COMMISSIONING EXPERIENCE WITH THE NSCL K1200 SUPERCONDUCTING CYCLOTRON

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ABSTRACT

The NSCL K1200, the largest of the superconducting cyclotrons, was commissioned during the first half of 1988. Internal beam was accelerated to the extraction radius of 1 m on February 22, 1988, and then after installation of the extraction elements, the beam was extracted on June 6. The first nuclear science research experiment used a 75 MeV/A ^{14}N beam and was completed in October, 1988.

This cyclotron is based on a 280 ton superconducting magnet with a magnetic field operating range of 3-5 T and a maximum magnetic rigidity of 5 T-m (K=1200). Typical maximum design energies are E/A=200 MeV for fully-stripped N=Z ions and E/A=48 MeV for q=26 ^{129}Xe ions. An ECR ion source and axial injection system has been used with this cyclotron from the beginning. A major initial success in the commissioning is the excellent agreement between the computer calculations and the actual beam trajectories in the intricate extraction system. Initial experience with all major subsystems will be discussed: magnetic field data,superconducting magnet, cryogenics, three phase rf system, ECR ion source/axial injection, and electric/magnetic extraction elements.

1. INTRODUCTION

Development of superconducting cyclotrons began in the early 1970's at two laboratories, AECL in Chalk River and the Cyclotron Laboratory of Michigan State University. The initial fruits of this work were the NSCL K500 cyclotron, first operated in 1982, and the Chalk River K520 cyclotron, first operated in 1985. Recently, two more superconducting cyclotrons, the NSCL K1200 (originally called the K800) and the Texas A&M K500, have produced external beams. The new NSCL machine represents a significant increase in size for isochronous cyclotrons, to a magnet rigidity of 5 T-m.

2. GENERAL DESCRIPTION OF THE NSCL K1200 SUPERCONDUCTING CYCLOTRON

The NSCL K1200 cyclotron utilizes a 280 ton, 60 MJ superconducting magnet that was completed in 1984. Early design studies of the K1200 were reported by Resmini, et al at the Indiana cyclotron conference in 1978 [1]. Since status reports and descriptions of this machine were presented in 1986 [2] and 1987 [3], only a short summary is given here. Several aspects of this cyclotron were significantly more challenging than those of the NSCL K500, due to larger mechanical forces in the magnet, the larger turn number, the higher dee voltage, the tighter pole-tip spiral, and the close proximity of intrinsic focussing resonances.

The energies of magnetic-rigidity limited heavy ion beams are given by the relationship: E/A = K(Q/A)**2 MeV, where the bending-limit k-value for this machine is K = 1200 MeV. For ions with Q/A greater than 0.33 the maximum energies are focussing-limited and are given by: $E/A = K_f(Q/A)$ MeV, where K_f is 400 MeV. The radio-frequency range is from 9 to 27 MHz, corresponding to ion energies from about 18A MeV to 200A MeV in first harmonic mode. Ion energies down to well below the Coulomb barrier are possible in the second or third harmonic modes. The 200A MeV energy is possible with fully stripped N=Z ions with 200 kV on the dees. The maximum energy heavy ions depend on the charge states available from the ion source, and hence are expected to increase with time as ion source technology develops. For example, 30A MeV xenon ions have been available for early runs, while energies above 50A MeV should be available in the not too distant future, using present and planned ECR ion sources [4].

The main magnetic field is produced by two pairs of circular superconducting coils, one pair just above and below the median plane and the other further from the median plane. Exciting these coils with different ratios of currents makes it possible to vary B_{ave} vs r over a wide dynamic range, in a way not possible in conventional isochronous cyclotrons, which always have iron-dominated main fields. The NSCL K1200 cyclotron is the first superconducting cyclotron in which the outer pair of coils is designed to run either positive (for nonrelativistic ions) or negative (for relativistic ions) relative to the inner pair [1]. In the former case B_{ave} is nearly constant with radius, while in the latter it can increase by over 20% from r=0. to r=1. m. Detailed trimming of B_{ave} vs r is done with a set of 21 trim coils wound with conventional copper conductor on the pole tips, just as in the K500. Vertical focussing is provided by a set of heavily-spiraled thick steel pole tips with three-fold symmetry.

This cyclotron was commissioned with an ECR ion source/axial injection system. The components of this system are of the same design as those in use with the NSCL K500 cyclotron for the past two years.[5,6] At the present time an ECR switchyard is under construction to make it possible to use any one of three ECR ion sources with either of the two cyclotrons as required for the scheduled experiments [4].

