# C70 ARRONAX IN THE HANDS-ON PHASE

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### *Abstract*

The C70 Arronax, is a high intensity (2x375 eμA) and high energy (70 MeV) multiparticle cyclotron which has started its hands-on phase since December 2010. The operating and maintenance group is accumulating experience on this machine. A review of the machine status and present possibilities in terms of beams capacities is thus presented in this paper. The status of the beamlines simulation is also given.

## INTRODUCTION

ARRONAX [1], an acronym for "Accelerator for Research in Radiochemistry and Oncology at Nantes Atlantique", is a high energy (70 MeV for protons) and high intensity (2*375 eμA for protons) multi-particle accelerator located in Nantes, France. ARRONAX can deliver beams in six experimental vaults: four are devoted to radionuclide production and equipped with an irradiation station connected to our hot cells via a rabbit system; one contains a neutron activator being tested at the time of this writing; and the last one is used for basic research in radiolysis, radiobiology and physics especially using the alpha and deuteron beams. The cyclotron reached its full specifications (24H in a row at 750 eμA for protons) in October 2010 but irradiations at low current started in March 2010 for radiochemical studies and process optimisations. 2011 was the hands-on phase, with an extensive program on optimisation of the beams and exploration of beam parameters for the users. This phase includes ramping up the intensity on targets and issues the safety of the machine and targets.

## C70 ARRONAX

ARRONAX is an isochronous cyclotron with four high hill sectors. The overall size of the cyclotron is of the order of 4m. The working RF frequency is 30.45 MHz with an RF cavity composed of two dees at a voltage of 65 kV. The characteristics of the beam for the four types of particles (proton, alpha, deutons, HH+) are given in [2]. Alpha ($He^{2+}$) particles can undergo a stretch of the inter-bunch time in the experimental hall by using deflectors in the injection line and the extraction line. This system, so-called alpha pulsing, allows inter-bunch time from 32.8 ns up to 5 s.

## THE MACHINE STATUS AND OPERATION

The cyclotron has run for more than one thousand hours RF equivalent time with the RF systems being shutdown most nights. This is due to the operation schedule and manpower resources. On average, every 1.5 days, a new particle and a new beam line are in use.

The change of particles between a first on-target beam and a second on-target beam varies from approximately 20 min up to 2.5 hours depending of the settings of the sources, i.e. types of particles, and the requirements on the preparation and optimisation of the beam on target.

Preparation includes installation of dedicated diagnostics at the end of the beamline such as supporting stands for alumina foils.

Beam optimisation and strategy for the beam transport is detailed in [2]. Various types of optimisation are performed with respect to the beamline in use and the mean intensity sent on target.

### *Operation on the Cyclotron*

Several modifications on the cyclotron have been and are being performed in 2011-12 which include:

- Installation of a new injection solenoid following damages on the water cooling circuit.
- Tightening of shims within the main coil by the IBA field team.
- Re-design of the water cooling system of a resistance for the alpha pulsing injection deflector.

### *Ramping up the Intensity on Target*

In 2011, the machine has been working over several occasions continuously for several days at 80 eμA with protons through a single beamline and also simultaneously through two beamlines. For this the beam is sent to an irradiation station where a rabbit containing the samples is located.

One of the runs is shown in Fig. 1 for a single line in use at 80 eμA. The stable part of the run is 95.4 hours. A Gaussian fit on the mean current measured on target <I> gives 80.23 eμA with a $\sigma_{<I>}$=1.35 eμA. The intensity losses (or breakdowns) which are seen as downward spikes on the figure are 1.6% of the overall time. These are seen as quench of the RF system. Several intensity spikes have also been measured with amplitude as high as 90 eµA.

Dual modes, with two proton beams at 80 eµA on targets, have shown a tendency for a broader intensity standard deviation with a measured $\sigma_{<I>}$=2.2 eµA, averaged over both beams. It also indicates that great care must be taken into the tuning of the beams and the use of the algorithm which perform the intensity stabilisation.

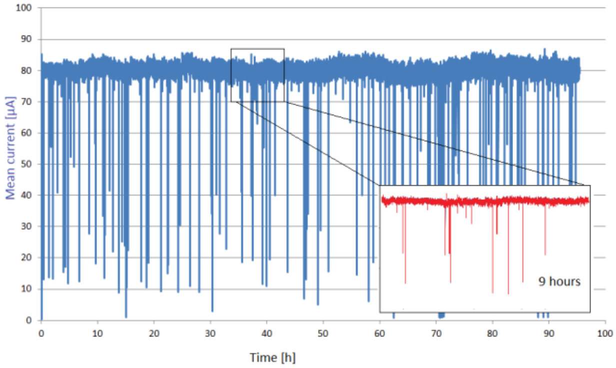

Figure 1: 95.4 hours of a single run at the intensity of 80 eµA and a close up view over 9 hours.

