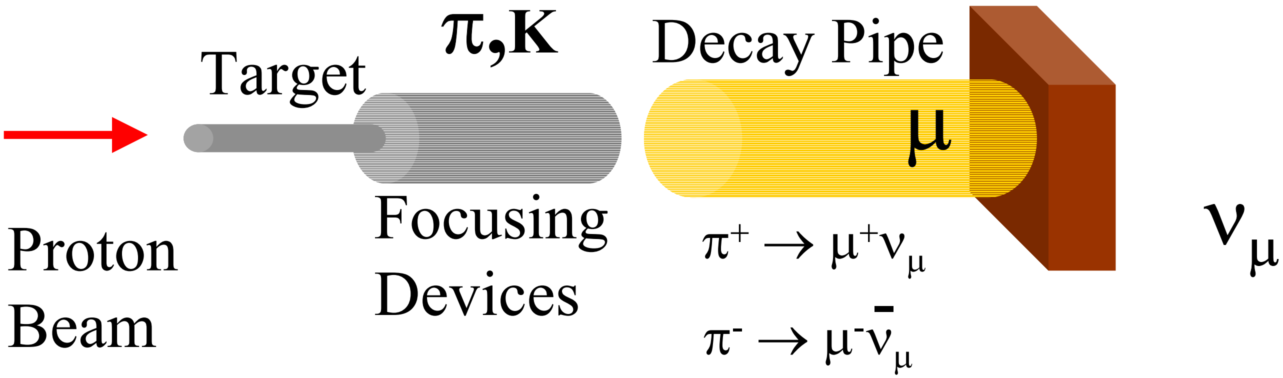
An Introduction to Neutrino Factories: History & Concepts

1. Pion Decay versus Muon Decay
2. From Pion Storage Rings to Intense Muon Source Concepts
3. An Aside: Muon Colliders
4. Neutrino Factory Studies in the US
5. Neutrino Factory Studies in the Europe
6. Neutrino Factory Studies in the Japan
7. Some Concluding Remarks

Pion Decays vs Muon Decays



CONVENTIONAL NEUTRINO BEAM

Almost pure ($\gtrsim$99%) ν_μ with ($\lesssim$1%) ν_e from $\pi \rightarrow \mu \rightarrow e$ chain & K decay (K_{e3})

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

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

$$\nu_\mu : \quad \frac{d^2N}{dx\, d\cos\theta} \sim \frac{1}{4\pi}\left[2x^2(3-2x) \mp 2x^2(1-2x)\, P \cos\theta\right]$$

$$\nu_e : \quad \frac{d^2N}{dx\, d\cos\theta} \sim \frac{1}{4\pi}\left[12x^2(1-x) \mp 12x^2(1-x)\, P \cos\theta\right]$$

NEUTRINO BEAM FROM MUON DECAYS

Nice beam properties, but $\tau_\mu = 100 \times \tau_\pi$ … so we will need a storage ring with long straight sections.

$x = 2E_\nu/m_\mu$, θ is the angle between the neutrino & μ spin, & P is the μ polarization, in the μ rest-frame :

HISTORY: Pion Storage Rings with Parasitic Muon Storage

Generating a neutrino beam by storing pions and kaons in rings with long straight sections was first proposed in the 1970's. Some of the secondary muons from the pion decays are also captured within the ring. Downstream of the straight sections there is a pulse of neutrinos from pion decay, followed by a longer pulse of neutrinos from muon decay.

Koshkarev, Preprint ITEP-33, 1974; CERN/ISR-DI/74-62.

Wojcicki (unpublished) 1974

Collins (unpublished) 1974

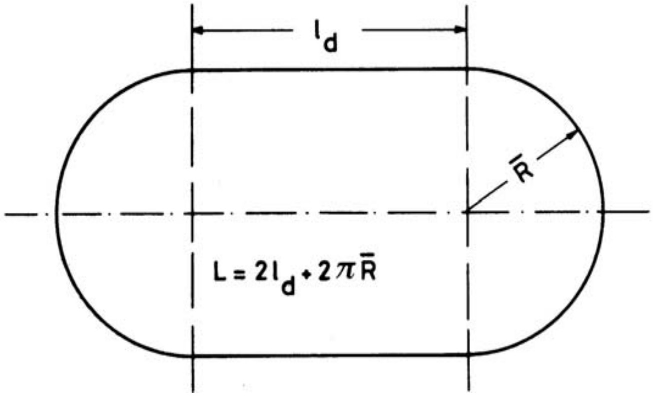
Cline & Neuffer, AIP Conf. Proc. 68, 846 (1980)

A. Bross et al; NIM A 332 (1993) 27

W. Lee et al, FNAL Proposal P860, 1992.

Unfortunately the intensity of the neutrino beams that can be produced in this way are too low (by many orders of magnitude) to produce useful neutrino beams for physics.

Koshkarev, CERN/ISR-DI/74-62 (also Wojcicki & Collins)



Collect high energy secondary particles from proton interactions, and store them in a ring with long straight sections.

The decaying mesons produce a neutrino beam downstream of the straight sections.

Rates from 10^{12} primary protons at 400 GeV

Particle	Momentum GeV/c	Δp GeV/c	$\Delta\Omega$ ster.	$\log \sigma_0$	Number of particles accepted
π^+	120 240	12 19	1,5 0,4	+ 1,5 + 0,75	$\sim 10^{10}$ $\sim 7.10^8$
π^-	120 240	12 19	1,5 0,4	+ 1,5 + 0,5	$\sim 10^{10}$ $\sim 4.10^8$
K^+	120 240	12 19	1,5 0,4	+ 0,75 0	$\sim 2.10^9$ $\sim 10^8$
K^-	120 240	12 19	1,5	0 - 1,75	$\sim 3.10^8$ $\sim 2.10^6$
$\bar{p}$	120 240	12 19	1,5 0,4	- 0,5 - 3	$\sim 4.10^7$ $\sim 10^5$
p	120 240	12 19	1,5 0,4	+ 1 + 1,5	$\sim 3.10^9$ $\sim 4.10^9$

Fundamental Problem

Production rates for high energy mesons are too low to be useful.

