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The BNL Super Neutrino Beam Project

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Abstract

BNL plans to create a very long base line super neutrino beam facility by upgrading the AGS from the current 0.14 MW to 1.0 MW and beyond. The proposed facility consists of three major components. First is a 1.5 GeV superconducting linac to replace the booster as injector for the AGS, second is the performance upgrade of the AGS itself for higher intensity and repetition rate, and finally is the target and horn system for the neutrino production. The major contribution for the higher power is from the increase of the repetition rate of the AGS from 0.3 Hz to 2.5 Hz, with moderate increase from the intensity. The accelerator design considerations to achieve high intensity and low losses for the new linac and the AGS will be presented. The target and horn design for high power operation and easy maintenance will also be covered.

1 INTRODUCTION

An accelerator based very long baseline experiment that can explore both Solar and Atmospheric neutrino oscillation parameters in a single experiment [1,2]. The facilities required for this program are: (1) a 1 MW ``Super Neutrino Beam" provided by an upgraded AGS proton driver accelerator at Brookhaven National Laboratory and (2) a 500 kT water Cherenkov detector, located in a deep underground laboratory at a distance of more than 2000 km from BNL. In the absence of oscillations, one could collect ~60000 events in a running period of 5x 10^7 sec. This is possible due to the long distance and wideband nature of the neutrino beam for the observation of several oscillations from one species of the neutrino to the other.

We have examined possible upgrades to the AGS complex that would meet the requirements of the proton beam for a 1.0 MW neutrino superbeam facility. We are proposing to replace part of the existing 200 MeV linac with coupled cavity structure from 116 MeV to 400 MeV and then add additional 1.1 GeV superconducting linac to reach a final energy of 1.5 GeV for direct H^- injection into the AGS.

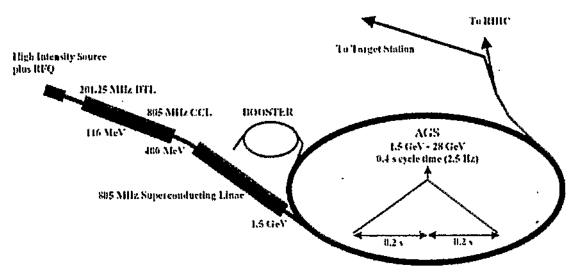
The requirements of the proton beam for the super neutrino beam are summarized in Table 1 and a layout of upgraded AGS is shown in Figure 1. Since the present number of protons per fill is already close to the required number, the upgrade focuses on increasing the repetition rate and reducing beam losses (to avoid excessive shielding requirements and to maintain activation of the machine components at workable level). It is also important to preserve all the present capabilities of the AGS, in particular its role as injector to RHIC.

Present injection into the AGS requires the accumulation of four Booster loads in the AGS, which takes about 0.6 sec, and is therefore not suited for high average beam power operation.

TABLE 1. AGS Proton Driver Parameters.

Total beam power	1 MW
Beam energy	28 GeV
Average beam current	42 μA
Cycle time	400 msec
Number of protons per fill	0.9 x 10^{14}
Number of bunches per fill	24
Protons per bunch	0.4 x10^{13}
Injection turns	230
Repetition rate	2.5 Hz
Pulse length	0.72 msec
Chopping rate	0.75
Linac average/peak current	20 / 30 mA

To minimize the injection time to about 1 msec, a 1.5 GeV linac will be used instead. The multi-turn injection from a source of 28 mA and 720 μsec pulse width is sufficient to accumulate 0.9×10^{14} particle per pulse in the AGS. The minimum ramp time of the AGS to full energy is presently 0.5 sec. This must be reduced down to 0.2 sec to reach the required repetition rate of 2.5 Hz to deliver the required 1 MW beam to the garget.



FGURE 1. Schematic diagram of the accelerators for the "neutrino production".

