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PROGRESS REPORT ON THE 500 MEV SUPERCONDUCTING CYCLOTRON*

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Summary

The 500 MeV first stage of an eventual two stage superconducting cyclotron system is in the final year of its construction phase. Major design features of the overall coupled system and construction status of the 500 MeV first stage cyclotron are reviewed.

Text

The MSU Cyclotron Laboratory is in the process of designing and constructing a large double cyclotron system[1] for the purpose of providing high quality beams of heavy ions with energies up to 200 MeV per nucleon for lighter heavy ions such as calcium and up to 20 MeV per nucleon for the heaviest particles such as uranium. Fig. 1 graphically depicts the goals of the project in terms of intensity contours vs. energy per nucleon and mass number. The operating range reaches well above the Coulomb barrier which is indicated by the lower solid lines in the figure for the two cases of identical projectile and target (A→A) and for a projectile of mass number A bombarding uranium (A→U). The operating range for essentially all projectiles also reaches above the expected onset of "sonic" or compressional wave phenomena in nuclei expected at around 20 MeV per nucleon and reaches into the region of coherent meson production and doubling of the nuclear density for a substantial number of lighter projectiles.

Fig. 2 is a schematic drawing showing major functional features of the coupled cyclotron system. Ions from a conventional cold cathode ion source are accelerated through approximately 100 turns in a first-stage superconducting cyclotron and are then extracted. These ions, with energy $E_1 = K_1 Q_1^2/A$, where K_1 is the energy parameter of the cyclotron (500 MeV at full field), Q_1 is the charge of the ion in units of the electron charge, and A is the mass of the ion in atomic mass units, are then transported in an isochronous transfer line and directed into the center of a second larger cyclotron with a nominal 800 MeV energy parameter. The beam direction is adjusted such that, taking account of the curvature of the ion as it passes into the field of the cyclotron, the orbit will finally arrive at a point where it is just tangent to a centered equilibrium orbit with length 1/3, 1/4, 1/5... of the length of the final extraction orbit in the previous cyclotron. A stripping foil placed at this point of tangency between the injection orbit and the innermost equilibrium orbit of the second cyclotron gives a charge change from a typical value of ≃ 8 to a typical value of ≃ 25. The magnetic field of the second cyclotron is set so that the rigidity of the after-stripping charge state matches the design rigidity of the injection orbit; the ion is therefore captured on this orbit and thereafter accelerated. Finally the beam is extracted from the second cyclotron and directed into a transport system which feeds to an array of experimental devices.

Fig. 3 gives a vertical section view of the first stage 500 MeV cyclotron and shows the general arrangement of major components. The superconducting element of the cyclotron is the main coil, a large solenoid-like coil of average diameter 65.5" and overall height approximately 40". The active winding of the coil divides into symmetric halves relative to a 3" median plane gap at the mid-height point. The winding on each side of median plane is further subdivided into a "small coil" close to the median plane and a "large coil" further away from the median plane with the mirror sections on each side of the median plane wired in series to preserve symmetry. The small coil and large coil sections are, however, independently powered and the different radial form factors of these coils (the small coil field rises with radius by approximately 15% relative to the central value, whereas the large coil field is practically flat) are used as the primary field shaping element to accomplish the isochronous matching required for ions of differing mass and energy.

Cooling for the main coil is provided by a conventional helium bath immersion system. The coil is housed in an annular cryostat with a 52" diameter warm bore and conventional room temperature components of the cyclotron are inserted from top and bottom in this warm bore. Where necessary, room temperature penetrations pass through the median plane slab of the coil for items such as beam extraction, electrostatic deflector power leads and supports, probes, etc. (Reentrant vacuum liners are provided for all of the median plane penetrations so that the insulating vacuum of the coil is entirely independent of both cyclotron and beam line vacuums and therefore safe from disruption by possible vacuum accidents in either of these systems.)

The radio frequency system[2] for the cyclotron is a "dee-in-valley" design with a dee in each of three valleys, each dee being electrically designed as a half wave resonator, i.e. with a quarter wave coaxial line tuning stub on both top and bottom. The broad range of charge to mass ratios involved in the design operating range (from 1/2 for the lightest ions to 1/40 for the heaviest ions) translates into a desire for a broad tuning range in the radio frequency system, namely from 9 MHz to 32.4 MHz (a smaller range could be used but would require greater use of harmonic acceleration with considerable degradation of beam quality). Each of the three dees is driven from an independent power amplifier with phasing circuits allowing relative phasing of the dees to be set at 0^o, 120^o, and 240^o. With such a "three-phase" system, acceleration on all harmonics (where the "harmonic" number is the ratio of the rf frequency to the orbital frequency) is in principle possible and use of harmonic numbers 1, 2, 3, 4, 5, and 7 is contemplated in covering the design operating range.

