RECENT DEVELOPMENTS IN SUPERCONDUCTING CYCLOTRONS

H.W.Schreuder, Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, Netherlands.

I. INTRODUCTION

Superconducting cyclotrons have come of age: three machines have been operating on a regular basis since several years. These first generation machines have benefited from improvement programs and new equipment, while proposals for further expansion of their capabilities have been elaborated. The most significant events of 1994 have been the first beams in two new machines: the AGOR cyclotron in Orsay (France) and the K800 cyclotron in Catania (Italy). The first beam of the machine in Catania, Ni ions at 30 MeV/A, crowned a long construction effort, requiring transport of the magnet from Milan and assembly of the accelerator at its final location on the island of Sicily. AGOR, the first machine of a new generation, accelerated and extracted α-particles with an energy of 50 MeV/A, proving the validity of a number of novel design features. The vitality of the concept of using superconducting coils in a cyclotron is demonstrated by new proposals for such machines, to be used in cancer therapy.

II. THE FIRST GENERATION

1. Catania

The Catania cyclotron [1], now being commissioned, is certainly the first cyclotron to have traveled more than 1200 km from the place of conception to its final site. Starting in 1992, subsystems have been moved from Milan to Catania for integration with a previously installed tandem accelerator into a dual accelerator. This operation was crowned with success when a Ni beam at 30 MeV/A was extracted on December 22, 1994. An overview of the cyclotron with beamlines for injected and extracted beams is shown is figure 1. Since design work started in the 1980's, the machine can be described as the last member of the first generation of cyclotrons with superconducting coils. Not surprisingly, its design closely parallels those of the MSU machines: several members of the Italian team have intensively collaborated in the MSU design studies. Similarly to the TASCC facility, a Tandem accelerator is used as an injector. However, at Catania the installation of a system for axial injection of the beams is being prepared. In this context, the project SERSE has been started in collaboration with CEN Grenoble (France), with the purpose of constructing an ECR ion source with superconducting coils. Since the cyclotron will predominantly accelerate heavy ions, beam diagnostics is centered on the application of visual techniques, pioneered at MSU [2], which exploit fluorescent screens and ccd camera's.

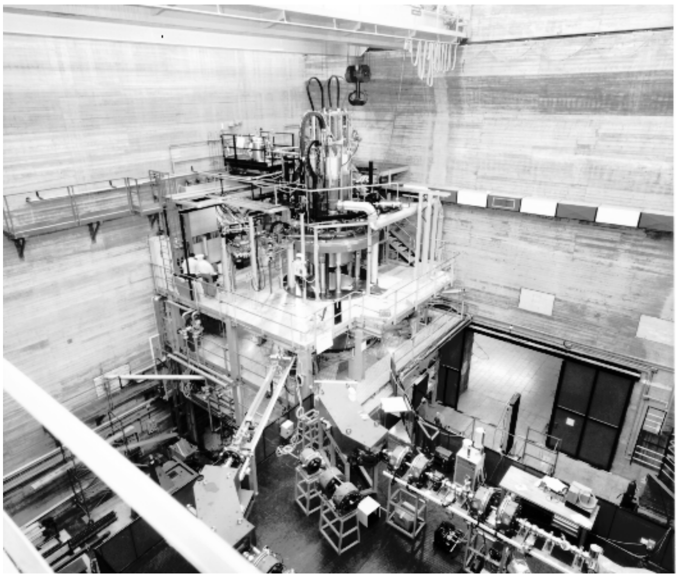

Figure 1: The Catania cyclotron with beam lines for injected and extracted beams.

The lower pole of the magnet is illustrated in figure 2, showing the main beam probe on its guiding track. The cylindrical housing on the probe is the air enclosure of the camera and the plate at 45° is the alumina scintillator. Interestingly, a movable copper plate can be made to slide in front of the scintillator. It is driven by a small coil, which rotates in the ambient magnetic field when current is applied to it, as a motor. Since ccd camera's are damaged by a radiation dose in excess of 10^5 Gy, the applicability of these instruments for viewing high-energy beams is limited.

