AGOR : RECENT ACHIEVEMENTS

H.W.Schreuder *(for the AGOR staff)
Institut de Physique Nucléaire, 91406 Orsay, France†

ABSTRACT

The AGOR cyclotron, in construction since 1987, is now in the phase of field mapping and final assembly. The first results of the field mapping campaign are available. The construction of the RF resonators is nearly completed and the extraction channels will soon be ready for mounting in the machine. All subsystems are controlled by their dedicated section of the control system, the software for the central control consoles is being written.

1. INTRODUCTION

The major design parameters of the AGOR cyclotron, allowing acceleration of protons as well as heavy ions, have been presented previously.[1,2] Here, only the most salient design features will be briefly recalled. The two superconducting main coils produce the required level and gradient of the main field, without requiring polarity reversal. The main cryostat is designed to have a nearly unobstructed median plane, allowing radial insertion of the extraction channels. The RF resonators have no insulator and can therefore reach the frequency of 62 MHz, required for the acceleration of 200 MeV protons. The absence of an insulator implies that the resonators are placed in the machine vacuum. Beam extraction is done with an electrostatic deflector, followed by a room-temperature and a superconducting electromagnetic channel. A channel with superconducting quadrupoles provides focussing in the final traversal of the magnet yoke. A recent picture of the machine is shown in fig.1.

2. MAGNET AND CORRECTION COILS.

The magnet is constructed as a circular yoke consisting of 6 rings, in which upper and lower pole plugs are

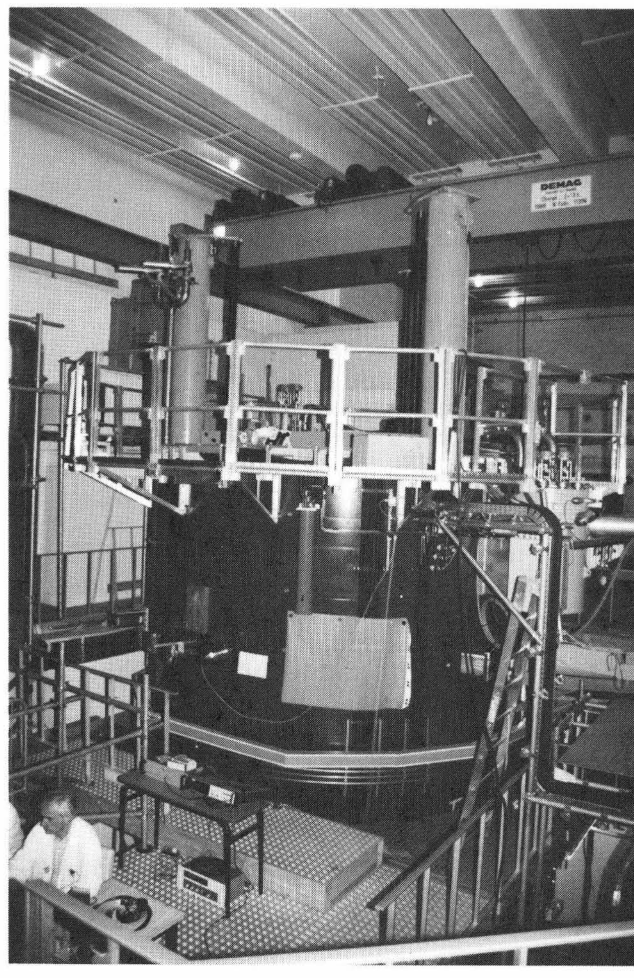

Figure 1. The AGOR cyclotron at the start of the field mapping campaign.

*permanent address: Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, Netherlands.

†Work jointly supported by the Institut de Physique Nucl'eaire et de Physique des Particules (IN2P3), France and by the Stichting voor Fundamenteel Onderzoek der Materie (FOM), Netherlands

inserted vertically. On the top and the bottom of the yoke lift mechanisms are permanently mounted. They are equipped with three motor-driven spindles for inserting and removing the poles from the yoke. The top pole can then directly be taken by the overhead cranes, the bottom pole lowers onto a rail-guided carriage, allowing sideways movement away from the yoke. When mounted, the position of the poles with respect to the yoke is defined by means of precision pins. Their coaxiality has been verified to be reproducible within approximately 0.01 mm after a significant number of removals and insertions. In the assembly hall, a motorized 'pole rotator' is used to select the proper up/down orientation of the poles for assembly operations.

