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INITIAL OPERATION OF THE MSU SUPERCONDUCTING CYCLOTRON

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Abstract

On August 31, 1982, the first beam was extracted from the Michigan State University superconducting K500 cyclotron. Shortly thereafter, the first experiment was performed with a 35 MeV/n carbon beam. The known operating characteristics of the K500 cyclotron are reported. Some of the technological innovations of the machine are described. Progress on the next phase of the project, the K800, is discussed.

K500 Operation

Many design features of the Michigan State University superconducting cyclotron have been reported in previous Particle Accelerator Conferences[1] and Cyclotron Conferences.[2] In this conference, papers in session Q,[3] W[4], and E[5] review additional aspects of the cyclotron. This project has had the help of many people and Fig. 1 shows the cyclotron staff at Michigan State as of May, 1982. In this picture appear about half the people who have contributed in various ways to the project.

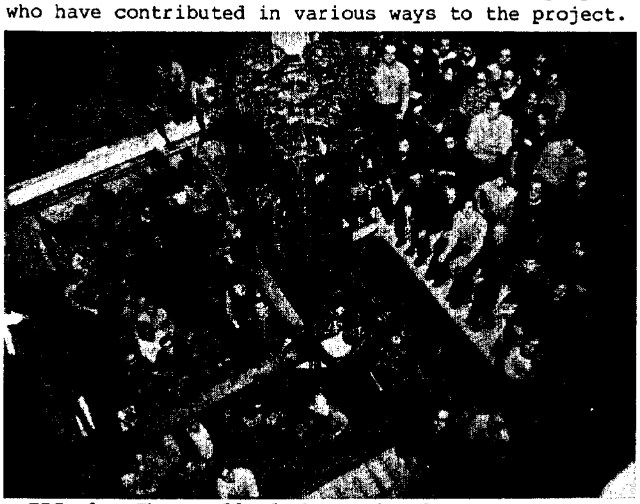

FIG. 1. The staff of the National Superconducting Cyclotron Laboratory as of May 1982, posing on top of the K500 cyclotron, just before installation of the roof shielding. About one half of the people who contributed to the construction of the K500 are in this group.

The picture also shows the top of the cyclotron, the roof shielding has been removed, and a good impression of the compactness of the K500 cyclotron is obtained; the outer magnet diameter is 10 feet. The upper stems of the three r.f. resonators are visible in the center of the picture. A sliding short, moving along the r.f. stems provides for tuning the frequency from 9 to 27.5 MHz.

Figure 2 is the first harmonic operating curve of the K500 cyclotron. The operating curve boundaries are the maximum magnetic field for the superconducting magnet (top), the upper frequency limit and maximum magnetic field focusing limit which coincides with the maximum dee and deflector voltage (right), the lower frequency limit (left) and the $\nu_r+2\nu_z=3$ resonance at the extraction radius (bottom). Different charge to mass ratios are plotted (diagonal lines from lower left to upper right) and the dee voltage required for constant geometry (diagonal lines from upper left to lower right). The beams that have been successfully accelerated are indicated by large dark circles. The

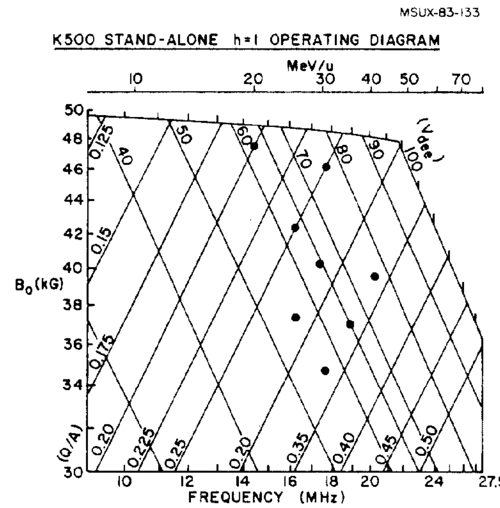

FIG. 2. The h=1 operating curve for the K500 cyclotron is shown. Dark circles represent developed operating points and span the full magnetic field range. Dee voltages as high as 100 kV have been obtained in a test run of the rf, but voltage holding capabilities of the deflector presently restrict the high energy per nucleon operating points.

operating range includes both high magnetic field (5T) and low field (3T) and a selection of many frequencies. The dee voltage in initial test operated at the 100 kV design level, but presently is restricted to lower values because of a misalignment which puts centeral region clearances to 0.7 of design value.

