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Review of Options for the SCL for the AGS Upgrade

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Collider Accelerator Department

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U.S. Department of Energy

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Summary

In this technical report we review options for the design of a 1.2-1.5 GeV Super-Conducting Linac (SCL) for the AGS Upgrade program toward a proton average beam power of 1 MWatt. At the present the only high-power proton SCL we can make reference to is the SCL of the SNS project. It is directly from this that we extrapolate here performance and cost for our study.

Present AGS Performance

With a typical mode of operation the present AGS accelerator facility can provide an average proton beam power of about 100 kW at the kinetic energy of 28 GeV. The layout of the accelerator complex is shown in Figure 1, and the ordinary proton cycle in Figure 2. Negative hydrogen ions (H^-) are generated by a 35-keV ions source, focused, bunched and pre-accelerated in a 750-keV RFQ, and finally accelerated to 200 MeV in the following Drift-Tube Linac (DTL). The beam is then transferred into the 1.5-GeV Booster that has a circumference of about a quarter of that of the AGS. Multi-turn injection into the Booster is done with the method of charge exchange. The Booster can accelerate at the repetition rate of 7.5 Hz. Since four Booster cycles are required for a complete fill of the AGS, about half second is spent for acceleration of the four pulses in the Booster. Once injection into the AGS is completed, the beam is finally accelerated to 28 GeV in about one second. The overall cycle may take up to three seconds, or more, depending on the presence of a high-energy flat top for slow spill extraction. The Booster acceleration period is thus an appreciable fraction of that of the overall AGS cycle. Heavy-Ions are accelerated in a similar fashion. They are generated by the HI Tandem, accelerated first in the Booster to a final energy that depends on the charge state and mass of the ion, transferred and accelerated to the AGS where, for instance, for Gold (Au) the final energy is about 12 GeV/u.

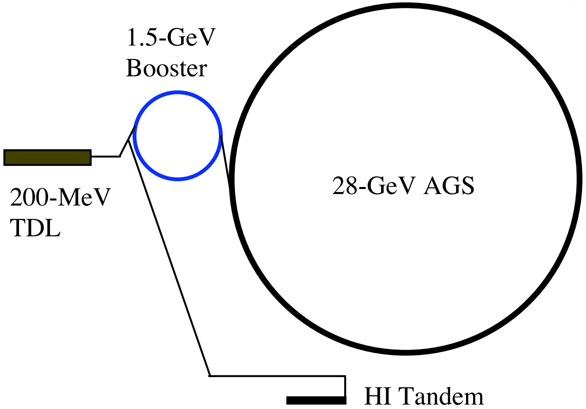

Figure 1. The AGS Accelerator Complex

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[*] Work performed under the auspices of the Department of Energy of United States

AGS Upgrade Program

An upgrade to an average proton beam power of 1 MW has been proposed [1], mainly by raising of the AGS repetition rate from 0.3 to 2.5 Hz, as shown in Table 1, where the Present performance is compared to that with Upgrade. Only a modest beam intensity increase of about 30% is required. The new mode of operation is sketched in Figure 3. The AGS cycle period is now only 0.4 sec, of which 0.2 seconds are for the acceleration proper and the other 0.2 sec for resetting of the guiding field. It has been proposed to accelerate the proton beam by a 1.2-GeV Super-Conducting Linac (SCL), from which directly inject into the AGS. The SCL operation is fast and its repetition rate can easily match that of the AGS Upgrade. In this mode of operation the Booster is entirely bypassed since otherwise would cause a considerable lengthening of the overall cycle. The SCL accelerates negative hydrogen ions (H^-), and multi-turn injection by the method of charge exchange is now done during the transfer into the AGS. In this mode of operation, of course, only protons, negative hydrogen ions and polarized protons can be accelerated in the SCL. The Heavy Ions generated by the Tandem will still have to be accelerated in the Booster before transfer to the AGS.

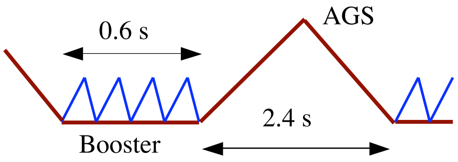


Figure 2. Typical AGS cycle for protons

Table 1. Present and Proposed AGS Performance

	AGS present	AGS upgrade
Kin. Energy	28 GeV	28 GeV
Rep. Rate	1 / 3 Hz	2.5 Hz
Protons/ Cycle	0.67×10^{14}	0.89×10^{14}
Ave. Power	0.10 MW	1.0 MW

Figure 4 shows the same AGS accelerator complex layout, but with the addition of the SCL inserted between the exit of the DTL and injection into the AGS. For the first phase of the AGS Upgrade program, a energy of 1.2 GeV for the SCL is estimated sufficient and necessary; but subsequently a higher energy of 1.5 GeV, comparable to that of the present Booster, has been assessed as desirable. We start by assuming that the 200-MeV DTL is part of the new injector. In order to achieve the required beam power in the AGS, it also operates at the repetition rate of 2.5 Hz, and it generates H^- beam pulses 0.72 msec long, at a peak current of 30 mA, as shown in Figure 5. This is within the present technical capabilities.

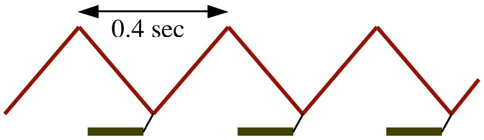


Figure 3. AGS Cycle with 1.2-GeV SCL

The design parameters of the SCL injector and of injection into the AGS are listed in Table 2 where they are compared to that of the SNS-SCL. This is the only proton superconducting Linac of similar performance under construction, that is expected to be operational during 2005. It is the only Linac we can compare and refer to for our performance and cost estimate. For its technical demonstration we shall simply have to wait. The two Super-Conducting Linacs have about the same final energy. They differ in the repetition rate by a factor of 24. Since the beam pulse length is of about the same duration (0.72 versus 1.0 ms), the overall duty cycle also differ by a factor of 33. As a consequence, though the average beam power in the AGS-SCL is a factor 35 lower than that in the SNS-SCL, the peak power values are comparable (25 versus 26 MW). But in the last analysis is the peak beam power figure that determines the design, performance and cost of a Super-Conducting Linac. Thus, apart from some minor differences, the SCL required as the new injector for the AGS upgrade is expected to be very similar to that of the SNS project.

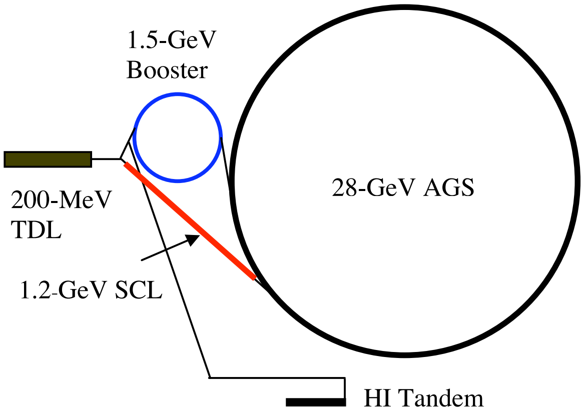


Figure 4. AGS Upgrade with 1.2-GeV SCL

The SNS-SCL

The layout of the SNS-SCL [2] is shown in Figure 6. It is 340 m long and is made of 4 sections. The first section is the room temperature 185.6-MeV Linac that in turn is made of a 2.5-MeV Front-End (FE, ion source and RFQ), a 402.25-MHz DTL section for acceleration to 86.8 MeV, and the final CCL section operating at 805 MHz. The room temperature Linac is 99.2 m long and is followed by a 2.35-m long matching section. The Super-Conducting Linac proper operates at 805 MHz. It is made in turn of three sections: (i) the 64.2-m long Medium-β section for acceleration to 387 MeV; (ii) the 94.7-m long High-β section for acceleration to a full 1.0 GeV; and (iii) a 71-m long Extra section for further acceleration to 1.3 GeV if required in the future.

