AGOR STATUS REPORT

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Abstract

The past three years of AGOR operation have been a period of steady improvement of the cyclotron. The two problems causing most down time: failure of the helium refrigerator system and water leaks in the RF acceleration electrodes have been solved. The latter required redesign of the connection between the electrode and the coaxial line and a four month shutdown to implement the modifications.

1 OPERATION

The AGOR cyclotron is operated for about 4500 hours per year, mainly in a weekly schedule running from Monday 15:00 to Saturday 15:00. For longer experiments operation continues through the weekend.

1.1 Available beams

In figure 1, the operating diagram of the AGOR cyclotron is shown, together with the beams produced so far. The pinching by the magnet of the electromagnetic channel EMC1, which is about 1 mm too high, limits the magnetic field to about 3.3 T and hence the K-value of the cyclotron to 450.

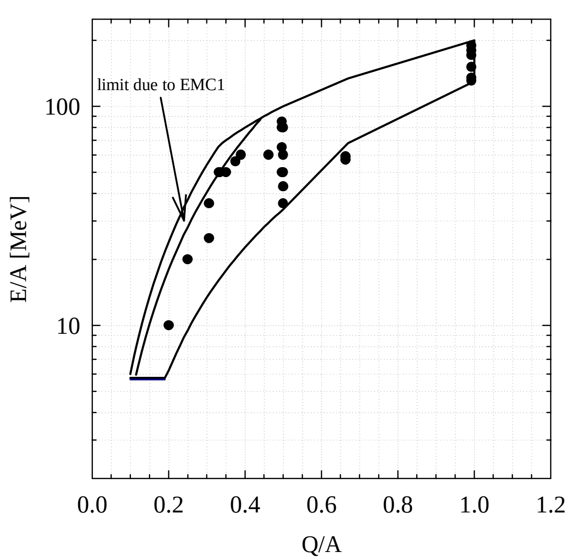

Figure 1: operating diagramme.

1.1 Beam time statistics

In table 1, AGOR beam time statistics are shown for the period 1998-2000. A standard 8760-hour year is divided in a period of about 3200 hours (consisting of most weekends and some holidays) in which AGOR is scheduled to be standby and about 5600 hours in which it could be operating. The large amount of scheduled shut down time in 2000 was caused by the modification of the RF resonators, which required a four months shutdown..

In spite of the large amount of scheduled shut down time in 2000, we did not have less hours of beam on target than in the preceding years. This, together with the dramatic fall in the amount of maintenance work is an indication that we have overcome at least some of the difficulties on which we have reported in 1998.

Table 1: beam time statistics

	1998	**1999**	**2000**
Beam on target	1576	1377	1487
Beam preparation	545	458	619
Machine studies	362	179	291
Scheduled maintenance	651	489	1020
Unscheduled maintenance	1422	2856	771
Scheduled standby	3360	3200	4352
Unscheduled standby	844	201	220
Total	8760	8760	8760

1.2 Experiments performed with AGOR

As can be seen in table 2, proton beams are in high demand at the KVI. Especially the 190 MeV proton beam, which can be produced again since the RF modification of last year, is a popular one. The proton beams account for about two thirds of the total beam time.

The rest of the time is dominated by deuteron and ^{3}He beams, while the heavier nuclei make up only a small fraction of the beams produced with AGOR.

Table 2: beams produced, 1998-2000

Particle, energy	**Shifts**
^{1}H(150-190 MeV)	350
^{2}H (65-85 MeV/A)	99
^{3}He (59 MeV/A)	80
^{3}He, ^{3}H (43 MeV/A)	3
^{4}He, ^{12}C, ^{16}O, ^{20}Ne (20-50 MeV/A)	22
^{40}Ar (50 MeV/A)	1

From January of 1998 until January of 2001, AGOR has produced 555 8-hour shifts of beam on target. 179 of those (32%) have been used for commissioning of detectors (BBS, Orsay, EuroSuperNova, Plastic Ball and In-Beam Polarimeter). Nuclear physics experiments got

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304 shifts of beam (55%), while the radiobiology programme received 52 shifts (9%). The remaining 4% (20 shifts) were used for various short experiments, among which irradiation of Antarctic ice and mica, and the characterization of ancient pottery with nuclear techniques.

The machines studies were mainly directed at optimization of cyclotron settings. Furthermore the feasibility of accelerating tritons [1] and sub-harmonic bunching [2] were studied.

2 CYCLOTRON SUBSYSTEMS

2.1 Cryogenic system

The cryogenic system of the AGOR cyclotron encompasses the main coils and two superconducting extraction channels, which are cooled by a Linde TCF-50 helium refrigerator.

As reported previously [3] a cryogenic leak is present in the main cryostat. This leak opens when the coil temperature is lowered to about 30 K and closes again some time (1 – 3 days) after the cryostat is filled with liquid helium. When the leak is open and the cryostat is filled the pressure in the space between the 4 K vessel and the 80 K screen deteriorates to such an extent that about 80 % of the total refrigerator capacity is needed to keep the cryostat filled. Under these circumstances the superconducting extraction channels cannot be operated.

