Muon Colliders

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CERN LHC2FC

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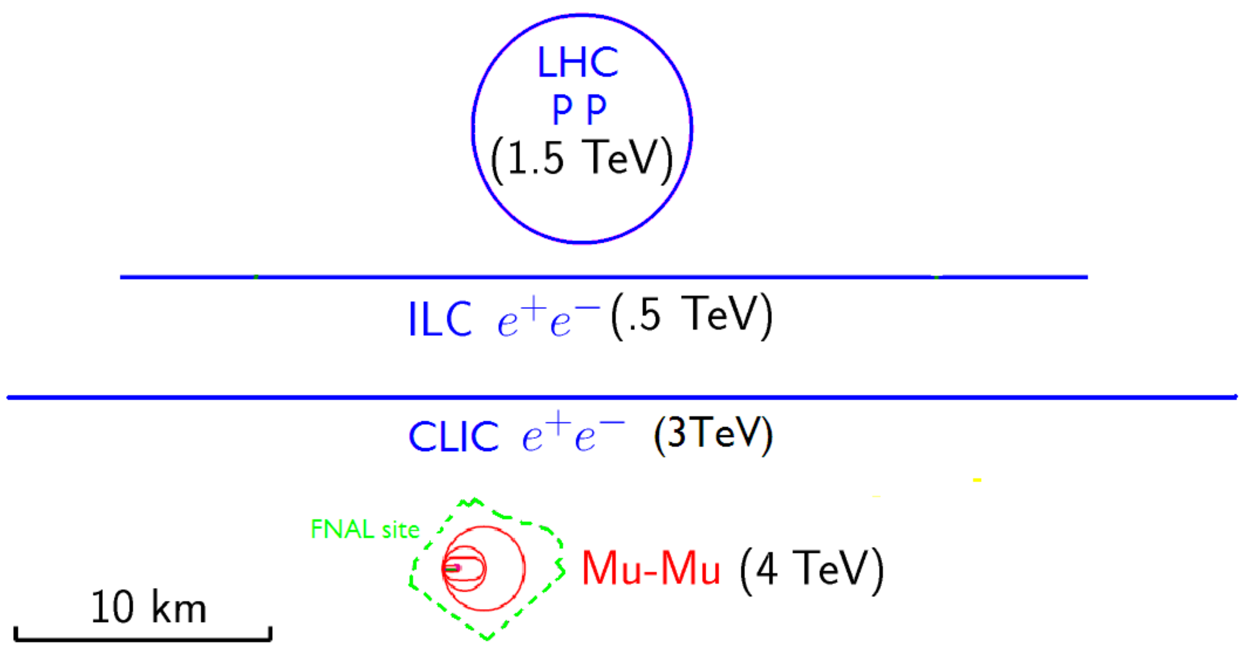
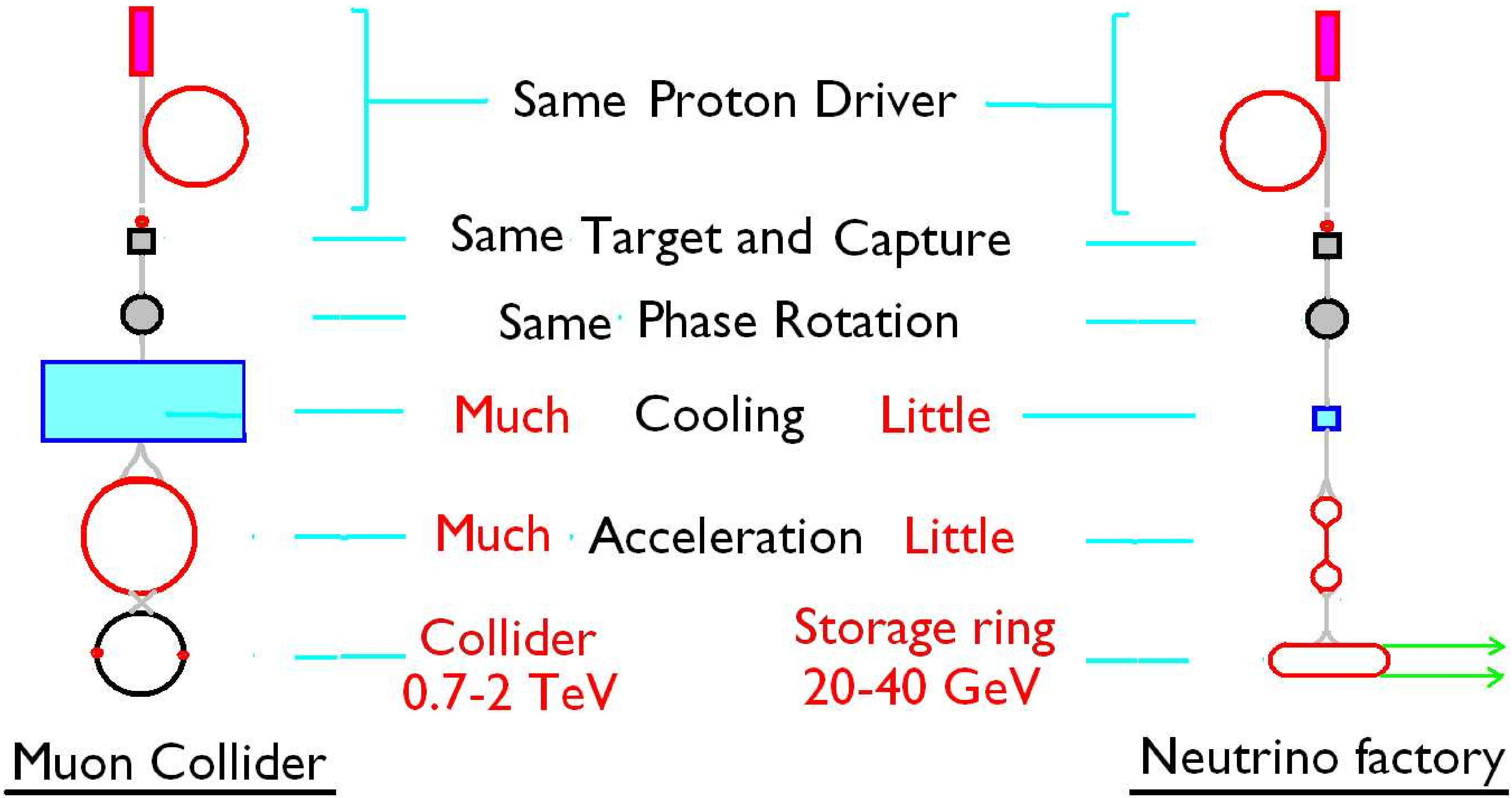
- Why ?
- The "easy" Parts
  - Driver
  - Target & capture
  - Acceleration
  - Collider ring
- The hard part: Muon Cooling
  - rf breakdown problem
  - Magnetic insulation
  - High pressure gas
- R&D Proposed Program
- Conclusion

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



Schematics of Collider and Neutrino Factory



- Much of the R&D is common and has been pursued by the same US collaboration
- Significant European role only in Neutrino Factory
- Recent FNAL involvement specifically in Collider

Collider Parameters

C of m Energy	1.5	4	TeV
Luminosity	1	3 (6)	10^{34} cm^{2}sec^{-1}
Beam-beam Tune Shift	0.1	0.1	
Muons/bunch	2	2	10^{12}
Ring <bending field>	5.2	10.4	T
Ring circumference	3	4	km
Beta at IP $= \sigma_z$	10	10	mm
rms momentum spread	0.1	0.12	%
Muon Beam Power	7.5	9 (18)	MW
Required depth for ν rad	13	135 (270)	m
Repetition Rate	12	6 (12)	Hz
Proton Driver power	4	1.8 (3.6)	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 $(\Delta E < 1\%)$ are comparable to CLIC's
- Depth for ν radiation for off site dose $<$ 1 mrem/year (1/10 US Federal limit)

THE EASY PART

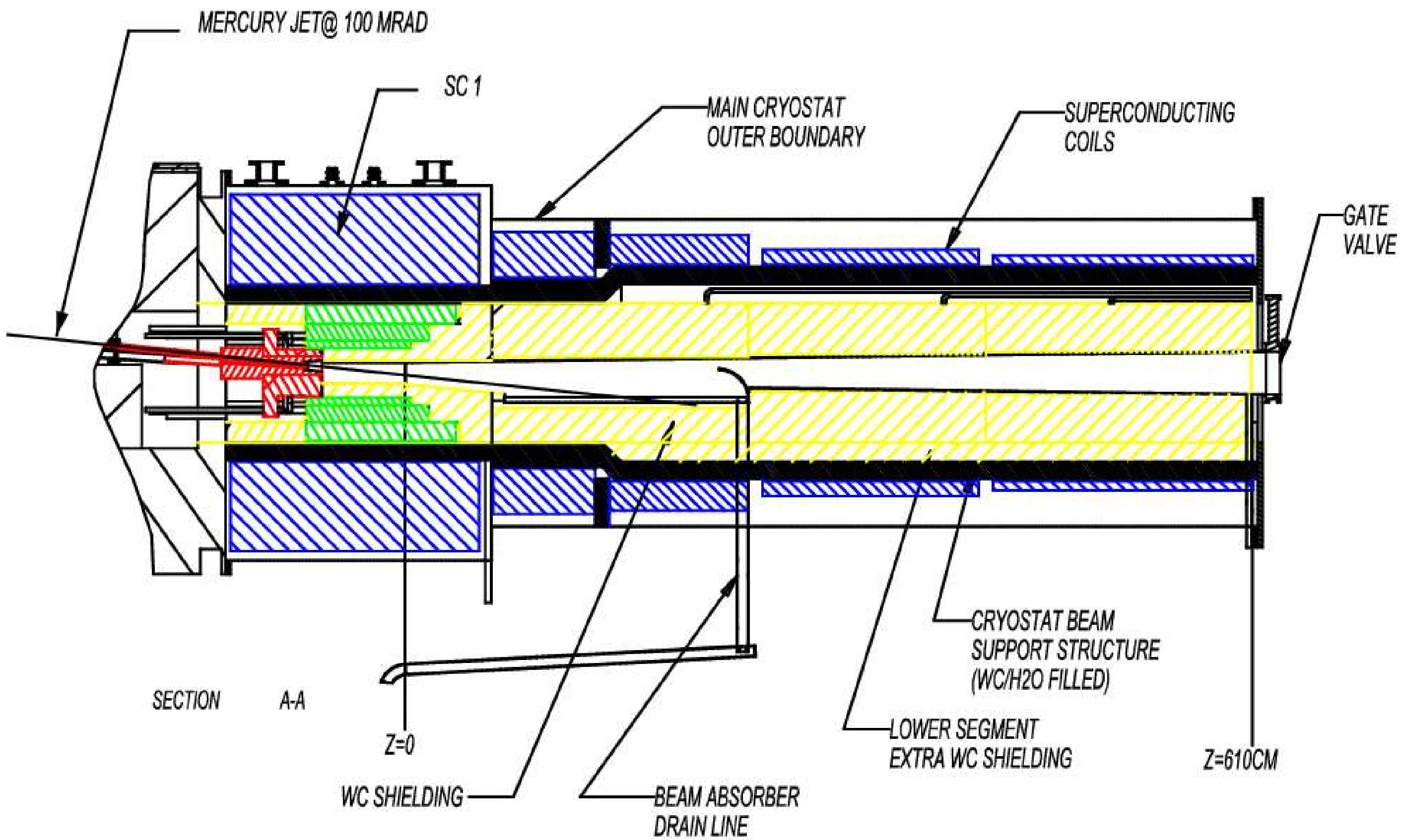
Proton driver

Need few (12 Hz), very large, very short (3 ns) proton bunches

p Energy	Intensity
56 GeV	40 Tp
8 GeV	250 Tp

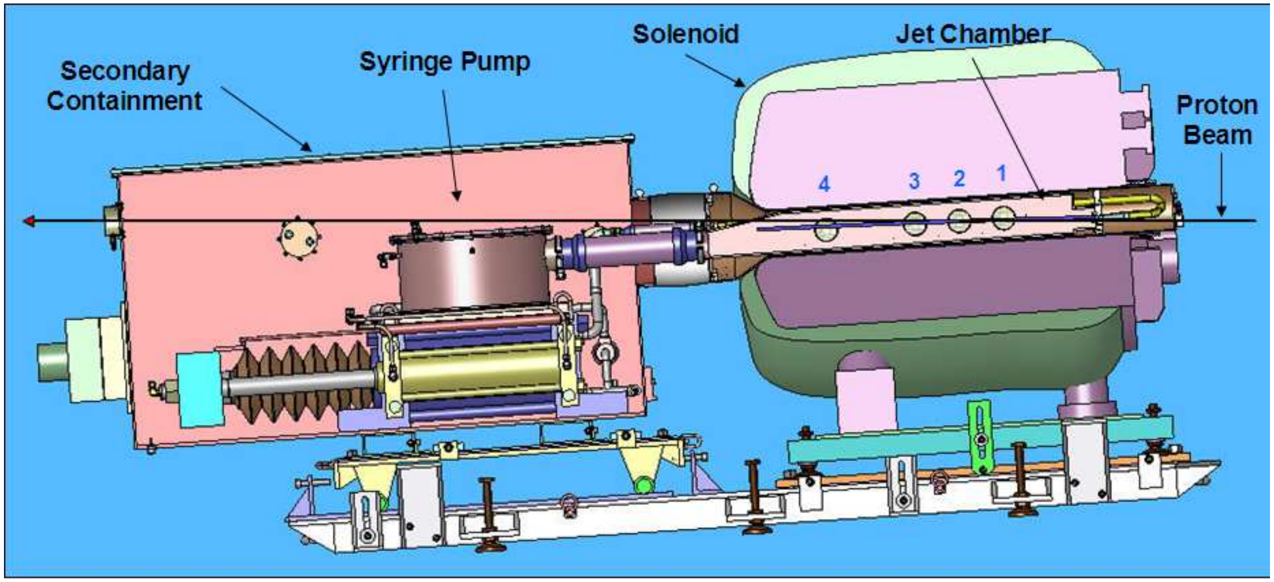
- FNAL Project X
  - 8 GeV H^- linac,
  - Accumulation (in the Re-cycler ?)
  - Acceleration to 56 GeV in the Main Injector
- Do it all at 8 GeV
  - Serious space charge
  - Requires very large acceptance accumulator
- Lower Energy Linac (2-4 GeV)
  - e.g. SPL
  - Plus synchrotron e.g. PS2

