Muon Colliders

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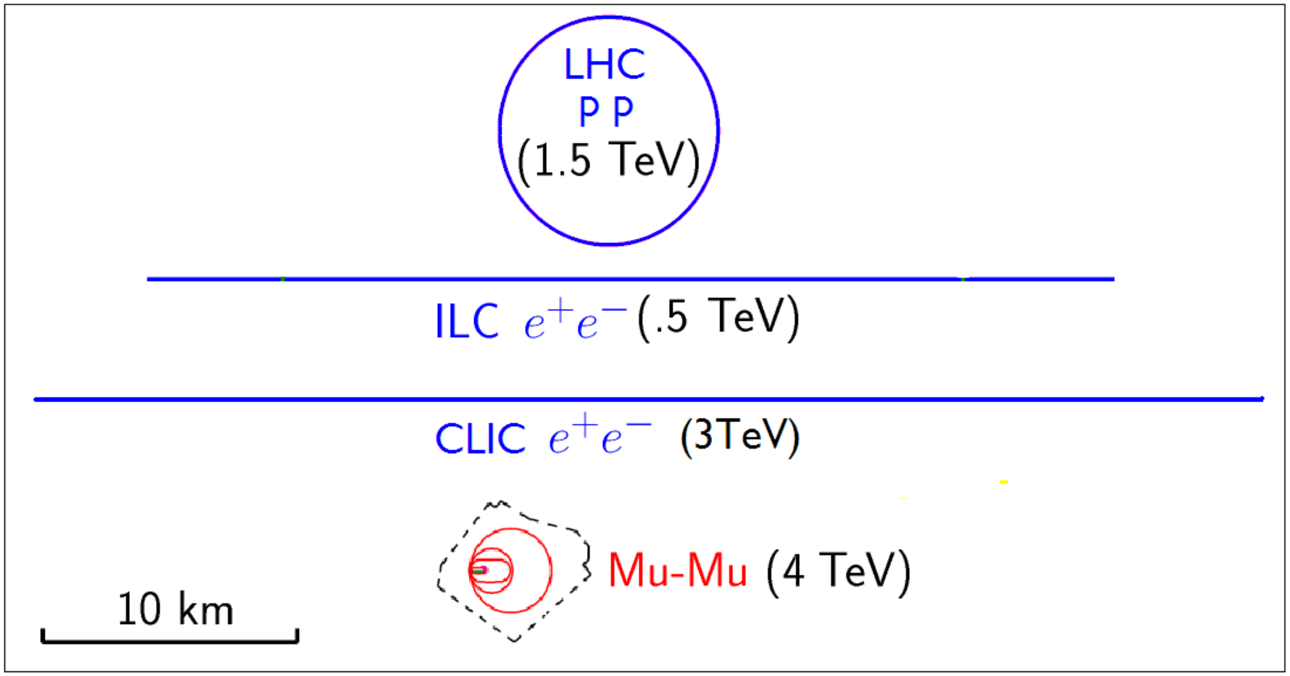
I would like to convince you that:

- A broad R&D program is underway
- 1.5 - 4 TeV Muon Colliders are "Plausible"
- With appropriate R&D funding, a Feasibility Study* possible by 2012
- A muon Collider could be part of a phased program
- Funding is essential if this is to be a real option

* By a 'Feasibility Study' we mean a study similar to that carried out for the neutrino factory. i.e. a rather detailed conceptual design and a rough estimate of the cost of the facility

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



Activities

- Essentially all Neutrino Factory R&D is relevant to Muon Colliders
- Activities with overlapping memberships
  - Muon Collider Task Force (MCTF) at Fermilab
  - Neutrino Factory & Muon Collider Collaboration (NFMCC) of Labs and Universities
  - Cooling component development by the MuCool collaboration
  - 200 MHz Superconducting RF development at Cornell
  - Experiments MICE, MERIT, EMMA
  - SBIR funded companies Muons Inc, Tech-X, PBL
- US program reviewed by 'Muon Technical Advisory Committee' (MuTac) and coordinated by 'Coordinating Group'
- Funding comes from multiple sources:
  - DOE & NSF funding of the NFMCC ($\approx$ 4 M$/year)
  - DOE funds from FNAL to the MCTF ($\approx$ 4 M$/year)
  - From Non-US support of experiments ($\approx$ 6 M$/year)
  - From SBIR grants ($\approx$ 2 M$/year)

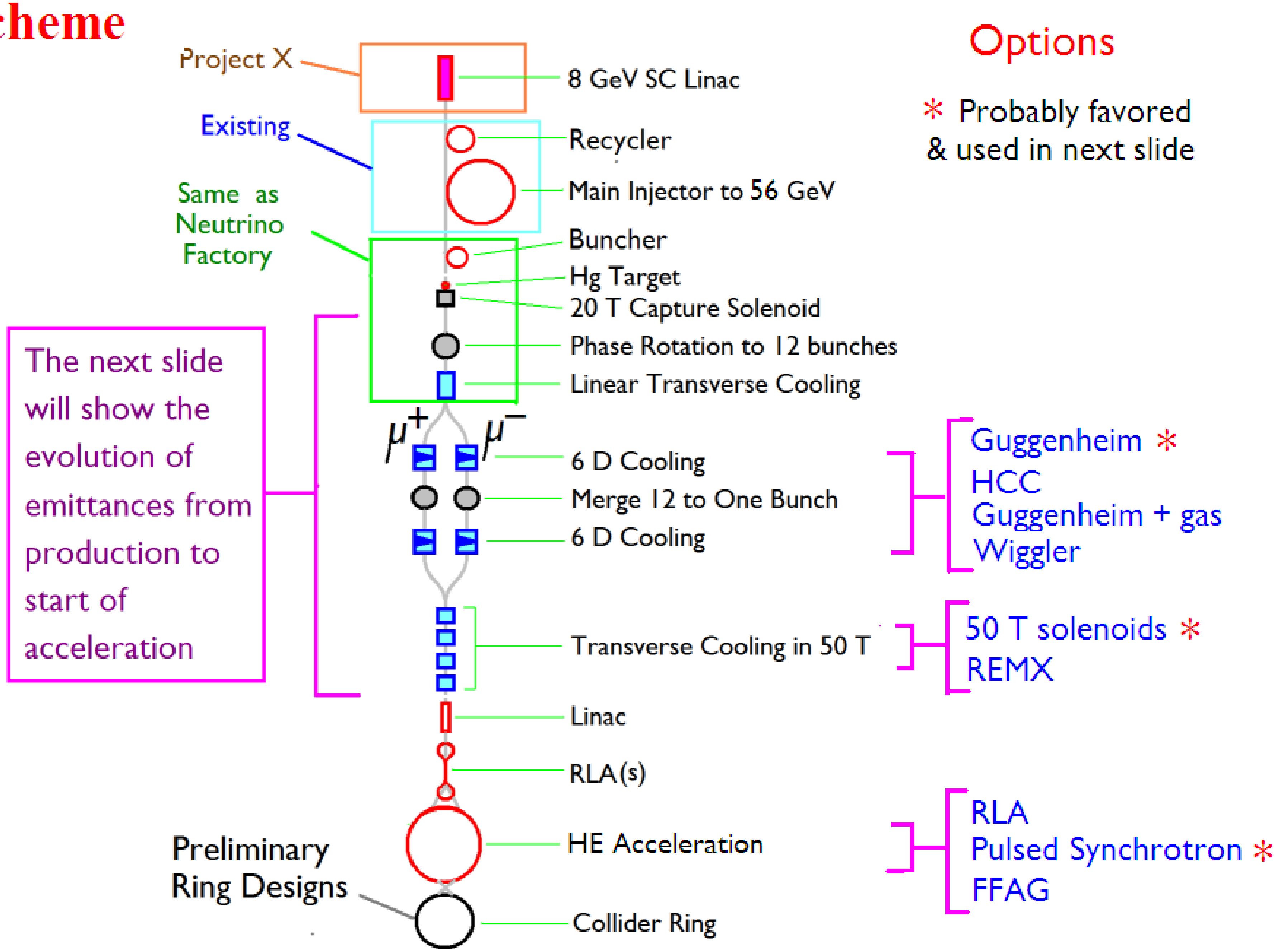
Collider Parameters

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	**≈4**	**≈ 1.8**	MW
Muon Trans Emittance	**25**	**25**	**pi mm mrad**
Muon Long Emittance	**72,000**	**72,000**	**pi mm mrad**

- Based on real Collider Ring designs, though both have problems
- Emittance and bunch intensity requirement same for all examples
- Luminosities are comparable to CLIC's
- Depth for ν radiation keeps off site dose $<$ 1 mrem/year

