Neutrino Factory

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INTRODUCTION

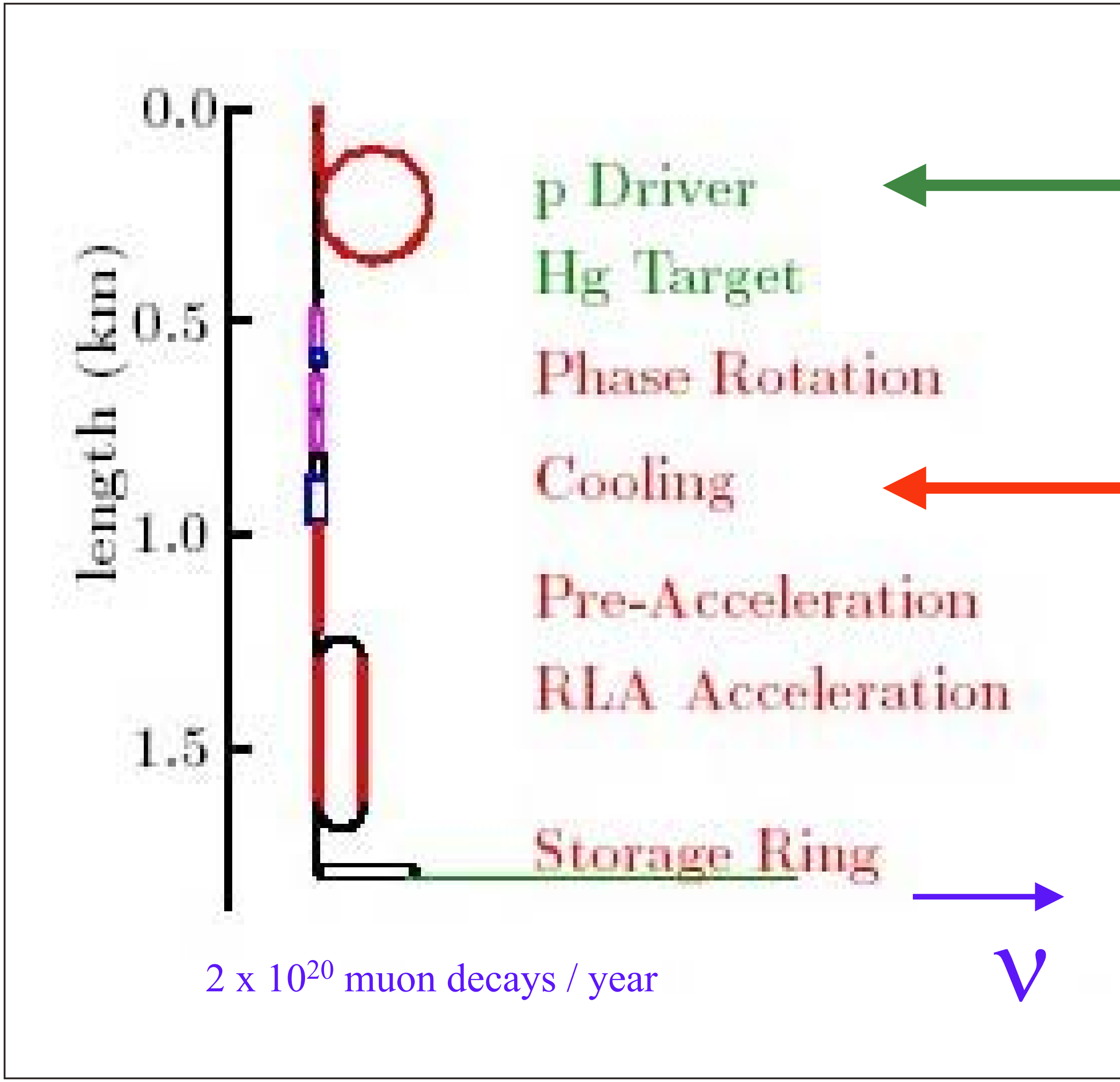
Neutrino oscillation physics is exciting. Neutrino Factories (NFs) are considered to be the ultimate tool for studying neutrino oscillations.

Fermilab and the Fermilab community are at center of the ongoing national and international Neutrino Factory R&D effort.

We believe we need about 10 years of well supported R&D before we have a cost effective design, and have adequately demonstrated the performance of the critical components.

