HIGH INTENSITY OPERATION OF A SUPERCONDUCTING CYCLOTRON

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We plan to upgrade the NSCL by coupling the existing K500 and K1200 superconducting cyclotrons. The K500 beam will be radially injected into the K1200 and stripped inside a dee. The main goal of the upgrade is to significantly increase the primary beam intensities, and as a consequence, the fragmentation production of radioctive secondary beams. Beam intensities of $6.x10^{12}$ pps at energies of 200 MeV/u are expected for light ions. The nuclear reactions segment of the experimental program will also benefit from the resulting higher energies for the higher mass region (e.g., 100 MeV/u for U). The acceleration scheme requires short bunch lengths to minimize beam loss and power dissipation at the deflectors. The short bunch lengths make the effects of the space charge forces of particular importance. Experimental data from a partially upgraded K500 are presented.

1 Introduction

1.1 Experimental Program Needs

In the last few years the experimental program at NSCL has been shifting toward experiments with radioactive nuclear beams (RNB's) which now comprise ≈70% of approved experiments. This trend seems to be worldwide, and as a consequence there has been a wave of projects to upgrade or build new facilities to produce more intense RNB's.

Traditionally two distinct methods have been used to produce RNB's. In the ISOL (Isotope Separation On Line) approach, an intense, energetic, primary beam is stopped in a specialized target. The resulting radioactive nuclei are extracted from the target, transported to an ion source, ionized, and then reaccelerated. In the fragmentation approach, heavier nuclei bombard a thinner target where fragmentation directly produces radioactive nuclei of approximately the primary beam energy. Both approaches are complementary and have their advantages and disadvantages. The NSCL has historically used the fragmentation method and upgrade options appropriate to this technique were explored. The yield of secondary beams for two typical ions of interest is shown in Figure 1[1]. The yield does not increase significantly above 500 MeV/u, and therefore the performance/cost ratio points to the desireablity of a maximum energy of 500 MeV/u.

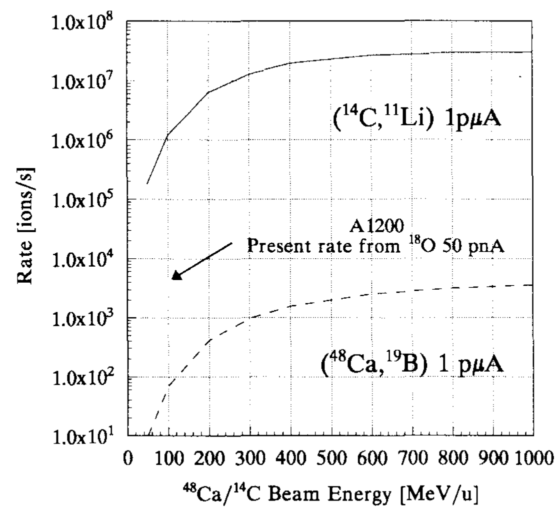

Figure 1: Secondary beam production rate for two ions of interest as a function of the primary beam energy. Present rate indicated for ^{11}Li production.

1.2 Options

Given the above considerations, we explored the design of a separated sector cyclotron capable of accelerating ions with Q/A=0.5 to energies of up to 500 MeV/u [2]. An accelerator design was evaluated which was similar to that given in the GANIL booster study[3] and to the more recent RIKEN conceptual design study[4]. Although the potential radioactive beam yield at this energy is high, the cost (estimated to be ≈70-100 millon US $) made it an unattractive option. In addition, the cost of an NSCL upgrade of this type would be further increased by the necessity of modifying existing 200 MeV/u beam transport and experimental equipment to accomodate the 500 MeV/u.

As an alternative, the coupling of our two existing superconducting cyclotrons, with the K500 used as an injector and the K1200 as the booster cyclotron, was considered. Although the final energy is limited to that of the K1200 (200 MeV/u for Q/A=0.5), the radioactive beam yield at 200 MeV/u is only reduced by approximately a factor 3 from that at 500 MeV/u. Since the existing cyclotrons, beam transport, and experimental equipment could be utilized fully, the upgrade costs can be reduced significantly. Therefore, this upgrade route was adopted and a proposal has been submitted to the National Science Foundation[5,6,7]. A layout of the facility can be found in reference [5].