The 15 correction coils are wound on the upper parts of the hill sectors and are made of water-cooled copper conductors, insulated with epoxy impregnated glass cloth. Figure 2 shows the lower pole, mounted in the yoke, equipped with correction coils. The radial arm of the field mapper is also shown. The power supplies for the correction coils have been installed and complete system tests have been performed in 1990.

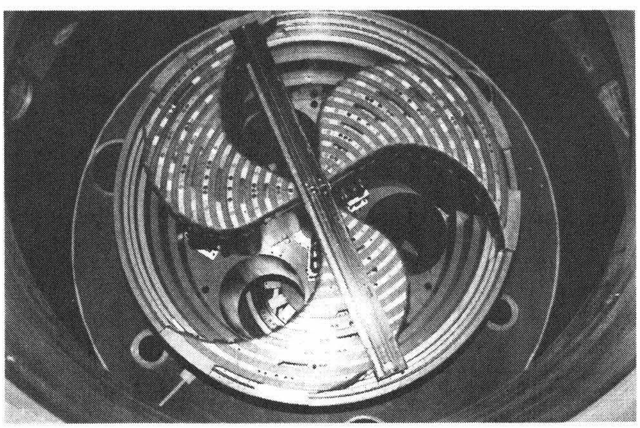

Figure 2. The lower pole with correction coils and field mapper.

3. MAIN COILS AND CRYOGENICS

The assembly of the main coils in their cryostat at the manufacturer Ansaldo (Genova, Italy) was completed in October 1991. Cooldown of the coils required 4 weeks, in agreement with expectations. The cooling rate was controlled for limiting the temperature difference between the warmest and the coldest coil to a maximum of 40 K in order to reduce stress in the coil impregnation due to shrinkage.

Factory acceptance tests were done in the first week of December when the heat input and the coplanarity and coaxiality of the two coil pairs were determined. The measured heat losses at 4 K and 80 K were 18 W and 70 W respectively and should be compared to the specified values of 12 W and 190 W. The coil position measurements were done with the coils at 50% of their maximum currents. In the absence of the magnet yoke, this excitation produces the maximum design value for the attractive force between the coils of 4.5 MN. The coplanarity and the coaxiality were found to be better than 0.1 mm each. Although the heat loss at 4 K is higher than specified, the cryostat and croils were provisionally accepted, after agreement had been obtained on improvements.

The system was finally delivered at the Orsay construction site on February 14, 1992, approximately 18 months later than the date foreseen in the contract.

Leak testing, assembly in the magnet yoke, cabling and cooldown proceeded without major difficulties, thanks to the dexterity of the assembly crew. Figure 3 shows the cryostat in the lower half of the magnet. Clearance between cryostat and yoke does not exceed 5 mm in any direction. The coils reached their operating temperature on May 12.

