Muon Colliders

THE HARD PART

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History

1969	Concept	Budker
1981	Ionization cooling	Skrinsky, Parkhomchuk
1983	First Outline	Neuffer
1994	My involvement	Palmer
1997	US Collaboration Formed	
2007	First Complete (almost) Scenario	
2014	P5 halts US mu-mu & I $\rightarrow$ EIC	
2020	Retire & I $\rightarrow$ Memoir	
2024	P5 restarts in US	

Why Electrons?

- There are three "kinds of Particles"

1. **Hadrons** mushy, like protons in an atom's Nucleus.
2. **Leptons** Point Like, like electrons & muons.
3. **Bosons** like photons of visible light, x-rays, or radio waves.

- High Energy Physicists learn by smashing beams of known particles on to others and observing what comes out. The more the energy, the richer the products.

  "If you throw VW bugs into a wall with enough energy, you can make a Mercedes 600"

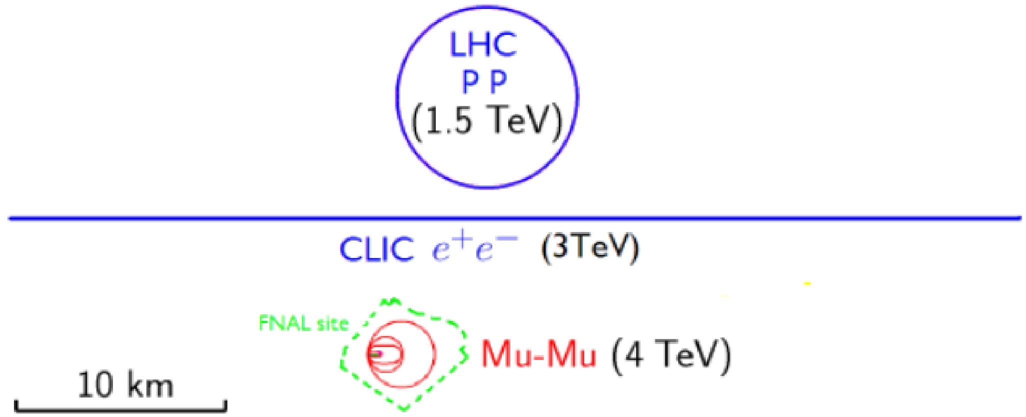
  With electrons (Golf balls with a VW's mass) $\rightarrow$ More detailed smashing

  "The smashing" can be on a

1. **"Fixed Target"** or, in a.
2. **"Collider,"** with an oncoming beam.

Why muons μ

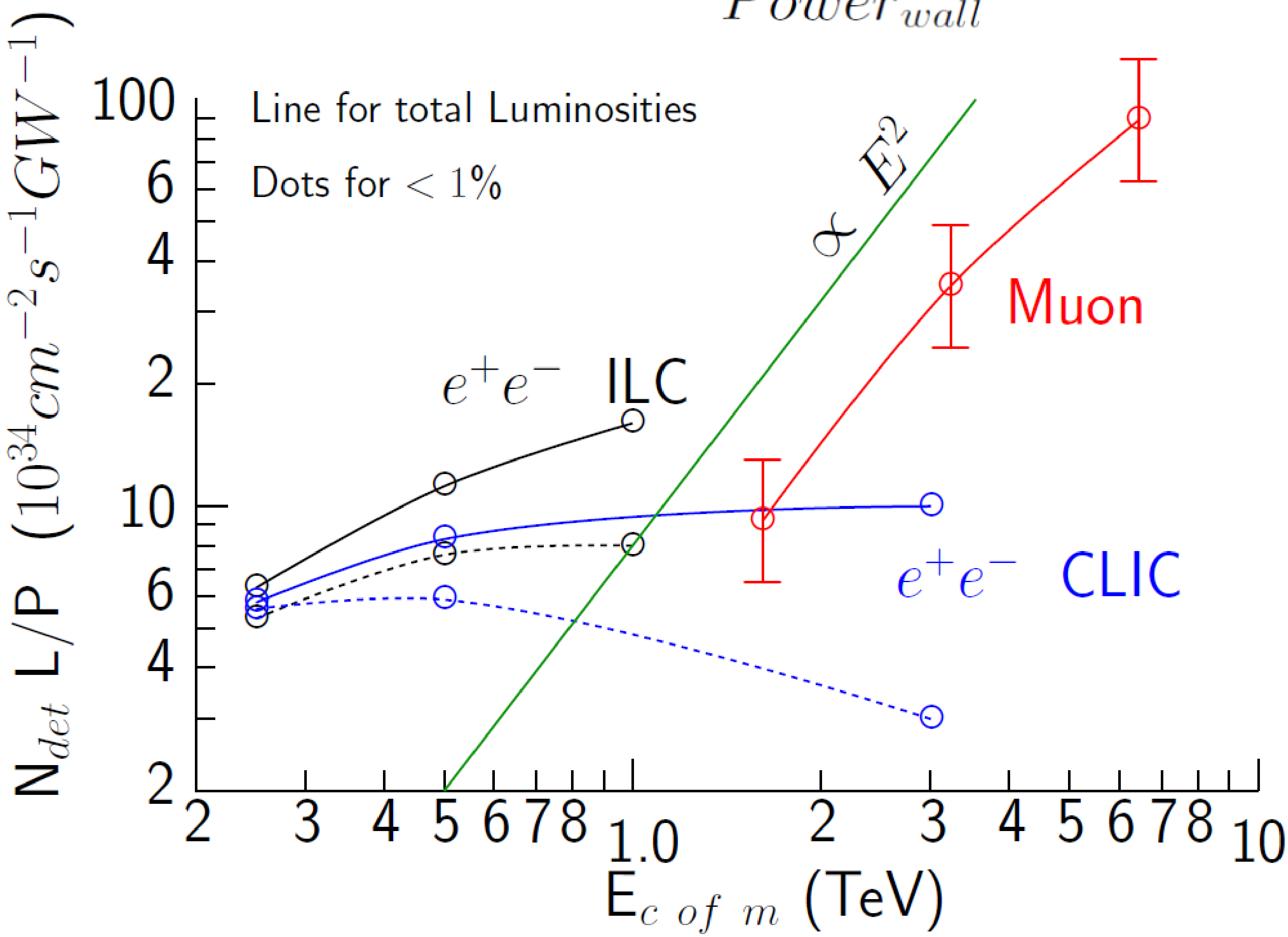
- Electrons are too light and, if disturbed, emit light (photons)
- & thus cannot be circulated in rings $\rightarrow$ Linear Colliders
- Muons 200 heavier, $\rightarrow$ rings OK $\rightarrow$ much smaller



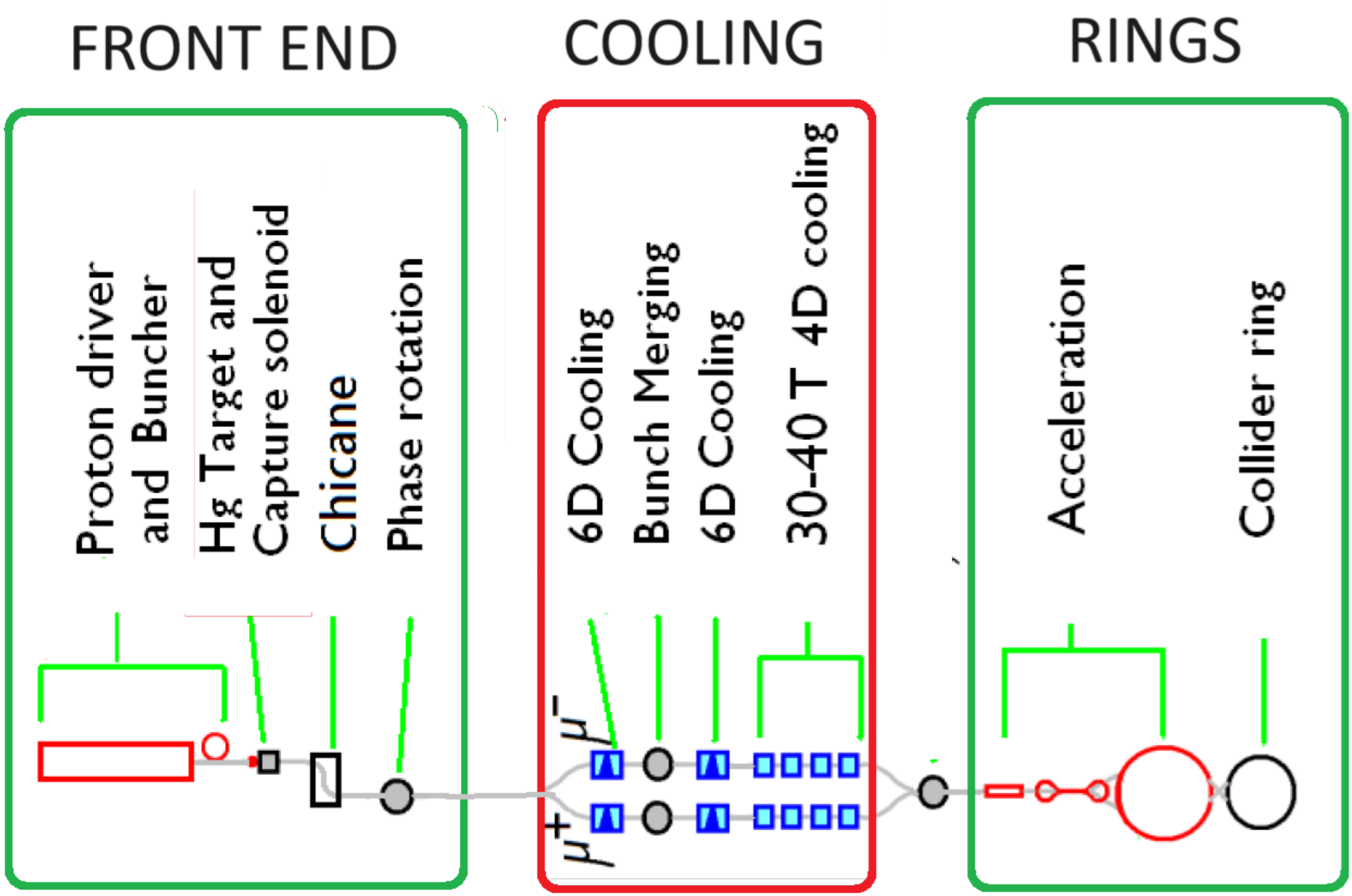
		$\mu^+\mu^-$	e^+e^-	factor
Luminosity/IP (100%)	10^{34} cm^{-2}s^{-1}	4	6	
Luminosity/IP (1%)	10^{34} cm^{-2}s^{-1}	4	2	2
Number of IPs		2	1	2
rms bunch height σ_y	μm	3	0.001	3000
Wall power	MW	216	570	0.38
Lepton power/Wall power	%	20.0	20.3	0.99

