Neutrino Factory

Physics and R&D Status

1. Motivation & Neutrino Factory Concept
2. Physics Reach
3. R&D

Neutrino Oscillations are Exciting

Stunning experimental results have established that neutrinos have nonzero masses and mixings

The Standard Model cannot accommodate neutrino mass terms, which require either the existence of right-handed neutrinos → Dirac mass terms, or a violation of lepton number conservation → Majorana mass terms.

We know that neutrino masses and mass splittings are tiny compared to the masses of any of the other fundamental fermions. This suggests radically new physics, which perhaps originates at the GUT or Planck Scale, or indicates the existence of new spatial dimensions.

Whatever the origin of the observed neutrino masses & mixings is, it will certainly require a profound extension to our picture of the physical world.

First Round of Neutrino Oscillation Physics Questions

Is three-flavor mixing the complete story ?
(Light sterile neutrinos ? Other deviations from three-flavor mixing ?)

There is one unmeasured angle (θ_{13}) in the mixing matrix. Is θ_{13} non-zero?

We don't know the mass-ordering of the neutrino mass eigenstates. There are two possibilities, the so-called "normal" hierarchy or the "inverted" hierarchy. Which mass hierarchy applies?

There is one complex phase (δ) in the mixing matrix accessible to ν oscillation measurements. If θ_{13} & $\sin\delta$ are non-zero there will be CP Violation in the ν-sector. Is there CP Violation in the Neutrino Sector ?