The three rf power amplifiers which drive the dees are located approximately 10' from the cyclotron in corner positions in the shield enclosure. Fig. 4 is a schematic drawing of the arrangement. The transmitter includes an impedance matching system consisting of an inductive coupling loop and a quarter wave resonant line constructed in a fashion similar to the dee stem. The main amplifier tube is a 4CW100,000 tetrode. Fig. 5 is an electrical circuit diagram for the rf system showing various tuning circuits and the single-side-band heterodyne tuning logic.

Beam extraction[3] is accomplished by two electrostatic deflectors of conventional design coupled with a series of inert magnetic elements called "focusing bars". These latter consist of sets of three iron bars arranged in a manner suggested by Hoffmann[4] which gives a combined dipole and quadrupole field component of good strength. Optical characteristics of the extraction system have been numerically studied over the full operating range of the machine; results show excellent beam characteristics. In particular, the

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size of the beam as it leaves the cyclotron is expected to be ≈ 1/2 the size of the beam at the corresponding point of the present MSU 50 MeV cyclotron which is in turn generally regarded as the beam quality landmark for cyclotrons.

The 500 MeV cyclotron utilizes a dual ion source system, one source coming from the top and one source from the bottom inserted in 2" diameter iron-free holes. This double source system is designed to allow quick changing of sources when cathodes fail (≈ 1 minute) and in most conditions maintenance operations on the source which is out of use can proceed while the cyclotron continues to run.

Primary vacuum pumping for the cyclotron will come from a system of three cryopanels located in the lower half of each of the three dees. These panels will feed from the main helium-liquifier system and are expected to give an operating vacuum of $\approx 1 \times 10^{-7}$ Torr. A small backup diffusion pump will also be provided for use when the system is operating with helium beams.

Fig. 6 is a photograph of the K500 construction site on March 1, 1979. At this point in the project a period of 8 months of ion source testing had just been completed[5] and the magnet top is raised and a worker on top of the magnet at the upper right in the photo is disconnecting parts of the source testing vacuum system. At the front center, three people are involved in discussion in front of the CTI Model 1400 helium liquifier and to their left is a 500 liter helium storage dewar. In front of the dewar is a small test vacuum chamber built for evaluation of various types of metal seals and cryopumping heads. The tall structure centered in the scaffolding behind the dewar and liquifier is one of the quarter wave tuning stems for the dee. This stem is about to be mounted on a test dee and test vacuum chamber in preparation for full power tests of the amplifier and resonator structure. The first of the three amplifiers is barely discernible in the picture and appears as a smaller cube stacked on top of a larger cube just below the person squatting at the right of the picture. (The small cube on top of the large cube to the left of the person squatting is not the amplifier). Tests of the amplifier into a resistive load gave excellent performance over the full frequency range (after correction of several small design errors). Based on these tests, amplifiers 2 and 3 are under construction.

Fig. 7 is a vertical section view of the K800 cyclotron. The general similarity of design is immediately clear, the major difference being a generally larger size (174" outer magnet diameter vs. 120" for the K500). A larger magnet center hole is also used to allow for installation of the stripping foil magazine and stripping foil positioner. Dee stem insulators have also been omitted, reacting to the questionable viability of such insulators at the higher field levels desired in the K800 (200 kV dee to ground) and also in view of the fact that dee positioning requirements are much less severe in the K800 due to the absence of a central region and this latter requirement was the main positive reason for introducing insulators in the K500.

Fig. 8 is a plan view of the K800 cyclotron showing the relative position of injection and extraction beam paths and also showing an unusual reverse spiral which is introduced in the hill structure near the center in order to optimize injection orbits. Fig. 9 shows a detailed plan view of some typical injection orbits and illustrates part of the broad computational survey of such orbits which has been carried out. The results of this survey establish that injection trajectories for all parts of the operating range can originate from a single steering magnet located approximately 7' from the outer diameter of the cyclotron. The inverted spiral hill design has a further desirable property, namely all injection trajectories reach the point of equilibrium orbit tangency in a hill region of the magnet so that the stripping foil mechanism can be inserted at ground potential rather than through the dee. Fig. 10 is a phase space diagram showing typical results of calculations of focusing characteristics of injection orbits. These calculations exhibit good linearity for beams of realistic size and establish phase space matching conditions which can easily be accommodated in the transfer line from cyclotron to cyclotron.

