R&D Toward a Neutrino Factory and Muon Collider

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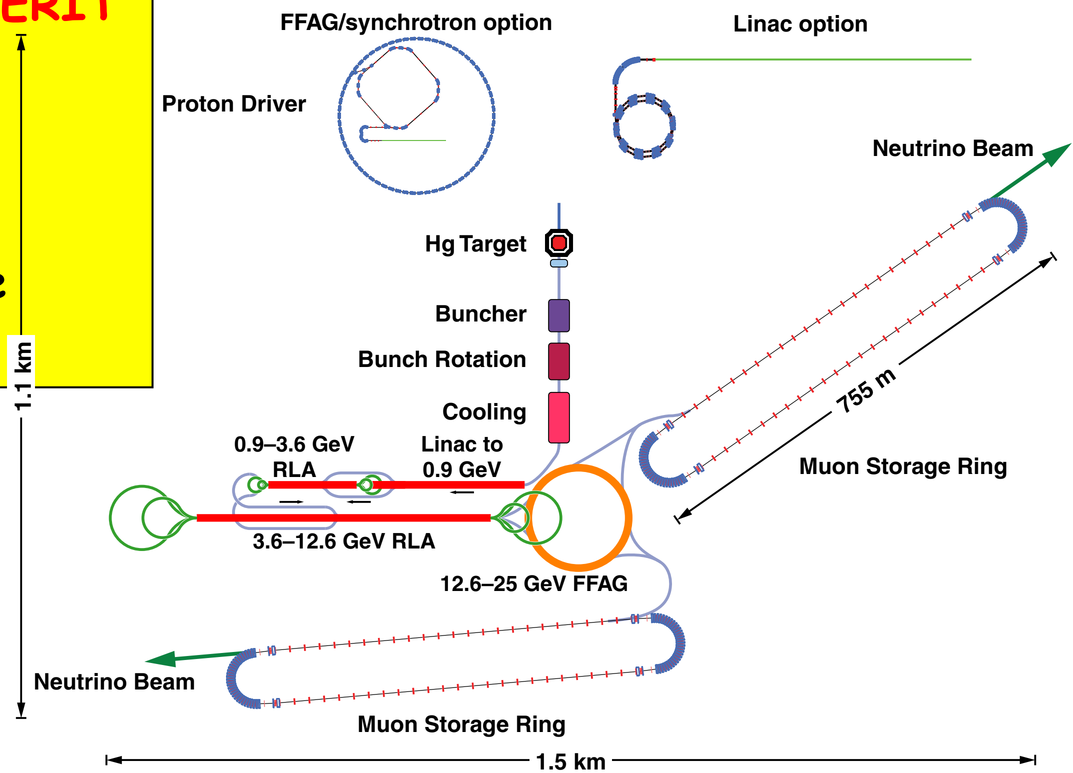
Introduction

- U.S. Neutrino Factory and Muon Collider Collaboration (NFMCC) explores techniques for producing, accelerating, and storing intense muon beams
  - near-term focus: muon storage ring to serve as source of well-characterized neutrinos ("Neutrino Factory") for long baseline experiments (~3000–7500 km)
  - longer-term focus: Muon Collider
    - Higgs Factory operating at few-hundred GeV or energy-frontier collider operating at several TeV
  - both types of machine are difficult, but have high scientific potential
  - common feature of these state-of-the-art machines is the need for a sustained R&D program
    - most modern projects (LHC, ILC, CLIC) share this need
- FNAL directorate and P5 attention have given Muon Collider R&D a higher profile
  - this is reflected in our recently submitted 5-year R&D plan

Neutrino Factory Ingredients

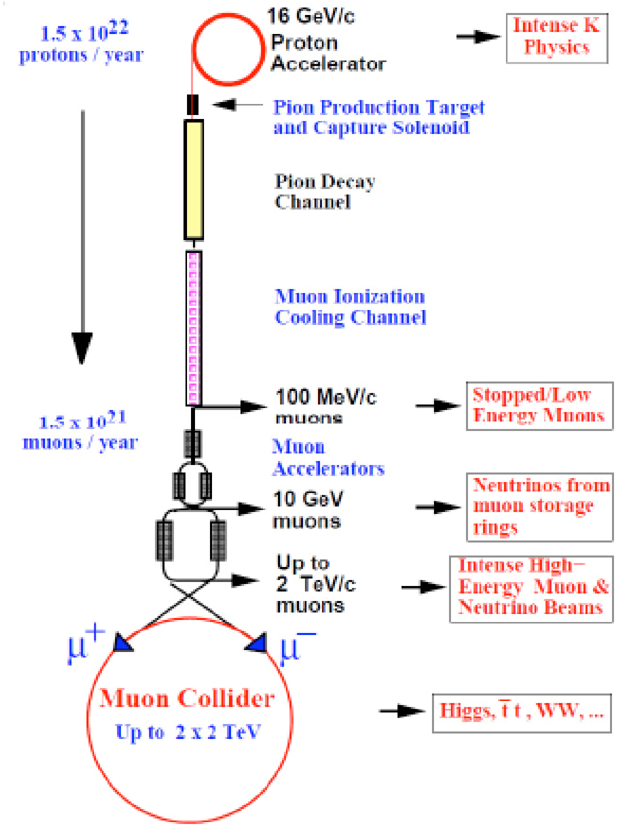
- Neutrino Factory comprises these sections
  - Proton Driver
    - primary beam on production target
  - Target, Capture, and Decay
    - create π; decay into μ ⇒ MERIT
  - Bunching and Phase Rotation
    - reduce ΔE of bunch
  - Cooling
    - reduce transverse emittance ⇒ MICE
  - Acceleration
    - 130 MeV → 25 GeV with RLAs or FFAGs
  - Decay Ring
    - store for 500 turns; long straight sections

