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MUON SOURCES

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Abstract. 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. Employing an intense muon source to carry out forefront low energy research, such as the search for muon - number non - conservation, represents one interesting possibility. For example, the MECO proposal at BNL aims for 2×10^{-17} sensitivity in their search for coherent muon - electron conversion in the field of a nucleus. To reach that goal requires the production, capture and stopping of muons at an unprecedented $10^{11} \frac{\mu}{sec}$. If successful, such an effort would significantly advance the state of muon technology. More ambitious ideas for utilizing high intensity muon sources are also being explored. Building a muon storage ring for the purpose of providing intense high energy neutrino beams is particularly exciting.We present an overview of muon sources and example of a muon storage ring based Neutrino Factory at BNL with various detector location possibilities.

INTRODUCTION

High intensity muon sources are needed in exploring neutrino factories, lepton flavor violating muon processes, and lower energy experiments [1] as the stepping phase towards building higher energy $\mu^+\mu^-$ colliders.

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.

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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.

A schematic concept of a Neutrino Factory Facility based on a muon storage ring, its components and a possible upgrade to a full muon collider is discussed in the following sections. 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 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 1) 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

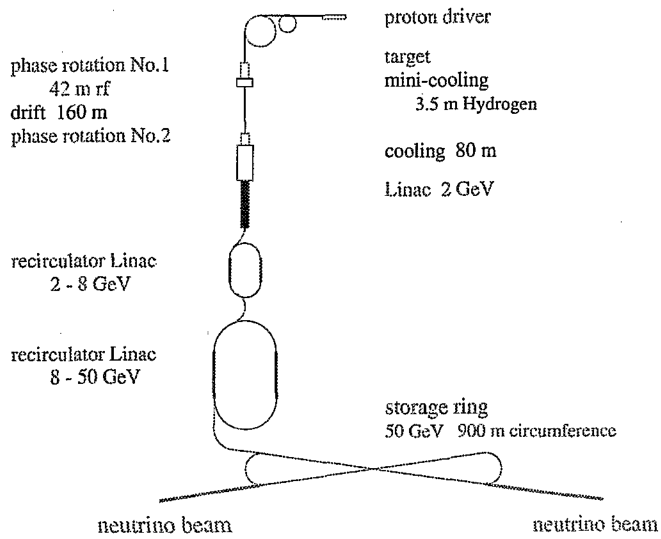

FIGURE 1. A schematic concept of a Neutrino Factory Facility based on a Bowtie Muon Storage lattice.

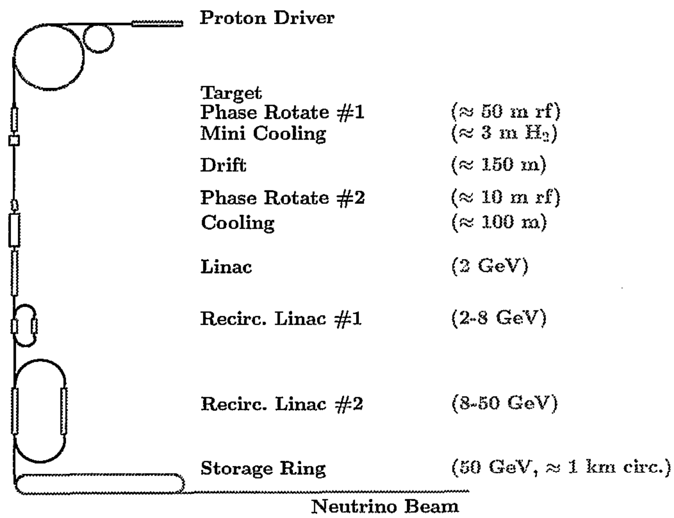

FIGURE 2. Overview of a Neutrino Factory Concept, with a Racetrack Muon - Storage Ring

the earth, such that neutrinos can be directed into two very distant detectors. Triangular-shaped storage rings also have this advantage.

Figure 2, illustrates components of a Neutrino Factory based on a Racetrack - shaped Muon Storage lattice Figure 1 and Figures 2 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 bowtie-shaped muon storage lattice will be discussed.