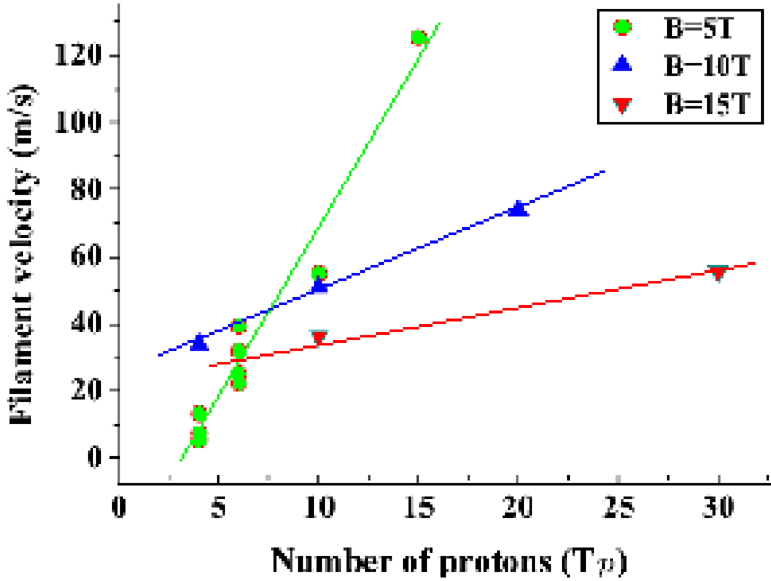
Target & Capture



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

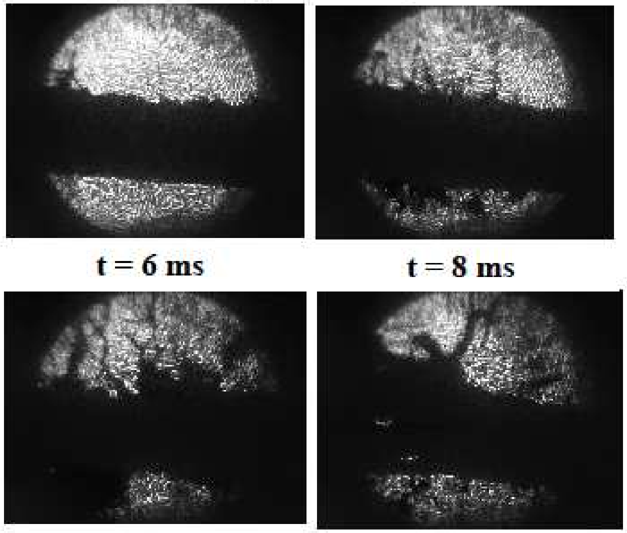
MERIT Experiment at CERN





- 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

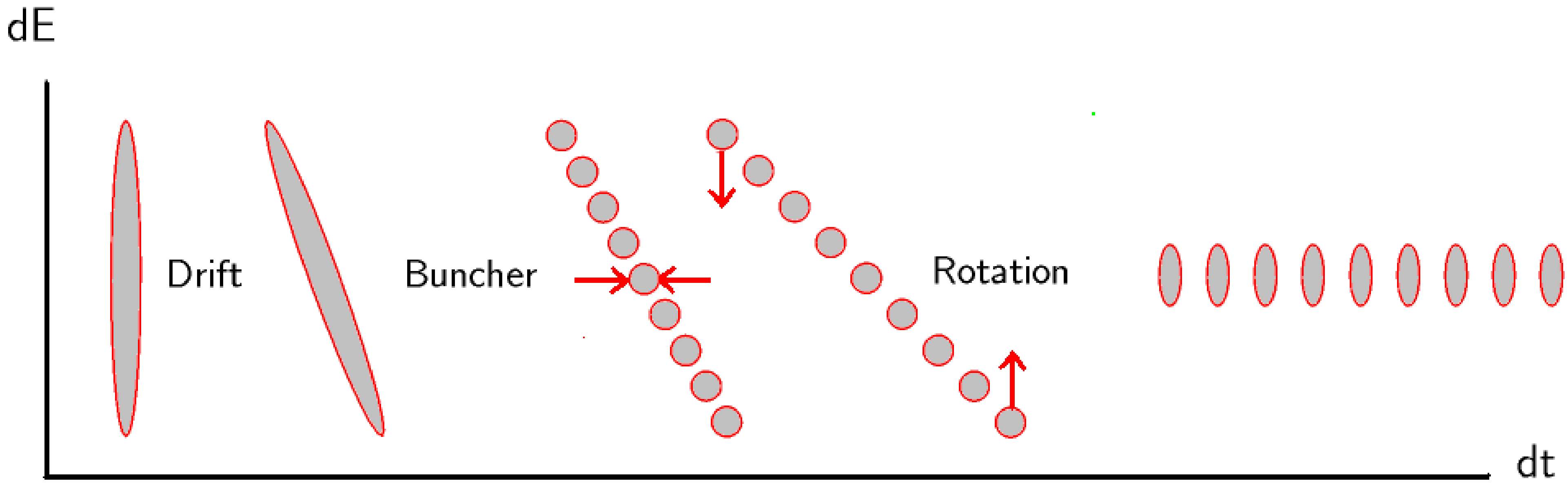


t = 6 ms   t = 8 ms

t = 10 ms   t = 14 ms

Phase Rotation

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

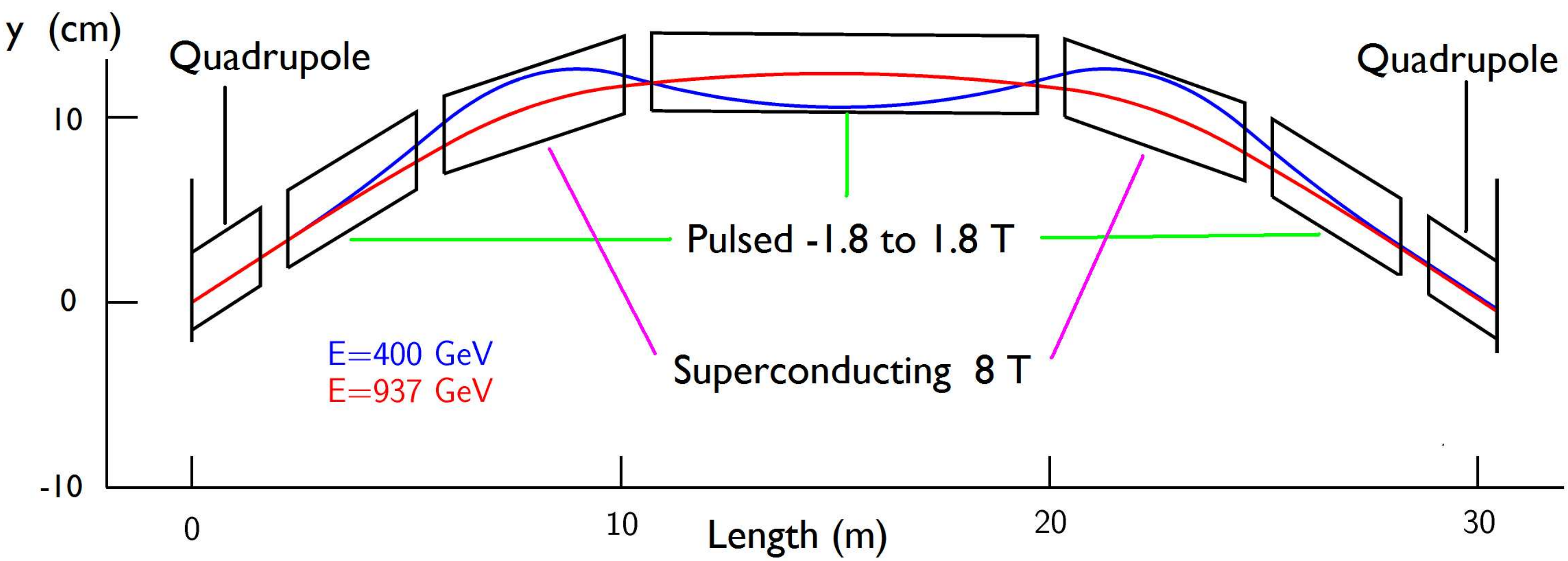


- Frequencies of bunching and rotation must change as function of drift

- Alternative system rotates first with induction linacs, then bunches
- But induction linacs are expensive

Acceleration

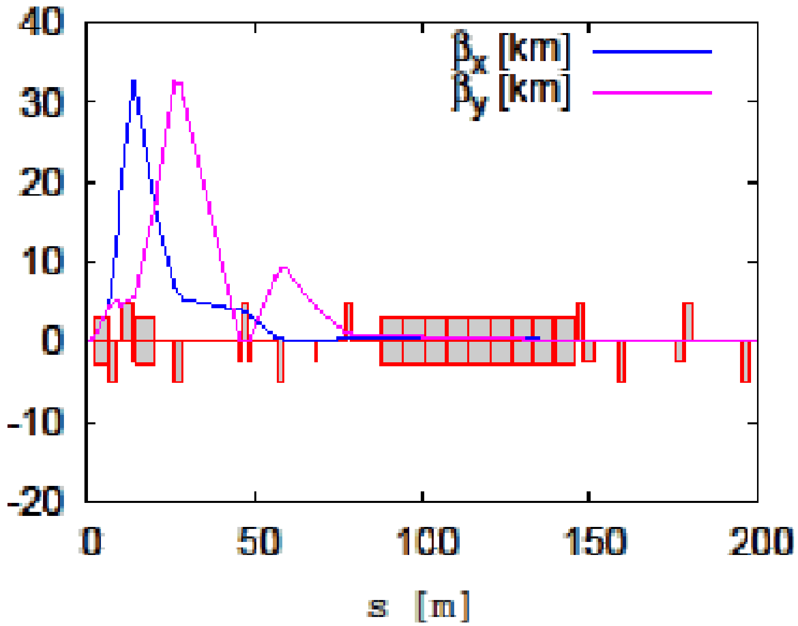
- Easy with Recirculating linear accelerators (RLAs)
  Using ILC-like 1.3 GHz rf
- Lower cost solution would use Pulsed Synchrotrons
  - Pulsed synchrotron 30 to 400 GeV (in Tevatron tunnel)
  - SC & pulsed magnet synchrotron 400-900 GeV (in Tevatron tunnel)
  - SC & pulsed magnet synchrotron 900-2000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

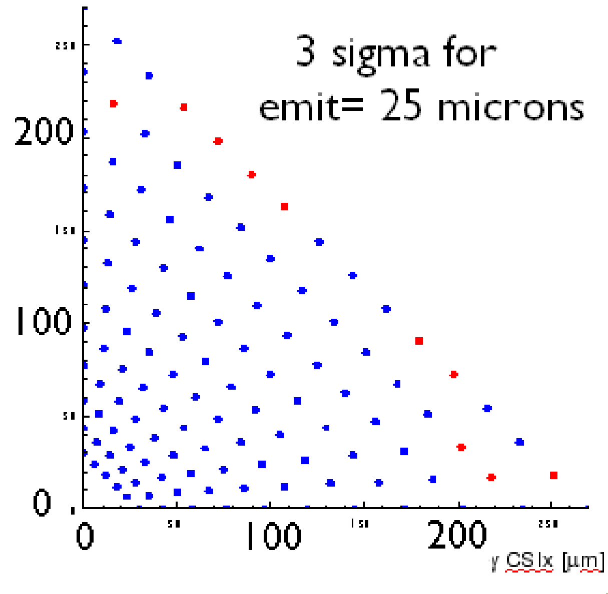


- Pulsed dipoles first oppose, and later support the bending form 8 T superconducting magnets

Collider Rings

- 1.5 TeV (c of m) Design (Gianfelice, Alexahin)



