NEUTRINO FACTORY - IONIZATION COOLING, EMITTANCE EXCHANGE, AND ν SUPERBEAM AT BNL?

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Abstract

Muon collider, neutrino factory and / or a neutrino superbeam are interesting and needed to provide a probe for fundamental particle physics. In our collabortion studies we have realized some important issues needed before building a collider (Cost, cooling demonstration, radiation, etc). Muon cooling is a key factor in design of Muon collider, (to a less degree) Muon storage ring, and Neutrino Factory. We present a brief overview on cooling and beam emittance dynamics, and discuss future neutrino Superbeam possibilities at BNL (to be further explored at Snowmass2001).

1 INTRODUCTION

In previous presentations we discussed the nuetrino factory [2] and upgrades to higgs muon collider [3], etc. Here we elaborate on some of the related issues such as cooling and emittance excahnge, the front end components e.g. target and capture in example for the BNL site specific study 2[6]. We conclude with a scenario of incrimental upgrading of the AGS as a conventional horn neutrino beam (upgrade(s)), to produce neutrino Superbeams to do oscillation experiments with detector(s) at various sites. This upgrade will not include building any new facility at BNL, as is required for neutrino factory facility e.g. the study 2, and the case of the FNAL Superbeam study which requires building of a new booster facility).

2 EMITTANCE EXCHANGE

For a collider, to obtain the needed luminosity, the phase space volume must be greatly reduced within the muon life time. Alternating solenoid lattices has been proposed as desirable for use in the earlier cooling stages of Muon Colliders, where the emittances are large. Since the minimum $\beta_\perp$'s must decrease in order to obtain smaller transverse emittances as the muon beam travels down the cooling channel. This can be done by increasing the focusing fields and/or decreasing the muon momenta, where the current carrying lithium lenses may be used (to get a stronger radial focusing and to minimize the final emittance) for the last few cooling stages. The use of 'bent solenoids' may provide the required dispersion for the momentum measurement. Where the off-momentum muons are displaced vertically by an amount: $\Delta y \approx \frac{P}{eB_s}\frac{\Delta P}{P}\theta_{\rm bend}$, where B_s is the field of the bent solenoid and $\theta_{\rm bend}$ is the bend angle. This equation, describes the deflection of the 'guiding ray' (or axis) of the helical muon trajectory and not the trajectory itself. Also, the muon's momentum cannot be determined simply by measuring the height of its trajectory at the entrance and exit of a bent solenoid. Rather, the height of the guiding ray must be reconstructed at both places, which requires precise measurements of the helical trajectories.

Fig. 1 shows a high intensity proton source is bunch compressed and focused on a heavy metal target. The pions generated are captured by a high field solenoid and transferred to "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, and must be rapidly accelerated to avoid decay. This can be done in recirculating accelerators or in fast pulsed synchrotrons. Muon collisions occur in a separate high field collider storage ring with a single very low beta insertion.

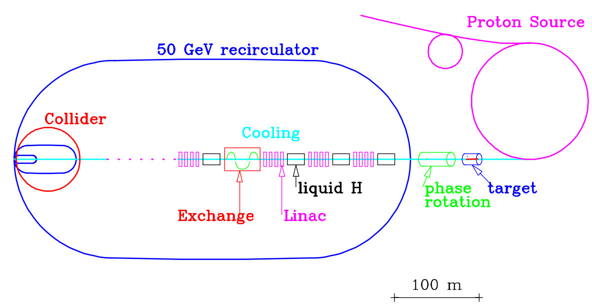

Figure 1: Schematic of How the solenoid and wedges are used in an accelerator and the other components,[4].