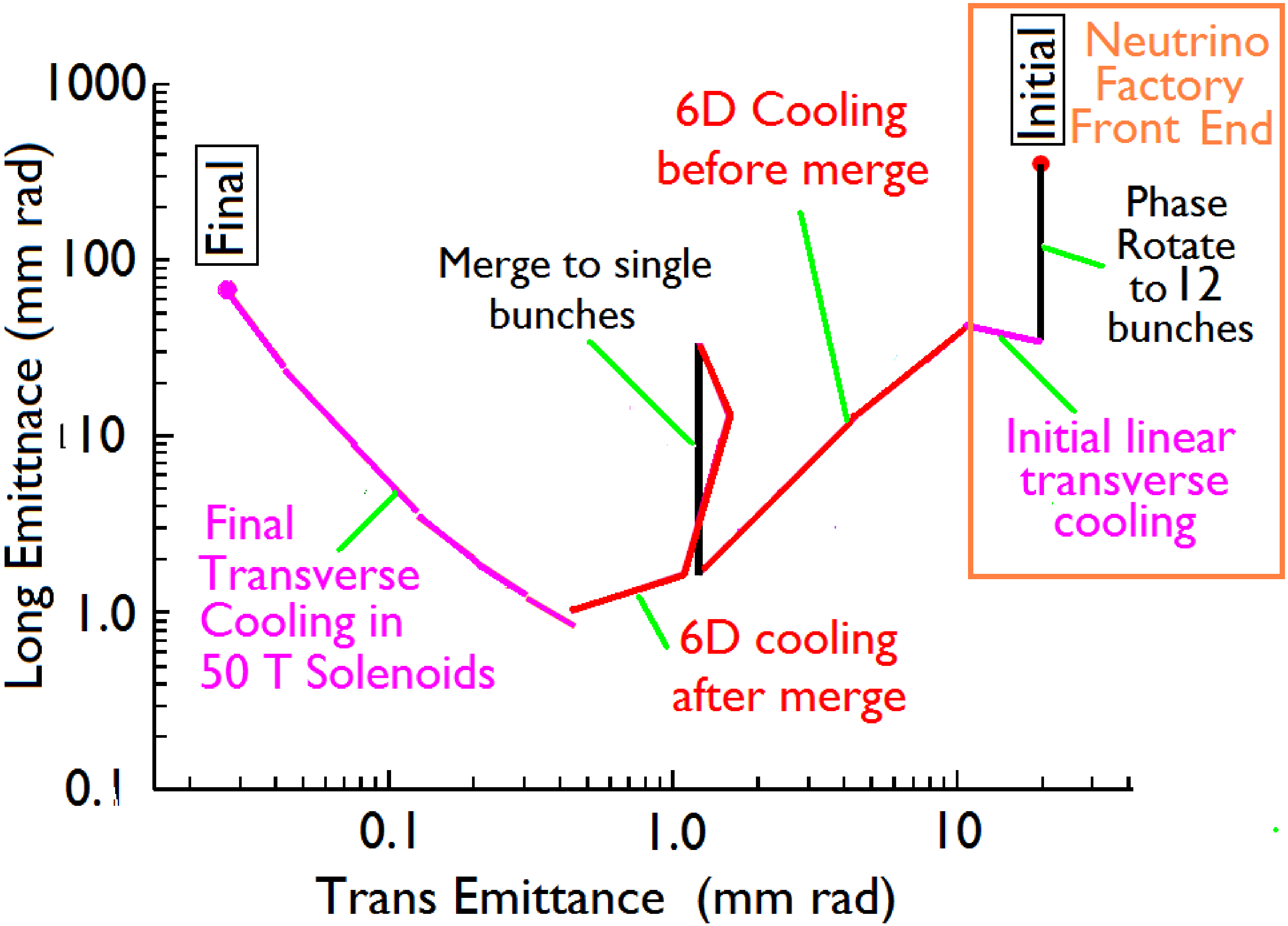
Other "low emittance" parameter sets exit that depend on the theoretical concepts of 'Parametric Ionization Cooling' (PIC) and 'Reverse Emittance Exchange' (REMX) that have, as yet, no practical realization

Scheme



More R&D needed to confirm viability and narrow the options

Emittances vs. Stage (Appendix 1 for transmission vs. emittance)



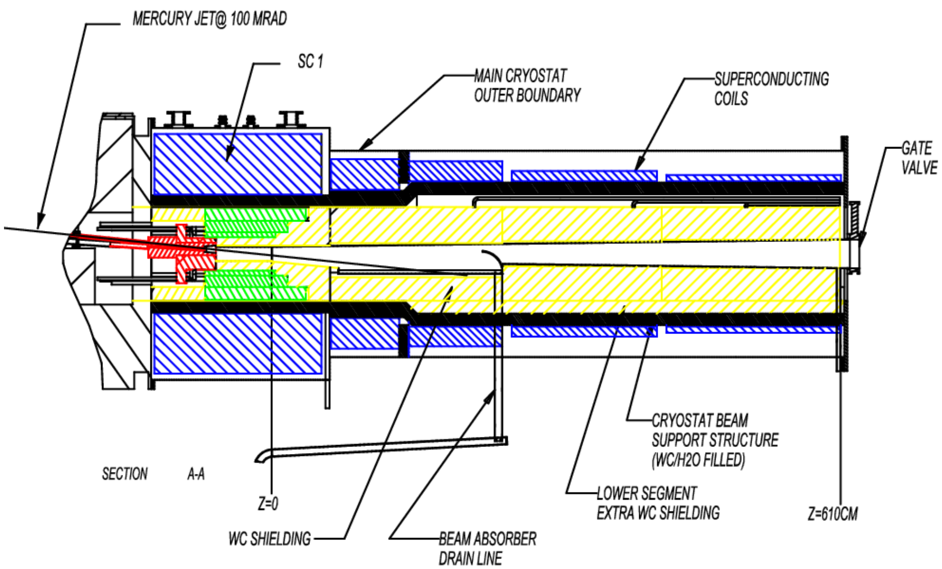
Every stage simulated at some level, but with many caveats

Proton driver (Appendix 2 for details)

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

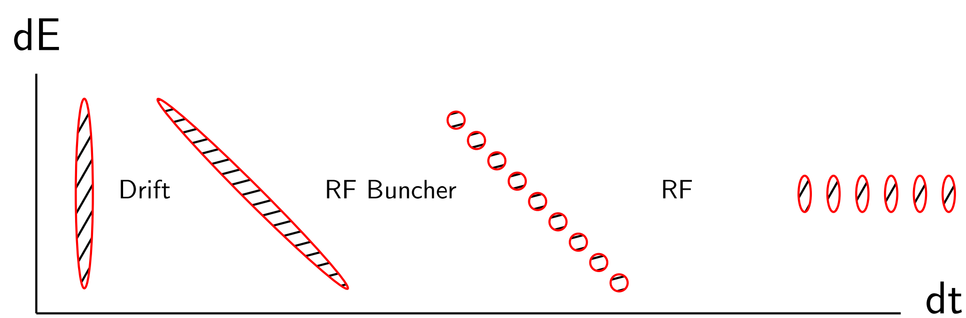
Target and Capture

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



Phase Rotation

Drifts & Multiple frequency rf
to Bunch, then Rotate

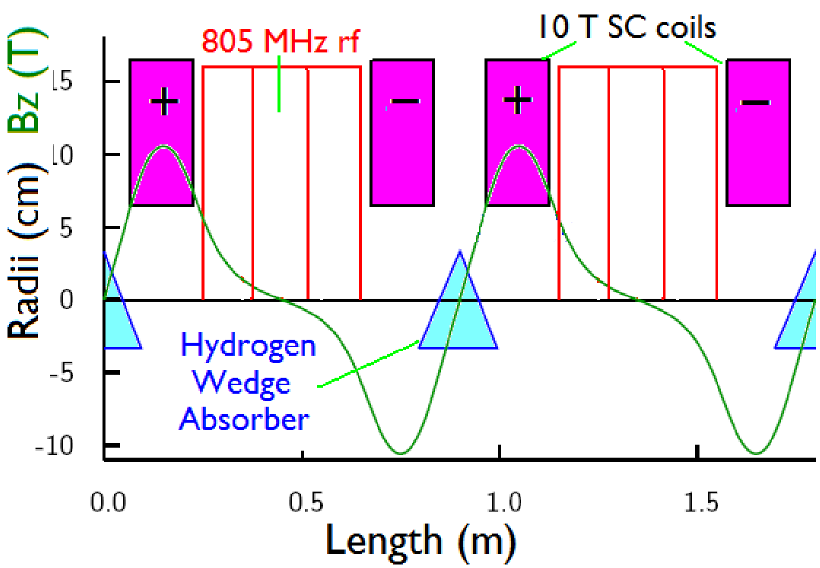


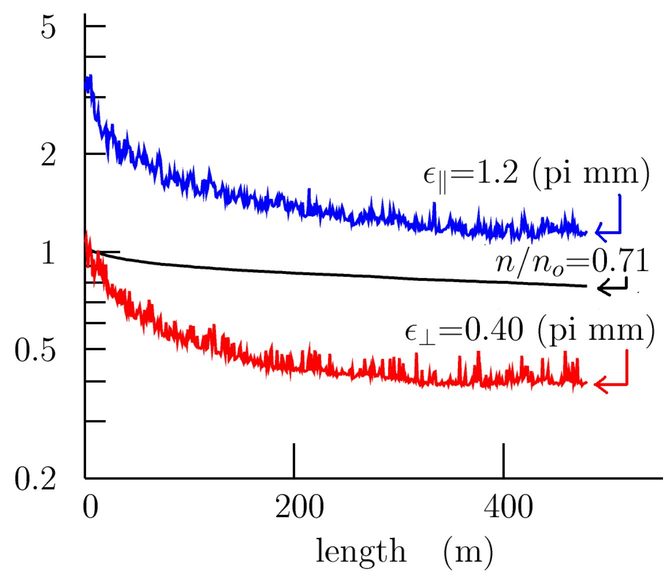
6D Cooling Several possibilities I will discuss two