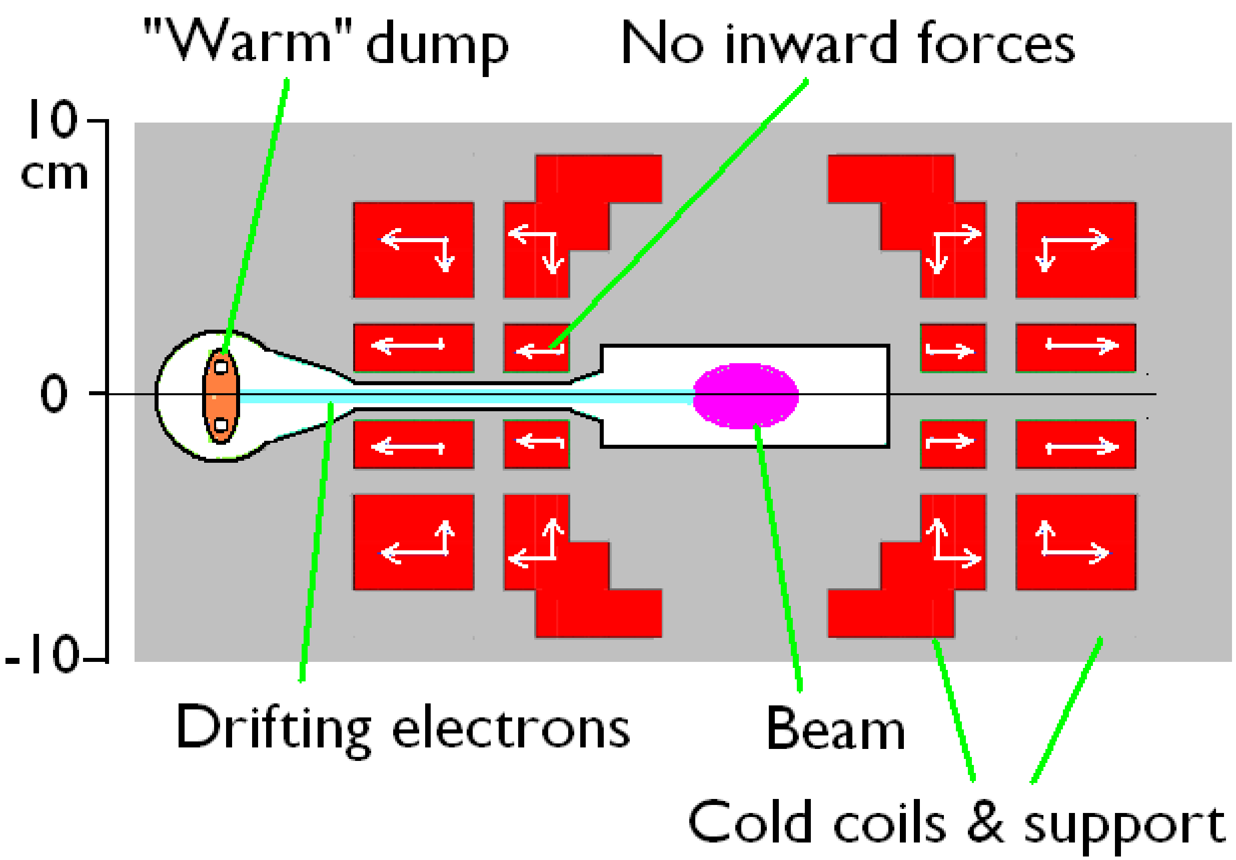


  - Meets requirements
  - But early dipole may deflect unacceptable background into detector

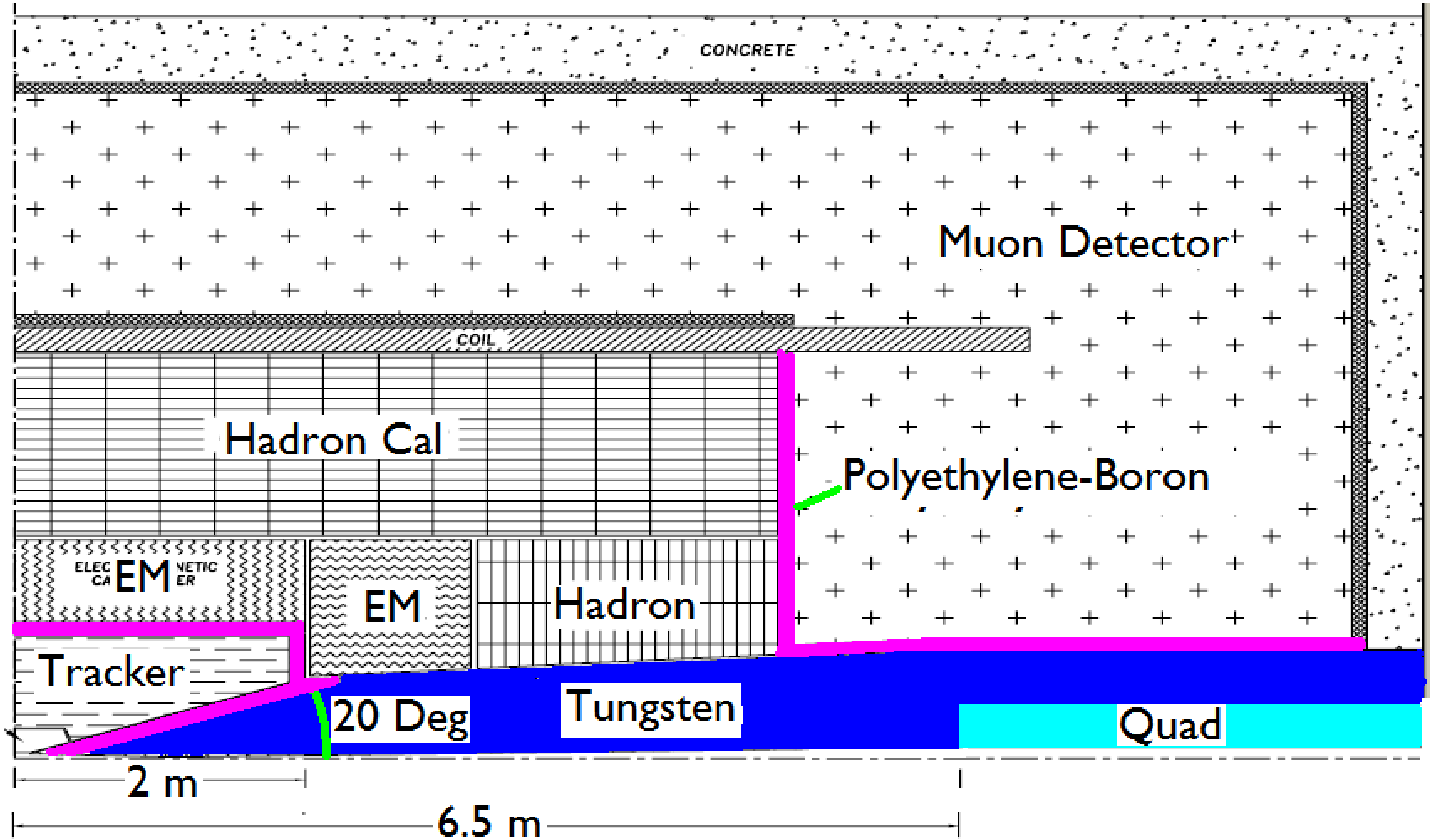
- 4 TeV (c of m) 1996 design by Oide had 3 mm β^*
  - Meets requirements in ideal simulation
  - But is too sensitive to errors to be realistic
  - 10 mm (used here) should be possible

Collider Ring Dipole Magnets

- Luminosity $\propto$ 1/circumference $\propto < B >$
  So very high field dipoles desirable
- 1/3 of beam energy (3-6 MW) to decay electrons
- 15 T HTS Open Mid-plane dipole (Gupta) is good option



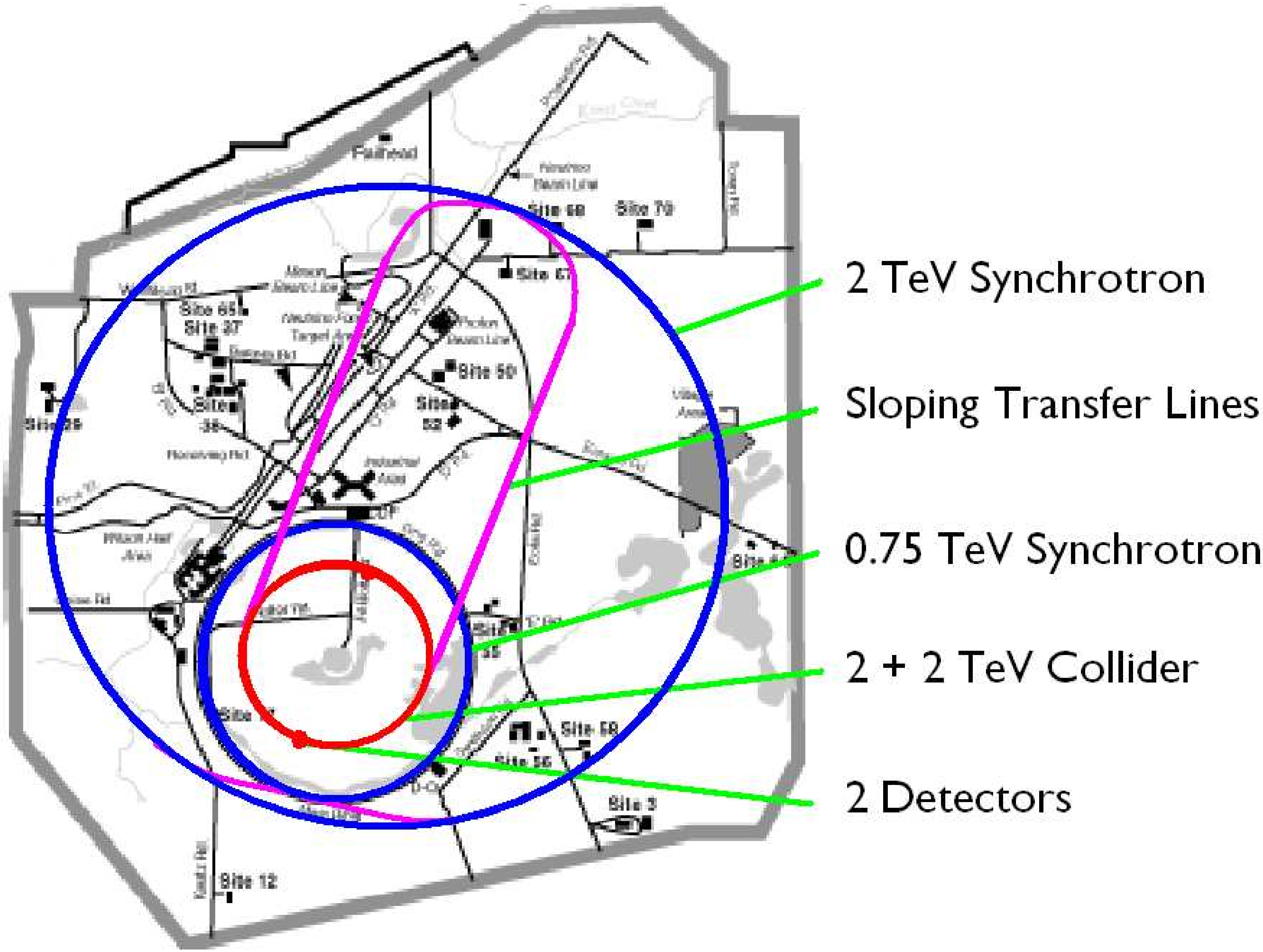
Detector From 1996 Study of 4 TeV Collider



- Sophisticated shielding designed in 1996 4 TeV Study (Stumer, Mokhov)
- GEANT simulations then indicated acceptable backgrounds
- But tungsten shielding takes up 20 degree cone

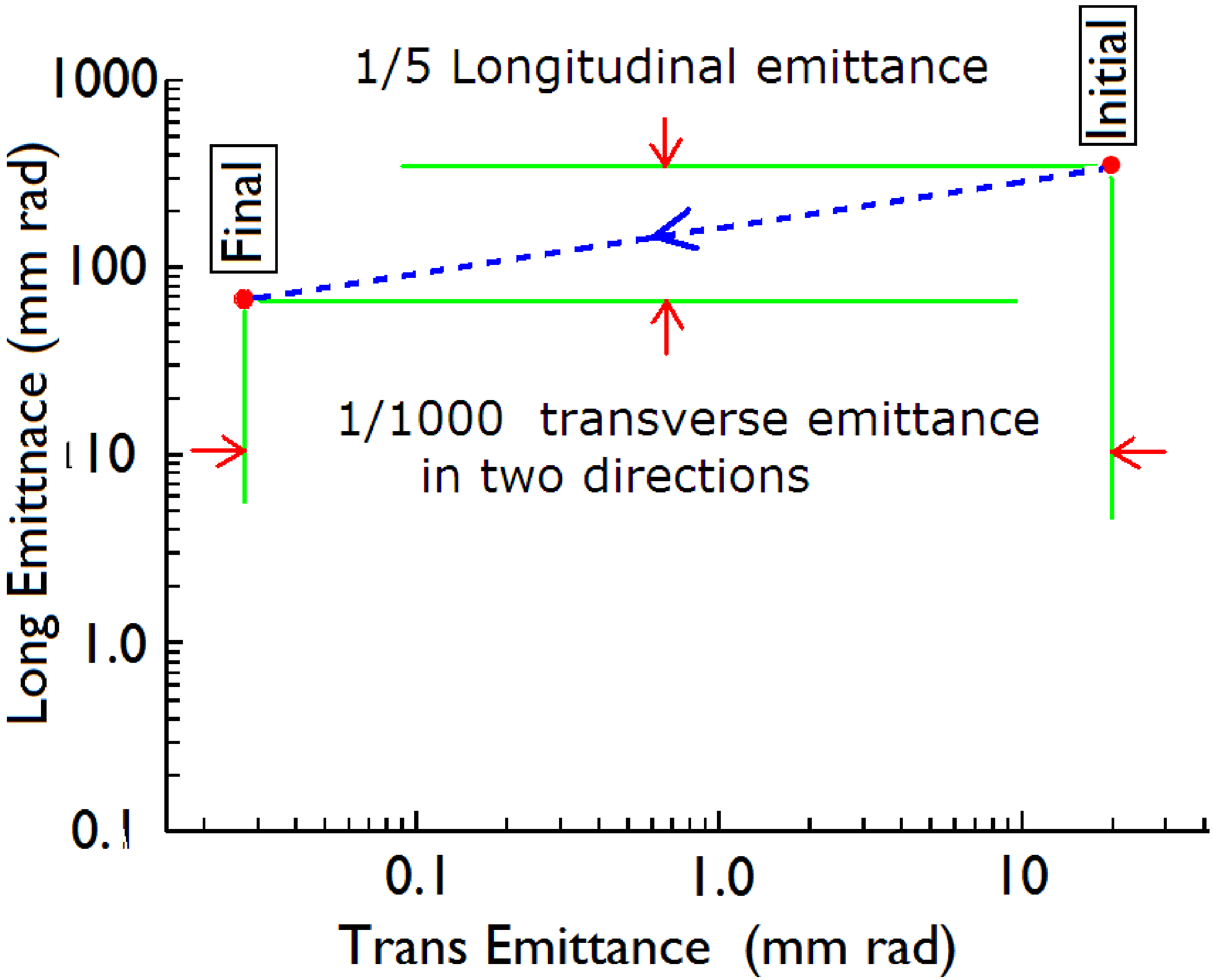
- Smaller angle should be possible now with finer pixel detectors

