THE AGOR CYCLOTRON PAST THE HALF-WAY MARK

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ABSTRACT.

The construction of the AGOR cyclotron has reached the stage where delivery of major subsystems is imminent. Construction of the split cryostat has started. The light ion source is operational and is controlled by a first segment of the control system. Superconducting extraction elements are in the design stage. Field measurements are scheduled to start in 1990, beam tests should start in 1992.

1. INTRODUCTION.

The AGOR cyclotron, a joint undertaking of the Kernfysisch Versneller Instituut (KVI), Groningen, Netherlands and the Institut de Physique Nucleaire (IPN), Orsay, France, will be a compact cyclotron with superconducting coils. The design having been presented at a previous conference, its main characteristics will be briefly reviewed 1) 2). This will be followed by a review of the different subsystems. Fig.1 shows the range of energies for ions of different charge states.

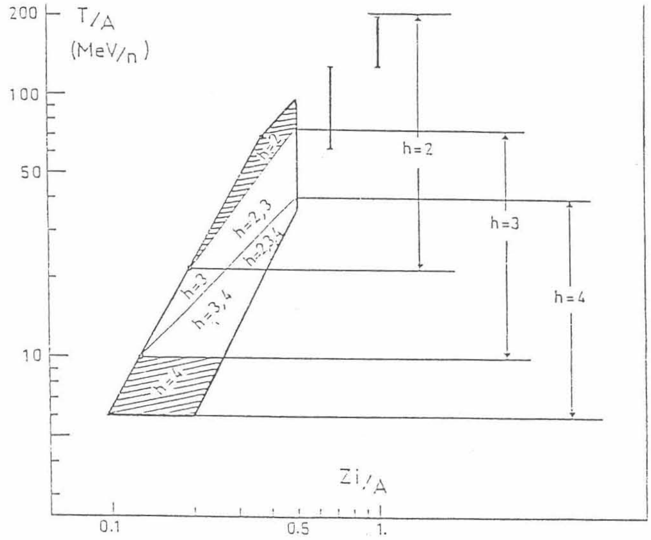

Fig.1: Beam energy vs. ion charge state.

The machine is unique in being designed for the acceleration of protons as well as heavy ions. The main parameters of the cyclotron are given in table 1.

Table 1 - Main cyclotron parameters.

Bending limit (Kb):	600 MeV
Focussing limit (Kf):	220 MeV
Pole diameter:	1.18 m
Number of sectors:	3
Minimum gap:	0.07 m
Range of field in centre:	1.75 - 4.07 T
Number of main coil pairs:	2
Energy stored in main coils:	58 MJ
He liquefier capacity:	50 l/h
Number of trim coils:	15
Max. power in trim coils:	32 kW
Number of RF cavities:	3
RF frequency range:	24 - 62 MHz
Nominal accelerating voltage:	85 kV
Max. RF power in cavity:	32 kW
Harmonic numbers used:	2, 3, 4.

The machine is now being built in Orsay and will, after initial beam tests, be transferred to the KVI for final installation. The project, initially approved in December 1985, has formally entered the construction phase in May, 1987. Procurement of components is well under way and the first items are now arriving in Orsay.

2. MAGNET.

Production of the magnetic circuit is nearing completion. Measurement of the saturation magnetization on samples of the castings yielded values of M = 2.16 (±0.01), exceeding the specified minimum value of 2.14 Tesla. Machining has been completed by the end of April and the magnet is now being assembled in the factory for dimensional checks. Shipping to Orsay will start within a few weeks and assembly on site is scheduled to start in June. Fig.2 shows three completed hill blocks.

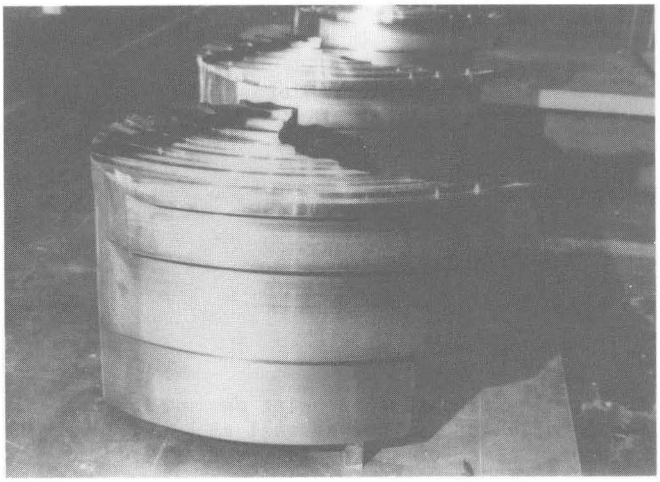

Fig.2: Three hill blocks after machining.