Higher Energy Prospects

$$Merit = \frac{Luminosity \times N_{detectors}}{Power_{wall}}$$

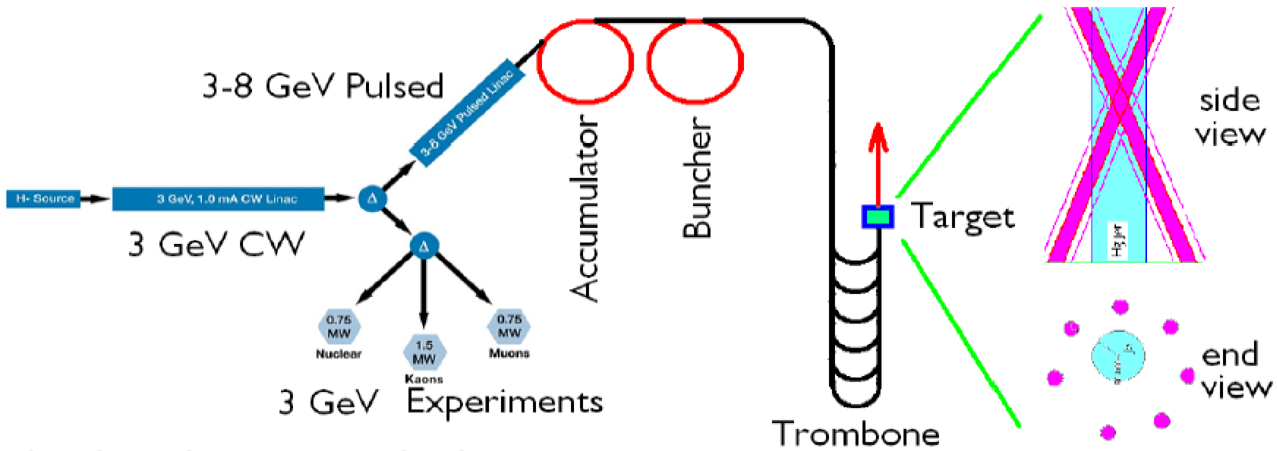


Schematic



FRONT END
COOLING
RINGS
Proton driver
and Buncher
Hg Target and
Capture solenoid
Chicane
Phase rotation
6D Cooling
Bunch Merging
6D Cooling
30-40 T 4D cooling
Acceleration
Collider ring
μ^-
μ^+

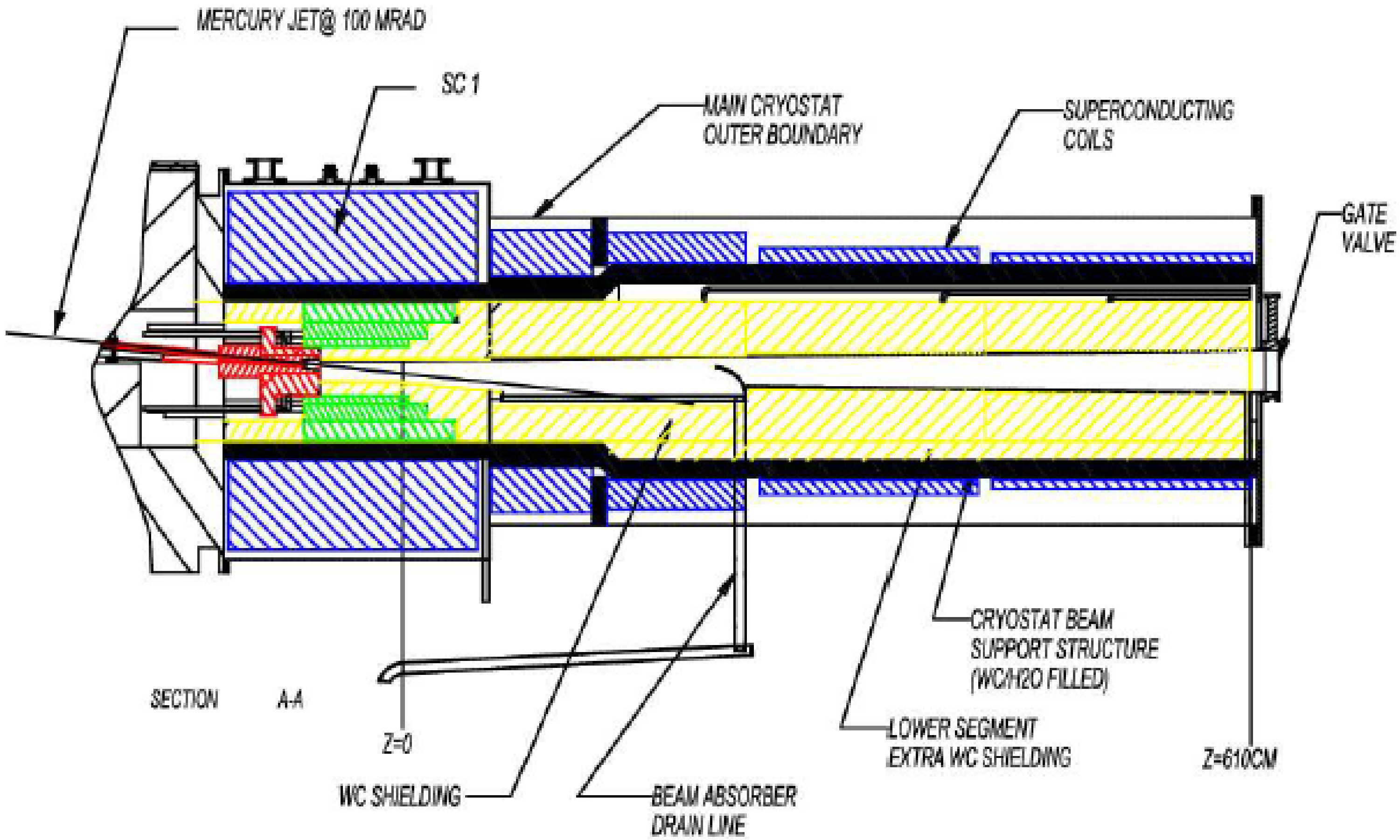
Proton Driver and target



The hard parts include:

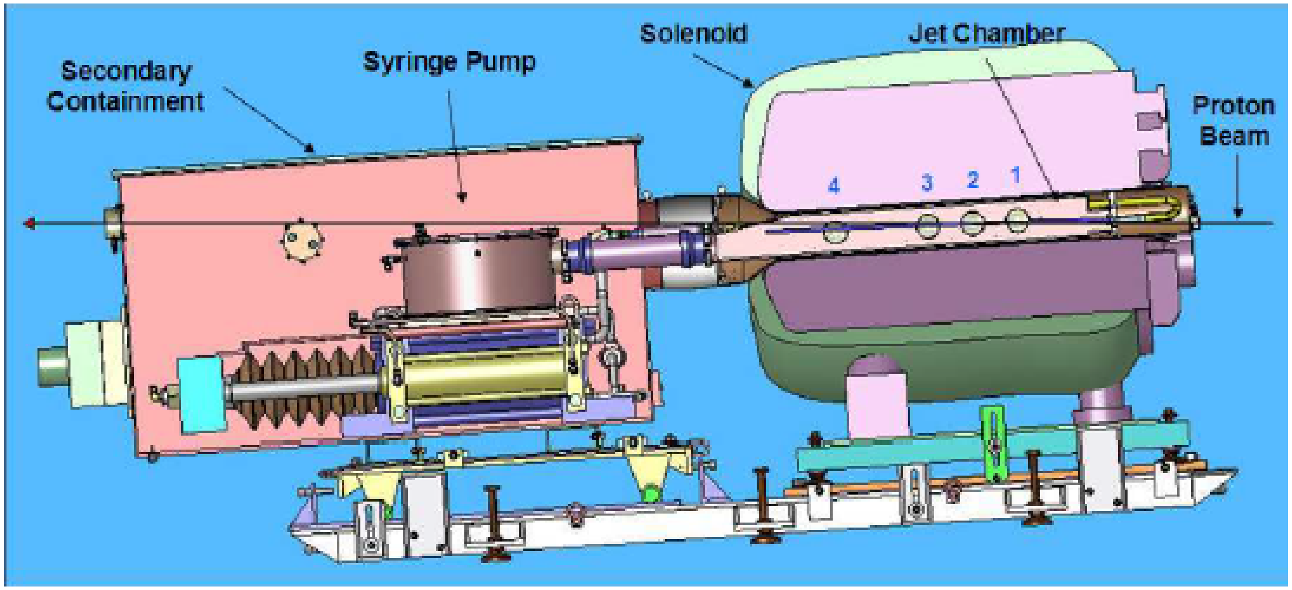
- Kicker system for Ankenbrandt's trombone
- Target area design to allow multiple beams
- And lots of details