Layout of 4 TeV Collider using pulsed synchrotrons



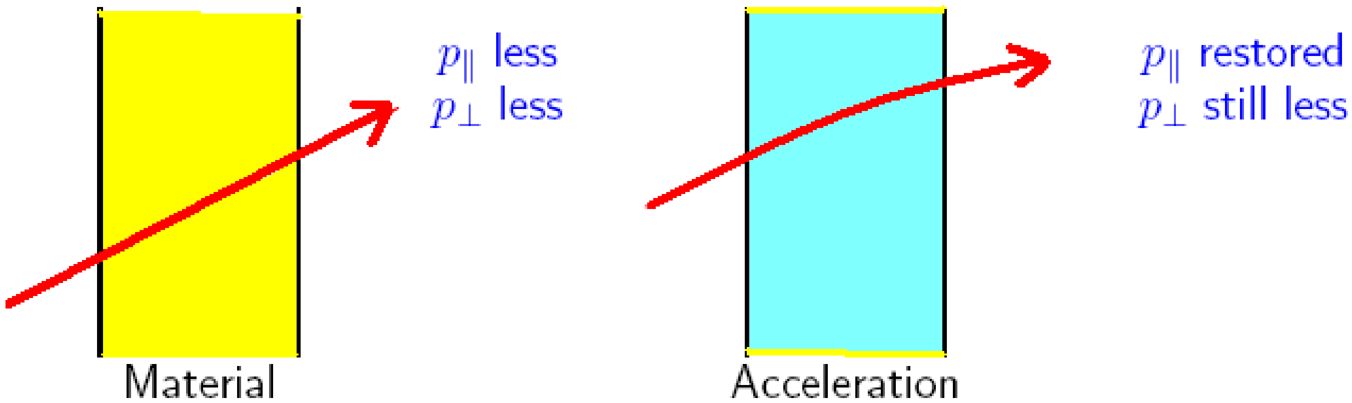
THE HARD PART

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



- Cooling by ionization loss
- Heating by Coulomb scattering
- Gives minimum Emittance:

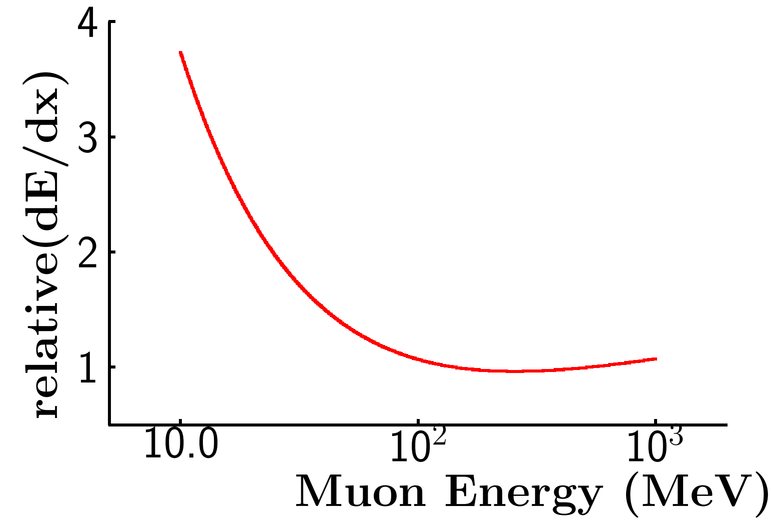
$$\epsilon_{x,y}(min) = \frac{\beta_\perp}{\beta_v} C(mat,E)$$

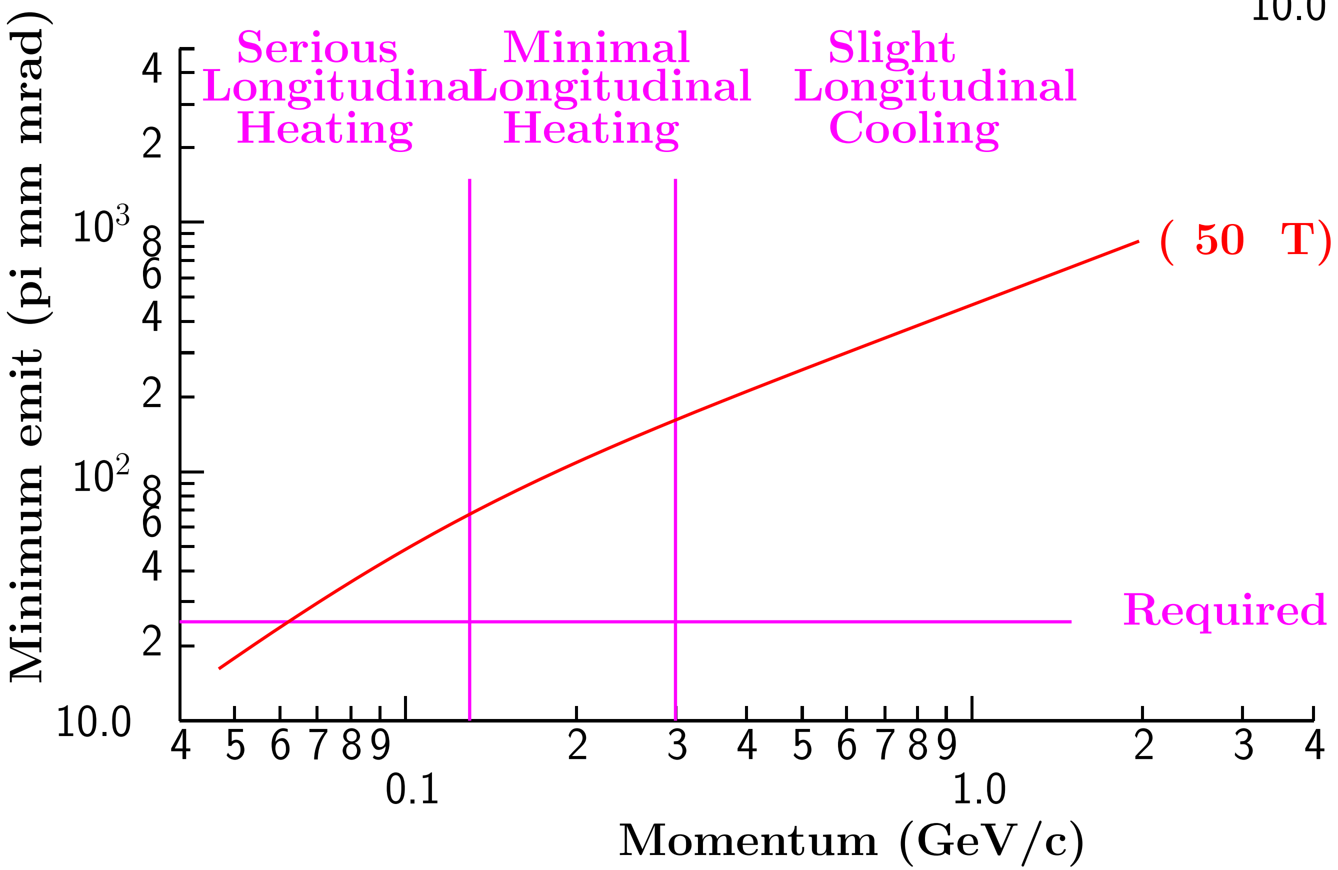
$$\propto \frac{C(mat,E)}{\beta_v \; B_z}$$

- $C(mat,E)$ least for hydrogen
- Falls with Energy as dE/dx rises

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)



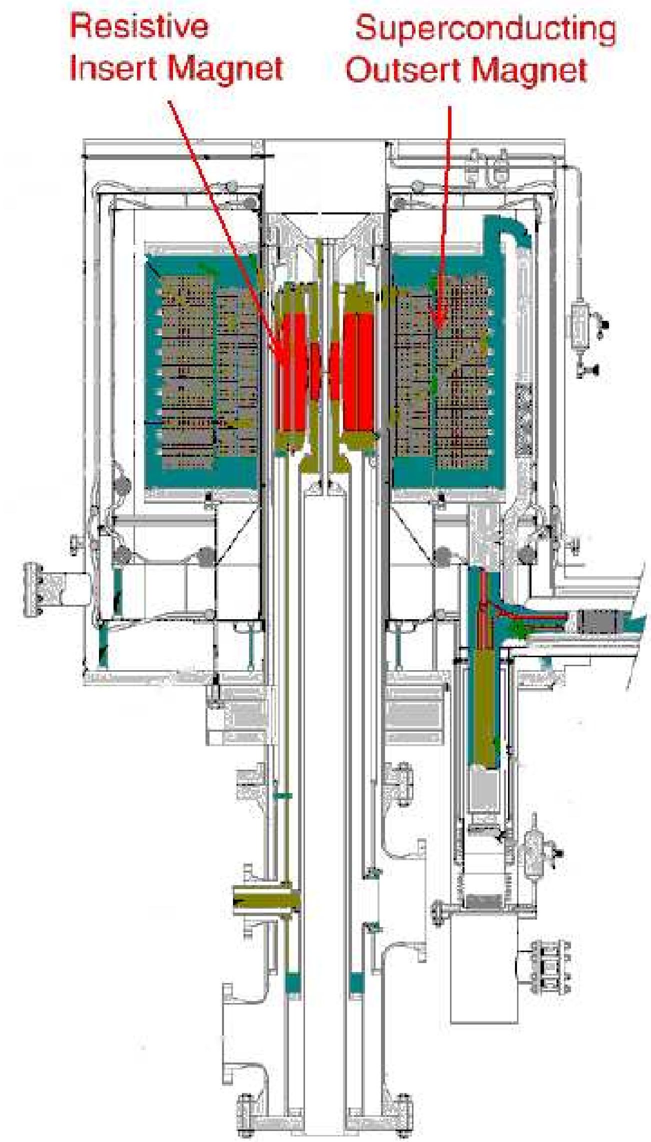


- Transverse emittance achieved, but Longitudinal emittance is increasing rapidly

Is 50 T Realistic ?

- 45 T hybrid at NHMFL, but uses 25W

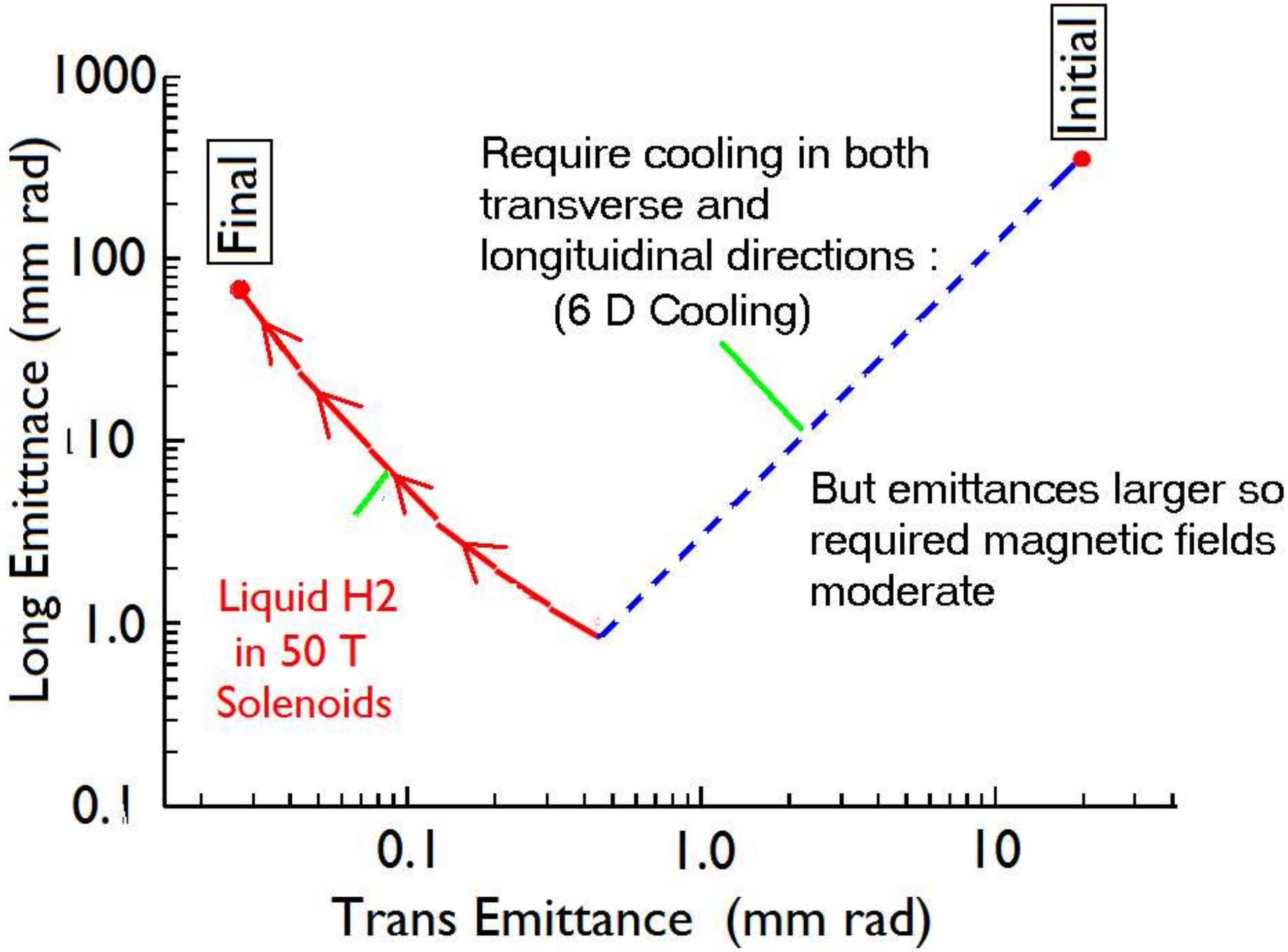
- HTS critical fields ≈ 100 T
- HTS current densities ≈ j_{Cu}
- 50 T HTS solenoids seem possible
- Design under study at NHMFL



