UPGRADING THE AGS TO 1 MW PROTON BEAM POWER *

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Abstract

The Brookhaven Alternating Gradient Synchrotron (AGS) is a strong focusing accelerator that is used to accelerate protons and various heavy ion species to an equivalent proton energy of 29 GeV. At this energy the maximum intensity achieved is around 7 x 10^{13} protons per pulse. This corresponds to an average beam power of about 0.2 MW. Future programs in high-energy physics, as for instance a neutrino factory with the AGS as the proton driver [1], may require an upgrade of the AGS to an average beam power of 1 MW, at the energy of 24 GeV. This can be achieved with an increase of the beam intensity to 1 x 10^{14} protons per pulse, a 1.2-GeV super-conducting linac as a new injector, and by upgrading the power supply and rf systems to allow cycling at 2.5 beam pulses per second.

1 INTRODUCTION

We have examined [1] possible upgrades to the AGS complex that would meet the requirements for the proton beam for neutrino factory operation. Those requirements are summarized in Table 1 and a layout of the upgraded AGS is shown in Figure 1. Since the present number of protons per fill is already close to the required number, the upgrade will focus on increasing the repetition rate and on reducing beam losses to avoid excessive shielding requirements and to maintain the machine components serviceable by hand. It is also important to maintain all the present capabilities of the AGS, in particular its role as injector to RHIC.

The AGS Booster was built to allow the injection of any species of heavy ion into the AGS but also allowed a four-fold increase of the AGS intensity since it is one quarter the size of the AGS with the same aperture. However, the accumulation of four Booster loads in the AGS take precious time and is not well suited for high average beam power operation.

We are proposing here to built a super-conducting upgrade to the existing 200 MeV Linac to an energy of 1.2 GeV for direct H^- injection into the AGS. This will be discussed in section 2. The minimum ramp time to full energy is presently 0.5 s, which will have to be upgraded to reach the required repetition rate of 2.5 Hz. Since the six bunches have to be extracted one bunch at a time, a 100-ms flattop has to be included which leaves in fact only 150 ms for the ramp up or ramp down cycle. The required upgrade of the AGS power supply will be described in section 3. Finally, the increased ramp rate and the final bunch compression requires a substantial upgrade to the AGS rf system. This will be discussed in section 4.

Table 1. AGS Proton Driver Parameters

Total beam power	1 MW
Beam energy	24 GeV
Average beam current	42 μA
Cycle time	400 ms
Number of protons per fill	1×10^{14}
Average circulating current	6 A
Number of bunches per fill	6
Protons per bunch	1.7×10^{13}
Time between bunches	20 ms
Rms bunch length	3 ns
Peak bunch current	400 A
Total bunch area	5 eVs
Rms bunch emittance	0.4 eVs
Rms momentum spread	0.5 %

The front end consists of a high-intensity negative-ion source, followed by a 750 keV RFQ, and the first 5 tanks of the existing room temperature Drift-Tube Linac (DTL) to accelerate protons to 116 MeV. The SCL is made of three sections, each with its own energy range, and different cavity-cryostat arrangement.

Table 2. AGS Injection Parameters

Injection turns	360
Repetition rate	2.5 Hz
Pulse length	1.08 ms
Chopping rate	0.65
Linac aver./peak current	20 / 30 mA
Momentum spread	± 0.15 %
Norm. 95% emittance	12 πμm
RF voltage	450 kV
Bunch length	85 ns
Longitudinal emittance	1.2 eVs
Momentum spread	± 0.48 %
Norm. 95% emittance	100 πμm

The proposed new injector for the AGS is a 1.2-GeV super-conducting linac upgrade with an average output beam power of about 50 kW. The injection energy is still low enough to control beam losses due to stripping of the negative ions that are used for multi-turn injection into the AGS. The duty cycle is about 0.5 %. The injection into the AGS is modeled after the SNS [2]. However, the