Table 2. Comparison of AGS and SNS SCL

	AGS	SNS
Kinetic Energy, GeV	1.2	1.0
Repetition Rate, Hz	**2.5**	**60**
Protons / pulse, 10^{14}	0.95 (*)	1.65
Ave. Beam Power, MW	**0.045** (**)	**1.56** (+)
Peak Beam Power, MW	25	26
Average Current, mA	**0.038**	**1.56**
Pulse Length, ms	0.716	1.0
Duty Cycle, %	**0.18**	**6.0**
Linac Ave. Cur., mA	21	26
Linac Peak Cur., mA	28	38
Chopping Ratio, %	75	68
Chopping Freq., MHz	8.01	1.058
No. Injected Turns	240	1060

(*) Including 5% for controlled beam loss
(**) Equivalent to 1 MW @ 28 GeV
(+) Including 10% for controlled beam loss

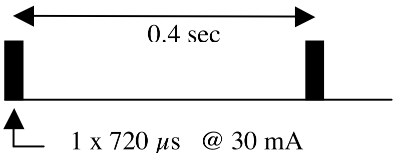
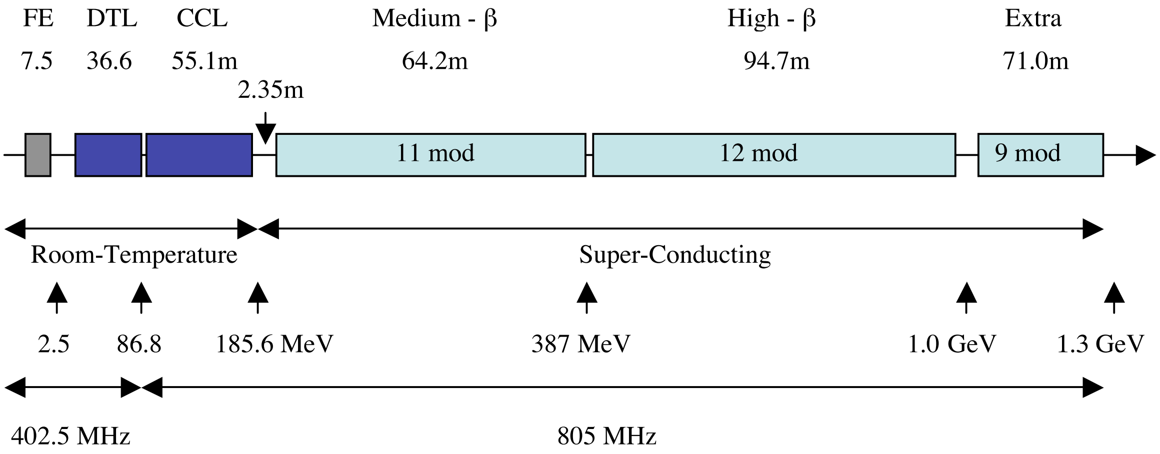


Figure 5. 200-MeV DTL Duty Cycle

The bottom of Figure 6 gives direct length and cost extrapolation of the same SNS-SCL also operating at either 1.2 or 1.5 GeV, rounded off as closely as possible, and the total cost as derived directly from the documentation of the SNS project. According to the same source, the total cost, including contingency and burden charges, of the SNS-SCL was 310.9 M$ in April 2002, that escalated to 322.5 M$ after a DOE review in October 2003, including also the cost of the 2.5-MeV Front-End and the Extra section[*]. To be noticed that, considering the shorter energy acceleration range, the SNS Medium-β section is relatively longer and more expensive than the High-β section (64 versus 95 meter, and about 80 versus 110 M$).



Length = 100 (RT) + 160 (1.0 GeV) + 30 (1.2 GeV) + 50 (1.5 GeV) m
Cost = 20 (FE) + 60 (RT) + 190 (1.0 GeV) + 30 (1.2 GeV) + 50 (1.5 GeV) M$
└▶ 80 + 110

Figure 6. Layout, Dimensions, Performance and Cost of the SNS-SCL

Possible Scenarios of the AGS-SCL

When applying the SNS-SCL design to the AGS Upgrade, one can conceive four possible scenarios.

Scenario I. It is possible to acquire the entire SNS-SCL as it is, since it will clearly perform also according to the AGS Upgrade requirements. The Scenario includes also the Front-End and the room-temperature section with expansion either to 1.2 or 1.5 GeV as desired. A possible location and layout of the entire Linac is shown (in Red) in Figure 7. It is on one side of the present 200-MeV DTL, and it is not connected to the AGS facility except that the end of the Linac is joined to the injection into the AGS by a straight transport line. For instance, injection can be aimed at station D20. There is no site limitation and the full length of the Linac can be easily accommodated. In this Scenario the length of the Linac is 290-340 m and the total cost 300-350 M$, respectively for 1.2-1.5 GeV, including that of a new tunnel. This approach is expensive but, being a copy of an existing project soon to be technically demonstrated, does not require research and development. Also, its construction would interfere the least with the operation of the existing accelerators.

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[*] I found this uncertain; but here I am assuming that indeed the total cost referred to includes also the Extra section fully developed.

Scenario II. One can take advantage of the present 200-MeV DTL, following that with an exact copy of the SNS-SCL extending from 185.6-MeV to either 1.2 or 1.5 GeV. But a problem now arises. The SNS-SCL length is 190-240 m whereas the path available on the site between the end of the DTL and the entrance of the AGS tunnel, that allows injection at station C-20, is of only 120 m. To circumvent this problem, the solution shown in Figure 7 (Blue line) is therefore not a straight line, and the SCL is bent in two straight sections in correspondence of about 1 GeV. Moreover, there is anyway already a large bend at the exit of the DTL, and there may be another at the entrance in the AGS tunnel to direct the beam toward injection at about C-20. The extrapolated cost for this Scenario is 220-270 M$ depending on the final energy, after having saved the cost for a new Front-End and room temperature Linac. The drawback of this Scenario is that, because of the several bends, horizontal dispersion along the transport is introduced, the effect of which on the beam dynamics and losses has to be evaluated. Also, the bends are to be gentle enough to avoid excessive stripping of the negative ions by the magnetic field.

