REVIEW OF SUPERCONDUCTING CYCLOTRONS

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Abstract

Six cyclotrons using superconductivity are now producing beams. Three more are nearing completion and designs are progressing for yet newer machines. Most of these cyclotrons are dedicated to nuclear physics research, but two are used for neutron radiation therapy and isotope production respectively and have their small size as most significant feature.
The design and the limitations of existing superconducting cyclotrons, as well as possible future developments are discused. Cyclotrons with different design, currently in the stage of construction, design or conception are briefly reviewed.

Historic overview

Development of cyclotrons with superconducting coils started in the early 70's, more or less simultaneously at Michigan State University (USA) and at Chalk River (Canada). The MSU machine was completed in 1982 [1], the Chalk River machine, due to non-technical difficulties, in 1985 [2]. A team from the university of Texas A&M built an improved version of the MSU cyclotron, which was commissioned in 1987 [3]. Fig.1 shows the Chalk-River machine as a typical example of this first generation.

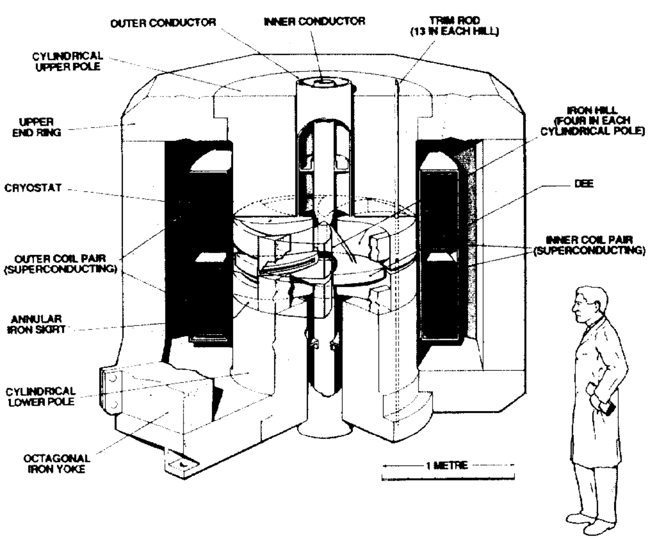

Fig. 1 The Chalk River superconducting cyclotron.

In the same period, a larger machine was designed and built at MSU, for which partial funding had already been obtained in 1975. This development was done with strong participation by the cyclotron group from Milano (Italy), who were working on a design proposal for a similar machine, to be used as a booster following a tandem accelerator. The MSU K-1200 became operational in 1988 [4], the Milano machine is now being moved to its final destination in Catania (Sicily) and is expected to produce beam by the end of 1991 [5].
In the early 80's design work was begun in Orsay on a machine capable of accelerating protons as well as heavy ions. This cyclotron, since named AGOR, is now being built in an international collaboration by the IPN, Orsay, France and the KVI, Groningen, Netherlands [6].

These machines, to be used for research in nuclear physics, are aimed at beam energies in the range 5-200 MeV/A, with an emphasis on heavy ions and relatively modest beam intensities. In contrast, the use of superconductivity has allowed the construction of low energy machines for medical applications that are close to tabletop size. A 50 MeV deuteron machine for neutron production, built at MSU and a 12 MeV proton machine for isotope production built by Oxford Instruments [7] fall into this category. The deuteron machine, shown in fig. 2, has been built into a gantry, allowing rotation around the patient during radiation therapy.

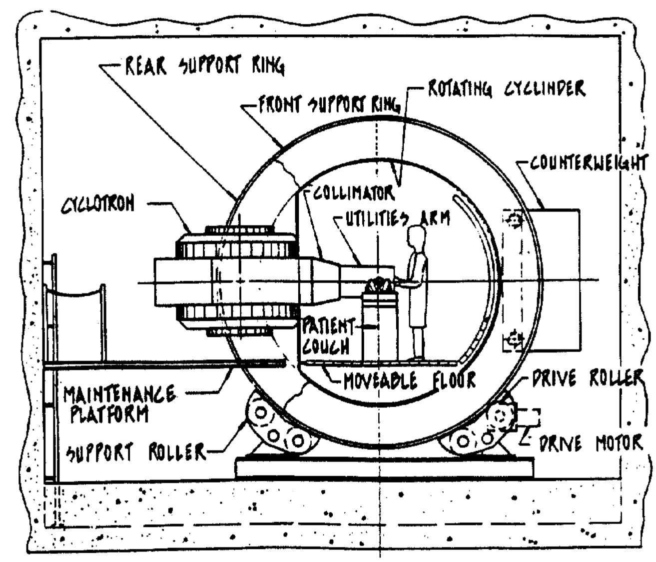

FIG. 2 -- Schematic view of the K100 neutron therapy cyclotron on a gantry to allow variations of the beam direction over a full 360°.

