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Jones, B. N.; Brandenburg, S.; van Goethem, M. J.

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AGOR STATUS REPORT

B. N. Jones, S. Brandenburg, M.-J. van Goethem, KVI-Center for Advanced Radiation Technology, University of Groningen, 9747AA Groningen, The Netherlands

Abstract

The operations of the superconducting cyclotron AGOR over the past years will be reviewed. Reliability issues encountered after nearly 25 years of operation and mitigation measures to warrant reliable operation for the coming decade will be discussed.

The research performed with AGOR has significantly shifted from fundamental physics to radiation biology and medical radiation physics, both in collaboration with the Groningen Proton Therapy Center, and radiation hardness studies. The radiation biology research will be substantially expanded in the coming years with a new beam line for image guided preclinical research. For this research new dose delivery modalities including scanning, spatial fractionation and very high dose rates are developed. In addition, a new program has been started on the production of exotic nuclei, for which a new superconducting solenoid fragment separator will be developed.

For the radiation hardness testing a cocktail beam at 30 MeV/amu with several ion species up to Xe has been developed and is now routinely delivered for experiments. A cocktail at 15 MeV/amu up to Bi is under development.

INTRODUCTION

The superconducting AGOR cyclotron, built by a French-Dutch collaboration in the period 1987 – 1994, has, after being transferred from Orsay (France), been operational in Groningen since the beginning of 1996. It can deliver beams of all elements, as is illustrated in the operating diagram in Fig. 1. The upper limit on the beam energy is determined by K_{bend} = 600 MeV and K_{foc} = 200 MeV; the lower limit by the lowest RF-frequency of 24 MHz and the location of the $\nu_r + 2\nu_z = 3$ resonance. The dots in the figure indicate the beams delivered for experiments over the years.

In the period 1996 – 2013 the beams delivered have mainly been used for research in nuclear physics (light ions) and on fundamental symmetries (heavy ions). Since 2014 the emphasis has shifted towards biomedical research, detector development and radiation hardness testing.

OPERATION

The cyclotron is operated 120 hours per week for about 26 weeks per year, which still meets current demand. From a technical perspective it is feasible to operate the cyclotron about 40 weeks per year; this would require additional operating staff to be recruited and trained.

With the shift from fundamental physics to radiation biology and physics and technology of particle therapy the number of individual experiments has significantly increased while their duration has strongly decreased from several days to typically 16 hours. It regularly happens that the cyclotron has to deliver a different beam every day of the week.

Over the past few years proton beams have been provided for over 80 % of the beam time, accelerated either as protons ($E_p \geq 120$ MeV) or as molecular hydrogen ($40 \leq E_p \leq 90$ MeV). The remainder of the beam time helium, carbon and oxygen beams with energies in the range 30 – 90 MeV/amu have been provided.

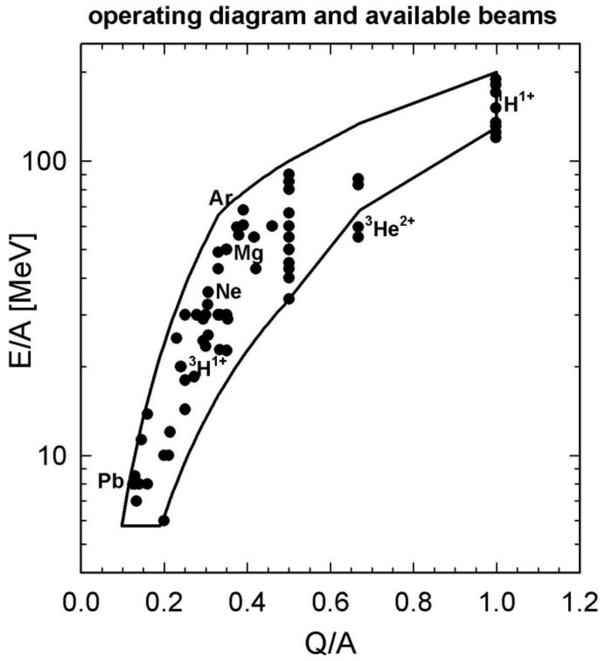

Figure 1: Operating diagram of the AGOR cyclotron.

