AGOR PERFORMANCE REPORT

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The AGOR cyclotron has started producing beams for experiments in Spring 1996. Since then, a large variety of beams have been produced, covering a large part of the operating diagram. The ECR ion source and the polarised proton source have been used intensively. The available beam diagnostic equipment proved to be effective tools for beam optimisation. The resulting beam properties are in satisfactory agreement with calculated values. The reliability of the machine is good and the reproducibility ranges from good to excellent.

1 Introduction

The AGOR cyclotron has been designed and built in a joint effort by the Institut de Physique Nucléaire (IPN) at Orsay (France) and the Kernfysisch Versneller Instituut (KVI) at Groningen (Netherlands) [6,7,12,17]. It has been in operation since early 1996, the experimental programme formally started in August, 1996 and the official inauguration of the facility took place on January 16, 1997. As reported at the Cape Town conference [17], the machine had produced its first external beam in April 1994 at the IPN and was then disassembled, moved to Groningen and reassembled.

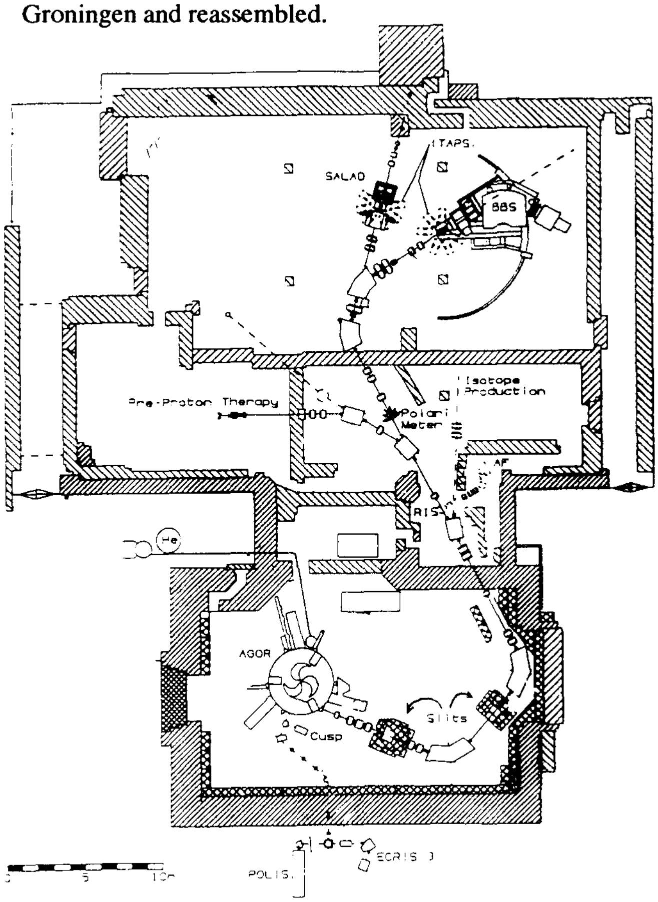

Figure 1: Lay-out of AGOR and experimental hall

The first beam was accelerated to extraction radius in October 1995. External beam was first produced in January 1996. The main mission of the cyclotron is to provide beams for research in nuclear physics. As a first step towards application-directed use of the cyclotron, a radiobiology programme has been started.

The lay-out of the AGOR facility is presented in figure 1, showing the cyclotron, the high-energy beam lines [16] and the experimental facilities, most notably the charged-particle spectrometer BBS and the Small Angle Large Acceptance (SALAD) set-up. The smaller vault is dedicated to radiobiological experiments, possible precursors for a proton-therapy facility.

2 Confirmation of specifications

The operating range of AGOR is presented in figure 2, showing the area in Q/A vs. E/A space covered by the cyclotron as defined by its specifications.