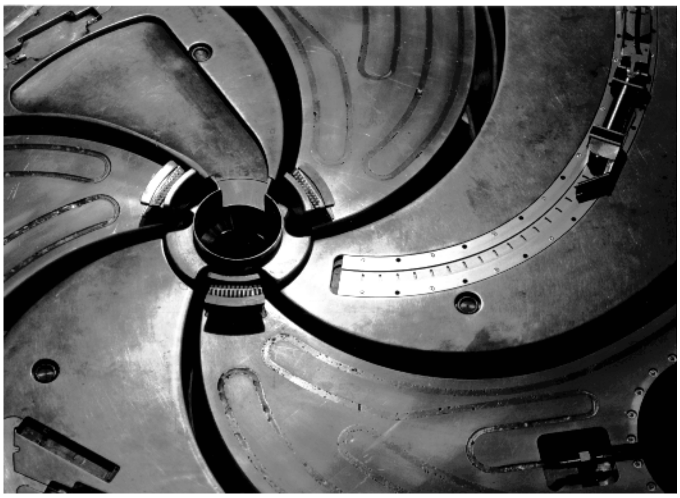

Figure 2: Catania: lower pole with beam probe.

2. MSU K1200 cyclotron

The K1200 cyclotron at MSU [3] has started operations in 1989. Its status as the most powerful machine in the class of cyclotrons with superconducting coils remains unchallenged. In recent years, development work has focused on commissioning new beams and approaching the operational design limits of the machine. This work has greatly profited from the successful development program for ECR ion sources. The superconducting ECR source is among the best in the world: it produces completely stripped ions up to Z≈18 and high Z ions with charge states up to 40^+, allowing the acceleration of Uranium ions to energies of 25 and 30 MeV/A. The range for Xenon beams has recently been extended upwards and is now 20-100 MeV/A. The highest energy beams are those with charge state Z/A=0.5, which can be accelerated to a maximum energy of 200 MeV/A: fully stripped O is a typical example. In addition to heavy ions, H_2^+ beams have been produced at that energy, adding the capability for producing proton beams, unexpected in this heavy -ion cyclotron. The machine has therefore demonstrated the capability of covering the entire periodic table. Operational experience has allowed the reduction of the time required for beam changes to typically 4 h. Table 1 presents a summary list of extracted beams as of October 1994.

Ion	Energy (MeV/A)	Ion	Energy (MeV/A)
H_2^+	140, 155	^{48}Ca	55, 100
^{4}He	40-170	^{51}V	50
^{6}Li	65-100	^{52}Cr	60
^{11}B	32	^{55}Mn	70
^{12}C	22-155	^{58}Ni	50-70
^{14}N	35-130	^{84}Kr	22-70
^{16}O	25-200	^{86}Kr	35-100
^{20}Ne	30-170	^{92}Mo	70
^{24}Mg	60	^{106}Cd	60
^{28}Si	50, 80	^{129}Xe	20-70
^{36}Ar	22-160	^{136}Xe	30, 35
^{40}Ar	25-115	^{197}Au	20-35
^{40}Ca	55	^{238}U	20, 25

Table 1: K1200 Extracted beams (summary)

3. TASCC

The design operating diagram for this coupled Tandem-Cyclotron accelerator [4] is now fully covered. In fact, as illustrated by figure 3, the diagram has been extended beyond the original specifications by accelerating ^{3}He beams to energies of 20 and 30 MeV/A. In 1994, a reliability of 90% has been obtained for the dual accelerator system. With the aims of increasing beam intensity and adding new elements to the beam list that are not available with the standard sputtering source, the Tandem has recently been equipped with an ECR ion source coupled to a charge-exchange channel. The source is optimized to produce high-intensity, singly charged ions. With a typical charge conversion efficiency of 12%, 15 μA of Bi $^{1-}$ ions are available to date for injection