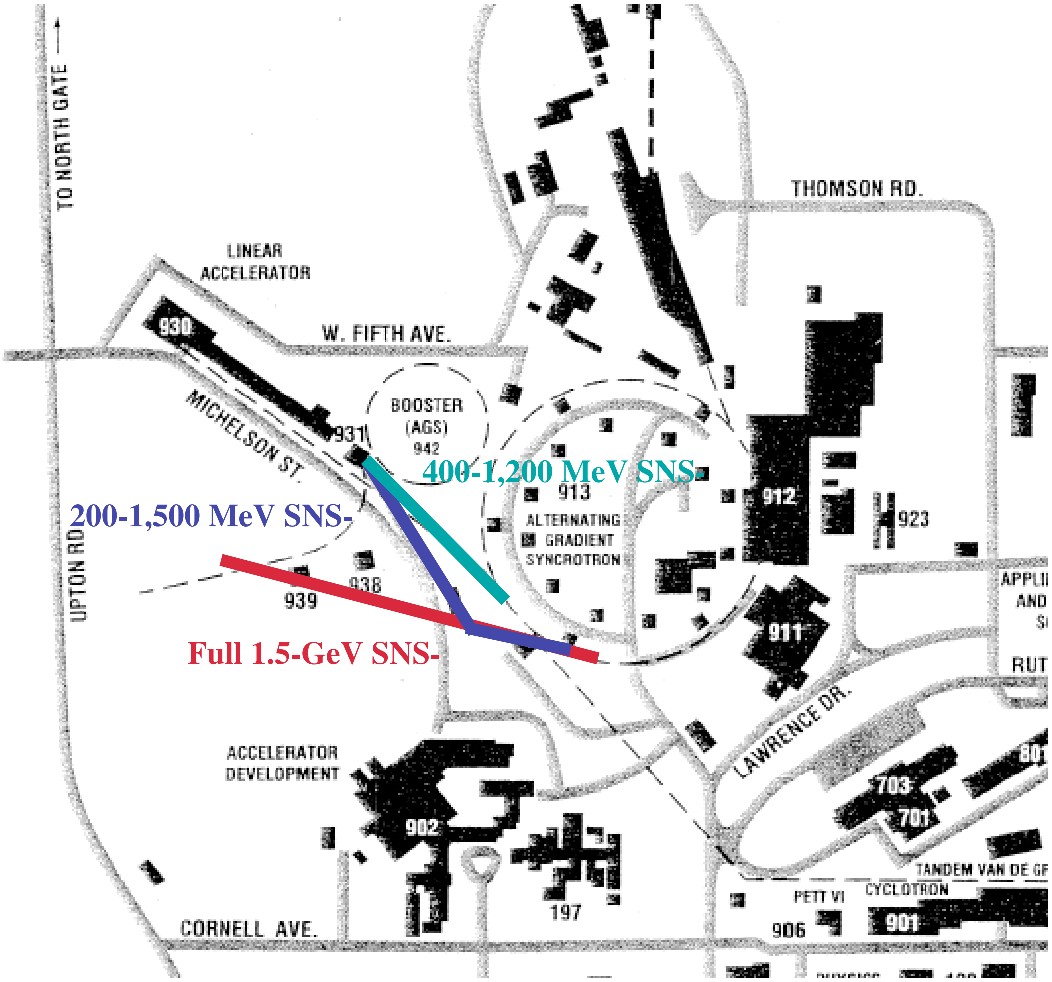

Figure 7. Three of the possible AGS-SCL Scenarios on the BNL Site

Scenario III. This assumes a major modification of the present 200-MeV DTL. Taking example from the Fermilab Linac Upgrade, the last four tanks could be replaced by a 805-MHz section, that can be at room temperature (as at Fermilab). The first five tanks, unchanged at 201.25 MHz, can still accelerate the beam to 115 MeV; and the subsequent new section accelerates to 400 MeV, still enclosed in the same Linac tunnel. The cost of this operation may be extrapolated from the Fermilab Upgrade (done in the late 80's) that we conservatively here set to 40 M$. Following this then we add the SNS-SCL High-β and Extra section for acceleration to either 1.2 or 1.5 GeV. Correspondingly the total length of the superconducting section is 120-170 m, and the cost 180-230 M$. This Scenario, also shown in Figure 7 (Turquoise line), is likely the least expensive and, for the energy of 1.2 GeV, can fit entirely the available space between the DTL and the AGS. For higher energies one may have to require installation of cryo-modules in the AGS tunnel all the way to the injection point. The advantage, like for the previous two other Scenarios, is that one has simply to copy the state of the art that is represented by the SNS-SCL.

Scenario IV. This has been our reference design all along [3]. For that we required a straight-line transport, as compact as possible, for acceleration over a path of about 120 m to at least 1.2 GeV. The solution of this Scenario is shown in Figure 8, with the cross-section of the Linac tunnel, cryogenic building and the klystron gallery given schematically in Figure 9 (prepared by T. Nehring). But in order to allow this Scenario on our agenda, differently from the other Scenarios, we had to re-design the Super-Conducting Linac sections. Indeed we have seen that using the geometry of the cryo-modules of both sections of the SNS-SCL, without modifications, one needs a total space of 190 m for acceleration to 1.2 GeV against the available 120 m. To get a more compact layout we had to design the AGS-SCL with three sections, instead of two as in the SNS-SCL: (i) a Low-β section from 200 to 400 MeV at 805 MHz, (ii) a Medium-β section from 400 to 800 MeV, and (iii) a High-β section from 800 MeV to 1.2 GeV, the last two sections both operating at 1.61 GHz. The Low-β section was considerably shortened with 4 instead of three cavities per cryo-module. Because of the higher accelerating gradient packing, the beam dynamics was found to be at the limit of longitudinal stability. The other sections operated at the higher RF frequency for a more compact accelerating gradient. Moreover, space like warm-to-cold transitions and warm insertions were considerably shortened to the limit of engineering. Because of the large deviations from the design of the SNS-SCL now the uncertainties on both the performance and the cost of the AGS-SCL increase.

A comparison of the four Scenarios described above is given in Table 3. Obviously Scenario I is the most straight forward and likely the most secure, but also the most expensive. Scenario II requires study of the dispersion, whereas Scenario III is the most economic and probably the most preferable, but requires a commitment to the modification of the 200-MeV DTL. Finally Scenario IV is the one that most deviates from the design of the SNS-SCL and therefore uncertain. Also this last Scenario does not allow acceleration to 1.5 GeV.

The cost for Scenario IV has been derived from the cost of the superconducting sections of Scenario II after this has been divided in two equal sums, one proportional to peak beam power, and thus unchanged, and the other to length.

