ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Milano

INFN/TC-90/001
8 Gennaio 1990

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INFN - Istituto Nazionale di Fisica Nucleare
Sezione di Milano

INFN/TC-90/001
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PRINCIPLES AND EVOLUTION OF THE CYCLOTRON

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Paper presented at the Workshop on Cyclotron Radioisotopes, J.R.C. Ispra (Italy), 19th October 1988.

ABSTRACT

The basic principles of operation of the cyclotron are described and the evolution of the machine design from its early days to the present time is reviewed. The main biomedical applications are briefly highlighted, and the present and future uses of cyclotrons in cancer therapy are discussed. The availability of standard models from commercial manufacturers and the existing facilities in Europe are also illustrated.

1. - INTRODUCTION

The principle of resonant particle acceleration in a static magnetic field was discovered by Ernest O. Lawrence in 1930. In 1932 the first cyclotron was built at Berkeley by Lawrence and Livingston: it used a magnet with pole faces 10 inch in diameter and accelerated protons to 1.2 MeV.(1) From that date, the technology of particle accelerators has undergone an impressive development, leading to the large synchrotrons and storage rings, with circumferences of up to several kilometres, which now accelerate particles to hundreds GeV.

Although cyclotrons have since long been overtaken by synchrotrons in terms of maximum energy achievable, they still hold a relevant position in the scientific community and a few hundreds of them are today operating all over the world. Their applications cover a wide range of fields, from atomic and nuclear physics to material science, biology and medicine. This versatility is due to the possibility of obtaining beams of good quality, extracting high currents, accelerating different species of ions, and yet maintaining a compact size, a reasonable cost and a limited power consumption.

One of the most important applications is radionuclide production: a good number of the cyclotron facilities operating nowadays, either in research centres, hospitals or industry, are partly or completely dedicated to this purpose. In the following we shall deal with the cyclotron concept in general, but pointing out any specific feature which is particularly relevant to this topic.

After a basic discussion on the principles of operation, a brief overview of the evolution of the cyclotron will be given. The principal biomedical applications will then be highlighted, with a hint to some current projects where cyclotrons play a major role. The availability of commercial machines will also be discussed, and the current european status of the cyclotron facilities will be illustrated.

2. - PRINCIPLES OF OPERATION OF THE CYCLOTRON

There is a number of excellent textbooks on particle accelerators, where an exhaustive treatment of the cyclotron operation can be found.(2-5) Here we will only give a very brief account of the theory underlying the cyclotron concept.

The operating principle is based on the fact that a charged particle moving in a uniform magnetic field experiences a force which guides it along a circular path, and that the period of revolution is independent of the particle velocity. The particle can thus be progressively accelerated by an electric field, up to a given energy value, slowly changing the revolution frequency. This variation is due to a relativistic effect which causes a loss of isochronism between the frequency of the accelerating field and that of the particle and ultimately sets the energy limit for the classical cyclotron. This problem can be overcome by different methods, as it will be discussed in the next section.

The force F acting on a particle subjected to both an electric and a magnetic field is given by the well-known expression:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v}\mathrm{x}\mathbf{B}) \qquad (1)$$

in which q and v are charge and velocity of the particle, and E and B are respectively the electric and magnetic fields. The bold quantities are vectors. The electric field is responsible for accelerating the ion and the magnetic field for bending its trajectory. At any point along the orbit, the centripetal force is equilibrated by the Lorentz force given by the second term of the above expression:

$$mv^2/r = qvB \qquad (2)$$

where m is the mass of the particle and r the radius of curvature of the orbit.

The revolution frequency f (also called Larmor frequency) is obtained from expression (2):

$$f = qB/2\pi m \qquad (3)$$

From this relation it is seen that the revolution period $\tau=1/f$ is independent of the particle velocity, as stated earlier. If B is in Tesla, expression (3) becomes:

$$f = 15.2 \bullet B \bullet (Z/A) \quad \text{(Mhz)} \qquad (4)$$

in which Z and A are respectively state of charge and atomic mass number of the ion. If a radiofrequency electric field is superimposed to the magnetic field, resonant acceleration occurs if the frequency of the external field, f_{RF}, is a multiple integer of the revolution frequency:

$$f_{RF} = h \bullet f \qquad (5)$$

h is called harmonic number. From (4) and (5) it is seen that there exists a well defined relationship between the magnetic field guiding the particle and the frequency of the accelerating force.

In a cyclotron two or more electrodes, connected to one or more radiofrequency systems, are placed inside a vacuum chamber between the poles of an electromagnet generating an uniform field (Fig. 1). The ions to be accelerated are either emitted by an internal source situated at the centre of the machine or - in higher energy cyclotrons - produced by an external source or a pre-accelerator and then injected into the central region. In any case, the ions start near the centre of the cyclotron and progressively gain energy at each crossing of the gap between adjacent electrodes, each time jumping to an orbit of larger radius. When they are within an electrode they are shielded from the electric field and only experience the magnetic force, thus travelling along a circular path which brings them back to the next acceleration step. Fig. 2 illustrates this principle in the case of a two electrode system. Although the electrodes may be of different angular extension according to the operation mode of the cyclotron, they are still called "dees" from their shape typical of the first machines, as it is shown in the figure.

At the end of the acceleration process, the particle beam is sometimes used to directly bombard an internal target, but is usually extracted from the machine and either used to hit a target placed just outside the extraction port or guided by a transport system to one or more experimental areas. In most cases extraction is achieved by means of a combination of electrostatic and magnetic devices, except for negative ion cyclotrons, for which the extraction procedure is much simpler (see Section 4). Fig. 3 shows the extraction process by means of an electrostatic deflector.

The maximum energy per nucleon, T/A, for non relativistic ions, obtainable from a cyclotron with a certain magnetic field strength, can be calculated starting from expression (2), which can be rewritten using the momentum p=mv of the particle:

$$p = qBr \qquad (6)$$

Since $T = p^2/2m$, equation (6) can be rearranged to give:

$$T/A = k \cdot (Br)^2 \cdot (Z/A)^2 \qquad (7)$$

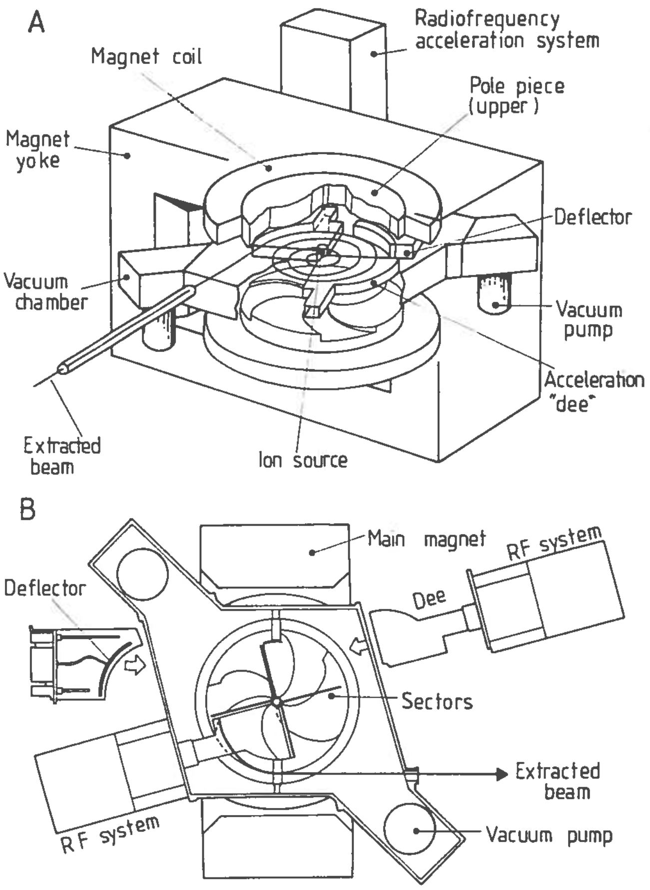


FIG. 1 - Schematic views of a cyclotron: a) isometric representation; b) sectional plan view (from ref. 21).