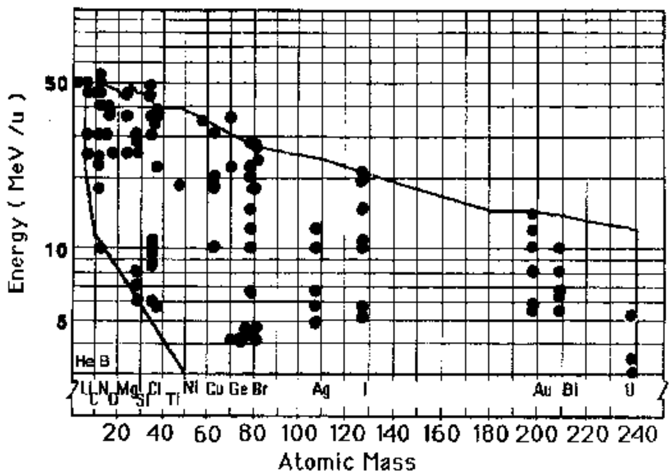

Figure 3: TASCC operating diagram

into the Tandem. Improvement by at least an order of magnitude is foreseen [5]. A long-term research and development program, aimed at understanding the problems of holding the high electric fields needed in the electrostatic deflector of a high magnetic field cyclotron, was started in 1991 [6]. The practical success of this research effort is demonstrated by an electric field of 175 kV/cm now being sustained in operating conditions [5].

4. TEXAS A&M

Like the other cyclotrons of the first generation, with the exception of the Catania facility, the cyclotron at Texas A&M University is in the phase of active utilization. This phase is characterized by intensive use of the machine and

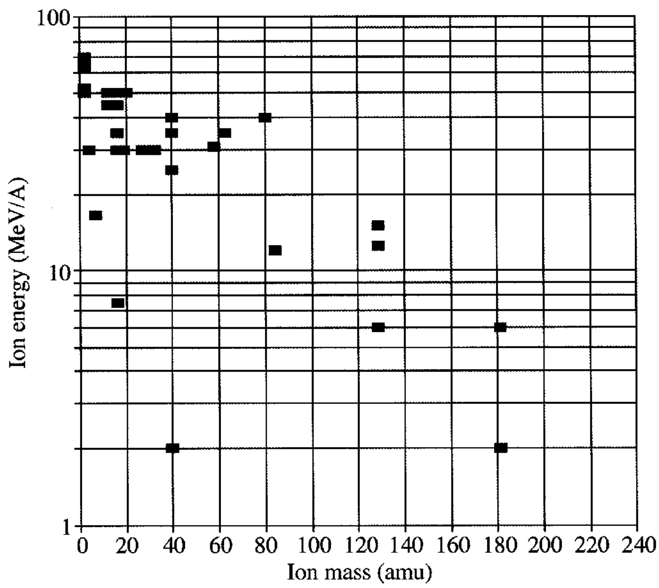

Figure 4: Representative beams extracted from Texas A&M K500 cyclotron.

gradual commissioning of new beams.Little time is available for technical developments, as is to be expected in an efficiently operated facility.

III. SECOND GENERATION: AGOR

This cyclotron, resulting from a French-Dutch international collaboration, can be considered to be the first of the second generation of cyclotrons with superconducting coils [7]. It has been designed to accelerate all elements of the periodic table, including protons. AGOR was constructed at the Institut de Physique Nucléaire (IPN) at Orsay (France) and was successfully tested with its first extracted beam of 50 MeV/A α-particles in April, 1994. The cyclotron was subsequently disassembled and transported to its final destination, the Kernfysisch Versneller Instituut (KVI) of Groningen University (Netherlands). Figure 4 shows the machine during reinstallation. The time schedule calls for final commissioning to start by mid-1995.
AGOR has been designed for a maximum proton energy of 200 MeV, close to the focusing limit of a three-sector cyclotron. The low value of the magnetic field required for proton acceleration, as well as the high rf frequencies needed, have

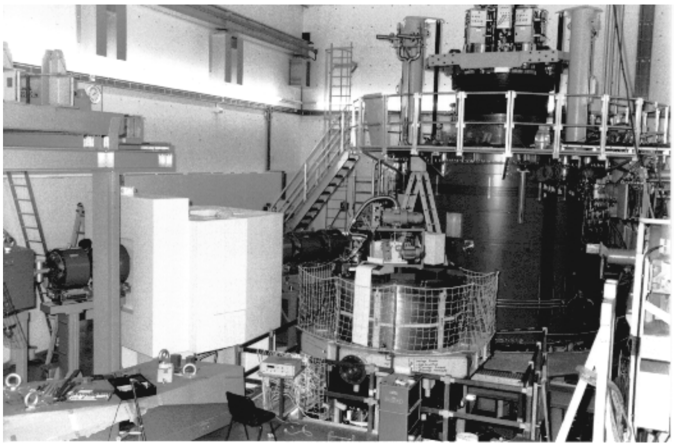

Figure 5: The AGOR cyclotron during reinstallation .

