SUPERCONDUCTING CYCLOTRONS

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Abstract - This paper outlines a brief historical review of the compact superconducting cyclotrons and presents the major concepts and some design features of this new class of accelerators. A preliminary comparison between the expected performances and the obtained ones in the operating superconducting cyclotrons is sketched out. Finally the main characteristics of the present projects are described by emphasizing the technical solutions.

Introduction

The high field superconductors, discovered in the late 1950's, have found application to the cyclotrons only 13 years ago. This delay has been determined by the primitive and unreliable state of the materials then available and the lack of a basic technology for large scale superconducting coils but also by the concourse of other causes. First at all the nuclear physicist community was, in the 1960's, mainly interested to use the very light ions, secondly the high field and the consequent compactness of a superconducting cyclotron seemed to present some severe obstacles to the acceleration and extraction of particles. The interest for the high energy heavy ions and the experience matured on bubble chamber superconducting coils connected with the possibility to obtain a net overall cost savings of about 50%, pushed, in the years 1973-75,some laboratories to reconsider the design problems of a superconducting cyclotron. The pioneering studies of a group at Chalk River in Canada [1,2] were followed almost immediately by preliminary proposals both in USA and in Europe . The enthusiasm for the possibilities offered by the superconducting cyclotron eclipsed the difficulties arising by the complexity and novelties of the design problems so that several laboratories were induced to initiate design studies. Actually up to now only six projects have been funded (three in USA and Canada as from 1975 and three in Europe as from 1981) and costruction has taken more time (7-9 years) than foreseen one. Four superconducting cyclotrons are in operation in USA [3,4,5] and Canada [6] and two are near to completion (Milan [7] and Munich [8]) in Europe.

The experience achieved up to now by various laboratories gives a rather clear view of the design reliability and performances of this type of accelerators so that it is possible to present the status of art in this domain. The paper will review the major design features of the superconducting cyclotrons particularly emphasizing the results and unsolved problems, then will show the design evolution in the more recent projects and the development of superconducting cyclotrons for medical purposes.

Main physical and technical features

Physical features

The basic principles of the superconducting cyclotron are the same as those of any cyclotron, the difference in respect to compact room temperature cyclotron consists in a different choice of parameters and in a more wide range of particles and energies with suitable beam intensities and qualities.

Particle beams. In principle all particles from hydrogen to uranium can be accelerated in a superconducting cyclotron. This capability is not confined only to stable isotopes or long lived radioisotopes of elements but extends also to short lived radioisotopes. Recently in the K500 superconducting cyclotron a beam of $^6He^{2+}$ (lifetime 805 ms) has been accelerated at nuclear physics energies by using the cyclotron analogue beam method [9]. Polarized light ions are foreseen for acceleration in two superconducting facilities [5,10].

Limits to obtain every ion beams arise only when the superconducting cyclotron is exploited as a booster: the lightest ions (p,d,α) can be excluded by constraints of injection process in the median plane [11] or the noble gas ions (He, Ne, Ar ...) are excluded if the injector is a Tandem.

Energy range. The energy range is depending by the charge to mass ratio Z_i/A of the accelerated particles and presents several limits given by parameter choice. The most important limit is connected with the maximum magnetic rigidity that the particles can achieve in the cyclotron: the specific energy per nucleon can be expressed in a non relativistic approximation (valid for the heaviest ions) by the formula:

$$(T/A) = 48.26(BR)^2\ (Z_i/A)^2 = K_b(Z_i/A)^2 \qquad (1)$$

where B is the average magnetic field at the extraction radius R. The parameter Kb (bending parameter) is used to classify the cyclotron size and performances. Typical values of Kb are ranging from 500 to 1200 MeV/n.