2 SUPERCONDUCTING LINAC (SCL)

Two modifications are needed for the injector linac: (1) Upgrade the 200 MeV linac to 400 MeV, based on the FERMILAB upgrade which was successfully completed in 1993 [4]; (2) Use the SNS high beta cryomodules [5] to 1.5 GeV or higher energies in the 130 meter space. The Fermilab 200 MeV linac was upgraded to 400 MeV by replacing last four DTL tanks with seven 805 MHz coupled cavity linac (CCL) modules [4]. These seven CCL modules fit within the existing linac tunnel enclosure, since the length of the CCL modules including the transition section is about 3 meters shorter than the last four DTL tanks. Since 1993, the Fermilab linac has successfully accelerated a peak current of 50 mA with pulse length of 50 μs at repetition rate of 15 Hz. The average accelerating gradient in the CCL is 7.5 MV/m, which is about four times higher than LAMPF at Los Alamos. The peak surface field is 37 MV/m, which is 1.35 Kilpatrick. Each module has 4 sections and each section has 16 cells. Each module is driven by a 12 MW klystron. The focusing lattice is FODO with quadrupole gradient of approximately 20 T/m. The achieved sparking rate at Fermilab is about 0.033% with RF pulse length of 50 μs [4]. Since our RF pulse length is about 1 ms, the sparking rate could be higher. It would require some R& D efforts to minimize the sparking rate. In the Fermilab design nose corner is not water-cooled. For our 1 ms long RF pulse length nose corner would require redesigning.

The SNS high beta module is 7.891 meters long (including the warm section) and has 4 sections of 6 cells. The geometric beta for these modules is 0.81. The design-accelerating field (E_0) is about 22.8 MV/m (E_0T=15.9 MV/m), 21 modules will accelerate H^- from 387 MeV to 1300 MeV. At present, cavity testing at JLAB [6] shows that the accelerating gradient of 30 MV/m (E_0T=21 MV/m) has been achieved. In 130 meter one can have 15 cryomodules. Assuming an accelerating gradient, E_0=31 MV/m, 15 cyromodules can accelerate H^- from 400 MeV to 1462 MeV. The energy can be upgraded to 1533 MeV if the accelerating gradient (E_0) of 33 MV/m (achieved at TESLA) becomes a reality in future for cavities with $\beta \leq 1$. Table II shows the general parameters for the linac.

The emittance of the existing 200 MeV linac is about 2 π mm rad (rms, nor), which has to be reduced to 1 π mm rad to lower the losses during the injection process into the AGS [7]. The existing ion source and RFQ will be relocated next to DTL tank 1 to meet the requirement [8]. The beam power at 1.5 GeV is only 54 kW, for hand on maintenance loss limit is watt/m, which translate to fractional loss limit of 3 x 10^{-3}. The estimated fractional loss is about 1 x 10^{-4}.

Table II: Injector Linac parameters

Kinetic Energy (GeV)	1.5
Beam Power (kW)	54
Average Beam Current (μA)	36
Number of Proton per Bunch (x 10^8)	8.70
Repetition Rate (Hz)	2.5
Beam Pulse Length (μs)	720
Chopping Rate (%)	65
Emittance (π mm mrad, nor)	1.0
Energy Spread (ΔE/E, 95%)	±0.001
Energy Jitter (δE, MeV)	2.5
Drift Tube Linac (DTL)	
Energy (MeV)	116.5
Number of Tank	5
Frequency (MHz)	201.25
Coupled Cavity Linac (CCL)	
Energy (MeV)	400
Frequency (MHz)	805.0
Number of Module	7
Number of Section per Module	4
Number of Cells per Section	16
Bridge Coupler Length (βλ)	3/2
Cavity Bore Radius (cm)	1.5
Accelerating Phase, ϕ_s (deg)	-32
Average axial field, E_0 (MV/m)	7.1-8.1
Kilpatrick	1.35
RF Power per module (MW)	<12
Transverse Focusing	FODO
Average Transverse Phase Advance (deg)	79
Quadrupole Bore Radius (cm)	2.0
Quadrupole Magnetic Length (cm)	8.0
Quadrupole Pole Tip Field (kG)	4.6
Superconducting Linac (SCL)	
Energy (GeV)	1.46
Frequency (MHz)	805.0
Number of Cryomodule	15
Number of Cavity per Cryomodule	4
Number of Cell per Cavity	6
Geometric Beta	0.81
Slot Length (m)	7.891
Warm Insertion Length (m)	1.6
Average Axial Field, E_0 (MV/m)	31
Peak Surface Field, E_p (MV/m)	51.2
Accelerating Phase, ϕ_s (deg)	-19.5
Number of Cavities per Klystron	1
Klystron Power (kW)	550
Temperature (°K)	2.1
Transverse Focusing	FODO
Transverse Phase Advance (deg)	70
Quadrupole Length (cm)	40
Quadrupole bore Radius (cm)	4.0

3 AGS UPGRADE

In its current operation, the AGS receives four batches of 1.5 GeV proton beam from the Booster synchrotron in about 0.5 second. The typical intensity achieved for slow extracted beam operation is about 70 x 10^{12}. In the proposed AGS upgrade for the neutrino beam program, a new 1.5 GeV superconducting linac will be used as injector which can provide 89 x 10^{12} proton with injection time of less than 1 ms. To provide 1 MW beam power for neutrino production, the AGS has to be cycled at 2.5 Hz, instead of 0.5 Hz. For this improved capability, several major upgrades of the AGS have to be implemented: (1) the new direct injection from the SCL with H^- stripping foil system; (2) the new main magnet power supply and its six-loop configuration for the powering of the lattice magnets; (3) the new RF accelerating cavity and its associated power switching system for doubling the accelerating voltage operated at 2.5 Hz; (4) the new single turn fast extraction system for beam delivery to the target; (5) the new collimation and radiation shielding system to keep the beam losses at an acceptable level.

