COOLING MUONS: WHY AND HOW?

The international MICE experiment
for neutrino factory and muon collider

1. Muon accelerators: why cooling?
2. The MICE experiment and the contribution of Harbin ICST
3. Neutrino questions
4. Muon Collider
5. Conclusions

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Spokesperson of the MICE experiment
MICE at Harbin, China
If you visit the Institute for Cryogenics and Superconductive Technology (ICST) At Harbin Institute of Technology you will see these objects:

- Wire winding spool
- Valves
- Superconducting wire test
- Cryogenic joints
- Cryostat
MICE/MuCool Coupling Magnets

Li Wang for MICE Group
Institute of Cryogenics and Superconductivity Technology
Harbin Institute of Technology, Harbin, China
Muon accelerators

Particle accelerators...

normally use stable particles found in ordinary matter:

-- Electrons
elementary objects, but acceleration at high energy cannot be made
with synchrotrons because of high synchrotron radiation energy losses
(\(\propto(E/m)^4\))

-- Protons or heavy nuclei
but protons are complex objects and only part of the energy is
used for the point-like collisions of interest

Would like elementary, heavy particle:

*** MUONS ***
The MUON:

is an elementary particle 200 times heavier than an electrons

Synchrotron radiation (and other radiation) is reduced as \((E/m)^4\)

Discovered in decay of cosmic rays such as pions (1937)

MUON is UNSTABLE and decays with production of neutrinos

Here

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \]

Decay time 2.2 \(\mu s\) (microseconds)
PROBLEM I:
How can one think of making a particle accelerator with unstable particles?

\[ \tau_\mu = 2.2 \ \mu s \]

Multiplied by speed of light \( c = 300'000 \) km/s this is
\[ c \cdot \tau_\mu = 660 \text{ meters} \]

AND... because of Einstein's relativity, the time expands with muon velocity:

\[ L = \frac{P}{m} \cdot c \cdot \tau_\mu \] (\( P = \) muon momentum)

\[
\begin{align*}
P &= 100 \text{ MeV/c} & \rightarrow & \quad 660 \text{ m} \\
P &= 1000 \text{ MeV/c} = 1 \text{ GeV/c} & \rightarrow & \quad 6.6 \text{ km} \\
P &= 10 \text{ GeV/c} & \rightarrow & \quad 66 \text{ km} \\
P &= 1000 \text{ GeV/c} & \rightarrow & \quad 6600 \text{ km}
\end{align*}
\]

This gives time to work.
Problem II: where do we find muons?

There are no muons in matter. We must produce them with a high intensity proton accelerator

\[ P + \text{target} \rightarrow \pi \pi \pi \pi \ldots \ X \]
\[ \pi \rightarrow \mu \nu \]

These muons are very disorderly.

They go in all directions and do not make a beam

They must be put to order …

… and aligned in the same direction to make a beam

This is called cooling the muons
Research on muon accelerators is supported

in USA:

Neutrino Factory and Muon Collider collaboration
(Department of Energy)
Muons Inc (a private company)
and various universities

In United Kingdom
UK Neutrino Factory collaboration

By European Union

In universities in Japan, Switzerland

AND IN CHINA!

>> 250 physicists around the world
Muon accelerators

Muon collider:

produce $\mu^+$ and $\mu^-$
cool intensely to get very small and parallel beams
("small emittance")
accelerate both beams
store in a colliding ring in opposite directions
collide:

$$\mu^+ (E) + \mu^- (E) \rightarrow \text{pure energy (2 E)}$$

Search for new particles of high energy
Produce directly particles related to mass (Higgs boson)
Intense K physics
Intense Low-E muons
Neutrino Factory
Higgs(es) Factory(ies)
Energy Frontier -> 5 TeV

Possible layout of a muon complex on the CERN site.

MICE at Harbin -- Alain Blondel
Muon accelerators

Muon collider: Neutrino Factory

produce $\mu^+$ and $\mu^-$
cool intensely to get very small and parallel beams
(“small emittance”)
accelerate both beams
store in a decay ring with long straight sections and let muons decay:

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

Produce very clean beams of high energy $\nu_e$ and $\bar{\nu}_e$ NEW!

