DEVELOPMENT OF MUON ACCELERATORS FOR NEUTRINO EXPERIMENTS

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OUTLINE

• Context
  – Neutrino landscape
  – Why muon accelerators?

• Towards a muon accelerator
  – Challenges
  – What is the R&D required?
  – System demonstrations

• Status & Prospects
Neutrino Landscape

- Neutrino physics has provided the only real evidence of physics beyond the Standard Model.
- These are exciting times with a variety of experiments internationally.
- Beyond the NOvA/DUNE/HyperK era:
  - Can we measure $\delta_{CP}$ with CKM precision?
  - Challenges: controlling systematic uncertainties.
  - If any anomalies or surprises, what new technologies will we need to improve measurements?
- Neutrino Factory facilities (NuStorm short-baseline, IDS-NF/NuMAX long-baseline) offer a path to precision measurements with controlled systematics.
Muons beams provide equal fractions of \( \nu_e / \bar{\nu}_\mu \) at high intensity for studies of neutrino mixing parameters → Neutrino Factory

- Well-known flavor content
- Well-defined energy spectrum

\[
\begin{align*}
\mu^+ & \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\
\mu^- & \rightarrow e^- + \nu_\mu + \bar{\nu}_e
\end{align*}
\]
AND MORE...

• Intense muon beams → improved search for charged lepton flavor violation

• A path to a lepton-antilepton collider:
  – $m_\mu/m_e \sim 200$
    • suppresses synchrotron radiation
    • large s-channel production

– Muons can be accelerated and stored in rings at much higher energy than electrons, with reduced beamstrahlung

– Compact Multi-TeV lepton collider offering a precision leptonic probe with exquisite energy resolution
CHALLENGES WITH MUON BEAMS

• If it was that easy, it would have been done

• Production
  – Muon beams come from tertiary production: p→π→µ
  – Challenges: High power multi-MW source, targetry to handle it, capture & transport

• Phase-space
  – Muon beams are produced with a large phase-space
  – Challenge: Phase-space reduction
    • For a µCollider, high luminosities $O(10^{34} \text{ cm}^{-2}\text{s}^{-1})$ necessitate tiny emittances
    • For a neutrino factory, cooling requirements not stringent

• Lifetime
  – $\tau \sim 2 \mu$s
  – Challenge: Cooling & acceleration must be done quickly
ORGANIZATIONAL CONTEXT

- **International Design Study for a Neutrino Factory** ([https://www.ids-nf.org/](https://www.ids-nf.org/))
  - Scope: deliver a reference design report detailing the physics performance of a neutrino factory, and define the specifications for the accelerator, diagnostics, and detector components

- **Muon Accelerator Program (MAP) in the U.S.** ([http://map.fnal.gov](http://map.fnal.gov))
  - “The mission of the Muon Accelerator Program (MAP) is to develop and demonstrate the concepts and critical technologies required to produce, capture, transport, accelerate, and store intense beams of muons for Muon Colliders and Neutrino Factories”
  - Approach: Muon Accelerator Staging Study, Initial Baseline Selection, R&D demonstrations
    - Allows to define a staged deployment of muon accelerator technologies, identify concepts and machine parameters, & demonstrate crucial technologies
**Neutrino Factory**

- **IDS-NF (an ideal NF)**
- **Proton driver**
  - Proton beam ~8 GeV on target
- **Target, capture and decay**
  - Create π, decay into μ (*MERIT*)
- **Bunching and phase rotation**
  - Reduce ΔE of bunch
- **Cooling**
  - Reduce εₜ (*MICE*)
- **Acceleration**
  - With RLAs/RCS/FFAG (*EMMA*)
- **Decay ring**
  - Baseline is race-track

- **U.S. Muon Accelerator Staging Study**
  - An incremental approach
  - *NuMAX @ 5 GeV*
  - Optimized for FNAL:SURF
**Neutrino Factory**

- **Muon Accelerator Staging Study**
  - An incremental staged approach
  - NuMAX @ 5 GeV
  - Optimized for FNAL: SURF

![Diagram of Neutrino Factory (NuMAX)](image)

- Muon Collider Goals:
  - 126 GeV $\Rightarrow$ ~14,000 Higgs/yr
  - Multi-TeV $\Rightarrow$ Lumi > $10^{34}$cm$^{-2}$s$^{-1}$
PROTON DRIVER

• Require a multi-MW proton source to produce \( O(10^{21}/yr) \) muons within accelerator acceptance
  – With a target & capture system to handle it

• Constraint is geographical and choice of host
  – LINAC:
    • High Power SPL (CERN)
    • PIP-II,III... (FNAL)
  – Rings:
    • Synchrotrons
    • FFAG J-PARC or RAL
TARGET: MERIT

- System demonstration experiment @ CERN (2007)
  - 20 m/s LHg jet
  - Injected in 15T field & impacted by pulsed beam (24 GeV, $10^{13}$/pulse)
  - Beam pulse energy 115 kJ
  - Measured Disruption Length: 28 cm $\rightarrow$ rep rate up to 70Hz
  - Proton beam power @ 70Hz, 115 kJ $\rightarrow$ 8MW
HIGH POWER TARGET

- MAP staging calls for 1-2 MW source and C-target
- Designs also developed for 4 MW LHg target
ACCELERATION

