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CYCLOTRONS FOR THE PRODUCTION OF RADIOACTIVE BEAMS*

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ABSTRACT

This paper describes the characteristics and design choices for modern cyclotrons. Cyclotrons can be used in 3 areas in the radioactive beam field: the production of high energy heavy ion beams for use in fragmentation, the spallation of targets with high energy protons, and the acceleration of radioactive beams from low energy to the MeV/u range.

CYCLOTRON CHARACTERISTICS

Three Generations of Cyclotrons

Cyclotrons are accelerators which have magnetic fields that are constant in time, and whose beams spiral outward from the center to the edge of the field. The first generation is the classical Lawrence cyclotron of the 1930's with flat poles and a fixed radiofrequency (rf). The particle angular frequency is

$$\omega = h\,BQ/M \qquad (1)$$

where B is cyclotron magnetic field, Q and M are particle charge and mass, and h is the harmonic number (ratio of rf to particle frequency). Axial focusing is provided by having the magnetic field decrease slightly with radius. As the beam accelerates its mass increases and its phase slips later relative to the rf, resulting in an upper limit to the energy. The maximum energies for cyclotrons of this type were 20 MeV for protons (Oak Ridge 86-inch) and 7 MeV/nucleon for light heavy ions (Dubna U-300), obtained by using very high dee voltages of 150-200 kV.

The second cyclotron generation is the frequency-modulated (FM) or synchro-

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cyclotron. These were built starting in the 1940's. In this design the relativistic mass increase is tracked by a decreasing radio-frequency, keeping the particles in phase with the accelerating voltage. In this way the upper proton energy was limited not by relativity but by economics, and reached 1000 MeV (Leningrad). The disadvantage of the FM cyclotron is that beam could be accepted from the ion source only a few per cent of the time, resulting in a pulsed beam with an intensity only a few per cent of that of the classical cyclotron. There is always an additional time microstructure in the beam due to the rf.

The third generation of cyclotrons has a magnetic field which increases with radius (and mass) and uses the sector focusing principle to provide enough axial focusing to overcome the defocusing of the average field. The radio-frequency can now be constant, like that of the classical cyclotron, giving 100% acceptance time from the ion source and high beam currents. The upper energy is limited by economics, as in the synchrocyclotron, resulting in proton energies as high as 590 MeV at PSI, Zurich. Designs for booster cyclotrons of up to 1.3 and 2 GeV protons have been done at PSI, Zurich1), and up to 8 GeV protons at TRIUMF2). Many cyclotrons of this third generation were built in the 1950's and 1960's, while many classical and FM cyclotrons were shut down. About 100 sector cyclotrons have been built, ranging in size from the compact machines for isotope production at 10-20 MeV protons to the large meson factories and multi-particle cyclotrons for nuclear research at hundreds of MeV. Another development which came along about the same time as the third generation was the wide range of energy variation made possible by rf systems tunable over a 2/1 or 3/1 range, which gave energy ranges up to 100 to 1, by changing harmonic number, h (Eq. 1). Trimming coils were used to shape the magnetic field for each energy. This also makes a wide range of particles available.

The size of a cyclotron is described by the energy constant K, defined by the equation:

$$E = K\,Q^2/A \qquad (2)$$

where E is the energy in MeV at maximum magnetic field, K is in MeV, Q is ion charge in electron charge units and A is mass in AMU. At low energies K is proportional to the $(B\rho)^2$ of the cyclotron magnet at full field, where ρ is the extraction radius.

Design Choices

There are several major design choices to be made when building a cyclotron. Four cyclotron designs are illustrated in Fig. 1 to show the difference in scale for the same K value3). They are shown with four sectors and four return yokes for easy comparison. In practice the traditional design, Case 2, has two return yokes (H magnet) and the superconducting single pole design, Case 4, has a single circular return yoke.

