Present Status and Future Possibilities at NSCL-MSU*

Richard C. York, T.A. Antaya, Henry Blosser, Don Lawton, Felix Marti,
D.J. Morrissey, B.M. Sherrill, John Vincent, and A.F. Zeller
National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, MI 48824-1321 USA

Abstract

The present experimental program of the National Superconducting Cyclotron Laboratory (NSCL) is supported by an ECR-ion-source-injected K1200 superconducting cyclotron. The plan to significantly increase the facility's output intensity for light ions and energy for heavy ions by coupling the existing superconducting K500 cyclotron output to the K1200 is presented. A concept is described to create an improved accelerating chain by utilizing an ECR-ion-source-injected K500 cyclotron to accelerate ions to 10-20 MeV/nucleon followed by horizontal, stripping injection into the K1200 for final acceleration to 100-200 MeV/nucleon.

1 INTRODUCTION

The NSCL proposes to couple the two superconducting cyclotrons (K500 and K1200) and to replace the existing fragment separator with one of increased capacity (A1900) as shown in Figure 1. The coupling of the cyclotrons (K500⊗K1200) will provide dramatic increases in the primary beam intensity and, for heavy ions, energy permitting a wide variety of experimental programs to be undertaken which are presently not feasible. The proposed upgrade is timely (~4 - 5 years project duration) and is cost-effective (~ 19M FY94 US$ in total project costs including labor and materials) since it relies on the existing cyclotrons and incorporates the present experimental facilities.

The upgraded NSCL facility will provide a unique resource to the world-wide nuclear science community by filling a need for both stable and radioactive ion beams in an interesting and nearly unique energy domain. The high energies (more than 100 MeV/nucleon for uranium) are an excellent match to the needs of studies of heated, compressed nuclear matter. The complementary aspects of the high intensity and low emittance primary beams of lighter ions, are an excellent match to the needs of the growing radioactive ion beam field, as they can be converted into very intense, good-quality secondary beams. To fully capitalize upon the increased primary beam intensities for the production of secondary radioactive beams, a large projectile-fragment separator (A1900) is proposed which will have a collection efficiency approaching 50% for fragmentation products compared to the 2-4% for the present NSCL system (A1200).

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2 PERFORMANCE

The maximum theoretically achievable energy is determined by the characteristics of the K1200 cyclotron. The improvements in energy and intensity that come with coupling the cyclotrons are a result of the lower charge states required from the ECR ion source in the K500⊗K1200 mode. These charge states have significantly more intensity than the higher K1200 stand-alone charge states needed to achieve the same final energy. As a consequence of this enhanced ion source intensity, the K500⊗K1200 will provide major gains in performance. For example, to achieve 200 MeV/A with the present K1200 stand-alone system, O^{8+} is necessary for which the maximum ion source intensity is 2 particle μA. With the K500⊗K1200 system, only O^{3+} is necessary from the ion source for which the intensity is 180 particle μA, nearly a factor of 100 higher. In other cases, particularly for the heavy ions, the gains are even larger.

Large gains in intensity are possible for all ions considered, and in addition, there are significant gains in energy for mid and high-mass nuclei due to the increase in the ion charge state upon injection into the K1200. Figure 2 shows these gains and also illustrates the possible trade-off of intensity for energy. Shown are contours of intensity as a function of E/A and A for the K500⊗K1200 operation (solid lines) and the present K1200 stand-alone operation (dashed lines). The intensities are also given at specific points for the K500⊗K1200 operation (solid) and stand-alone operation (open). For lighter ions ($A \leq 40$), the intensity is increased by a factor of 100 - 1000. For example, ^{40}Ar beam intensities of 3.3×10^{12} particles/s at E/A = 180 MeV are estimated for the K500⊗K1200, as compared to 5.6×10^{8} particles/s at E/A = 115 MeV presently achievable by stand-alone K1200 operation – an intensity gain larger than a factor of 5000. For heavier beams, the intensity gains for highly charged ions effectively result in higher energy beams (by factors of 2 - 4). Note that energies of over 100 MeV/nucleon are possible for uranium, while intensities up to 1 particle μA are possible for lighter ions.

The maximum possible energy (as shown in the uppermost curve of Figure 2) is determined by the focussing and bending limits of the K1200 cyclotron for fully stripped ions. Because of ion source limitations, this limit can, as a practical matter, only be achieved for light ions even