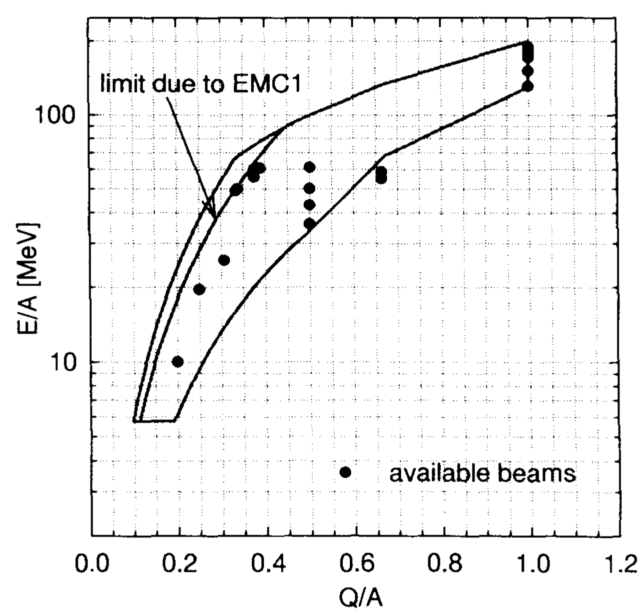

Fig.2: AGOR operating diagram

In this diagram, the beams developed so far are indicated with dots. It is seen that most of the specified area has been covered, most notably the unique part corresponding with the acceleration of protons, where the 190 MeV beam is very close to the theoretical focusing limit. Up till now, the borderline representing the bending limit has not been reached. This is due to a temporary limitation, associated with the first electromagnetic deflection channel EMC-1, which will be discussed in a later section. Figure 2 also shows that the low-energy limit, associated with the $\nu_r + 2\nu_z = 3$ resonance, has proved to be conservative in the case of $^{3}He^{2+}$ beams, where acceleration and extraction of beams with energies beyond the lower limit of the diagram has been demonstrated.
AGOR has operated in all harmonic modes (2, 3 and 4) foreseen in its design [10]. Changing the harmonic mode is easy, since it only requires insertion of the appropriate inflector and an adjustment of the relative rf phases of the resonators.
Apart from the multicusp ion source, used for producing singly-charged ions and α-particles, an atomic-beam source with ECR ioniser for polarised protons and deuterons as well as an ECR ion source are available to inject beam into AGOR. In table1 all beams are listed that have been produced so far.

Table 1: list of available beams

Ion	Q/A	E/A (MeV)	Analogue beams
$^{1}H^{1+}$	0.9928	131	
		151	
		171	
		181	
		190	
$^{2}H^{1+}$	0.4965	50	
$^{3}He^{1+}$	0.3316	50	
$^{3}He^{2+}$	0.6634	59	
		55	
$^{4}He^{1+}$	0.2499	20	
$^{4}He^{2+}$	0.4998	36	
		43	$^{16}O^{8+}$
		50	$^{12}C^{6+}$, $^{14}N^{7+}$, $^{16}O^{8+}$
		60	same as above
$^{13}C^{6+}$	0.4615	60	
$^{15}N^{5+}$	0.3334	50	$^{36}Ar^{12+}$
$^{16}O^{6+}$	0.3752	56	
$^{36}Ar^{14+}$	0.3893	60	
$^{36}Ar^{11+}$	0.3059	36	
$^{36}Ar^{11+}$	0.3059	25	
$^{40}Ar^{8+}$	0.2002	10	

As suggested by the number of table entries, not much time is needed to develop a new beam. Usually, not more than 6 hours are needed to transfer a new beam from the last Faraday cup in the injection beam line to the beam stop at the beginning of the high-energy beam lines. Of course, much less time is needed when a known analogue beam with a similar Q/A value has already been developed.