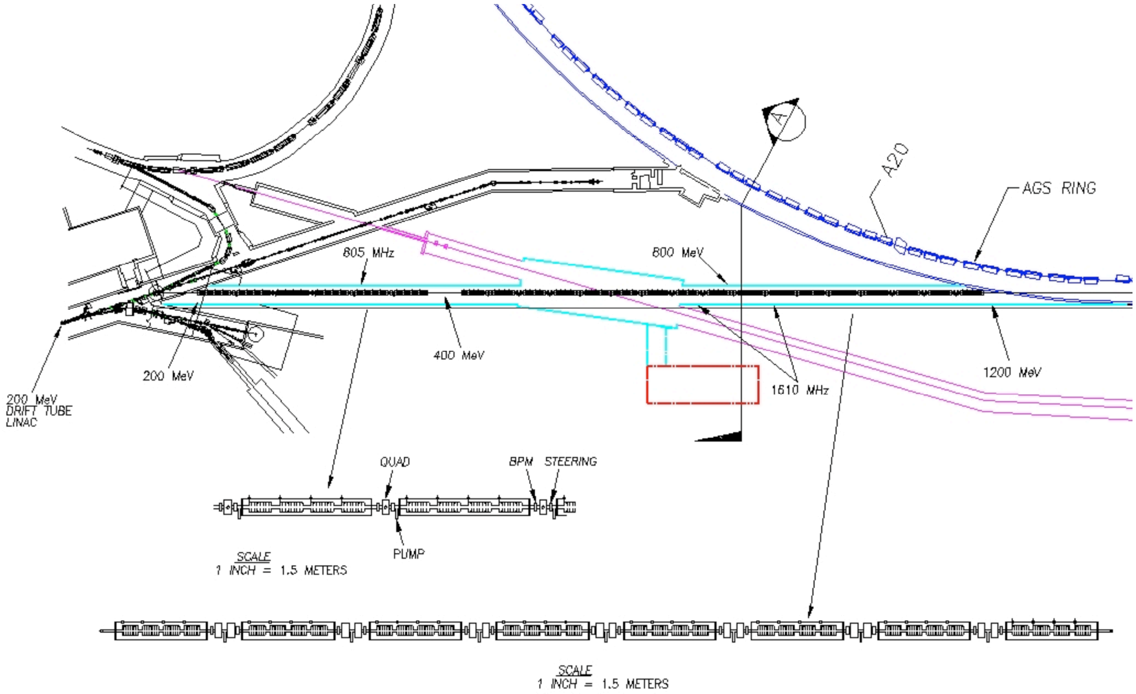

Figure 8. Reference Design of the 1.2-GeV AGS-SCL

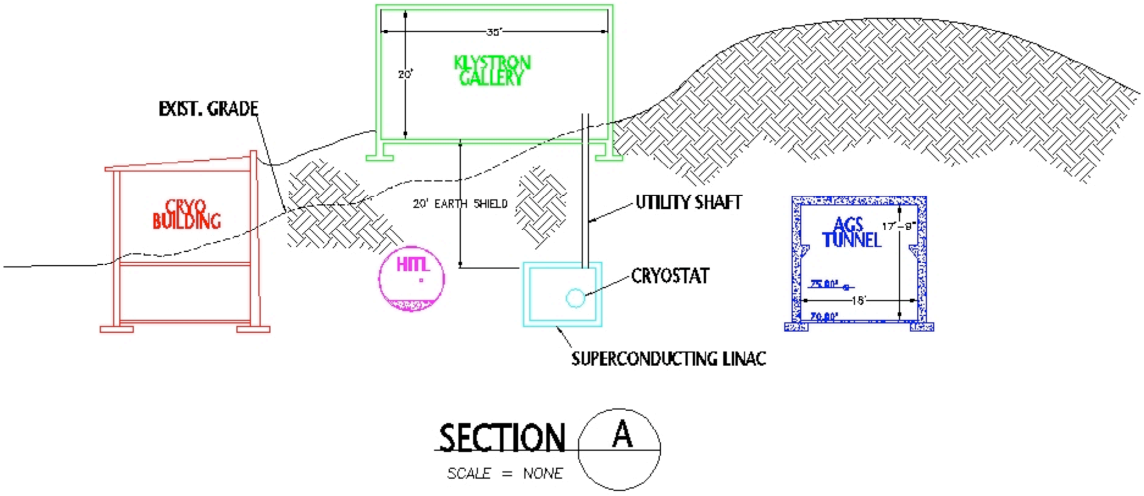

Figure 9. Cross-section of building and enclosures of the 1.2-GeV AGS-SCL

Table 3. Comparison of AGS-SCL Scenarios

	Scenario I	**Scenario II**	**Scenario III**	**Scenario IV**
Feature	Full Straight SNS Linac	Full Bent SNS Linac	DTL Upgrade to 400 MeV	Major departure from SNS design
Energy Range	0 - 1.5 GeV	0.2 – 1.5 GeV	400 MeV 1.2 GeV	200 MeV 1.2 GeV
Length, m	290 / 340	190 / 240	120 / (170)	120
Cost, M$	300 / 350	220 / 270	190 / (240)	**180** (??)
Comments	Too Expensive but is SNS-SCL	Horizontal Bending	Difficult Upgrade to 1.5 GeV	Uncertain Cost and Perform. Estimate

Revision of the Reference 1.2-GeV AGS-SCL Design

The original design of the 1.2-GeV AGS-SCL assumed a RF of 1.61 GHz for the Medium and High-β sections. That frequency has not been demonstrated yet in any other accelerator facility, though we have received reassurance from electronic industries that power amplifier sources could be easily made available. Moreover, the design of RF couplers, waveguides, circulators and electronic components for that frequency requires considerable and costly program of research and development. We have thus considered at this stage the possibility to make use of the same 805 MHz RF frequency for the entire AGS-SCL as done in the SNS-SCL, except that we shall still continue to employ three β-sections, because of the larger required increment in energy (1.2 versus 1.0 GeV) and to optimize further the transit time factors with three different types of cavity cells. For comparison, the layout of the two SCL is shown in Figure 10. Cost and length are compared in Table 4.

