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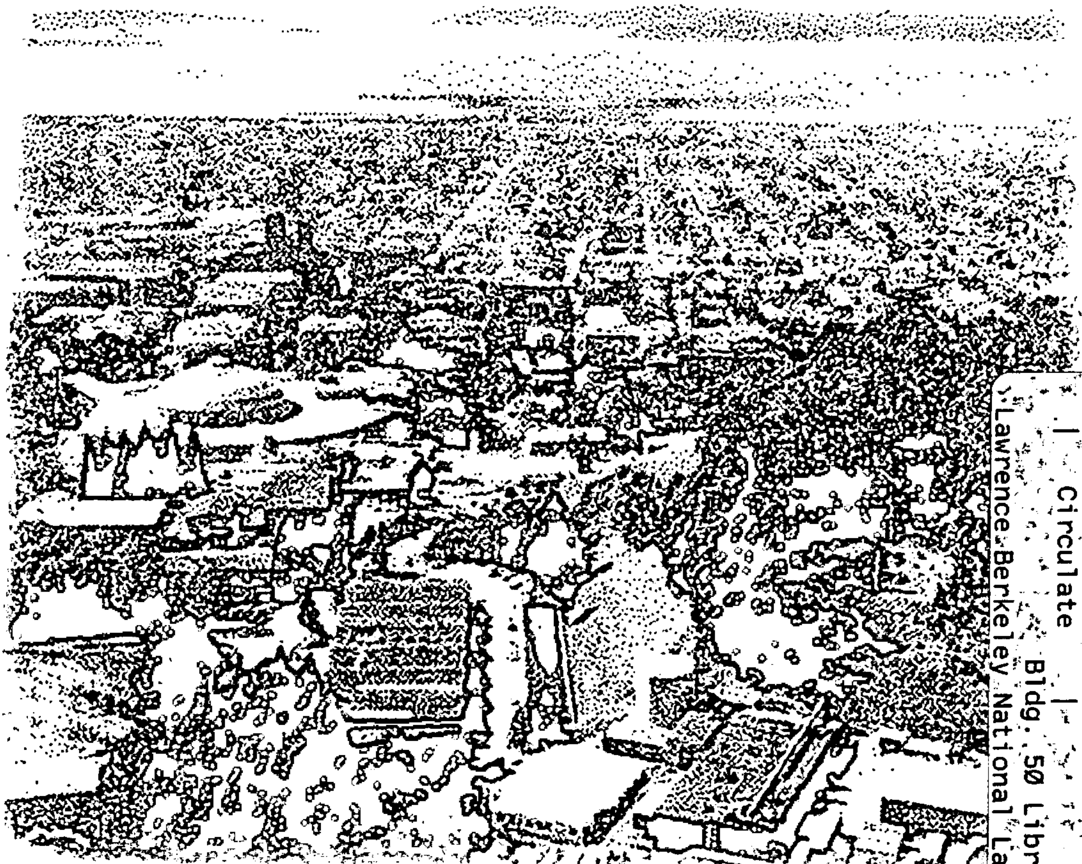
Accelerator and Fusion Research Division

November 1998



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NISOL Secondary Accelerator Scoping Study[1]

November, 1998

1. Introduction and Overview

The secondary accelerator system of a next-generation ISOL facility (NISOL) must provide cw beams of heavy ions with a wide variety of masses at energies up to 15 MeV/n. Because the primary mission of the facility is to provide radioactive, secondary beams, high efficiency and flexibility are also key requirements. As a user facility, the design must be highly reliable and robust. An upgrade path to extend the performance to higher energies is also an important consideration. The secondary accelerator can accept beam from the NISOL target/ion source system or from a stable-beam ion source. These injected beams can be mass analyzed in a high resolution isobaric mass analyzer, or can be delivered directly to the secondary accelerator. In either case, the majority of reaction products in the NISOL target have been removed from the beams prior to injection into the secondary accelerator. To maximize the intensities of the radioactive beams, initial acceleration must be accomplished with charge state $q = 1$ for masses up through $A = 140$. For higher masses, initial acceleration is accomplished with $q = 2$. The design ion for this accelerator system has a mass = 140, and a charge state = 1. Only one stripping stage is assumed as a reasonable tradeoff between intensity and efficiency. For the design ion, this still permits over 10% of the beam injected into the accelerator system to be delivered the user experiment.

Modern linac technology provides the most cost effective approach to meeting these requirements. We propose to use a linac system comprising two room temperature radio frequency quadrupoles (RFQs) using split coaxial resonators, followed by a heavy ion linac using independently-phased, superconducting resonator cavities. Superconducting cavities are now a well established technology that can be used for beams with energies down to about 20 keV/n. The RFQs in this design efficiently boost the energy from approximately 2 to 22 keV/n. The proposed design is based on existing, proven technology; further developments leading to the availability of multiple-charge-state ion sources with high "species efficiency" and superconducting resonators with higher accelerating gradients, could result in more efficient designs.

The results of a survey[2] of available stripping data are shown in Fig. 1. These data are displayed as mean charge state *versus* atomic number for various different stripping energies up to >10 MeV/n. The experimental data are "binned" into in bands corresponding to different stripping energies. The trends are very systematic, with the mean charge state almost independent of atomic number at the lowest stripping energies, and increasing significantly with atomic number for higher stripping energies. For accelerator design optimization, it is convenient to parameterize these experimental data by the solid lines shown at 0.01, 0.02, 0.05, 0.1, 0.2, 0.5 and 1 MeV/n. Using this parameterization, a plot of accelerator length versus stripping energy exhibits a broad minimum around 0.5 MeV/n (see Fig. 2). This energy is sufficient to elevate the charge-to-mass ratio *q/m* to at least

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[1] This report was prepared by Lawrence Berkeley National Laboratory for ORNL.

[2] Data compiled by M. McMahan, privvate communication.