The 4-ton Oxford machine, shown in fig.3 requires a room size of only 8.5*7.3 m^2, including shielding and an automated radiochemistry set-up. Its first external beam was obtained in March 1990.

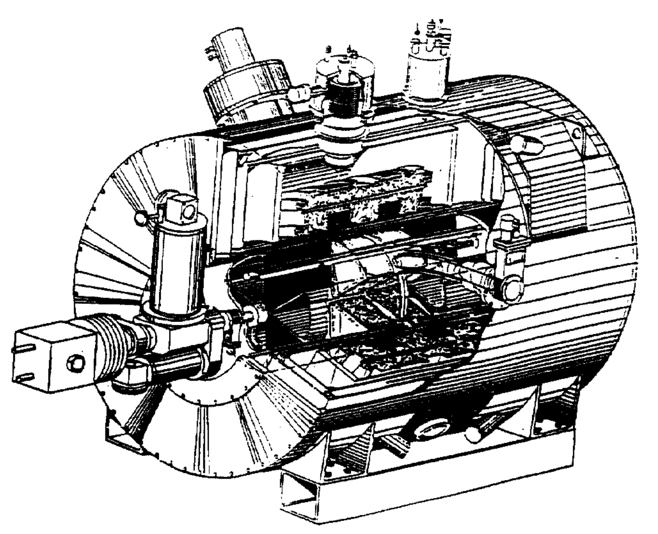

Fig. 3 OSCAR, a miniature 12 MeV proton machine made by Oxford Instruments.

The TRITRON, a booster for an MP tandem, is in construction in Munich (Germany) and will be discussed in a later section.

Compact superconducting cyclotrons

All compact superconducting cyclotrons use solenoidal main coils for producing high magnetic fields.
The azimuthal field modulation is produced by thick, spiralled pole sectors presenting narrow pole gaps. In order to reduce the stray magnetic field the magnetic circuit is completed by a yoke that entirely surrounds the coils. In the Oxford design additional coils are used instead of an iron yoke to reduce the stray field. All valley sectors are occupied by RF resonators, allowing a high energy gain per turn. Because of the small pole gap and the desire for low stray fields, the inductive parts of the resonators extend vertically, in most cases through the bottoms of the valleys.

Physical limitations

The most fundamental high energy limit in any cyclotron for the most relativistic ions (i.e.protons) is fixed by the stopband resonance at nur=N/2, in which N equals the number of magnet sectors. In a 3-sector machine the highest energy is thus limited to approximately 250 MeV/A.

For heavier ions a basic limitation on the maximum energy is given by the 'bending limit' as determined by the pole radius and the maximum field and expressed as the machine bending constant Kb: E/A < (Q/A)*(Q/A)*Kb.

The strength of the vertical focussing produced by fully saturated pole tips is fixed and therefore limits the allowable field index and therefore the maximum beam energy. The focussing power of a given magnetic field is expressed as the focussing constant Kf. The corresponding maximum beam energy is then E/A < (Q/A)*Kf. The MSU K-1200 has the very high Kf = 400, which allows the energy for fully stripped ions to approach the stopband limit for a 3-sector machine. Surpassing this value would constitute a considerable design challenge, as discussed in a later section.

In addition to these upper bounds, the fixed flutter amplitude also leads to a low field limit, which is determined in a 3-sector machine by the resonance nur+2*nuz=3. This resonance is linked to the rise of nuz at the magnet edge. Low-energy beams which have a low field index and thus a high value of nuz are therefore pushed to this resonance. In most 3-sector machines this limit occurs at a field level of approximately 3 T. in the AGOR machine a spiral groove in the hills has lowered this limit to 1.8 T.

Orbit scaling is a desirable feature in a compact cyclotron, i.e. the orbits of all beams should be similar [8]. This feature is obtained when the strength of the electric fields scales with charge state and magnetic field as E = C * (Q/A) * B**2. It is to be noted that the required electric fields are proportional to Q/A. It is therefore desirable to tune the design in such a way that the electric field limit coincides with the focussing limit discussed before.

