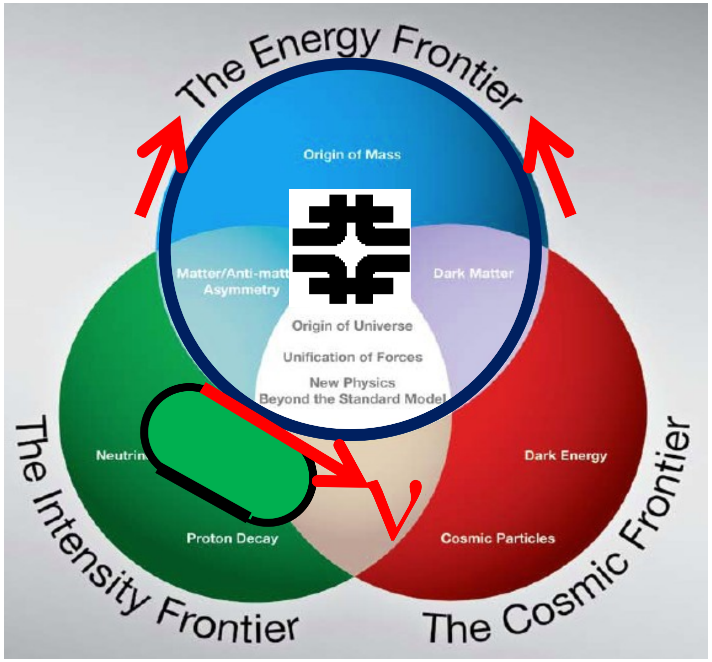

Muon Collider
Design and R&D

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Americas Linear Collider Physics Group Meeting—Eugene, OR
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Introduction

- Muon-based collider would 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
  - organizations have now merged to form Muon Accelerator Program (MAP)
- Recent interest by Fermilab management has spurred increased effort to understand Muon Collider design

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 or beamstrahlung
      - narrow energy spread at IP compared with e^+e^- collider
      - re-uses expensive RF equipment (circular $\Rightarrow$ fits on existing Lab sites)
  - neutrino sector
    - Neutrino Factory beam properties

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu$$

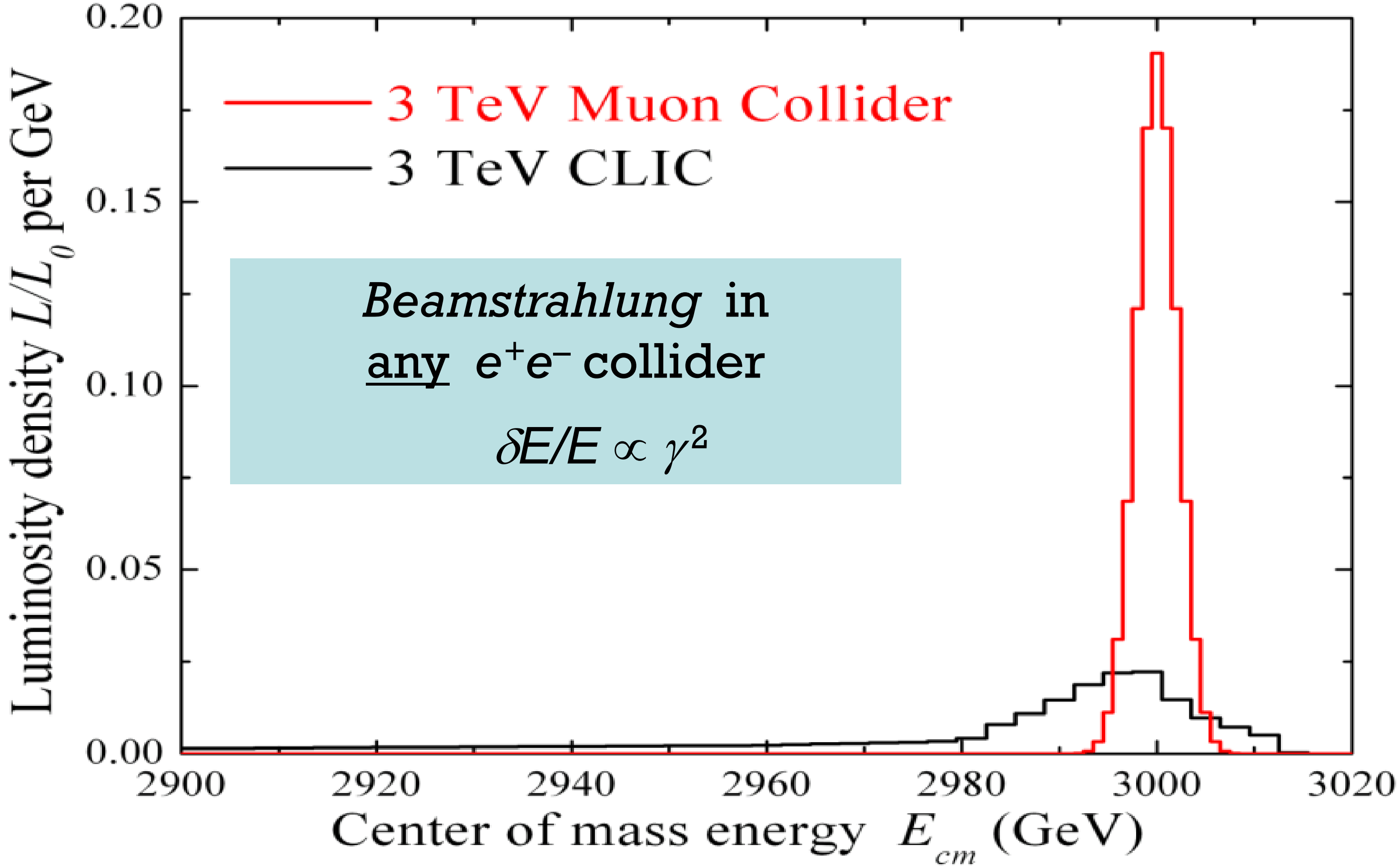
Produces high energy ν_e, above τ threshold

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

Unmatched sensitivity for CP violation, mass hierarchy, and unitarity

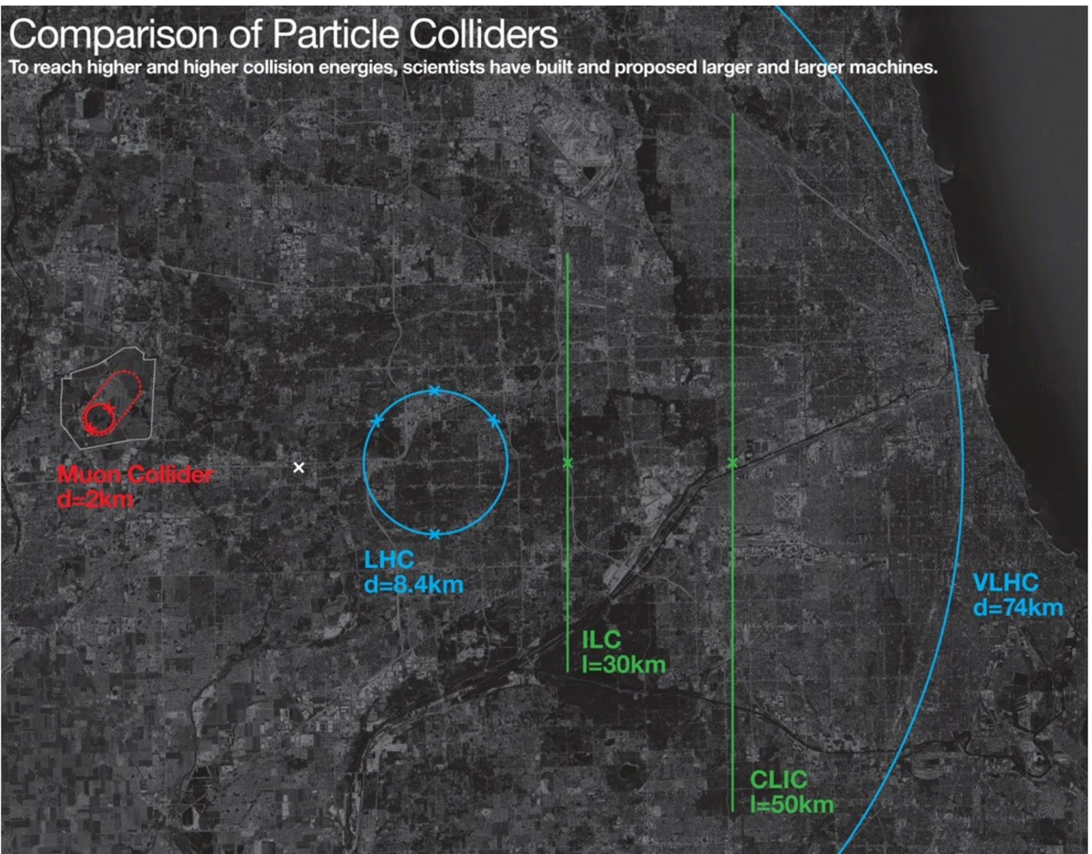
Collider Energy Spread

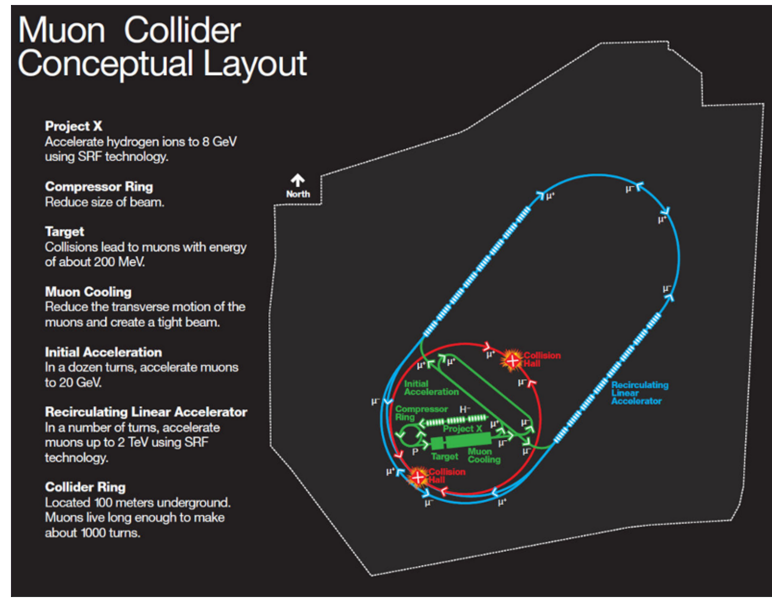
- **High muon mass greatly reduces beamstrahlung**



