AN UPGRADE TO THE NSCL TO PRODUCE INTENSE BEAMS OF EXOTIC NUCLEI*

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Abstract

A substantially less costly alternative to the Rare Isotope Accelerator (RIA) project has been developed at Michigan State University (MSU). By upgrading the existing facility at the National Superconducting Cyclotron Laboratory (NSCL), it will be possible to produce stable beams of heavy ions at energies of ≥200 MeV/u with beam power >65 kW. The upgrade will utilize a cyclotron injector and a superconducting driver linac at a base frequency of 80.5 MHz. A charge-stripping foil and multiple-charge-state acceleration will be used for the heavier ions. The 9 MeV/u injector will include an ECR source, a bunching system, and the existing K1200 superconducting cyclotron with axial injection. The superconducting driver linac will largely follow that proposed by MSU for RIA [1], using cavities already designed, prototyped, and demonstrated. Radioactive ion beams will be produced in a high-power target via particle fragmentation. The existing A1900 Fragmentation Separator and experimental areas will be used, along with a new gas stopper and a re-acceleration system.

INTRODUCTION

Lower cost and reduced scope alternatives to the Rare Isotope Accelerator (RIA) project have been explored at Michigan State University (MSU). Among the options evaluated is the utilization of the existing infrastructure at the National Superconducting Cyclotron Laboratory (NSCL). The layout of the proposed upgrade is shown in Figure 1.

Since cyclotrons make use of rf acceleration structures for multiple passes, they offer a less costly option than superconducting linacs to accelerate ions to intermediate energies. At the present time, the highest power accelerator is the cyclotron complex at the Paul Scherrer Institute (PSI), with a beam power in excess of 1 MW. The outstanding performance of the PSI accelerator is due in large part to the utilization of a single ion species, large rf systems, and the provision of significant space for extraction. However, the driver beam for the production of radioactive beams must cover a large range of stable isotopes at variable energies, making it difficult to obtain a high performance extraction system under all conditions. In addition, a superconducting linac can simultaneously accelerate multiple charge states, while cyclotrons can accelerate only one charge state at a time. Therefore, for a given ion source performance, a linac will provide a greater beam power.

Nonetheless, a cost savings could be realized by the utilization of an existing cyclotron as an injector for a superconducting linac, and we have explored this option. The concept of injecting a linac from a cyclotron is not new having been considered in Ref. [2]. There are two superconducting cyclotrons at the NSCL, the K1200 and the K500, both operating with variable rf frequency and both capable of accelerating all ions from hydrogen to uranium at variable energies. The K1200 was found to provide a better performance match for linac injection, and that possibility is shown in Figure 1. Also shown in Figure 1 is the possibility of utilizing a Radio Frequency Quadrupole (RFQ) system followed by low-β superconducting linac structures to provide the initial acceleration.

CYCLOTRON INJECTOR

To inject into a linac, it is necessary for the base rf frequency of the linac to be a harmonic of the cyclotron rf frequency. In this way, all beam bunches from the cyclotron will be accelerated by the linac and no loss of intensity will occur, provided the acceptance of the linac is larger than the phase space of the cyclotron beam.

The energy of the ions extracted from the cyclotron is determined by the orbital frequency $\omega_0 = 2\pi\, f_O$. This frequency is determined by the rf frequency f_{RF} and the harmonic number h ($h = f_{RF}/f_O$). The base frequency of the linac is 80.5 MHz. Since our cyclotrons operate between 9 and 27 MHz, the highest possible frequency is f_{RF} = 20.125 MHz.

