AGS Proton Driver

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Abstract..

1. INTRODUCTION

After more the 40 years of operation the AGS is still at the heart of the Brookhaven hadron accelerator complex which presently consists of a 200 MeV Linac for the pre-acceleration of high intensity and polarized protons, two Tandems 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. For several years now the AGS is holding the world intensity record with more than 7×10^{13} protons accelerated in a single pulse.

We are examining here the 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 superconducting upgrade to the existing 200 MeV Linac to an energy of 1.2 GeV for direct H minus 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 extracted one bunch at a time, as is presently done for the operation of the g-2 experiment, 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 a three-fold 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. The final section describes possible upgrade paths towards a 4 MW operation.

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 x 1014
Average cicrculating current	5.3 A
Number of bunches per fill	6
Number of protons per bunch	1.7 x 1013
Time between extracted bunches	20 ms
Rms bunch length at extraction	3 ns
Peak bunch current	400 A
Total bunch area	5 eVs
Rms bunch emittance	0.4 eVs
Rms momentum spread	0.5 %

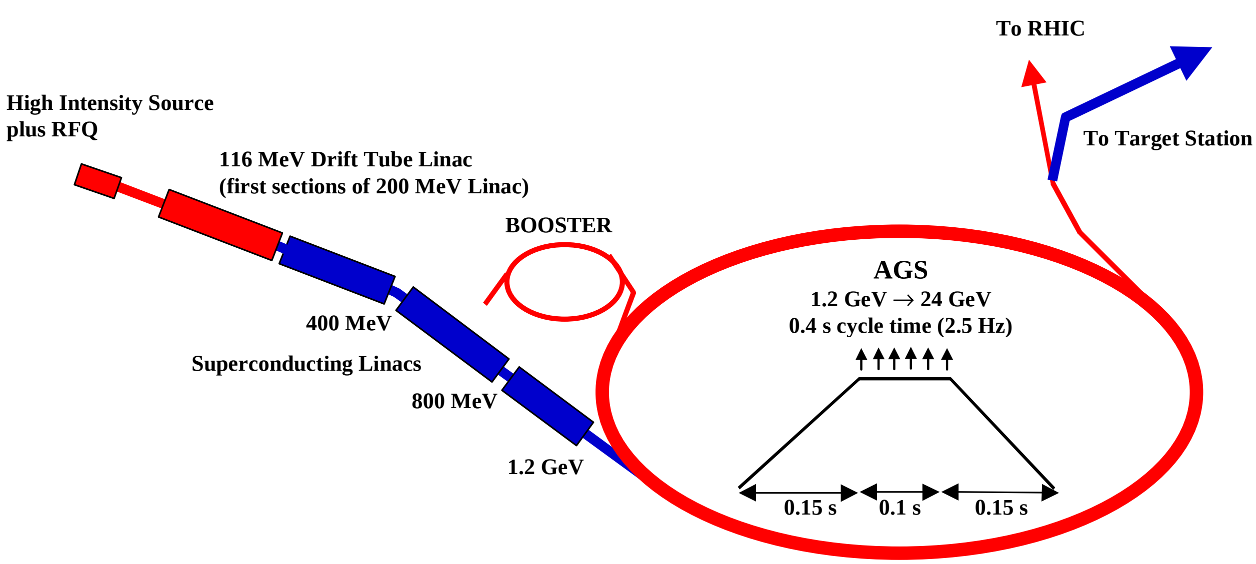

Figure 1. AGS proton driver layout

The front end consists of the existing high intensity negative-ion source, followed by the 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.

The front-end of the Linac is made of an ion source operating with a 0.25% duty cycle at the repetition rate of 2.5 Hz. The beam current within a pulse is 37.5 mA of negative-hydrogen ions. The ion source seats on a platform at 35 kVolt. The beam is pre-chopped by a chopper located between the ion source and the RFQ. The beam chopping extends over 65% of the beam length, at a frequency matching the accelerating rf at injection into the AGS. Moreover, the transmission efficiency through the RFQ is taken conservatively to be 80%, so that the average current of the beam pulse in the Linac, where we assume no further beam loss, is 25 mA.

The combination of the chopper and of the RFQ pre-bunches the beam with a sufficiently small longitudinal extension so that each of the beam bunches can be entirely fitted in the accelerating rf buckets of the following DTL that operates at 201.25 MHz. The DTL is a room temperature conventional Linac that accelerates to 116 MeV.