RELIABILITY ISSUES

After nearly 25 years of operation reliability issues start to appear on certain sub-systems of the accelerator. These are to a large extent related to availability of spare parts and components and, for the control system, incompatibility with current hardware and standards for communication. In addition, wear and tear necessitates replacement of certain components.

Control System

The central control system of the AGOR accelerator facility is based on the commercial Vsystem software package [2]. We have recently ported the system from the 32-bit to the 64-bit version in order to maintain compatibility with modern hardware. Depending on the specific requirements local control is performed by PLC's (vacuum, cryogenics, cooling) and locally developed microprocessor-based systems communicating over BITBUS (power supplies, beam diagnostics). Both suffer from obsolescence. We have therefore started a program stretching over several years to gradually replace all PLC's and to phase out BITBUS. Upgrade of the PLC-based systems to the latest version is nearly complete. BITBUS-based systems are replaced by PLC's where possible, thus creating a stock of spare parts. Options for replacement of the remaining BITBUS-based systems, in particular in the RF-system are being evaluated.

Radiofrequency System

The RF-system of the AGOR cyclotron operates rather reliably. The tetrodes of the 55 kW RF amplifiers, which for all beams operate below 22 kW, all have well in excess of 100,000 running hours and we observe no degradation of the cathode emission. Breakdown of power transistors in the dual 1 kW solid state preamplifiers of each amplifier is the main source of malfunctioning and we are considering replacement. The low-level electronics (amplitude, phase and tuning regulation) and the position control of the RF-cavities require, although reliable, overhaul because of obsolescence of key components.

Extraction Channels

The extraction system of the AGOR cyclotron consists of an electrostatic deflector (ESD), a room temperature electromagnetic channel (EMC1) and two superconducting electromagnetic channels (EMC2 and QPOLE). EMC1 and EMC2 consist of the dipole, gradient and compensation winding; QPOLE consists of a quadrupole doublet with horizontal and vertical steering.

The ESD operates at moderate voltage ($V \leq 50$ kV) and field strength ($E \leq 10$ MV/m), resulting in very reliable operation. Occasionally reconditioning by means of flowing oxygen gas in the gap is required.

The EMC1 operates at high current densities (up to 140 A/mm^2) and small winding dimensions (3 x 4 mm^2 with 2 mm ∅ cooling channel). The total power dissipation in the channel is up to 80 kW in less than 2 kg of Cu. Adequate cooling necessitates high flow velocities, resulting in erosion in the sharp bends of the windings at the entrance and exit of the channel. Both the original EMC1 and a copy put into operation ten years ago increasingly suffer from water leaks in bends. The repair of these leaks is a major source of downtime, which can only be mitigated by building another EMC1. In order to avoid the sharp bends, the channel has been completely redesigned exploiting an in-house developed bending technique. An additional benefit of the new design is a reduction of the number of brazings by a factor four from over 200 to 52. The new EMC1 is currently under construction in our workshop and will be commissioned in 2020.

The superconducting channels operate very reliably. Malfunctioning of the redundant quench detection caused a rupture of the superconducting wire of the QPOLE. While the repair itself was straightforward, getting access was complicated due to the need to cut the cryostat wall and weld it again after the repair.

Cryogenic System

The main coils and the two superconducting extraction channels are cooled by a Linde TCF-50 cryoplant operating in mixed mode: for the main coils it acts as a refrigerator (gas return at 4.5 K) while for the extraction channels it supplies liquid helium (gas return at 300 K). Overall, this system has proved to be very reliable over the years. However, for the past year we experienced a transient instability during filling of any of the three cryostats precluding operation for a period of several days up to two weeks. No signs of excessive heat loss in either transfer lines or cryostats were observed and also detailed analysis of the extensive diagnostics information did not provide an insight in the cause of this problem. After the last standard maintenance cycle, during which essentially all transfer lines are warmed up and evacuated the problem now seems to have disappeared.

At the end of 2018, we installed a new Kaeser helium compressor and upgraded the cryogenic control system. The motivation for this project were energy savings and spare parts running out at the manufacturer. The new compressor operates at variable frequency, which has resulted in an energy savings of 15% for the accelerator facility as a whole. The payback time for this investment is six to seven years. The new compressor has been equipped with a heat recovery system that provides about 75 % of the heat needed for heating the building.

