MICE STATUS REPORT

MICE Collaboration

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Outline

- Introduction: towards a Neutrino Factory
- The MICE cooling experiment
- MICE beamline
- The MICE Cooling channel
- The MICE spectrometers
  - MICE trackers
  - MICE PID instrumentation
    - Upstream PID detectors
    - Downstream electron muon calo (EMC)
    - The TOF system
- Conclusions
Neutrino Factory
International Scoping Study baseline

- Proton Drive (4 MW, 2 ns bunch)
- Target, Capture, Drift ($\pi \rightarrow \mu$) & Phase Rotation
  - Hg Jet
  - 200 MHz train
- Cooling
  - 30 $\mu$m ($\perp$)
  - 150 $\mu$m (L)
- Acceleration
  - 103 MeV $\rightarrow$ 25 GeV
- Decay rings (baseline is race-track design):
  - 7500 km L
  - 4000 km L

ISS Accelerator WG report: RAL-2007-023
ν beams: conventional and nufact beams

- Problem in conventional ν beams: a lot of minority components (beam understanding)
- Following muon collider studies, accelerated muons are ALSO an intense source of “high energy” ν

\[ \mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e \quad \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e \]

- Crucial features:
  - high intensity (x 100 conventional beams)
  - known beam composition (50% ν_μ, 50% ν_e)
  - Possibility to have an intense ν_e beam
- Essential detector capabilities:
  - detect μ and determine their sign
Neutrino Factory: physics channels

<table>
<thead>
<tr>
<th>$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$</th>
<th>$\mu^- \rightarrow e^- \bar{\nu}<em>e \nu</em>\mu$</th>
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<tr>
<td>$\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu$</td>
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- Disappearance
- Appearance (challenging)
- Appearance (atm. oscillation)
- Disappearance

**Reference' Neutrino Factory:**
- $\geq 10^{21}$ useful decays/yr; exposure '5 plus 5' years

- Two baselines ($\approx 7500$ km & $\approx 4000$ km)
  - 50 kT magnetised iron detector (MIND) with MINOS performance - Golden Channel Detector
  - Backgrounds (for golden channel):
    - Sign of $\mu$ mis-ID'd
    - Charm decays
  - $E_{\text{res}} \sim 0.15 \times E_\nu$

"Golden" $\rightarrow$ Sign of $\mu$ observed in detector opposite to that stored in decay ring

$\mu^+ \rightarrow \nu_e \rightarrow \nu_\mu n \rightarrow \mu^- p$
IDS Study - Physics Reach

3σ contours shown


$\sin^2 2\theta_{13}$

Hierarchy

$\delta CP$

**SPL:** 4MW, 1MT H$_2$OC, 130 km BL  
**T2HK:** 4 MW, 1MT H$_2$OC, 295 km BL  
**WBB:** 2MW, 1MT H$_2$OC, 1300 km BL  

**NF:** 4MW, 100KT MIND, 4000 & 7500 BL  
**BB350:** $\gamma=350$, 1MT H$_2$OC, 730 km BL

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Neutrino Factory R&D

- **High power (MW) proton driver**
- **Target and collection (HARP/MERIT)**
  - Maximize $\pi^+$ and $\pi^-$ production
  - Sustain high power (MW driver)
  - Optimize pion capture

- **Muon cooling (MICE)**
  - Reduce $\mu^+ / \mu^-$ phase space to capture as many muons as possible in an accelerator

- **Muon acceleration**
  - Has to be fast, because muons are short-lived! (RLA, FFAG, ...)

