AGOR: INITIAL BEAM TESTS, TRANSPORT AND COMMISSIONING

H.W.Schreuder, for the AGOR team

Kernfysisch Versneller Instituut, Zernikelaan 25, 9747 AA Groningen, Netherlands.

The AGOR cyclotron, in construction since 1987, has delivered its first external beam in April, 1994 at the construction site in Orsay. During a short testing period, several unique features of this machine have been validated. The active electromagnetic extraction channels have been operated successfully, proving correct cancellation of their stray magnetic fields at the radius of the $\nu_r = 1$ resonance. In beam diagnostics, the capability of centering the beam using novel beam centering probes and a simple software procedure, has been demonstrated. Similarly, the beam phase measuring equipment and associated algorithms have been used to optimize the rf-phase history of the beam, using the currents in the main coils and the correction coils as free parameters. After two weeks of beam testing, disassembly of the machine was started, which was then transported from Orsay (France) to Groningen (Netherlands), a distance of 700 km. Reassembly of the magnet yoke was completed in December and the superconducting coils were cooled down in May. The position of the coils was checked and corrected at different field values. The vacuum pumps were started in August, revealing no important leaks in the cyclotron. Tests of the RF system and the extraction channels are programmed to take place in September.

1 Historical Introduction

The history of the AGOR project is summarized in the following table:

Conceptual design at IPN, Orsay:	1982-1984
Funding acquired, contract signed:	Dec. 1995
Design :	1985 - 1987
Construction:	1987 - 1993
Field mapping:	Summer 1992
Assembly completed:	Nov. 1993
Vacuum chamber repair:	Dec.'93-Feb.'94
System tests:	Feb. - Mar.'94
Internal beam (200 MeV α):	March 1994
Beam outside magnet:	April 1994
Disassembly:	May - July '94
Transport to Groningen:	June - Dec.'94
Reassembly:	Oct.'94-Sep.'95
Magnet test:	June 1995
Start of commissioning:	Sep. 1995

A graphical summary of the project planning is presented in figure 1, where the expected time until beam extraction is shown versus time from start of the project. Completion of the design after 1.5 year has evidently led to a reappraisal of the estimations. The slope of the curve is consistently smaller than 45°, indicating overly optimistic predictions related, at least in part, to very late delivery of a few key subsystems.

2 Overview of AGOR specifications.

Since the specifications of the AGOR cyclotron and several design details have been reported at previous conferences [1,2,3,4], they are here only briefly summarized. AGOR has been designed to accelerate all elements, explicitly including protons, which can be accelerated to a maximum energy of 200 MeV. This energy is interesting from the

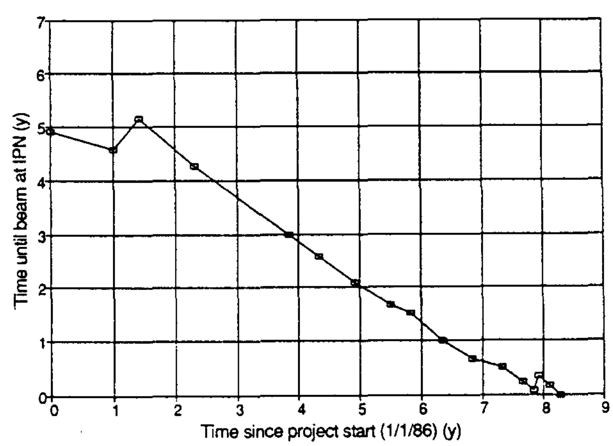

Figure 1: Overview of AGOR planning

point of view of nuclear physics and also for studies on cancer therapy. For all other ion a minimum charge state Q/A > 0.1 is required. Harmonics 2, 3 and 4 are used to limit the rf frequency range to 24 - 62 MHz. The machine performance in terms of final energy as a function of ion

