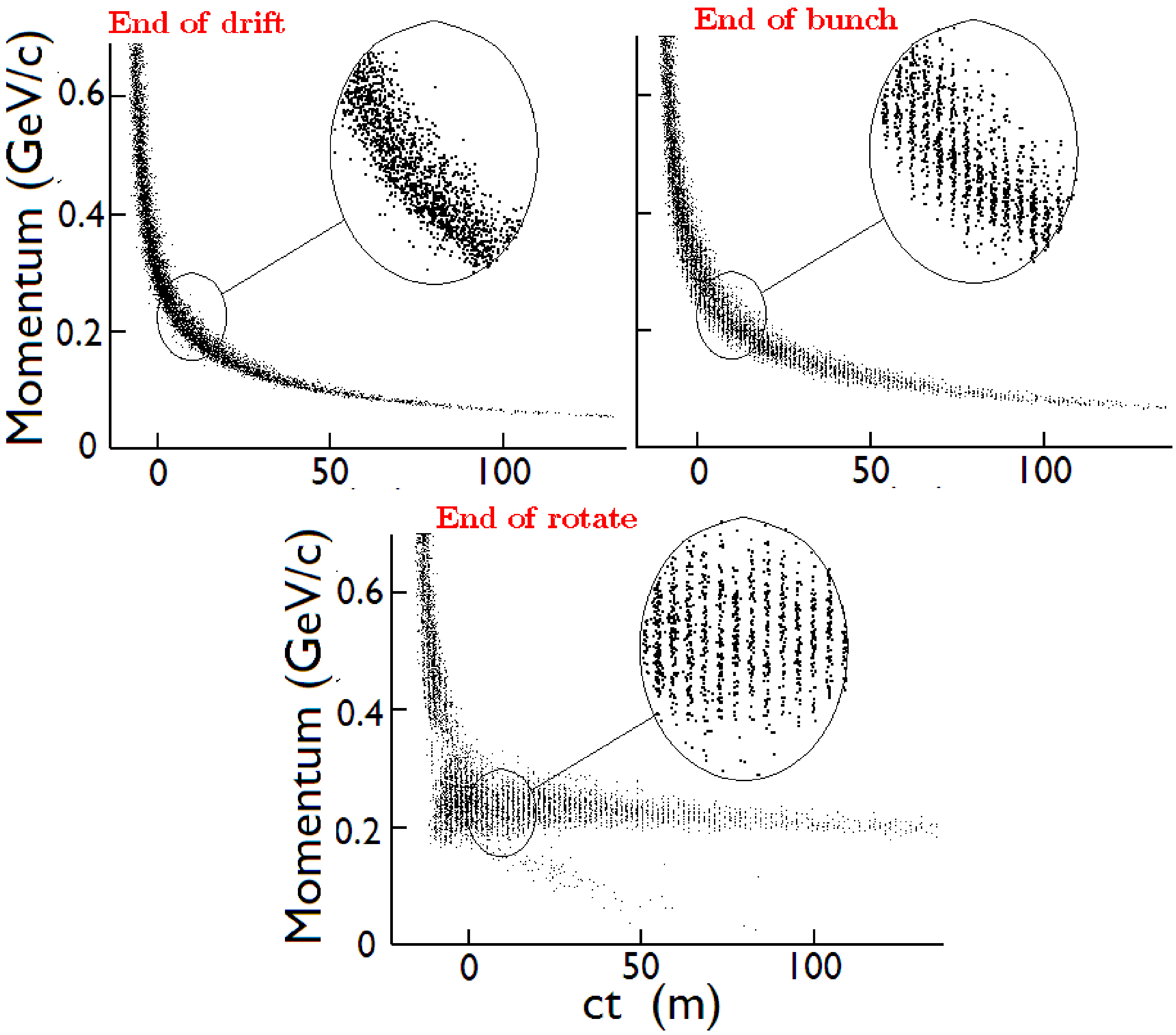
Mercury target

110 m Drift

50 m 300-220 MHz
Buncher

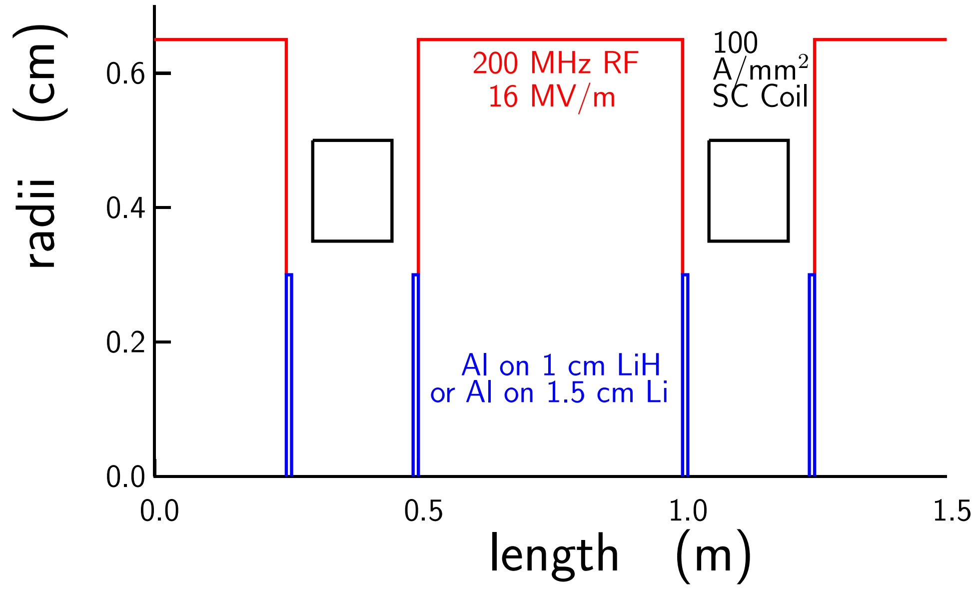
50 m 220-200 mHz
Rotation

Start of Cooling



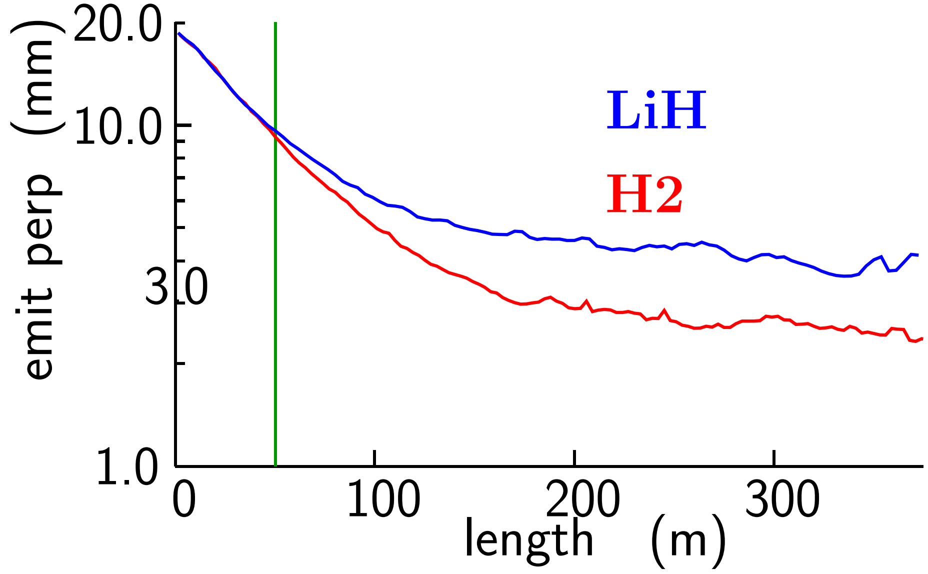
#2 Initial Linear cooling

Only Ionization cooling is fast enough



- Linear channel cools both signs transversely
- Tapering the focus field should improve performance

  (not yet assumed)