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Muon ionization cooling

Stochastic cooling is too slow. A novel method for $\mu^+$ and $\mu^-$ is needed: **ionization cooling**

**principle**

1. reduce $p_t$ and $p_l$
2. heating
3. re-acceleration

**reality (simplified)**

- Build a section of cooling channel long enough to provide measurable cooling (10%) and short enough to be affordable and flexible
- Wish to measure this change to 1%
- Requires measurement of emittance of beams into and out of cooling channel to 0.1%
- Cannot be done with conventional beam monitoring device
- Instead perform a single particle experiment:
  - High precision measurement of each track ($x,y,z,px,py,pz,t,E$)
  - Build up a virtual bunch offline
  - Analyse effect of cooling channel on many different bunches
  - Study cooling channels parameters over a range of initial beam momenta and emittances
MICE setup: cooling + diagnostics

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Cools and measures about 100 muons/s

Spectrometer solenoid 1
Matching coils 1.1+1.2
Focus coils 1
Focus coils 2
Focus coils 3
Matching coils 2.1+2.2
Spectrometer solenoid 2

Coupling Coils 1+2

RF cavities 1
RF cavities 2

Liquid Hydrogen absorbers 1,2,3

Trackers 1 & 2
measurement of emittance in and out

Beam PID
TOF 0
Cherenkov
TOF 1

Diffusers 1&2

Incoming muon beam

Downstream particle ID:
TOF 2
Calorimeter

μ
MICE installation status (2009)

- Target
- Beamline
- PID detectors
MICE Beamline

- ISIS 800 MeV proton synchrotron at RAL
- Titanium target, grazing ISIS beam
- $\pi$ captured by quad triplet and momentum selected by dipole
- Followed by 5T decay superconducting solenoid (5 m long): contain $\pi$ and decay $\mu$
- Second dipole momentum select muons
MICE Target

- Titanium target (UK) dipped into ISIS beam at end of 20 ms beam cycle at ~0.4 Hz
- This requires fine control of the position of the target as well as high acceleration (~80 g)
- Original target ran 190K dips into beam, but failed December 2008 (Tip melted)
- A simplified design is being constructed
- Understand target operation
  - Beam loss
  - Dip depth and timing
  - How affect ISIS
  - Number of particles in MICE beamline
Decay Solenoid

- 5T superconducting solenoid (PSI)
- Problem:
  - Quenched at ~290A (870 A is required for normal running at 5 T)
- Solution:
  - Missing multi-layer insulation caused quenches → installed March/April
- Cooled down
- Ran up to full operating current April 2009

![Graph](image)

Magnet current

- 870 A

![Graph](image)

- 4.6 K
The beamline has been operated over a range of momenta, producing positrons, pions and protons. TOF0 and KL detectors have been used to record beam profiles. Time of flight have been used to identify pions and protons.

300 MeV/c pion beam profile in TOF0. Left: 2D beam profile
MICE cooling channel

- \[ \frac{d\varepsilon_n}{ds} = - \frac{1}{\beta^2} \left( \frac{dE_\mu}{ds} \right) \frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3} \frac{\beta}{2E_\mu m_\mu X_0} (0.014)^2 \]

Minimize heating term:
- Absorber with large X_0
- SC solenoid focusing for small \( \beta_T \)

- High gradient reacceleration
  - 10% reduction of muon emittance for 200 MeV muons requires \(~20\text{MV RF} \)

- Challenge: integration of these elements in the most compact and economic way

- 3 Liquid Hydrogen absorbers
- 8 cavities 201MHz RFs, 8MV/m
- 5T SC solenoids
Cooling Channel

- Liquid hydrogen absorbers (Japan) alternating with normal conducting 201 MHz RF cavities
  - First absorber fabricated at KEK
  - Test soon with LH$_2$

- LH2 absorbers inside absorber-focus-coil (AFC) module (UK) with superconducting coils to provide strong focus at absorber
  - Delivery expected Feb 2010 first AFC module

- RF cavities (US) inside Coupling Coil modules (China)
  - Challenges due to operation inside magnetic field
RF Module

- **RF Cavities**
  - LBNL responsible for design and fabrication of cavities
  - Copper procured for first 5 cavities
  - Formed into half shells - delivery end 2009

- **RF Coupling Coils**
  - Final design of RFCC modules done
  - Harbin Institute of Technology responsible for design and fabrication of coupling coils
  - LBNL responsible for RF cavity integration with coils
  - Fabrication underway - first unit delivery summer 2010