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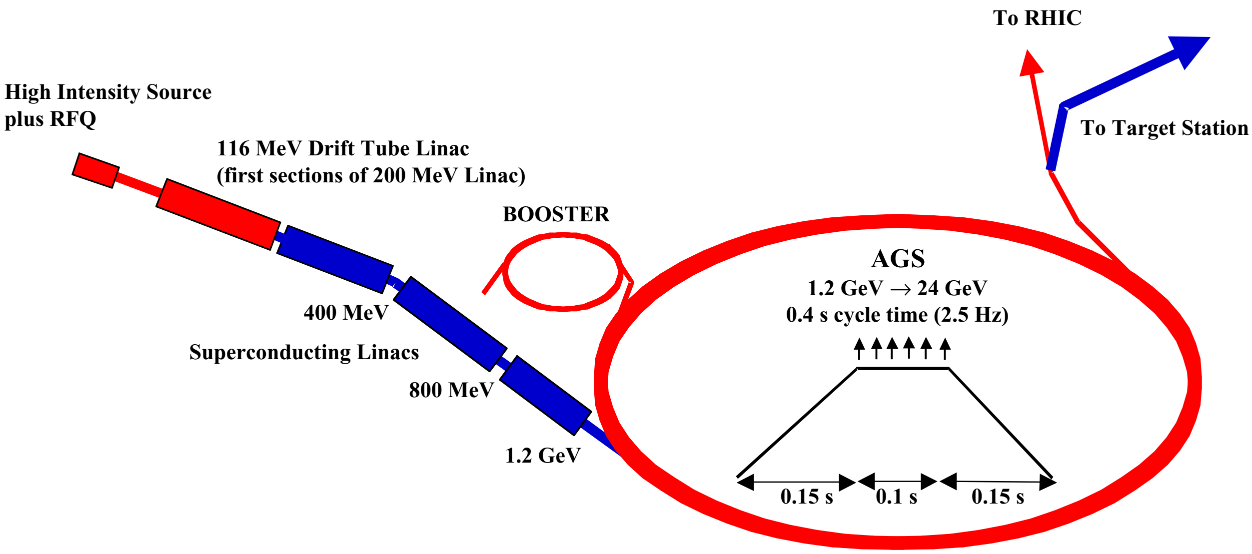

Figure 1. AGS Proton Driver Layout

repetition rate and consequently the average beam power is much lower. The larger circumference of the AGS also reduces the number of foil traversals. Beam losses at the injection into AGS are estimated to be about 3 % of controlled losses and 0.3 % of uncontrolled losses [1]. The AGS injection parameters are summarized in Table 2.

2 SUPERCONDUCTING LINAC

The super-conducting linacs accelerate the proton beam from 116 MeV to 1.2 GeV. The presented configuration follows a similar design described in detail in [3,4]. All three linacs are built up from a sequence of identical periods. Each period is made of a cryo-module and a room-temperature insertion that is needed for the placement of focusing quadrupoles, vacuum pumps, steering magnets, beam diagnostic devices, bellows and flanges. The cryo-module includes 4 identical cavities, each with 4 or 8 identical cells.

The choice of cryo-modules with identical geometry, and with the same cavity/cell configuration, is economical and convenient for construction. But there is, nonetheless, a penalty due to the reduced transit-time-factors when a particle crosses cavity cells, with lengths adjusted to a common central value β_0 that does not correspond to the particle's instantaneous velocity. This is the main reason to divided the super-conducting linac into three sections, each designed around a different central value β_0, and, therefore, with different cavity/cell configurations. The cell length in a section is fixed to be $\lambda\, \beta_0 / 2$ where λ is the rf wavelength.

The major parameters of the three sections of the SCL are given in Table 3. The low energy section operates at 805 MHz and accelerates from 116 to 400 MeV. The following two sections, accelerating to 800 MeV and 1.2 GeV respectively, operate at 1.61 GHz. A higher frequency is desirable for obtaining a larger accelerating gradient with a more compact structure and reduced cost.

Table 3. Parameters of the Super-Conducting Linac

	Low	Medium	High
Beam Power, kW	16	32	48
Kinetic Energy, MeV	116-400	400-800	800-1200
Velocity, cβ	0.4560	0.7131	0.8418
	0.7131	0.8418	0.8986
Frequency, MHz	805	1610	1610
Protons / μBunch, 10^8	9.32	9.32	9.32
Temperature, °K	2.0	2.0	2.0
Cells / Cavity	4	8	8
Cavities / Cryo-Module	4	4	4
Cell Length, cm	9.68	6.98	8.05
Cell reference velocity, $c\beta_0$	0.520	0.750	0.865
Cavity internal diameter,	10	5	5
Cavity Separation, cm	32	16	16
Cold-to-Warm transition,	30	30	30
Acceler. Gradient, MeV/m	11.9	22.0	21.5
Cavities / Klystron	4	4	4
No. of Klystrons	18	10	9
Klystron Power, kW	720	1920	2160
Energy Gain / Period, MeV	16.0	42.7	48.0
Length of a period, m	4.2	4.4	4.7
Total length, m	75.4	43.9	42.6

The local gradient has a maximum value that is limited by three causes: (1) The surface field limit at the frequency of 805 MHz is taken to be 26 MV/m. For the following two sections the surface field limit at 1.61 GHz is 40 MV/m. (2) The rf couplers can provide at most an rf power of 400 kW. (3) To make the longitudinal motion stable, we can only apply an energy gain per cryo-module that is a relatively small fraction of the beam energy [3].

For the pulsed-mode of operation of the super-conducting cavities the Lorentz forces could deform the cavity cells enough to detune them off resonance. This has to be controlled with a thick cavity wall and additional supports. Also, a significant time to fill the cavities with rf power is required before the maximum gradient is reached and beam can be injected. The expected fill time is short compared to the beam pulse length of 1 ms.