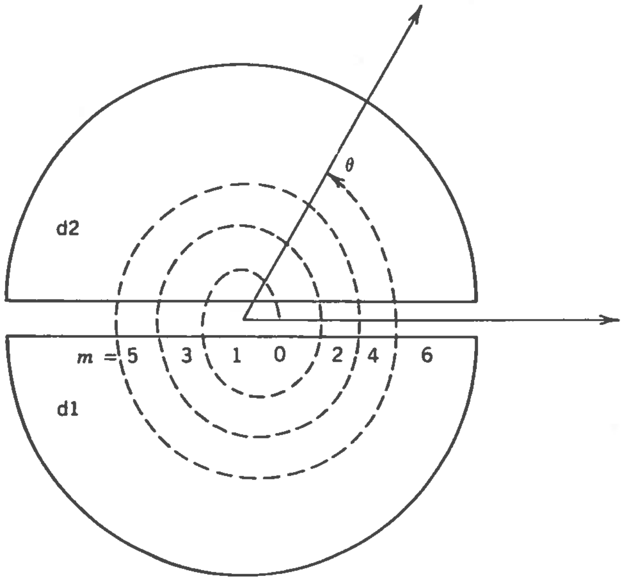


FIG. 2 - Acceleration process for a two electrode system (from ref. 5).

in which $k = e^2/2m_p$, with e = elementary charge and m_p = proton mass. Here B and r are the magnetic field and orbit radius at the extraction. The term $K = k \cdot (Br)^2$ is called the bending limit (or K-value) of the accelerator. If B is in Teslas and r in metres:

$$K = 48 \cdot (Br)^2 \quad \text{(MeV)} \qquad (8)$$

For protons $T/A \approx K$, whilst for fully stripped ions $T/A \approx 0.25 \cdot K$. The actual maximum energy obtainable is usually lower than the limit given by expression (7) because of constraints related to focussing and extraction of the beam.

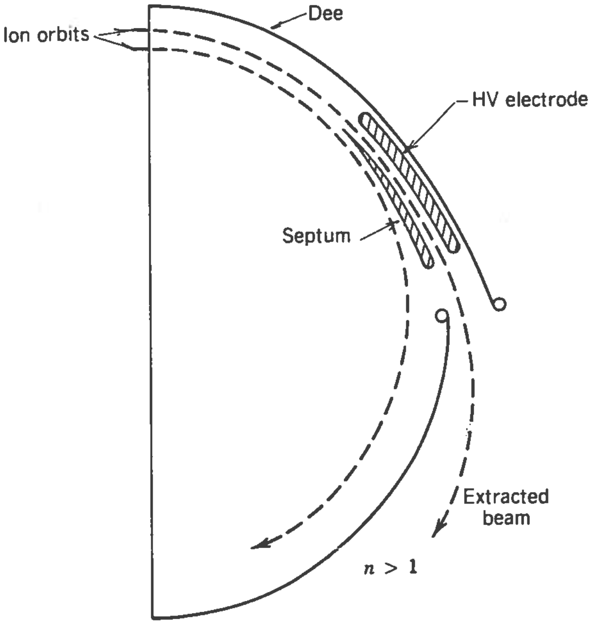


FIG. 3 - Extraction of ions using an electrostatic deflector (from ref. 5).

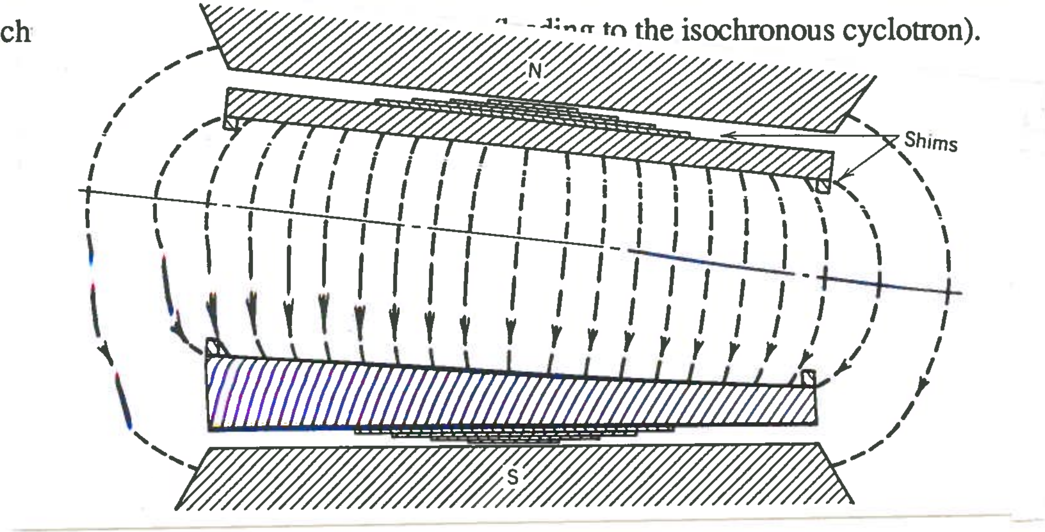
3. - EVOLUTION OF THE CYCLOTRON

From the pioneering work of Lawrence and Livingston, the cyclotron has undergone a series of major developments. The demand for higher and higher beam energies and intensities, as well as the possibility of accelerating heavy ions, has led to a number of technical improvements and different solutions to the cyclotron concept. Here we shall briefly review the fundamental steps of this evolution.

3.1. - The classical cyclotron

The classical cyclotron is a non relativistic machine, characterized by magnetic field with cylindrical symmetry and weak focussing. In order to have radial and axial focussing at the same time, the field must slightly decrease with radius (Fig. 4). From expression (3) it is seen that the decrease of the magnetic field, along with the relativistic increase of the mass of the particle, causes a decrease of the revolution frequency f with radius. Since the frequency f_{RF} of the acceleration system is constant, after a number of turns this leads to a loss of isochronism between f and f_{RF}: if this situation protracted, the particles would come to the gap between the electrodes later and later until they would no longer gain energy but would start to undergo deceleration. Therefore the energy limit is due to the loss of isochronism.

This problem was realized fairly early.(6) The only possible solution to increase the final energy is to increase the dee voltage, but there exist limits here too (100 - 150 kV), so that the practical limit for the energy obtainable from the classical cyclotron is about 20 MeV for protons. Neverthel there were two possible solutions to this problem: frequency modulation (leading to the synch ding to the isochronous cyclotron).



3.2. - The synchrocyclotron

The synchrocyclotron, or frequency-modulated (FM) cyclotron, represented the first solution to the relativity problem. Its realization became possible soon after the discovery of the principle of phase stability in 1945. Like the classical cyclotron, the FM cyclotron consists of a magnet with large poles producing an uniform field with rotational symmetry, slightly decreasing with radius in order to provide focussing in both transverse planes. The frequency of the electric field applied between the dees, however, is not constant, but varies in accordance with the particle energy in order to match the gyrofrequency of the ions given by expression (3). Thus f_{RF} diminishes with increasing beam energy to compensate for the simultaneous decrease of the magnetic field and the relativistic increase of the particle mass.

In principle, there is no upper limit to the energy that can be obtained from the FM cyclotron, but since magnet size increases with final energy (roughly speaking, the magnet volume increases as the cube of the kinetic energy) the obvious limitation is related to weight and cost of the iron. With the Leningrad synchrocyclotron, energies have been reached up to 1 GeV for protons, but the magnet weight is about 7800 tonnes.