3 Beam measurements

3.1 Radial probe

As in most other cyclotrons, the radial beam probe is the workhorse for beam diagnostics [14]. The AGOR probe covers the radial range between 250 and 940 mm; at 920 mm it crosses the path of the extracted beam, close to the exit of extraction channel EMC-1. The probe is equipped with a stopping block and an insulated 0.5 mm diameter tungsten wire, fixed at r = -6 mm from the block. As shown in the perspective view of the target head, figure 3, the height of the wire is half that of the block. Thus, information is obtained on the vertical behaviour of the beam as well as on radial current density and, of course, total current.
Since the probe runs along a straight line, the angle of incidence of the beam is a function of radius through the changing spiral angle of the hill sectors. As a result, particles with a large range may not be stopped, creating a real problem for intensity measurements of the proton beams (130 - 190 MeV).

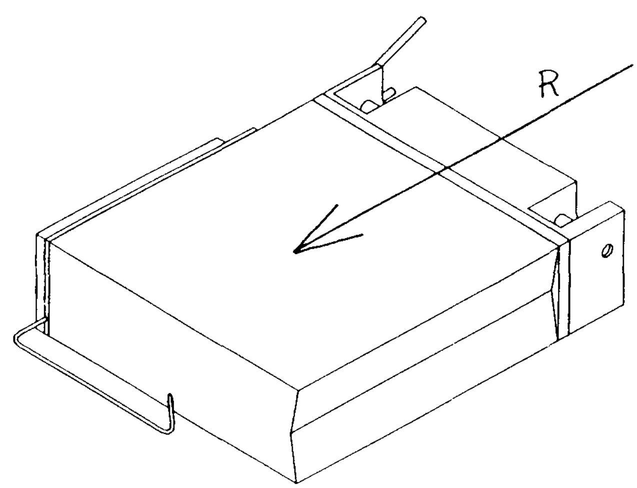

Figure 3: perspective view of radial probe head with measuring wire

This is illustrated in figure 4, which shows a radial probe plot for 190 MeV protons. The decrease in beam current between 300 mm and 850 mm is nearly entirely due this effect. However, the corresponding curve for the current on the tungsten wire is free of this artefact. The bump around R=910 mm represents the extracted beam.

As expected in the design stage, correct beam centring is essential for obtaining a good extraction efficiency. The centring probes [14] can be used for determining the beam centring error by measurement of the location of individual turns at 120 degree intervals in the radial range of 210-240 mm.

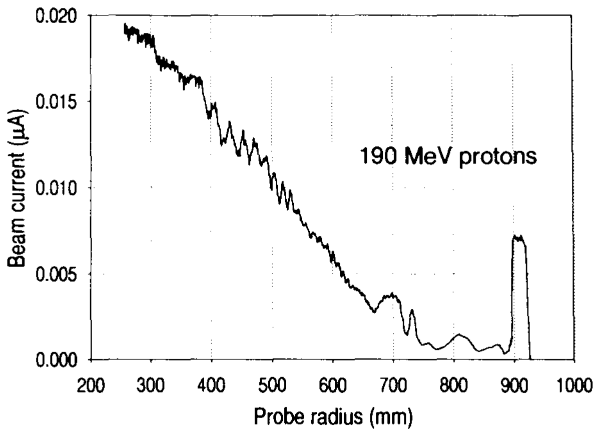

Figure 4: radial probe scan for 190 MeV protons: current on block electrode

Unfortunately, a series of technical trivialities have prevented us from utilising these probes other than incidentally. Instead, the radial probe has been used, although the resulting quantitative determination of amplitude and phase of the coherent radial oscillation is less precise. Nevertheless, the beam may be centred by following a simple procedure. It consists of rotating the vector of the first-harmonic field component, produced by the (sectored) correction coil nr.3, and measuring the amplitude and phase of the resulting coherent oscillation with the radial probe.

