# INJECTOR LINAC FOR THE BNL SUPER NEUTRINO BEAM PROJECT*

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### *Abstract*

BNL plans to upgrade the AGS proton beam power from the present 0.14 MW to higher than 1.0 MW and beyond for a neutrino facility. We have examined possible upgrade to the AGS accelerator complex that would meet the requirements of the proton beam of 1.0 MW for neutrino superbeam facility. 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. To increase the AGS repetition rate we are proposing to replace booster with a 1.5 GeV linac. We will replace part of existing 200 MeV linac with coupled cavity structure from 116 MeV to 400 MeV and then add an additional 1.1 GeV superconducting linac to reach a final energy of 1.5 GeV for direct H- injection into the AGS. We will present possible choices for the upgrade and our choice and its design.


## INTRODUCTION

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[1,2,3]. 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 neutrino superbeam 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 cycles in the AGS, which takes about 0.6 sec, and is therefore not suited for high average beam power operation. To minimize the injection time to about 1 ms, a 1.5 GeV linac will be used instead. The multi-turn injection from a source of 28 mA and 720 μs pulse width is sufficient to accumulate $0.9\times10^{14}$ particle per pulse in the AGS. The minimum ramp time of the AGS to full energy is presently 0.5 s. This must be reduced down to 0.2 s to reach the required repetition rate of 2.5 Hz to deliver the required 1 MW beam to the target.

Table 1: AGS Proton Driver Parameters.

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

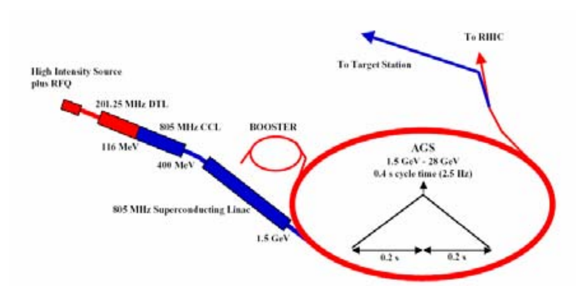


Figure 1: Schematic diagram of the accelerators for the neutrino super beam production.

## INJECTOR LINAC

Two modifications are needed for the injector linac:
(1) Upgrade the 200 MeV linac to 400 MeV. (2) Add superconducting linac to 1.5 GeV or higher energies in the 130 meter space.

### *Present Linac Upgrade to 400 MeV*

The present linac is an Alvaraz-type drift-tube linac (DTL) consisting of nine tanks operating at a frequency of 201.25 MHz that accelerates H- ions to 200 MeV. To achieve 400 MeV, in the same length new structure should have higher accelerating gradients. The choices of technologies were super conducting and warm.

The low velocity super conducting structures which have been primarily developed for heavy ions linacs (half-wave, quarter-wave, spoke resonators, etc) can be envisaged owing to their high accelerating field capabilities. Multi cell elliptical cavities cannot be used for $\beta$ <0.5 because to their poor mechanical stability and their high peak surface field over accelerating field ratio. The spoke resonators are simple, highly mechanical stable

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and compact in size and have achieved quite high accelerating gradient corresponding to peak surface filed of about 40MV/m and 100 mT. However, since an excessive longitudinal phase advance must be avoided, full advantage of the high gradient available with super conducting cavities cannot be taken at low energy. As a result, the energy gain per real estate meter in a super conducting linac is about two times lower than the normal conducting DTL linac in this energy range.

In the warm structure to get higher accelerating gradient there following choices, (1) disk and washer and (2) side coupled cavity. The disk and washer has high efficiency and strong coupling however it mode structure and construction are very complex. The side-coupled linac (CCL) is easy to build, and better understood and has proven.

The last choice has to made is the transition energy between DTL and the CCL. As the particle velocity increases shunt impedance of DTL decreases and shunt impedance of CCL increases, and they cross over about $\beta$=0.4 (100 MeV).

The Fermilab 200 MeV linac was upgraded to 400 MeV by replacing last four DTL tanks with seven 805 MHz coupled cavity linac 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 or we will reduce the peak field to 1.1 Kilpatrick and get about 350 MeV instead of 400 MeV. In the Fermilab design nose corner is not water-cooled. For our 1 ms long RF pulse length nose corner would require redesigning.

### *Superconducting Linac*

SNS studies show that the accelerating H- ions from 400 MeV to 1300 MeV optimized geometric beta for the cavity is 0.81 with the accelerating gradient E0 of 21 MV/m. The optimized beta for the range of 400 MeV to 1500 MeV will be little higher. For accelerating gradient of 31 MV/m, the phase slip per cell for the end cavities at 400 MeV is about 90 degrees for six-cell-cavity, therefore geometric beta cannot be higher than 0.81 at 400 MeV and E0 of 31 MV/m and six cells section. We could choice two geometric beta cavity or six or eight cavity per cryo-module but in the given length and cost minimization, presently our choice one type of beta cavity with geometric beta of 0.81. However we are further looking into it.

### *Warm Insertion*

SNS warm insertion is 1.6 meter long and has the following elements: (1) quadrupole doublets for transverse focusing and both horizontal and vertical steering dipoles for the equilibrium correction, (2) Beam diagnostics like wire scanner, BPM, current monitors, special diagnostics devices, etc, (3) two bellows in the vacuum beam line and a tee for the a flange to accommodate a pumping port and valve for the warm section pump down, (4) a precise alignment system and supporter for quadrupole alignment. We looking into if these warm insertions can be cold, so we have one or two cryo-module rather than 15 cryo-modules to save longitudinal real estate, which is occupied by the cold to warm transition in the SNS/CEBAF style configuration. Primary problems could be with cold quadrupole section are; (1) diagnostics devises, for example wire scanner has to move into in side the cryo-module and in case of wire breaks, (2) quadrupole alignment. TESLA cryo-modules have twelve 9-cell cavity, BPM and quadrupole, but no wire scanner. For now, we have chosen 1.6 meter long SNS style warm insertion.

We have considered FODO lattice instead of doublet lattice to shorten the warm insertion, and found the beam size is twice compared to the doublet lattice, leading aperture to rms beam size ratio of only 6, which is very uncomfortable. So we choose the doublet lattice leaving warm section 1.6 m long.

### *Cryomodule*

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.

In the SCL, each cryomodule consists of four cavities and each cavity consists of six cells. There is a power coupler for each cavity. The cavities are to be immersed in a helium vessel operating at 2.1°K and 0.04 bar. The power couplers are to be cooled by 4.5 °K helium flow at 3 bar. The heat shield is to be cooled between 30 and 50 °K. Based on the SNS design, parameters and heat loads of a cryomodule are given in Table III. The static heat load consists of heat conduction and thermal radiation.

Table 2: 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, $\phi_s$ (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, $\phi_s$ (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 |

The dynamic heat loads results from rf operation. The dynamic heat load is assumed to be 10% of the SNS because the duty cycle for the SCL is about 5% that of SNS.

Table 3: Parameters and heat loads of a cryomodule.

| | |
|---|---|
| Number of cryomodule | 15 |
| Number of Cavity per module | 4 |
| Number of cell per cavity | 6 |
| Length | 7.9 m |
| 2 °K static heat load | 28 W |
| 2 °K dynamic heat load | 3.3 W |
| 4.5 °K static load for coupler | 0.2 g/s |
| 4.5 °K dynamic load for couplers | 0.1 g/s |
| Shield heat load including transfer line | 200 W |

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