R&D Toward a Neutrino Factory and Muon Collider

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Introduction

- Muon-based storage ring or collider would be a powerful tool in the experimentalist's arsenal
  - storage ring can serve as powerful neutrino source
  - collider can explore energy frontier
- Design and performance evaluations for such facilities have been ongoing for more than 10 years
  - until recently, two entities involved in coordinated program
    - Neutrino Factory and Muon Collider Collaboration (NFMCC)
    - Muon Collider Task Force (MCTF)
  - organizations have now merged to form Muon Accelerator Program (MAP)
- Recent interest by Fermilab management has spurred increased effort to develop Muon Collider design

Muon Accelerator Program

- **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
  - includes participation in MICE and planning for 6D cooling experiment
- **Milestones**

Caveat: depends on funding level

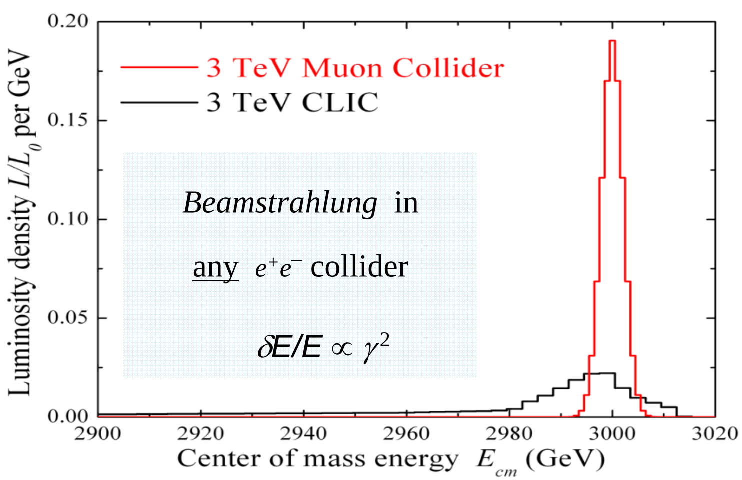
MAP deliverables.

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

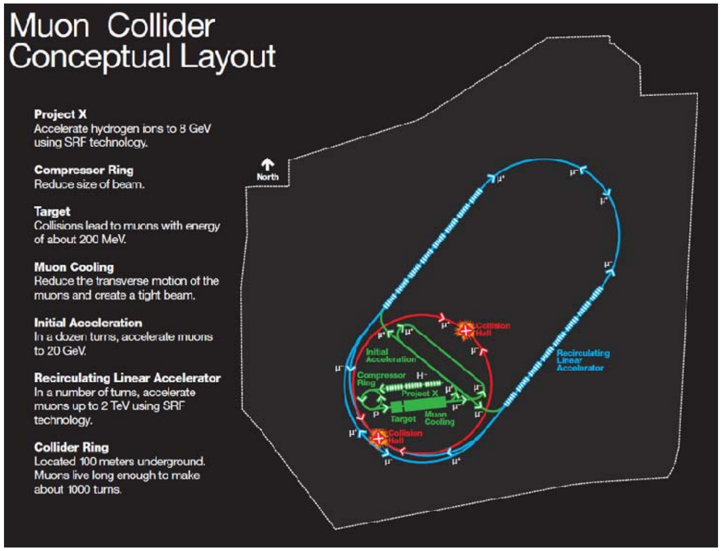
Note: parallel Physics & Detector Study being launched

Muon Accelerator Advantages (1)

- **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**
      - **reuses expensive RF equipment (circular ⇒ fits on existing Lab sites)**



Muon Collider would provide world-class science program at Fermilab



Muon Accelerator Advantages (2)

— neutrino sector

- Neutrino Factory beam properties

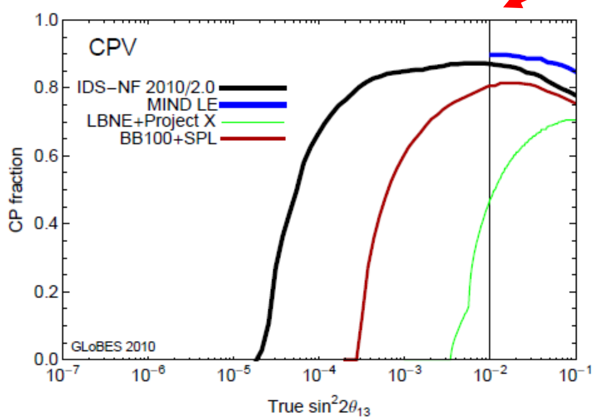
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \overline{\nu}_\mu$$