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

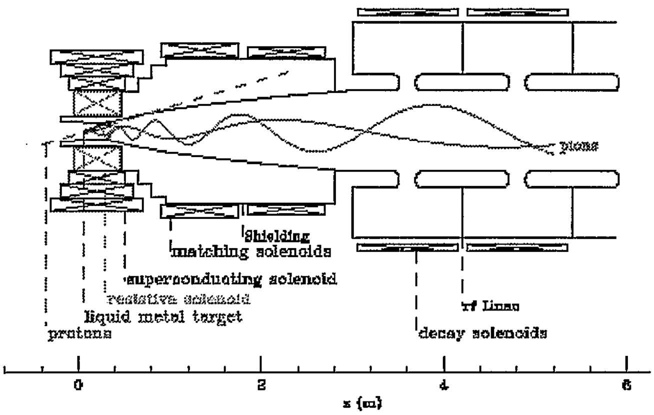

FIGURE 3. A Schematic of Targetry, Pion Capture, and beginning of Phase Rotation.

NEUTRINO FACTORY 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 liquid mercury jet solution is used. The capture solenoid is likely to be the same as described in the muon collider status report [13]. Figure 3, 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. Figure 4 illustrates schematics of a Muon source front-end compenents, and Fig. 5 shows the muon emittance variation in the target-to-linac channel.

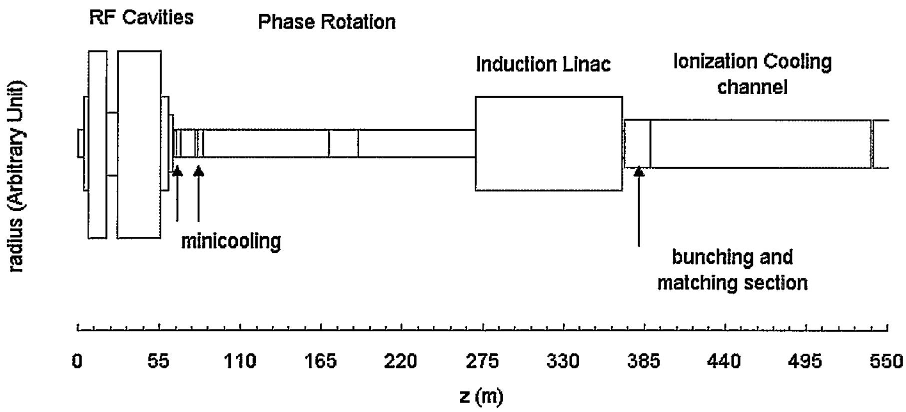

FIGURE 4. Schematics of the Muon Source from Target to Linac.

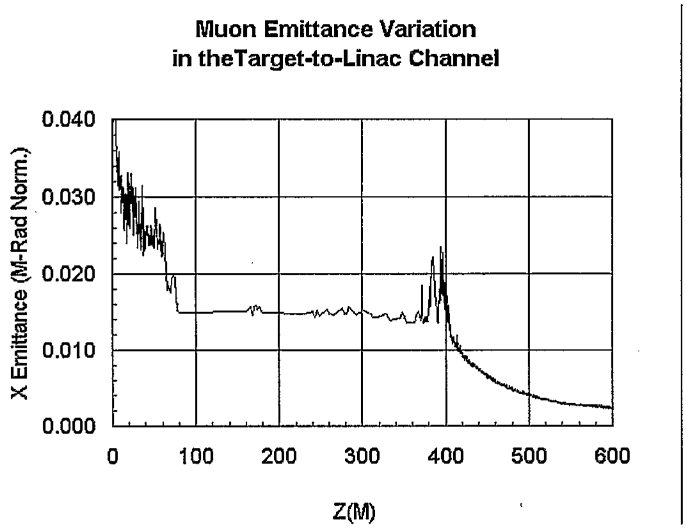

FIGURE 5. Muon emittance variation in Target to Linac channel.

COOLING, ACCELERATION, STORAGE

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 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 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.