Size Matters

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





Muon Collider would provide world-class science program at Fermilab

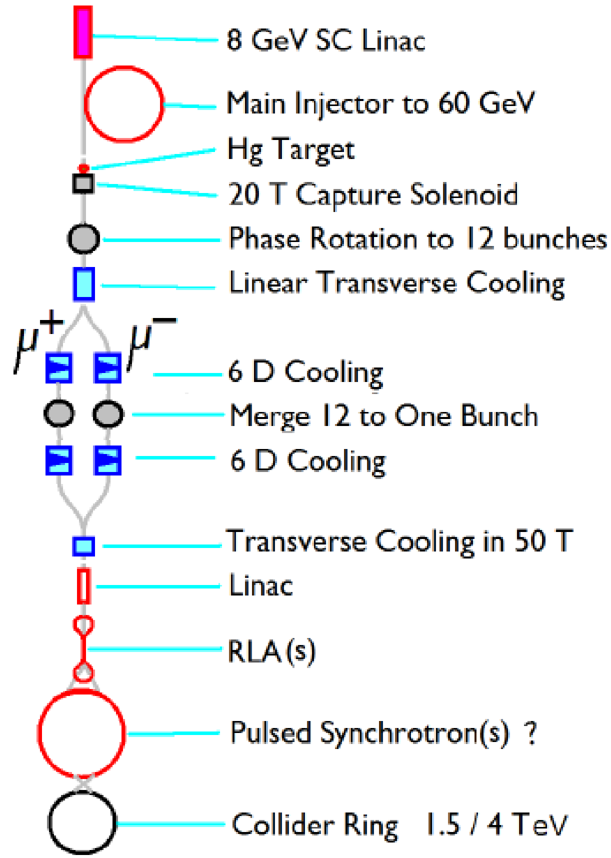
Muon Beam Challenges

- 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 emittance cooling
    - high-acceptance acceleration system and collider/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
  - decay electrons give rise to heat load in magnets and backgrounds in collider detector

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

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 μ ⇒ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse and long. emittance
    - ⇒ MICE → 6D experiment
  - Acceleration
    - ~5 MeV → ~1 TeV
    - with RLAs, FFAGs or RCSs
  - Collider Ring
    - store for ~1000 turns



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

Muon Collider Parameters

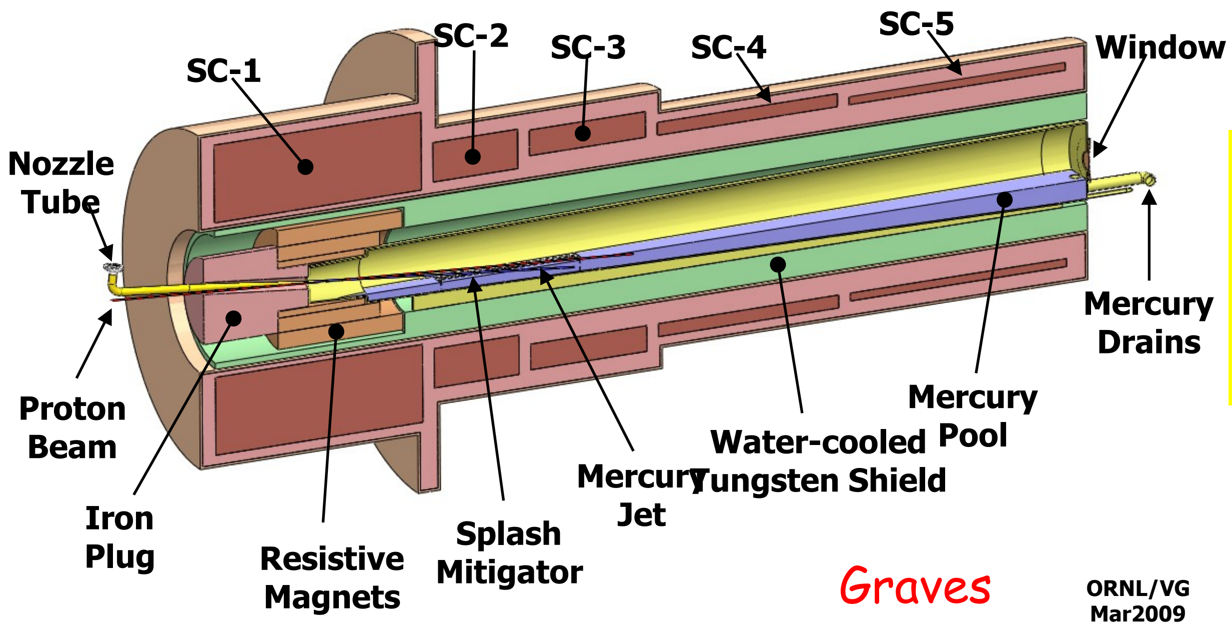
- Example parameters for MC scenarios given below [Alexahin, Palmer]

Parameter	Value	
$E_{c.m.}$ (TeV)	1.5	3.0
Luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	4×10^{34}
Beam-beam tune shift	0.087	0.087
Muons per bunch	2×10^{12}	2×10^{12}
Beam stored energy (kJ)	480	960
Circumference (km)	2.6	4.5
Avg. dipole field (T)	6	8.4
Bunch length, rms (mm)	10	5
β^* (mm)	10	5
$\delta p/p$	0.001	0.001
f_{rf} (MHz)	805	805
V_{rf} (MV)	20	230
Repetition rate (Hz)	15	12
Proton beam power (MW)	~4	~4
$\varepsilon_{\perp}$, norm. (μm)	25	25
ε_{L}, norm. (mm)	72	72

Target and Pion Capture (1)

- **Baseline target is free Hg-jet**
  - *this is the "context" for evaluating Proton Driver needs*
- **Capture based on 20-T solenoid, followed by tapered solenoidal channel to bring field down to 1.5 T**

Muon Collider / Neutrino Factory Target Concept

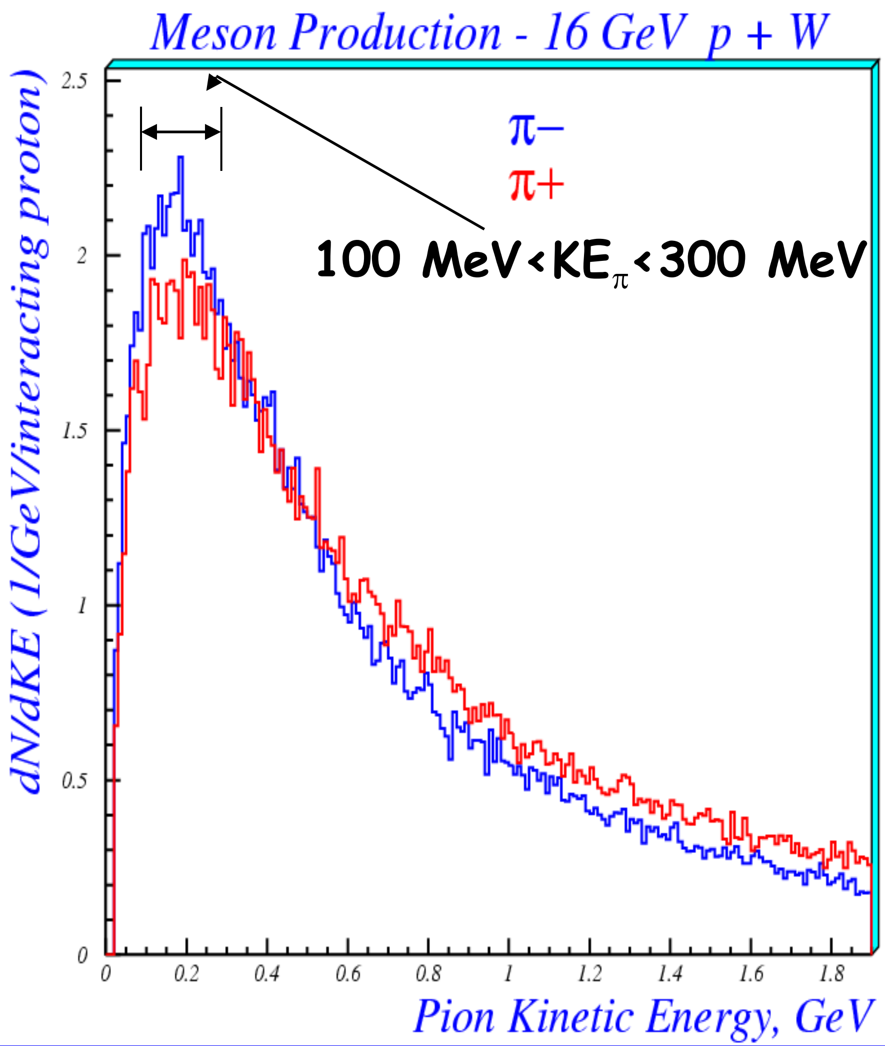


High radiation environment remains a formidable challenge

Graves

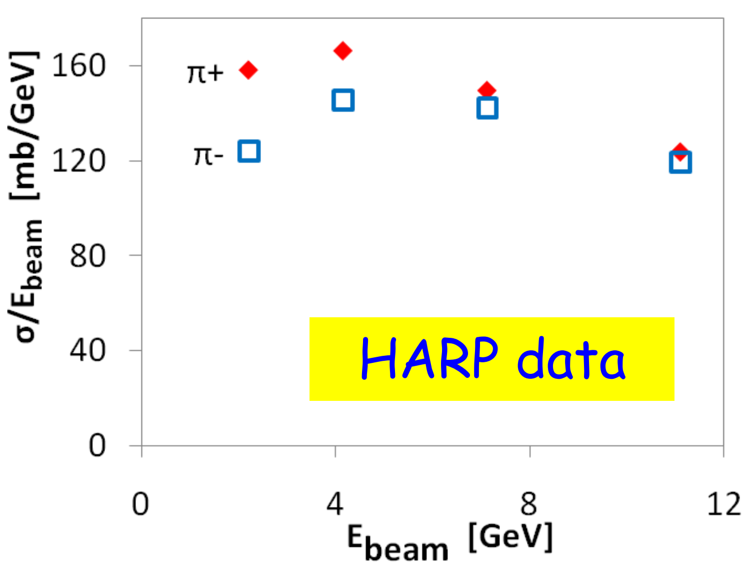
Target and Pion Capture (2)