2 Coupling Scheme

The concept of coupling the K500 to the K1200 is not new. The original proposal for the NSCL[8,9] had envisioned the coupling of the two cyclotrons with the K500 operating as an injector with an internal PIG source. However, during the period of the initial construction, the development of ECR ion sources made it more appropriate to inject directly into the K1200. However, the performance level reached by ECR ion sources has once again made the coupling of the two cyclotrons an attractive option.

At the time of the original proposal, the charge states achievable from PIG sources were quite low, and several harmonic ratios (5:2, 3:1, 7:2, 4:1 and 5:1) were required to cover the whole operating diagram. In the present scheme, only one coupling mode is necessary (2:1). This single harmonic mode produces the full range for heavy ions and all but the lowest energy range presently available for light ions. Since the capability of directly injecting the ECR beam into the K1200 will be retained, there will be no loss in the energy range of the present facility.

The single coupling ratio simplifies the design of the stripper mechanism by allowing a larger stripping radius and by requiring a smaller range of motion of the stripper foil. The K500 extraction radius is 0.66 m and the injection radius of the K1200 will be 0.33 m with an extraction radius of 1.00 m, giving a velocity multiplication of approximately 3. The tenfold increase in energy requires that the K500 deliver beams with energies below 17 MeV/u. For example, to produce the highest energy (200 MeV/u) oxygen beam, $^{16}O^{3+}$ would be accelerated in the K500 and then stripped to 8+ in the K1200. A selection of typical beams is shown in Table 1. The ECR ion source intensities assumed in the performance estimates of Table 1 have already been achieved in large part by the superconducting ECR. The ECR solid feed beam performance was estimated by scaling the room temperature ECR solid beam performance to the higher performance levels of the superconducting ECR (SCECR) since solid feed is yet to be implemented in the SCECR. A graphic summary of the performance increase is shown in Figure 2, where the coupled cyclotron operating diagram is presented with intensity contours given in particles per second for the present (dashed) and for the upgraded (solid) facility.

In our performance estimates we assume a 10% loss in each cyclotron. To decrease the losses at extraction, we plan to reduce the beam phase width to $\approx 3^o$rf by phase selection at low energy in the K500, and a rebuncher in the coupling line. In the absence of space charge, this phase width would provide separated turns at extraction.

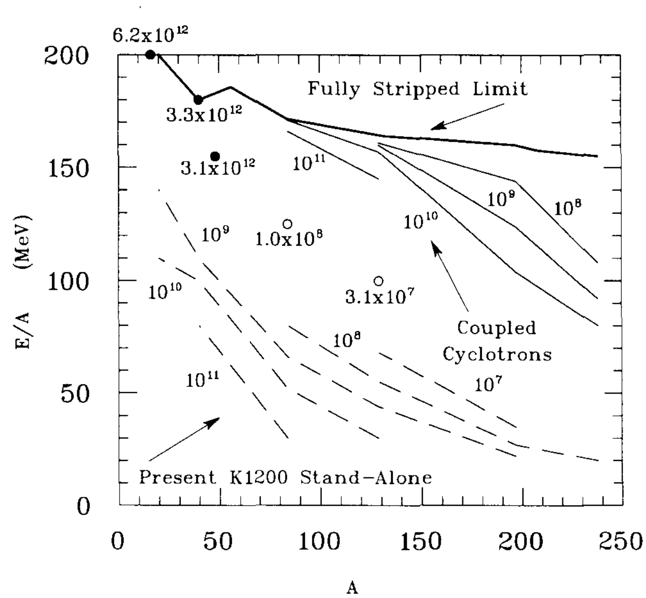

Figure 2: Operating diagram for the present K1200 stand-alone cyclotron (open circle points and dashed countours) and for the coupled facility (filled circles and solid contours). The intensity countours are labeled in particles per second.

When the effect of space charge is included, that is no longer true.