One choice is between a magnet which has one main coil around the pole (Cases 2 and 4), and a magnet which has separate coils around each pole or "separated sectors"

(Cases 1 and 3). The single coil design has the advantage of compactness, giving low complexity and cost. It uses a simple ion source in the cyclotron center, or a larger external source injecting beam along the magnet axis into the center region. The separate sector design eliminates the central region and therefore requires an injector accelerator to inject beam radially through an empty valley. Space in the valleys can be used for high voltage accelerating cavities.

A second design choice is between the usual normal conducting coils providing average fields up to about 17 kG, and superconducting coils giving 50 kG. All the components of the superconducting designs are smaller in linear size by the ratio of the magnetic fields, about a factor of 3, for the same energy. In addition, the magnetic flux is lower by the same factor, so the return yoke can be smaller. The smaller size results in a cost advantage, especially for high energy cyclotrons. So superconducting cyclotrons of conventional size have been designed for much higher energies than were available previously. Their disadvantage is that components must be fitted into a smaller space and it is more difficult to hold dee voltage and to extract the beam at the highest energies.

The first cyclotrons were built with one main coil as in Fig.1, Case 2. An early example is the LBL 88-Inch Cyclotron, Fig. 2, a multi-particle, variable energy 3-sector cyclotron for light and heavy ions. The 3 to 1 frequency range gives an energy range of 9 to 1. Use of harmonic 3 in addition to harmonic 1 (Eq. 1) increases the particle frequency range downward by a factor of 3 and the energy range downward by a factor of 9.

Later some machines were built with separated sector magnets, as in Fig. 1, Case 1. An example is shown in Fig. 3 for the Osaka heavy ion booster design4). We can see the electrostatic septums and magnetic channels used for both injection and extraction of the beam. The 590 MeV proton meson factory at PSI, Zurich was the first of the separated sector cyclotrons5). It is injected with a high intensity proton beam from a smaller separated sector cyclotron. This cyclotron has 4 high voltage cavities which give separate turns at extraction. It has over 99% extraction efficiency of a 200 μA beam, keeping the beam loss and residual activity at a low level.

One advantage for heavy ions of having two stages of acceleration is that the beam can be stripped to a higher charge state between stages, considerably reducing the size of the second stage for a given energy, as shown in equation (2) above. This is done at the GANIL cyclotron in France6), Fig. 4. Two identical K=400 separate sector cyclotrons are coupled, with stripping of the heavy ion beam in between. A small injector cyclotron supplies beam for this system.

The beam is usually extracted from a cyclotron with an electrostatic channel having a thin septum to separate the internal and external beams, followed by a magnetic channel. At high beam power the septum is vulnerable to damage by the beam. Another solution for proton beam extraction is the use of negative hydrogen ions, H^-. Here a thin stripping foil at extraction radius is used to strip off the two electrons from H^-, giving a proton, which reverses curvature and rapidly leaves the magnetic field, as shown in Fig. 5 for the 500 MeV, 100 μA meson factory at TRIUMF, Canada7). This simple method of extraction gives an efficiency of nearly 100%. This technique of stripping extraction has been used on some smaller isotope production cyclotrons, such as the 30 MeV, 500 μA cyclotron built by IBA in Belgium[8)].

An important technical development, pioneered at Chalk River and Michigan State University, is the use of superconducting main coils to reduce the size and cost of cyclotrons[9)]. Thus far these cyclotrons have been of the single pole type, Fig. 1, Case 4, although one design for a separate sector machine, Fig. 1, Case 3, was studied at Munich[10)]. The Michigan State K-500 cyclotron[11)] is shown in Fig. 6.

CYCLOTRONS VS. OTHER ACCELERATORS

The choice of accelerator type is based on a combination of performance and cost. The performance includes the particle types available, the energy range, the beam intensity, and the beam emittance and time structure. A summary of accelerator types is given in Table 1:

Table 1. Comparison of Accelerator Types

Accelerator	Advantages	Disadvantages
Cyclotron	High Intensity: 500 μA p Medium energy: 1 GeV p	
DC Accel.	Easy E Variation	Lim. E: 50 MeV p Lim. intensity at high E
Linac	High intensity: 1 mA p High energy: GeV range	High cost at high energy <100% DF for norm cond
Synchrotron	High energy: TeV range	Lim. intensity: 100 μA <100% duty factor

In this table the intensities are average values. All the accelerators can be designed for multi-particle and variable energy energy operation by suitable selection of design parameters and ion sources. No disadvantages are shown for the cyclotron, perhaps because of the author's point of view.

