Muon Colliders

R. B. Palmer (BNL)

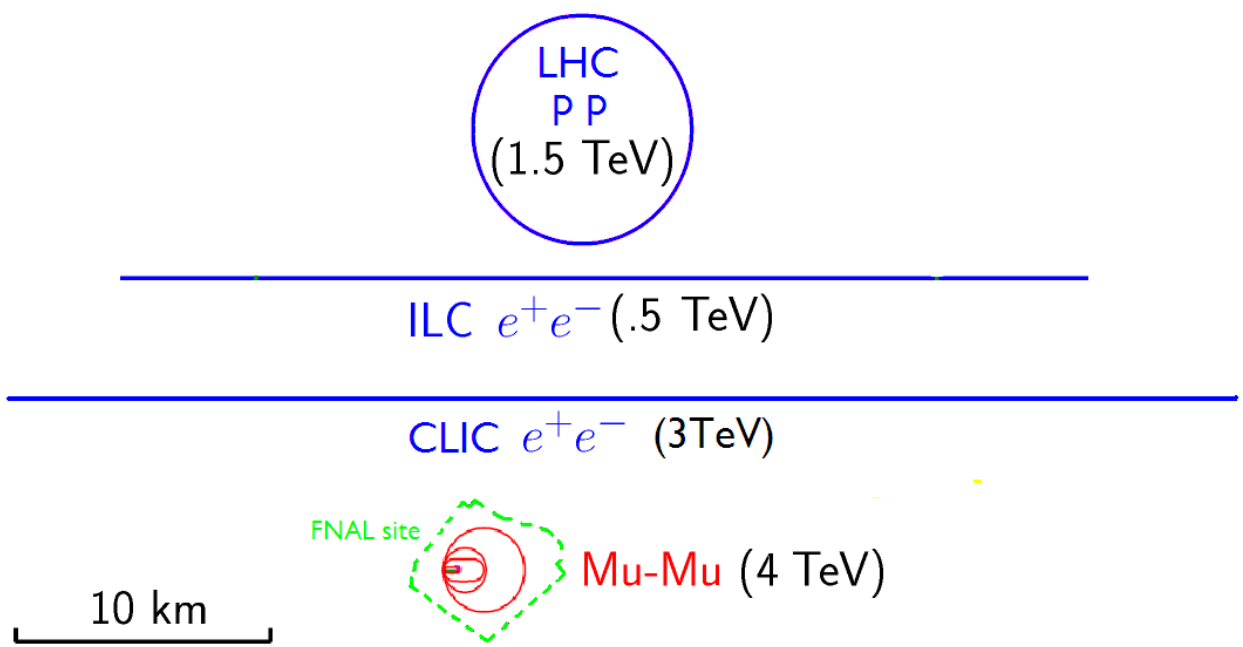
BNL Instrumentation Seminar

Jan 21 2009

- Why ?
- The easy Parts
  - Driver
  - Target & capture
  - Acceleration
  - Collider ring
- The hard part: Muon Cooling
  - rf breakdown problem
  - Magnetic insulation
  - High pressure gas
  - My greatest Anxiety
- Conclusion

Why a Muon Collider?

- Point like interactions as in linear e^+e^-
- Negligible synchrotron radiation:
  Acceleration in rings Small footprint Less rf Hopefully cheaper
- Collider is a Ring
  $\approx$ 1000 crossings per bunch Larger spot Easier tolerances 2 Detectors
- Negligible Beamstrahlung Narrow energy spread
- 40,000 greater S channel Higgs Enabling study of widths



Collider Parameters

C of m Energy	1.5	4	TeV
Luminosity	1	4	10^{34} cm^{2}sec^{-1}
Muons/bunch	2	2	10^{12}
Ring circumference	3	8.1	km
Beta at IP $= \sigma_z$	10	3	mm
rms momentum spread	0.1	0.12	%
Required depth for ν rad	13	135	m
Repetition Rate	12	6	Hz
Proton Driver power	$\approx$4	$\approx$ 1.8	MW
Muon Trans Emittance	25	25	pi mm mrad
Muon Long Emittance	72,000	72,000	pi mm mrad

- Emittance and bunch intensity requirement same for both examples
- Luminosities are comparable to CLIC's
- Depth for ν radiation keeps off site dose $<$ 1 mrem/year

THE EASY PART

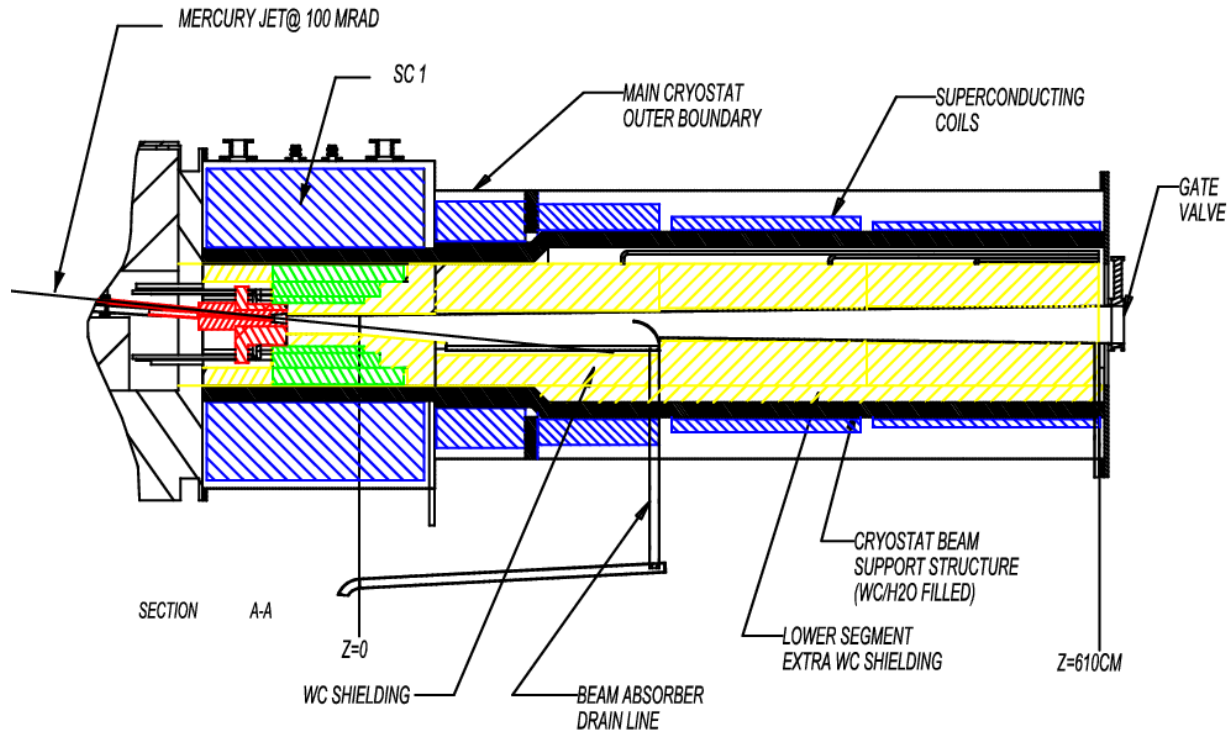
Proton driver

- Project X (8 GeV H^- linac),
- Together with accumulation in the Re-cycler
- And acceleration to 56 GeV in the Main Injector
- Provide the required 12 Hz protons with power = 4 MW

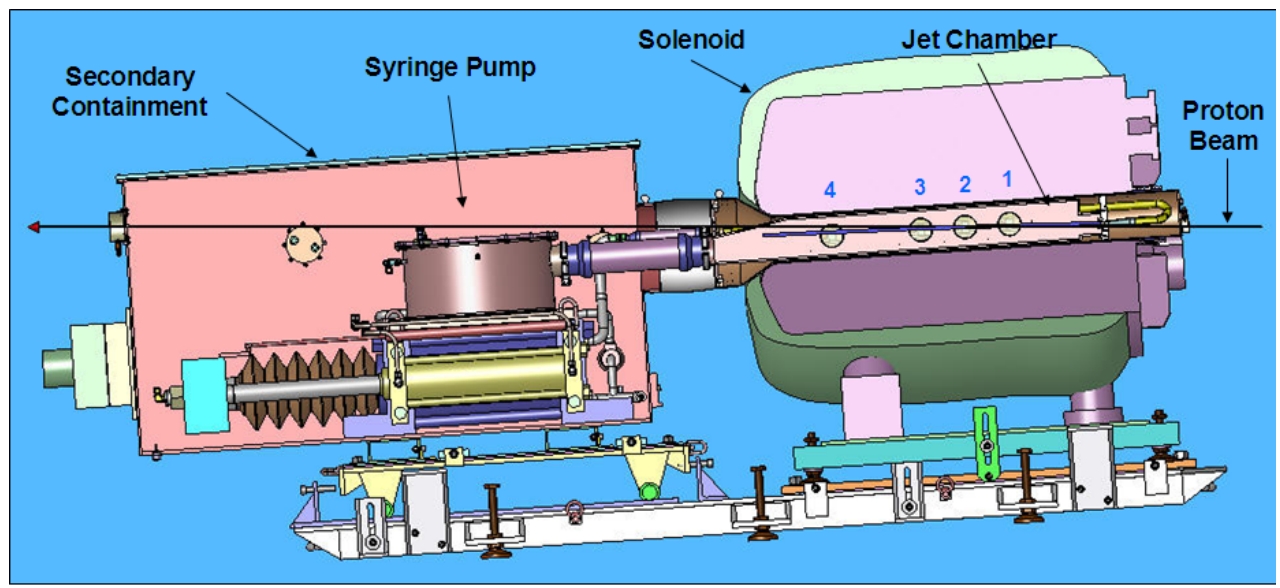
- Alternatives include
  - Doing it all at 8 GeV
  - Sequence of synchrotrons
  - Even an upgrade of the AGS

Target & Capture

- Mercury Jet Target
  20 T capture
- Adiabatic taper to 2 T

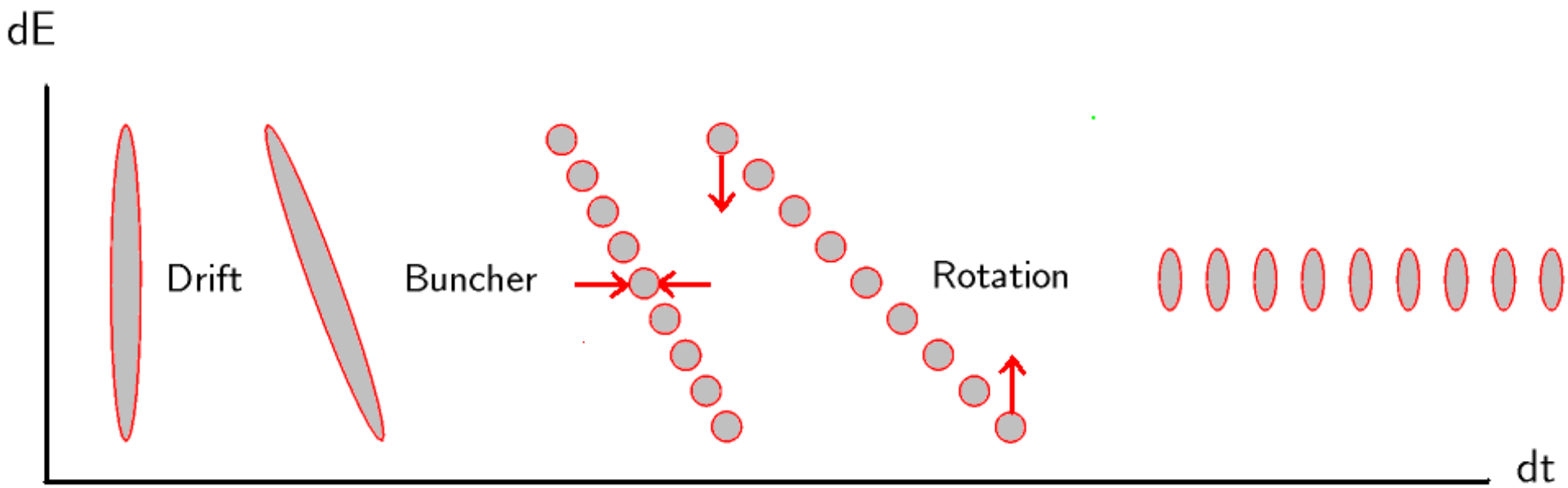


- MERIT Experiment at CERN
  - H. Kirk (BNL) & K. McDonald
  - BNL Inst Div (Tsang) designed and built optical diagnostics
- Up to 36 Tp
- No problems seen