The refrigerator has a nominal cooling power of 50 W at 4 K and 600 W at 80 K together with a production of 60 litres of liquid helium per hour. On the basis of liquid production tests we estimate its actual capacity to be 10 – 20 % less. The cooling at 4 K is used for the main coils; that at 80 K for the 80 K screens of the main coils (working on the principle of *in situ* re-condensation of nitrogen) and one of the extraction channels, while the produced liquid is used to cool the extraction channels and all the current feedthroughs.

As the system is completely closed – only losses are compensated with He 5.0 gas – no gas purification in front of the refrigerator has been installed. Consequently any impurities in the gas are frozen out in the refrigerator, leading to degradation of its performance. In the period summer 1997 – summer 1999 an air leak of 5×10^{-3} $mbar \cdot l \cdot s^{-1}$ caused continuous pollution, requiring a warm-up cycle of the refrigerator every two – three weeks. In combination with the cryogenic leak in the cryostat this led to a large reduction in up-time. The leak was caused by a combination of the leaking shaft feedthrough of the compressor, which is located at the low-pressure side of the compressor, and a clogged filter, causing the pressure at the compressor entrance to drop below atmospheric pressure. After repair, warm-up cycles have been made only for maintenance reasons (3 – 4 times a year).

Now we have regained control over the time at which and the length of the period during which the refrigerator is shut down, also the abovementioned cryogenic leak is much more well-behaved. After a planned shutdown of the refrigerator, the leak will in most cases only cause its effect on the cooling power for a day, while previously a refrigerator shutdown also meant that we did not have enough cooling power to turn on the extraction channels for the better part of a week.

2.2 Radio-frequency system

In the summer of 1998 a water leak (into the accelerator vacuum) occurred in the cooling pipes of one of the acceleration electrodes. The leak was only present when the RF power applied to the resonator exceeded a frequency dependent limit, which made it impossible to locate and repair the leak. Cyclotron operation was continued with the constraint that proton energies above 150 MeV were not possible. A method to repair the leak *in situ* with an epoxy coating on the inside of the pipe was developed and tested successfully. When this method was applied to the defective tube the leak, at the vacuum feedthrough of the tube, sprang open permanently, thus allowing a repair by conventional methods.

Three months later, after continuous operation at the highest proton energy, a leak occurred at a similar position in another resonator. This was interpreted as evidence for a structural problem with the vacuum feedthroughs of the cooling pipes. Detailed analysis of the RF power distribution and the cooling of the resonator section concerned showed a differential thermal expansion between the cooling tube and the copper skin of the resonator of about 0.2 mm at maximum power and frequency. The several thousand thermal cycles over a period of three years caused fatigue, finally leading to rupture of the pipe.

To solve the problem additional cooling of the copper skin and flexibility of the cooling tubes were necessary, requiring a major modification of the junction between the acceleration electrode and the coaxial line:

- a water-cooled copper block was soldered to the resonator skin using Wood's metal.
- the vacuum feedthroughs of the cooling tubes were reconstructed, including stainless steel bellows to compensate possible differential expansion.
- the connection between the mechanical structures of the coaxial line and the acceleration electrode, ensuring the correct position of the electrode, was reconstructed.

Applying the modifications to all six half-resonators required a four month shutdown in the summer of 2000.

After the modification the cyclotron has delivered 190 MeV protons for extended periods without further problems with the resonator cooling. The improved cooling of the resonator is also reflected in the smaller travel of the tuning trimmers.

2.3 Extraction channels

Although the discomfort (clogging of inserts because of the accumulation of copper sludge) has been strongly reduced by giving EMC1 a separate cooling water circuit, erosion of the channel by cooling water continues to be a threat. Work on a new EMC1 channel, which should also bring the present K-value limit of 450 (caused by pinching of the channel at high magnetic fields) back to the design value of 600, is progressing slowly.

2.4 Diagnostics

Using a layered target on the radial probe, we have studied the vertical motion of some beams [4]. In the case of 190 MeV protons, this proved to be an excellent tool to optimize the high energy proton beams, since they appear to suffer from vertical beam dynamics effects [4]. At the end of the optimization round, the transmission through the cyclotron and the extraction channels was about 40%, which is modest, but as good as the best transmission we have on record for this beam.

3 FUTURE DEVELOPMENTS

The physics research programme conducted with the beams provided by AGOR has sofar been focussed on nuclear structure, nuclear reaction dynamics and few body physics. In the coming years these programmes will gradually be replaced by a programme focusing on precision experiments on nuclear β-decay using radio-active atoms and ions trapped in a magneto-optical or Penning trap. The investment for the construction of the set-up for these experiments (fragment separator, RF-cooler and traps) and improvements of the cyclotron has been allocated by the university and the funding agency.

These nuclides will mainly be produced through reactions in inverse kinematics. This implies that the emphasis will shift from protons to heavy ions. The required beam intensities are expected to increase significantly. To meet these requirements a development program on the ECR ion source (metallic ions) and the axial injection system (higher efficiency) have been defined.

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