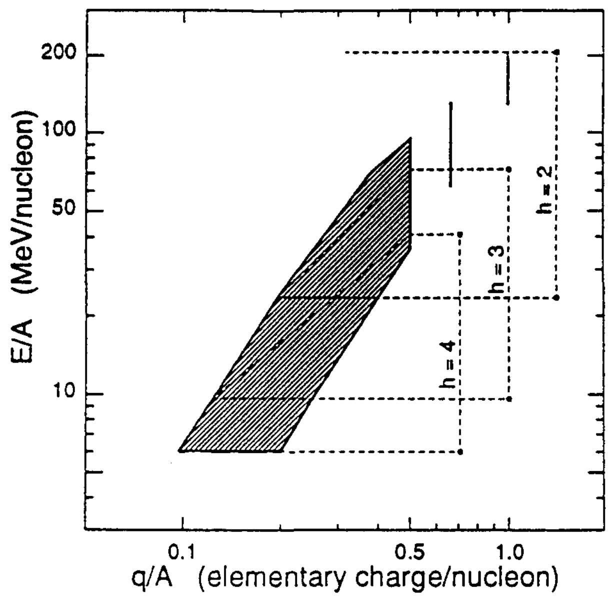

Figure 2: AGOR operating diagram. The thick lines and the hatched area indicate possible beams.

charge state is given in figure 2, which also shows the energy range associated with the different harmonic modes of acceleration.
The basic parameters of the cyclotron are recapitulated in tabular form below.

Bending limit (Kb):	600 MeV
Focusing limit (Kf):	220 MeV
Pole diameter:	1.88 m
Number of sectors and rf resonators:	3
Minimum gap:	0.07 m
Range of field in centre:	1.75 - 4.07 T
Number of main coil pairs:	2
Maximum energy in main coils:	58 MJ
Magnet weight:	360 tons
Number of trim coils:	15
Max. power in trim coils:	32 kW
RF frequency range:	24 - 62 MHz
Nominal accelerating voltage:	85 kV
Max. RF power per cavity:	32 kW
Harmonic numbers used:	2, 3, 4.

Table 2: Basic parameters of the AGOR cyclotron.

3 AGOR subsystems, operational experience

3.1 Main coils and cryostat

The design of the main coils and their cryostat, as presented at previous conferences[1,5], is particular in two main aspects. The coils are vacuum impregnated and are cooled with liquid helium only at their outer surfaces. As a result, they are not cryogenically stable and have therefore been designed to be capable of absorbing the stored energy without damage, in case of a quench. The cryostat has the feature of a nearly unobstructed median plane, allowing radial access to extraction channels. The system was successfully operated at Orsay. However, after a few months a helium leak appeared with a leak rate of up to 10^{-2} mbar.l.s^{-1}. In an effort to remedy this problem, the cryostat was warmed up and opened during the period of transfer of the cyclotron to Groningen. Unfortunately, the leak proved to be undetectable at room temperature. When the cryostat was cooled down in Groningen the leak reappeared. It is the dominating factor determining the rate of helium evaporation of the cryostat. Therefore, an additional vacuum pump was installed and the capacity of the liquid helium plant was increased. These measures seem to be adequate for assuring normal operation of the cyclotron. This was illustrated after transfer of the magnet to the KVI when a field of 4.1 T, slightly higher than the design maximum field, was reached during tests. During these tests the coils were aligned with respect to the median plane and with respect to the pole axis to better than 0.25 mm, as shown in figure 3.

