A Cooling Demonstration is Crucial for the Neutrino Factory / Muon Collider Future

David B. Cline
UCLA
Center for Advanced Accelerators

1. Arguments Based on History
   - SPPS vs. ISABELE
   - NLC and FFTB

2. Arguments Based on a Neutrino Factory
   a) The Major Goal of a Neutrino Factory - CP Violation
   b) Comparison of Future LBL Experiments and a $10^{19}$ Muon Decay Factory

3. Arguments Based on a Higgs Factory Muon Collider
   a) The Higgs Boson may be observed before we understand the Neutrino CKM Matrix
   b) A Balanced Program requires the Muon Collider

4. Why a Demonstration is Important for the Particle Community to Judge this Project?

---------- SUMMARY ----------
My View

Before we decide to abandon the cooling expensive in MuCool we must defend this decision. [This is a little bit a problem in the University vs Lab Culture vs Research]

We will ask the HEP Community to back a Multi-Billion project. [This is a Serious Issue]

What is needed to make the case for a Neutrino Factory/Muon Collider
A Little History about Stochastic Cooling

~ 1964 S. Vainsencher Invents Stochastic Cooling

~ 1973 First Very Small Demonstration, SC at ISR ~ 180 MeV, decrease in beam size

~ 1976-78 Development Concept, a PP Collider using SC + Electron Cooling

~ 1978-79 First Operation of SCC Ring at CERN Prog. 9

CRASH Program at CERN (FNAL mum) later

1982 First PP Collider

1983 W/LZ Discovery at CERN
The other History

Isaac - 1973-74
First discussion
1975-76: Isaac approach expensive

~ 77-78 Mach 2 at energy too low - M = 80-90 km
By then

~ 1984-85 Isaac cancelled

--- The demonstration of S.C.
By ICF was the difference - the CERN particles
Community Bet on: The Super

My viewpoint
What has this group provided in terms of a real proof of principle for a muon collider/neutrino factory since the last summary??

- Compare with the NLC

- FFB measured around 160 nm

- NLCTA demonstrated a small piece of the NLC

- Passed reviews etc. etc.

  +JLC test setup...
THE NEUTRINO FACTORY: BEAM AND EXPERIMENTS

A. Blondel¹, A. Buenos, M. Campanelli², A. Cervera³,
D.B. Cline⁴, J. Collot⁵, M. de Jong⁶, A. Donini⁷,
F. Dyda⁸, R. Edgecoat⁹, M.B. Gavela¹⁰, J.J. Gómez-Cadenas¹¹,
M.C. Gonzalez-García¹², P. Grub⁴, D.A. Harris¹³, P. Hernández¹⁴,
Y. Kuno¹⁵, P.J. Litchfield¹⁶, K. McFarland¹⁷, O. Mena¹⁸,
P. Migliozzi¹⁹, V. Palladino¹⁴, J. Panman¹⁰, I.M. Papadopoulos¹⁶.
A. Para¹¹, C. Peña-Garay¹⁰, P. Perez¹⁵, S. Rigolin¹⁶,
A. Romanino¹⁷, A. Rubbia², P. Strobin¹⁰,¹⁴, S. Wojcicki¹⁸

Abstract

The discovery of neutrino oscillations marks a major milestone in the history of neutrino physics, and opens a new window to the still mysterious origin of masses and flavour-mixing. Many current and forthcoming experiments will answer open questions; however, a major step forward, up to and possibly including CP-violation in the neutrino-mixing matrix, requires the neutrino beams from a neutrino factory. The neutrino factory is a new concept for producing neutrino beams of unprecedented quality in terms of intensity, flavour composition, and precision of the beam parameters. Most importantly, the neutrino factory is the only known way to generate a high-intensity beam of electron neutrinos of high energy. The neutrino beam from a neutrino factory, in particular the electron-neutrino beam, enables the exploration of otherwise inaccessible domains in neutrino oscillation physics by exploiting baselines of planetary dimensions. Suitable detectors pose formidable challenges but seem within reach with only moderate extrapolations from existing technologies. Although the main physics attraction of the neutrino factory is in the area of neutrino oscillations, an interesting spectrum of further opportunities ranging from high-precision, high-rate neutrino scattering to physics with high-intensity stopped muons comes with it.

