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MUON SOURCES
NEUTRINO FACTORY to MU+- COLLIDERS

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Muon Sources – ν Factory to $\mu^{\pm}$ Colliders[1]

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Abstract. Employing intense muon sources to carry out forefront low energy research, such as the search for muon - number non–conservation, or for the purpose of providing intense high energy neutrino beams (ν factory) represents very interesting possibilities. If successful, such efforts would significantly advance the state of muon technology and provides intermediate steps in technologies required for a future high energy muon collider complex. High intensity muon: production, capture, cooling, acceleration and multiturn muon storage rings are some of the key technology issues that needs more studies and development. A muon collider require basically same number of muons as for the muon storage ring Neutrino Factory, but would require more cooling, and simultaneus capture of both $\pm\mu$. We present an overview of Muon Sources - Neutrino Factories, example of a muon storage ring at BNL, and possible upgrades to a full Muon Collider.

INTRODUCTION

A full high energy muon collider may take considerable time to realize. However, intermediate steps in its direction are possible and could help facilitate the process. Building a muon storage ring for the purpose of providing intense high energy neutrino beams is particularly exciting. Such neutrino factories could have their own world class research program, with neutrino oscillation studies as the primary focus. High intensity muon experiments, neutrino factories, and other intermediate steps toward the muon collider are extremely important. They will greatly expand our abilities and build confidence in the credibility of high energy muon colliders.

Many of the recent, exciting results in neutrino physics have been obtained by non-accelerator experiments, although the neutrino mass and mixing parameters appear to require a new generation of accelerator based experiments. For this, an intense source of well-collimated neutrinos is needed.

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Excitement is high in the accelerator physics community because Atmospheric-neutrino results suggest that the long-baseline accelerator experiments such as MINOS [4], K2K [3], and NGS [5] should also find neutrino oscillations. Further, the LSND experiment that was conducted at a short-baseline accelerator facility, can be confirmed by future accelerator experiments such as MiniBooNE [6], ORLanD [7], and CERN P311 [8]. Moreover, physics associated with some interpretations of the solar-neutrino deficit may be accessible to studies in accelerator-based experiments, if neutrino-beam fluxes can be improved by 1-2 orders of magnitude.

To obtain a factor of 100 improvement in neutrino flux, the best prospect appears to be neutrino-beams derived from a muon-storage-ring, rather than from direct pion decays. However, such an approach requires considerable development before it can be realized in the laboratory.

In the following sections we present schematics of a Neutrino Factory Facility concept (based on various muon storage rings), its components and a possible upgrade to a full muon collider. The examples described are based on some of the scenarios being explored by our Neutrino Factory and Muon Collider Collaboration, [10].

NEUTRINO FACTORY - FACILITY

A neutrino factory based on a muon storage ring is a challenging extension of present accelerator technology. Conventionally, neutrino beams employ a proton beam on a target to generate pions, which are focused and allowed to decay into neutrinos and, muons [4]. The muons are stopped in the shielding, while the muon-neutrinos are directed toward the detector. In a neutrino factory, pions are made the same way and allowed to decay, but it is the decay muons that are captured and used. The initial neutrinos from pion decay are discarded, or used in a parasitic low-energy neutrino experiment. But the muons are accelerated and allowed to decay in a storage ring with long straight sections. It is the neutrinos from the decaying muons (both muon-neutrinos and anti-electron-neutrinos) that are directed to a detector.

In a Neutrino Factory, a proton driver of moderate energy ($<$ 50 GeV) and high average power,(e.g., 1-4 MW), similar to that required for a muon collider, but with a less stringent requirements on the charge per bunch and power is needed. This is followed by a target and a pion-muons capture system. A longitudinal phase rotation is performed to reduce the muon energy spread at the expense of spreading it out over a longer time interval. The phase rotation system may be designed to correlate the muon polarization with time, allowing control of the relative intensity of muon and anti-electron neutrinos. Some cooling may be needed, to reduce phase space, about a factor of 50 in six dimensions. This is much smaller than the factor of 10^6 needed for a muon collider. Production is followed by fast muon acceleration to 50 GeV (for example), in a system of linac and two recirculating linear accelerators (RLA's), which may be identical to that for a first stage of muon collider such as a