The K1200 was found to have a favorable operating regime. We show in Figure 2 the operating region for the K1200 cyclotron in the Q/A vs. B plane for a fixed rf frequency of 20.125 MHz (Q/A = dimensionless charge to mass ratio, E/A = kinetic energy per nucleon, B = magnetic field). The curves define the possible combinations for different cyclotron harmonics. The figure indicates the band of Q/A values available for uranium with A = 238 and charge states from +28 to +32. This band intersects the h = 2 and h = 3 lines. The intersection with the h = 2 curve is limited to the high field region near 5 T, and is not a desirable region to operate because the fringe field of the cyclotron makes injection more difficult. On the other hand, the intersection with the h = 3 curve is at the more favorable field of approximately 3.5 T and provides an extraction energy of 9.3 MeV/u.

SUPERCONDUCTING LINAC

A superconducting linac largely following the MSU design proposed for RIA will be used to accelerate stable isotopes to ≥200 MeV/u.

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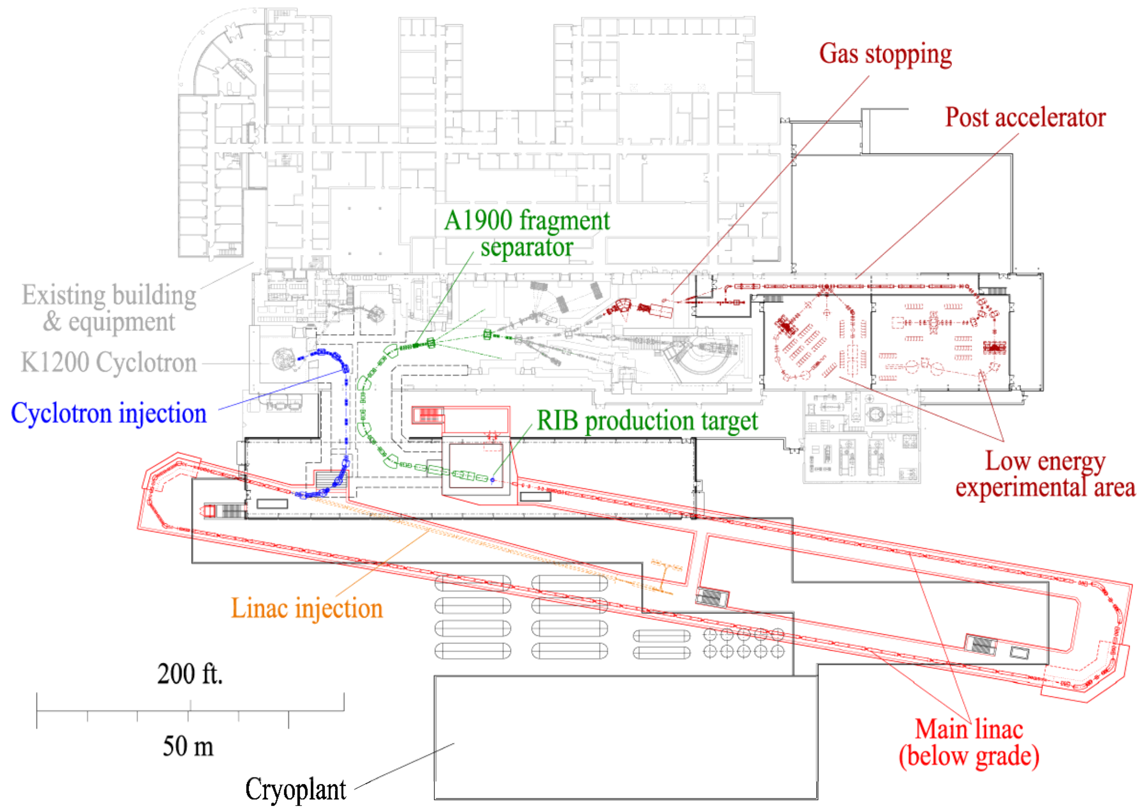

Figure 1: Layout of NSCL upgrade. Grayed regions are existing infrastructure and experimental equipment. The blue line shows a possible injection path for 9 MeV/u K1200 cyclotron beams into a subterranean superconducting linac. Also shown in orange is an alternative linac injection system using an RFQ and superconducting accelerating structures. A single radioactive beam production target is proposed, followed by a reconfiguration of the existing A1900 fragment separator. A low-energy program will be supported by a gas stopping and re-acceleration system with an associated experimental area.