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

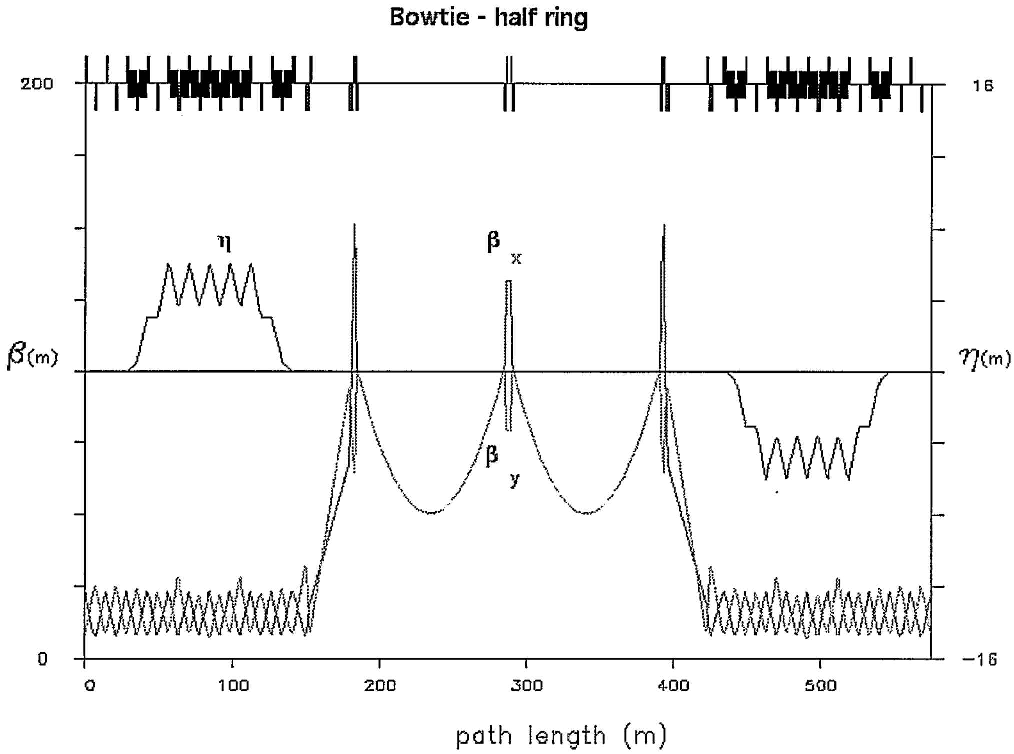

FIGURE 6. Example of Lattice Functions for Bowtie-shaped Half Ring.

MUON STORAGE RING

A racetrack–shaped muon storage - ring, with two long straight sections (illustrated in Figure 2), can be configured to deliver one neutrino beam to an arbitrary detector site.

A planar bowtie-shaped ring (illustrated in Figure 1), lattice has two long-straight sections, two short-straight sections and two arcs. Bowtie - shaped and 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 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.

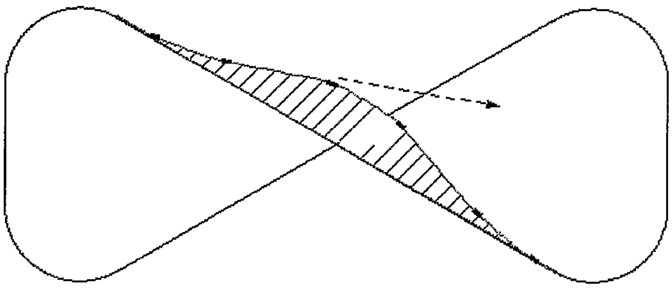

FIGURE 7. Lattice functions for Bowtie-shaped Ring with Bypass. The arrow illustrates direction of a neutrino beam to additional detector site(s) via the Bypass.

MUON SOURCE AT BNL

As 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 8), 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 Neutrino Factory and Muon Collider Collaboration, and requires additional studies for a BNL site specific example.

Figure 8 shows schematics of space angles [20] 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.

DISCUSSION

Employing an intense muon source to carry out forefront low energy research, such as the search for muon - number non - conservation, represents one interesting possibility, which requires the production, capture and stopping of muons at an unprecedented $10^{11}\frac{\mu}{sec}$. If successful, such an effort would significantly advance the state of muon technology.

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.