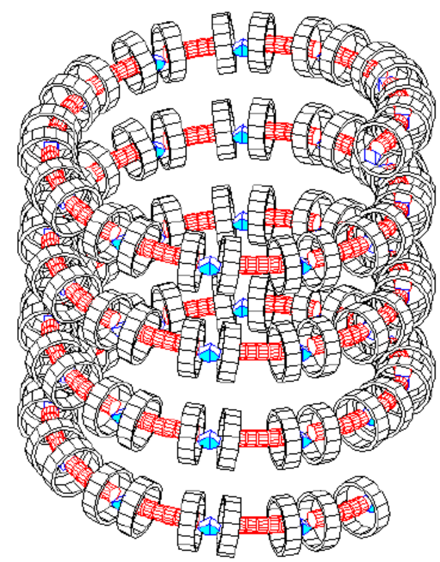
a) "Guggenheim" Lattice (as simulated for slide 6)

- Lattice arranged as 'Guggenheim' upward helix
- Bending gives dispersion
- Higher momenta pass through longer paths in wedge absorbers giving momentum cooling (emittance exchange)
- Starting at 201 MHz and 3 T, ending at 805 MHz and 10 T

e.g. 805 MHz 10 T cooling to 400 mm mrad



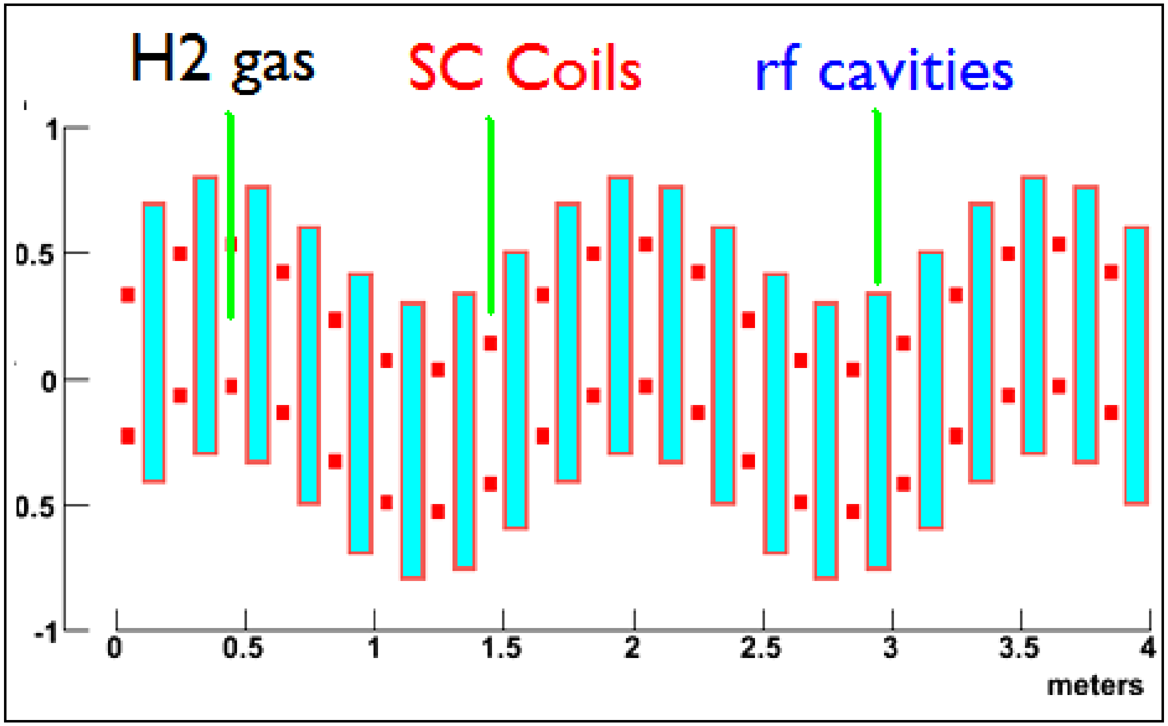




Possible/probable problem of rf breakdown in magnetic fields, as simulated

b) Helical Cooling Channel (HCC)

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

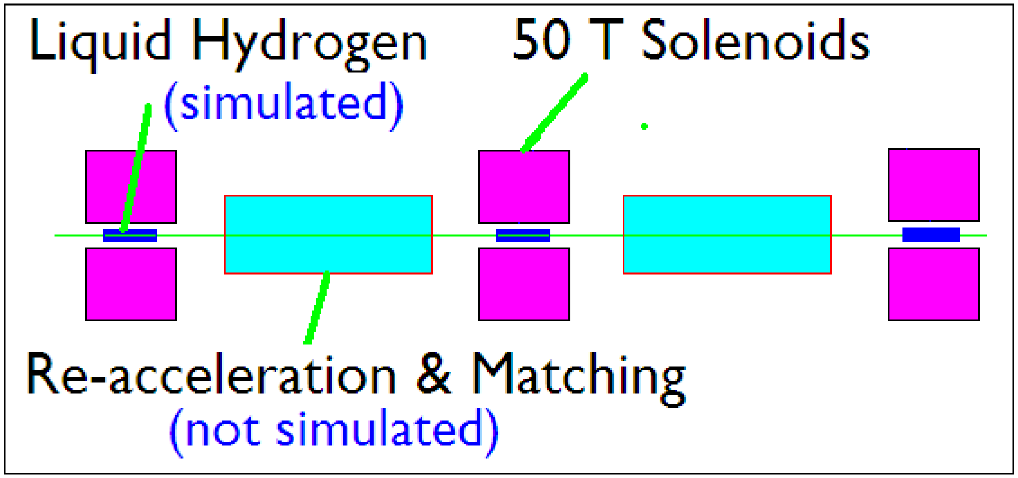


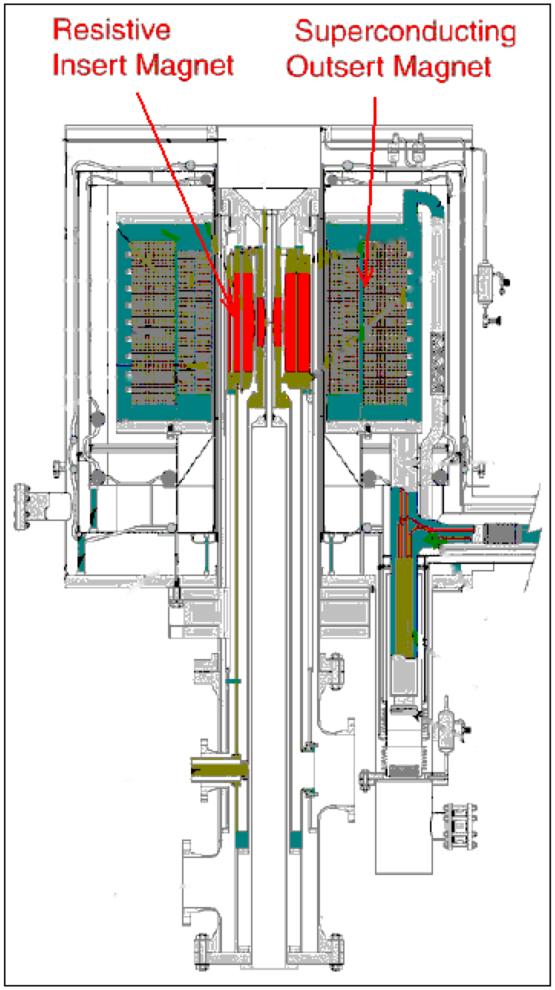
- Inital Bz=4.3 T
- Final Bz=13.6 T
- But final $\epsilon_{\perp}$=900 mm mrad
  c.f. 400 mm mrad in slide 6 scheme