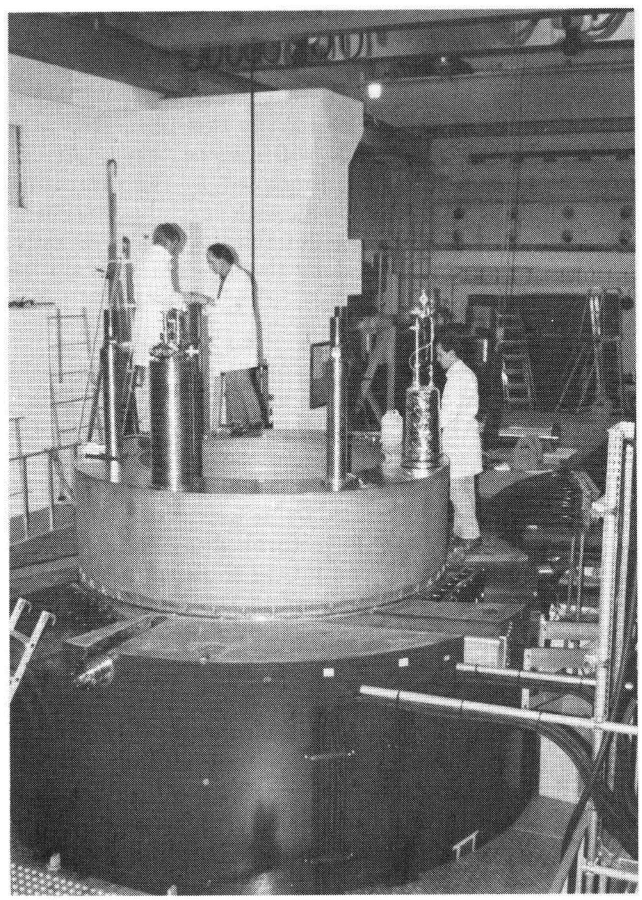

Figure 3. The cryostat, placed in the lower half of the yoke.

The liquid helium plant, centered around a TCF50 machine by Sulzer, has passed its final acceptance tests in 1991. Its nominal capacity is 600 W at 80 K, 50 W at 4 K while maintaining a helium liquefaction rate of

15 l/h. The installation is controlled through a PLC in which all standard operating procedures are programmed so that human intervention is not required for day-to-day operation of the cryostat and coils.

More details on the low-temperature tests on the coils are presented elsewhere in this Conference.[3)]

4. FIELD MAPPING

The field mapping operations will be performed in a number of sequential phases. In the first phase, the median plane field is mapped at 4 different field levels in order to determine the shimming required to optimize the currents in the correction coils. In a second phase, after completion of the shimming operations, the median plane field will be mapped for 25 sets of currents in the two main coils of the cyclotron. In this phase the field maps of the correction coils will also be taken. At the end of this phase the field produced by the extraction channel EMC-1 will be mapped, with special attention to its stray field in the region of circulating beam. Finally, in a third phase, the field along the injection axis will be mapped.

The design of the mapper for the median plane field has been inspired by the radial mapper used for measuring the field of the MSU K1200 cyclotron,[4)] and uses a radially moving search coil on a rotating arm. The height of the radial arm is only 16 mm, allowing field maps to be taken with the RF electrodes in place (of which only the central region noses have to be dismounted). This feature is important for the future transfer to the KVI: it will not be necessary to remove the resonators from the poles for allowing verification field maps to be taken after reassembly of the magnet.

The data acquisition software provides on-line error checking of the data in each radial series using polynomial functions in a sliding 5 cm interval around each measuring point. Tests using calculated field maps indicated that single errors of 2 mT can easily be detected and this is confirmed by experience gained with measured data. A suite of off-line data analysis routines has been readied well in advance. It allows spectral analysis, the production of contour plots, creation of difference maps, centering analysis etc.

As an example, fig.4 represents a spectral analysis of one of the first maps, taken at a central field of 2.2 T, at a radius of 0.8 m. Although erroneous data have not been corrected, the noise level is less than 1 mT.

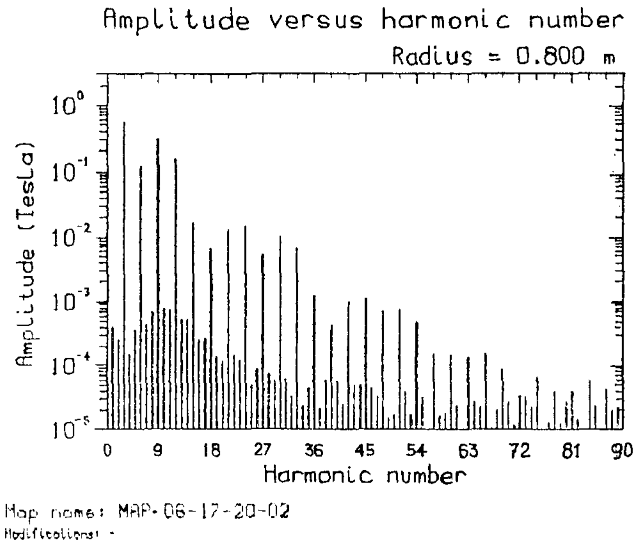

Fig.4. Measured field at $B_0 = 2.2\ T$: spectral analysis at r=0.8 m.