Fig. 11 is a composite coupling diagram showing the operating range covered by the several coupling modes. The 9 MHz lower frequency of the rf system immediately sets one major boundary; this is marked by the horizontal line at approximately 18 MeV per nucleon. Below this line particles in the second stage cyclotron must run in the second harmonic mode; above the line first harmonic is used. The dashed line labeled 3:1 is the lower limit of the operating range in the so-called 3:1 mode, i.e., with the first stage cyclotron running on harmonic 3, and the second stage on harmonic 1; the dashed curve labeled 4:1 is similarly the lower limit in the 4:1 mode, etc. In the region above each dashed curve the solid curves with numerical labels 2, 4, etc. indicate the upper energy limit which can be achieved for ions leaving the ion source in the first cyclotron in the charge state corresponding to the labeled value on the curve. Thus, if the ion source is able to produce charge 14 uranium ions, these would run in the 3:1 coupling mode and energies up to 38 MeV per nucleon could be obtained. Finally, the figure assumes that when low energy lighter ions are needed (the region at the left of the figure) these will be provided by the injector cyclotron operating in the stand-alone mode.

Fig. 12 is a floor plan of the experimental hall for the overall system. Major experimental devices are noted on the drawing. In the 1980-1983 period, the K500 cyclotron will be used on its own in support of the experimental heavy ion program. The arrangement of the experimental floor during these years will be as shown in Fig. 13. The extraction point for the K500 cyclotron is shifted by 120° in the stand-alone configuration vs. the injector configuration, which is a relatively easy operation in view of the fact that all magnet holes are reproduced with three sector symmetry in constructing the magnet. The stand-alone beam transport system uses existing room temperature dipole magnets for beam steering, whereas the beam transport system for the coupled system will be fully superconducting.

References

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1. Conceptual Design Report for Phase II of a National Superconducting Cyclotron Laboratory for Research with Heavy Ions, Michigan State University Cyclotron Laboratory Report 282, December 1978.

2. J. Riedel, Proceedings of the 8th International Conference of Isochronous Cyclotrons, IEEE Transactions of Nuclear Science, to be published.

3. M.M. Gordon and E.M. Fabrici, Ibid.

4. C. Hoffman (private communication).

5. M. Mallory, paper presented at this conference.

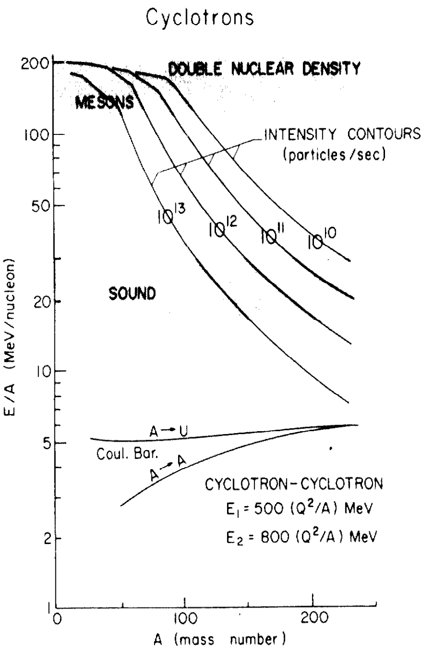


Figure 1. The intensity goals of the coupled superconducting cyclotron project as a function of maximum energy per nucleon and projectile mass. Also shown are the nuclear Coulomb Barrier, the region of expected sonic phenomena, the region of coherent meson production, and the region of double nuclear density.

