DESIGN OF 1.2-GEV SCL AS NEW INJECTOR FOR THE BNL AGS*

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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 beam power of 1 MW at the energy of 28 GeV. The facility is to be used primarily as a proton driver for the production of intense neutrino beams [1, 2]. A study of a proton Super-Conducting Linac (SCL) as the new injector to the AGS has just been completed [3] and found feasable. We are now initiating a second design phase with more emphasis on engineering considerations, namely: cryogenics, cryostat design, RF cavity design, RF power couplers and power sources, conventional engineering, and insertions for transverse focusing and other beam utilities. Some of these issues are addressed in this paper.

THE AGS UPGRADE

The present (typical) AGS performance is compared with the AGS Upgrade in Table 1. A comparison is also made with the SNS project [4]. At the moment the AGS provides acceleration of protons to 28 GeV with an average power of 100 kW. The Upgrade proposes operating the AGS at a much higher repetition rate, from the present one pulse every three seconds to 2.5 pulses every second. This needs a completely new power supply system [5]. The AGS magnets are presently being tested to assess their capability to be ramped at the higher repetition rate [6]. As shown in Table 1, most of the power increase in the Upgrade will be the result of the higher repetition rate and a modest beam intensity increase of about 30%, as can be reasonably expected with the new injector. In fact, the present injector, made of the 200-MeV room-temperature Drift Tube Linac (DTL) followed by the 1.5-GeV Booster, will not be capable to follow the higher repetition rate of the AGS. For instance, four Booster cycles are required to fill the AGS to the desired beam intensity, and this lengthen considerably the AGS cycle period.

A Super-Conducting Linac (SCL) that accelerates protons at the repetition rate of 2.5 Hz is thought to be the best alternative to the Booster. In this Scenario, the beam from the 200-MeV DTL is injected into the SCL for acceleration in a single pass to the final energy of 1.2 GeV, and then directly injected into the AGS, thus by-passing the Booster as shown in Figure 1. To get the required intensity per AGS cycle, multi-turn injection, by charge exchange, is done in the AGS itself, so that the SCL will also need to accelerate negative Hydrogen ions (H^-). The main parameters that summarize the goal of the AGS Upgrade are given in Table 2.

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Table 1: Comparison of Projects Performance

	AGS Present	AGS Upgrade	SNS
Kinetic Energy, GeV	28.0	28.0	1.0
Protons / Cycle, x 10^{14}	0.67	0.89	1.56
Repetition Rate, Hz	1/3	2.5	60
Ave. Power, MW	0.10	1.0	1.4
Linac Pulse Length, ms	--	0.72	1.0
Linac Duty Factor, %	--	0.18	6.0
Linac Peak Current, mA	--	28.0	38.0

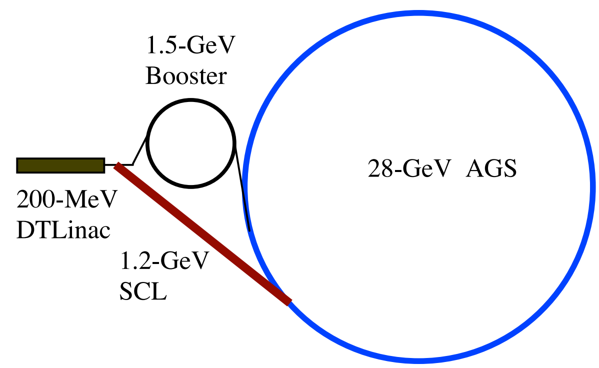

Figure 1: BNL Accelerator Facility and AGS Upgrade

THE SUPER-CONDUCTING LINAC (SCL)

The beam energy at the exit of the SCL is 1.2 GeV. The beam intensity is adjusted to yield the required average beam power of 1 MW at 28 GeV. The repetition rate of the SCL is 2.5 Hz, with a duty cycle of 0.2%. The beam is transferred to the SCL from the present 200-MeV DTL. The SCL is made of three sections (see Figure 2): Low-Energy (LE) from 200 MeV to 400 MeV, operating at 805 MHz; Medium-Energy (ME) from 400 MeV to 800 MeV, operating at 1,610 MHz; and High-Energy (HE) to the final 1.2 GeV, also operating at 1.61 GHz.

