THE NSCL COUPLED CYCLOTRON PROJECT - OVERVIEW AND STATUS

R.C. York, H.G. Blosser, T.L. Grimm, F. Marti, J. Vincent, X. Wu, A. Zeller

Introduction

The present experimental nuclear physics program at the NSCL is based on an Electron Cyclotron Resonance (ECR)-ion-source-injected K1200 superconducting cyclotron. In the last few years, the nuclear physics experiments performed at the NSCL have increasingly made use of radioactive ion beams. Experiments of this type now comprise ~70% of the program with the fraction promising to grow in future years.

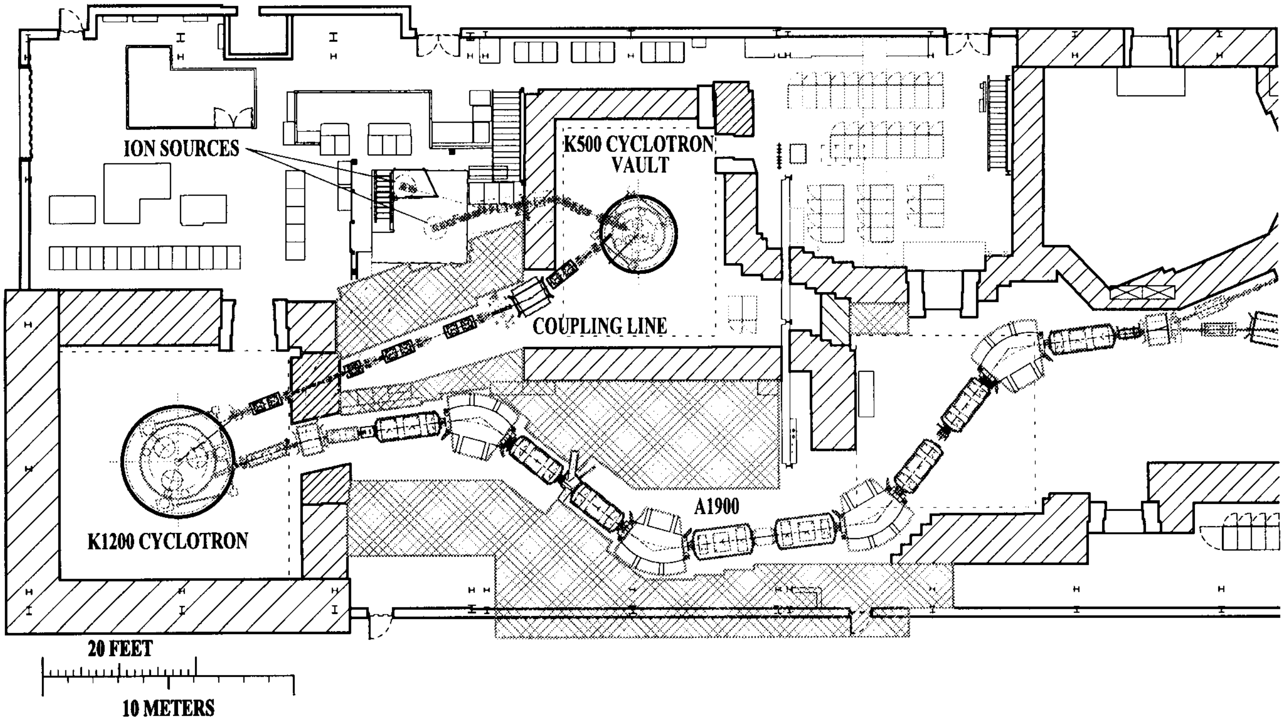

Figure 1. Operating diagram for the present K1200 stand-alone cyclotron and the coupled cyclotron system. Intensity contours in particles per second are given for the K1200 stand-alone cyclotron (dashed) and the coupled cyclotron operation (solid). The intensity is also given at specific points for the K1200 stand-alone (open) and coupled cyclotron (solid) operation.

Worldwide there are significant physics programs that use ion beams of radioactive species as a unique tool to support research in nuclear structure and nuclear astrophysics. Two complementary processes are used to produce the radioactive beams. A technique called Isotope Production On-Line (ISOL) stops a primary, non-radioactive beam in a thick production target. The radioactive species produced are then transferred to an ion source where they are ionized and accelerated to final energy. A second technique called Projectile Fragmentation (PF) uses a primary, nonradioactive beam on a thin ($\Delta E/E \cong 10\%$) production target. In this case, the radioactive species produced have nearly the velocity of the primary beam and a downstream magnetic transport system (fragment separator) is used to select a particular radioactive species. The PF technique is used at the NSCL with the fragment separator as the first element of the beam switchyard.