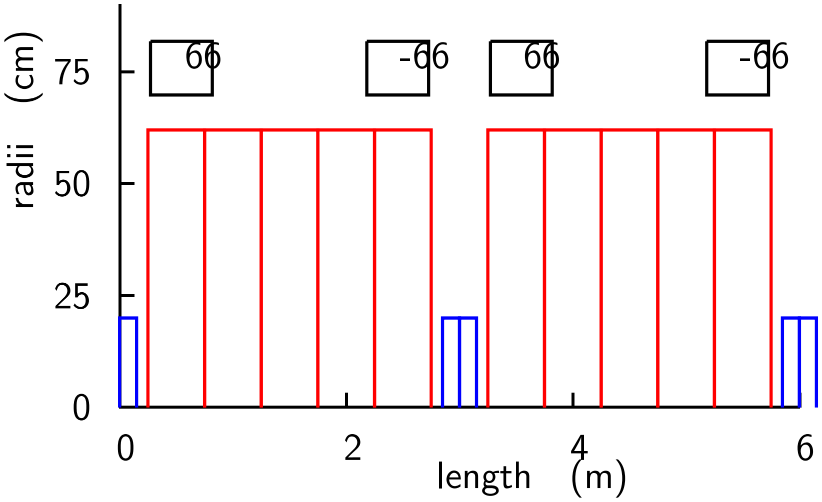


- Negligible difference between LiH and H2 before 50 m

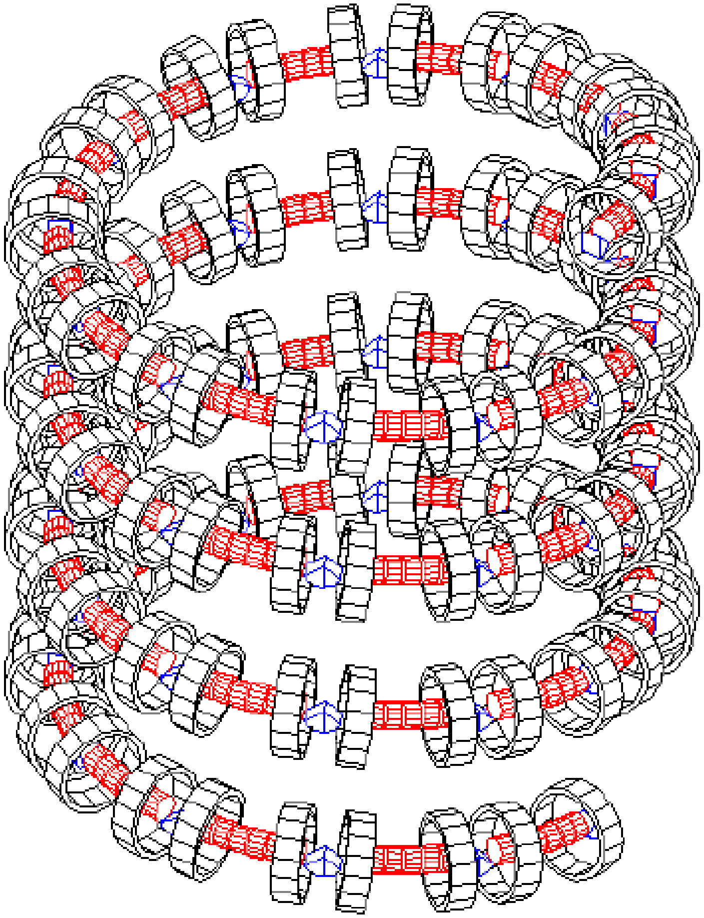
- MICE Experiment at RAL will demonstrate Ionization Cooling

#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

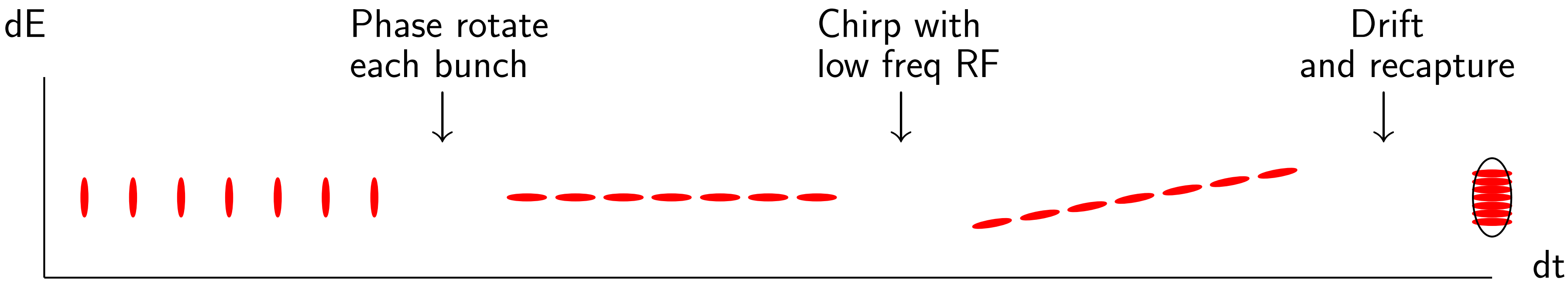


'Guggenheim'

#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 (≈ 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