Simpler and often seen as first step towards muon colliders

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With an unrealistic 10 pb\(^{-1}\)/MeV scan:

![Graph showing the Higgs boson peak with data points and fitted curve.](image)

With a three-point energy scan:

<table>
<thead>
<tr>
<th>Observable</th>
<th>With 100 pb(^{-1})</th>
<th>With 2.5 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>±0.1 MeV/c(^2)</td>
<td>±0.05 MeV/c(^2)</td>
</tr>
<tr>
<td>Width</td>
<td>±0.5 MeV</td>
<td>±0.1 MeV</td>
</tr>
<tr>
<td>(\sigma_{peak})</td>
<td>±1 pb</td>
<td>±0.2 pb</td>
</tr>
</tbody>
</table>

**Statistics limited!**

Still to be tried:

A scan in \(\delta E/E\)
Higgs Factory #2: $\mu^+ \mu^- \rightarrow H, A$

SUSY and 2DHM predict two neutral heavy Higgs with masses close to each other and to the charged Higgs, with different CP number, and decay modes.

Cross-sections are large. Determine masses & widths to high precision.

Telling H from A:
bb and tt cross-sections (also: hh, WW, ZZ.....)

investigate CP violating H/A interference.
Fermilab Muon Complex - Vision
MICE at Harbin -- Alain Blondel

-- Neutrino Factory -- CERN layout --

A possible layout of a neutrino factory

Cooling!

Acceleration!

Target!

\[ \mu^+ \rightarrow e^+ \nu_e \nu_\mu \]

Oscillates \( \nu_e \leftrightarrow \nu_\mu \)

Interacts giving \( \mu^- \)

Wrong sign muon

Interacts giving \( \mu^+ \)
INNO ~7000 km (Magic distance)
Neutrinos are special particles with no charge and (almost no mass)
Mass was discovered by neutrino oscillations (1998-2002)

* Why 12 orders of magnitude between elementary fermion masses?

**Neutrino masses lead to the phenomenon of quantum oscillations
where $\nu_\mu$ beam transforms into a $\nu_e$ beam,
Over distances of hundred to thousands of kilometers

***NEUTRINO MASSES ARE PROBABLY KEY TO THE EXISTENCE OF MATTER
IN A UNIVERSE MADE ORIGINALLY OF EQUAL AMOUNTS OF
MATTER AND ANTIMATTER. WHERE DID ANTIMATTER GO?
neutrino mixing (LMA, natural hierarchy)

\[ \nu_3 \]
\[ \sin^2 \theta_{13} \]

\[ \nu_2 \]
\[ \sin^2 \theta_{12} \cos^2 \theta_{13} \]

\[ \nu_1 \]
\[ \cos^2 \theta_{12} \cos^2 \theta_{13} \]

\[ \nu_e \] is a (quantum) mix of
\[ \nu_1 \] (majority, 65%) and \[ \nu_2 \] (minority 30%)
with a small admixture of \[ \nu_3 \] (< 13%) (CHOOZ)

\[ U_{MNS} : \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin \theta_{13} e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix} \]
Consequences of 3-family oscillations:

I There will be $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\tau \leftrightarrow \nu_e$
oscillation at $L_{\text{atm}}$

$$P (\nu_\mu \leftrightarrow \nu_e)_{\text{max}} \approx \frac{1}{2} \sin^2 2\theta_{13} + \ldots \text{ (small)}$$

II There will be CP or T violation

$$\text{CP: } P (\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P (\nu_\mu \leftrightarrow \nu_e)$$
$$\text{T: } P (\nu_\mu \leftrightarrow \nu_e) \neq P (\nu_e \leftrightarrow \nu_\mu)$$

III we do not know if the neutrino $\nu_1$ which
contains more $\nu_e$
is the lightest one (natural?)
or not.
\[ P(\nu_e \to \nu_\mu) = |A|^2 + |S|^2 + 2AS \sin \delta \]

\[ P(\bar{\nu}_e \to \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2AS \sin \delta \]

\[ \frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} = A_{CP} \frac{\sin \delta \sin(\Delta m^2_{12} L/4E) \sin \theta_{12} \sin \theta_{13}}{\sin^2 2\theta_{13} + \text{solar term...}} \]