Considerable improvements on the performances of a superconducting cyclotron can be achieved for heaviest ions by increasing their state charge: the most efficient method consists in accelerating the beam in two stages and resorting to an intermediate stripping process. The Fig. 1 shows the specific charge state for several ions, after the stripping in a solid foil, as a function of the incident ion energy [12]. In the same figure the specific charge states of the ions emerging from a PIG source and from a stripping foil,after acceleration in a first stage cyclotron (Kb=500) equipped with a PIG source, have been reported. The stripping process is very efficient for the heaviest ions but it is very expensive because it requires a powerful accelerator as injector. The development in the last years of ECR sources [13-16], which deliver highly stripped ions, makes possible to reach the energy range, presently covered by two stage facilities,by exploiting a superconducting cyclotron alone. In Fig.2 the performances of the ECR and PIG sources are compared: from these data it appears evident that ECR sour-

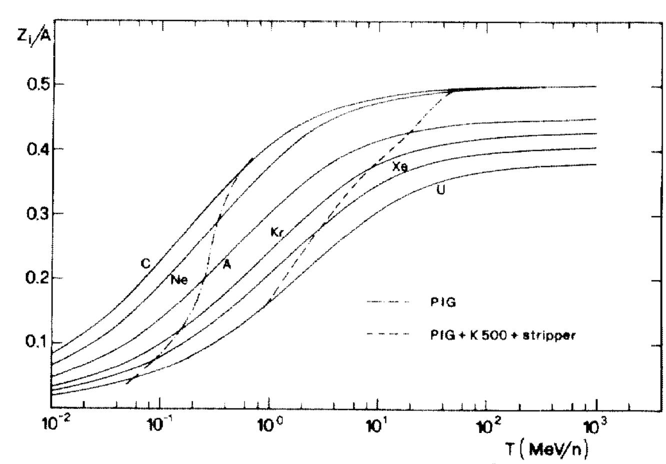

Fig. 1 Average specific charge of several ion beams emerging by a stripper foil as a function of the incident energy.

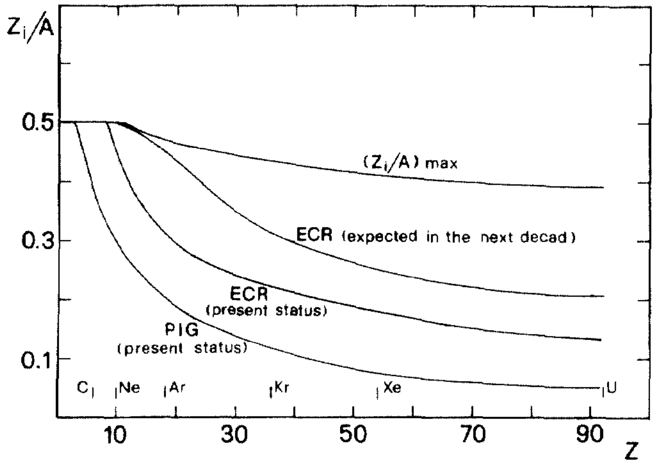

Fig. 2 Specific charges by PIG and ECR sources. The upper curve represents the specific charge for fully stripped ions.

ces can produce charge states 2-3 times higher than the ones of PIG sources,allowing for the heaviest ions an increase of a factor 5-10 of the maximum energies.

The second upper limit comes by lack of focusing for the more relativistic particles. In a superconducting cyclotron the azimuthal modulation is constant for every magnetic field level, so that the flutter becomes insufficient to overcome the isochronous field defocusing in the case of the more relativistic ions [17]. The specific energy depends linearly by the specific charge:

$$(T/A) = Kf(Zi/A) \qquad (2)$$

where Kf (focusing factor) can vary between 100 and 400 Mev/n.

A further reduction of the light particle energies can be produced by the extraction process. If an electrostatic deflector with a fixed geometry is used, the ratio of electric to magnetic force must be maintained constant for all particles and energies. This condition requires an electrostatic field:

$$E = (2C/eR)\ Kf \qquad \text{relativistic ions}$$
$$E = (2C/eR)\ Kb\ (Zi/A) \qquad \text{heavy ions}$$

where R is the extraction radius and C a parameter depending mainly by the sharpness of the field edge and by azimuthal extent of the extraction path (typically C = 0.02-0.04). If the electrostatic field cannot reach the values above-mentioned an extraction barrier which behaves in the same way as the focusing barrier, will limit the maximum energies achieved by the cyclotron.

A lower limit on the energies is determined by designer choice of the lowest magnetic field. In particular this limitation can arise by the inhomogeneous saturation of the poles when the field is too lowered, or by the fact that the particles approach dangereous resonances.

Additional limitations can be introduced by a too low accelerating voltage (particles do not clear the injection device) or by the lowest RF frequency (if the harmonic number is fixed).

The Fig. 3 summarizes the impact of the various limits on the operating regime of a superconducting cyclotron with Kb=800 and Kf=200.