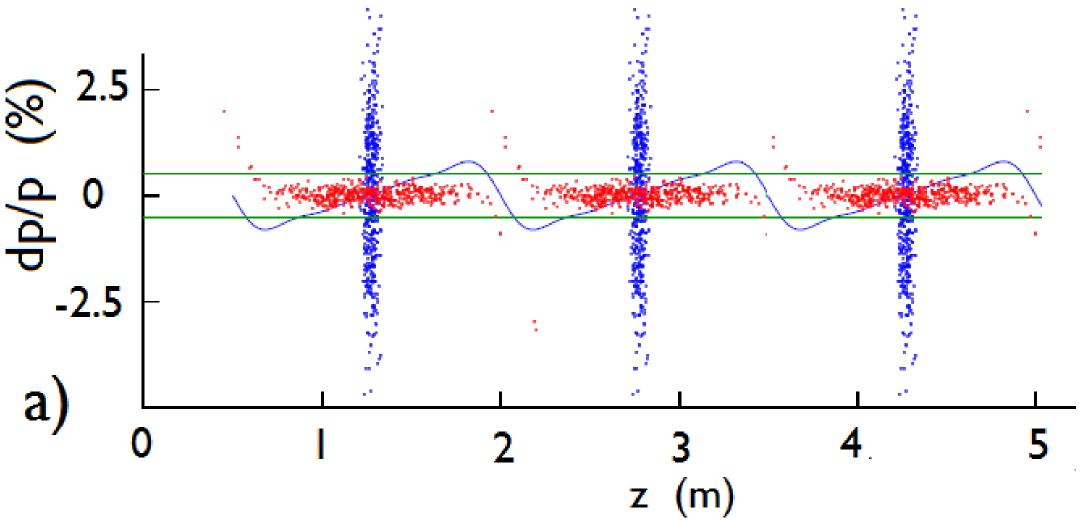
Merging Scheme

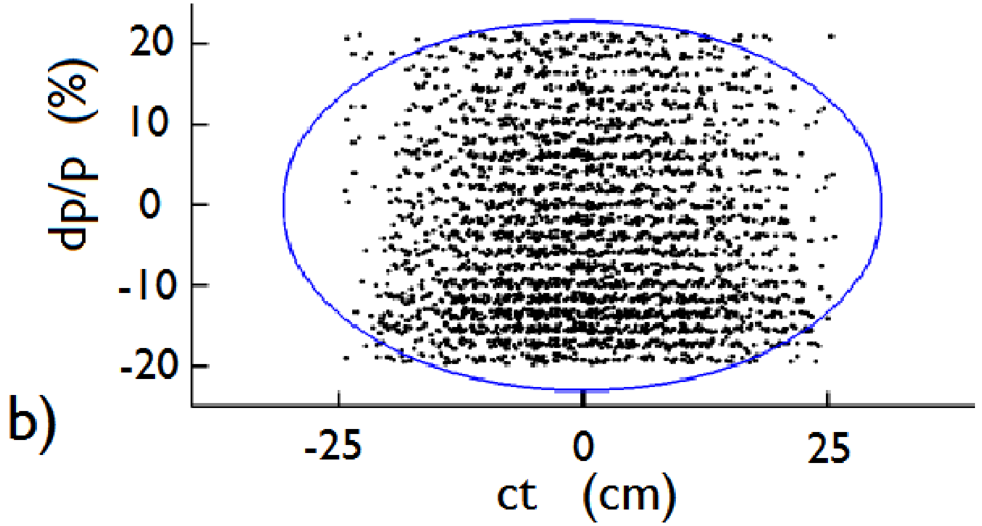


Bunch Merging Simulation

- 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

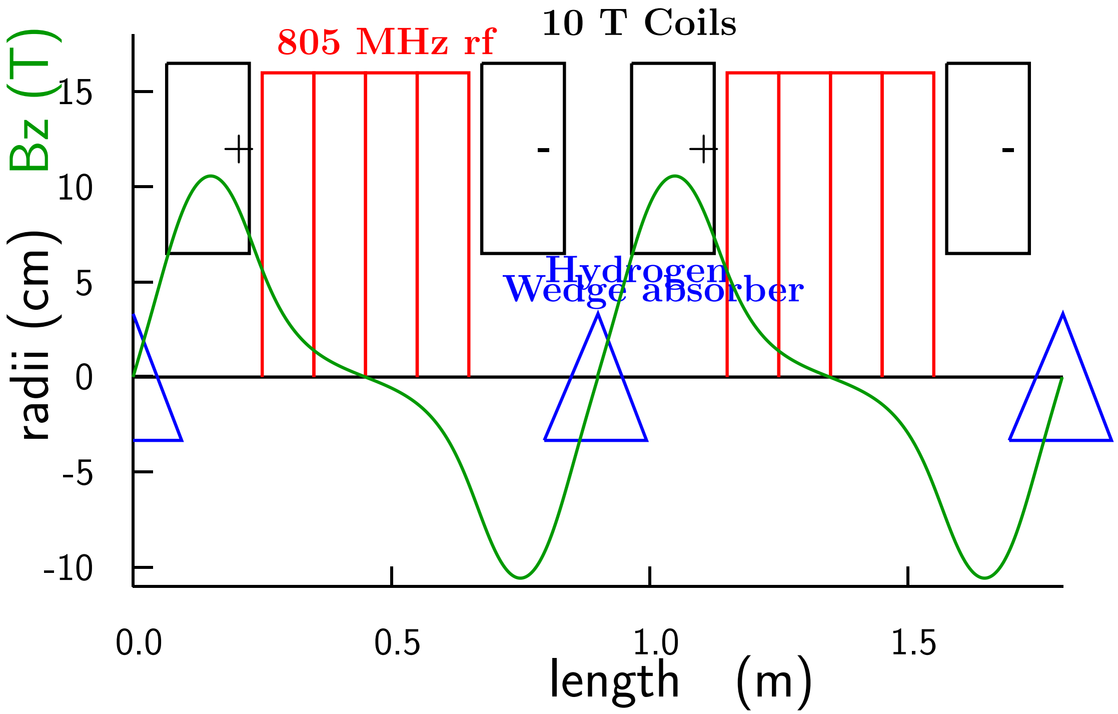