Phase Rotation

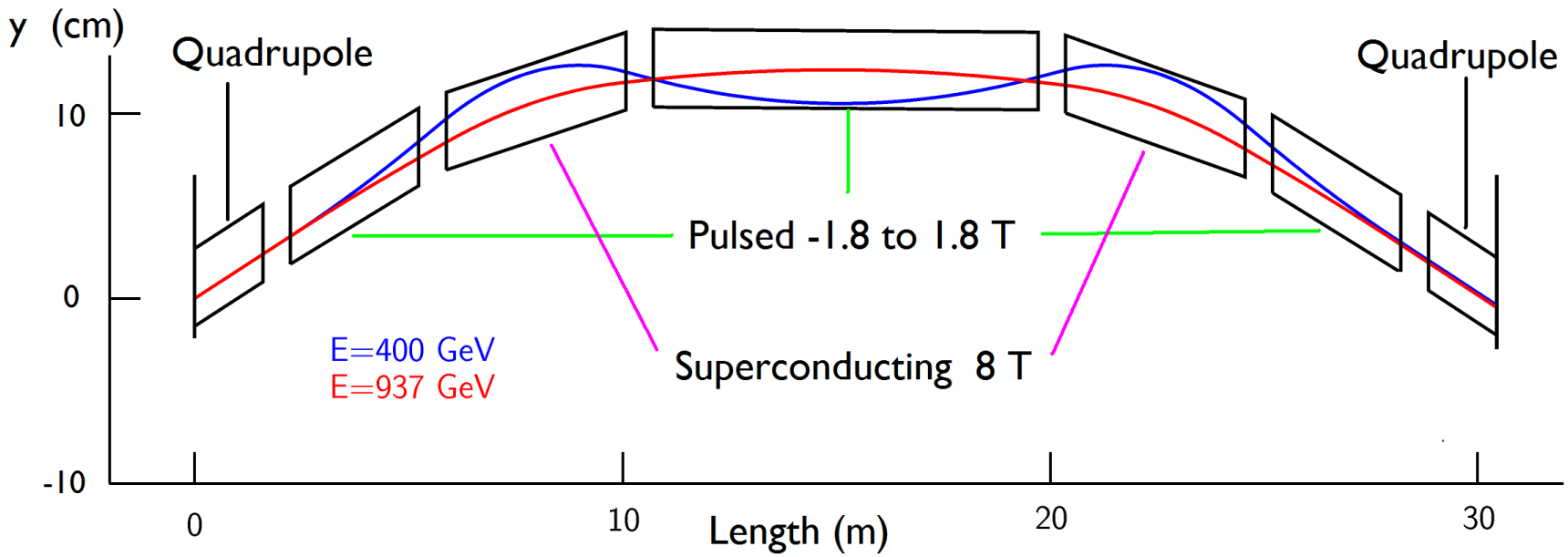
- Neuffer method:
- Bunch first, then Rotate



- Frequencies of bunching and rotation must change as function of drift
- Older system rotated first with an induction linac, then bunched
- But induction linacs are expensive

Acceleration

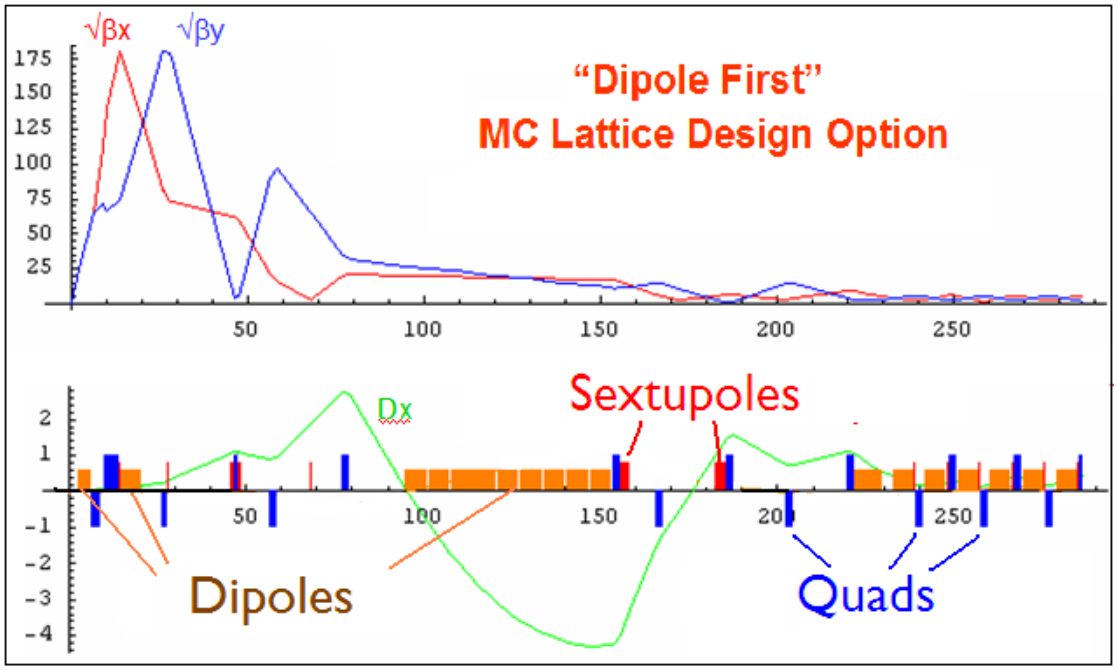
- Sufficiently rapid acceleration is straightforward in Linacs and Recirculating linear accelerators (RLAs)
  Using ILC-like 1.3 GHz rf
- Lower cost solution would use Pulsed Synchrotrons
  - Pulsed synchrotron 30 to 400 GeV (in Tevatron tunnel)
  - SC & pulsed magnet synchrotron 400-900 GeV (in Tevatron 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

Collider Rings

- 1.5 TeV (c of m) Design



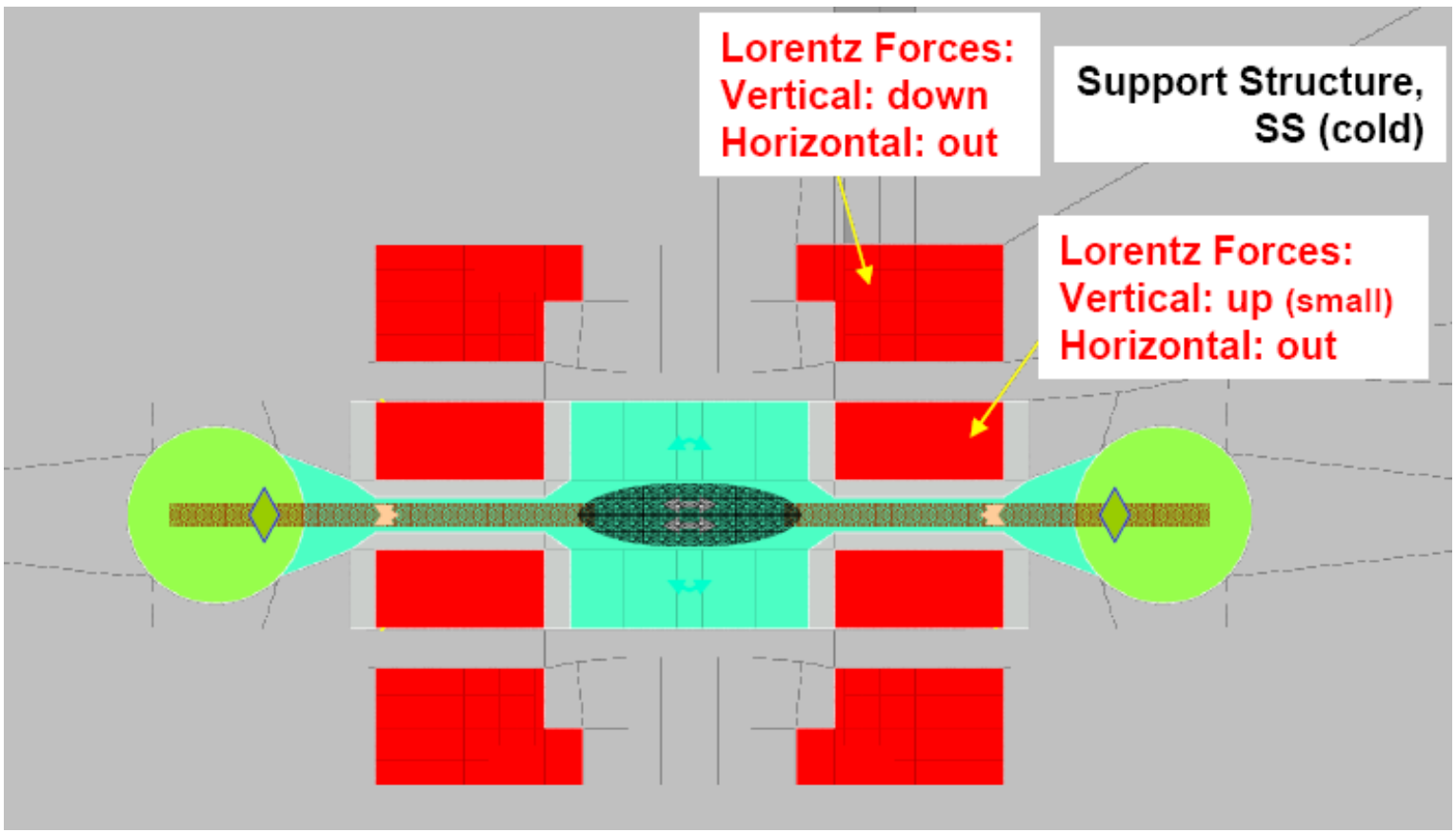
  - Nearly meets requirements
  - But early dipole may deflect unacceptable background into detector

- 4 TeV (c of m) 1996 design by Oide
  - Meets requirements in ideal simulation
  - But is too sensitive to errors to be realistic

- The experts believe that the required rings should be possible

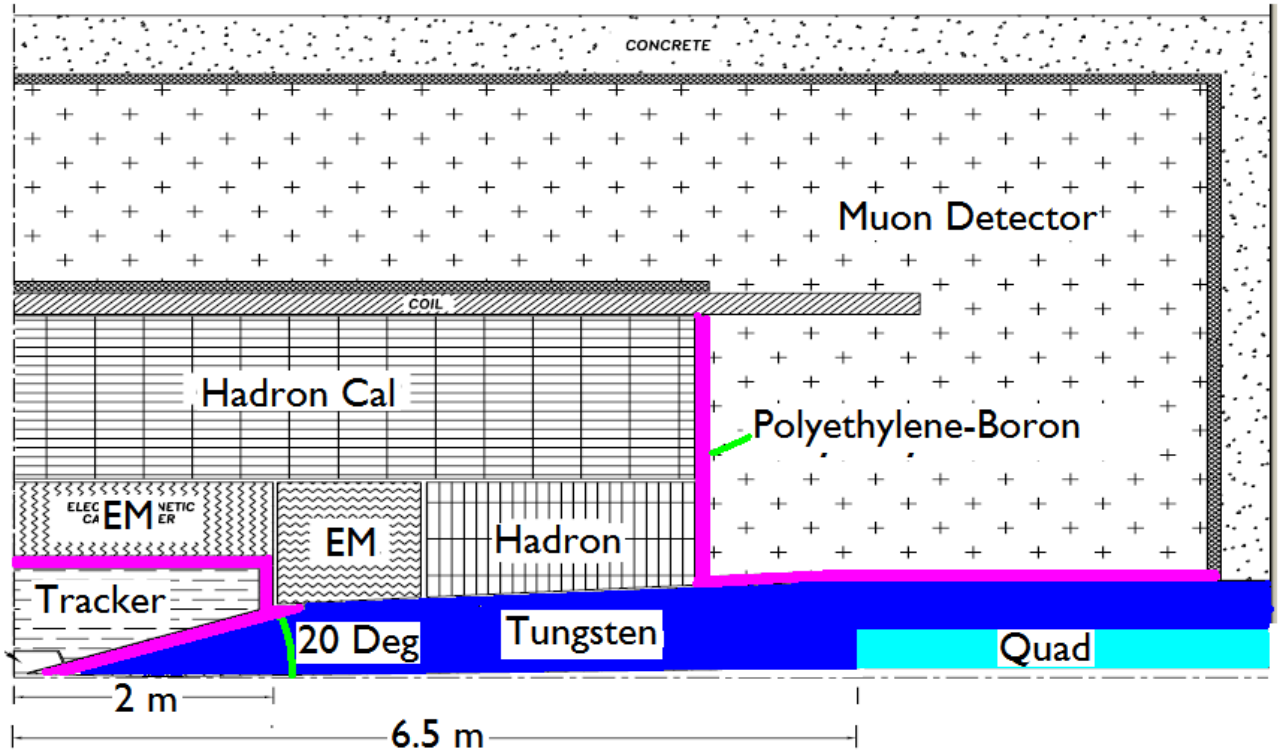
Collider Ring Dipole Magnets

- Luminosity $\propto 1/$circumference $\propto < B >$
  So very high field dipoles desirable
- 1/3 of beam energy geven to decay electrons
  Means ot absorb their energy required
- HTS Open Mid-plane dipole (BNL R Gupta) is good option