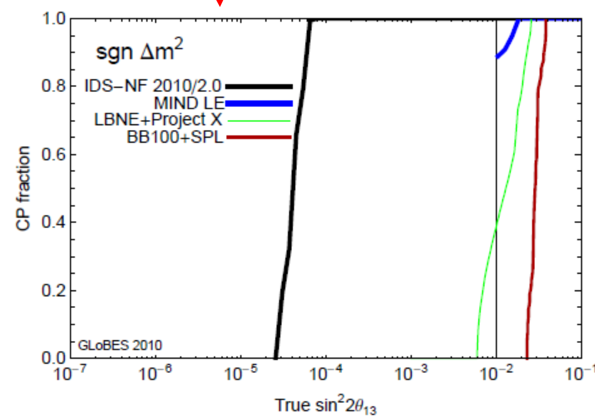
$$\mu^- \to e^- \overline{\nu}_e \nu_\mu \Rightarrow 50\% \overline{\nu}_e + 50\% \nu_\mu$$

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, ν mass hierarchy, and unitarity





Muon Beam Challenges

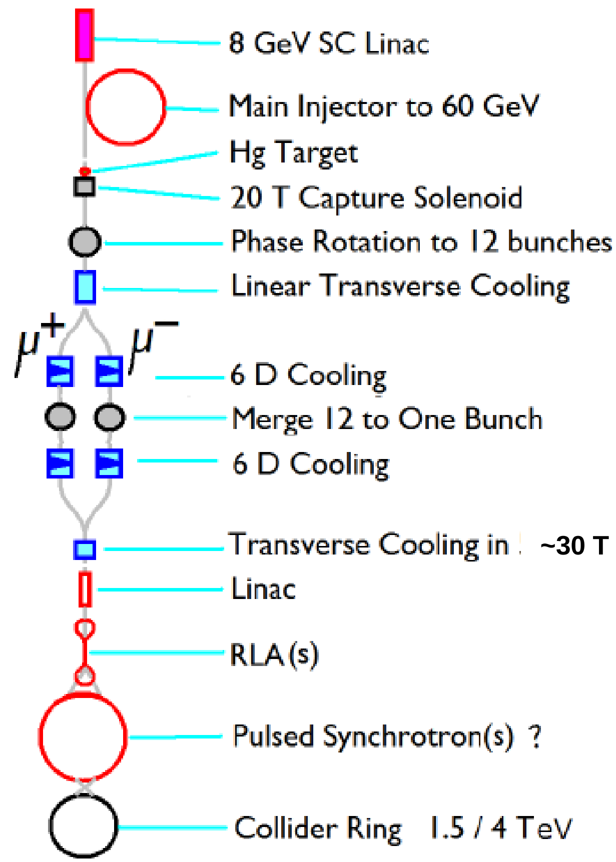
- **Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)**
  - low production rate
    - need target that can tolerate multi-MW beam (+ source to provide it!)
  - large energy spread and transverse phase space
    - need emittance cooling
    - high-acceptance acceleration system and 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!

- **R&D program can turn these challenges into opportunities**

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]**

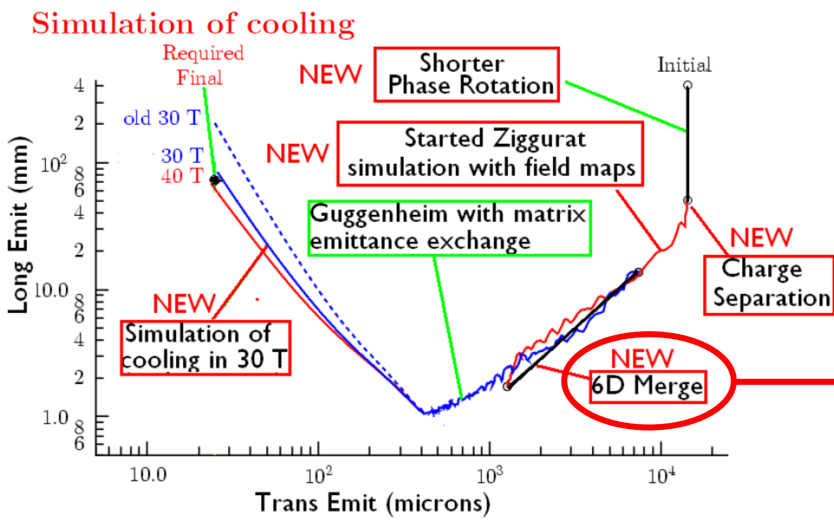
Parameter	Value	
$E_{c.m.}$ (TeV)	1.5	3.0
Luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	4×10^{34}
Beam-beam tune shift	0.087	0.087
Muons per bunch	2×10^{12}	2×10^{12}
Beam stored energy (kJ)	480	960
Circumference (km)	2.6	4.5
Avg. dipole field (T)	6	8.4
Bunch length, rms (mm)	10	5
β^* (mm)	10	5
$\delta p/p$	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