- **RF power**
  - ~1MW in 1ms pulse at 1 Hz per cavity
  - 4 sets of amplifiers (LBNL, CERN) being refurbished at Daresbury Lab (UK)
  - First test summer 2009
Muon Emittance measurement

Each spectrometer measures 6 parameters per particle:
- \( x, y \), \( x' = \frac{dx}{dz} = P_x/P_z \)
- \( y' = \frac{dy}{dz} = P_y/P_z \), \( t' = \frac{dt}{dz} = E/P_z \)

Determines, for an ensemble (sample) of \( N \) particles, the moments:
- Averages \( \langle x \rangle \), \( \langle y \rangle \) etc...
- Second moments: \( \text{variance}(x) \) \( \sigma_x^2 = \langle x^2 \rangle - \langle x \rangle^2 \) etc...
- \( \text{covariance}(x) \) \( \sigma_{xy} = \langle x.y \rangle - \langle x \rangle \langle y \rangle \)

Covariance matrix

\[
M = \begin{pmatrix}
\sigma_x^2 & \sigma_{xy} & \sigma_{xt} & \sigma_{xx'} & \sigma_{xy'} & \sigma_{xt'} \\
\sigma_{xy} & \sigma_y^2 & \sigma_{yt} & \sigma_{yy'} & \sigma_{yt'} & \sigma_{xty} \\
\sigma_{xt} & \sigma_{yt} & \sigma_t^2 & \sigma_{tt'} & \sigma_{xtt'} & \sigma_{ytxy} \\
\sigma_{xx'} & \sigma_{yy'} & \sigma_{yt'} & \sigma_{yy'} & \sigma_{yy'} & \sigma_{xtt'} \\
\sigma_{xy'} & \sigma_{yt'} & \sigma_{xtt'} & \sigma_{xtt'} & \sigma_{tt'} & \sigma_{xx'} \\
\sigma_{xt'} & \sigma_{ytxy} & \sigma_{ytxy} & \sigma_{ytxy} & \sigma_{ytxy} & \sigma_{xx'} \\
\end{pmatrix}
\]

Evaluate emittance with:

\[
\varepsilon^{6D} = \sqrt{\det(M_{xx'y't'})}
\]

\[
\varepsilon^{4D} = \sqrt{\det(M_{xx'y'})} = \varepsilon_{\perp}^2
\]

Getting at e.g. \( \sigma_{x'y'} \) is essentially impossible with multiparticle bunch measurements.

Compare \( \varepsilon^{in} \) with \( \varepsilon^{out} \)

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1. must be sure particles considered are muons throughout
   a) reject incoming e, p, \( \pi \)
      \( \Rightarrow \) TOF 2 stations 10 m flight with 70 ps resolution
   b) reject outgoing e \( \Rightarrow \) EMR Calorimeter

2. measure 6 particle parameters
   i.e. \( x, y, t, \frac{p_x}{p_z}, \frac{p_y}{p_z}, \frac{E}{p_z} \)

3. measure widths and correlations ...
   resolution in all parameters must be better than 10% of width
   at equilibrium emittance (correction less than 1%)
   \( \sigma^2_{\text{meas}} = \sigma^2_{\text{true}} + \sigma^2_{\text{res}} = \sigma^2_{\text{true}} \left[ 1 + (\frac{\sigma_{\text{res}}}{\sigma_{\text{true}}}^2) \right] \) (n.b. these are
   r.m.s. !)