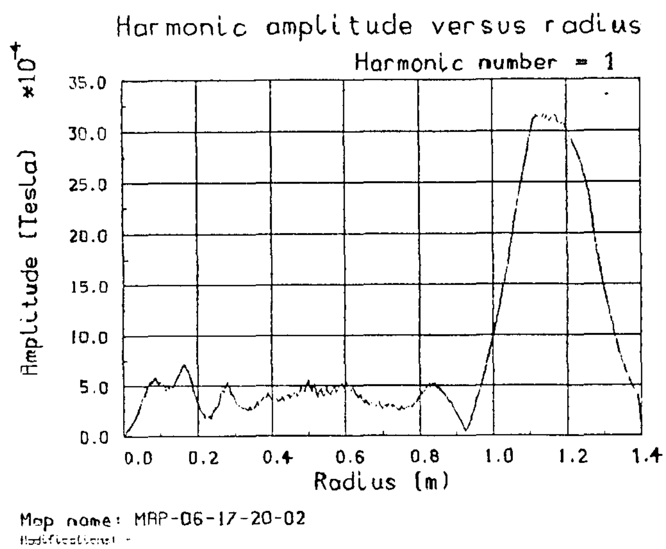

Fig.5. Measured field at $B_0 = 2.2\ T$: first harmonic amplitude as a function of radius.

Figure 5 shows the first harmonic amplitude as a function of radius derived from the same uncorrected data. The large peak at 1.2 m radius is caused by an as yet uncorrected centering error of the main coils of approximately 0.5 mm.

5. RF SYSTEM

The electrical design of the RF resonator system for the AGOR cyclotron and the building blocks for the stabilization of amplitude and phase have been described at a previous conference.[5)] Since then, the mechanical design of the resonators and the RF liners - which are also vacuum lids covering the magnet poles - has been completed and their construction is now nearly complete. Figure 6 shows one of the vacuum lids (or RF liners) after final cleaning at the factory. The design required machining of electron-beam welds. This has resulted in a number of vacuum leaks that have been difficult to repair. The lids are fixed to the hill sectors by means of 13 BeCu bolts per sector, each, of course, having a vacuum cover. The picture also shows dust covers on the apertures for the phase probes. Near the centre the mounting holes for the three centring probes[6] are visible.

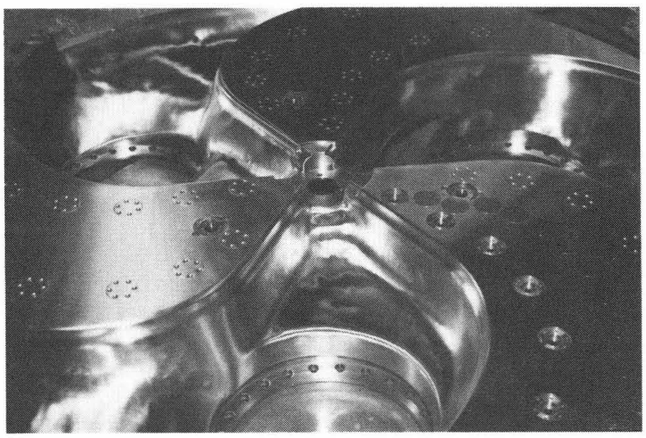

Fig.6. AGOR vacuum lid and RF liner.

The accelerating electrodes have been completed and have been fixed to the central conductors of the coaxial resonators. Figure 7 shows an interior view of one half electrode with its supporting frame and the mounting flange for a cryopump.[7]

The outer conductors and the positioning mechanisms for the short circuits have all been delivered on site. The drive mechanism for short-circuit positioning has been tested for reproducibility and position resolution. The results, better than 0.01 mm in both cases, were significantly better than the 0.04 mm specified contractually.

The three RF power amplifiers have been accepted after extensive tests at nominal power output. The regulation electronics for the three resonators have been built, as well as for the buncher in the injection beam line. Complete system tests have been performed on all regulation systems, using one of the power amplifiers and a test resonator. The measured amplitude stability was 1.2 10^{-4} and the phase was stable within 0.2 deg. The tests of the sliding RF contacts were satisfactory: the temperature rise at nominal current and at 60 MHz agreed with calculations as well as with extrapolations based on measurements at lower frequencies.