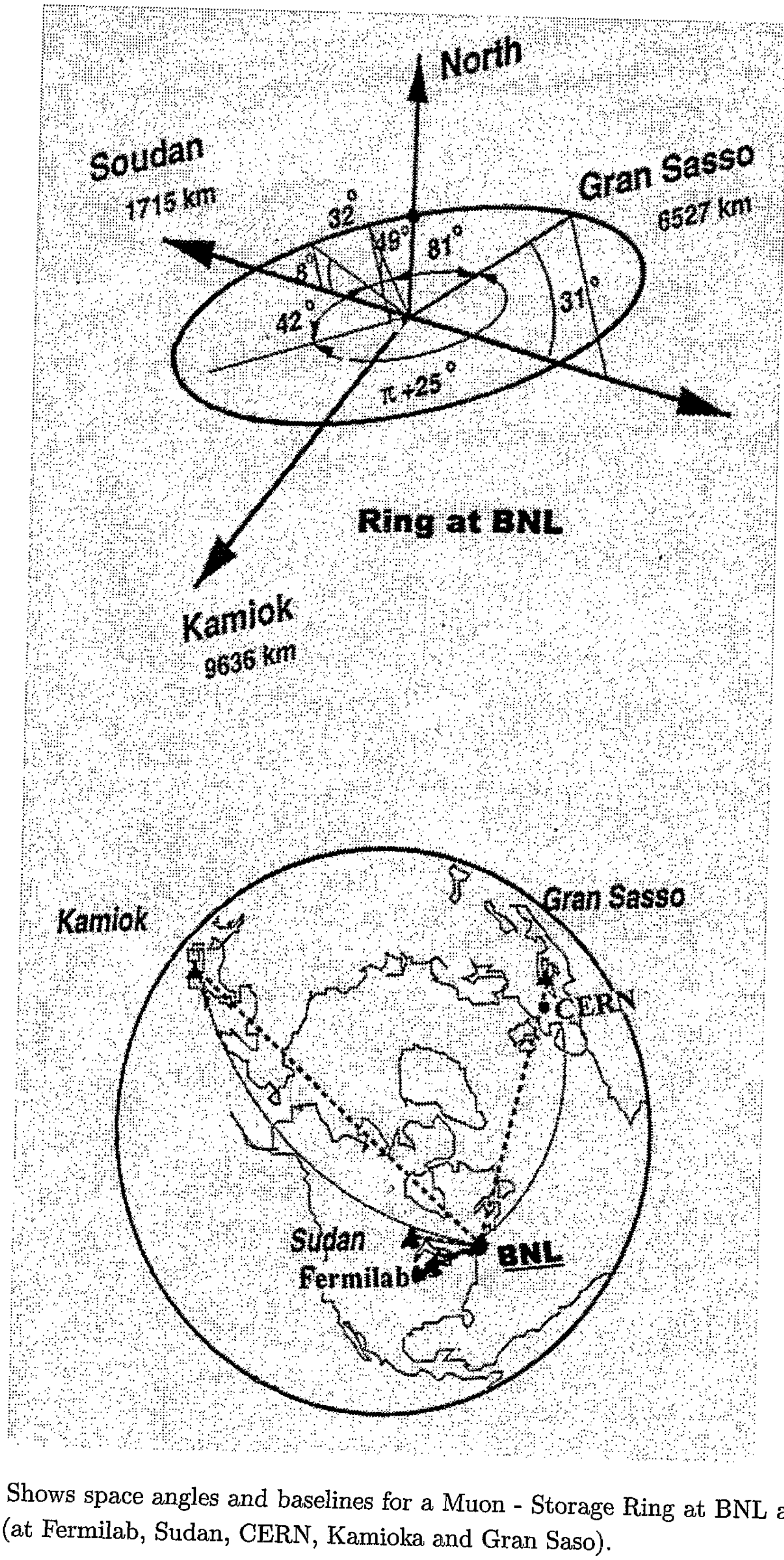

FIGURE 8. Shows space angles and baselines for a Muon - Storage Ring at BNL and possible detector sites (at Fermilab, Sudan, CERN, Kamioka and Gran Saso).

A 20 GeV muon storage ring intense muon (neutrino) source at BNL is very interesting but expensive? An alternative source of intense muons are the conventional Horn Beams which may 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 $\simeq$ $10 GeV$ 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. [2]- [25].

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