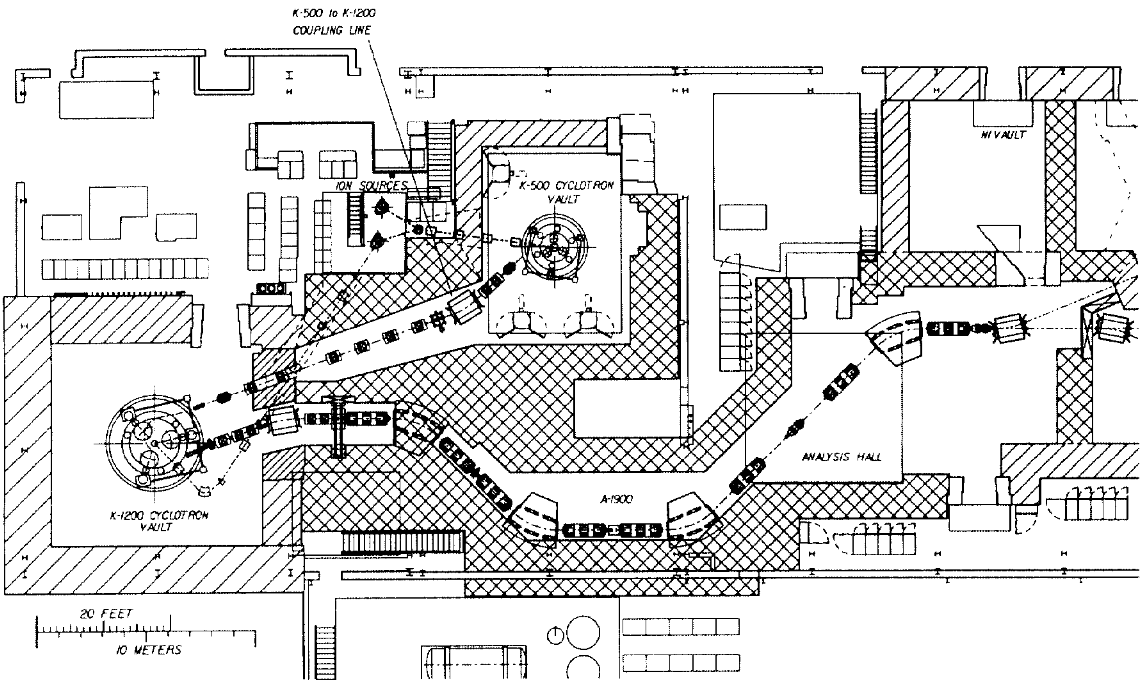

Figure 1: Proposed new accelerator area of the National Superconducting Cyclotron Laboratory.

for coupled operation. Therefore, the maximum achievable energies depend largely on the maximum charge state which can be produced for a given nucleus. There is also a low energy limit for coupled cyclotron operation. It is primarily determined by constraints on the K500 beams for injection into the K1200 cyclotron and the associated low yields of lower charge state ions in the stripping process. The minimum energy of ions with Q/A=0.5 in the K1200 cyclotron (for coupled operation) is given by E/A$\geq$140 MeV; lower energies require magnetic fields below 3T which would cause the ions to cross the $\nu_r + 2\nu_z = 3$ resonance during acceleration. It is possible that stripping to lower charge states could be achieved by tuning the thickness of the stripper foil, in which case lower energies could be reached. However, since the stand-alone operation capability of the K1200 will be retained, the gains from coupled operation will be in addition to presently available capabilities. Conversion to the K1200 stand-alone operating mode could be achieved within a few hours without breaking the K1200 vacuum.

3 DESIGN

The present NSCL nuclear physics research program is carried out with beams from the K1200 superconducting cyclotron. In recent years, the K500 has been used for accelerator component tests, and since late 1993, has been operated to develop technical information for the design of the coupled cyclotron system. The concept of coupling the two cyclotrons is not new having been proposed in 1976.[1]. During the construction phase, the advent of ECR ion source technology provided a more attractive option which was pursued, the direct injection into the K1200. Ironically, it is the features of the ECR ion source production (high production rates for ions of appropriate charge states) which make the reconsideration of coupling so compelling. The available charge states allow a harmonic ratio (K500:K1200) of 2:1 which provides a larger injection radius into the K1200, greatly simplifying the inclusion of the stripping foil system.

As in the present operations, ions of charge state Q_1 will be produced in an ECR ion source, transported from the ion source area to a point below the K500 and axially injected into the K500 central region. Ion currents of up to 5 -10 particle μA will be accelerated in the K500 in approximately 230 turns to energies of several tens of MeV/u. The beams will then be transported to the K1200 with a system of magnetic elements and an rf system (used to control the bunch length between the two cyclotrons) and injected through an existing horizontal port to a point at approximately one third of the K1200 extraction radius ($\sim$0.33 m) where they will be stripped to a higher charge state Q_2. Finally, the beam of charge state Q_2 will be accelerated in the K1200 to final energies of $\leq$200 MeV/u and extracted. Following the K1200, the extracted beam will be optically matched to a new beam analysis system. In order to produce and separate rigid neutron-rich nuclei at optimal production energies, the separator (A1900) will have $\approx$30% greater rigidity than that of the cyclotron (K1200). As with the present A1200 analysis system, the A1900 will be positioned as the first element of the switch yard so that any beam, including separated fragments, can be delivered to any of the experimental areas.