IDS-NF Baseline Layout



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 Accelerator Advantages

- Muon-beam accelerators can address several of the outstanding accelerator-related particle physics questions
  - neutrino sector
    - Neutrino Factory beam properties

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

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

Produces high energy neutrinos, 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 studies of CP violation and mass hierarchy

  - 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 ($\Rightarrow$ fits on existing Lab sites)

Muon Beam Challenges

- Muons created as tertiary beam ($p \rightarrow \pi \rightarrow \mu$)
  - low production rate
    - need target that can tolerate multi-MW beam
  - 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!

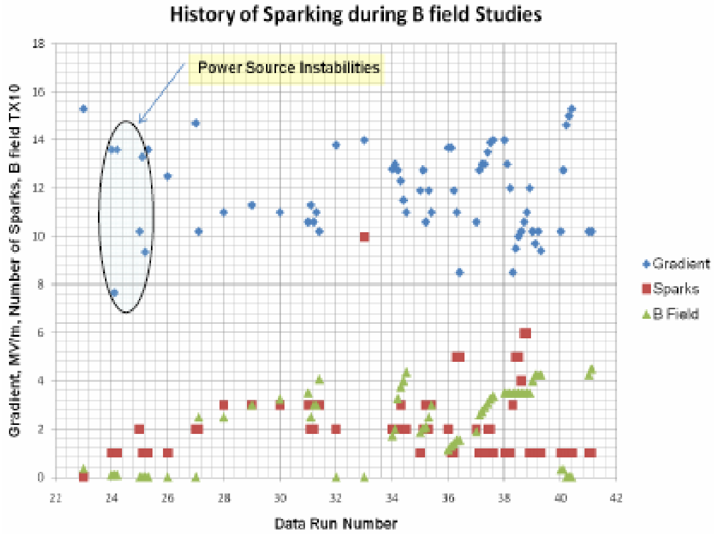
- Decay electrons give rise to heat load in magnets and backgrounds in collider detector

R&D Overview

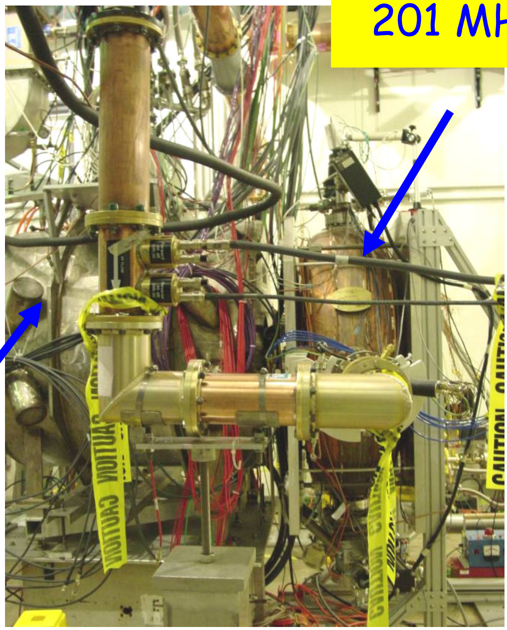
- NFMCC R&D program has the following components:
  - simulation and theory effort
    - supports both Neutrino Factory and Muon Collider design [Palmer talk]
      - NF work presently done under aegis of IDS-NF WE6RFP067
  - development of high-power target technology ("Targetry")
  - development of cooling channel components ("MuCool")
- We participate in system tests as an international partner
  - MERIT (high-power Hg-jet target) [completed; analysis ongoing]
  - MICE (ionization cooling demonstration)
  - EMMA (non-scaling FFAG electron model)
    - would validate potentially more cost-effective acceleration system
- Hardware development and system tests are major focus
  - simulation effort has led to cost-effective Neutrino Factory design
    - and progress toward a complete Muon Collider scenario
      - just as for NF, simulations will guide hardware and system tests

MuCool R&D (1)

- MuCool program does R&D on cooling channel components in MuCool Test Area at Fermilab
  - RF cavities, absorbers
- Motivation for cavity test program: observed degradation in cavity performance when strong magnetic field present
  - 201 MHz cavity easily reached 19 MV/m without magnetic field
  - initial tests in fringe field of Lab G solenoid show some degradation
    - and lots of scatter