Detector From 1996 Study of 4 TeV Collider

I Stumer (BNL)

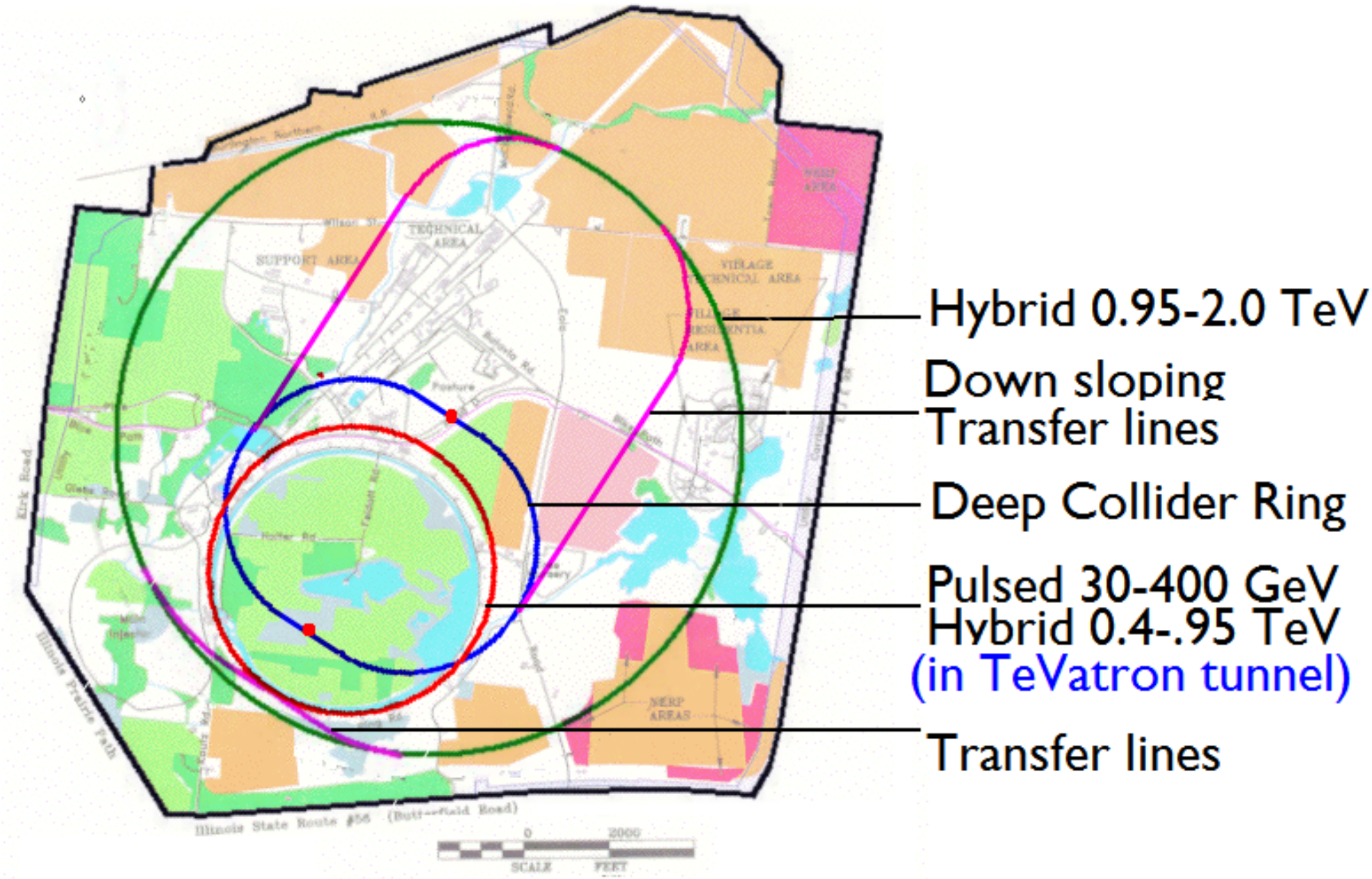


- Sophisticated shielding designed in 1996 4 TeV Study
- GEANT simulations then indicated acceptable backgrounds
- Would be less of a problem now with finer pixel detectors

BUT

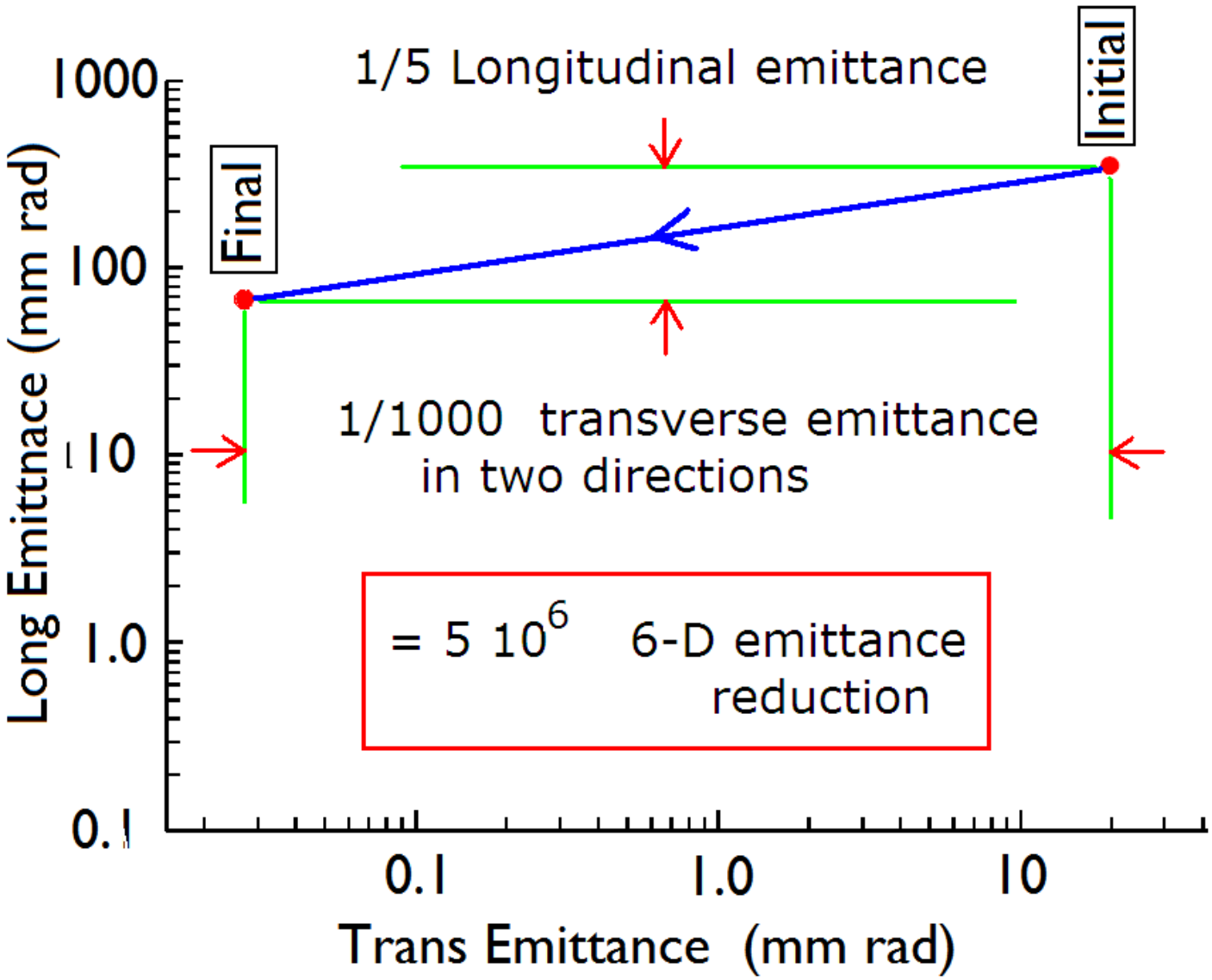
- Tungsten shielding takes up 20 degree cone

Layout of 4 TeV Collider using pulsed synchrotrons



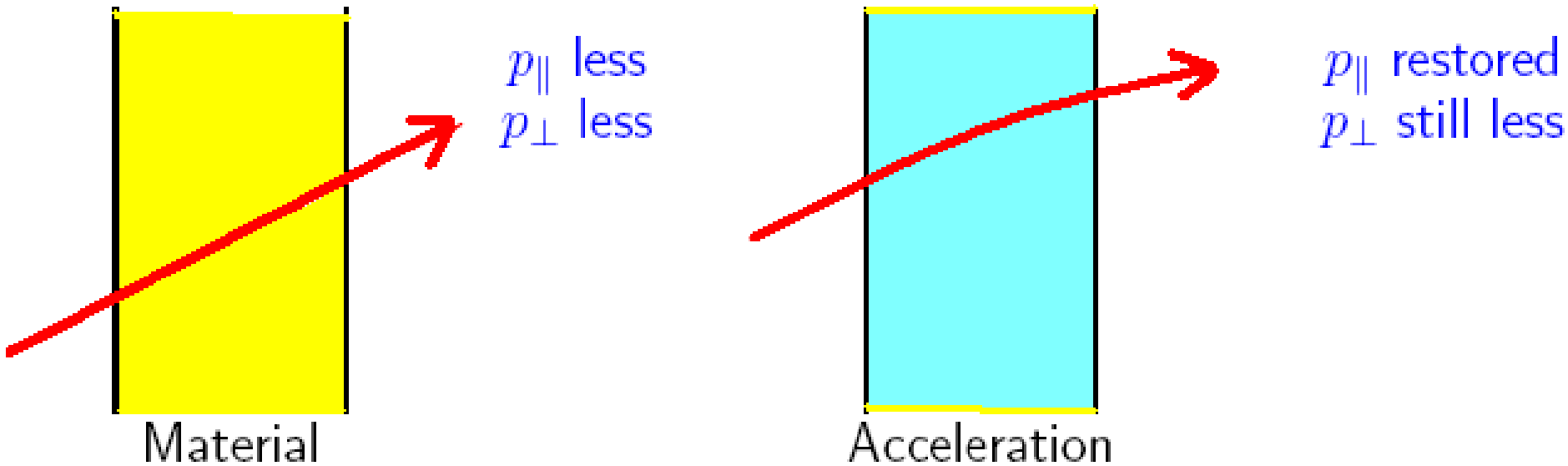
THE HARD PART

Muon Cooling



Transverse Ionization Cooling

- Radiation cooling fails because mass is too high
- Electron beam and stochastic cooling are too slow
- Only Ionization cooling should work

