Muon Collider Complex

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Workshop on Muon Collider Physics—Fermilab
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Outline

- Introduction
- Muon accelerator pros & cons
- Muon collider ingredients
- Implementation concepts
- R&D program
- R&D issues
- Possible U.S. scenario
- Summary

Introduction

- Muon-based collider will be a powerful tool in the experimentalist's arsenal
- Design and performance evaluations for such a facility have been ongoing for more than 10 years
  - two entities involved in coordinated program
    - Neutrino Factory and Muon Collider Collaboration (NFMCC)
    - Muon Collider Task Force (MCTF)
  - coordination done by leadership of the two organizations
    - NFMCC: A. Bross, H. Kirk, M. Zisman
    - MCTF: S. Geer, V. Shiltsev
  - organizations will soon merge to national Muon Accelerator Program (MAP)
- Recent interest by Fermilab management has spurred increased effort to understand Muon Collider design
  - and increased enthusiasm by DOE to support the required R&D effort

Muon Accelerator Advantages

- **Muon-beam accelerators can address several of the outstanding accelerator-related particle physics questions**
  - **energy frontier**
    - **point particle makes full beam energy available for particle production**
      - **couples strongly to Higgs sector**
    - **Muon Collider has almost no synchrotron radiation**
      - **narrow energy spread at IP compared with e^+e^- collider**
      - **uses expensive RF equipment efficiently (⇒ fits on existing Lab sites)**
  - **neutrino sector**
    - **Neutrino Factory beam properties**

$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \overline{\nu}_\mu$$

$$\mu^- \to e^- \overline{\nu}_e \nu_\mu \Rightarrow 50\% \overline{\nu}_e + 50\% \nu_\mu$$

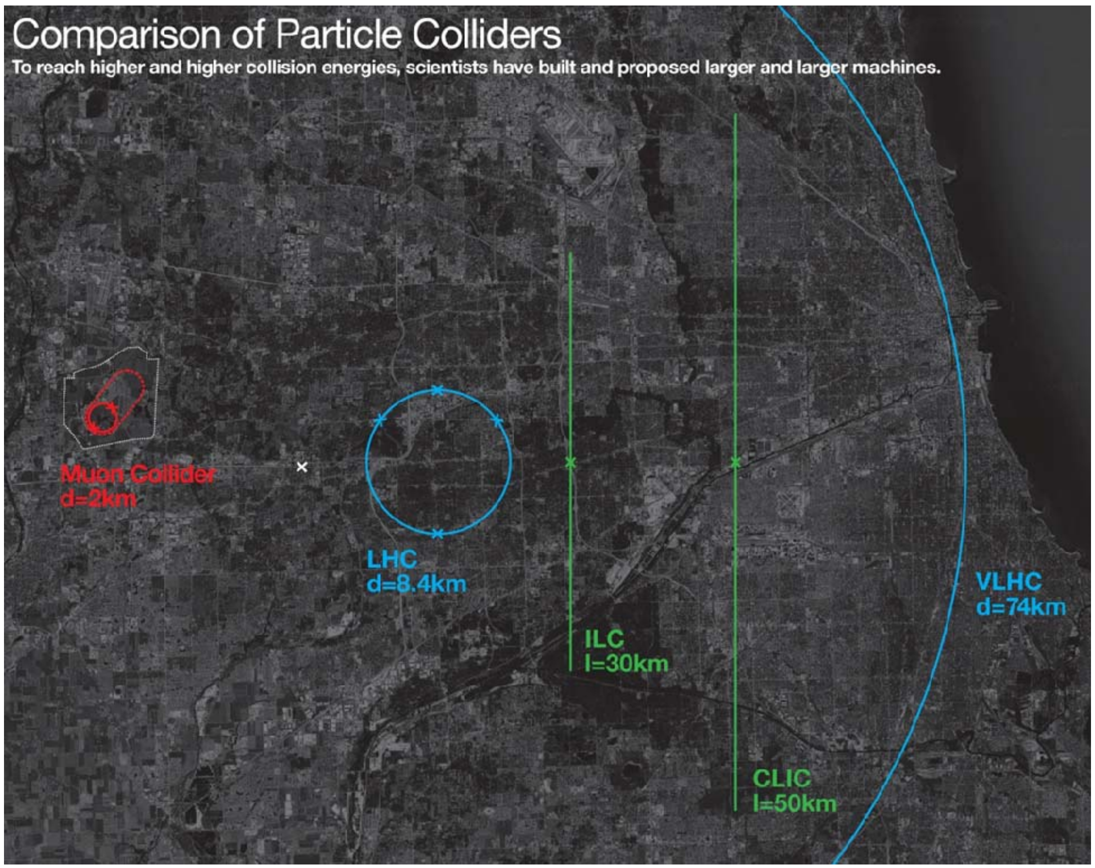
Produces high energy ν_e, above τ threshold

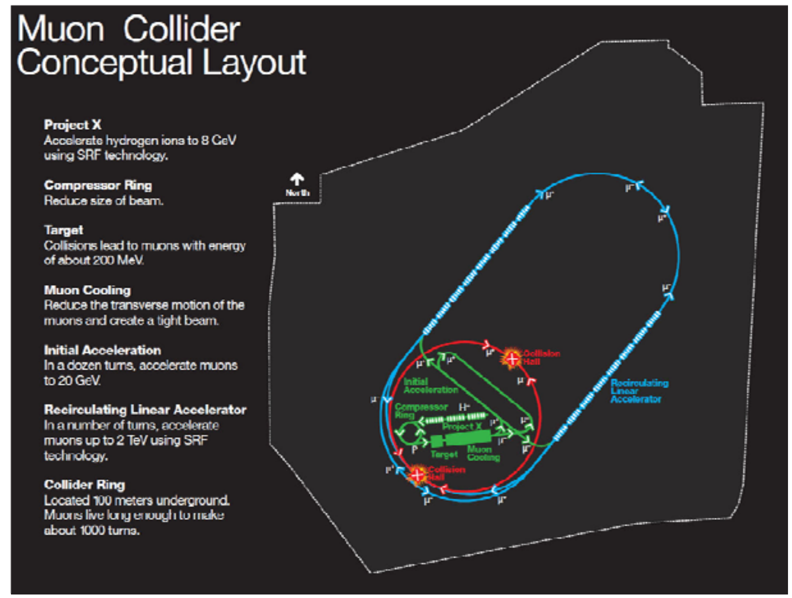
    - **decay kinematics well known**
      - **minimal hadronic uncertainties in the spectrum and flux**
    - **$\nu_e \to \nu_\mu$ oscillations give easily detectable "wrong-sign" μ (low background)**

Unmatched sensitivity for CP violation, mass hierarchy, and unitarity

Size Matters

- The larger the accelerator footprint, the more lawyers' properties are intersected
  - muon accelerator will fit on present Fermilab site





Muon Collider would provide world-class science program at Fermilab

Muon Beam Challenges

- **Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)**
  - **low production rate**
    - **need target that can tolerate multi-MW beam (+ source to provide it!)**
  - **large energy spread and transverse phase space**
    - **need solenoidal focusing for the low energy portions of the facility**
      - **solenoids focus in both planes simultaneously**
    - **need emittance cooling**
    - **high-acceptance acceleration system and decay ring**

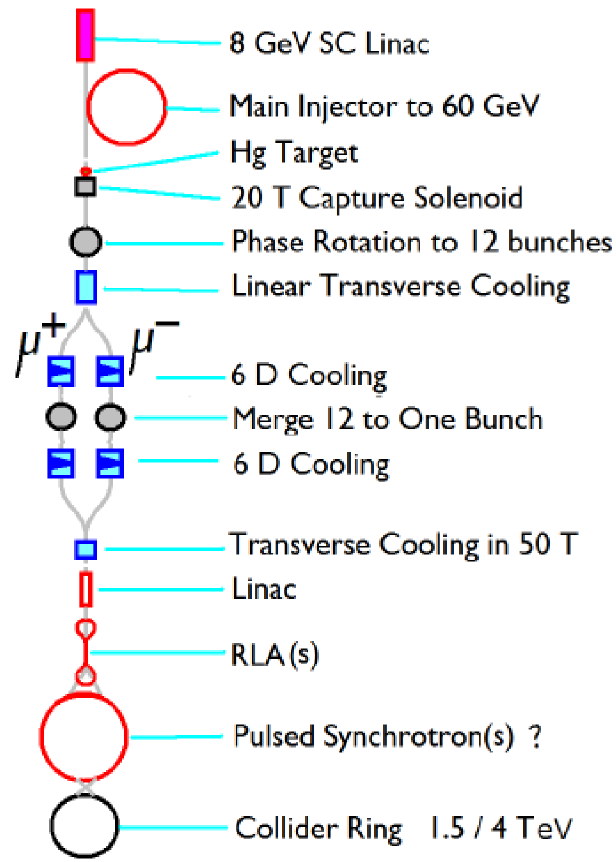
- **Muons have short lifetime (2.2 μs at rest)**
  - **puts premium on rapid beam manipulations**
    - **high-gradient RF cavities (in magnetic field) for cooling**
    - **presently untested ionization cooling technique**
    - **fast acceleration system**

If intense muon beams were easy to produce, we'd already have them!