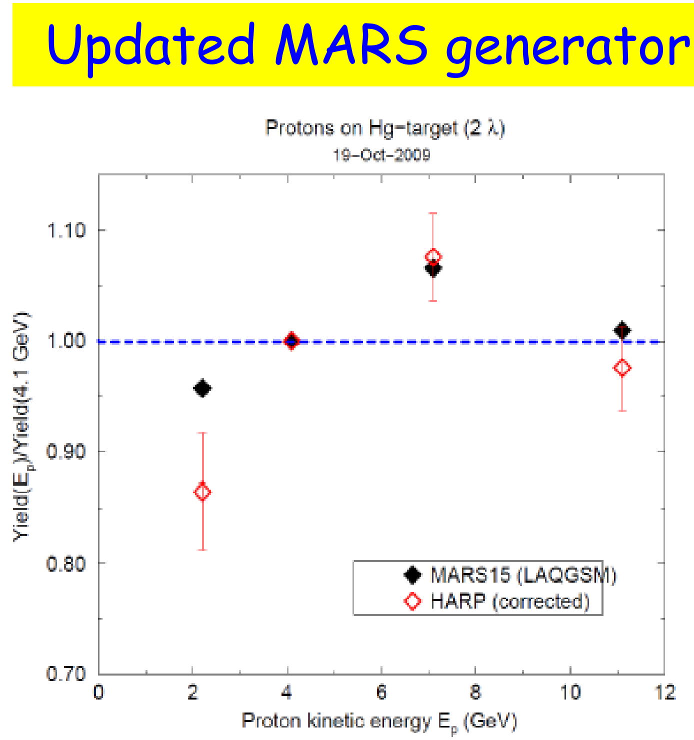
- **Capture of low energy pions is optimal for cooling channel**



Proton Beam Energy

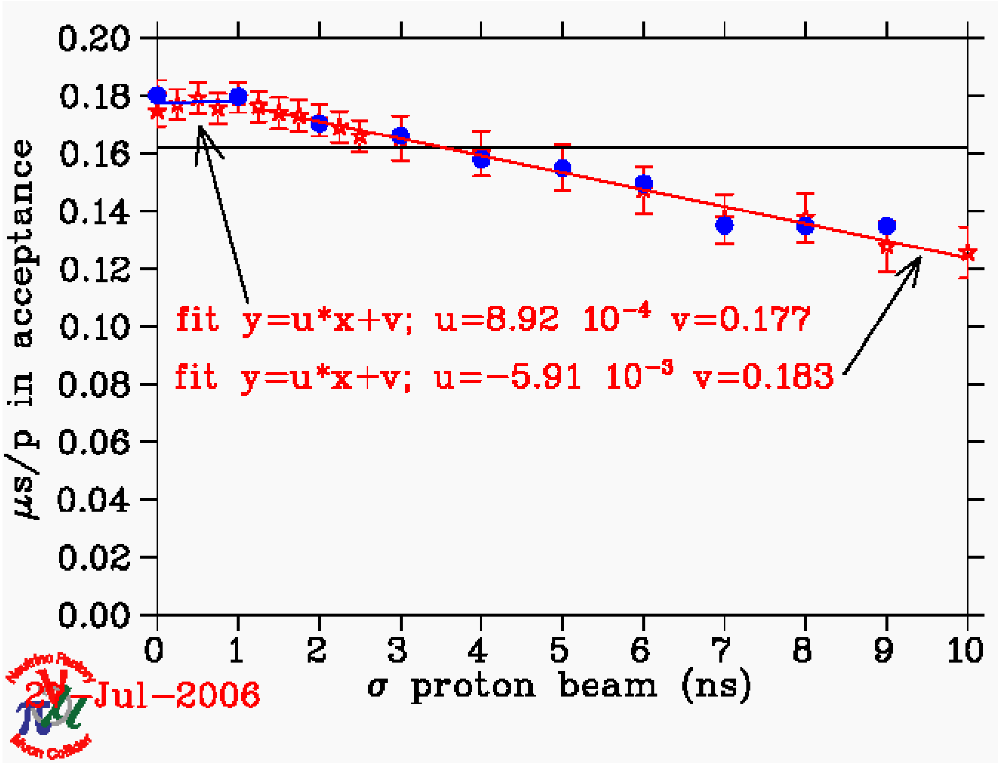
- Muon production estimate based on MARS15 (Kirk, Ding)
  - optimum energy ~8 GeV
    - assessed optimum target radius and thickness (radiation lengths)
- Using improved MARS meson generator (Mokhov)
  - based on HARP data





Bunch Length

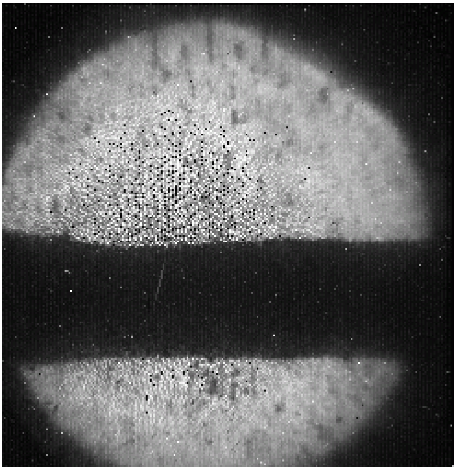
- When production is evaluated after the cooling channel, there is a preference for **short** proton bunches
  - 1 ns is preferred, but 2-3 ns is acceptable
    - for intense beam and "modest" energies, easier said than done
      - linac beam requires "post-processing" rings to give such parameters



Repetition Rate (1)

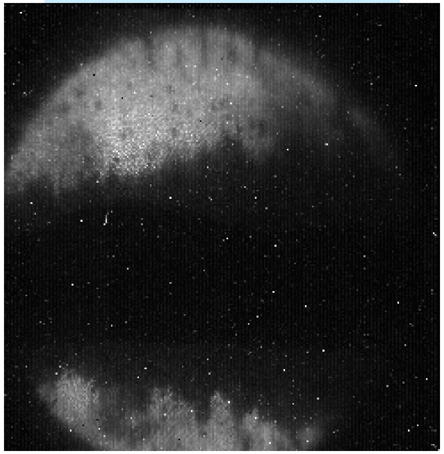
- Maximum proton repetition rate limited by target "disruption"
  - MERIT experiment demonstrated that Hg-jet can tolerate up to 70 Hz
    - disruption length of 20 cm takes 14 ms to recover with 15 m/s jet
  - nominal value taken for proton driver: 50 Hz for NF; ~15 Hz for MC

Undisrupted

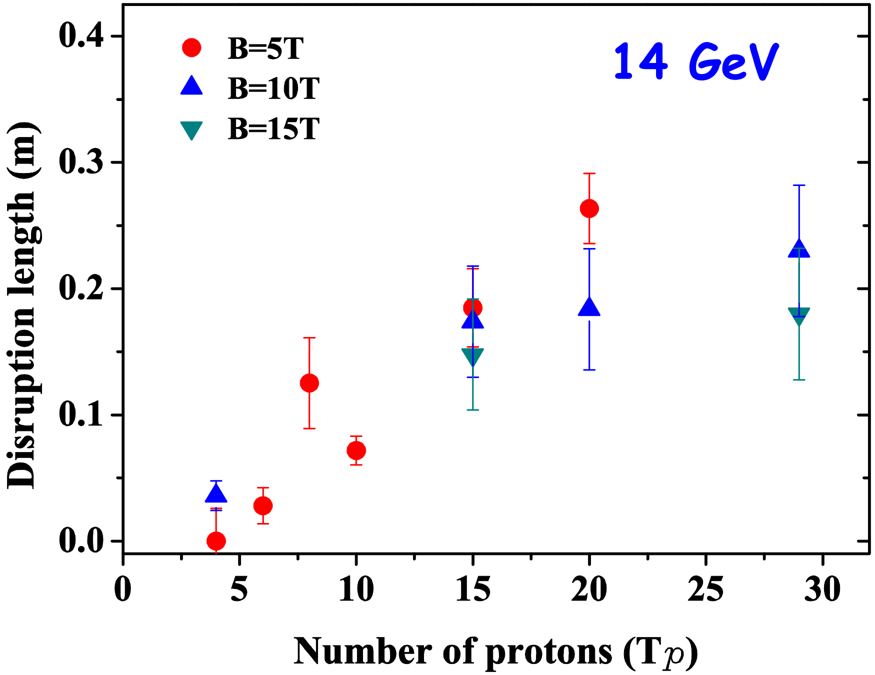


t=0

Disrupted

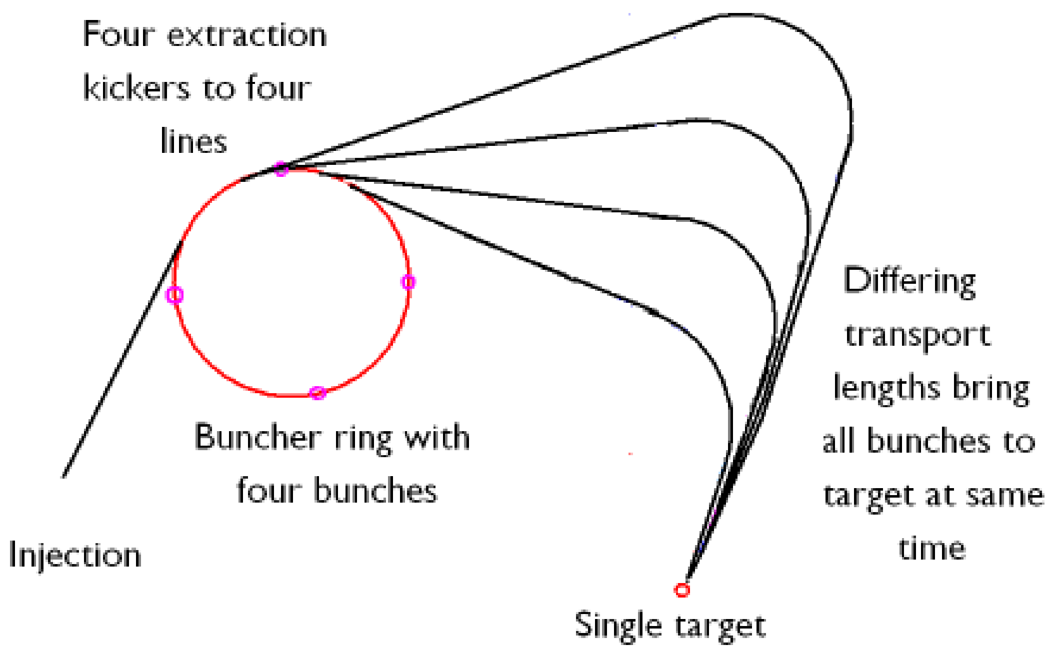


t=0.375 ms



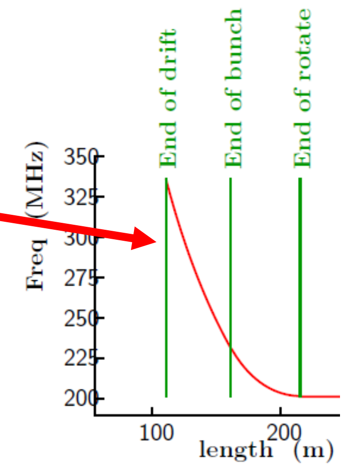
Repetition Rate (2)