Orbit calculations for the K1200 indicated that the magnetic field tolerances are much more stringent than they were with the K500 [7,8]. The extraction calculations are much more tedious and the magnetic extraction bar designs are more intricate. Fig. 1 is a section view of the K1200 median plane showing schematically the extraction system elements; there are two electrostatic deflectors, 8 passive magnetic focussing bars, one passive magnetic dipole bar, and 8 magnetic compensating bars, involving in total 26

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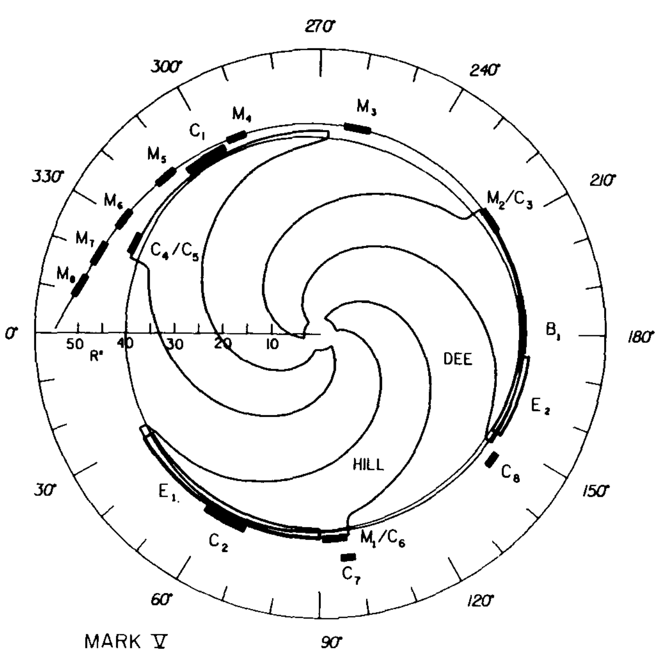

Fig. 1. Section view of the median plane of the K1200 cyclotron. For scale, the outside diameter of the cryostat, the largest circle shown, is 2.9 m. The outside diameter of the steel yoke (not shown) is 4.4 m.

mechanical positioning drives. In addition, there is a resistive-coil steering magnet [9] in the exit channel of the steel yoke (not shown in the figure).

The NSCL K1200 superconducting cyclotron is part of the overall NSCL Phase II facility. The original proposal was to use the K500 with an internal PIG ion source as an injector for the K1200, but with the higher charge state ions now available from ECR ion sources the present plan is to use the two cyclotrons independently. The floor plan indicated in Fig. 2 still allows for coupling the cyclotrons in the future if that becomes desirable. The maximum magnetic rigidity of beams from the K1200 cyclotron is 1.6 GeV/c, about 30% higher than that of the 800 MeV protons at LAMPF. The beamline magnets shown in the floor plan are superconducting to transport these beams within the limited space of the NSCL highbay area.

3. SUMMARY OF INITIAL PERFORMANCE

After accelerating the first internal beam to full radius on February 22, 1988, there was a shutdown to finish installation of extraction elements and their mechanical drives. An additional delay was caused by the shorting of two of the rf power tetrodes as described below. In late May beam studies resumed, but initial attempts to extract beam were unsuccessful. Opening the machine for inspection revealed an error of about 2 mm in the position of the second of the four drives on the first electrostatic deflector, which had caused the beam to hit the inner side of the septum before reaching extraction radius. With this problem fixed, on June 6 an 18 MeV per nucleon 20Ne(3+) beam was extracted to a beam stop beyond the coil cryostat. All machine parameters, including extraction element positions were in excellent agreement with calculations. A radiogram of the beam stop showed that the beam spot was about 4 mm in diameter and within 5 mm of the calculated position. The extraction efficiency was about 25%, with 1/2 of the loss in the first deflector.

Fig. 3 is an operating diagram in the space of the currents in the two main magnet coils, with I(alpha) being the current in the coil near the median plane and I(beta) that in the coil away from it. Moving to the right along the nearly horizontal grid lines is in the direction of increasing magnetic flux, while moving down along the nearly vertical lines is in the direction of increasing relativistic parameter. The labels and arrows indicate the ions, energies, and dates of the beams extracted in the early commissioning. The 40Ar(7+) beam at 30 MeV per nucleon ran at a central field value of 45 kG, the highest for any of the beams run so far. This is a near analog beam of 86Kr(15+) and $^{129}Xe(22+)$, which were developed soon after and used in research runs. The highest rf dee voltage used to date is 130 kV for a 100 MeV per nucleon $^{14}N(6+)$ beam, which was extracted and used for research runs after the early beams indicated in Fig. 3.