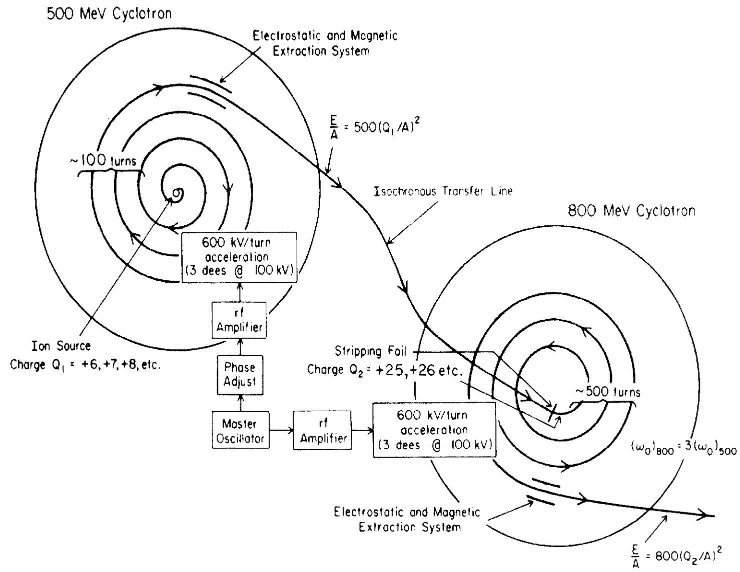


Figure 2. Schematic diagram of the coupled cyclotron system showing major functional elements.

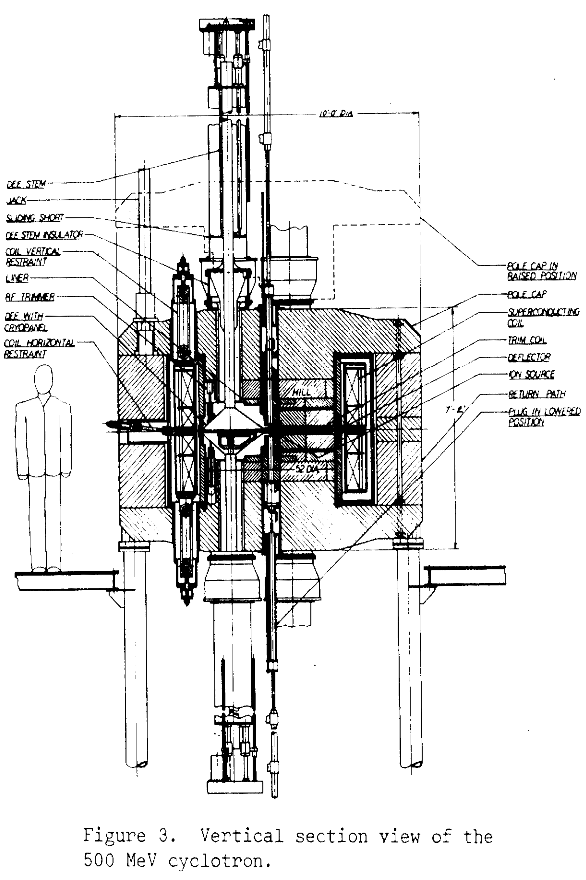


Figure 3. Vertical section view of the 500 MeV cyclotron.

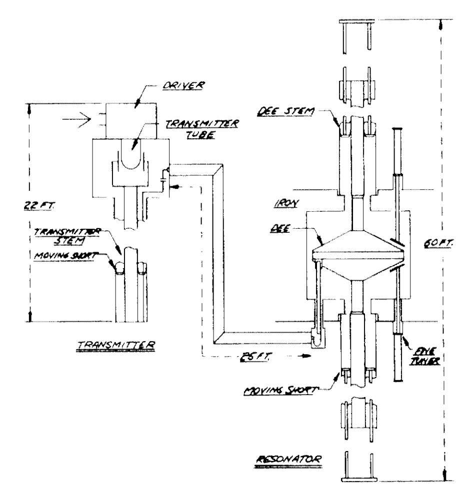


Figure 4. Schematic diagram showing major elements of one of the three radio frequency transmitters and radio frequency resonator structures.