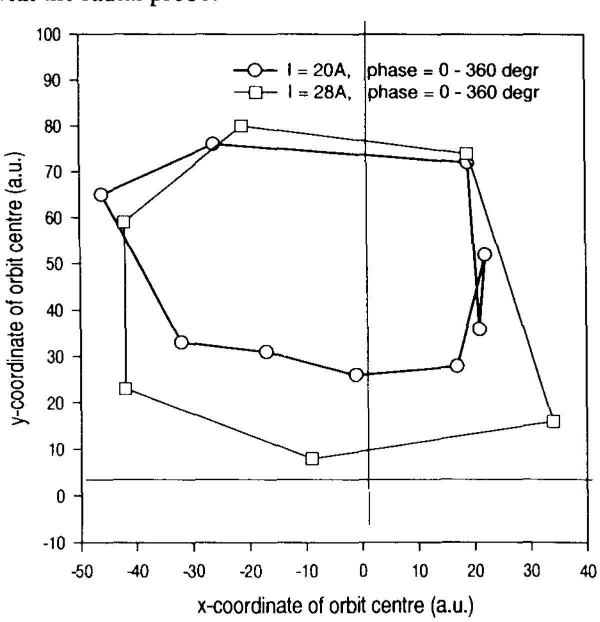

Figure5: coherent radial oscillation vs. excitation of harmonic coil nr.3

The data from two series of such measurements are shown in figure 5; they allow a very good estimation of the optimum setting of the correction coil parameters. In day-to-day practice, however, this procedure is not often used, since it is found that a perfectly centred beam results from tuning the amplitude and phase of correction coils 3 for maximum current of the extracted beam. As an illustration, a radial probe plot for 59 MeV/A $^3He^{2+}$ beam is presented in figure 6, showing a coherent amplitude of approximately 0.2 mm at 600 mm radius. Incidentally, the figure also shows a transmission efficiency of 85% through the first two extraction channels ESD and EMC-1.

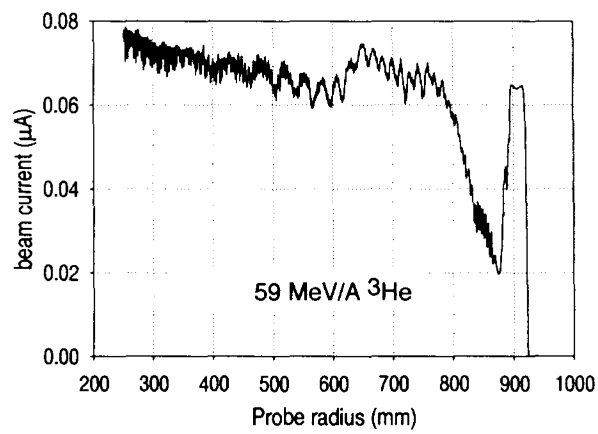

Figure 6: radial probe (block) current vs. radius for 59 MeV/A 3He beam

3.2 Determination of Dee voltage

Since attempts to measure X-ray spectra originating from the rf accelerating voltage have not yet succeeded, radial probe traces have been used to obtain an estimate of the energy gain per turn experienced by the beam. Taking a

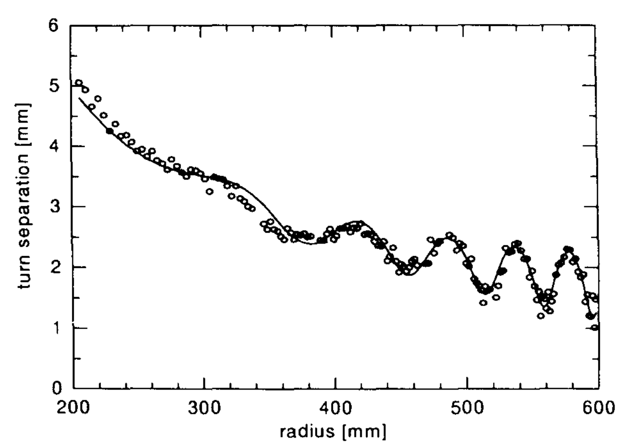

Figure 7: radius gain per turn as a function of radius

scan displaying separated turns to R=600mm, a plot, shown in figure 9, was made of the radius gain per turn as a function of radius. The modulation is caused by a coherent radial oscillation. Using ν_r values, obtained from field maps, the radial gain per turn can be calculated. The resulting curve has been fitted to the measured points by varying the oscillation amplitude and phase as well as the energy gain per turn. The accuracy of this measurement is estimated to be 1-2%.