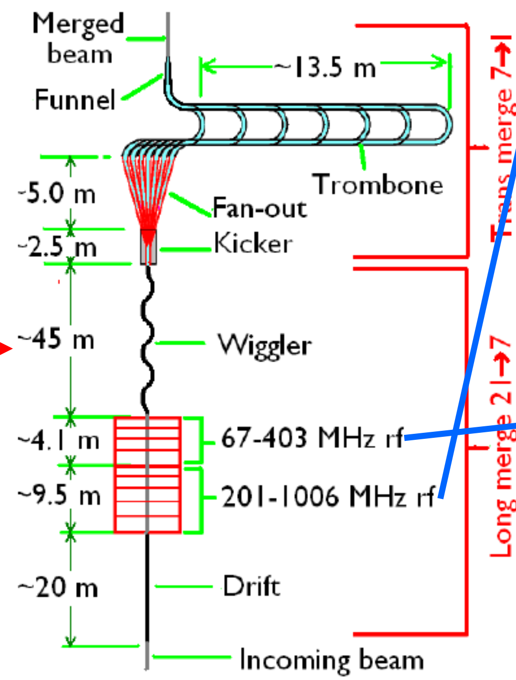
R&D Overview

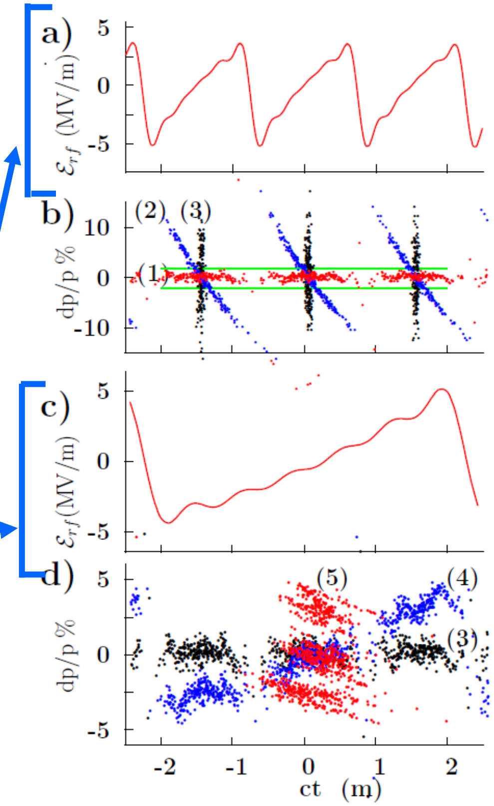
- To address technical challenges and validate design choices, need substantial R&D program
- MAP R&D program has the following components:
  - simulation and theory
    - both Neutrino Factory (under IDS-NF aegis) and Muon Collider design
  - technology development
    - development of cooling channel components ("MuCool")
    - development of high-power target technology ("Targetry")
  - participation in system tests as an international partner
    - MERIT (high-power Hg-jet target) [completed]
    - MICE (ionization cooling demonstration)
    - 6D cooling experiment
      - first assess need, then plan (if needed)
        - carrying out a 6D experiment *not* part of initial phase of MAP

Simulations

- **Simulations in support of collider design are progressing (Palmer, Fernow)**
  - **need to define a 6D cooling "trajectory" in (longitudinal, transverse) emittance space**
  - **final cooling concepts described in next talk (Palmer)**

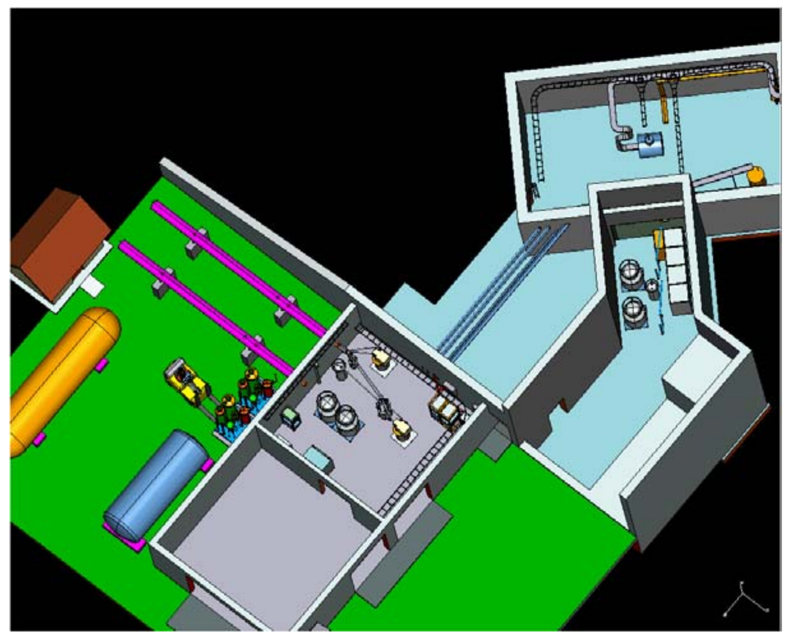






MuCool R&D

- **MuCool program does R&D on cooling channel components**
  - RF cavities, absorbers
    - focus in recent years has been RF
- **Make use of MuCool Test Area (MTA) at Fermilab**
  - located at end of 400 MeV linac and shielded for beam tests
    - first beam arrived February 28, 2011