In about 10 years we will be know more about the oscillation parameters, know the cost of a Neutrino Factory (based on the R&D) and know the geographical location of the Linear Collider. One possible branch of the decision tree has a Neutrino Factory in Fermilabs future.

NEUTRINO FACTORY DESIGN



Proposed FNAL Proton Driver Upgrade could be used for a Neutrino Factory

Fermilab hosts the muon cooling channel R&D – MUCOOL Collaboration

Fermilab community is making key contributions to the Neutrino Factory design effort.

Beam Properties at a Neutrino Factory

$$\mu^+ \to e^+ \, \nu_e \, \bar{\nu}_\mu \;\to\; 50\% \; \nu_e \, , \; 50\% \; \bar{\nu}_\mu$$

$$\mu^- \to e^- \, \bar{\nu}_e \, \nu_\mu \;\to\; 50\% \; \bar{\nu}_e \, , \; 50\% \; \nu_\mu$$

Decay kinematics well known → minimal systematic uncertainties in:

1. Spectrum
2. Flux
3. Comparison of neutrino with antineutrino results

… but, most important, there are ν_e as well as ν_μ in the initial beam.

Electron Neutrinos & Wrong-Sign Muons

The primary motivation for interest in neutrino factories is that they provide electron neutrinos (antineutrinos) in addition to muon anti-neutrinos (neutrinos). This enables a sensitive search for $\nu_e \rightarrow \nu_\mu$ oscillations.

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \quad \overset{CC}{\Rightarrow} \quad \mu^+$$

$$\nu_e \downarrow$$

$$\nu_\mu \quad \underset{CC}{\Rightarrow} \quad \mu^-$$

$\nu_e \rightarrow \nu_\mu$ oscillations at a neutrino factory result in the appearance of a "wrong-sign" muon … one with opposite charge to those stored in the ring:

Backgrounds to the detection of a wrong-sign muon are expected to be at the 10^{-4} level $\Rightarrow$ background-free $\nu_e \rightarrow \nu_\mu$ oscillations with amplitudes as small as $O(10^{-4})$ can be measured !

Signal Rates & Signal/Background

Note: backgrounds for $\nu_e \rightarrow \nu_\mu$ measurements (wrong-sign muon appearance) are much easier to suppress than backgrounds to $\nu_\mu \rightarrow \nu_e$ measurements (electron appearance).

Many groups have calculated signal & background rates. Recent example
Hubner, Lindner & Winter; hep-ph/0204352

JHF-SK: Beam = 0.75 MW, M_{fid} = 22.5 kt, T = 5 yrs
JHF-HK: Beam = 4 MW, M_{fid} = 1000 kt, T = 8 yrs
Entry-Level NUFACT: Beam = 1×10^{19} decays/yr, M_{fid} = 100 kt, T = 5 yrs
High-Performance NUFACT: Beam = 2.6×10^{20} decays/yr, M_{fid} = 100 kt, T = 8 yrs

$\Delta m_{32}^2 = 0.003\ eV^2$, $\Delta m_{21}^2 = 3.7\times10^{-5}\ eV^2$, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{12} = 0.8$, $\delta = 0$

	Superbeams		Neutrino Factories	
	JHF-SK	JHF-HK	Entry Level	High Performance
Signal	140	13000	1500	65000
Background	23	2200	4.2	180
S/B	6		360	

Oscillation Measurements at a Neutrino Factory

There is a wealth of information that can be used at a neutrino factory. Oscillation parameters can be extracted using events tagged by:

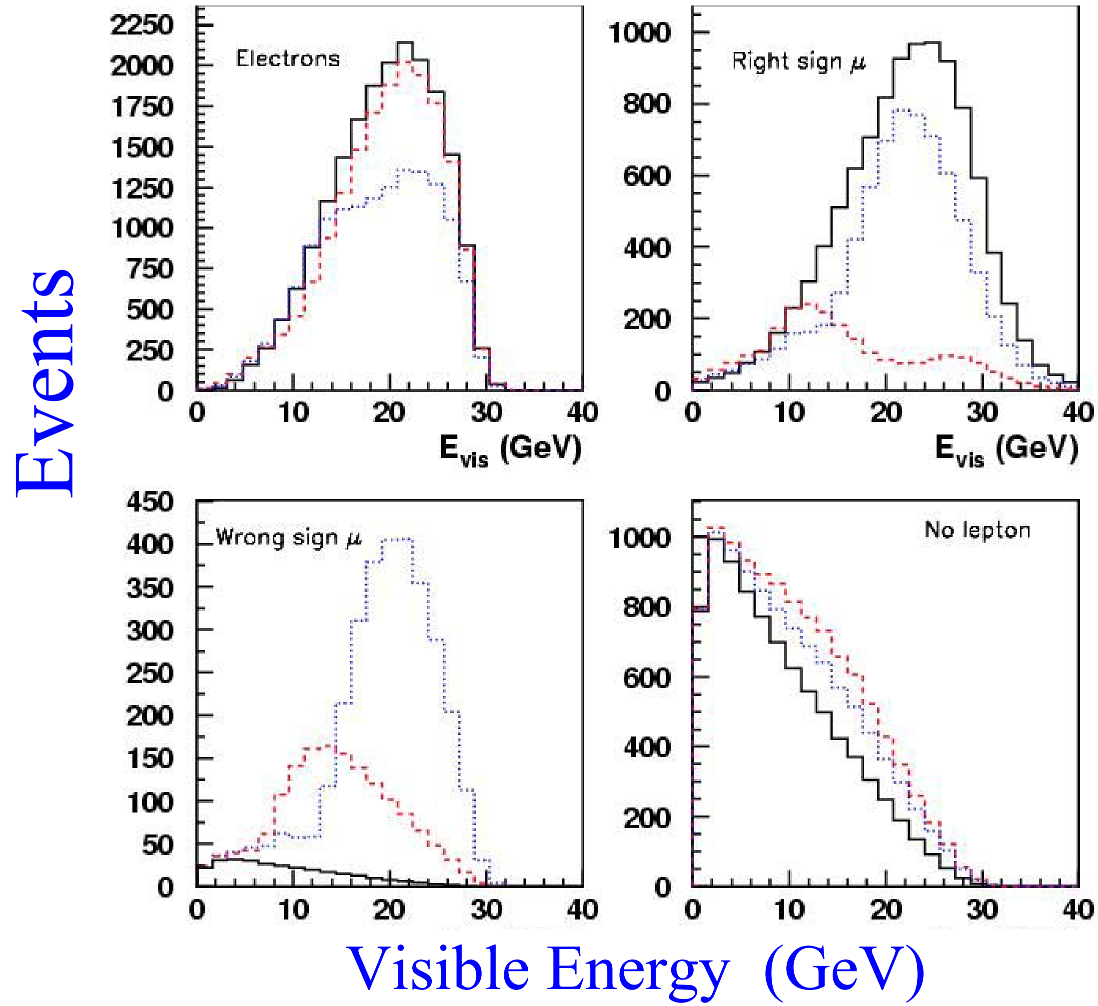
a) right-sign muons
b) wrong-sign muons
c) electrons/positrons
d) positive τ-leptons
e) negative τ -leptons
f) no leptons

×2 (μ^+ stored and μ^- stored)