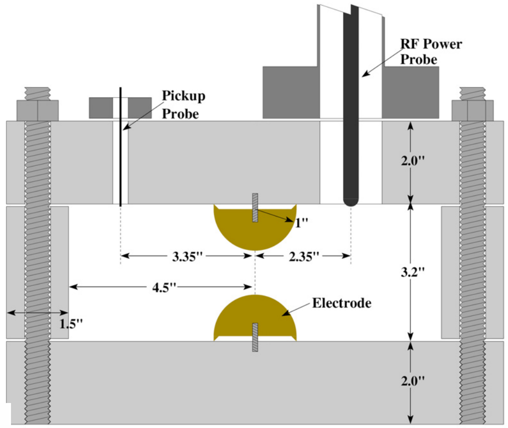
5-T solenoid

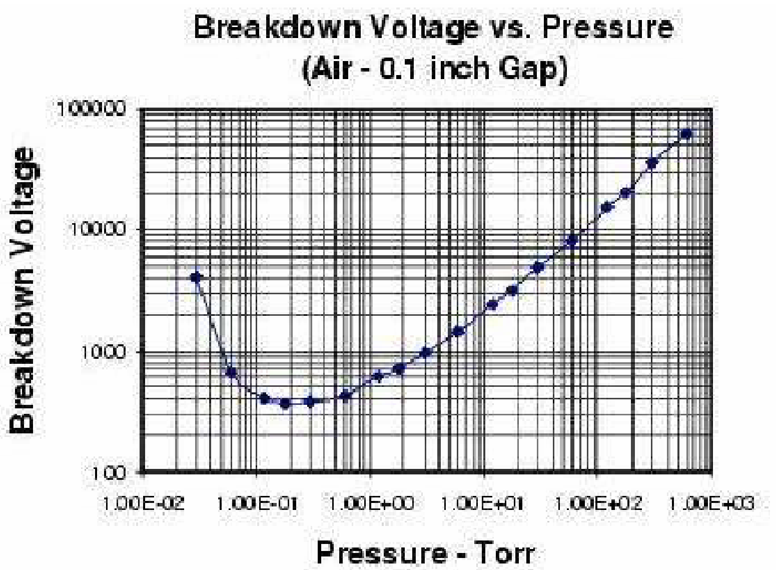


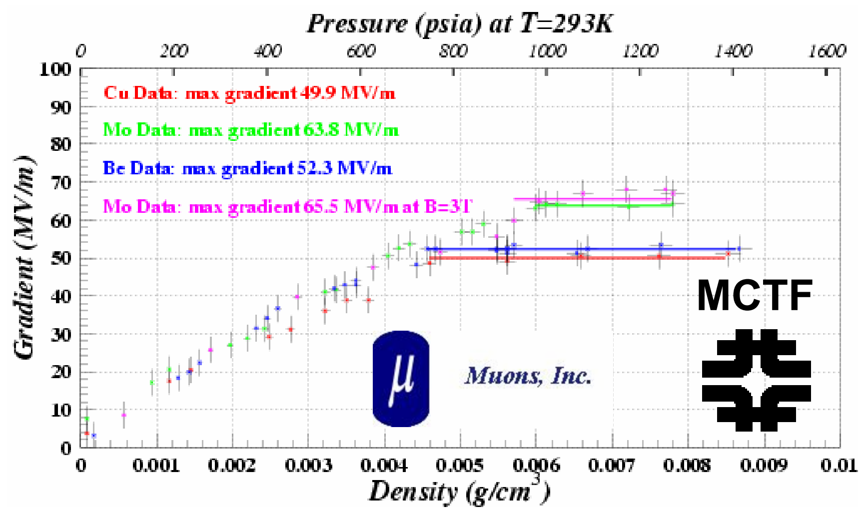
MuCool R&D (2)

- **Tested pressurized button cavity at MTA** FNAL + Muons, Inc.
  - use high-pressure H_2 gas to limit breakdown (⇒ no magnetic field effect)

Remaining issue:
What happens when high intensity beam traverses gas?