NCRF Strategy

- **Continue assessment of alternative RF technologies**
  - goal: identify ≥1 approach to eliminate (or reduce to acceptable level) gradient degradation in magnetic field
    - vacuum cavities
      - reduce or eliminate surface electric field enhancements
        - SCRF processing techniques (electropolish plus HP water rinse)
        - ALD techniques (smooth surface with conformal coating at molecular level)
      - materials studies
        - look for materials resistant to damage (Be looks interesting)
    - high-pressure gas-filled RF ("HPRF") cavities
      - use beam tests to see if gas breaks down with intense beam

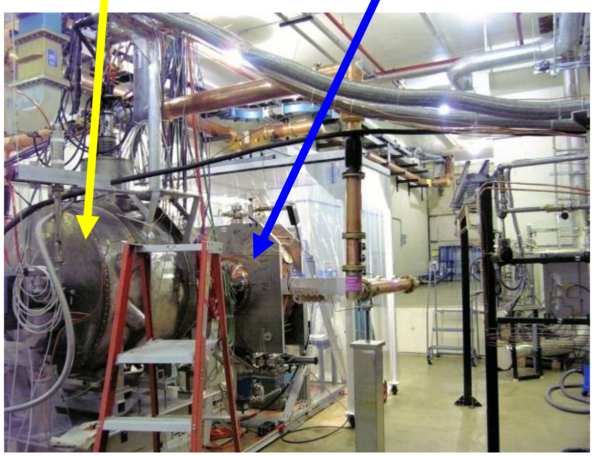
MuCool Results (1)

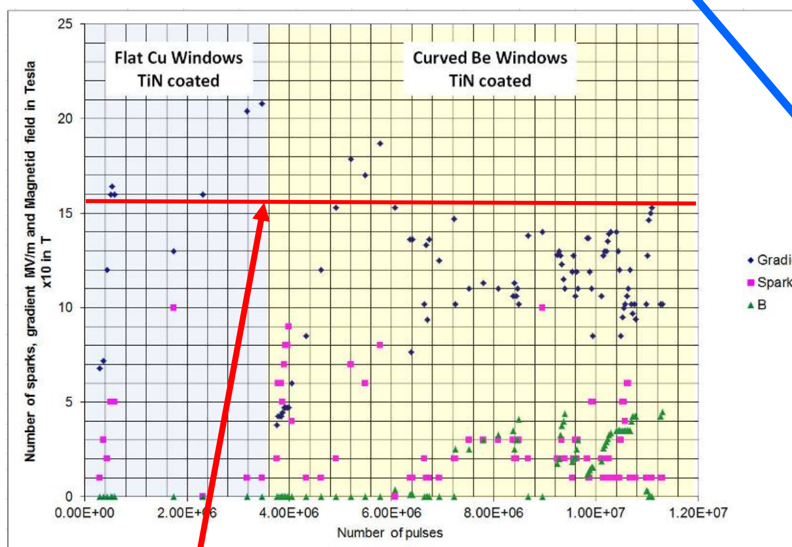
- **201-MHz cavity shows degradation**
  - **reached 21 MV/m without magnetic field**
  - **initial tests in fringe field of 5-T solenoid give reduced gradient**
    - **and lots of scatter**
  - **awaiting coupling coil to achieve realistic field**