- **Decay electrons give rise to heat load in magnets and backgrounds in collider detector**

Muon Collider Ingredients

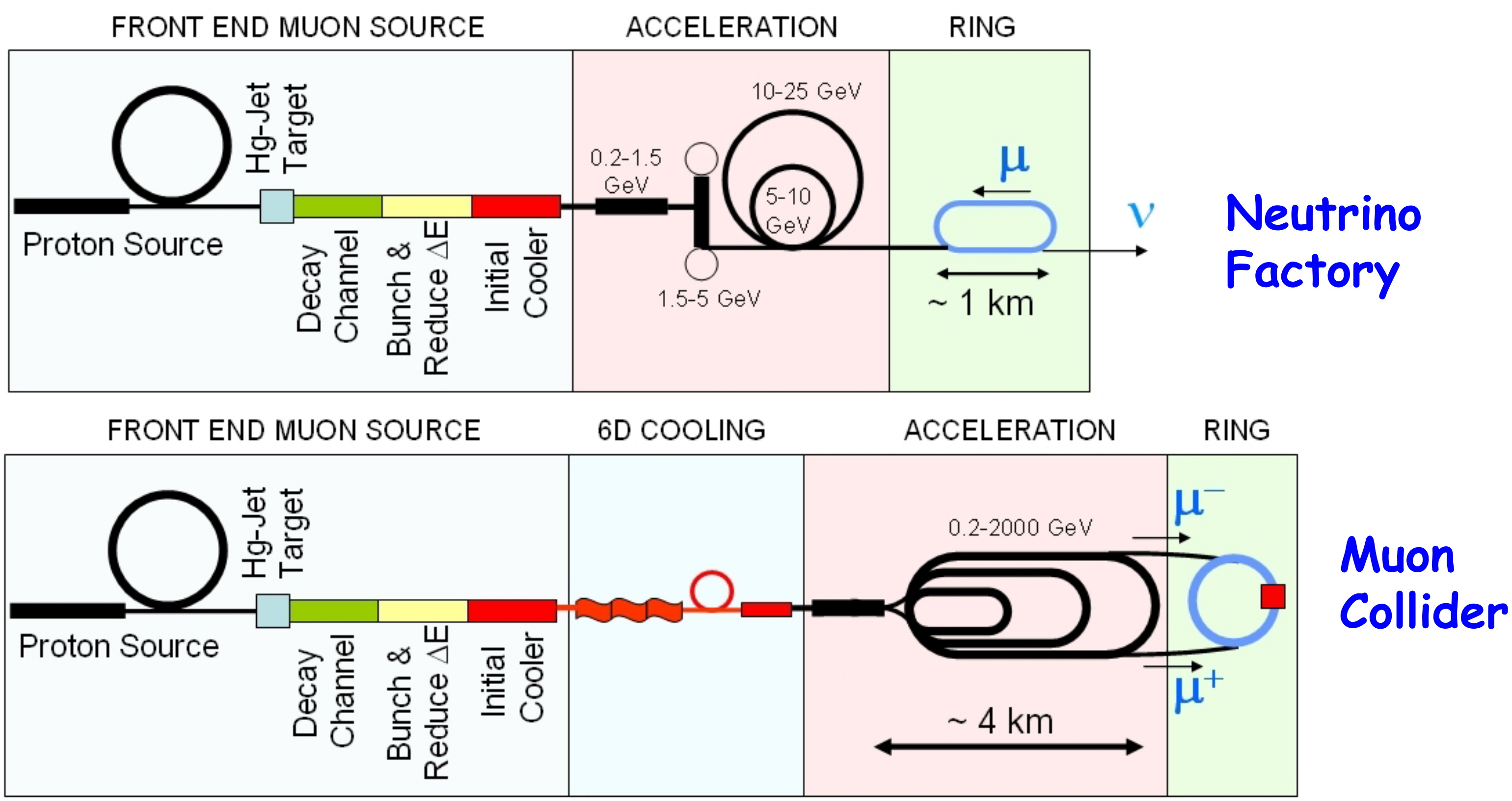
- Muon Collider comprises these sections (similar to NF)
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into $\mu \Rightarrow$ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce long. and transverse emittance
      $\Rightarrow$ MICE $\rightarrow$ 6D experiment
  - Acceleration
    - 130 MeV $\rightarrow$ ~1 TeV
      with RLAs, FFAGs or RCSs
  - Collider Ring
    - store for 500 turns



Much of Muon Collider R&D is common with Neutrino Factory R&D

Muon Collider Front End

- **Baseline Muon Collider beam preparation system identical to that for Neutrino Factory**
  - downstream portions (6D cooling, acceleration, collider) are distinct
    - much more cooling and acceleration needed for collider



Muon Collider Requirements

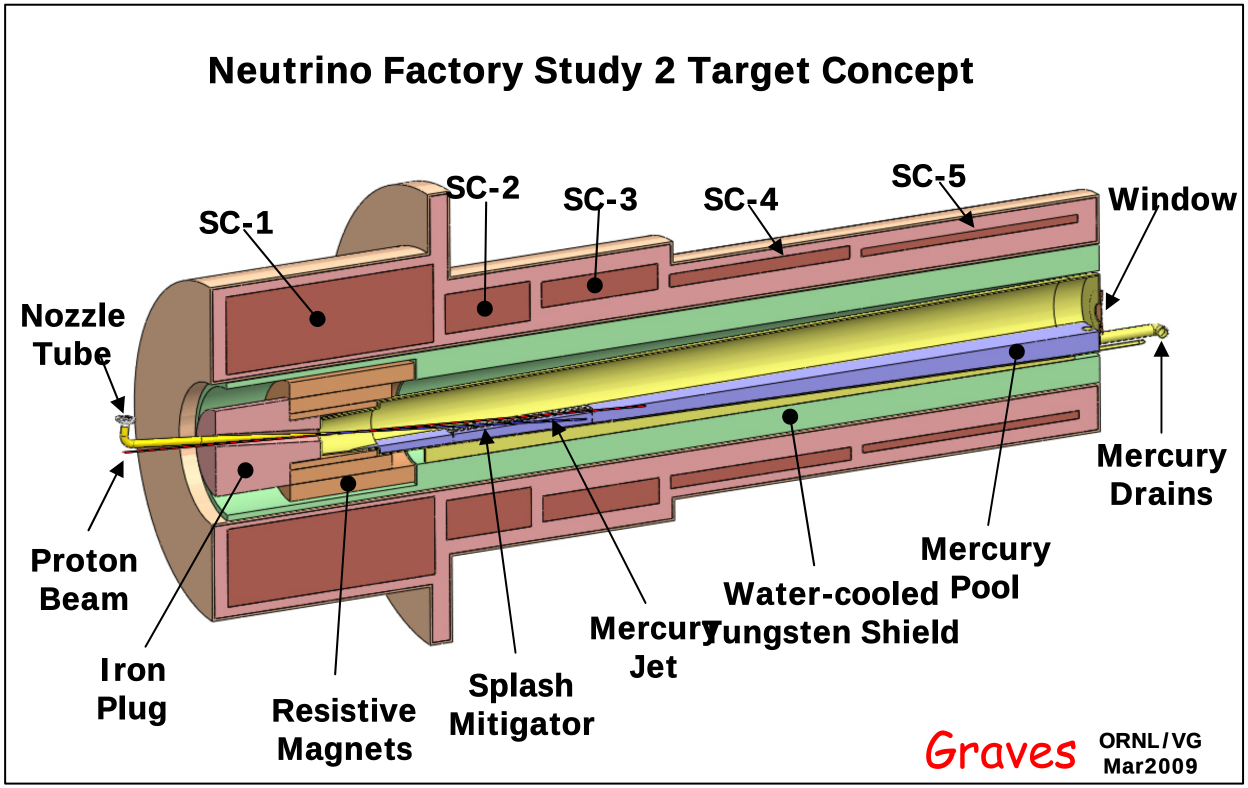
- Typical example parameters for MC scenarios given below [Alexahin, Palmer]
  - caveat: power estimates based on assumed transmission values
    - could go up or down...
      - smart money is on "up"

√s (TeV)	1.5	3
Av. Luminosity / IP (10^{34}/cm²/s)	0.77	3.4
Max. bending field (T)	10	14
Av. bending field in arcs (T)	6	8.4
Circumference (km)	3.1	4.5
No. of IPs	2	2
Repetition Rate (Hz)	15	12
Beam-beam parameter/IP	0.087	0.087
β* (cm)	1	0.5
Bunch length (cm)	1	0.5
No. bunches / beam	1	1
No. muons/bunch (10^{11})	20	20
Norm. Trans. Emit. (μm)	25	25
Beam size @ IP (μm)	6	3
Energy spread (%)	0.1	0.1
Norm. long. Emit. (m)	0.07	0.07
Total RF voltage (MV) at 800MHz	77	886
μ+ in collision / 8GeV proton	0.008	0.007
8 GeV proton beam power (MW)	4.8	4.3

Needed to meet luminosity specification

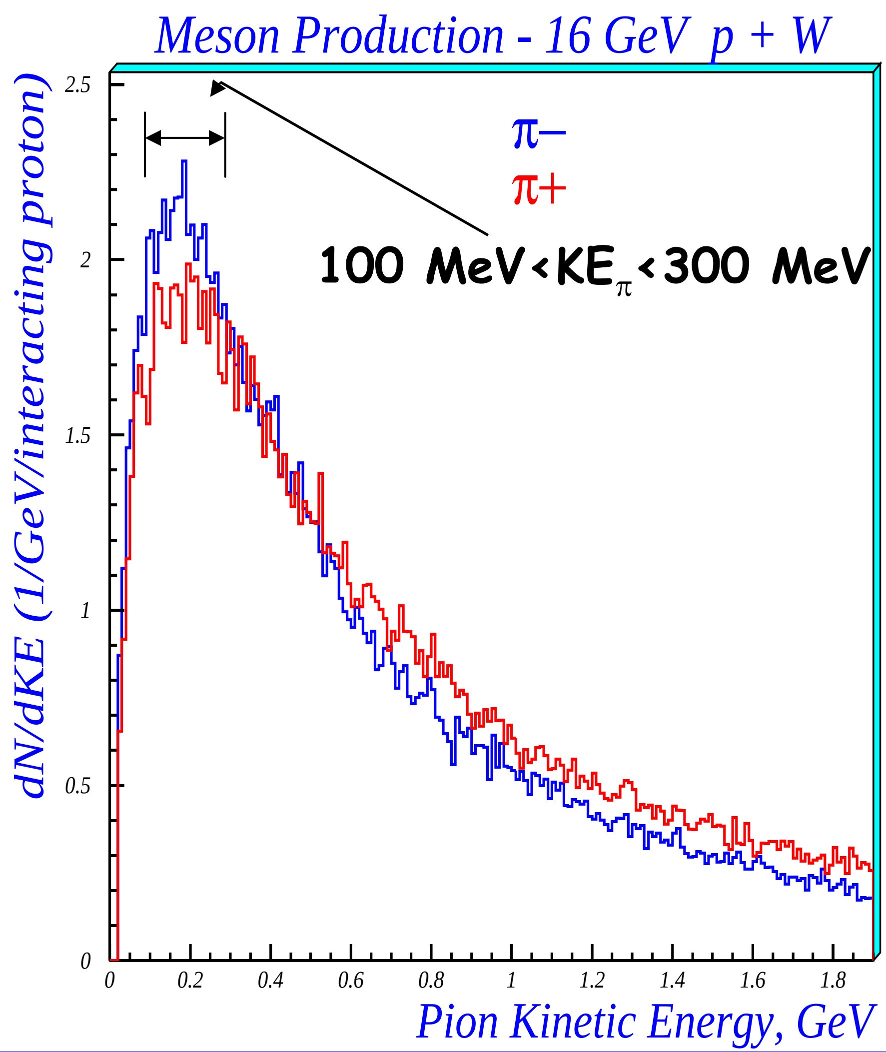
Pion Capture (1)