Neutrino Factory Concept - 1

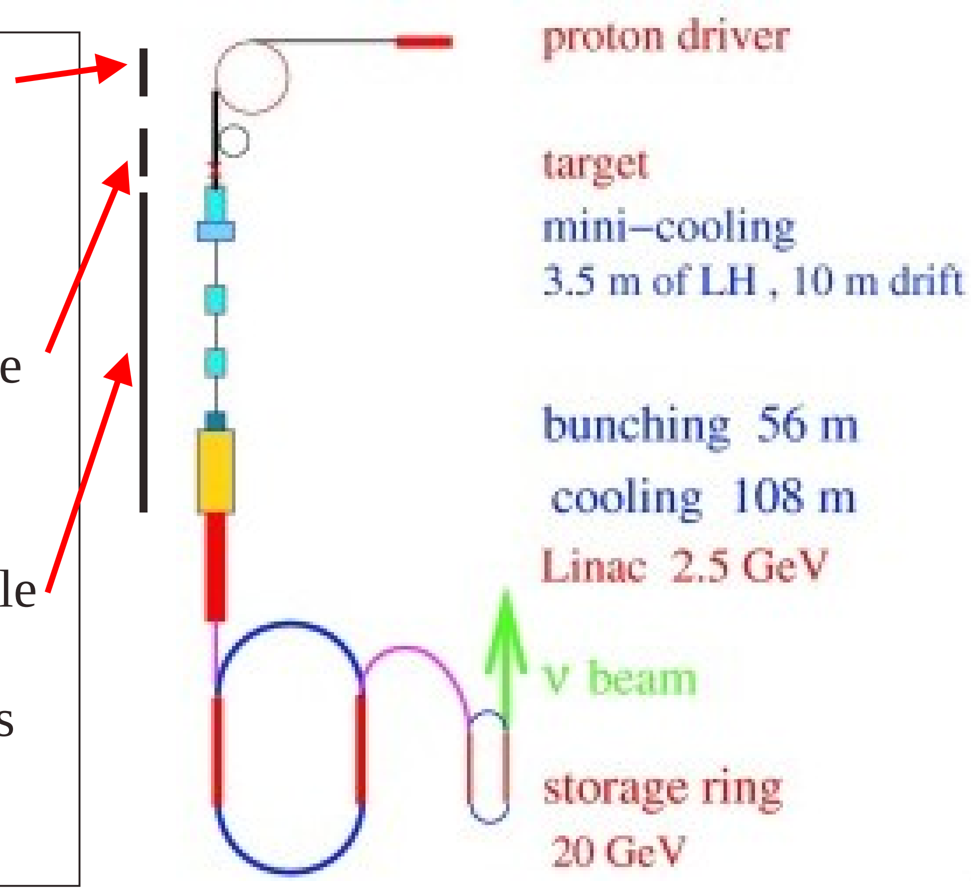
Example: US Design Study 2

1. Make as many charged pions as possible
   - INTENSE PROTON SOURCE

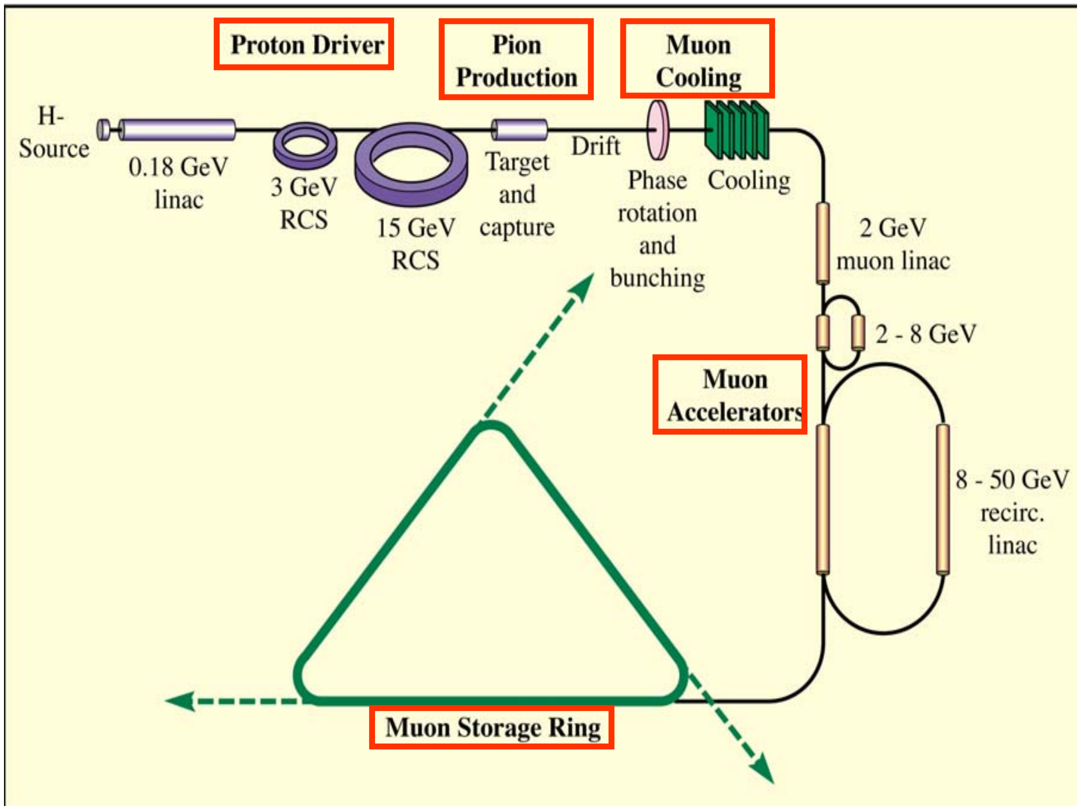
   (In practice this seems to mean one with a beam power of one or a few MW)

2. Capture as many charged pions as possible
   - Low energy pions
   - Good pion capture scheme

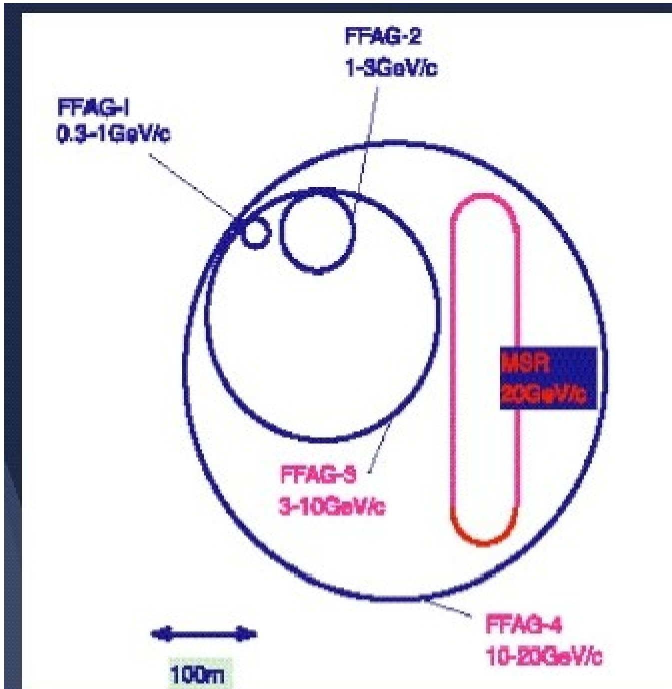
3. Capture as many daughter muons as possible within an accelerator
   - Reduce phase-space occupied by the μs
   - Muon cooling – needs to be fast otherwise the muons decay



Neutrino Factory Concept - 2



CERN Design



Series of FFAGs for muon acceleration

- 0.3-1.0 GeV
- 1-3 GeV
- 3-10 GeV
- 10-20 GeV

Japanese Design

Beam Properties at a Neutrino Factory

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

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

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 $\nu_e \to \nu_\mu$ oscillations.

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

$$\nu_e \; ✵ \; \nu_\mu \quad \underset{CC}{\Downarrow} \quad \mu^-$$

$\nu_e \to \nu_\mu$ 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 $\Downarrow$ background-free $\nu_e \to \nu_\mu$ oscillations with amplitudes as small as $O(10^{-4})$ can be measured !