4. robust against noise from RF cavities

   **Statistical precision**
   \( 10^5 \) muons \( \Rightarrow \Delta \left( \varepsilon^\text{out} / \varepsilon^\text{in} \right) = 10^{-3} \) in ~ 1 hour

   Systematics!!!!!
MICE Detectors

• **Particle identification: TOF, CKOV, Calorimeter**
  
  - **Upstream**
    - Time of Flight TOF0 + TOF1
    - 2 Aerogel threshold Cherenkov detectors
    - $\pi/\mu$ separation up to 360 MeV/c
    - Beam purity better than 99.9%
  
  - **Downstream**
    - TOF2
    - EMC Calorimeter
      - Kloe-like (KL) Lead-scintillating fiber sandwich layer (built)
      - Electron-Muon Ranger (EMR) (to be built)
        » 1m$^3$ block extruded scintillator bars
        » Also measure muon momentum
    
    - $\mu/e$ separation

• **Particle tracking**
  
  - Scintillating Fiber trackers
  - Measure position and reconstruct momentum
MICE Tracker

- **Scintillating fiber trackers**
  - Reduce transverse emittance by 10%
  - Trackers need to measure this reduction to 0.1% precision
  - Determine $x, x', y, y'$ and momentum
  - High resolution on order of 1 fiber needed

- **Design**
  - 350 $\mu$m scintillating fiber doublet layers
  - Active area has diameter of 30 cm
  - 5 measurement stations with 3 planes each
Spectrometer Status

• **Trackers**
  - Both trackers completed
  - Cosmic ray test of tracker1 at RAL:
    • Light yield measured 11 PE
    • Measured resolution consistent with goal of 430 μm
    • Efficiency – 99% hit efficiencies
  - First to be installed in beam inside 4 T solenoid magnet (US) ~1m long with 5 SC coils

• **Magnets**
  - First spectrometer solenoid built
  - Undergoing cooldown followed by magnet performance tests
  - Then ship to FNAL for field measurements
  - Second will follow later
PID apparatus: overview

MICE Particle ID Important to insure high muon purity for muon cooling measurement.

- **Upstream:**
  - TOF0,1 X/Y hodoscope with 10m path, 70 ps resolution
  - 2 Aereogel threshold Cherenkov detectors (n=1.07 and n=1.12)
  - $\pi/\mu/e$ separation at better than 1% at 230 MeV/c

- **Downstream:**
  - 0.5% of $\mu$ s decay in flight: need electron rejection at $10^{-3}$ to avoid bias on emittance reduction measurement
  - TOF2 X/Y hodoscope
  - EMC Calorimeter for MIP vs E.M. Shower (KL (built) + EMR (in future))
The upstream part (inside DSA)
**Upstream: CKOVa/CKOVb**

Aerogel box

- **CKOV PMTs** (from CHOOZ)
- Radiator
- Reflector Panels (not shown)
- 8" PMT port

Aerogel radiator compartment
Performances in beam of CKOVa,b

- Took data in MICE beamline
- Typical light spectrum from single PMT
- Muon tagging efficiency 98%

CKOVA: mean pulse height ≈200 channels (20 pe)
CKOVB: mean pulse height ≈250 channels (25 pe)
The downstream calorimeter
electron-muon calorimeter (EMC)

- EMC is not primarily intended for energy measurements
- It’s main role is to provide $e/\mu$ separation
- In MICE proposal this was provided by a CKOV counter + an em calorimeter (KL)
- Now it will be provided by KL + a sandwich calorimeter (EMR to be constructed)
- KL (KLOE-light) is a fiber spaghetti calorimeter with a design similar to the KLOE one
- EMR is a fully active calorimeter (10 layers) with increasing thickness
KL assembly

Lead-fibers modules

KL’s frame

Iron mag. shielding bar

Installation in temporary position after Q9 at RAL

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KL performances in beam

KL response to 300 MeV/c π beam

The typical MIP distribution and the correlation left-right of the photomultiplier signals with cosmics.

KL response to 100MeV e+ beam
**PID system upgrade: the EMR Calorimeter**

- 70 cm of fully active scintillator, highly segmented

- Light collected by WLS fibers, read by Multi-anode PMTs

- Track Properties:
  - Muons show tracks;
  - Electrons converted in EM showers in KL show scattered hits

- $dE/dx$ along $Z$
  - Muons have constant $dE/dX$ up to the Bragg peak
  - Electrons have large fluctuations in Energy loss which tends to decrease with $Z$
Full prototype mounted

Front-end electronics

Read-out based on 2 board: the FEE and the repeater which transfer the information from the FEE to the VME crate.