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 0.25 %. The injection into the AGS is modeled after the SNS. However, the 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 2% of cotrolled losses and 0.2 % of uncontrolled losses. This is based on a comparison with the actual experience in the AGS Booster and the predicted losses at the SNS using the quantity $N_P / (\beta^2\gamma^3 A)$, which is proportional to the Laslett tune shift, as a scaling factor. This is summarized in Table 2. As can be seen the predicted 2% beam loss is consistent with both the AGS Booster experience and the SNS prediction.

TABLE 2. Comparison of H minus injection parameters

	AGS Booster	SNS	1 MW AGS
Beam power, Linac exit, kW	N/A	1000	54
Kinetic Energy, MeV	200	1000	1200
Number of Protons N_P, 10^{12}	15	200	100
Vertical Acceptance A, π mm-mrad	192	480	108
$\beta^2\gamma^3$	0.57	6.75	9.56
$N_P / (\beta^2\gamma^3 A)$, $10^{12} / \pi$ mm-mrad	0.136	0.062	0.097
Total Beam Losses, %	5	0.1	2

The AGS injection parameter are summarized in Table 3. The result of a simulation of the 360 turn injection process with a two-harmonic rf system is shown in Figure 2 resulting in a longitudinal emittance of 4.2 eVs per bunch. Such a small emittance is important to limit beam losses during transition crossing and to allow for effective bunch compression before extraction from the AGS.

TABLE 3. AGS injection parameter

Injection turns	360
Repetition rate	2.5 Hz
Pulse length	1.05 ms
Chopping rate	0.65

Linac peak current	25 mA
Momentum spread	± 0.2 %
Norm. 95% emittance	12 πμm
RF voltage	100 kV
Bunch length	324 ns
Longitudinal emittance	4.2 eVs
Momentum spread	± 0.44 %
Norm. 95% emittance	100 πμm