Targetry R&D

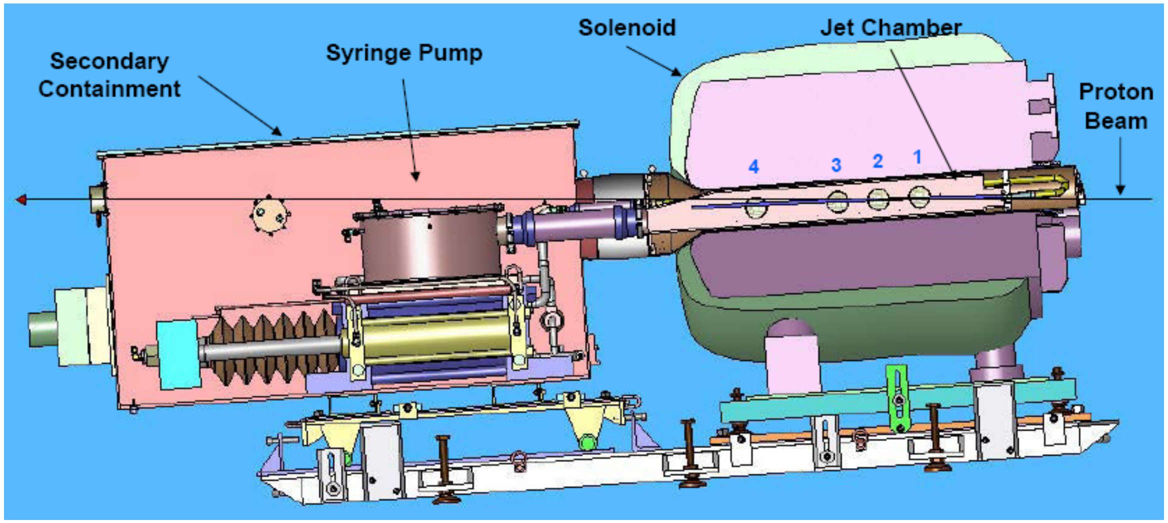
- Target capable of handling 4 MW beam of protons is a real challenge
  - solid, powder, and liquid-jet target schemes have been studied
    - solid and powder target work mainly in UK
    - Hg-jet target work initiated by NFMCC
      - initial beam tests performed at BNL in 2001 (no magnetic field)
  - MERIT system test constitutes proof-of-principle test of Hg jet target in 15 T solenoid
    - carried out in collaboration with CERN and RAL

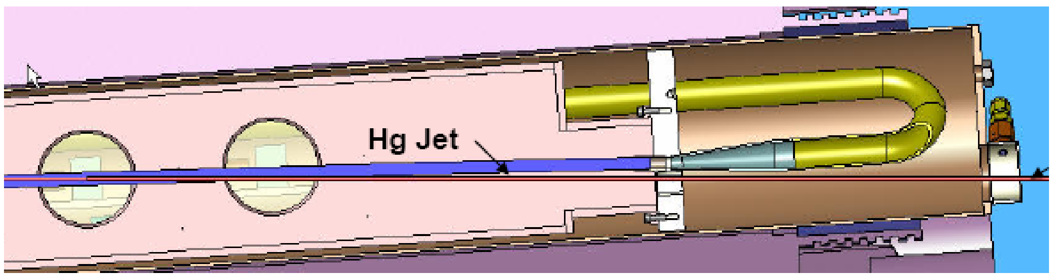
- MERIT looked at behavior of jet in magnetic field
  - disruption length
  - filament velocity
  - production fall-off due to jet disruption ("pump-probe")

MERIT abstracts submitted to this meeting:
TU4GRI03, TU6PFP085, WE6PFP086, WE6RFP010

MERIT Experiment

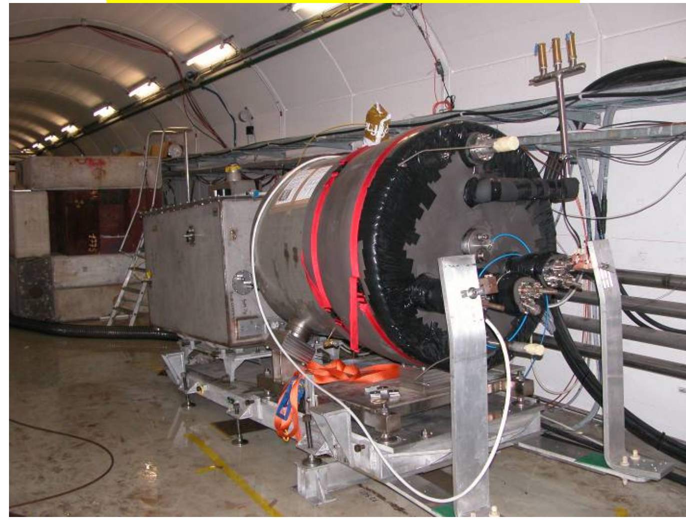
- MERIT completed beam test of Hg-jet target in 15-T magnetic field using CERN PS