Typical RF voltages are 100 kV for machines with focussing constants of approximately 200 MeV and 200 kV for the MSU K-1200 (this value has not yet been achieved). The problem of voltage holding is most severe in the crowded central region: in the first turn the energy gain must be sufficient for clearing the inflector housing while the orbit radius and therefore the electrode gaps are are small due to the high magnetic field. A high accelerating voltage is not essential for beam extraction, since orbit separation can be obtained by orbit precession, at least for low-intensity beams.

Subsystem design

Magnet: the magnetic field in these cyclotrons is certainly not cylindrically symmetric. It is therefore noteworthy that full fledged 3-D design tools have not been required for designing these magnets [9].
Separate methods are used for the calculation of the azimuthally averaged magnetic field and for the azimuthal field modulation. For the average field, two-dimensional finite element methods are used (e.g. the POISSON code) in which the magnet is divided into cylindrical sections in which the azimuthally averaged iron content is approximately constant. The material in these sections is taken to be homogeneous with a permeability adjusted to represent the correct iron/air ratio in that section. For calculating the flutter, the pole surfaces are assumed to be fully saturated and the field in the median plan is obtained by summing the contributions from all surface elements of the poles. Field measurements have shown the accuracy of the average field to be in the order of 1% in absolute value. The assumption of constant magnetization being incorrect at the sector edges, the flutter is overestimated by a few percent. This effect increases with decreasing field level: a reduction of the field modulation by 6% was found in a 3-D calculation of the AGOR field at an average level of 1.8 T.

Main coils: since the main coils produce up to 70% of the total field, the shape of this field contribution must be adjustable for the different slopes required for beams of different energies. This is obtained by partitioning the coils in two sections that can be individually excited. The combination of high currents and the tendency to economize on the yoke cross section leads to strong axial forces on the coils, in some cases of opposite sign for different sets of currents. The maximum force between upper and lower coil sets ranges from 14 MN attractive in the Chalk River machine to 4 MN in AGOR. Careful design and stress and deformation analysis of the coil support structure, using 3-D finite element methods, are therefore required [10]. The coils of most cyclotrons are bath cooled and are therefore cryostable. Tritron and AGOR use impregnated coils cooled by liquid helium on their outside surfaces. The consequent lack of cryostability imposes limits on the stresses inside the winding package: shear stress must be kept lower than 20 MPa and hoop stress should not exceed 150 Mpa.
Refrigeration is required at 4K and at 80K. At 4K thermal loss is mainly due to conduction through coil supports and is approximately 30 W for the larger of these machines. A large source of heat loss is associated with the current leads, at which 1.5 l of liquid helium is evaporated per kA of transported current. The load at 80 K is mainly radiation determined and is typically 500 W. This need can be met either by a supply of liquid nitrogen or by cold helium gas from the main refrigerator.

Injection: Since high charge states can only be produced in voluminous ion sources, nearly all compact cyclotrons use external sources. For heavy ions, an ECR source or even a tandem accelerator is used. Tandem beams are injected in the median plane and are launched on the first orbit by stripping. ECR beams are axially injected at energies of typically 20-30*Q keV. The small radius of the first orbit implies the need to extend the noses of the accelerating electrodes to a few cm from the magnet axis. This results in conflicts between requirements for voltage holding, gap transit time, positioning tolerances and acceptance etc. A review of the design of such a central region is given in [8].

RF system: The minimum amplitude of the RF voltage on the accelerating electrodes is determined by the requirement of clearing the obstacles in the central region. Since the isochronism of the magnetic field can