Many people believe CP is the key to convincing governments and the HEP community to approve such a project somewhere in the world.
- Energy of circulating muons
  The higher the better; default: 50 GeV/c.
- Charge sign of circulating muons
  Both signs needed; as far as possible the same intensity; no concurrence of both signs.
- Injected muons per year
  Baseline $10^{21}$; upgradable to $10^{22}$ or more
- Fraction of ‘useful’ decays
  25% or larger.
- Beam divergence in long straight sections
  Less than $0.1/(\beta\gamma) = 0.2$ mrad at 50 GeV/c, known to better than 10%.
- Geometric configuration of the storage ring
  ‘Triangle’ or ‘bow-tie’.

This Does Not Agree with the 1019 Entry Level XF from FNAL Study.

But Assume a 10KT Detector Only

!! CP Violation !!

Lynn Hewpt
Parameters of Neutrino Oscillation

Three-generation mixing

\[
\begin{pmatrix}
C_{12}C_{13} & C_{13}\sin \delta \\
-C_{23}\sin \delta - C_{12}S_{13}S_{23} & -C_{12}C_{23}\sin \delta - S_{12}S_{13}S_{23} \\
S_{23}\sin \delta - C_{12}S_{13}C_{23} & -C_{12}S_{23}\sin \delta - S_{12}S_{13}C_{23}
\end{pmatrix}
\]

If LSND wrong, solar/atm right

(Standard Theorist's Scenario):

(SBL Reactors)  \[ P_{ee} = 1 - 4S_{13}^2C_{12}^2S_{\Delta \text{atm}}^2 \]
(LBL Reactors)  \[ P_{ee} = 1 - 4S_{12}^2C_{12}C_{13}^4S_{\Delta \text{solar}}^2 \]

\[ -4S_{13}^2C_{13}^2S_{\Delta \text{atm}}^2 \]

(LBL)  \[ P_{\mu\mu} = 1 - 4C_{13}^2S_{23}^2(1 - C_{13}^2S_{23}^2)S_{\Delta \text{atm}}^2 \]
(LBL)  \[ P_{\mu e} = 4S_{13}^2C_{13}^2S_{23}^2S_{\Delta \text{atm}}^2 \]
(LBL)  \[ P_{\mu \tau} = 4C_{13}^4S_{23}^2C_{13}^2S_{\Delta \text{atm}}^2 \]

Assuming we know:

- \( \theta_{23} \) & \( \Delta m_{23} \) (atmospheric)
- \( \theta_{12} \) & \( \Delta m_{12} \) (solar)

Then \( P(\mu \to e) \) and \( P(\mu \to \tau) \) are both \( 0 \).
Neutrinos will cross the Alps

In a move that significantly extends the scope of European collaboration in particle physics, CERN is collaborating with the Italian National Institute of Nuclear Physics in a new project. A beam of high-energy neutrinos will be sent from CERN to detectors that will be built at the Italian Gran Sasso Laboratory, 730 km away from CERN, and 120 km from Rome.

The first historic Alpine crossing was General Hannibal’s march on Turin, in about 200 BC. The advent of modern communications brought a need for transalpine railway links. The first tunnel to breach the Alps was the 14 km Frejus/Mont Cenis tunnel, the construction of which began in 1851. It was soon followed by the 14 km St Gotthard tunnel in Switzerland. Now physics crosses the Alps too.

However, neutrinos need no tunnel to cross a mountain range – most of them can pass through rock. Contemptuous of matter, a neutrino beam can even pass through the 13,000 km of the Earth and emerge on the other side. There is, however, a slight neutrino casualty rate that makes experiments with neutrinos possible. If there are plenty of neutrinos, it is probable that enough of them will interact to produce a detectable signal. Of the $10^{20}$ neutrinos to be sent to Gran Sasso annually from CERN, about 2500 will interact, on route, with each 1000 tons of target material.

It took about half a century to discover that the neutrino (nature’s most unpredictable particle) comes in three different kinds – electron, muon, or tau – according to the type of weakly interacting particle (lepton) they escort. Physicists are now convinced that these three varieties of neutrinos are not immutable, as was first thought, but they subtly rearrange their lepton allegiance in flight. In physics language, the neutrinos oscillate from one kind to another as they travel.

Positive evidence for neutrino oscillations so far comes overwhelmingly from extra-terrestrial neutrinos, from de Sun or from the interactions of high-energy cosmic rays in the atmosphere. To probe these oscillations under controlled conditions requires synthetic neutrinos. These neutrinos are produced via the decay of high-energy particles, which are generated by beams in an accelerator (CERN Courier November 1998 p13). The oscillations depend on the distance between the neutrino source and the detectors – the baseline.