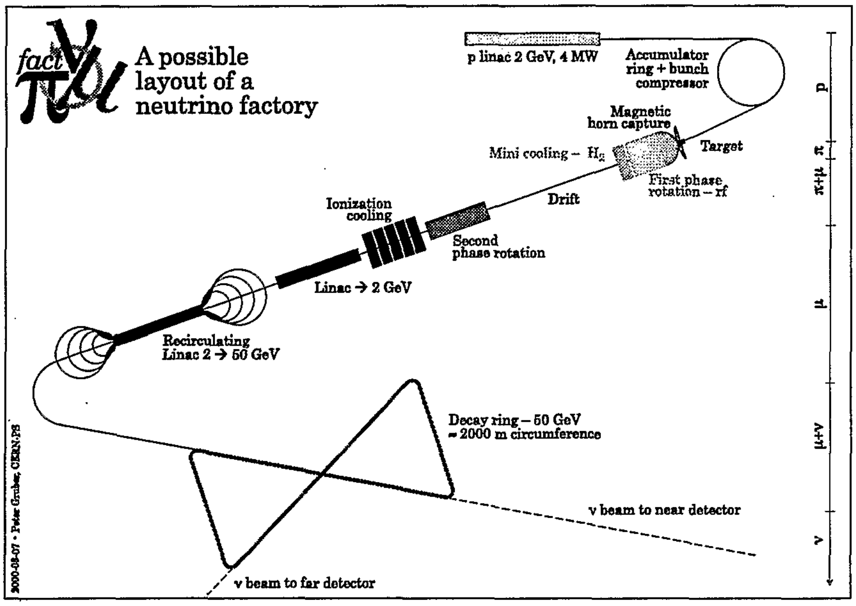

FIGURE 1. A schematic concept of a Neutrino Factory Facility based on a muon storage lattice for CERN.

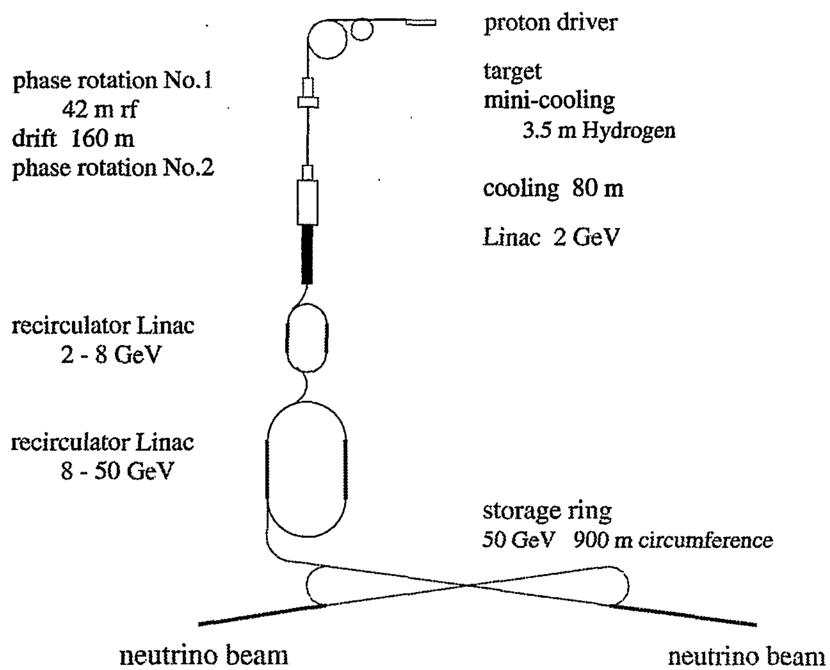

FIGURE 2. A schematic concept of Neutrino Factory Facility based on a bowtie muon storage lattice .

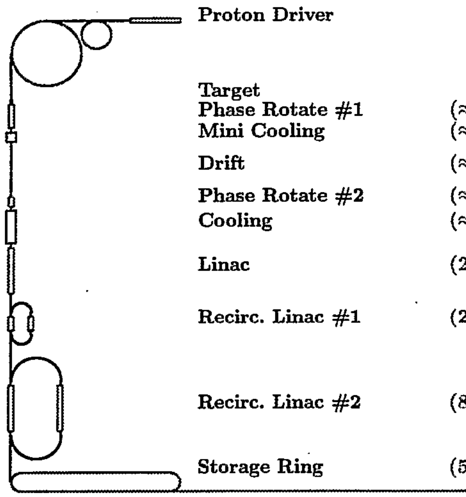

FIGURE 3. Overview of a Neutrino Factory Concept, with a Racetrack Muon - Storage Ring

Higgs Factory. A muon-storage ring with long straight sections could point to one or more distant neutrino detectors for oscillation studies, and to one or more near detectors for high intensity scattering studies.

