ON-GOING OPERATIONS WITH THE CYCLOTRON C70 ARRONAX

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Abstract

The multi-particle cyclotron C70 Arronax, located at Nantes, France is used to accelerate non- concurrently four types of particles downstream several beamlines. The particle energy and intensity range of the cyclotron has allowed a wide variety of application including radiolysis, neutron and isotope productions, and physics experiments. Also regular operations are performed both with dual beam runs at 2x100 µA for isotope production and at 350 µA for neutron production using 70 MeV proton beams. At low intensity, 70 MeV alpha beam is one distinctive feature of the machine with the possibility to use pulsed beam with variable time between two consecutive bunches. The status of the machine is presented as well as the operational updates on the beamlines, including the alpha particle pulsing system, the newly installed alpha degrader and beam loss monitor being developed for high intensity runs.

INTRODUCTION

The cyclotron Arronax [1] (Accelerator for Research in Radiochemistry and Oncology at Nantes Atlantique), running since 2010, the year of its commissioning, has started in 2011 its hands-on phase. This phase includes, particularly, ramping up the intensity on targets, constitution and optimization of beams for users, as well as issuing the safety of the machine and targets. It is a phase which is being scheduled into regular uses of separated low and high intensity beam periods.

The cyclotron delivers beams separately in six vaults surrounding the main cyclotron vault. In addition to the cyclotron and magnet systems, the main vault houses two particle sources, an injection line, both of which are located on top of the cyclotron, and the secondary water cooling systems used for irradiation stations and faraday cups e.g., distribution manifolds, de-ionisation columns, and pumping. An adjacent room accommodates other technical systems such as vacuum reading devices, source power supplies, and the primary water cooling system. Several upgrades are being studied for Arronax that will use the adjacent room.

C70 ARRONAX

The multiparticle isochronous cyclotron is based on 65 kV RF cavities with a frequency of 30.45 MHz. The maximum radius for the accelerated particles is of the order of 1.2 m with an average hill magnetic field of ~1.6 T. Without beam loading, the RF power is 20 kW. The characteristics of the beam for the four types of particles (proton, alpha, deuterons, HH+) are given in [2].

THE MACHINE OPERATION AND STATUS

The cyclotron has accumulated, over the first 8 months of 2013, 2000 hours RF equivalent time. The high intensity runs in dual-mode have increased to an average intensity on each target of 100 eµA for radioisotope production and several runs have been performed on the neutron activator at 350 eµA for more than 22 hours.

In addition to the existing ones, new beams have been optimized for users which expand the possible use to beamlines and energies, particularly close to the limits of the machine. Great care on the optimization procedure has been applied, relying first on dual-mode optimization when possible (H+ and D+) and second on machine intensity radial scans as discussed later in this paper. Table 1 gives some of the new possibilities.

Table 1: New Optimised Beams at Arronax

Extracted Particles	Energy (MeV)	Beamlines Name
H+	30	Ax1/P1
D+	16	A1/P3/A2/P2
D+	34	Ax
He2+	67.5	Ax5

So far, the best transmission rates measured from the injection down to the end-station are of the order of 30% for protons, 24% for deuterons, and 10% for all other particles. In terms of intensity, the highest losses are at the beginning of the acceleration within the cyclotron (for radius <200 mm) and in some specific locations in the beamlines. The beamline transport strategy described in [2] is focusing on minimizing these later losses.

Arronax has performed regular runs over several days at approximately 2x100 eµA with protons sent simultaneously in two beamlines. A sample of one run is shown in Fig. 1. This sample is 80 hours long and illustrates a very stable run. The mean current on target is $<I>$=101.2 eµA with $\sigma_{<I>}$=5.3 eµA. Breakdowns are approximately 1.3% of the overall time. For this particular sample the vacuum in the center of the machine is $4x10^{-7}$ mbar. The neutral current (H^0), mainly due to

ISBN 978-3-95450-128-1

beam gas scattering, is measured to be 18.6 eμA (8.6% level) on average. The neutral current participates highly in the machine inner wall activation and is kept to a minimum by maintaining a vacuum as low as possible during runs, and by adapting the magnet's strength within the cyclotron. The neutral current has continuously been decreasing and in August 2013 reached a 4.5% level.