The 15 sets of correction coils are in construction, they will be mounted on the magnet poles in September. Most of the coils will be wound in a double layer, using conductor with a rectangular cross-section. The centre of the two layers is taken to the outside, where the two sections are electrically connected in series. The cooling channels are connected in parallel in order to guarantee sufficient flow of coolant. Dissipation in these coils is expected not to exceed 32 kW for any point of operation.

The design of the field mapping equipment is in progress, it will be similar to the equipment used at MSU for mapping the K800 machine: a radially moving search coil is connected to a precision voltage to frequency converter and a NMR system is used for calibration and stability checks. After re-installation at the final site, we foresee the need for taking field maps for verification. In order to simplify disassembly, transport and reassembly procedures, we plan to do these with the pole vacuum covers in place. The radial measuring arm is therefore designed to be compatible with the resulting 35 mm gap. In addition, operation in vacuum will be possible, allowing us to measure the stray field of the superconducting extraction channel emc2.

3. SUPERCONDUCTING COILS AND CRYOSTAT 3)

The main characteristics of the coils and the cryostat are recapitulated in Table 2.

Table 2: Characteristics of coils and cryostat.

conductor:	NbTi Rutherford cable.
filaments:	60 um diameter
conductor:	coil 1: 3.0 * 5.3 mm2 coil 2: 5.5 * 8.6 mm2
current:	coil 1: 850 A coil 2: 1800 A
stored energy:	58 MJ
quench voltage:	1000 V
cooling req'd at 80 K:	190 W
cooling req'd at 4.5 K:	12 W
current leads:	7.5 l/s liquid helium

The coils will be fully vacuum impregnated for preventing any conductor movement and will be enclosed in a stiff stainless steel structure which guarantees the required positional accuracy. However, the coils are not designed to adhere to this structure and their outer surface will be in contact with liquid helium. The stresses under load and the resulting deformations of coils and support structure have been analyzed with a 3-D finite element code. The maximum hoop stress in the conductor is 110 MPa and the deformations do not exceed 0.25 mm.

The radiation shield is filled with liquid nitrogen. The evaporated gas is reliquified in a recondensor, cooled with He gas from the liquefier. In case of liquefier outage, liquid nitrogen can be supplied to the shield from an external supply.

Current status: the contract for the construction of the cryostat and the superconducting coils was awarded to Ansaldo of Genua (Italy); it calls for delivery at Orsay in September 1990. The the conductor is now being fabricated and construction of the coil bobbins and the cryostat is scheduled to start in July.

The cryogenic system external to the cryostat has been designed with the following goals: i) reasonable spare capacity, ii) minimization of electrical power consumption, iii) reliability, iv) low cost of re-installation at the final site. The system consists of a liquefier plant, a 1000 l storage dewar, a transfer line (4 K and 80 K) and a relatively small gas storage vessel: 20 m^3 at 15 Bar. The liquid helium plant is specified for the following simultaneous production rates:

Cooling power at 80 K:	600 W
Cooling power at 4 K:	50 W
liquid helium production:	15 l/h

In pure liquefier mode the nominal production rate of liquid helium is 50 l/h. The order for the cryogenic subsystem, including installation at Orsay, has been granted to Sulzer of Winterthur (Switzerland). On-site system tests are scheduled to start in February 1990.

4. RF SYSTEM. 4)

Early in 1988 a full scale model of a resonator was constructed from copper covered plywood to an estimated dimensional accuracy of 2 mm, allowing measurements of the resonance frequency for different positions of the short circuits, the voltage distribution along the electrodes and the distribution of current in the shorting plates. Using these results as inputs in the cavity calculations, we now foresee a maximum power input of 32 kW for obtaining the nominal accelerating voltage of 85 kV in the machine centre. The current density in the short circuit will not exceed 35 A/cm, well below the limit of the planned rf contacts. Three 70 kW power amplifiers are on order at Herfurth GmbH (Hamburg, FRG) and are now undergoing factory acceptance tests. Engineering for the construction of the resonators is completed and the tendering procedure for their construction is well under way. We hope to receive the resonators by summer 1991. Prototypes of all modules of the low-level electronics have been built and tested. Series production has been started some time ago and assembly into cabinets is progressing.

5. INJECTION.(5)

The multi-cusp ion source, made by IBA, Louvain (Belgium) and shown in fig.3, has successfully passed all acceptance tests.