A planar bowtie - shaped ring (illustrated in Figure 2) can be designed and oriented to send neutrino beams to any two detector sites. Since, there is no net bending, the polarization may be preserved. (A disadvantage of the Bowtie - shaped ring is that it may need extra bending. Since there is geometry constrains on the ratio of short to long straight sections, the ring circumference may increase.) With the ring in a tilted plane, both long straight sections would point down into the earth, such that neutrinos can be directed into two very distant detectors. Triangular-shaped storage rings also have this advantage.

Figure 3, illustrates components of a Neutrino Factory based on a racetrack - shaped muon storage lattice [10].

Figure 2 and Figures 3 show examples of the scenarios being explored by our Collaboration, [10].

In the following sections, a description and simulation of target through cooling-channel and a bowetie-shaped muon storage lattice will be discussed.

FRONT-END SYSTEM

The number of pions per proton produced with an optimized system varies linearly with the proton energy, Thus, the number of pions, and the number of muons into which they decay, is essentially proportional to the proton beam power.

Table 1 presents possible parameters for proton drivers at BNL and FNAL. The target requirements are very similar to those for the muon collider, except the instantaneous shock heating is somewhat less because protons are distributed in a larger number of bunches. In the scheme presented here, it is assumed that the

TABLE 1. Example of parameters for various Proton driver scenarios at BNL and FNAL.

	BNL_1	BNL_2	$FNAL_1$	$FNAL_2$
Energy [GeV]	24	24	16	16
Power [MW]	1	4	1	4
Rep. Rate [Hz]	2.5	5	15	15
p's/fill	10^{14}	$2\ 10^{14}$	$2.5\ 10^{13}$	10^{14}
Bunches	6	6	4	4
Circumference [m]	807	807	474	474
Bunch spacing [m]	135	135	118	118
σ_t [nsec]	1	1	1	1

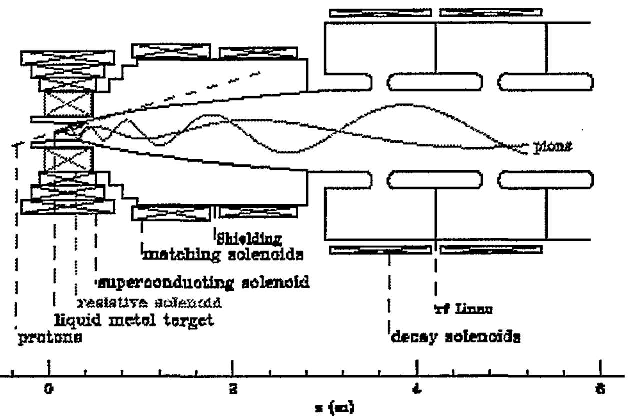

FIGURE 4. A Schematic of Targetry, Pion Capture, and beginning of Phase Rotation.

liquid mercury jet solution is used. The capture solenoid is likely to be the same as described in the muon collider status report [9]. Figure 4, shows the pion production target, solenoidal capture, decay channel and beginning of phase rotation. At the end of this first phase rotation stage, the bunch length increases by about a factor of 6 and the energy spread decreases by the same amount. Whether this first stage of phase rotation can be eliminated is being investigated. An example of designs and simulations being explored by NFMCC is illustrated in Figure 5 (shows schematics of a Muon source front-end compenents), Fig. 6 (Particle composition in the target-to-linac channel), and in Fig. 7 (the muon emittance variation in the target-to-linac channel).