The NSCL is now in the process of an upgrade which will dramatically increase its capability by coupling the two existing superconducting cyclotrons (K500 and K1200) and by replacing the existing fragment separator (A1200) with one of increased capacity (A1900) as shown in Figure 1. The coupling of the cyclotrons will provide dramatic increases in the primary beam intensity, and for very heavy ions, energy; permitting a wide variety of experimental programs to be undertaken which are presently not feasible. The upgraded facility will provide a unique resource to the worldwide 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 (90 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 for lighter ions, are an excellent match to the needs of the growing radioactive ion beam field, as they provide very intense, good-quality secondary beams.

Performance

Dramatic gains in intensity are possible for all ions considered, and in addition, there are significant gains in energy for mid and high-mass nuclei. Displayed in Figure 2 are contours of intensity as a function of E/A and A for the coupled operation (solid lines) and the present K1200 stand-alone operation (dashed lines). The intensities are also given at specific points for the coupled operation (solid) and stand-alone operation (open). Note that energies of 90 MeV/nucleon are possible for uranium, while intensities up to 1 particle μA are possible for lighter ions.

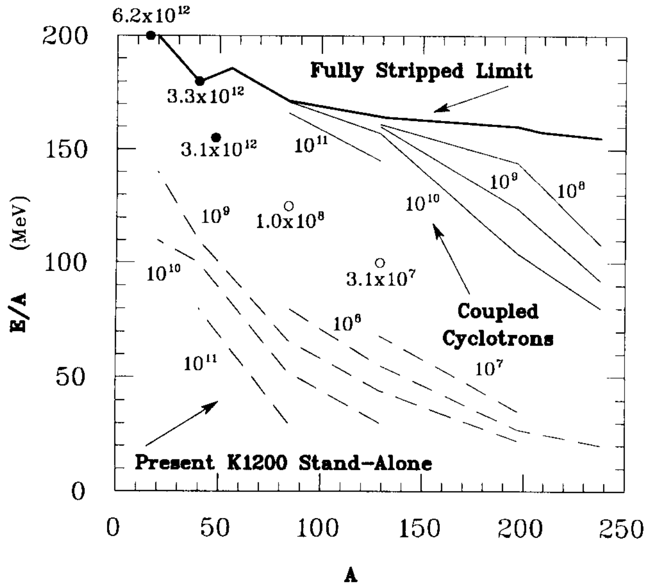

Figure 2. Operating diagram for the present K1200 stand-alone cyclotron and the coupled cyclotron system. Intensity contours in particles per second are given for the K1200 stand-alone cyclotron (dashed) and the coupled cyclotron operation (solid). The intensity is also given at specific points for the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

The maximum possible energy (as shown in the uppermost curve of Figure 2) is determined by the focusing 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 for coupled operation. Therefore, the maximum achievable energies depend largely on the maximum charge state that 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 after stripping. The minimum energy of ions with Q/A=0.5 in the K1200 cyclotron (for coupled operation) is given by E/A=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.

In order to produce and separate rigid neutron-rich nuclei at optimal production energies, the new separator (A1900) will have ~20% greater rigidity than that of the cyclotron (K1200), and will have a collection efficiency for fragmentation products approaching 50% compared to the 2-4% for the present NSCL system (A1200). The combination of increased primary beam intensities and increased fragment separator capacity will significantly increase the intensity of the radioactive beams. The estimated intensity of selected radioactive beams for the coupled cyclotron operation is compared to present performance in Table 1.

Design

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 220 turns to energies of $\leq$17 MeV/u. The beams will then be transported to the K1200 and injected through an existing horizontal port to a point at approximately one third of the K1200 extraction radius ($\simeq$0.33m) where they will be stripped to a higher charge state Q_2. Finally, the beam 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. As with the present analysis system, the A1900 will be positioned as the first element of the switchyard so that any beam, including separated fragments, can be delivered to any of the experimental areas.

