The MICE Beam Line Instrumentation (Trackers and PID) for precise Emittance Measurement

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on behalf of the MICE Collaboration
1. Motivation for MICE: Neutrino Factory and Muon Collider
2. MICE aims
3. Ionization cooling
4. MICE beam line
5. MICE detectors: TOF, Cherenkov, Calorimeters (KL and EMR) and tracker
6. Preliminary detector performance
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New baseline Neutrino Factory for high $\theta_{13}$: 10 GeV/c muon storage ring

4D muon ionization cooling essential for $10^{21}$ $\mu$/year

Study II cooling cell

International Design Study for a Neutrino Factory
Interim Design Report
IDS-NF-020

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Neutrino Factory

- Neutrino Factory optimisation depends on value of $\theta_{13}$
- At $\sin^2 2\theta_{13} \sim 0.1$ optimum is $\sim 10$ GeV NF with $\sim 2000$ km baseline
- Neutrino Factory offers best sensitivity and smallest $\Delta\delta_{CP} \sim 5^\circ$ out of all future facilities

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Cooling essential to deliver Neutrino Factory performance

Emittance: $18 \text{ mm rad} \rightarrow 7.5 \text{ mm rad}$
Muon yield: $0.08 \mu/\text{p.o.t.} \rightarrow 0.19 \mu/\text{p.o.t.}$

Increase in performance: 2.4
At the energy frontier, a multi-TeV muon collider fits inside most major laboratories, has better energy resolution than $e^+e^-$ linear colliders and has enhanced coupling to the Higgs.

- A Muon Collider requires 6D ionization cooling
- A Neutrino Factory is the first step towards a Muon Collider
The Muon Ionization Cooling Experiment (MICE) is a UNIQUE facility at RAL to measure muon ionization cooling in a cell of the NF Study II design.

Absorbers: liquid hydrogen and other low Z absorbers (LiH).

The aim of MICE is to measure ~10% emittance reduction (cooling) from 140-240 MeV/c muons with 1% precision: \( \frac{\Delta \varepsilon}{\varepsilon_{in}} = 10^{-3} \)

See talk Ken Long at Accelerator session
International Muon Ionization Cooling Experiment (MICE): Belgium, Bulgaria, China, Holland, Italy, Japan, Switzerland, UK, USA based at Rutherford Appleton Laboratory (UK): ~150 collaborators
Goals of MICE:
- design, engineer, and build a section of cooling channel
- measure performance under different beam conditions
- show that design tools (simulation codes) agree with experiment
- demonstrate operation LH$_2$ close to high gradient RF in high B fields

Principle

1. Ionization:
   \[ \frac{d\varepsilon}{dz} \approx -\frac{\varepsilon}{E_\mu \beta^2} \frac{dE_\mu}{dz} \]

2. Multiple scattering:
   \[ \frac{\beta_{\perp}}{2m\beta^3} \frac{(13.6\text{MeV})^2}{E_\mu X_0} \]

Practice

Ionization: cooling term
Multiple scattering: heating term
Implementation in Steps

**STEP I**

**COMPLETED**

**STEP IV**

2013

**STEP VI**

Aim: 2016
MICE beam and instrumentation fully constructed and operational
MICE beam detectors

- MICE: single particle spectrometer
- Particle Identification:
  - Time of flight counters (TOF0,1,2)
  - Two aerogel threshold Cherenkov counters (CKOV)
  - MICE Calorimeters: purity >99.9%
    - Kloe-light (KL) lead-scintillating fibre preshower
    - Electron-Muon Ranger: 1 m³ of extruded scintillator bars

Beamline under construction
Time-of-Flight

- Time-of-flight system:
  - X/Y scintillator hodoscopes
  - TOF0: $\sigma_t = 51$ ps
  - TOF1: $\sigma_t = 53$ ps*
  - TOF2: $\sigma_t = 52$ ps
  - Magnetic field: $B_{||} \sim 200 - 300$ G
    \[ B_{\perp} \sim 1 \text{kG} \]
  - CAEN V1724 FADC
  - CAEN V1290 TDC

* Faulty PMTs giving 58 ps for TOF1 were recently replaced
Cherenkov

- Two threshold Cherenkov counters:
  - Aerogel radiators
  - CKOVa: $n_a = 1.07$
  - CKOVb: $n_b = 1.12$

Preliminary CKOV performance
KL Preshower

Calorimeters:

- KLOE-light (KL): lead extrusion with extruded scintillating fibres as in KLOE calorimeter but with lighter Pb to fibre ratio.
- Performs electron-muon separation for 0.5% of muons that decay – requires electron rejection at 0.1% level.

Assembly TOF2-KL

Performance KL vs TOF

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**Electron Muon Ranger**

- MICE EMR:
  - Electron-muon ranger: 1 m$^3$ extruded scintillator bars with WLS fibre
  - 24 X/Y modules (48 planes) with 59 bars/plane: 2832 bars
  - Electrons give EM showers and muons give tracks
  - dE/dx also used to separate electrons from muons (constant energy loss)

- Prototype tested at RAL
- Full detector under construction for STEP IV
MICE Tracker

- Scintillating fibre tracker:
  - Performs emittance measurement: $x$, $x'$, $y$, $y'$
  - 350 $\mu$m scintillating fibre doublet layers
  - Two trackers: 5 stations per tracker, 3 planes per station
  - Inside 4 T superconducting solenoid
  - Trackers built, solenoids being commissioned

Resolution: 661 $\mu$m (including MS)

Yield: ~11 PE
Efficiency = 99.8%
Read out by VLPC 80% QE
MICE reconstruction

- Instrumentation used in physics analyses for Step I:
  - Measured nine elements of $(\varepsilon, p)$ matrix for positive and negative particles
    $(\varepsilon = 3, 6, 10 \text{ mm rad}; p = 140, 200, 240 \text{ MeV/c})$

- MICE Step I completed: beam line paper completed
  - The Beam Line and Instrumentation of the Muon Ionization Cooling Experiment at ISIS
    JINST 7 (2012) P05009

![Histograms](image)
Physics analyses for Step I:
- Developed novel method to measure emittance using TOF detectors
Conclusions

- MICE aims to perform the first measurement of ionization cooling
- MICE is a unique contribution to the Neutrino Factory and Muon Collider R&D activities
- MICE detectors constructed and commissioned: TOF system (TOF0,1,2), two CKOVs and KL
- EMR is currently under construction
- Trackers completed but need to be integrated with tracker solenoids
- MICE Step I has been successfully delivered
- Preparations for MICE Steps IV and VI well underway.