be sufficiently good to allow at least 1000 turns in the machine, the energy gain per turn does not have to be very high on this account.
Even then, voltage holding is an essental problem in a compact machine. Unfortunately, the well-known Kilpatrick criterion [11] is not valid in the presence of a magnetic field, and the treatment and cleanliness of the electrode surfaces as well as the composition of the vacuum rest vapour have an important influence on voltage holding, of which no quantitative knowledge seems to be available. In practice, MSU has reported 100 kV/cm parallel to the magnetic field on a total surface of the order of 100 cm^2, approximately 30% higher than the Kilpatrick criterion.
The high voltage in the gaps is accompanied by high currents in the short circuits. Linear densities may be as high as 60 A/cm and require carefully designed and cooled RF contacts [12], [13].
The range of orbital frequencies of the ions is approximately 6-20 MHz and acceleration is done on harmonics 1, 2, 3 or 4. Resonators are half-wave coaxial line structures in nearly all machines, quarter wave stubs extending up and down through holes in the upper and lower magnet poles. Tuning is done by means of moveable short circuits. For first harmonic acceleration the resonators are long. The internal conductor must therefore be mechanically supported by means of an insulator which is placed as close as possible to the median plane and which also serves as a vacuum seal. However, the insulator poses an upper limit to the rf frequency and is therefore not feasible in a proton machine such as AGOR. For the resonator design, the classical method of curvilinear squares supported by a certain amount of model work continues to be used. The use of tools such as POISSON and SUPERFISH is required when isolators or non-cylindrical configurations need detailed analysis. The fields inthe resonators must obey strict phase relations, depending on the number of resonators and the harmonic number. Precision and stability must be well below and the regulation electronics must provide an amplitude stability of 1/10000.

<u>Extraction</u>: Beam extraction from a compact cyclotron must overcome the following main difficulties:
i) The high magnetic field leads to small orbit separation from acceleration. It is therefore very difficult to obtain single turn extraction and orbit separation has to be obtained by orbit precession following passage through the nur=1 resonance at the pole edge. The orbit separation that can be obtained in this way is, however, limited by other resonances and the strong non-linearity of the field. For this reason the first extraction element is invariably an electrostatic deflector: its septum is thin and the penetration of its field into the region of circulating beam is negligeably small. However,
ii) An electrostatic deflector is relatively ineffective. This is caused by long-known limits on voltage holding [14] in a strong magnetic field. A realistic maximum for the product VE of fieldstrength and voltage seems to be approximately 8.E11 V*V/m, corresponding e.g. to a voltage of 80 kV over a 8 mm gap [15]. The effect of such an electrical field is rather small: it is typically equivalent to a reduction of the magnetic field with 0.1 T. Additional magnetic extraction elements are therefore needed.
iii) The field fall-off near the magnet edge implies the presence of a number of resonances, some of which must be passed. In fig.4 a typical resonance diagram is presented, showing the different resonances associated with beam extraction. Because of these resonances, beams are very sensitive to field imperfections, the most dangerous of which are the first harmonic field component, which must not exceed a few gauss, and the second harmonic of the field gradient with a maximum of typically a few gauss/cm. Imperfections have various origins:
a) intrinsic asymmetries due to imperfect machining or assembly of the magnet. Typical machining and assembly tolerances on the poles and the hill sectors are therefore 0.1 mm or even lower.
b) Imperfectly centrered main coils. Off-centering may be required for reducing stresses in the radial coil supports if the yoke has no azimuthal symmetry.
c) Stray fields of magnetic extraction elements.

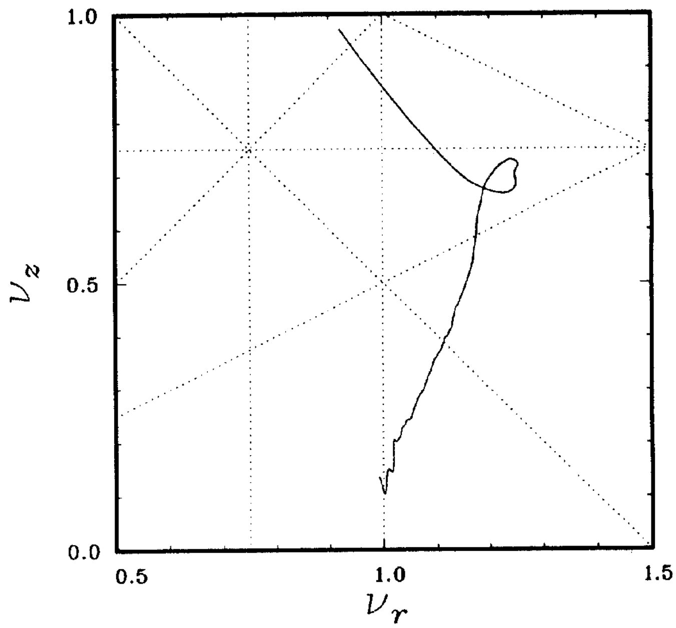

Fig.4: Typical resonance diagram, showing the approach of the nur+2*nuz=3 resonance.

iv) Pre-extraction orbits do not scale with particle momentum: the smallest extraction radii are associated with the lowest energy beams with low Q/A values which have a high magnetic rigidity.