- Based on 20-T solenoid, followed by adiabatically tapered solenoidal channel to bring field down to 1-2 T
  - baseline target is free Hg-jet
    - this is the "context" for evaluating Proton Driver needs



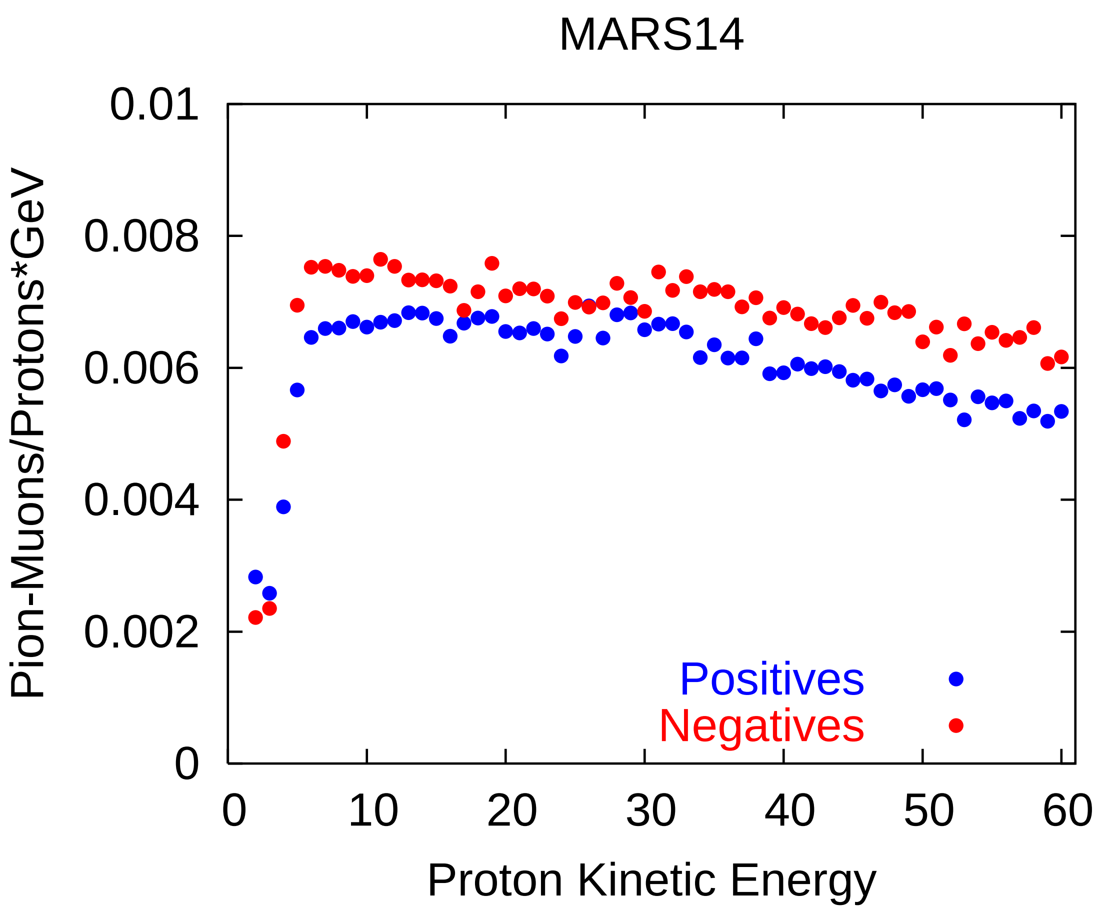
Pion Capture (2)

- **Capture of low energy pions is optimal for cooling channel**



Proton Beam Energy (1)

- **Meson production originally evaluated with MARS14 code (Kirk)**



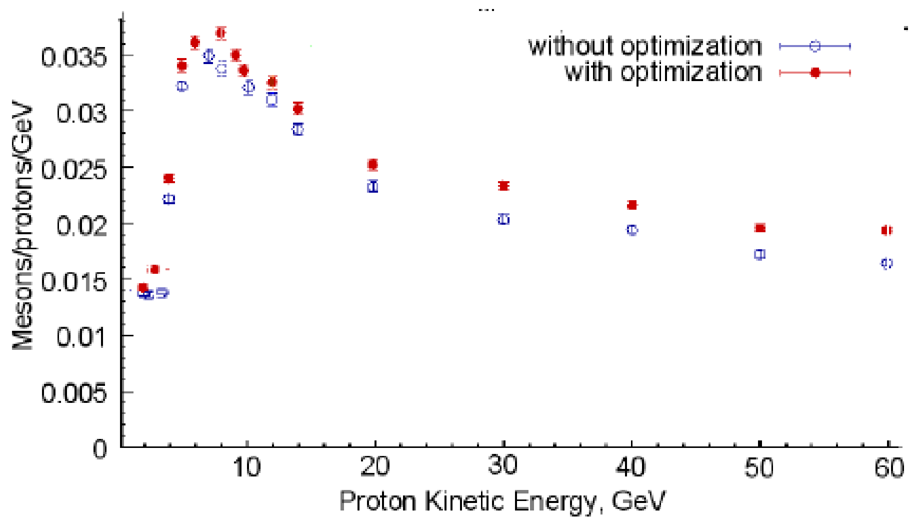
μ^-: 6 – 11 GeV

μ^+: 9 – 19 GeV

Adopted 10 $\pm$ 5 GeV as representative range; higher *E* does not hurt much, but doesn't help either

Proton Beam Energy (2)

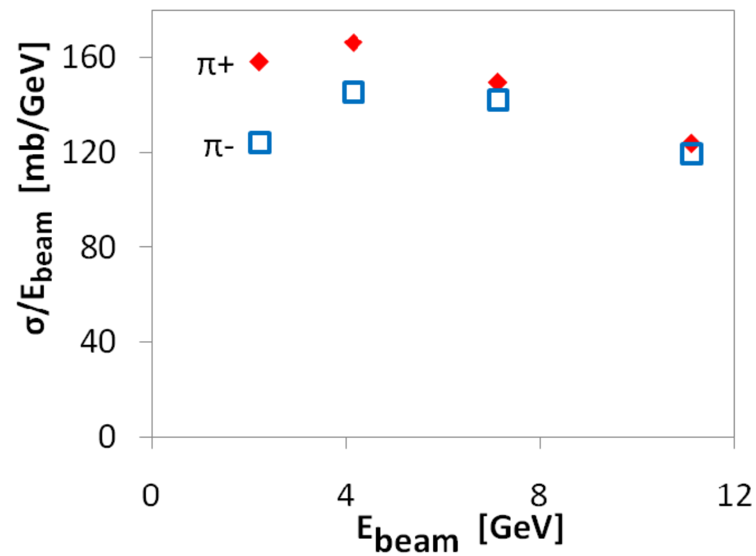
- **More recent estimates of muon production based on MARS15**
  - **determined optimum target radius and thickness (radiation lengths)**
- **Predicts low-energy fall-off even more extreme than with MARS14**
  - **high-energy fall-off also larger**
    - **at 60 GeV, down by about half from peak**



Proton Beam Energy (3)

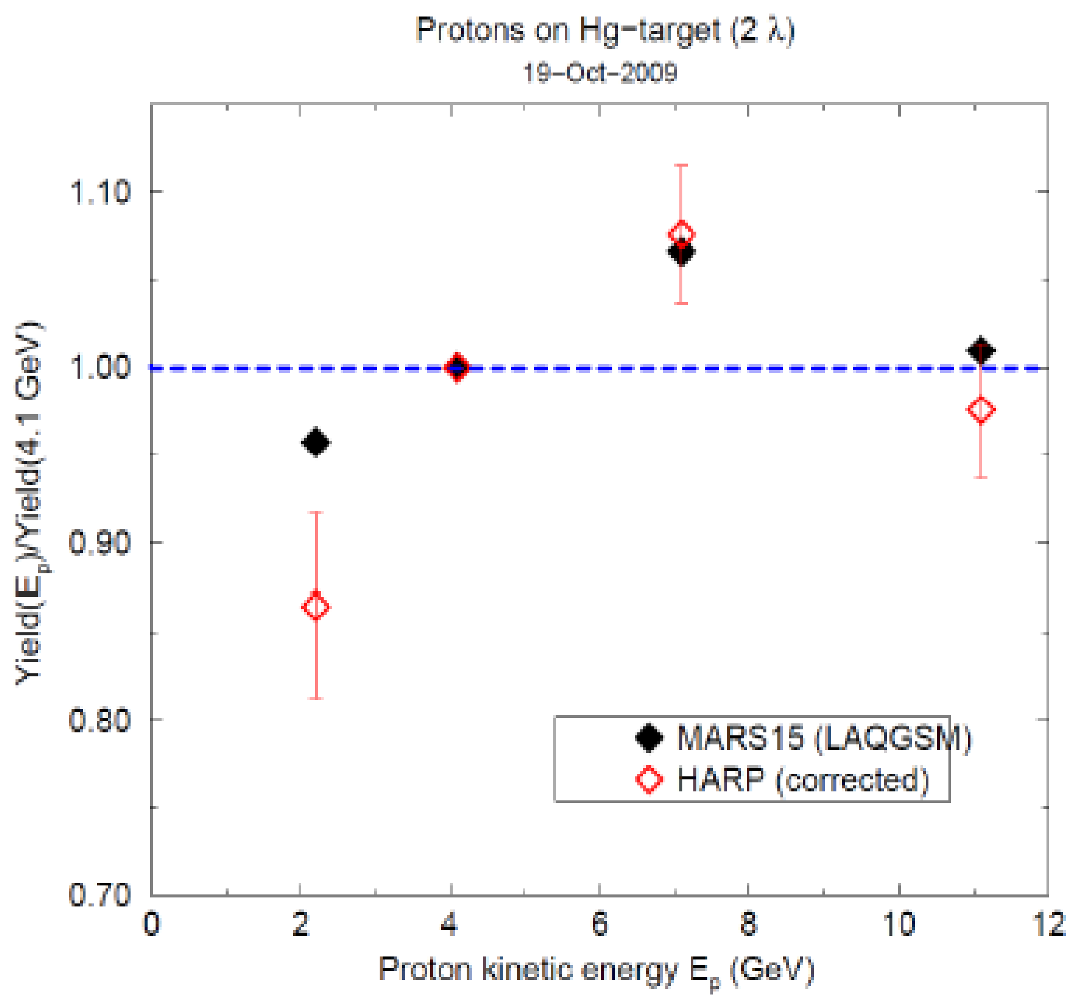
- **Steep fall-off predicted at low energy influences choice of energy range**
  - **as does desire for short bunches**