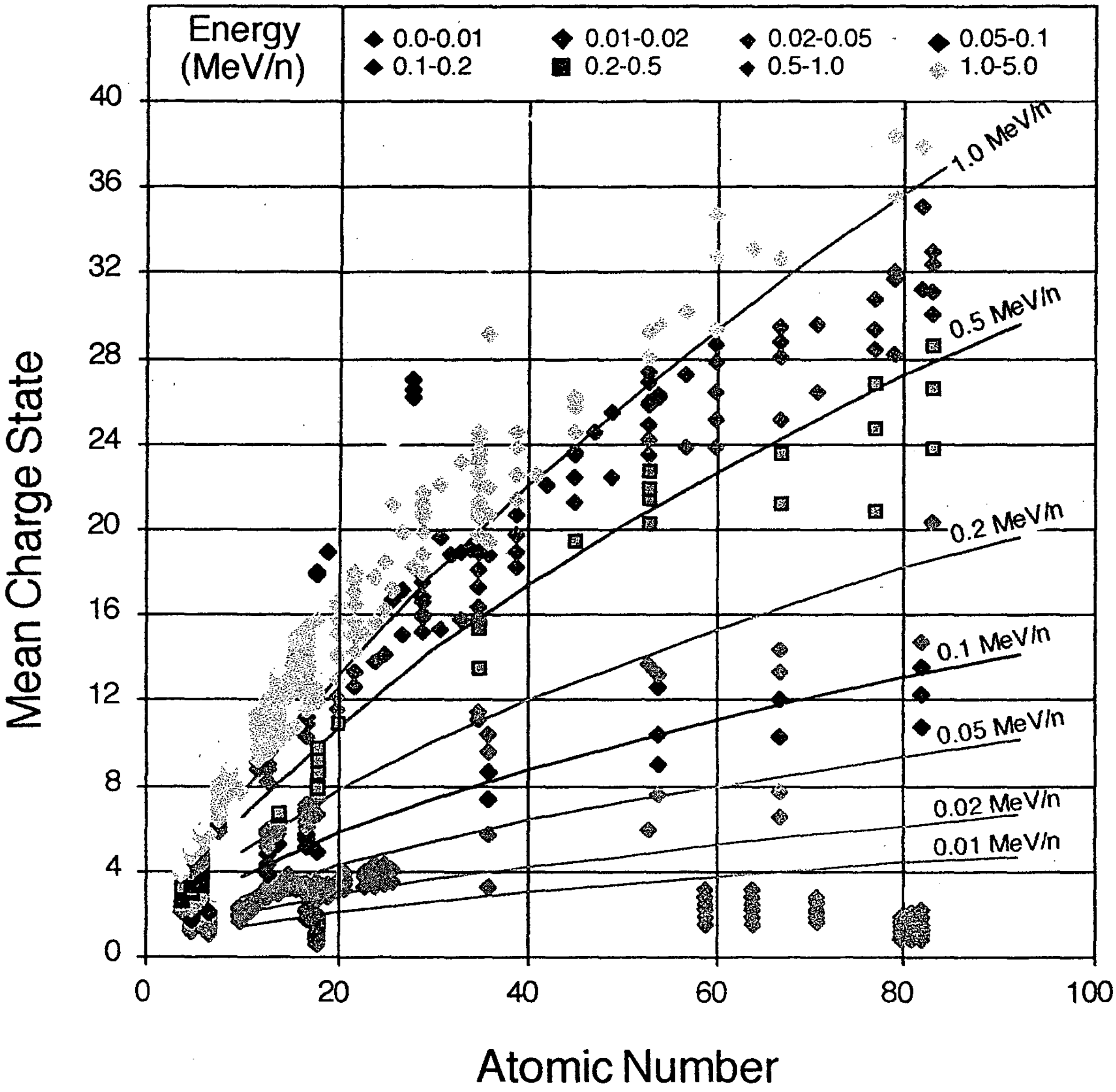

Figure 1. Summary of experimental stripping data. The mean charge state is shown as a function of atomic number for various stripping energies.

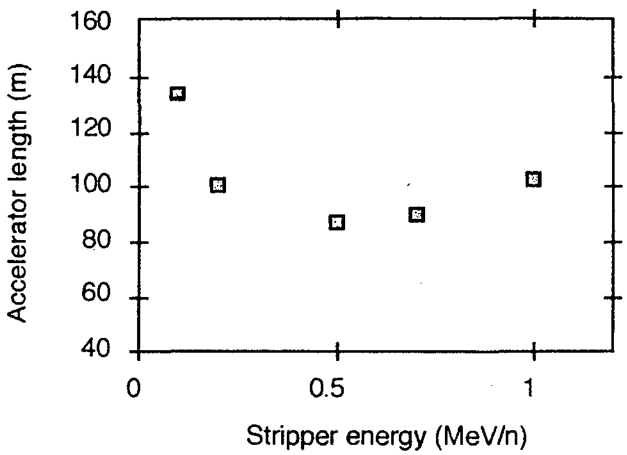

Figure 2. Optimization of stripper location

0.126 (U^{30+}). For this study, we have chosen 0.5 MeV/n as the preferred location for a foil stripper.

Provision for a second, non-equilibrium stripper following the second RFQ is recommended for flexibility, but the linac is designed to accommodate all anticipated requirements with a single stripper at 0.5 MeV/n, which is sufficient to achieve the highest possible beam intensities at reasonable cost.

A schematic layout of the proposed secondary accelerator and beam transport system is shown in Fig. 3. In this scheme, the beam accelerates to a maximum energy of 15 MeV/n and is delivered to a representative suite of experimental areas. By extending the building, a performance upgrade to higher energies and additional space for an expanded experimental program is straightforward. The principal components are briefly described in the following sections.

2. Radio Frequency Quadrupoles

The two RFQs, operating at 12 MHz, incorporate a split coaxial resonator (SCR) geometry, similar to the 25 MHz RFQ used in the KEK/University of Tokyo RIB complex, and similar to the structure recently investigated at ANL. The first RFQ structure is 3 m in length and accelerates the beam from ~2 to 10 keV/n. The second structure is 6 m in length and continues the acceleration to 22 keV/n, sufficient to be further accelerated directly by 4-gap, superconducting cavities operating at 24 MHz.

The tank diameter for both RFQs is ~1.5 meters. The internal accelerating structure is divided into modules to ensure mechanical stability and minimize the required rf power needed for a 100 kV peak intervane voltage. The 3-meter-long structure will be divided into two modules, and the 6-meter-long structure into three modules.

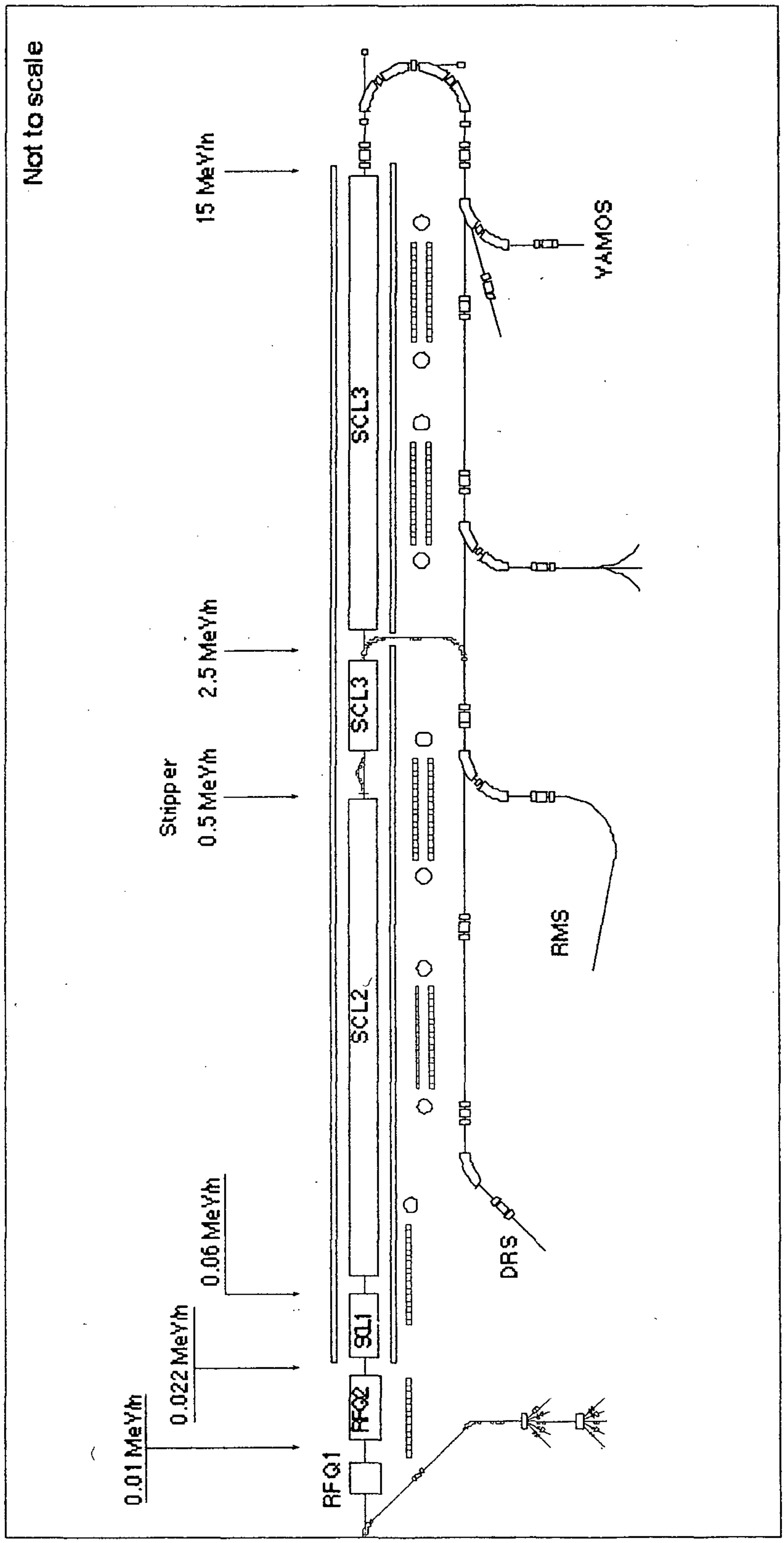

Figure 3. Conceptual layout of the secondary accelerator systems for NISOL.