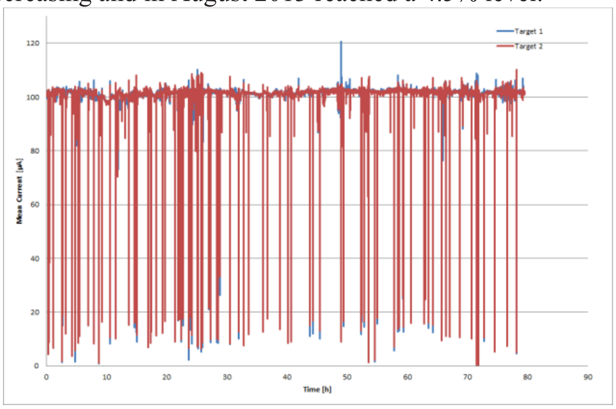

Figure 1: 80 hours of a dual-mode run at the intensity of 101.2 eμA on each beamline.

Even for steady runs such as the one presented in Fig. 1, several target intensity spikes are measured. Here, 43 seconds above 6% of the average current are totalised. Most of these spikes are observed as sudden dissymmetry target intensities between both beamlines in use. These kinds of high intensity fluctuations have to be avoided at a maximum as they can lead to destruction of the target. Although, at the time of writing, some of the spikes are not completely understood; the control system is being modified to accommodate and avoid such rapid changes.

The main modification on the machine in 2013 has been on the re-installation of the alpha pulsing system in the injection line. The alpha pulsing has been tested with the beam dump described in [3] and has shown the capacity with the dedicated diagnostics to ensure time structure and geometry of the beam.

The newly installed alpha particle energy degrader has further been tested pointing to a degradation of the intensity transmission rate (~40% in the beamline at the degrader location) due to expected beam blow-up. Additional beam optimisation procedures and adaptation of the degrader are underway to maximise radioisotopes production stability.

Additional to the beam transport strategy leading the optimization in the beamline, performed in 2012-13, are scans with a dedicated probe of the intensity versus the radius within the cyclotron. Figure 2 illustrates some of these scans. The intensity drops in the figure at slightly more than the equivalent of 70 MeV.

Several magnet conditions were used for these scans including modification of the values of the dees' secondary local coils, called harmonics in the machine. These coils shift the overall spiral trajectory in one radial direction. The preliminary checks indicated a 300 keV change in the drop while the external harmonics are steered by 3A – a relatively high value.

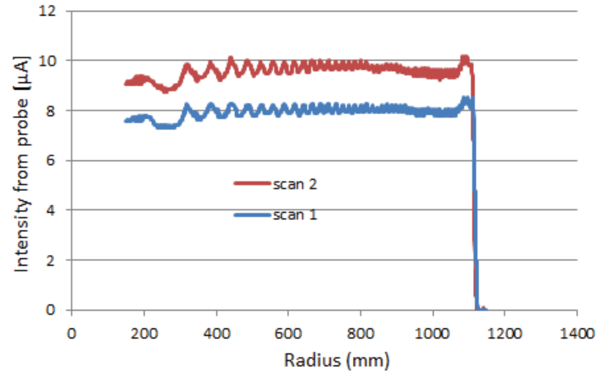

Figure 2: Intensity radial scan inside the cyclotron performed with the probe.

As a first step, these scans are becoming integrated to the optimization procedure, as they show changes from dual-mode to single-mode and the impact of the various magnets (basically main, compensation and harmonic coils of the machine). The considered value at the present time is the radius of the drop at 90% of the stable flat scan.

MAINTENANCE

All the electrical cables used for intensity measurements in the irradiation stations have been replaced to prevent radiation aging, as well as the power supplies for several magnet systems. The main corrective interventions in 2013 are given in Table 2 and show that the water cooling system, with e.g., several leakages on the de-ionization columns need specific care. It should be noted the beams are stopped in cooling water.

Table 2: Intervention Percentage on the Cyclotron Parts

Cyclotron Parts	Percentage of Intervention
Water cooling	21%
Stripper foils	11%
Magnets	14%
RF (Amplifier)	11%

Additionally, the water-cooled TH535 tetrode, located under the cyclotron and part of the last stage 110 kW RF amplifier, has been replaced after 3580 hours of run time. The 0.8 μm thick carbon based stripper foils, used for proton extraction, have been, on average, exchanged after 12000 eμAh (proton-equivalent integrated current). This mean lifetime is in continuous increase mainly due to more stable operations over the years. The maximum lifetime of a stripper has been 20300 eμAh.