Signal and Background

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

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

JPARC-SK:	Beam = 0.75 MW,	M_{fid} = 22.5 kt,	T = 5 yrs
JPARC-HK:	Beam = 4 MW,	M_{fid} = 1000 kt,	T = 8 yrs
NUFACT:	Beam = 2.6×10^{20} decays/yr,	M_{fid} = 100 kt,	T = 8 yrs

$\Delta m_{32}^2 = 0.003\ \mathrm{eV}^2$, $\Delta m_{21}^2 = 3.7 \times 10^{-5}\ \mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{12} = 0.8$, $\delta = 0$

	Superbeams		Neutrino Factory
	JPARC-SK	JPARC-HK	
Signal	140	13000	65000
Background	23	2200	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:

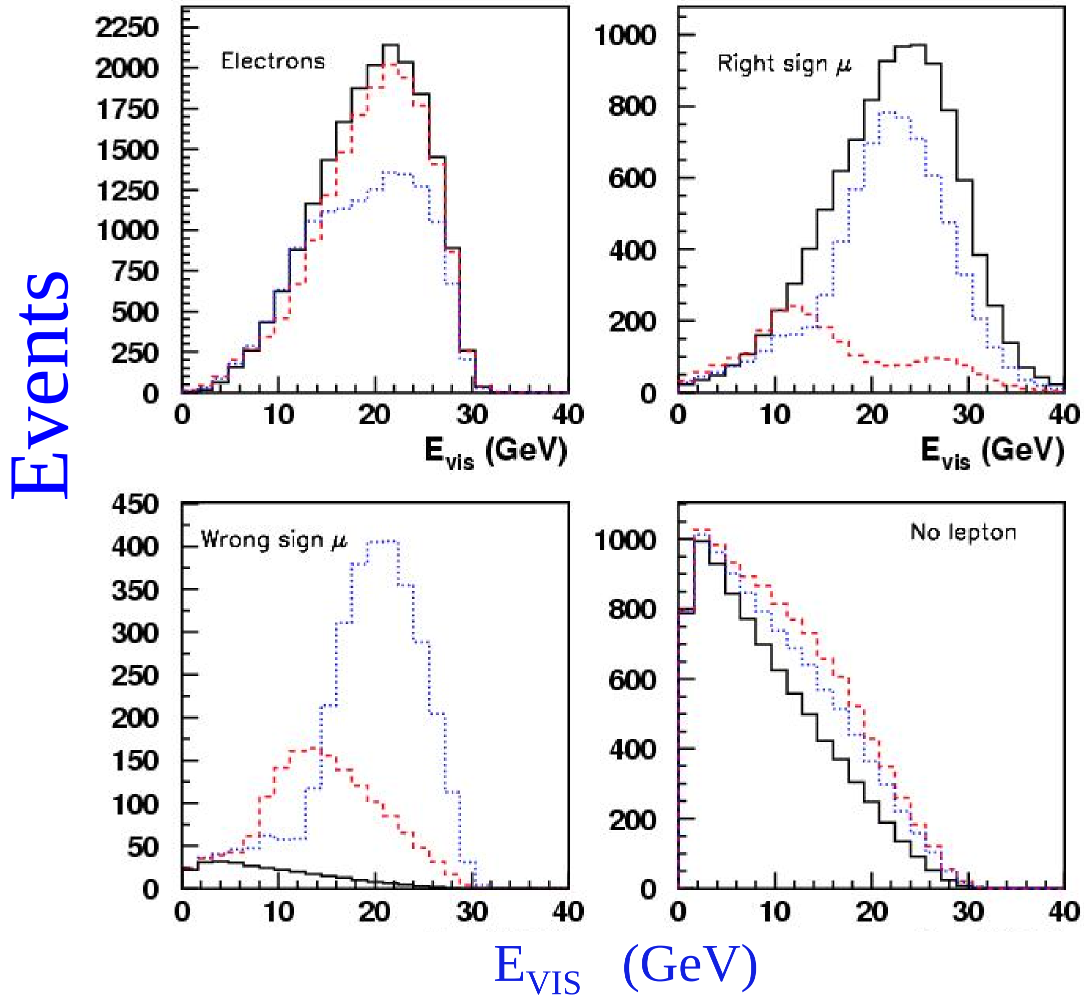
a) right-sign muons
b) wrong-sign muons
c) electrons/positrons
d) positive τ-leptons
e) negative τ -leptons
f) no leptons

⑨2 (μ^+ stored and μ^- stored)

<u>Note</u>: $\nu_e \rightarrow \nu_\tau$ is specially important (Ambiguity resolution & Unitarity test): *Gomez-Cadenas et al.*