Since the beam power requirement of 1 MW is for the energy of 28 GeV, after acceleration in the AGS, the average beam power in exit of the SCL is very modest, of only 40 kW. Table 1 compares the SCL performance for the AGS Upgrade with that of the SCL of the SNS project. It is to be noticed that the two Linac projects differ in the repetition rate and, thus, in the duty cycle, whereas they both require about the same pulse length. Though the average beam power is considerably lower in the AGS-SCL, because of the much lower repetition rate, nevertheless the peak power value during the duration of the beam pulse is comparable to, or even higher than the SNS-SCL, because both projects require about the same peak beam intensity. Similarly, it is expected that also the total peak RF power is about the same in both projects. On the other end, the peak values of the performance are those that determine the design of the SCL.

A major constraint in the design of the AGS-SCL is a space limitation. There is a linear distance of about 120 m between the exit of the 200-MeV DTL and injection into the AGS tunnel (see Figure 3). The SCL will have to be accommodated over that distance and kept straight with some engineering consequences and challenges that are discussed below. Otherwise it may be argued that the AGS-SCL is in principle equivalent to the SNS-SCL and could follow in principle the same design, since both share similar beam requirements.

Table 2: Parameters of the AGS Upgrade Scenario

Linac Ave. Power	37.5 kW	Ion Source Current	100 mA
Kin. Ener. in exit	1.2 GeV	DTL Trans., %	30
β	0.8986	Chopp. Ratio, %	75
Momen, GeV/c	1.92	Peak Current, mA	28
Magn. Rigid., T-m	6.41	Ave. Current, mA	21
Repet. Rate, Hz	2.5	Injection Loss, %	5.0
DTL Current, μA	37.6	Inj. Protons / Turn	3.74 x10^{11}
Protons / pulse*	9.38 x10^{13}	No. Injec. Turns	239
AGS Circum., m	807.076	Pulse Length, ms	0.716
Inj. Rev.. Freq.,	0.3338	Duty Cycle, %	0.179
Inj. Rev. Period, μs	2.996	Bunching Factor	4
Bend. Radius, m	85.378	Norm. Emit.	100
Inject. Field, kG	0.7507	Emit., π mm-mrad	48.8
Extrac. Field, kG	11.30	Space-Charge Δν	0.187
RF at Inject, MHz	8.01	RF at Extr, MHz	8.91

*Including 5% contingency for controlled beam loss during injection.

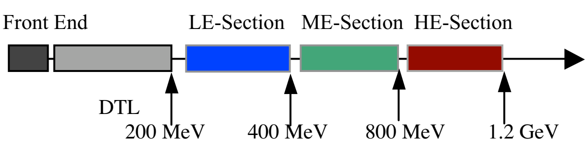

Figure 2: Layout of 1.2-GeV SCL for the AGS Upgrade

THE LINAC FRONT-END

The Front-End of the Linac is made of the present negative-ion source for which some minor modifications may be required to allow operation at 0.2% duty cycle at the repetition rate of 2.5 Hz. The ion source extracts protons at the potential of 35 kVolt, and is followed by the 0.75-MeV RFQ that works at 201.25 MHz. The beam will have to be chopped at the downstream end of the RFQ at a frequency matching the accelerating RF (8.0 MHz, harmonic number = 24) at injection into the AGS, over a beam extension of 75%.

At the moment the ion source is capable of generating short beam pulses of 100 mA (peak), but operation has typically shown an output current, in exit of the 200-MeV DTL, considerably lower. We expect that, with all minor modifications done as required, the peak current around 30 mA can be reached. The DTL also operates at 201.25 MHz, and this frequency dictates the choice of the RF design of the SCL where the accelerating frequency is to be a multiple of it. Also the DTL itself will require few modifications to allow a longer beam pulse and a higher repetition rate.