- Short muon lifetime requires rapid acceleration
- A range of acceleration technologies:
  - Choice dependent on energy range
  - Superconducting LINACs
  - Recirculating Linear Accelerators w/ multipass arcs
  - Rapid Cycling Synchrotrons
  - Fixed-field Alternating Gradient accelerators (FFAG)
  - EMMA: a proof-of-principle system demonstration
EMMA

- **EMMA**
  - Electron Model for Many Applications
  - Hosted by Daresbury Lab
  - Study injection/extraction & beam dynamics
  - 42 doublets, 19 1.3 GHz RF cavities

- **FFAG**
  - Fixed-field → no ramping required
  - Alternating gradient → control of aperture

- Stable acceleration demonstrated with electrons
  - accelerated from 12 to 18 MeV in 6 turns
  - No observable growth in beam oscillation amplitude

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COOLING

• To accelerate an intense beam of $\mu$ from $\pi$ decays
  – *Either* must accept large beam emittances in a cost-effective way
  – *Or* must cool $\mu$ beams to reduce emittance and increase flux

• Short lifetime means that muon cooling is challenging
  – None of the traditional cooling methods work for muons

• Ionization cooling is the only practical technique
MUON IONIZATION COOLING

• Utilize energy loss in materials

• Muons cool via dE/dx in low-Z medium

- Absorbers: 
  \[ E \rightarrow E - \left( \frac{dE}{dx} \right) \Delta s \]
  \[ \theta \rightarrow \theta + \theta_{\text{rms}} \]

- RF cavities between absorbers replace \( \Delta E \)

- Net effect: reduction in \( p_\perp \) at constant \( p_\parallel \), i.e., transverse cooling

\[
\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2} \frac{dE_\mu}{ds} \epsilon_N + \frac{\beta_\perp (0.014 \text{ GeV})^2}{2 \beta^3 E_\mu m_\mu X_0} \quad (\text{emittance change per unit length})
\]

\( \Rightarrow p_\perp \) restored by RF re-acceleration
MUON IONIZATION COOLING EXPERIMENT

- The physics is understood, but the technology must be demonstrated as viable
- MICE @ RAL will be the first demonstration
MICE

- Track & measure momentum (and emittance)
  - Before & after passing through absorber

4T Superconducting solenoid

Scintillating fibre tracker
MICE

- LiH, LH2 absorbers to cool
- Strong focussing to minimize heating
MICE

- RF acceleration to restore $p_L$

201 MHz RF Cavity
MICE
MICE

- Measurement program underway to characterize absorber materials and measure change in $\varepsilon_t$
- Subsequently adding RF will demonstrate sustainable ionization cooling
RF

• Cooling requires:
  – Large accelerating gradient to restore energy lost in absorbers
  – Operation of cavities in high B-fields
  – Issues: RF breakdown, field emission

• R&D important for both νFactory, μCollider
  – RF impacts capture, bunching, cooling, acceleration

• MuCool program at MTA@FNAL
  – Component characterization
  – Also a test-bed for MICE RF
COOLING TECHNOLOGY RF

- **MICE RF Cavity**
  - 201 MHz operated in fringe field of 5T solenoid
  - >14 MV/m, < 10^{-6} spark rate
    - SCRF-type surface preparation
- **High Pressure gas-filled RF**
  - operated in 3T field with beam
  - Performance extrapolates to NF/MC requirements
- **Vacuum RF**
  - 805 MHz cavity operated in 5T field under vacuum, > 20 MV/m
  - Performance consistent with models

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Several key technical challenges have been, and are being, addressed.

At the same time, the technology exists right now to build e.g. a NuStorm-like facility that can:

- Deliver physics ($\nu_e + N$ cross sections, sterile neutrinos...)
- Constrain systematics for superbeam experiments
- And be a proving ground for $\mu$ accelerator technologies.
PATHS FORWARD....

νSTORM – the First NF?

μ decay ring: P = 3.8 GeV/c ± 10%

No new technologies required!
Could be deployed now!

SuperBIND Detector

Fermilab Configuration

Far Detector

Near Hall

To Far Hall

Far Hall @1.9km
PATHS FORWARD....

The MAP Muon Accelerator Staging Study ⇒ NuMAX

- PIP-II: 0.8 GeV
- PIP-III: 2.2 GeV
- Dual-Use (p & μ) Linac
- 3.75 GeV 650 MHz
- μ+ & μ− Chicane
- NuMAX
- 5 GeV Storage Ring optimized for Fermilab-to-SURF baseline
- NuMAX Staging:
  - Commissioning
    - 1MW Target
    - No Muon Cooling
    - 10kT Detector
  - NuMAX+
    - 2.75 MW Target
    - 6D Muon Cooling
    - 34kT Detector

Front End → Buncher → Accumulator

μ pre-Linac
1.0 GeV 325 MHz

Target & Capture Solenoid

6D Cooling

~281 m

COOL’15 - Jefferson Laboratory, Newport News, Va, USA
September 28, 2015

Fermilab

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SUMMARY

• Muon beams offer a path to
  – A Neutrino factory → precision measurements
  – A compact Multi-TeV lepton-antilepton collider
  – A staged approach can deliver essential physics now while at the same time proving the R&D for further stages

• Several key technical hurdles have been addressed:
  – High power target (MERIT)
  – Realizable cooling channel designs (MICE)
  – Breakthroughs in RF and cooling technology (MuCool)
  – Significant progress in collider & detector design concepts

*Muon Accelerators offer a unique opportunity for the future of neutrino physics & HEP*