	^{11}Li	^{19}Ne	^{32}Mg	^{56}Ni	^{132}Sn
Present Facility	2.5×10^3	6×10^7	1.2×10^3	7×10^4	2
Upgraded Facility	4×10^6	1×10^{10}	3×10^6	4×10^8	4×10^4
Gain	1.6×10^3	1.7×10^2	2.5×10^3	5×10^3	2×10^4

Table 1. Intensities (ions/second) of representative radioactive beams achievable with the K1200 stand-alone operation (Present Facility) compared to those predicted for the coupled cyclotron operation using the A1900 fragment separator (Upgraded Facility).

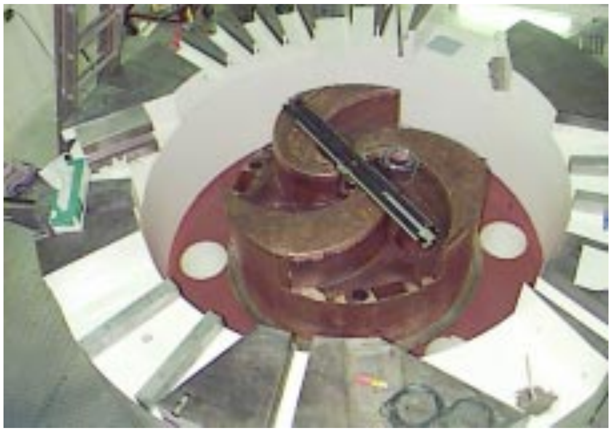

Figure 3. K500 field mapping apparatus in situ

Since the project inception, design changes have been made primarily due to considerations of the optimal method of mitigating the effects of the space charge forces. The original concept was to bunch the beam in the K500 to a length of approximately ±1.5° FWHM. This bunch length was to have been maintained over the path between the cyclotrons by employing an additional rf system in the K500-to-K1200 transport system to produce a velocity tilt on the beam. It was felt that the short bunch length would increase the extraction efficiency of the K1200. However, since the shorter bunch length increases the longitudinal energy spread for high intensity beams, we now believe that better performance will be obtained by using longer bunch lengths of 15° to 30° [1,2].

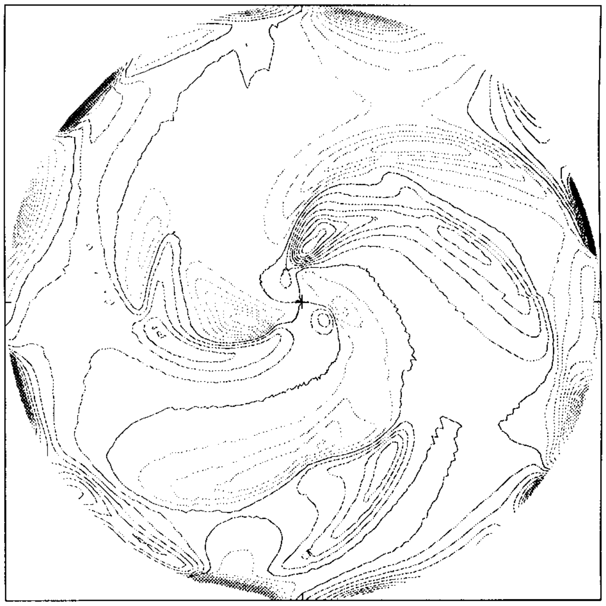

Figure 4. Representative K500 magnetic field error map with 5 gauss contour levels.

Project Scope and Status

The project has been segmented into six areas. The scope and status of each task is discussed in turn below.

1.1 ECR-to-K500 Injection Line

To increase the ECR-to-K500 transmission efficiency, the ECR voltage was increased from about 18 kV to 30 kV and the focusing and diagnostics of the ECR-to-K500 transport lattice was enhanced. All of this work has been completed on schedule. The performance requirement was a 50% transmission over this segment, and 75% transmission efficiency has been achieved.

1.2 K500 Cyclotron

The K500 cyclotron was completed in 1982 as the world’s first superconducting cyclotron, and as such was prototypical. The K500 had known reliability issues, undesirable magnetic field harmonics, and a relatively poor beam chamber vacuum. When the K1200 was later constructed, the lessons learned were applied, and therefore, the K1200 has significantly better attributes and a notable reliability of >90%.

The K500 was first completely disassembled to make significant improvements to the cyclotron vacuum system including the modification of vacuum surfaces, utilization of rubber in lieu of indium seals, redesign of the cryopump system, and the repair of cracks from atmosphere to vacuum in the pole cap steel.