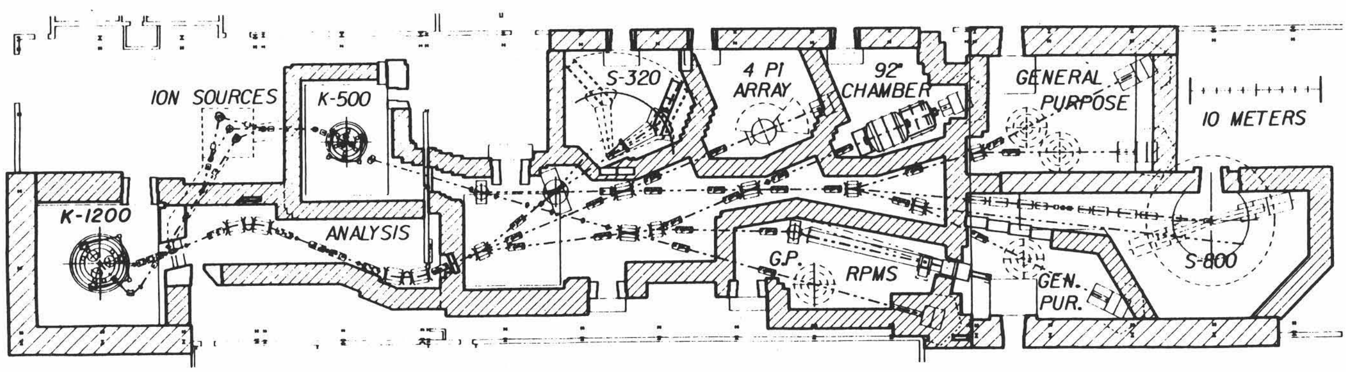

Fig. 2. The highbay floorplan of the complete NSCL Phase II Facility as presently planned; showing the two cyclotrons, the ion source switchyard, the beam transport system to deliver the beam from either cyclotron to any experimental area, and the various experimental devices.

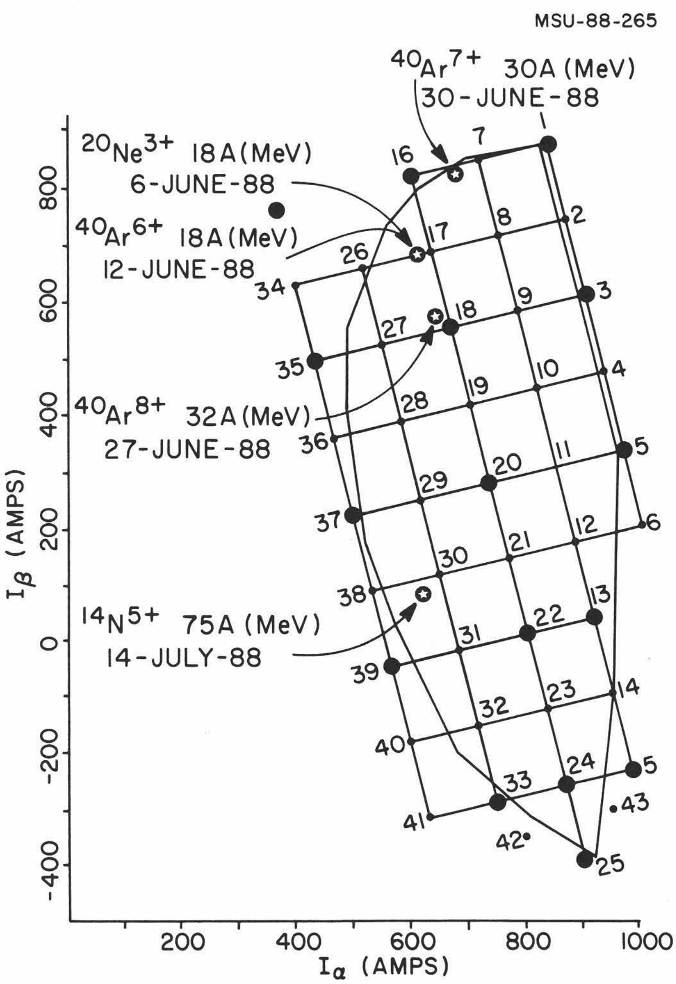

Fig. 3. An operating diagram of the K1200 cyclotron in the space of the two main coil currents, I(alpha) and I(beta). The numbered grid points were proposed field maps, with the bold points being the ones mapped to date. The labelled stars are the operating points for the beams extracted during the commissioning period.