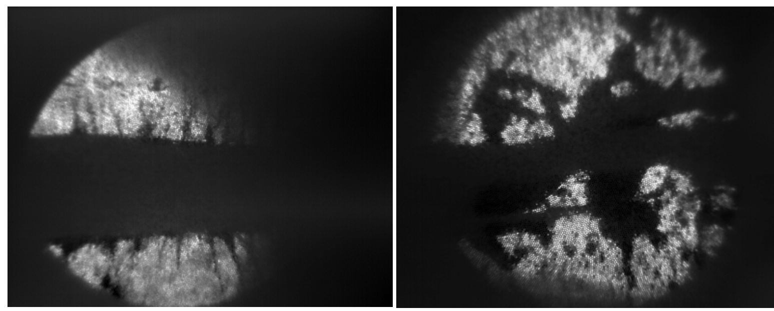




Schematic of MERIT experimental setup

Installation at CERN

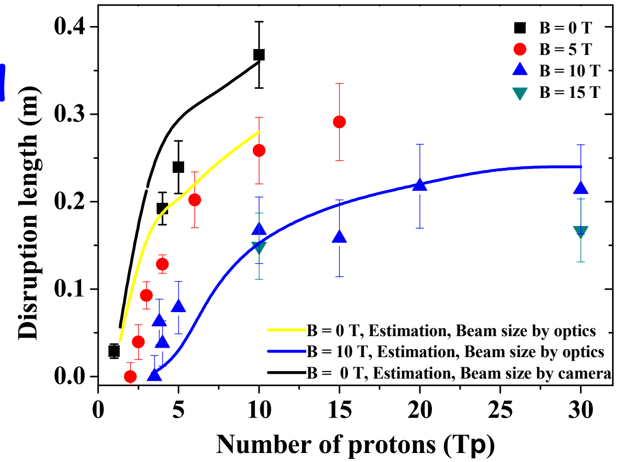




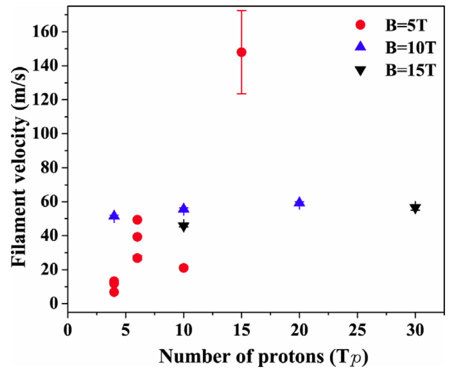
During After
10 Tp

MERIT Results

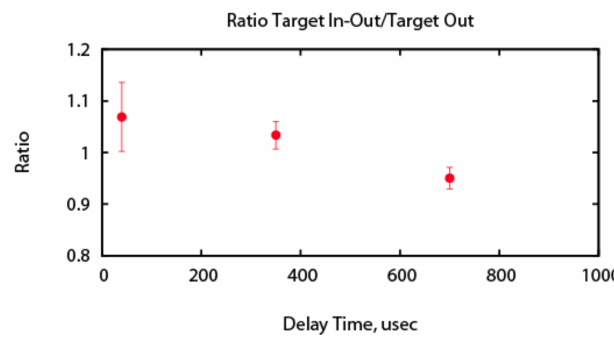
- Monitor disruption optically with fast camera [WE6RFP010]
  - no disruption for pulses with <2 Tp
  - disruption length smaller at higher magnetic field



- Estimate filament velocity
  - max. value ~60 m/s
    - suppressed at high B



- Study time-dependence of π production
  - look for degradation due to jet disruption
    - ~5% loss for long times (>400 μs)



MERIT Conclusions

- Power handling of target is adequate
  - disruption length of 28 cm ⇒ 70 Hz rep. rate at 20 m/s
  - 115 kJ per pulse x 70 Hz gives 8 MW of beam power
    - 4 MW design value seems "comfortable"

MERIT serves as a satisfactory proof-of-principle of Hg-jet concept

- Issues to pursue (none require beam)
  - look for damage to containment vessel from 60 m/s filaments
  - splash mitigation in Hg beam dump (from both beam and spent jet)
  - system aspects of continuous flow device

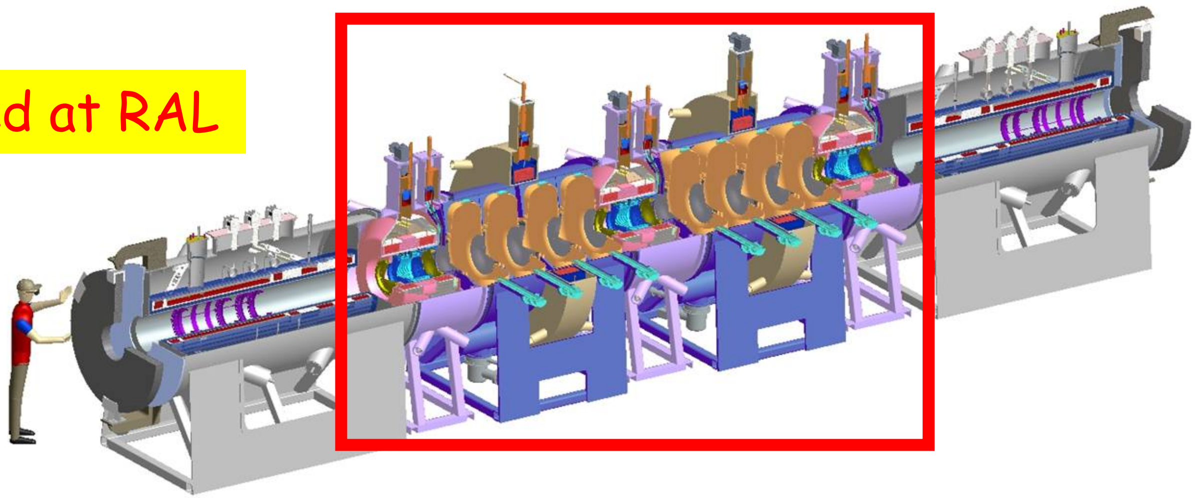
MICE

- Neutrino Factory (≈10^{21} ν_e aimed at far detector per 10^7 s year) or Muon Collider depends on ionization cooling
  - straightforward physics but not experimentally demonstrated
  - facility will be expensive (O(1B$)), so prudence dictates a demonstration of the key principle
- 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 will teach 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