3.3 Phase probes

The phase probes have been used frequently for the optimisation of newly developed beams. The electronics have successfully been redesigned in order to increase simplicity [2]. Since the circuit has to be tuned to the rf frequency, setting up these measurements is not (yet) done by the operators of the cyclotron. Phase optimisation is particularly important for the most relativistic beams, i.e. for protons. Unfortunately, at the corresponding high rf frequencies, there is a considerable background signal from the resonators at the second harmonic of the rf frequency, making reliable measurements very difficult. The origin of this spurious signal is not yet understood.

4 Properties of extracted beams

4.1 Transmission

The transmission factors of the injection, acceleration and extraction processes present a good overall picture of the performance of an accelerator. These data for AGOR are given in the following overview.

Injection efficiency:	10 - 30 % (with buncher)
Extraction efficiency:	40 - 90 %
Total transmission:	10 - 25 %

4.2 Intensity

Since nearly all beam-time is used for nuclear physics experiments, only small beam intensities have been required. Typical values are 2-50 enA on target. One request, mistaken in hindsight, for 500 enA of the ^{40}Ar beam at 25 MeV/A could be satisfied without difficulty.

4.3 Phase-space

Only a few measurements have been made on the emittance of the extracted beam. The radial and vertical emittance are 4π and 6π mm.mrad respectively; the momentum spread is 10^{-3} and the pulse width, as measured by the experimentalists, corresponds to a phase width of 15 - 18 rf degrees. Except for the vertical emittance, these figures are in reasonable agreement with expected values. The relatively large vertical emittance may be associated with a possible median plane problem near R=720 mm, for which other indications have been found.

4.4 Q/A resolution

When the 60 MeV/A beam at Q/A=0.5 had to be developed, an opportunity presented itself for determining the Q/A resolution of the cyclotron by measuring the extracted beam current as a function of rf-frequency. The injected beam, produced by the ECR ion-source fed with CO_2 gas and helium, was found to contained fully stripped ^{16}O, ^{12}C and ^{4}He ions, as well as $^{14}N^{7+}$, probably from a leak in the ion source.

The measured data points are presented in figure 8. The measured resolution in Q/A is 1.4×10^{-4} fwhm.

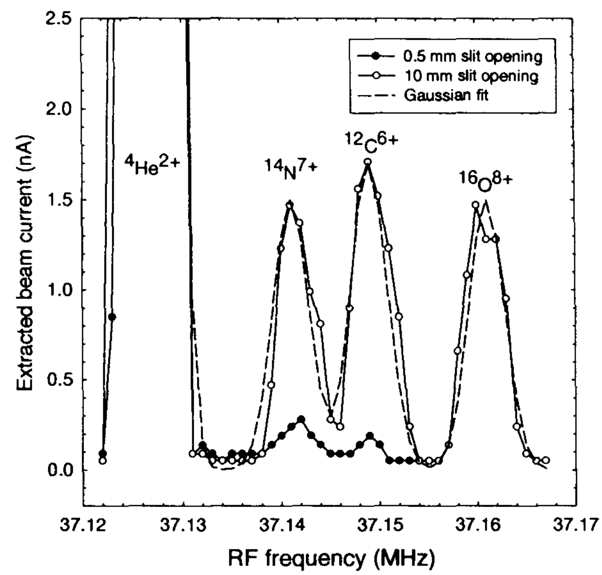

Figure 8: beam current as a function of rf-frequency; ion-source gas: CO_2 and He

4.5 Reproducibility

Since AGOR, like all other cyclotrons with super-conducting coils, operates with fully saturated poles, the reproducibility and the stability of the magnetic field are excellent. In AGOR, these desirable qualities are limited by the temperature dependence of the saturation magnetisation of the iron in the magnet poles. This effect is most serious for the lightest ions (protons), which require a high precision in the field because of their relativistic mass increase and which are accelerated at field levels down to 1.75 T.