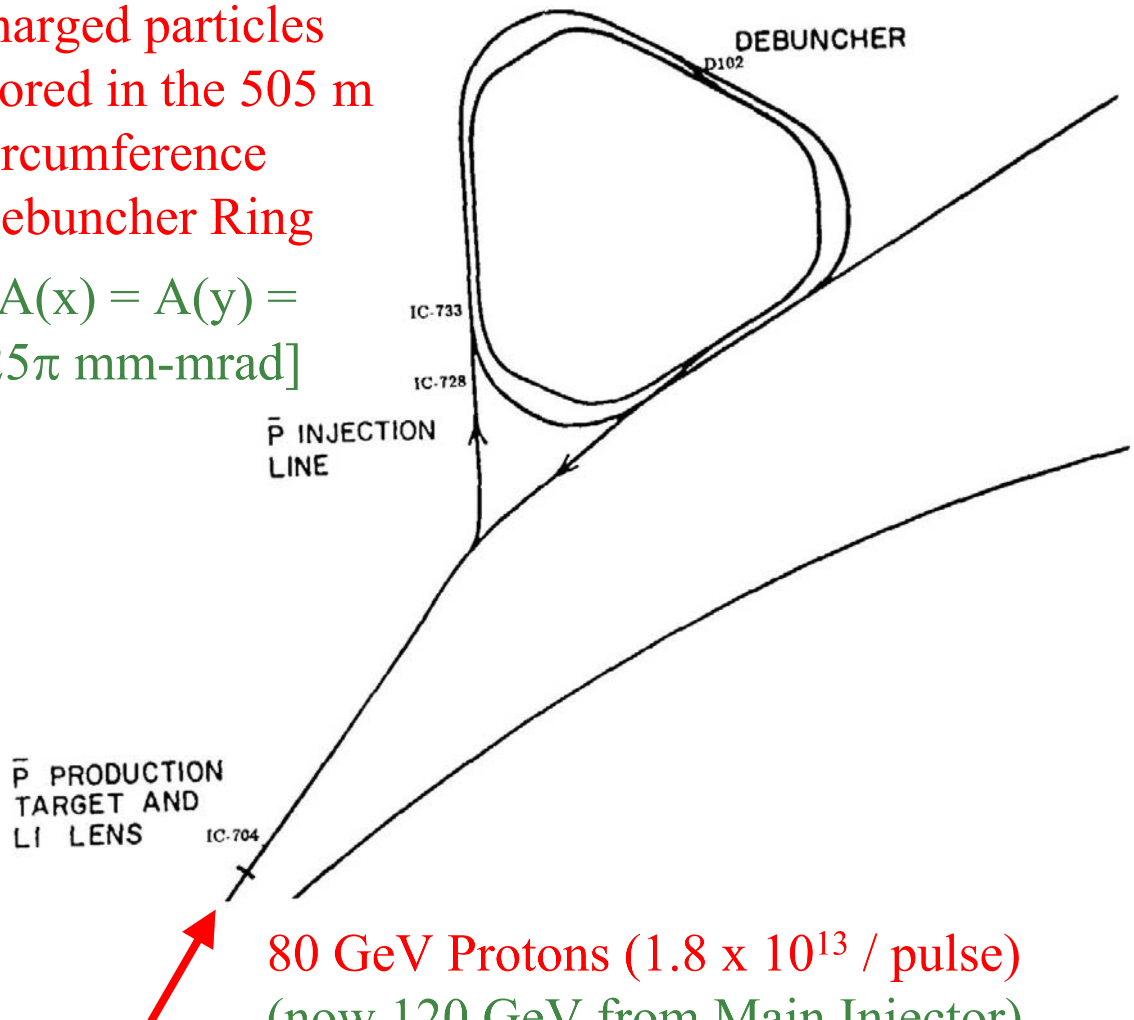
Production rates are higher for lower energy mesons, but the storage ring acceptance is only big enough to capture a tiny fraction of them.

Using The Fermilab Antiproton Debuncher as a Muon Storage Ring

Cline & Neuffer, AIP Conf. Proc. 68, 846 (1980)

8.9 GeV/c (±2%) negatively charged particles stored in the 505 m circumference Debuncher Ring

[A(x) = A(y) = 25π mm-mrad]



80 GeV Protons (1.8 x 10^{13} / pulse)
(now 120 GeV from Main Injector)

Pion lifetime = 1 turn

Estimated 10^{10} muons/pulse from $\pi \rightarrow \mu\nu$ decay) within the ring.

$\rightarrow 8 \times 10^{8}$ ν per pulse down-stream of one straight section.

One pulse every 10 secs
$\rightarrow 8 \times 10^{14}$ ν per year

We now know that for long baseline neutrino oscillation experiments, this beam intensity is too low by about five orders of magnitude !

Measuring Captured Muons in a Storage Ring

A. Bross et al; NIM A 332 (1993) 27

After each turn the antiprotons are delayed (wrt pions, muons …) by about half the bunch spacing … so there is a clear time separation every other turn.

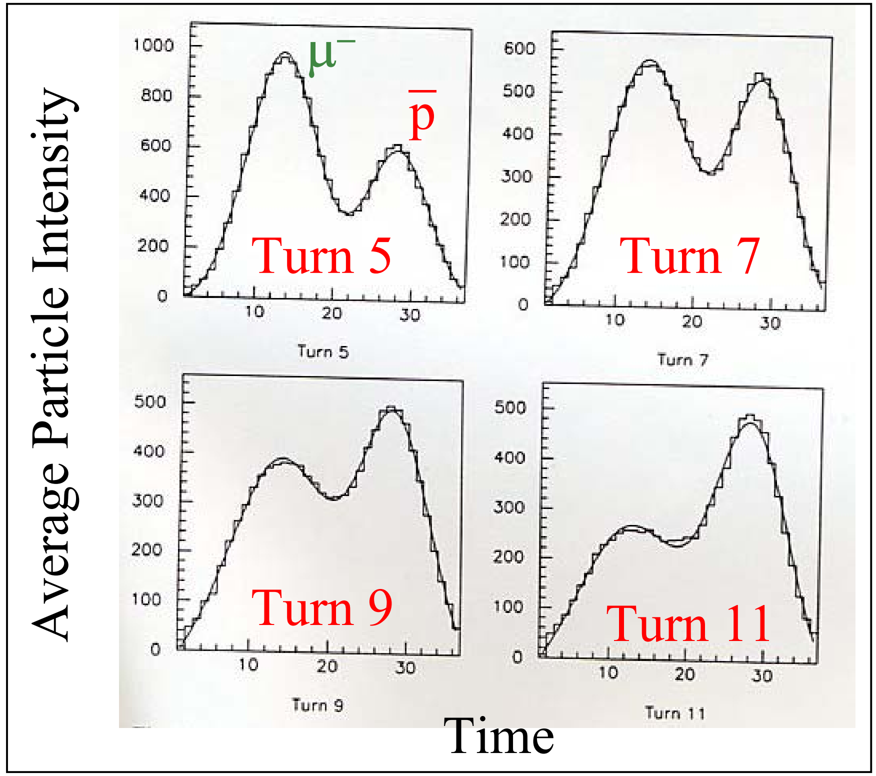
The protons arrive at the target in a train of 84 bunches ($\sigma_t = 1$ ns) with a bunch spacing of 19 ns)

Measured $5 \times 10^8\ \pi$ captured per 10^{12} protons on target

Calculated 0.018 muons per captured π

After 3 turns measure 0.025 muons per (initially) captured π

$\rightarrow$ $(2.0 \pm 0.4) \times 10^{-5}$ muons / POT



Turn	Flux ($\beta = 1$)	Flux ($\bar{p}$)	$(\beta = 1)/\bar{p}$	$\mu/\bar{p}$
1	33572	–	–	–
3	6251	2126	2.94	0.80
5	2232	1287	1.73	1.12
7	1597	1171	1.36	1.27
9	1306	1132	1.15	1.14
11	934	1122	0.83	0.83

P860: A Search for Neutrino Oscillations using the Fermilab Debuncher

W. Lee et al, FNAL Proposal P860, 1992.

3 x 10^{12} protons/pulse & one pulse every 2.1 secs → $\sim 3 \times 10^4$ useful pulses / day

One muon captured / 3×10^4 protons on target

3 x 10^{12} captured muons / day

In dedicated running with a modified Debuncher this could be increased to 5.4 x 10^{13} muons/day

Straight section length = $0.13 \times$ circumference, and first few turns (dominated By pion decay) must be excluded → $\sim 5.3 \times 10^{12}$ useful muon decays / day → $\sim 10^{15}$ useful muon decays / year

Experiment not approved, the beam intensity was too low to address the physics.

Pion storage rings with parasitic muon storage do not give useful neutrino beams … so what's needed ?

Given our present knowledge of neutrino oscillation parameters, over the last couple of years it has become apparent we need about 10^{20} useful muon decays per year to address the relevant oscillation physics questions.

Hence, we need to find a way of increasing the number of muons stored in the ring by about FIVE ORDERS OF MAGNITUDE !