The deflector voltage needed for the successful extraction of the very highest energy beams has not been achieved in the cyclotron, although a test stand model was successful. Work continues toward upgrading this device. Table 1 is a list of the beams accelerated; it encompasses most of the light gases and the normal charge states that have been obtained elsewhere.

Table 2 is a listing of the significant events in the K500 project and indicates a time of approximately 8 years from conception to initial extraction of the beam. The project was funded in two grants; the first stage was the construction and successful testing of the superconducting magnet, this was followed

Table I

Ions Accelerated on the K500 as of March 1983

Ion	Q/A	Energy (MeV/n)
$^{2}H^{1+}$	.4966	53
$^{4}He^{1+}$	.25	25
$^{4}He^{2+}$	.5	52.5
$^{12}C^{3+}$	.25	25
$^{12}C^{4+}$	.33	25,30,35,40
$^{14}N^{4+}$	.2857	25,30
$^{16}O^{3+}$	.1876	17.3
$^{20}Ne^{5+}$	.25	25
$^{20}Ne^{6+}$	.30	30

by the conversion of the magnet into the K500 cyclotorn. Funding for the entire cyclotron from project conception would have shortened the time to completion, but at that time, felt that it was better to firmly establish the magnet characteristics before proceeding with the cyclotron.

Table II

K500 Significant Events

Event	Date
Magnet Proposal	July, 1974
Funding for K500 Magnet	Sept. 24, 1975
Coupled Cyclotron Proposal	Sept. 1976
K500 Cyclotron Proposal	Feb. 1977
K500 Magnet Operated	May 26, 1977
Funding for K500 Cyclotron	July 26, 1977
K500 Internal Beam	Nov. 21, 1981
K500 External Beam	Aug. 31, 1982
1st Beam to Experiment	Sept. 13, 1982
1st Outside User Experiment	Feb. 23, 1983

Figure 3 is an internal beam probe trace of $^{12}C^{4+}$ showing beam intensity from 26 to 27 inches. It includes the region where the beam has been deflected by both electrostatic deflectors (29 to 30 inches), the distance from 27 to 30 inches is the separation distance between the last internal turn and the deflected beam at the probe location. The distance between 29 to 30 inches reflects the width of the probe and not the beam width. The extraction efficiency was 35%. With the implementation of phase clipping, higher extraction efficiencies will be obtained. The beam trace also indicates little beam attenuation, as a function of radius, thereby verifying the quality of the accelerator vacuum. A He^{1+} beam has been successfully accelerated, with a total attenuation of 50%, (helium gas is not pumped by the cryopanels). The beam extraction radial emmitance has been measured to be less than 1 mm mrad. Figure 4, is the energy spread measurement of a 35 MeV/n carbon beam and indicates a $\Delta E/E$ of less than .2% fwhm that includes target thickness and detector resolution. This measurement implies excellent stability of the magnetic fields and rf dee voltages.

K500 Technological Innovations

It is very difficult to claim that new techniques and methods are totally innovations of a specific project since in most cases some aspect of the ideas were incorporated or used elsewhere. Accepting the disclaimer above, I describe five areas that are significant developments of this project.