The cw rf power requirements are 20 and 40 kW for each of the two structures, respectively. The thermal power density on the internal cavity surfaces is small, due to the low frequency of operation. Controlled-temperature water cooling will be required. Vacuum requirements for the RFQs are modest, a pressure requirement of ~10^{-7} Torr can be readily met with conventional pumping systems. Most of the gas load will be from outgassing from the internal cavity surfaces.

External bunching is used: the RFQ units include only an accelerator section, accounting for their relatively short length. Other energy trim and bunching cavities together with quadrupole and steering magnets will be needed as part of the RFQ system.

Ions with different mass will exit the mass separator system with different velocities. The cells within the RFQ are of fixed length with spacing tailored to the ion velocity; the velocity profile of the beam must be constant, independent of ion. In particular, there are fixed velocity requirements at the entrance and exit of each RFQ. In order to satisfy this requirement, the RFQs are placed on 300 kV high voltage platforms similar to the one presently in use at the Oak Ridge HRIBF facility. A summary of preliminary RFQ parameters is given in Table 1.

Table 1. Key RFQ parameters.

Parameter	RFQ1	RFQ2
q/m	1/140	1/140
Input energy [keV/n]	2.8	10
Output energy [m]	10	22
Duty Factor	100%	100%
Transmission	>85%	>90%
RF power [kW]	20	40
Frequency [MHz]	12	12
Diameter [m]	1.5	1.5
Length [m]	3	6
Number of modules	2	3

3. Heavy Ion Linac Systems

All of the acceleration beyond the RFQs is provided by independently-phased, quarter-wave, superconducting resonators. These systems take the beam from an energy of 22 keV/n to 15 MeV/n. Singly-charged ions are accelerated to 0.5 MeV/n where a stripper is used to elevate the charge state to a charge-to-mass ratio $q/m \geq 0.126$. Focusing is provided by superconducting quadrupole triplets. Allowing space for beam diagnostics and a beam extraction system at 2.5 MeV/n, and assuming accelerating gradients achievable with presently available technology, a total length of about 115 m is required.

We describe here a heavy ion accelerating scheme based on three superconducting linac segments distinguished by three rf frequencies, 24, 48 and 96 MHz. A summary of the accelerating schedule with accelerating parameters is provided in Appendix A.

3.1 Superconducting Segment 1

This is a short section consisting of 11 superconducting cavities operating at 24 MHz which raises the energy from 22 to 60 keV/n. The cavities each have 4 accelerating gaps. For the design ion, with a charge to mass ratio $q/m = 1/140$, the first four cavities operate with 2 MV/m accelerating gradient and the remaining seven cavities operate with a 3 MV/m accelerating gradient. A separate rf amplifier is used for each cavity. These cavities are 3.3 $\times\ \beta\lambda/2$ in length and are separated by superconducting quadrupole triplets. Triplet focusing minimizes the beam size in the cavities, reducing the longitudinal-transverse coupling and maintaining the lowest possible emittance of the beam through the linac. The length of each triplet is $1.5 \times 3.3 \times \beta\lambda/2$, and can be determined at any point along the linac from the Table in Appendix A. The maximum quadrupole gradient is approximately 300 T/m. Some grouping of the quadrupoles is possible to reduce the number of separate designs and the number of power supplies and control points.

The total length required in this segment for cavities and quadrupoles is 5 m. This comprises 11 four-gap cavities and 10 quadrupole triplets, with an additional quadrupole focusing triplet at the entrance to the section. The cavities and quadrupoles are immersed in liquid helium dewars operating at 4.5 deg K. The effective real estate gradient for this segment is 1.1 MV/m. We increase the total length requirement for this section to 6 m to allow for beam diagnostic devices and inter-dewar spaces.

3.2 Superconducting Segment 2

The second segment continues the acceleration of the unstripped beam from 60 to 500 keV/n. It is similar to the first segment, except the four-gap, quarter-wave cavities operate at 48 MHz and have an effective accelerating gradient of 4 MV/m over their effective length. A separate rf amplifier is again used for each cavity. Each cavity is $3.3 \times \beta\lambda/2$ in length and is separated by superconducting quadrupole triplets. As in the first segment, quadrupole triplets are inserted between each four-gap cavity. They also operate with a maximum gradient of 300 T/m over their effective lengths.

The total length required in this segment for cavities and quadrupoles is 38 m, and comprises 68 four-gap cavities and 68 quadrupole triplets which are immersed in liquid helium dewars operating at 4.5 deg K. The effective real estate gradient for this segment is 1.6 MV/m. We increase the total length requirement for this section to 46 m to allow for beam diagnostic devices and inter-dewar spaces.

3.3 Superconducting Segment 3

The final (poststripper) segment continues the acceleration from 0.5 to 15 MeV/n. Beams in the postripper segment have a charge-to-mass ratio $q/m \geq 0.126$ (see discussion in section 3.4 below). The configuration of this section is a little different. The quarter-wave, superconducting cavities operate at 96 MHz and contain two gaps. These cavities have an effective accelerating gradient of 4 MV/m. The accelerating length of each cavity is assumed to be $1.2 \times \beta\lambda$. Due to the higher velocities and shortness of the cavities, quadrupole triplets are placed between every fifth cavity. The quadrupole gradients are approximately the same as those in the previous sections, so the quadrupole triplet technology can be the same as in all the other quadrupole triplets.

The total length required in this segment for the two-gap cavities and the quadrupole triplets is 44 m. There are 145 two-gap cavities and 29 quadrupole triplets. The effective real estate gradient for the post-stripper segment is 2.6 MV/m. We increase the total length requirements for the segment to 53 m to allow for beam diagnostics and inter-dewar spaces.

3.4 Stripper section

A foil stripper is used at the 0.5 MeV/n point, located between the second and third superconducting segments. For uranium, the worst case, the most probable charge state is U^{30+} ($q/m = 0.126$), with medium-mass ions stripping to q/m up to 0.17. The efficiency for stripping in the medium to high mass range is ~20%. The lightest ions, such as $^{11}Li^{1+}$, will be fully stripped at this energy with very high efficiency (~90%).

A four-magnet chicane is used in the stripper section to analyze the charge state spectrum produced by the stripper and to select a particular charge state for injection into the post stripper segments for further acceleration. This will simplify the tuning of the linac and help to ensure that the maximum possible intensity can be delivered to the user. A spacing of 4 m between linac segments two and three is provided to accommodate both the stripper, the chicane and associated diagnostics.

3.5 Low Energy Beam Pick-off (2.5 MeV/n)

In order to efficiently deliver beams to the low energy experimental areas, another 4-m-gap is provided at the 2.5 MeV/n point in the post stripper linac segment. This point is located about 65 m downstream from the start of the sc linac system. As shown in Fig. 2, two 90 deg bends can be used to bend the beam away from the linac axis and direct it into the main beamline used to transport the accelerated radioactive beams to the low energy experimental areas.