Beam intensities and qualities. Intensity and quality (emittance, energy spread and duty cycle) of the beams are depending by the source and by coupled accelerator types. The expected values of these parameters for the maximum energy beams delivered by three different facilities are reported in Table I. These data have been confirmed by the operating cyclotrons at Michigan [18] and Chalk River [6]. It is notable that in many cases

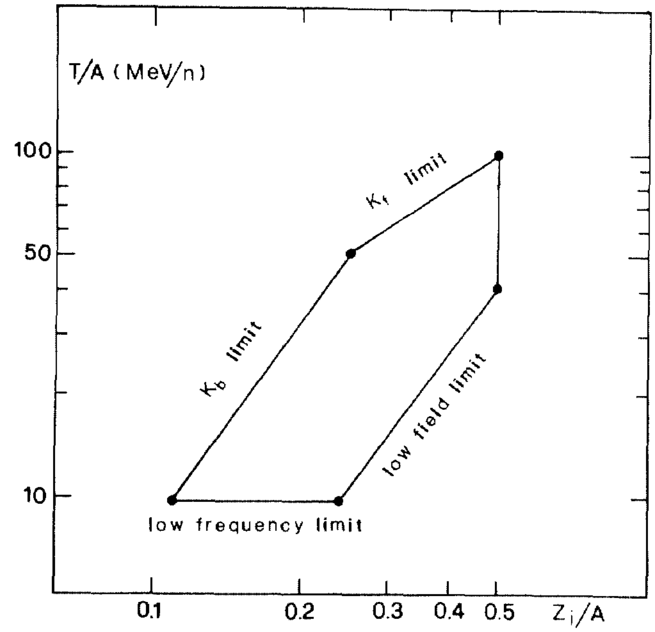

Fig. 3 Operating diagram of a superconducting cyclotron.

of interest the intensity is not limited by the cyclotron (source, extraction) but rather by the experiment requirements (usually data processing limits).

Table I

Intensity and quality of beams (at maximum energies)

Parameters	Tandem Cyclotron	Cyclotron Cyclotron*	Cyclotron ECR source
Intensity (pps) Light ions	2-10 10^{11}	1-5 10^{12}	1-5 10^{11}
Intensity (pps) Heavy ions	.5-5 10^{10}	1-10 10^{10}	.5-5 10^{10}
Energy spread (%)	.05-.1	.1-.2	.1-.2
Emittance (mmrad)	1-3Π	3-10Π	3-10Π
Duty cycle (%)**	2-3	2-3	2-3

* PIG external source
** Beam bunching (6-10 RF degrees)

Technical features

Magnet structure. The most evident characteristic of a compact superconducting cyclotron is its closed structure arising by cryostat and magnetic field requirements. The Fig. 4 shows an exploded view of a typical superconducting cyclotron.

Magnetic field design. The saturation regime of the iron greatly simplifies the design of the magnet. Although the poles have a tridimensional structure it is possible to calculate the magnetic field with a precision of 0.2-0.4% by using a bidimensional code (POISSON) for average field and a magnetic mass (or current) code for the azimuthal variation of the field. The tested accuracy of this procedure makes possible to avoid the more expensive calculations with tridimensional codes (GIFUN or TOSCA) and, as more important result, has eliminated the need of design and construction of a model [19].

Superconducting coils. The chief characteristic of a superconducting cyclotron is obviously represented by superconducting coils which give up to 60% of the to-