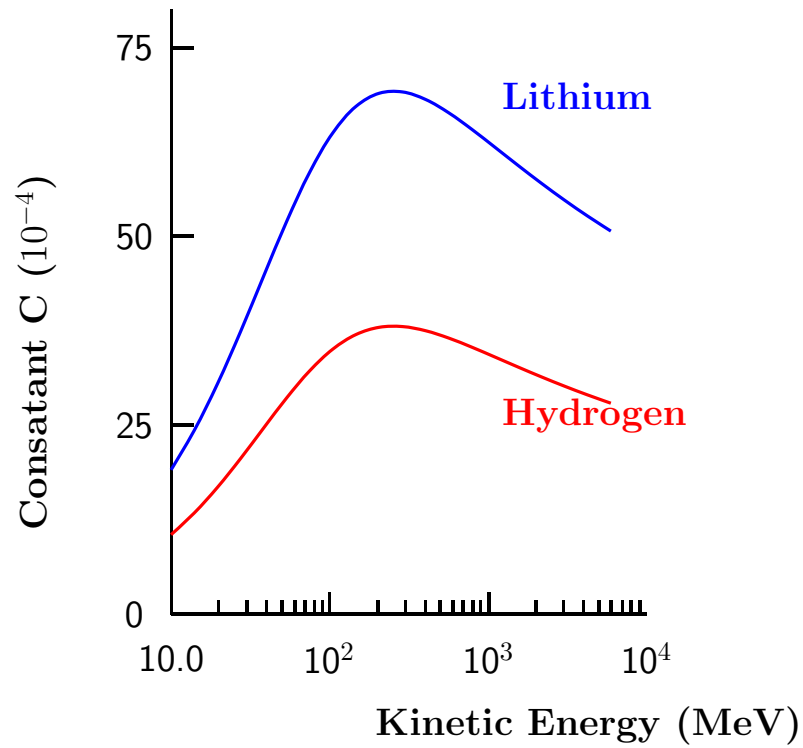


Minimum Emittance

- Cooling by ionization loss
- Heating by Coulomb scattering
- Minimum Emittance:

$$\epsilon_{x,y}(min) = \frac{\beta_\perp}{\beta_v} C(mat, E)$$

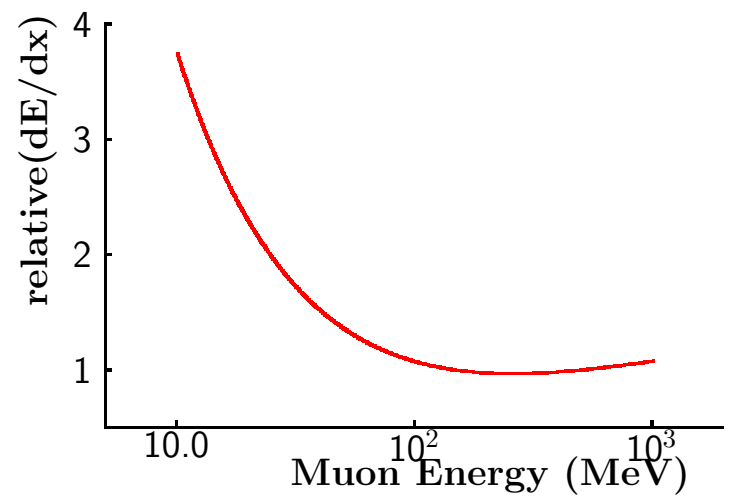
$$\propto \frac{C(mat, E)}{\beta_v B_z}$$



To reach $\epsilon_\perp$ of 25 μm

- Use liquid hydrogen for absorbers
- Use highest practical solenoid field ($\approx$ 50 T)
- Use sufficiently low energy ($\approx$ 6 MeV)

- This works but slope of dE/dx causes dp/p, and thus longitudinal emittance, to rise

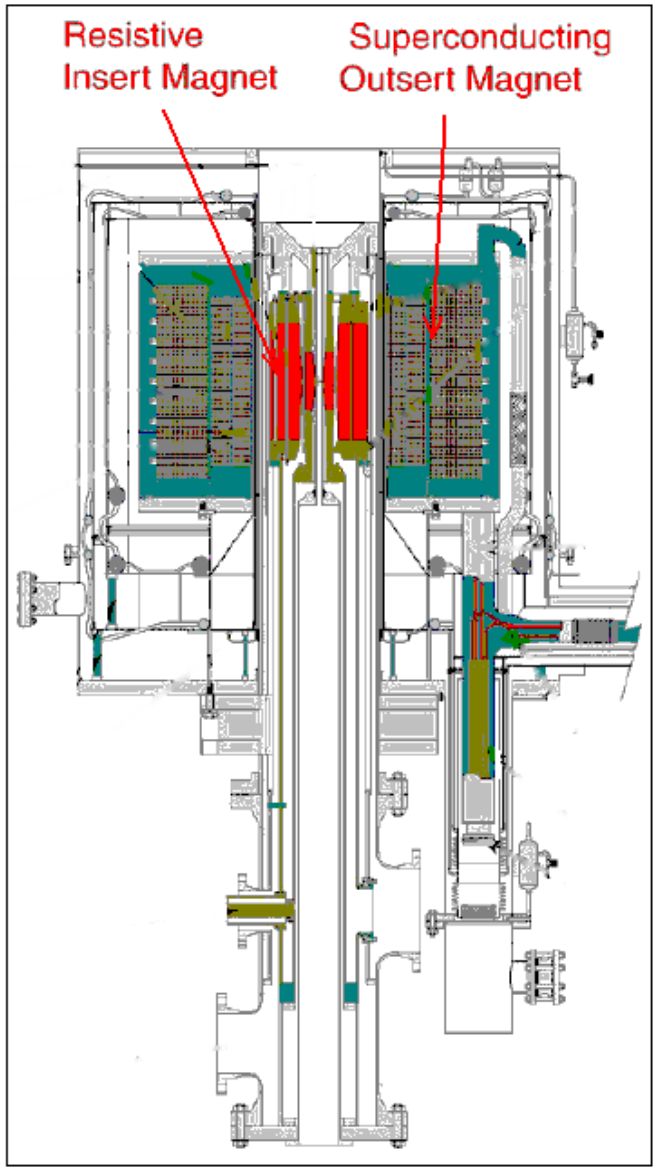


Is 50 T Realistic ?

- 45 T hybrid at NHMFL, but uses 25W
- We need $\approx$ 5 solenoids
- 125 MW not crazy

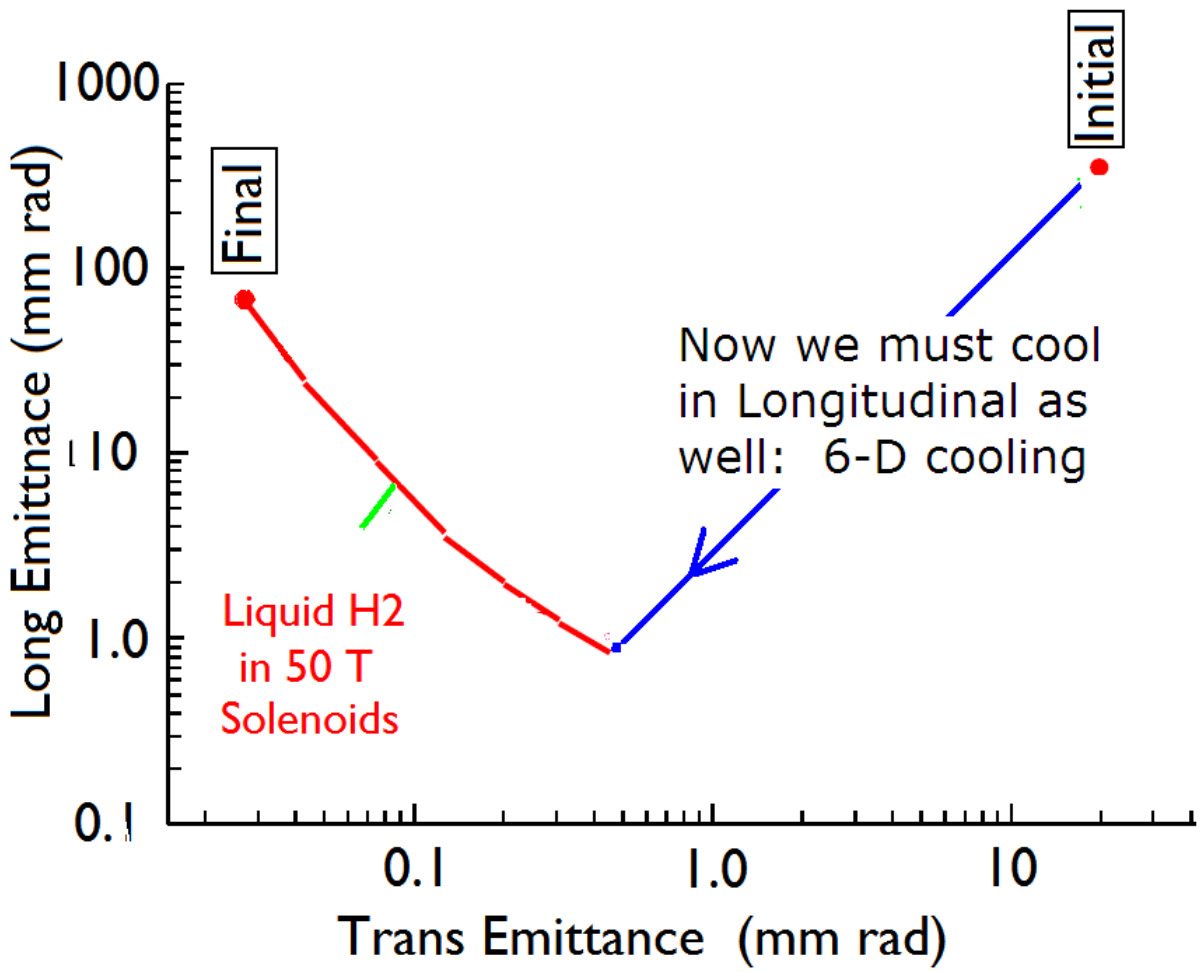
- But HTS critical fields $\approx$ 100 T
- HTS current densities $\approx j_{Cu}$
- 50 T HTS solenoids seem possible

- 34 T insert already tested
- 30 T all HTS designed at NHMFL



NHMFL 45 T Hybrid Magnet

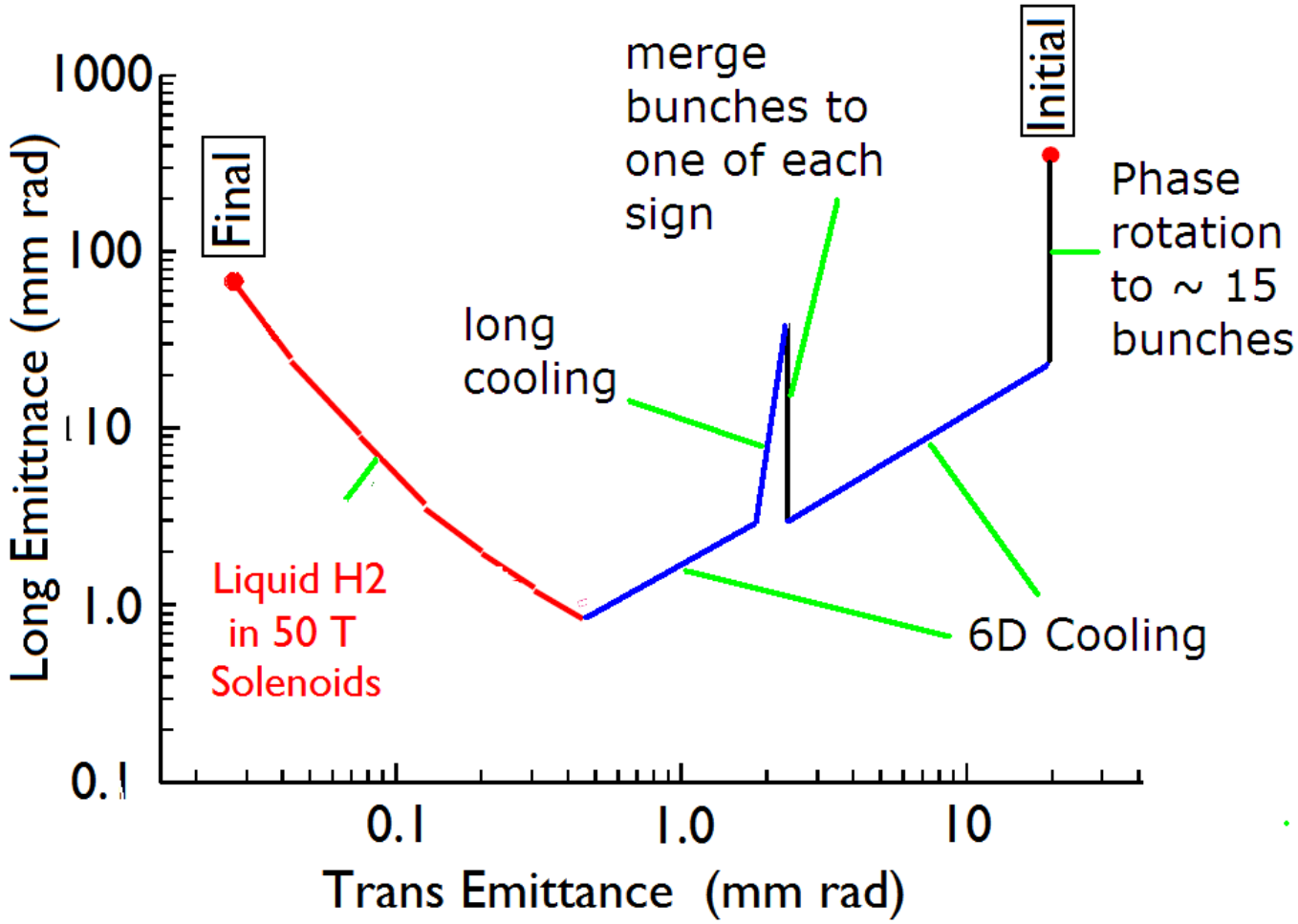
6D Cooling Simulation (In ICOOL R.Fernow)