201 MHz cavity

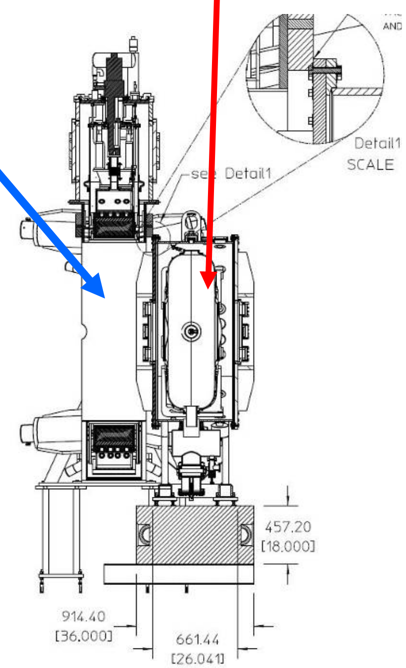
201 MHz cavity

5-T solenoid





Design Gradient

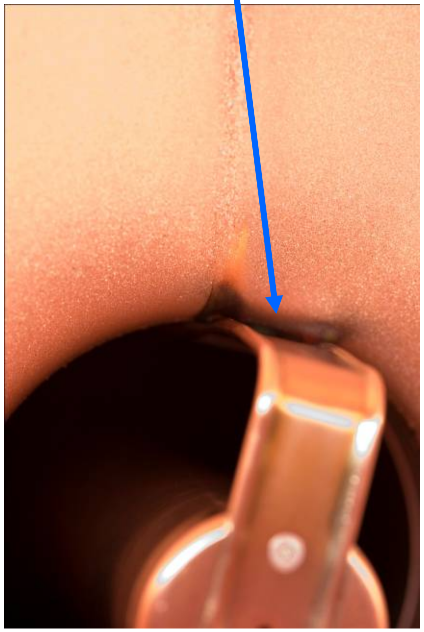


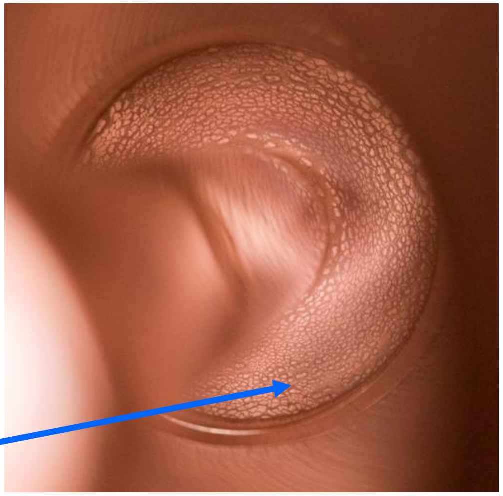
MuCool Results (2)

- **201-MHz cavity damage confined to coupler region**

Cavity inner surfaces still pristine

Arcing at loop



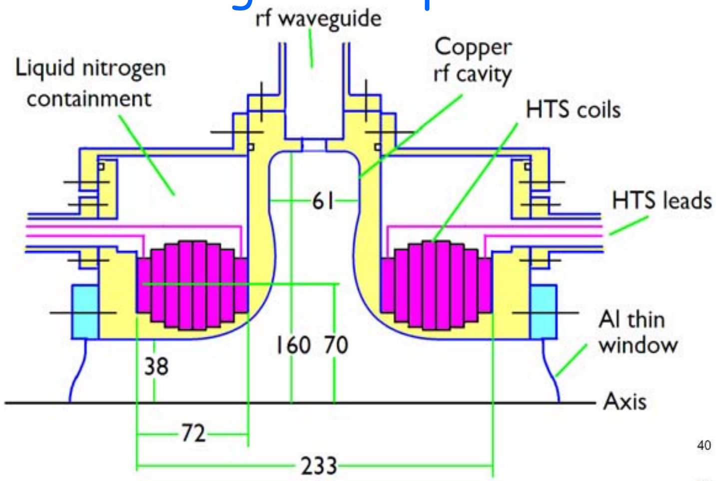


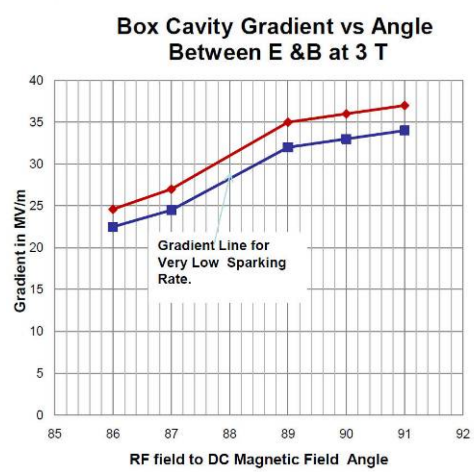
Cu deposition on TiN coated ceramic RF window

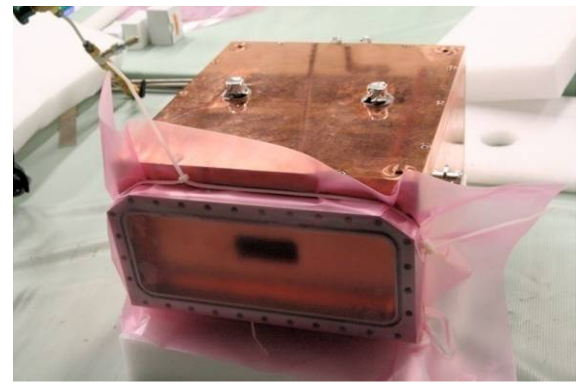
MuCool Results (3)

- "Box" cavity used to assess magnetic insulation efficacy
  - magnetic field lines parallel to cavity walls
    - such cavities have practical disadvantages but deemed worthy of test