Figure 5 is a close up picture of one layer of the superconducting coil and shows its compactness. The wire in each layer is continuously wound on a stainless steel bobbin. A 0.040 inch insulation space and helium passage (50% of the cross sectional area) separates each coil layer. This method of winding the coil,

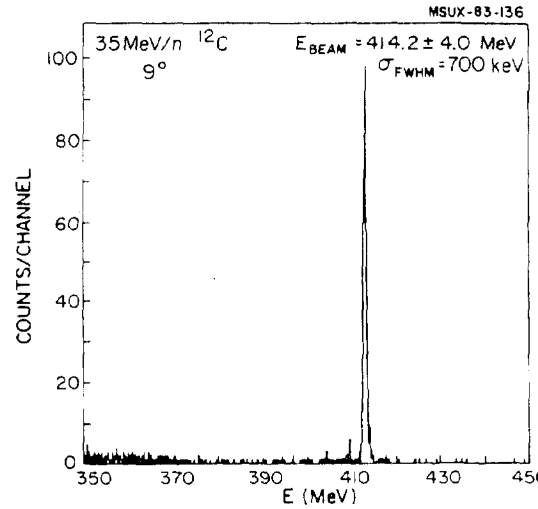

FIG. 4. The energy spread measured by scattering from a gold foil is found to be less than $\Delta E/E$ = .2% fwhm. This spread contains the target thickness and detector resolution and indicates excellent stability of the rf and magnetic field at this early stage of operation.

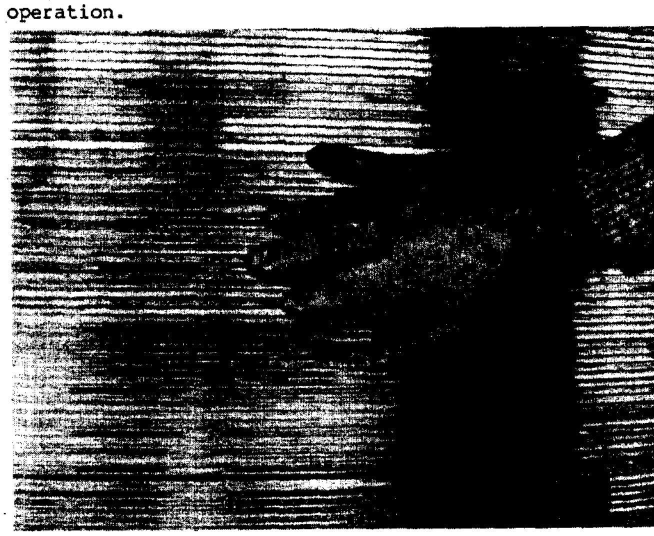

FIG. 5. A close up picture of one layer of superconducting wire on the bobbin of the K800. This compact layer type winding was the first to be employed on such a large coil and is one of the significant developments of the project.

although common in manufacturing small coils, was the first for a large superconducting coil. The length of the wire needed resulted in having 10 splices in the coil. This technique leads to substantial savings in winding time, coil alignment and coil compactness.

Figure 6 is the measured and calculated average magnetic field of the K500 magnet as a function of radius for three excitations. The results indicate that the magnetic field was closely predicted and re-

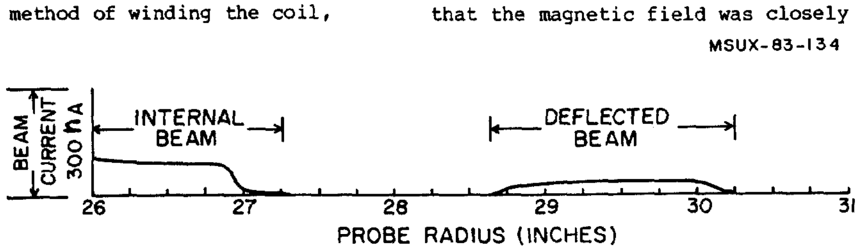

FIG. 3. A $^{12}C^{4+}$ beam probe trace for the outer radius of the cyclotron is shown. The beam attenuation appears to be small, thereby attesting to good vacuum. An extraction efficiency of 35% (29 to 30 inch) was obtained for this non phase clipped beam.