led to unusual design features.
i) It is a desirable analytical as well as operational feature of these cyclotrons that their magnets operate with saturated poles. This allows fields to be accurately calculated and to be obtained with excellent reproducibility. Since 200 MeV protons and a typical pole radius of 1m combine to an average field of only 2 T, the valleys in the AGOR poles are very deep to ensure saturation of the hills. ii) The revolution frequency of 200 MeV protons in a 2 T field is 31 MHz. For efficient acceleration using three RF resonators, the harmonic number should be at least 2, implying 62 MHz as the maximum accelerating frequency. Conventional half-wave coaxial resonators are used, in which the short circuit plate must be placed at about 40 cm from the median plane for obtaining this frequency [8]. This leaves insufficient space for a high-voltage feedthrough insulator. The entire resonator, including the movable short-circuits, is therefore placed in the machine vacuum. Since the stems of the electrodes have a length of 2 m (imposed by the low-frequency limit of 24 MHz), the required position accuracy of the accelerating electrodes of 0.3 mm, as indicated by central region orbit calculations, makes for a difficult mechanical design of the resonators.
Other novel design features are the following:
a) The magnet design aims at perfect three-fold symmetry to avoid conflicting criteria for main coil centering: minimization of radial force on coils versus minimization of the first harmonic in the beam region. For this reason, passive magnetic channels are not employed for beam extraction but active electromagnetic channels are used instead [9]. Such channels can be designed to provide deflecting fields up to 0.4 T and are therefore more powerful than electrostatic deflectors, which are fieldstrength-limited to the equivalent of typically 0.1 T. Their conductor configuration must be designed to provide deflection and focusing, as well as a high degree of cancellation of the magnetic field in the beam extraction region.
b) The arsenal of beam diagnostic equipment is shown in figure 6, representing a cross-section through AGOR's median plane and indicating the location of this equipment.

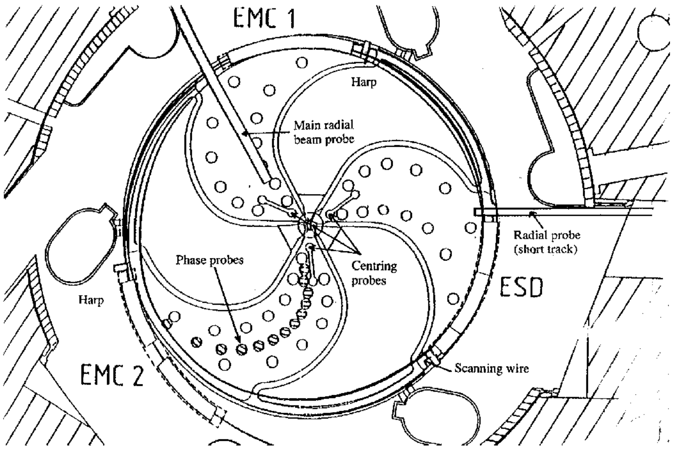

Figure 6: AGOR: cross-section through median plane, showing diagnostic equipment.

Novel features are the centering probes installed at R=0.3 m in each of the hills. Their active element is a tungsten wire scanning the beam density over a circular orbit with a 3 cm diameter. The off-centredness of the beam can be determined from the scans made by the three probes. Figure 7 represents the output of such a scan, demonstrating the ease with which individual turns can be located.
Conceptually simple, but uncommon, is the systematic use of diagnostic elements in the path of the extracted beam: each extraction channel has a diagnostic (harp, scanning wire) at its entrance and a total beam current measuring device at its exit.