System Description

- MICE includes one cell of the FS2 cooling channel
  - three Focus Coil (FC) modules with absorbers (LH_2 or solid)
  - two RF-Coupling Coil (RFCC) modules (4 cavities per module)
- Along with two Spectrometer Solenoids with scintillating fiber tracking detectors
  - plus other detectors for confirming particle ID and timing (determining phase wrt RF and measuring longitudinal emittance)
    - TOF, Cherenkov, Calorimeter

Experiment sited at RAL



Status of MICE

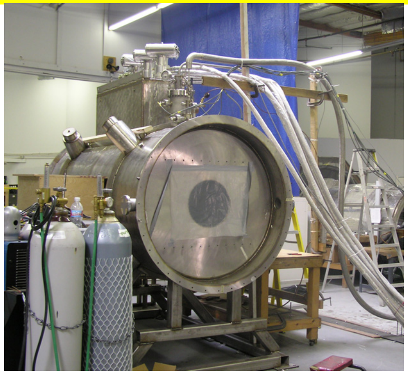
- **Civil engineering nearly completed**
  - main "missing piece" is RF infrastructure for Steps 5 and 6
    - installation of RF power sources and connection of RF power to cavities

MICE abstracts submitted to this meeting:
MO6PFP069, MO6PFP070, TU5PFP095, TU6RFP057, TU6RFP065, WE5PFP005, WE6PFP095, WE6RFP040, WE6RFP041, TH5RFP047, TH6PFP057, TH6REP051

Cooling Channel Components

- All cooling channel components are now in production

Spectrometer Solenoid (Wang NMR)

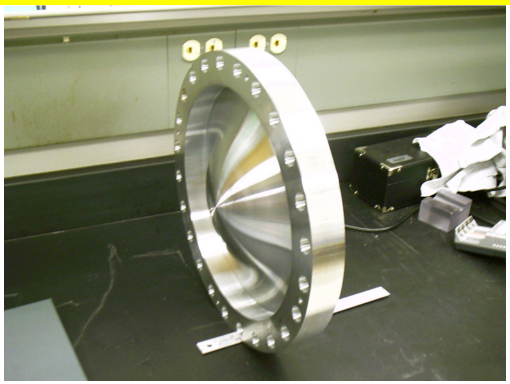


CC large test coil (HIT)

CC mandrel (Qihuan Co.)

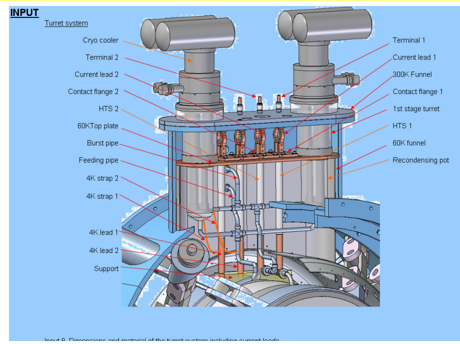
Absorber (KEK)

Absorber window (U-Miss)