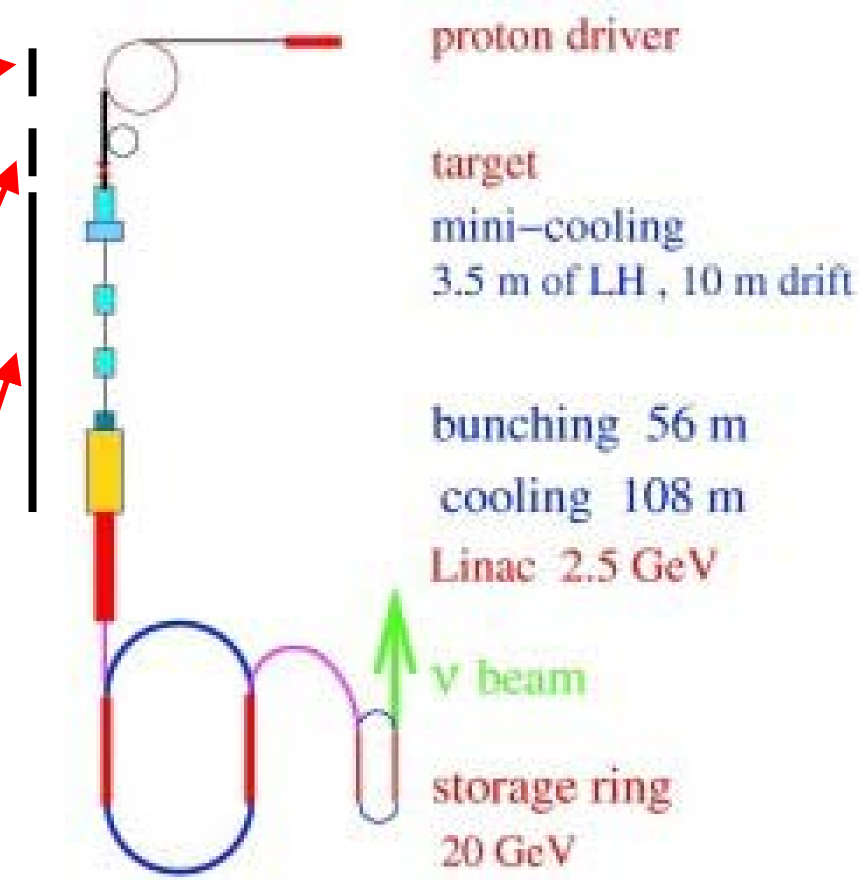
We need an intense muon source

Intense Muon Source Recipe

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



The intense muon source is the key to a Neutrino Factory

HISTORY: Intense Muon Source Concepts

A useful neutrino beam facility based on a muon storage ring requires at least a millimole of muons (10^{21}) to be collected per year. The critical concepts for the development of millimole per year muon sources are :

Pion Collection:

Dijikibaev & Lobashev, Sov. J. Nucl. Phys. 49(2), 384 (1989)

Palmer et al., BNL-61581 (1995)

Ionization Cooling:

Kolomensky, Sov. Atomic Energy Vol. 19, 1511 (1965)

Skrinsky & Parkhomchuk, Sov. J. Part. Nucl. 12:223-247 (1981)

Neuffer, Proc. 12th Int. Conf. High Energy Accels (1983) 481; Part. Acc. 14(1983) 75

Skrinsky & Parkhomchuk, Proc. 12th Int. Conf. High Energy Accelerators (1983) 485

Palmer, Neuffer, & Gallardo, AIP Conf. Proc. 335 (1995) 635

By the end of the 1980's all of the basic concepts for millimole muon sources were in place, ready for the serious development of a realistic scheme (requiring lots of invention) .

Reducing the Energy Spread: Phase Rotation

Pion production peaks at low energies [$E \sim O(m_\pi)$], and the spectrum is broad. Therefore we want to capture low energy pions over as broad an energy range as practical.

Before we can cool the beam transversely and accelerate it we must capture the muons in an rf-system … the parameters of practical rf systems limit the energy spread that can be tolerated.

We can reduce the energy spread using "phase rotation":-

1. Allow the beam particles to drift $\rightarrow$ fast ones arrive early, slow ones late.
2. Apply a time-dependent accelerating field that accelerates the late particles and deccelerates the early particles.

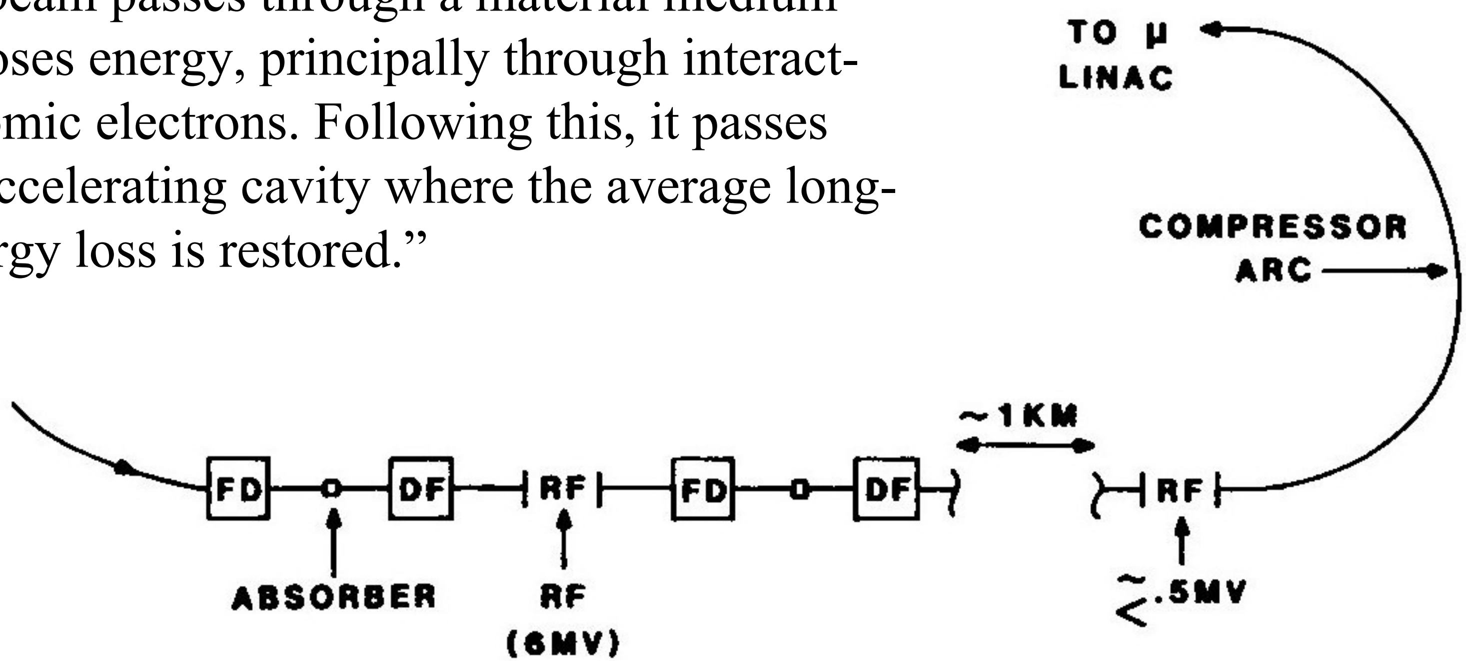
This process increases the bunch length but decreases the energy spread.

Ionization Cooling - 1

Neuffer, Proc. 12th Int. Conf. High Energy Accelerators (1983) 481

After phase rotation the muons can be captured into bunches using an rf system. However, the transverse phase space is too large to be accepted by a normal accelerating system. We need to cool the beam.