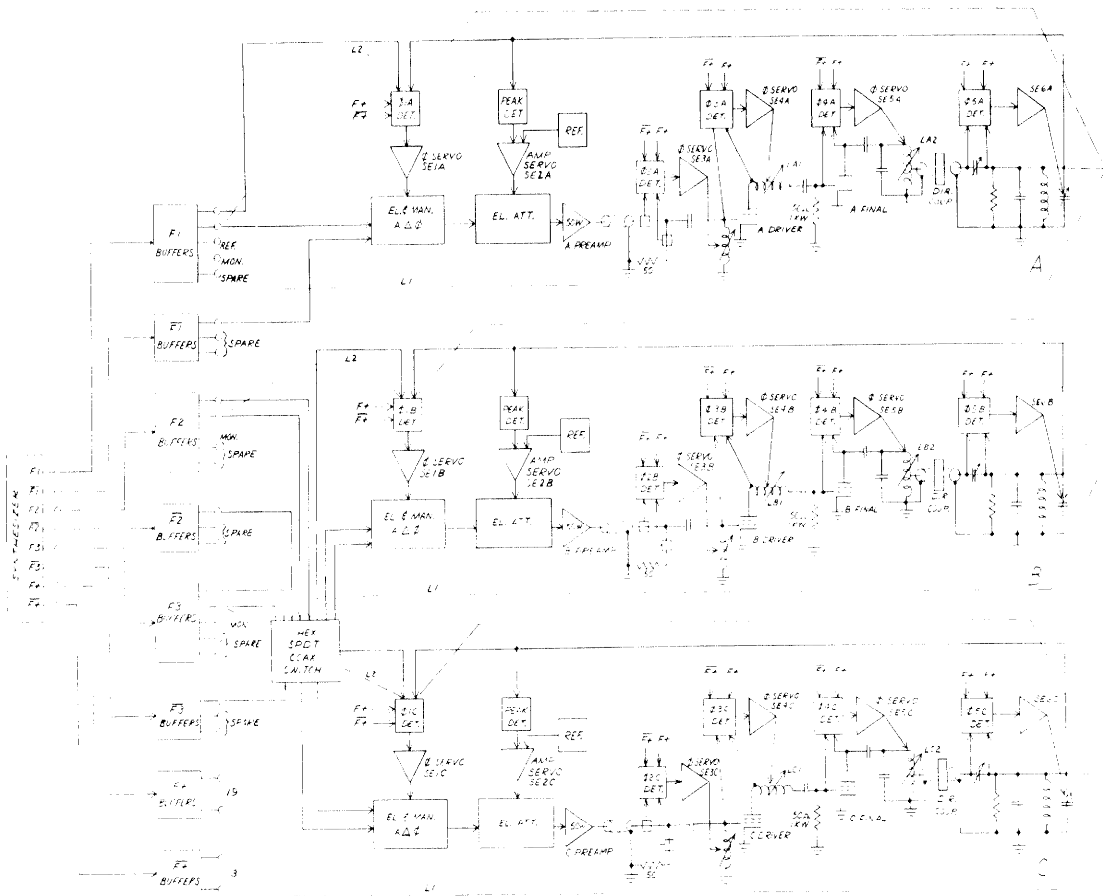


Figure 5. Circuit diagram of the rf system. The three resonators are represented by lumped resistances, capacitors, and inductors at the right above the letters A, B, and C. The special synthesizer at the left furnishes basic frequencies F_1, F_2, and F_3, phased shifted by 120°, frequencies $\bar{F}_1$, $\bar{F}_2$, and $\bar{F}_3$ phase shifted by 90° from F_1 etc. and frequencies F+, and $\bar{F}$+, are 2 Mhz sidebands.