3 MUON COOLING

To obtain the needed collider luminosity, the phase-space volume must be greatly reduced (lesser degree in a neutrino factory storage ring), within the muon life time. The Ionization cooling is the preferred method used to compress the phase space and reduce the emittance to obtain high luminosity muon beams. We noted that, the ionization losses results not only in damping, but also heating: transverse heating appears due to multiple Coulomb scattering and longitudinal one is due to so named "straggling" of the ionization losses (we note that, this straggling is produced by fast "knock-on" ionization electrons).The longitudinal muon momentum is then restored by coherent re-acceleration, leaving a net loss of transverse momentum (transverse cooling).To achieve a large cooling factor the process is repeated many times. The transverse cooling can be expressed (neglecting correlations) as

$$\frac{d\epsilon_n}{ds} = \frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(0.014GeV)^2}{2\,E_\mu m_\mu\,L_R} + ..., \quad (1)$$

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where β = v/c, ϵ_n is the normalized emittance, $\beta_\perp$ is the betatron function at the absorber, dE_μ/ds is the energy loss, and L_R is the radiation length of the material. The first term in this equation is the cooling term, and the second is the heating term due to multiple scattering. To minimize the heating term, a strong-focusing (small $\beta_\perp$) and a low-Z absorber (large L_R) is needed. In ionization method,

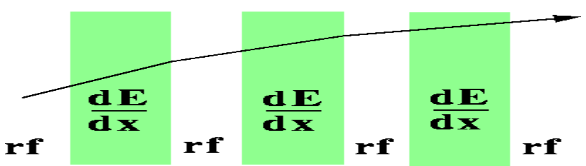

Figure 2: A schematic of ionization cooling of the transverse phase-space occupied by a muon beam.

muons passing through a material medium lose momentum and energy through ionization interactions in transverse and longitudinal directions. The normalized emittance is reduced due to transvers energy losses.

Damping rates (decrements) of individual particles in the absence of wedges (natural damping rate) are defined by the following formula:

$$\begin{aligned} \lambda_\perp &= -\frac{dE}{dz}_{ion} \frac{1}{2\beta^2\gamma mc^2} \\ \lambda_\parallel &= -\frac{1}{z}\frac{d}{dp}\left[\left(\frac{dE}{dz}\right)_{\text{ion}} \frac{1}{v}\right] \end{aligned} \tag{2}$$

Where $\lambda_\perp$ and $\lambda_\parallel$ are natural transverse and longitudinal damping respectively. Here $\left(\frac{dE}{dz}\right)_{\text{ion}}$ is the ionization losses of energy, m is the muon mass, β,γ are relativistic parameters, p, v are momentum and longitudinal velocity of muons being cooled. It was established, that the sum of all increments is invariant of the cooling system.

Figure 3 illustrates a proton beam hitting a target through capture solenoid channel.

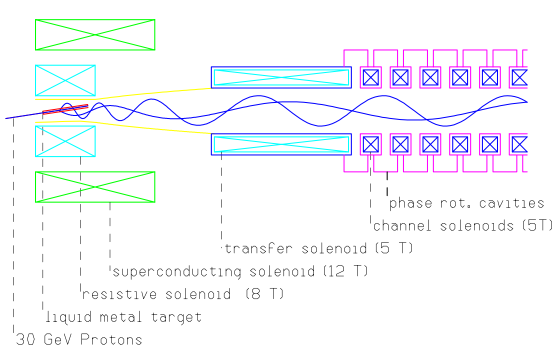

Figure 3: Shows the front end for a neutrino Factory: a proton beam hitting the target, through capture solenoid channel.

4 BNL AGS - PROTON DRIVER

AGS is the injection system for the Relaticistic Heavy Ion Collider (RHIC) accelerator complex at BNL. It consists of a 200 MeV linac for the pre-acceleration of high intensity and polarized protons, two Tandem Van de Graaff for the pre-acceleration of heavy ion beams, a versatile Booster that allows for efficient injection of all three types of beams into the AGS and, most recently, the two RHIC collider rings that produce high luminosity heavy ion and polarized proton collisions. The AGS has intensity of aboout 7×10^{13} protons accelerated in a single pulse.

The AGS upgrade requirements as the proton beam driver for the Nueutrino Factory operation (study 2[6]), at BNL are summarized in Table 1 and a layout of the upgraded AGS is shown in Fig. 4. The proposed AGS upgrade, requires replacement of the present Booster, and to build a superconducting upgrade to the existing 200 MeV linac to reach an energy of 1.2 GeV for direct H$^-$ injection into the AGS. The repetition rate is increased from 0.5 to 2.5 Hz, and (with $10^{14}ppp$), the total charge is about 30% higher than the present performance of AGS. Table 2, gives a comparison of AGS (at present), and AGS upgraded to 1 MW (as in study 2[6]). With the AGS rf harmonic number of 24, the Linac beam will be injected into 18 buckets, and a bunch merge of 3 to 1 will take place later in the cycle to produce 6 bunches in the AGS[6].