The distributions are sensitive to the oscillation parameters

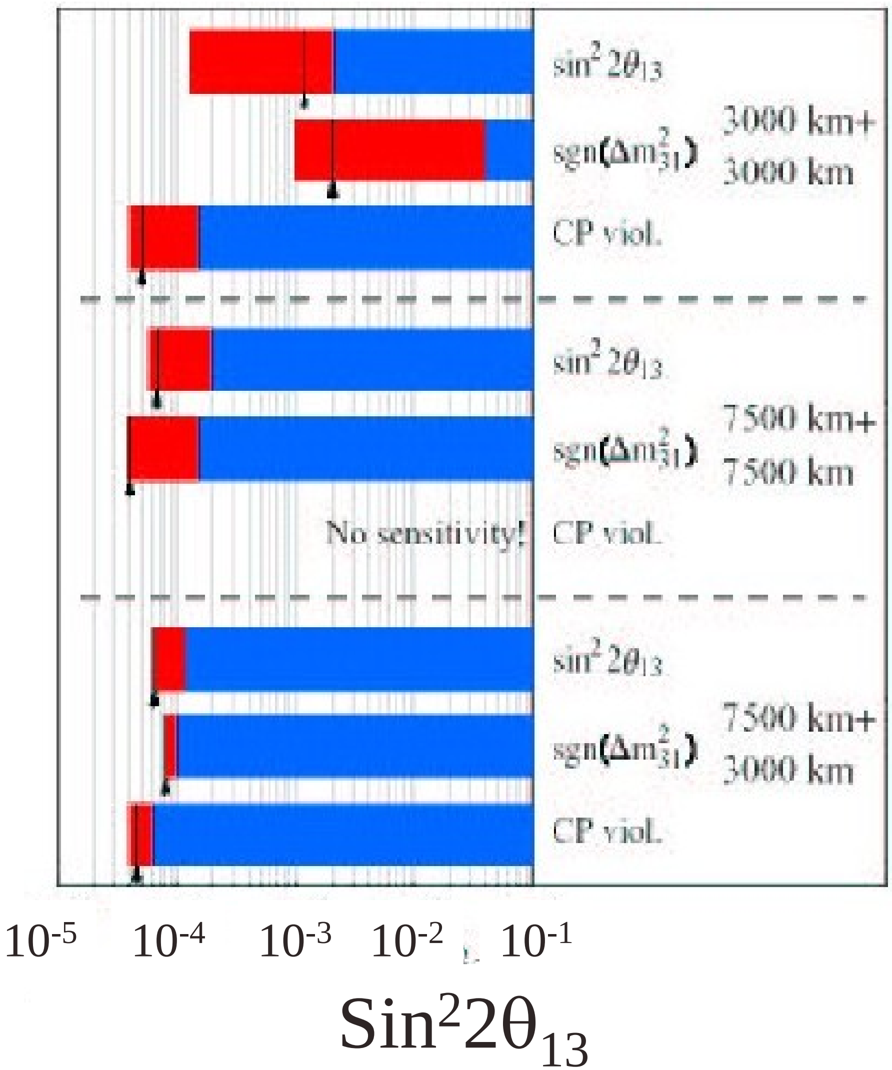
Simulated distributions for a 10kt LAr detector at L = 7400 km from a 30 GeV nu-factory with 10^{21} μ^+ decays.



Bueno, Campanelli, Rubbia; hep-ph/0005

Neutrino Factory Sensitivity if θ_{13} is Small

Huber, Winter; Phys. Rev. D68, 2003



The full physics program (Establishing the magnitude of θ_{13}, Determining the mass hierarchy, & searching for CP Violation) can be accomplished provided $Sin^2 2\theta_{13} > O(10^{-4})$!

In addition the $\nu_e \rightarrow \nu_\tau$ is unique to Neutrino Factories, & is very important (see for example Gomez-Cadenas et al)

Neutrino Factory R&D is a Global Endeavour

Over the last few years there has been tremendous progress on the design, simulation, and hardware development

In the US Neutrino Factory R&D is being pursued by the Muon Collaboration – 130 members – accelerator & particle physicists from Labs and Universities. The focus of the activity has been on both design and detailed simulation, and on hardware development of the critical components (cooling channel and targetry).

In Europe there has also been some significant design work and also experiments on muon scattering and particle production.

In Japan the emphasis has been on a scheme using large acceptance accelerators (FFAGs) … both design and hardware development.

The R&D is ready for the next big steps which involve Global Collaborations.

Neutrino Factory R&D Sub-Activities

Nearly all of the regional Neutrino Factory R&D has, from the start, had a healthy level of global collaboration. Examples: MUSCAT, MUCOOL, Targetry, HARP, Design Studies I and II, …

Four areas have emerged as being the keys to realizing a Neutrino Factory:

- Design and Simulation.
- Muon Ionization Cooling.
- Targetry.
- Acceleration.

Design & Simulation

US Feasibility Study 1: Finished March 00. Established feasibility & identified the required R&D. Failed performance goal by a factor of a few.

US Feasibility Study 2: Finished April 01. Met performance goal.

US Recent Progress: New ideas expected to yield significant cost savings.

Europe: CERN-based Design Study: Similar in general to US design, but different in detail → interesting alternative solution with comparable performance, although less detailed simulation & engineering.