The IDEAS integrated circuit used (VA series) has 2 working mode:

* Threshold detection

* Peak sampling (Sample and Hold)

In threshold mode an FPGA is used to reduce the amount of information sent to the repeater.

In Peak Sampling mode the peak amplitude of all the channels are read sequentially.

 Cosmic rays setup

* External scintillator trigger
* 4 silicon strips external tracker (2 "x" and 2 "y" measurements of each cosmic ray)
* SW prototype in horizontal position
* ≤10^5 events acquired

Preliminary Results

* Big number of photoelectrons in PM
* SiPM also an option (but maybe too early)

<table>
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<tr>
<th>event: 35</th>
<th>0: threshold at 60</th>
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A test is on-going at CERN with high energy electrons!
TOF system requirements

- Exp trigger, upstream/downstream PID and measure of $t$ vs RF
- Work in a harsh environment (high incoming particle rate, high fringe fields from solenoids, X rays from converted $e^-$) with good timing performances ($\sigma_t \sim 50$ ps)

Tof resolution can be expressed as:

$$\sigma_t = \sqrt{\frac{\sigma_{\text{scint}}^2 + \sigma_{\text{PMT}}^2 + \sigma_{\text{pl}}^2}{N_{pe}}} + \sigma_{\text{elec}}$$

Some points to look to have high resolution TOFs

- $\sigma_{\text{pl}}$ dominated by geometrical dimensions $\sim \sqrt{(L/N_{pe})}$
- $\sigma_{\text{scint}} \sim 50-60$ ps (mainly connected with produced number of $\gamma$'s fast and scintillator characteristics, such as risetime)
- $\sigma_{\text{PMT}}$ PMT TTS (typically 150-300 ps)

- HARSH Environment (shielding from B, RF noise, high particle rate)
TOF design

• “conventional” X/Y scintillator structure with readout at both ends, to provide redundancy & intercalibration with inc. μ

• problem: choice of PMTs for high incident particle rate (1 MHz) and solenoid B fringe field ($B_{\parallel} \sim 200-300$ G, $B_{\perp} \sim 1K$ G)
Magnetic field shielding

With an external cage B field is reduced to tolerable levels for conventional R4198 PMTs (solution adopted for TOF1)

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Downstream PID Layout

Distance to center of MICE = 6011

Distances to centers
- Virostek: 450
- 1st plane TOF2: 537.5
- 2nd plane TOF2: 562.5
- KL: 638
• for TOF2 massive box ARMCO local shielding (D0-like) solution
• PMT studies show solution is adequate.

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First results in beam for TOF0-TOF1

After time-walk correction + time calibration

The time difference between the vertical and horizontal slabs in the same station can be used also to measure the time resolution obtained after the calibration. The resolution on the difference in the calibrated pixels in TOF0 (TOF1) is ~ 102 (124) ps. This translates into ~ 51 (62) ps resolution for the full detector with crossed horizontal and vertical planes.
• Time of flight between TOF0 and TOF1 for the so called positron (red) and pion (blue) beams

• The first peak which is present in both distributions is considered as the time of flight of the positrons and is used to determine the absolute value of the time in TOF1. A natural interpretation of the other two peaks in the time of flight spectrum from the so called pion beam is that they are due to forward flying muons from pion decay and pions themselves, but the calculated time of flight of nominal 300 MeV/c pions is ~ 29.4 ns instead of ~ 30.0 ns, where the third peak maximum is positioned.

• This difference may be partly explained by the energy loss inside the TOF0 and the two upstream Cerenkovs, that amounts to ~ 17 MeV.
The MICE Schedule

- Experiment designed to grow with each step providing important information
Conclusions

- Beamline in place and commissioning begun
- Decay solenoid working
- PID detectors (TOF0, TOF1, CKoV, KL) in place and working well
- Tracker1 performing well and ready for installation when first tracking solenoid will arrive
- First emittance measurement Fall 2009
- First cooling 2010