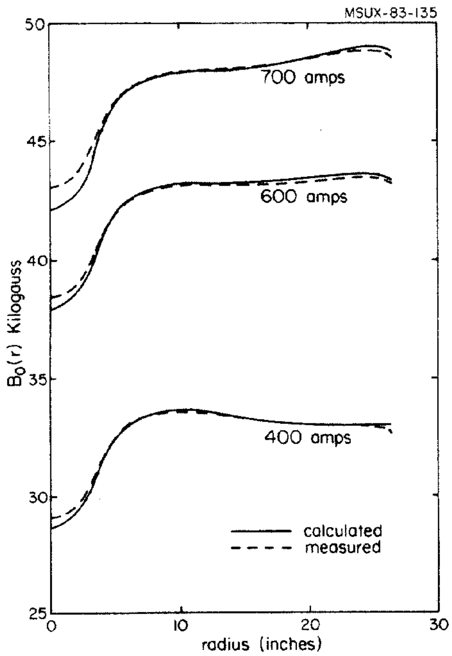

FIG. 6. The measured and calculated average magnetic field of the K500 magnet are shown for three excitations as a function of radius and are in excellent agreement except at the center. An added piece of iron was included in the magnet. Complex magnetic fields can now be determined analytically by computer codes.

finement in the computor code now achieves better 0.1% agreement with the average field. In the old K50 cyclotron at MSU, the magnetic field shape was determined in a model magnet, requiring many physical changes until the correct geometry was obtained. Using analytical techniques, one is now able to calculate the cyclotron complex magnet field shapes by computor.

The K500 is the first operating cyclotron with three independently phased dees, thereby allowing various harmonic beam acceleration modes. Figure 7 is the K500 cyclotron r.f. electrical circuit diagram for the three dees (one per valley). Due to the high magnetic field of the K500, it becomes necessary to achieve a large energy gain per turn in order to have adequate turn spacing at extraction. The successful first harmonic operation of the three dees is clearly illustrated by the previously shown energy spread measurement. The problem of dee to dee coupling required some modification to the initial concepts but has been successfully resolved.

Figure 8 is a timing measurement of x-rays produced by sparks from the dees. A method developed on the old K50 cyclotron of measuring the end point energies of x-rays[6] provides a technique for calibrating the dee voltage. It has been discovered that the x-rays are time correlated and can be used to measure dee to dee phasing on the K500. A phasing calibration between dee to dee of less than $.1^{o}$ appears to be possible.

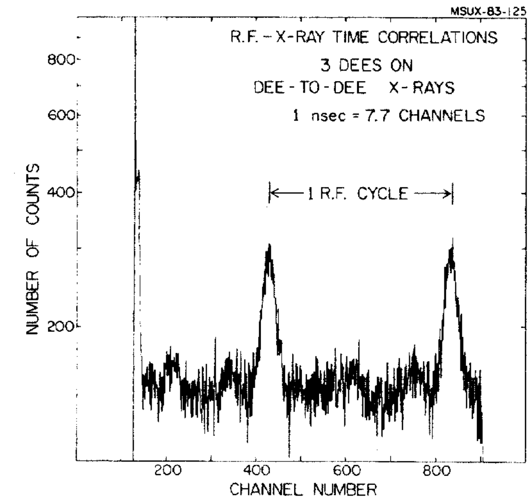

FIG. 8. Time correlated X-rays from dee to dee were detected for the first time. Using this nuclear technique, it should be possible to absolutely calibrate the dee to dee phase to $.1^{o}$.