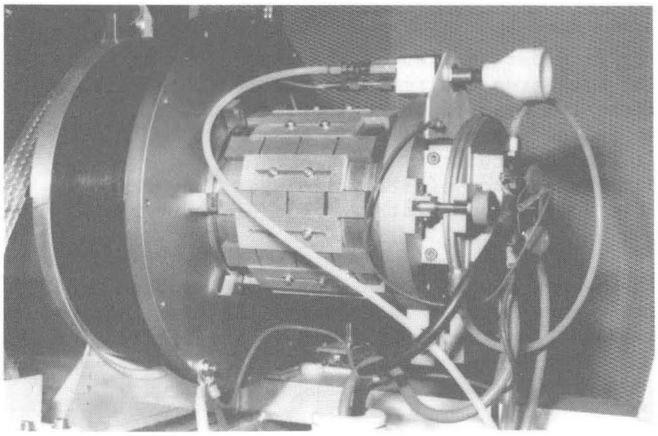

Fig.3: Multi-cusp ion source.

The test set-up is shown in fig.4. It will later serve as the first section of the injection beamline.(6)

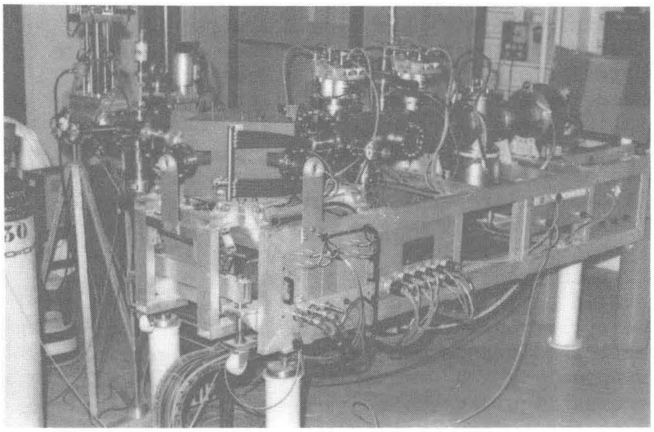

Fig.4: Ion source test stand.

The ion-optical design of the injection path has now been frozen and the design of the section containing the achromatic 90 degree bend onto the vertical axis of the cyclotron has been completed. The orbits in the central region have been calculated using 'refraction' at equipotential planes, measured on a 5:1 model in an electrolytic tank . Although harmonic modes 2,3 and 4 are required for accelerating all beams, a single geometry of the central region has been found which allows acceleration in all harmonic modes without adjustments other than a change of inflector. The beams are electrically centrered to within 3 mm. Subsequently these orbits will be magneticaly centered at r= 25 cm, where centering probes are located, by using correction coil sets 2 and 3. At the beginning of acceleration the particles have the usual negative rf phase in order to obtain electric vertical focussing. A central field bump is used to shift the rf-phase of the particles back to the top of the rf waveform.

6. EXTRACTION.

Beam dynamical calculations are done for six different beams that span the operating range of the cyclotron as illustrated in fig.5.

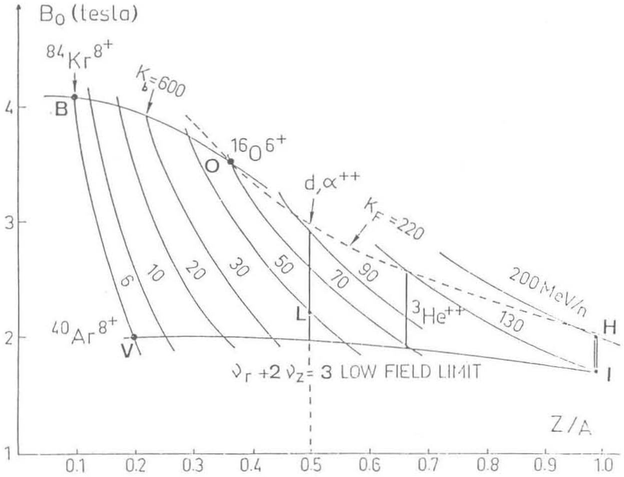

Fig.5: Operating diagram, showing representative beams used in extraction calculations.

For tracking the particle orbits, field maps may be used which are obtained by superimposing the calculated channel fields on the main magnetic field map. These channel fields are therefore spatially referenced to the cyclotron rather than to the orbits, allowing a realistic assessment of the influence of field imperfections both inside and outside the channels. This is particularly important for low-energy heavy ion beams which intrinsically have a rather high emittance. These beams will be extracted in multi-turn mode and we use Monte-Carlo methods to construct the 6-dimensional emittance.