The challenges of further acceleration and storage of the muon beam will be substantially easier if we reduce the transverse phase area of the beam by an additional factor of 10. This may not be accomplished in a single step of ionization cooling, but involves alternating ionization cooling and rf acceleration, all in a magnetic channel. The acceleration from $\sim$ 100 MeV to e.g., $\sim$ 50 GeV may be accomplished in recirculating linacs with superconducting rf cavities, after which muons are injected into a muon storage ring. The desire for multiply directed neutrino beams with

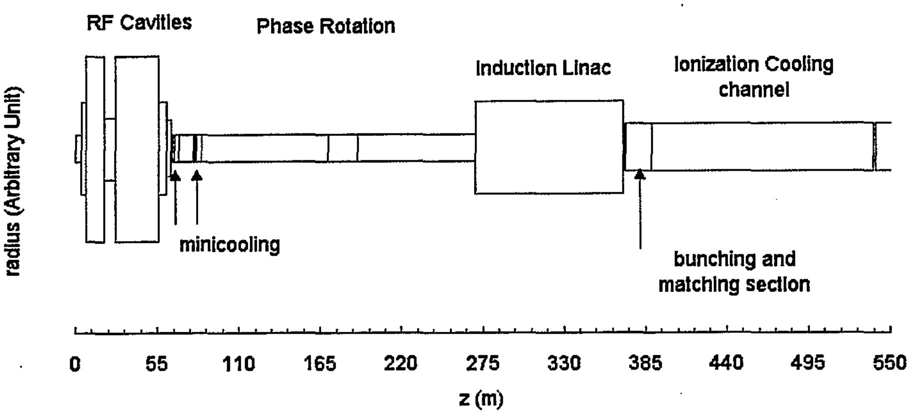

FIGURE 5. Schematics of the Muon Source from Target to Linac.

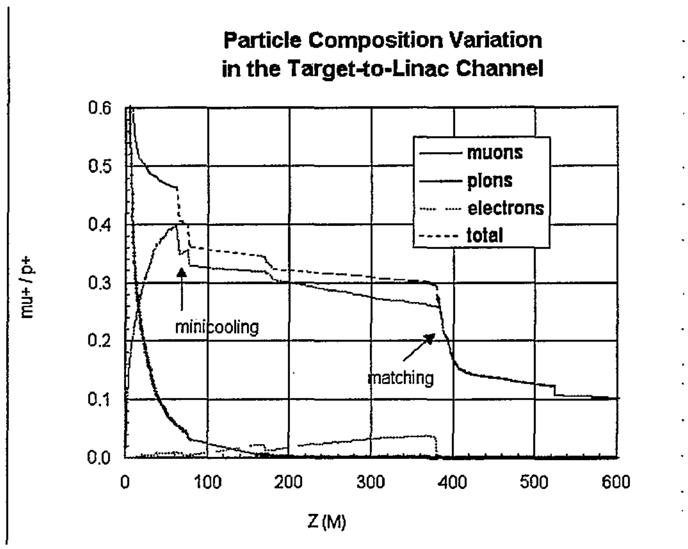

FIGURE 6. Particle Composition from Target to Linac.

very small angular divergence may require a more novel design for the storage ring, with a plane that is far from horizontal. The R&D needs for a muon collider are very similar, but with additional challenges in cooling and storage ring design. At least four orders of magnitude more cooling (including continual exchange between transverse and longitudinal emittance) are required for a muon collider than a neutrino factory. Also, a different ring is needed to maximize collider luminosity than simply to hold the muons while they decay.

Ionization cooling that has been proposed involves passing the beam through an absorber in which the muons lose transverse- and longitudinal-momentum by ionization loss (dE/dx). The longitudinal momentum is then restored by coherent re-acceleration, leaving a net loss of transverse momentum (transverse cooling). The process is repeated many times to achieve a large cooling factor. The beam energy spread can also be reduced using ionization cooling by introducing a transverse variation in the absorber density or thickness (e.g. a wedge) at a location

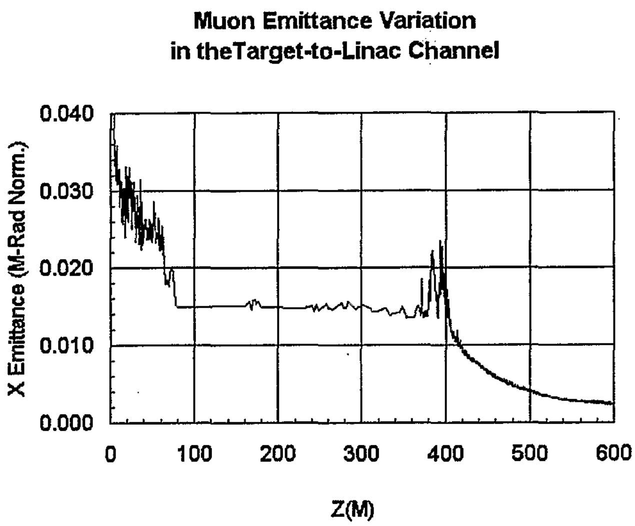

FIGURE 7. Muon emittance variation in Target to Linac channel.