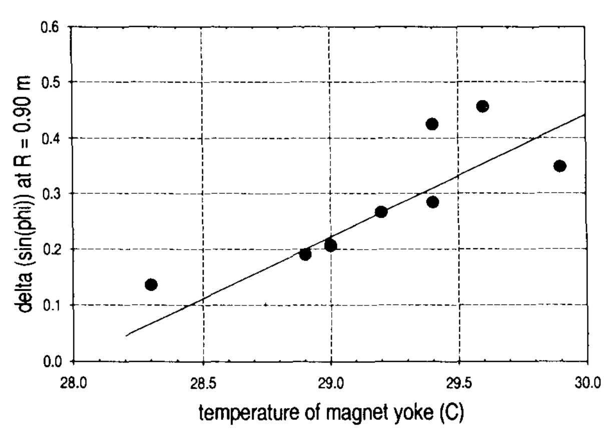

Figure 9: field corrections as a function of yoke temperature

Such a low field is produced mainly by magnetisation of the poles. Figure 9 presents the field corrections applied by the cyclotron operators during a two-week 190 MeV proton run as a function of the temperature of the magnet yoke. The slope of the line in figure 8 corresponds with a temperature coefficient $\Delta(\sin\varphi)/\Delta T = 0.22$, as discussed in another contribution to this Conference [3].
The reproducibility of the machine is such that, when the parameter values have been loaded, very often the beam comes out of the machine immediately on removing the injection beam stop.

5 Subsystem performance

5.1 Cryogenics

The cryogenic system requires much attention. This is due to the combination of two difficulties: a cryogenic helium leak to the isolation vacuum of the main cryostat, and a sub-nominal capacity of the liquefier [4]. The leak has an unfortunate tendency of slowly increasing. To counteract the resulting increase in partial helium pressure, a third diffusion pump had to be installed on the last remaining port of the cryostat. This was a complex operation requiring on-site machining, since the pump had to replace a bolted-on cover without breaking the vacuum. A third problem is that of insufficient gas purity, possibly associated with leaking, but not easily demountable, current leads in the extraction channels. As a result, the liquefier has to be purged at intervals ranging between 2 and 4 weeks. Also, the PLC-driven control system for the liquefier features randomly occurring (but predictably infuriating) bugs that switch off the cold box or the helium compressors. Nevertheless, the resulting availability of the cryogenic installation is increasingly satisfactory.

5.2 Radio Frequency

The AGOR RF-system [8], discussed in detail in another section of these Proceedings [1], functions according to specifications. It is capable of reliably producing the required rf voltages - up to 80 kV at 60 MHz - with the required stabilities of amplitude and phase. At the highest voltages, breakdowns occur a few times per shift. After a breakdown, re-establishing the voltage requires 1-2 minutes of operator intervention. At lower voltages breakdowns can be less then one per day.

5.3 Extraction

The lay-out of the extraction elements in the AGOR cyclotron is recalled in figure 9. It is a median plane section, showing the four active extraction channels [6,11,13,15]: an electrostatic deflector (ESD) a normal conducting electromagnetic channel (EMC-1), an electromagnetic channel with superconducting coils (EMC-2) and a superconducting focusing channel (Qpole).