The location of the extraction hardware in the cyclotron is shown in the median plane section of the machine of fig.6.

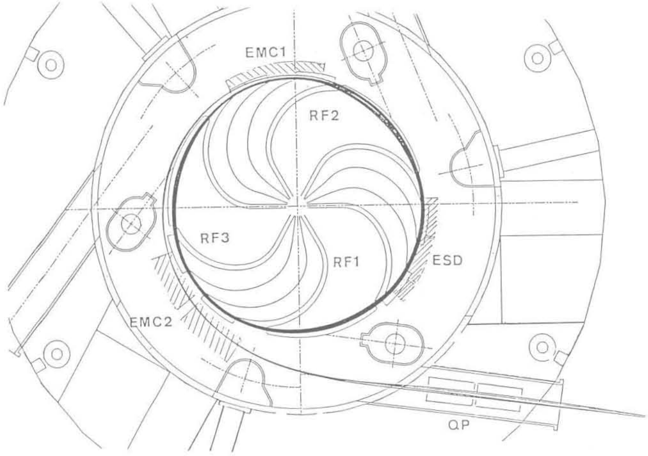

Fig.6: Median plane section, showing the locations of extraction elements.

The first element is an electrostatic deflector (esd), which is followed by two electromagnetic channels (emc1 and emc2). Final focussing is provided by two quadrupoles located in the passage through the magnet yoke. The required range of excitation for the deflecting channels is given in table 3.

Table 3: Minimum and maximum excitations of the extraction channels

deflector	E kV/cm	B (T)	-dB/dx (T/m)
esd	14-105	--	--
emc 1	--	0.09-0.26	8-10
emc 2	--	0.01-0.24	10-16
q-poles	--	--	15

Due to the varying degree of orbit scalloping, the electrostatic deflector will be made in three sections for adapting its shape to that of the orbits. Similarly, emc2 will have two sections.7) Calculations on heating by multiply scattered beam particles have encouraged us to pursue the design of a superconcucting emc2. In fact, a 3 mm thick 80 K shield surrounding the beam tube is sufficient for preventing scattered protons of 200 MeV to quench the coils. We also plan to make the final quadrupoles superconducting. For emc1 superconcuctivity seems to be excluded since the small distance (14 mm) between the circulating and the extracted beams precludes the use of a 80 K shield. Fig.7 shows a cross-section of the conductor configuration of emc1. In previous designs iron was used for creating part of the required gradient and for partially compensating the stray field.

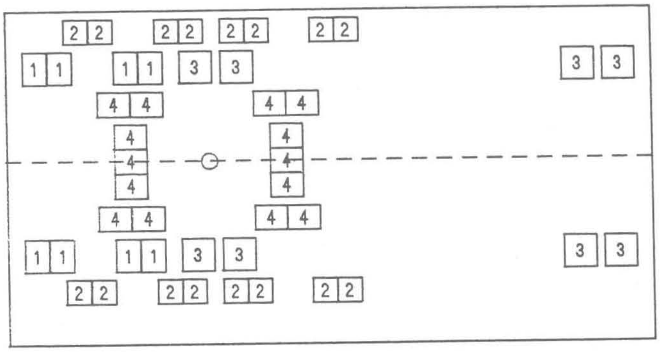

Fig.7: Cross-section of the conductors of emc1. The cyclotron centre is at the left, the circle marks the axis of the extracted beam.
4: deflecting coil
2: gradient coil
3: compensation of stray field at long range
1: compensation of stray field at short range.

In the new design the use of iron has been avoided and we now succeed in reducing the first harmonic component of the stray field to an amplitude of less than 1 gauss in the region of nur=1.

7. VACUUM.

The poles of the AGOR cyclotron, in contrast to those of most other machines, will be separated from the beam region by a vacuum cover that also serves as RF liner. As a result the surface exposed to vacuum is reduced and the correction coils are in air. The main complications arising from this approach are the difficulties (and the cost) of design and construction due to the intricate shape of the liner. The required pressure in the cyclotron has been estimated to be approximately 10 mbar, for a beam loss not exceeding a few percent. This corresponds to a pumping speed for air of 5000 l/s. Cryopanels located inside the accelerating electrodes will be used as main pumping elements. In addition, turbomolecular pumps are foreseen on the outside of the cyclotron. Design pumping speeds for the cryopanels are 1500 l/s for air and 1000 l/s for H2. Each panel is cooled by a small cryogenerator mounted on the rf resonator structure on top of the cyclotron. Heat is transferred over the vertical distance of 3 m between refrigerator and cryopanel by a system of two coaxial heat pipes. It uses liquid/gaseous nitrogen and liquid/gaseous H2 at the temperature levels of 80 K and 20 K respectively. Measurements on a prototype have shown that the power available at the cryopanel is 36 W at 80 K and 2 W at 20 K. Pumping speeds of 1400 l/s and 1800 l/s have been obtained for N2 and H2 respectively.