Japan: FFAG-based Design: Use large acceptance accelerators → very different from US & EU designs. Performance similar to US design, but less detailed simulation & engineering.

We are working towards a "World Design Study" with an emphasis on cost reduction.

Why we are optimistic/enthusiastic – US perspective:

	Study 2	Now	Factor
PHASE ROTATION			
Beam Line (m)	328	166	51 %
Acceleration (m)	269	35	13 %
Acc Type	Induction	Warm RF	
COOLING			
Beam Line (m)	108	51	47 %
Acceleration (m)	74	34	46 %
Absorbers	Liquid Hydrogen	Solid Li or LiH	
ACCELERATION			
Beam Line (m)	3261	$\approx$ 700	$\approx$ 21 %
Tun Length	1494	$\approx$ 700	$\approx$ 47 %
Acc Length	288	$\approx$ 130	$\approx$ 45 %

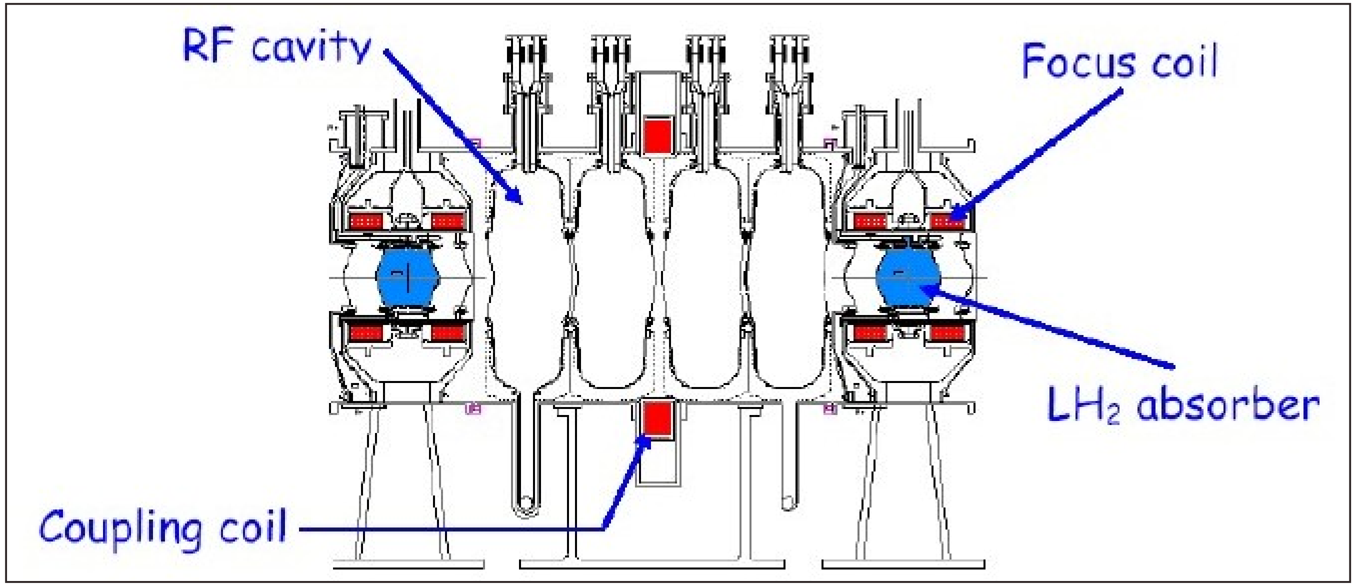
Note: In the Study 2 design roughly ¾ of the cost came from these 3 roughly equally expensive sub-systems.

New design has similar performance to Study 2 performance but keeps both μ^+ and μ^- !

In addition there are those great alternative ideas from Europe and Japan … so with a Global Design Study the prospects for very significant cost reduction are excellent.