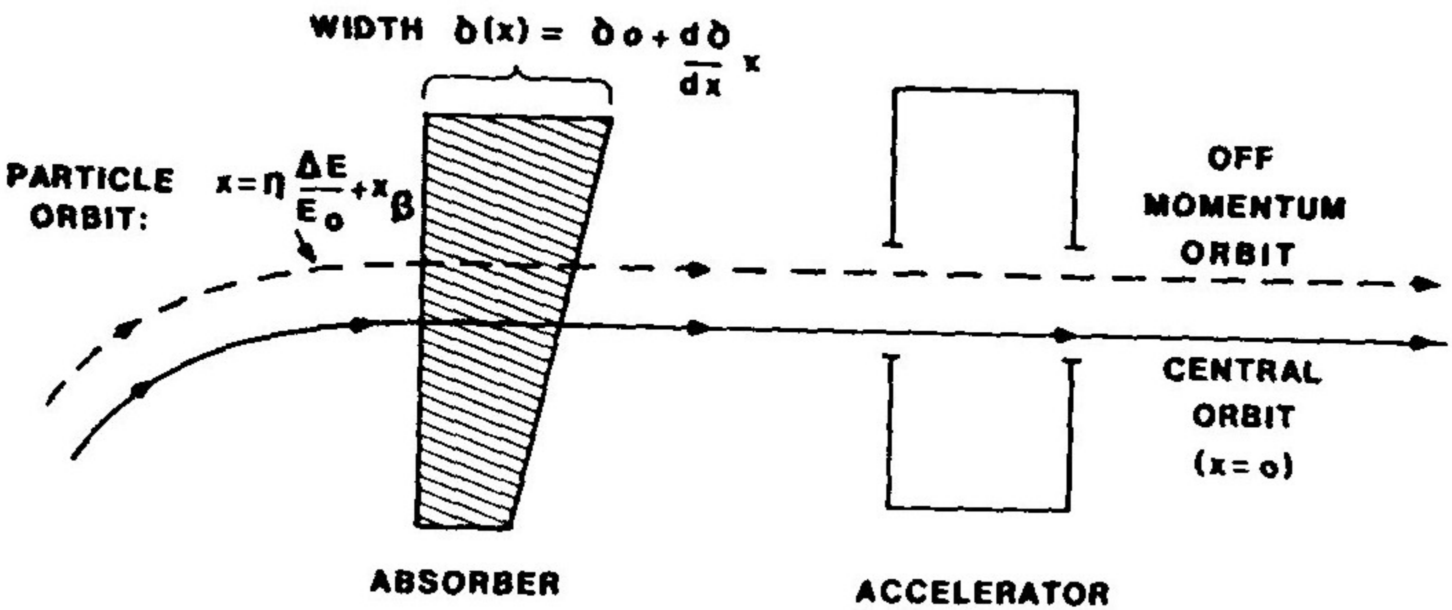
"The muon beam passes through a material medium in which it loses energy, principally through interactions with atomic electrons. Following this, it passes through an accelerating cavity where the average longitudinal energy loss is restored."



Ionization Cooling - 2

Neuffer, Proc. 12th Int. Conf. High Energy Accelerators (1983) 481

"An exchange in cooling rate between the longitudinal and a transverse dimension can be obtained if a *wedge* absorber in a non-zero dispersion region is used."



An Important Aside: Muon Colliders

Taking the initial concepts and developing a realistic millimole muon source required a large effort, and therefore needed a strong motivation. The initial motivation came from the exciting possibility of building a Muon Collider:

Budker, Proc. 7th Int. Conf. High Energy Accel., Yerevan, 1969, p.33

Neuffer, Fermilab Physics Note FN-319 (1979); Particle Accelerators 14 (1983) 75.

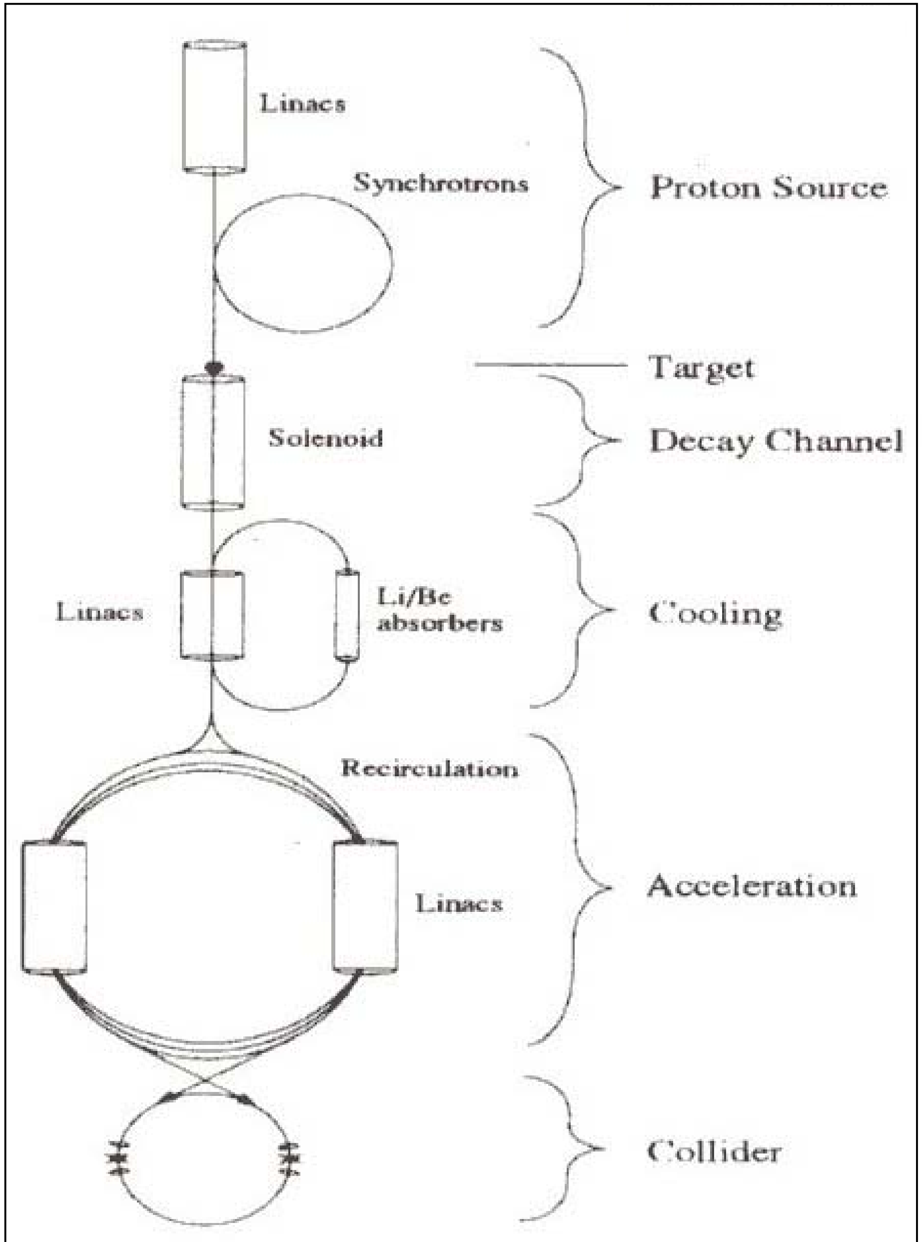
Skrinsky & Parkhomchuk, Sov. J. of Nucl. Physics 12 (1981) 3

Muon Collider: A Feasibility Study (Snowmass 1996),
BNL-52503, FNAL-Conf-96/092, LBNL-38946

Higgs Factory Design Study, physics/9901022,
Phys.Rev.ST.Accel Beams 2, 081001 (1999)

Detailed studies have shown that Muon Colliders are probably feasible, but are very challenging and require a lot of hardware development.

Muon Collider Concept in 1996



Muon Collider: A Feasibility Study (Snowmass 1996), BNL-52503, FNAL-Conf-96/092, LBNL-38946

		4 TeV	.5 TeV	Demo.
Beam energy	TeV	2	.25	.25
Beam γ		19,000	2,400	2,400
Repetition rate	Hz	15	15	2.5
Muons per bunch	10^{12}	2	4	4
Bunches of each sign		2	1	1
Normalized *rms* emittance ϵ^N	$10^{-6}\pi$ m − rad	50	90	90
Bending Field	T	9	9	8
Circumference	km	7	1.2	1.5
Average ring mag. field B	T	6	5	4
Effective turns before decay		900	800	750
β^* at intersection	mm	3	8	8
rms beam size at I.P.	μm	2.8	17	17
Luminosity	$cm^{-2}s^{-1}$	10^{35}	5×10^{33}	6×10^{32}

Muon Collider Collaboration: May 1997

In May 1997, at its Orcas Island Meeting, the Muon Collaboration became a formal entity, with initially ~100 physicists and engineers participating. The collaboration subsequently requested funding support from the US DOE.