8. CONTROL SYSTEM.

The AGOR control system consists of a network of RT (real-time) microVAX computers, coupled through Ethernet and using the VAXeln operating system software. For interfacing to the accelerator equipment, a modular system is used, based on the Bitbus(tm) field bus. In close cooperation with industry several modules have been developed, among which a power supply interface, a general positioning interface, a simple stepmotor interface, and an interface for a 'harp' beam profile monitor. In all of these, the intelligence available in the basic Bitbus chip is used for implementing device specific functions. A notable design feature of the power supply interface is the implementation, illustrated in fig.8, of local control which allows avoiding the possible discontinuity on switching between 'local' and 'remote' by directing both local and remote control information through the interface.

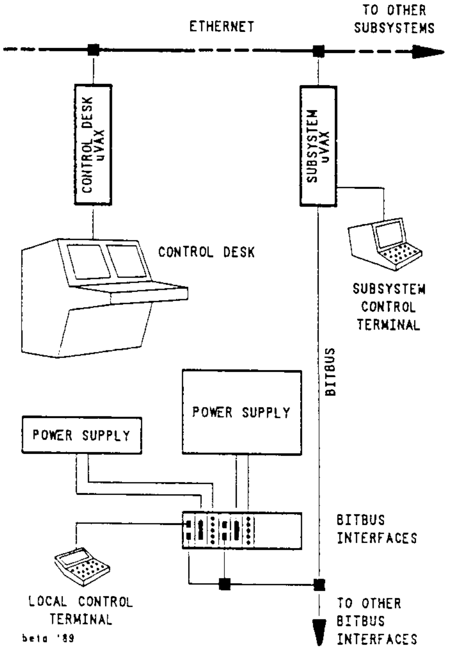

Fig.8: The power supply interface using Bitbus.

From the software point of view, the cyclotron consists of elementary physical and logical 'objects' that may refer to each other to form logical objects of a higher level. Thus, the logical object 'diafragm' refers to the objects 'slit' and 'beam current multimeter'. The software representing an object consists of a database record and executable code. The representation of an object on a control console is considered to be an object by itself. Since September 1988, the ion source set-up is controlled by a first section of the control system built along these lines. Temporarily, the operator interface is provided by a simple video terminal, but we are preparing the selection of the graphics hardware and software for the real control desk.

9. PROJECT STATUS.

The current status of the project in the context of the overall project planning is shown in table 4, which shows major milestones both past and future.

Table 4: AGOR milestones.

Conceptual design:	1983
Agreement FOM - IN2P3:	Dec.1985
AGOR Design Report:	Oct.1986
Formal start construction:	May 1987
Civil engineering completed:	Apr.1988
Magnet construction:	Jan.1988-Jun.1989
RF amplifier construction:	Jan.1988-Apr.1989
RF resonator engineering:	Jun.1988-May 1989
Main coils&cryostat construct:	Jun.1988-Aug.1990
Cryopump prototype test:	Jul.1988
Control system in use:	Sep.1988
Ion source delivered:	Oct.1988
Overhead cranes installed:	Nov.1988
Magnet assembly:	Jul.1989
Helium liquefier installed:	Jan.1990
Mount cryostat in magnet:	Sep.1990
Field mapping:	Oct.1990-May 1991
Start mounting resonators:	Aug.1991
Start beam tests:	Aug.1992

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REFERENCES:

(1) S.Gales, AGOR, a superconducting cyclotron for light and heavy ions. Proc. 11th Conf. on Cyclotrons and their Applications (Ionics, Tokyo, 1987), p.184.

(2) J.P.Schapira et al., Axial injection system for the superconducting cyclotron AGOR, ibid., p.495.

(3) K.Pieterman et al. AGOR cryogenics: a status report. These proceedings.

(4) S.Brandenburg et al. The RF system of the superconducting cyclotron AGOR. These proceedings.

(5) J.P.Schapira et al., AGOR central region design studies. These proceedings.

(6) M.Malard et al., AGOR axial injection using a positive light ion multicusp source. These proceedings.

(7) S.Gustafsson, K.Pieterman et al., A Superconducting electromagnetic channel for AGOR. These proceedings.

(8) A.Horbowa, S.Buhler, The AGOR cryopumps. These proceedings.