The K500 was thereafter reassembled and guided by magnetic field maps, yoke steel modifications were made which reduced the undesirable field harmonics [3]. Figures 3 and 4 show, respectively, the field mapping apparatus in situ and a representative field map analysis.

The K500 rf system will be replaced with one following the K1200 system design. The rf amplifiers are improved copies of the K1200 design. To date, high power measurements have been performed on all three amplifiers achieving the expected performance and tuning range. The rf resonators closely follow the K1200 design. These efforts are nearing completion and the K500 system should be operational by the end of 1998 approximately six months ahead of schedule.

1.3 K500-to-K1200 Coupling Line

A magnetic system will be used to transport beam from the K500 to the K1200. In large part, the elements for this line will be provided by magnets reassigned from the existing A1200 fragment separator. Information from the recent K500 field mapping has been used to design a lattice that should provide fully six-dimensional phase space matching between the two cyclotrons. The slot length necessary for the bunch length control rf system will be reserved should it prove desirable in the future to implement such a system. The development of coupling line operational strategies will be done during 1998 with hardware implementation during 1999 and 2000.

1.4 K1200

Figure 5. K1200 stripping foil mechanism.

Installation of a mechanism to position the thin carbon stripping foils and improvement of the robustness of the extraction septa are the primary K1200 upgrade activities. (The capability to operate the K1200 in stand-alone mode will be retained.) The foil mechanism inside the cyclotron has been designed and construction initiated. Shown in Figure 5 is the mechanism that will be placed inside a K1200 dee and will be used to position one of the 33 carbon stripping foils at the appropriate position of the injected beam. The design of a loading system, which will allow foil replacement without interrupting the cyclotron vacuum, is in progress. A program to improve the K1200 extraction system was begun about two years ago and is planned to continue until the coupled cyclotron commissioning in the year 2001. Significant progress has been made in the understanding of the physics driving the extraction efficiency and a detailed discussion may be found in these proceedings [1].

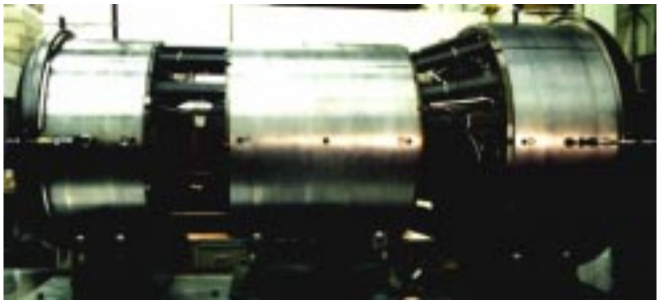

Figure 6. Cold mass of the A1900 quadrupole triplet approximately 2.2 m in length.

1.5 A1900 Fragment Separator

A major element of the upgrade is a new fragment separator with an increased rigidity and greater collection efficiency. The optics design has been completed and the details presented elsewhere [4]. The initial design was based on the use of superconducting quadrupoles with cos(2θ) wire distribution. All of the NSCL experience has been in the fabrication of iron-dominated quadrupoles energized with random-wound superconducting coils. Since the cos(2θ) technology would have provided only about a 20% increase in the capture efficiency over the NSCL iron-dominated design and yet presented a significant risk to the project cost and schedule, the NSCL quadrupole technology was chosen. The mechanical designs are finished, fabrication activities are well underway, and it is anticipated that the magnets will be complete during 2000. The magnet design details are presented elsewhere [5].

The A1900 will use 24 quadrupoles configured in eight triplet packages, and four 45^o dipoles in a reverse bend geometry so that incoming and outgoing beams are coaxial. Of the 24 quadrupoles, 16 have multipole packages consisting of a sextupole and octupole pair to correct the higher-order effects. There are five different quadrupole designs (QA (4), QB(12), QC(4), QD(2), and QE(2)) required with the required number per type given in parentheses. By the spring of 1998, two QD's, a QB, QC, and QE had been constructed and successfully tested to currents significantly exceeding the design specifications. The first triplet (QD,QE,QB) is now under construction (See Figure 6.) and it is expected that two of the triplets will be completed by the end of 1998.