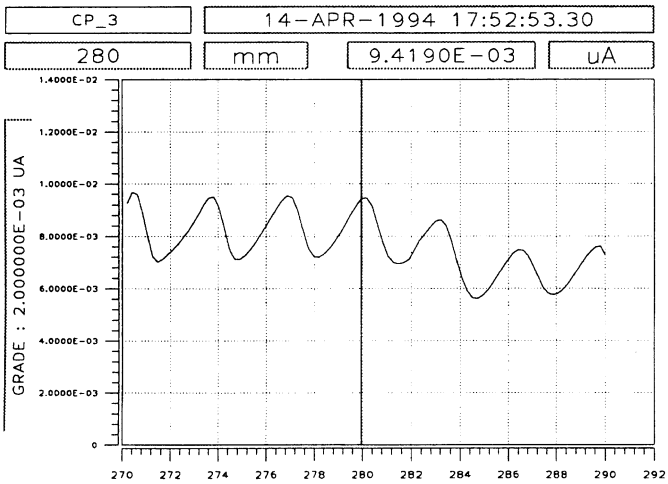

Figure 7: Output of a radial scan with one of the centering probes.

The utility of this arrangement was convincingly demonstrated the first time the beam was threaded through the long - nearly one full turn- path out of the cyclotron.. For beam phase measurements, an array of 13 electrostatic beam pickup probes has been installed, also shown in figure 6. Experiments with the 200 MeV α beam proved that the probes and the associated electronics are capable of producing valid phase information at a beam current as low as 80nA.

IV. UNCONVENTIONAL CYCLOTRONS

1. TRITRON.

The superconducting, separated orbit cyclotron Tritron [10], which has been in construction at the Munich Technical University for some time, is approaching the beam test phase. Tests have already demonstrated that the operation of the rf cavities is not perturbed by the stray field from the superconducting magnets and that their nominal voltage of 530 kV can be obtained. Assembly was completed early in 1994, when faults in the inter-coil connections became apparent. These have been remedied, and Tritron is now being cooled down in preparation for beam. Figure 8 shows the magnet sectors, the RF resonators and the injection magnets.

The concept of the separated orbit cyclotron is intrinsically suited for high-intensity beams, since it provides for longitudinal stability. There is thus more freedom for selecting the transverse focusing frequencies than in the case of the isochronous cyclotron. The very concept of a SOC implying a large energy gain per turn, it is significant for possible future proposals that the recent tests have demonstrated that the very high rf accelerating voltages can be obtained with superconducting cavities. It is remarkable that a design study for a 1 GeV, 10 mA machine seems to present no insurmountable difficulties.

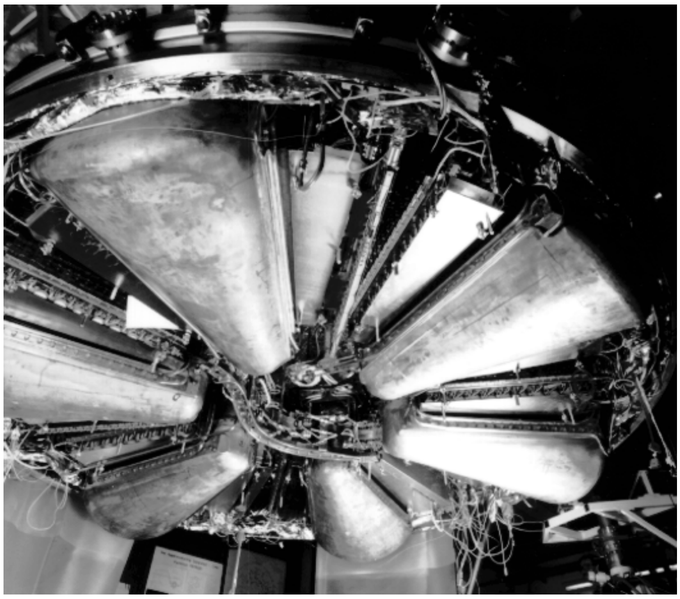

Figure 8: Tritron assembled (as seen from below).

2. OSCAR

The only cyclotron with superconducting coils to be commercially available, Oscar has been on the market since several years [11]. Nine machines of these 12 MeV proton cyclotrons have been installed and a tenth is now under construction. Most machines are used to produce PET isotopes. The beam current has been raised to 150 µA. The design of the machine is based on the magnet technology developed for MRI magnets; the coils are used in persistent mode. The remarkably small size of this cyclotron is demonstrated in figure 9, showing two of these machines side by side.