... need large values of \( \sin \theta_{12} \), \( \Delta m^2_{12} \) (LMA) but *not* large \( \sin^2 \theta_{13} \)

... need APPEARANCE ... \( P(\nu_e \to \nu_e) \) is time reversal symmetric (reactors or sun are out)

... can be large (30%) for suppressed channel (one small angle vs two large)

... at wavelength at which ‘solar’ = ‘atmospheric’ and for \( \nu_e \to \nu_\mu \), \( \nu_\tau \)

... asymmetry is opposite for \( \nu_e \to \nu_\mu \) and \( \nu_e \to \nu_\tau \)
TWO unique qualities:

1. Possible asymmetry between neutrino and antineutrino oscillations
2. Possible transition of neutrino to antineutrino

==> possible solution to the disappearance of antimatter in the early universe.

A NEUTRINO FACTORY IS THE BEST TOOL INVENTED SO FAR TO STUDY THE ASYMMETRY BETWEEN NEUTRINO AND ANTINEUTRINO OSCILLATIONS
Major challenges

High-power target
- 4MW
- good transmission
MERIT experiment (CERN)

Fast muon cooling
MICE experiment (RAL)

Fast, large aperture accelerator (FFAG)
EMMA (Daresbury)

ISS baseline
Transport of a disorderly muon beam:

Solenoidal magnetic field:

(superconducting) coils

Muons have helical trajectories
and are contained
High intensity proton accelerators pose many challenges but certainly one of the most critical one is the

**Target!**

Typical Dimensions: \( L \approx 30 \text{ cm}, R \approx 1 \text{ cm} \)

\[ \rightarrow 4 \text{ MW of protons (i.e. 40 000 light bulbs!)} \]

into a big cigar….

it would immediately go to smoke.
Target: Hg jet tests

**E951**
- 1 cm
- \( v = 2.5 \text{ cm/s} \)
- 24 GeV 4 TP p beam
- No B field

**CERN/Grenoble**
- 4 mm
- \( v = 12 \text{ m/s} \)
- No p beam
- 0, 10, 20T B field

Hg jet dispersal properties:
- proportional to beam intensity
- velocities \( \sim \frac{1}{2} \) times that of “confined thimble” target
- largely transverse to the jet axis
- delayed 40 ms

- The Hg jet is stabilized by the 20 T B field
- Minimal jet deflection for 100 mrad angle of entry
- Jet velocity reduced upon entry to B field

This qualitative behaviour can be observed in all events.
MERIT EXPERIMENT at CERN
BNL, MIT, ORNL, Princeton University CERN, RAL

Splash velocity
– 24 GeV beam

Demonstrated liquid mercury jet technology for neutrino factory and muon collider up to >4MW on target Oct 22-Nov 12 2007

April 2008

20TP, 15T

V = 65 m/s

t=0.050 ms

t=0.175 ms

t=0.375 ms

10TP, 10T

V = 54 m/s

t=0.075 ms

t=0.175 ms

t=0.375 ms

1. Ethymiopoulos, CERN

20TP, 10T
IONIZATION COOLING

principle:

this will surely work..!

Cooling is necessary for Neutrino Factory and crucial for Muon Collider. Delicate technology and integration problem. Need to build a realistic prototype and verify that it works (i.e. cools a beam).

Can it be built? Operate reliably? What performance can one get?

**Difficulty:** affordable prototype of cooling section only cools beam by 10%, while standard emittance measurements barely achieve this precision.