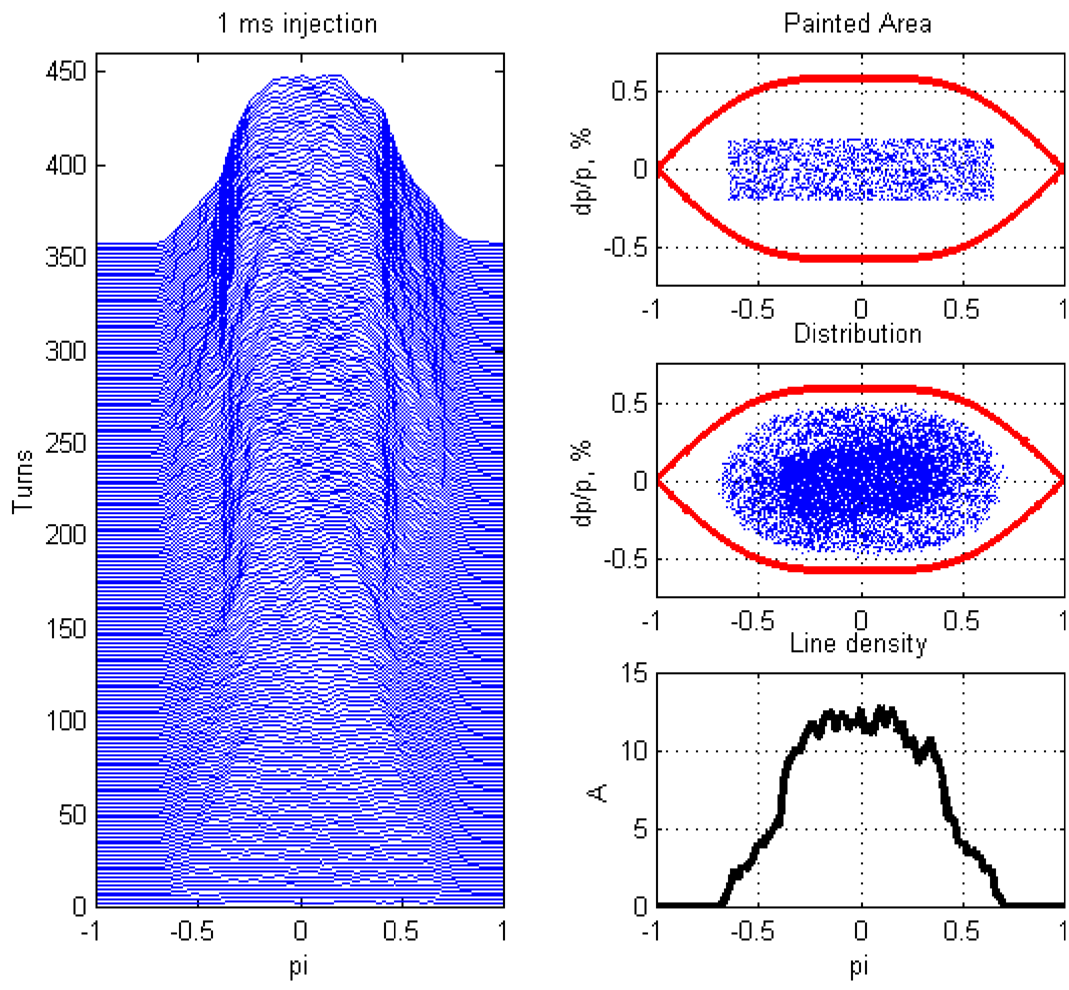

Figure 2. AGS injection with double RF

Since the intensity of 1×10^{14} is only marginally higher than the present intensity of 7×10^{13} no new instabilities are expected during acceleration and transition crossing. However, significant more rf voltage per turn and rf power will be required. This will be addressed in section 4.

2. SPERCONDUCTING 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 [1]. All three linacs are built up from a sequence of identical periods as shown in Figure 2. 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.

FIGURE 2. Configuration of the cavities within the cryo-modules (cryostats)

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 superconducting 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

$$\frac{l \cdot \beta_0}{2}$$

where l is the rf wavelength.

The major parameters of the three sections of the SCL are given in Table 2. Transverse focussing is done with a sequence of FODO cells with half-length equal to that of a period. The phase advance per cell is 90 degrees . The rms normalized betatron emittance is 0.3 π mm-mrad. The rms bunch area is 0.5 π degree MeV. The rf phase angle is 30 degrees .

The length of the Linac depends on the average accelerating gradient. The local gradient has a maximum value that is limited by three causes: (1) The surface field limit is taken to be 26

MV/m. For a realistic cavity shape, we set a limit of a 13 MV/m on the axial electric field. (2) There is a limit on the power provided by rf couplers that we take here not to exceed 400 kW, including a contingency of 50% to avoid saturation effects. (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 in exit of the cryo-module. The conditions for stability of motion have been derived in ref. [1].

The proposed mode of operation is to operate each section of the SCL with the same rf input power per cryo-module. This will result in some variation of the actual axial field from one cryo-module to the next. If one requires also a constant value of the axial field, this could be obtained by adjusting locally the value of the rf phase.

For the pulsed-mode of operation of the superconducting 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.

TABLE 2. Parameters of the super-conducting linacs

	Low energy	Medium energy	High
Beam power, Linac exit, kW	18	36	54
Kinetic Energy Range, MeV	116 … 400	400 … 800	800 … 1200
Velocity Range, c	0.4560…0.7131	0.7131…0.8418	0.8418…0.9017
Frequency, MHz	805	1610	1610
Protons / μBunch, 10^8	2.33	2.33	2.33
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	0.520	0.750	0.865
Cavity internal diameter, cm	10	5	5
Cavity Separation, cm	32	16	16
Cold-to-Warm transition, cm	30	30	30
Accelerating Gradient, MeV/m	11.9	22.0	21.5
Cavities / Klystron	4	4	4
No. of Klystrons (or periods)	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

3. AGS MAIN POWER SUPPLY UPGRADE

Present Mode of Operation

The present AGS Main Magnet Power Supply (MMPS) is a fully programmable 6000 A , ±9000 V SCR power supply. A 9-MW Motor Generator, made by Siemens, is a part of the main magnet power supply of the accelerator, which allows to pulse the main magnets up to 50 MW electric peak power, while the input power of the motor generator remains constant. The maximum power into the motor ever utilized is 7 MW, that is the maximum average power dissipated in the AGS magnets did never exceed 5 MW.

The AGS ring consists of 240 magnets hooked up in series. The total resistance R is 0.27 ohm and the total inductance L is 0.75 henry. There are 12 super-periods, A through L, of 20 magnets each, divided in two identical sets of 10 magnets per super-period.

Two stations of power supplies are each capable of delivering up to 4500V 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. Figure 3 displays the magnet current, voltage of a 2.5-Hz cycle. 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 three identical sections, each powered similarly to the present whole AGS except that now the magnet loads is 1/6 of the total resistance and inductance. Every section will have to be powered separately with its own feed to the ring magnets and an identical system of power supplies, as shown in Figure 4**.**

Figure of AGS mmps cycle

FIGURE 3. Current and voltage cycle for 2.5 Hz operation. Also shown are the AGS dipole field and average power.

Although the average power is not higher than now the peak power required is approximately 100 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 will have to be around 30 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.

Figure of power supply connection to AGS magnets

FIGURE 4. Schematic of power supply connections to the AGS magnets for the 2.5 Hz operation

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. Also, the increased eddy-currents will increase the sextupole fields during the ramp and will add about 20 units of chromaticity. The present chromaticity sextupoles will probably have to upgraded to correct this.