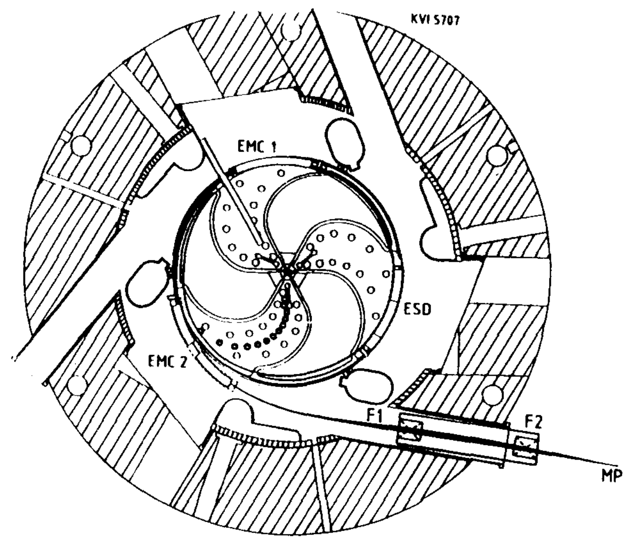

Figure 10: extraction channel lay-out

ESD has been operated close to the design maxima for voltage and field-strength: 50 kV over a 6 mm gap. Since early 1995, it has been taken out of the cyclotron only once, to clean the titanium cathode where a spark-inducing particle was found. During operation at the highest voltage, sparking occasionally occurs. This is remedied by applying a flow of oxygen gas to the electrode region. Generally, the problem has disappeared after about 30 minutes.

EMC-1 is the most highly stressed component of the cyclotron, since the current density in its conductors can be as high as 140 A/mm^2. During the past two years, winding shorts have occurred on three occasions. In all cases, the fault could be remedied by the insertion of kapton foil. On one occasion a brazed connection has sprung a small leak. This repair took nearly two weeks. The measurements of the water outlet temperatures of each individual winding, installed for providing an additional security interlock, have proven to be very useful for locating the winding shorts mentioned above. The short-circuits are due to insufficient insulation of the copper conductors, which are embedded in anodised aluminium plates. On the first tests of the channel, the anodisation failed, mostly at the edges of the plates. This was remedied by inserting kapton foil, at the expense, however, of construction height, which was increased by 1.8 mm. As a result, the channel is now clamped between the magnet poles at fields above 3 T. A new channel, using plasma-sprayed alumina deposits on the copper conductors, is being constructed.
In 1997, the small-diameter inserts at the water exit connections to the conductors were frequently clogged by deposits of metallic and oxidised copper. Since this

occurred only during long runs of the 190 MeV proton beams, we suspect radiolysis of water to be involved.

EMC-2 and Qpoles have functioned with great reliability, but not without occasional cryogenic inconveniences. Their helium consumption is in agreement with calculated values: approximately 25 l/h for both channels together, including transfer line losses. The focusing and two-dimensional steering capabilities of the Qpole channel make the matching of the beam to the high-energy beam-line incredibly straightforward and easy.

5.4 Vacuum

During operation, the machine vacuum is typically 2.10^{-6} mbar. This value is higher than the design goal, since the cryopumps [9] are not operational. Leaks in the connection of the pumps to the mounting flange in the rf-resonators prevented their operation. In addition, cold leaks were detected in two of the heatpipes. An improvement programme, in collaboration with our former construction partners at the IPN (Orsay), has been started, aiming at re-installation of the cryopumps during the next winter shut-down. In the mean time, the two cryogenic extraction channels are efficient replacement pumps.

5.5 Ion sources

Three ion sources are available for producing beams to be injected into the cyclotron. The ECR source and the source of polarised protons and deuterons are located in a room outside the cyclotron vault. They are connected through the "Low Energy Beamline" (LEB). The multicusp source is located in the vault very close to the cyclotron. The beams produced so far are listed below:

ECR:	^{3}He, ^{12}C, ^{15}N, ^{16}O, ^{36}Ar, ^{40}Ar beam current > 10 μA
Polarised ions:	$^{1}H^{1+}$ and $^{2}H^{1+}$ used so up till now. polarisation degree: up to 60%.
Multicusp:	hydrogen and helium ions only.

Acknowledgements

Every day, many persons contribute with great enthusiasm to the efficient operation and the further development of AGOR: cyclotron operators, vacuum technicians, electronics engineers and technicians, specialists in cryogenics and cooling and, last but not least, software specialists. Their creativity and hard work has been essential for obtaining the results presented in this contribution.

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