Since the beginning of 2012, several runs were performed on the neutronic activator. They have shown both the capacity to stand at a high intensity and a relatively stable beam with the safety conditioned by the target requirements. These requirements were mostly on the stability of the transverse position and dimension of the beam down the beamline: the dimension was insured by the online collimator's reading and a minimum 4% of the intensity was kept during operation. Part of these runs were the definition of the operational modes concerning the ramping up from 0 up to 200 eµA and up to 300 eµA and testing of the experimental setup. The task for the ramping up was to keep a large beam on target while increasing in steps the intensity. Figure 2 shows the various steps of a run up to 300 eµA. The intensity on target is given by the blue line while the neutral current (electron stripped H-) within the cyclotron is of the order of 10% at 200 eµA (red line). An integrated intensity over time of more than 1200 µAh was reached (green dashed line).

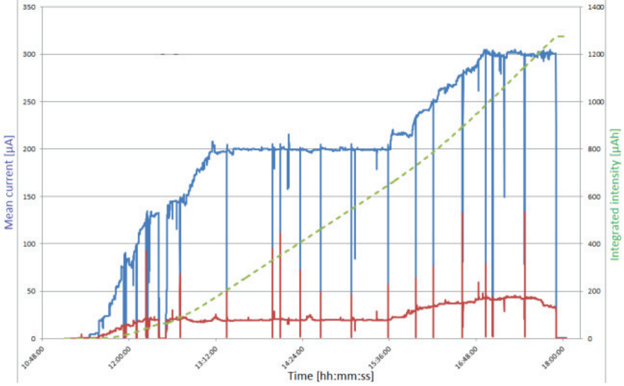

Figure 2: run over 8 hours up to 300 eµA on target.

### *Operation at Low Intensities*

Deuterons and alpha particles have been extensively used in the vault for basic researches.

Deuterons have been prepared and used for energies ranging from 16.4 MeV up to 34 MeV, with transverse sizes of the beam of the order of a few cm. The approximate size and position of the beam was checked using alumina foils positioned at the location of the targets. The intensity range used was from 50 nA up to 1.2 eµA. The upper limit for the intensity being constrained by safety issues on the beamline exit window made of kapton and the need to keep low background activation in the vault.

Alpha particles are used on several beamlines at the energy of 18.4 MeV/n for intensities down to a few hundred of α−equivalent pA. A users-made dedicated ionisation chamber combined with an integrator measures such a low current.

In 2011, low intensity alpha beams were reached by decreasing the Pantechnik Supernanogan Electron Cyclotron Source (ECR), at a stable level, together with the injection quadrupole triplet. In order to ease the optimisation, in 2012 the solenoid installed straight downstream the ECR source has been used. This allows increasing the envelope of the beam and loss of particles at approximately 400 KeV before acceleration within the cyclotron. The first tests indicate good intensity stability down to a few pA.

### *Alpha Pulsing*

First tests on the pulsing of alpha beam have shown the possibilities of the deflection system to increase the inter-bunch time from 33 ns up to 5s. These tests were performed with a self-made 10 mm aperture beam dump located downstream the collimator. In order to test and verify further the pulsing system in a more user-mode fashion, the beam dump was moved away in the air, 150 mm from the exit window. A simple support has been designed for this purpose and is shown in Fig. 3. The tests with this setting and pulsing at 330 ns inter-bunch time have indicated that beam optimisation based on the beamline quadrupole is possible but is time consuming. Still work has to be performed to further tune both the beam crossing time in the experimental hall and dimension of the beam.

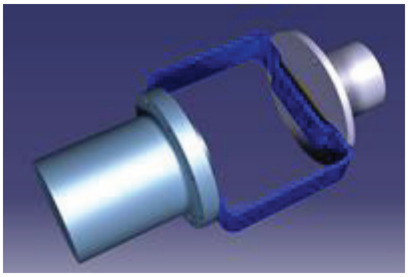

Figure 3: The beam dump installed 150 mm downstream the exit window.