The duty factor (DF) is 100% for DC accelerators, while the others have rf structure, but can be 100% on a macroscopic (millisecond) scale for cyclotrons and superconducting linacs. Normal conducting linacs may be developed for 100% macroscopic DF in the future. Synchrotrons can approach 100% DF by slow extraction or by the addition of a stretcher ring.

ACCELERATOR REQUIREMENTS FOR RADIOACTIVE BEAMS

Accelerators can be used for three functions in the production of radioactive beams:

1) Production of primary beams which fragment in a target into radioactive species traveling at beam velocity.

2) Cooling and deceleration of beams from item 1) above, to lower energies as required for experiments.

3) Production of primary beams to bombard a target, producing radioactive species by spallation at very low energy in the target.

4) Acceleration of the radioactive beams from item 3) above, up to energies required for experiments.

Requirements 1, 3 and 4 above can be met with cyclotrons and will be discussed in the following sections. Requirement 3 can be met by a storage ring such as the ESR ring at GSI.

CYCLOTRONS FOR RADIOACTIVE BEAMS

Fragmentation Production

A high energy ion beam is produced by the accelerator and fragmented in a production target. The radioactive species produced are travelling at beam velocity. They are separated in a spectrometer and sent to a detector system to measure their properties or to a secondary target to study nuclear reactions. An early experiment of this type was done at the LBL Bevatron with 200 MeV/u ^{48}Ca12). More recently the higher intensity of the GANIL cyclotrons13) were used to extend the range of radioactive species with a beam of 55 MeV/u of ^{48}Ca. Cyclotrons are good candidates for this application because of their high intensities and energies, and well developed capabilities for multi-particle, variable energy operation. To obtain high energy heavy ions one can use a two stage cyclotron system like that of GANIL, with stripping between cyclotrons, or a superconducting cyclotron like the Michigan State K-800 (1200). These are both fed with high charge state ECR sources.

Spallation Production

In this method a high intensity primary beam bombards a target and produces many radioactive species at very low energy by spallation of the target nuclei. This method has been developed extensively by the Isolde group at CERN14), which has used the beams of 600 MeV protons and 910 MeV alphas from the synchrocyclotron. Much development work has been done on optimizing the target and measuring the yields of many elements with a high resolution spectrometer. The CERN synchrocyclotron is a second generation cyclotron producing a few μA of protons.

To optimize the yield of radioactive species a third generation cyclotron such as the one at PSI could be used for beams of 590 MeV protons at 200 μA. This cyclotron is being upgraded to 1 mA current. Either a two stage cyclotron system like PSI, or a single stage cyclotron can be used here.

One important requirement is that the beam losses in the cyclotron must be kept very small to prevent damage to components and to limit high residual radiation, since the beam power of a 600 MeV beam at 200 μA is 120 kW. The turns of a proton beam must be well separated at extraction radius by having a low average field and high energy gain per turn, as is done at PSI. An alternative is accelerating H^- and using stripping extraction, as at TRIUMF. In this case separate turns are not necessary but the cyclotron is large because a low magnetic field must be used to prevent v x B stripping of the weakly bound H^- ion in the 100 MeV range.

There is a real cost advantage if the energy can be kept low. If an optimum target is chosen, an energy of 100-200 MeV at higher current may be competitive with 600 MeV where thicker targets can be used, since the width of the isotope distribution of a given element varies very slowly with bombarding energy[15)].