4. Cryogenic Systems

The cryogenic systems must provide 4.5 deg K service to the components of the secondary accelerator facility: approximately 225 rf cavities, and 108 quadrupole triplets located in the linac. The rf power supplied to each cavity is only a few watts. The largest consumption of rf power will be by the fast tuners. Most of this power can be dissipated at LN_2 temperature, not at LHe temperature, to minimize the load on the helium liquifier. These superconducting components are housed in a series of approximately 40 dewars located along the 115 meter length of the linac. It is also economical to plan for cryogenic pumping of the beam transport lines using the cryogenic return line, since this is accomplished without requiring additional cryogenic capacity.

The cryogenic systems required to support the NISOL facility include compressors, a cold box, a distribution system and a dewar system. A cryogenic plant with a room temperature power of ~1 MW is required to support the superconducting elements of the facility. Such a system is readily available from the commercial sector. It is customary to separate the compressors in a separate building to isolate the noise and vibration. The compressors will conveniently fit into a 4-m-high building with a footprint of 6 m × 11 m. Light crane service (5 ton) should be provided for maintenance. The cold box has a diameter of 3.4 m. It will be located closer to the accelerator system and housed in a 7.3-m-high building with a footprint of approximately 6 m × 7 m. Maintenance of this equipment will also require a 5 ton crane.

The cryogenic components of the linac are housed in a series of approximately 40 dewars. Cold surfaces within and between the dewars provide an excellent vacuum for the accelerator systems. Sufficient space is provided between dewars for diagnostics or other beam access that may be needed. Standard distribution lines for the working fluids are provided between the compressors, cold box, dewars, and beamlines.

5. Heavy Ion Beam Transport Systems

The general layout of the NISOL secondary accelerator systems (see Fig. 2) forms a "U-shaped" configuration with the accelerator systems on one leg and the beam transport systems on the other. The representative suite of experimental systems established at this time by the NISOL planning team is used to define a preliminary set of requirements for these beam transport systems. Radioactive beams must be transported from three points along the accelerator chain: fully accelerated beam (maximum energy, 15 MeV/n), partially accelerated beam (maximum energy, 2.5 MeV/n), and "unaccelerated" beam. The layout allows for future expansion to higher energies by extension of the building, linac and beam transport systems.

The 15 MeV/n system accepts beam from linac and transports it to one of 5 experimental areas. In order to transport a beam of $^{238}U^{30+}$ ($q/m = 0.126$), the line is designed for a rigidity $B\rho = 4.44$ T-m. All other beams would have higher q/m and therefore lower rigidity. A mass $m = 140$ beam will have a rigidity of about 4 T-m, so designing this line to accommodate uranium beams can be done for essentially the same cost. Standardized magnet designs can be used, and the layout provides adequate space for diagnostics and easy-to-tune beam transport. Dipole magnets with 45 deg bends and straight-through ports could be used to facilitate tuning the beam to the different experimental areas. These straight-through ports also allow placement of Faraday cups in the 180 deg bend section. Together with a cup at the exit of the linac, these can be used to facilitate tuning up the linac and ensuring the beam is properly matched into the beamline.

The 2.5 MeV/n system is used to transport beam to experiments utilizing lower energy beams that don't require operation of the full linac system. The pick-off point for this beamline is approximately 65 m downstream from the start of the superconducting linac system. Four 45 deg magnets are used to turn the beam away from the linac axis and direct it back along the beamline leading toward two of the experimental areas. The maximum magnetic rigidity of these beams is 1.8 T-m.

The unaccelerated beam transport system is used to deliver radioactive beams to an experimental area for mass traps and other apparatus for material science and biomedical studies. These beams have about 100 keV of energy, $q/m \geq 1/140$, and a maximum rigidity $B\rho = 0.5$ T-m.

A preliminary estimate of the number and types of magnets required for these three beamline systems is given in Table 2. No switching magnets are listed for the 15 MeV/n beam transport line pending further definition of the experimental layout.

Table 2. Beam transport magnets.

Magnet type	15 MeV/n beam transport	2.5 MeV/n beam transport	Unaccelerated beam transport
Dipoles [45 deg]	11	4	2
Switch. magnets	0	0	2
Dipole correctors	14	3	12
Quad singlets	8	6	24
Quad triplets	12	1	2

The beamlines are cryogenically pumped using the 20 deg K return system from the main linac cryosystem.

6. Diagnostics

Because the primary purpose of the systems described here is to accelerate *secondary* beams, the intensities of these beams will vary widely, and for some experiments be very low. Additionally, it is anticipated that there will be a large number of ions and operational modes that will require frequent retuning of the accelerator during its operational lifetime. While a detailed study of beam diagnostics is beyond the scope of the present study, it is clear that efficient operation will require a facility that is well instrumented with beam diagnostics and that these instruments cover a wide dynamic range of intensities from ~ 10^2 -10^{10} ions/sec.

Several features have been incorporated at the conceptual level to facilitate efficient operation of the facility. These include, for example: the use of a separate, stable-beam ion source that can be used for initial commissioning and to tune out "pilot" beams; a charge state analyzer in the stripper area to select a particular charge state for injection in to the post stripper; and the incorporation of a large number of spaces between dewars in the linac which permit frequent access to the beam for placement of diagnostics. Additionally, the general layout of the external beamlines provides ample space for locating diagnostics devices.

7. Conclusions

The design of this accelerator requires no substantial advances in technology. The design is flexible and robust, using a large number of short, independently-phased cavities, and providing for a wide range of ion species acceptance and energy variability. The triplet focusing between cavities reduces the beam size and renders it round in the accelerating gaps, thereby reducing the potential for emittance blowup. The total length required to house the proposed accelerator is about 140 m. This includes space for the RFQs, the superconducting linac segments, inter dewar spacing, and the various short sections of beamline that are required from the exit of the isobaric separator to and including the 180 deg turn in the 15 MeV/n transport line. The estimated total installed power requirement for the accelerator and beam transport systems is about 2.2 MW (not including the user experimental apparatus). R&D to develop reliable high gradient resonators could lead to a more efficient, compact design, but at this time, it is prudent to base the designs on established performance capabilities.

As discussed in section 1, a second, optional, non-equilibrium stripper following the second RFQ is recommended to add flexibility, but the linac is designed to accommodate all anticipated requirements with a single stripper at 0.5 MeV/n; this approach will achieve the highest possible beam intensities and reliability at reasonable cost.

Some multiplexing of multiple ion species should be possible. For ions of similar rigidities, the quadrupoles can be tuned to a compromise field, and cavity gradients switched to the appropriate levels for the two ions. The cavities have a Q-value on the order of 10^8, indicating that it would take on the order of 1 second to significantly change the cavity gradient. Multiplexed operation may be particularly valuable for setting up a new experiment which requires only occasional or low levels of beam. The bandwidth of the focusing system is quite large, and rigidity ranges of 2:1 should be possible without retuning.

In summary, the development of a secondary accelerator system to meet the requirements of NISOL appears to be straightforward and for the most part can be based on proven technology with established performance parameters.

8. Acknowledgments

The authors are pleased to acknowledge the support and guidance from Fred Bertrand and Jerry Garrett at Oak Ridge National Laboratory. We also gratefully acknowledge engineering support from Missy Ogan (ORNL) for help with the civil construction aspects of the proposed facility, and from Shlomo Caspi, Ron Scanlan and Ron Yourd (LBNL) for engineering support. Support from Margaret (Peggy) McMahan with the stripping data and discussions with J. Kalnins on beam transport aspects is also gratefully acknowledged.