A complication:

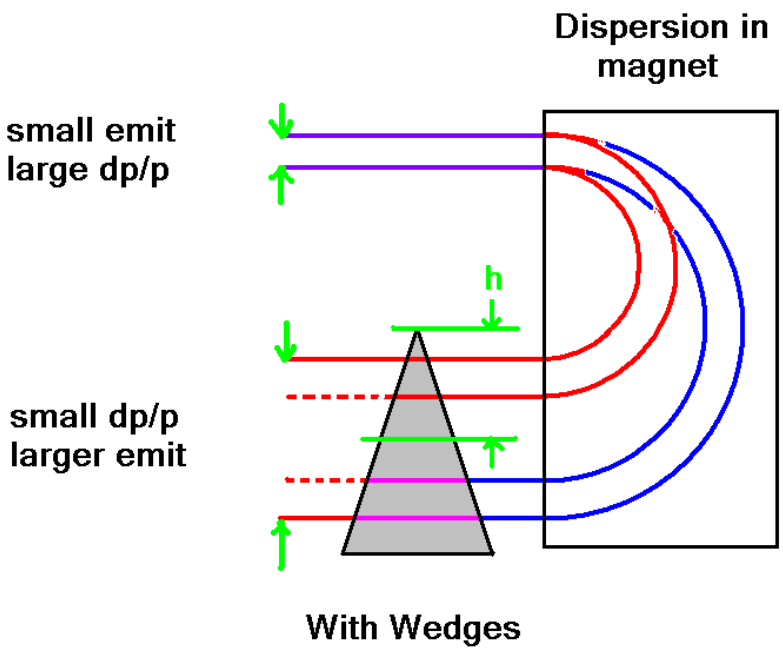
- Phase rotation made 15 bunches of each sign
- We require only one of each sign
- Must be recombined at some point

Bunch merging



- 6D-cooling till long emittance 1/15
- Merge
- Re-cool longitudinal

Trans cooling + Emittance Exchange = 6D Cooling



dp/p reduced But σ_y increased
Long Emit reduced Trans Emit Increased

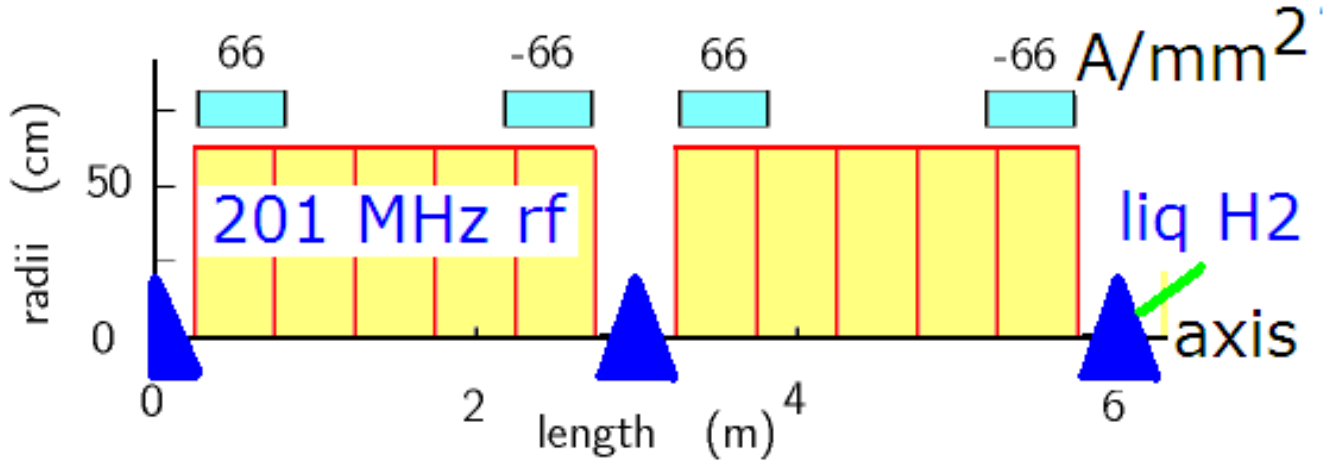
Emittance Exchange

We need lattices with:

- Substantial solenoid focusing
- Large momentum acceptance
- Dispersion
- Hydrogen wedge absorbers
- And Acceleration

Super-FOFO Lattices (Andy Sessler)

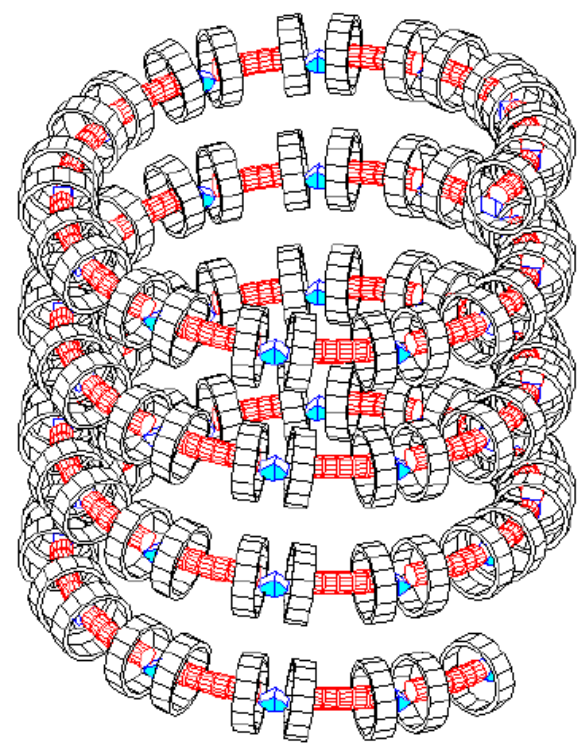
Lattice without bending



Bending added

to generate dispersion for 6D-cooling

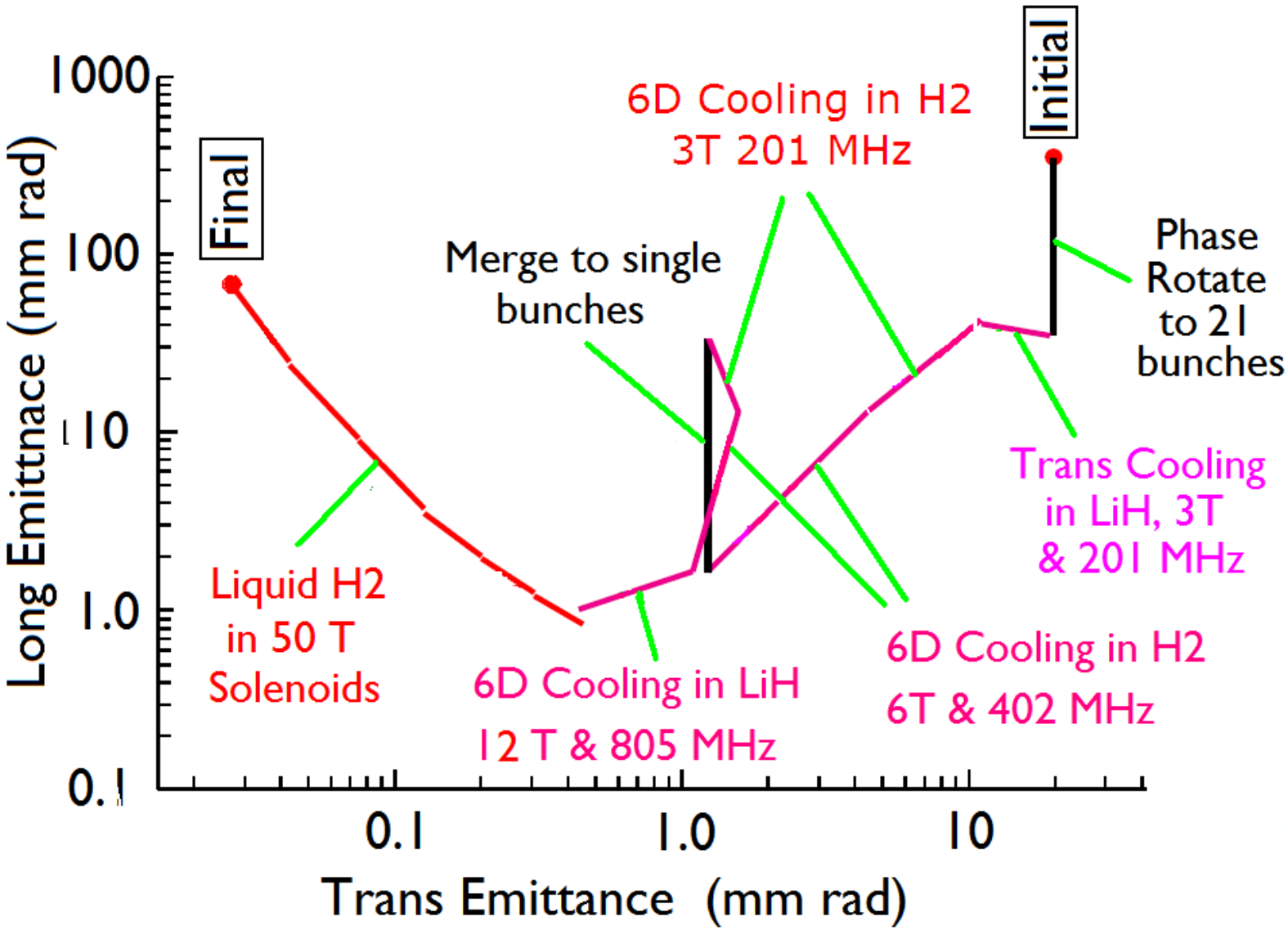
Guggenheim geometry



Parameters

Stage	freq (MHz)	Grad MV/m	Mag (T)
Initial	201	12	3
Mid	402	17	6
Final	805	20	12

Complete Cooling System

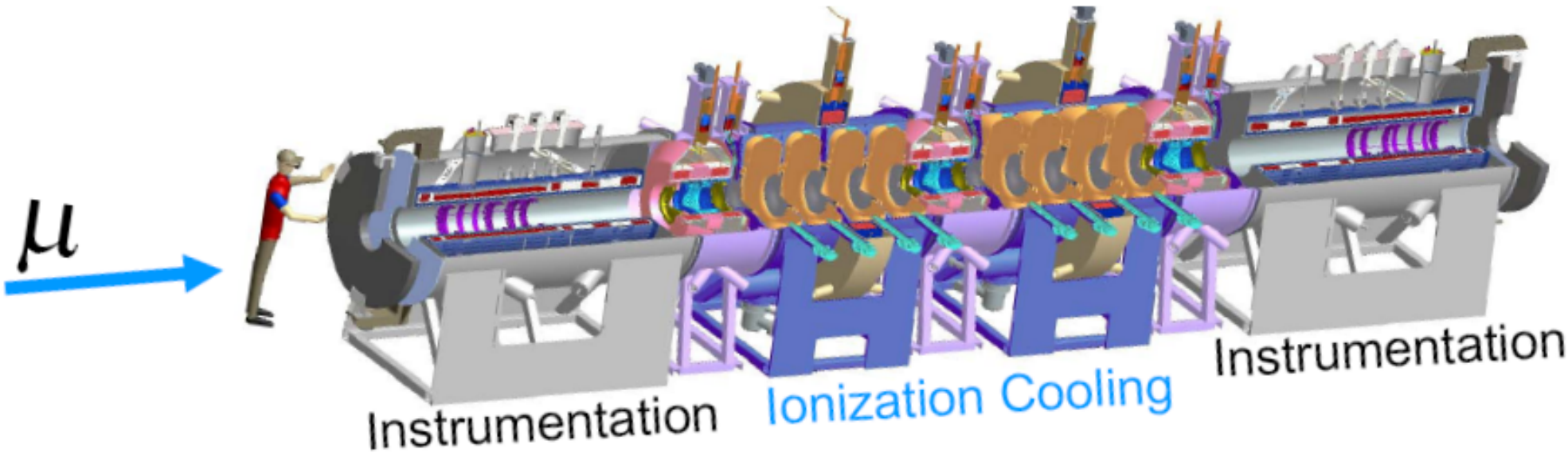


- All parts sumulated as some level

Muon Ionization Cooling Experiment (MICE)