- **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]**

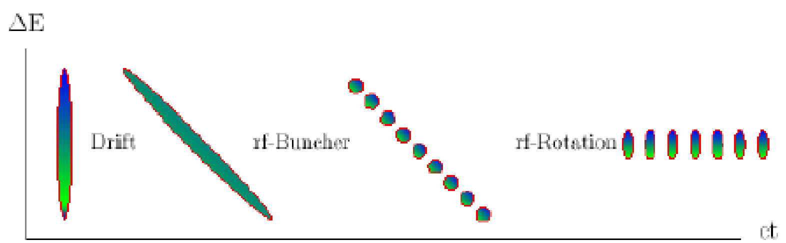


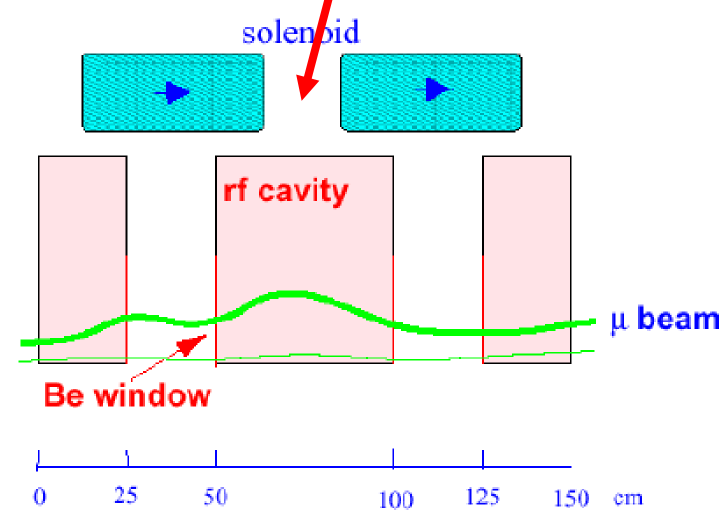
Bunching and Phase Rotation

- Beam from target unsuitable for downstream accelerators
  - must be "conditioned" before use
    - create beam bunches for RF acceleration (201 MHz)
    - reduce energy spread
  - accomplished with RF system with distributed frequencies
  - optimization of length and performance under way
    - for MC prefer shortest possible bunch train



Neuffer scheme

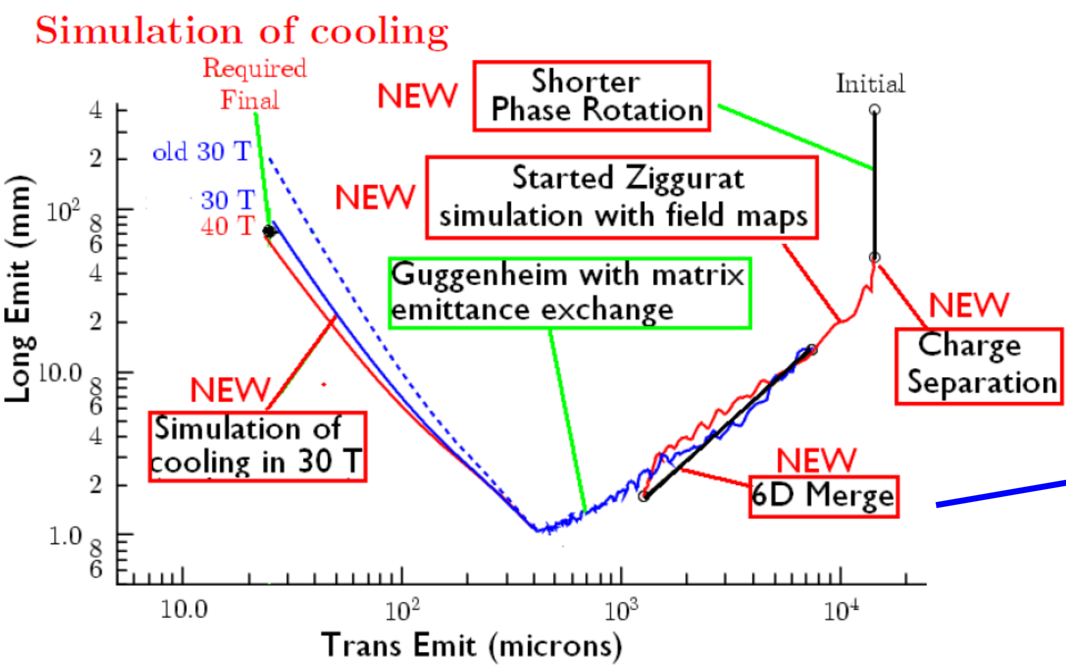


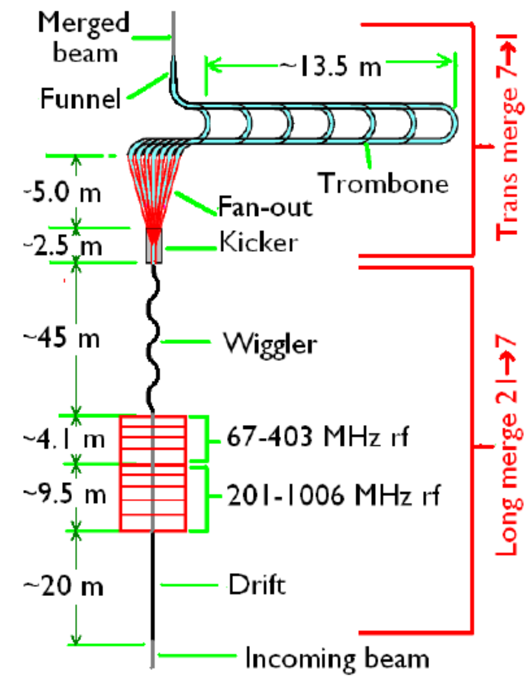


Muon Bunch Merging

- For MC, ultimately want only single μ^+ and μ^- bunches
  - do bunch merging operation at some point in the beam preparation system
    - latest concept is to do bunch merging in 6D
      - some longitudinal merging and some transverse

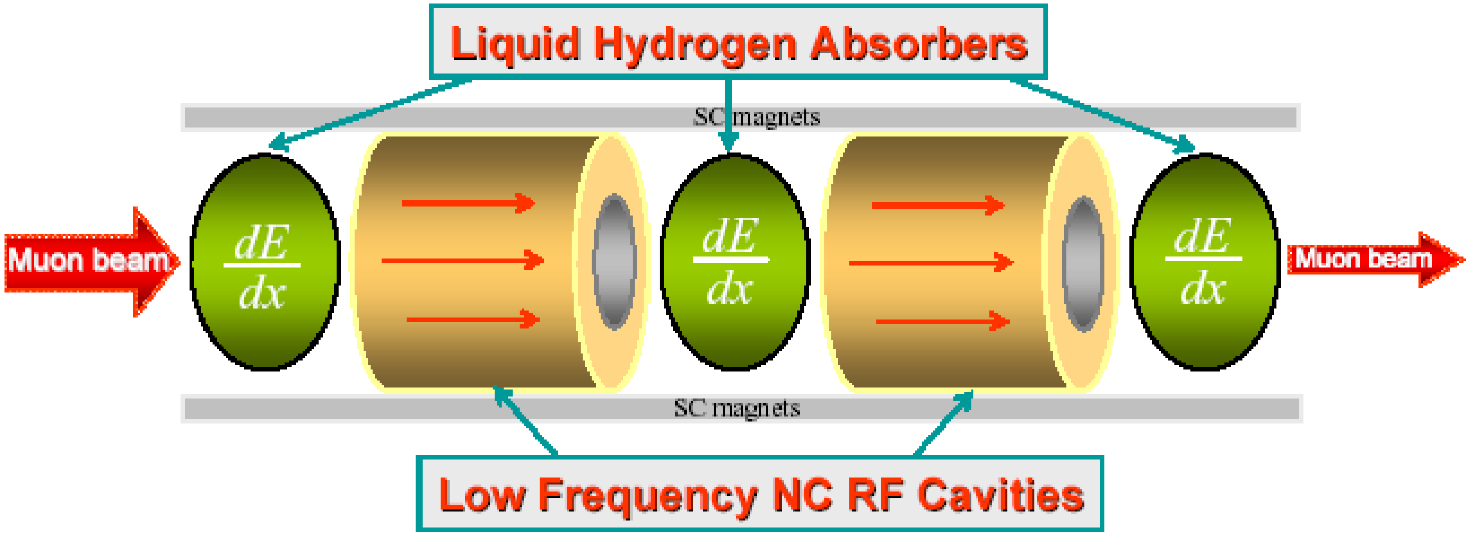
Palmer, Fernow





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)



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**

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

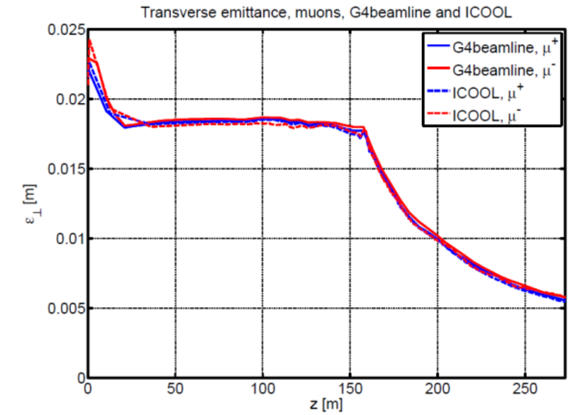
Cooling Heating

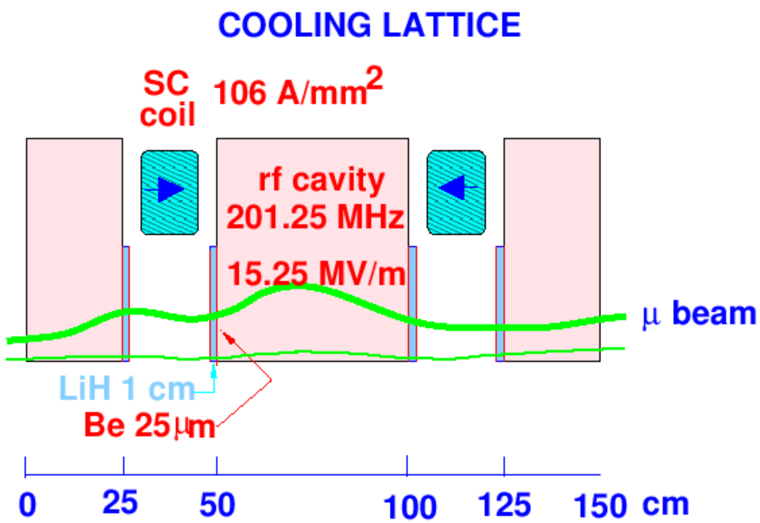
$$\varepsilon_{x,N,equil.} = \frac{\beta_\perp (0.014\text{GeV})^2}{2\beta m_\mu X_0 \left|\frac{dE_\mu}{ds}\right|}$$