- **Recent inspection [Strait] of HARP data indicates that the fall-off predicted by MARS at low energy is not real**



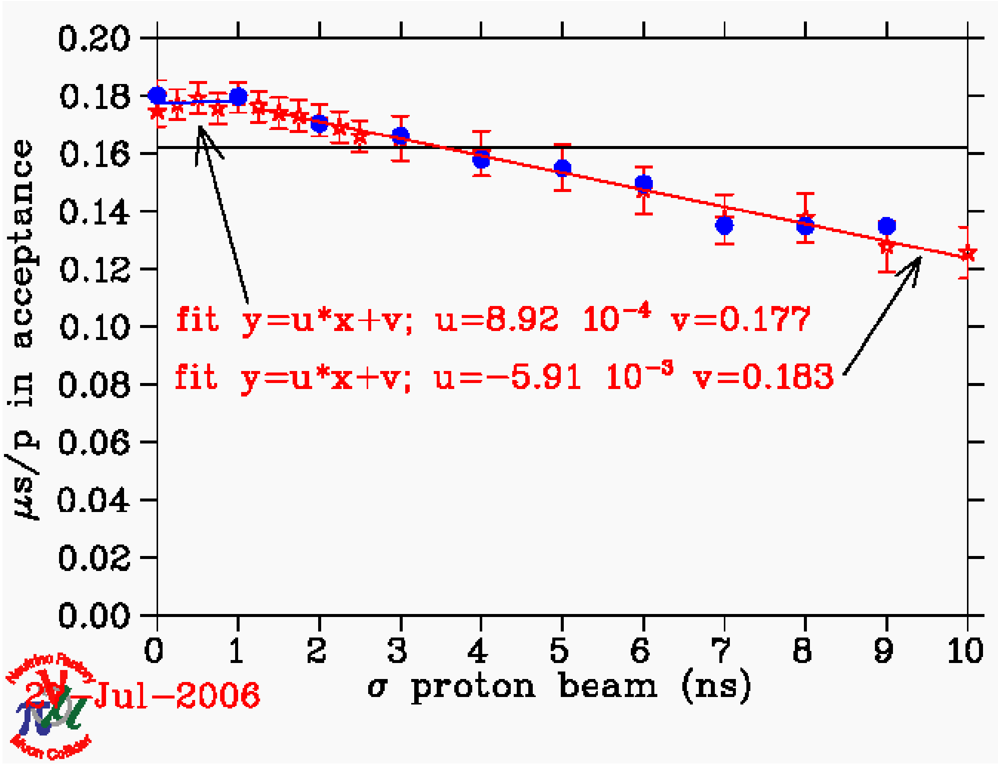
Proton Beam Energy (4)

- MARS meson generator (Mokhov) being improved based on HARP data



Bunch Length

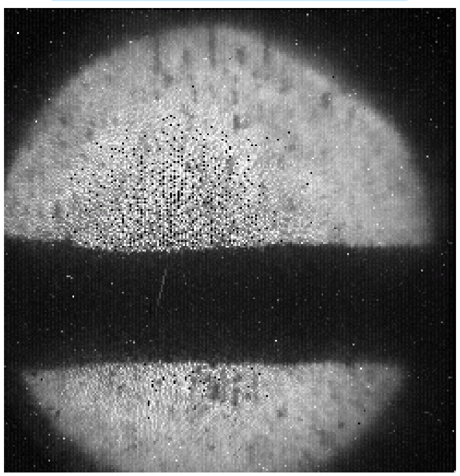
- **When evaluated after the cooling channel, there is a preference for short proton bunches**
  - 1 ns is preferred, but 2-3 ns is acceptable
    - for intense beam and "modest" energies, easier said than done
      - linac beam requires "post-processing" to give such parameters



Repetition Rate (1)

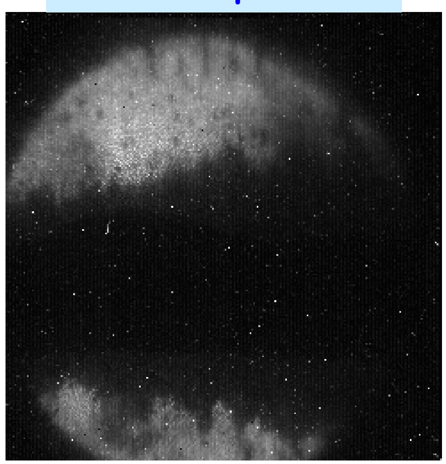
- Maximum proton repetition rate limited by target "disruption"
  - MERIT experiment demonstrated that Hg-jet can tolerate up to 70 Hz
    - disruption length of 22 cm takes 15 ms to recover with 15 m/s jet
  - nominal value taken for proton driver: 50 Hz for NF; ~15 Hz for MC

Undisrupted

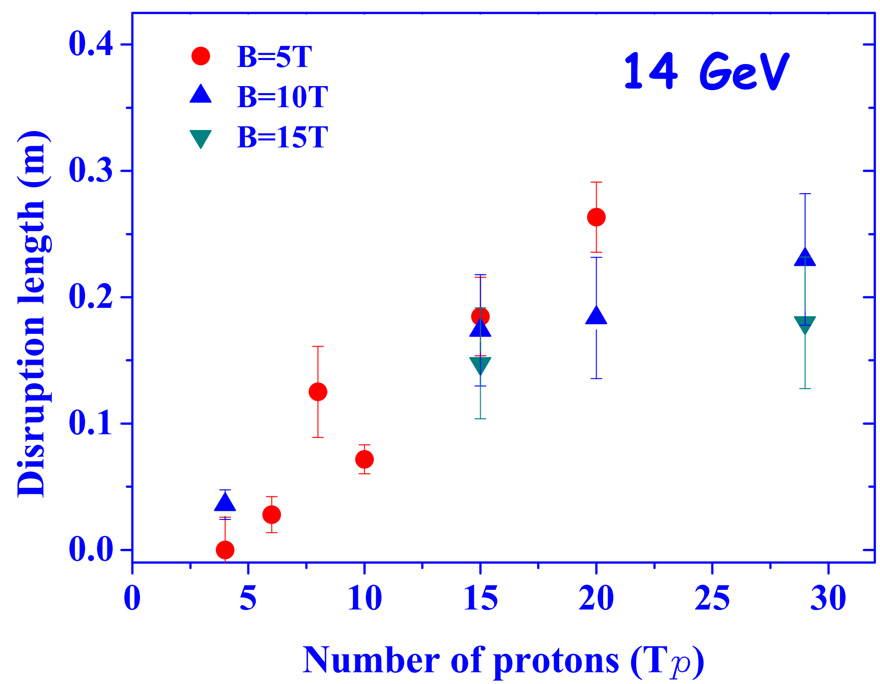


t=0

Disrupted

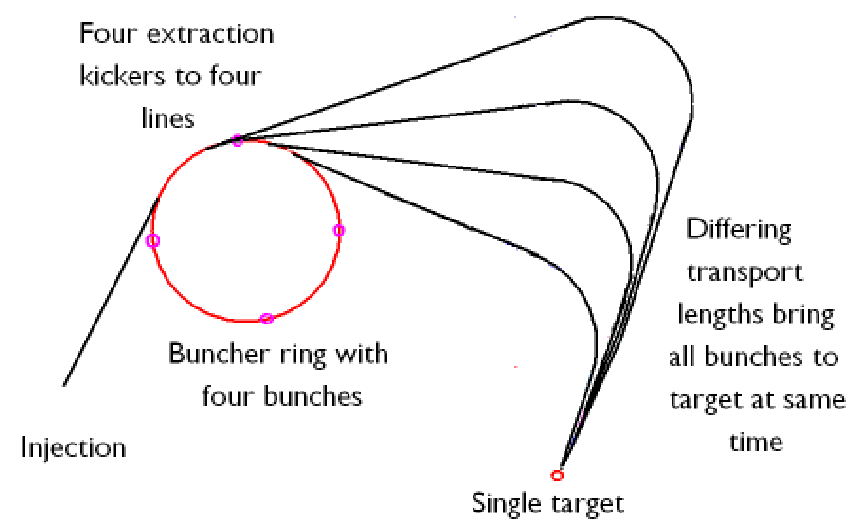


t=0.375 ms



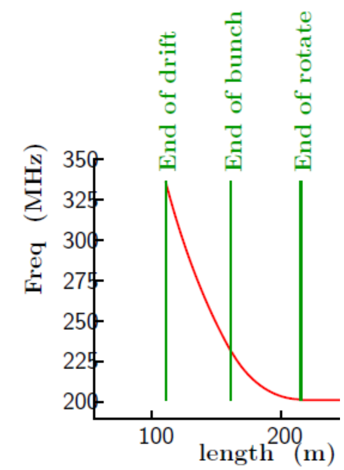
Repetition Rate (2)

- **Minimum repetition rate limited by space charge tune shift in compressor ring**
  - **to get desired intensity at target at 8 GeV, can use "workarounds"**
    - **use separate bunches in ring and combine at target by transport through "delay lines" [Ankenbrandt, Palmer]**
  - **for Muon Collider, where fewer bunches desired, could possibly merge bunches at higher energy (must increase power for same production)**
    - **no scheme for this yet developed**

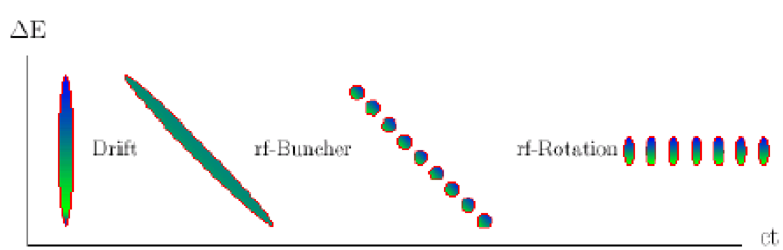


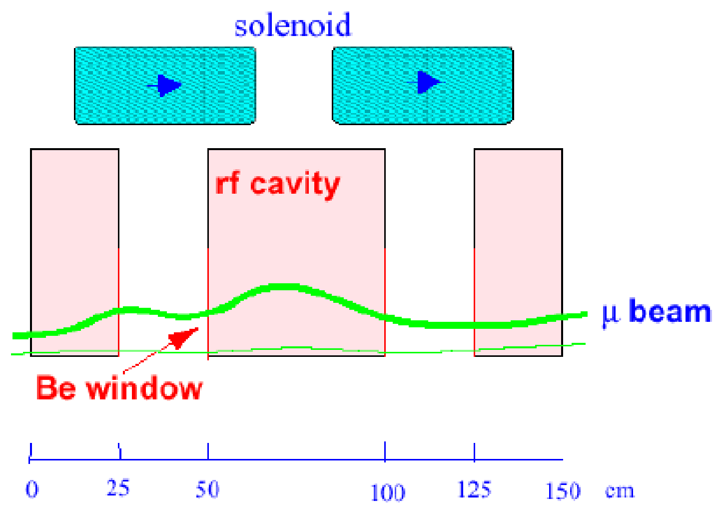
Bunching and Phase Rotation

- **Beam from target unsuitable for downstream accelerators**
  - **must be "conditioned" before use**
    - **reduce energy spread**
    - **create beam bunches for RF acceleration (201 MHz)**
  - **accomplished with RF system with many frequencies**
    - **has same RF issues as cooling channel (covered later)**
  - **optimization of length and performance under way**
    - **for MC prefer shortest possible bunch train**