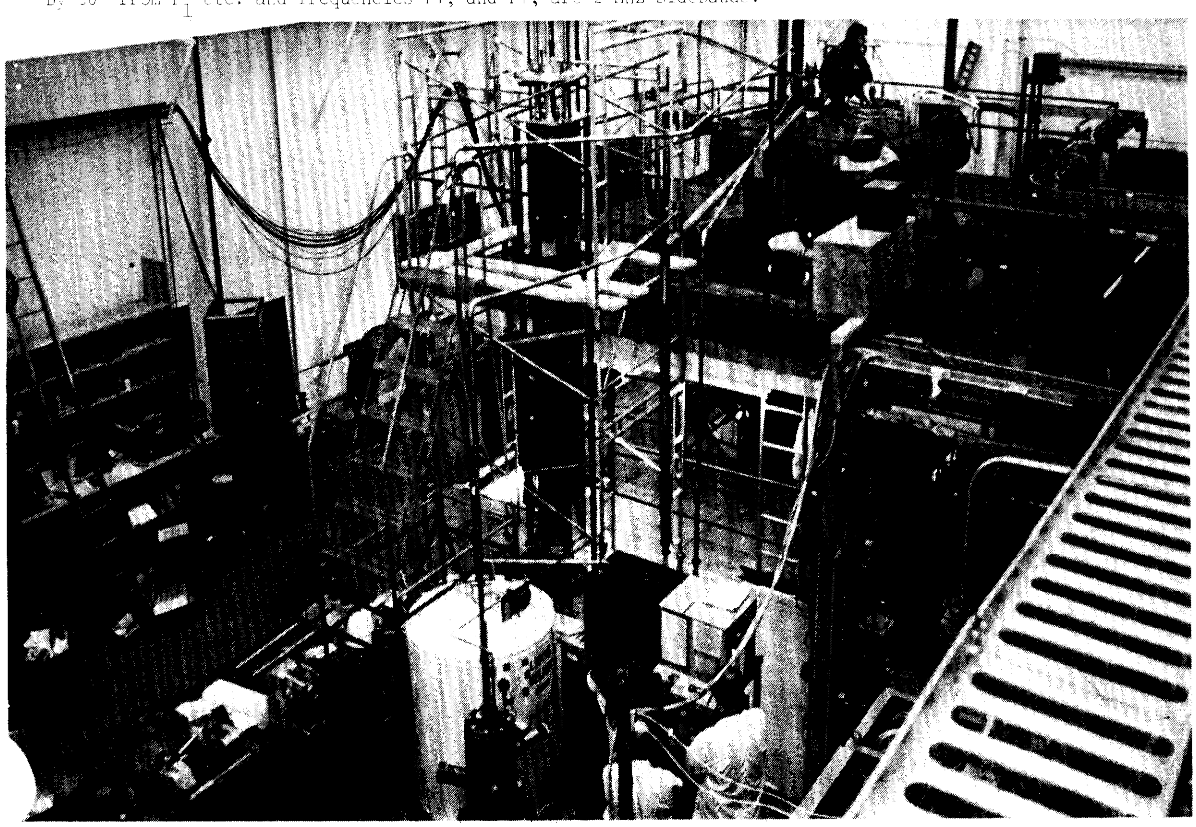


Figure 6. View of the 500 MeV cyclotron construction site on March 1, 1979. (See text for details.)

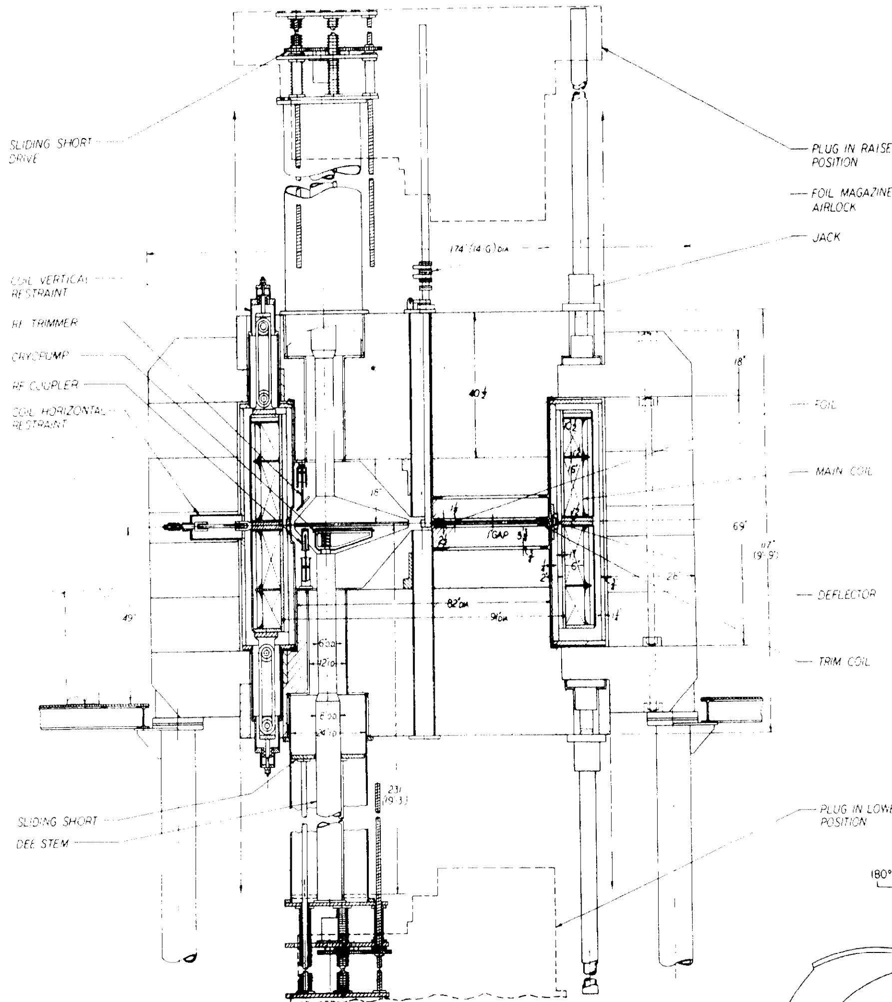
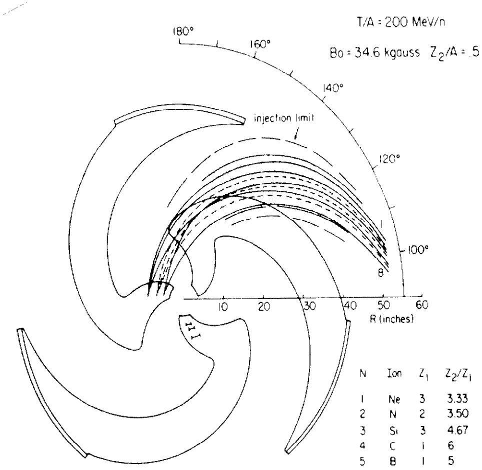