Ionization Cooling - MUCOOL

New MUCOOL Test Area Completed – FNAL



LH2 Absorber Cryostat – KEK

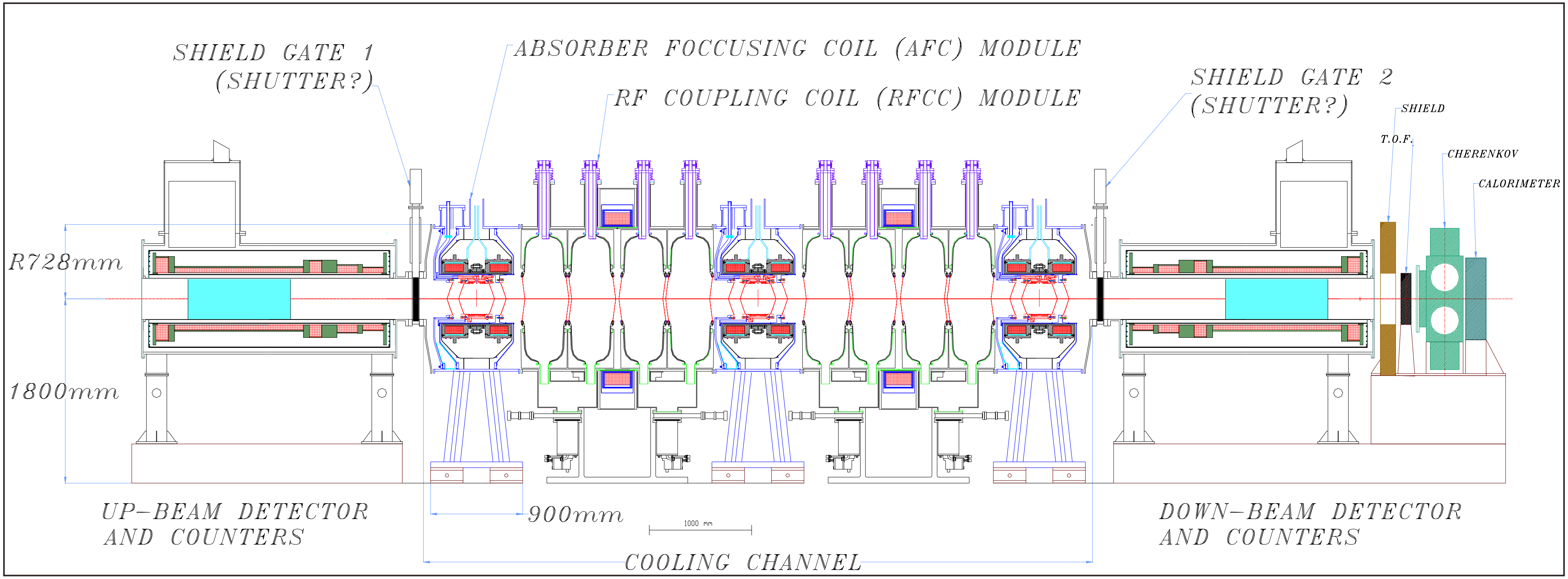
Thin absorber windows Tested – new technique – ICAR Universities

201 MHz half-shell ebeam welding of Stiffening – JLab

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

MICE – a Global Muon Ionization Cooling Experiment

Build & operate a section of a realistic cooling channel & measure its performance in a muon beam (at RAL) for various operation modes & beam conditions.



Has Scientific Approval and is seeking funding.

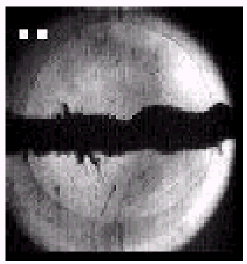
Spokesperson is Alain Blondel – if you are interested Alain would welcome enquiries.

Targetry: The Study 2 Design used a 20 m/s Hg Jet in a 20 T Solenoid

BNL E951 Hg Jet Tests

- 1cm diameter Hg Jet
- V = 2.5 m/s
- 24 GeV 4 TP Proton Beam
- **No** Magnetic Field

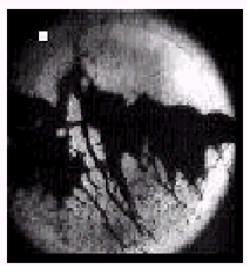
t = 0 ms



t = 0.75 ms

t = 2 ms

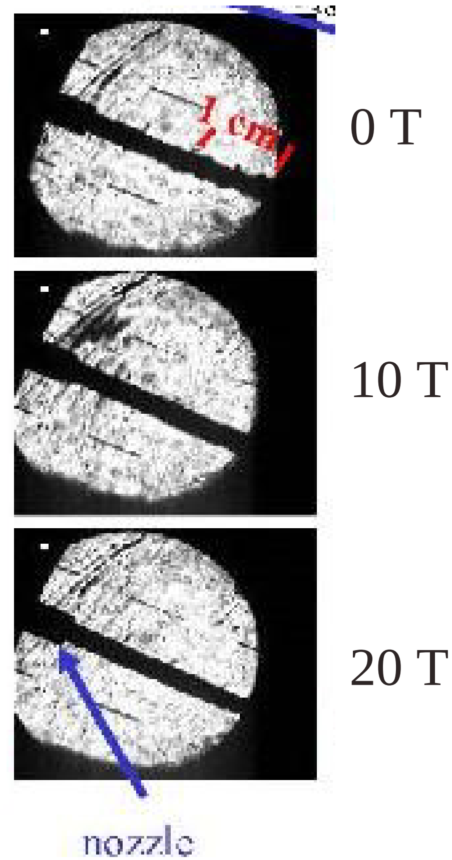
t = 7 ms



t = 18 ms

CERN/Grenoble Hg Jet Tests

- 4 mm diameter Hg Jet
- v = 12 m/s
- **No** Proton Beam



Targetry: Proposal to test a 10m/s Hg Jet in a 15T Solenoid with an Intense Proton Beam

Note: The solenoid is under construction, and the Hg-jet under development.