Engineering integration of rf not well defined
Possible problem of rf breakdown with intense muon beam transit

Final Transverse Cooling in High Field Solenoids

- Lower momenta allow transverse cooling to required low transverse emittance, but long emittance rises: Effectively reverse emittance exchange





NHMFL 45 T Hybrid Magnet

- ICOOL Simulation of cooling
  but with ideal matching & re-acceleration
- 45/50 T Solenoids
  - 45 T hybrid at NHMFL, but uses 30 MW
  - 30 T all HTS under construction
  - 50 T Design with HTS tape has rad=57 cm

- Alternative Reverse Emittance Exchange (REMEX) proposed, but no realization yet

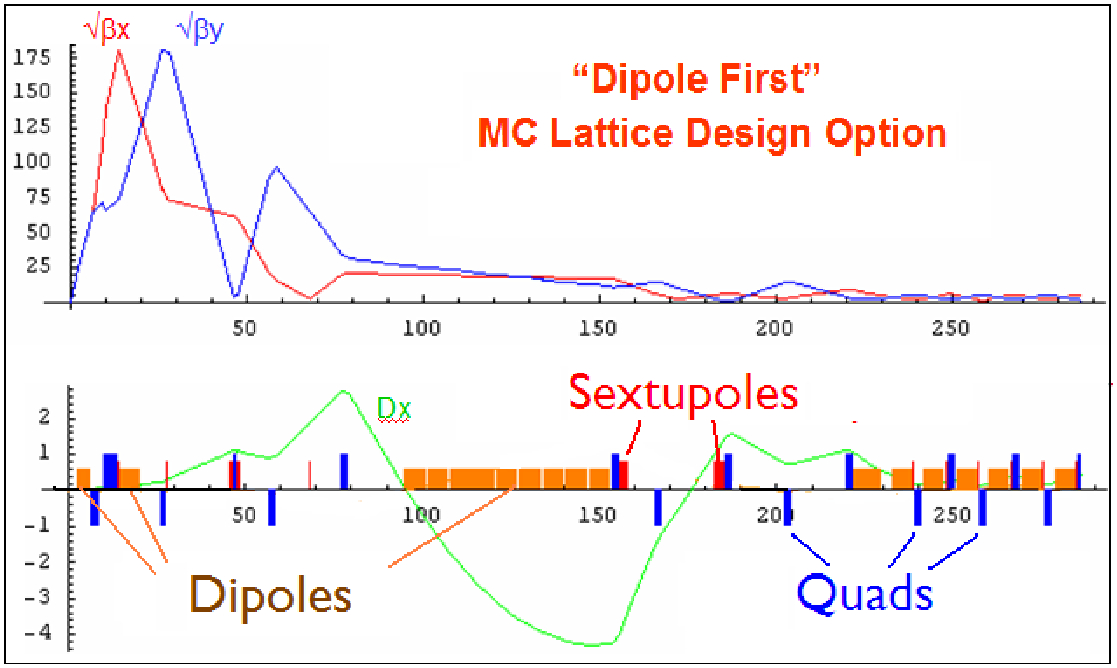
Acceleration

- 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 (See Appendix A3)
- Fixed Field Alternating Gradient (FFAG) accelerators could also play a role

Collider Ring

- 1.5 TeV (c of m) Design

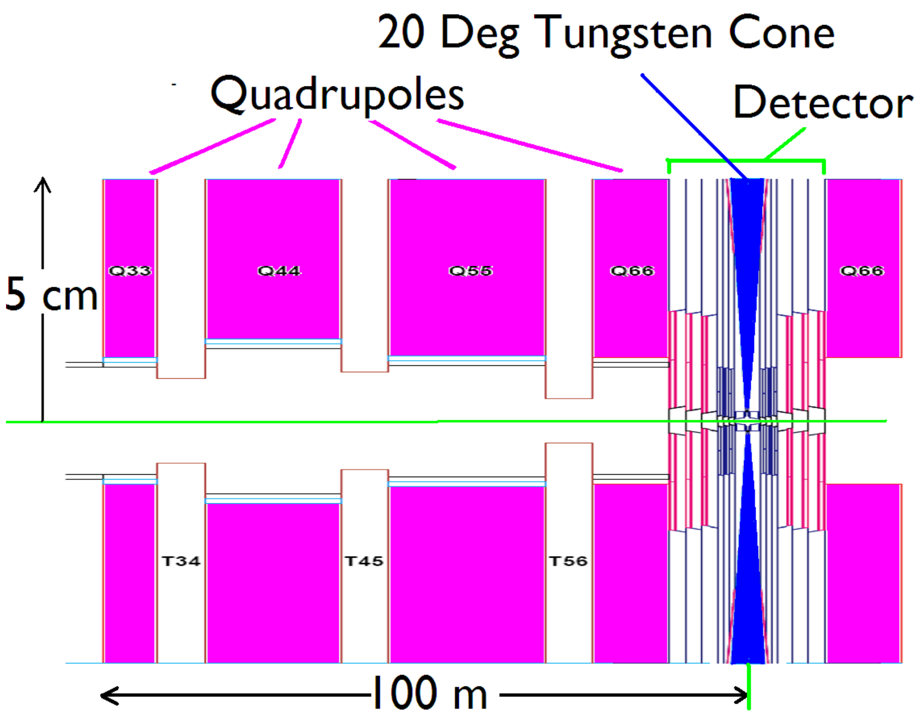


  - Nearly meets requirements
  - But early dipole may deflect unacceptable background into detector

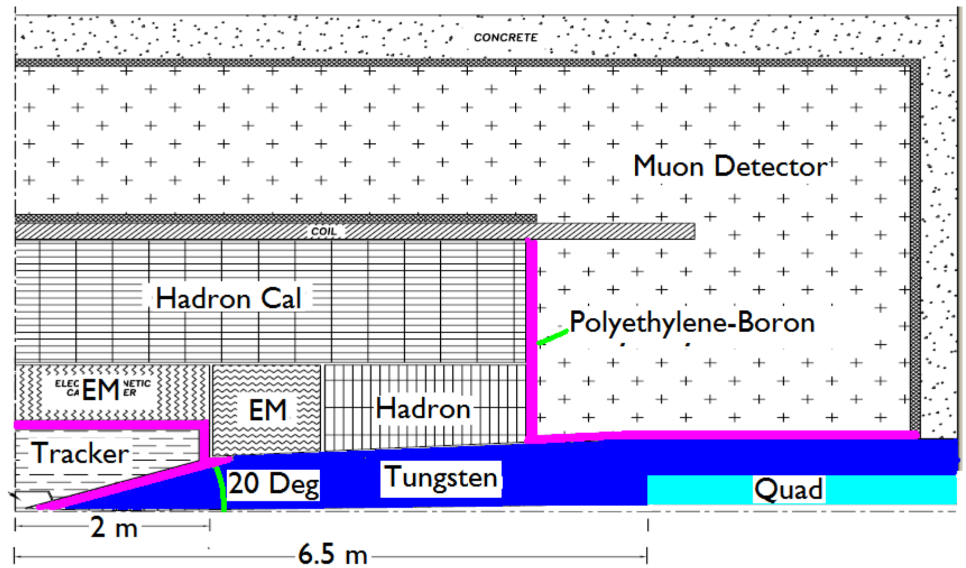
- 4 TeV (c of m) 1996 design by Oide
  - Meets requirements in ideal simulation
  - But is too sensitive to errors to be realistic