Table 1: AGS proton driver parameters.

Total beam power (MW)	1
Beam energy (GeV)	24
Average beam current (μA)	42
Cycle time (ms)	400
Number of protons per fill	1×10^{14}
Average circulating current (A)	6
No. of bunches per fill	6
No. of protons per bunch	1.7×10^{13}
Time between extracted bunches (ms)	20
Bunch length at extraction, rms (ns)	3
Peak bunch current (A)	400
Total bunch area (eVs)	5
Bunch emittance, rms (eV-s)	0.3
Momentum spread, rms	0.005

Table 2: Comparison of H$^-$ injection parameters.

	AGS, $\langle 1\ MW\ AGS\rangle$
Beam power at linac exit [kW]	3, $\langle 54\rangle$
Kinetic energy [MeV]	200, $\langle 1200\rangle$
No. of protons $N_{\rm P}$ (10^{12})	15, $\langle 100\rangle$
Vert. Accept, A [π mm mrad]	89, $\langle 55\rangle$
$\beta^2\gamma^3$	0.57, $\langle 9.56\rangle$
$N_P/(\beta^2\gamma^3 A)$ [$10^{12}/\pi$ mm mrad]	0.296, $\langle 0.190\rangle$
Total beam losses [%]	5, $\langle 3\rangle$
Total lost beam power [W]	150, $\langle 1440\rangle$
Circumference (m)	202, $\langle 807\rangle$
Lost beam power/meter [W/m]	0.8, $\langle 1.8\rangle$

5 NEUTRINO SUPERBEAM AT BNL

Conventionally, neutrino beams employ a proton beam on a target to generate pions, which are focused and allowed to decay into neutrinos and, muons.The muons are stopped in the shielding, while the muon-neutrinos are directed toward the detector. An alternative source of in-

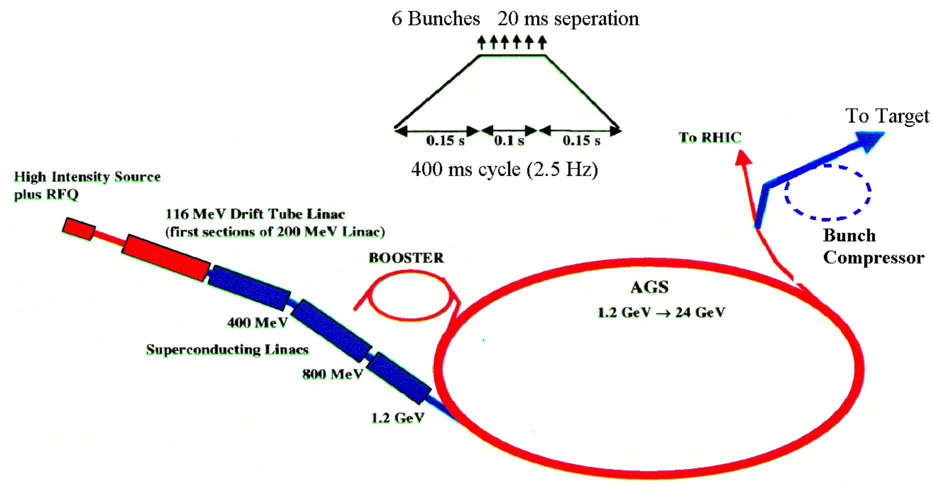

Figure 4: AGS proton driver layout. Where the Booster is replaced by Superconducting Linacs

tense muons are the conventional Horn Beams (very efficient) which seems to be not only competitive with the lower energy muon storage rings (μSR) but also at a lower cost. Low energy neutrino physics is a very competitive way to study neutrino oscillations. E.g., with $\nu_\mu \rightarrow \nu_e$ or $\nu_e \rightarrow \nu_\mu$, measure $\sin^2 2\theta_{13}$, CP violation, etc.