The distributions are sensitive to the oscillation parameters

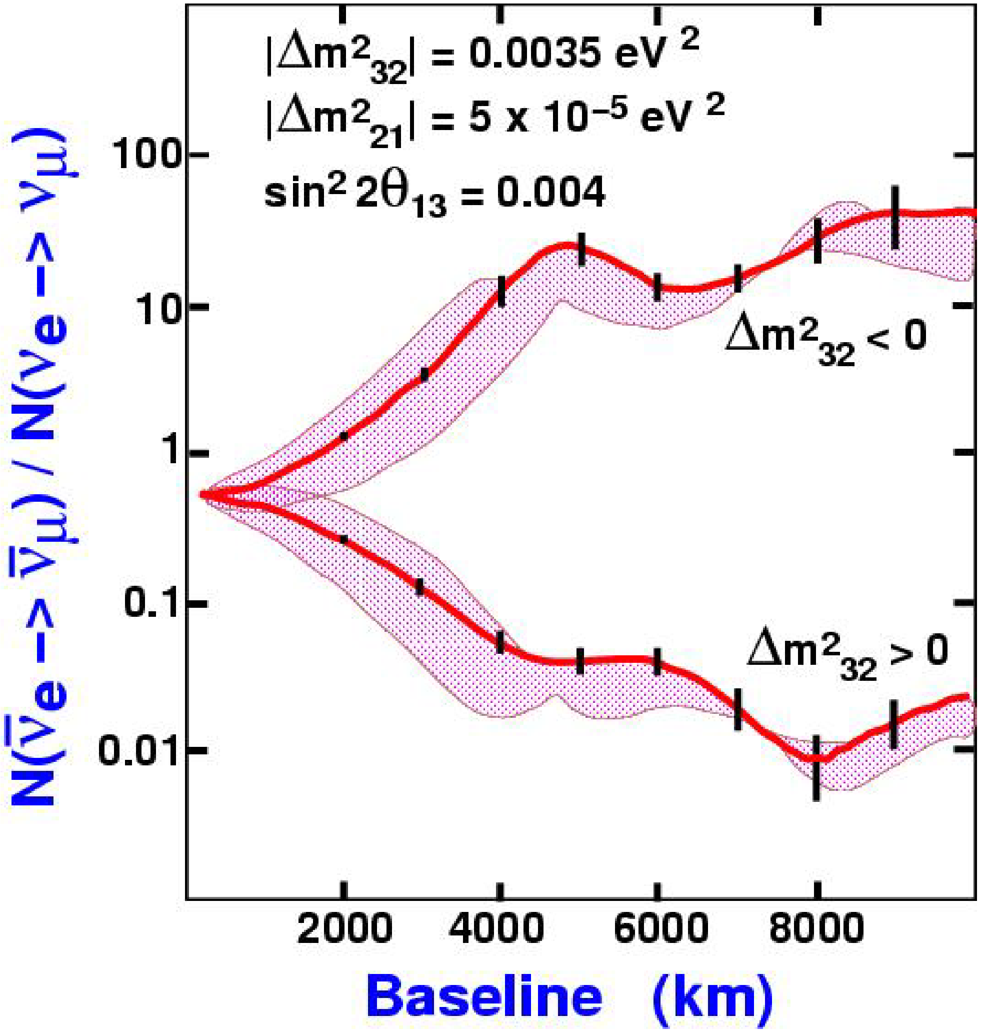
Bueno, Campanelli, Rubbia; hep-ph/00050007

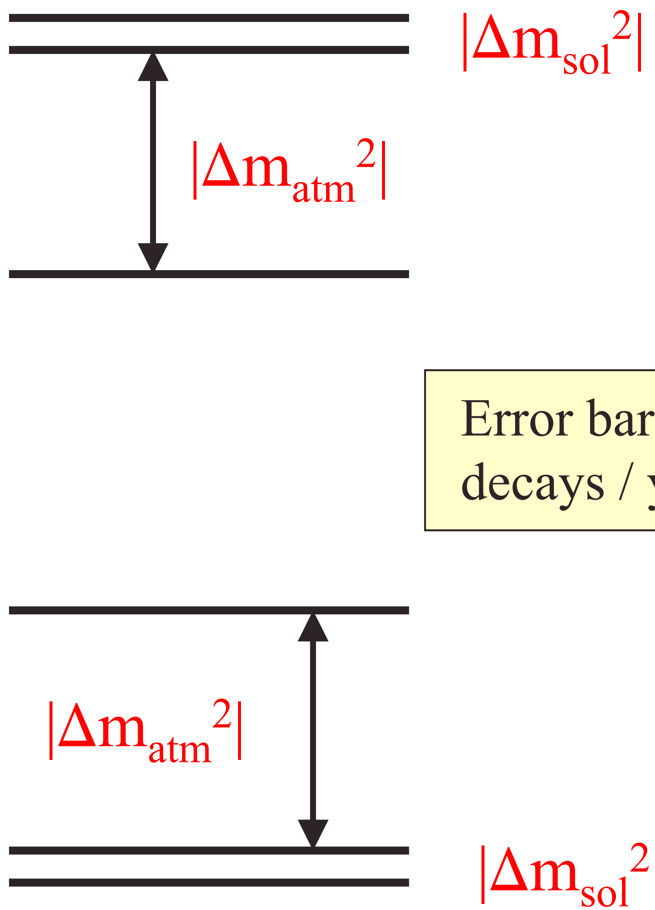
Simulated distributions for a 10kt LAr detector at L = 7400 km from a 30 GeV nu-factory with 10^{21} μ^+ decays.