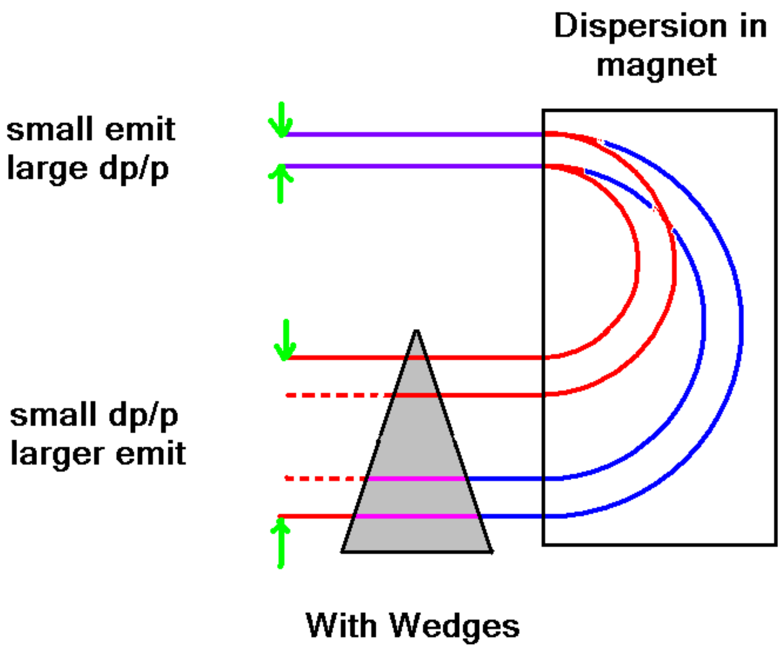
NHMFL 45 T Hybrid Magnet

50 T Cooling Simulation (In ICOOL R.Fernow)

Using six 50 T coils



Trans cooling + Emittance Exchange = 6D Cooling



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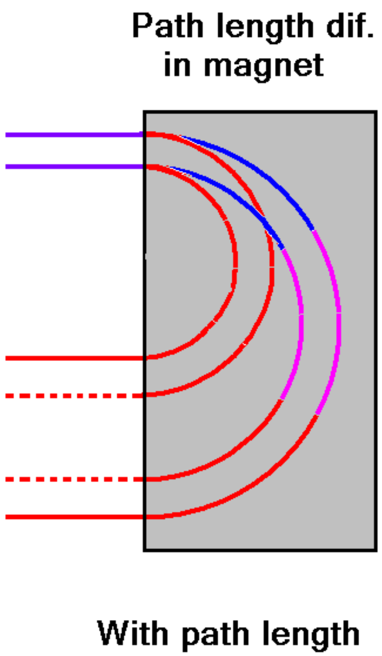


dp/p reduced
But σ_y increased

Long Emit reduced
Trans Emit Increased

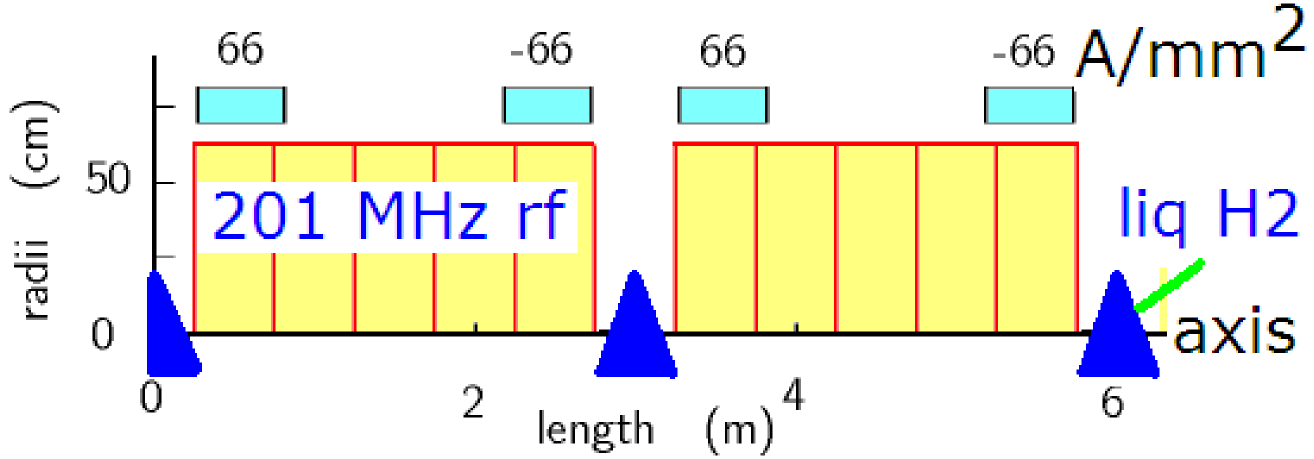
= Emittance Exchange

Need lattices with:

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

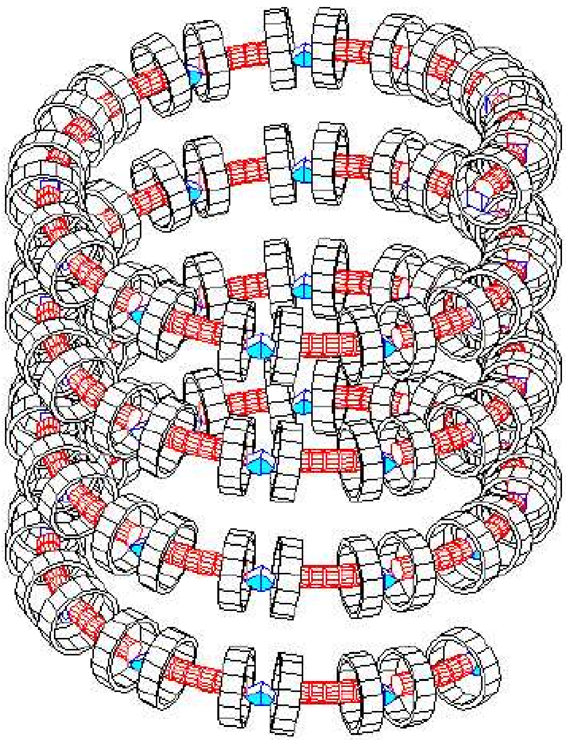
Super-FOFO Lattices (Andy Sessler)

Lattice without bending



Bending added

to generate dispersion for 6D-cooling
Guggenheim geometry

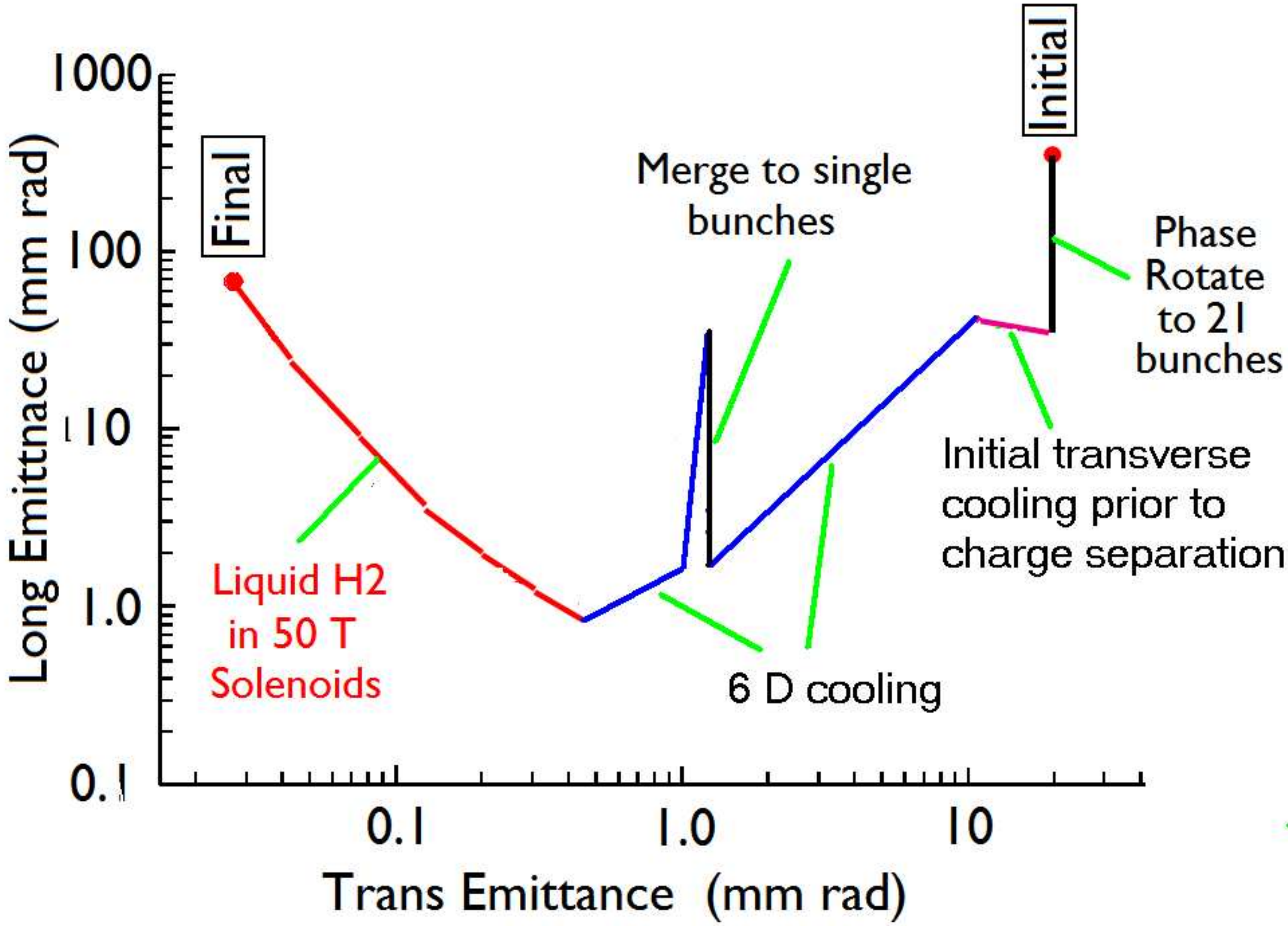


Parameters

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

Slight complications: Pre-cooling & Bunch merging

- Phase rotation made 15 bunches of each sign
  We require only one of each sign
- Charges must be separated for 6 D cooling
  Pre cooling assumed to facilitate this