Unfortunately, the present DTL delivers a beam with an exceedingly large transverse emittance of which the normalized (rms) value is 2 π mm-mrad (against 0.4 π mm-mrad for the SNS). Adoption of this value in the design has, of course, some consequences on the choice of the internal diameter of the superconducting cavities, and of the design of the transverse focusing during the transport along the SCL. It is therefore desirable to check where intensity limitations and beam size growth occur along the DTL, and plan for possible cures. Also it is necessary to determine more precisely the longitudinal extension and spread of the beam bunches for matching and acceleration in the SCL.

THE DESIGN OF THE SCL

The main parameters of the three AGS-SCL sections are given in Tables 3 and 4 where they are also compared to the SNS-SCL. Each section is made of a number of identical periods, and each period is made of a cryostat and an insertion as shown in Figure 4. In order to get the entire length to fit the space available on the BNL site, we opted for a compact design with a large number of cavity cells per cavity (8), and a large number of cavity per module (4). Each of the three sections is made of cavity cells of the same length adjusted to an intermediate value β_0 of the beam velocity (what is now considered more or less a standard design procedure). To get the most compact design, we also minimized the spacing between cavities, the length of the cold-warm transitions, and the length of the warm insertions, as compared to the SNS-SCL design. This choice raises some concern about packing the essential components that need to be addressed.

Yet, we did not want to exceed the surface limit beyond the present state of the art. We are aware that the field of RF superconductivity is progressing fast, and that in a near future larger accelerating gradients may be feasible. This choice is consistent with that of the SNS-SCL, but we have chosen a higher frequency, 1.61 GHz, for the last two sections, to reach a higher accelerating field gradient. Should one demonstrate that higher gradients are possible at 805 MHz, that frequency can then be adopted for the last two sections. Otherwise the selection of 1.61 GHz does not seem to present problems, except that because of the reduced internal diameter we had to take a transverse focusing system made of quadrupole doublets. Because of the difference in the RF frequency between them, we have allowed a space of 4.5 m between the end of the LE and the beginning of the ME section for proper longitudinal and transverse matching.

RF POWER SOURCES AND CAVITIES

The best strategy is to energize cavities individually with a single, independent RF power source, namely one coupler directly connected to a single klystron. This should insure better phase stability in the operation of the

SCL. Moreover, our design, shown in Table 4, limits the amount of the RF peak power to 400 kW per cavity.

determine if they are sufficiently decoupled from each other.