- The experts believe that the required rings should be possible

Detector From 1996 Study of 4 TeV Collider



Shielding



Detector

- 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

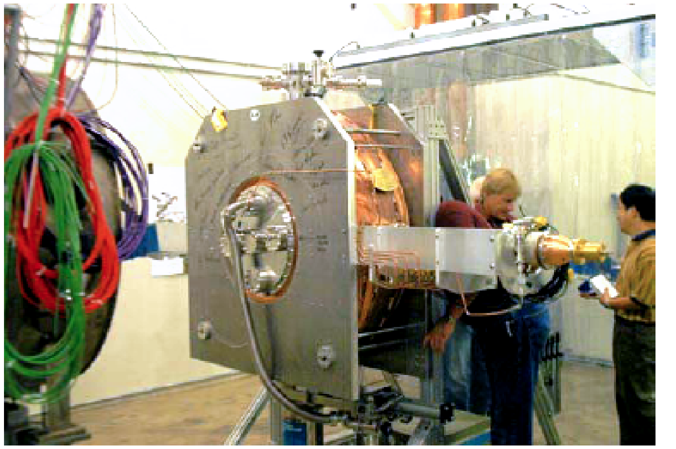
BUT

- Tungsten shielding takes up 20 degree cone

Ongoing R&D

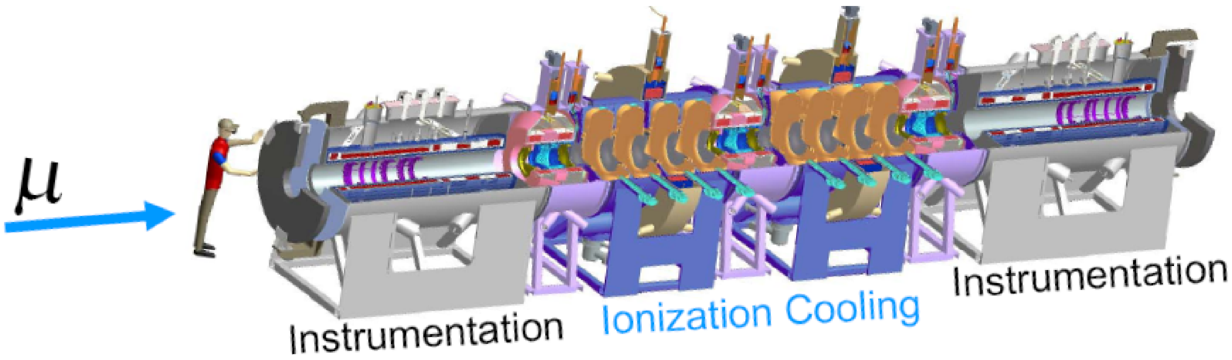
a) MuCool, and MuCool Test Area (MTA) at FNAL

- Liquid hydrogen absorber tested
- Open & pillbox 805 MHz cavities in magnetic fields
- 201 MHz cavity tested to 19 MV/m in $B =\approx$ 300 G
  Soon: 201 MHz in 1T, then 3T
- High pressure H2 gas 805 MHz pillbox cavity tested
- Soon: 805 MHz gas Cavity with proton beam



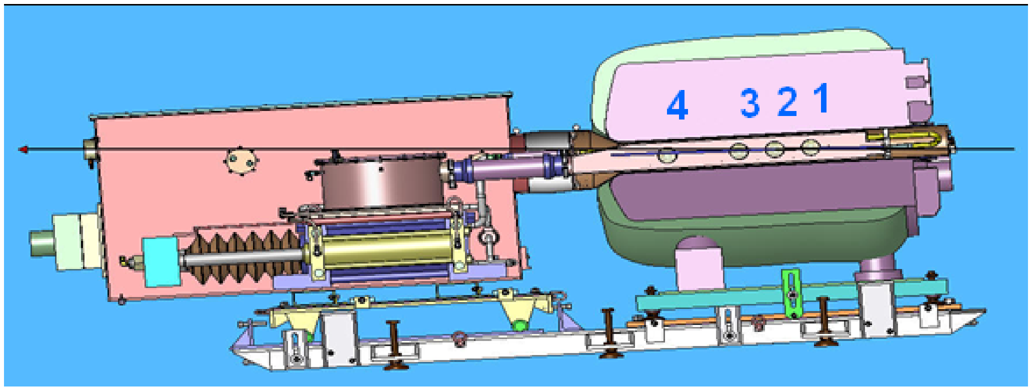
b) MICE at Rutherford Appleton Lab

- Will demonstrate transverse cooling in liquid hydrogen, including rf re-acceleration
- Will demonstrate 6D cooling without rf re-acceleration



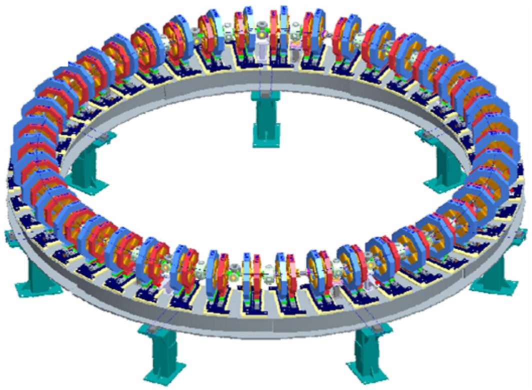
c) MERIT

- Demonstration at CERN of Hg jet target in 15 T magnetic field & 3 10^{13} 24 GeV protons (cf 4 10^{13} spec)



d) EMMA

- At Daresbury, UK   Electron model of Fixed Field Alternating Gradient (FFAG) Acceleration with parameters similar to those for muon acceleration

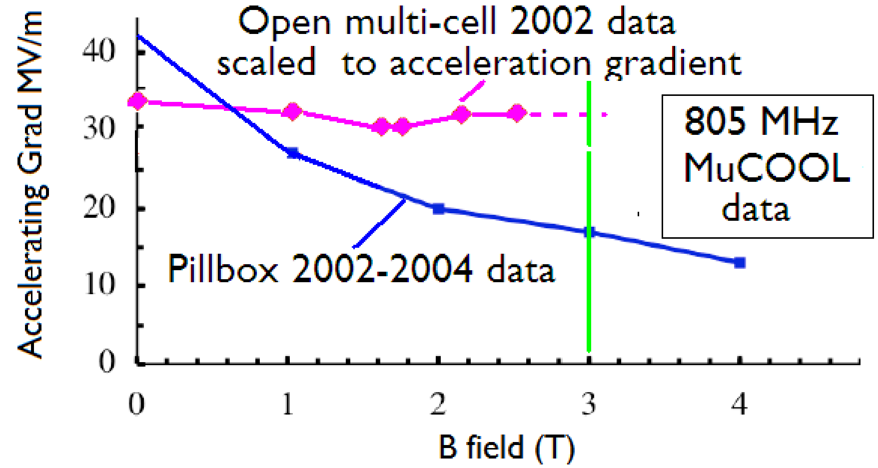


e) 201 MHz SRF

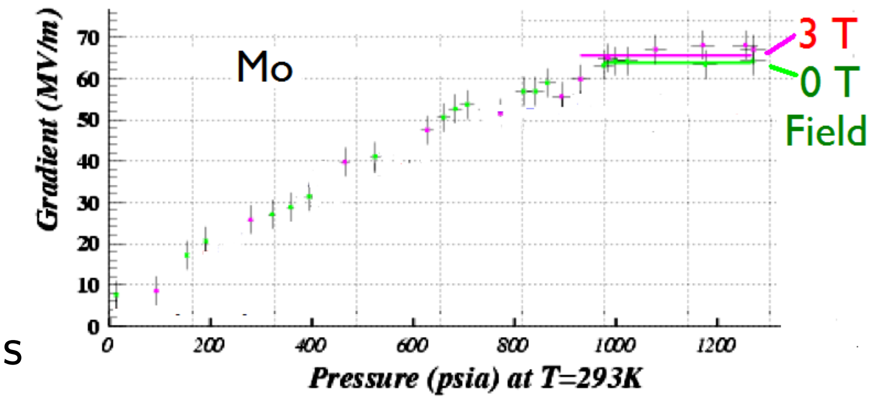
- Cornell - CERN Collaboration
- 17 MV/m expected
- Achieved 11 MV/m with unexpected Q slope
- Program now on hold, but should be restarted

Key Issues

- Pillbox cavity breakdown in mag field
  - Multi cell open Cavity better than pillbox
  - Open Cavities with coils in irises should provide "magnetic insulation" *
    Experiments needed



- Gas filled cavities shown
  to have no loss with magnetic field
  But gas may breakdown with beam
  Experiment coming in MTA



- Design & simulation of HCC with spaced coils

- Collider ring designs meeting acceptance criteria
  a) Without causing backgrounds in detector
  b) Stable against errors

- Design matching and re-acceleration in 50 T cooling

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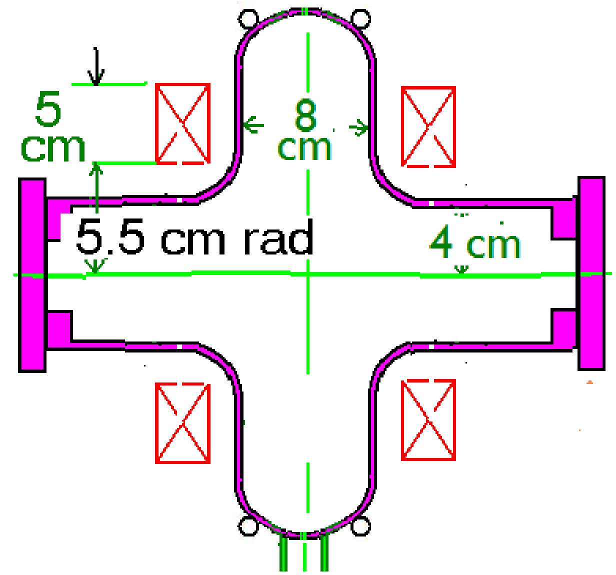
* See Appendix 4