Appendix A: Linac Acceleration Table

The following table summarizes the superconducting linac parameters. Incidental gaps in the accelerator are not included. A single stripper is assumed at 0.5 MeV/n. The design ion is $q/m = 1/140$; ions with mass $m > 140$ are accelerated in the prestripper sections with charge state q=2+. The geometry of each resonator is specific to its exact energy. A filling factor of 0.5 is assumed in the superconducting structures. Four-gap resonators are assumed in the prestripper segments and two-gap resonators in the post stripper sections.

Focusing device between each cavity
Cavity Length = $\beta\lambda/2$ × 3.3
L_foc/L_cav=1.50

Item	**V_acc** (MV)	***q/m***	**KE** (keV/n)	β	**freq** (MHz)	$\beta\lambda/2$ (cm)	$B\rho$ (T-m)	**Eacc** (MV/m)	**L_cav** (cm)	**L_focus** (cm)	**Σ Lth** (m)
1 SC Part 1	0.283	0.007	24.0	0.007	24	4.47	3.15	2	14.13	21.19	0.35
2 SC Part 1	0.295	0.007	26.1	0.007	24	4.66	3.29	2	14.76	22.14	0.72
3 SC Part 1	0.308	0.007	28.3	0.008	24	4.85	3.42	2	15.39	23.08	1.11
4 SC Part 1	0.320	0.007	30.6	0.008	24	5.05	3.56	2	16.02	24.03	1.51
5 SC Part 1	0.500	0.007	34.1	0.009	24	5.33	3.76	3	16.65	24.98	1.92
6 SC Part 1	0.528	0.007	37.9	0.009	24	5.62	3.96	3	17.59	26.39	2.36
7 SC Part 1	0.556	0.007	41.8	0.009	24	5.90	4.16	3	18.53	27.80	2.83
8 SC Part 1	0.584	0.007	46.0	0.010	24	6.19	4.36	3	19.47	29.21	3.31
9 SC Part 1	0.613	0.007	50.3	0.010	24	6.47	4.56	3	20.42	30.63	3.82
10 SC Part 1	0.641	0.007	54.9	0.011	24	6.76	4.76	3	21.36	32.04	4.36
11 SC Part 1	0.669	0.007	59.6	0.011	24	7.05	4.96	3	22.31	33.46	4.92

Item	**V_acc** (MV)	***q/m***	**KE** (keV/n)	β	**freq** (MHz)	$\beta\lambda/2$ (cm)	$B\rho$ (T-m)	**Eacc** (MV/m)	**L_cav** (cm)	**L_focus** (cm)	**Σ Lth** (m)
1 SC Part 2	0.930	0.007	66.2	0.012	48	3.71	5.23	4	23.25	34.88	5.50
2 SC Part 2	0.490	0.007	69.7	0.012	48	3.81	5.37	4	12.25	18.38	5.80
3 SC Part 2	0.503	0.007	73.3	0.012	48	3.91	5.50	4	12.57	18.86	6.12
4 SC Part 2	0.516	0.007	76.9	0.013	48	4.00	5.64	4	12.89	19.33	6.44
5 SC Part 2	0.528	0.007	80.7	0.013	48	4.10	5.78	4	13.21	19.81	6.77
6 SC Part 2	0.541	0.007	84.5	0.013	48	4.20	5.91	4	13.53	20.29	7.11
7 SC Part 2	0.554	0.007	88.5	0.014	48	4.29	6.05	4	13.84	20.77	7.45
8 SC Part 2	0.566	0.007	92.5	0.014	48	4.39	6.18	4	14.16	21.24	7.81
9 SC Part 2	0.579	0.007	96.6	0.014	48	4.48	6.32	4	14.48	21.72	8.17
10 SC Part 2	0.592	0.007	100.8	0.015	48	4.58	6.46	4	14.80	22.20	8.54
11 SC Part 2	0.605	0.007	105.1	0.015	48	4.68	6.59	4	15.12	22.68	8.92
12 SC Part 2	0.617	0.007	109.5	0.015	48	4.77	6.73	4	15.44	23.15	9.30
13 SC Part 2	0.630	0.007	113.9	0.016	48	4.87	6.86	4	15.75	23.63	9.70
14 SC Part 2	0.643	0.007	118.5	0.016	48	4.97	7.00	4	16.07	24.11	10.10
15 SC Part 2	0.656	0.007	123.2	0.016	48	5.06	7.14	4	16.39	24.59	10.51
16 SC Part 2	0.668	0.007	127.9	0.017	48	5.16	7.27	4	16.71	25.07	10.93
17 SC Part 2	0.681	0.007	132.7	0.017	48	5.26	7.41	4	17.03	25.55	11.35
18 SC Part 2	0.694	0.007	137.7	0.017	48	5.35	7.54	4	17.35	26.02	11.79
19 SC Part 2	0.707	0.007	142.7	0.017	48	5.45	7.68	4	17.67	26.50	12.23
20 SC Part 2	0.720	0.007	147.8	0.018	48	5.55	7.82	4	17.99	26.98	12.68
21 SC Part 2	0.732	0.007	153.0	0.018	48	5.64	7.95	4	18.31	27.46	13.14
22 SC Part 2	0.745	0.007	158.3	0.018	48	5.74	8.09	4	18.63	27.94	13.60