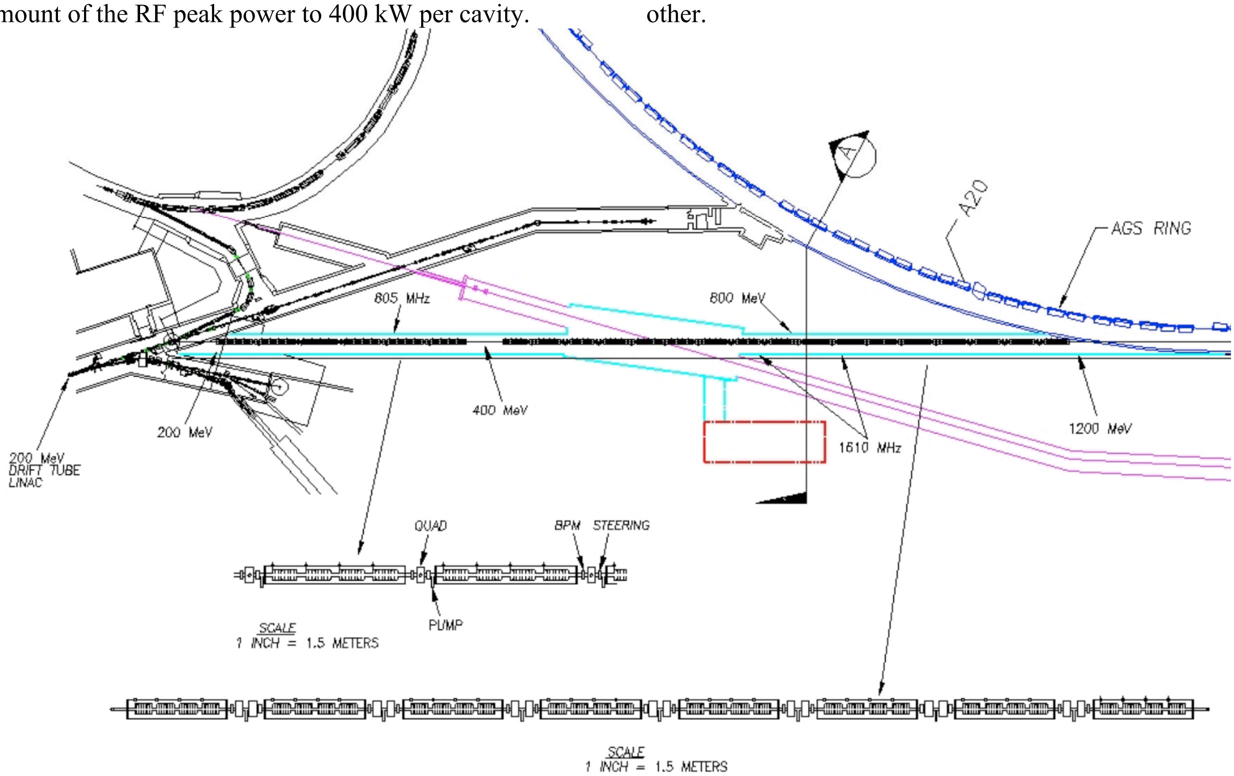

Figure 3: Layout of the 1.2-GeV SCL between the DTL and the AGS

Table 3: General Parameters of the SCL (AGS and SNS)

Linac Section	LE	ME	HE	SNS M-β	SNS H-β
Ave. Beam Power, kW	7.52	15.0	15.0	321	949
Ave. Beam Curr., μA	37.6	37.6	37.6	1560	1560
Init. Kin. Energy, MeV	200	400	800	185.6	391.4
Final Kin.Energy, MeV	400	800	1200	391.4	1000
Frequency, MHz	805	1610	1610	805	805
Protons / Bunch x 10^8	8.70	8.70	8.70	5.9	5.9
Temperature, °K	2.1	2.1	2.1	2.1	2.1
Cells / Cavity	8	8	8	6	6
Cavities / Cryomodule	4	4	4	3	4
Cavity Separation, cm	32.0	16.0	16.0	38.5	38.5
Cold-Warm Trans., cm	30	30	30	71	76
Cavity Inter. Diam., cm	10	5	5	8	8
Warm Insert., m	1.079	1.379	1.379	1.60	1.60
Accel. Grad., MeV/m	9.1	19.8	19.8	9.2	14.0
Ave. Grad., MeV/m	**5.29**	**9.44**	**10.01**	**3.20**	**6.54**
Cavities / Klystron	1	1	1	1	1
RF Couplers / Cavity	1	1	1	1	1
Rf Phase Angle	30°	30°	30°	20.5°	19.5°
Transv. Focusing	fodo	Doub	Doub	Doub	Doub
Phase Adv. / cell	90°	90°	90°	--	--
Norm. rms Emit., π μm	**2.0**	**2.0**	**2.0**	**0.41**	**0.41**
Rms Bunch Area, π eV-µs	1.7	1.7	1.7	1.7	2.3

Local accelerating gradient, real estate gradient, and actual axial field are also shown in Tables 3 and 4 for each of the three sections, and compared to the SNS-SCL design. A single cavity cell has been designed with SUPERFISH. The next step will be to plot the actual field distribution with all the cells in one cavity, and also the field generated by the four cavities in one cryostat to