CP-Violation & the pattern on neutrino masses

Barger, Geer, Raja, Whisnant, PRD 62, 073002
S. Geer, hep-ph/0008155





Error bars → 2×10^{20} decays / yr for 5 years

$\sin^2 2\theta_{13}$, sign Δm^2_{32} & CPV Sensitivity

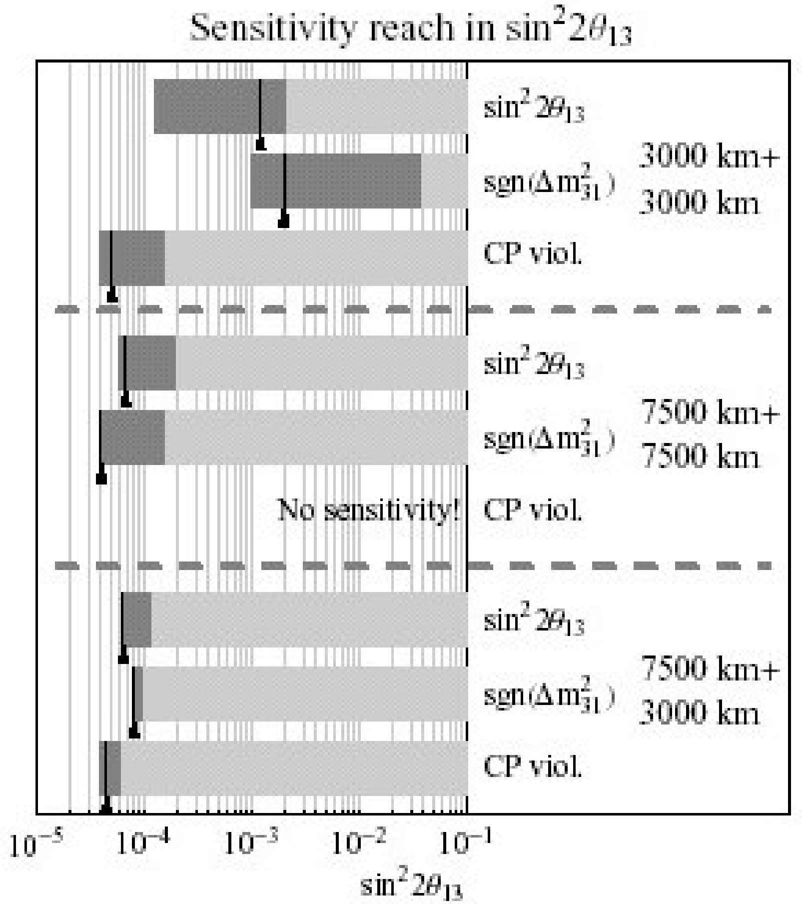


FIG. 3: The sensitivity reaches as functions of $\sin^2 2\theta_{13}$ for $\sin^2 2\theta_{13}$ itself, the sign of $\Delta m^2_{31} > 0$, and (maximal) CP violation $\delta_{CP} = \pi/2$ for each of the indicated baseline-combinations. The bars show the ranges in $\sin^2 2\theta_{13}$ where sensitivity to the corresponding quantity can be achieved at the 3σ confidence level. The dark bars mark the variations in the sensitivity limits by allowing the true value of Δm^2_{21} vary in the 3σ LMA-allowed range given in Ref. [19] and others ($\Delta m^2_{21} \sim 4 \cdot 10^{-5}\,\mathrm{eV}^2 - 3 \cdot 10^{-4}\,\mathrm{eV}^2$). The arrows/lines correspond to the LMA best-fit value.

Huber & Winter, hep-ph/0301257
(50 GeV Neutrino Factory)

With 2 carefully chosen baselines, the correlations & ambiguities can be overcome at a Neutrino Factory.

The calculated $\sin^2 2\theta_{13}$ reach (3σ) is below 10^{-4} for all three physics goals (measuring $\sin^2 2\theta_{13}$, determining the mass hierarchy, & observing maximal CPV) !!

Neutrino Interaction Experiment Reasons to Build a Neutrino Factory

50 GeV ν-Fact: $10^6 - 10^7$ events/kg/year

Broad program – many experiments

1. Precise σ(ν) measurements
2. Structure Functions (no nuclear corrections) → individual quark flavor parton distributions
3. Precise α_s measurements (from non-singlet str. Fus.)
4. Study of nuclear effects (e.g. shadowing)for, separately, valence & sea quarks
5. Spin structure functions
6. Single tagged charm mesons & baryons(1 ton detector → 10^8 flavor tagged charm hadrons/year) → D^0-$\bar{D}^0$ mixing
7. Electroweak tests → $\sin^2\theta_W$ & $\sigma(\nu - e^-)$
8. Exotic interaction search (clean initial state)
9. Neutral heavy leptons (10-100 MeV/c^2)
10. Anomalous ν interactions in EM fields

Neutrino Factory R&D at Fermilab

Fermilab is the host for MUCOOL – development of a muon cooling channel → 70 Scientists from 16 Institutions. MUCOOL is organized much like a particle physics experiment, is subjected to an annual external technical review and multi-Laboratory Directorate-Level oversight.

