AGS UPGRADE TO 1-MW WITH A SUPER-CONDUCTING LINAC INJECTOR*

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Abstract

It has been proposed to upgrade the Alternating Gradient Synchrotron (AGS) accelerator complex at the Brookhaven National Laboratory (BNL) to provide an average proton beam power of 1 MW at the energy of 28 GeV. The facility is to be primarily used as a proton driver for the production of intense neutrino beams [1]. This paper reports on the feasibility study of a proton Super-Conducting Linac (SCL) as a new injector to the AGS. The Linac beam energy is 1.2 GeV. The beam intensity is adjusted to provide the required average beam power of 1 MW at 28 GeV. The repetition rate of the SCL-AGS facility is 2.5 beam pulses per second.

INTRODUCTION

The AGS upgrade requires operation of the accelerator at the rate of 2.5 cycles per second, and a new injector capable to follow the operation at 2.5 Hz. The present injector made of the 200-MeV room-temperature Linac and of the 1.5-GeV AGS-Booster will not be able to achieve the goals of the upgrade.

The proposed new injector is a 1.2 GeV Super-Conducting Linac (SCL) with an average output beam power of 45 kW. The choice of the energy value is determined in part by the capability to limit beam losses due to stripping of the negative ions that are used for multi-turn injection into the synchrotron, and in part to fit the entire SCL on a straight line between the exit of the 200-MeV room-temperature Linac and the injection point selected into the AGS.

The SCL is composed of three parts: (i) a Front-End, that is the present 100-mA negative-ion source, followed by the 0.75-MeV RFQ, (ii) the room-temperature Linac that accelerates protons to 200 MeV, and (iii) the SCL proper. This in turn is made of three sections, each with its own energy range, excitation RF frequency, and different cavity-cryostat arrangement. The three sections are labeled: Low-Energy (LE), Medium-Energy (ME), and High-Energy (HE). The beam leaves the present room-temperature Linac at the energy of 200 MeV, and, after a bend of 17.5°, enters a straight tunnel, where the SCL proper is located, about 120 meter long, to join the AGS tunnel. A schematic view of the new injector is given in Figure 1. The main injector and AGS parameters are given in Table 1.

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THE NEW INJECTOR

The project described corresponds to an average SCL beam current of 37.6 μA, that yields the required average beam power of 1 MW at the top energy of 28 GeV, including also a controlled beam loss of about 5% during multi-turn injection into the AGS. The average beam power in exit is 45 kW, considerably less than the 1-MW level of the equivalent 1.0-GeV SCL for the Spallation Neutron Source (SNS) [2]. Thus the concern about component activation by the induced radiation from uncontrolled beam losses is greatly reduced. The repetition rate of 2.5 beam pulses per second gives a beam intensity of 0.94 x 10^{14} protons accelerated per AGS cycle; that is about 30% higher than the intensity routinely obtained with the present injector. At the end of injection, that takes about 240 turns, the space-charge tune depression is $\Delta\nu = 0.2$, assuming a bunching factor (the ratio of beam peak current to average current), during the early part of the acceleration cycle, of 4. Also, with the normalized beam emittance of 100 π mm-mrad, the actual beam emittance at 1.2 GeV is $\varepsilon = 50\ \pi$ mm-mrad. The SCL beam pulse length is 0.72 ms, and the beam duty cycle 0.18%.

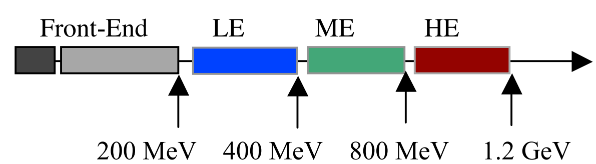

Figure 1. Schematic of the new AGS Injector.

The front-end of the Linac is made of the present ion source with minor power supply modifications to operate with a longer pulse width. The ion source is located on a platform at 35 kV, and is followed by the 0.75-MeV RFQ that works at 201.25 MHz. The beam is to be periodically chopped by a chopper located downstream the RFQ. The beam chopping extends over 75% of the beam extension, at a frequency matching the AGS accelerating rf (8.0 MHz, harmonic number = 24) at injection into the AGS. Moreover, the transmission efficiency through the RFQ and the DTL is low, so that at present a beam current of 35 mA can be achieved at 200 MeV. Thus we assume that the average current of the beam pulse in the SCL, where we assume no further beam loss, is conservatively 21 mA.