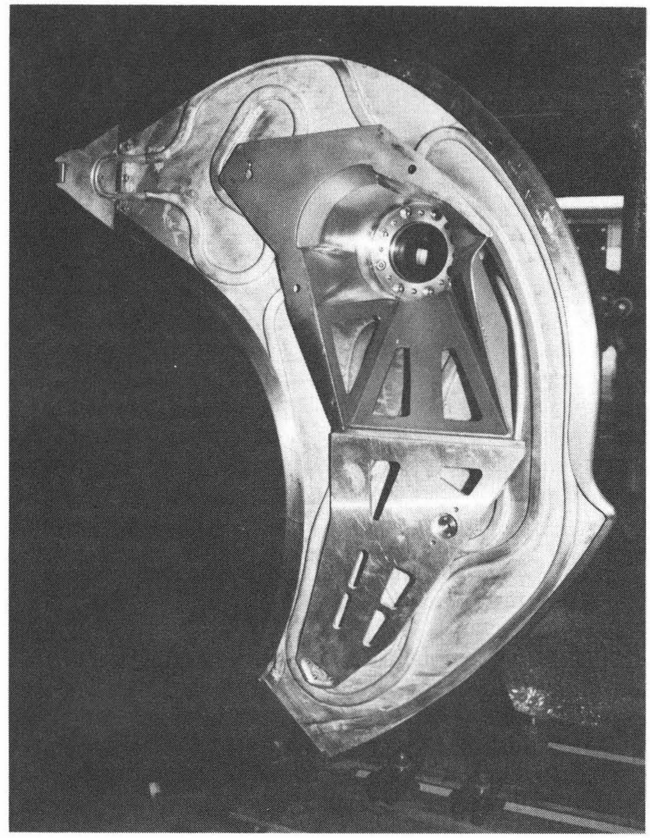

Fig.7. Interior view of acceleration electrode.

6. EXTRACTION

6.1. Overview

Beam extraction in the AGOR cyclotron is done via three deflectors and a focussing channel, shown in overview in figure 8. Beam deflection is achieved with an electrostatic deflector, an electromagnetic channel with water-cooled copper coils and an electromagnetic channel with superconducting coils. The two electromagnetic channels are provided with gradient coils for focussing. The quadrupole channel provides focussing and beam steering facilities before the beam enters the external beam line. All deflectors are inserted in the machine through radial apertures in the magnet yoke in the median plane. The machine vacuum is sealed with elastomer seals on one of the three large flanges in the median plane section of the cryostat.

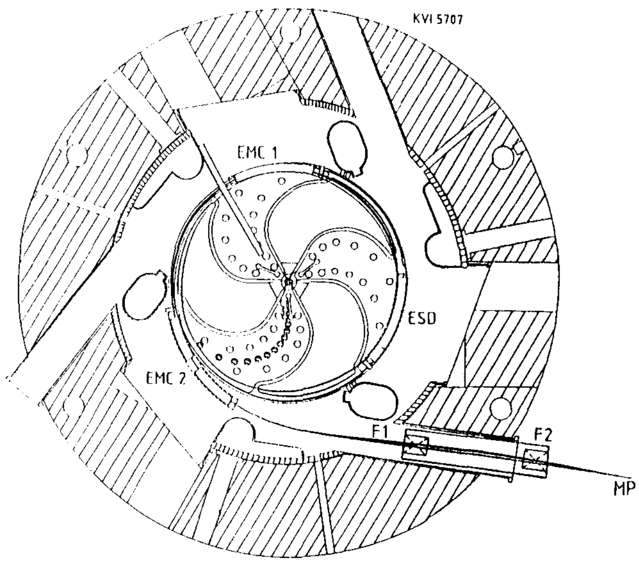

Fig.8. Midplane section of AGOR, showing location of the extraction channels.

When the channel is in place, a large fraction of the aperture in the yoke is closed with a wedge-shaped block of iron, in order to limit the reduction in yoke reluctance associated with the large radial hole. The blocks are moved into and from the magnet using a chariot on a set of rails. The same equipment is used for removing and inserting the channel.