Item	**V_acc** (MV)	***q/m***	**KE** (keV/n)	***β***	**freq** (MHz)	***βλ/2*** (cm)	***Bρ*** (T-m)	**Eacc** (MV/m)	**L_cav** (cm)	**L_focus** (cm)	**Σ Lth** (m)
23 SC Part 2	0.758	0.007	163.7	0.019	48	5.84	8.23	4	18.95	28.42	14.08
24 SC Part 2	0.771	0.007	169.1	0.019	48	5.93	8.36	4	19.26	28.90	14.56
25 SC Part 2	0.783	0.007	174.7	0.019	48	6.03	8.50	4	19.58	29.38	15.05
26 SC Part 2	0.796	0.007	180.4	0.020	48	6.13	8.64	4	19.90	29.85	15.54
27 SC Part 2	0.809	0.007	186.1	0.020	48	6.22	8.77	4	20.22	30.33	16.05
28 SC Part 2	0.822	0.007	191.9	0.020	48	6.32	8.91	4	20.54	30.81	16.56
29 SC Part 2	0.834	0.007	197.9	0.021	48	6.42	9.04	4	20.86	31.29	17.08
30 SC Part 2	0.847	0.007	203.9	0.021	48	6.52	9.18	4	21.18	31.77	17.61
31 SC Part 2	0.860	0.007	210.0	0.021	48	6.61	9.32	4	21.50	32.25	18.15
32 SC Part 2	0.873	0.007	216.2	0.021	48	6.71	9.45	4	21.82	32.73	18.70
33 SC Part 2	0.886	0.007	222.5	0.022	48	6.81	9.59	4	22.14	33.21	19.25
34 SC Part 2	0.898	0.007	228.8	0.022	48	6.90	9.73	4	22.46	33.69	19.81
35 SC Part 2	0.911	0.007	235.3	0.022	48	7.00	9.86	4	22.78	34.17	20.38
36 SC Part 2	0.924	0.007	241.9	0.023	48	7.10	10.00	4	23.10	34.65	20.96
37 SC Part 2	0.937	0.007	248.5	0.023	48	7.19	10.14	4	23.42	35.13	21.54
38 SC Part 2	0.950	0.007	255.3	0.023	48	7.29	10.27	4	23.74	35.61	22.14
39 SC Part 2	0.962	0.007	262.1	0.024	48	7.39	10.41	4	24.06	36.09	22.74
40 SC Part 2	0.975	0.007	269.0	0.024	48	7.48	10.55	4	24.38	36.57	23.35
41 SC Part 2	0.988	0.007	276.0	0.024	48	7.58	10.68	4	24.70	37.05	23.97
42 SC Part 2	1.001	0.007	283.1	0.025	48	7.68	10.82	4	25.02	37.53	24.59
43 SC Part 2	1.014	0.007	290.3	0.025	48	7.78	10.96	4	25.34	38.01	25.23
44 SC Part 2	1.026	0.007	297.6	0.025	48	7.87	11.09	4	25.66	38.49	25.87
45 SC Part 2	1.039	0.007	305.0	0.026	48	7.97	11.23	4	25.98	38.97	26.52
46 SC Part 2	1.052	0.007	312.5	0.026	48	8.07	11.37	4	26.30	39.45	27.17
47 SC Part 2	1.065	0.007	320.0	0.026	48	8.16	11.50	4	26.62	39.93	27.84
48 SC Part 2	1.078	0.007	327.7	0.026	48	8.26	11.64	4	26.94	40.41	28.51
49 SC Part 2	1.090	0.007	335.4	0.027	48	8.36	11.78	4	27.26	40.89	29.19
50 SC Part 2	1.103	0.007	343.2	0.027	48	8.45	11.91	4	27.58	41.37	29.88
51 SC Part 2	1.116	0.007	351.2	0.027	48	8.55	12.05	4	27.90	41.85	30.58
52 SC Part 2	1.129	0.007	359.2	0.028	48	8.65	12.19	4	28.22	42.33	31.29
53 SC Part 2	1.142	0.007	367.3	0.028	48	8.75	12.32	4	28.54	42.81	32.00
54 SC Part 2	1.154	0.007	375.5	0.028	48	8.84	12.46	4	28.86	43.29	32.72
55 SC Part 2	1.167	0.007	383.8	0.029	48	8.94	12.60	4	29.18	43.77	33.45
56 SC Part 2	1.180	0.007	392.2	0.029	48	9.04	12.73	4	29.50	44.25	34.19
57 SC Part 2	1.193	0.007	400.6	0.029	48	9.13	12.87	4	29.82	44.73	34.93
58 SC Part 2	1.206	0.007	409.2	0.030	48	9.23	13.01	4	30.14	45.21	35.69
59 SC Part 2	1.218	0.007	417.8	0.030	48	9.33	13.14	4	30.46	45.69	36.45
60 SC Part 2	1.231	0.007	426.6	0.030	48	9.42	13.28	4	30.78	46.17	37.22
61 SC Part 2	1.244	0.007	435.4	0.030	48	9.52	13.42	4	31.10	46.65	38.00
62 SC Part 2	1.257	0.007	444.3	0.031	48	9.62	13.55	4	31.42	47.13	38.78
63 SC Part 2	1.270	0.007	453.3	0.031	48	9.72	13.69	4	31.74	47.61	39.58
64 SC Part 2	1.282	0.007	462.4	0.031	48	9.81	13.83	4	32.06	48.09	40.38
65 SC Part 2	1.295	0.007	471.6	0.032	48	9.91	13.97	4	32.38	48.57	41.19
66 SC Part 2	1.308	0.007	480.9	0.032	48	10.01	14.10	4	32.70	49.05	42.00
67 SC Part 2	1.321	0.007	490.3	0.032	48	10.10	14.24	4	33.02	49.53	42.83
68 SC Part 2	1.334	0.007	499.8	0.033	48	10.20	14.38	4	33.34	50.02	43.66

Strip to q/m>0.126=30/238 at 500 keV/n

Strip to *q/m* >0.126=30/238 at 500 keV/n 2-gap cavities; length = 1.2 * $\beta\lambda/2$

Focus between every 5th cavity
29 focusing devices
Cavity Length = $\beta\lambda/2$ × 1.2

Non-focus intercav length = 5.00
L_foc/L_cav = 1.50

Item	**V_acc** (MV)	***q/m***	**KE** (keV/n)	β	**freq** (MHz)	$\beta\lambda/2$ (cm)	$B\rho$ (T-m)	**Eacc** (MV/m)	**L_cav** (cm)	**L_focus** (cm)	**Σ Lth** (m)
1 SC Part 3	0.490	0.126	561.5	0.035	96	5.41	0.86	4	12.24	18.36	43.97
2 SC Part 3	0.260	0.126	594.2	0.036	96	5.56	0.88	4	6.49	5.00	44.08
3 SC Part 3	0.267	0.126	627.8	0.037	96	5.72	0.91	4	6.67	5.00	44.20
4 SC Part 3	0.274	0.126	662.4	0.038	96	5.87	0.93	4	6.86	5.00	44.32
5 SC Part 3	0.282	0.126	697.9	0.039	96	6.03	0.96	4	7.05	5.00	44.44
6 SC Part 3	0.289	0.126	734.4	0.040	96	6.18	0.98	4	7.23	10.85	44.62
7 SC Part 3	0.297	0.126	771.7	0.041	96	6.34	1.01	4	7.42	5.00	44.74
8 SC Part 3	0.304	0.126	810.1	0.042	96	6.49	1.03	4	7.61	5.00	44.87
9 SC Part 3	0.312	0.126	849.4	0.043	96	6.65	1.06	4	7.79	5.00	45.00
10 SC Part 3	0.319	0.126	889.6	0.044	96	6.80	1.08	4	7.98	5.00	45.13
11 SC Part 3	0.327	0.126	930.7	0.045	96	6.96	1.11	4	8.17	12.25	45.33
12 SC Part 3	0.334	0.126	972.8	0.046	96	7.12	1.13	4	8.35	5.00	45.47
13 SC Part 3	0.342	0.126	1015.9	0.047	96	7.27	1.15	4	8.54	5.00	45.60
14 SC Part 3	0.349	0.126	1059.8	0.048	96	7.43	1.18	4	8.73	5.00	45.74
15 SC Part 3	0.357	0.126	1104.8	0.049	96	7.58	1.20	4	8.91	5.00	45.88
16 SC Part 3	0.364	0.126	1150.6	0.050	96	7.74	1.23	4	9.10	13.65	46.11
17 SC Part 3	0.371	0.126	1197.4	0.051	96	7.90	1.25	4	9.29	5.00	46.25
18 SC Part 3	0.379	0.126	1245.2	0.052	96	8.05	1.28	4	9.47	5.00	46.39
19 SC Part 3	0.386	0.126	1293.9	0.053	96	8.21	1.30	4	9.66	5.00	46.54
20 SC Part 3	0.394	0.126	1343.5	0.054	96	8.36	1.33	4	9.85	5.00	46.69
21 SC Part 3	0.401	0.126	1394.1	0.055	96	8.52	1.35	4	10.04	15.05	46.94
22 SC Part 3	0.409	0.126	1445.6	0.056	96	8.67	1.38	4	10.22	5.00	47.09
23 SC Part 3	0.416	0.126	1498.1	0.057	96	8.83	1.40	4	10.41	5.00	47.25
24 SC Part 3	0.424	0.126	1551.5	0.058	96	8.99	1.43	4	10.60	5.00	47.40
25 SC Part 3	0.431	0.126	1605.8	0.059	96	9.14	1.45	4	10.78	5.00	47.56
26 SC Part 3	0.439	0.126	1661.1	0.060	96	9.30	1.48	4	10.97	16.46	47.83
27 SC Part 3	0.446	0.126	1717.4	0.061	96	9.46	1.50	4	11.16	5.00	48.00
28 SC Part 3	0.454	0.126	1774.6	0.062	96	9.61	1.53	4	11.35	5.00	48.16
29 SC Part 3	0.461	0.126	1832.7	0.063	96	9.77	1.55	4	11.53	5.00	48.32
30 SC Part 3	0.469	0.126	1891.8	0.064	96	9.92	1.58	4	11.72	5.00	48.49
31 SC Part 3	0.476	0.126	1951.8	0.065	96	10.08	1.60	4	11.91	17.86	48.79
32 SC Part 3	0.484	0.126	2012.8	0.066	96	10.24	1.63	4	12.10	5.00	48.96
33 SC Part 3	0.491	0.126	2074.7	0.067	96	10.39	1.65	4	12.28	5.00	49.13
34 SC Part 3	0.499	0.126	2137.5	0.068	96	10.55	1.68	4	12.47	5.00	49.31
35 SC Part 3	0.506	0.126	2201.3	0.069	96	10.70	1.70	4	12.66	5.00	49.48
36 SC Part 3	0.514	0.126	2266.0	0.070	96	10.86	1.72	4	12.85	19.27	49.81
37 SC Part 3	0.521	0.126	2331.7	0.071	96	11.02	1.75	4	13.03	5.00	49.99
38 SC Part 3	0.529	0.126	2398.4	0.072	96	11.17	1.77	4	13.22	5.00	50.17
39 SC Part 3	0.536	0.126	2465.9	0.073	96	11.33	1.80	4	13.41	5.00	50.35