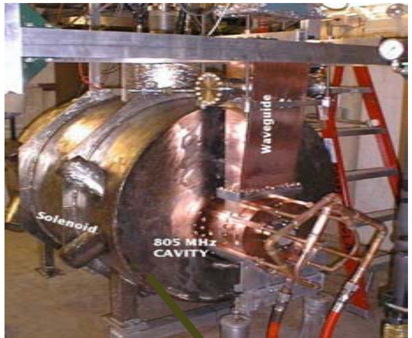
Support for MUCOOL comes from non-base program funds earmarked for accelerator R&D, plus some effort from the Laboratory.

Fermilab staff also provide critical contributions to the national Neutrino Factory design effort.

Both MUCOOL and the design effort are a part of the Neutrino Factory and Muon Collider Collaboration (Muon Collaboration) → 130 scientists.

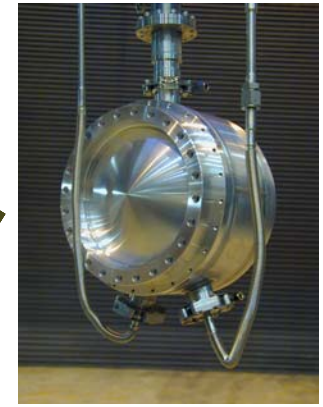
MUCOOL: Develop & test all of the components needed for a cooling channel

5T Cooling Channel
Solenoid – LBNL
& Open Cell NCRF Cavity
operated at Lab G – FNAL



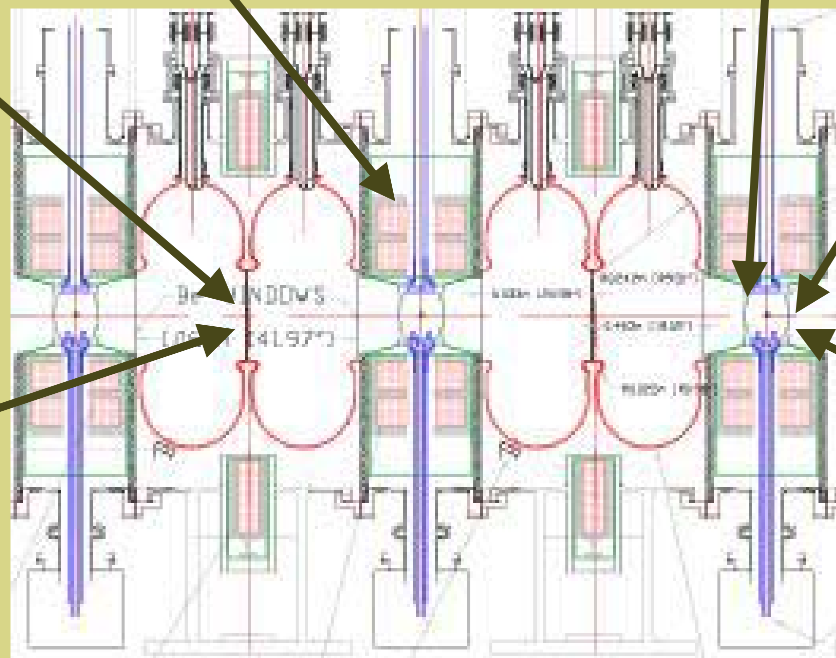
Bolometer detectors for
Window Beam profile
Measurements– U. Chicago

High-Gradient RF Tests in
High Magnetic Field
– FNAL



Liq.H Absorber – KEK
To be tested at FNAL

Tested Be-Windows for
RF Cavities -- LBNL



Liq. H RF Liq. H RF Liq. H
COOLING CHANNEL DESIGN

Thin absorber windows
Tested – new technique
– ICAR Universities

MUCOOL Test Area

Need an area to test cooling channel RF cavities operating next to a liquid hydrogen absorber within an appropriate magnetic field.