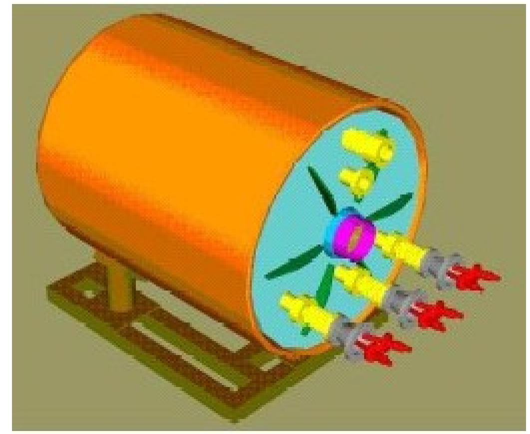
CERN-INTC-2003-033
INTC-I-049
26 April 2004

A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments
Committee

Studies of a Target System for a 4-MW, 24-GeV Proton Beam

J. Roger J. Bennett[1], Luca Bruno[2], Chris J. Densham[1], Paul V. Drumm[1],
T. Robert Edgecock[1], Tony A. Gabriel[3], John R. Haines[3], Helmut Haseroth[2],
Yoshinari Hayato[4], Steven J. Kahn[5], Jacques Lettry[2], Changguo Lu[6], Hans Ludewig[5],
Harold G. Kirk[5], Kirk T. McDonald[6], Robert B. Palmer[5], Yarema Prykarpatskyy[5],
Nicholas Simos[5], Roman V. Samulyak[5], Peter H. Thieberger[5], Koji Yoshimura[4]

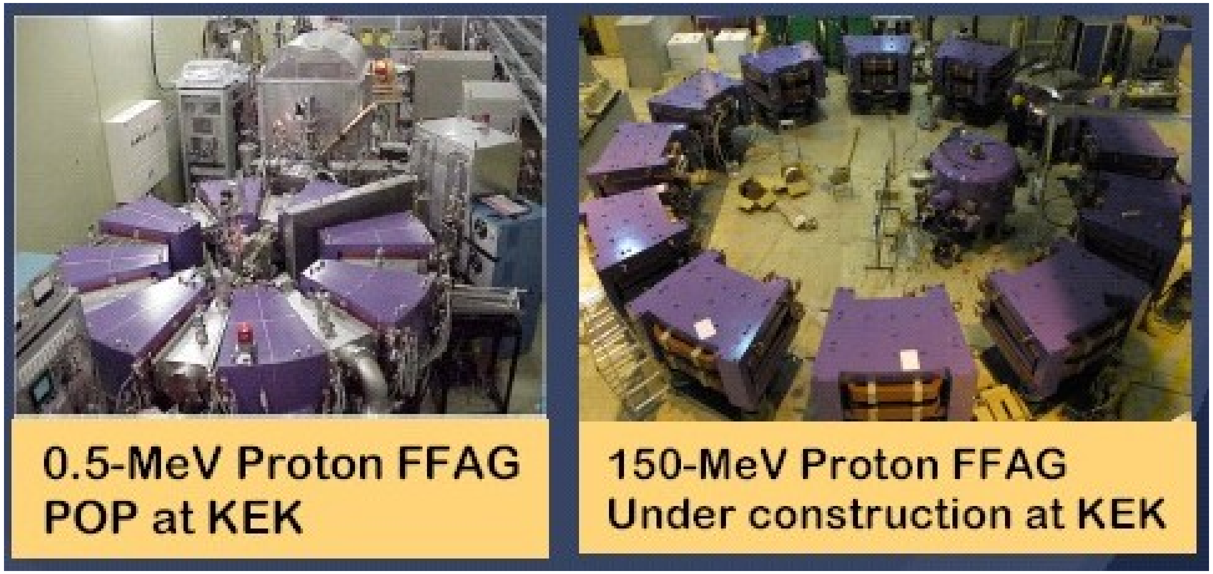
Spokespersons: H.G. Kirk, K.T. McDonald
Local Contact: H. Haseroth