Figure 7. Vertical section view of the 800 MeV cyclotron.



N	Ion	Z_1	Z_2/Z_1	h_1
1	Ne	3	3.33	3
2	N	2	3.50	3
3	Si	3	4.67	4
4	C	1	6	5
5	B	1	5	4
6	O	2	4	3
7	S	3	5.33	4
8	N	1	7	5

Figure 9. Computed injection trajectories in the 800 MeV cyclotron for a variety of ions (200 MeV per nucleon magnetic field).

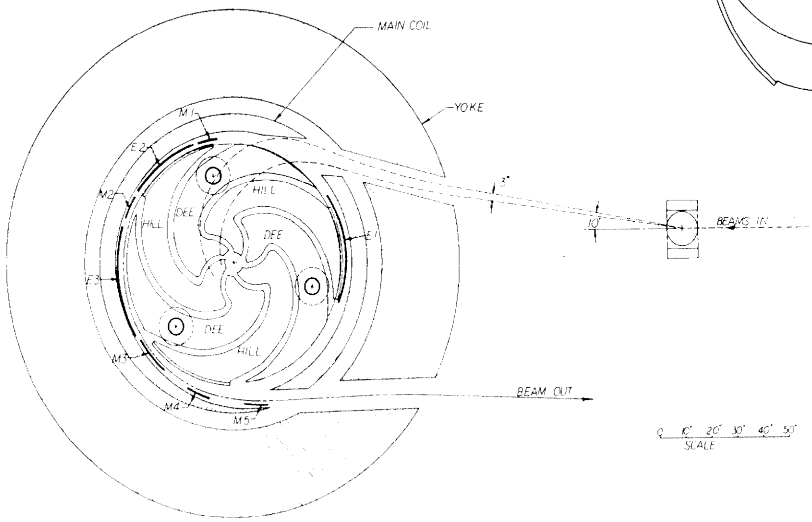


Figure 8. Plan view of the 800 MeV cyclotron, showing relationship of injection and extraction orbits.

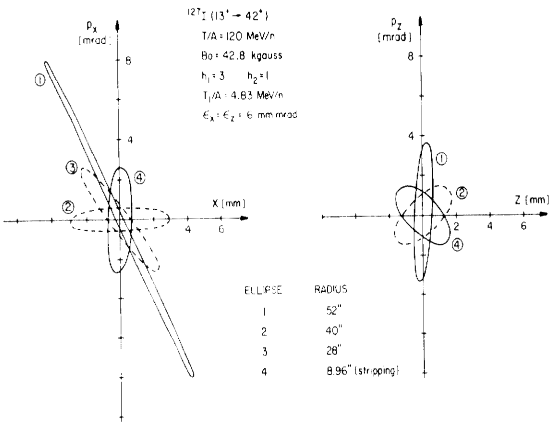


Figure 10. Radial and axial phase space distribution at various points along a typical injection orbit.