Acceleration of Radioactive Beams

The radioactive beams produced by spallation, described above, come out of the target by diffusion or recoil and then pass into an ion source. The beam can then be accelerated to low energies, such as 60 kV at Isolde, for analysis and counting in a magnetic spectrometer. It can also be accelerated to the MeV/u range for research in astrophysics or nuclear physics. The accelerators available for this application are those listed in Table 1. Single ended DC accelerators have the disadvantage of having the ion source in the terminal. Tandem DC accelerators have the disadvantage of having to use negative ions, which are not available in all species. Linacs can accelerate all species if designed appropriately. Superconducting linacs have the advantage of running at 100% duty factor, and so can accept beam continuously. Cyclotrons also have 100% duty factor and can easily cover the energy range up to 100 MeV/u of interest for nuclear physics research. Cyclotron options for accelerating beams to 1 MeV/u at TRIUMF have been reviewed by Mackenzie[16)].

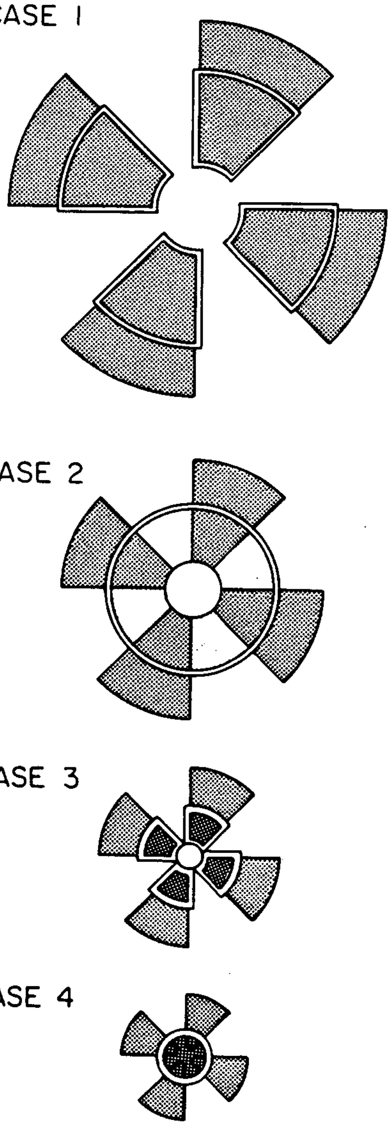
An important factor for all these accelerators is whether the ion source can produce multiply charged ions at high efficiency, as well as singly charged ions. If this is possible the cost of the accelerating system is greatly reduced for reaching the higher mass and energy ranges. The ECR source easily produces higher charge states, but thus far has given poor efficiency for charge states greater than 1. R&D is needed to optimize the higher charge state efficiency of ECR sources, and also to minimize the transit time in the source for short half-life beams. If the charge state is one, a multiple accelerator system with stripping between stages would be most economical.

REFERENCES

1. Joho, W., Proc. Tenth Int'l Conf. on Cyclotrons and their Applications, p. 611, IEEE, New Jersey (1984).
2. Craddock, M. K., Kost, C. J., Mackenzie, G. H. and Richardson, J. R., Proc.

Ninth Int'l Conf. on Cyclotrons and their Applications, p. 209, Les Editions de Physique (1981).