PLANS FOR THE FUTURE

In 2018 funding has been obtained for further expansion of the biomedical research at the AGOR cyclotron and for a research programme on the properties of neutron-rich heavy nuclei. For both programmes new experimental platforms will be installed at existing beam lines. Consequently, the BBS magnetic spectrometer [3] used for nuclear structure research and the TRIμP fragment separator [4] are being decommissioned. In Fig. 2 the new lay-out of the experimental hall is displayed.

Biomedical Research

The University of Groningen (UG) and the University Medical Center Groningen (UMCG) have recently established a clinical proton therapy center, which started treating patients at the beginning of 2018, at the UMCG-campus. In conjunction with this center an extensive R&D programme encompassing radiation biology, physics and technology as well as clinical studies has been established. The AGOR accelerator facility is the key infrastructure for in particular the radiation biology and physics and technology R&D in this programme.

For the radiation biology research a new beam line with 3D X-ray and bioluminescence imaging at the irradiation position, thus providing the capability to perform individually optimized small animal irradiations, will be built in the coming years. At the new irradiation platform several new dose delivery modalities will be available, including pencil beam scanning, spatial fractionation and very high dose rates (> 1000 Gy/s). The platform will be operated as an open access facility.

Plans for a further additional beam line for particle therapy physics and technology R&D are currently being developed.

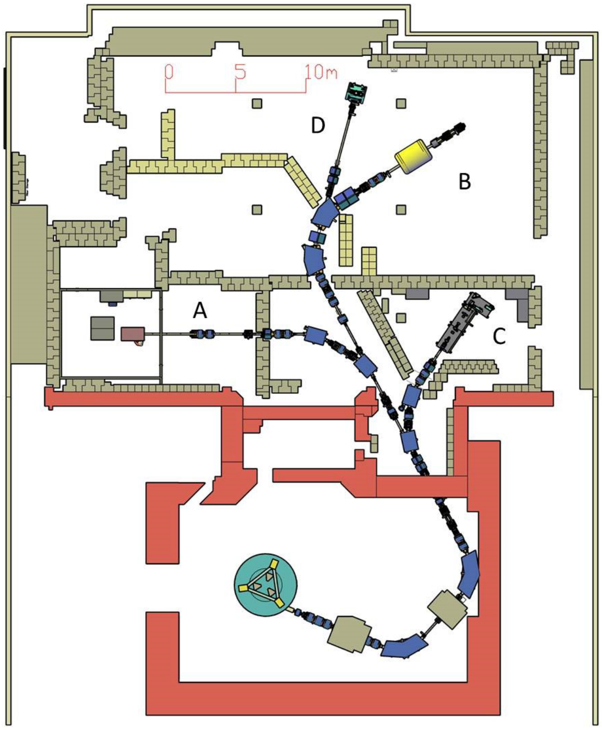

Figure 2: New floorplan of the AGOR facility.
A: image guided radiation biology.
B: superconducting solenoid separator
C: in-air irradiation
D: in-vacuum irradiation

Heavy Element Research

A new experimental research program on the production of neutron-rich heavy nuclei using multi-nucleon transfer in reactions between heavy nuclei (e.g. 136Xe on 208Pb) [5] has recently been started at the University of Groningen. The AGOR cyclotron will provide the heavy ion beams in the mass range A = 140 – 160 with energies around 10 MeV/A for the experiments, requiring substantial development work to produce rare earth elements beams. A new experimental station consisting of a 3 T superconducting solenoid fragment separator followed an MR-ToF mass spectrometer will be installed at one of the existing beam lines (see Fig. 2).

Radiation Hardness Testing

The radiation hardness testing at our facility is expanding. In addition to the proton beams we now also provide heavy ion beams for this. We have commissioned a cocktail of various ions up to 129Xe with an energy of 30 MeV/amu for in air testing. Using a thin Au scatter foil ions fluxes $\geq 10^6$ ions/(cm^2s) in a field of 30 × 30 mm are available for all ions. The homogeneity of the field is better than 10 %. foil. Higher fluxes and larger fields can be achieved with the scanning system that has been installed at both the in-air and in –vacuum irradiation stations. Beam purity is warranted by producing the various ions in the cocktail in two different ECR-sources. Switching between sources requires changing the setting of one switching magnet only. First experiments by external users will be performed in the autumn of 2019.

A cocktail with ions up to 209Bi at 15 MeV/amu, to be delivered to the vacuum irradiation facility, is under development.

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