Item	V_acc (MV)	q/m	KE (keV/n)	β	freq (MHz)	$\beta\lambda/2$ (cm)	$B\rho$ (T-m)	Eacc (MV/m)	L_cav (cm)	L_focus (cm)	Σ Lth (m)
40 SC Part 3	0.544	0.126	2534.5	0.074	96	11.49	1.82	4	13.60	5.00	50.54
41 SC Part 3	0.551	0.126	2603.9	0.075	96	11.64	1.85	4	13.78	20.68	50.88
42 SC Part 3	0.559	0.126	2674.4	0.076	96	11.80	1.87	4	13.97	5.00	51.07
43 SC Part 3	0.566	0.126	2745.7	0.077	96	11.96	1.90	4	14.16	5.00	51.26
44 SC Part 3	0.574	0.126	2818.0	0.078	96	12.11	1.92	4	14.35	5.00	51.46
45 SC Part 3	0.581	0.126	2891.3	0.079	96	12.27	1.95	4	14.53	5.00	51.65
46 SC Part 3	0.589	0.126	2965.5	0.080	96	12.42	1.97	4	14.72	22.08	52.02
47 SC Part 3	0.596	0.126	3040.6	0.081	96	12.58	2.00	4	14.91	5.00	52.22
48 SC Part 3	0.604	0.126	3116.7	0.082	96	12.74	2.02	4	15.10	5.00	52.42
49 SC Part 3	0.611	0.126	3193.7	0.083	96	12.89	2.05	4	15.28	5.00	52.62
50 SC Part 3	0.619	0.126	3271.7	0.084	96	13.05	2.07	4	15.47	5.00	52.83
51 SC Part 3	0.626	0.126	3350.6	0.085	96	13.21	2.10	4	15.66	23.49	53.22
52 SC Part 3	0.634	0.126	3430.5	0.086	96	13.36	2.12	4	15.85	5.00	53.43
53 SC Part 3	0.641	0.126	3511.3	0.087	96	13.52	2.15	4	16.04	5.00	53.64
54 SC Part 3	0.649	0.126	3593.1	0.088	96	13.68	2.17	4	16.22	5.00	53.85
55 SC Part 3	0.656	0.126	3675.8	0.089	96	13.83	2.20	4	16.41	5.00	54.06
56 SC Part 3	0.664	0.126	3759.5	0.090	96	13.99	2.22	4	16.60	24.90	54.48
57 SC Part 3	0.671	0.126	3844.1	0.091	96	14.15	2.25	4	16.79	5.00	54.70
58 SC Part 3	0.679	0.126	3929.6	0.092	96	14.30	2.27	4	16.98	5.00	54.92
59 SC Part 3	0.687	0.126	4016.1	0.093	96	14.46	2.30	4	17.16	5.00	55.14
60 SC Part 3	0.694	0.126	4103.6	0.094	96	14.62	2.32	4	17.35	5.00	55.36
61 SC Part 3	0.702	0.126	4192.0	0.095	96	14.77	2.35	4	17.54	26.31	55.80
62 SC Part 3	0.709	0.126	4281.3	0.096	96	14.93	2.37	4	17.73	5.00	56.03
63 SC Part 3	0.717	0.126	4371.6	0.097	96	15.09	2.40	4	17.91	5.00	56.26
64 SC Part 3	0.724	0.126	4462.9	0.098	96	15.24	2.42	4	18.10	5.00	56.49
65 SC Part 3	0.732	0.126	4555.0	0.099	96	15.40	2.45	4	18.29	5.00	56.72
66 SC Part 3	0.739	0.126	4648.2	0.100	96	15.56	2.47	4	18.48	27.72	57.18
67 SC Part 3	0.747	0.126	4742.2	0.101	96	15.71	2.50	4	18.67	5.00	57.42
68 SC Part 3	0.754	0.126	4837.3	0.102	96	15.87	2.52	4	18.85	5.00	57.66
69 SC Part 3	0.762	0.126	4933.2	0.103	96	16.03	2.55	4	19.04	5.00	57.90
70 SC Part 3	0.769	0.126	5030.2	0.104	96	16.18	2.57	4	19.23	5.00	58.14
71 SC Part 3	0.777	0.126	5128.0	0.105	96	16.34	2.59	4	19.42	29.13	58.63
72 SC Part 3	0.784	0.126	5226.8	0.106	96	16.50	2.62	4	19.61	5.00	58.87
73 SC Part 3	0.792	0.126	5326.6	0.107	96	16.65	2.64	4	19.79	5.00	59.12
74 SC Part 3	0.799	0.126	5427.3	0.108	96	16.81	2.67	4	19.98	5.00	59.37
75 SC Part 3	0.807	0.126	5529.0	0.109	96	16.97	2.69	4	20.17	5.00	59.62
76 SC Part 3	0.814	0.126	5631.6	0.110	96	17.12	2.72	4	20.36	30.54	60.13
77 SC Part 3	0.822	0.126	5735.1	0.111	96	17.28	2.74	4	20.55	5.00	60.39
78 SC Part 3	0.829	0.126	5839.6	0.112	96	17.44	2.77	4	20.73	5.00	60.64
79 SC Part 3	0.837	0.126	5945.1	0.113	96	17.59	2.79	4	20.92	5.00	60.90
80 SC Part 3	0.844	0.126	6051.5	0.114	96	17.75	2.82	4	21.11	5.00	61.16
81 SC Part 3	0.852	0.126	6158.8	0.115	96	17.91	2.84	4	21.30	31.95	61.70
82 SC Part 3	0.859	0.126	6267.1	0.116	96	18.06	2.87	4	21.49	5.00	61.96
83 SC Part 3	0.867	0.126	6376.4	0.117	96	18.22	2.89	4	21.67	5.00	62.23
84 SC Part 3	0.875	0.126	6486.5	0.118	96	18.38	2.92	4	21.86	5.00	62.50