Capture



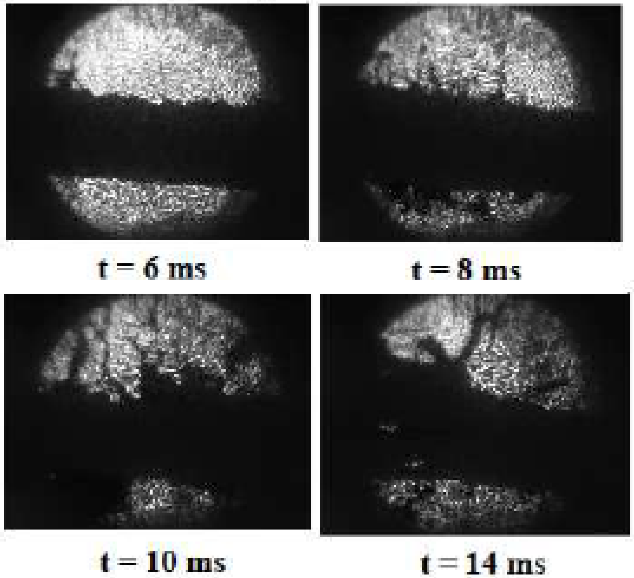
- Mercury Jet Target
- 8 cm rad, 20 T capture (capture pt$\leq$240 MeV/c)
- Adiabatic taper to 2 T

Hg Target (MERIT Exp at CERN)



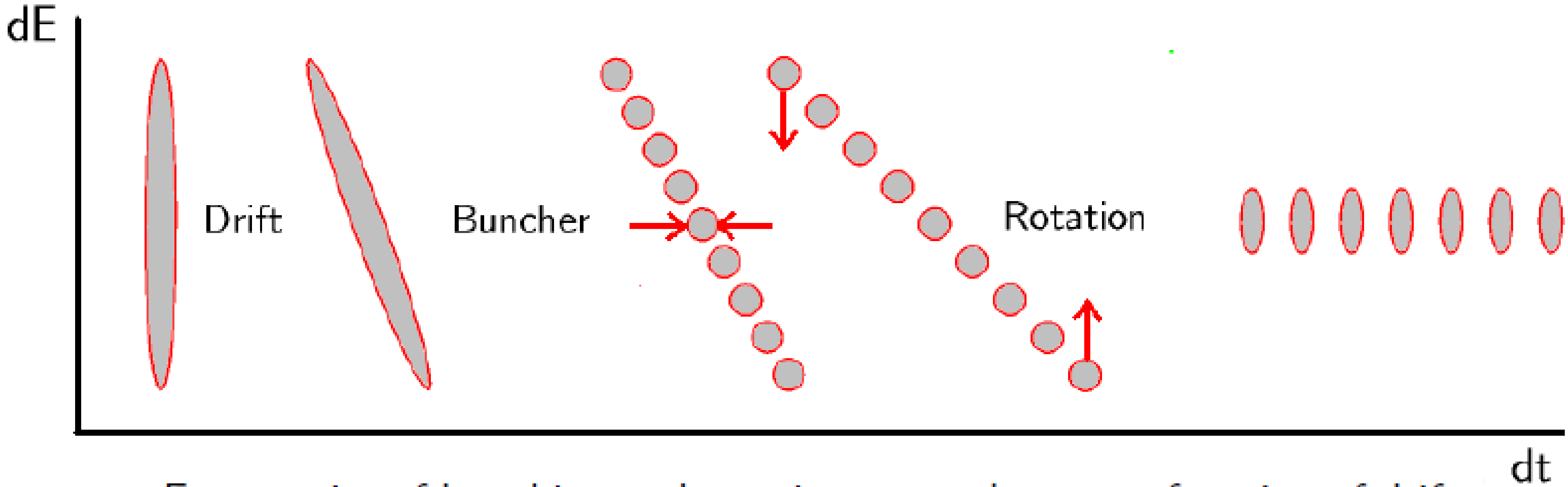
- 15 T pulsed magnet
- 1 cm rad mercury jet
- Up to 30 Tp   cf 40 Tp at 56 GeV
- Magnet lowers splash velocities
- Density persists for 100 micro sec
- No problems found

Images of Jet Flow at Viewport 3, B=10T, N=10Tp, L=17cm, 2ms/frame



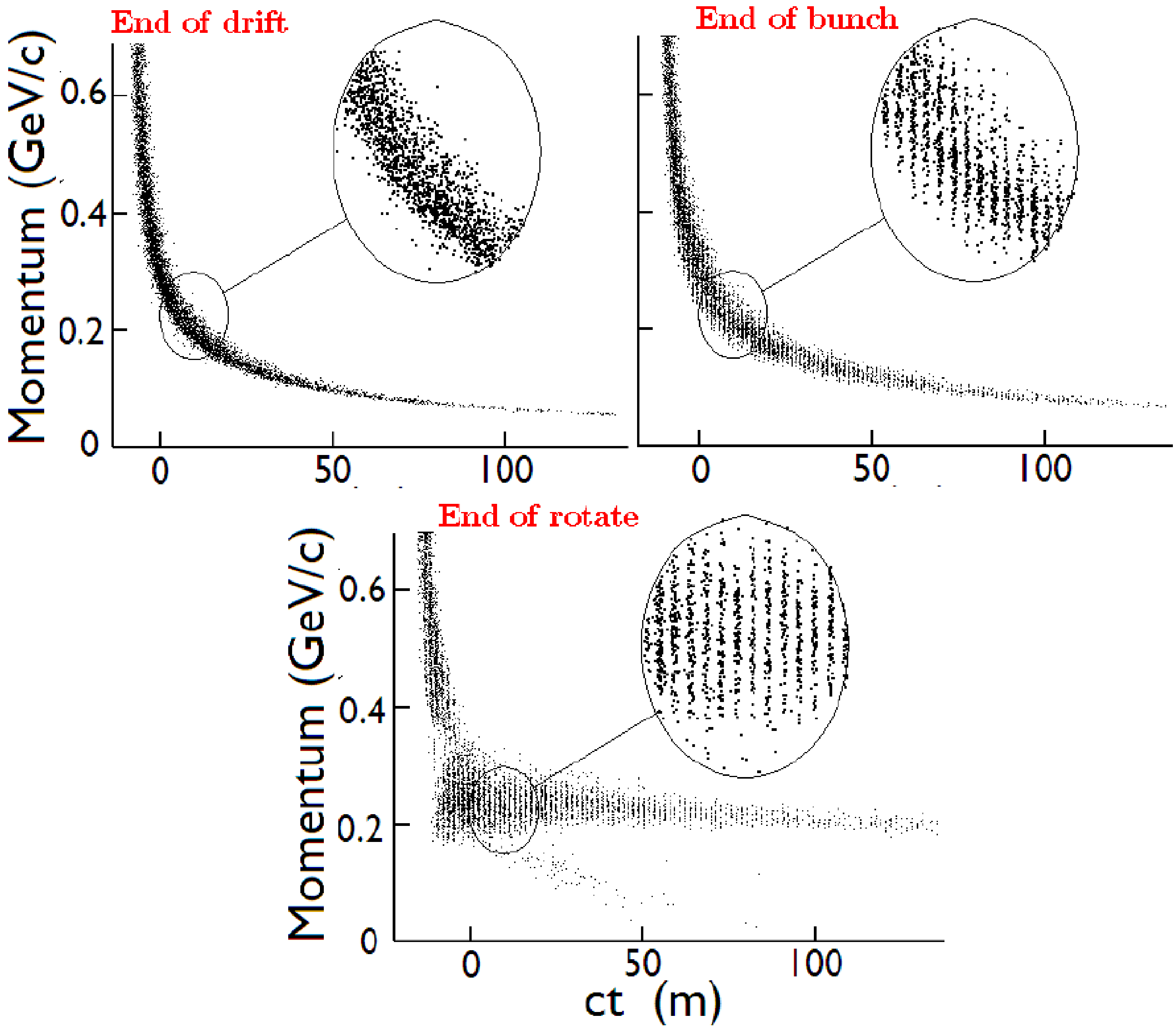
Phase Rotation

- To capture $\pm$ 100% dp/p
- Phase rotate to 15 bunches $\pm$ 8% dp/p
- Bunch first, then Rotate (Neuffer method:)

