BEAM LOSS ESTIMATES AND CONTROL FOR THE BNL NEUTRINO FACILITY*

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Abstract

The requirement for low beam loss is very important both to protect the beam component, and to make the hands-on maintenance possible. In this report, the design considerations to achieving high intensity and low loss will be presented. We start by specifying the beam loss limit at every physical process followed by the proper design and parameters for realizing the required goals. The process considered in this paper include the emittance growth in the linac, the H^- injection, the transition crossing, the coherent instabilities and the extraction losses,

THE SUPERBEAM FACILITY

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 [1].

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 s, 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 0.9×10^{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	0.9×10^{14}
Number of bunches per fill	24
Protons per bunch	0.4×10^{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

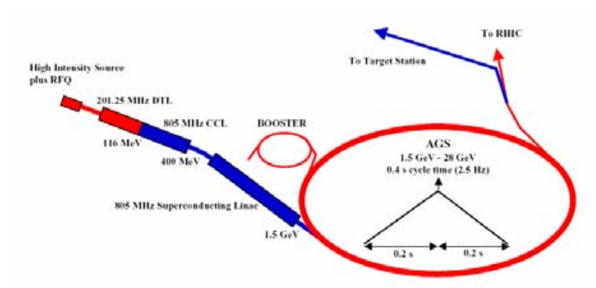

Figure 1. Schematic diagram of the accelerators for the "neutrino production".

BEAM LOSS LIMITS

The most stringent limitations of high power proton accelerators with beam power near or higher than 1.0 MW are the beam losses and its associated performance and safety issues. It is a generally accepted rule of thumb that the uncontrolled losses should be kept to be less than 1W/m. This level of loss would result in about 100 mren/h residual radiation 4 hours after shut down to allow for hands-on maintenance. It would also not damage most of accelerator components. For localized loss point capable of higher losses, such as injection and extraction areas, special collimation and shielding are usually needed.

Following this criteria, we have done systematic studies of possible losses during physics operation. The results are listed in Table 2. There the 1W/m criterion is roughly equivalent to 3×10^{-3}, when translated into percentage of total beam loss distributed along the circumference of the AGS which is 800m. We will present several processes in this report, more detailed discussions are given in reference [1].

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Table 2: Loss limits and estimated losses.

Location	Loss Limit	Estimated Loss
Linac (0.2-1.5 GeV)	$3.0 \mathrm{x} 10^{-3}$	$1.0 \mathrm{~x} 10^{-4}$
HEBT (1.5 GeV)	$1.0 \mathrm{~x} 10^{-3}$	$1.0 \mathrm{~x} 10^{-5}$
Injection (1.5 Gev)	$3.5 \mathrm{~x} 10^{-2}$	$3.0 \mathrm{~x} 10^{-2}$ $1.0\mathrm{x}10^{-2}$ (Controled)
Transition (9.0 GeV)	$5.0 \mathrm{~x} 10^{-3}$	$4.0 \mathrm{~x} 10^{-3}$
Collimators (9.0 GeV)	$3.0 \mathrm{~x} 10^{-3}$	$3.0 \mathrm{~x} 10^{-4}$
Extraction (28 GeV)	$2.5 \mathrm{~x} 10^{-3}$	$1.0 \mathrm{~x} 10^{-3}$
RTBT (28 GeV)	$1.0 \mathrm{~x} 10^{-4}$	$1.0 \mathrm{~x} 10^{-5}$
Target (28 GeV)	1.0	0.25
Decay Channel (28 GeV)	1.0	0.25
Beam Dump	1.0	0.50

INJECTION

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 $\mu g/cm^2$ 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.

A direct effect of linac beam emittance is the halo/tail generation in the circulating beam [2]. Figure 2 shows the estimated halo/tail generation in the beam as a function of normalized RMS emittance of linac beam, using beam parameters given in Table 3. Here, the Halo/tail generation is defined as the ratio of number of particles with emittance larger than the designed acceptance of 49π mm-mrad to the total number of particles in the circulating beam. The existing ion source and RFQ has to be relocated next to DTL tank 1 to meet emittance requirement for the AGS injection with low loss [3].