3. Burleigh, R. J., Clark, D. J. and Glasgow, L. R., Proc. Seventh Int'l Conf. on Cyclotrons and their Applications, p. 604, Birkhauser, Basel (1975).
4. Miura, I., et al., Proc. Eleventh Int'l Conf. on Cyclotrons and their Applications, p. 207, Ionics Publ. Co., Tokyo (1986).
5. Joho, W., Proc. Eleventh Int'l Conf. on Cyclotrons and their Applications, p. 31, Ionics Publ. Co., Tokyo (1986).
6. Joubert, A., et al., Proc. Tenth Int'l Conf. on Cyclotrons and their Applications, p. 3, IEEE, New Jersey (1984).
7. TRIUMF Proposal and Cost Estimate, Ed. E. W. Vogt and J. J. Burgerjon, TRIUMF, Canada, p. 75 (1966).
8. Bol, J. L., et al., Nucl. Instr. Meth. B40/41, 874 (1989)
9. Blosser, H. G., Proc. Ninth Int'l Conf. on Cyclotrons and their Applications, p. 147, Les Editions de Physique (1981).
10. Trinks, U., Proc. Tenth Int'l Conf. on Cyclotrons and their Applications, p. 605, IEEE, New Jersey (1984).
11. Blosser, H. G., Proc. Eighth Int'l Conf. on Cyclotrons and their Applications, IEEE Trans. NS-26, 2040 (1979).
12. Westfall, G. D., et al., Phys. Rev. Lett. 43,1859 (1979).
13. Guillemaud-Mueller, D., et al., Z. Phys. A -Atomic Nuclei 333, 189 (1989)
14. Isolde Users' Guide, CERN 86-05, Ed. H.-J. Kluge, CERN (1986).
15. Silberberg, R. and Tsao, Ap. J. Suppl. 25, 315 (1973).
16. Mackenzie, G. H., TRI-85-1, TRIUMF, Vancouver, p.210 (1985).

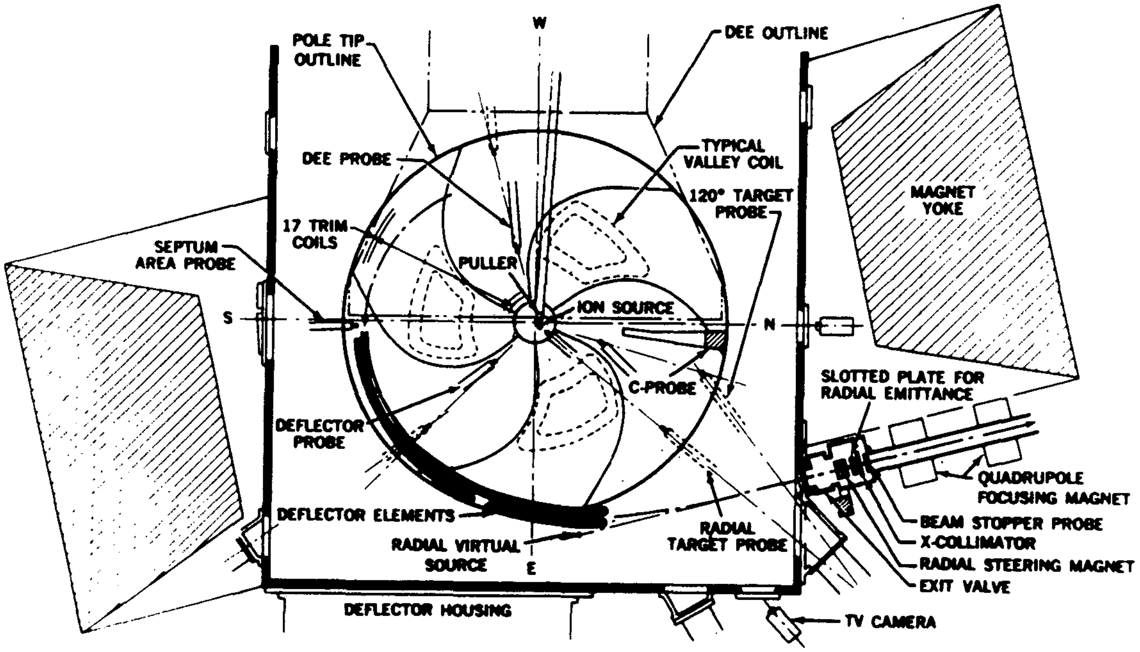


	Poles	Coil conductance	$B_{AVG.}$ (kG)	Pole radius	Magnetic flux
CASE 1	4	Normal	8.5	6	6
CASE 2	1	Normal	14	3.6	3.6
CASE 3	4	Super	25	2	2
CASE 4	1	Super	50	1	1