For the new project, protons from CERN’s SPS synchrotron, with an energy of up to 450 GeV, will be focused on a target to produce pions and kaons. These particles will then be magnetically focused to point towards the Gran Sasso Laboratory. After about 1000 m, most of these pions and kaons will have decayed, producing electron- and muon-neutrinos. The remaining strongly interacting particles will be removed by a beam stop (which the neutrinos can hardly see”). CERN will construct the neutrino source, while Gran Sasso will host the detectors and provide the infrastructure at the far end.

After an initial round of proposals for experiments to detect the neutrinos, two – OPERA and ICARUS – are well defined. OPERA will use the emulsion target techniques developed for the CHORUS neutrino experiment at CERN, and further refined for the DONUT study at Fermilab. While CHORUS used a mere 700 kg of emulsion, OPERA will use 200 tons of emulsion, which will be interspersed with thin lead plates. Vital to this work are Japanese emulsion technology and sophisticated automated emulsion scanning techniques developed in Japan and in Europe.

ICARUS is based on the liquid argon detector used to track and identify particles and developed for the ICARUS neutrino detector. It will be supplemented by the NOE magnetized spectrometer. ICARUS will use 9.3 kilotons of liquid argon in four modules, which will be separated by NOE spectrometers.

The main goal is to see the appearance of tau neutrinos in Gran Sasso. These particles will not be present in the beam when it leaves CERN, but may be produced on route.

Data taking for these new experiments is planned to begin in May 2005. In addition to existing equipment at CERN, two-thirds of the 71 million Swiss francs needed for the project is being provided by the Italian National Institute of Nuclear Physics (INFN). So far, voluntary contributions from Belgium, France, Germany and Spain have been announced.

Long baseline neutrino studies are under way in Japan, where the KEK Lab sends particles to the 250 km distant Superkamiokande detector (CERN Courier October 1999 p5). In the US, the MINOS project is sending particles from Fermilab to detectors in the Soudan mine, 730 km away (CERN Courier October 1999 p6). The main thrust of these studies is to chart the disappearance of neutrinos that were initially present in the beam.
ICARUS Event

(CANOE)

\[ \nu_e + p \rightarrow \tau + \Delta^{++} \]
(with \( \tau \rightarrow e\nu\nu \), and \( \Delta^{++} \rightarrow p\pi^+ \))
In the text:

- $\delta^2 m = 5 \times 10^{-3} \text{ eV}^2$
- $\delta^2 m = 5 \times 10^{-4} \text{ eV}^2$
- $\delta^2 m = 2.5 \times 10^{-3} \text{ eV}^2$

Below the diagram:

- $E_\mu \sim 5-7 \text{ GeV}$
- $<E_\nu> \sim 3 \text{ GeV}$
- Optimize for $L = 732 \text{ km}$
- For $\nu_e \rightarrow \nu_e$
- But for $\nu_\mu, e \rightarrow \nu_e$
- Need $\sim 10-20 \text{ GeV}$
DETECTION of $\nu_e \to \nu_x$ at $\delta^2 m = 2.5 \times 10^{-3}$ eV$^2$

We neglect $\beta^+ + N \rightarrow \beta^+ + X$

in the analysis.

$P_{\nu e} \approx 10^{-1}$

NGS neutrino reference beam

Neutrino improved beam

Low Energy $\nu_x$ Beam

$P_{\bar{\nu} e} \approx 10^{-1}$

$\nu_e \to \nu_x$

$\nu_x$ in Beam

Events with

$\Delta p$

CNAG

Fig. 2

$\nu_x$ - Visible Energy (GeV)
Figure 5.17: ICANOE 90% C.L. exclusion region in case no $\nu_\mu \rightarrow \nu_e$ are experimentally observed.

\[ \Delta m^2 (eV^2) \]

\[ \sin^2 2\theta \]

\[ \nu_\mu \leftrightarrow \nu_e \]

90% C.L.