The higher energy obtainable from the FM cyclotron is paid with a marked reduction in the beam intensity. This is because the non constancy of the radiofrequency electric field causes only a few particle bunches to be accelerated at the same time, thus producing a pulsed output. Moreover, the ions have to perform a greater number of revolutions with respect to other types of cyclotrons, both because the final energy is higher and because the dee voltage is lower (due to phase stability requirements). The low dee voltage has also an influence on the extraction process, which is more critical due to the less separation of the orbits and is achieved by a method (pulsed extraction) different from that used in the other cyclotrons and briefly pointed out in the previous section. The low extraction efficiency further reduces the intensity of the output beam.

3.3. - The AVF cyclotron

A completely different approach to the solution of the energy problem intrinsic in the classical cyclotron was proposed by L. H. Thomas in 1938, but his idea was not put at work until the early 1950's, when the first AVF (or isochronous) cyclotron was built. The AVF cyclotron is a much more versatile machine than the previous types of cyclotron. Its development offered new and interesting possibilities, such as the achievement of high extraction efficiency, better beam quality and the acceleration of heavy ions.

AVF means azimuthally-varying-field: in fact, the cylindrical symmetry of the magnetic field is given up in order to satisfy the requirements of both relativity and focussing at the same time. The field can now be expressed as a superposition of an average value and a modulation, the latter being dependent on the azimuthal angle θ:

$$B(r,\theta) = \langle B(r)\rangle + \mathrm{Mod}(r,\theta) \qquad (9)$$

In an AVF cyclotron the RF frequency is constant whilst the average magnetic field $\langle B\rangle$ rises with radius to compensate for the relativistic increase of the particle mass; thus expression (3) becomes:

$$f = q\langle B\rangle/2\pi m\gamma \qquad (10)$$

in which γ is the relativistic factor (the ratio of total energy to rest energy). The azimuthal variation of the field is achieved by adding to the poles of the magnet equally spaced wedge-shaped expansions having the same angular extension, as illustrated in Fig. 5a. The alternating of regions of high field (hills) and low field (valleys) produces a modulation in the field amplitude, as shown in Fig. 5b, which generates an extra component of the vertical focussing force overcoming the defocussing effect due to the radial increase of the field. Because of this field configuration, the bending radius of the particles is not constant with azimuth, and therefore the equilibrium orbit is not a perfect circle (this effect is called "scalloping" of the orbit). Thus it is customary to define an average bending radius $\langle r\rangle$, so that equation (6) now reads:

$$p = q\langle B\rangle\langle r\rangle \qquad (11)$$

The maximum energy obtained from an AVF cyclotron is about 500 MeV for protons, with beam intensities as high as several hundreds microAmpères. The demand for high beam currents (much higher than those achievable with the FM cyclotron) was in fact the main reason that boosted the development of the AVF cyclotron. The principle of Thomas focussing was taken into consideration only several years after its formulation because in the 1930's it was thought that the

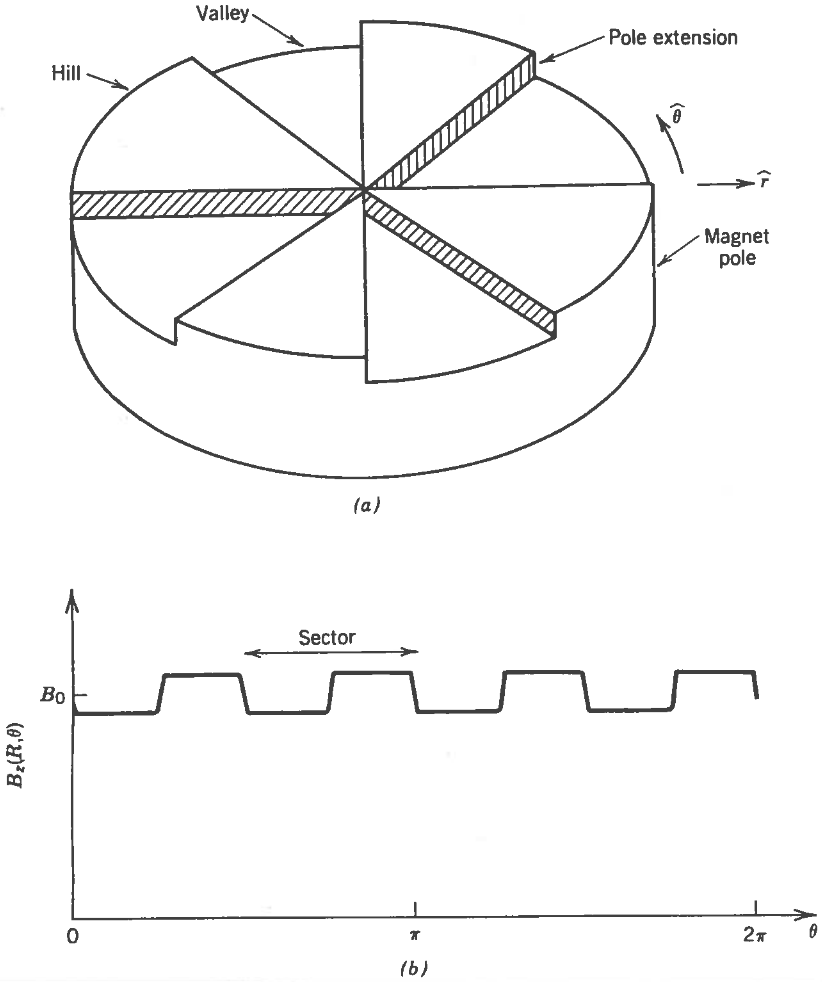


FIG. 5 - Magnetic field in AVF cyclotron: a) magnet pole; b) vertical field amplitude as function of azimuth θ at constant radius (from ref. 5).

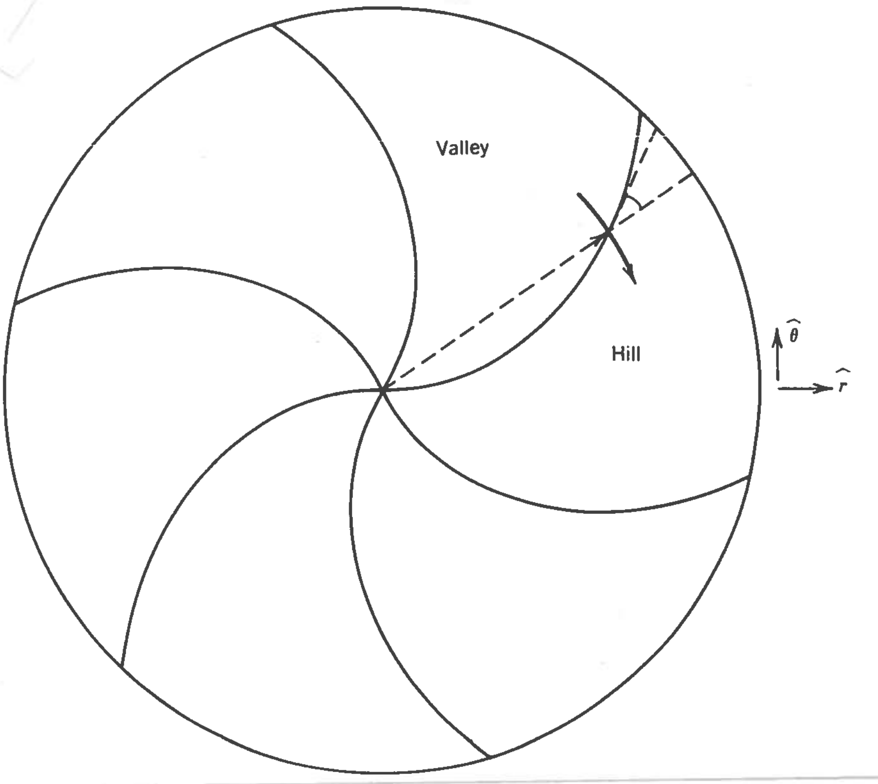


FIG. 6 - Magnet pole with spiral sectors (from ref. 5).

realization of an azimuthally varying magnetic field represented too much of a challenge for the technology of that time. Moreover, the FM cyclotron was able to satisfy the immediate needs of the experimentalists.