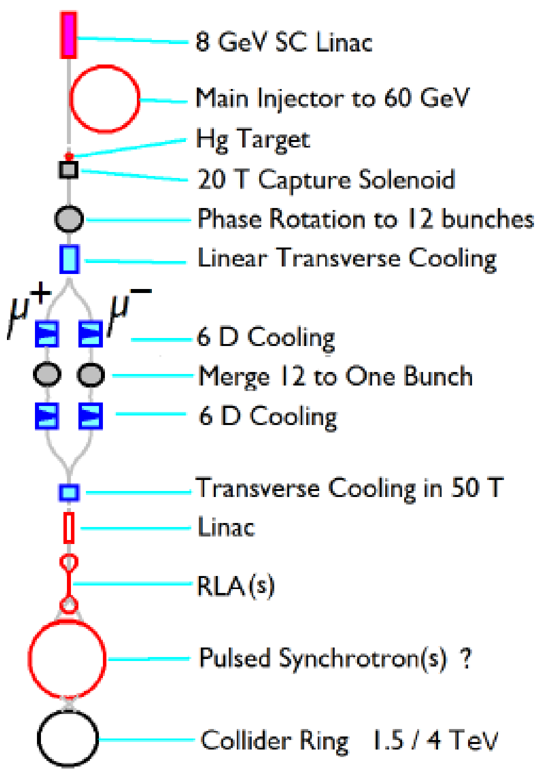
Neuffer scheme

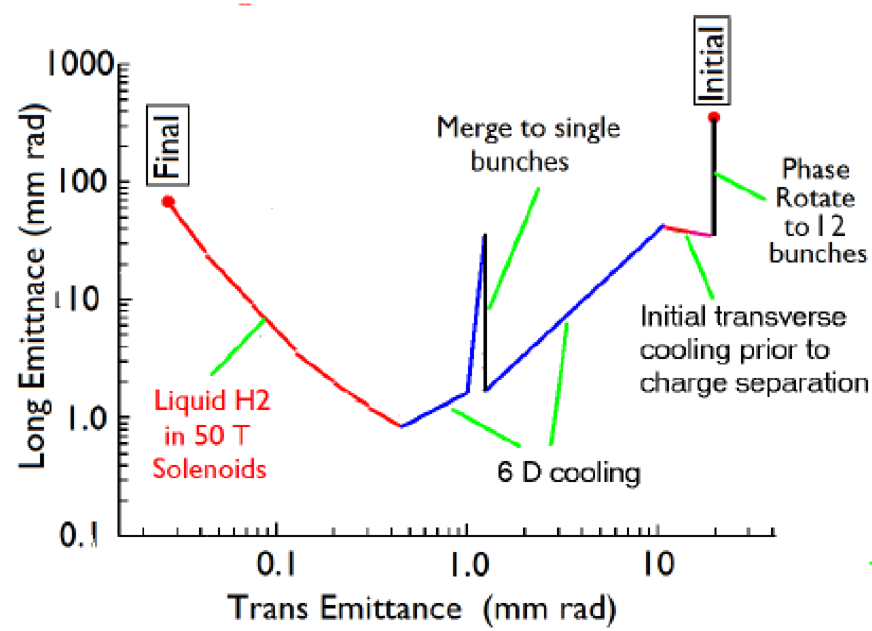




Bunch Trains?

- For MC, ultimately want only single μ^+ and μ^- bunches
  - plan is to do a bunch merging operation at some point in the beam preparation system
    - longitudinal emittance increases and then is cooled again

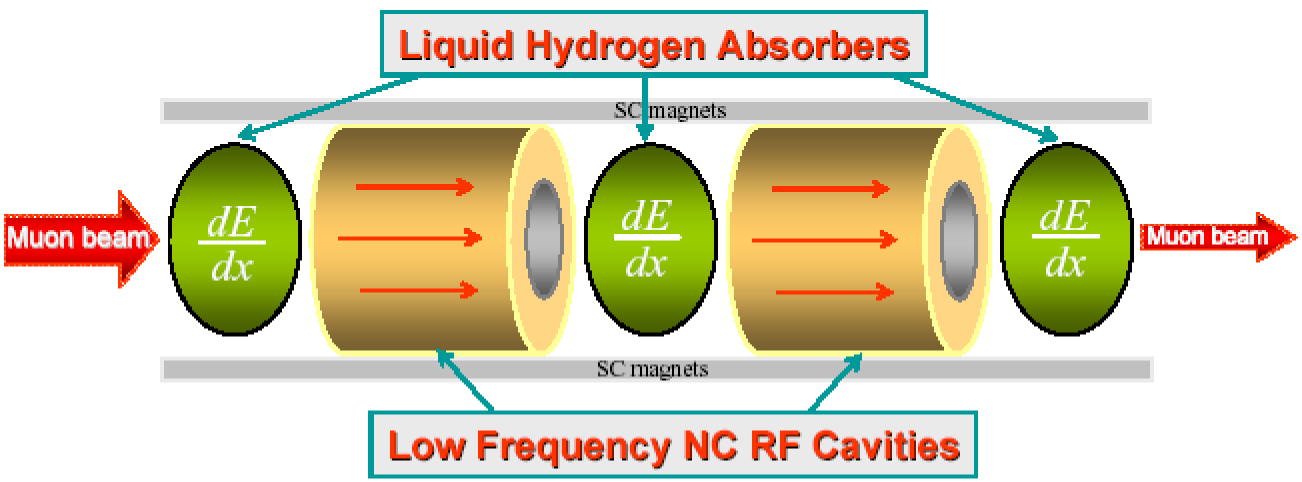




Ionization Cooling (1)

- **Ionization cooling analogous to familiar SR damping process in electron storage rings**
  - energy loss (SR or *dE/ds*) reduces p_x, p_y, p_z
  - energy gain (RF cavities) restores only p_z
  - repeating this reduces $p_{x,y}/p_z$ (⇒ 4D cooling)

  - presence of LH_2 near RF cavities is an engineering challenge
    - we get lots of "design help" from Lab safety committees!



Ionization Cooling (2)

- There is also a heating term
  - for SR it is quantum excitation
  - for ionization cooling it is multiple scattering

- Balance between heating and cooling gives equilibrium emittance

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left|\frac{dE_\mu}{ds}\right|\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

Cooling Heating

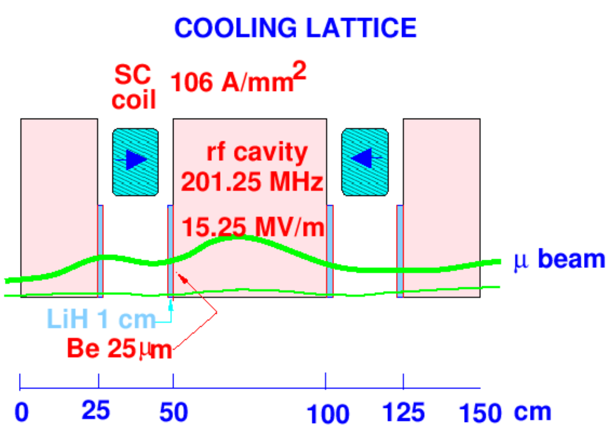
$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta m_\mu X_0 \left|\frac{dE_\mu}{ds}\right|}$$

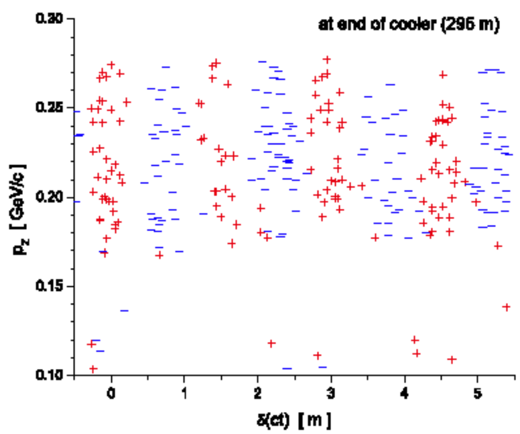
  - prefer low $\beta_\perp$ (strong focusing), large X_0 and dE/ds (H_2 is best)

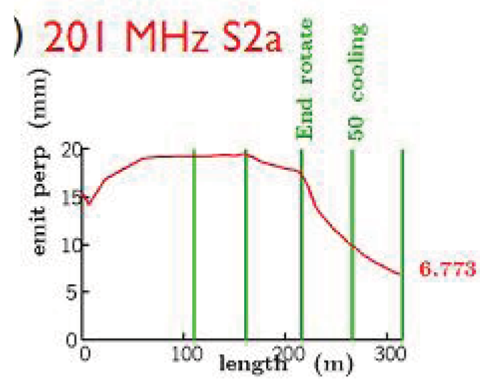
Initial Cooling Channel

- ISS compared all extant designs (Palmer)
  - FS2, FS2a, CERN, KEK channels

- Performance of FS2a channel found to be best
  - meets goal (with both signs) of 10^{21} useful decays per year
    - for ~4 MW of 5–15 GeV protons (2 ns bunches)
      - some margin in beam power would be prudent
  - chose this as baseline configuration for NF studies