The combination of the RFQ and of the subsequent bunchers bunches the beam with a sufficiently small longitudinal extension so that each of the beam bunches at 201.25 MHz can be reasonably fitted in the accelerating rf buckets of the following room-temperature Linac that operates also at 201.25 MHz. The required modifications and cost of the Front-End and the 200-MeV room-temperature Linac are described elsewhere [3]. The design of the transfer of the beam from the exit of the SCL to the injection location into the AGS is given in [4], whereas the process of injection proper into the AGS is described in [5].

Table 1. Injector and AGS Parameters for 1-MW Upgrade

Increm. Linac Ave. Power, kW	37.5
Kinetic Energy, GeV	1.2
β	0.8986
Momentum, GeV/c	1.92
Magnetic Rigidity, T-m	6.41
Repetition Rate, Hz	2.5
Linac Average Current, μA	37.6
Linac No. of Protons / pulse	9.38×10^{13}
AGS Circumference, m	807.076
Revol. Frequency, MHz	0.3338
Revolution Period, μs	2.996
Bending Radius, m	85.378
Injection Field, kG	0.7507
Chopping Ratio, %	75
Peak Current, mA	28
Average Current, mA	21
Injection Loss, %	5.0
Injected Protons per Turn	3.74×10^{11}
Number of injected Turns	239
Linac Pulse Length, ms	0.716
Linac Duty Cycle, %	0.179
Bunching Factor	4
Norm. Emitt., π mm-mrad	100
Emittance, π mm-mrad	48.8
Space-Charge $\Delta\nu$	0.187

THE SUPER-CONDUCTING LINAC (SCL)

The SCL accelerates the proton beam from 200 MeV to 1.2 GeV. The configuration and the design procedure of the SCL is described in detail in [6]. It is typically a sequence of a number of identical periods as shown in Figure 2. Each period is made of a cryo-module of length L_{cryo} and of an insertion of length L_{ins}. The insertion is needed for the placement of focusing quadrupoles, vacuum pumps and valves, steering magnets, beam diagnostic devices, bellows, and flanges. It can be either at room temperature or in a cryostat as well. Here we assume that the insertions are at room temperature. The cryo-module includes M identical cavities, each of N identical cells, and each having a length NL_{cell}, where L_{cell} is the length of a cell. To avoid coupling by the leakage of the field, cavities are separated from each other by a sufficiently long drift space d. An extra drift of length L_w may be added internally on both sides of the cryo-module to provide a transition between cold and warm regions. Thus, the length of a cryo-module is

$$L_{cryo} = MN\,L_{cell} + (M-1)\,d + 2\,L_w$$

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 length adjusted to a common central value β_0 that does not correspond to the particle instantaneous velocity. To minimize this effect, the SCL is divided in three sections, each designed around a different central value β_0, and, therefore, with different cavity/cell configuration. The cell length in a section is fixed to be

$$L_{cell} = \lambda\beta_0 / 2$$

where λ is the RF wavelength. We adopted an operating frequency of 805 MHz for the LE-section of the SCL, and 1,610 MHz for the subsequent two sections, ME and HE. The choice of the large RF frequency in the last two sections has been dictated by the need to achieve as a large accelerating gradient as possible so the SCL would fit entirely within the available space. The major parameters of the three sections of the SCL are given in Tables 2 and 3. The total expected cost is around 100 M\$ for the SCL alone, excluding modifications of the Front-End, the room-temperature 200-MeV Linac, and of the transport and injection into the AGS.

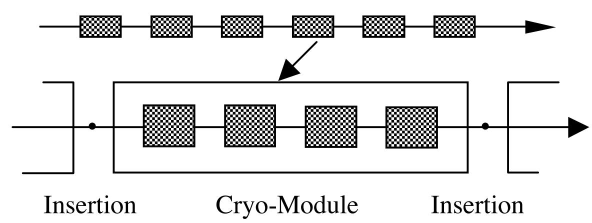

Figure 2. Configuration of a Proton Super-Conducting Linear Accelerator

The length of the SCL depends on the average accelerating gradient. The local gradient has a maximum value that is limited by three causes: (1) For a realistic cell shape, we set a limit on the average axial electric field to 15 MV/m at 805 MHz, and 30 MV/m at 1,610 MHz. (2) There is a limit on the peak 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. The conditions for stability of motion have been derived in [6].

The number of cells and cavities may vary in principle from section to section, but we have found it convenient here to adopt the same distribution in all sections. There is one klystron feeding a single coupler to a single cavity. The total length of the SCL injector proper from end to end is about 130 meter, including a 4.5-m long matching section between LE and ME sections. When averaged over the real estate, the actual acceleration rate is about 5 MeV/m in the LE section and 10 MeV/m in the ME and HE sections. Efficiencies, defined as the ratio of beam power to required total AC power, is relatively high for a pulsed Linac, ranging between 9 and 15%.