A further component of the axial focussing force can be created by giving the sectors a spiral shape, as illustrated in Fig. 6. In effect, if the spiral angle is made large this component is predominant over the Thomas force.

3.4. - The separated sector cyclotron

The next stage of the cyclotron evolution is represented by the separated sector cyclotron. Focussing of the beam is still achieved by the AVF principle, but the magnet is now splitted into a number of distinguished units (sectors). This design offers several advantages. The modular construction of the magnet greatly reduces the mass of the iron, so that the accelerator can be made larger (thus increasing the final energy) without a correspondent, cubic increase in the magnet weight. Focussing is enhanced, due to the increased modulation of the magnetic field deriving from the use of small magnet gaps, which also reduces the power consumption. Plenty of space is available between adjacent sectors for allocation of RF cavities, diagnostics equipment and injection and extraction elements. More powerful cavities can be used to increase the energy gain at each gap crossing: this in turn means a larger separation of the orbits, resulting in a higher extraction efficiency.

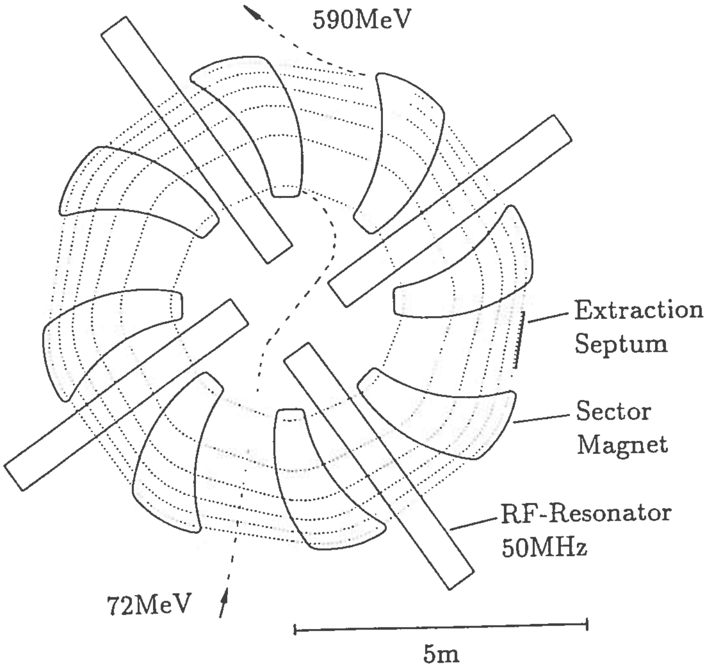


FIG. 7 - Sketch of the 590 MeV separated sector cyclotron at PSI (from ref. 7).

On the other hand, the ions can not be accelerated from zero energy. The cyclotron has thus to be coupled to a pre-accelerator (which may be an electrostatic accelerator, a linear accelerator or another cyclotron) supplying a certain energy (which can be as high as several tens MeV) to the particle beam, before it can be injected into the main machine. The largest facility of this kind is the 8-sector cyclotron of the Swiss PSI (formerly SIN), accelerating protons to 590 MeV. Fig. 7 is a schematic plan view of the machine, while Fig. 8 shows the whole facility. Very high beam currents (about 1 mA) are achieved by means of a particular technique, i.e. "flattopping" the RF [illegible] adding extra cavities operating on the third harmonic of the fundamental

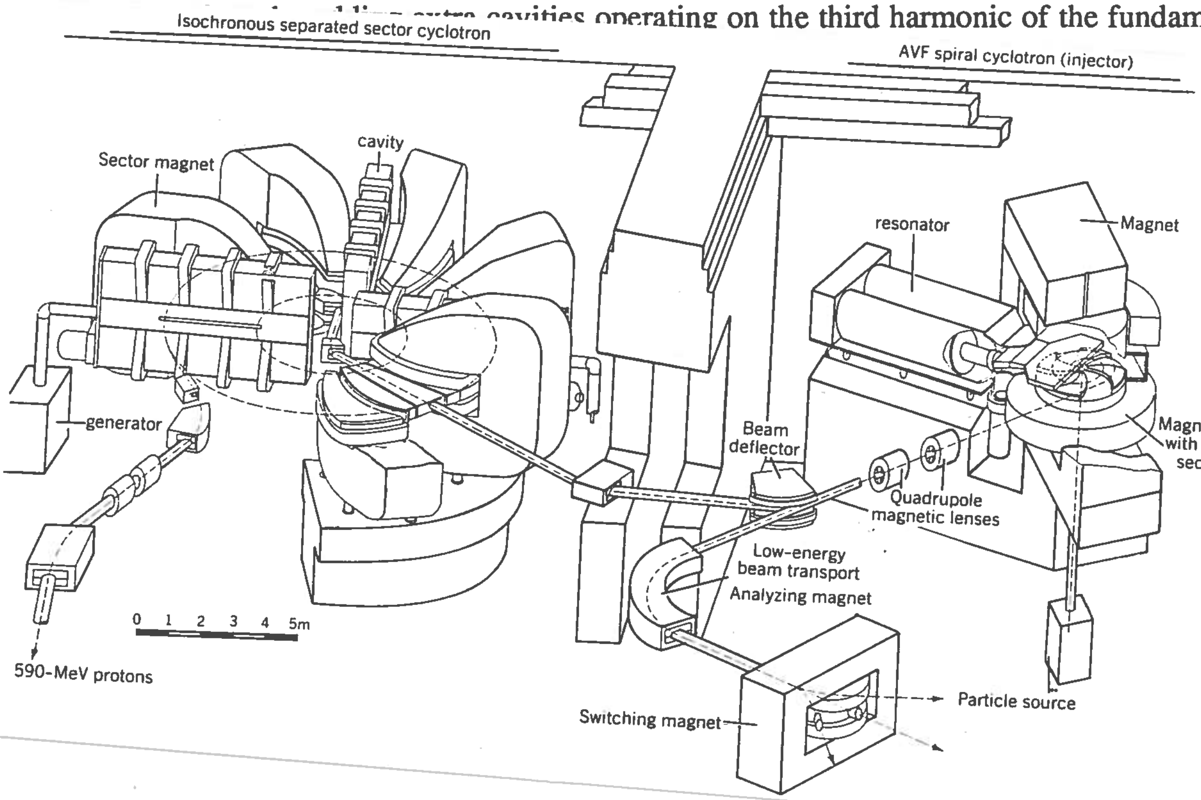


FIG. 8 - The PSI facility, with the injector AVF cyclotron and the 590 MeV separated sector cyclotron (from ref. 5).

3.5. - The superconducting cyclotron

We have seen from expression (7) that the maximum energy obtainable from a cyclotron, for a given species of ion, is a function of machine radius and magnetic field. The types of cyclotron described earlier were based on the increase of the former parameter, although by use of different technical solutions. The discovery of superconductivity opened the possibility of generating higher magnetic fields (typically two to four times higher than those produced by conventional magnets) by means of superconducting coils. The first project of this kind was undertaken at the Michigan State University (U.S.A.)(9,10) and at present a number of superconducting cyclotrons are under development (one of which at the University of Milan(11)) or already operational.

The high magnetic field obtained in a superconducting cyclotron allows the construction of a compact accelerator, with a reduction in size, magnet weight and cost. On the other hand, new technological problems arise, such as those due to cryogenics aspects. Moreover, the coils are subjected to intense forces caused by the strong magnetic field and therefore particular care is required to maintain them fixed in their position, since any small movement can cause a quench. Additional problems are represented by the reduced dimensions of the machine, which make difficult the allocation of equipment (such as vacuum pumps, RF systems and diagnostics elements) in the vacuum chamber, and the little separation of the orbits (caused by the strong magnetic field) which in turn means problems in the extraction of the beam.