As previously,in the example of the BNL- AGS with proton beam energy of $E_p \simeq 28GeV$, if one considers the BNL P889 study, and increase the number of proton on target (p.o.t.) e.g., from 2×10^{20} $p.o.t./yr$ to 6×10^{21} $p.o.t./yr$ one gains a factor of 30, $E^{peak}_{\nu_\mu} \simeq 1GeV$, with $\nu_\mu \rightarrow \mu^-$, at $L = 1km$ no oscillation, $N_{\mu^-} \simeq 4.43 \times 10^{-15}/kTon/p.o.t. \times 6 \times 10^{21} p.o.t./yr \simeq 2.7 \times 10^7/kTon/yr$, (Fiducial Mass $\rightarrow$ 1/2). This is Comparable to a muon storage ring with $E_\mu \simeq 10\ GeV$, 2×10^{20} $\mu\ decays/yr$, with $L = 10\ km$; $\nu_\mu \rightarrow \mu^-$ or $\overline{\nu}_e \rightarrow e^+$; and $N_{\mu^-} \simeq 1.5 \times 10^7/kTon/yr$.

That is, (we have about the same event rates), with the same p.o.t. and detector size, $1\ GeV\ \nu^{peak}_\mu$ Horn $\simeq$ $10GeV$ μ Storage Ring (statistically, if L/E is fixed). With upgraded proton source (e.g., 6×10^{14} $p.o.t./yr$), larger detectors (e.g., $45kTon$, (preferable $> 500kTon$)), at about $300km$, with low energy ν_μ and $\overline{\nu}_\mu$ from a Horn (e.g. 300 times the BNL-P889 study) one should measure θ_{13}, θ_{23} (High precision), $\Delta m^2{}_{31}$ and will have some CP violation capability (e.g., one should measure $sin^2 2\theta_{13} \sim > 0.007$ which is impressive).

If we increase L to 10 or 100 times longer, in the example of the BNL-P889 study with Detectors at 1, 3, 24, 68 km, then with 340 times the P889 event rate at $L \simeq 260\ km$ most of $\nu_\mu \rightarrow \nu_\tau$ ($\Delta m^2_{31} \simeq 3 \times 10^{-3}\ eV^2$), number of $\nu_\mu \rightarrow \nu_e \rightarrow e^-$, ($5 \times 10^4\ sin^2\theta_{23}\ sin^2 2\theta_{13} \simeq 175\ events$, ($sin^2 2\theta_{13} \gtrsim 0.007$)), and 3σ measurements of $A_{CP} \simeq 0.15 \pm 0.05$. *Upgraded* ν_μ, $\overline{\nu}_\mu$ *Horn Facility potentially is powerful*. However, the are questions (targetry R&D issues) that needs to be addressed. E.g., how high intensity can a conventional horn tolerate? How about using a solenoid magnet as a focusing device? Solenoid may be able to handle the high intensity proton currents better?

6 SUMMARY

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 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 $1\ GeV \nu^{peak}_\mu$ 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.

In light of recent information from the labs, and cost estimates for upgrade of the AGS to 1 MW (Neutrino factory study 2 at BNL[6]), if the NLC goes to Fermilab, there will not be funding for building a neutrino factory facility, or any other new facility such as a new booster at FNAL. However, at much smaller costs incremantal upgrades of the AGS at BNL could permit the continuation of the neutrino oscillation experiments with detctor(s) placed at various site(s). Some of the on going superbeam studies for Fermilab, can be applied to BNL neutrino Superbeam possibilities.

7 REFERENCES

[1] The AGS data and Figures were provided and obtained from collaborators and Feasibility study collaboration [6] and presentations; also [4], and [5]; and references thereins.

[2] Z. Parsa *"Neutrino Factory ...to Muon Colliders: Physisics and Facilities"*, PAC2001.

[3] Z. Parsa *"Higgs Factory and Potentials"* PAC2001.

[4] *Future High Energy Colliders* Z. Parsa, ed., AIP CP **397**, 1997. C.M. Ankenbrandt etal, *Status of muon collider research and development and future plans*, Phys. Rev. ST Accel. Beams **2**, 081001 (1999), MUCOOL Collab proposal(98); and references therein.

[5] http://puhep1.princeton.edu/mumu/; www.fnal.gov/projects/ and collaboratoon page: ww.cap.bnl.gov/mumu

[6] *Neutrino Factory Feasibility study-2* and presentations: www.bnl.gov/mumu/sudyii.