Design concept







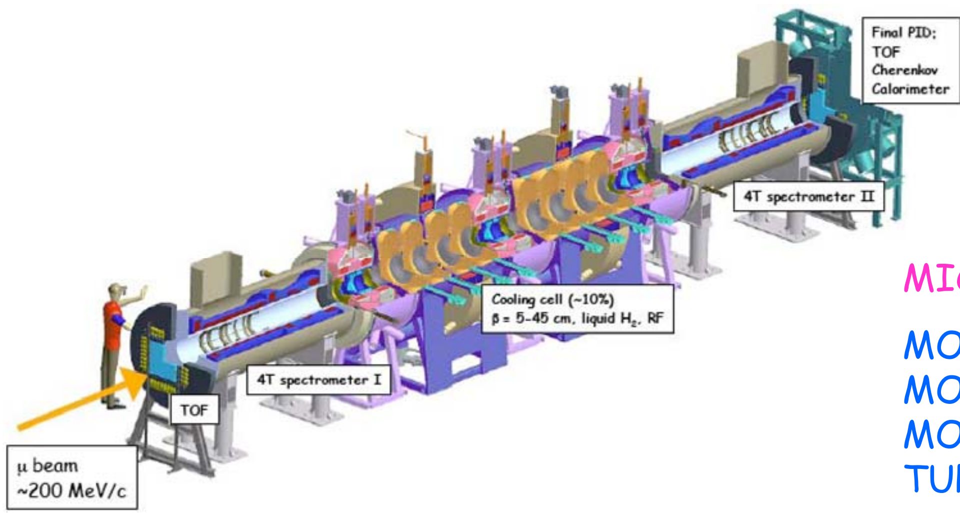
Operated stably at 50 MV/m at B = 0 but only 35 MV/m at 3 T

MICE (1)

- **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**
  - **show that design tools (G4MICE, ICOOL, G4beamline) agree with experiment**
    - **gives confidence that we can optimize design of an actual facility**
- **Getting components fabricated and operating teaches us about both cost and complexity of a muon cooling channel**

One cell of FS2 cooling channel

upstream and downstream detectors for PID and emittance measurement

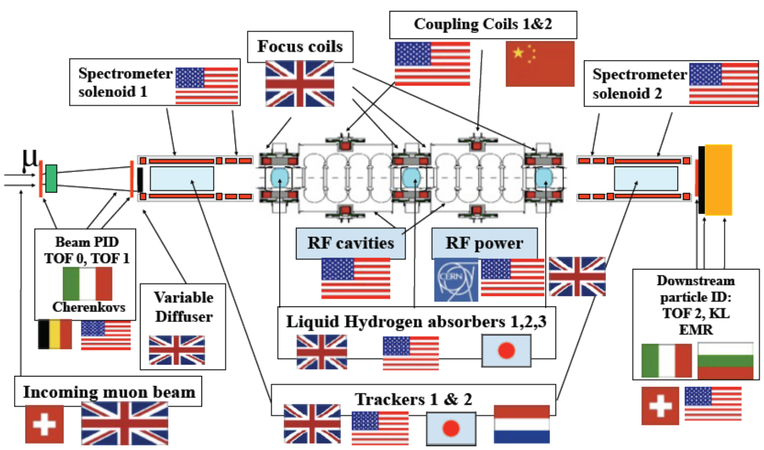


MICE papers at PAC11:

MOP021, MOP022 MOP023, MOP037, MOP053, MOP058, MOP060, MOP061, TUP173, TUP282, TUP290

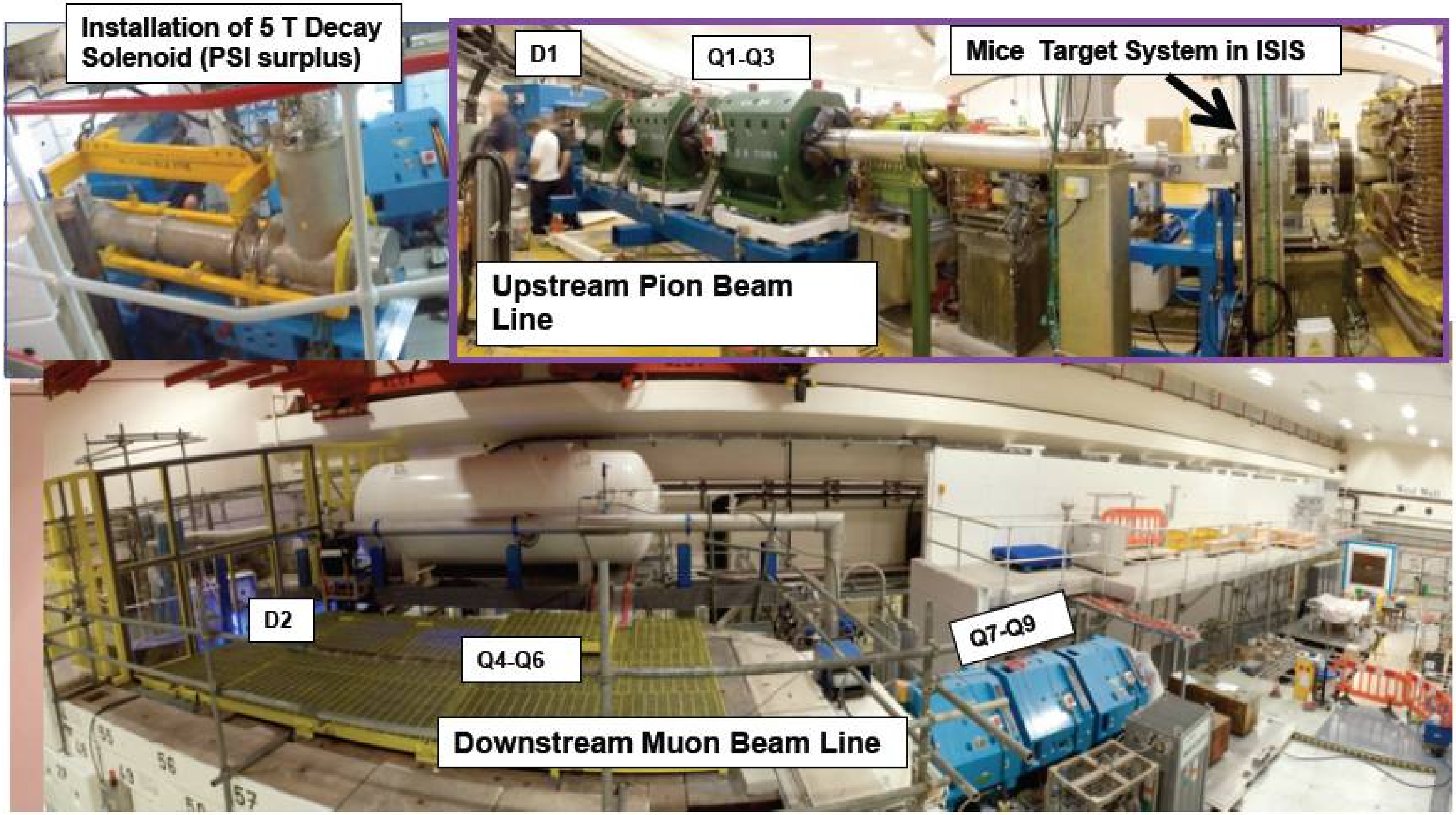
MICE (2)

- **International collaboration of ~130 scientists/engineers**
  - ***experiment uses secondary beam from 800 MeV ISIS synchrotron at RAL***



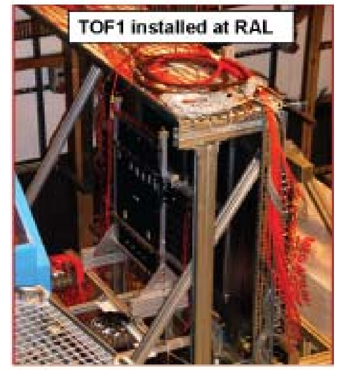
MICE Status (1)

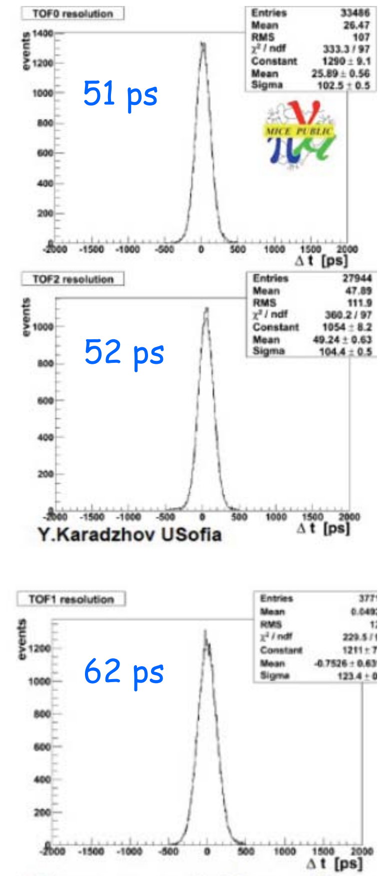
- **Beam line installed and fully operational**



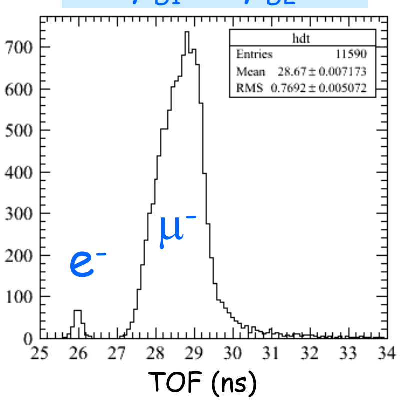
MICE Status (2)