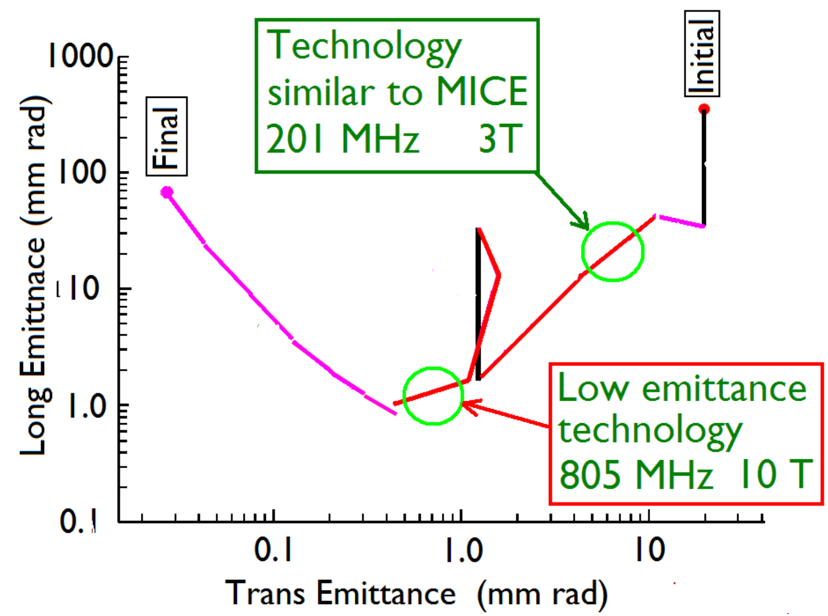
Key R&D Studies Needed for Technology Choices

- Test new 805 MHz open cavity in external fields, with coils in irises, and with HP gas
- Test 201 MHz cavity in magnetic fields (Planned)
- Test gas cavity in beam (Planned)
- Test 201 MHz gas filled cavity
- Integration of rf in HCC & its simulation

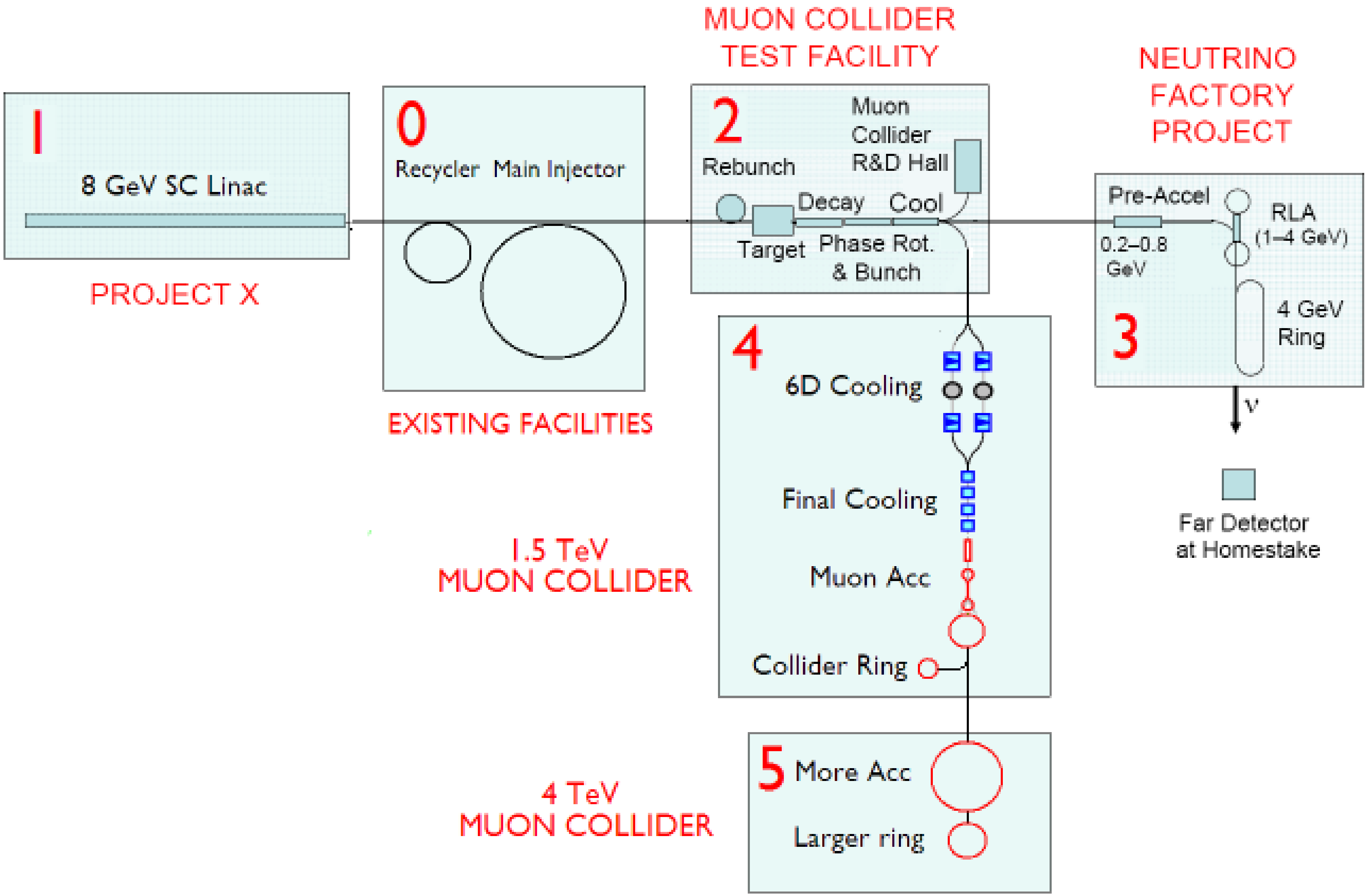


Also needed

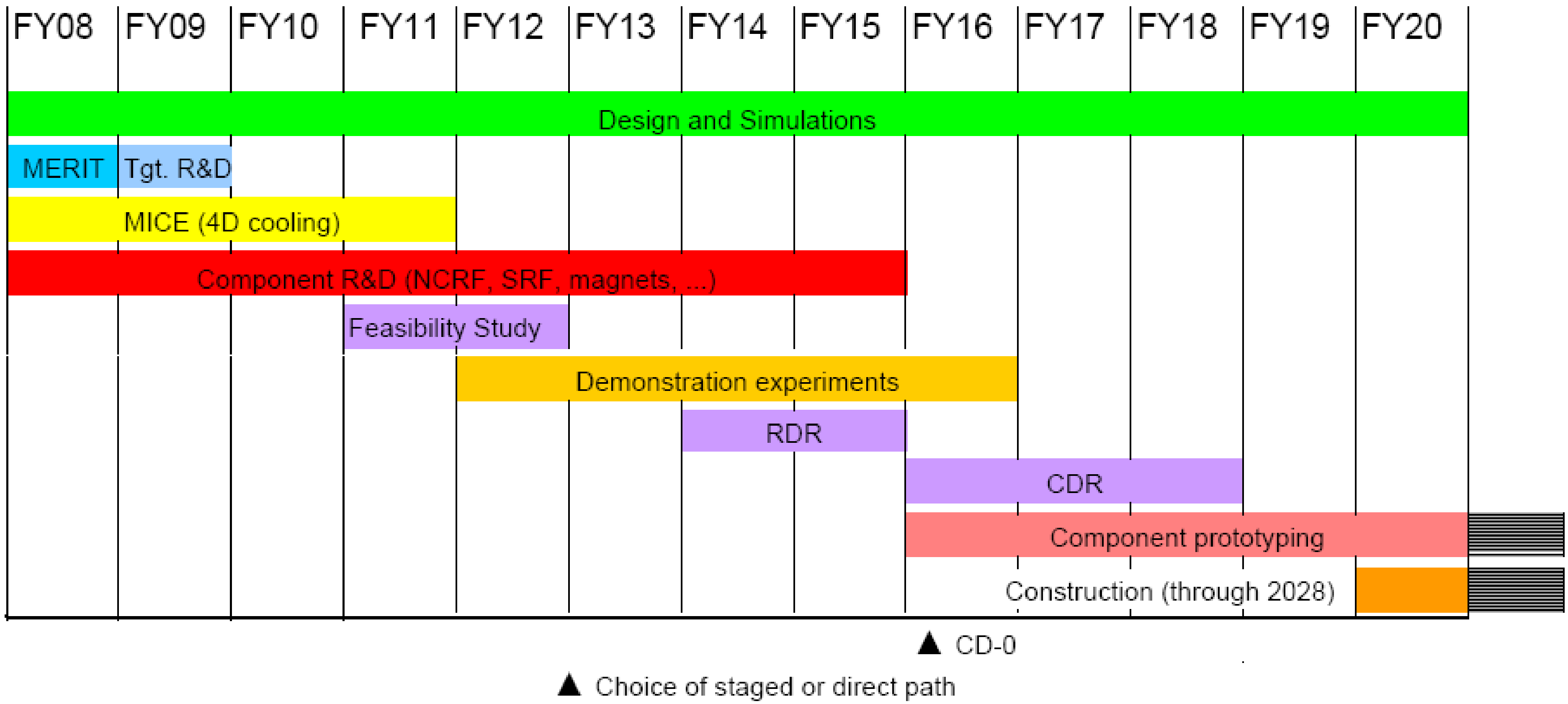
- Prototype 6D cooling to low trans emittance
  Inc. construction of liquid hydrogen Wedge
- Build and test short section of HCC with rf
- And many others (see Appendix 5)