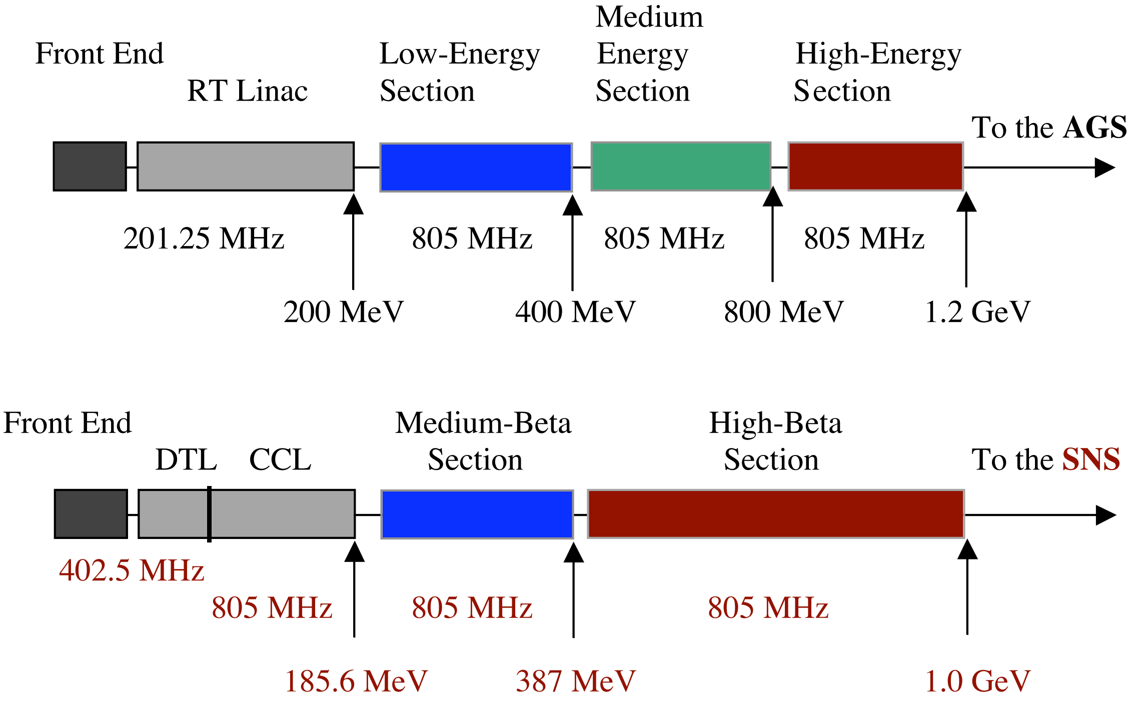

Figure 10. The AGS and SNS Super-Conducting Linacs

Table 4. Cost and Length Comparison of AGS and SNS SCL

	SNS	**AGS**
Energy	185.6 MeV - 1.0 GeV	200 MeV - 1.2 GeV
Length, m	160	120
Cost, M$	190	180
Average Gradient, MeV/m	5.09	8.33
Cost/Length, M$/m	1.2	1.5
Cost/Energy, M$/MeV	0.23	0.18

Each of the SCL section is made of a sequence of cryo-modules (or cryostats) as shown in Figure 11. Each cryo-module contains a number of cavities all with the same number of RF cells. The cavities are designed to operate in π mode; thus the gap g of a cell, to optimize the energy transfer to the particle, is adjusted to match half of wavelength according to $g = \beta_c \lambda / 2$, where β_c is a reference value equal to all the cells in the same section, somewhere in between the entrance and exit values of the particle velocity β. We follow very closely the design of the SNS-SCL, and we adopt one RF coupler per cavity and one klystron per coupler. Cavities are separated by a distance long enough to avoid coupling, and at the both ends of a cryostat there is a cold-to-warm transition. Finally, cryo-modules are separated by warm insertions long enough to accommodate focusing quadrupole magnets, vacuum pumps, steering magnets, beam position monitors and other components. The *active length*, where there is accelerating field, is essentially the sum of all the RF cells involved. The *inactive length* is the total length of all the drifts listed above where there is no acceleration. For an optimized and efficient acceleration it is important that the ratio of *active* to *inactive length* is a large as possible. Another important parameter is the transit time factor T of a particle of a given velocity crossing a cell or a cavity since the field varies in time as the particle travels. The actual *accelerating gradient* in the *active length* is then given by $G = T E_{acc} \cos \phi_s$, where ϕ_s is the phase lag between a beam bunch and the RF waveform, and E_{acc} is the average axial RF electric field. These quantities have about the same values in the two SCL.

To accommodate the AGS-SCL within the allowable space, we have also reduced the overall *inactive length* as shown in Table 5. The *active length* remains essentially the same in both SCL, since the geometry of the RF cells is also the same. The major geometrical changes are as follows: (i) The internal diameter of the cavities has been raised from 8 to 10 cm, to provide more transverse aperture since we are adopting a single quadrupole per period for focusing; and also because the beam emittance from the BNL DTL is a factor 3 larger than the value in the SNS-SCL; (ii) The cavity separation lowered from 38.5 cm down to 32 cm, that may require a more detail inspection of cavity coupling and stray field by running codes like SUPERFISH; (iii) The warm-to-cold transitions lowered from 71-76 cm down to 44 cm, that requires a careful engineering analysis to verify whether it is possible to accommodate all the required cryogenic piping in such reduced space; (iv) The warm insertion lowered from 1.6 m down to 1.0 m, that will force us to a FODO arrangement of the focusing quadrupoles. All other dimensions remained unchanged as in the SNS-SCL design. All the proposed modifications for the AGS-SCL require a careful engineering analysis to ensure their feasibility, and that do not cause too severe constrain to the design, fabrication, and operation of the components.

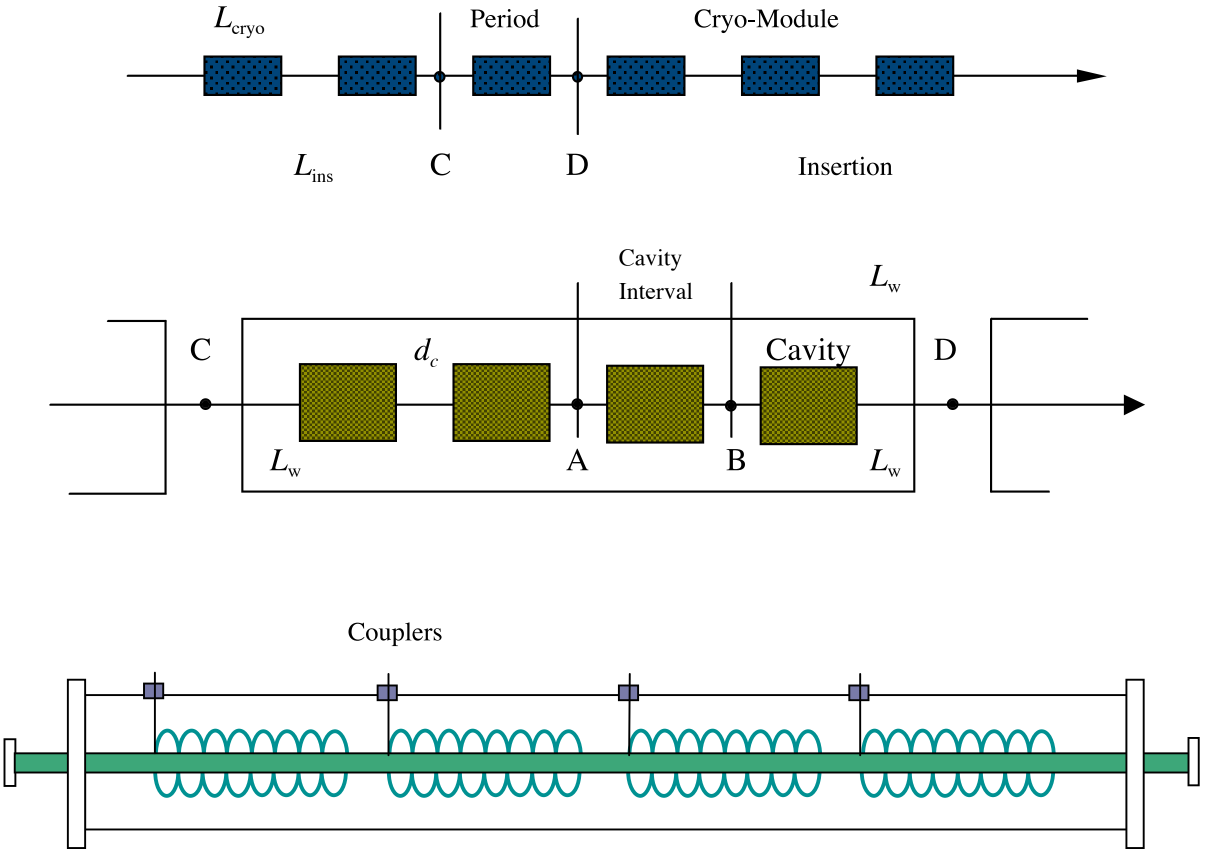

Figure 11. Sequence of Cryostats, Cavities and RF Cells in one SCL Section

Table 5. Inactive versus Active Length Distribution in the SNS and AGS SCL (805 MHz)