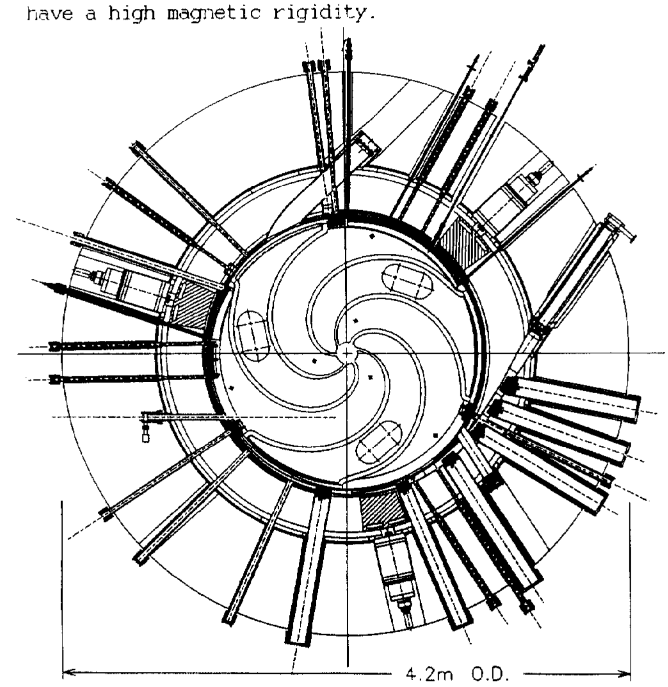

Fig.5: Median plane section of the MSU K-1200, showing the magnetostatic extraction elements.

The entrance of the electrostatic deflector is thus at the smallest radius for the stiffest beams, resulting in high deflecting fields. At the same time, the large width of the nur=1 resonance [16] leads to an enhanced sensitivity to field perturbations which must typically be controlled to 0.1–0.2 mT in a 5 T main field.

As explained above, magnetostatic elements are used in most machines. As an example, fig.5 shows a median plane section of the MSU K-1200 machine, showing the number and location of these elements. The radial positions of these have to be adjusted for different beams, so that yoke and vacuum penetrations, positioning mechanisms and motor drive systems are required for all channels. Instead of magnetostatic elements, electromagnetic channels may be used as shown in fig.6 which represents a median plane section of the AGOR cyclotron. These must provide focussing as well as deflection and must satisfy stringent requirements on the stray field at the location of the circulating beam. Although the separation between circulating and extracted beam at the first channel typically is only 1–2 cm, very careful design of the conductor configuration allows a reduction of the stray field to approximately 1 mT for a deflecting field of 0.2 T, as shown in fig.7. For deflectors at such small distances from the circulating beam, use of superconductivity is not feasible. Copper conductors are therefore used at high current densities (exceeding 100 mA/mm2) because of space limitations. Further along the extraction path superconducting channels can be envisaged: the Chalk River and AGOR cyclotrons feature such channels.

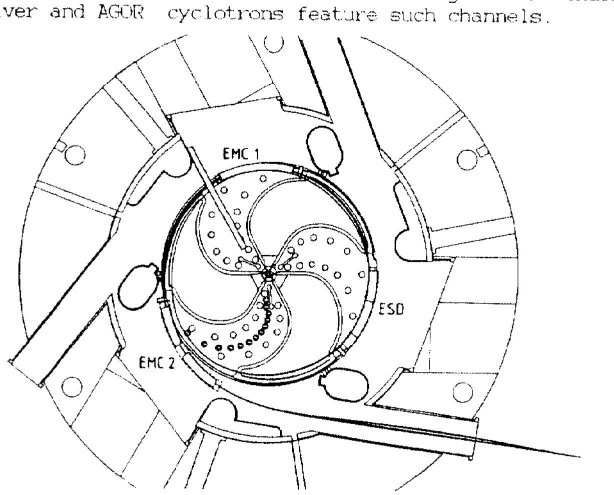

Fig.6: Cross section of the AGOR cyclotron, showing the three extraction devices ESD, EMC1, EMC2.