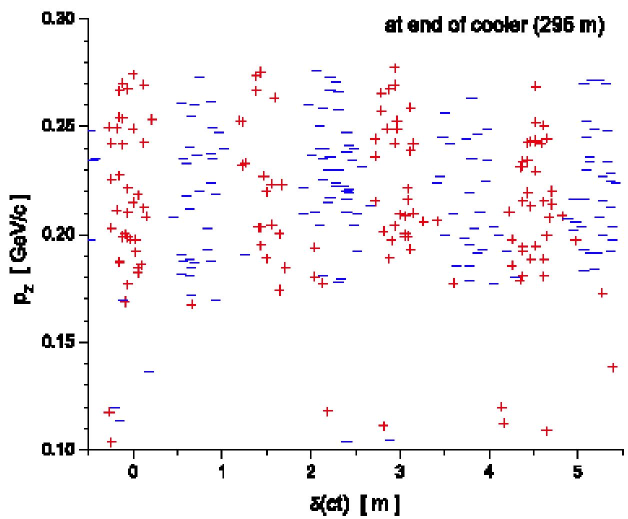
  - prefer low $\beta_\perp$ (strong focusing), large X_0 and *dE/ds* (LH_2 is best)
    - presence of LH_2 near RF cavities is an engineering challenge

Initial Cooling Channel

- Performance of baseline 4D channel meets NF goal (**with both signs**) of delivering 10^{21} muons per year
  - for ~4 MW of 8 GeV protons (2 ns bunches)
    - both signs transmitted

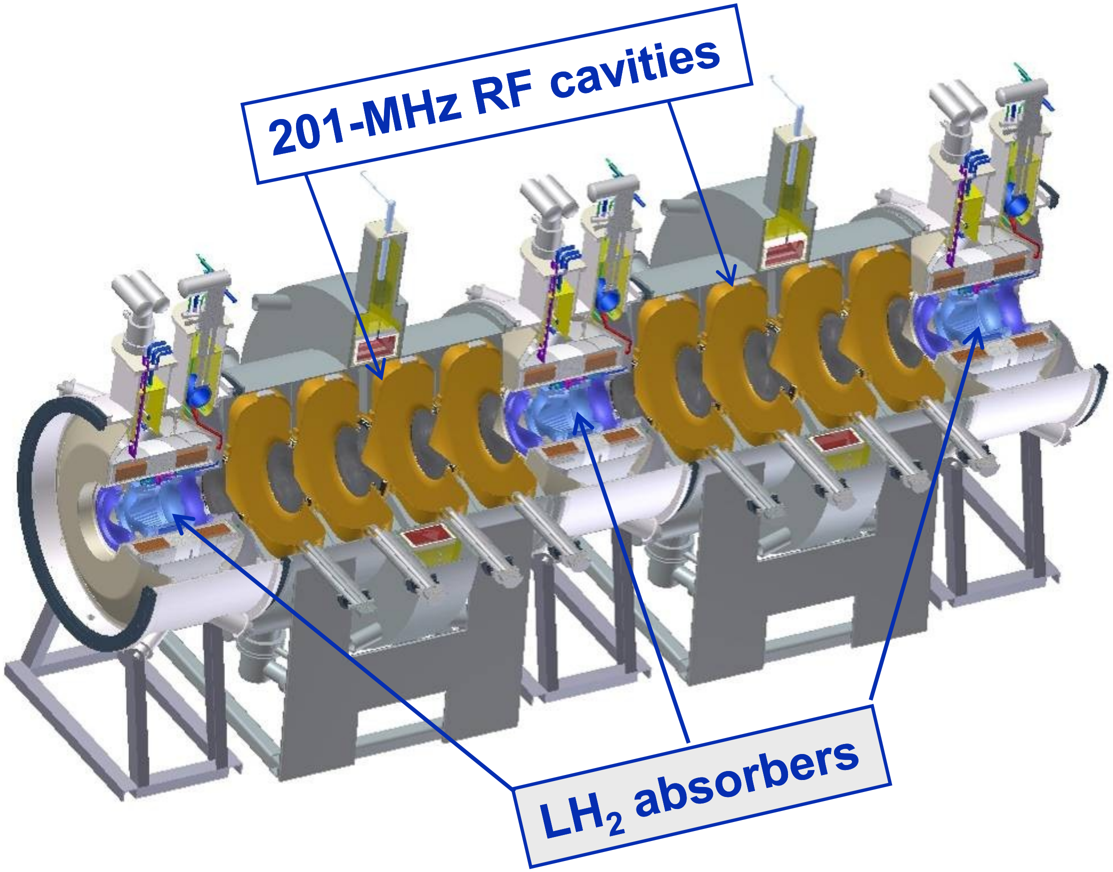






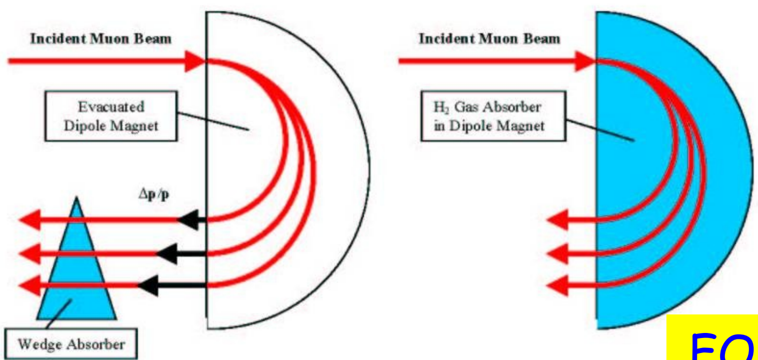
Cooling Channel Implementation

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



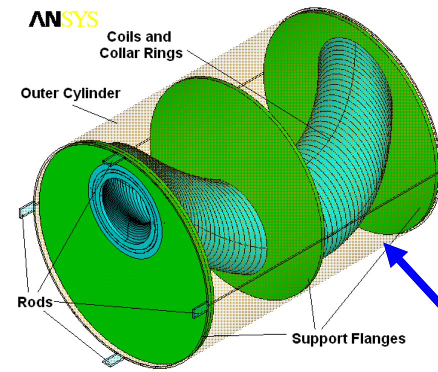
6D Cooling

- 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

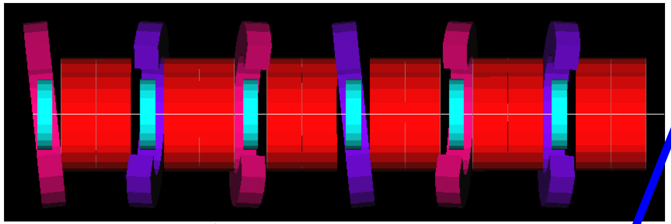


Muons, Inc.

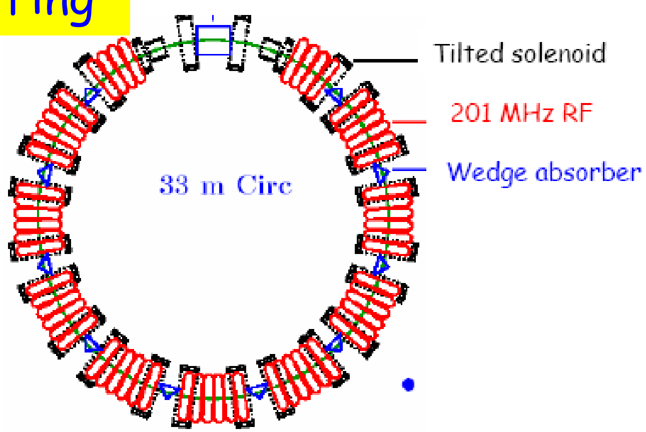
HCC

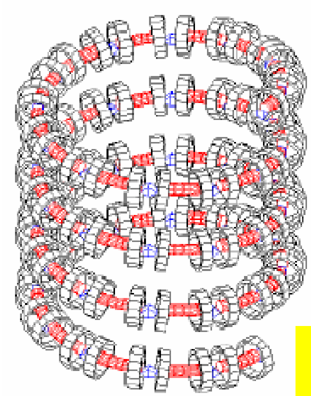


FOFO Snake



Cooling ring





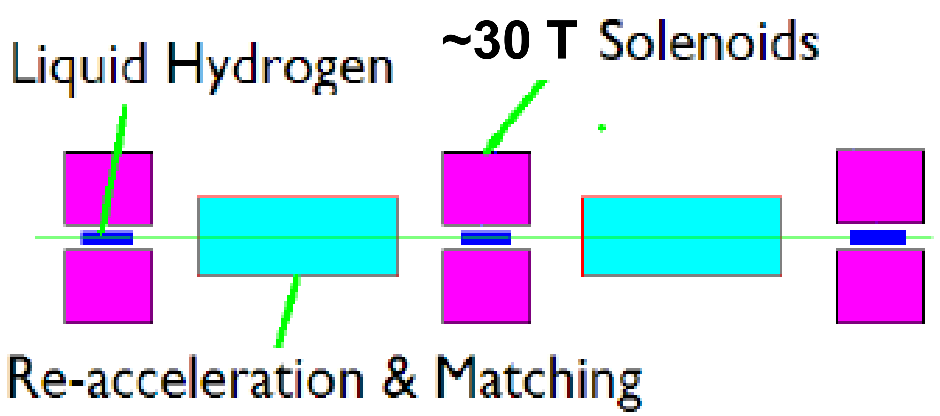
Single pass; avoids injection/extraction issues

"Guggenheim" channel

Final Cooling

- Final cooling to 25 μm emittance requires strong solenoids
  - not exactly a catalog item ⇒ R&D effort
  - latest design uses 30 T
    - not a hard edge but "more is better"
- 45 T hybrid device exists at NHMFL
  - very high power device, so not a good "role model"
  - exploring use of HTS for this task
    - most likely technology to work

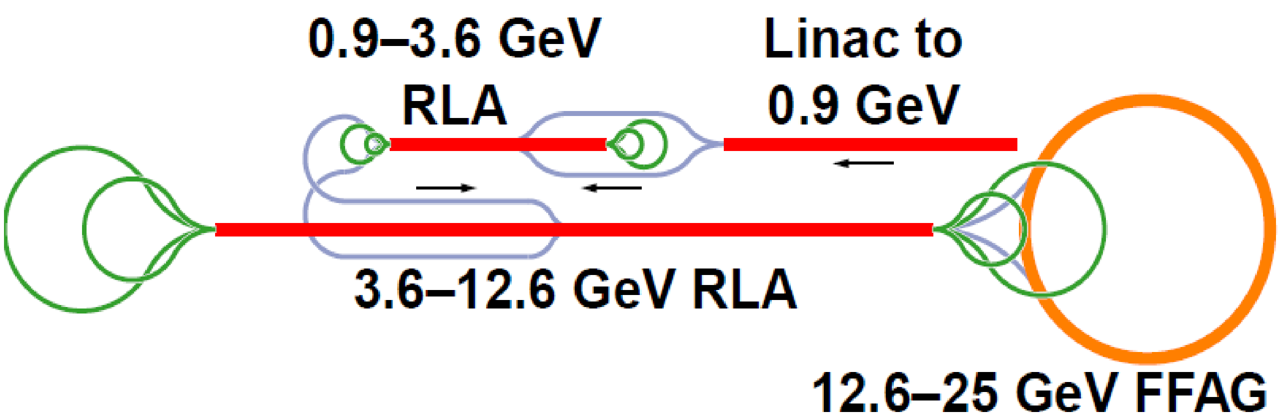
Palmer, Fernow



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)