The construction of superconducting cyclotrons for routine applications is not only promising, but is becoming a reality. In particular, two examples should be mentioned. First, a compact, superconducting cyclotron has been design and built by the MSU group and recently installed at the Harper-Grace Hospital in Detroit, for use in neutron therapy: this will be better discussed in section 5. Second, a commercial company is developing an ultralight H^- cyclotron with superconducting coils but no conventional return yoke.(12) Two versions of the accelerator should be built: a 12 MeV model for hospital-based installation, for the on-line production of positron emitting radionuclides for PET studies, and a 17 MeV version to be used for neutron radiography. In the latter case, the little overall weight of the cyclotron and the neutron moderator (about 2 tonnes) would allow the whole assembly to be installed on a mobile unit (e.g., a lorry) for easy transportation and use on the field.

3.6. - The superconducting separated orbit cyclotron

We shall conclude this overview of the cyclotron evolution by briefly describing a type of accelerator which represents a new concept in cyclotron design. At Munich University a project is under development for the realization of a separated orbit cyclotron (called "Tritron") with a K-value of 88 MeV, with both magnets and RF cavities superconducting.(13,14) This design is an improvement of an idea first proposed in the mid-Sixties(15,16) for an accelerator with individual magnetic channels: the ions follow a spiral path inside narrow channel magnets (Fig. 9). This design combines the features of a cyclotron, a synchrotron and a linear accelerator (from the sketch in Fig. 9, the accelerator looks like a rolled up linac!). The high energy gain of 3 MeV/turn ensures a separation of the orbits large enough to realize separated magnetic channels: thus the average magnetic field can increase with machine radius in order to satisfy the condition of isochronism, but at the same time the field gradient can be adjusted locally to guarantee vertical focussing.

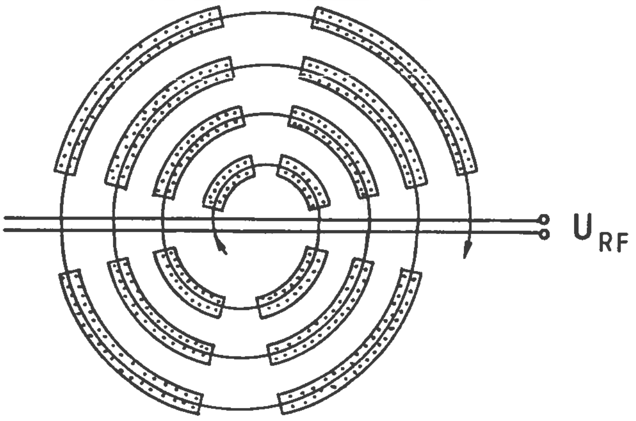


FIG. 9 - Sketch of the Tritron showing the acceleration gap and the individual magnetic channels around each orbit (from ref. 7).

The cyclotron, which will work with a 13 MV tandem as injector, consists of 12 sector magnets and 6 RF cavities, enclosed in a single vacuum chamber. The accelerator is extremely light and compact (Fig. 10) and because of its peculiar design it also possesses the property of phase focussing. This feature provides the Tritron with the possibility of achieving beam intensities much higher than those obtained with conventional cyclotrons.

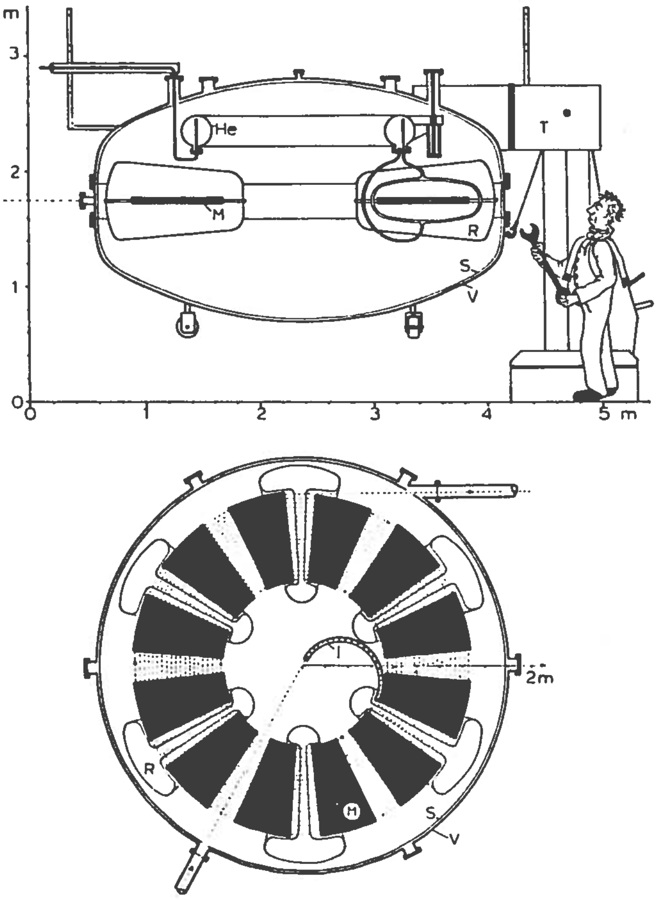


FIG. 10 - Vertical and horizontal cross sections of the Tritron. M: magnets, R: rf cavities, I: injection magnet, V: vacuum vessel, S: 80 K shield, He: support and liquid helium reservoir, T: support. The dotted lines indicate the 20 separated turns (from ref. 13).

4. - NEGATIVE ION CYCLOTRONS

A category of cyclotrons which has gained a widespread popularity, in particular for radionuclide production purposes, is that one accelerating negative ions.$^{(17\text{-}19)}$ This type of cyclotron offers the advantage of an easy extraction of the beam, with virtually 100% extraction efficiency (versus typical values of 60-80% for positive ion accelerators). Extraction is achieved by simply "stripping" the ions of their electrons, a procedure that instantaneously reverses the state of charge and hence the bending radius of the particles, directing them out of the machine. By a proper choice of the position of the stripping foil (or foils), it is possible to obtain an easy variation of the energy of the particles, to direct the beam to different extraction channels and even extract more than one beam at the same time, without the need of modifying the parameter setting of the accelerator. On the other hand, a better vacuum is usually needed than in the case of positive ion cyclotrons, since early stripping of the ions by the residual gas molecules affects the performance of the accelerator and produces an undue activation of the vacuum chamber.

The factor which in the past has been the limiting one, the availability of intense negative ion sources, is now overcome, even if the existing sources are only capable of producing H^- and D^- ions. However, for radioisotope production this capability meets most of the requirements. In effect, the intense external beam currents (in some cases several hundreds microAmpères), allowed by the combination of the high intensity ion source and the full extraction efficiency, need be best exploited by splitting the beam and making use of different irradiation channels at the same time. The possibility of having several extraction ports (which is not possible with positive ion cyclotrons), even if not used simultaneously, offers the additional advantage of simplifying the cyclotron operation by having several targets permanently installed in position, and this is an obvious advantage in the case of routine radionuclide production (e.g., in hospital-based facilities). This is in effect the actual trend followed by commercial cyclotron manufacturers (see Section 6).

5. - BIOMEDICAL APPLICATIONS

Apart from nuclear physics, cyclotrons are employed for applied research in many disciplines. One of the main fields in which they have met a major interest is biomedicine,(20,21) and in particular the two most important applications are represented by radionuclide production and cancer radiotherapy.