	SNS - med	**SNS** - high	**AGS** - LE	**AGS** - ME	**AGS** - HE
β_c	0.61	0.81	0.615	0.740	0.851
Cell, cm	11.36	15.08	11.45	13.78	15.84
# Periods	11	12	6	7	6
# Cavities	3	4	4	4	4
# Cells	6	6	8	6	6
Cavity Diam.	8 cm	8 cm	10 cm	10 cm	10 cm
Cavity Separ.	38.5 cm	38.5 cm	32 cm	32 cm	32 cm
W-C Tran.	71 cm	76 cm	44 cm	44 cm	44 cm
Warm Insertion	1.60 m	1.60 m	1.00 m	1.00 m	1.00 m
Period Length	5.835 m	7.894 m	6.504 m	6.150 m	6.642 m
Section Length	64.19 m	94.73 m	39.03 m	43.03 m	39.85 m
Linac Length	**158.9 m**		**121.9 m**		

RF Comparison and Considerations of the 200-400 MeV Sections

The Low-β section of the AGS-SCL has about the same energy range of the Medium-β section of the SNS-SCL, and thus the two sections would be expected to be of about the same design, also because they both use the same RF frequency of 805 MHz, and have the same β_c reference value. Nevertheless, for obvious reasons that will be explained below, the Medium-β section of the SNS-SCL is too long with a lower accelerating average gradient. That length would not possibly fit on the chosen BNL site, and we had to consider a more compact arrangement. Inspection of Table 5 shows a major deviation in our design: there are four cavities in each cryo-module, instead of three, and there are 8 RF cells instead of 6. The total number of RF cells is about the same, 198 in the SNS and 192 in the AGS SCL, indicating that the energy average gain per cell is about the same, as it should be, but there are fewer number of cryo-modules in our design: 6 against 11. This yields to a considerable shorter length of the section (39 versus 64 m), though each period is somewhat longer (6.5 versus 5.8 m), and to an energy gain per period almost as twice as large, as shown in Table 6. The reason is that the *active* to the period length ratio is also considerably higher. There is nonetheless a concern about too large an energy gain per period; the study of the beam dynamics [4] shows that one is really operating very close to the stability limit of the longitudinal motion. To avoid this, the SNS-SCL was expressly designed with a lower average gradient, and thus with a more diluted Medium-β section leading to a softer evolution of energy oscillations. Operating so close to the longitudinal stability limit is a concern for a potential of beam loss [5] and consequent activation of the RF and mechanical components. Otherwise, the local accelerating gradients as well as the required peak RF power in the couplers is about the same.

RF Comparison and Considerations of the High-Energy Sections

The high energy sections of both the SCL adopt about the same design. Both operate at 805 MHz, and have similar RF cells geometry. Both include 4 cavities, all with 6 RF cells, in each of the cyo-modules. There are 13 cryo-modules in the AGS-SCL versus the 12 in the SNS-SCL. Since the acceleration energy range is 200 MeV larger in the AGS-SCL, that means that the local accelerating gradient, that is in the *active length*, is higher, as one can see by inspecting Table 6. The numbers have been derived assuming a constant energy gain per cryo-module, that is constant accelerating gradient G. Though less than in the low-energy section, also here the ratio of *active length* to the period

Table 6. RF Comparison between the different Sections of the SNS and AGS SCL

	SNS - med	**SNS** - high	**AGS** - LE	**AGS** - ME	**AGS** - HE
ΔE / Period, MeV	18.31	51.08	33.33	57.14	66.67
Active/Period Length	0.350	0.459	0.563	0.538	0.572
Gradient, MeV /m	8.96	14.10	9.10	17.28	17.55
Axial Field E_{acc}, MV/m	--	--	14	21	19
RF Phase, ϕ_s	--	--	30°	25°	20°
Coupler Power, kW	408	522	350	600	700

length is higher by 20-30%. Consequently the average axial field E_{acc} is also higher, but still expected to be within the surface limit. The RF power in the couplers is also correspondingly higher.

Engineering Verification

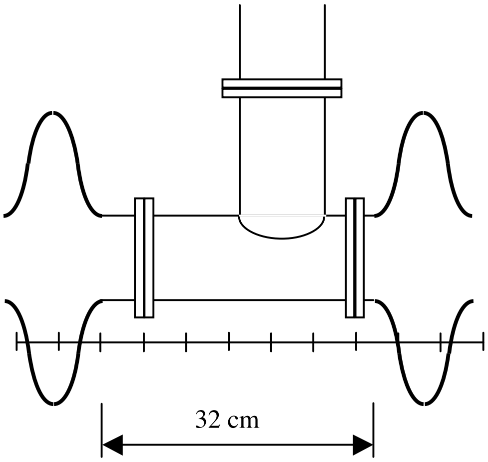

Figure 12. Power Coupler in the Inter-Cavity Space

It is important at this point to verify that the space specifications given above for the modified AGS-SCL are consistent with the manufacturing of the cryostats, the accommodation of the beam components in the warm insertions, and that there are no major obstacles or limitations to the implementation of the entire SCL on the selected BNL site. For instance Figure 12 shows, more or less in scale, the inter-cavity space and the RF power coupler with flanges, the dimension of which have been taken from the SNS design. The space seems to be indeed adequate; but there is the concern that a similar coupler to remove losses to the Higher Order Modes (HOM) may also be required, and in that case there may not be sufficient space between cavities. The concern is not really directed to the power loss to be absorbed by the cryogenic system, since this in the AGS-SCL is a factor 45 lower than in the SNS-SCL, but in the single bunch and bunch-to-bunch instabilities that may result from the spurious resonating modes of the cavities.

Figure 13 is an outline of a Warm Insertion with several beam components. There is room for only one quadrupole about 35 cm in length; otherwise there is a reasonable amount of space. It is also possible to place the steering magnet and the Beam Position Monitor (BPM) within the aperture of the quadrupole magnet if even more space is required.