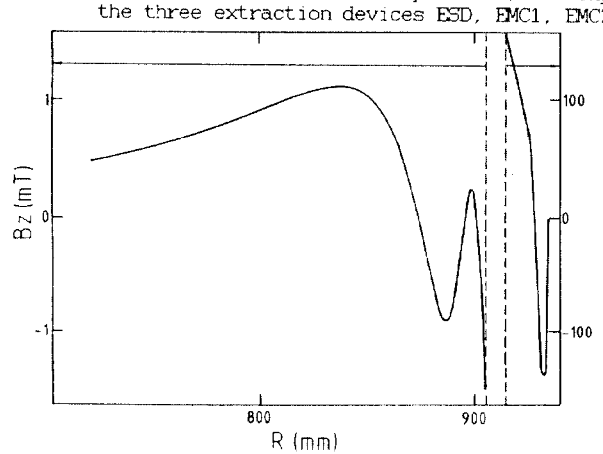

Fig.7 The magnetic fields inside and outside the extraction channel EMC1.

<u>Vacuum</u>: The vacuum requirements in these cyclotrons are modestly in the low 10^-7 torr range. Pumping access to the accelerating chamber, however, is difficult. For this reason most compact machines use cryopanels located inside the RF accelerating electrodes, augmented by turbopumps located outside the yoke and therefore severely conductance limited in pumping speed. In the MSU and Chalk River machines, the main liquefier is used to supply liquid helium to the cryopanels. In the Milano and AGOR cyclotrons separate cryogenerators are used. In Milano a specially designed unit is located close to the cryopanel inside the machine [17]. In AGOR a cryogenerator on top of the cyclotron is used to condense nitrogen and hydrogen. The liquids are transported down by gravity through insulated pipes mounted inside the inner conductor of the RF resonator to evaporators connected to the pumping panels. The evaporated gas rises and is recondensed [18].

<u>Other superconducting cyclotrons</u>

A few proposals for higher energy machines are, or have been, based on a design based on fully separated sectors. The first of these was the SUSE project, developed in the early 80's by a group in Munich [19]. This project for a Kb=1400 MeV machine was not funded. Its injector TRITRON, shown in fig.8, was funded in 1987 [20] and is now in an advanced stage of construction.

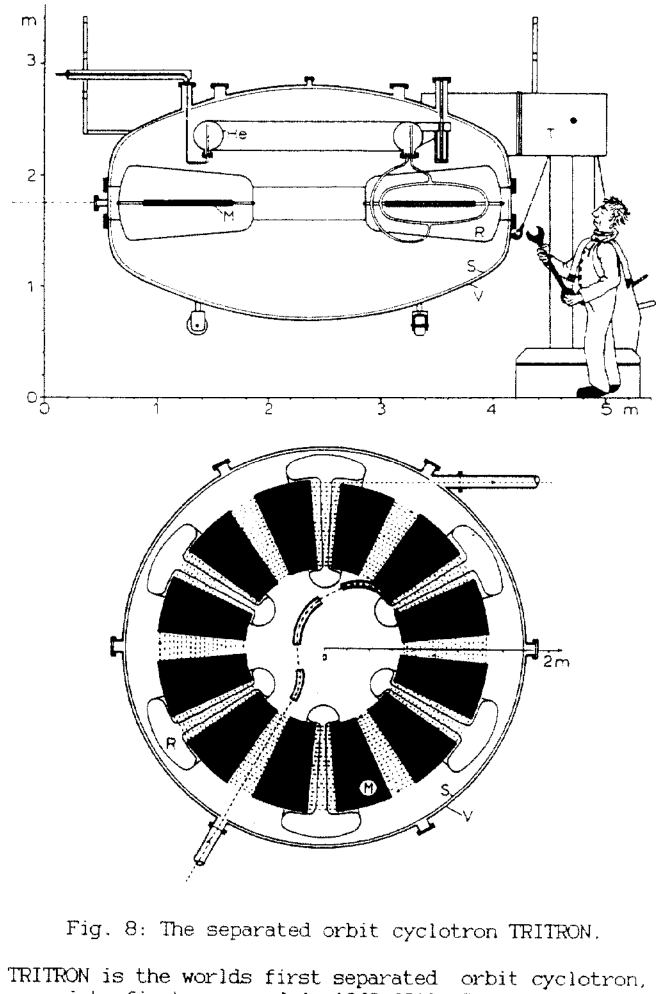

Fig. 8: The separated orbit cyclotron TRITRON.

TRITRON is the worlds first separated orbit cyclotron, a variety first proposed in 1963 [21]. It has a 20-turn spiral of channel magnets with a field of approximately 1.4 T, produced by superconducting coils.