3 ECR and Low Energy Beam Line

The requirements on the ion source are quite different in the coupled cyclotron mode, where the performance emphasis will be on low and intermediate charge states as opposed to the high charge states in the present stand-alone mode. For example, $^{16}O^{3+}$ and $^{40}Ar^{7+}$ will be used to achieve the maximum energies in the coupled mode as opposed to $^{16}O^{8+}$ and $^{40}Ar^{18+}$ in the stand-alone mode. To mitigate the effect of space charge, the ECR will be operated at a peak voltage of 30 kV instead of the present 20 kV. Higher voltages were considered, but not pursued, to simplify source operation and maintenance. The present low energy beam line will be upgraded to generally increase focusing and to better match the acceptance of the cyclotron. At the present time, new focusing elements (electrostatic quadrupoles) are being tested. To further enhance the K500 injection efficiency, we will reduce the effect of the cyclotron fringe field by improving the beam line shielding. The performance estimates have been calculated assuming that 50% of the ECR output is transported in a 75πmm mrad phase space. The effect of space charge forces on the injection line have been calculated with the codes TRANSOPTR[10] and SPOT[11]. No major effect was found, since small readjustments of the focusing elements were sufficient to recover the zero

Ion	A	K500 Q1	K500 Energy (MeV/u)	K1200 Q2	Stripping Ratio Q2/Q1	Stripping Efficency %	K1200 Extracted Energy (MeV/u)	K1200 Extracted Intensity (pnA)	(particles/s)
O	16	3	16.7	8	2.67	100	200	1000	6.2×10^{12}
O	16	3	12.5	8	2.67	100	140	1000	6.2×10^{12}
S	36	6	13.6	16	2.67	93	155	557	3.5×10^{12}
Ar	40	7	15.3	18	2.57	88	180	530	3.3×10^{12}
Kr	84	15	14.7	36	2.40	2.2	170	3.4	2.1×10^{10}
Kr	84	15	14.0	35	2.33	20	160	32	2.0×10^{11}
Kr	84	14	13.6	34	2.43	49	155	80	5.0×10^{11}
Xe	129	22	14.0	52	2.36	1	160	0.6	3.7×10^{9}
Xe	129	22	13.6	51	2.32	5	155	3.3	2.1×10^{10}
Xe	129	21	12.9	49	2.33	27	145	18	1.1×10^{11}
Au	197	29	10.2	67	2.31	4	110	0.8	5.0×10^{9}
Au	197	26	8.6	61	2.35	20	90	7.7	4.8×10^{10}
U	238	32	8.6	74	2.31	2	90	0.2	1.2×10^{9}
U	238	28	6.9	66	2.36	18	70	3.6	2.2×10^{10}

Table 1: K500⊗K1200 parameter details for selected ions.

current beam envelope. These calculations did not include a buncher in the injection line. We also plan to study the influence of the buncher although we do not expect a large effect because the debunching induced by the traversal of the yoke and the spiral inflector prevents a narrow phase width at the injection point.

4 K500 Cyclotron

The K500 was the first superconducting cyclotron to become operational (1982). Many improvements implemented in the K1200 were developed from the experience gained with the K500 and our further experience with the K1200 has suggested many improvements for the K500. Our future plans involve disassembling the iron pieces and rebuilding major parts of the rf system to improve the mechanical design and amplifiers. A significant upgrade of the vacuum system will be carried out to achieve an average pressure of $\approx 10^{-7}$ torr. This vacuum is required to minimize beam loss for high charge state heavy ions (Xe^{22+}, U^{32+}). A rotation of 120° of the whole magnet will yield an extracted beam pointed toward the K1200 and reduce the required bend in the coupling line. A new h=2 central region has been implemented and several beams have been extracted. A first turn slit in the central region and two phase selection pins provide the necessary cuts to achieve a narrow phase width[12]. We have achieved a phase width of 3.5° FWHM and extraction efficiencies of 80%. Extracted currents of 2 $p\mu A$ of oxygen at 15 MeV/u have been achieved. Several components are unstable and further refurbishing of the K500 should make the goal of 90% extraction efficiency achievable.