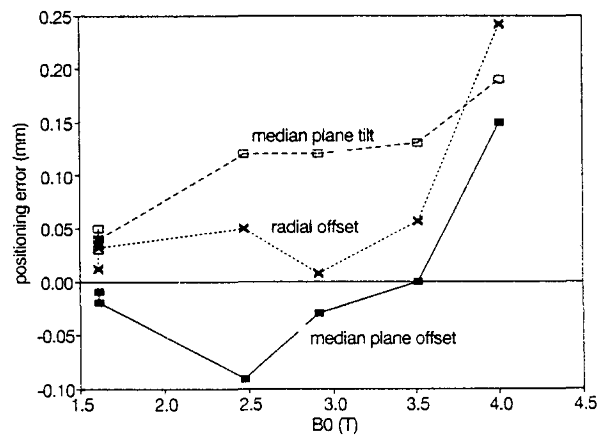

Figure 3: Measured coil alignment

3.2 Magnet

The AGOR magnet has carefully been designed[6] to avoid perturbation of the 3-fold symmetry and thus to avoid a conflict between minimization of the first harmonic field component and minimization of the radial force on the main coils. This has also been one of the considerations for the design decision to use three active deflectors, rather than a dozen or so passive magnetic channels and associated compensating bars. Symmetry has also dictated the triplication of the tangential passage through the yoke for the extracted beam. The additional apertures are used to connect the turbomolecular pumps to the accelerating chamber, as they provide a reasonable pumping conductance of approximately 300 l/s. The symmetry of the magnet is broken only by the ac motors associated with the pole lift mechanisms.
Field mapping [4] was done in three phases: In the first phase, maps were taken at B=1.8 T and at B=3.9 T. These

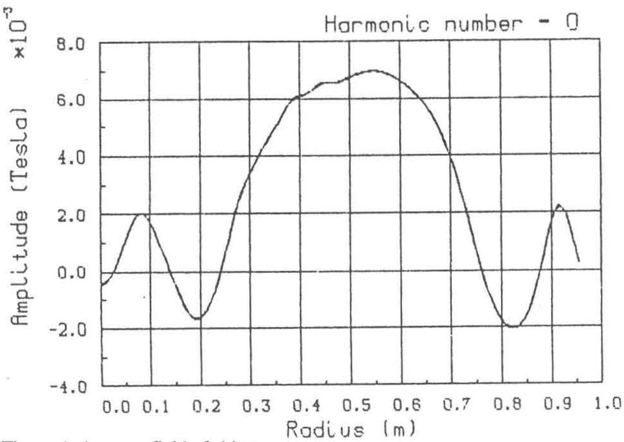

Figure 4: Average field of shims

were used to determine optimum shimming of the average magnetic field to minimize trimcoil currents. In addition, small corrections were made to minimize the residual first harmonic. The contribution of the shims to the average magnetic field is shown in figure 4.

In the second phase, maps were taken over the entire operating diagram of the machine and the field contributions of the trim coils were measured. Data analysis proved to be complicated because of missing and spurious radial position markers. This problem could be resolved (exactly) by off-line analysis. The overall precision of the maps finally was limited by integrator noise to approximately 0.5 - 1 Gauss. The third phase of mapping, one year after completion of the main series of field maps, was aimed at the measurement of the stray field and the internal field of extraction channel EMC-1. Maps with a radial resolution of 0.5 cm were obtained by addition of two maps, taken at two positions of the channel. The results, an example of which is shown in figure 5, were in satisfactory agreement with calculated values.

3.3 *Radio Frequency system*

The rf system[8] consists of three half-wave resonators, symmetric with respect to the median plane, which are mounted on the pole plugs of the magnet. The liner of the resonators, together with the cryostat inner walls, constitutes the beam acceleration chamber. The frequency range of the resonators is 24-62 MHz. Because of this rather high maximum frequency, no vacuum feedtrough / insulator can be used. Therefore, the entire resonator is in vacuum. The main characteristics of the resonators: frequency vs. position of the sliding short, Q-factor, power requirements and size of the coupling loop, were measured and proved to be in good agreement with the calculated values.

The sliding shorts consist of two concentric rings, which can move relative to each other. On the upper short, this movement is used to match the impedance of the coupling loop; on the lower short it is used for fine tuning of the resonator during operation.

The tuning of the resonator is maintained by a computer-controlled digital servo loop. The input of the loop is the phase difference between the incident wave from the power amplifier and the current in the short. The output of the loop is a displacement of the trimmer section of the lower short. If the asymmetry with respect to the midplane due to this displacement exceeds a pre-determined limit, both shorts are slowly moved until the trimmer section has returned to its nominal position.