For convenience, cyclotrons can be divided into three classes, according to their K-value as defined by expression (8) in Section 2 (which may coincide with the maximum energy for protons): $K<18$ MeV, 18 $MeV<K<40$ MeV and $K>40$ MeV respectively. Each class is capable of specific performances. In the case of radioisotope production, for instance, cyclotrons belonging to the first class ("baby cyclotrons") are mainly capable of producing the short-lived positron emitters ^{11}C, ^{13}N, ^{15}O and ^{18}F for PET studies. Cyclotrons of the second class can produce most of the radionuclides of present and future interest in industrial quantities, whilst cyclotrons of the third class are capable of producing some ultra-pure radionuclides exploiting higher energy nuclear reactions.

Since radionuclide production and the related topics are the subject of specific talks of the workshop, here we will only give a very brief account of the other most important medical application: cancer radiotherapy with fast neutrons and charged particles.

5.1. - Neutron and charged particle radiation therapy

The bases on which the use of fast neutrons in cancer therapy stands are essentially radiobiological.(22-24) Apart from the very first attempts at the end of the 1930's, the investigations about the potential benefits of using fast neutron beams in tumour radiotherapy were started in 1966 at Hammersmith Hospital, London, and later undertaken at several centres all over the world. Up to now no final conclusions have been drawn, but the studies performed until the early 1980's have been penalized by a number of technical shortcomings and thus carried out under conditions far worse than those offered by modern megavoltage radiotherapy units. At present clinical trials are under way at a number of new facilities specifically designed to this purpose and based on a high energy cyclotron ($K>50$ MeV).(25,26) These trials will provide a correct intercomparison with standard radiotherapy treatments and make clear whether neutron therapy can be considered, for specific tumour types and sites of treatment, a superior therapeutic tool.(27,28)

As it was mentioned earlier, an interesting development in cyclotron design has brought to the realization of a compact, superconducting cyclotron, mounted on a movable assembly which can rotate around an isocentre (Fig. 11).(29,30) This arrangement avoids the need for a beam transport system and a complex rotating gantry (see Fig. 12), which are standard features in modern neutron therapy facilities,(26) ensuring at the same time optimal treatment conditions. The accelerator, installed at the Harper-Grace Hospital in Detroit, costs about 1/3 of a room temperature neutron machine. The magnet weighs 22 tonnes, the average magnetic field is about 4.6 Teslas and the maximum field is 5.4 Teslas.

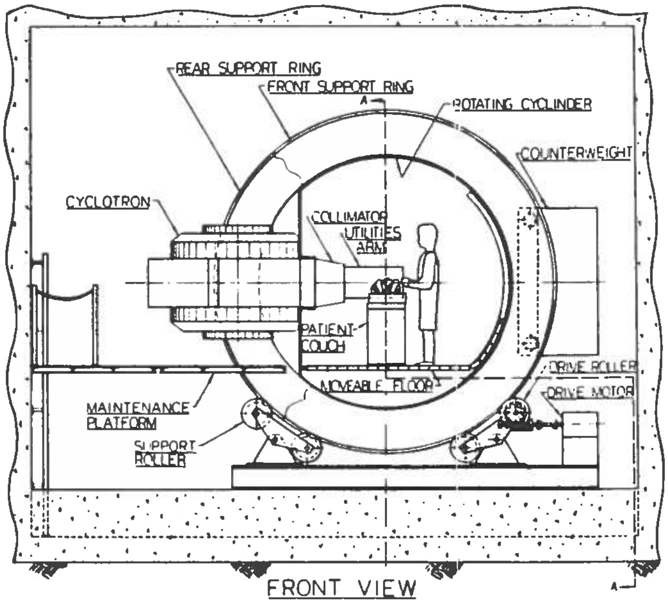


FIG. 11 - Sectional view of the Detroit superconducting cyclotron for neutron therapy (from ref. 29).

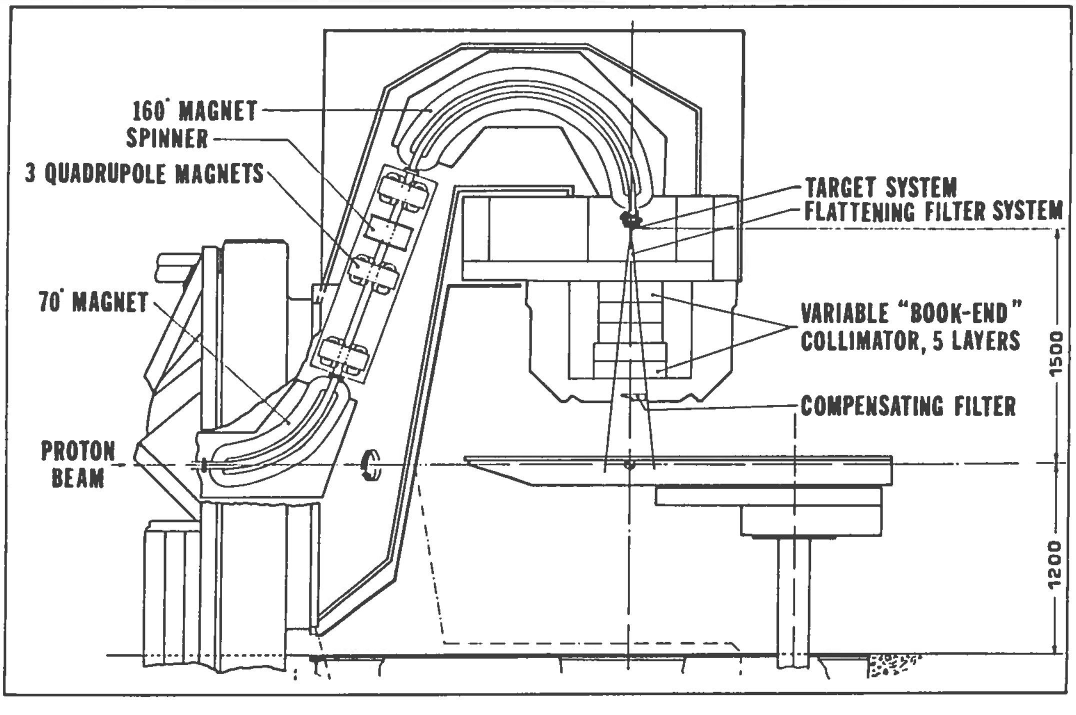


FIG. 12 - Sectional view of an isocentric neutron therapy gantry (from ref. 26).

Proton therapy(22,31) was started in 1961 at the Harvard Cyclotron Laboratory (U.S.A.) and is currently carried out or planned at several facilities in the U.S.A., in Japan, in the U.S.S.R., in Europe and in South Africa.(32-40) The advantages offered by the use of protons in radiation therapy are essentially dosimetric: low lateral scattering, limited range and increasing dose with increasing penetration in tissue. These features allow a very selective irradiation of the target volume with a considerable sparing of the adjacent structures. Skin sparing is also greatly enhanced with respect to photons. In the irradiation of extended tumours the narrow Bragg's peak need to be spread out on a larger volume by modulating the energy of the beam. This can be achieved, for instance, by a rotating aluminum degrader of variable thickness. Although in this case the surface dose increases, sparing of the skin and of the healthy tissue is still considerable. On the other hand, the treatment of most of the tumours requires proton energies in the range 150-250 MeV, i.e. the use of large and expensive cyclotrons and treatment units.

However, the treatment of a specific class of tumours, that of ocular melanomas, only requires 60-70 MeV protons(41) without the necessity of an isocentric unit, and is therefore more affordable. The first trials reported very positive results(42-44) and this technique is now considered a valid alternative to enucleation. Following these first successes, a number of hospital-based installations have been recently set up to undertake a clinical programme.