International collaboration at RAL, UK

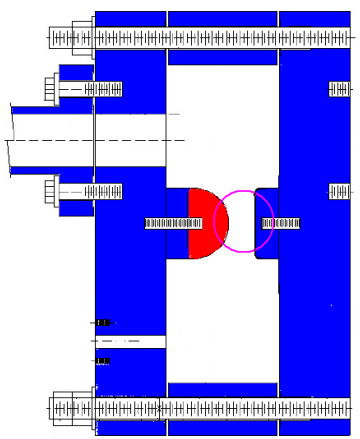
- Will demonstrate transverse cooling in liquid hydrogen, including rf re-acceleration
- Uses a somewhat different version of 'Super FOFO'
  But, as now configured, has now bending or emittance exchange



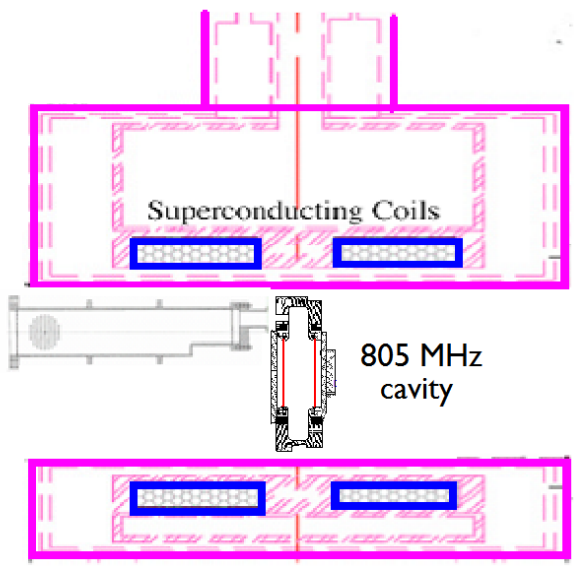
- Allows early test of emittance exchange without re-acceleration
- Later phase might test emittance exchange with re-acceleration

MuCool, and MuCool Test Area (MTA) at FNAL

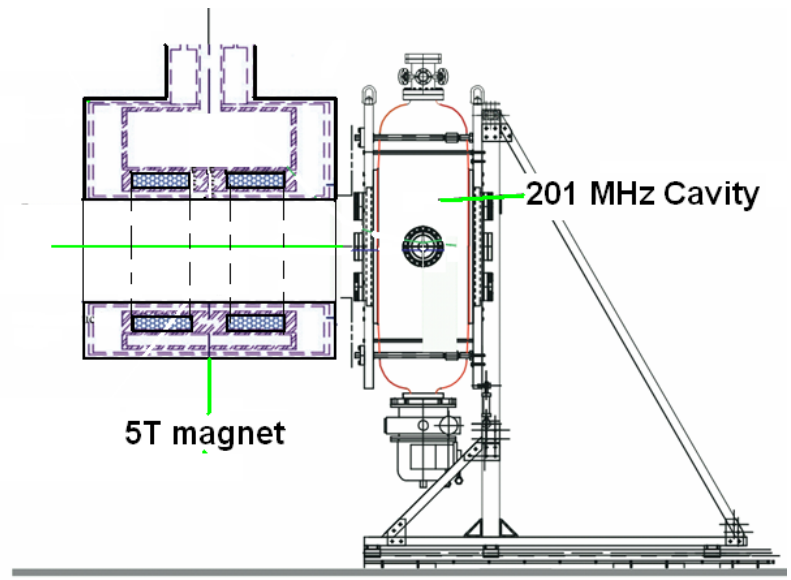
- Liquid hydrogen absorber tested
- Open & pillbox 805 MHz cavities in magnetic fields to 4 T
- 201 MHz cavity tested to magnetic field of 0.7 T
  Later to 2T
- High pressure H2 gas 805 MHz pillbox cavity tested
- Soon: 805 MHz gas Cavity with proton beam



HP Gas cavity



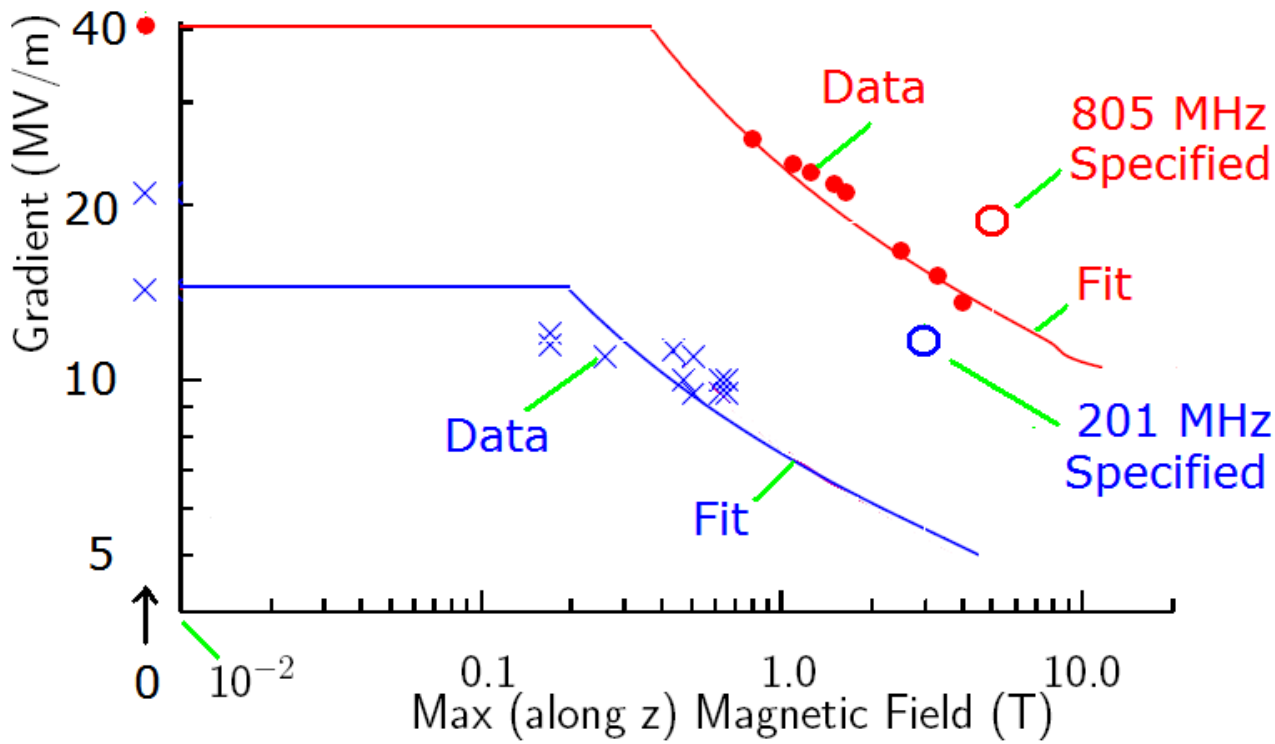
805 MHz in 4 T magnet



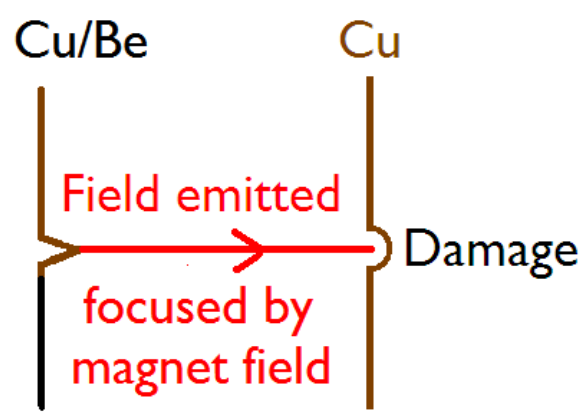
201 MHz next to magnet

Experimental results on breakdown in fields

Experiments show breakdown in required fields



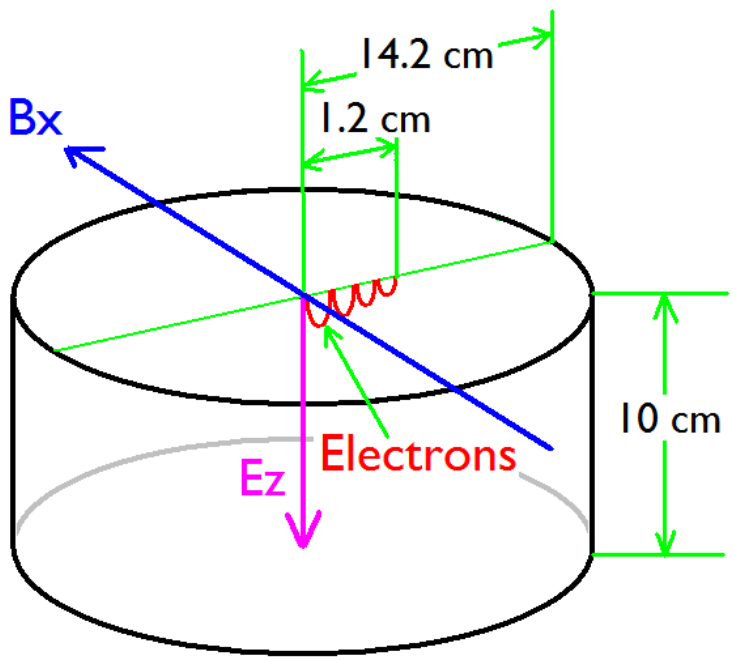
Fits from new theory
(Palmer Gallardo Stratakis)

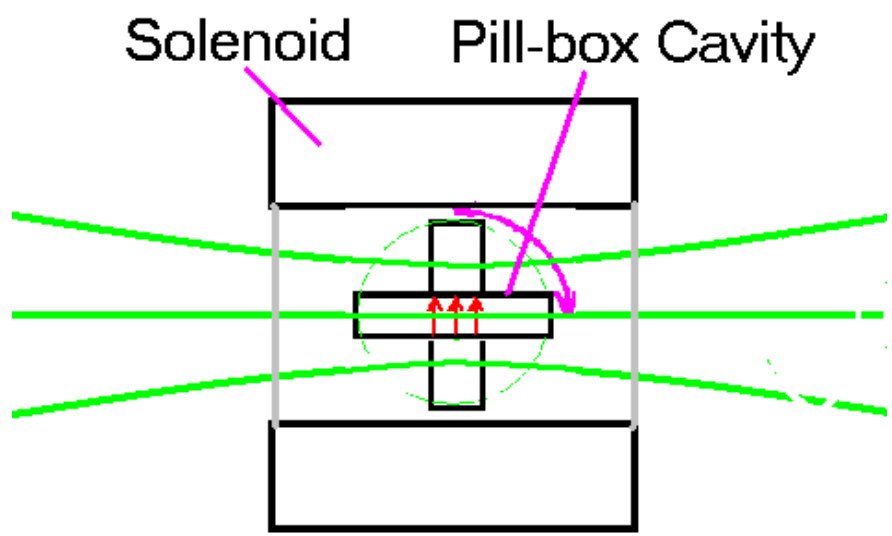


Magnetic Insulation Concept

- If magnetic field lines are parallel to an emitting surface
- All field emitted electrons will return to the surface with low energies and do no damage

A first experiment (Under constriction at FNAL)