The new MUCOOL Test Area has just been completed at the end of the Linac … funded from non-base program funds.

In a couple of years time we would like to bring an intense beam to this area → engineering test of cooling channel component performance.

MUCOOL - WORLD CONTEXT

MUCOOL is developing & testing cooling channel components.

The international Muon Ionization Cooling Experiment (MICE) will use these components to demonstrate a short cooling section in a muon beam at the Rutherford Lab.

MUCOOL & MICE have been identified by the external technical review committees as providing "the critical test that must be made before a Neutrino Factory could be built".

MICE has just received scientific approval. Hence, MUCOOL is On the critical R&D path for a Neutrino Factory.

MICE Approval

CCLRC

Professor Alain Blondel & Professor Dan Kaplan
Neutrino Physics Group
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Nucleaire et Corpusculaire
Université de Genève
Quai Ernest-Ansermet 24
CH-1211
Geneve 4
Switzerland

Department of Physics
Imperial College London
Prince Consort Road
LONDON SW7 2BZ

Our Ref: JVW/ osd/MICE2 2003-10-24

24-October-2003

Dear Alain,

The last few months have seen the international MICE project proposal peer reviewed at both a national and an international level. The scientific case, technical merits and timeliness of the proposal have been strongly endorsed in each case. CCLRC accepts the strong endorsement of the proposal by the Astbury panel and consequently considers the proposal to have full scientific approval.

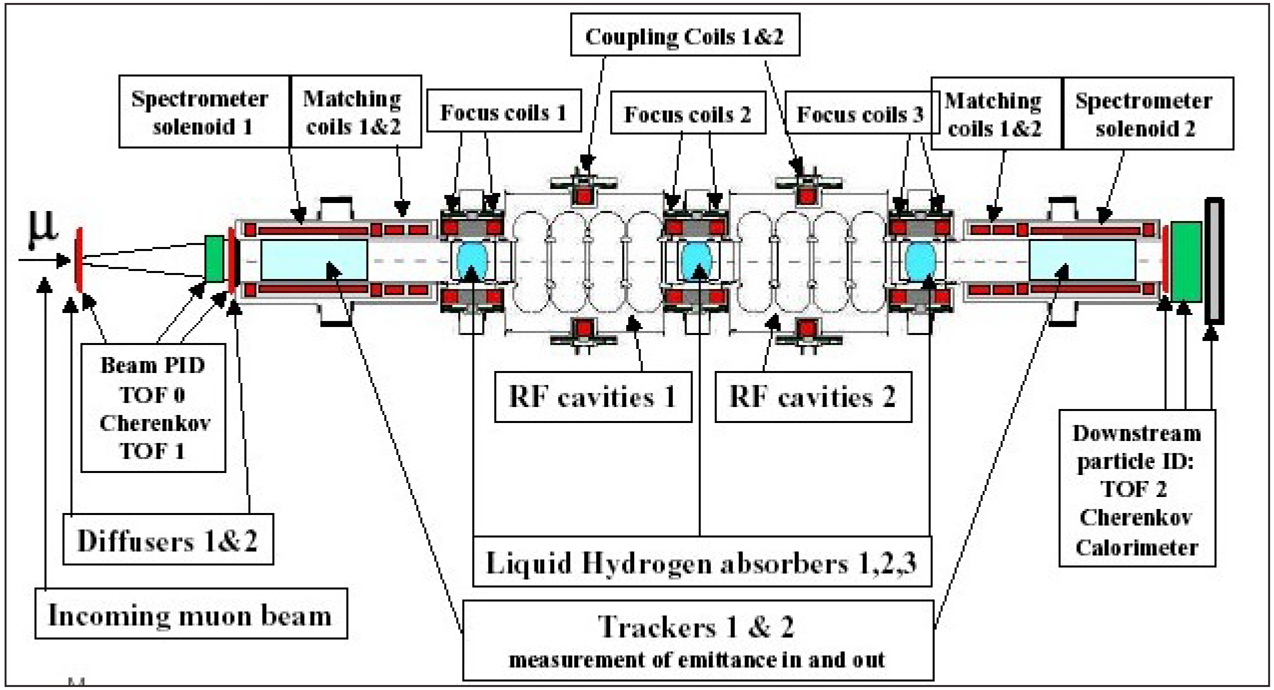
Progress of the project is now dependent on satisfactory funding arrangements being in place together with an appropriate project management structure. These arrangements will require scrutiny to ensure "best value" for UK and other investors. Within the UK this will be ensured by an independent review through the "Gateway" process that will be managed by the Joint MICE Project Board.