Table 2. General Parameters of the SCL

Linac Section	LE	ME	HE
Ave. *increm.* Power, kW	7.52	15.0	15.0
Average Beam Current, μA	37.6	37.6	37.6
Initial Kinetic Energy, MeV	200	400	800
Final Kinetic Energy, MeV	400	800	1200
Frequency, MHz	805	1610	1610
Protons / Bunch $\times 10^8$	8.70	8.70	8.70
Temperature, ^{o}K	2.1	2.1	2.1
Cells / Cavity	8	8	8
Cavities / Cryo-Module	4	4	4
Cavity Separation, cm	32.0	16.0	16.0
Cold-Warm Transition, cm	30	30	30
Cavity Internal Diameter, cm	10	5	5
Length of Warm Insertion, m	1.079	1.379	1.379
Accelerat. Gradient, MeV/m	10.5	22.9	22.8
Ave. Gradient, MeV/m	**5.29**	**9.44**	**10.01**
Cavities / Klystron	1	1	1
No. of rf Couplers / Cavity	1	1	1
Rf Phase Angle	30^o	30^o	30^o
Transverse Focussing	FODO	Doubl.	Doubl.
Phase Advance / FODO cell	90^o	90^o	90^o
Norm. rms Emitt., π mm-mrad	**2.0**	**2.0**	**2.0**
Rms Bunch Area, π ^{o}MeV	0.5	0.5	0.5

A Super-Conducting Linac is most advantageous for a continuous mode of operation (CW). There are two problems in the case of the pulsed-mode of operation. First, the pulsed thermal cycle introduces Lorentz forces that deform the cavity cells out of resonance. This can be controlled with a thick cavity wall strengthened to the outside by supports. The actual design of a cavity cell is described in detail in [7]. Second, there is an appreciable period of time to fill the cavities with RF power before the maximum gradient is reached [6]. During the filling time, extra power is dissipated also before the beam is injected into the Linac. The extra amount of power required is the ratio of the filling time to the beam pulse length. The filling times are also shown in Table 3.

TRANSVERSE FOCUSING

The upgrade makes use of the present 200-MeV room-temperature Linac, with proper power supply modifications for larger pulse width. This Linac provides a negative ion beam with an emittance of 2.0 π mm-mrad. To avoid uncontrolled beam losses that may cause radiation activation, one requires that the ratio of inner cavity radius to rms beam size is at least a factor of 6 all over the length of the SCL. This is difficult to achieve in the ME and HE section where the inner aperture is of only 5 cm because of the larger RF frequency. We have thus adopted in these two sections transverse focusing with doublets of quadrupoles, whereas a FODO singlet sequence was found adequate in the LE section.

Table 3. Summary of the SCL Design

Linac Section	LE	ME	HE
Velocity, β: In	0.5662	0.7131	0.8418
Out	0.7131	0.8418	0.8986
Cell Reference β_0	**0.615**	**0.755**	**0.851**
Cell Length, cm	11.45	7.03	7.92
Total No. of Periods	6	9	8
Length of a period, m	6.304	4.708	4.994
FODO-Cell ampl. func., β_Q, m	21.52	8.855	8.518
Total Length, m	*37.82*	*42.38*	*39.96*
Coupler rf Power, kW (*)	263	351	395
Energy Gain/Period, MeV	33.33	44.57	50.10
Total No. of Klystrons	24	36	32
Klystron Power, kW (*)	263	351	395
$Z_0T_0^2$, ohm/m	378.2	570.0	724.2
$Q_0 \times 10^{10}$	0.97	0.57	0.64
Transit Time Factor, T_0	0.785	0.785	0.785
Ave. Axial Field, E_a, MV/m	13.4	29.1	29.0
Filling Time, ms	0.337	0.273	0.239
Ave. Dissipated Power, W	2	11	8
Ave. HOM-Power, W	0.2	0.5	0.4
Ave. Cryogenic Power, W	65	42	38
Ave. Beam Power, kW	7.52	15	15
Total Ave. rf Power, kW (*)	17	31	30
Ave. AC Power for rf, kW (*)	37	69	67
Ave. AC Power for Cryo., kW	46	30	27
Total Ave. AC Power, kW (*)	83	99	94
Efficiency, % (*)	9.05	15.21	16.08

(*) Including 50% rf power contingency.

CONCLUSION

The proposed SCL for the 1-MW AGS upgrade is not much different in size and scope from the equivalent accelerator of the SNS project. Though the average values of beam and RF power are considerably lower, because of the smaller duty cycle, nonetheless peak values are comparable to the SNS SCL, since we use similar pulse width and current.

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