Spokesperson:	Bob Palmer (BNL)
Associate Spokespeople:	Andy Sessler (LBNL) Alvin Tollestrup (FNAL)

The collaboration embarked on three areas of intensive activity:

1. Theory and design simulations
2. Targetry R&D
3. Cooling channel R&D

The Collaboration received its first significant funding in Spring 1998.

Change of Focus: Muon Colliders to Neutrino Factories

In the summer of 1999 the Muon Collider Collaboration became the Neutrino Factory & Muon Collider Collaboration (often abbreviated to Muon Collaboration or MC), and the emphasis of the R&D changed from Muon Colliders to Neutrino Factories.

This happened because:

i) The MC, which had been studying low energy muon colliders, high energy muon colliders, and neutrino factories (proposed in Nov. 1997) had just had their first MUTAC review, and were told to focus on an in-depth end-to-end study of one thing. The MC had to chose !

ii) Muon Colliders were by then known to be technically challenging. A less demanding "learning project" was perceived to be desirable to drive the development of intense muon sources; a Neutrino Factory for example.

iii) Driven by the SuperK atmospheric neutrino results, and the prospects of measuring CP violation in the neutrino sector, the neutrino community had lots of enthusiasm for Neutrino Factories.

HISTORY: Neutrino Factory Papers (with the most citations)

The work on Muon Collider design by the US Muon Collider collaboration established the probable feasibility of a millimole per year muon source. The idea of using a Muon Collider type muon source together with a storage ring with long straight sections to produce an intense neutrino source was proposed in November 1997 :

Geer, Workshop on Physics at the First Muon Collider & Front End of a Muon Collider, Nov. 1997; FERMILAB-PUB-97-389; PRD 57, 6989 (1998)

De Rujula, Gavela, Hernandez; hep-ph/9811390, Nucl. Phys.B547:21-38,1999.
Barger, Geer, Raja & Whisnant, hep-ph/9911524, Phys. Rev. D62:013004, 2000
Barger, Geer, Raja & Whisnant, hep-ph/0003184, Phys. Rev. D62:073002, 2000
Cervera, Donini, Gavela, Gomez Cadenas, Hernandez, Mena & Rigolin, hep-ph/0002108, Nucl. Phys. B579:17-55, 2000.
Freund, Linder, Petcov, Romanino, hep-ph/9912457, Nucl. Phys. B578:27-57, 2000

This early work established Neutrino Factories as the tool of choice for probing very small values of θ_{13}, precision parameter measurements, determining the neutrino mass hierarchy, and searching for CP violation in the lepton sector.

The Neutrino Factory Concept

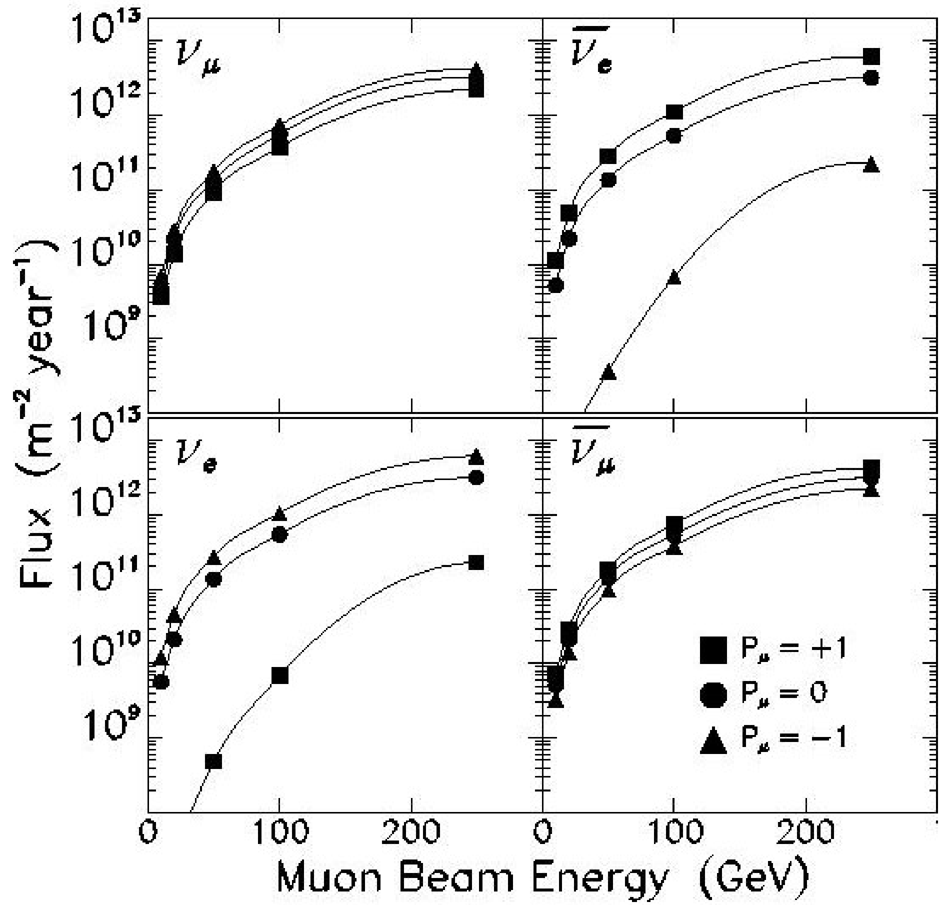
S. Geer, FERMILAB-PUB-97-389; PRD 57, 6989 (1998)

1. Proposed using a Muon-Collider-type Muon source, together with a muon storage ring with long straight sections, to produce a very intense neutrino source (later called a Neutrino Factory)

2. Calculated fluxes → thousands of events in a reasonably sized detector on the other side of the Earth !)

3. Proposed using wrong-sign muons to search for $\nu_e \rightarrow \nu_\mu$ oscillations → impressive sensitivity

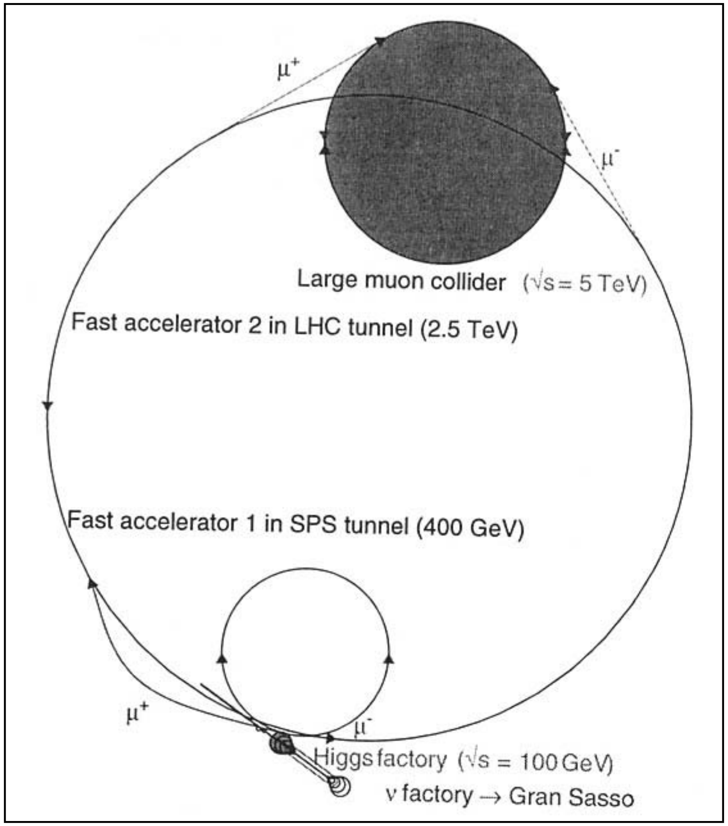
Fluxes on the other side of the Earth (L = 10,000 km)