6.2. Electrostatic Deflector

The electrostatic deflector* has two hinges, allowing adaptation of its shape to the variations of orbit scalloping with magnet excitation. The radial positions of the entrance, the exit and the two hinges can be adjusted through motor driven positioning mechanisms. Read back of the actual positions is done by means of potentiometers attached to the driven object itself, in vacuum. Similarly, hermetically sealed limit switches are attached to the moving parts in the machine vacuum. The field strength does not exceed 105 kV/cm over a 7 mm gap. Although these values are rather conservative, tests have been made to ascertain voltage holding capabilities. The high voltage feed-through , equipped with an internal damping resistor, was successfully tested in a set-up in a 0.4 T magnet. The same set-up was used to test the high voltage insulators. Finally, a short section, including a hinge, of the channel in its final transverse geometry was successfully tried, including hinge movement under full voltage. The channel is is construction at the IPN, Orsay and will be completed in September.

*the collaboration of R.Dubois (CERN) in the design is gratefully acknowledged

6.3. First Electromagnetic Channel EMC-1

The electromagnetic extraction channel EMC-1[2)] has four water-cooled copper coil sets. Two of the coils are used to produce the deflecting field of up to 0.2 T and the focussing gradient of 13 T/m, the other two coils are used for long range and short range compensation of the stray field in the region of circulating beam. An optimisation code is used to calculate the currents in the two sets of correction coils in order to minimize the stray field at the radius of $\nu_r - 1$. Figure 9 shows an example of the median plane field obtained in this way. The field inside the channel as well as the stray field in the region of the circulating beam will be mapped.

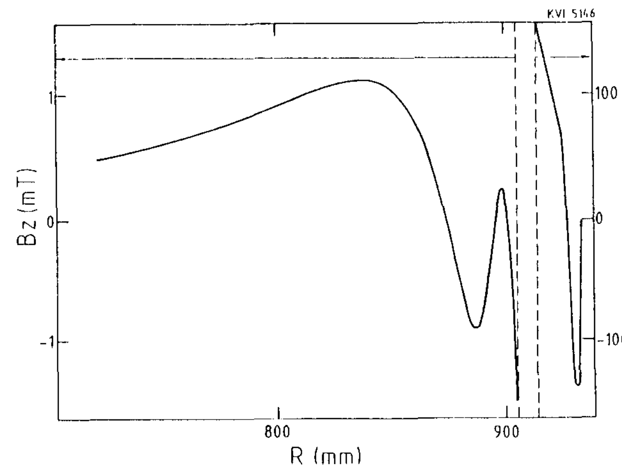

Fig.9. The radial field profile produced by EMC-1.

Since the available space is very limited, the available cross-sections for copper and for the hole for passage of the coolant are small. The smallest conductor has a size of 4×3 mm with a central hole of 2 mm diameter. The resulting current densities in the conductors are rather high: up to 144 A/mm^2 and the total power dissipation in the channel is 100 kW. Careful calculations have therefore been made on the cooling circuits, numbering 18 and mounted in parallel on single inlet and outlet manifolds, in order to have correct predictions for the water flow and the required water inlet pressure. The necessary flow can be obtained with a pressure drop of 22 Bar, produced by an additional high-pressure pump. The water velocity is in the range 8-11 m/s. The risk of cavitation occurring at these velocities was studied theoretically and experimentally[8)] using the cavitation coefficient S as a parameter. This coefficient is given by the expression $S = 2(P - P_s)/v^2 \times r$ in which P denotes the local pressure, P_s the saturation pressure of the vapour, v the velocity of the flow and r the density of the fluid. Measurements, using a microphone to detect the noise of cavitation, have shown that cavitation occurs for $S < 8$. It was therefore decided to adjust the pressure drop in each of the hydraulic circuits by means of inserts at the outlet, raising the water pressure inside the channel. The resulting safety margin in the parameter S is at least a factor 2 for all circuits. The channel has been completed and is illustrated in fig.10 and fig.11, showing the complexity and the density of conductors and water tubes.

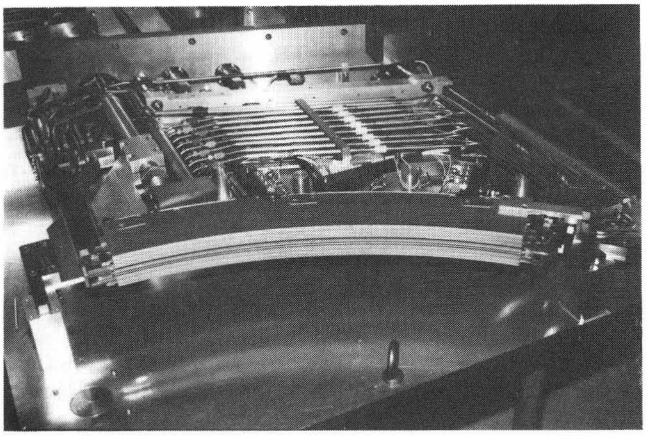

Fig.10. EMC-1: Overview of the completed channel.