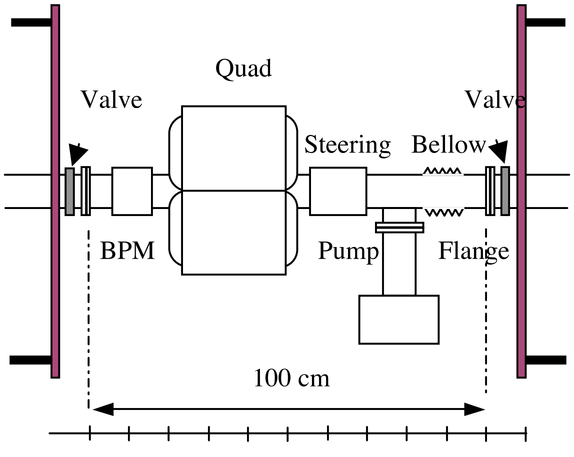

Figure 13. Warm Insertion with Beam Components

The design of the Low-β section is the one that most deviates from the SNS-SCL design. Figure 14 gives evidence that four cavities, each with 8 cells, can reasonably well be inserted in a cryostat of the assigned dimension for that section. Similarly, Figure 15 shows more details about the bridging of two cryo-modules together. We opt for a vertical layout where the RF couplers are installed directly above the cavities, and joined to the waveguides by means of a RF window in a direct straight line, avoiding bending. The power sources, in our case klystrons, are then located in a gallery above the

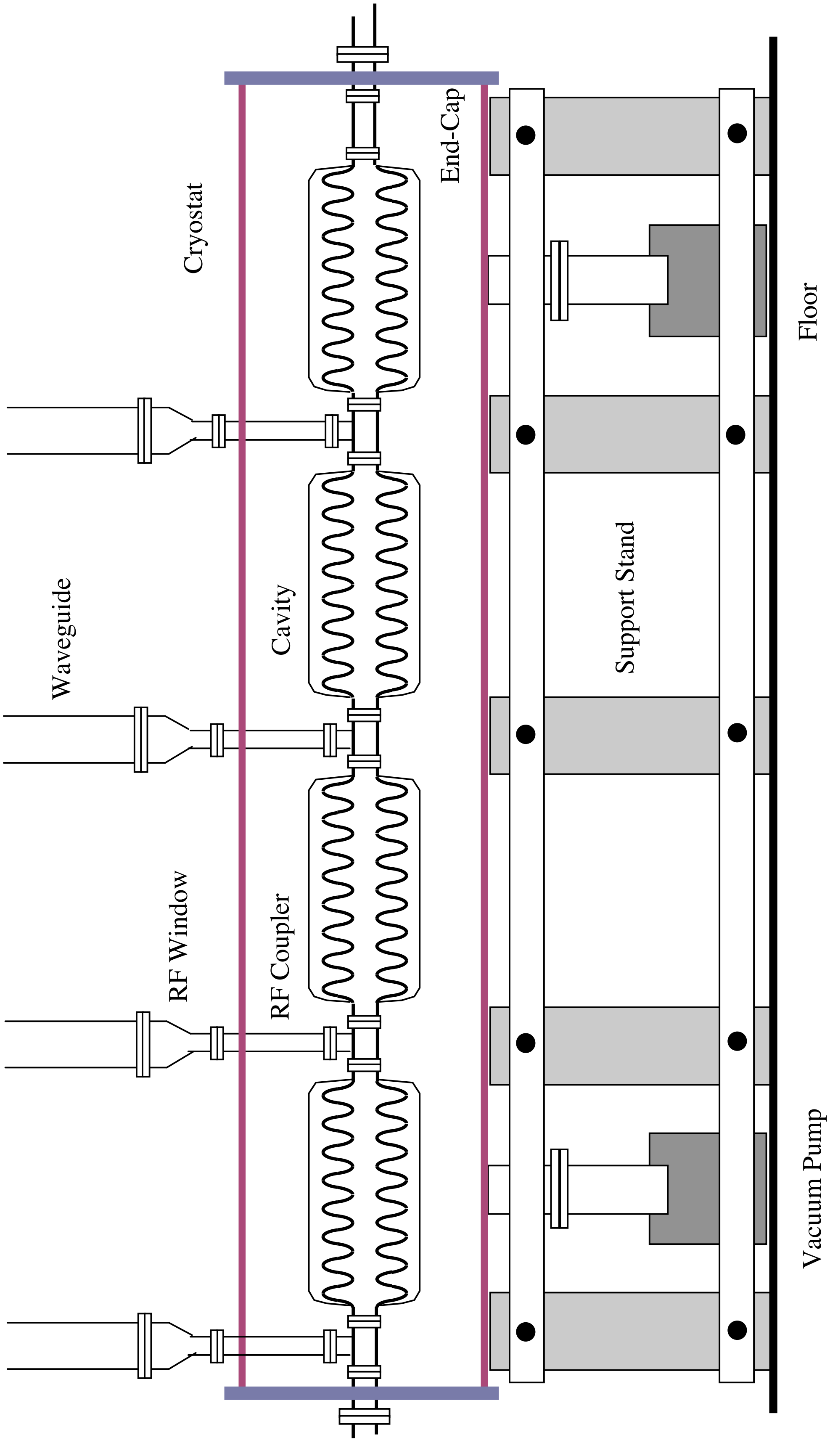

Figure 14. Assembly of a Low-β Section Cryo-Module

Linac tunnel. The same Figure 15 shows the piping for the Helium flow just above the cryostats. This arrangement is different from the one adopted by the SNS design where the couplers and the Helium piping are located below, an arrangement that in our view causes some logistic problem and difficulty of access. The SNS arrangement was suggested by the choice to isolate the vacuum and the helium flow in case of a single cryostat failure, so it could be possible to disconnect it for replacement without warming up the rest of the section. But here in case of failure we propose disconnecting the entire section where the failure occurs from the other two, bringing the entire section to warm temperature, and operating the replacement. This simplifies considerably the refrigeration piping with disconnect elements located only at each end of the section that includes 6 modules in the Low and High-β sections (each 40 m long) and 7 in the Medium-β section (44 m long). But the same procedure will require a longer period of time to operate a replacement, at best may be one week. Adopting this procedure, there is then hope that a shorter cold-to-warm transition of 44 cm at each end of the cryostat can indeed be sufficient.

Conclusion

We have demonstrated that a 1.2-GeV SCL for the AGS Upgrade is feasible and that can be designed to fit the space available between the end of the BNL 200-MeV DTL and the entrance to the AGS tunnel. The design is similar to that of the equivalent SNS-SCL, the only one we have today to make reference to for performance and cost comparison. Yet we had to adopt some major modifications (namely deviations) to shorten the entire SCL from 190 down to 120m. This was accomplished in two substantial ways: (i) By reducing the length of the drifts, namely the inter-cavity spacing, the cold-to-warm transitions, and the warm insertions; (ii) By making a more compact design of the Low-β section with four cavities per cryo-module and 8 RF cells per cavity. The first way raises of course some engineering concerns that though do not seem to us at the moment very compelling; the second way pushes the longitudinal motion to a limit of stability, and we worry here about the effect of possible errors.

By extrapolating from the SNS-SCL, it seems that the total cost of the AGS-SCL project is about 180 M$ (all included). On the other end, a bottom up cost estimate gave as a result a lower figure of about 100 M$, but without including burden charges that remained to be specified.

Concerning the possibility to raise the energy from 1.2 to 1.5 GeV, it is obvious that with the adopted Scenario (IV) it will not be possible to add more cryo-modules as part of a subsequent section (1,200 to 1,500 MeV). Nevertheless Superconducting RF Cavity is still a fresh new technology with surprises and advancement almost every day. Thus it cannot be excluded that in the near future higher gradients can be achieved and with that also higher power RF couplers. If this is the case, then it may be sufficient to raise the power (and, with that, the gradient) by 30 % in the entrance of all the couplers of the Medium and High-β Sections. By doing this, it should be noticed, the longitudinal phase oscillation reaches about 180^{o} on the first period of each of the two Sections, as presently is the case for the Low- β Section.