Table 3: Simulation parameters.

Horizontal beta at the injection	28.0 m
Vertical beta at the injection	8.0 m
Horizontal emittance of injected beam	2π mm-mrad
Vertical emittance of injected beam	2π mm-mrad
Horizontal beam size at injection, σ_x	5.2293 mm
Vertical beam size at injection, σ_y	2.7952 mm
Horizontal Foil size (2.5 σ_x)	13.0731 mm
Vertical foil size (2.5 σ_y)	6.9878 mm

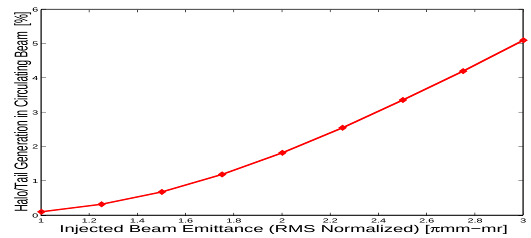

Figure 2: The estimated halo/tail generation in the circulating beam as functions of normalized RMS emittance of injected beam.

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. In addition to the final emittance in the AGS, The total loss during injection is also of great concern. The beam loss during the injection process is about 1.8 W/m compared to 4.0 W/m for SNS as shown in Table 4. Since this is a localized loss, special collimation and shielding have to be provided.

Table 4: Beam loss at injection.

	SNS	1MW AGS
Beam power, Linac Exit, kw	1000	50
Kinetic Energy, MeV	1000	1200
Number of Proton N_p, 10^{12}	100	100
Vertical Acceptance A, πμm	480	55
$\beta^2\gamma^3$	6.75	9.56
$N_p/(\beta^2\gamma^3\ A)$, 10^{12}/πμm	0.031	0.190
Total Beam Loss, %	0.1	3
Total Beam Loss Power, W	1000	1440
Circumference, m	248	807
Loss Power per meter, W/m	4.0	1.8

TRANSITION

The proton beam crosses the transition energy at γ_t = 8.5. During a non- adiabatic time ±Tc, 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%[4]

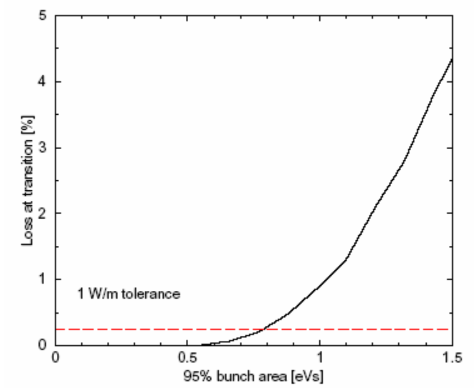

Figure 3: Expected fractional beam loss during transition as a function of the initial (95%) longitudinal beam area obtain with computer code TIBETAN.

INSTABILITIES

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 some 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 x 1013 is only marginally higher than the current intensity of 7.3 x 1013. The beam instability during acceleration and transition crossing can be avoided.

Given high intensity, the bunch spacing is the most crucial parameter in possible electron multipacting. In RHIC, with bunch spacing 108 ns, weak electron multipacting was observed at cold regions, at the bunch intensity of 2x 10^{11} protons. The electron cloud caused some pressure rise, but no head load observed. At KEK PS, electron multipacting has been observed by electron detectors, at the beam transition and top energy [5]. For the PS at KEK, the revolution time is 1.13 µs, with 9 bunches in the ring, the bunch spacing is 126ns. Bunch intensity is 4 x 10^{11} protons. The electron cloud is visible, but weak, making little damage to the operation. However, it is uncertain what will happen if the bunch intensity become much higher.

To raise the AGS RF voltage to 1 MV, with limited space in the AGS, it is necessary to use the harmonic number 24. With the revolution time of 2.7 µs, this implies that the bunch spacing will be 117 ns. For the AGS with 24 bunches, the bunch intensity will be 3.9 x 10^{12} protons with the bunch length of 16 ns at the transition and 17 ns at the extraction. The electron cloud effect needs to be studied by more machine experiments and computer simulations to assure reliable operation.

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.

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