Because of the high power dissipation, the time available for reacting to a sudden loss of coolant is limited to approximately 0.5 s. Apart from standard securities such as flow switches, pressure surveillance and thermal switches in the water outlets, two additional interlocks have been introduced. An analog temperature measurement using thermistors provides a continuous surveillance of the water outlet temperature, and creates an interlock signal when a predetermined limit is exceeded. In addition, the power supplies have an internal interlock based on measurement of the load resistance.

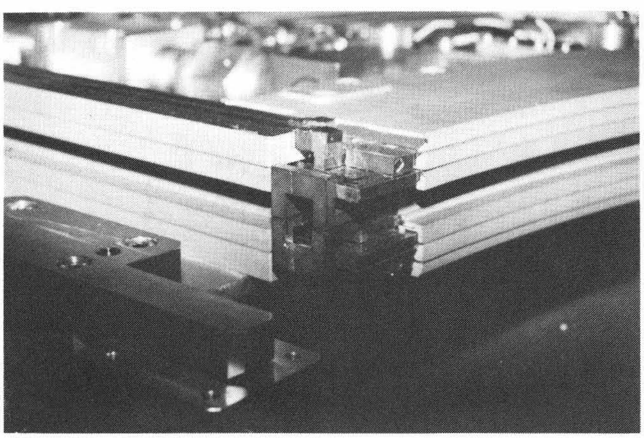

Fig.11. EMC-1: Detail of conductor lay-out at the channel exit.

6.4. Second Electromagnetic Channel EMC-2

The design of AGOR's second electromagnetic channel EMC-2 has been described at a previous conference,[9,10] and a detailed description of its construction is presented elsewhere in this Conference.[11] The channel is built in two hinged sections, having identical conductor geometries. The optical axis are circular arcs with lengths of 17.5 degrees and having slightly different radii. The beam aperture is 16×12 mm. There are three coils: the first produces a field drop of up to 0.4 T, the second produces a focussing gradient of up to 22 T/m and the third produces a compensatory field at the location of the circulating beam. Positioning of the channel is done by three motor driven rods located at the entrance, at the swivel joint and at the exit of the channel. Inside the channel bore, a shielding tube intercepts beam particles that would otherwise be lost on the 4 K winding mandrel of the coils. This tube is cooled with gaseous helium to a temperature of approximately 10 K, at least 10 W of beam power can be dissipated without the superconducting coils going normal. The channel is surrounded by a thermal shield, nominally at a temperature of 80 K. The channel is situated in the machine vacuum so that no superinsulation could not used. The thermal losses are estimated to be 3 W at 4 K and 10 W at 80 K, apart from possible beam loss. The superconductor is NbTi in copper and is used at up to 40% of the critical current. The coil mandrels and the superconducting coils are nearing completion at the Low-Temperature group at the University of Twente (Netherlands), assembly with the support structure and the positioning mechanisms as well as cryogenic and vacuum tests will be done by Leybold (Netherlands), who are expected to deliver the channel at the Orsay site in September 1992.

6.5. Focussing Channel

The focussing channel[12] is the final element of the AGOR extraction system. It consists of two focussing elements equipped with superconducting coils, located in the tangential hole in the magnet yoke for passage of the extracted beam. Their maximum gradient is 36 T/m over an effective length of 0.20 m. The conductor configuration is shown in fig.12, which also shows the soft iron tube shielding the extracted beams from the magnetic field, which reaches 0.22 T at the maximum central field of 4.05 T.