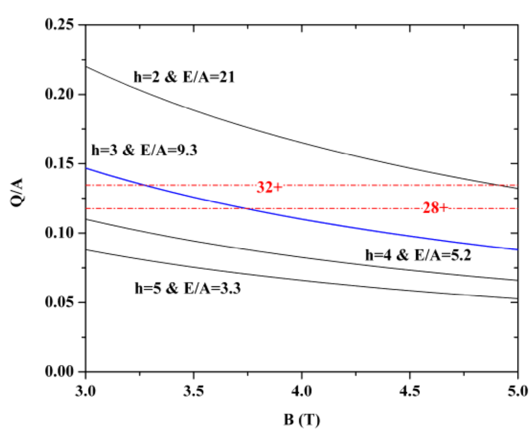

Figure 2: Operating region of the K1200 for a cyclotron rf frequency of 20.125 MHz. The solid curves give the relation between Q/A of the accelerated ion and the magnetic field B for different harmonics. The two horizontal dashed straight lines define a band of possible charge states from +28 to +32 for U^{238}.

The uranium beam acceleration is the most challenging, and drives the linac design. With the cyclotron injector, the 9 MeV/u uranium +29 will be extracted and matched to that required for the 80.5 MHz, $\lambda/4$, β_{opt} = 0.085 superconducting structures that will be used to provide acceleration to 12 MeV/u. Alternatively, a Radio Frequency Quadrupole (RFQ) and β_{opt} = 0.041 and β_{opt} = 0.085 $\lambda/4$ superconducting structures at 80.5 MHz could be used to provide the first acceleration to 9 MeV/u though in this case two charge states (+28 and +29) will be accelerated.

At 12 MeV/u, the uranium beam will be stripped to charge states 73±2 and matched into the downstream acceleration segments. A second and final increase in charge states to 89±1 will be achieved at 112 MeV/u, with final acceleration to 200 MeV/u. The required superconducting accelerating structures are given in Table 1.

Drawings of the superconducting cavities are shown in Figure 3. With the exception of the β_{opt} = 0.43 $\lambda/2$ structure at 322 MHz, all the cavities have been prototyped and tested to design specifications. The MSU RIA cavity complement did not require the β_{opt} = 0.16 $\lambda/4$ cavity at 161 MHz and utilized a β_{opt} = 0.47 elliptical structure at 805 MHz in lieu of the β_{opt} = 0.43 $\lambda/2$ cavity. These modifications were implemented to increase the linac longitudinal acceptance to accommodate the roughly ten times greater longitudinal emittance of the cyclotron injector. The output specifications for some example beams are given in Table 2.

Table 1: Superconducting Cavities for the Heavy Ion Linac, with and without a Cyclotron Injector

Type	f (MHz)	β_{opt}	# of cavities with cyclotron	# of cavities without cyclotron
λ/4	80.5	0.041	0	18
λ/4	80.5	0.085	31	106
λ/4	161	0.16	58	58
λ/2	322	0.285	92	92
λ/2	322	0.4	205	205

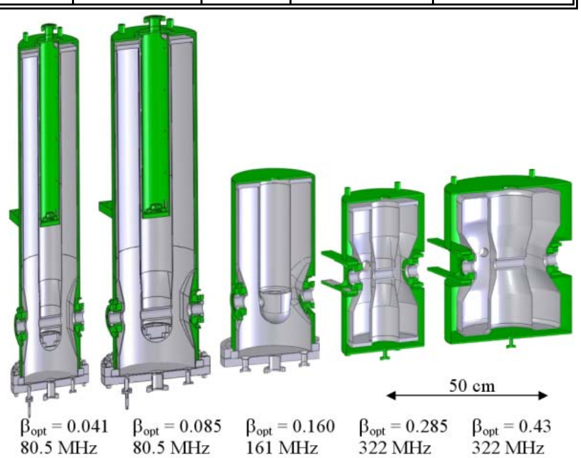

Figure 3: Superconducting accelerating structures for the linac.