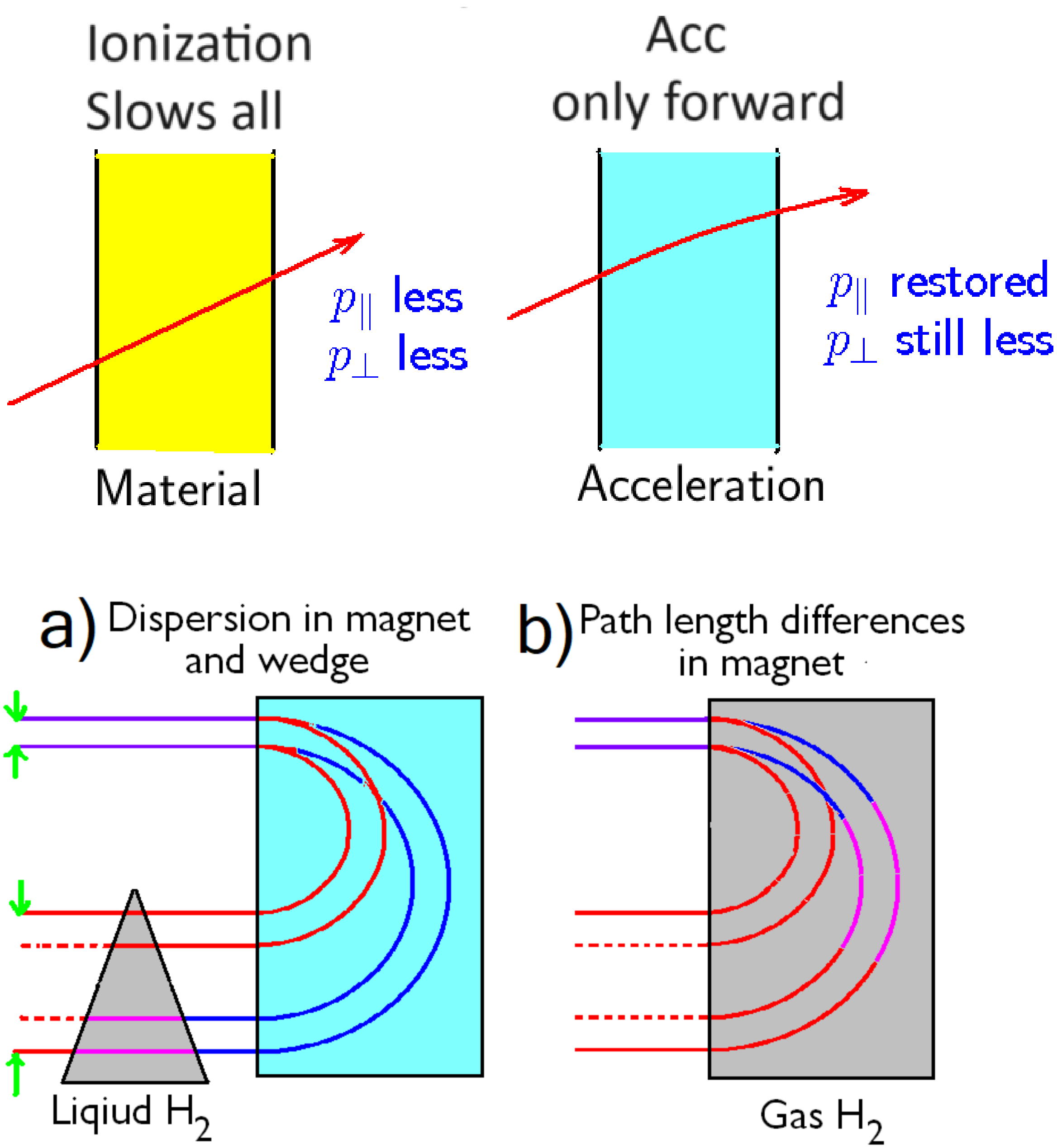


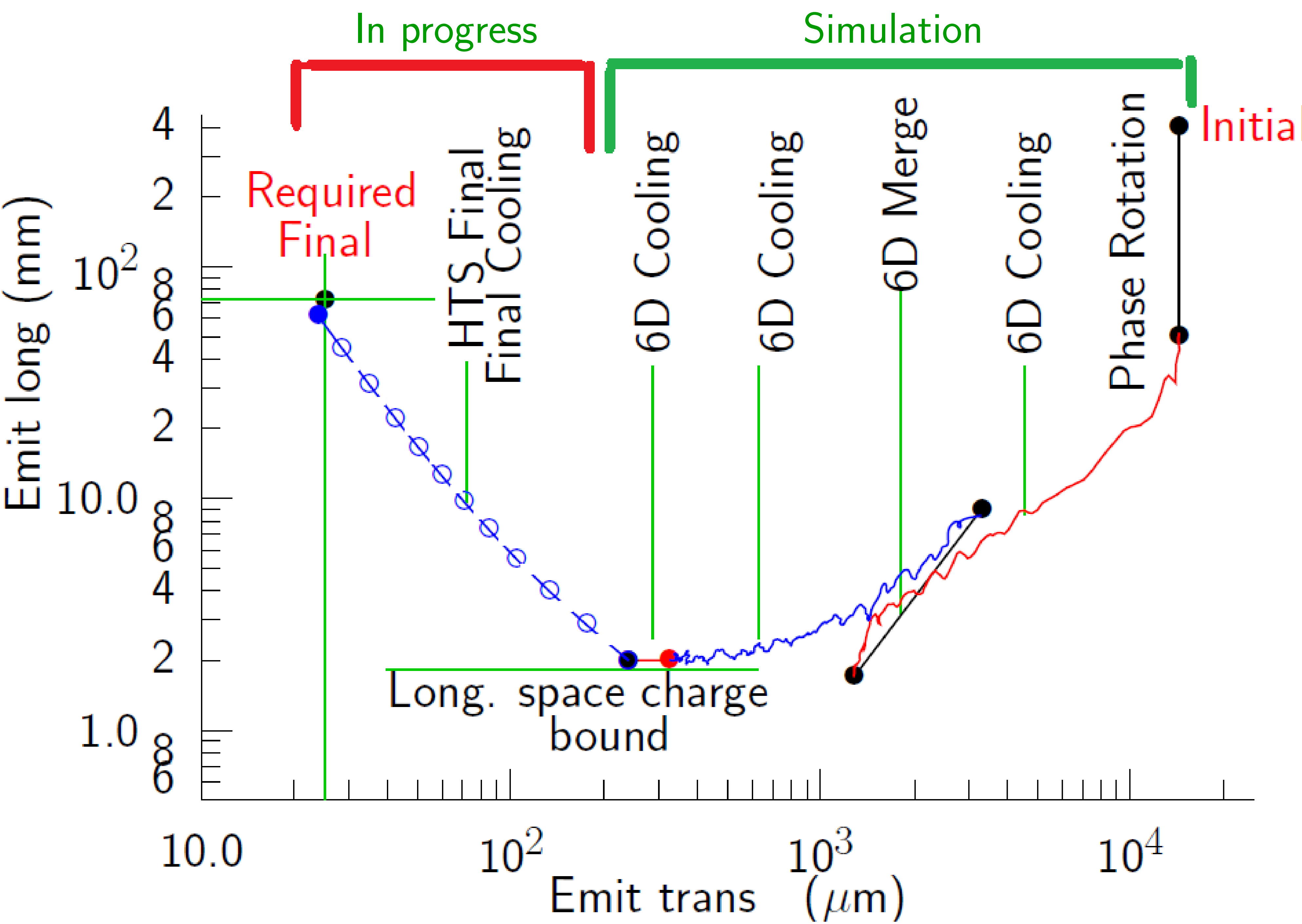
- Frequencies of bunching and rotation must change as function of drift
- Alternative system rotates first with induction linacs, then bunches
- But induction linacs are expensive