Helium leaks in the cryostat of large superconducting magnets are a common problem and a new technique was developed to find them. Figure 9 shows the level of liquid helium in the magnet cryostat as a function of time. The helium leak rate detected in the cryostat vacuum jacket is also recorded. It was observed that the leak rate of helium into the vacuum jacket increases after the liquid helium level passed through the magnet median plane. Using this information, a helium leak

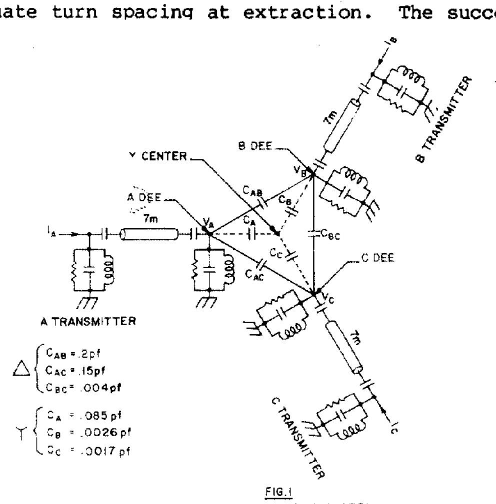

FIG. 7. The rf electrical circuit diagram for the K500 dees are shown. The K500 cyclotron was the first cyclotron using three independently phased dees and single turn extraction requires excellent control of the dee to dee phases and amplitudes.

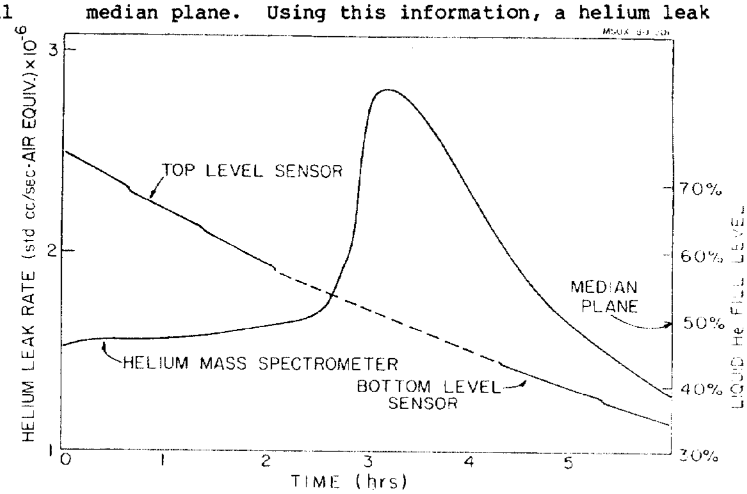

FIG. 9. The liquid helium height in the coil is shown as a function of time and as the level crossed the median plane of the cyclotron, an increase in the helium signal from the vacuum chamber was detected. A leak was later found at this location and fixed.

was found at the median plane and welded. By using this technique[7], and another[8] using the difference in vicosity and density of helium as a function of temperature, we have developed ways of finding all helium leaks in our cryostat.

Conclusions

With the K500 cyclotron running, our major construction efforts are now being shifted to completion of the K800 cyclotron. Figure 10, 11 and 12 depicts the magnet, coil, and helium refrigerator. It is expected that the K800 superconducting magnet will be tested this year.