The conditioning of the resonators for the first beam tests in Groningen (45 kV, 34 MHz) has posed no problems: all three resonators operated stably and without discharges after a few hours of conditioning.

3.4 *Diagnostics*

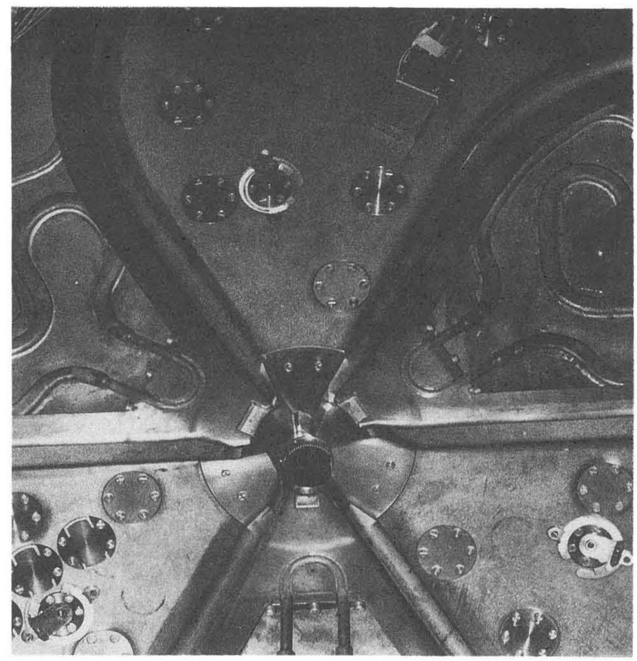
Figure 5: Lower pole with radial probe, centering probes and phase probes

Figure 5 shows a number of diagnostic tools installed on the lower magnet pole: three centering probes, two of a total of 13 rf phase probes and the main radial beam probe.

The centering probes are designed to be used in conjunction with the sectored correction coils nr. 2 and 3 to optimize beam centering before the onset of precessional mixing. During beam tests in Orsay, these probes proved to be very successful and easy to use. A sample probe trace is shown in figure 6, reproducing a hard copy from the screen of the operator workstation. To facilitate beam extraction, diagnostic elements are available at the entrance and exit of each of the extraction channels.

The system for measuring the rf-phase of the beam, the pick-up electrodes of which have been shown in figure 5, has been successfully tested, as well as the software procedure for optimizing the phase history by adjustment of the currents in the main coils and the correction coils. The sensitivity of the low-level electronics was sufficient to produce usable signals at a beam intensity of only 80 nA. The result of such a phase optimization is summarized in figure 7.