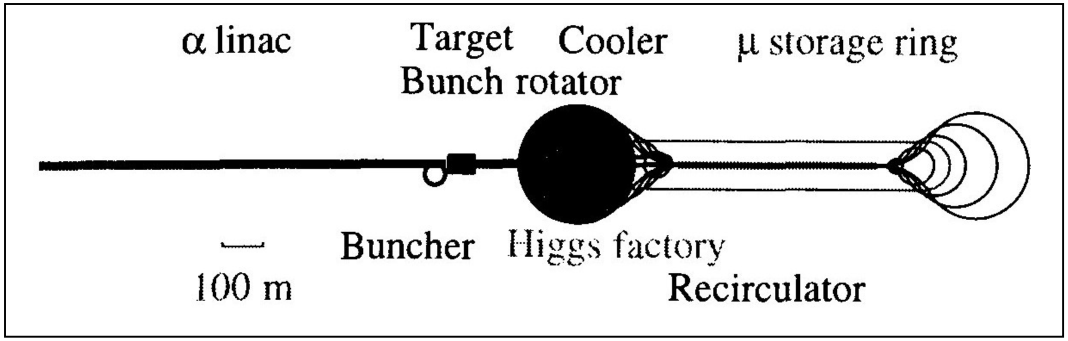


CERN Initial Study

B. Autin, A. Blondel, J. Ellis (Editors), "Prospective Study of Muon Storage Rings at CERN", CERN 99-02, ECFA 99-197 (April 1999).

"This report presents the conclusions of a six-month prospective study, encouraged by ECFA, on the physics opportunities and accelerator issues presented by muon colliders, and by extension, muon storage rings."



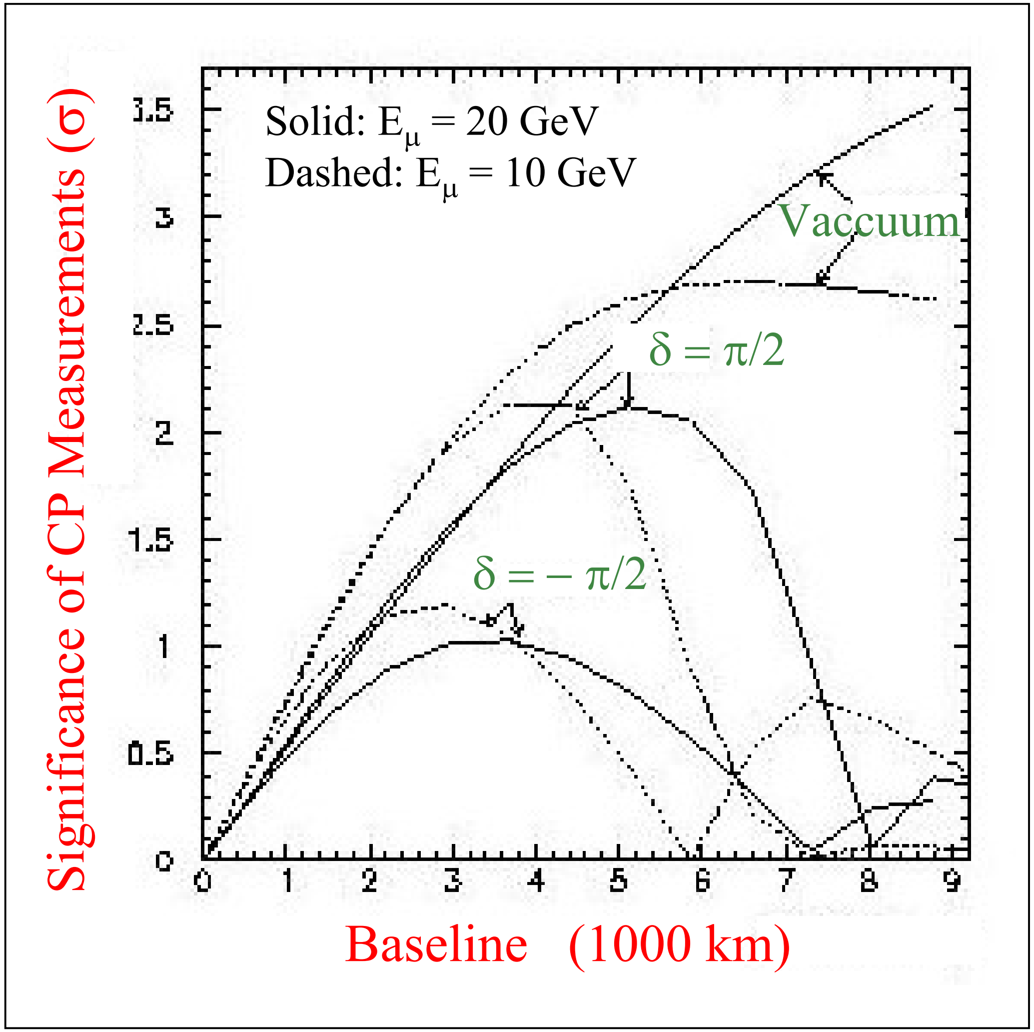


Reviewed US design ideas, putting them in the context of a possible future CERN facility.

Considered three steps: Neutrino Factory → Higgs Factory → High Energy Muon Collider

Consolidating the Physics Case: CP Violation

De Rujula, Gavela, Hernandez; hep-ph/9811390, Nucl. Phys.B547:21-38,1999



In 1998 (published in 1999) De Rujula et al showed that Neutrino Factory measurements might be able to measure CP violation in the lepton-sector provided the solar neutrino solution was the MSW Large Mixing Angle solution.

This result fueled the interest in Neutrino Factories.

Neutrino Factory Design and Physics Studies

The emerging evidence for neutrino oscillations from the Super-K Experiment, together with the widespread interest in the Neutrino Factory concept, led to a series of detailed Neutrino Factory design studies, which established technical feasibility and defined the R&D that needs to be done enable these new neutrino sources to become a reality.

US Design Study 1 (Eds. Finley, Holtkamp) ;
http://www.fnal.gov/projects/muon_collider/nu-factory/

US Design Study 2 (Eds. Osaki, Palmer, Zisman, Gallardo) ;
http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

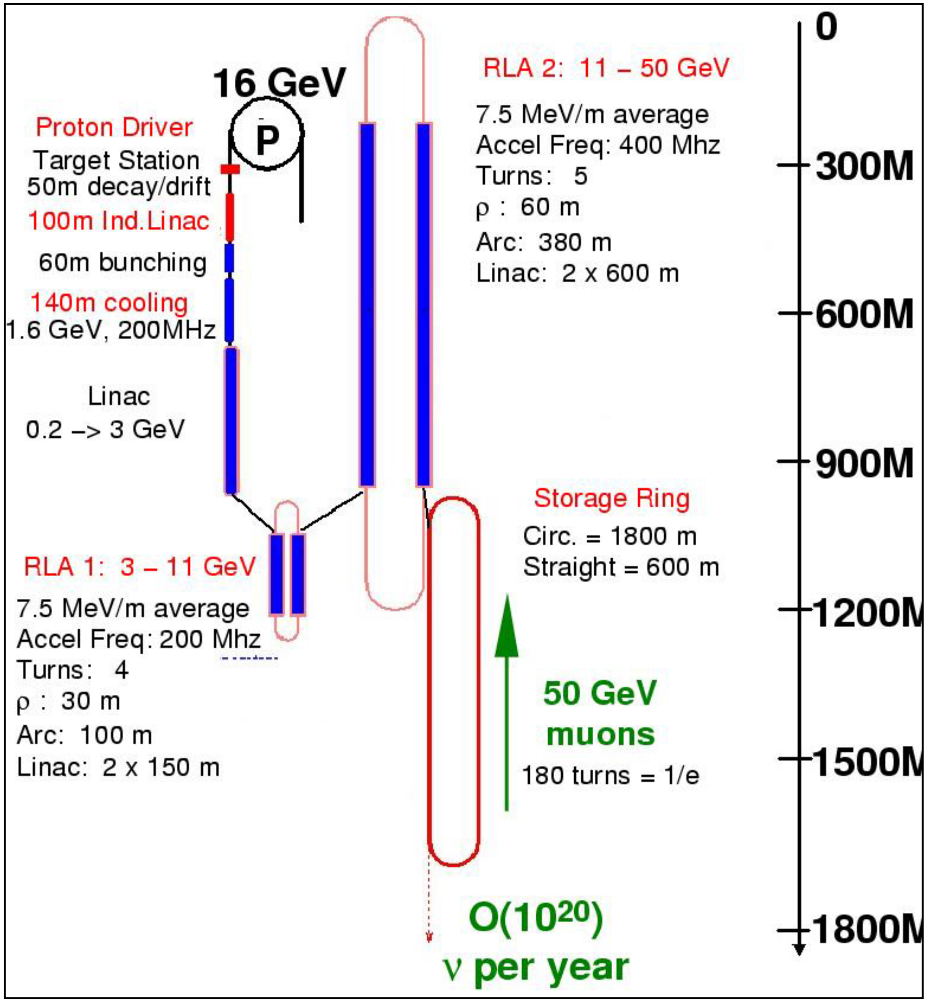
Physics Study: (Eds. Geer, Schellman) hep-ex/0008064
Front-End Physics Study: M. Mangano et al, hep-ph/0105155
Muon Collider ν physics: Bigi et al, hep-ph/0106177 (B. King initial work)