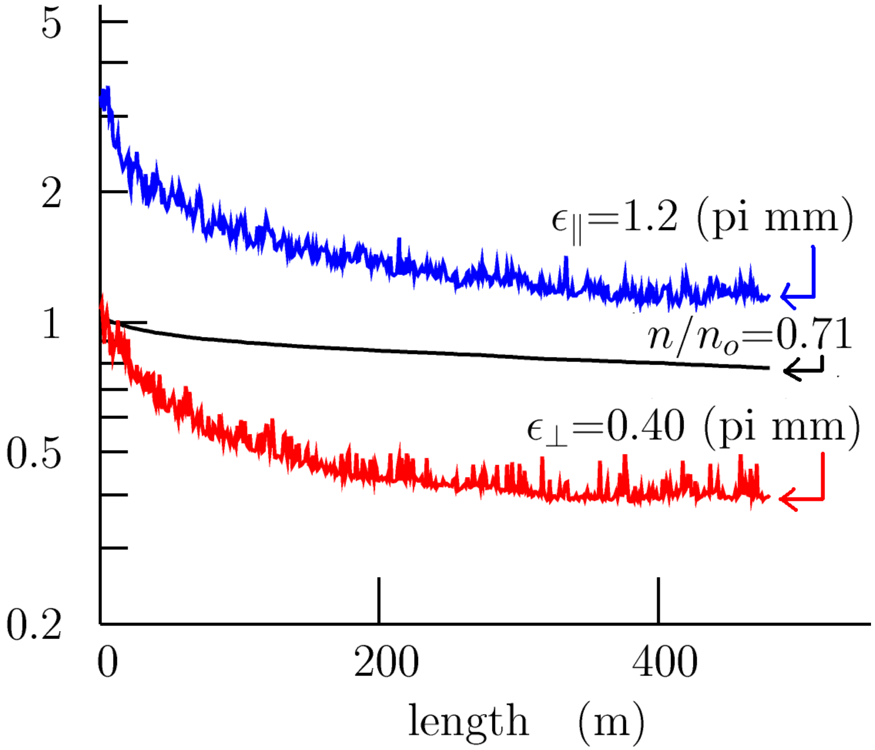


Cooling after merge

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

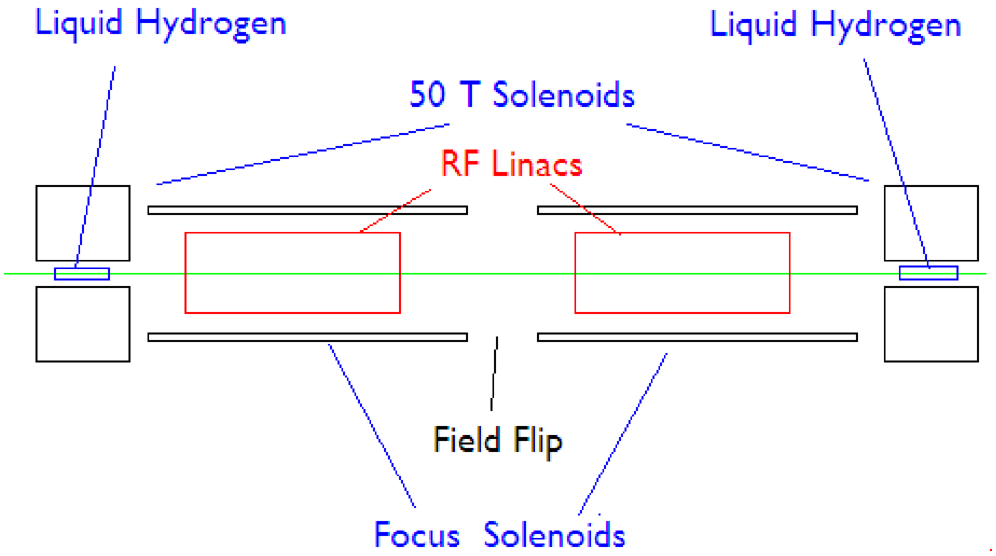
- #8 Last 6D cooling in higher field lattice
  - Uses 10 T high current density (150 A/mm^2) solenoids