Limit at Super K $\delta^2_{13}$ results in

\[ S^2\theta_{13} \leq 6 \times 10^{-3} \text{ 90\% CL} \]
FIG. 3. Reach in \( \sin^2 2\theta_{13} \) for the observation of 10 \( \mu^- \) events from \( \nu_e \to \nu_\mu \) oscillations, shown for three values of \( \Delta m^2 \) spanning the favored SuperK range. The curves correspond to the LAM scenario in Table I. The curves correspond to 10\(^{-1}\) decays \( \Delta m^2 \), a 50 kt neutrino factory with a 30 km baseline, and a minimum muon detection threshold of 2.5 GeV. 

Neutrino Oscillations: ICARO, CNCS, TRIDENT
Uncertainty in CP Violation Detection

\[ R(\nu_e \rightarrow \mu) - R(\nu_e \rightarrow \bar{\nu}_\mu) \]

\[ \approx -\frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 5 \]

\[ \times \sin (\delta_{21} \sin^2 \theta_{12}) \]

Depends on unknown \( \theta_{12}, \theta_{13}, \delta \), \( m_{12} \)

Possible Parameters

1. \( \theta_{23} = \theta_{12} = 45^\circ \)  
   Full \( B^1 \)
   Mixing

2. \( \theta_{13} = 0 \)  
   No CP

\( \theta_{23} \approx 45^\circ, \theta_{12} \) large

\( \theta_{13} \sim 10^\circ \) (limit \( \theta_{13} \) (1.002))

\( \delta^2 m_{12} \sim 10^{-5} + i 0 \)

CP Violation

No CP

Same as (b) but \( \delta^2 m_{12} \sim 10^{-10} \)

(Vacuum Solution)
Figure 7: The signal-over-noise ratio of the CP-odd asymmetry of Eq. 2 as a function of the distance, after subtracting the fake matter induced asymmetry. The thick line corresponds to the spectrum-integrated asymmetry, while the dashed lines correspond to the asymmetry computed in five energy bins of equal width $\Delta E_\nu = 10$ GeV. The neutrino-mixing parameters correspond to the LMA-MSW solution to the solar anomaly: $\Delta m_{23}^2 = 2.8 \times 10^{-3}$ eV$^2$, $\Delta m_{12}^2 = 1 \times 10^{-4}$ eV$^2$, $\theta_{12} = 22.5^\circ$, $\theta_{23} = 45^\circ$, $\theta_{13} = 13^\circ$ and $\delta = 90^\circ$. The muon momentum is $E_\mu = 50$ GeV/c and the matter parameter $d$ is varied with the distance according to Ref. [50].
FIG. 14. Reach in $\sin^2 2\theta_{13}$ that yields $3 \sigma$ discrimination between (a) $\delta = 0$ and $\pi/2$ with $\delta m_{32}^2 > 0$, (b) $\delta = 0$ and $\pi/2$ with $\delta m_{32}^2 < 0$, (c) $\delta = 0$ and $-\pi/2$ with $\delta m_{32}^2 > 0$, and (d) $\delta = 0$ and $-\pi/2$ with $\delta m_{32}^2 < 0$. The discrimination is based on a comparison of wrong-sign muon CC event rates in a 50 kt detector when $10^{21}$ positive and negative muons alternate decay in the neutrino factory. The reach is shown versus baseline for four storage ring energies. The oscillation parameters correspond to the LAM scenario.
Double Field Flip Cooling Channel for Neutrino Factory (front-end simulation)

V. Balbekov

Fermi National Accelerator Laboratory, Batavia, IL 60510

April 23, 2000

Abstract

Results of front-end simulation of a cooler for neutrino factory are presented. Precooling part is similar to that described in [2] with a small difference including new design of a minicooler and buncher. The cooling channel of 217 m length consists of 3 solenoids with almost uniform magnetic field, and 2 special fast field-flip sections. The 1st flip is performed at relatively small field $B = \pm 3$ T to weaken a perturbation of longitudinal motion. Then the field increases adiabatically, and the 2nd field flip is performed at $B = \mp 7$ T. Maximal magnetic field on the coil is 8 T. Slow acceleration is used to decrease the particle loss due to growth of longitudinal emittance at the cooling. Transmission of the cooling channel is about 75%, transverse and longitudinal emittances of the cooled beam are 2.1 mm and 75 mm.

With 16 GeV proton driver and carbon target, the system provides 0.1 muon per incident proton.