A Phased Approach



Time Line and Funding Needs



8	11	13	20	25	25	25	35	40	40	R&D Funds M$/year

- 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

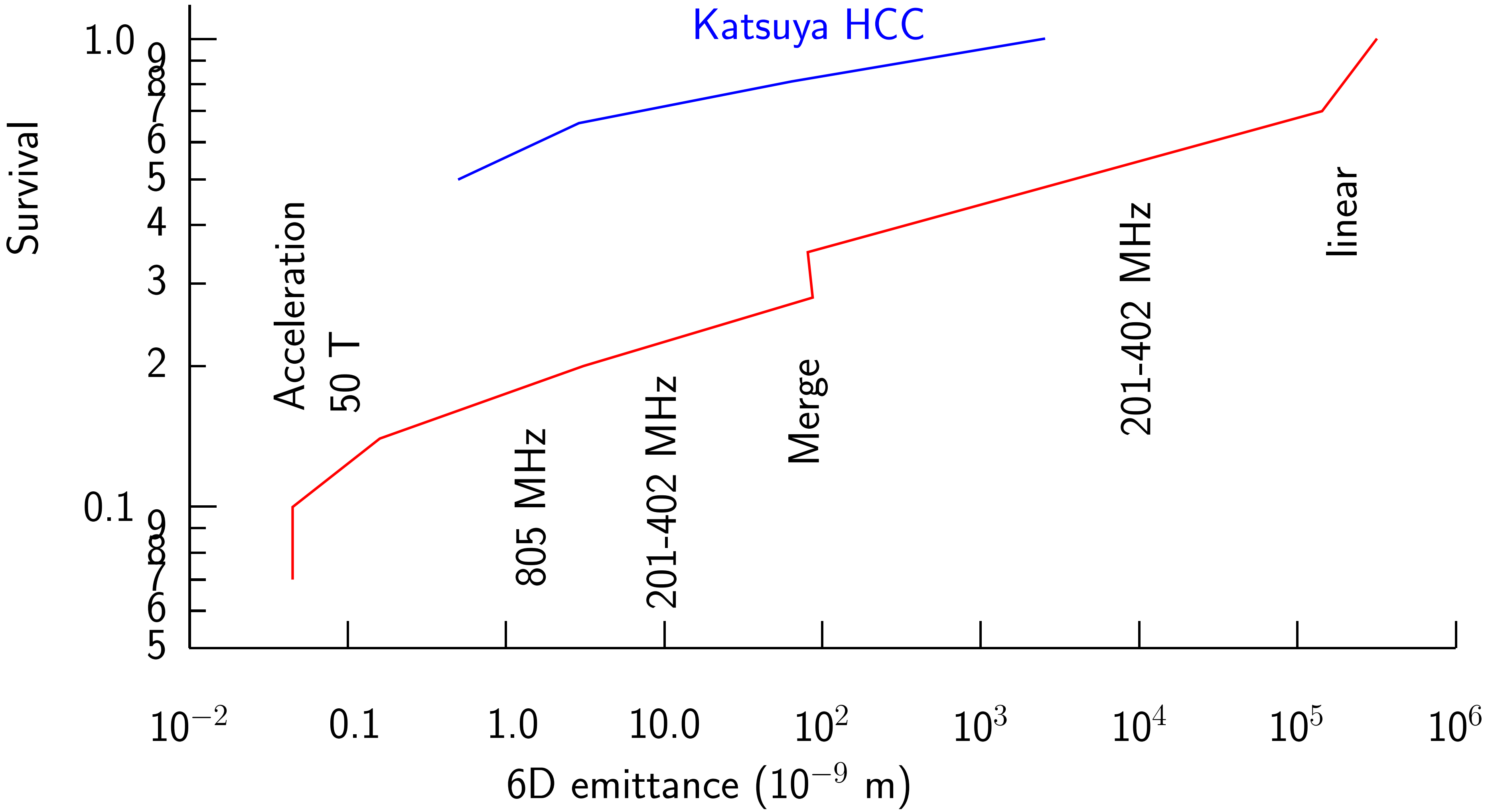
Conclusion

- 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 now

Appendices

1. Muon loss vs 6D emittance during cooling and acceleration
2. Project X as proton Driver for MC
3. Hybrid Pulsed Synchrotron + Layout at FNAL
4. Magnetic insulation with coils in irises
5. Needed R&D

A1) Estimated losses vs 6D emittance



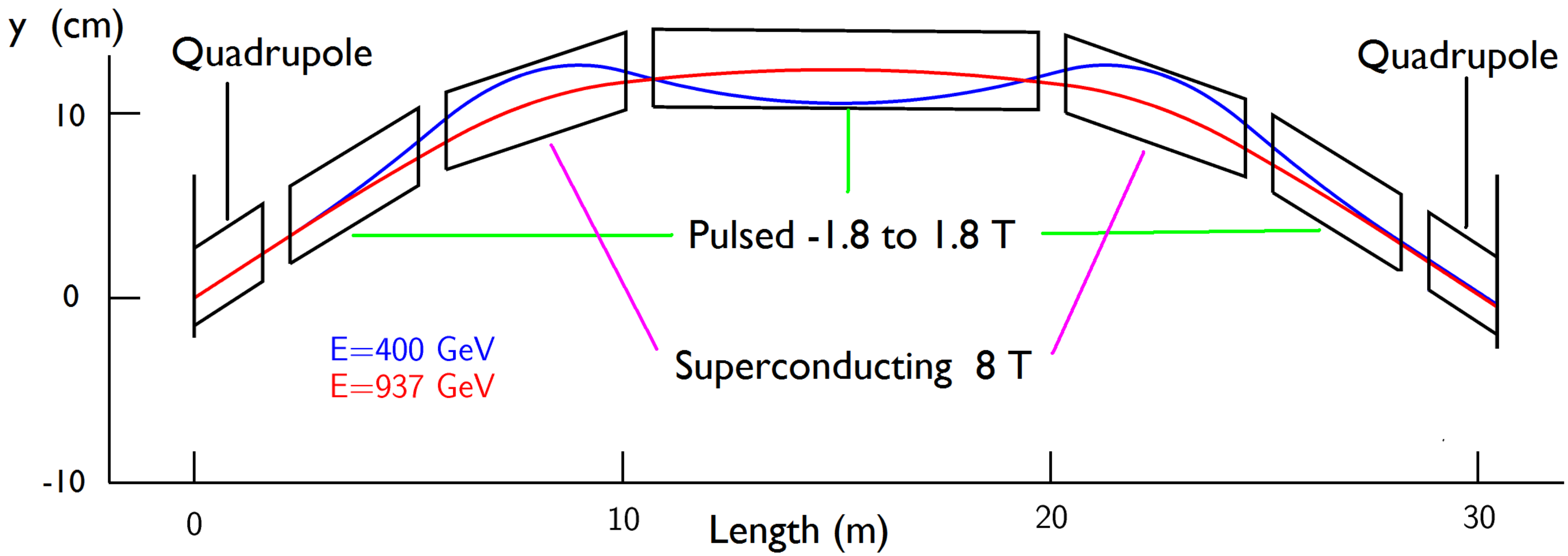
A2) Project X as proton Driver for MC

- Project X: 8 GeV Linac 9 mA at 5 Hz
- For required power, the pulse length is upgraded 1→2 msec (10^{14} p/p)
- Accumulate 3 trains in Recycler Ring (3 10^{14} p)
- Accelerate to 56 GeV in Main Injector at 1.7 Hz
- → New Buncher Ring*: Re-bunch to 3 ns on h=7 (4 10^{13} p) and extract at 12 Hz
- Average proton power 4 MW

* The buncher ring could be a low field ring in the MI tunnel, or a smaller high field ring elsewhere.