The turn separation is 4 cm and six superconducting cavities with a maximum rf voltage of 530 kV at a fixed frequency of 170 MHz provide acceleration. It will function as an energy multiplier by a factor 4.9 for the tandem beams injected into it, final energies being 44 MeV for protons, 20 MeV/A for fully stripped ions and 7.6 MeV/A for ions with Q/A=0.3.

A more recent proposal for a separated sector cyclotron is the EULIMA project [22]. It has four sectors, powered by a common set of circular coils, as shown in fig.9. The machine is intended for cancer treatment by ion irradiation and will accelerate ions like C, O and Ne to energies up to 400 MeV/A. The ions are to be produced in an ECR ion source and will be injected axially.

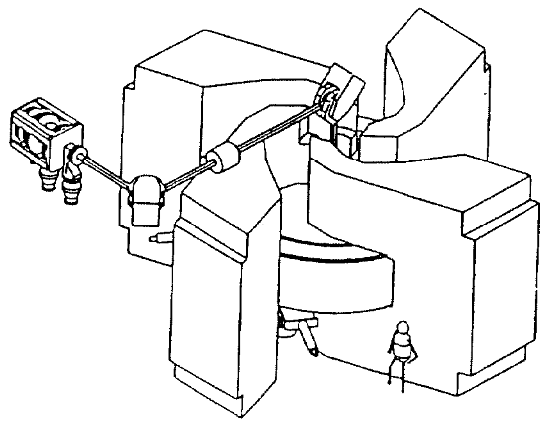

Fig.9: EULIMA, a proposed separated sector cyclotron for radiation therapy.

At GANIL (Caen, France), a feasibility study is being made for an additional third separated sector cyclotron for boosting the beam energy to 100 MeV/A for low charge state ions and to 500 MeV/A for fully stripped ions. The design is shown in fig.10.

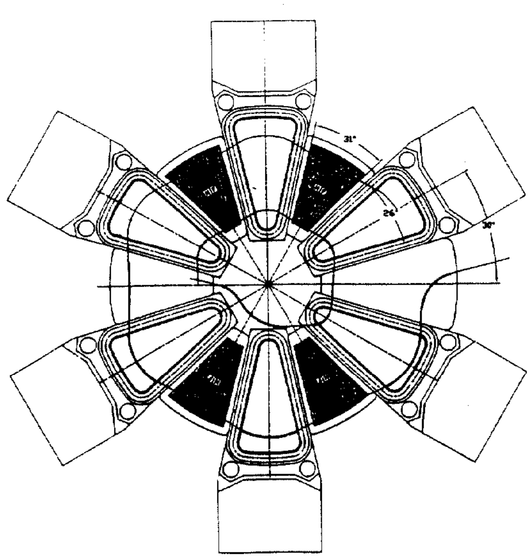

Fig. 10: CSS3, the preliminary design for a GANIL booster.

In Belgrade (Yougoslavia), conceptual design studies have been made on the feasibility of an air-core superconducting cyclotron [24]. This approach eliminates the constraints associated with the constancy of the flutter inherent in the use of saturated iron magnet poles.

Future developments

Energies surpassing 200 MeV/A require (at least) fourfold symmetry as well as higher bending and focussing constants than obtained in the MSU K1200. However, surpassing these parameters in a compact cyclotron seems to present a number of considerable challenges: i) a higher focussing constant would require an even tighter spiral, which is at least undesirable for orbit dynamics and which presents problems for the rf resonator design. ii) A higher bending constant, whether obtained through higher field or through increased size, will lead to high voltage problems for rf and/or for extraction. In addition, the strong attractive forces on the poles will present a serious engineering problem. iii) Extraction will be very difficult, although the AGOR design has a certain margin for further development. Although superconducting channels having essentially zero stray fields have been designed [25], the close distance to the high energy beams causes heating through beam loss and makes the cryogenic design of such a channel very difficult.

The development towards very compact low-energy machines is likely to be continued, e.g. for on-line production of positron emitting nuclides for PET systems.

A not yet fully explored possibility is a synchrocyclotron with superconducting coils, which could be a competitor for a separated sector machine in applications where high average beam currents are not required. A preliminary design of such a machine with K=250 has been made by H.Blosser at MSU [26].

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(ICCA is used as an abbreviation for "International Conference on Cyclotrons and their Applications".)

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