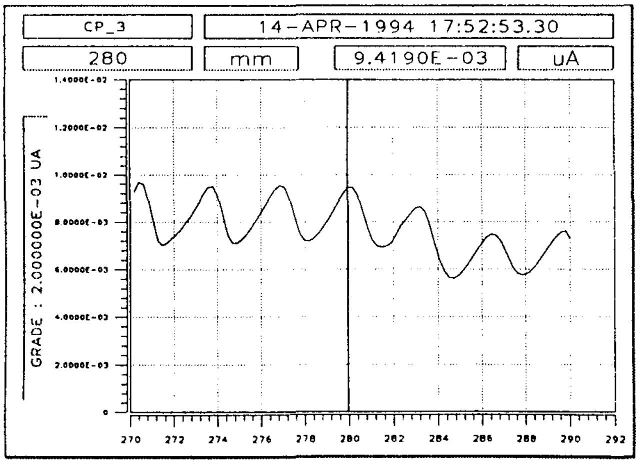

Figure 6: Beam current on centering probe nr.3 as a function of radius

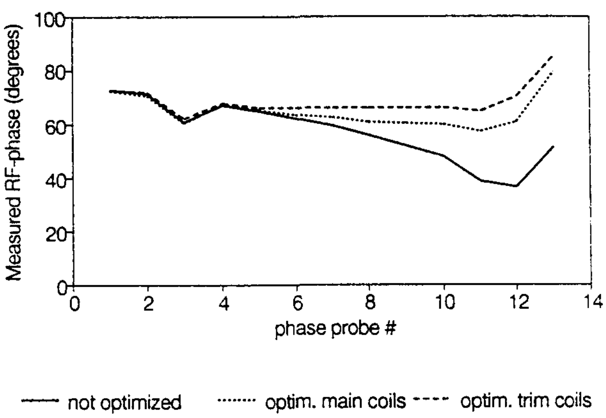

Figure 7: Measured beam phase optimization

3.5 *Extraction*

Three channels, each with a length of approximately 50 degrees, are used to extract the beam. The first channel is a classical electrostatic deflector, built with two hinges to allow adaptation to the variation in orbit scalloping at different values of the magnetic field. During beam tests at Orsay, the channel has operated satisfactorily at the conditions required for the first test beam: 48 kV over a 7 mm gap. Since conditioning to 105 kV/cm proved to be difficult, it was decided to reduce the gap to 6 mm before re-installing the deflector after transport to Groningen. At the same time, capillary tubes were installed to allow the injection of gas (oxygen) during conditioning. The second extraction channel, EMC-1[4], uses copper conductors at a current density of up to 144 A/mm^2 to produce a deflecting field of up to 0.22 T as well as a focusing gradient of maximum 13 T/m. The high dipole field allows the electrostatic deflector to operate at the relatively modest maximum field of 105 kV/cm. Since the internal beam circulates at a distance of only 10 mm from its conductors, the channel has two additional correction coils. Their currents are calculated to minimize EMC-1's contribution to the first harmonic field component at the location of the ν_r=1 resonance. Beam tests in Orsay have demonstrated these calculated values to be correct: at nominal currents the channel produced no detectable perturbation of the internal beam. The third channel uses superconducting coils [11] to produce a field of up to 0.4 T. At low magnetic fields this element actually operates at inverted polarity to inflect the ions back onto the extraction path. The power dissipation in the 4K part of the channel was measured to be approximately 6 W, slightly lower than anticipated. Finally, a focusing channel [12] is situated in the yoke passage. It has two focusing elements with maximum gradient of 32 T/m, equipped with superconducting coils. Horizontal and vertical steering capabilities are also included in this channel. The dissipation at 4 K was measured to be 4 W, in agreement with the design value.

3.6 *Vacuum*

Two turbomolecular pumps are connected to the median plane through tangential tubes, each having a conductance of approximately 300 l/s. These pumps are used for pumping down and for providing pumping speed for noble gases. Three cryopanels, located in the upper sections of the rf accelerating electrodes, each provide a pumping speed of 1500 l/s for air and 1000 l/s for hydrogen. The panels are cooled by commercial cryogenerators, installed outside the magnet, and capable of delivering 50 W at 80 K and 5 W at 20 K. Heat transfer between cryogenerators and cryopanels is accomplished by means of heatpipes [7] consisting of an 80K and a 20 K circuit. In the 80 K circuit heat is transferred by condensation (at the cryogenerator) and evaporation (at the cryopanel) of nitrogen. For the 20 K circuit a similar scheme, using hydrogen, was successfully tested. However, a curiosity driven trial with a helium-filled circuit using thermosyphon circulation was so successful that the potentially dangerous hydrogen has now been replaced with helium gas.
At the KVI, the vacuum chamber, complete with rf resonators, was first pumped down in August 1995, using turbomolecular pumps only. A pressure of 10^{-5} mbar was obtained in a few days. Since then, two of the three cryopanels have reached operational status.