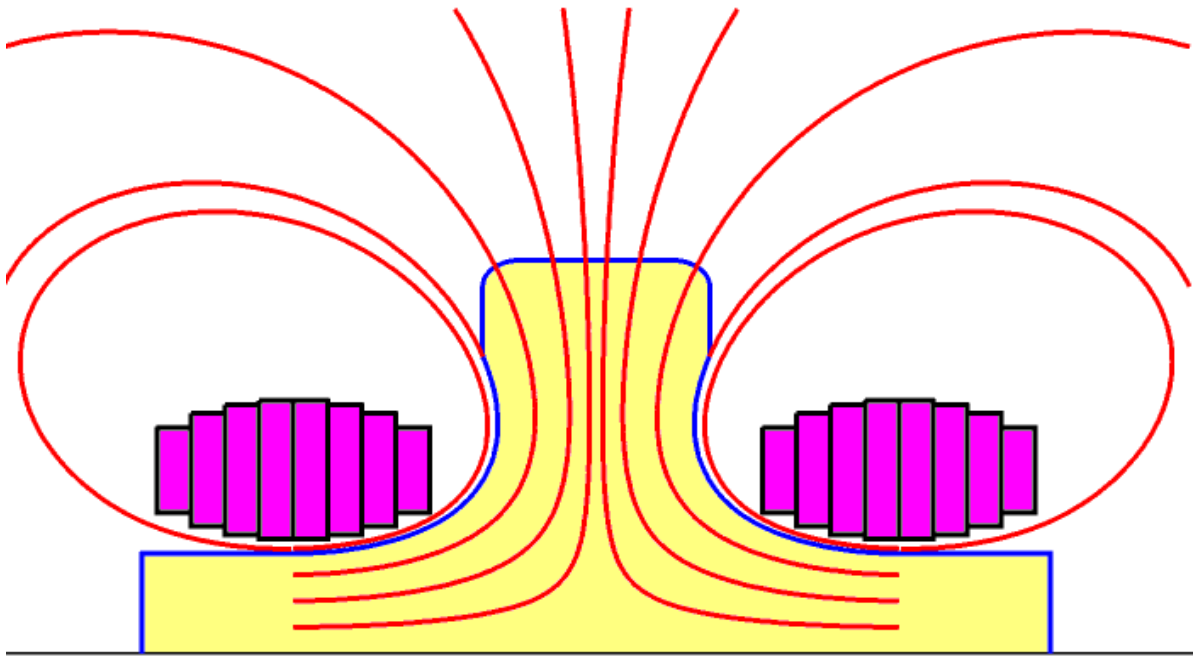


. Simulation

Experiment in 4 T solenoid

Simple Magnetically Insulated Accelerting Cavity

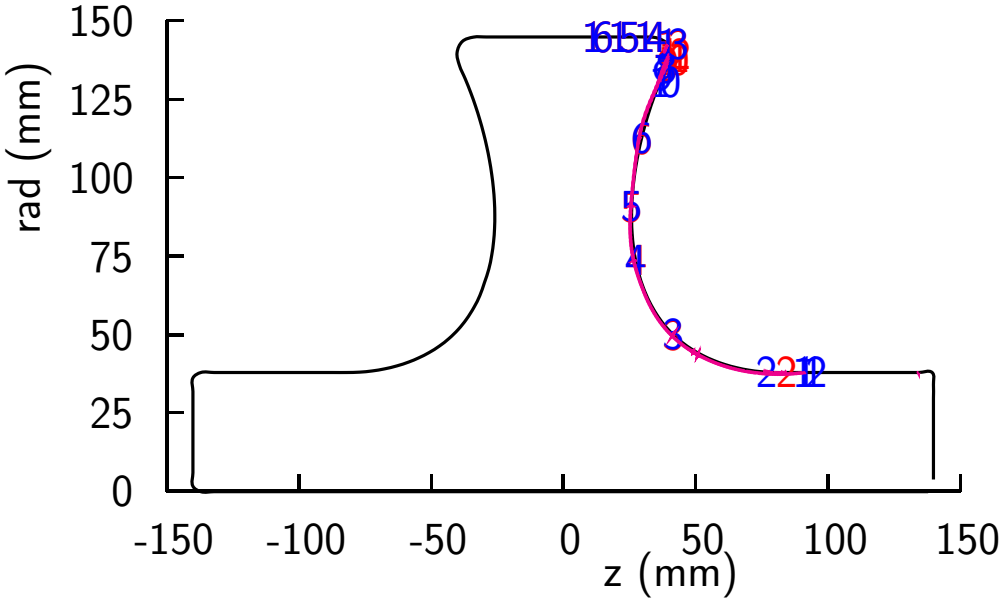
Form cavity surface to follow magnetic field lines

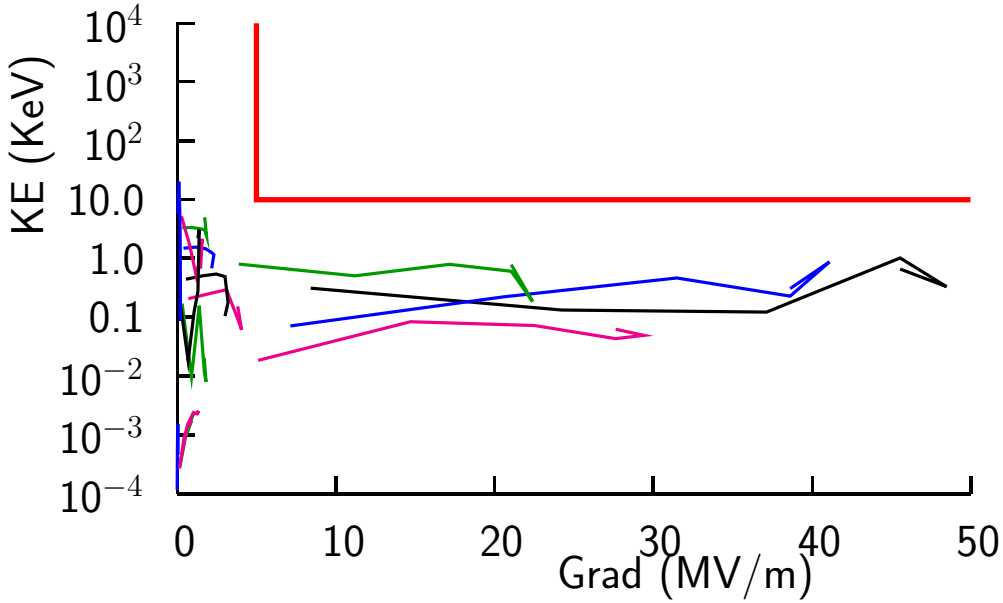


- No dark current, No X-Rays !
- No danger of damaging surfaces
- But secondary emission → problems ? Grateful to SLAC for help

Track electrons from different locations and phases

Using CAVEL (R.Fernow)

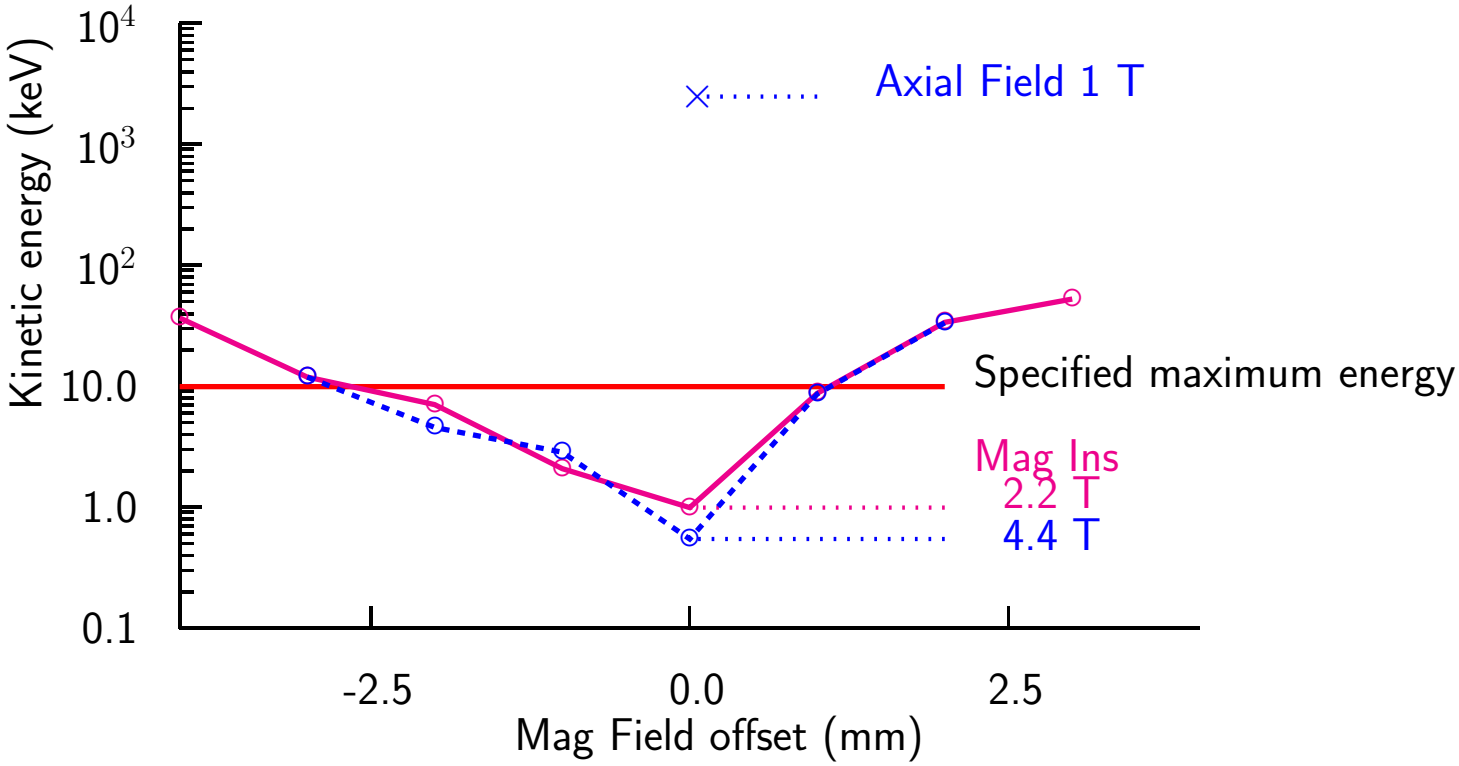




- Tracks remain close to surfaces
- No track with $\mathcal{E} > 5$ MV/m has final energy $>$ 10 keV with plenty to spare

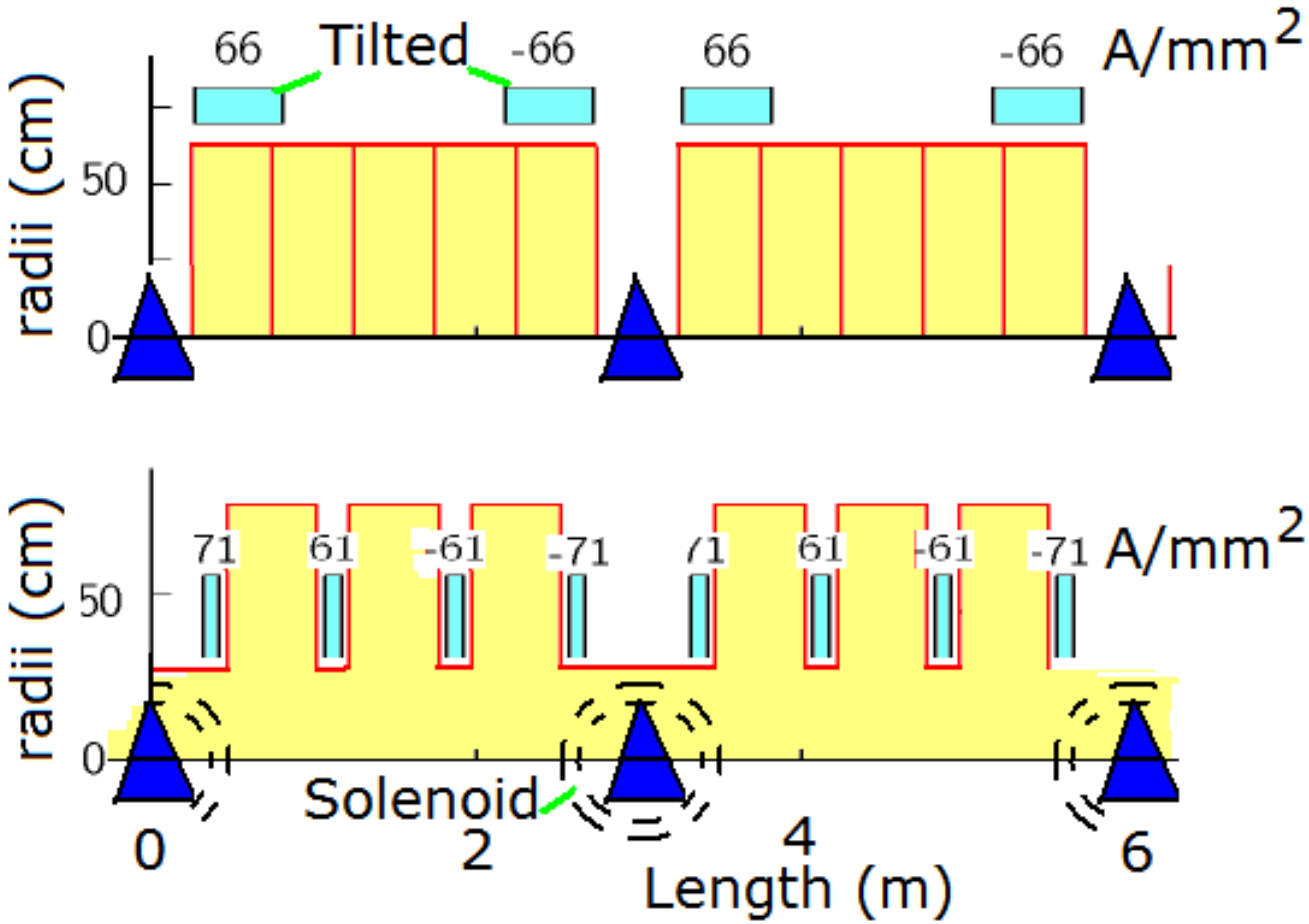
Sensitivity to errors

For tracks starting with $\mathcal{E} > 5$ MV/m :
plot maximum final energies vs. z displacement of magnetic fields