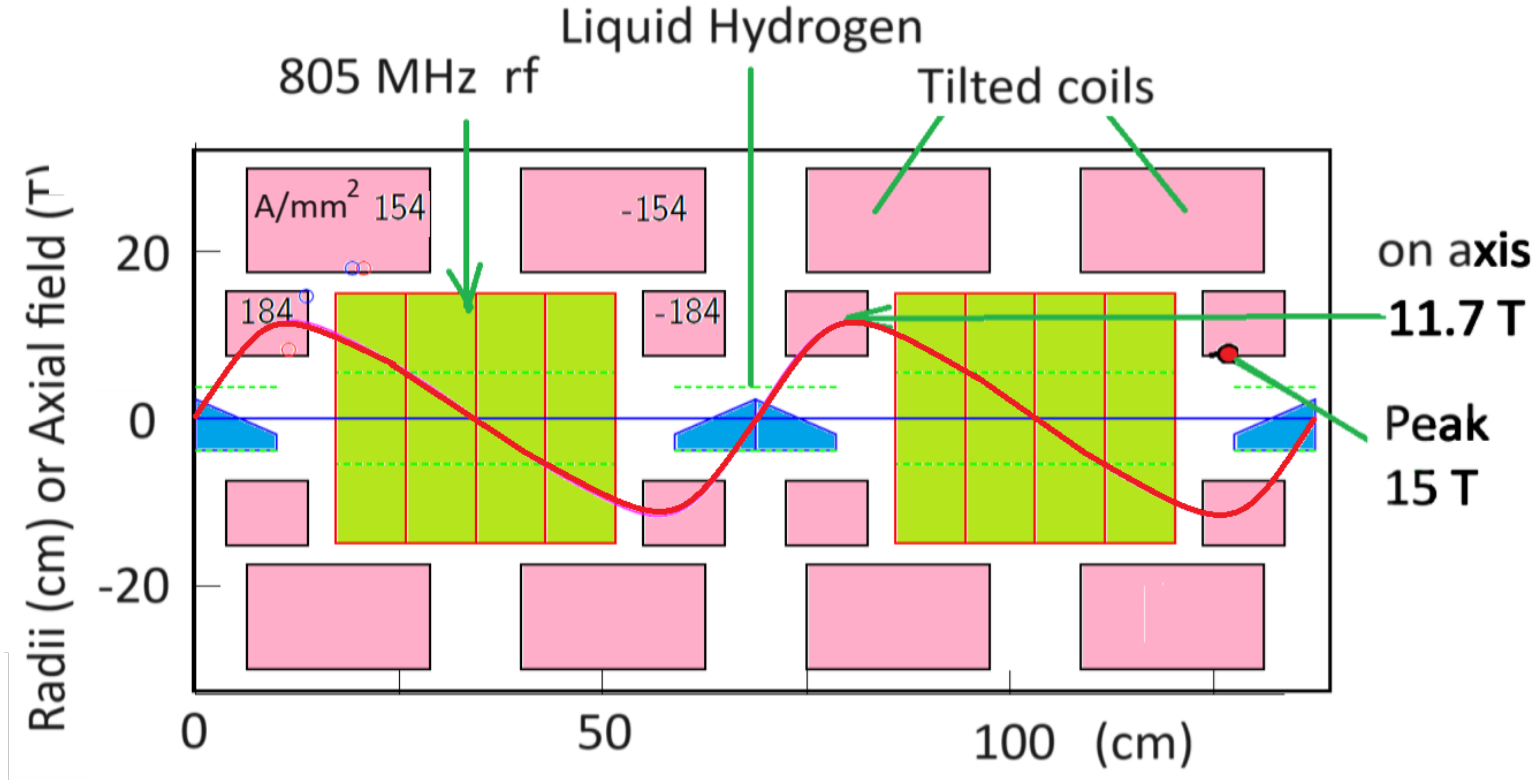
Phase Rotation Simulation



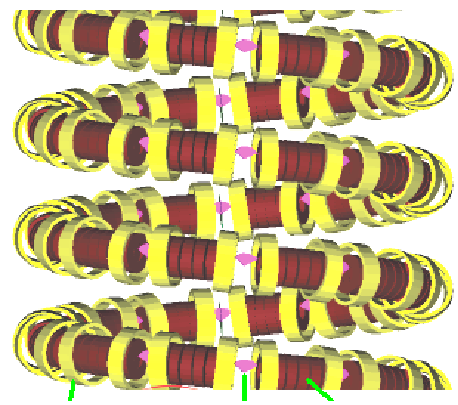
Cooling Concept



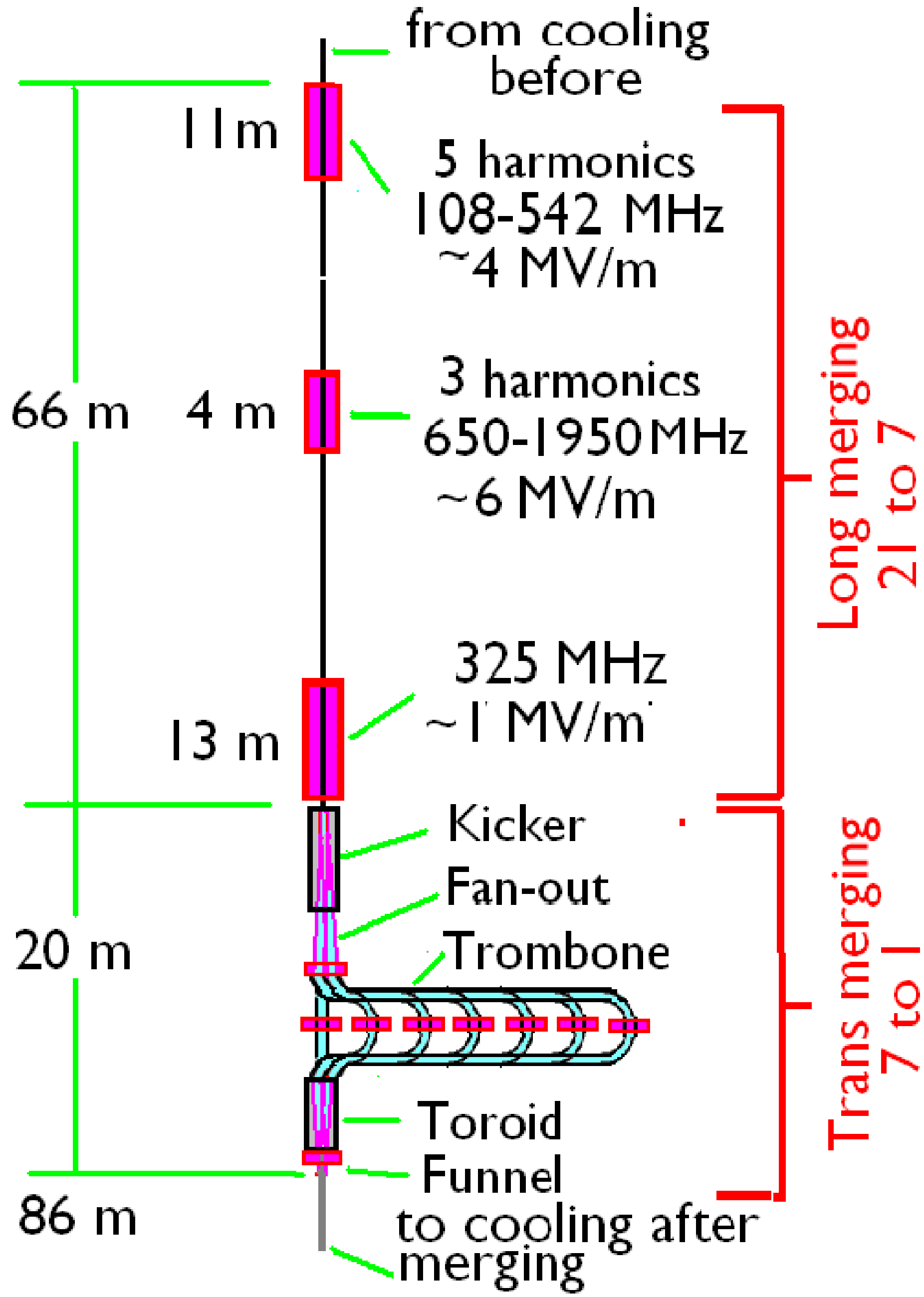

In progress
Simulation
Initial
Required
Final
HTS Final
Final Cooling
6D Cooling
6D Cooling
6D Merge
6D Cooling
Phase Rotation
Long. space charge
bound
Emit long (mm)
Emit trans (μm)
10.0
10²
10³
10⁴
1.0



Stage	MHz	MV/m	Fld T
Before	201	12	3
Merge	402	17	6
Merge			
After	201	12	3
Merge	402	17	6
	805	20	12
Final			