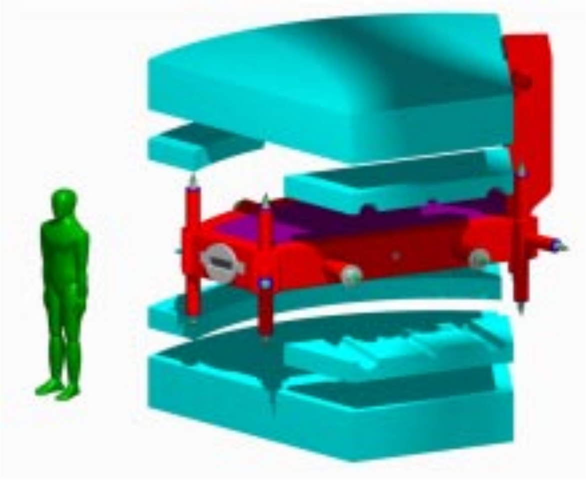

Figure 7. A1900 dipole CAD design.

The four dipoles in the A1900 system will have a length of 2.5 m, a maximum pole-tip field of 2 T, and be energized by superconducting coils. A CAD drawing of the dipole system is given in Figure 7. The cryostat elements are in fabrication with nearly half of the required superconducting coils wound and ready for installation.

2 Project Cost and Schedule

The coupled cyclotron project is jointly funded by Michigan State University and the National Science Foundation. The total project cost is approximately 19.5 M$ (including labor costs) with Michigan State University contributing about 6 M$ and NSF about 13.5 M$. The first NSF funds were received in 1997.

The planned project schedule is given in Figure 8 where the star symbols are the 14 project milestones. By May 1998, the project has achieved seven project milestones (solid) on or ahead of schedule. By about the end of 1998, the accelerator chain through the K500 cyclotron will be complete and most of the A1900 fragment separator magnets constructed. Beginning in mid-1999, the K1200-supported experimental nuclear physics program will be stopped for a period of approximately 18 months to reconfigure the facility and install new equipment. A six months commissioning period is planned in 2001 with project completion scheduled during that year.

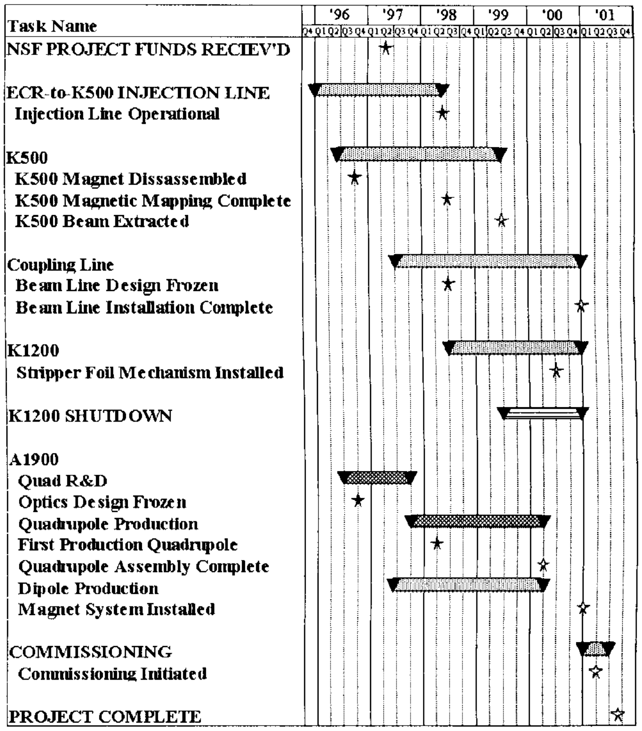

Figure 8. Major Coupled Cyclotron Project milestones by calendar year. Achieved milestones are solid black.

References

1. H. Blosser, et al., “Numerical Study of Efficiency of Multi-Turn Extraction in the K1200 Cyclotron”, these proceedings.
2. F. Marti, et al., Beam Dynamics Issues of the NSCL Upgrade”, these proceedings.
3. T. L. Grimm, et al., “Compensation of Magnetic Field Imperfections in the NSCL K500 Superconducting Cyclotron”, these proceedings.
4. X. Wu, et al., “Tracking Studies and Performance Simulations of the NSCL A1900 Fragment Separator”, Proceedings of the 1997 Particle Accelerator Conference, to be published.
5. A.F. Zeller, et al., “Magnetic Elements for the A1900 Fragment Separator at the NSCL”, Adv. in Cryogenic Engineering, **43**, 1998, in press.