CCLRC therefore approves the project subject to a satisfactory progress through Gateway. The MICE proponents are now encouraged to actively seek funds to support MICE.

Yours sincerely

Professor J V Wood
Chief Executive

Cc Professor Ian Halliday, PPARC
Professor Ken Peach, CCLRC



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Progress towards Cost Reduction

Study 2 Design: ¾ of the cost in 3 roughly equally expensive systems:

Phase Rotation

	Study 2	Now	Factor
Tot Length (m)	328	166	51%
Acc Length (m)	269	35	13%
Acc Type	Induction	Warm RF	

Cooling Channel
(Linear channel→ Ring)

	Study 2	Now	Factor
Tot Length (m)	108	33	30%
Acc Length (m)	54	37	21%
Acc Grad (MV/m)	16	12	66%

Acceleration
RLA → FFAG

	Study 2	Now	Factor
Vac Length (m)	3261	1094	34%
Tun Length (m)	1494	1094	49%
Acc Length (m)	288	102	35%
Acc Grad (MV/m)	16	8	50%

The Fermilab Community has been at the center of all of these new ideas

Towards a Recommendation

Neutrino Factory R&D is a part of the ongoing scientific program of Fermilab, and is central to both the national and international R&D efforts.

The present Long Range Planning process is not an isolated exercise … but is pursued within the context of the plan laid out in the Gilman HEPAP Report of 2002.

I believe that the Neutrino Factory R&D program at Fermilab should be pursued at a level that is consistent with the intent of the HEPAP report … and that should be the basis of the Neutrino Factory R&D recommendation of the Fermilab Long Range Planning Committee.

HEPAP Subpanel Recommendation

Accelerator R&D

"We give such high priority to accelerator R&D because it is absolutely critical to the future of our field. ... As particle physics becomes increasingly international, it is imperative that the United States participates broadly in the global R&D program."

Neutrino Factory & Muon Collider R&D

"We support the decision to concentrate on intense neutrino sources, and recommend continued R&D near the present level of 8M$ per year. This level of support is well below what is required to make an aggressive attack on all of the technological problems on the path to a neutrino factory."

Support from Technical Reviewers and Laboratory Management

The annual external technical review this year was in January, and resulted once again in a very positive report. The Laboratory Directorate Level Oversight Group said:

The successful record of progress is epitomized by the summary judgment in the report, namely that "Overall, MUTAC was impressed by the accomplishments since the last meeting, particularly given the strained financial situation. MUTAC can enthusiastically assure MCOG that the limited funding is being well and carefully utilized."

MCOG has concluded that it is imperative that DOE seek to provide enhanced R&D funding for this work if it is to meet either the intent or the recommendations of the Long Range Plan laid out in the 2002 Gilman Report of HEPAP.

Support from the Community

6 January, 2003

To: John O'Fallon

From: J. Conrad
W. Louis
D. Michael
M. Shaevitz
S. Wojcicki

Dear John,

We would like to encourage you to increase support for Neutrino Factory R&D in FY04.

Neutrino oscillation physics has entered a very exciting period. In the not-too-distant future we expect that results from MiniBooNE and MINOS will add to the excitement. No matter what the results are from these experiments it is already clear that more ambitious long-baseline experiments will be needed in the future. It also seems increasingly likely that we will ultimately need the full power of a Neutrino Factory to unambiguously determine all of the parameters that describe neutrino oscillations. This will be particularly true if the LMA solution to the solar neutrino problem is confirmed (which initial KamLAND results suggest is the case), or if MiniBooNE and/or MINOS make discoveries that indicate there is more going on than just three-flavor mixing.

The HEPAP subpanel recommended a funding level for Neutrino Factory R&D at the FY01 level of 8M$ per year. We understand that since that recommendation support for the all important R&D has been significantly reduced. We believe it is important to maintain an investment in the long-term future. Since the HEPAP subpanel presentations the R&D seems to have made good progress, and the physics case for an eventual Neutrino Factory has, if anything, grown stronger. We would therefore like to encourage a restoration of the support for Neutrino Factory R&D to the level that the subpanel recommended.

cc: Steve Geer
Bob Palmer