R&D Toward a Neutrino Factory and Muon Collider

Michael S. Zisman
Center for Beam Physics
Accelerator & Fusion Research Division
Lawrence Berkeley National Laboratory

2009 Particle Accelerator Conference—Vancouver
May 5, 2009
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 $\pi$; decay into $\mu \Rightarrow$ MERIT
  - Bunching and Phase Rotation
    - reduce $\Delta E$ of bunch
  - Cooling
    - reduce transverse emittance
      $\Rightarrow$ MICE
  - Acceleration
    - $130$ MeV $\rightarrow 25$ GeV
      with RLAs or FFAGs
  - Decay Ring
    - store for 500 turns; long straight sections
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 long. and transverse emittance
      ⇒ MICE → 6D experiment

  - **Acceleration**
    - 130 MeV → ~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
      \[
      \begin{align*}
      \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu & \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu \\
      \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu & \Rightarrow 50\% \bar{\nu}_e + 50\% \nu_\mu
      \end{align*}
      \]
    - decay kinematics well known
      - minimal hadronic uncertainties in the spectrum and flux
    - $\nu_e \rightarrow \nu_\mu$ oscillations give easily detectable “wrong-sign” $\mu$ (low background)
  - 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)

Produces high energy neutrinos, above $\tau$ threshold
Unmatched sensitivity for studies of CP violation and mass hierarchy
Muon Beam Challenges

- **Muons created as tertiary beam (p → π → μ)**
  - 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

- **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
    - 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
MuCool R&D (2)

- Tested pressurized button cavity at MTA — use high-pressure H₂ 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
MERIT Results

- Monitor disruption optically with fast camera \([\text{WE6RFP010}]\)
  - 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 \(\pi\) production
  - look for degradation due to jet disruption
  - ~5% loss for long times (>400 \(\mu\)s)
MERIT Conclusions

• Power handling of target is adequate
  — disruption length of 28 cm $\Rightarrow$ 70 Hz rep. rate at 20 m/s
  — 115 kJ per pulse $\times$ 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 ($\approx 10^{21} \nu_e$ 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
    o 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)

STEP I
- 17 Aug 09
- 02 Sep 09
- Fix DS + new target
- Run: Sep 09

STEP II
- 26 Oct 09
- 15 Nov 09
- Deliver SS-1 Jun 09
- Run: Q4 2009

STEP III/III.1
- 24 Dec 09
- 17 Jan 10
- Deliver SS-2 Sep 09
- Run: Q1 2010

STEP IV
- 22 Mar 10
- 11 Apr 10
- Deliver FC-1 Feb 10
- Run: Q2-3 2010

ISIS shut down (provisional) Aug 2010 - Apr 2011

STEP V
- 24 May 10
- 06 Jun 10
- Deliver FC-1 Feb 10
- Run: Q2-3 2010

ISIS shut down (provisional) Aug 2010 - Apr 2011

STEP VI
- Run: 2011

Run 2011-2012
5-year R&D Plan (1)

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

Sponsoring Laboratory participation
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
    o established ability of Hg-jet to tolerate >4 MW of protons
  — MICE experiment is progressing
    o Hall preparations nearly complete; major components all in production
    o 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!