3 AGS MAIN POWER SUPPLY UPGRADE

The AGS ring consists of 240 magnets hooked up in series with a total resistance R = 0.27 Ω and a total inductance L = 0.75 H. There are 12 super-periods of 20 magnets each. Two stations of power supplies are each capable of delivering up to 4500 V and 6000 A. The two stations are connected in series and the magnet coils are arranged to have a total resistance R/2 and a total inductance of L/2. The grounding of the power supply is done only in one place, in the middle of station 1or 2 through a resistive network. With this grounding configuration, the maximum voltage to ground in the magnets will not exceed 2500 Volt. The magnets are hi-potted to 3000 Volt to ground, prior of each starting of the AGS MMPS after long maintenance periods.

To cycle the AGS ring to 24 GeV at 2.5 pulses per second and with ramp time of 150 ms, the magnet peak current is 4300 Amp and the peak voltage is 25 kV. The cycle includes a 100 ms flat-top for the six single-bunch extractions. The total average power dissipated in the AGS magnets has been estimated to be 3.7 MW. To limit the AGS coil voltage to ground to 2.5 kV the AGS magnets will need to be divided into six identical sections, each powered similarly to the present half AGS power system, except that now the magnet loads is 1/6 of the total resistance and inductance. In this manner we will have six identical stations of power supplies as one existing station, all hooked up in series**.** Note that only station 1 will be grounded as it is done presently.

The peak power required is approximately 110 MW exceeding the 50 MW rating of the existing motor generator. The new motor-generator should also operate with 6 or 12 phases to limit or even eliminate phase-shifting transformers so that every power supply system generates 24 pulses. The generator voltage may have to be around 15 kV line-to-line. In this case the generator current is approximately equal to the magnet current as it is presently the case. Also, the generator needs to be rated at a slip frequency of 2.5 Hz.

Running the AGS at 2.5 Hz requires that the acceleration ramp period decreases from 0.5 sec down to 0.15 sec. That is, the magnet current variation dI/dt is about 3.3 times larger than the present rate. Eddy-current losses on the vacuum chamber are proportional to the square of dI/dt, that is 10 times larger. However, this still significantly smaller than the present ramp rate of the AGS Booster and does not require active cooling.

4 AGS RF SYSTEM UPGRADE

At 2.5 Hz the peak acceleration rate is three times the present value for the AGS. With 10 accelerating stations each station will need to supply 270 kW peak power to the beam. The present power amplifier design, employing a 300 kW power tetrode will be suitable to drive the cavities and supply power to the beam. The number of power amplifiers will be doubled so that each station is driven by two amplifiers of the present design. This follows from the necessity to supply 2.5 times the rf voltage. An AGS rf station comprises four acceleration gaps surrounded by 0.35 m of ferrite stacks. The maximum voltage capability of a gap is limited by the ability of the ferrite to supply the magnetic induction. When the AGS operates at 0.5 Hz the gap voltage is 10 kV. At 2.5 Hz we will need up to 25 kV per gap and this taxes the properties of the ferrite. Above a certain threshold value of B_{rf} (20 mT for AGS ferrite 4L2) a ferrite becomes unstable and excessively lossy. The only free variable is the rf frequency. If we operate the rf system at the 24th harmonic of the revolution frequency (9 MHz) then the required voltage of 25 kV can be achieved with a safe value for B_{rf} of 18 mT.

The next concern is the power dissipation in the ferrite and the thermal stress that is created by differential heating due to rf losses in the bulk of the material. We know from experience that below 300 mW/cm^3 ferrites can be adequately cooled. The power density is also proportional to B_{rf}^2 and depends on the quality factor μQ of the ferrite. We have data on ferrite 4M2 (used in the Booster and SNS) at 9 MHz and 20 mT where the power dissipation is 900 mW/cm^3. The details of the acceleration cycle determine the rf voltage program that is needed. For the proposed cycle a peak voltage of 1 MV (40 gaps each with 25 kV) is needed but for only 20 ms during acceleration. An additional 100 ms operation at 1 MV is required for the bunch compression. Together this is a duty factor of less than 0.3 giving an average power dissipation of less than the limit.

With the rf system operating on harmonic 24 there will be 24 rf buckets but we need all the beam in 6 bunches to extract to the production target. This can be arranged by filling 18 of the 24 buckets with 6 triplets of bunches. At the end of the acceleration cycle the triplets will be merged adiabatically into 6 single bunches [6] using separate 100 kV/turn harmonic 6 rf cavities. The final bunch emittance would be at least 5 eVs per bunch after the 3-to-1 bunch merge. With 100 kV/turn of the harmonic 6 rf system the total bunch length will be 80 ns for a 5 eVs bunch. The rf system will then be switched back to harmonic 24 and 1 MV/turn where the bunch is now mismatched. By strongly modulating the rf voltage with a frequency close to twice the synchrotron frequency the tumbling bunch can be kept from de-cohering.

5 REFERENCES

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