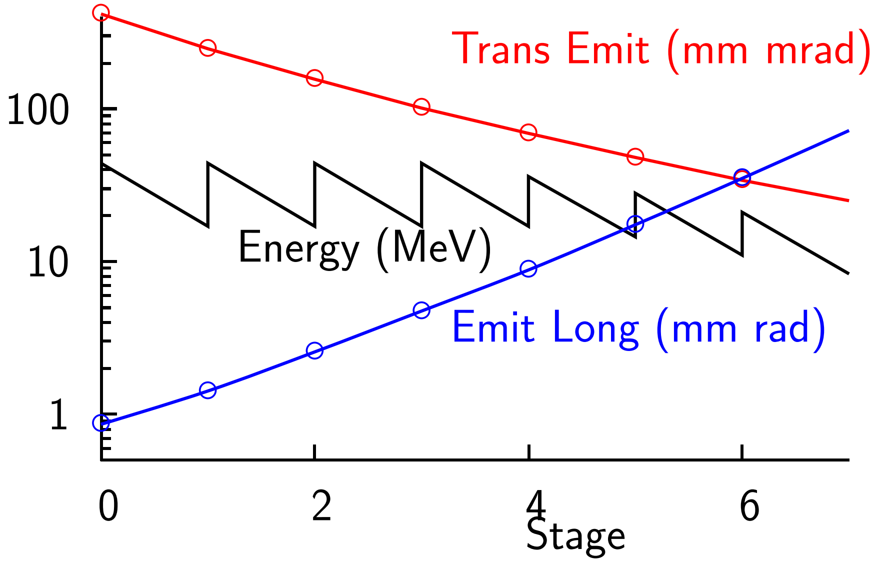




#9 Transverse Cooling in Very High Field Solenoids

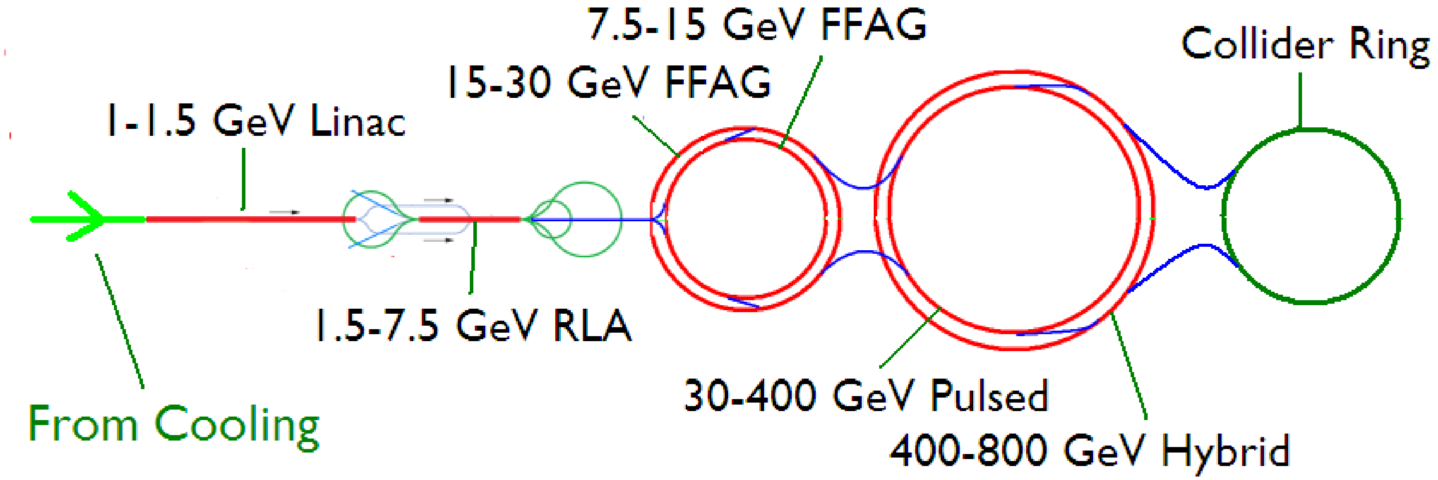
- Lower momenta allow strong transverse cooling, but long emittance rises:
- Effectively reverse emittance exchange