Although synchrotrons are also being considered for proton radiotherapy, so far most of the patients have been treated using synchrocyclotrons primarily used for physics research. Future dedicated facilities will have to make a choice between the two types of accelerator.(45) A preliminary design for a rotatable 250 MeV proton synchrocyclotron has been carried out by the MSU group: as it is shown in Fig. 13, the accelerator plus the beam line can be rotated around an isocentre allowing a 360° irradiation of the patient. The overall weight of the accelerator, counterweight and support would be about 150 tonnes.

In addition to the dosimetric advantages already mentioned for protons, heavier ions (in

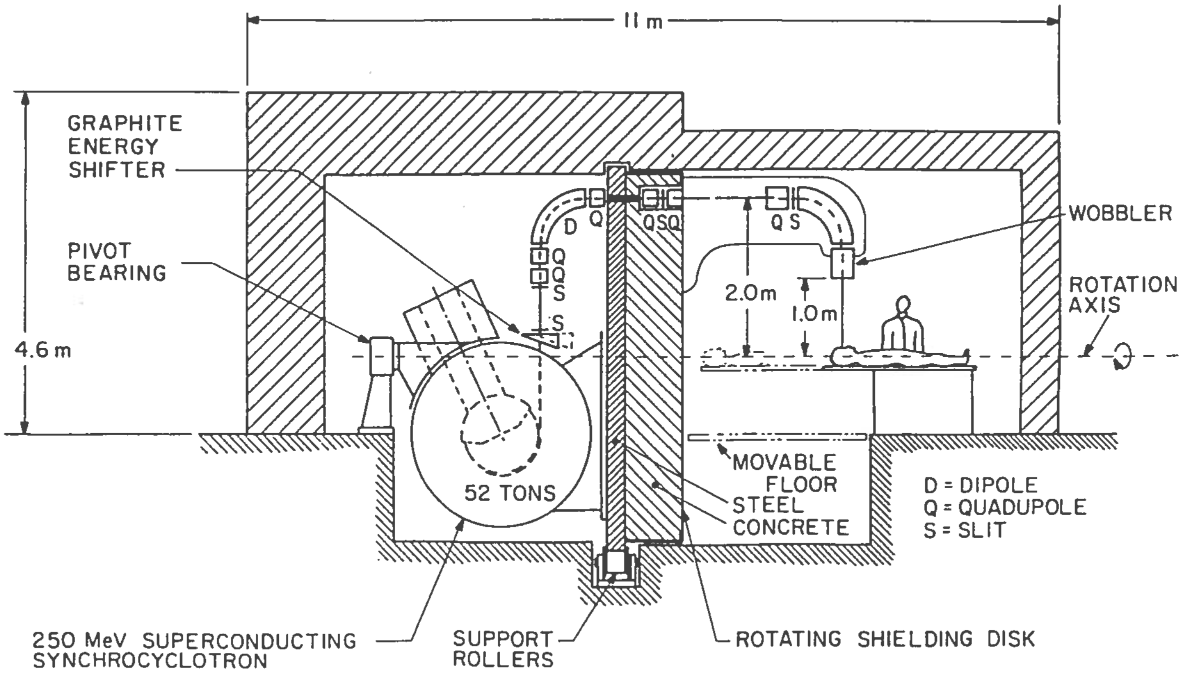


FIG. 13 - 250 MeV proton synchrocyclotron for radiation therapy (from ref. 7).

particular carbon, oxygen and neon) show an increased biological effect at the end of their range in tissue.(22) These combined properties probably make them the best radiotherapeutic tool, but the size and cost of a facility based on a cyclotron delivering heavy ions of several hundreds MeV per nucleon are considerable. Experimental cancer therapy has been carried out at the Lawrence Berkeley Laboratory (U.S.A.)(46) since 1975. Beams of pions are also used for therapeutic purposes at PSI (Switzerland) and TRIUMF (Canada).

A design study is presently being carried out for an EUropean Light Ion Medical Accelerator (EULIMA)(47), based on a separated sector cyclotron (four sectors) with one superconducting coil and an average magnetic field of 2-3 Teslas. The cyclotron should provide beams of light ions with $Z/A = 0.5$ (C^{6+}, O^{8+}, Ne^{10+}) with an energy of 400 MeV/amu, and should treat at least 1000 patients per year. Since it will need to be coupled with a pre-accelerator, it is planned to be installed either at Louvain-la-Neuve (Belgium) or Nice (France) and use the existing cyclotron (already employed for radiation therapy) as injector.

6. - COMMERCIAL CYCLOTRONS

Several models of cyclotrons of the three classes mentioned at the beginning of the previous section, accelerating light ions (protons, deuterons, ^3He and ^4He ions), are presently marketed by different manufacturers (Table 1). These companies also produce auxiliary equipment such as beam line components and targetry, processing systems, therapy units and positron emission tomographs. Most of these commercially produced accelerators are installed in hospitals, institutes for medical research and companies producing and trading radioisotopes, and are dedicated to activities in the biomedical field, particularly radionuclide production and neutron therapy. More than one hundred of these machines have been installed all over the world.(20,21)

Two trends should be mentioned. First, the growing interest toward PET applications have recently boosted the development of dedicated, low energy proton and deuteron machines, for the

TABLE 1 - Commercial cyclotron manufacturers.

CGR-MeV (now General Electric)	France
Computer Technology and Imaging	U.S.A.
Scanditronix AB	Sweden
The Japan Steel Works	Japan
Ion Beam Applications	Belgium
Techsnabesport	U.S.S.R.

on-line production of ^{11}C, ^{13}N, ^{15}O and ^{18}F. These accelerators are more compact, simpler to run and maintain, less expensive and require less shielding and infrastructures than multi-purpose cyclotrons, and are therefore ideal for hospital installation. They are usually supplied in conjunction with dedicated targetry and automated radiochemistry units. Second, the advantages offered by negative ion cyclotrons, mentioned in Section 4, make them particularly suited for routine use in hospital centres or for commercial radionuclide production, if there are not parallel requirements for other specific applications. This fact has led to an increasing interest by most of the manufacturers in the development and commercialization of such a type of accelerator.

7. - EUROPEAN STATUS

Fig. 14 shows the distribution of cyclotrons throughout Europe and Table 2 lists the existing facilities, specifying their location, the K-value of the machine as defined by expression (8) of Section 2, the accelerated particles and the applications the installation is dedicated to. This collection of data, which may possibly be non completely updated, refers to the end of 1988.