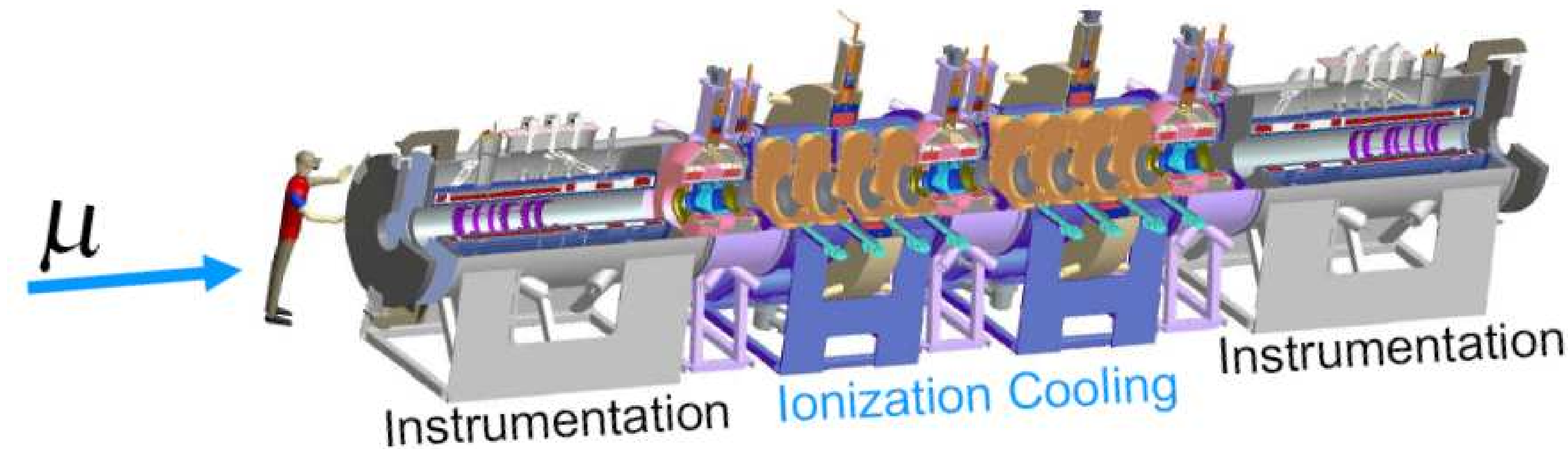


All simulated (at some level) assuming working rf in focusing magnetic fields

Muon Ionization Cooling Experiment (MICE)

International collaboration at RAL, US, UK, Japan (Blondel)

- 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

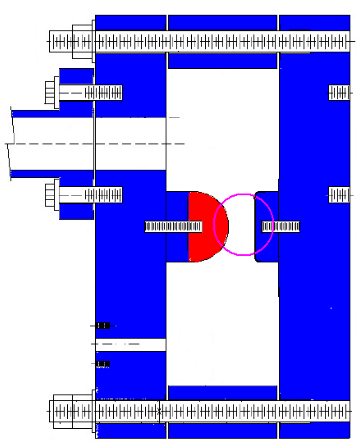


- Allows early test of emittance exchange without re-acceleration
- Later phase might test emittance exchange with re-acceleration

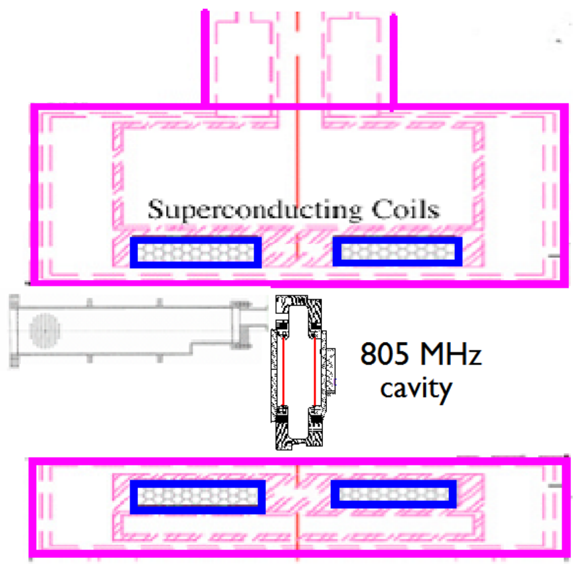
MuCool, and MuCool Test Area (MTA) at FNAL

International collaboration US, UK, Japan (Bross)

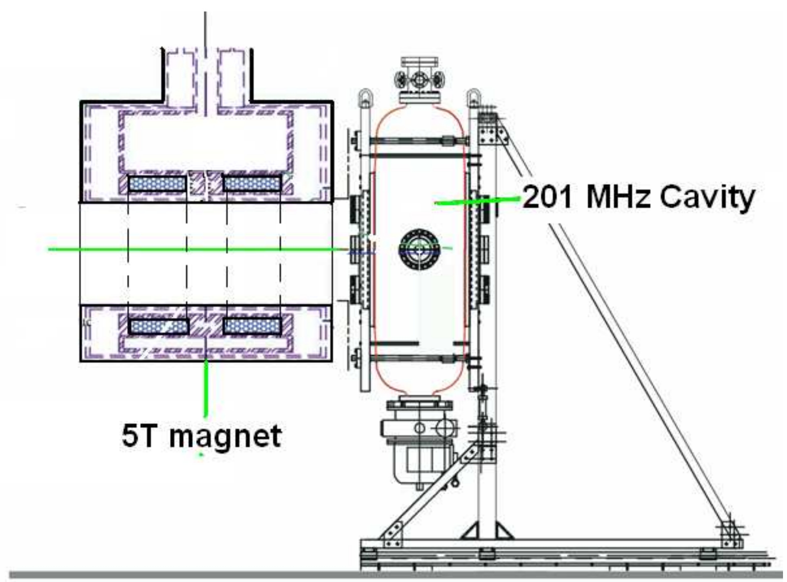
- Liquid hydrogen absorber tested
- Open & pillbox 805 MHz cavities in magnetic fields to 4 T
- 201 MHz cavity tested to magnetic field of 0.7 T
  Later to 2T
- High pressure H2 gas 805 MHz pillbox cavity tested
- Soon: 805 MHz gas Cavity with proton beam



HP Gas cavity



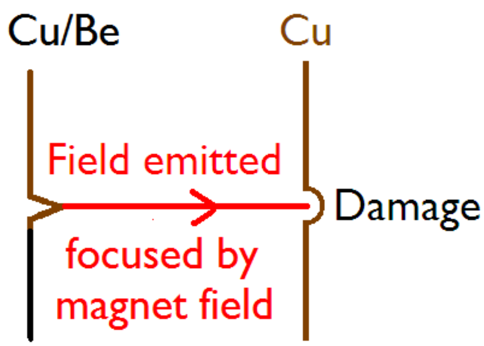
805 MHz in 4 T magnet

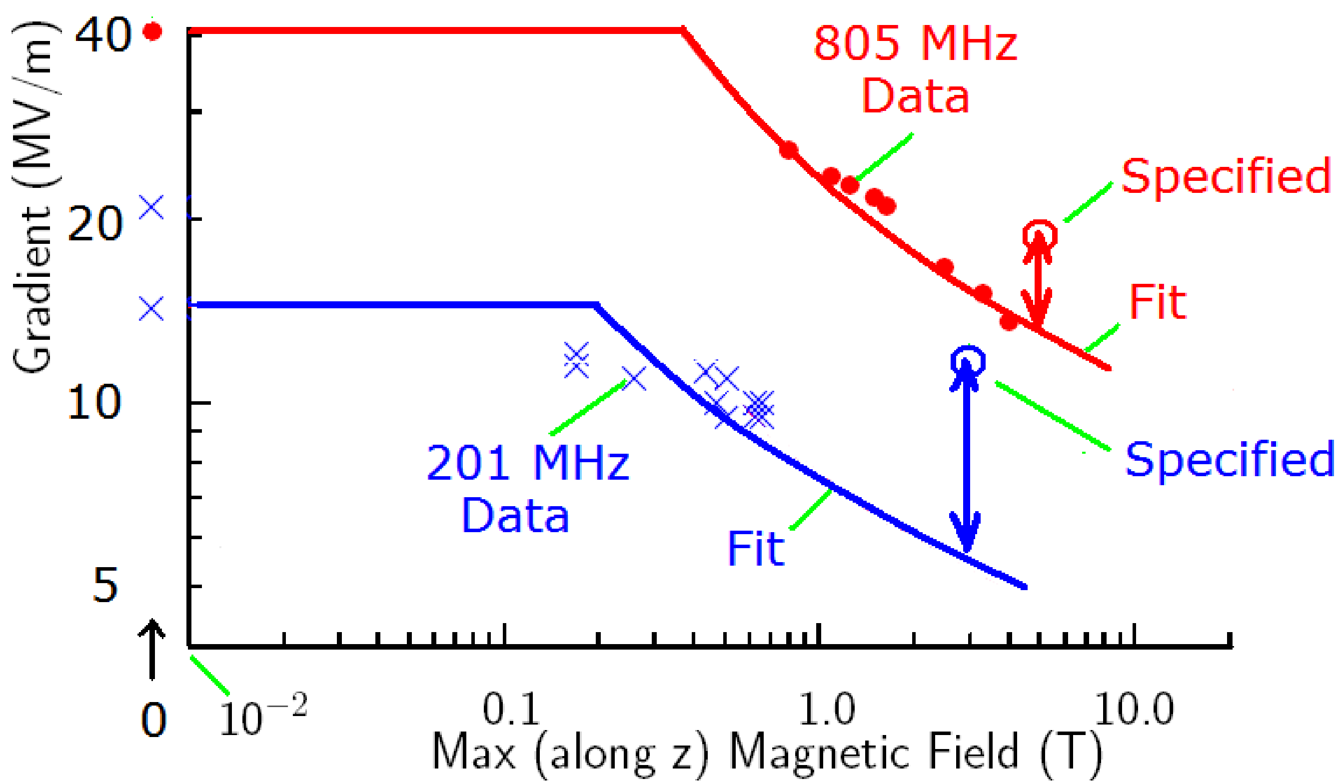


201 MHz next to magnet

Experiments show breakdown in specified mag fields

Fits from proposed explanation (Palmer Gallardo Stratakis)





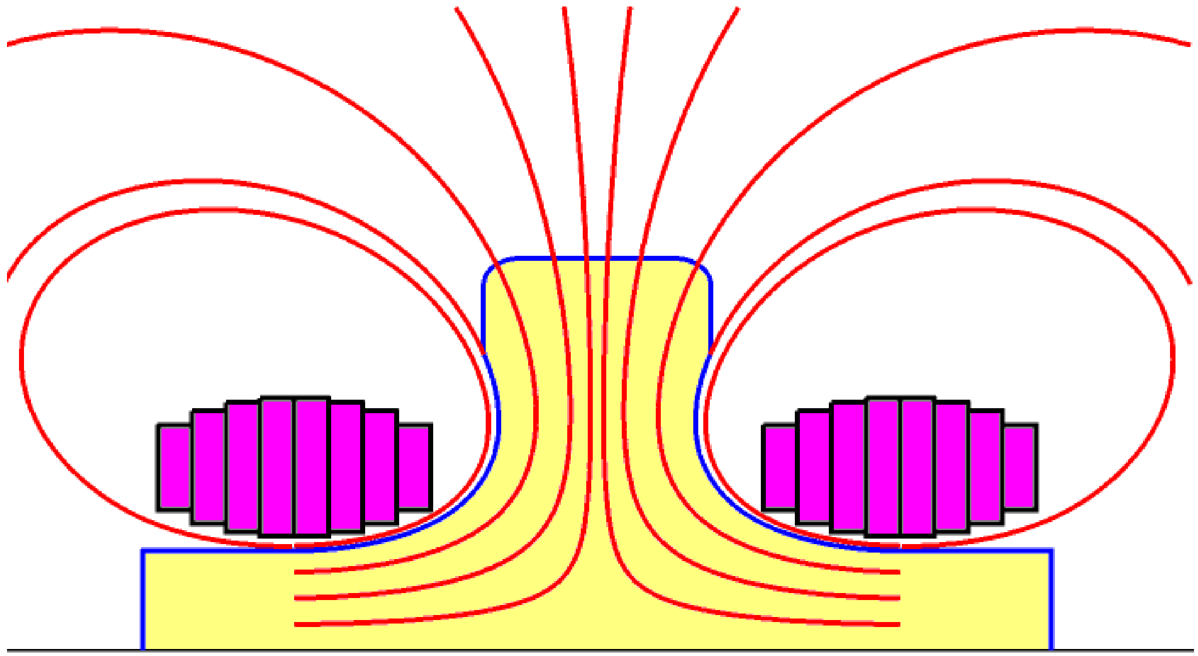
Possible solutions

- Magnetic Insulation
- High pressure hydrogen gas

Possible Fix 1) Magnetic Insulation (Palmer)