Table 4: Summary of the SCL Design (AGS and SNS)

Linac Section	LE	ME	HE	SNS M-β	SNS H-β
Velocity, β: In	0.566	0.713	0.842	0.550	0.708
Out	0.713	0.842	0.892	0.708	0.875
Cell Reference β_0	**0.615**	**0.755**	**0.851**	**0.61**	**0.81**
Cell Length, cm	11.45	7.03	7.92	11.36	15.08
Total No. of Periods	6	9	8	11	12
Length of a period, m	6.304	4.708	4.994	5.839	7.891
Cell ampl. func., β_Q, m	21.52	8.855	8.518	--	--
TOTAL LENGTH, M	*37.82*	*42.38*	*39.96*	*64.23*	*93.09*
Coupler rf Power, kW (*)	263	351	395	408	522
Energy Gain/Period, MeV	33.33	44.57	50.10	18.71	50.72
Total No. of Klystrons	24	36	32	33	48
Klystron Power, kW (*)	263	351	395	408	522
$Z_0T_0^2$, ohm/m	378.2	570.0	724.2	220-440	170-570
Q_0 x 10^{10}	0.97	0.57	0.64	> 0.5	> 0.5
Transit Time Factor, T_0	0.785	0.785	0.785	0.785	0.785
Ave. Axial Field, MV/m	13.4	29.1	29.0	12.4	18.9
Filling Time, ms	0.337	0.273	0.239	--	--
Ave. Dissip. Power, W	2	11	8	58	104
Ave. HOM-Power, W	0.2	0.5	0.4	7.4	10.8
Ave. Cryog. Power, W	61	61	58	158	266
Ave. Beam Power, kW	7.52	15	15	321	949
Ave. RF Power, kW (*)	17	31	30	606	1737
Ave. AC Pow. RF, kW(*)	37	69	67	891	2555
Ave. AC Pow. Cryo., kW	24	24	23	112	189
Ave. AC Power, kW (*)	61	93	90	1003	2743
Efficiency, % (*)	12.3	16.1	16.7	31.8	34.4

(*) Including 50% rf power contingency.

Table 4 also gives the cavity filling times that ought to be compared to the length of the beam pulse duration. The filling time will cause a lengthening of the RF duty cycle with additional power dissipation. Another effect of the pulsed mode of operation is the mechanical distortion of the cavity cells by Lorentz forces. The distortion will be controlled with cavity stiffners and piezo-tuners. The cavity also has a 4 mm thick niobium wall to make it more robust and stiffer. The mechanical distortion will be compensated enough to avoid an excessive shift of the resonance frequency. But the problem in the AGS-SCL is expected to be less severe than in the SNS-SCL because of the lower repetition rate.

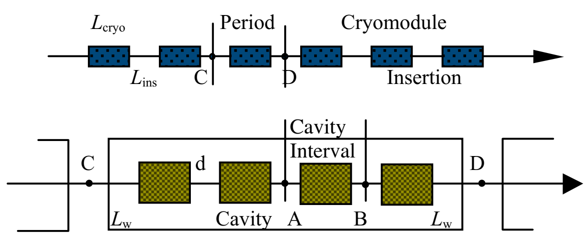

Figure 4: Sequence of Cryostats and Insertions

CRYOSTAT DESIGN

A simplified sketch of a cryostat is shown in Figure 5. In our desire for compactness, the cavity separation is 6.4 times the internal radius as compared to 9.6 times in the SNS-SCL design. The cavity separation should be large enough not only to sufficiently decouple one cavity from the next, but also to allow sufficient space for the coupler sitting next on the side of each cavity. Also the transition between cold and warm regions is here taken to be of just 30 cm, against the 70-80 cm adopted in the SNS-SCL design. The internal diameter of the cavities is 10 cm in the LE section of the SCL with an outer diameter of 34 cm. In the last two sections the values are 5 and 17 cm respectively. The overall dimensions of the Cryostat depend on the cryogenic insulation scheme.