**Solution:** measure the beam particle-by-particle

*state-of-the-art particle physics instrumentation will test state-of-the-art accelerator technology.*
10% cooling of 200 MeV/c muons requires ~ 20 MV of RF single particle measurements \( \Rightarrow \) measurement precision can be as good as \( \Delta \left( \frac{\varepsilon_{\text{out}}}{\varepsilon_{\text{in}}} \right) = 10^{-3} \) never done before.
THE MICE COLLABORATION -130 collaborators-

Universite Catholique de Louvain, Belgium

University of Sofia, Bulgaria

The Harbin Institute for Super Conducting Technologies, PR China

INFN Milano, INFN Napoli, INFN Pavia, INFN Roma III, INFN Trieste, Italy

KEK, Kyoto University, Osaka University, Japan

NIKHEF, The Netherlands

CERN

Geneva University, Paul Scherrer Institut, Switzerland

Brunel, Cockcroft/Lancaster, Glasgow, Liverpool, ICL London, Oxford, Daresbury, RAL, Sheffield, UK

Argonne National Laboratory, Brookhaven National Laboratory, Fairfield University, University of Chicago, Enrico Fermi Institute, Fermilab, Illinois Institute of Technology, Jefferson Lab, Lawrence Berkeley National Laboratory, UCLA, Northern Illinois University, University of Iowa, University of Mississippi, UC Riverside, University of Illinois at Urbana-Champaign, Muons Inc., USA
MICE Collaboration across the planet

Incoming muon beam

Variable Diffuser

Beam PID TOF 0, TOF 1

Cherenkovs

Spectrometer solenoid 1

Focus coils

Spectrometer solenoid 2

Coupling Coils 1&2

RF cavities

RF power

Liquid Hydrogen absorbers 1,2,3

Spectrometer

Trackers 1 & 2

Coupling Coils 1&2

RF power

Spectrometer

Trackers 1 & 2

Coupling Coils 1&2

RF power

Spectrometer

Trackers 1 & 2

Coupling Coils 1&2

RF power

Spectrometer

Trackers 1 & 2

Downstream particle ID: TOF 2, KL SW Calorimeter
Challenges of MICE:
(these things have never been done before)

1. Operate RF cavities of relatively low frequency (201 MHz) at high gradient (nominal 8MV/m in MICE, 16 MV/m with 8 MW and LN2 cooled RF cavities) in highly inhomogeneous magnetic fields (1-3 T) dark currents (can heat up LH₂), breakdowns

2. Hydrogen safety (substantial amounts of LH₂ in vicinity of RF cavities)

3. Emittance measurement to relative precision of 10⁻³ in environment of RF bkg requires low mass (low multiple scattering) and precise tracker fast and redundant to fight dark-current-induced background precision Time-of-Flight for particle phase determination (±3.6° = 50 ps) complete set of PID detectors to eliminate beam pions and decay electrons and...

4. Obtaining (substantial) funding for R&D towards a facility that is not (yet) in the plans of a major lab
Aspirational MICE Schedule

STEP I
First particles Mars 2008!
=> May 2009

STEP II
September 2009

STEP III/III.1
November 2009
to spring 2010

STEP IV
Spring 2010

STEP V
Fall 2010

STEP VI
2011
THE MICE HALL at Rutherford Appleton Lab (UK)

MICE experiment will fit here!
Operation of RF cavities at high gradient in magnetic field

Dark current backgrounds measured on a 805 MHz cavity in magnetic field!
with a 1mm scintillating fiber at d=O(1m)

This will be also a source of backgrounds for MICE:
RF cavity (800 MHz) at Fermilab being pushed to its limits (35 MV/m) to study dark current emission in magnetic field. Sees clear enhancement due to B field. Various diagnostics methods
photographic paper, scintillating fibers

Microscope

BCT and solid state counters have demonstrated this and allowed precise measurements
Real cavities will be equipped with Be windows which do not show sign of being pitted contrary to Cu.

Copper windows were pitted.

Cu splashes on the Be window.
Prototype RF cavity in MuCool Test Area

Harbin Coupling Coil (late 2009)

-- Alain Blondel
Conclusions

Muon Collider and Neutrino Factory are a new line of particle accelerators that are now seriously considered around the world.

Neutrino Factory offers superb possibilities for study of neutrino oscillations, and in particular neutrino CP violation (asymmetry between neutrino and antineutrino properties). It is the first step towards muon colliders.

Muon cooling is a key technology for these novel machines, and the MICE experiment is the first experimental demonstration.

ICST Harbin project, Coupling Coils, are crucial components of MICE and of the fundamental research in RF cavities in magnetic field.