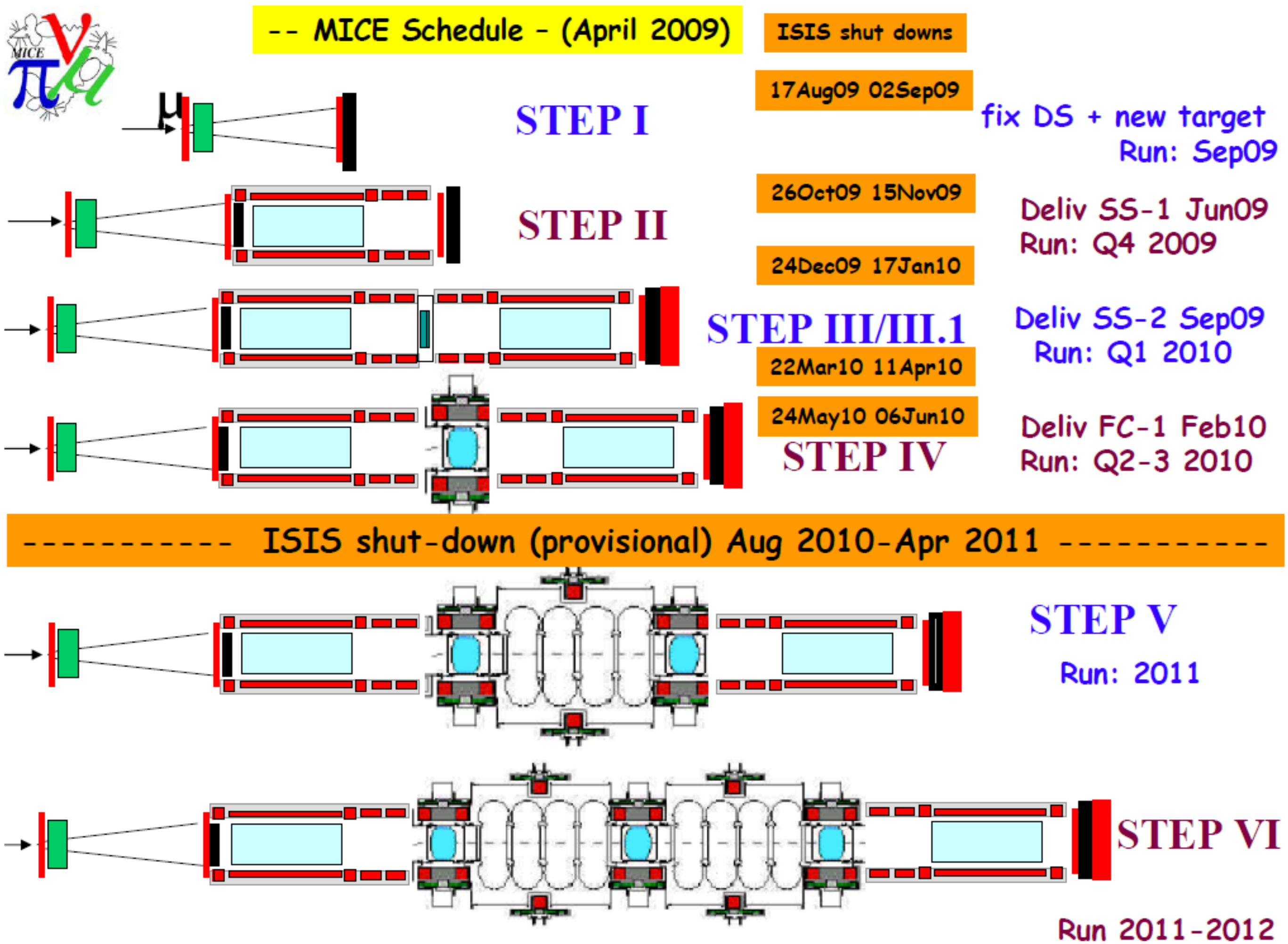
Cavity half-shell (Acme)

FC (Tesla Eng., Ltd.)



MICE Provisional Schedule

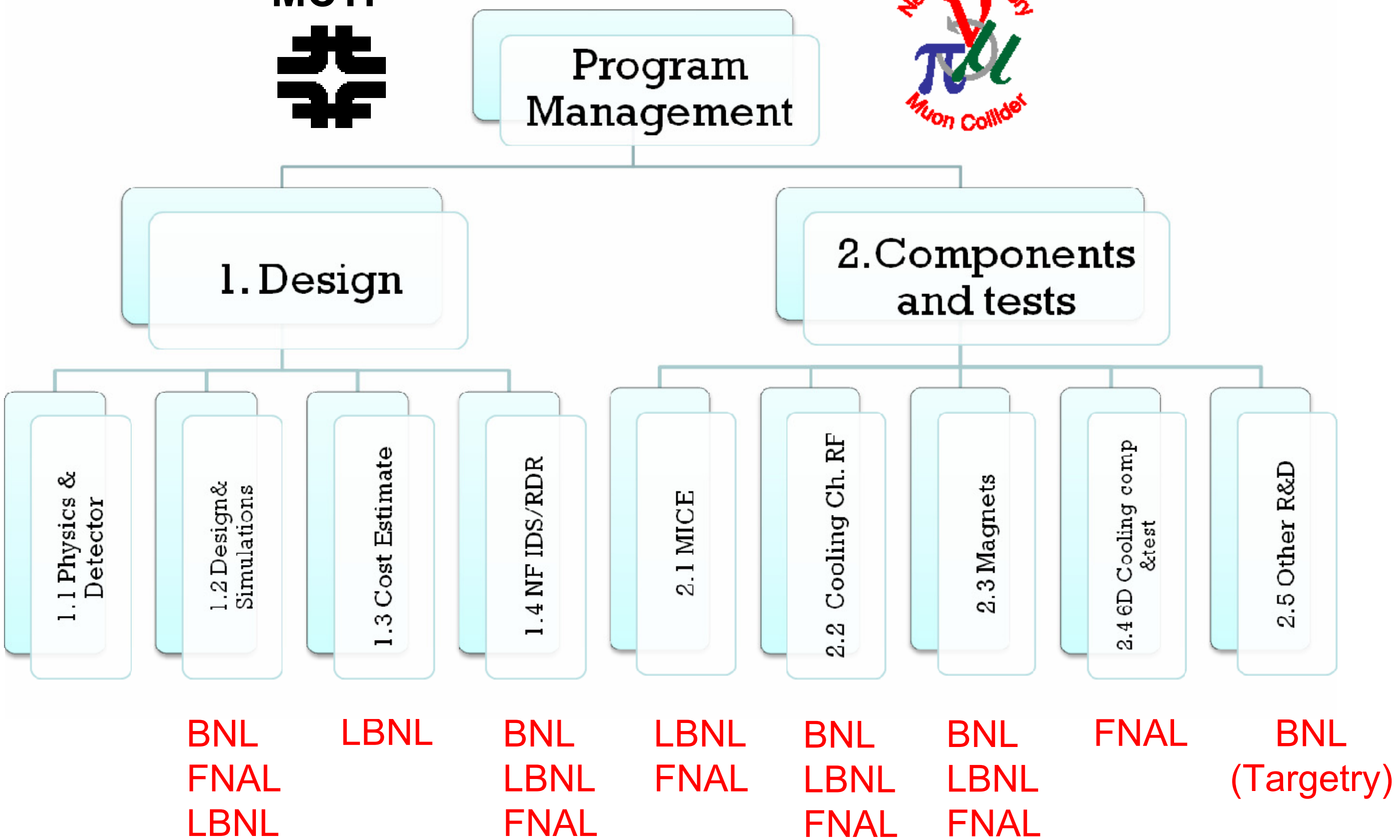
- Provisional staging plan (some delays have occurred)