Computerized Maintenance Management System (CMMS), which will be in use by 2015, will support the general maintenance work.

Radiological Environment

The operation of the cyclotron, because of high intensity runs, leads to important ambient radioactive levels in the vaults that have to be taken into account for any maintenance purpose. The ambient level is a contribution of several momentary and build-up radiation types ranging from activation of air, water cooling of the irradiation station, and materiel of the cyclotron. Berthold LB 112 detectors measure at the vault entrance an average of 30 mSv/h for the cyclotron vault, and approximately 5000 mSv/h for the vault housing the targets, when in runs for isotope production.

For any intervention in the main vault, precaution must be taken. The cyclotron has to be inactive for at least three hours, at which time ambient levels drop to 0.250 mSv/h. After a 72 hour machine-stop, the ambient level is of the order of 30 µSv/h, with some specific locations remaining relatively active. These locations correspond essentially to de-ionization columns of the water cooling system, stripper foils flanges, external RF cavities walls, and extraction vacuum chambers.

MACHINE AND BEAMLINES ADAPTATION

The alpha pulsing system based on deflectors and the alpha particle energy degrader discussed earlier are described in more details in [2,3].

Further modifications on the beamlines are being done at Arronax. One of these is dealing mainly with the irradiation station and their foreseen future high intensity use for Rubidium metal (RbM) targets, in collaboration with INR-Troisk (Institute for Nuclear Research at Troisk-Russia). The modification includes water temperature, conductivity, and pressure measurements close to the irradiation station with a National instrument CompactRIO data analysis system.

In addition, beamline simulations, damages on sealing joints, and activation locations have pointed out the possibilities for beam losses in the beam pipe walls. As a corrective action, a carbon ring has been installed to protect the joints. To further tackle these local losses, and to provide an understanding of them, a first home-made candidate Beam Loss Monitors (BLM) based on an air-ionization chamber was devised, within a Memorandum of Understanding with IThemba LABS - South Africa, and installed in one beamline. The primary goals were to check mechanical suitability around several beam pipes, electronics, and the chain of data measurements. The BLM characteristics are given in Table 3 and are shown mounted on the beam pipe of one of the beamline loss locations (behind a 3.7m thick wall) in Fig. 3.

First signals were obtained at low power supply (50 V up to 600 V) and a new 4-channel CAENels data acquisition system, combined with a labview software, was used. The measurements, performed during a non-dedicated run at high intensity, indicated the background level and capacity of the BLM to follow slight changes in the beam transport.

Table 3: BLM Characteristics

Characteristics	Values
Mechanical dimensions	250 x 250 x 30 mm
Chamber volume	65.7 cubic cm
Number of sectors	4
Max high voltage	1000V
Data reading frequency range	10 Hz to ~1 kHz

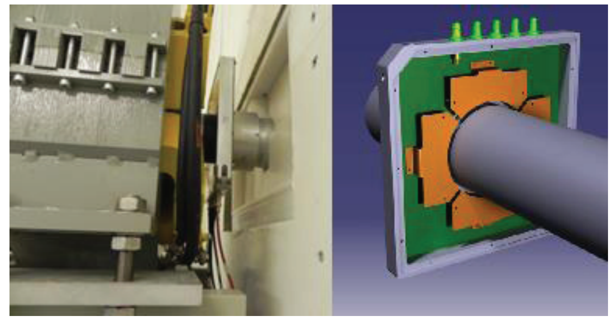

Figure 3: On the right, BLM installed between the wall and a quadrupole. On the left, the designed BLM.

More tests are foreseen, particularly with the electromagnetic compatibility of the cables in the central main vault, and data reading capabilities when beams are wrongly steered or backscattered particles are numerous. If proven adequate, BLM installation is foreseen in several locations on the beamlines.

As discussed earlier, the water cooling system requires specific studies and modifications. This encompasses the relocation of the water system distribution and the de-ionization columns located in the central vault, possibly to the adjacent technical room. This room will benefit for servicing the cyclotron, and houses some of the electronic systems such as for the RbM irradiation station, the BLM, and other additional monitors.

CONCLUSION

The cyclotron C70 Arronax has increased beam time and intensity on targets for isotope production and neutron activation. At the same time, beams have been optimised to offer a wider range of energy for user requirements. This will continue as the procedure and beam transports check are being extended.

Further, various upgrades are being performed on the beamlines, the irradiation stations, and the cyclotron environments.

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ISBN 978-3-95450-128-1