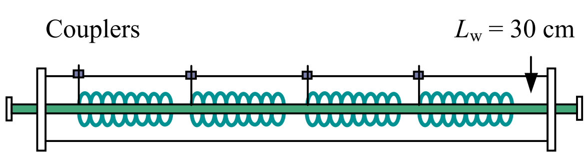

Figure 5: Layout of a Cryostat with Cavities (cryogenic shields are not shown)

CRYOGENIC SYSTEM

Because of the low average beam power, the average losses of the beam bunches to the cavity HOM are also very low and do not present much of a load to the refrigeration system. For the same reason, HOM couplers are not required. Most of the thermal losses to be concerned with are the static losses through the side walls and the end caps of the cryostat. In sum, the Cryogenic System is of a modest size when compared to that of the SNS-SCL. The total refrigeration power required is about 180 W, assuming a cryogenic temperature of 2.1 °K in the cavity region. This low value is required not necessarily to limit the amount of power, but primarily for stability considerations to avoid repetitive and occasional quenching of the cavities. Thus three cooling intermediate stages are proposed: 2, 5 and 80 °K. This is the major cause of the large transverse size of the cryostat that may reach about one meter in diameter. Still the space allowed for the cold-warm transition of only 30 cm is too limited and remains a concern.

COLD VERSUS WARM INSERTIONS

The insertions separate cryostats, and their main function is for the placement of quadrupoles and of other beam components, such as steering magnets, beam position and profile monitors, vacuum ports, valves and flanges. Again for compactness, we have reduced the space allowed to the insertion to 1.08 m for the LE section and 1.38 m of the ME and HE sections, down from the 1.6 m in the SNS-SCL. A single quadrupole is located in the LE section insertions, and a quadrupole doublet in each insertion of the ME and HE sections. The quadrupoles have an effective length of 30 cm and at most have a gradient of 2 kG/cm. Figure 6 shows a possible configuration of the insertion in a warm environment. It is indeed feasible to place all the required components in the allowed drift length. Nevertheless it remains the issue and the concern of the cold-warm transition that may be too short. To remove such a concern a solution is to place also the insertion in a cold environment, probably just at the liquid nitrogen temperature. The magnet strength is too low to warrant for superconductivity, and one has to take leads out from the various sensors and power supplies out for processing. This issue, whether the insertion should be maintained also in a cold environment or kept warm, is presently being studied. In particular, the possibility of using cold (80 °K) copper wound 2 kG/cm insertion quadrupoles is also under investigation.

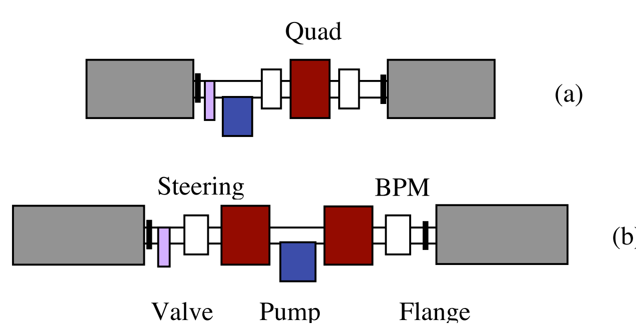

Figure 6: Insertions with Quadrupole Singlet (a) and Doublet (b)

CONTROL OF BEAM LOSSES

The most stringent design requirements are encountered at the beginning of the LE section, where the energy gain per module should be kept low enough to avoid instability of the longitudinal motion. Longitudinal mismatch cannot be avoided in a high-gradient SCL [7] but it can be controlled. A longitudinal mismatch could be the source of a beam halo in the momentum plane when space charge forces are taken into account. Such effects also exist for transverse motion, and in principle mismatch, halo formation, and the consequent uncontrolled beam losses cannot be avoided. For a safe operation and maintenance we shall take a limit of distributed, uncontrolled beam loss not exceeding 1 W/m. The consequences of the beam losses of course are expected to be more severe at the high energy end than at the low one. Thus, over a total length of 120 m, the total allowed uncontrolled beam losses are 120 W, that is about 0.25% of the average beam power. The beam dynamics issues are to be addressed to assess the feasibility of this level of loss. Since the beam loss by halo formation (longitudinal or transverse) is actually determined by the intensity of a single bunch, the dynamics is not expected to be much different in the AGS and SNS Linacs, with the exception that, because of the lower repetition rate, more fractional losses can be tolerated in the AGS-SCL.