CERN Study (Eds. Autin, Blondel, Ellis) April 1999, CERN 99-02
Japanese Study (Eds. Kuno , Mori) May 2001
Status Report (Ed. Raja) Aug. 2001, hep-ex/0108041

US Design Study 1 (completed April 2000)

N. Holtkamp, D. Finley (editors); 279 authors.

Six-month study with full participation of the Muon Collaboration, and important contributions from Labs around the world → Lots of engineering.



Proton driver: Upgraded FNAL Booster

Carbon target in 20T capture solenoid

50m decay channel (1.25T)

Muon energy spread reduced using induction linac (phase rotation)

Muons bunched at 200 MHz

Transverse phase space reduced using an ionization cooling channel

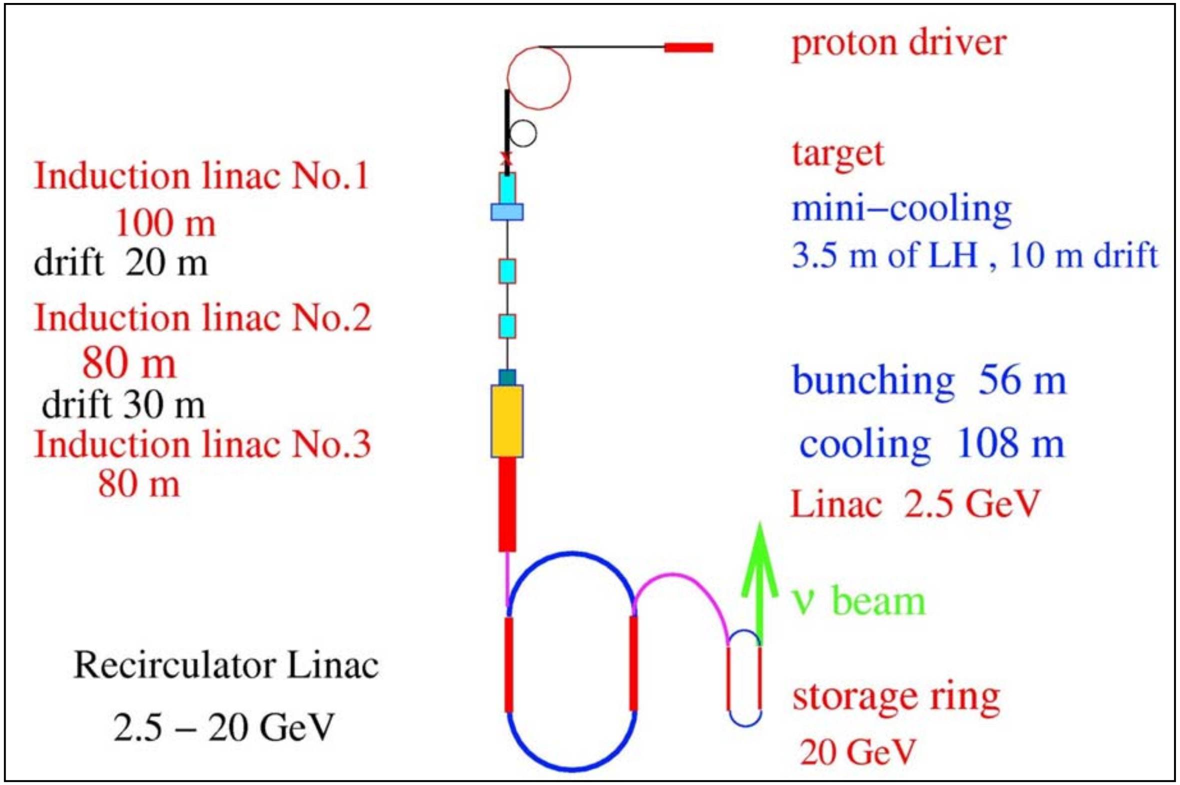
Acceleration to 50 GeV in RLAs

US Design Study 1 Result

“The result of this study clearly indicates that a neutrino source based on the concepts presented here is technically feasible. According to our current understanding it will not quite meet the intensity specified and it should probably have an energy lower than originally specified (50 GeV). There is clear indication though that we would and should improve the performance, and also how it could be done … .”

US Design Study 2 (completed May 2001)

Osaki, Palmer, Zisman, Gallardo (editors); 200 authors.



Based on upgraded BNL AGS

Hg jet target, better induction linac & cooling channel designs

Achieved 6 x Study 1 muon rate
>> 2×10^{20} useful μ decays / year

Present US Organization

http://www.cap.bnl.gov/mumu/mu_home_page.html

Muon Collaboration (~130 members)

S. Geer	(FNAL)	Co-Spokesperson.
Palmer	(BNL)	Co-Spokesperson
M. Zisman	(LBNL)	(Project Manager)

Muon Collab. Oversight Group (MCOG)