In order to maintain the advantage provided by the higher ion source intensities, the overall beam transmission for the K500$\otimes$K1200 (ion source to K1200 extrac-

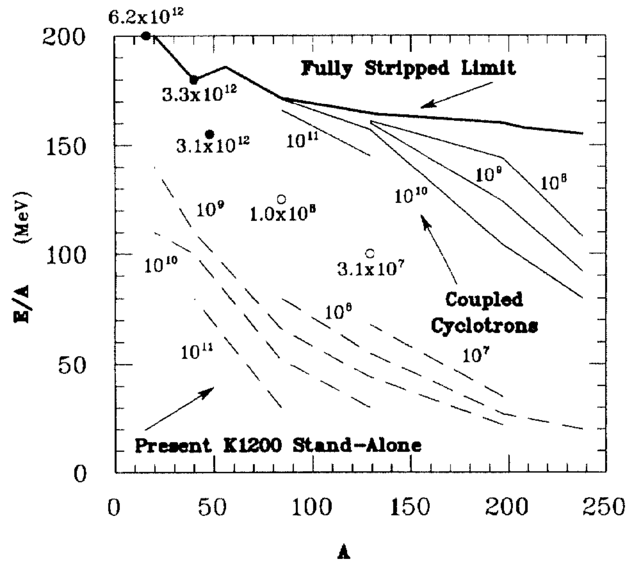

Figure 2: Operating diagram for the present K1200 stand-alone cyclotron and the K500⊗K1200 system. Intensity contours in particles per second are given for the K1200 stand-alone cyclotron (dashed) and the K500⊗K1200 (solid). The intensity is also given at specific points for the K1200 stand-alone (open) and the K500⊗K1200 (solid) operation.

tion) must be similar to that of the present K1200 operation. The K500⊗K1200 system requires injection into and extraction from two separate cyclotrons and in order to maintain the same overall transmission, the losses at each stage must be reduced for the K500⊗K1200 system. The estimated intensities for K500⊗K1200 operation have been calculated under the following assumptions:

The ion source performance is taken to be that in large part already achieved at the NSCL with the superconducting ECR.

The transmission from ion source to K500 inflector will be ~ 50% as compared to the present K1200 operational value of ~20%. To achieve this, the ion source brightness will be increased by raising the operating voltage from ~ 18 kV to ≥30 kV and the injection transport will use increased focusing to maintain the beam quality in spite of the effects of space charge. In addition, the transmission efficiency will be enhanced due to the significantly lower external magnetic fields for the K500 relative to the K1200 (~factor of 4) in the critical injection area.

The RF capture efficiency in the K500 in a ±1.5° FWHM phase width will be 6%. A two-harmonic buncher will be used in lieu of the present single-harmonic buncher. The extraction efficiency in the K500 will be 90%. A much smaller bunch length (~3° FWHM as compared to the present 30°) will be used. In addition, a new central region will be used to allow the more efficient second harmonic operation which will provide increased turn separation at extraction.

The beam transmission between K500 and K1200 will be 90%. To optimally control the bunch length in the accelerating system in the presence of significant longitudinal space charge forces, an rf system will be used to control this parameter between the cyclotrons.

The extraction efficiency in the K1200 will be 90%. Again, a much smaller bunch length (~3° FWHM as compared to the present 30°) will be used.

These assumptions provide an overall transmission efficiency (ion source to K1200 extracted current) of 2% times the stripping efficiency, which is a function of ion species and energy and ranges in value from 1 to 100% for the cases considered. This level of transmission is equivalent to the present K1200 stand-alone operation.

4 PROJECT

The total project consists of the following major tasks:

The ECR ion source operating voltage will be increased in order to mitigate space charge effects and increase the beam brightness. The existing coupling line between the K500 and the ECR ion sources will be modified in order to provide for efficient transport of high intensity beams.

The K500 cyclotron will be refurbished to obtain the operating reliability which is currently achieved by the K1200 cyclotron. Beyond implementation of improved K1200-like engineering solutions, a new central region will be used to allow more efficient operation at the second harmonic and a higher performance extraction septum will be installed.

A new coupling line between the K500 and the K1200 will be implemented. An rf system will be used in the coupling line to control the bunch length during transfer to the K1200.

Injection hardware will be installed and the extraction hardware improved in the K1200. However, the capability to operate the K1200 cyclotron in the stand-alone mode will be retained.

The present fragment separator (A1200) will be replaced with a much higher performance system (A1900) allowing the selection of heavy, neutron rich beams of higher rigidity.

The NSCL high bay area will be extended by approximately 60 feet in order to provide a staging area for magnet construction and refurbishing of the K500. A building addition will be constructed near the present cryogenic plant to house a cryogenic system of increased capacity, and the radiation shielding will be increased.

5 REFERENCES

[1] "Conceptual Design Report for Phase II of a National Superconducting Cyclotron Laboratory for Research with Heavy Ions", East Lansing, MI USA, 1978.