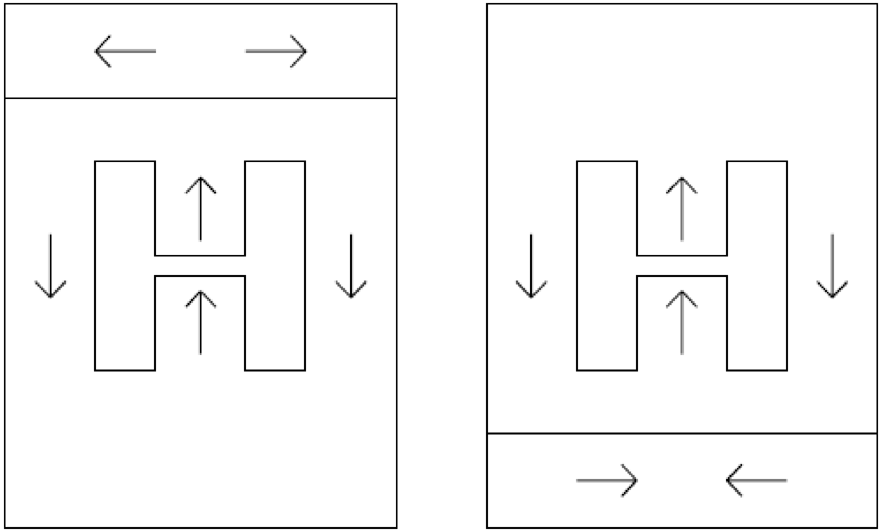
- **High-energy scheme**

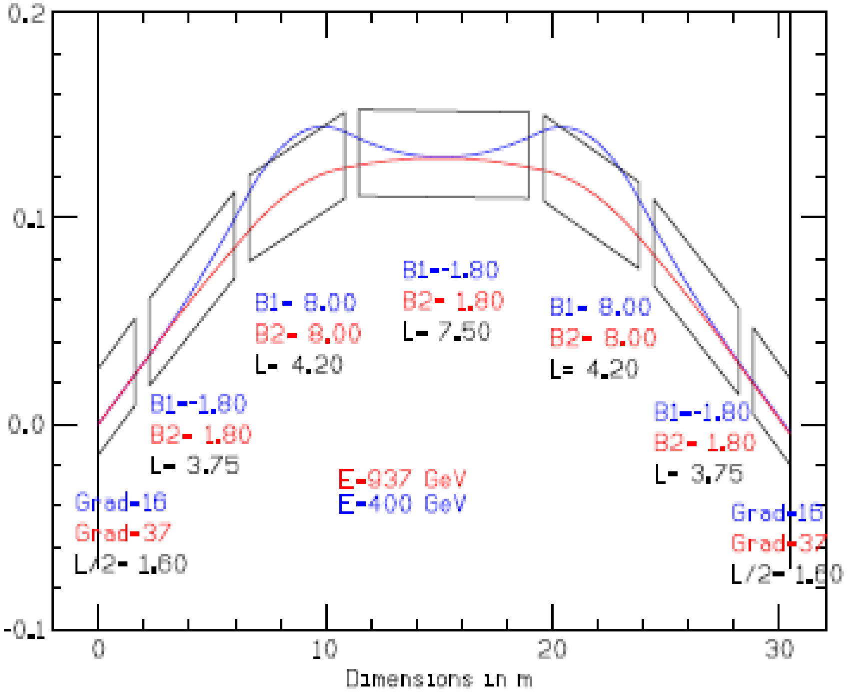
Summers

  - **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

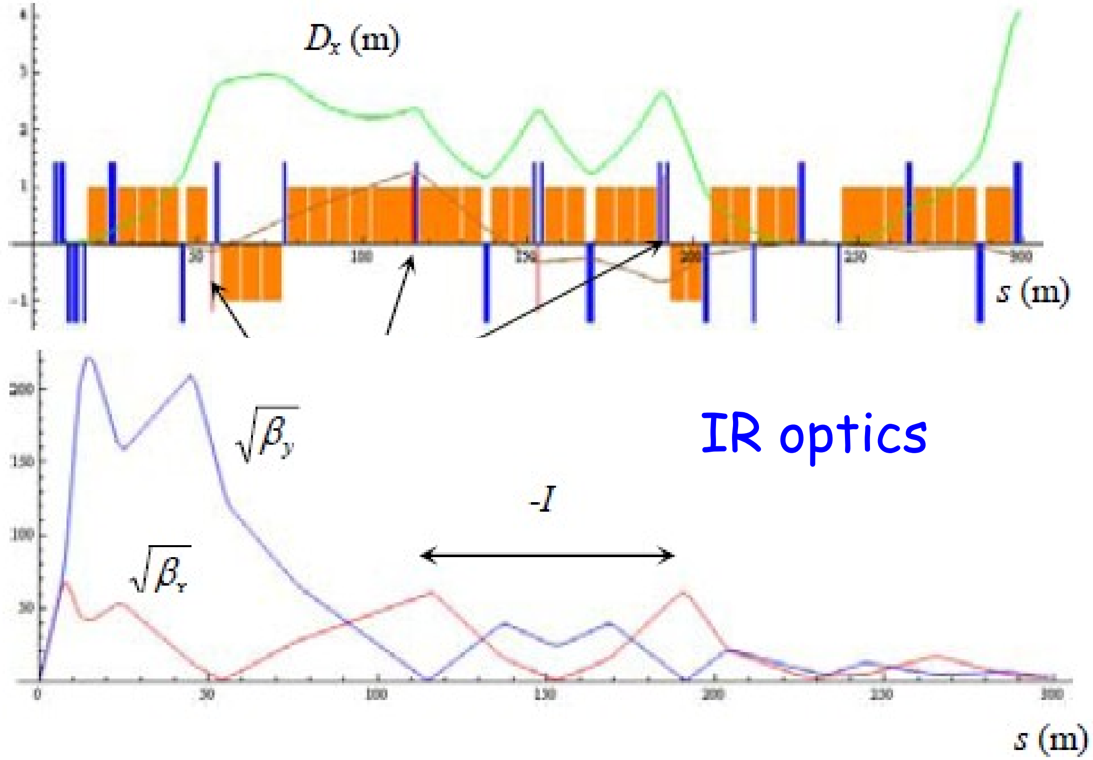
Use grain-oriented Si steel dipoles for low-energy RCS





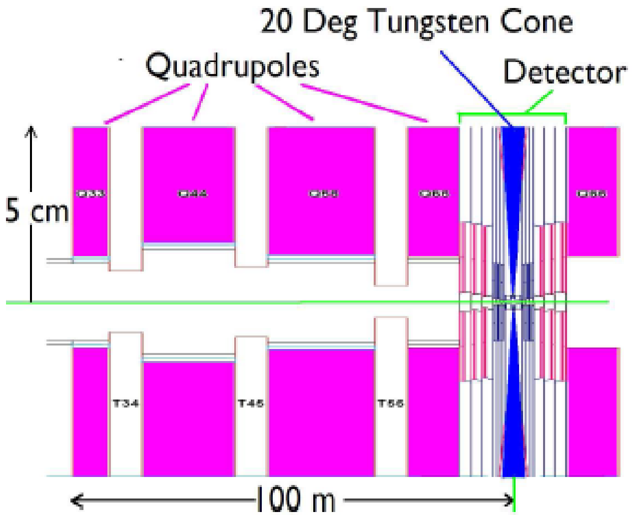
Collider Ring

- Lattice design for 1.5 TeV collider has been developed (Alexahin, Gianfelice-Wendt)
  - dynamic aperture ~4.7σ (no errors, no misalignment, no beam-beam)
  - momentum acceptance 1.2%
  - work on 3 TeV collider lattice getting under way

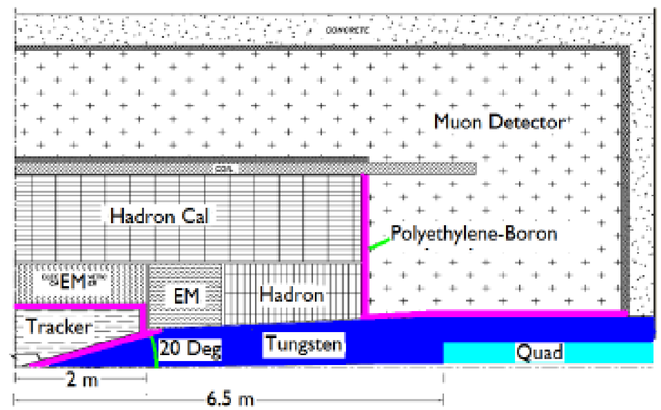


Machine-Detector Interface

- **MDI is a key design activity**
  - needed to assess ultimate physics capability of facility
  - needed to assess and mitigate expected backgrounds
    - recent work suggests shielding cone can be reduced from 20° to 10°
- **Successful collider requires that detector and shielding be tightly integrated into machine design**
  - hope some participants here will contribute to this effort!



Shielding



Detector

R&D Program

- To validate design choices, need substantial R&D program
  - three categories (simulations, technology development, system tests)
  - under way in many places
    - for NF, "loose but effective" international coordination
    - MC presently mainly a US enterprise
      - but desire and hope for broader participation
- U.S. activities now managed via MAP

Muon Accelerator Program (1)

- Set up by Fermilab (at DOE's request) to deliver
  - Design Feasibility Study (DFS) report on Muon Collider
    - include "cost range" at the end of the process
  - technology development to inform the MC-DFS and enable down-selection
  - NF Reference Design Report (RDR) under auspices of IDS-NF
    - this will include (Fermilab) site-specific design and overall costing
    - also includes participation in MICE
- Milestones

Caveat: depends on funding level

MAP deliverables.