3.7 *Control system*

The AGOR control system, probably one of the last accelerator control systems to be home-built, is structured in three layers: the operator, data and controller levels. The machines serving the operator and data layers are interconnected via Ethernet.
The top-level operator layer provides an intuitive, graphical, user interface and runs on workstations under VMS. It uses the SL-GMS package, operating on top of X-Motif, to handle windows and mouse interrupts. Software for com-

munication with the data layer has been in-house written in C.
The data layer collects information from the cyclotron and uses algorithms and tabular data for processing. Five RT-VAX machines are used, which are interconnected through Ethernet The software in this layer is divided over jobs that loosely correspond with major cyclotron subsystems such as main coils, injection etc. Each job consists of a number of processes, each responsible for a specific, hardware-related function. Each process contains a database with fixed attributes and dynamic data. Data exchange between processes is done exclusively by message passing. Message handling is done by a specific process, the 'Post Office'. Since process names are constrained to be unique, address information nor knowledge of the location of a process are required. For all processes at the data level, a simple user interface using VT200 terminals is available. This interface provides direct access to any parameter known to the system.
At the controller level PLC's and intelligent Bitbus controller cards provide the interfacing with accelerator equipment such as power supplies, motors, end switches and valves. Interlocks and basic functionality such as ramps are implemented here. Communication with the data level is done through Bitbus.

4 Disassembly, transport and reinstallation

Disassembly of the cyclotron started in May 1994 and was essentially complete in 3 months, the first trucks with peripheral equipment arriving in Groningen in June 1994. Transfer of the magnet required intermediate storage: i) because the overhead cranes were to be re-used at KVI and ii) for solving the tower of Hanoi problem associated with the 6 magnet rings (50 ton each). No damage has occurred that could unequivocally be identified as being caused by transport. However, a broken helium tube was found in the cold box of the helium liquefier, as well as a defective weldment. The magnet poles were transported complete with RF resonators and vacuum chamber installed. This implies that the iron of the poles was not touched and that mechanical checks after reassembly of the magnet should be sufficient to guarantee that no new field imperfections have been introduced during transport-related operations. As a consequence, field mapping in Groningen has not been foreseen to be necessary. The installation of the heavy equipment proceeded rapidly: the magnet was installed and aligned in December 1994. When the axial alignment of the poles was verified, the change with respect to the set-up in Orsay was found to be insignificant: (0.02 ±0.05)mm. For several reasons, reinstallation of the cryogenic system took much more time than foreseen. The most important being the implementation of more cooling power in the liquid helium plant In the RF resonators many leaks in the water cooling circuits of the short-circuits successively occurred, requiring brazing operations in the limited space between the outer conductor and its surrounding vacuum wall.
Reassembly of AGOR was completed by the end September 1995, figure 8 shows the machine installed at its final site.

Beam tests at KVI

The injection beam line was the first subsystem to be tested with beam: in April '95 a 1 μA beam of 37 keV α-particles was taken to a beam stop located at 1 m below the magnet yoke. After completion of the machine, a usable vacuum of 1.5 10^{-6} mbar was obtained after 7 days of pumping, using the two turbomolecular pumps and one cryopump. On October 4, exactly one year after the arrival of the overhead cranes at the KVI, the first beam was accelerated to a radius of 80 cm, using the parameter values that had been used during the beam tests at Orsay. AGOR seems to have been faithfully reproduced.

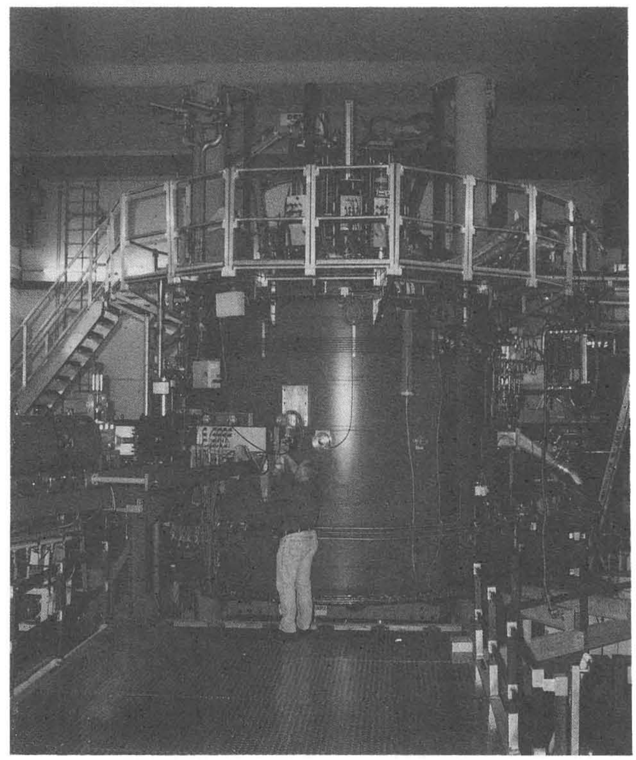

Figure 8: AGOR installed at the KVI.