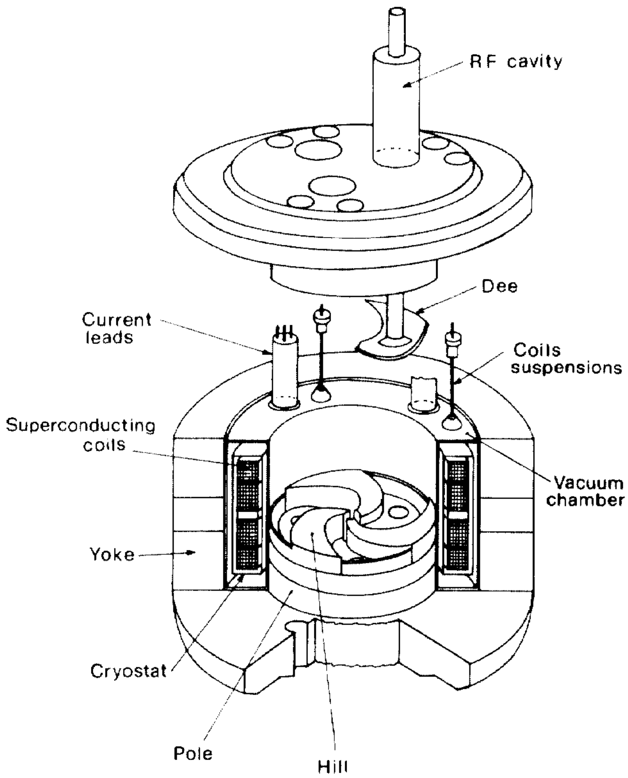

Fig. 4 Exploded view of a compact superconducting cyclotron.

tal magnetic field. The coils contribute also to shape suitably the field gradient necessary for the isochronous acceleration of every ion. This shaping is obtained by dividing the coils in two sections and supplying them separately to obtain a nearly zero gradient (heaviest ion acceleration) or a gradient up to 1.0-1.5 T/m (light ion acceleration).

The design and construction of the coils are a very complicated task. The main problems arise by the necessity to conciliate the magnetic field requirements, determined by particle dynamics, with superconductivity requirements related to stability and safety of the coils [20]. For example in the first generation of superconducting cyclotrons the stability of the superconductor against thermal perturbances has been obtained with a close contact between the liquid helium and bare conductor by means of a labyrinth of internal passages in the coil. This solution, which assures the cryogenic stability of the coil, makes it quite vulnerable to possible electrical shorts or grounds due to small metal fragments. Three superconducting coils (Chalk River [21], MSU [22] and Milan [23]) have suffered this trouble, fortunately the problem was not calamitous though certainly quite onerous. To overcome this problem the AGOR group has designed superconducting coils which are completely impregnated by epoxy resin. This solution, never applied for large coils, is based on the recent experience acquired with indirect cooling of thin solenoids [24,25].

Radiofrequency system. The closed structure of the yoke and cryostat, adopted in these cyclotrons, has imposed a radiofrequency resonator configuration which differs from that one usually adopted in the conventional cyclotrons. The resonators are assembled vertically and arrive near the median plane through large holes machined in the valleys and yoke. The three dee configuration adopted by all projects (excepted Chalk River project)has required the solution of the problem of operating the three resonators indipendently [26]. The problem of the sliding shorts, which must support linear current densities up to 40-50 A/cm without burning,has been solved using fingers or spheres of high capacity silver graphite [27].

Electrostatic deflectors. The deflector housing in a superconducting cyclotron is very small because of narrow magnet gap and the radial barrier presented by the cryostat. The reduced size and the high magnetic field limit the maximum electrostatic field achievable in the deflectors. Up to now the electrostatic field of 140 kV/cm in a gap of 8 or 7 mm has not been yet reached [28- 30].Extensive works are in progress in MSU and Milan laboratories and improvements are expected in a short time.

Project description

Although the superconducting cyclotron can be considered a young component in the accelerator family, two generation can be recognized in the present projects. The first one is represented by a two stage facilities (Chalk River, MSU, Milan , Texas A&M), the second one includes projects with a superconducting cyclotron alone (AGOR) or separated sector cyclotron with superconducting magnets (SuSe). Fig. 5 shows the operating schemes of the different projects.

Since each of these projects has original peculiarities worth mentioning, a short description of them will be given in the following.