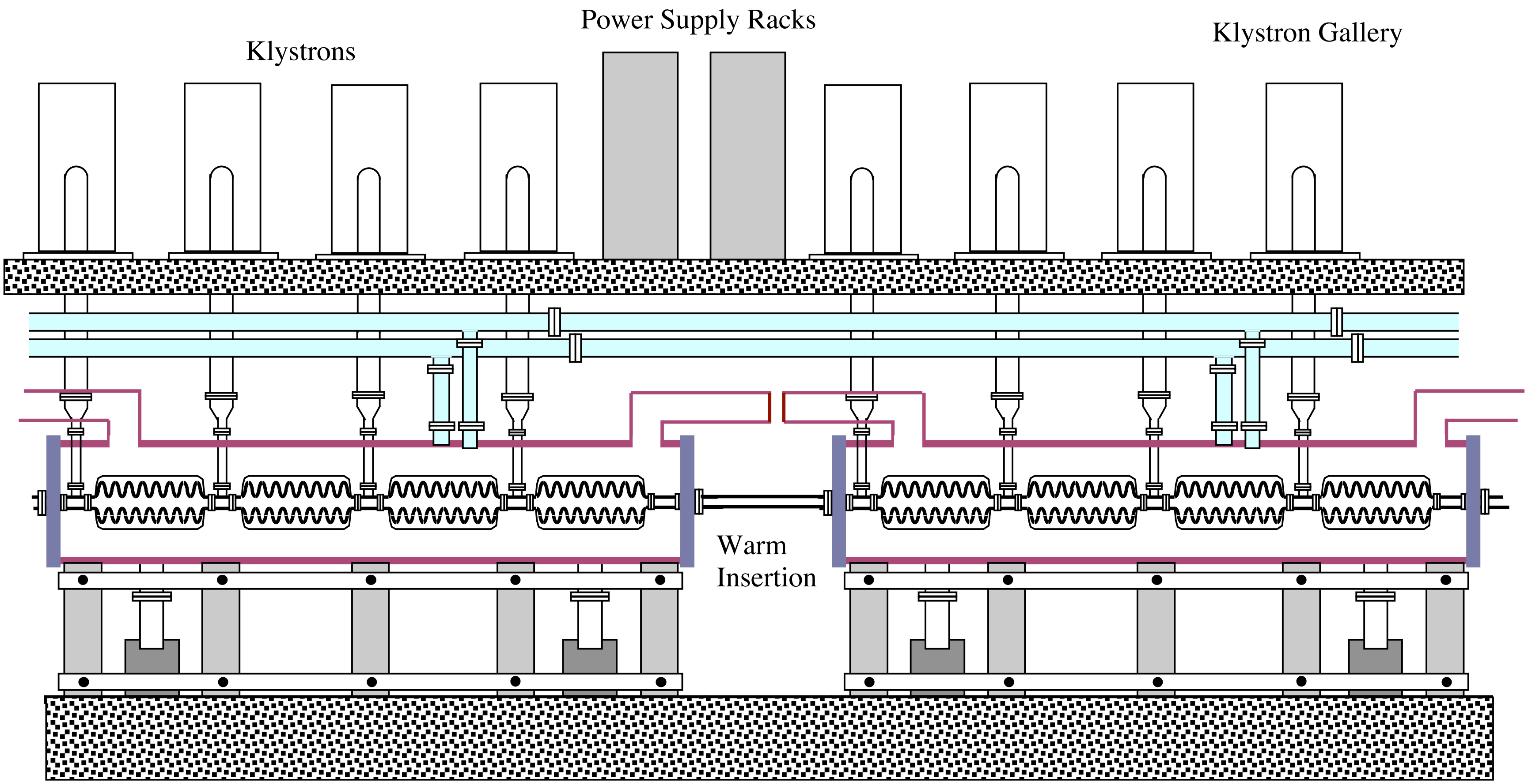

Figure 15. Assembly of two Low-β Section Cryo-modules with Warm Insertions

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I have discussed this project with several experts in the field from many institutions in Europe and in the States. I have received from all advice, suggestions and useful comments for which I am grateful. I have learned a lot from their expertise. In particular, I am grateful to D. Raparia, T. Nehring, J. Tuozzolo, K. C. Wu, and others at BNL for their assistance and contribution to this project.

Appendix: Summary Tables

Table A1. General Parameters of the AGS-SCL

Linac Section	**LE**	**ME**	**HE**
Ave. *increm.* Beam Power, kW	7.5	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	805	805
No. of Protons / Bunch x 10^8	8.70	8.70	8.70
Temperature, °K	2.1	2.1	2.1
Cells / Cavity	8	6	6
Cavities / Cryo-Module	4	4	4
Cavity Separation, cm	32.0	32.0	32.0
Cold-Warm Transition, cm	44	44	44
Cavity Internal Diameter, cm	10	10	10
Length of Warm Insertion, m	1.00	1.00	1.00
Accelerating Gradient, MeV/m	9.1	17.3	17.6
Ave. (real-estate) Gradient, MeV/m	5.12	9.30	10.04
Cavities / Klystron	1	1	1
No. of rf Couplers / Cavity	1	1	1
Rf Phase Angle	30°	25°	20°
Method for Transverse Focussing	FODO	FODO	FODO
Betatron Phase Advance / FODO cell	90°	90°	90°
Norm. rms Emittance, π mm-mrad	1.0	1.0	1.0
Rms Bunch Area, π eV- μs	1.75	1.75	1.75

Table A2. Summary of the AGS-SCL Design

Linac Section	**LE**	**ME**	**HE**
Velocity, β: In	0.5659	0.7128	0.8416
Out	0.7128	0.8416	0.8985
Cell Reference β_0	0.615	0.740	0.851
Cell Length, cm	11.45	13.78	15.85
Total No. of Periods	6	7	6
Length of a period, m	6.505	6.147	6.643
FODO-Cell ampl. func., β_Q, m	22.09	20.87	22.56
Total Length, m	*39.03*	*43.03*	*39.86*
Coupler rf Power, kW (*)	350	600	700
Energy Gain/Period, MeV	33.33	57.14	66.67
Total No. of Klystrons	24	28	24
Klystron Power, kW (*)	350	600	700
R_s/Q_0, ohm	120.5	145.0	166.7
Q_0 x 10^{10}	1.27	1.41	1.50
Ave. Axial Field, E_{acc}, MV/m	14.2	20.6	18.9
Filling Time, ms	0.21	0.23	0.19
Ave. Dissipated Power, W	0.52	1.38	1.11
Ave. HOM-Power, W	0.21	0.35	0.47
Ave. Cryogenic Power, W	66.8	73.8	69.3
Ave. Beam Power, kW	7.5	15	15
Total Ave. rf Power, kW (*)	13.7	29.1	283
Ave. AC Power for rf, kW (*)	30.3	64.7	63.0
Ave. AC Power for Cryo., kW	47.4	52.3	49.2
Total Ave. AC Power, kW (*)	78	117	112
Efficiency, % (*)	22.1	22.1	22.1

(*) Including 50% rf power contingency
Cryo-Efficiency 0.141 %
Beam Duty Cycle 0.179 %