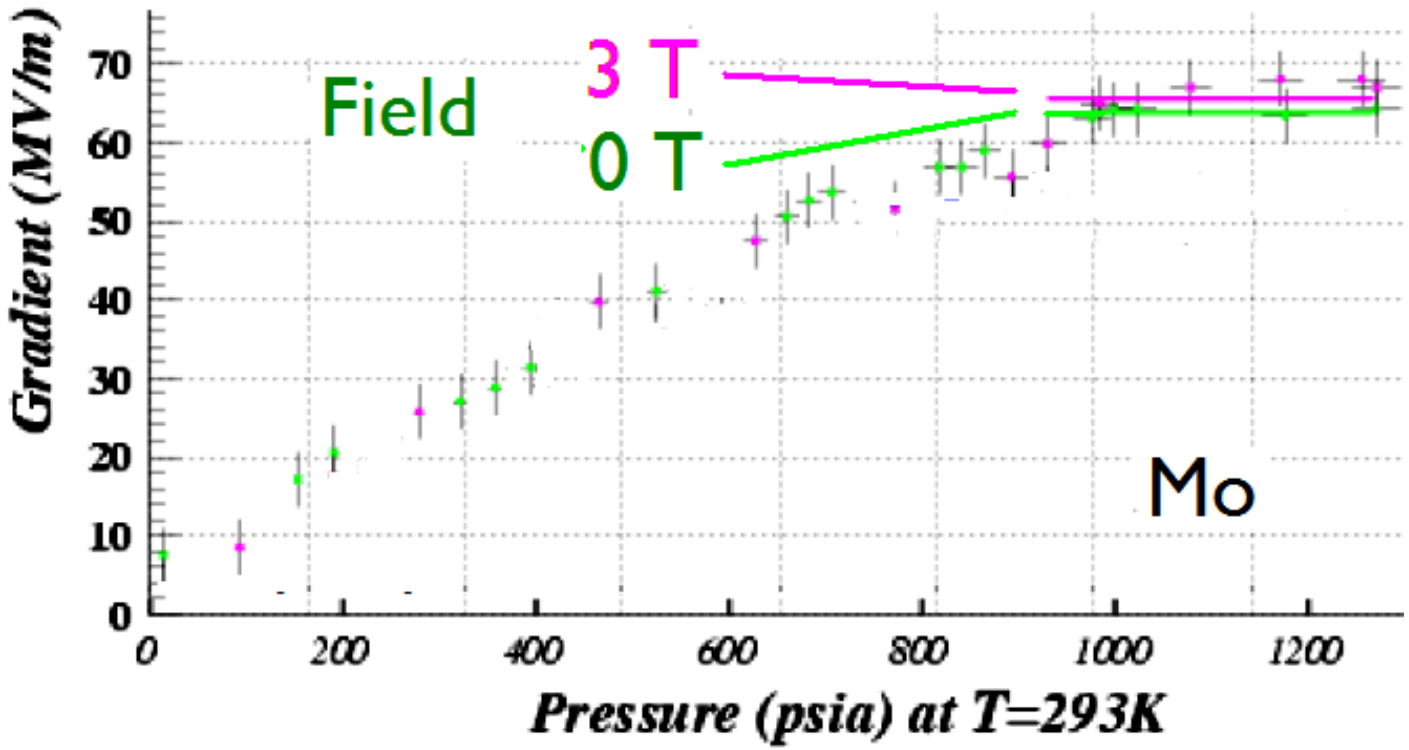


- Meets requirements for axial displacements up to $\pm$ 1 mm
- Little effect of doubling the strength of the magnetic fields
- Energies down by $>$ 2 orders of magnitude from axial field case

Incorporation of Magnetic Insulation in lattices



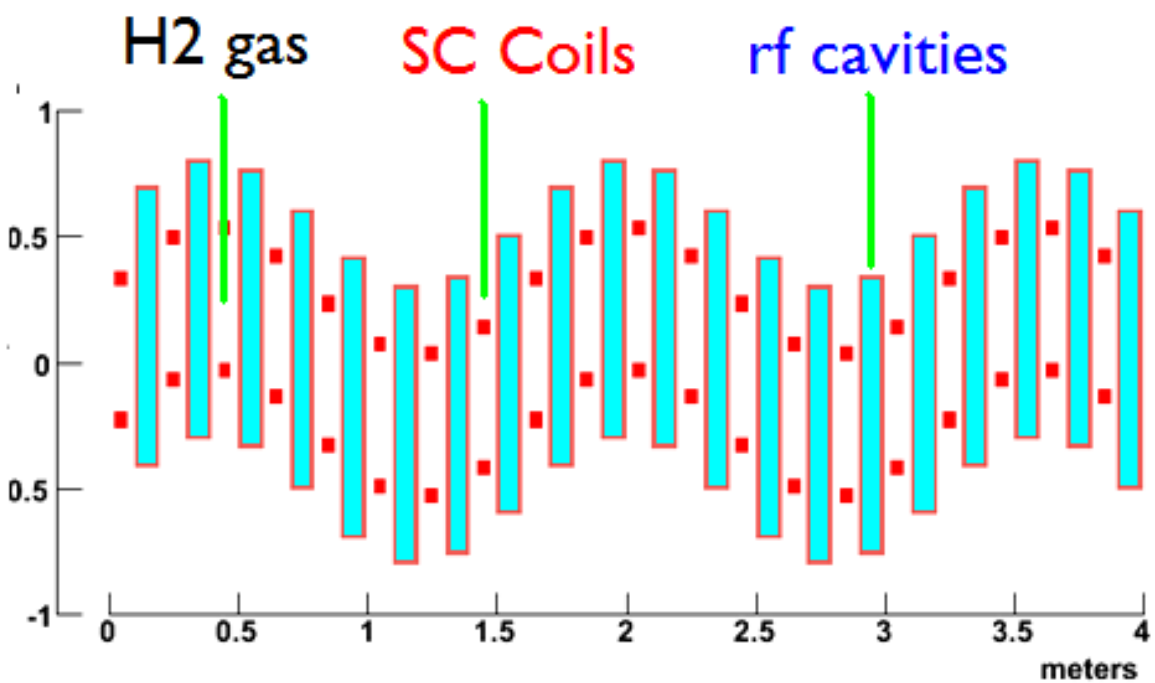
Alternative Fix for rf in magnets (Rol Johnson)



- High pressure hydrogen gas suppresses breakdown
- and can be used as primary absorber
- Lattices must have low better everywhere
- Emittance exchange using LiH wedges
  Or systems with longer paths for higher momenta (e.g. HCC)

Helical Cooling Channel (HCC) (Derbenev Johnson)

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

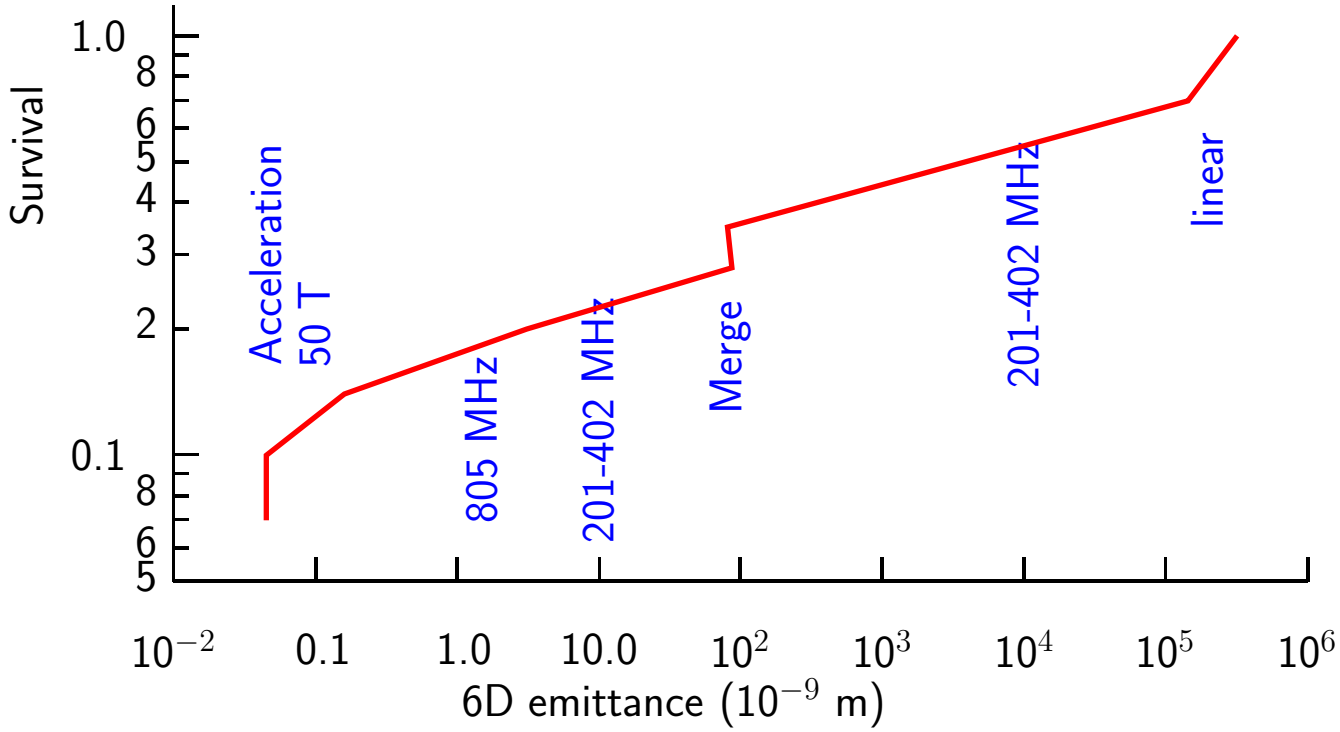


- Requied Fields 50-100% higher than in Guggenheim
- But transmission probably better

- Engineering integration of rf not solved
- Possible problem of rf breakdown with intense muon beam transit

My greatest anxiety

- Collider parameters assumed 7% muon transmission



- This is an optimistic estimate, based on pre-magnetic Insulation lattices
- Magnetically Insulated lattices appear to have less transmission
- Lower overall transmission:
  - lowers luminosity by the square ($\mathcal{L} \propto \mathrm{N}^2$)
  - or increases proton power by inverse square ($P \propto N^{-2}$)

Conclusion

- All stages for a "baseline" design have been simulated at some level
- Matching and tapering and 50T re-acceleration remains to be designed
- Detector design and shielding has been studied and looks ok
- Collider ring designs exist for both 1.5 TeV and 4 TeV colliders although both still have problems
- High field ring (open mid-plane?) dipoles need development
- 50 T all superconducting solenoids need development, but existing hybrid designs are backup

- The biggest technical problem is rf breakdown in magnetic fields solutions:
  - Magnetically insulated cavities
  - High pressure hydrogen gas filled cavities

- My greatest anxiety is excessive muon loss in cooling

- But Muon colliders, if their problems can be solved are probably the cheapest route to muti TeV energies