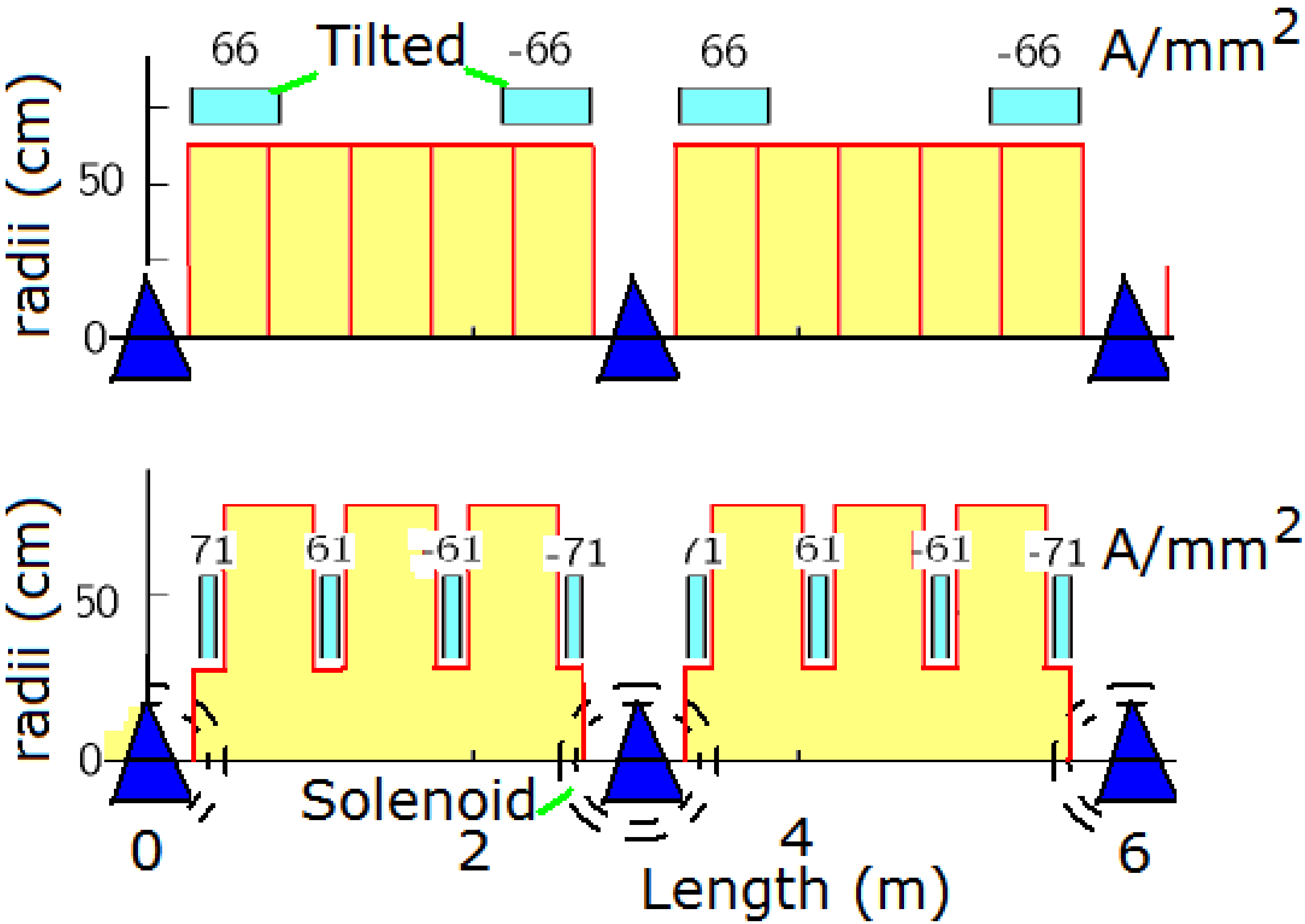
- If magnetic field lines are parallel to an emitting surface
- All field emitted electrons will return to the surface with low energies and do no damage

Form cavity surface to follow magnetic field lines



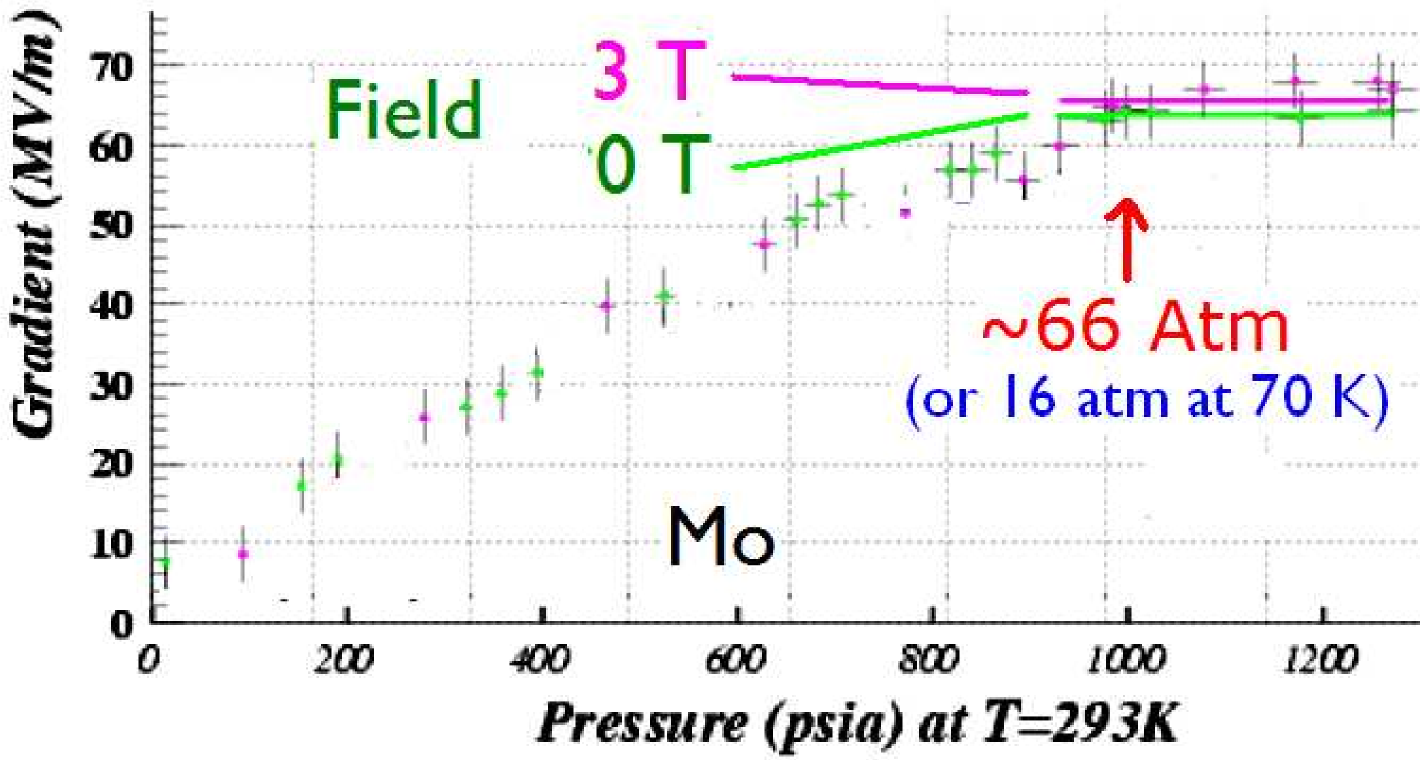
- No dark current, No X-Rays !
- No danger of damaging surfaces
- But secondary emission → problems ? (Li SLAC)

Incorporation of Magnetic Insulation in lattices



Particle losses increased - need to understand why

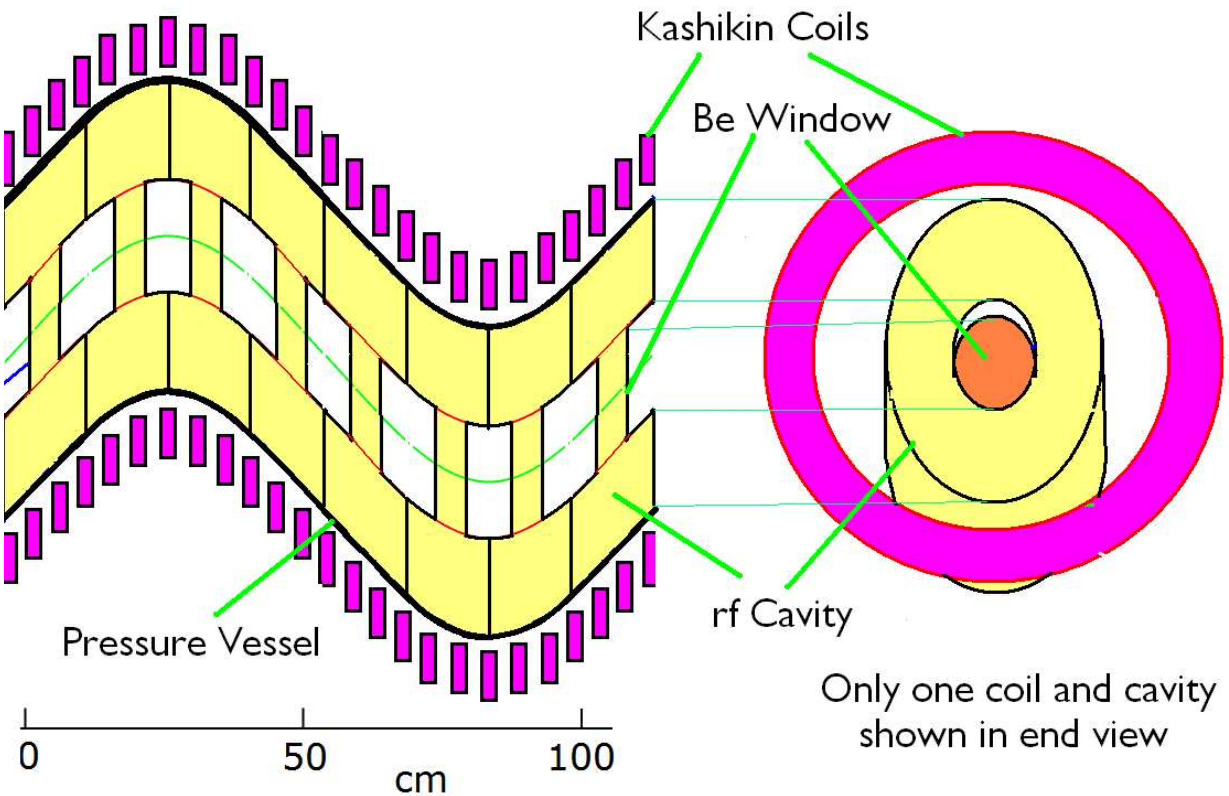
Possible Fix 2) High Pressure Gas (Johnson)



- High pressure hydrogen gas suppresses breakdown
- And can be used as primary absorber
- Lattices must have low beta 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)



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

- Engineering and safety are a concern
- Possible problem of rf breakdown or rf loss with intense muon beam transit
- Experiment with p beam soon at FNAL

Current Organizations

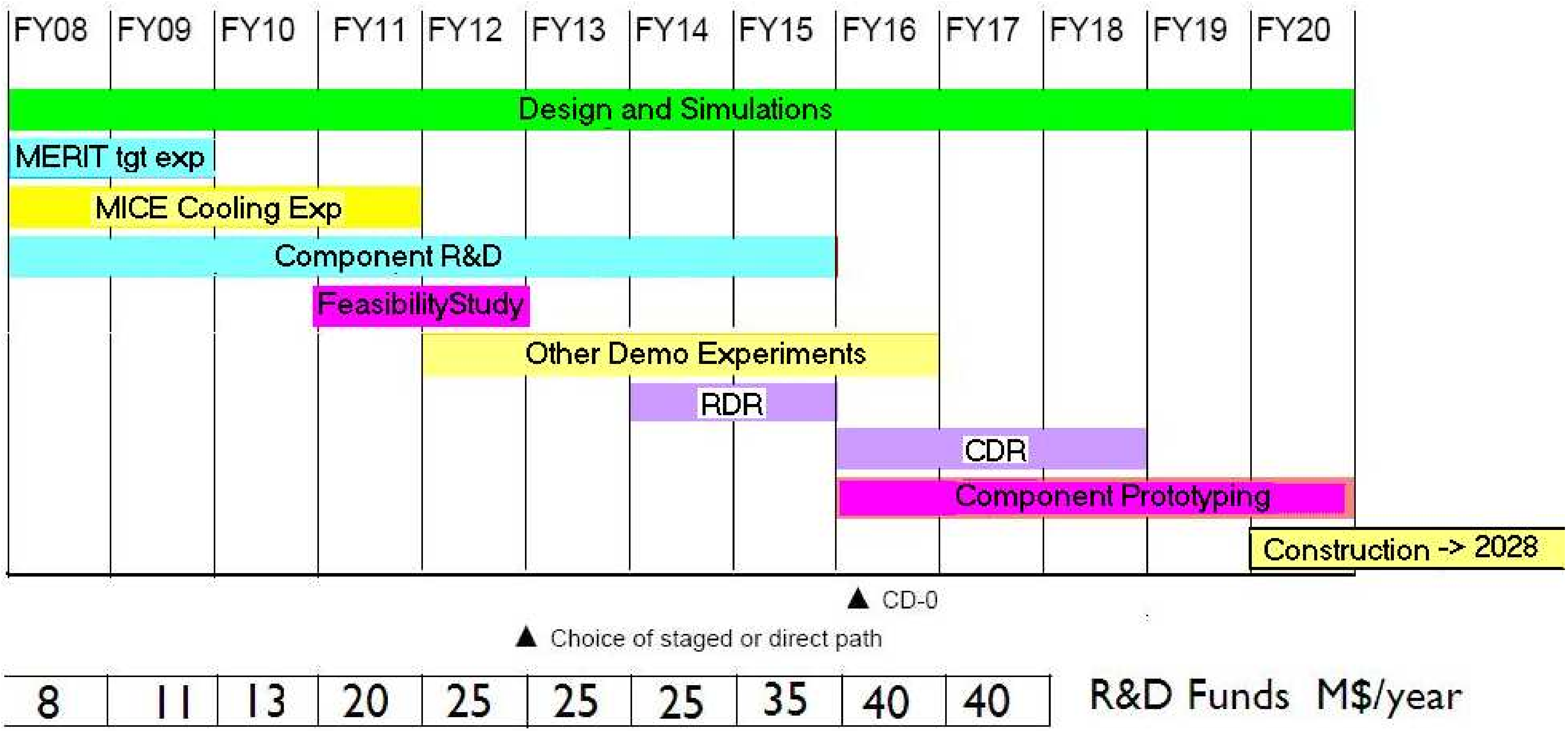
- Neutrino Factory and Muon Collider Collaboration (NFMCC)
  - US Labs and Universities (Founded in 1997)
  - 2 spokespersons (Bross, Kirk) and Project manager (Zisman)
  - Funded primarily by DoE
- Muon Collider Task Force
  - Set up by FNAL Director in 2007
  - Coordinated with NFMCC
- Total current effort $\approx$ 8 M$/year