4. SUBSYSTEM PERFORMANCE

The subsystems consisting of the main superconducting magnet and its power supply, the liquid helium refrigerator system, and the beam chamber cryopump/vacuum system all ran well and did not limit performance during the commissioning period. The beam chamber is pumped primarily by three sets of liquid helium and liquid nitrogen cooled cryopanels located just below the median plane within the rf dee structures. The vacuum in this region is about 5x10**(-7) torr, so that there has been insignificant vacuum attenuation of the beams accelerated to date.

There has been excellent agreement between cyclotron parameters predicted by calculations based on the measured magnetic fields, and those needed to actually extract beam. The cyclotron and extraction system were designed and constructed based on magnetic fields calculated by a combination of two-dimensional (POISSON) calculations and current sheet models to introduce three-dimensional effects. A new magnetic field mapper was developed for the K1200 [10] and the set of maps on the grid points indicated by the bold black points in Fig. 3 were recorded in late 1987 [11]. A new interactive beam orbit code, MONSTER [8], was developed to calculate internal and extracted beams in fields interpolated between measured grid points. Although there are some small differences between the calculated and measured magnetic fields and there are first harmonic field imperfections with amplitudes up to 10 gauss at extraction radius, the MONSTER calculations indicated that the cyclotron would work without any magnet shimming. The beams extracted during this commissioning period have confirmed the accuracy of these predictions and the reliability of the field maps.

The ion source/injection system is of the same design as that currently used on the K500 cyclotron. The smaller of the two present NSCL ECR ion sources, the compact source, was used for the commissioning of the K1200. The reliability and stability of this system was of great benefit during the commissioning period. The only current problem with this system is due to the large fringe magnetic field of the K1200 magnet at the location of the horizontal sections of the injection beamline. Modifications to the shielding and/or optical elements in this beamline will be necessary to increase the injection efficiency. Internal beam currents of 10-100 enA have been achieved and have provided external currents adequate for several initial nuclear science research experiments.

The electrostatic deflectors in the K1200 are an evolution of those in the K500. The first deflector in the K1200 is longer, and is built in three sections with two hinges and four mechanical drives. In both of the K1200 deflectors one of the drives doubles as a high voltage feedthrough. The peak voltage requirement has been reduced in the design from the 100 kV and 7 mm gap in the K500, to about 85 kV with the same gap in the K1200. The high voltage feedthrough is of a new design which is an evolution of one developed at Texas A&M for their K500. The K1200 deflectors have been conditioned to 50 kV in the cyclotron so far and have been used at voltages up to about 45 kV for the beams extracted to date. The reliability and voltage limitations of the new designs have not been established.

The rf system has generally performed very well during the commissioning period, except for a problem associated with the high power tetrodes in the three final amplifiers. Delays have been incurred due to screen to filament shorts in three of these tubes. After these failures the machine was operated with a tube on loan from the cyclotron group at Oak Ridge National Laboratory, and a rebuilt version of one of the shorted tubes. The precise cause of the problem has not yet been established, but the magnetic shielding of the tubes has been improved and the reliability and sensitivity of the crowbar protection circuit of the 1.2 megawatt anode power supply have been upgraded. In the meantime alternate amplifier designs, utilizing other tubes, are being studied. Three of the rf coupler vacuum feedthrough insulators have also failed so far. This has not been a major problem, but design modifications and alternate geometries are being developed. The rf system was operated at voltages as high as 120 kV for early beams, but inspection of the beam chamber indicated heavy sparking in the central region where the dee tips have the smallest curvatures and one gap was as small as 14 mm, indicating the need for some design changes in these components. New dee tips were fabricated with larger curvatures and the gaps were adjusted to make the narrowest one 20 mm. Also the copper liner above and below the dee tips was coated with plasma sprayed tungsten to reduce erosion. Since these changes the dee voltages have been operated at up to 136 kV with insignificant sparking.

Studies of the extracted beam have shown that the passive focussing bars M2-M8 in combination with the active resistive-coil in the exit channel of the yoke can be used to control both the position and angle of the external beam over a wide dynamic range of cyclotron fringing field conditions. These components plus a superconducting quadrupole triplet just outside the yoke are used to give the beam the correct position, direction, and focus at the first object point about 3 m from the yoke.

5. ACKNOWLEDGEMENTS

The commissioning of the K1200 cyclotron at the NSCL is a major milestone which was made possible by the coordinated efforts of many people over a period of several years. The contributions of all these people are highly appreciated.

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