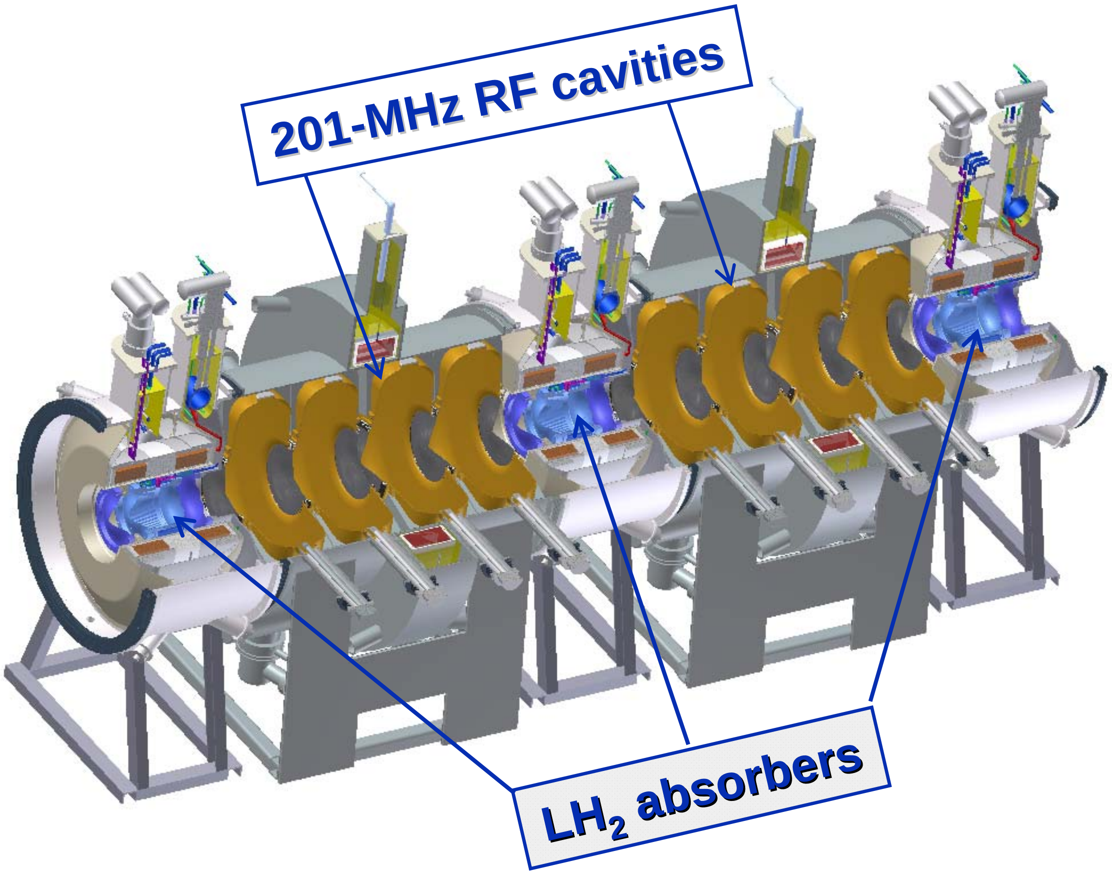






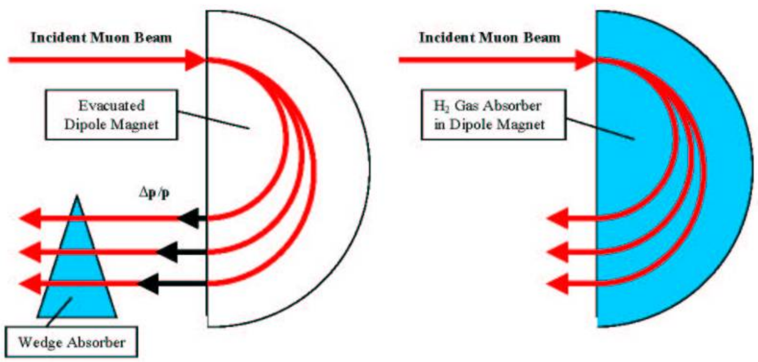
Cooling Channel Implementation

- **Actual implementation is complex**
  - **example shown (from MICE) is earlier cooling channel design**
    - **baseline design was subsequently simplified (somewhat)**



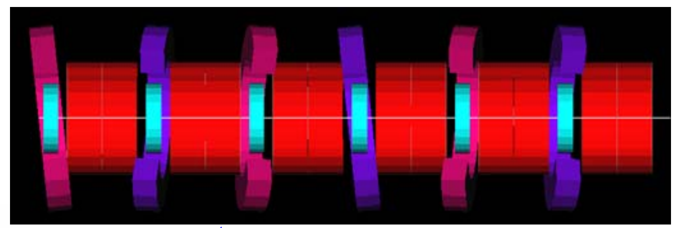
6D Cooling

- For MC, need 6D cooling (emittance exchange)
  - increase energy loss for high-energy compared with low-energy muons
    - put wedge-shaped absorber in dispersive region
    - use extra path length in continuous absorber

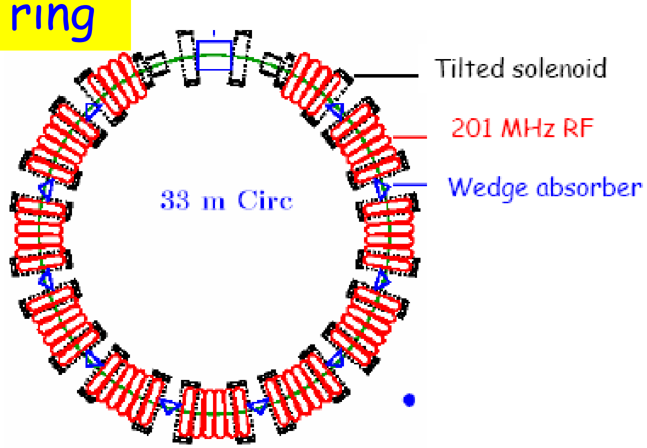


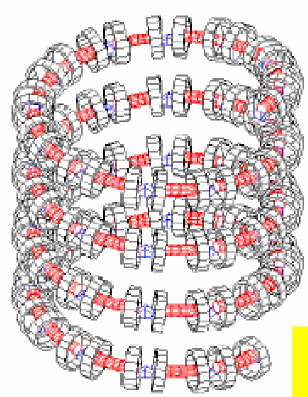
Muons, Inc.

FOFO Snake



Cooling ring





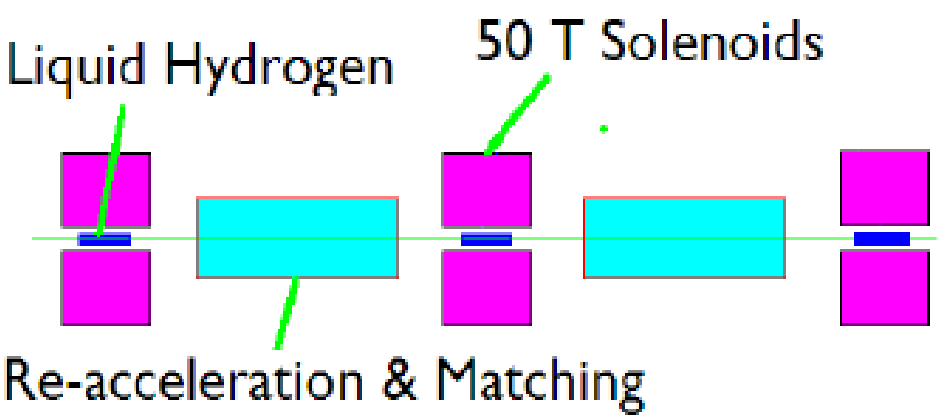
Single pass; avoids injection/extraction issues

"Guggenheim" channel

Final Cooling

- Final cooling to 25 μm emittance requires strong solenoids
  - not exactly a catalog item ⇒ R&D effort
  - 50 T is not a hard edge, but "more is better"

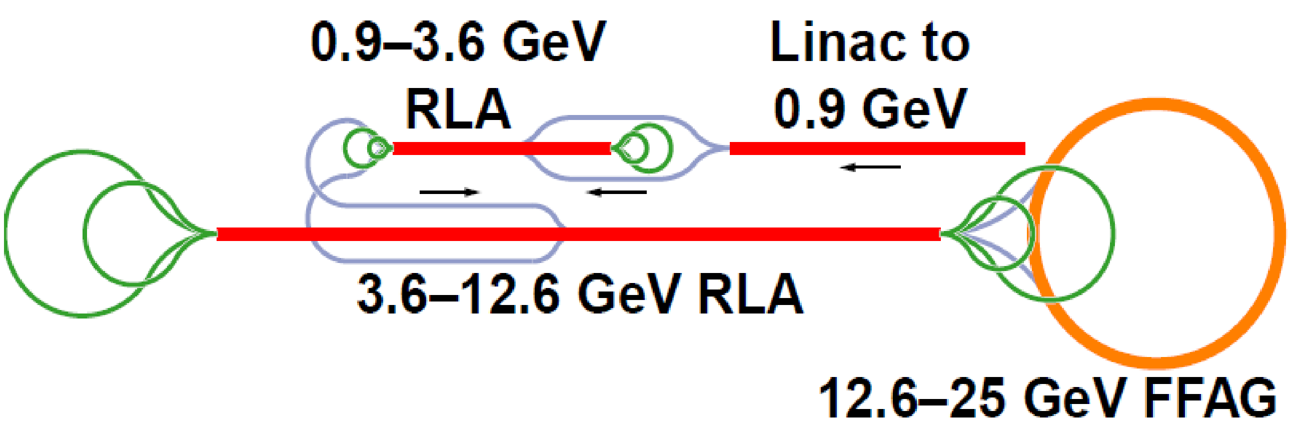
- 45 T hybrid device exists at NHMFL
  - very high power device
  - exploring use of HTS for this task
    - most likely technology to work



Acceleration (1)

- **Low-energy scheme**
  - **linac followed by two dog bone RLAs, then non-scaling FFAG**
    - **keeps both muon signs**
  - **system accommodates 30 mm transverse and 150 mm longitudinal acceptance**