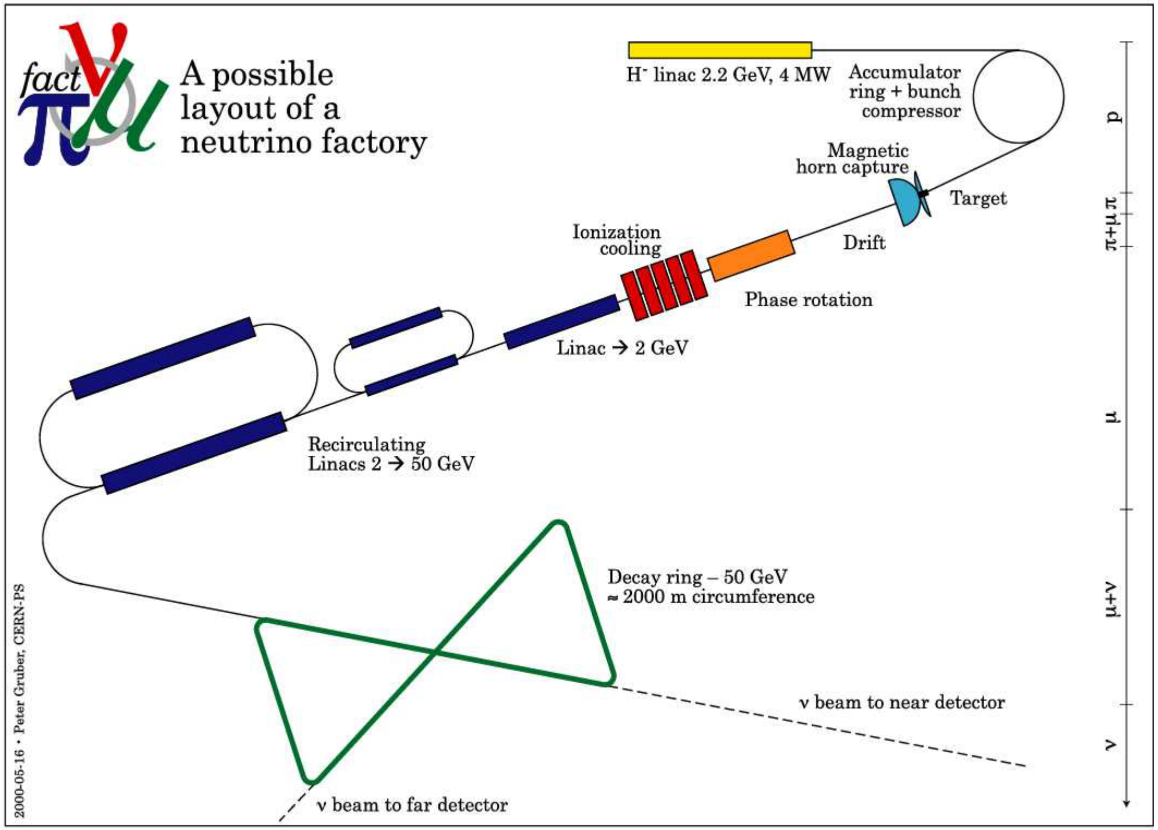
T. Kirk	(BNL)	Chair
S. Holmes	(FNAL)	
P. Oddone	(LBNL)	

Muon Technical Advisory Committee (MUTAC)

H. Edwards	(FNAL)	Chair
M. Breidenbach	(SLAC)	
G. Dugan	(Cornell)	
M. Harrison	(BNL)	
J. Hastings	(BNL)	
Y.-K. Kim	(LBNL)	
C. Leemann	(Jefferson)	
J. Lykken	(FNAL)	
A. McInturff	(LBNL)	
U. Ratzinger	(GSI)	
R. Ruth	(SLAC)	
K. Yokoya	(KEK)	

CERN Studies

http://muonstoragerings.web.cern.ch/muonstoragerings/



Similar to US scheme but alternative technologies:

Lower energy proton driver (2.2 GeV protons)

Pion capture with magnetic horn

RF for phase rotation (no induction linac)

Transverse cooling channel With 44/88 MHz (not 200 MHz) RF cavities.

European Organization

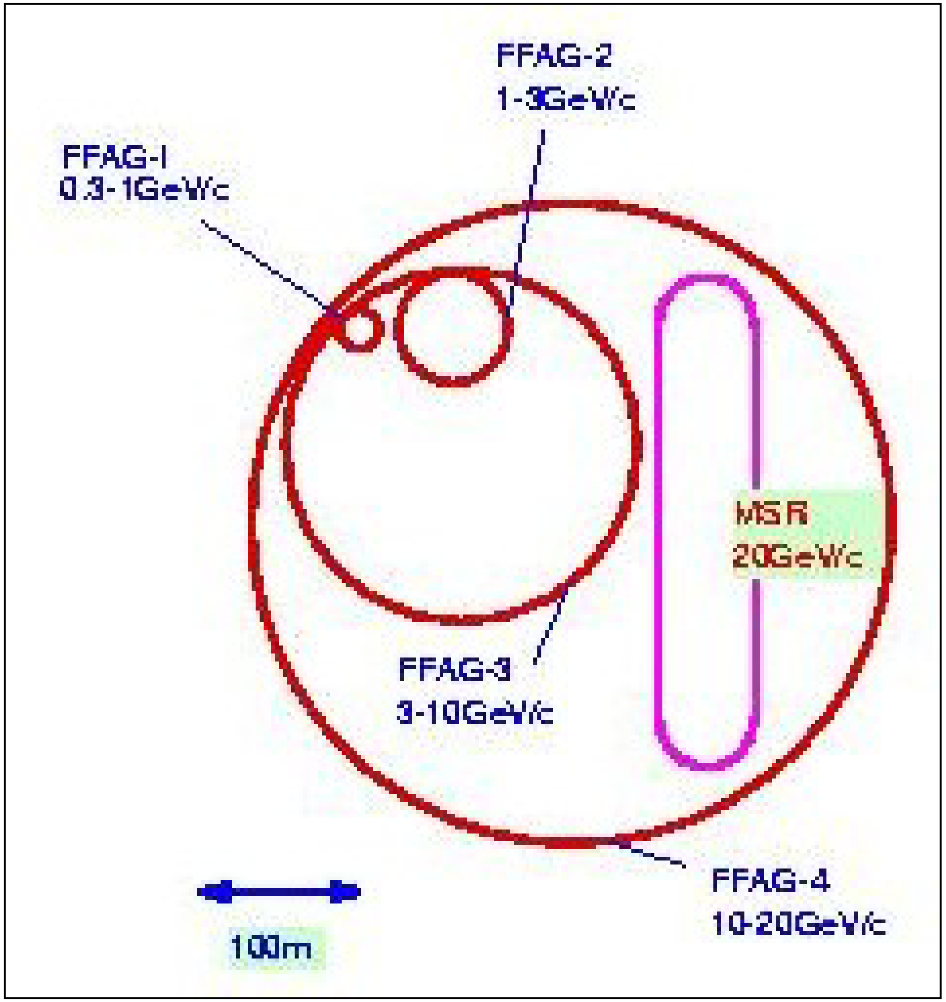
EMCOG created April 2002. Its task is to “report to the funding agencies & laboratory directors, and be the point of contact with ECFA, and with other similar organizations in the US, and eventually in Japan.”

European MCOG (EMCOG)

Carlo Wyss (CERN director of accelerators, chair)
A. Mosnier, F. Pierre (CEA-DAPNIA)
O. Boine-Frankenheim, I. Hofmann (GSI)
M. Napolitano (Napoli)
A. Pisent (Legnaro)
S. Katsanevas, M. Lieuvin (IN2P3)
R. Eichler (PSI)
K. Peach (RAL)
A. Blondel (Switzerland and ECFA Contact)

"A Feasibility Study of a Neutrino Factory in Japan" - 1

http://www-prism.kek.jp/nufactj/index.html



NuFACTJ Working Group, May 2001
(Editors: Y. Kuno, Y. Mori)
7 Authors

Scheme based on very large acceptance accelerators – no muon cooling needed (although some cooling would be beneficial)

"A Feasibility Study of a Neutrino Factory in Japan" - 2

The Japanese Neutrino Factory Plan is based on an evolution of The new Japan Hadron Facility which is currently under construction & is expected to begin operation in 2007 → 0.8 MW 50 GeV proton synchrotron.

Neutrino Factory

- 1×10^{20} muon decays/year at one straight section
- Based on 1-MW 50-GeV PS
- Muon energy: 20 GeV
  - Energy is determined by cost and physics topics.
- Location: JAERI Tokai campus

Neutrino Factory-II

- 4.4×10^{20} muon decays/year at one straight section
- Based on upgraded 4.4-MW 50-GeV PS
- Muon energy: 50 GeV

Final Remarks

Neutrino Factory R&D is being pursued by collaborations in Europe, Japan, and the US. These collaborations consist of particle and accelerator physicists from laboratories and universities. This way of doing business is both stimulating and fruitful.

It takes a significant time to bring a new accelerator concept to fruition … but along the way there are opportunities to make a big impact on our field. Accelerator R&D provides a wonderful opportunity for particle physicist to participate part-time in an activity that can make a big difference.

Neutrino physics is exciting. Ultimately how well we manage to explore neutrino oscillation physics will probably depend more on accelerator improvements (higher neutrino fluxes, better beams, proton driver upgrades, neutrino factories) than on detector improvements. Collaborations between particle physicists interested in neutrino oscillations and accelerator physicists make sense !