- 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)

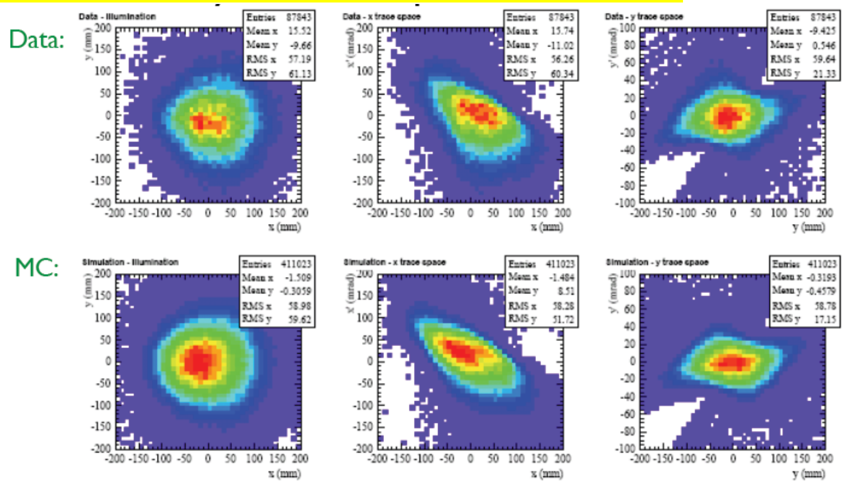




Select muons with two dipoles: $p_{D1} = 2p_{D2}$



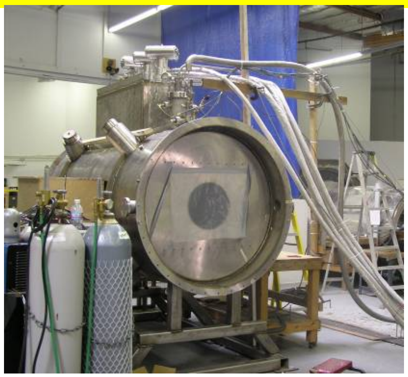
TOF detectors can measure emittance (well reproduced by simulations)



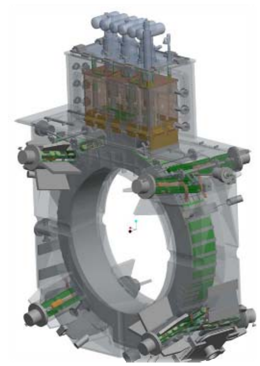
MICE Components

- All MICE cooling channel components are now in production

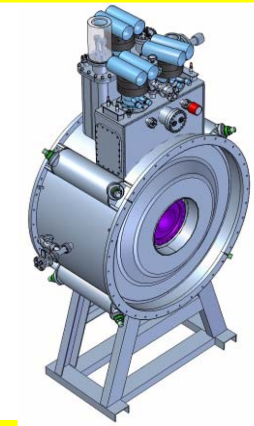
Spectrometer Solenoid (Wang NMR)



CC cryostat (SINAP) & coil (Qi Huan Co.)

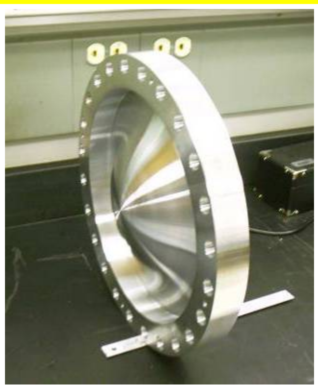


FC (Tesla Eng., Ltd.)



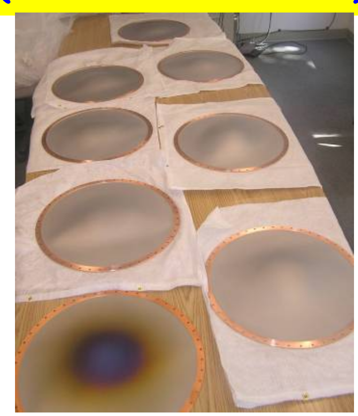
Absorber (KEK/Mirapro)

Absorber window (U-Miss)



Cavities (Applied Fusion)

Be windows (Brush-Wellman)



Summary

- R&D toward a NF and MC is making steady progress
  - MERIT experiment completed
  - MICE experiment is progressing
    - beam line and detectors functioning; major components all in production
    - looking forward to first ionization cooling measurements soon!
  - MuCool RF studies to understand and mitigate gradient degradation remain a high priority

66 papers submitted to PAC11

- MAP R&D plan has been developed and approved
  - deliverables include MC-DFS and NF-RDR, including cost estimates
- Development of muon-based accelerator facilities offers great scientific promise and remains a worthy—and challenging—goal to pursue
  - community-wide workshop in late June 2011

Hope to See You in Telluride!

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