Bogacz

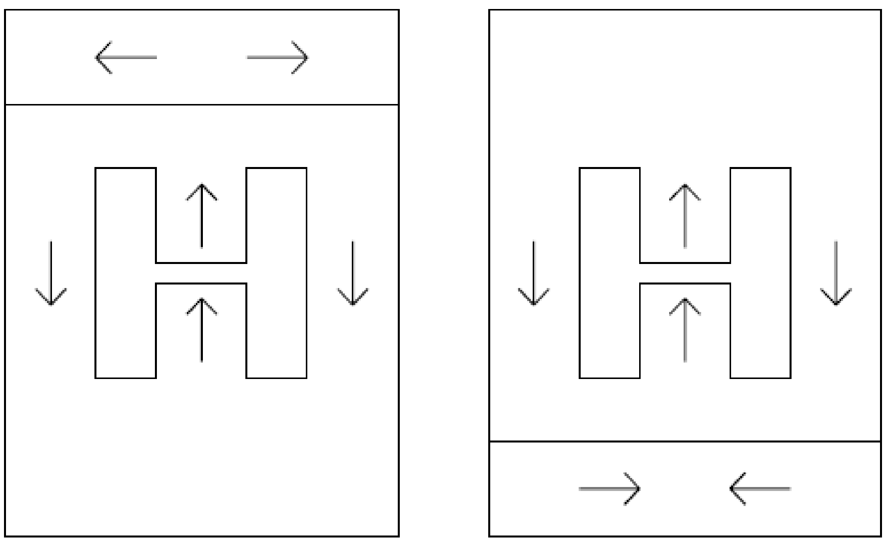


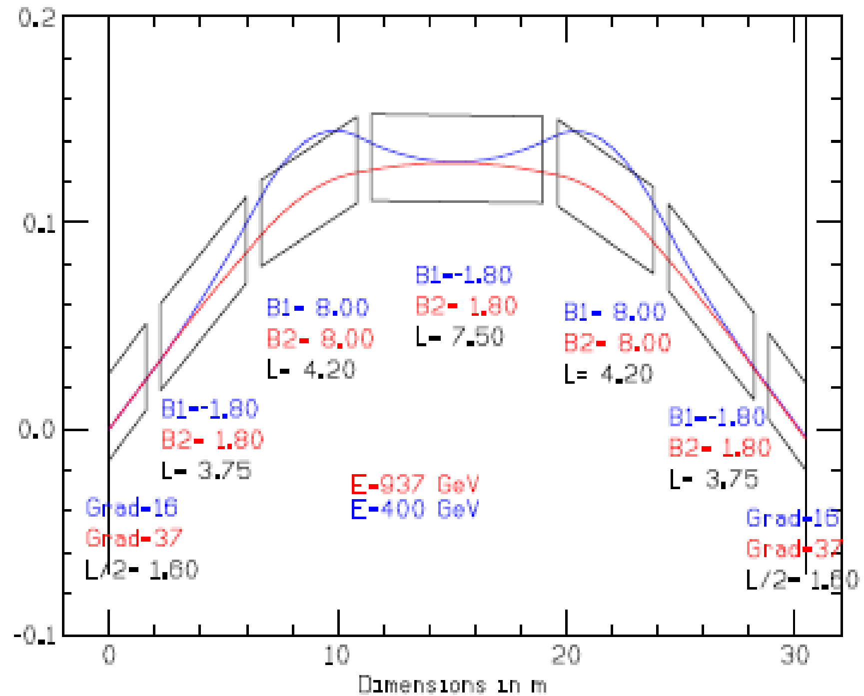
Acceleration (2)

- **High-energy scheme**
  - **to reach 1.5 TeV, use pair of rapid-cycling synchrotrons in Tevatron tunnel**
    - **30-400 GeV + 400-750 GeV**

Use combination of conventional and SC dipoles for high-energy RCS

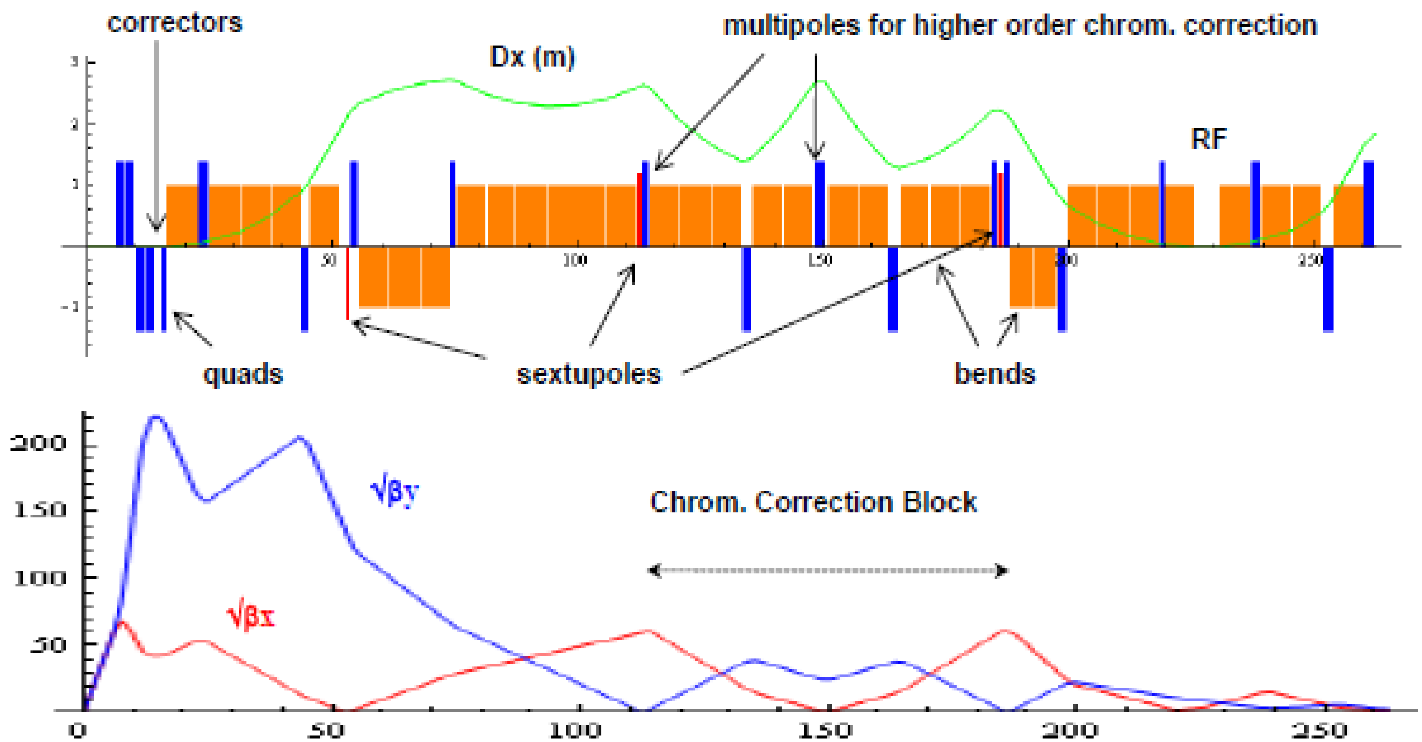
Use grain-oriented Si steel dipoles for low-energy RCS





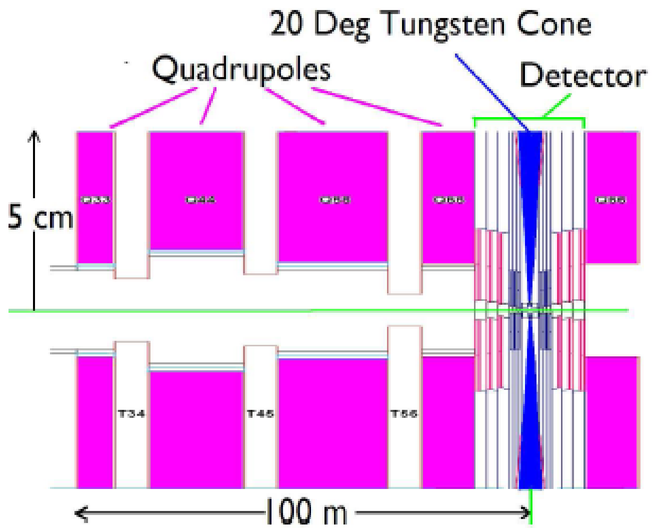
Collider Ring

- **Lattice design for 1.5 TeV collider being developed (Alexahin, Gianfelice-Wendt)**
  - **dynamic aperture ~4.5σ (no errors, no misalignment, no beam-beam)**
  - **momentum acceptance 0.8%**
  - **progress is encouraging**

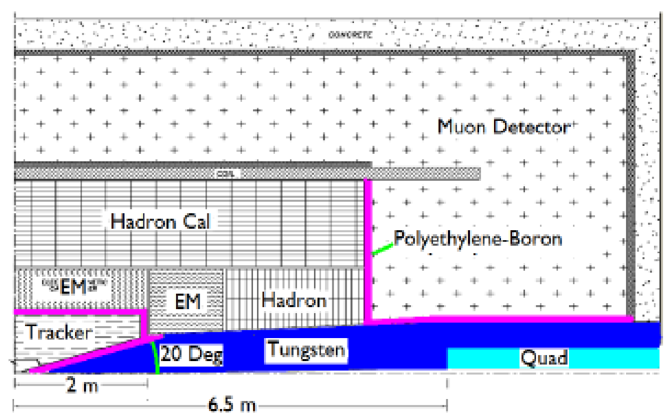


Machine-Detector Interface

- **MDI will be a key design activity**
  - needed to assess ultimate physics capability of facility
  - needed to assess and mitigate expected backgrounds
- **Successful collider requires that detector and shielding be tightly integrated into machine design**
- **Participants at this meeting will contribute to this effort!**



Shielding



Detector

R&D Program

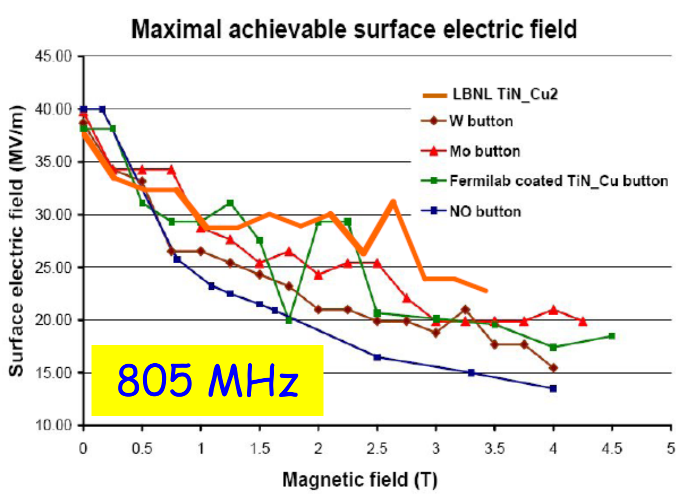
- To validate design choices, need substantial R&D program
  - three categories (simulations, component development, system tests)
  - under way in many places
    - for NF, "loose but effective" international coordination
    - MC presently a US endeavor
      - but hope for broader participation
- Simulations include design and performance optimization
  - front end now under IDS-NF auspices (Berg, Pozimski, Prior)
- Component R&D includes development of RF, magnets, absorbers (MuCool program)
  - especially high-gradient RF in a magnetic field (Bross, Torun, Li, Moretti, Palmer, Huang, Norem, ...)
- System tests carried out by international collaborations
  - proof-of-concept tests to validate overall performance and cost