where there is dispersion (the transverse position is energy dependent). Theoretical studies have shown that, assuming realistic parameters for the cooling hardware, ionization cooling can be expected to reduce the phase-space volume occupied by the initial muon beam by a factor of $10^5 - 10^6$. Ionization cooling is a new technique that has not yet been demonstrated. Special hardware needs to be developed to perform transverse and longitudinal cooling. It is recognized that understanding the feasibility of constructing an ionization cooling channel that can cool the initial muon beams by factors of $10^5 - 10^6$ is on the critical path to the overall feasibility of the muon collider concept.

STORAGE RINGS

Figure 3 illustrated a racetrack - shaped configuration, with two long straight sections. and Figure 2 a bowtie-shaped ring. The planar ring can be designed and oriented to send neutrino beams to any two detector directions and with bypass(es) that could be added, to send beams to additional detector sites. In the bowtie-shaped lattice design, the lattice has two long-straight sections, two short-straight sections and two arcs. A racetrack muon storage - ring can be configured to deliver one neutrino beam to an arbitrary detector site. Bowtie - shaped, triangle shaped rings can be configured to deliver neutrino beams to two arbitrarily selected detector sites. This can be done by appropriate choice of, 1) the ring plane, 2) the orientation of the ring in that plane and 3) the angle at the crossing point between the two long straight sections. By inclusion of bypasses, additional detector sites may be accessible from a single muon storage-ring source.

A bypass would lie in a plane that includes the original long straight section (but differs from that of the ring), and begin and end on one of the long straight sections. Its magnets would be powered when one desires to send the muons along

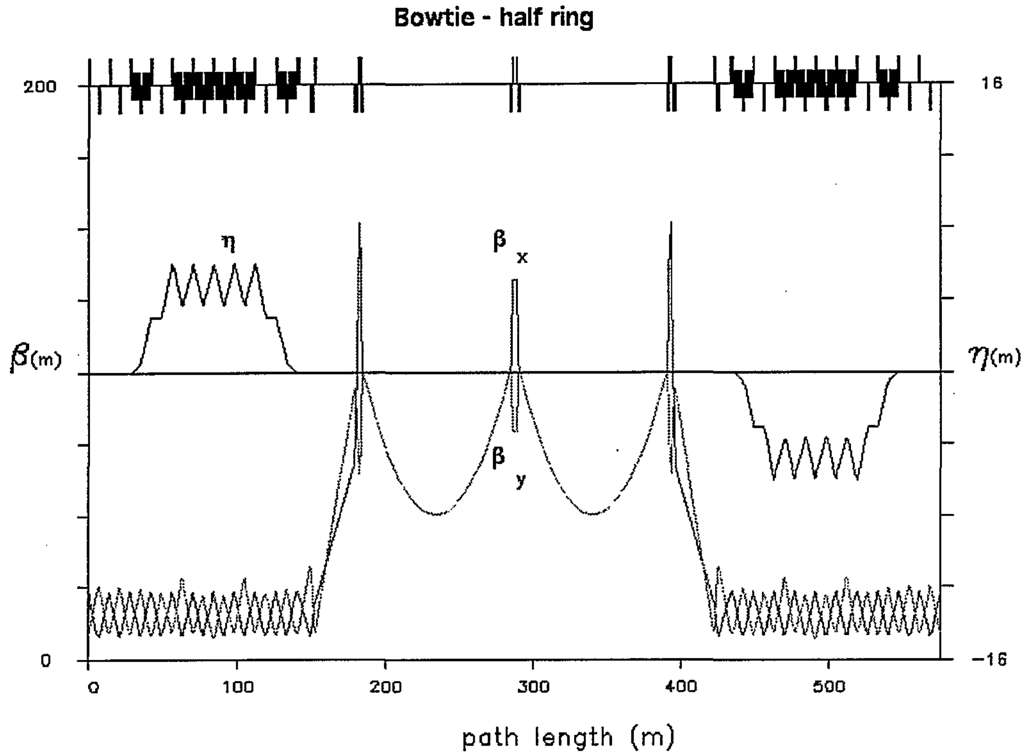

FIGURE 8. Example of Lattice Functions for Bowtie-shaped Half Ring.