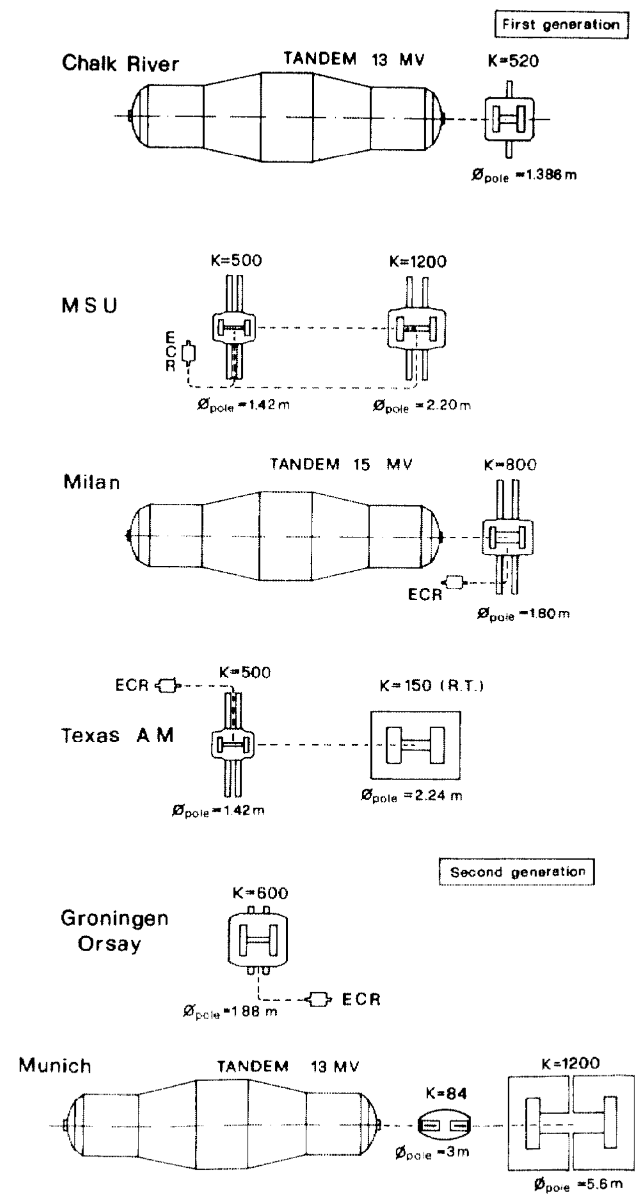

Fig. 5 Operating schemes of the present heavy ion facilities.

First generation

Chalk River project. The TASCC (Tandem Accelerator Superconducting Cyclotron) facility is in operation from 1985 and is the first superconducting cyclotron to be injected from a Tandem [6]. It is a four sector machine (Kb=500, Kf=100) in which the four dees are connected to two symmetric resonators located on the magnet axis. This design allows to avoid the problem of three phase neutralisation and takes advantages of the stable 0 and Π mode operation of coupled resonator pairs. However this simple and elegant solution prevents the axial injection and the exploitation of an external source. Another characteristic of this cyclotron is represented by trim rods (movable iron cylinders inserted in the sector hills) wich replace the trim coils for the fine tuning of the magnetic field.

MSU project. It is the only project which doesn't use an existing accelerator and which consists of two coupled superconducting cyclotrons (K500 and K800).
K500- The superconducting cyclotron K500 (three sectors, Kb=500, Kf=160) is in operation as from 1982 with an internal PIG source and has improved its performances with an external ECR source and axial injection in 1986.The cyclotron has delivered several beams (H2,He,C,N,O,NE,Ar,Kr,...) in the energy range 8-50 MeV/n with intensities at experimental targets of 0.5 - 100 pnA. The most important operating problems consist in the main coil internal short, the He impurities (water, oil, neon) in the cryogenic system, the dust particles on the electrostatic deflector which limit the maximum electrostatic field at about 85 kV/cm.
K800 - The superconducting cyclotron K800 (three sectors, Kb=800, Kf=400) is the largest superconducting cyclotron presently in operation. Although the K800 can be considered a scaled and improved K500 system the difficulties are considerably enhanced (larger number of turns, higher dee voltage, tighter spiral, proximity of the operating point to 3/2 radial stop band). Nevertheless the cyclotron has accelerated a beam just two months before this Conference [4] by injecting axially the beam delivered by an external ECR source.
The K500 - K800 coupling program is presently shelved awaiting additional data in the ECR source development.

Milan project. The project funded in 1981 foresees the design, construction and test with an external ECR source of the superconducting cyclotron at the LASA Laboratory in Milan and its coupling with the 15 MV Tandem of the South National Laboratory (LNS) in Catania [7]. The machine (three sectors, Kb=800, Kf=210) presently under test for the superconducting coils and magnetic field will be probably the first large superconducting cyclotron operating in Europe (1989).Remarkable characteristics of this cyclotron are the use of only one RF harmonic (2nd harmonic) for all ion acceleration, the opposite currents in the two sections of the main coils (to limit the trim coils power) and the large exploitation of the computer control. The Fig. 6 shows the magnet during the assembling of the cryogenic circuit for the superconducting coil test.