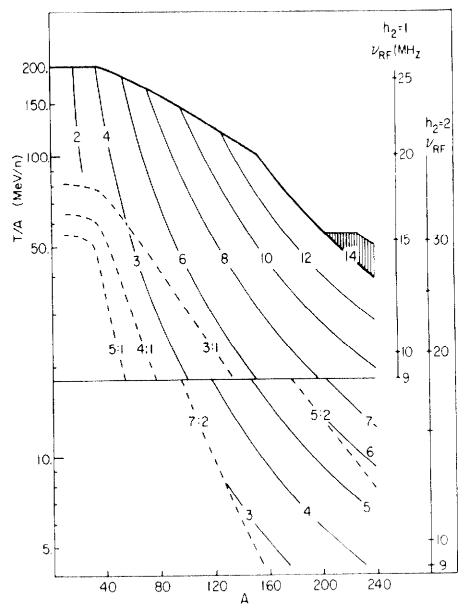


Figure 11. Overall coupling diagram for the double cyclotron system. (See text for details.)

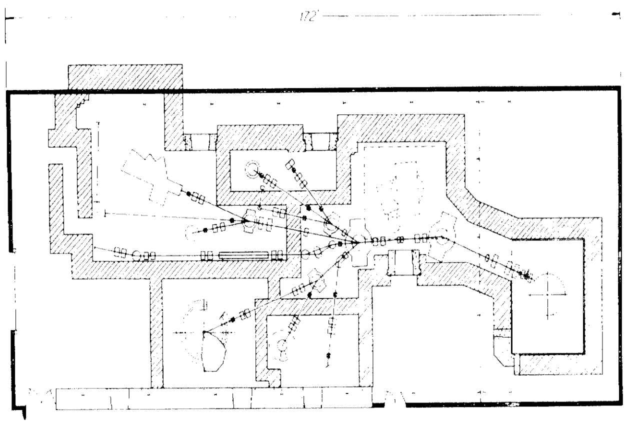


Figure 13. Plan view of the experimental hall as it will be set up in the years 1980 to 1983, while the 500 MeV cyclotron is in use as a stand alone accelerator. The location of the present 50 MeV cyclotron is shown in dashed outline at right center.

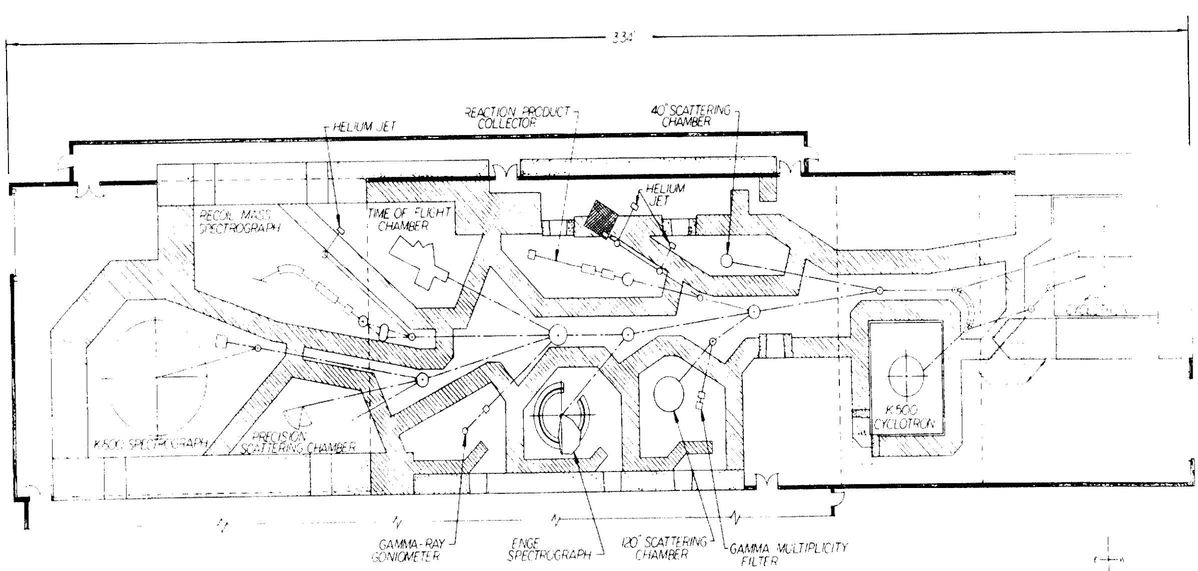


Figure 12. Floor plan of the extended high bay which will house accelerators and experimental halls. Vertical dashed lines show the boundaries of the original building and of the 500 MeV cyclotron extension.