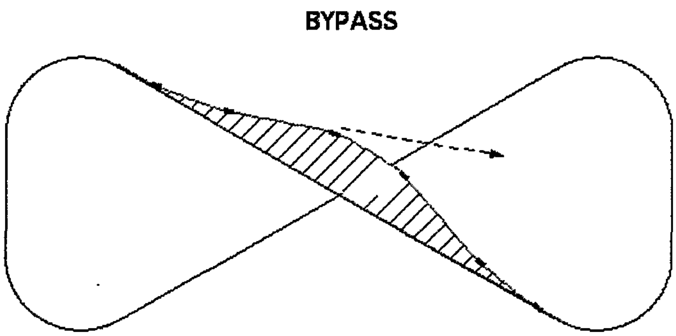

FIGURE 9. Lattice functions for Bowtie-shaped Ring with Bypass. The arrow illustrates direction of a neutrino beam to additional detector site(s) via the Bypass.

the deformed bypass path rather than along the normal straight path. In such a bypass, dipoles would produce a roughly triangular path in the bypass plane, one of whose sides would point to the desired detector. The two necessary degrees of freedom are provided by the angle between the bypass and ring planes and by the magnitude of the deflection given by the bypass dipoles. To suppress the dispersion pairs of dipoles should be placed 180 deg apart, in FODO cells.

MUON STORAGE RING BASED NEUTRINO SOURCE AT BNL?

As is known, the BNL-AGS proton beam parameters are very suited for use as a source for muon storage ring based neutrino factory and muon collider. Table 2 illustrates basic BNL-AGS proton beam properties.

With a muon storage ring - neutrino source at BNL (Figure 10), detectors at Fermilab or Soudan, Minnesota (1715 km), become very interesting possibilities. The feasibility of constructing and operating such a muon-storage-ring based Neutrino-Factory, including geotechnical questions related to building non-planar storage rings (e.g. for BNL-fermilab; at 8° angle for BNL-Soudan, and 31° angle for BNL-Gran Sasso) along with the design of the muon capture, cooling, acceleration, and storage ring for such a facility is being explored by our growing Neutrino Factory and Muon Collider Collaboration (NFMCC), but requires additional studies for a BNL site specific example.

Conventionally, neutrino beams employ a proton beam on a target to generate pions, which are focused and allowed to decay into neutrinos and, muons [4]. The muons are stopped in the shielding, while the muon-neutrinos are directed toward the detector. In a neutrino factory, pions are made the same way and allowed to decay, but it is the decay muons that are captured and used. The initial neutrinos from pion decay are discarded, or used in a parasitic low-energy neutrino experiment. But the muons are accelerated and allowed to decay in a storage ring with long straight sections. It is the neutrinos from the decaying muons (both muon-neutrinos and anti-electron-neutrinos) that are directed to a detector.

Figure 10 shows schematics of space angles [19] and baselines for example of a muon storage neutrino source at BNL, with detectors (placed at Fermilab; Soudan; Minnesota (1715 km); or Gran Sasso, Italy (6527 km)) at various global locations.

MUON COLLIDER

Fig. 11 shows a schematic of a muon collider components [9]. A high intensity proton source is bunch compressed and focused on a heavy metal target. The pions

TABLE 2. BNL- AGS Proton Beam Properties

Parameters	BNL-AGS	Muon Collider
Proton Energy [GeV]	24	16 - 24
Proton/Bunch	1.6×10^{13}	5×10^{13}
Bunch No.	6	2
Proton/cycle	1.0×10^{14}	1.0×10^{14}
Bunch Length [μs]	2.2	1
Bunch spacing [ns]	440	1000