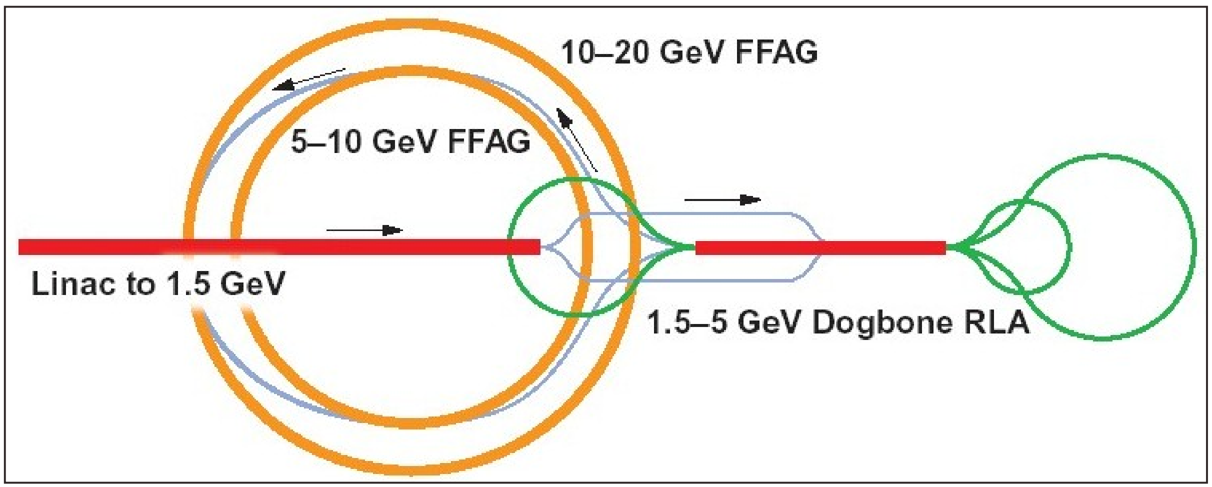


Participating Institutions

1) RAL
2) CERN
3) KEK
4) BNL
5) ORNL
6) Princeton University

Acceleration





New US Acceleration Scheme … still evolving

Much progress in Japan with the development and demonstration of large acceptance FFAG accelerators.

Latest ideas in US have lead to the invention of a new type of FFAG (so-called non-scaling FFAG) which is interesting for more than just Neutrino Factories, & may require a demonstration experiment (plans are developing).

Perhaps US & Japanese concepts are merging to produce something better ??

Summary

Neutrino Oscillations provide us with exciting experimentally driven science. We might be in for big surprises.

Neutrino Factories offer a new type of neutrino beam with impressive statistical and systematic precision, and flexibility. If θ_{13} is smaller than O(0.01) they will offer a way forward … but only if we invest in the R&D so that the option exists when the time comes.

The R&D is becoming increasingly global in character. Much technical progress has been made, and there are excellent prospects for significant cost reduction … hopefully to be explored by a "World Design Study".

The critical Neutrino Factory experiments requiring support are MICE & the proposed targetry experiment at CERN.

Large θ_{13} Neutrino Factory Study

How close can δ_{CP} be to 0 or π and CP Violation still be observed at a Neutrino Factory ? Numbers from Huber, Lindner & Winter:

	LMA-I ($\Delta m^2_{21} = 7 \cdot 10^{-5}\,\text{eV}^2$)			
Experiment/Combination	$\delta_{CP} = 0°$	$\delta_{CP} = 90°$	$\delta_{CP} = 180°$	$\delta_{CP} = 270°$
$\sin^2 2\theta_{13} = 0.1$				
JHF-HK	2° (17°)	8° (51°)	2° (17°)	9° (53°)
NuFact-II@3 000 km	31° (119°)	41° (123°)	23° (105°)	33° (119°)
JHF-HK+NuFact-II@3 000 km	1° (11°)	6° (45°)	1° (10°)	6° (47°)
NuFact-II@3 000 km+NuFact-II@7 500 km	10° (72°)	18° (91°)	10° (68°)	12° (75°)
JHF-SK+Reactor-II	126° (360°)	125° (360°)	111° (360°)	165° (360°)
NuMI+Reactor-II	294° (360°)	283° (360°)	328° (360°)	215° (360°)
JHF-SK$_{\alpha c}$+NuMI$_{\alpha c}$	127° (360°)	132° (360°)	125° (360°)	125° (289°)
$\sin^2 2\theta_{13} = 0.01$				
JHF-HK	14° (127°)	29° (125°)	15° (141°)	36° (104°)
NuFact-II@3 000 km	10° (67°)	20° (80°)	4° (39°)	20° (85°)
JHF-HK+NuFact-II@3 000 km	3° (26°)	8° (53°)	2° (21°)	9° (54°)
NuFact-II@3 000 km+NuFact-II@7 500 km	5° (42°)	6° (49°)	3° (28°)	4° (39°)
JHF-SK+Reactor-II	328° (360°)	221° (360°)	324° (360°)	190° (360°)
NuMI+Reactor-II	360° (360°)	360° (360°)	360° (360°)	232° (360°)
JHF-SK$_{\alpha c}$+NuMI$_{\alpha c}$	329° (360°)	228° (360°)	316° (360°)	177° (360°)

The errors in δ_{CP} for $\Delta m^2_{31} = 3 \cdot 10^{-3}\,\text{eV}^2$, $\sin^2 2\theta_{23} = 1$, and $\sin^2 2\theta_{12} = 0.8$. The errors are defin

← NF brings modest improvement (factor of 2 ?) in δ_{CP} 1σ sensitivity

← NF brings significant improvement (factor of 5 ?) in δ_{CP} 1σ sensitivity