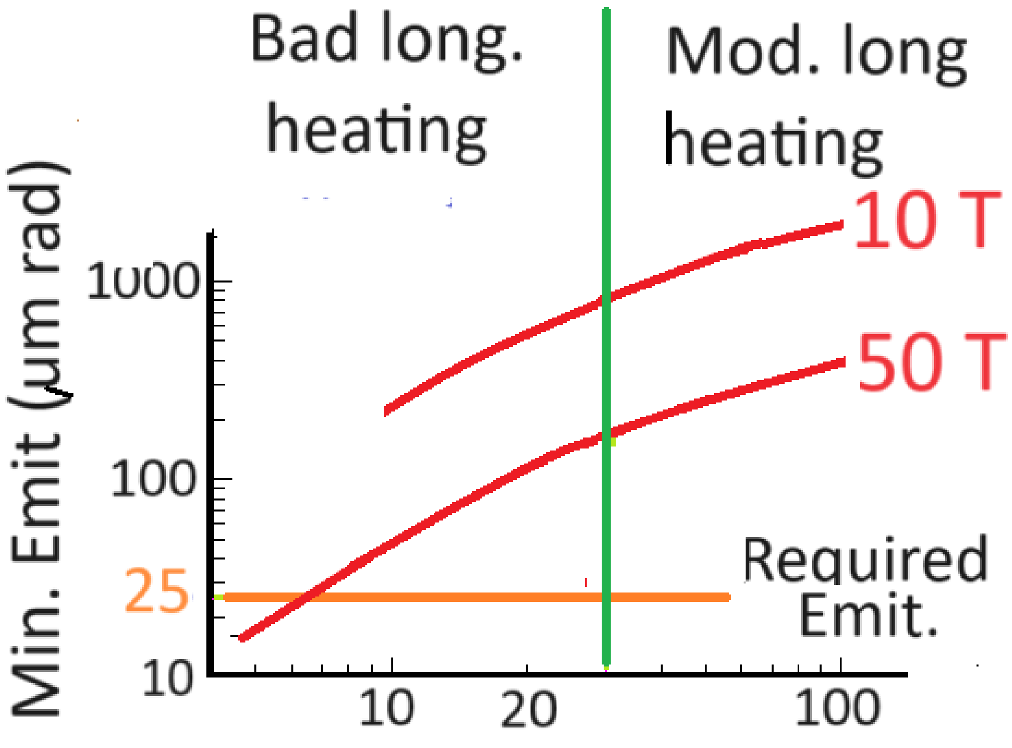


Palmer Guggenheim or
Balbakov Straight ~ 1 Km



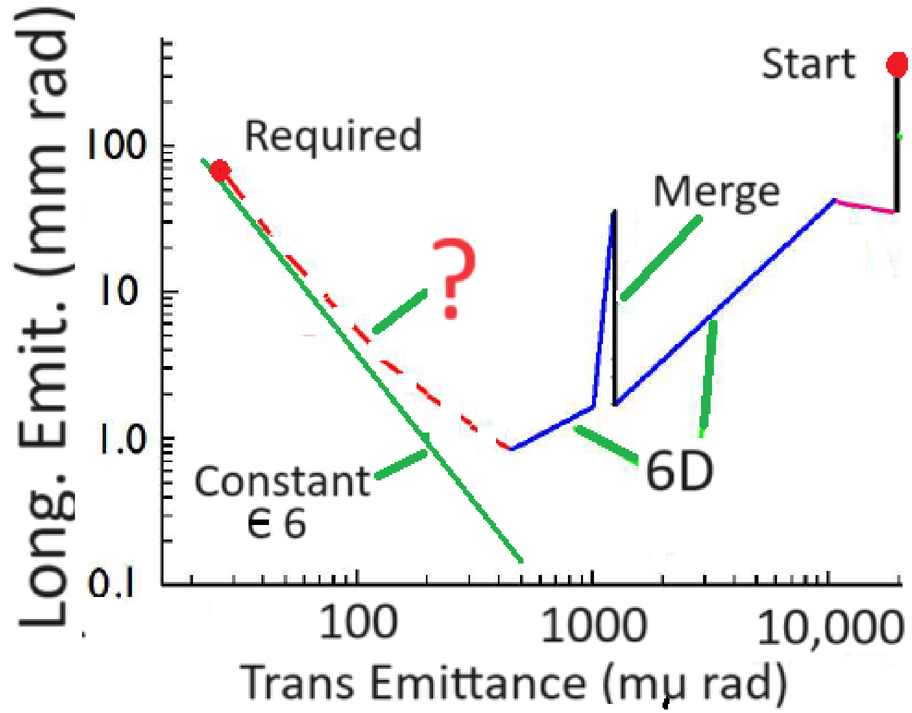
from cooling
before
11m
5 harmonics
108-542 MHz
~4 MV/m
66 m
4 m
3 harmonics
650-1950MHz
~6 MV/m
325 MHz
~1 MV/m
13 m
Long merging
21 to 7
Kicker
Fan-out
Trombone
20 m
Toroid
Funnel
86 m
to cooling after
merging
Trans merging
7 to 1

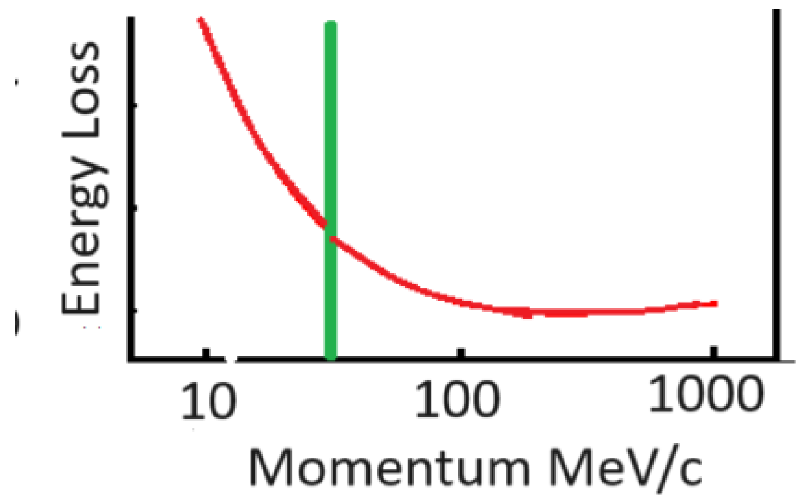
Final Cooling problem



No hope with ~10 T

OK with 50 T but low E
and long. emit. growing





Final Cooling Approaches

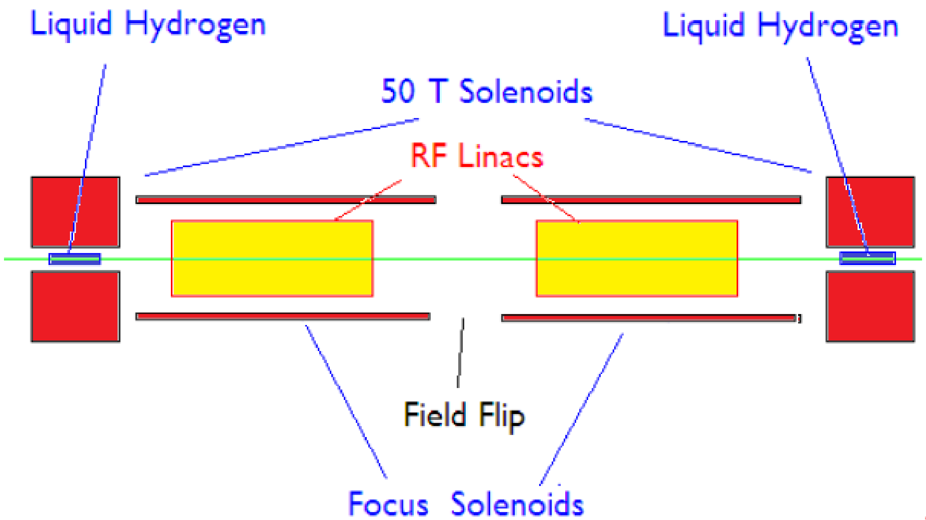
Earlier slides represent the collaboration-at-large's vision up to 2014. Thanks to Rick Fernow's ICOOL, almost every part had been simulated at a reasonable level. Except for 'final cooling.'

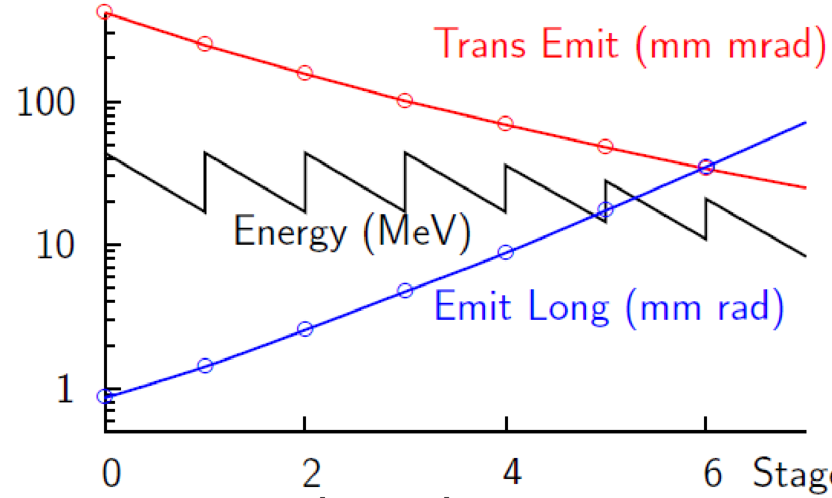
My notion of Final Cooling has many stages each of which use liquid hydrogen in ≈50 T fields. The ndividual stages have been simulated, but when put all together had failed to meet our requirements. I do not believe there is a fundamental problem, but it needs work as discussed below.

And there are other ideas: David Neuffer has alternative scheme which I have not yet studied then enough to report. And their may be other ideas out there. For the moment,

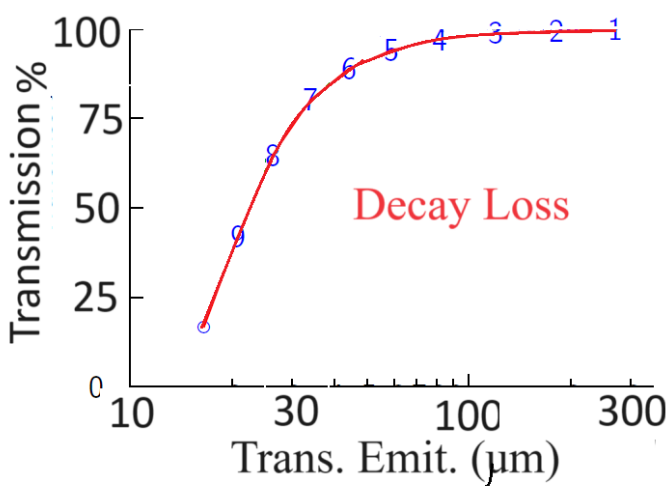
I do not yet deem this the "Hardest Part". We fixed other problems. I think we will fix this one. But I think we badly need a collaboration workshop to look at the possibilities. This is the fun part.

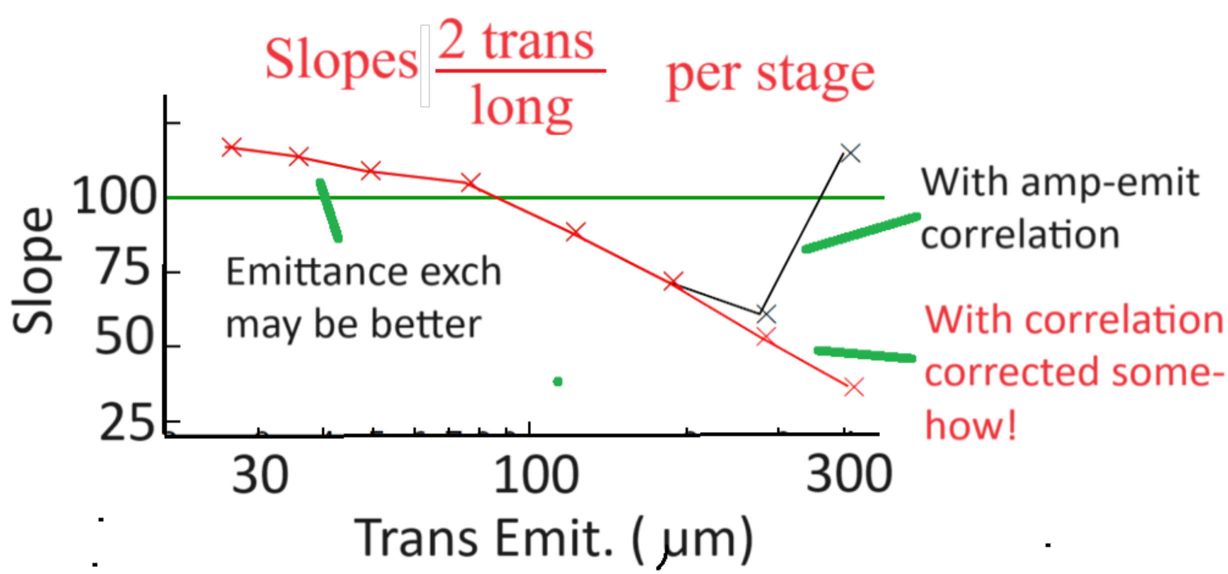
Transverse Cooling in Very High Field Solenoids