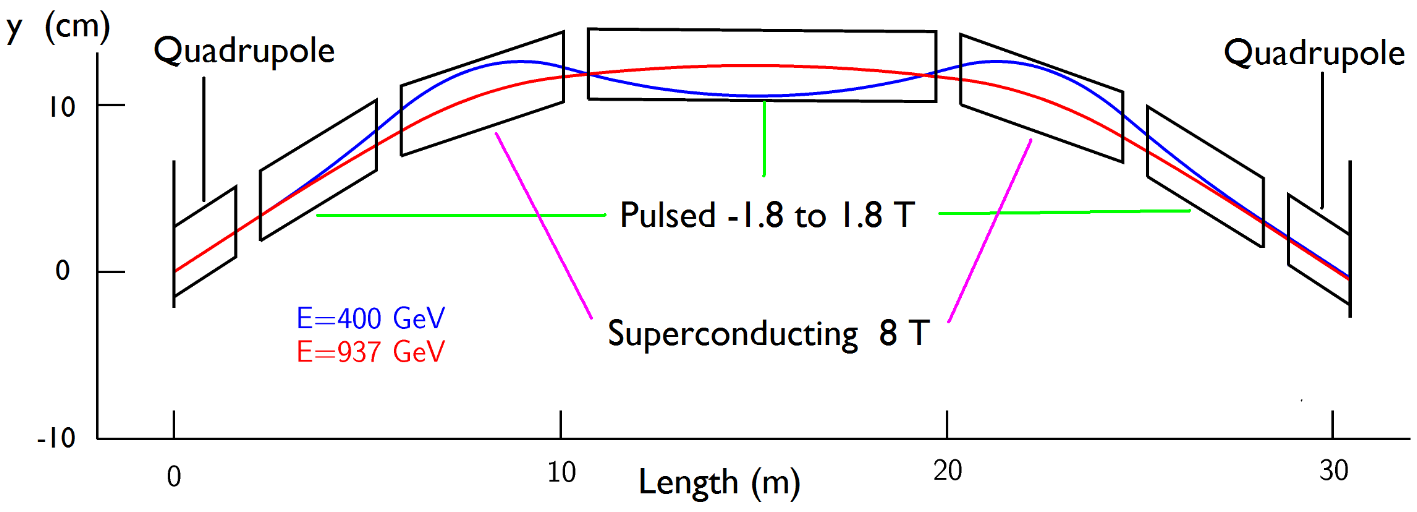


- 50 T HTS Solenoids
  - Layer wound allowing current to vary with radius
  - Vary ss support with radius to keep strain constant
  - Existing HTS tape at 4.2 deg. gave 50 T with rad=57 cm
- 7 solenoids with liquid hydrogen
- ICOOL Simulation (Ideal Matching and reacceleration, Transmission 97%)