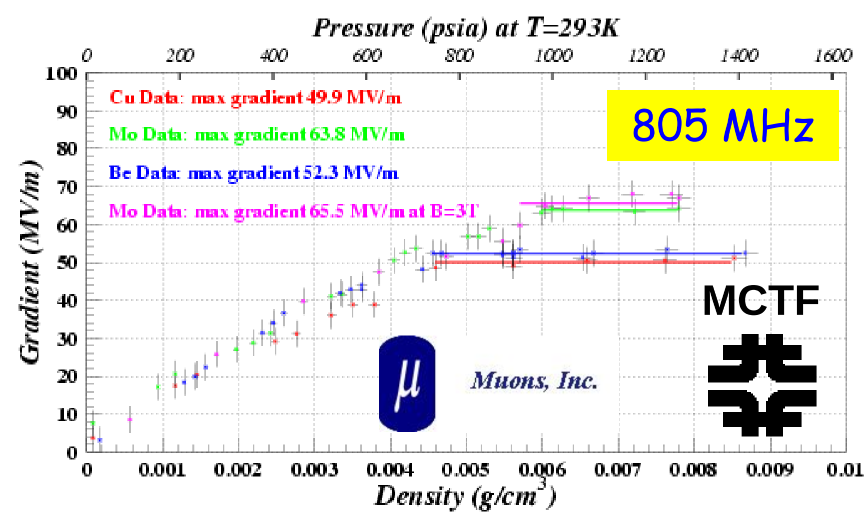
R&D Issues

- Main Muon Collider R&D issues include:
  - simulations
    - optimization of subsystem designs
    - end-to-end tracking of entire facility
  - components
    - operation of normal conducting RF in an axial magnetic field
    - development of low-frequency SRF cavities
    - development of high-field solenoids for final cooling
    - development of fast-ramped magnets for RCS
    - decay ring magnets that can withstand the mid-plane heat load from muon decay products
  - system tests
    - high-power target proof-of-concept [MERIT]
    - ionization cooling channel proof-of-concept [MICE]
    - future 6D cooling experiment

NCRF Issue

- Main challenge for cooling channel is operation of RF in axial magnetic field
  - applies equally to bunching and phase rotation section
- R&D has shown that maximum gradient degrades in magnetic field for "vacuum" RF
  - HPRF does not show this effect
  - evaluating different cavity materials and response of HPRF to beam

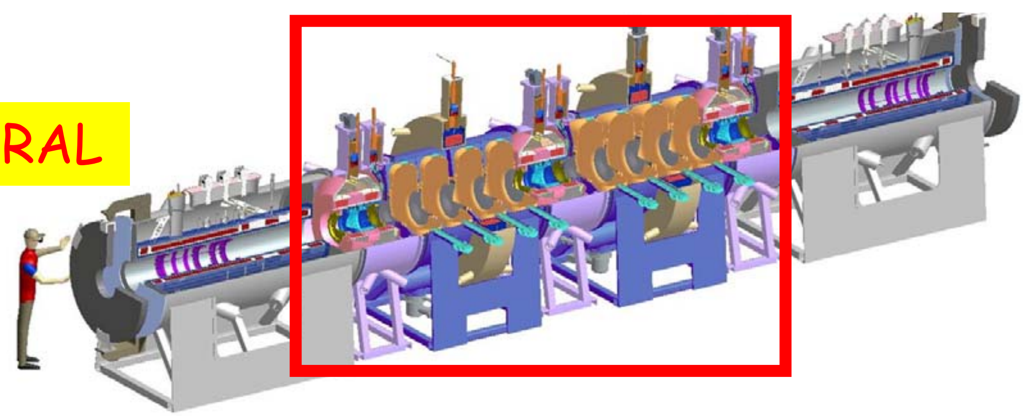




MICE

- Cooling demonstration aims to:
  - design, engineer, and build a section of cooling channel capable of giving the desired performance for a Neutrino Factory
  - place this apparatus in a muon beam and measure its performance in a variety of modes of operation and beam conditions
- Another key aim:
  - show that design tools (simulation codes) agree with experiment
    - gives confidence that we can optimize design of an actual facility
- Getting the components fabricated and operating properly is teaching us a lot about both the cost and complexity of a muon cooling channel
  - measuring the "expected" cooling will serve as a proof of principle for the ionization cooling technique

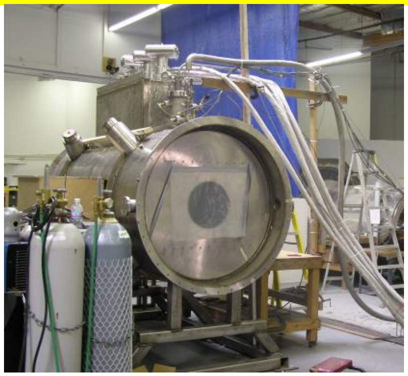
Experiment sited at RAL



MICE Components

- **All MICE cooling channel components are now in production**

Spectrometer Solenoid (Wang NMR)

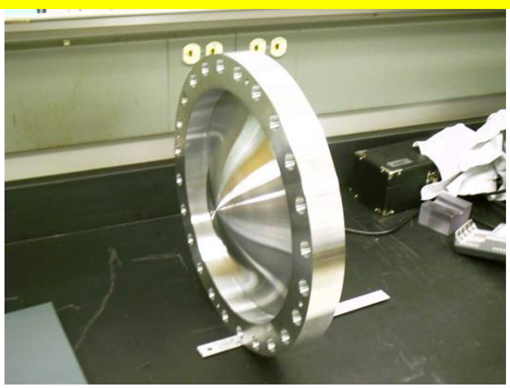


CC large test coil (HIT)

CC mandrel (Qi Huan Co.)

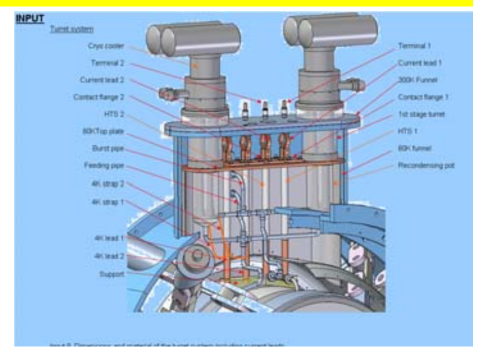
Absorber (KEK)

Absorber window (U-Miss)



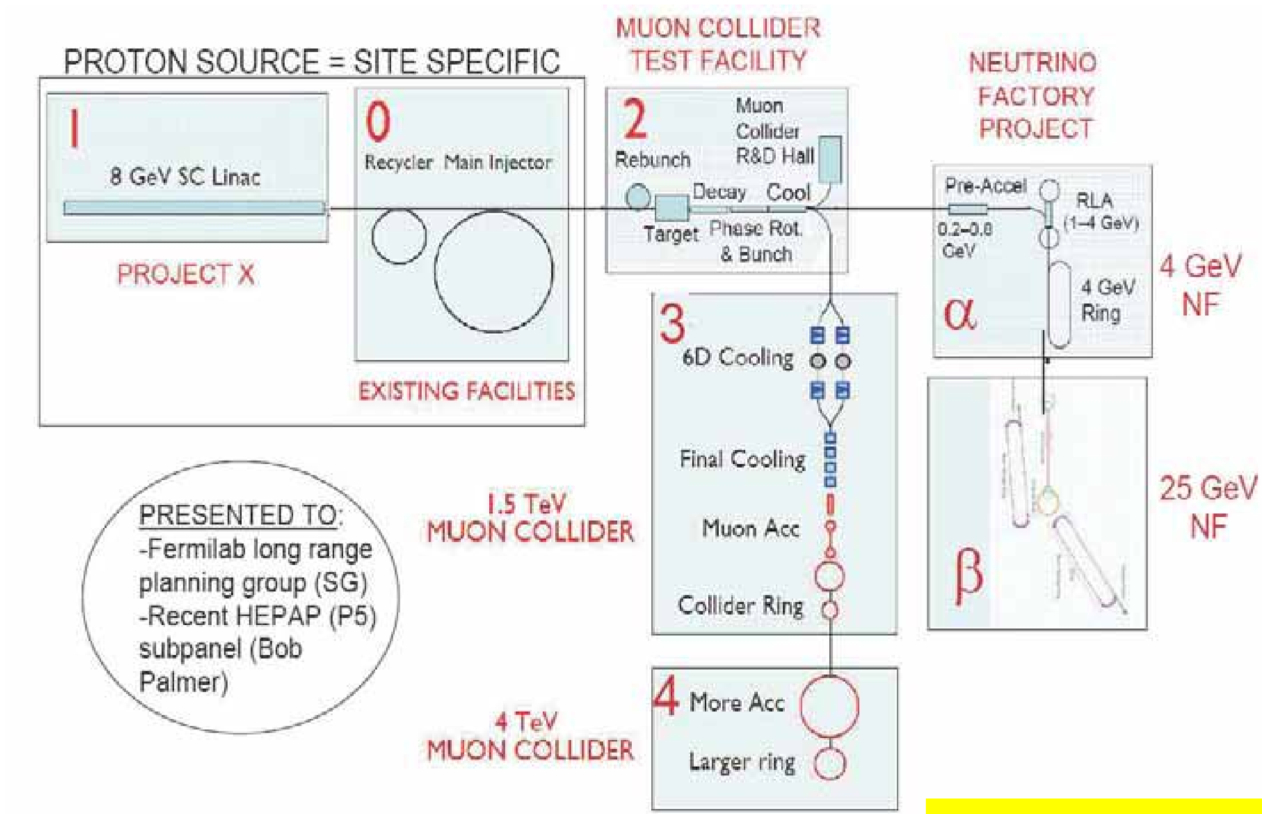
Cavities (Applied Fusion)

FC (Tesla Eng., Ltd.)



Possible U.S. Scenario

- **Possible muon beam evolution at Fermilab**



Note: this is thus far only a *concept*, there is no formal request for funding.

Summary

- R&D toward a MC making steady progress
  - MERIT established ability of Hg-jet to tolerate >4 MW of protons
  - MICE is progressing (major components all in production)
    - looking forward to first ionization cooling measurements in a few years!
  - DOE will review 5-year R&D plan aimed at MC soon
    - new combined organization being created to manage R&D program
- Machine design is progressing well
  - promising collider lattice
  - performance of all subsystems simulated to some degree
    - end-to-end simulations remain to be done
- Development of muon-based accelerator facilities offers great scientific promise and remains a worthy—and challenging—goal to pursue