Texas A&M project. The superconducting cyclotron of this project is very similar to K500 of MSU and is used as injector in a Kb=150 conventional cyclotron [5]. This facility is provided with an axial injection from an ECR source and from a polarized deuton source already operating in the laboratory.

Second generation.

AGOR project. This project is a collaboration between the Groningen and Orsay Universities. The project, developed in the early years of this decade,represents the first example of an heavy ion facility with only a stage [10].Its most remarkable characteristics consist in the possibility to accelerate protons up to 200 MeV, in a new configuration of the coil sections, in the choice of fully impregnated coils and in the compactness of the RF cavities. The Fig. 7 shows a sketch of the machine whose completion is expected in 1992.

Munich project. This project represents the next step in the evolution of superconducting cyclotrons. To overcome the difficulties of extraction of high energy particles the Munich group has studied the feasibility of a separated sector cyclotron with superconducting magnets (SuSe) [31] The proposed facility is constituted by three accelerators: a 13 MV Tandem, a superconducting separated orbit cyclotron (Tritron) and a separated sector cyclotron (SuSe). The facility would accelerate fully stripped light ions up to 300 MeV/n.

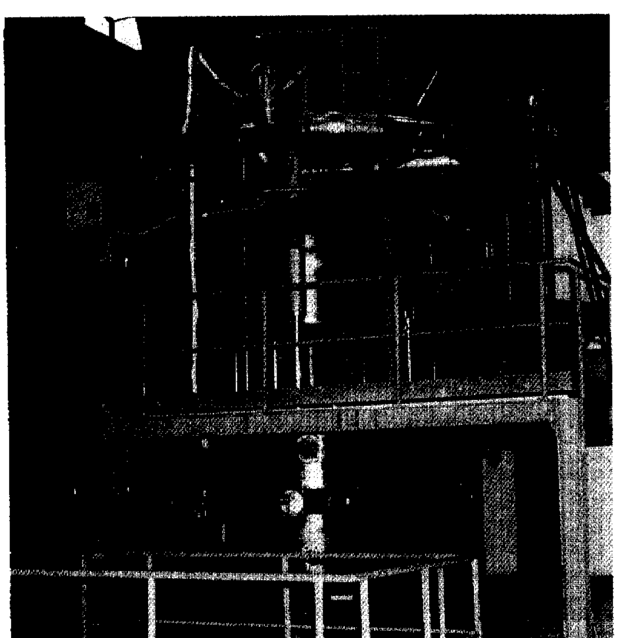

Fig. 6 Magnet of the Milan cyclotron during the assembly.

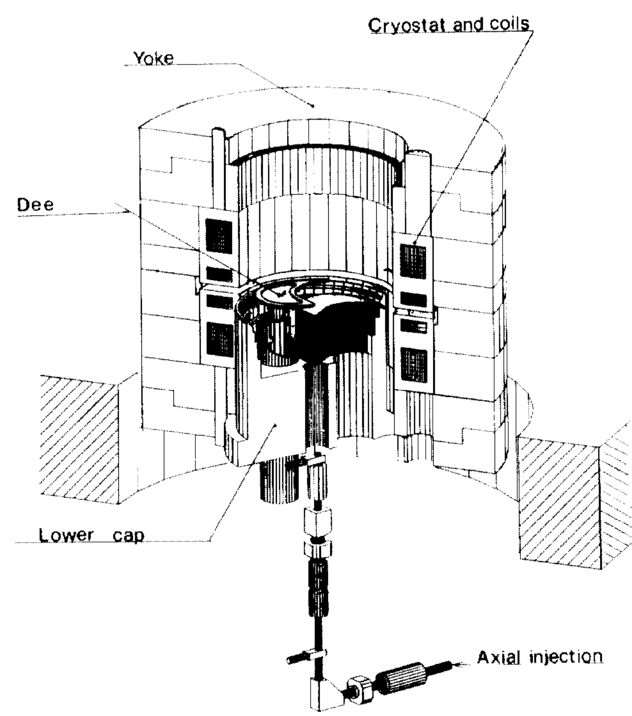

Fig. 7 Simplified cutaway wiew of AGOR cyclotron.