5 Coupling Line

One of the major modifications with respect to the original coupling proposal will be the rotation of the K500 cyclotron by 120°. In this orientation, the beam will be aimed more directly toward the K1200 and only a 20° bend will be necessary in lieu of the originally proposed 130°. The matching between the two cyclotrons will be accomplished by means of eight quadrupoles, a 20° dipole, two small ±1.5° dipoles and two combined function magnets located as the last element of the K500 extraction and the first element of the K1200 injection, just inside the yoke. This combined function element is essential in matching the injected beam to the eigenellipse at the position of the stripper foil inside the K1200. It will also provide a fine adjustment in the location of the injected beam for centering. At present we are evaluating superconducting magnets which can provide a 10 T/m gradient. As the line is not isochronous, a rf buncher will be installed to maintain the bunch length during the transport process. The buncher will operate in harmonics 4-10 and below 200 kV peak voltage.

6 K1200 Cyclotron

The K1200 is essentially ready for injection, and only the stripper foil mechanism needs to be implemented. We are now at an advanced stage in the design and prototyping. The reliability of the electrostatic deflector at high voltage and high power will be the most challenging

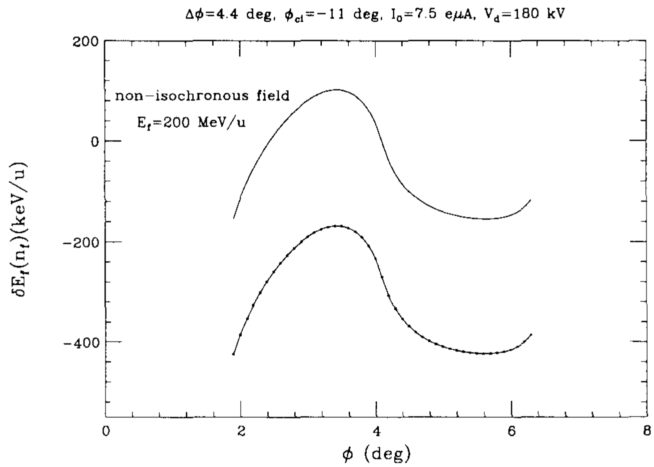

Figure 3: Energy spread of the last two turns in the K1200 with space charge (see text).

subsystem in the proposed upgrade, and a development program has been started to assure the reliable operation at full beam power. The present deflector has very limited cooling of the ground electrode, and none on the high voltage cathode. The high voltage electrode runs at 80 kV with a gap of 6 mm to the septum. To minimize the losses at extraction, the present molybdenum septum (0.25 mm thick) will be replaced with a thinner foil and tensioned to decrease the distortions under high temperature. Individually mounted tungsten or carbon foils are being considered.

The space charge forces have a dominant role in determining the optimum beam phase width that minimizes the energy spread at the extraction radius. This optimum phase width is a function of the circulating current. Figure 3 shows[13] the energy spread of the last two turns in the K1200 cyclotron for an ion with Q/A=0.5 and final energy of 200 MeV/u. The model assumed a realistic (i.e partially non-isochronous) field with an elliptical charge distribution in (z,p_z) and triangular in the azimuthal direction, with a constant profile in radius. For a beam current of 7.5 eμA and a dee voltage of 180 kV, the optimum width was found to be 4.4^o, giving separated turns for the central ray. As the energy spread induced by the space charge forces normalized to the energy gain per turn is inversely proportional to the cube of the voltage gain per turn, any increase in dee voltage will have a beneficial impact on extraction efficiency. Although separated turns at extraction is not required, several components of the K1200 will be improved to increase the voltage holding capability.

7 Cost and Schedule

The cost of the upgrade (including labor) is estimated at $\approx$ 19 (FY94) million dollars. Of this amount 7 million dollars have been requested from Michigan State University with the remainder from the US National Science Foundation. A significant fraction (4.6 M$) of the total cost is for replacement of the present A1200 fragment separator with a higher performance (A1900) device described elsewhere[7]. A five year project schedule has been developed to minimize interruption (18 months) of the experimental program and to provide for a two and a half year operating period of the nearly finished S800 spectrograph. Due to the much higher radiation levels expected with the higher beam intensities, a major reconfiguration of the shield walls will be necessary.

Acknowledgments

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