4 CYCLOTRON STRUCTURES WITH SAME K

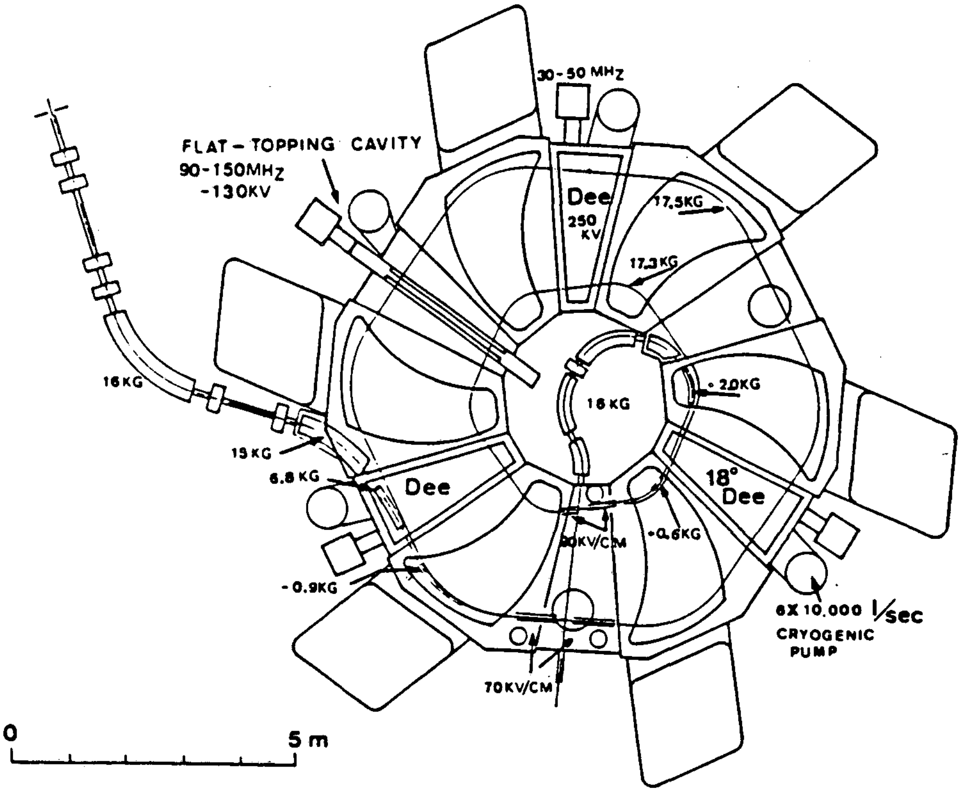
XBL 757-3586

Fig. 1. Four cyclotron designs, showing relative scale. Single pole vs. separate sector and normal vs. superconducting.