4 BEAM TRANSFER LINE

The beam is transported ~ 190 m from the AGS to the U-line spur using present RHIC transfer line magnets. The new beam transport begins at this point. To direct the beam toward the Homestake mine in South Dakota, the beam must be bent 68 degrees, 4 seconds to the west of the U-line direction and 11.26 degrees downward. BNL is located on an aquifer that is the sole-source for Suffolk county drinking water. A beam layout has been developed that takes the beam up and over a 42-meter (beam height) hill to the production target and decay channel. This keeps the target; decay channel and beam dump at or above the present ground level and well above the Long Island water table. Figure 2 shows a 3-dimensional view of this beam transfer line. A beam layout was developed to incorporate separate vertical and horizontal bends. The 17-degree vertical bend up begins near the end of the present U-line tunnel about 80 meters from the beginning of the new transport. The 80-meter drift before beginning the vertical bend up is necessary to avoid conflicts with the RHIC transfer line utilities and entrance labyrinths. This bend is followed by a 46-meter drift to allow the beam to reach a height sufficient to allow, after a 68-degree horizontal bend and a vertical downward bend, a 200-meter decay tunnel (target to dump) down the hill to a dump, keeping the front face of the dump at ground level. In order to come out of the horizontal and final vertical bend with the beam heading toward Homestake the actual bend angles had to be adjusted to account for the fact that the bends are accomplished on the hill. The ``ground level" horizontal and vertical angles, relative to the U-line beam direction, that point the beam toward Homestake are 68 and 11.3 degrees respectively. The required horizontal bend is 72.1 degrees followed by a 17.2 vertical bend down in the y-z plane defined by the beam as it exits the horizontal bend.

5 TARGET STATION AND NEUTRINO BEAM

To achieve the 1 MW upgrade option of the proton driver at BNL, serious consideration must be given to the target selection. In evaluating the various choices of target materials and of target/horn configurations, the following concerns are being addressed:

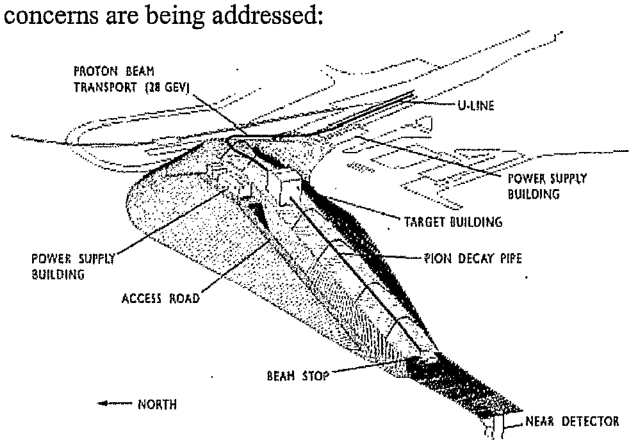


Figure 2: Elevation view of the neutrino beam line to Homestake, South Dakota.

- Optimization of neutrino flux,
- Heat removal from the target and horn,
- Survivability of the target intercepting energetic, high intensity proton bunches,
- Irradiation and integration issues.

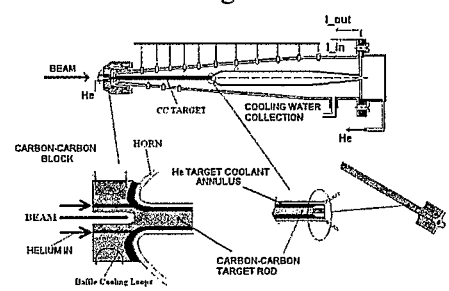


Figure 3: Proposed graphite target and horn configuration

The design of the target/horn configuration is shown in Fig. 3.The material selected for the superbeam experiment is a Carbon-Carbon composite. It is 3-D weaved material and exhibits extremely low thermal expansion for the temperatures up to 1000 °C while for the higher temperatures it responds like graphite. This property is significant in the sense that the thermo elastic stresses induced by intercepting the beam will be quite small thus extending the life of the target.