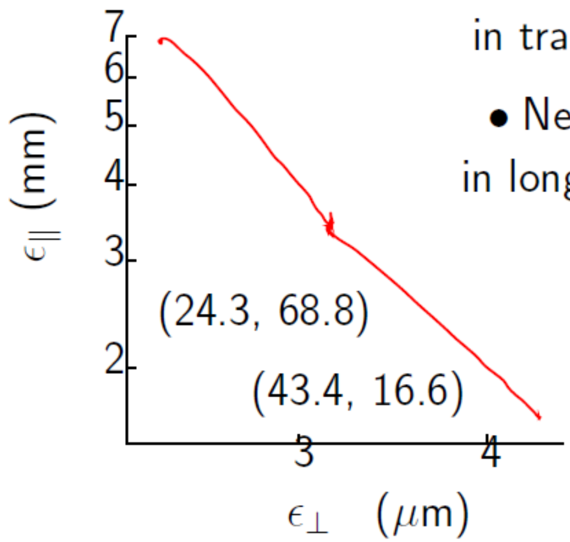


no matching between stages

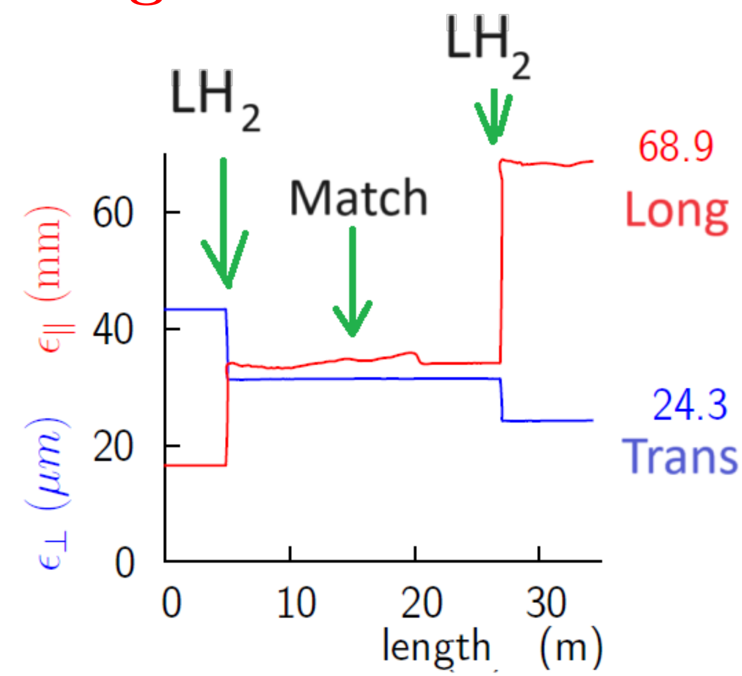




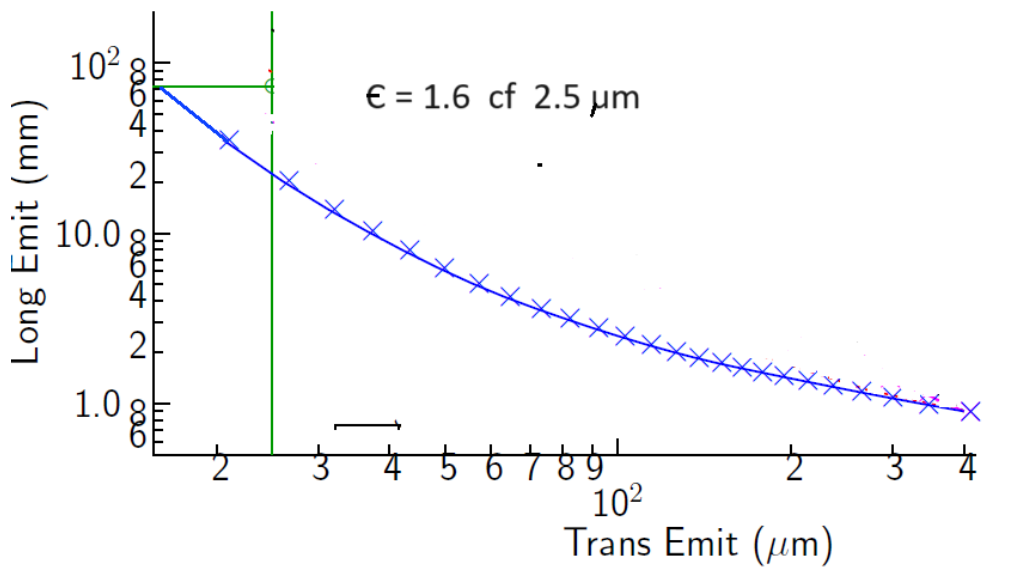
Full simulation between last 2 stages



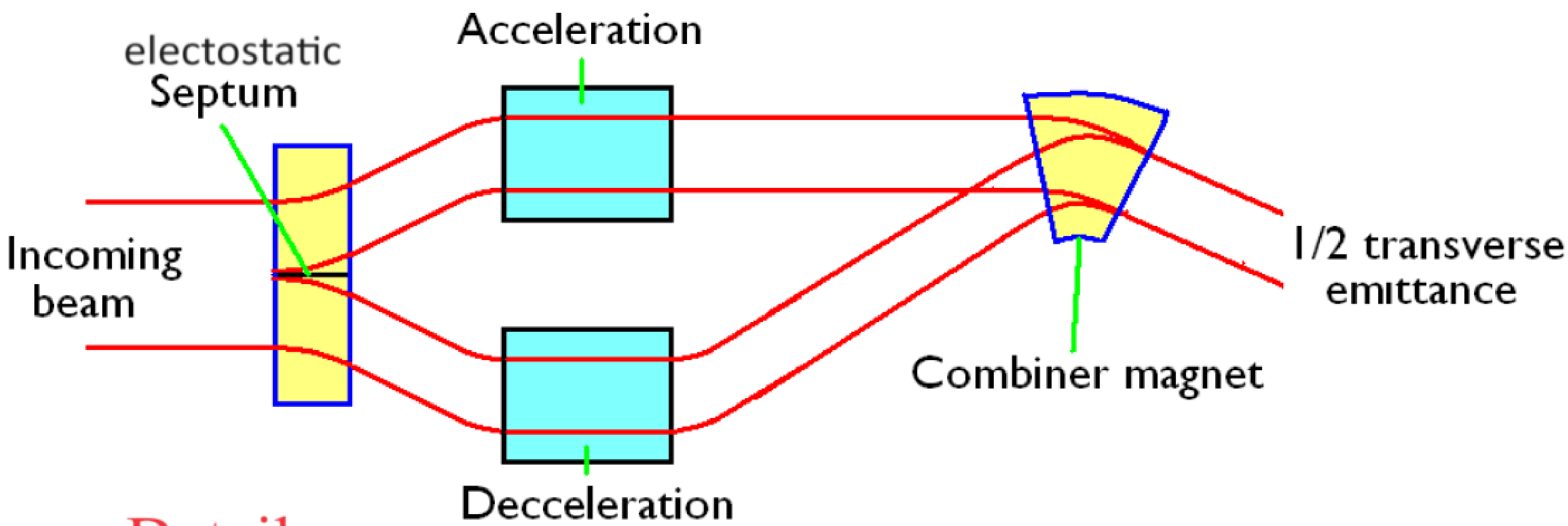
- Negligible increase in transverse emittance
- Negligible increase in longitudinal emittance