## BEAM SIMULATION

Simulations of the beams through the lines are performed using both G4beamline [3] and PSI-transport [4] for the various types of particles, and primarily for protons and alpha. The simulations have indicated that losses of particles occur in specific locations such as behind the 3.70 m wall separating the cyclotron vault from the target vaults. Radio-activity measurements confirm the losses locations. All of this work has triggered the necessity to study possible beam loss diagnostics. A first candidate technology is based on an ionisation chamber positioned around the beampipes.

## SOFTWARE UPDATE

Most of the software updates are dedicated to the online beam diagnostics. A labview-based code has been implemented to analyse the data from the profilers installed for low intensity beams. An example of the screen is shown in Fig. 4.

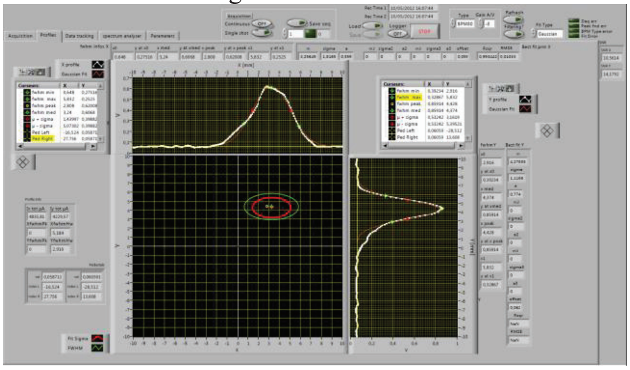

Figure 4: Screen shot of the online beam profile data acquisition system for the profiler NEC-80.

The online software is in its first stage of development and is foreseen to be used further for tuning beam transverse location.

## DEGRADER AND ENERGY MODIFICATION

The 70 MeV alpha particles are extracted with an electrostatic deflector within the cyclotron. To adapt the energy of these particles to user's requirements, an energy beam degrader has been installed in one of the beamline upstream an irradiation target. The degrader will allow reaching energies of the order of 28 MeV.

It is constituted of a rotating aluminium wheel with twenty 1.25 mm thick plates as shown in Fig. 5. The inner core is water cooled. The whole system is sealed to be in the vacuum and mounted on an actuator to move the plates in front of the beam.

At the time of writing the degrader has undergone first water leakage check while installed in the beamline. Further tests are required before sending the first beam e.g. the vacuum seal and control system software.

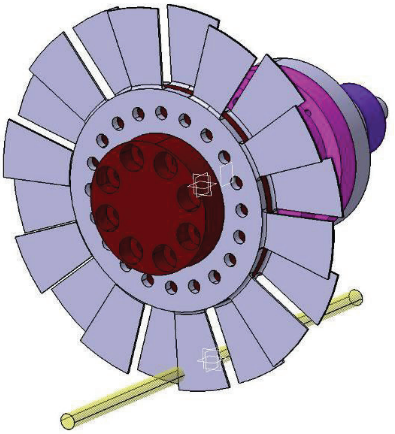

Figure 5: the 1.25 mm thick rotating wheel for the alpha particle degrader.

Additionally, a proton energy degrader has been installed to later deliver beams with energies below the C70 minimum (30 MeV). It is also located on an actuator on the top of the alpha degrader. Water encapsulated in a 10 mm aluminium window is the base for the energy loss and brings the beam in the range from 10 to 30 MeV.

## CONCLUSION

The C70 ARRONAX has seen within the year 2011and beginning of 2012 an extension of its use in term of energy range and intensities. This will keep on as energy degraders are being used for various particles.

The test runs on targets have also indicated its possibilities to sustain high intensity for protons in single and dual modes. This will continue on in 2012 with ramp ups of the intensity on target. Further diagnostics and beam data acquisition software which are essential for performance checks are particularly being studied. This includes beam loss monitors.

## ACKNOWLEDGMENT

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## REFERENCES

[1] J. Martino, "ARRONAX, a 70 MeV cyclotron for Radiochemistry and Nuclear Medicine," Proc. 18th Conf. on Cyclotrons and their Applications, Catania 2007.

[2] F. Poirier et al., "The C70 ARRONAX and Beam Line Status", IPAC11-WEPS069, Sept. 2011 and references therein.

[3] T.J. Roberts et al., "G4beamline Simulation Program for Matter dominated Beamlines", EPAC08-WEPP120, June 2008.

[4] U. Rohrer, "PSI Graphic Transport Framework", based on CERN-SLAC-FERMI by K.L. Brown et al.