5-year R&D Plan (1)

- NFMCC and Fermilab MCTF have jointly proposed a 5-year R&D plan to DOE

MCTF



Sponsoring Laboratory participation

5-year R&D Plan (2)

- Main deliverables
  - design and simulations
    - MC Design Feasibility Study (DFS)
      - intended to be a "high-end" feasibility study
        - includes physics and detector studies
        - engineering and costing not fully detailed (component level costing, not bottom-up)
      - defines R&D program (extends beyond 5-yr plan)
    - NF RDR (IDS-NF leaders set standards)
      - help with engineering and costing (select areas)
      - participate in, and in some cases lead, accelerator design of various subsystems [Berg talk; Bross talk]
  - component development and testing
    - demonstrate key technologies
    - allow down-selection of cooling channel schemes
      - may not pick unique optimal scheme, but will identify the most promising approaches

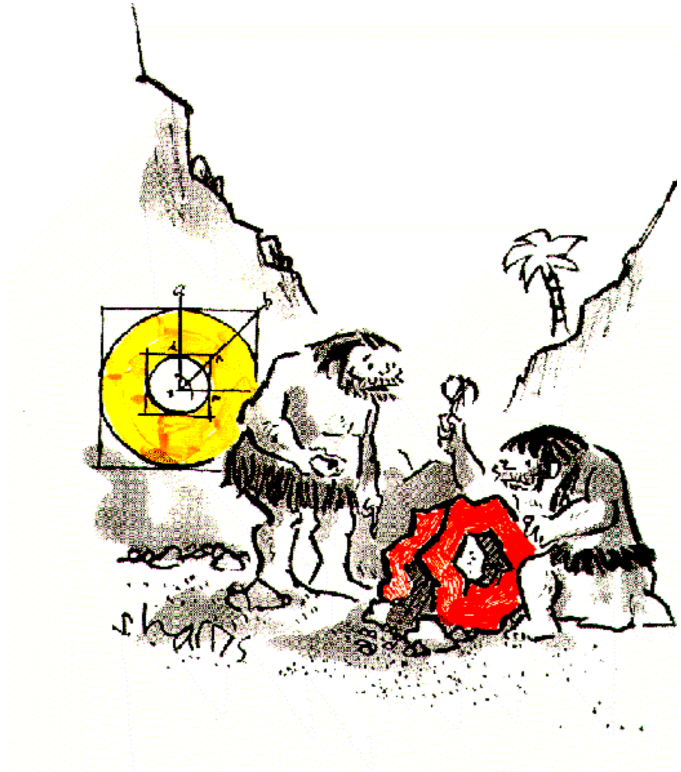
Summary

- R&D toward a NF and MC is making steady progress
  - MERIT experiment completed and analysis is well along
    - established ability of Hg-jet to tolerate >4 MW of protons
  - MICE experiment is progressing
    - Hall preparations nearly complete; major components all in production
    - looking forward to first ionization cooling measurements in a few years!
  - MuCool RF studies to understand and mitigate gradient degradation remain a high priority
- An aggressive 5-year MC+NF R&D plan has been developed and submitted for funding
  - 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

Final Thought

- **Challenges of a muon accelerator complex go well beyond those of standard facilities**
  - **developing solutions requires substantial R&D effort to specify**
    - **expected performance, technical feasibility/risk, cost (matters!)**

Critical to do experiments and build components.
Paper studies are not enough!



"I guess there'll always be a gap between science and technology."