$\mu/p = 0.1$

$\mu/p = 0.2$ Bob Palm (Fermilab, 1984)
IT SEEMS CLEAR

THAT A NEUTRINO FACTORY MUST HAVE COOLING

Thus:

1) Cooling must be demonstrated to the particle community someday

2) Waiting until 201X (2015?)
   (when X factory is built "EGER THE QUESTION"

3) The university groups can help - but they can not just do simulation and RR studies for 15 years!!!
WHY WE SHOULD NOT FORGET THE HIGH PROTON MY COLLIDER

- How long will it take to determine the "CKM" T2P6!!

PARAMETER FOR Y SECTOR

\[ \Theta_{23} \]

K2K [NA3] ESTABLISH SK EFF All

MINOS ~ 2003

\( \text{App. Exp} \) ICARUS/OPERA ~ 2005

\[ \Theta_{23} \text{ by 2006?} \]
\( \Theta_{13} \): The key answer for CP

\( \Theta_{12} \): Most determines when

Solar \( y \): Solution correct

\( \sin \theta \): "Conclusively"

It could take a decade to provide evidence that CP can be measured.

LSND Effect: Min Beam at FNAL

\( \Delta m^2 \): \( 2003 ?? \) \( \text{vs.} 2005 \)

Hard to believe we will have these parameters before 2005.
Higgs Physics

Now - strong evidence that one low mass CM < 325 GeV exist (Bill Marciano talk at my G4 and write-up)

By 2007 - likely discovery at LHC (will be a strong argument for the NL e)

If mu collider be big factory

It is likely Higgs discovered before

We know Y parameter

Arguments for to define Y factory
COOLING

Statement like \( \frac{\text{Varies}}{\text{time}} \)

"It's only 0.6/0k etc. etc.

Ionization cooling is

A delicate balance between
cooling and [Multiple] heating

It is not generally simple

to prove that cooling will

occur unless the system is

fully simulated — and

people may question how

full the simulation is —

Experimental demonstration

of cooling needed
Beam heating effects

Effects of multiple and Moliere scattering

It was very clear from the talk of P. Spontz (May 18) and A. Toulouse that large angle scattering is a serious effect on cooling (always worried)

\[ \text{Cooling} \rightarrow \text{M. Scatt.} \rightarrow \text{No M. Scatt.} \]

This is one question people ask about cooling.
Fig. 2 A comparison between Moliere theory and the electron scattering data of Andrevsky et al on aluminum, beryllium and lithium. The scattering angle is plotted in radians.

Do we understand Moliere scattering?

E875 - Try to measure it!
E875: Study of $\mu$ scattering

TRIUMF

Univ. Birmingham
Imperial College, London
RAL
UCLA

A Good Team of "young" people

You have to start soon where
Need to learn how to do the experiment

21 June - 15 July
Run I - solid
Run II - liquid
My viewpoint
It will not be productive to go to Snowmass 2001 with

1) An entry level P. Fat (10^9) which has marginal
   physical reach
   AND

2) Claiming that cooling
   can curb a factor
   at 4-8 increase
   but with no plans
   to demonstrate
   cooling by experiment

...
I believe:

We should have

A PLAN FOR THE

PROOF OF PRINCIPLE
OF COOLING BY

THE SNOWMASS 2001

MEETING FOR

THE PARTICLES

COMMUNITY TO

RESPOND TO
A small group (?) vs start a study (?)

1. whose a mum been may be Joel, CBRK, TRIUMF BNL,
   FNR Cornell, PSI, KG Ketekere et al
   in the world (state with the beam)

2. try again to define
   a sensible demonstration
   experiments before summer 2001
   (may pick up collaborate there)

3. university people to show
   try to help this process
   (NSF, DOE ??)

--- the next talk by Kirk is a start
**Final Comments**

1. In spite of all the experts, it is NOT CLEAR THAT A $10^{21} - 10^{22}$ $\mu$ decay neutrino factory is EASIER than a Higgs factory $\mu^+ \rightarrow \mu^0$.

   **Introspective vs. Cooling**

   $10^{21} - 10^{22}$ for $g_0$?

   **THE U.S. Situation**

2. NLC almost ready to go but seems too expensive for Bush & Gore.

   Administration with Congress.

   *This could change in the Bush Administration.*

3. No real funds to do extensive R&D for $\nu$ Pu/Mu cooler.

   *Howard*

   Need a breakthrough to rapid change priority in USA.

   Demonstration like the Ice Run.
Would you buy a T.V. set that had never been turned on but were told it was all based on a computer simulation (I would not) and no other TV set had ever been demonstrated (all based on Maxwell's Equations)?