Table 2: Final Beam Energy and Power of Selected Ions for Cyclotron and Linac Injector Options

	Beam	H^1	Ar^{40}	Kr^{86}	Xe^{136}	U^{238}
Cyclotron Injector	Beam Energy (MeV/u)	-	250	230	220	200
	Beam Power (kW)	-	100	75	75	65
Linac Injector	Beam Energy (MeV/u)	525	265	230	220	200
	Beam Power (kW)	400	400	400	400	400

End-to-end beam dynamics simulations through the superconducting linac were done with the IMPACT code [3] using the extracted beam parameters from cyclotron simulations. Figure 4 shows the phase space evolution along the linac after injection from the cyclotron. The linac injection results are transversely similar but with a much smaller longitudinal emittance (1.3 vs. 30 π keV/u ns). In Figure 4, the blue curves are for the case of no errors. The red curves are the worst case of 50 seeds at each position. The acceleration and focusing elements alignment errors utilized a ±2σ Gaussian distribution with σ =1 mm. The rf system errors assumed a flat distribution of ±0.5° rf phase and ±0.5% rf amplitude. For uranium, the linac acceleration to 12 MeV/u is Segment 1, the second accelerating section to 112 MeV/u is Segment 2, and the final acceleration to 200 MeV/u occurs in Segment 3.

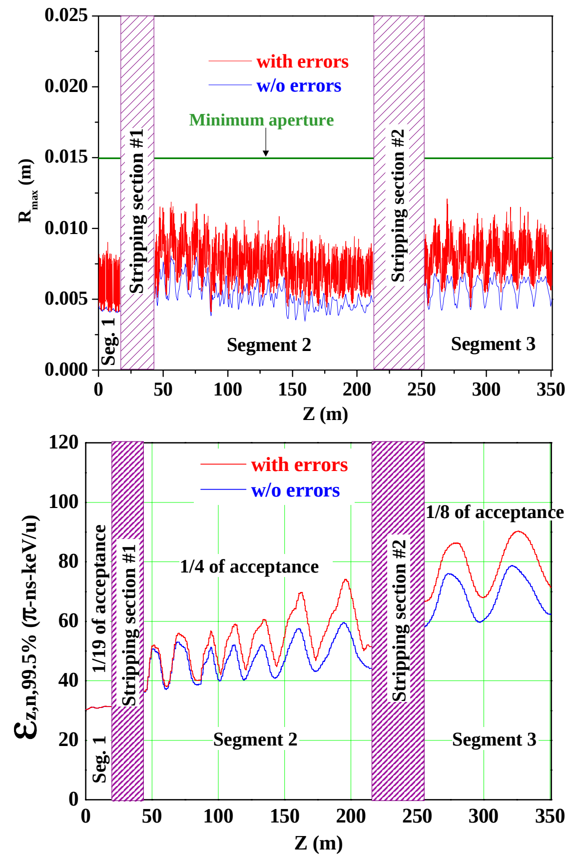

Figure 4: Beam simulation results for the transverse (top) and longitudinal (bottom) phase space, with and without errors.

SUMMARY

A heavy ion linac and injector are being studied for an upgrade to the NSCL facility. The cyclotron injector is the less expensive option. However, the relative performance as given in Table 2 favors the linac injector option, particularly for the heavier ions.

REFERENCES

[1] X. Wu et al., “End-to-end Simulations for the MSU RIA Driver Linac” *Proceedings of LINAC2004*, Lübeck, Germany, August 2004.

[2] R. E. Laxdal and W. Joho, *Proc. European Part. Accel. Conf.*, 1992, p. 590.

[3] J. Qiang, M. A. Furman and R. D. Ryne, *J. Comput. Phys.* **198**, 278 (2004).