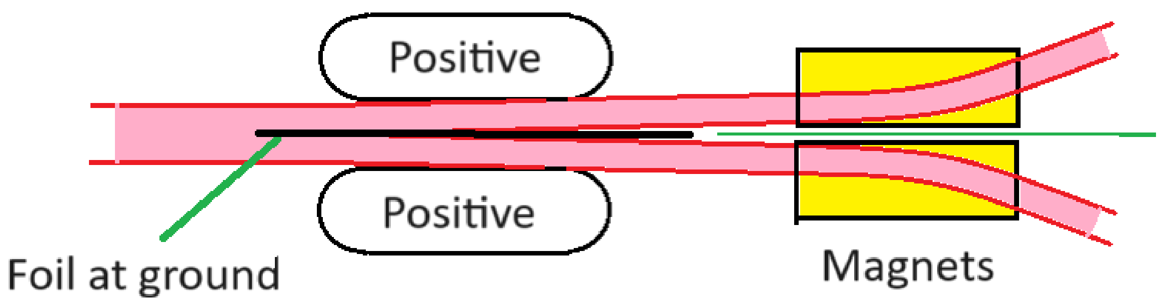
More steps



Septum Emittance Exchange for late stages



Detail



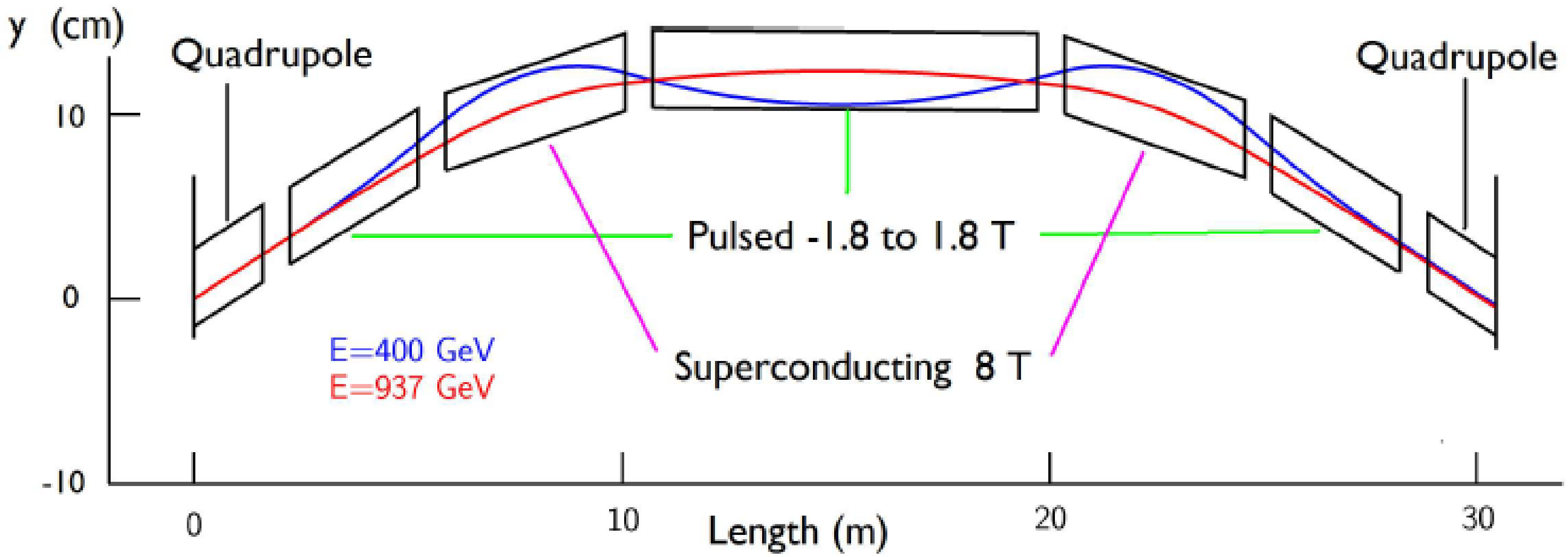
Done first in x, then in y

Could cut into 3 instead of 2 using two stages of Electrostatics

It can be done at whatever energy is easiest

Acceleration

- Easy with Recirculating linear accelerators (RLAs)
  Using ILC-like 1.3 GHz rf
- Lower cost solution would use Pulsed Synchrotrons
  - Pulsed synchrotron 30 to 400 GeV (in Tevatron tunnel)
  - SC & pulsed magnet synchrotron 400-900 GeV (in Tevatron tunnel)
  - SC & pulsed magnet synchrotron 900-2000 GeV (in new tunnel)



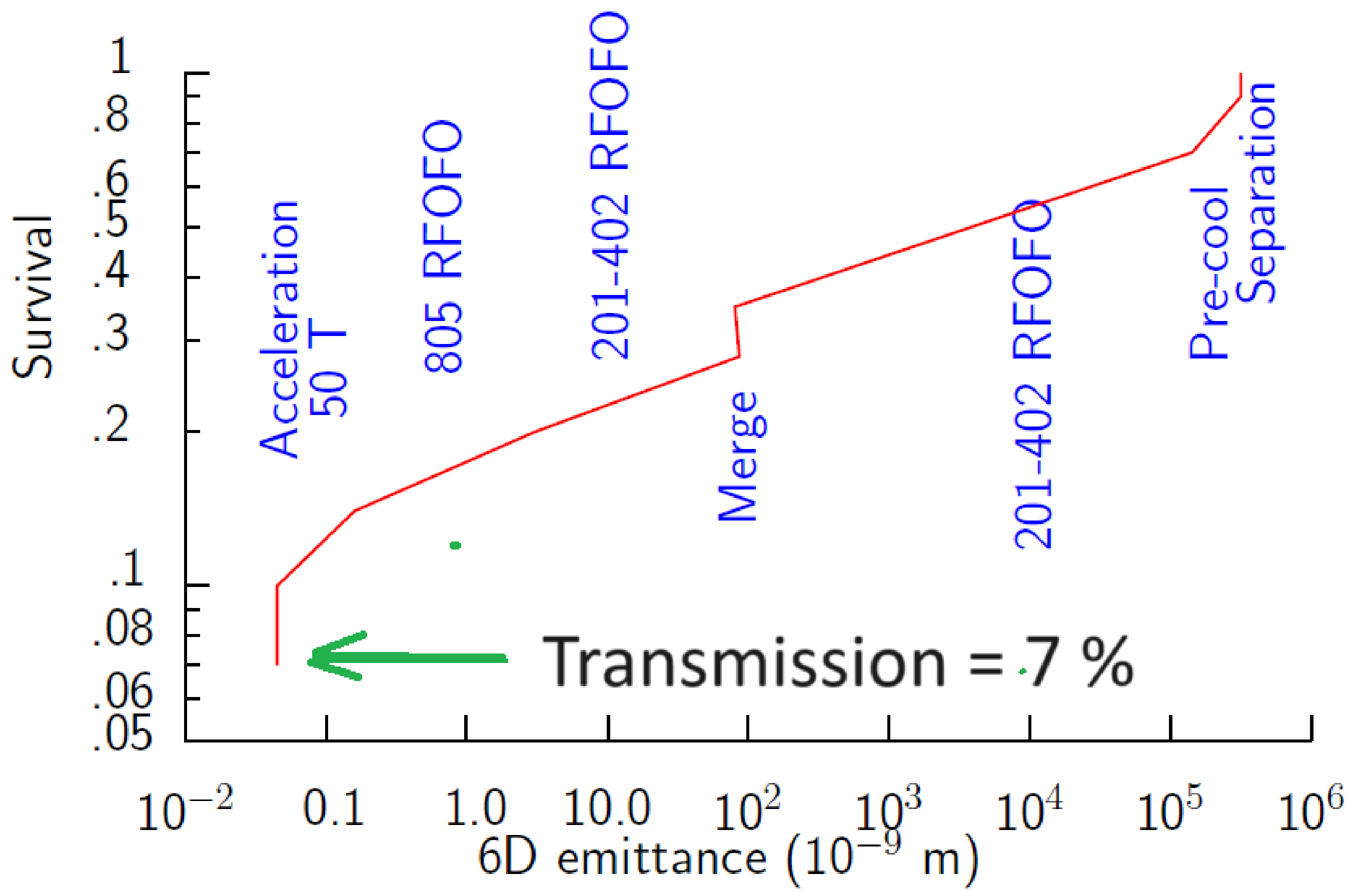
- Pulsed dipoles first oppose, and later support the bending form 8 T superconducting magnets

Muon Collider Rings

C of m Energy	0.126	1.5	3	6	TeV
Luminosity	0.008	1	4	12	10^{34} cm^{-2}sec^{-1}
Muons/bunch	4	2	2	2	10^{12}
Ring <bending field>	4.4	6.04	8.4	11.6	T
Ring circumference	0.3	2.6	4.5	6	km
β^* at IP $= \sigma_z$		10	5	2.5	mm
rms momentum spread	0.004	0.1	0.1	0.1	%
Depth		135	135	540	m
Wall Power		216	230	270	MW
Repetition Rate	30	15	12	6	Hz
Proton Driver power	4	4	3.2	1.6	MW
Muon Trans Emittance	200	25	25	25	μm
Muon Long Emittance	1.5	72	72	72	mm

6 TeV case is a blind extrapolation from 1.5 and 3 TeV designs, adjusted for same neutrino radiation

Transmission



If just a few of these steps have higher losses, then the actual luminosity could drop enough that it fails to justify its cost. We must guard against settling for lower performance in any step.

Consider the technologies used

1. 4 MW driver and trombones for high charge bunches
2. Hg target in High Radiation
3. Superconducting solenoids for capture in High Radiation
4. Superconducting dipoles for cooling several designs
5. Liquid hydrogen absorbers and rf in very limited space
6. Trombones for merging
7. Superconducting solenoids for final cooling
8. Induction Linacs for low energy acceleration
9. Electrostatics for emit exchange
10. Deep tunneling for neutrino radiation avoidance
11. Superconducting dipoles for muon rings (Lum$\propto$ Field B)
12. Unprecedented instrumentation to keep all working

Can you name a technology that is NOT needed?

The Hard Part

The hard part will be the engineering all these many technologies.

Only the pulsed magnets and ring dipoles will, as in the SSC, LHC, and TeVatron projects, employ many of identical components.

For the others, the majority, only a few cases of each component, will be required. This means that the ratio of R&D cost, over the construction cost, will be significantly higher - perhaps twice that for previous HEP projects. The DoE, and European funding sources, will have to understand this. It will be expensive.

In 2014, I sympathized wit P5. On a falling annual budget, the US HEP budget was, just, not sufficient to cover such R&D.
Now is different: In collaboration with CERN and other European Labs, it may be doable. We have to collaborate

I thank members of my group at BNL, those here at FermiLab, and in other US and European groups, that brought us here.

We have much still to do.

I also thank P5 for re-starting Muon Collider work and FermiLab for my invitation for this colloquium

I take these as an early present
For my 90th birthday later this month