A3) Hybrid Pulsed Synchrotron

- Pulsed synchrotron 30 to 400 GeV
  (in Tevatron tunnel)
- Hybrid SC & pulsed magnet synchrotron 400-900 GeV
  (in Tevatron tunnel)

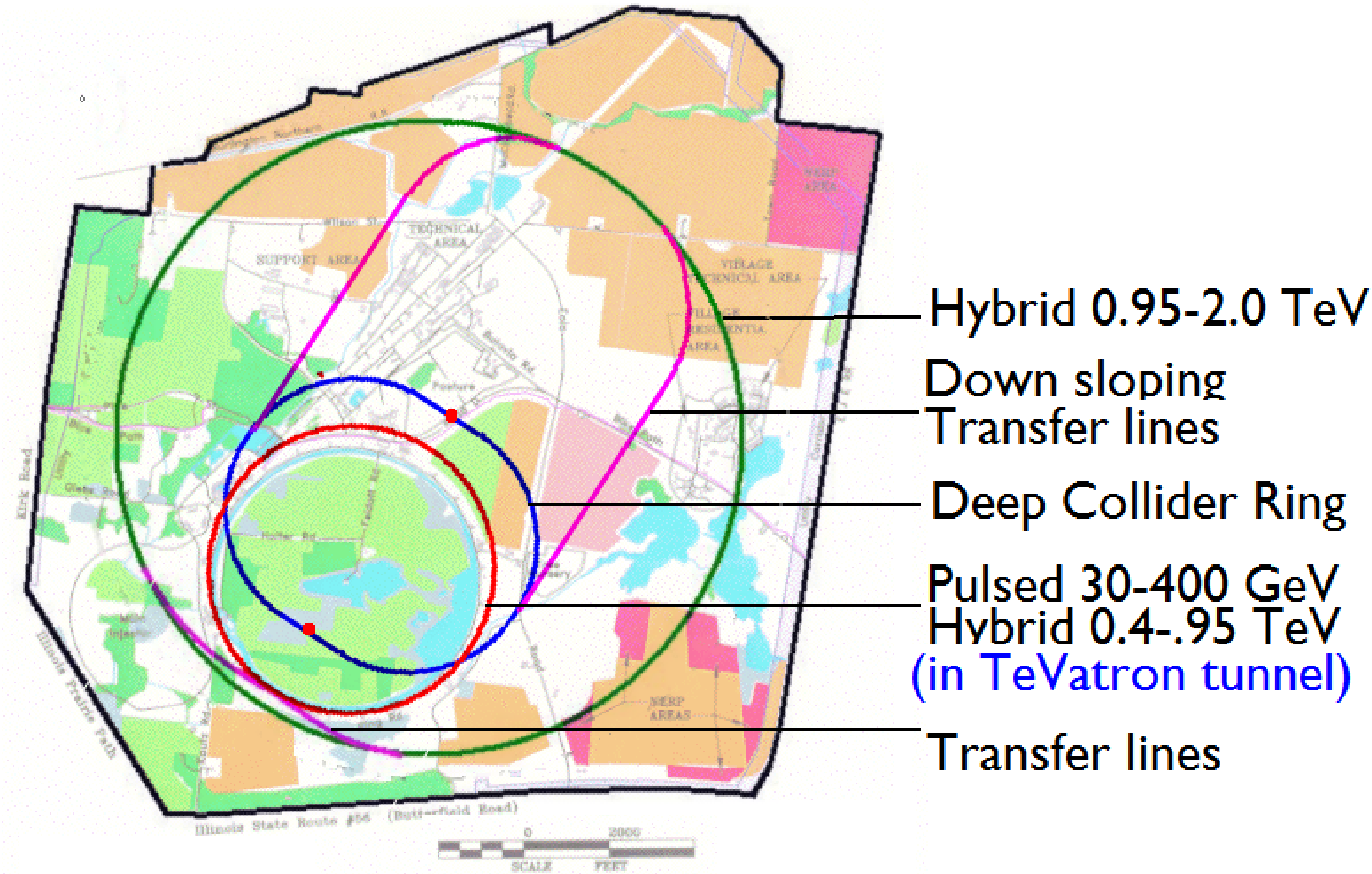


- Pulsed dipoles first oppose, and later support the bending form 8 T superconducting magnets
- A similar hybrid site filler would accelerate 0.9 to 2 TeV for a 4 TeV c of m collider

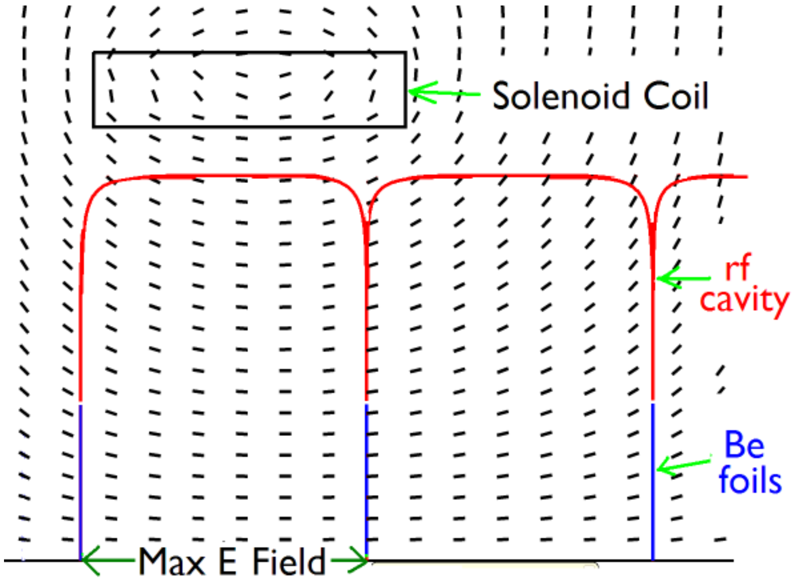
Details

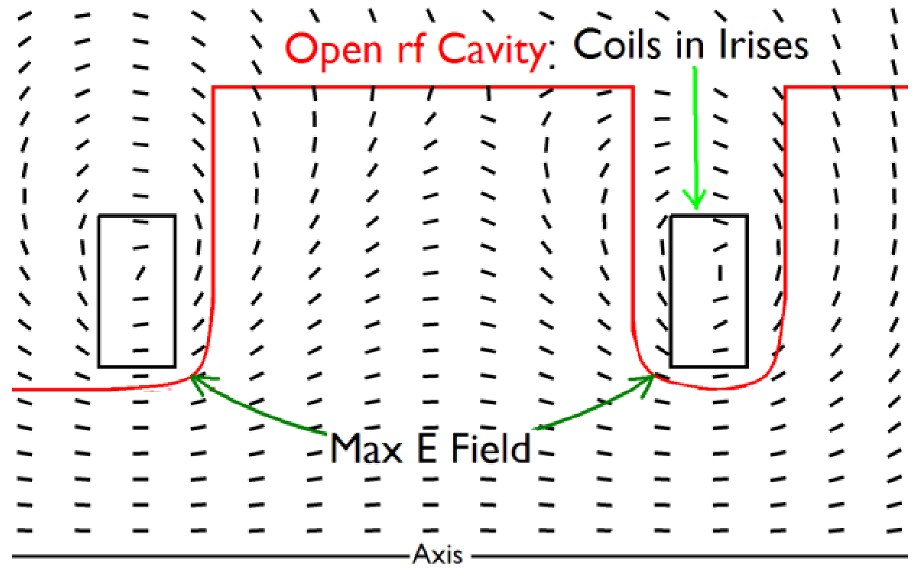
- Both rings have lattices similar to Tevatron and fit in the Tevatron Tunnel
- For 30-400 GeV
  - Ramped quadrupoles 2.2 to 30 T/m in 0.57 msec (400 Hz)
  - Ramped dipoles -0.13 T to 1.8 T in 0.59 msec (400 Hz)
  - 13 GV of superconduction 1.3 GHz rf
  - muon Survival 80%
- For 400-750(937) GeV
  - 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

Layout of 4 TeV Collider using pulsed synchrotrons



A4) Magnetic insulation with coils in irises





201 MHz Pillbox

Open + coils in irises

- In Pillbox cavity the max E field is parallel with magnetic field lines
  electrons emitted from field regions are focused onto opposite (or the same) high field region
- In Open cavity with coils in irises the maximum E field is almost perpendicular to the magnetic field lines
  electrons emitted from high field regions are trapped

A5) Needed R&D Studies

- Test new 805 MHz open cavity in external fields and with coils in irises
- Test 201 MHz cavity in magnetic fields (Planned)
- Test gas cavity in beam (Planned)
- Test 201 MHz gas filled cavity
- Demonstrate 6D cooling to low trans emittance
  Inc. construction of liquid hydrogen Wedge
- Build and test: short length of HCC with rf
- Study HTS to reduce power of 50 T magnets
- Study effects on Hg jet entering the magnet
- Re-start 201 MHz superconducting rf work
- Build model of pulsed synchrotron magnet
- Prototype of "open mid-plane" Collider Ring Magnet