R&D Needed to establish "feasibility"

- Demonstrate mercury jet target (essentially done by MERIT)
- Demonstrate ionization cooling (should be done by MICE)
- Solve rf Breakdown problem
- Achieve, as nearly as possible, an end to end simulation
- Get a first estimate of cost

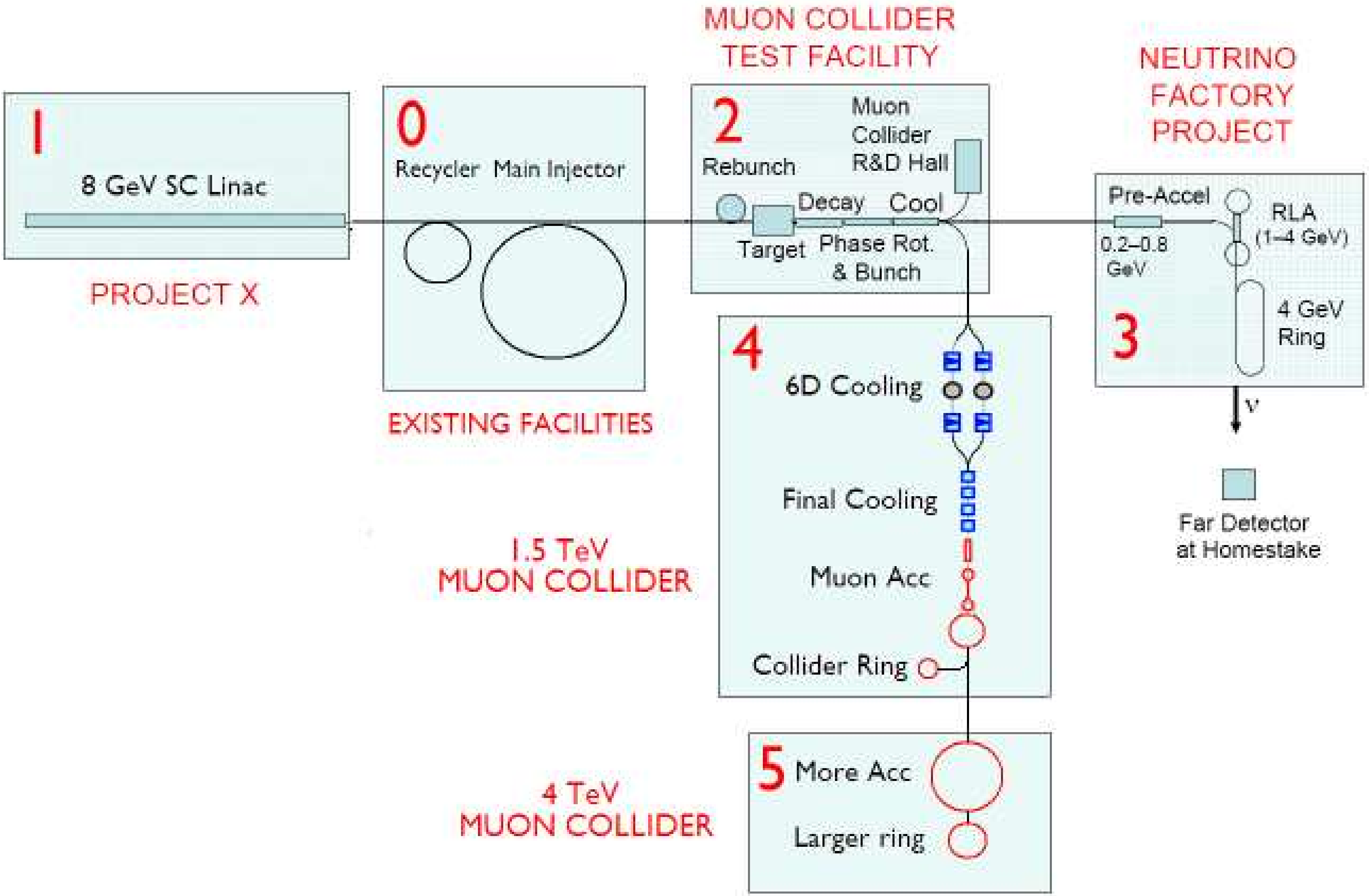
Desired time to establish "feasibility" : 2012

Time Line and Funding Needs (as presented to P5)



- Funding request includes that for Neutrino Factory R&D
- Funding increase ($\approx 3\times$) needed if Muon Collider is to be credible option by 2012

A Phased Approach (as presented to P5)



Conclusion (as presented to P5)

- A broad and significant R&D program is already underway
- With an expanded program, we expect to be able to complete a "Feasibility Study" by 2012, that would
  - Establish the feasibility of a Muon Collider
  - Greatly narrow the technology options
  - Include, as near as possible, an end-end simulation, and
  - Give a first rough cost estimates for two energies
- A Muon Collider could then be part of a phased program:
  - Project X
  - Muon Collider R&D area
  - Neutrino Factory
  - 1.5 TeV collider
  - 4 TEV collider
- But for a Muon Collider to be a realistic option in 2012, increased funding for R&D is needed

Appendices

- Luminosity dependence
- Neutrino radiation
- Open mid-plane ring dipole
- Transmission
- Pulsed synchrotron details

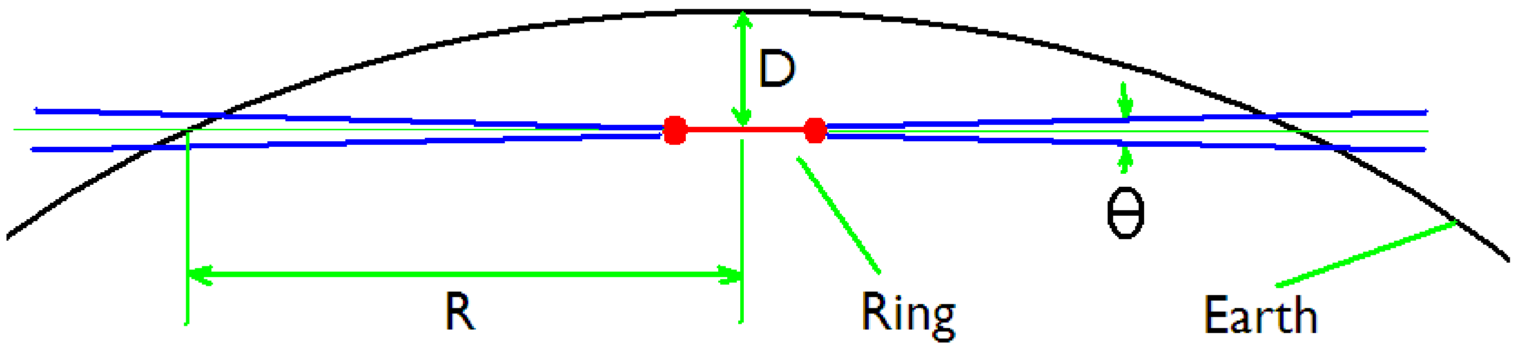
Luminosity Dependence

$$\mathcal{L} \;=\; n_{\text{turns}}\; f_{\text{bunch}}\; \frac{N_\mu^2}{4\pi\sigma_\perp^2} \qquad\qquad \Delta\nu \propto \frac{N_\mu}{\epsilon_\perp}$$

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

- Higher $\mathcal{L}/P_{\text{beam}}$ requires lower β^* or correction of $\Delta\nu$
- Lower emittances do not directly improve Luminosity/Power
- But for fixed $\Delta\nu$, $\epsilon_\perp$ must be pretty small to avoid N_μ becoming unreasonable

Neutrino Radiation Constraint



$$\text{Radiation} \propto \frac{E_\mu\ I_\mu\ \sigma_\nu}{\theta\ R^2} \propto \frac{I_\mu\ \gamma^3}{D} \propto \frac{\mathcal{L}\ \beta_\perp}{\Delta\nu\ \ < \mathrm{B} >}\ \frac{\gamma^2}{D}$$

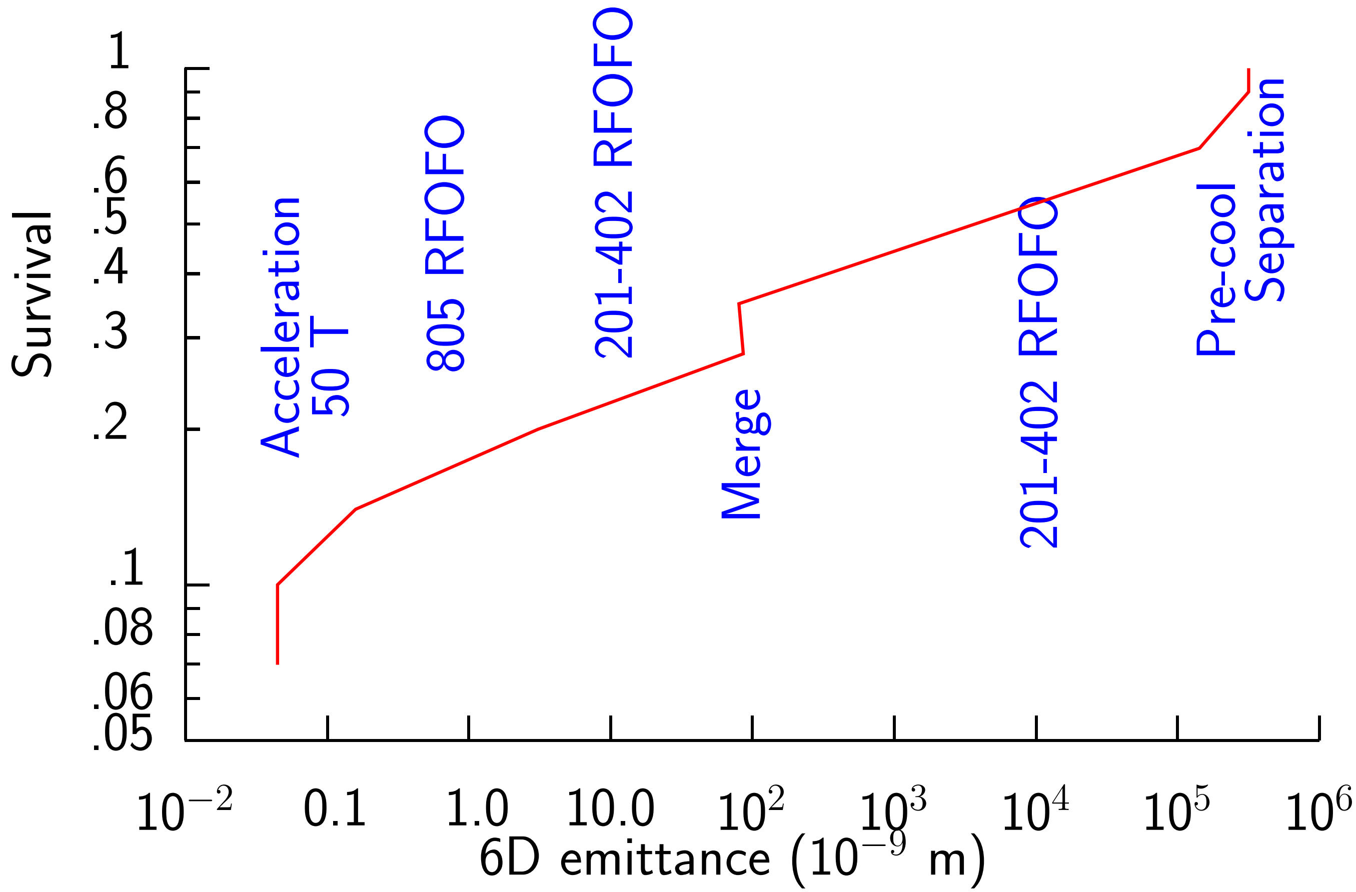
For fixed $\Delta\nu$, $\beta_\perp$ and $< B >$; and $\mathcal{L} \propto \gamma^2$:

$$\text{Radiation} \propto \frac{\beta_\perp}{\Delta\nu\ \ < B >\ \ D}\ \gamma^4$$

For D=135 m R=40 Km for 4 TeV
For D=540 m R=80 Km for 8 TeV
OK up to 8 TeV, but a problem higher

Muon Transmission

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 ($P \propto N^{-2}$)

Pulsed Synchrotron Details

- Both rings have lattices similar to Tevatron and fit in the Tevatron Tunnel
- For 30-400 GeV
  - Ramped quadrupoles 2.2 to 30 T/m in 0.57 msec (400 Hz)
  - Ramped dipoles -0.13 T to 1.8 T in 0.59 msec (400 Hz)
  - 13 GV of superconduction 1.3 GHz rf
  - muon Survival 80%
- For 400-750(937) GeV
  - Longer ramped quads 13 T/m to 30 T/m in 0.92 msec (150 Hz) quads
  - Fixed 8 T dipoles, alternating with
  - Ramped dipoles -1.8 T to 1.8 T in 0.92 msec (550 Hz)
  - Dipoles initially opposed, then act in unison
  - 8 GV of superconduction 1.3 GHz rf
- Magnet details
  - Pulsed magnets use .28 mm grain oriented Si steel ok at 1.8 T
  - Cables of multiple insulated 2 mm wires
  - OK single turn Voltage 3100 V
  - Losses in the yoke steel (520+910=1430 kW total at 13 Hz)
- rf details
  - 36 10 MW klystrons ? (this number for 3 Hz, not 13 Hz)
  - 3 cells per coupler
  - 5 MW to modulators, 1 MW to cryogenics
  - Loading is 8%: wakefields and HOM need study