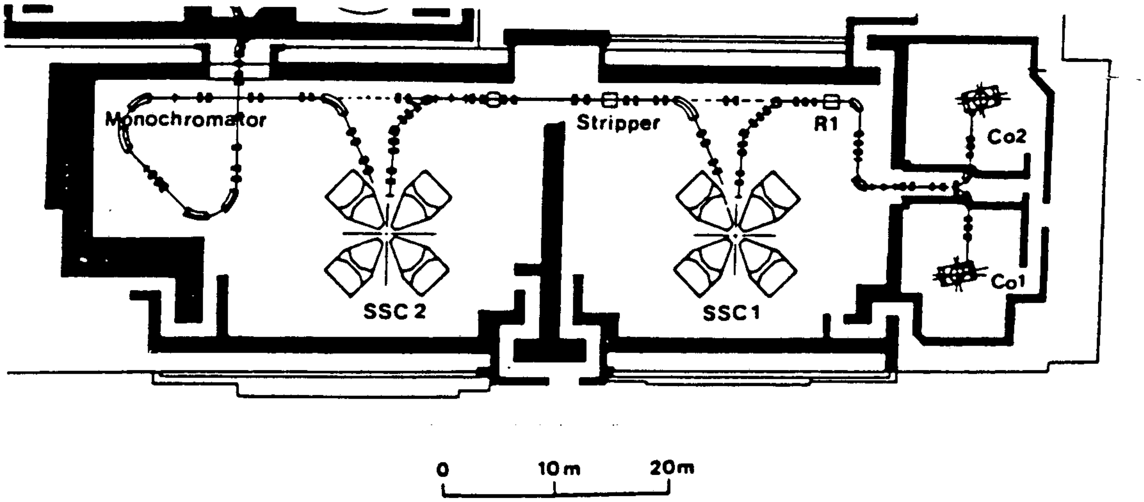
XBL 678-4699

Fig. 2. LBL 88-Inch Cyclotron, a typical multiparticle, variable energy cyclotron with heavy ion beams up to 32 MeV/u. A Case 2 example.



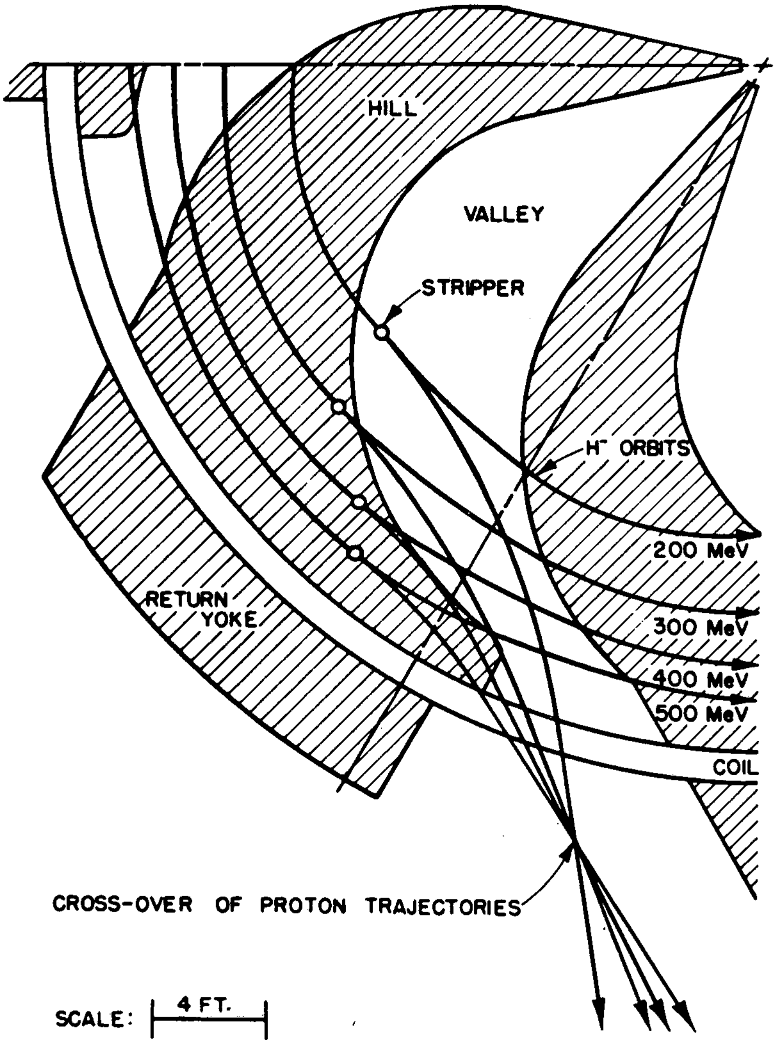
XBL 8910-3721

Fig. 3. The Osaka separate sector cyclotron, showing 6 magnet sectors, 3 dees and injection and extraction channels. A Case 1 example.