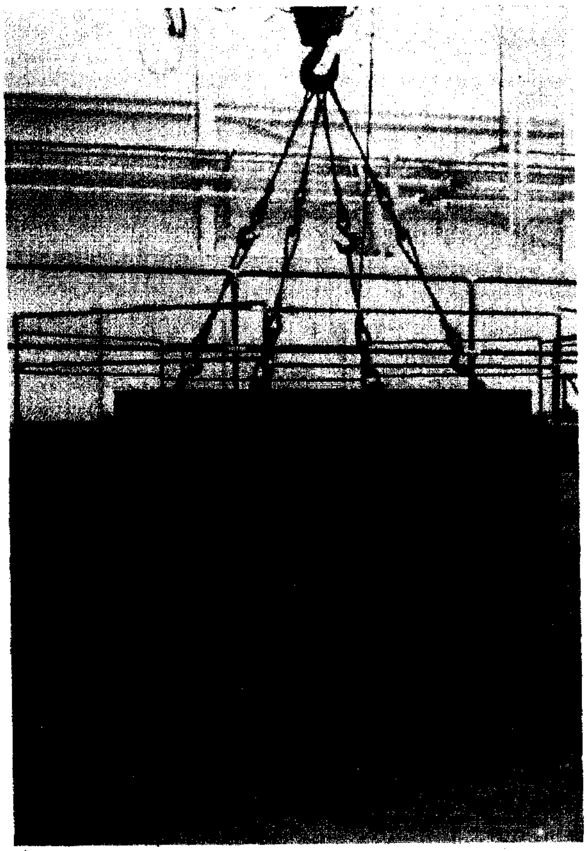

FIG. 10. A picture of the K800 steel being assembled is shown. The magnet diameter is 14 ft., 7 inches and weighs 265 tons.

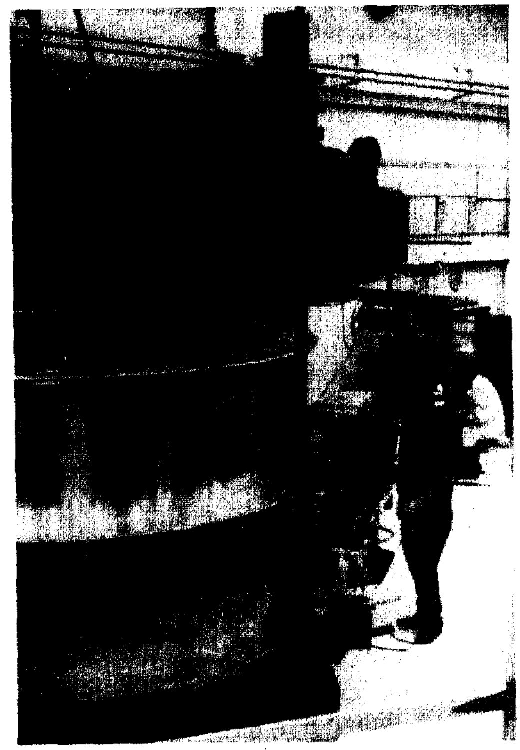

FIG. 11. The coil winding line for the K800 superconducting coil is depicted. The wire is pretensioned, cleaned, tested for voids, insulated, and checked for dimensions. A splicing station is located near the wire spool mount.

FIG. 12. The liquid helium refrigerator for the K800 magnet is shown. The refrigerator has been operated since July 1982 and has achieved 80% of expected capacity.

References

1. H. Blosser and F. Resmini, "Progress Report on the 500 MeV Superconducting Cyclotron", IEEE Trans. Nucl. Sci. NS-26, No. 3, (June 1979) 3653.
2. Peter S. Miller, "Status Report on the 500 MeV Cyclotron", Ninth International Conference on Cyclotrons and their Applications, les editions de Physique, (Sept. 1981) 191.
3. M.M. Gordon, "Perturbation of Radical Oscillation in a Superconducting Cyclotrons due to Assymetry in Dee Voltage or Phase", Session Q of this Conference.
4. T. Antaya, "Operating Experience with an Ion Source in a Superconducting Cyclotron", Session W of this Conference.
5. J. Riedel, "Three Phase R.F. Systems for Superconducting Cyclotrons", Session E of this Conference.
6. P. Miller and E. Kashy, "Absolute Calibration of Dee Voltage by x-ray Endpoint", Seventh International Conference on Cyclotrons and their Applications, Birkhauser (Aug. 1975) 171.
7. M.L. Mallory and H.W. Laumer, "Leak Detection with Liquid Helium", Nucl. Instr. and Meth. 177 (1980) 481.
8. M.L. Mallory and H.G. Blosser, "A Method for Localizing Small Helium Leaks in Large Cryogenic Vessels", Nucl. Instr. and Meth. 155 (1978) 573.

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