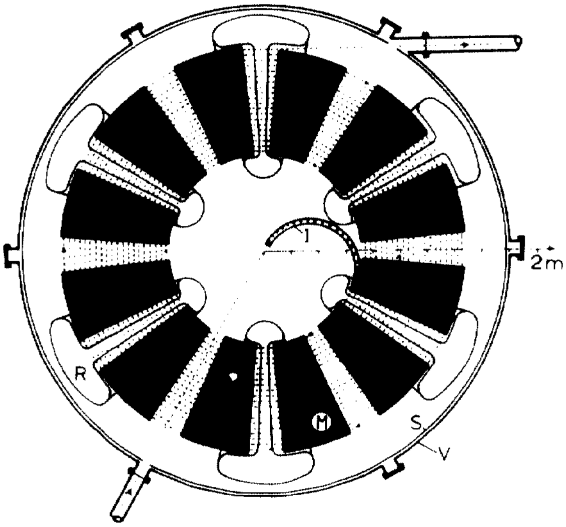

Fig. 8 Cross section of Tritron M:magnets, R: accelerating cavities, V:vacuum tank.

The second stage Tritron [32],now under development,is a completely new machine in which the orbits of the particles are separated from the injection to the extraction region.It consists of 12 flat superconducting magnets with 20 neighbouring channels for the spiral orbit and of six superconducting cavities with a 3 MV accelerating voltage per turn.The Fig. 8 shows a schematic cross section of this machine.

Applied physics cyclotrons

The reduced size and weight of a compact superconducting cyclotron are wonderful characteristics in order to obtain a movable apparatus for medical applications. In the last years three medical facilities have been proposed. The first facility [33], now in operation accelerates an internal beam of 50 MeV deuterons to produce neutron beams for therapy. It is mounted in a ring type gantry in order to move in a full 360 degrees arc about a supine patient (Fig. 9). The second cyclotron, proposed by English firms, would accelerate negative hydrogen ions in a magnet without yoke [34] up to 12 or 17 MeV. With a weight of 2000 kg it will be transportable by a special car and will deliver radioisotopes for PET or other imaging procedures (12 MeV protons) or neutron beams for radiography (17 MeV protons).

On the other hand a large superconducting cyclotron (EULIMA) for cancer treatment has been proposed in Europe [35]. The machine consisting of separated sectors with a superconducting coil alone would accelerate light ions (C,O,Ne) completely stripped up to a maximum energy of 450 MeV/n.

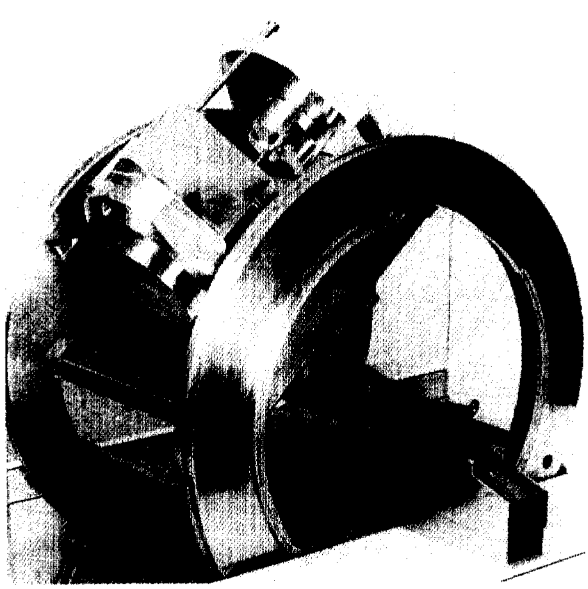

Fig. 9 Model of compact superconducting cyclotron mounted on the isocentric gantry.

Conclusions

The compact superconducting cyclotron is the most suitable machine for the heavy ion acceleration. Furthermore the experience with the operating cyclotrons shows that this type of machine is very reliable and it is easily operated if supported by a computer. The main motivation in the choice of superconducting cyclotron, in spite of its design complexity, is the possibility to reduce the size of the accelerator, building and shields, lowering the total cost of the project. This motivation becomes ever more valid with the evolution from a two stage to only one stage facility, evolution supported by the development of new sources delivering high charge states. The one stage facility for the energy range 10 - 100 MeV/n becomes an enterprise economically accessible to a single laboratory because it is possible to use almost completely the existing structures. Probably at this moment the obstacle to a diffusion of this facility in the nuclear physics laboratories is represented by the project complexity and by the time required to complete the construction.

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