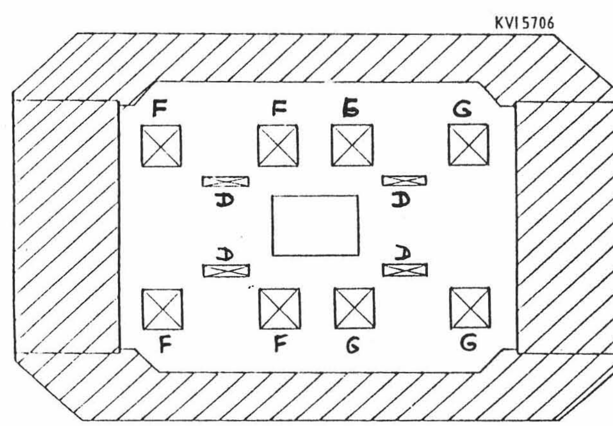

Fig.12. Cross-section of the focussing channel at the location of the first active element. F and G are gradient coils, D indicates dipole coils

The first lens has an additional dipole coil for horizontal beam steering. In both lenses, 2.5 mrad of vertical steering can be obtained by disequilibrating the currents in the upper and lower coils. Beam profiling harps at the entrance and exit provide positioning and steering information.

7. PROJECT STATUS

Important delays in the construction of two major subsystems, the superconducting coils and cryostat and the RF resonators, have retarded the initial project schedule by approximately one year. However, field mapping is now foreseen to be completed in September and assembly of the RF resonators on the magnet poles will then start. Next on the main line of our planning are vacuum installation and tests and RF measurements and tests. We hope to be able to start beam tests at Orsay in June 1993. In the mean time, the K160 cyclotron, in regular operation at the KVI since 1972, has been decommissioned on January 24 and is being dismantled. The beamlines and the experimental equipment have been taken away and the shielding in the experimental hall is being rearranged and reinforced. Installation of the AGOR beam lines, described elsewhere in this Conference,[13] and experimental set-ups will start this fall. Disassembly of AGOR will start on completion of the beam tests in Orsay, in mid-1993. The interleaving of this operation with transport to Groningen and reassembly is intricate, since we do not have a large area for intermediate storage. In any case, the parts last to be disassembled will be the first to be required on the assembly site. This is painfully true for the overhead cranes. The entire operation of moving the cyclotron is scheduled to be completed in 16 months.

8. REFERENCES

1) S.Gales, "AGOR, a Superconducting Cyclotron for light and heavy Ions," in **Proceedings of the 11-th International Conference on Cyclotrons and their Applications** (Ionics, Tokyo, 1987) p.184.
2) H.W.Schreuder, "The AGOR Cyclotron past the half-way mark" **Proceedings of the 12-th International Conference on Cyclotrons and their Applications** (World Scientific, Berlin, 1989) p.21.
3) K.Pieterman et al, "Low-temperature Tests of the AGOR Cryostat and Coils" in these Proceedings.
4) L.H.Harwood, J.A.Nolen, "Plans for Magnetic Mapping of the NSCL K800 Cyclotron Magnet. " in **Proceedings of the 10-th International Conference on Cyclotrons and their Applications** (IEEE, East Lansing, 1984) p.101.
5) S.Brandenburg et al., "The RF System of the Superconducting Cyclotron AGOR" in **Proceedings of the 12-th International Conference on Cyclotrons and their Applications** (World Scientific, Berlin, 1989) p.197.
6) B.Laune et al., "The diagnostics system for the AGOR superconducting Cyclotron" in these Proceedings.
7) S.Bühler, A.Horbowa, "The AGOR Cryopumps" in **Proceedings of the 12-th International Conference on Cyclotrons and their Applications** (World Scientific, Berlin, 1989) p. 224.
8) E.Martin et al. "Etude technologique de l'ensemble canal electromagnetique d'extraction EMC1 du cyclotron AGOR" **AGOR technical note NT/EXT/01/10/91** (in french).
9) S.Gustafsson, "A Superconducting Extraction Channel for AGOR" in **Proceedings of the 12-th International Conference on Cyclotrons and their Applications** (World Scientific, Berlin, 1989) p.354
10) K.Pieterman et al., "A Design Study for a superconducting Extraction Element for AGOR" in **Proceedings of the 12-th International Conference on Cyclotrons and their Applications** (World Scientific, Berlin, 1989) p.358
11) K.Pieterman et al., "The AGOR Superconducting Extraction Channel EMC-2," in these Proceedings.
12) H.W.Schreuder et al. "Superconducting quadrupole channel for the AGOR Cyclotron" in these Proceedings.
13) J.M.Schippers, "The Beam-Guiding System of AGOR." in these Proceedings.