Deliverable	Nominal schedule
MC DFS	
Interim	FY14
Final + cost range	FY16
MICE hardware completion	FY13
RF studies (down-select)	FY12
IDS-NF RDR	FY14
6D cooling definition	FY12
6D cooling section component bench test	FY16
6D demonstration proposal	FY16

Note: parallel Physics & Detector Study being launched

Muon Accelerator Program (2)

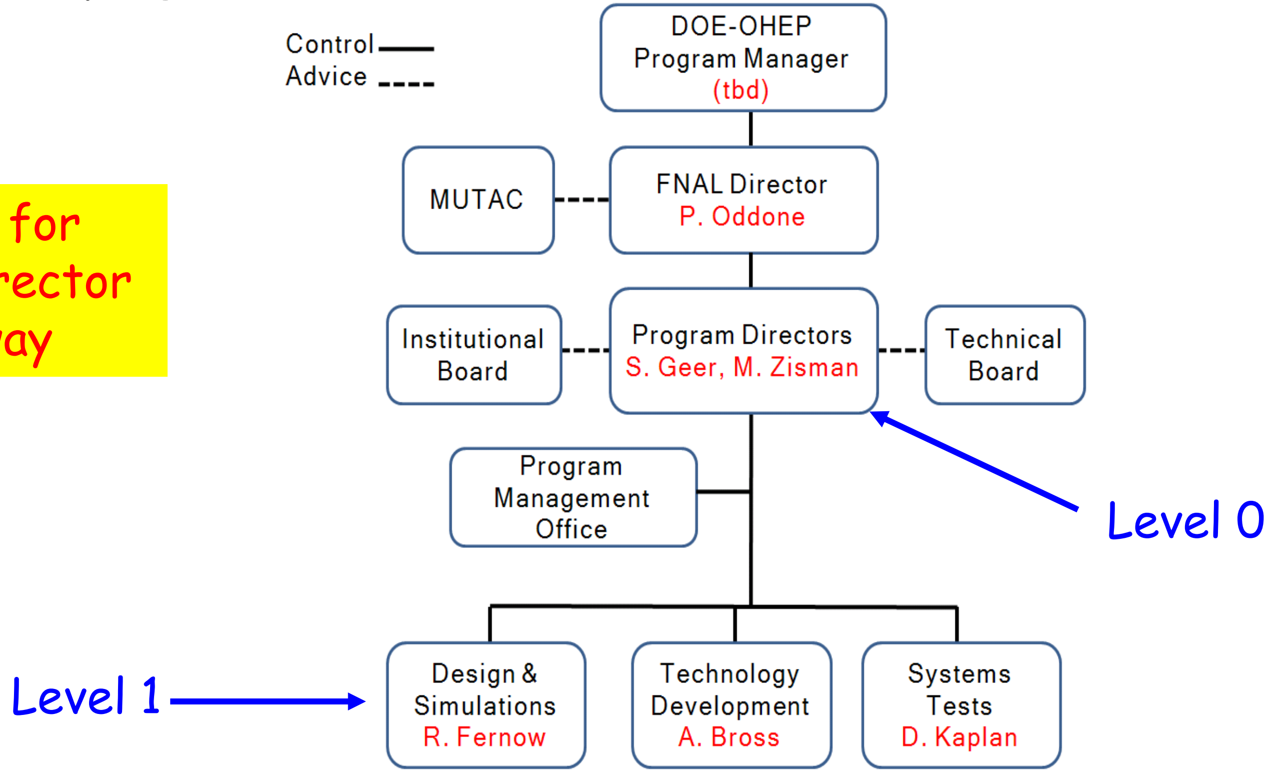
- **Mission statement**

  The mission of the Muon Accelerator Program (MAP) is to develop and demonstrate the concepts and critical technologies required to produce, capture, condition, accelerate, and store intense beams of muons for Muon Colliders and Neutrino Factories. The goal of MAP is to deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility. Coordination with the parallel Muon Collider Physics and Detector Study and with the International Design Study of a Neutrino Factory will ensure MAP responsiveness to physics requirements.

MAP Organization

- Interim upper-level organization was put in place by Fermilab management
  - tasked with preparing proposal and defending it at subsequent review (August 2010) ✓
    - carrying out R&D program ✓

Note: search for "permanent" Director now under way

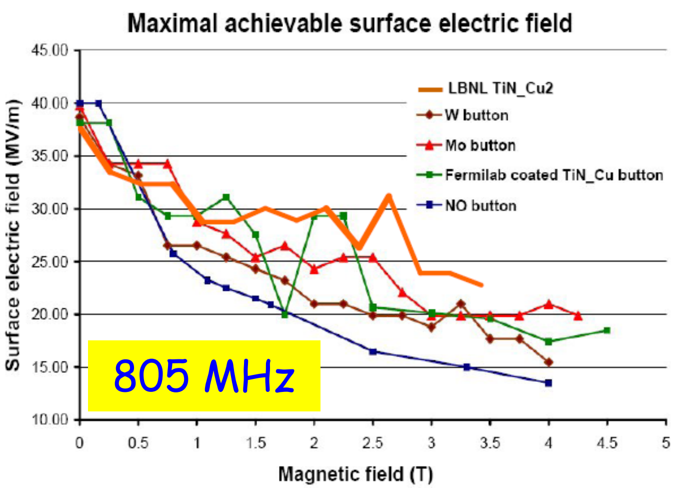


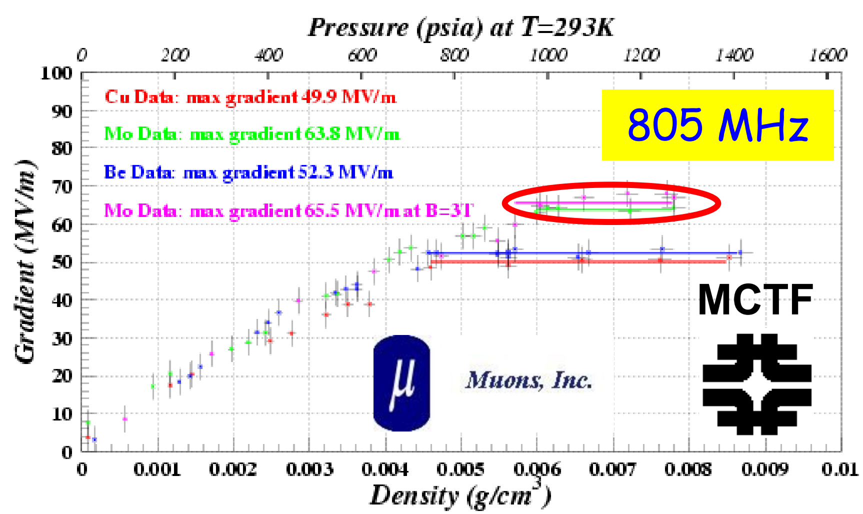
R&D Issues

- Main Muon Collider R&D issues include:
  - simulations
    - optimization of subsystem designs
    - end-to-end tracking of entire facility
  - technology
    - 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] ✓
    - 4D ionization cooling channel proof-of-concept [MICE]
    - preparations for 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
  - evaluating different cavity materials
  - HPRF does not show this effect
    - need to evaluate response of HPRF to beam



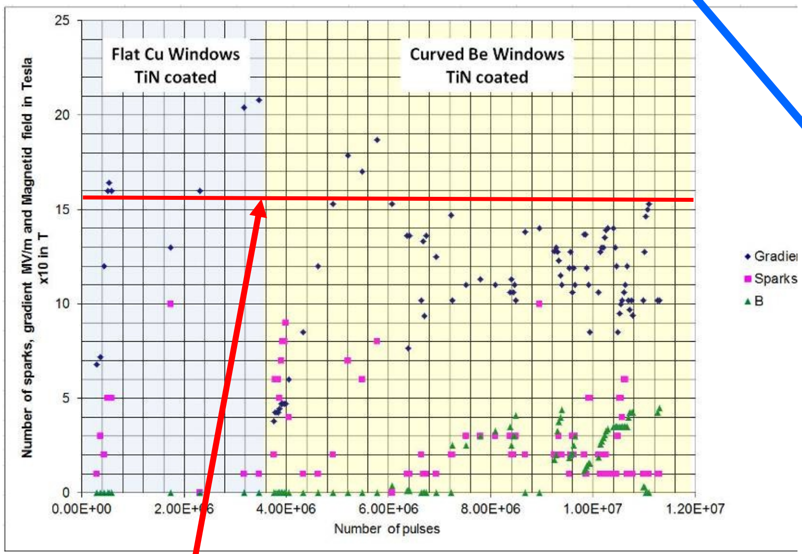


MuCool Results

- 201-MHz cavity shows qualitatively similar behavior
  - reached 21 MV/m without magnetic field
  - initial tests in fringe field of 5-T solenoid show degradation
    - and lots of scatter
  - awaiting coupling coil to achieve realistic field

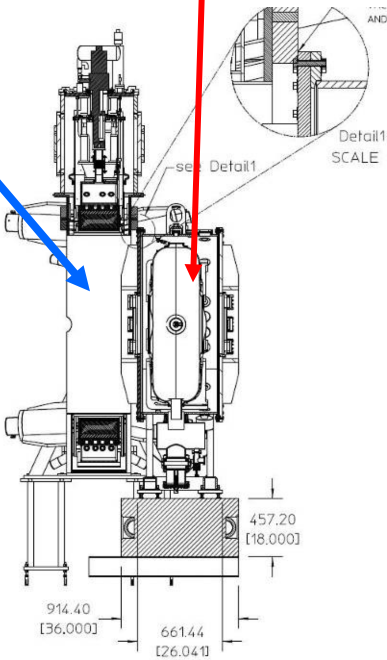
201 MHz cavity

5-T solenoid



Design Gradient

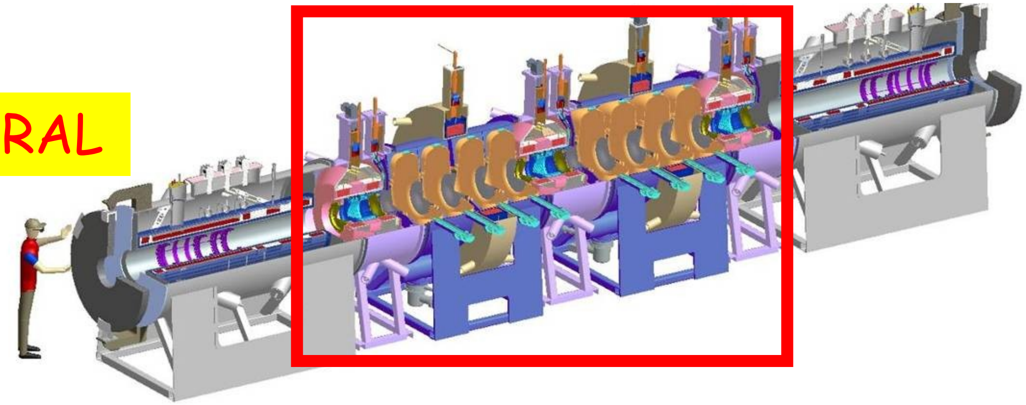
201 MHz cavity



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

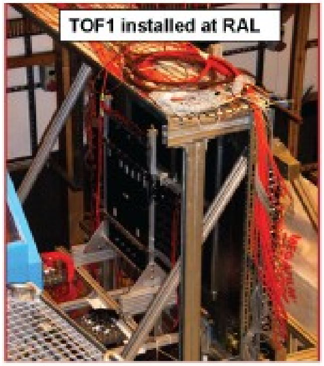


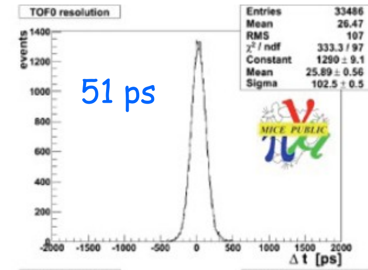
MICE Status (1)