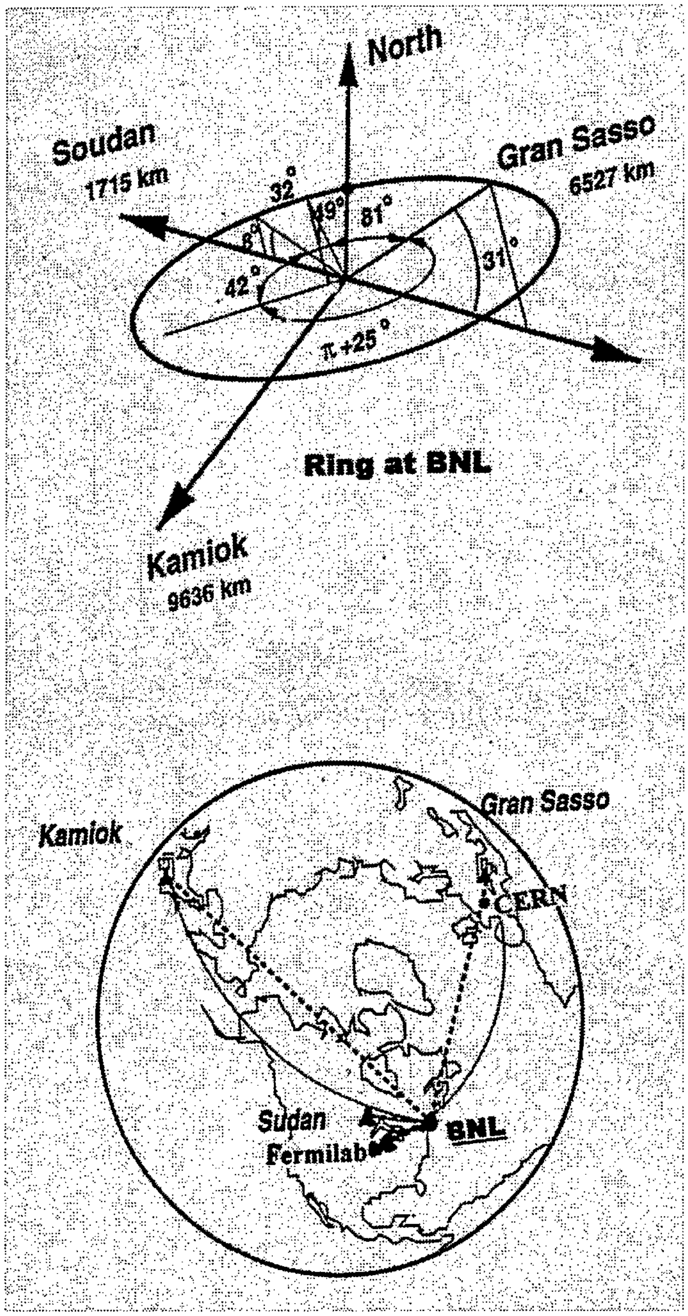

FIGURE 10. Shows space angles and baselines for a Muon - Storage Ring at BNL and possible detector sites (at Fermilab, Sudan, CERN, Kamioka and Gran Saso).

generated are captured by a high field solenoid and transferred to a solenoidal decay channel within a low frequency linac. The linac reduces, by phase rotation the momentum spread of the pions and of the muons into which they decay. Subsequently, the muons are cooled by a sequence of ionization cooling stages. Each stage consists

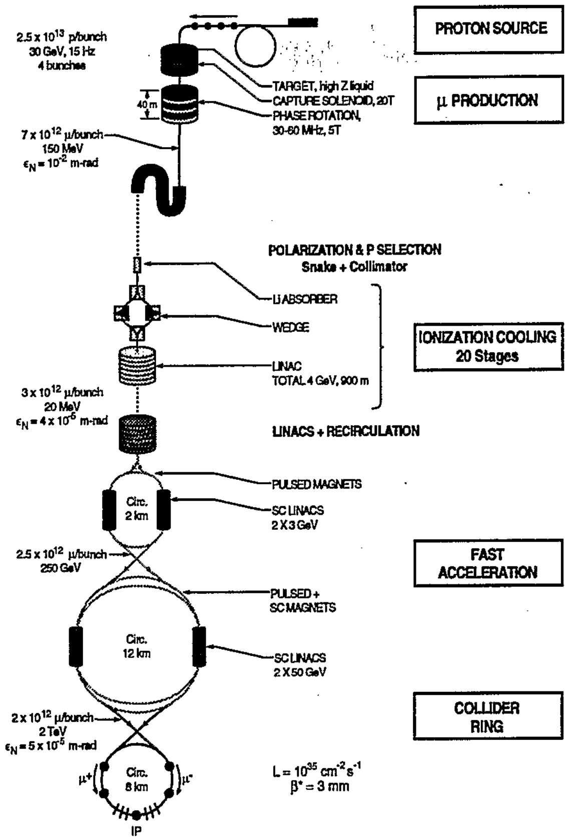

FIGURE 11. Schematic of a 4 TeV Muon Collider.