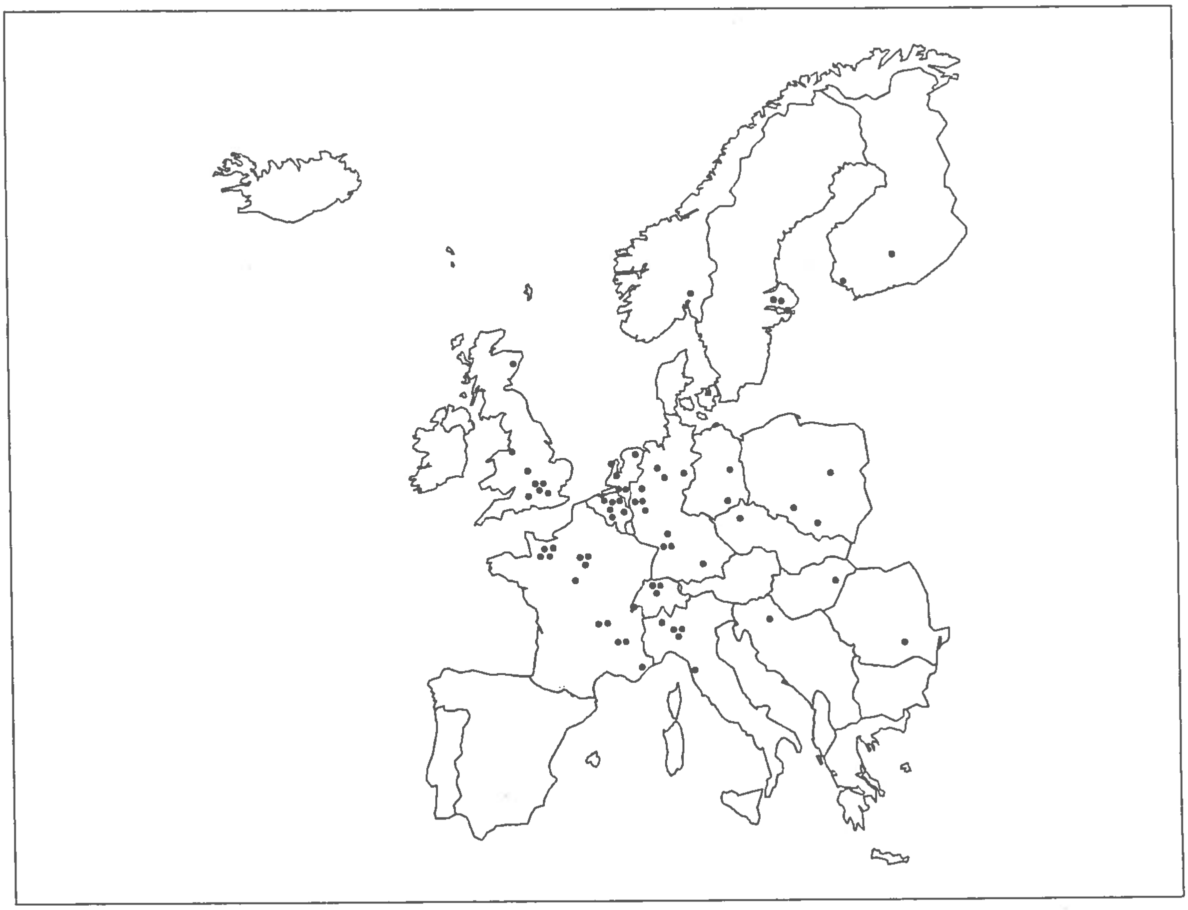


FIG. 14 - Cyclotrons in Europe.

TABLE 2 - European Status (end of 1988).

Location	K-value	Particles	Utilization
Belgium			
Brussels (U)	40	p,d,α	IP
Fleurus (U)	110	p,d,α	IP
Gent (U)	29	p,d,He-3,α	IP,PR,NT,BA
Liege (U)	29	p,d,He-3,α	BA,IP,PR
Louvain-la-Neuve (U)	130	LI,HI	PR,IP,NT,BA
Louvain-la-Neuve (U)	30	H^-	PR
Czechoslovakia			
Rez (U)	40	p,d,He-3,α	PR,IP,BA
Finland			
Åbo (U)	20	p,d,He-3,α	IP,BA,PR
Jyväskylä (U)	20	p,d,He-3,α	PR
France			
Caen (U)	380	HI	PR
Caen (H)	16	p,d	IP
Grenoble (U)	90	LI	PR,BA
Grenoble (U)	160	HI	PR
Lyon (H)	16	p,d	IP
Lyon (U) (6)	56	d,α	BA,IP,PR
Nice (H)	65	p	BA,NT (1)
Orleans (H)	50	p,d,He-3,α	MS,NT,BA,IP
Orsay (H)	29	p,d,He-3,α	IP
Orsay (U)	75	HI	PR
Orsay (U) (6)	223	p,d,He-3,α	PR,IP
Germany			
Berlin (U)	130	HI	PR
Bonn (U)	60	LI	PR,IP
Braunschweig (U)	28	p,d,He-3,α	PR,BA
Essen (H)	28	p,d,He-3,α	NT,BA,IP
Dresden (U)	30	p,d	IP,BA,NT
Göttingen (U) (6)	14	d,α	PR
Hannover (H)	35	p,d,He-3,α	IP
Heidelberg (H)	22	p,d,He-3,α	IP,BA
Jülich (U)	180	p,d,He-3,α,LI	PR,IP
Jülich (U)	28	p,d,He-3,α	PR,IP,BA
Karlsruhe (U)	104	d,α,LI	PR,IP,MS
Karlsruhe (U)	42	H^-	IP,MS
Munich (U)	22	p,d,t,He-3	IP

TABLE 2 (continued)

Location	K-value	Particles	Utilization
Hungary			
Debrecen (U)	20	p,d,He-3,α	PR,IP,BA
Italy			
Ispra (EC)	40	p,d,α	MS,IP
Milan (U)	800	LI,HI	(2)
Milan (U)	40	p,d,He-3,α	(3)
Milan (H)	11	H^-	IP
Pisa (H)	16	p,d	IP
Yugoslavia			
Zagreb (U)	30	p,d,α	BA,PR
The Netherlands			
Amsterdam (U)	30	p,a	PR,IP
Eindhoven (U)	30	p,d,He-3,α	IP,BA,PR
Eindhoven (U)	3	p	(4)
Groningen (U)	160	p,α,LI,HI	PR,IP,BA
Petten (I)	30	p,d,He-3,α	IP
Norway			
Oslo (U)	35	p,d,He-3,α	PR
Poland			
Krakow (U)	60	p,d,α,LI	(1)
Swierk (U)	30	H^-	IP
Warszawa (U)	180	LI,HI	(1)
Romania			
Bucharest (U)	40	p,d,He-3,α	BA,MS
Sweden			
Stockolm (H)	17	p,d	IP
Uppsala (U) (6)	200	p,d,α,LI	PR,BA (5)
Uppsala (I)	40	p,d,He-3,α	PR

TABLE 2 (continued)

Location	K-value	Particles	Utilization
		Switzerland	
Geneva (CERN) (6)	800	p,He-3,LI	PR
Villigen (U)	135	p,α,LI	PR,IP,BA
Villigen (U)	72	p	BA,IP
Villigen (U)	590	p	PR,BA,MS
		United Kingdom	
Aberdeen (H)	28	p,d,α	IP
Amersham (I)	30	p,d	IP
Amersham (I)	42	H^-	IP
Amersham (I)	40	p	IP
Bebington (H)	62	p	NT,IP
Birmingham (U)	25	D^+,He-3,α	IP,PR
Harwell (U)	86	p,LI,HI	PR,IP,MS
London (H)	40	p,d,He-3,α	IP,BA

Location: U = University or Government, H = Hospital, I = Industry, EC = European Community. Accelerated particles: LI = Light ions, HI = Heavy ions. Utilization: IP = Isotope production, BA = Biomedical applications, NT = Neutron therapy, PR = Physics research or accelerator development, MS = Material studies. Notes: (1) Under completion, (2) Superconducting cyclotron, under construction, (3) Project under development, (4) Minicyclotron ILEC, (5) Recently reconstructed, (6) Synchrocyclotron.

8. - CONCLUSIONS

From its early days the cyclotron has undergone a number of major technical developments. Although fundamental physics is now in general carried out by means of larger accelerators (synchrotrons and storage rings), cyclotrons still play a relevant role in many different fields, from research to industry, from biomedicine to material science. The commercial versions marketed by a few manufacturers now offer a good degree of reliability. Parallel developments have also occurred in ancillary systems, such as computer control, beam diagnostics and external ECR ion sources, as well as targetry and radiochemical processing units.

Developments are still going on in the field. The construction of superconducting cyclotrons has led to the acceleration of heavy ions to energies of several tens MeV/amu with machines of compact size. Besides their use for fundamental nuclear physics, superconducting cyclotrons are likely to find increasing applications in different fields.(48) A new concept in cyclotron design, the Tritron, is also been currently developed. The challenge of high intensity beams has been successfully managed, and there are now commercial machines capable of simultaneous extraction of two beams, with up to 500 μA total beam current. Multiple beam operation has also been achieved,(49) as well as the acceleration of radioactive ion beams.(50-53)

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