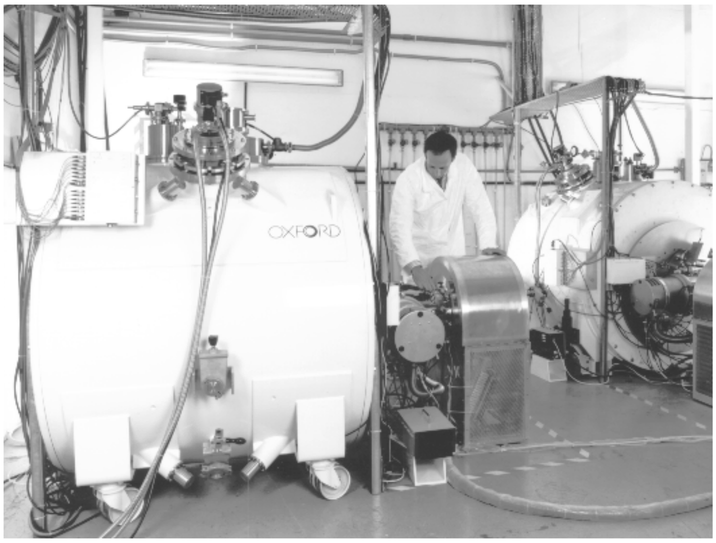

Figure 9: Two 12 MeV Oscar cyclotrons.

V. PROPOSALS

1. Cyclotrons for proton therapy.

There exists a widespread interest in using energetic ion beams for cancer therapy, as illustrated by a large number of conference contributions as well as by proposals for accelerators dedicated to this activity. Because of penetration depth, protons with energies of 200-250 MeV are the projectiles of choice. Indeed, the dedicated proton therapy facility at Loma Linda University is already operational since 1993. The Massachusetts General Hospital in Boston has ordered a 230 MeV proton cyclotron with IBA (Belgium). This machine has copper coils and is scheduled to be operational in 1998.

MSU

Approximately one year ago, the National Superconducting Cyclotron Laboratory at MSU published a design report for a 250 MeV cyclotron for proton therapy [12]. As is to be expected, this machine has superconducting main coils. The cyclotron will have an internal ion source. and its central region will be equipped with slits, so that pencil beams with very sharp time resolution will be accelerated and extracted. The small radial emittance will result in a nearly 100% extraction efficiency and allows the electrostatic deflector to have a small gap, leading to conservative voltage holding requirements. Although the slits will have sub-millimeter apertures, the transmitted current is estimated to be a few μA. Since the required beam current on target is typically 10 nA, the rf accelerating voltage will be pulsed with an appropriate duty cycle.

Milan

The Milan group, after having completed the design and construction of the K800 MeV cyclotron that is now being commissioned at its final site in Catania, has started a design study of a 230 MeV proton cyclotron with superconducting coils, to be used for radiotherapy [13]. The design aims at low costs of construction and of operation. For this reason, the coils will operate in persistent mode. Heat input will be minimized by using two thermal shields at 80 K and 20 K respectively, which are cooled by separate refrigerators of modest capacity. The liquid helium evaporation rate is expected to be only 10 l/day. The magnet has a diameter of 2.8 m and a height of 1.8 m and is therefore very compact.

2. NSCL Proposal

The K1200 cyclotron at NSCL is increasingly used for the production of radioactive beams. Evidently, improvement of the intensity of the primary beam is highly desirable. The laboratory has therefore elaborated a proposal [14], which aims at an increase in intensity with 3 to 4 orders of magnitude and at an increase of the highest attainable energy to 100 MeV/A for heavy ion beams up to A=200. In order to obtain a high charge state after final stripping, high-energy beams from the existing K500 cyclotron are to be injected into the K1200. The proposal calls for upgrades on most K500 subsystems to achieve reliable operation at beam currents up to 10 pμA. The K500 will be injected from one of the available ECR ion sources. Since only modest charge states are required for the K500, the required high intensities can be readily obtained. As a result, the K1200 will produce more intense heavy ions at higher energies.

VI. REFERENCES

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