CONVENTIONAL ENGINEERING

The entire SCL will be accommodated in one straight tunnel that joins the exit of the 200-MeV DTL enclosure to the entrance to the AGS tunnel (see Figure 3). The Linac tunnel can be 10′ wide and 10′ high with a square shape extending over 120 m. The Klystron Gallery is located directly on top of the SCL tunnel, 35′ wide and 20′ toll, with a crane moving longitudinally (see Figure 7). Directly above the RF cavities, at one side of the gallery, vertical utility shafts connect components above to the cryostats below. There will be a shaft directly above each insertion to connect power supplies and operate beam sensors and other utilities. Waveguides will also convey RF power from the klystrons above, sitting on benches, to each of the RF couplers below. The Klystron Gallery covers the entire length of the Linac of course and can be used also to accommodate the operation and control room. The Refrigerator Building will also sit above, facing the central part of the Klystron Gallery, but will occupy only a surface of 150′ x 20′. From the Refrigerator Building, piping will be launched in both directions down the SCL tunnel for the flow of refrigerants (He and N). The cryogenic control can also be located in the same Refrigerator Building.

COST AND SCHEDULE

We used the similarities in the performance between the AGS and the SNS SC Linacs, especially regarding the peak values, to determine the cost of the AGS-SCL by simple scaling. The expected total cost is under 100 million US dollars, and the project could be built in a period not exceeding 5 years.

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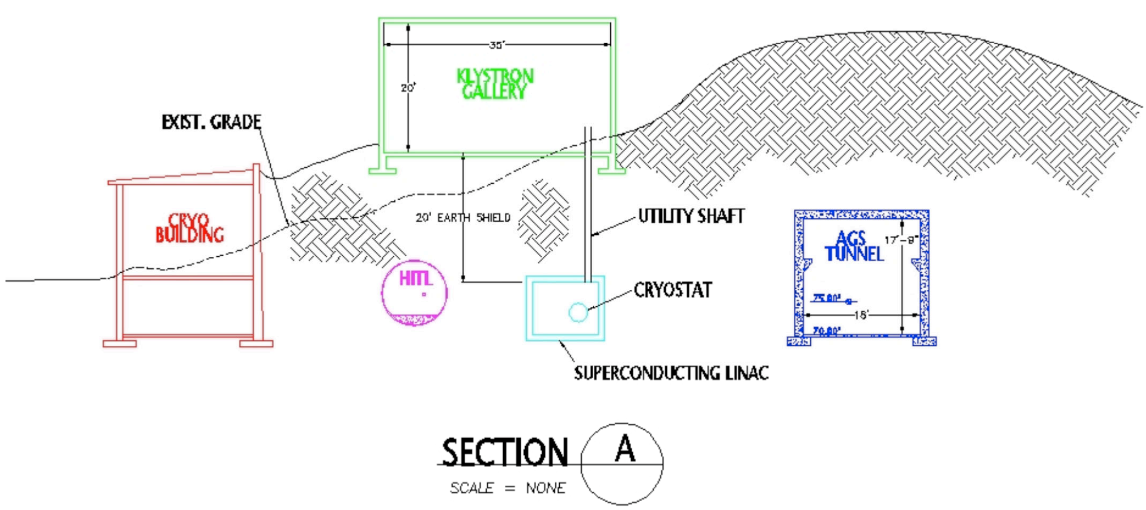

Figure 7: Cross-Section of Enclosures of the BNL-AGS Facilities