Item	V_acc (MV)	q/m	KE (keV/n)	β	freq (MHz)	$\beta\lambda/2$ (cm)	$B\rho$ (T-m)	Eacc (MV/m)	L_cav (cm)	L_focus (cm)	Σ Lth (m)
85 SC Part 3	0.882	0.126	6597.7	0.119	96	18.53	2.94	4	22.05	5.00	62.77
86 SC Part 3	0.890	0.126	6709.8	0.120	96	18.69	2.97	4	22.24	33.36	63.32
87 SC Part 3	0.897	0.126	6822.8	0.121	96	18.85	2.99	4	22.43	5.00	63.60
88 SC Part 3	0.905	0.126	6936.8	0.122	96	19.00	3.02	4	22.61	5.00	63.87
89 SC Part 3	0.912	0.126	7051.7	0.123	96	19.16	3.04	4	22.80	5.00	64.15
90 SC Part 3	0.920	0.126	7167.6	0.124	96	19.32	3.07	4	22.99	5.00	64.43
91 SC Part 3	0.927	0.126	7284.4	0.125	96	19.47	3.09	4	23.18	34.77	65.01
92 SC Part 3	0.935	0.126	7402.2	0.126	96	19.63	3.12	4	23.37	5.00	65.30
93 SC Part 3	0.942	0.126	7520.9	0.127	96	19.79	3.14	4	23.56	5.00	65.58
94 SC Part 3	0.950	0.126	7640.6	0.128	96	19.94	3.17	4	23.74	5.00	65.87
95 SC Part 3	0.957	0.126	7761.2	0.129	96	20.10	3.19	4	23.93	5.00	66.16
96 SC Part 3	0.965	0.126	7882.7	0.130	96	20.26	3.22	4	24.12	36.18	66.76
97 SC Part 3	0.972	0.126	8005.3	0.131	96	20.41	3.24	4	24.31	5.00	67.05
98 SC Part 3	0.980	0.126	8128.7	0.132	96	20.57	3.27	4	24.50	5.00	67.35
99 SC Part 3	0.987	0.126	8253.1	0.133	96	20.73	3.29	4	24.68	5.00	67.65
100 SC Part 3	0.995	0.126	8378.5	0.134	96	20.88	3.32	4	24.87	5.00	67.94
101 SC Part 3	1.002	0.126	8504.8	0.135	96	21.04	3.34	4	25.06	37.59	68.57
102 SC Part 3	1.010	0.126	8632.0	0.136	96	21.20	3.37	4	25.25	5.00	68.87
103 SC Part 3	1.017	0.126	8760.2	0.137	96	21.35	3.39	4	25.44	5.00	69.18
104 SC Part 3	1.025	0.126	8889.4	0.138	96	21.51	3.42	4	25.63	5.00	69.48
105 SC Part 3	1.033	0.126	9019.5	0.139	96	21.67	3.44	4	25.81	5.00	69.79
106 SC Part 3	1.040	0.126	9150.6	0.140	96	21.83	3.47	4	26.00	39.00	70.44
107 SC Part 3	1.048	0.126	9282.6	0.141	96	21.98	3.49	4	26.19	5.00	70.75
108 SC Part 3	1.055	0.126	9415.5	0.142	96	22.14	3.52	4	26.38	5.00	71.07
109 SC Part 3	1.063	0.126	9549.4	0.143	96	22.30	3.54	4	26.57	5.00	71.38
110 SC Part 3	1.070	0.126	9684.2	0.144	96	22.45	3.57	4	26.75	5.00	71.70
111 SC Part 3	1.078	0.126	9820.0	0.145	96	22.61	3.59	4	26.94	40.41	72.37
112 SC Part 3	1.085	0.126	9956.8	0.146	96	22.77	3.62	4	27.13	5.00	72.70
113 SC Part 3	1.093	0.126	10094.5	0.147	96	22.92	3.64	4	27.32	5.00	73.02
114 SC Part 3	1.100	0.126	10233.1	0.148	96	23.08	3.67	4	27.51	5.00	73.34
115 SC Part 3	1.108	0.126	10372.7	0.149	96	23.24	3.69	4	27.70	5.00	73.67
116 SC Part 3	1.115	0.126	10513.2	0.150	96	23.39	3.72	4	27.88	41.83	74.37
117 SC Part 3	1.123	0.126	10654.7	0.151	96	23.55	3.74	4	28.07	5.00	74.70
118 SC Part 3	1.130	0.126	10797.2	0.152	96	23.71	3.77	4	28.26	5.00	75.03
119 SC Part 3	1.138	0.126	10940.5	0.153	96	23.86	3.79	4	28.45	5.00	75.37
120 SC Part 3	1.145	0.126	11084.9	0.154	96	24.02	3.81	4	28.64	5.00	75.70
121 SC Part 3	1.153	0.126	11230.1	0.155	96	24.18	3.84	4	28.83	43.24	76.42
122 SC Part 3	1.161	0.126	11376.4	0.156	96	24.34	3.86	4	29.01	5.00	76.76
123 SC Part 3	1.168	0.126	11523.6	0.157	96	24.49	3.89	4	29.20	5.00	77.10
124 SC Part 3	1.176	0.126	11671.7	0.158	96	24.65	3.91	4	29.39	5.00	77.45
125 SC Part 3	1.183	0.126	11820.8	0.159	96	24.81	3.94	4	29.58	5.00	77.79
126 SC Part 3	1.191	0.126	11970.8	0.160	96	24.96	3.96	4	29.77	44.65	78.54
127 SC Part 3	1.198	0.126	12121.8	0.161	96	25.12	3.99	4	29.96	5.00	78.89
128 SC Part 3	1.206	0.126	12273.7	0.162	96	25.28	4.01	4	30.14	5.00	79.24
129 SC Part 3	1.213	0.126	12426.6	0.163	96	25.43	4.04	4	30.33	5.00	79.59

Item	**V_acc** (MV)	q/m	**KE** (keV/n)	β	**freq** (MHz)	$\beta\lambda/2$ (cm)	$B\rho$ (T-m)	**Eacc** (MV/m)	**L_cav** (cm)	**L_focus** (cm)	**Σ Lth** (m)
130 SC Part 3	1.221	0.126	12580.4	0.164	96	25.59	4.06	4	30.52	5.00	79.95
131 SC Part 3	1.228	0.126	12735.2	0.165	96	25.75	4.09	4	30.71	46.06	80.72
132 SC Part 3	1.236	0.126	12890.9	0.166	96	25.90	4.11	4	30.90	5.00	81.08
133 SC Part 3	1.243	0.126	13047.6	0.167	96	26.06	4.14	4	31.09	5.00	81.44
134 SC Part 3	1.251	0.126	13205.2	0.168	96	26.22	4.16	4	31.27	5.00	81.80
135 SC Part 3	1.258	0.126	13363.7	0.169	96	26.38	4.19	4	31.46	5.00	82.16
136 SC Part 3	1.266	0.126	13523.3	0.170	96	26.53	4.21	4	31.65	47.48	82.95
137 SC Part 3	1.274	0.126	13683.7	0.171	96	26.69	4.24	4	31.84	5.00	83.32
138 SC Part 3	1.281	0.126	13845.1	0.172	96	26.85	4.26	4	32.03	5.00	83.69
139 SC Part 3	1.289	0.126	14007.5	0.173	96	27.00	4.29	4	32.22	5.00	84.07
140 SC Part 3	1.296	0.126	14170.8	0.174	96	27.16	4.31	4	32.40	5.00	84.44
141 SC Part 3	1.304	0.126	14335.1	0.175	96	27.32	4.34	4	32.59	48.89	85.25
142 SC Part 3	1.311	0.126	14500.3	0.176	96	27.47	4.36	4	32.78	5.00	85.63
143 SC Part 3	1.319	0.126	14666.5	0.177	96	27.63	4.39	4	32.97	5.00	86.01
144 SC Part 3	1.326	0.126	14833.6	0.178	96	27.79	4.41	4	33.16	5.00	86.39
145 SC Part 3	1.334	0.126	15001.6	0.179	96	27.94	4.44	4	33.35	50.02	87.23

This section can be continued as a future upgrade to 25 MeV/n

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