5 Beam lines

A floor plan of the cyclotron vault and the experimental area is shown in figure 9. It shows the location of AGOR and the present lay-out of the beam lines with analyzing magnets as well as the principal experimental set-ups. The ion-optical design 9 is designed to produce either non-dispersed or dispersion matched beams on the target of the QQD "Big Bite Spectrometer" (BBS). In addition to the beam line leading to the spectrometer, a beam line leading to the ppγ setup next to the spectrometer has been installed, as well as a beam line leading to the West area, in which a gantry (beam swinger) for proton therapy is planned.

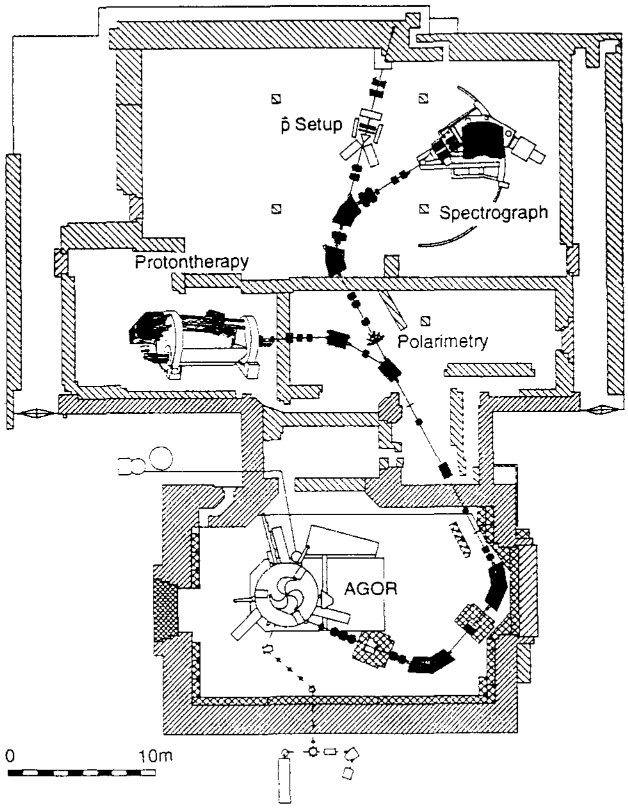

Figure 9: Floor plan of cyclotron vault and experimental area at the KVI.

In the beam lines, diagnostics are performed by means of the following equipment: wire grids (harps) for profile measurements, residual gas profile monitors [14], capacitive pick-ups for beam position measurement [15], inductive probes for beam intensity determination [15] and, of course, faraday cups and other beam stops. All diagnostic elements are controlled by a VISTA based system, using Bitbus for communication.

Acknowledgments

The task of designing, constructing, testing, disassembling, transporting, reassembling and commissioning of an accelerator as complicated as a compact cyclotron with superconducting coils is a considerable one, which requires a team in which many competent persons collaborate efficiently. At the outset, the bi-national character of the AGOR project has produced some misgivings, which, however, proved to be unnecessary. Indeed, it is a great pleasure to acknowledge the excellent teamwork which has characterized this project and which is largely due to Sydney Gales, the project leader until June, 1995. It is equally important to emphasize the support given by the two funding agencies, the Institut de Physique Nucléaire et de Physique des Particules (France) and the Stichting voor Fundamenteel Onderzoek der Materie (Netherlands), who have spared no efforts to support AGOR.

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