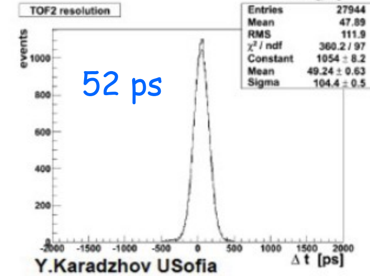
- Beam line installed and fully operational

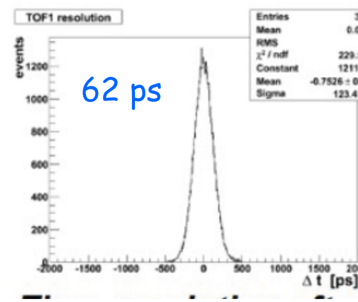
MICE Status (2)

- Particle ID can suppress unwanted particles (pions, protons, decay electrons) to 10^{-3} level
  - use
    - TOF counters (3 sets) ✓
    - Cherenkov counters (2) ✓
    - KL sampling EM calorimeter ✓
    - Electron-muon ranger (under construction)

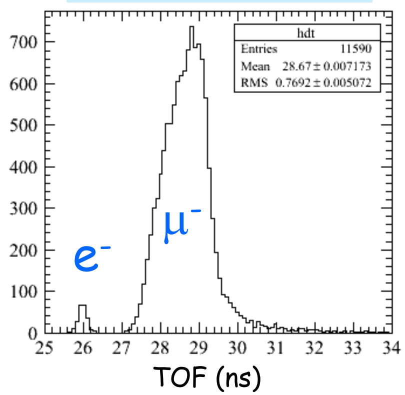




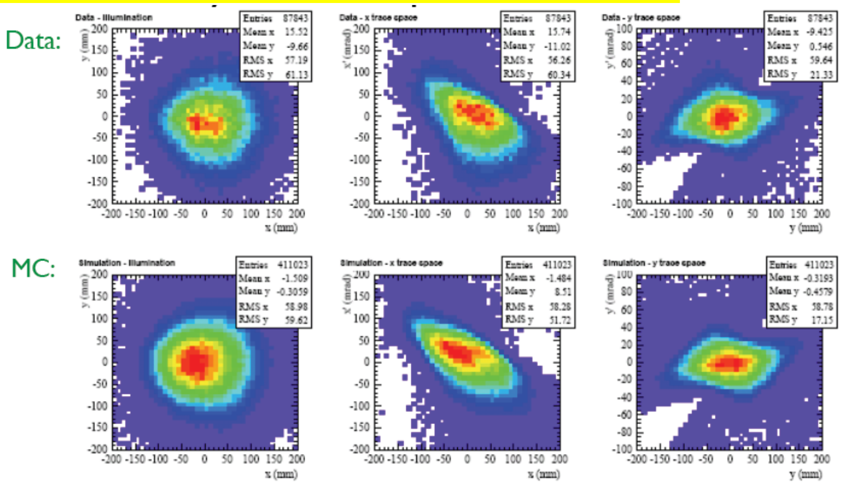




Select muons with two dipoles: $p_{D1} = 2p_{D2}$



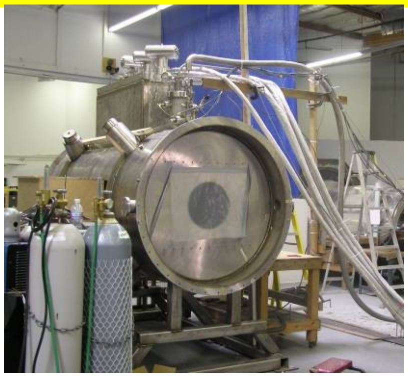
TOF detectors can measure emittance (well reproduced by simulations)



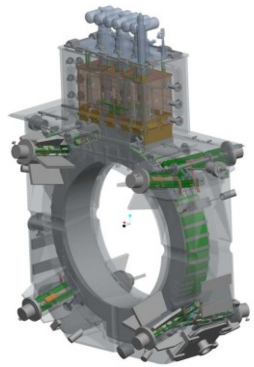
MICE Components

- All MICE cooling channel components are now in production

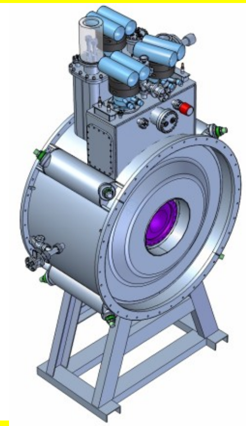
Spectrometer Solenoid (Wang NMR)



CC cryostat (SINAP) & coil (Qi H

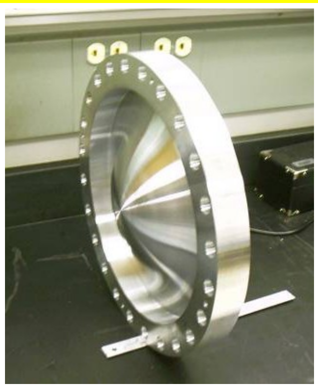


FC (Tesla Eng., Ltd.)

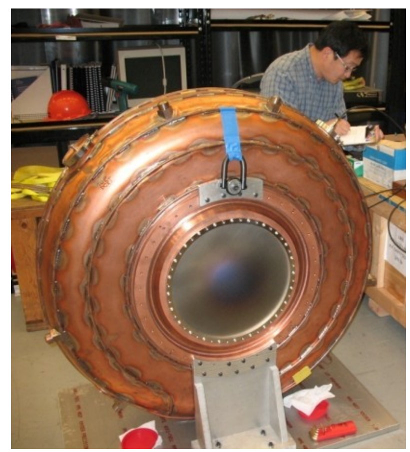


Absorber (KEK)

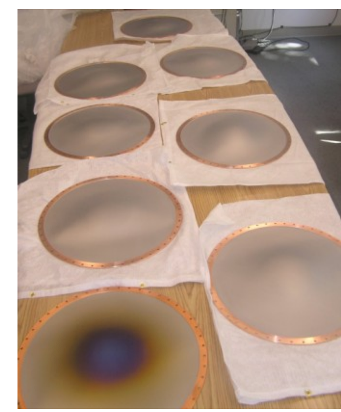
Absorber window (U-Miss)



(Applied Fusion)



Be windows



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 soon!
- Machine design is progressing well
  - promising collider lattice
  - performance of all subsystems simulated to some degree
    - end-to-end simulations remain to be done
- Community meeting on MC takes place this summer
  - June 27-July 1, 2011 at Telluride
- Development of muon-based accelerator facilities offers great scientific promise and remains a worthy—though challenging—goal to pursue

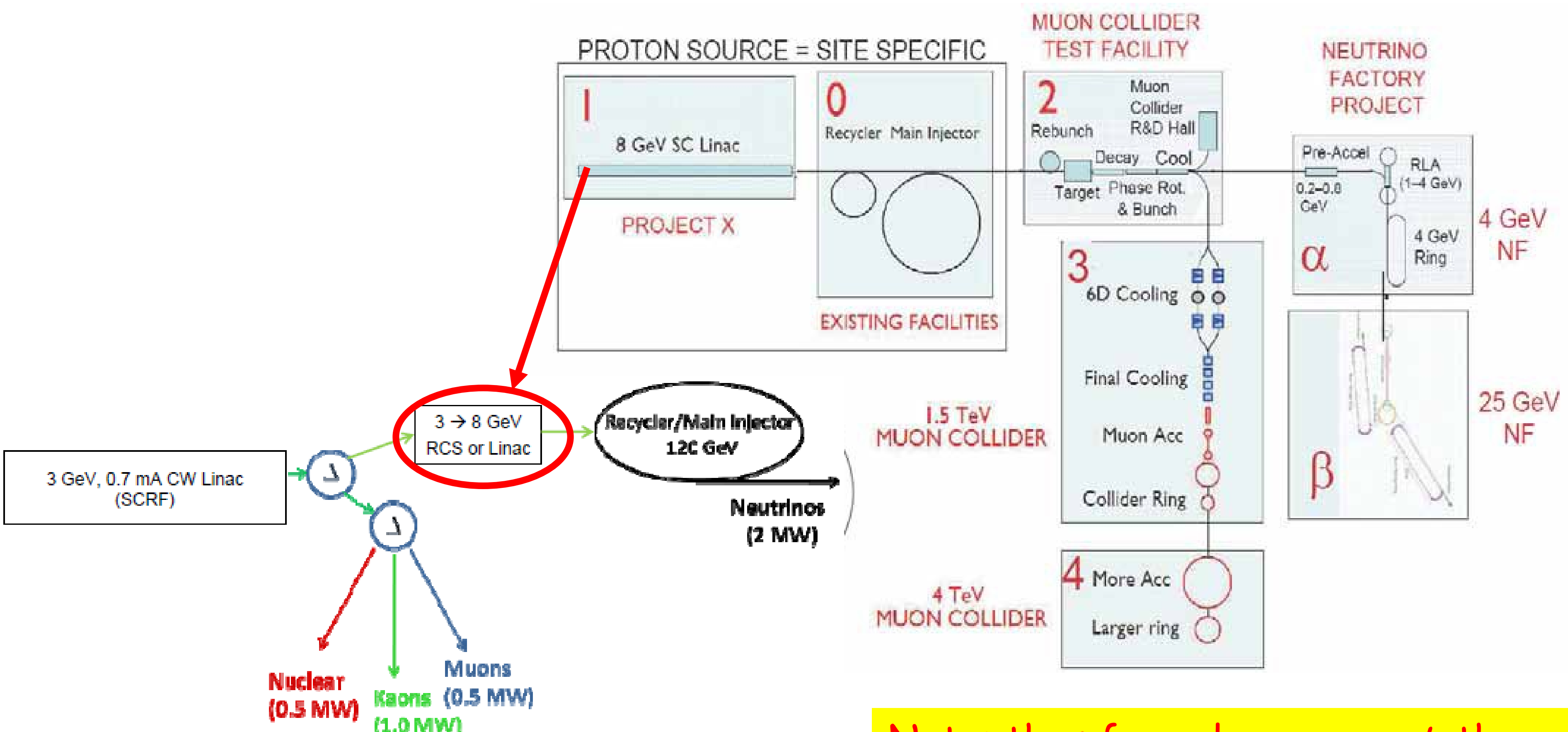
Hope to See You in Telluride!

http://conferences.fnal.gov/muon11/

Backups

Possible U.S. Scenario

- **Concept for muon beam evolution at Fermilab**



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