6 BEAM DYNAMICS ISSUES

For 1 MW super neutrino beam facility, the AGS has new injection scheme and 10 times more proton per second then current AGS operations, these results in new beam dynamics issues to consider. These issues are; (1) injection painting, (2) transition crossing, (3) ring impedances, and (4) magnetic multipoles generated by eddy current due to higher rape rage in the AGS magnets.

1.5 GeV H^- will be injected through 300 μg/cm^2 stripper carbon foil into the AGS for 240 turns. Beam loss in the injection process is one of the most important issues for a high power proton accelerator. For super neutrino beam operation following are the relevant power and beam loss estimate during the injection: (1) 54 kW injected beam power at 1.5 GeV, 0.90 kW H^- ions missing the foil, (3) 0.90 – 5.4 kW H^0 from stripping foil (This rate depends on the foil thickness of the stripping foil), and (4) 54 W stripped electron. An optimum thickness and size of the injection foil is needed to balance these losses against aforementioned H^- and H^0 losses. There are additional beam losses due to (a) nuclear scattering, (b) multiple scattering, and (c) energy loss and struggling as some part of the circulating proton traverse through the foil. To reduce these looses an optimization of the collapse time of the injection bump magnet is needed.

For longitudinal painting, simulations shows that a relatively low rf voltage of 450 kV at injection is necessary to limit the beam momentum spread to about 0.5% and longitudinal emittance of 0.8 to eVs per bunch and the chopping rate 0.65. Such a small longitudinal emittance is important to limit beam losses during the transition crossing in the AGS.

The proton beam crosses the transition energy at $\gamma_T = 8.5$. During a non- adiabatic time $\pm T_c$, the beam may experience emittance growth and beam loss caused by chromatic non-linear mismatch, beam self-field mismatch and beam instabilities. It is necessary to use the transition jump method to effectively increase the rate of transition crossing. The required amount of transition jump $\Delta\gamma_T=\pm0.5$ during a time of 1 ms or shorter. The expected beam loss is about 0.2% for a 0.8 eVs longitudinal beam emittance. While the condition for machine hands-on maintenance of average beam loss of 1 W/m corresponds to a fractional uncontrolled beam loss of 0.3%[9]

The beam instability considered for the super neutrino beam operation for the AGS at high energy are; (a) longitudinal instability around transition, and (b) the transverse instability above transition. The longitudinal impedance needs to be less than 12 Ω to avoid longitudinal microwave instabilities. The measured AGS longitudinal impedance is about 30 Ω. All bellows in the AGS (about 450) are unshielded. The chamber steps, including the connection from dipole to quadrupole and the BPM housing, are not tapered. With limited effort of shielding and tapering, the AGS impedance can be reduce to about 12 Ω. The longitudinal space charge impedance is about 10 Ω at transition, which is capacitive, has the effect of canceling the inductive broadband impedance. In summary, since the required intensity of 8.9×10^{13} is only marginally higher than the current intensity of 7.3×10^{13}. The beam instability during acceleration and transition crossing can be avoided.

Presently the magnet cycle of the AGS accelerator has a period of ~3.5 s with rise time of 200 ms between the injection energy and top energy. The proposed magnet cycle of 2.5 Hz for the neutrino production operation will reduce the time between the injection and extraction to ~90 ms. The time varying magnetic flux generated by the excitation of the main magnet generates eddy currents in the wall of the vacuum chamber of the circulating beam. The eddy currents generated on the wall of the vacuum chamber have the following adverse effect: (a) ohmic heating on the wall of the vacuum chamber; (b.) introduce magnetic multipoles including dipole field. Experimental measurements of the temperature rise of the vacuum chamber of the AGS have been performed for a single AGS c-type magnet when the coil of the magnet is subject to time varying sinusoidal current and found the rise in temperature is acceptable. Calculations shows that the magnetic multi-pole generated due to the eddy current are low enough not to cause beam instability.

7 CONCLUSIONS

We have produced a design for 1 MW AGS-based neutrino superbeam facility which can be further upgraded to 4 MW by combination of the following improvements 1) increase the AGS intensity to 1.8×10^{14} ppp, and 2) increase the AGS rep rate to 5.0 Hz, 3) raise the proton beam energy to 40 GeV and 4) improve on the horn focusing at the target. The associated problem in beam dynamics, power supply, rf system, beam losses and radiation protection are under study and shown to be feasible if such a capability is required by the physics experiments

Several R&D programs in the design of the superconducting cavity and the irradiation testing of target materials are actively pursued to improve on the design.

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