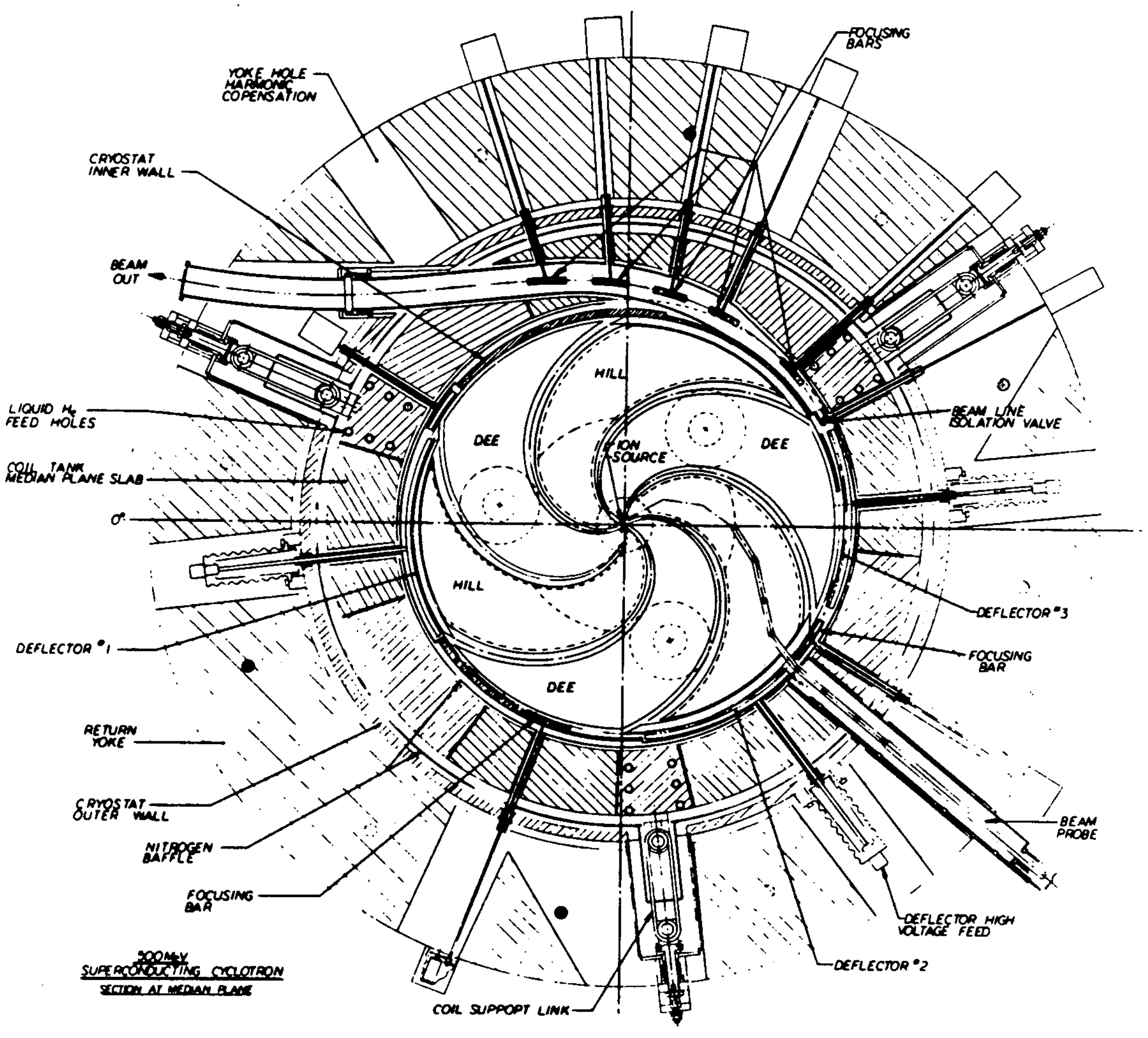
XBL 8910-3724

Fig. 4. The GANIL coupled separate sector cyclotrons. Stripping is done between cyclotrons to increase the energy of the second stage.



XBL 8910-3722

Fig. 5. The stripping used by TRIUMF for high efficiency extraction with H^- beams, giving high currents of 200 μA.



XBL 8910-3725

Fig. 6. Michigan State University K-500 superconducting cyclotron, Case 4. This is the most compact design, and lowest cost for high energies.

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