Acceleration

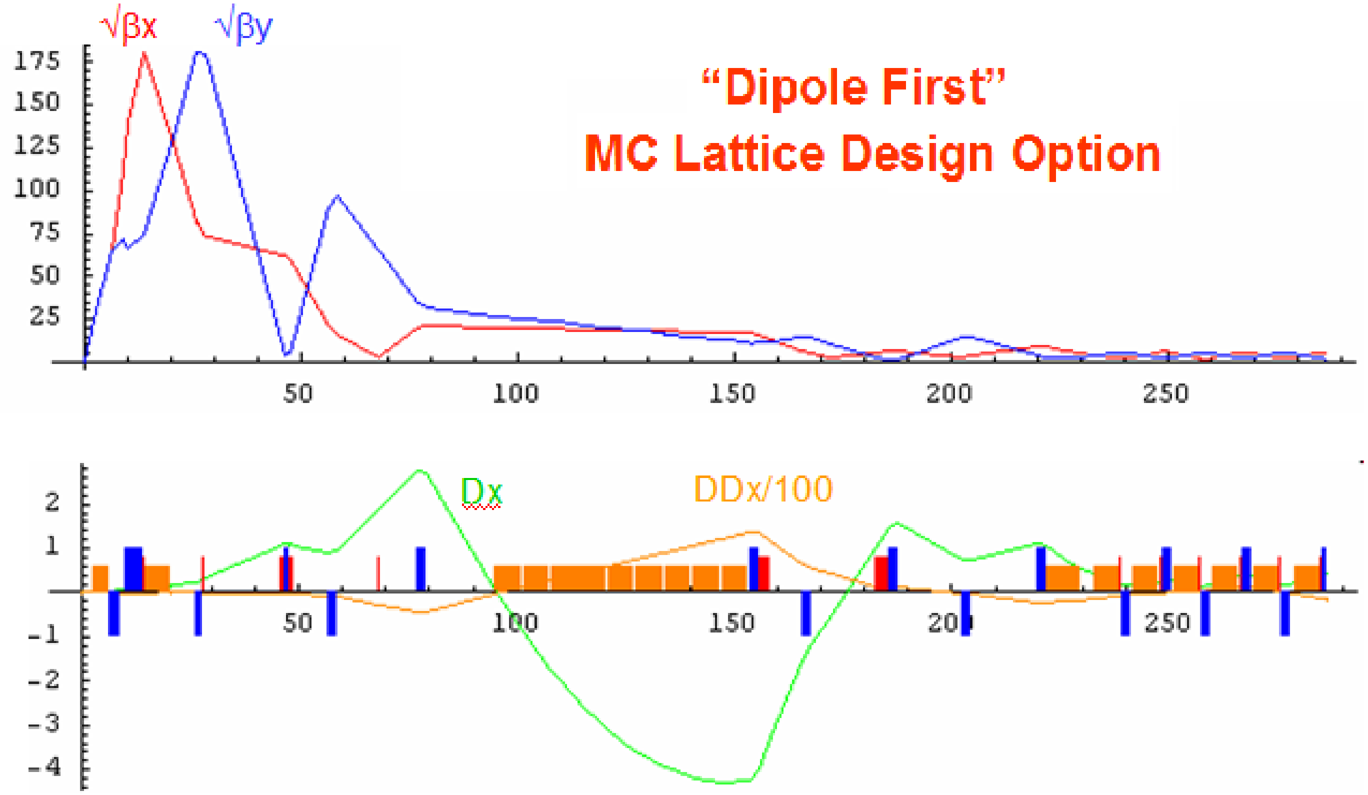


- Hybrid SC and pulsed synchrotron 400-750(930) GeV (in Tevatron tunnel)



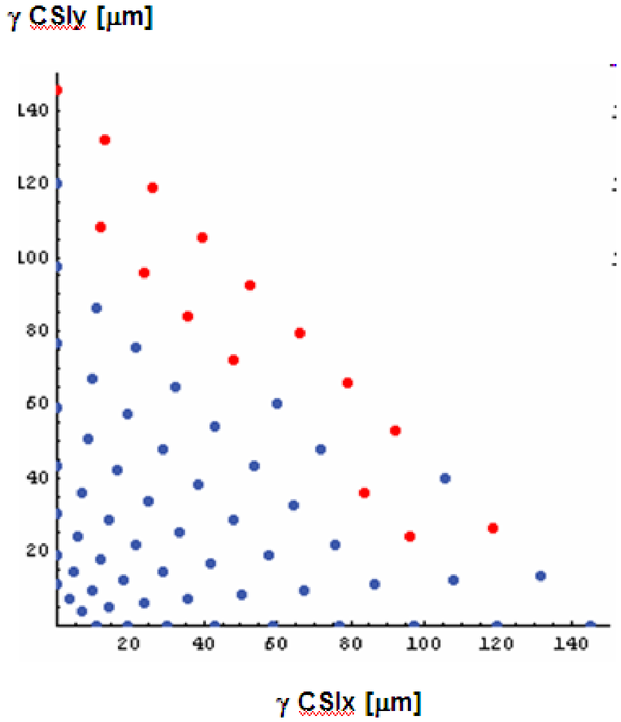
- All RLAs with ILC cavities is an alternative but more expensive

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



“Dipole First”
MC Lattice Design Option

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 at 1.25 sigma during acceleration

Ongoing Studies

- Fuller simulations
- Space charge tune shifts (moderate, but not in simulations)
- Possible breakdown of vacuum RF in the specified magnetic fields
  - Being studied experimentally by MUCOOL Collaboration
  - Possible solution 1) Gas filled cavities
  - Possible solution 2) Open Cavities with coils in irises
- Planar wiggler lattice replacing Guggenheims (cools both muon signs)
- Fast Helical cooling in hydrogen gas
  Another alternative to RFOFO Guggenheims being studied by Muons Inc
- Design of 50 T solenoids
- Use of more, but lower field (e.g. 35 T) final cooling solenoids
- Design detector shielding

Conclusion

- New 1.5 TeV Collider lattice has more conservative IP parameters
  - Luminosity 1×10^{34} achieved with bunch rep rate ≈12 Hz
    but requires depth ≈ 135 (m) to limit neutrino radiation
  - Collider ring must be deep (eg 135 m of ILC) to control neutrino radiation
  - 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 problem with rf breakdown in specified magnetic fields
  - Solutions with gas in cavities appear to work
  - Designs with open cell rf are promising
- Lower cost acceleration possible using pulsed magnets in synchrotons
  - Rings fit in Tevatron tunnel
  - Second ring uses hybrid of fixed and pulsed magnets