4. AGS RF SYSTEM UPGRADE

5. UPGRADE TO 4 MW

An upgrade to 4 MW beam power is possible by increasing the linac energy to 1.5 GeV, which allows for doubling the number of protons per pulse to 2×10^{14}, and upgrading the AGS repetition rate to 5 Hz. To achieve the required bunch length compression a separate "compressor ring" will be needed.

Compressor ring parameter

Circumference	200	m
Bending field	4.15	Tesla
Kinetic energy	24	GeV
Transition gamma	38.4	
eta	-0.00074	
Betatron tune, x/y	14.8/9.2	
Maximum beta function, x/y	12.9/19.8	m
Dispersion function	0.12	m
Chamber radius	25	mm
Maximum beam radius, x/y	7.0/8.6	mm
Acceptance, x/y	48.5/31.6	πμm
Beam emittance, x/y	3.8/3.8	πμm
Accp./emit. ratio, x/y	12.8/8.3	
Natural chromaticity, x/y	-2.5/-1.7	(norm)

- Operated below transition.
- Very small slippage factor, quasi-isochronous ring.
- Very small dispersion.
- Acceptance/emittance ratio > 8, with the consideration of extremely tight beam loss limit.
- Chromaticity needs to be corrected.

RF parameter

RF frequency	5.94	MHz
Harmonic number	4	

RF Voltage	200	KV
Bucket height, in dp/p	$\pm$4.2	%
Bucket area	222	eVs
Bunch area	10	eVs
Synchrotron frequency, center	91.5	Hz
Synchrotron frequency, edge	82.6	Hz

- Bunch is injected from the AGS, unmatched. It is extracted immediately after a bunch rotation.
- Very low RF voltage required, because of the very small slippage. For the same bucket height, RF voltage in the AGS needs to be 5.3 MV.
- Bunch rotation takes a quarter of synchrotron period, i.e. 3 ms, or 4500 turns.

Longitudinal aspect

	Inj.	Ext.	
Particle per bunch	0.17	0.17	10^{14}
Bunch rms length	5/17	0.9/3	m/ns
Peak current	65	363	A
Beam momentum spread	$\pm$0.4	$\pm$2.24	%
Longitudinal emittance	10.5	10.5	eVs
Broadband impedance	5	5	j Ω
Long. space charge imp.	-1.66	-1.66	j Ω
Keil-Schnell threshold	3.75	25.5	Ω
Effective RF voltage	200	248	KV

- Longitudinal microwave instability threshold is low at the injection, because of the small slippage factor and low dp/p.
- Bellows will not be shielded, in order to avoid finger contact arcing, but the chamber steps will be tapered. Broadband impedance of j 5 Ω is reasonable to achieve.
- Combination of the broadband and space charge impedance is j3.34 Ω, slightly lower than the K-S threshold. Since it is below the transition, beam instability is not expected.
- The overall inductive impedance below the transition has a focusing effect, which is shown as the increase of the effective RF voltage in the bunch rotation.

Transverse aspect

	Inj.	Ext.	
Broadband impedance	0.51	0.51	jMΩ/m
BB imp. induced tune shift	0.0003	0.0017	
Space charge inc. tune spread	0.003	0.016	

Chromatic tune spread, $\xi = 2$	0.22	1.32	
Chromatic frequency, $\xi = 2$	59.4	59.4	GHz

- Transverse impedance is low for compressor ring, $Z_T \propto R$.
- Strong focusing also helps for less tune shift.
- Comparing to the AGS, the beam is transversely more stable. This is just opposite to the longitudinal instability.
- Space charge incoherent tune spread is small.
- But if the chromaticity is not corrected, the chromatic tune spread is large.
- Chromatic frequency is very large, because of the small slippage factor, the high revolution frequency, and the high tune.
- Normalized chromaticity may need to be controlled within the range of 1%.

Conclusion

- The scheme of 1 MW proton driver is feasible.
- AGS beam intensity is modestly higher than the normal high intensity proton operation. Since the proposed beam emittance is larger, the beam instability is not expected to be a problem.
- Beam loss limit is tight at the AGS, which may require some upgrade.
- Compressor ring design requires very low RF voltage. Also the potential well effect helps for the short bunch production.
- Required impedance is reasonable to achieve.
- Acceptance/emittance ratio of 8 is much larger than the existing and proposed high intensity proton accelerators. Together with the large momentum aperture, the beam loss can be controlled.
- Chromaticity control at the compressor ring is tight, and may need some study.

REFERENCES

1. A. Ruggiero, "Design Considerations on a Proton Superconducting Linac" BNL Internal Report 62312, 1995.