of energy loss, acceleration, and emittance exchange by energy absorbing wedges in the presence of dispersion. Once they are cooled the muons must be rapidly accelerated to avoid decay losses. This can be done in recirculating accelerators (as at CEBAF) or in fast pulsed synchrotrons. Muon collisions occur in a separate high field collider storage ring with a single very low beta insertion.

It is expected that the first stage, proton driver would be 16 to 30 GeV; but would be much faster pulsed, keeping the number of protons per pulse the same or smaller than the AGS, which is about 6×10^{13} protons per pulse and with some upgrade to about 10^{14} protons per pulse.

Roughly one expect to get 1 muon/proton on target which would give luminosity between 10^{34} to 10^{35} the envisioned muon collider. Although the accelerating component is large, the other components can fit within it and the whole machine is compact enough to fit on existing Brookhaven or Fermilab sites. For more information on the Muon Collider and parameters under study, see e.g. [9], [22] – [26].

Table 3 shows examples of the parameters of potential muon colliders at 100 GeV, 500 GeV and 4 TeV center of mass energy. The 100 GeV collider would be interesting for the study of the lowest mass Higgs. The 4 TeV collider should be in the

TABLE 3. Parameters of $\mu^+\mu^-$ collider Rings.

Energy (C.M.) TeV	4	0.5	0.1
Beam Energy TeV	2	0.25	0.05
Beam γ	19,000	2,400	473
Rep. rate Hz	15	2.5	15
p Energy GeV	30	24	16
p/pulse	10^{14}	10^{14}	5×10^{13}
μ/bunch	2×10^{12}	4×10^{12}	4×10^{12}
Bunches/sign	2	1	1
Beam Power MW	38	0.7	1.0
ϵ_N π mm-mrad	50	90	195
Bending Field T	9	9	
Circumference km	8	1.3	0.3
Ave. ring field B T	6	5	3.5
Effective turns	900	800	450
β^* mm	3	8	9
IP beam size μm	2.8	17	187
β_{max} km	200-400	10-20	1.5
Lumin. $cm^{-2}s^{-1}$	10^{35}	10^{33}	2×10^{31}

energy range of most of the heavy Higgs in the minimal SUSY model (if that is the correct theory).

SUMMARY

Building a muon storage ring for the purpose of providing intense high energy neutrino beams is particularly exciting. Such neutrino factories could have their own world class research program, with neutrino oscillation studies as the primary focus (see e.g. Indeed, if very high intensities, $\sim 10^{21} \frac{\nu}{year}$, are attained and nature has been kind in her neutrino mass and mixing parameters, one could envision a complete exploration of the 3×3 neutrino mixing matrix and even the detection of CP violation in the oscillation phenomena. If a neutrino factory is successfully accomplished, it would provide a major advancement. Its ambitious goals would test essentially all aspects of the muon collider concept, muon production, collection, cooling and acceleration. Furthermore, if properly coordinated, the neutrino factory complex might be suitably expanded into the First Muon Collider, perhaps a Higgs factory with center of mass energy $\sim$ 100 GeV.

High intensity muon experiments, neutrino factories, and other intermediate steps toward the muon collider are extremely important. They will greatly expand our abilities and build confidence in the credibility of high energy muon colliders. many would prefer, but remember, Rome was not built in a day.

At BNL, a 20 GeV muon storage ring intense muon (neutrino) source would be very interesting but expensive? An alternative source of intense muons are the conventional Horn Beams which seems to be not only competitive with the lower energy muon storage rings but also at a lower cost. For example, with the same number of proton (p) on target and same size (kTon) detector the BNL – AGS 1 $GeV\nu_{\mu}^{peak}$ Horn $\simeq$ $10GeV$ Muon Storage Ring (statistically if L/E is fixed). Upgraded Horn facility is potentially powerful. Further R&D on $6 \times 10^{14}p/sec$ driver and target at BNL are important for both the muon storage ring and Horn. For more info. see references, [2] - [30].

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