STUDIES AND UPGRADES ON THE C70 CYCLOTRON ARRONAX

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Abstract

The multi-particle cyclotron C70 Arronax is fully running since 2010 and its RF run time has increased up to 4400 hours in 2015. The accelerator is used for a wide variety of experiments (physics cross-sections, radiolysis, radiobiology) and radio-isotope productions. This requires runs with 7 orders of intensity range from a few pA up to 350 µA and a large range of particles energy.

Machine and beamline studies are continuously needed. For example magnet intensity scan inside the cyclotron and in the beamlines, respectively with compensation coils and the quadrupoles have been done. These scans caracterise performances of the machine and help both operations and mitigation of particle losses. Additionally beam loss monitors and control systems are being devised to support further the high intensity and precision requirements on the runs. Also a pulsed train alpha beam system located in the injection has been designed. The proof of principle with a dedicated run has been performed.

The results of the machine studies and status of these developments are presented in this paper.

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 [2]. Arronax has gradually increased the number of hours it uses the cyclotron.

The cyclotron delivers beams separately in six vaults surrounding the main cyclotron vault [3]. Five of the vaults are used for high intensity beams and the sixth one, beamline for experiments, is dedicated to low and ultra-low intensity (<100 electric pA).

The priority list for production of radio-isotopes covers both isotopes for imaging and therapy. It includes, but not exclusively, ^{82}Sr, ^{64}Cu, ^{211}At and ^{166}Ho. ^{211}At requires an energy degrader that has been installed in one of the beamline and as for ^{166}Ho, a neutronic activator is in use, all at intensities above 10µA.

RANGE OF OPERATION

The cyclotron provides four types of positively charged particles (proton, alpha, deuterons, HH+) which intensity and energy can be modified according to the experimental needs. Figure 1 shows a map of the operation range for each particle at intensity from a few nA up to 100s of µA on the target with energies from 32 MeV up to 70.3 MeV for protons. Protons and deuterons have the widest energy range mainly due to cross-section measurements being performed at Arronax on numerous physics production channels [4]. Several runs with protons for ^{82}SR production have started in 2016 at 150µA on target, extending the production capacities at Arronax.

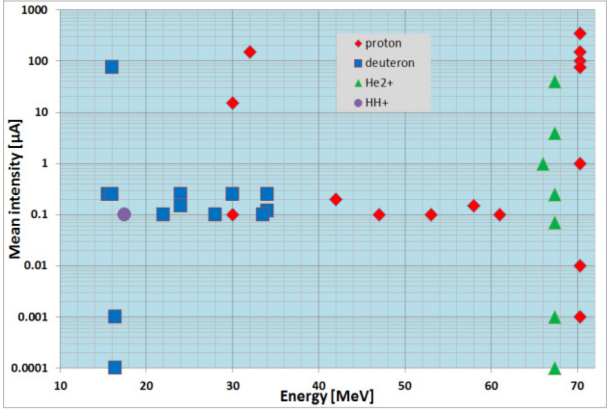

Figure 1: The operation range for the C70 Arronax with the 4 particles in use.

THE MACHINE OPERATION

The use of the cyclotron, here expressed in term of number of RF hours, has increased over the years up to 4400h in 2015 as shown in Fig.2, being limited mostly by manpower. Each year includes 4 main preventive maintenances that are performed over a week. Also, a Computerized Maintenance Management System (CMMS) – MaintiMedia from Tribofilm, is in place since 2015, to support the general maintenance follow-ups.

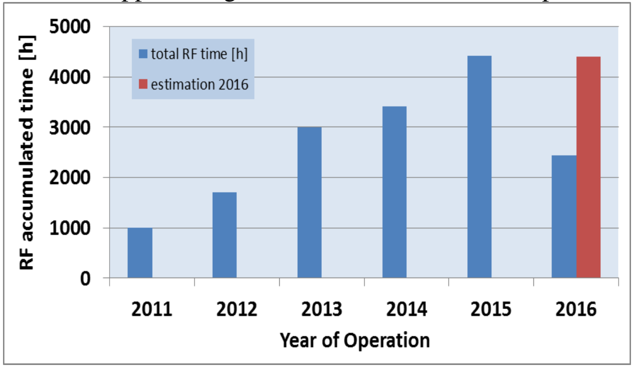

Figure 2: RF accumulated time per year since 2011 and as of august for 2016 and estimation for this year.

The settings on the machine parameters at the beginning of a run are systematically adjusted to increase the transmission rate and as the operation last and magnets elements temperature increase, parameters such as main coils are optimised. In the case of new beam parameters e.g. new particle energy and/or intensity, being developed, systematic studies are planned.

The studies include transmission rate and also scans with various settings on the machine as shown later.

Table 1: Transmission Rate for the 3 Main Particles

Particles	Estimated Intensity in cyclotron [μA]	Transmission rate (End-of_line/injection)
H+	252	43%
D+	64	37%
He2+	26.6	10%

The transmission rate from the faraday in the injection to the end-of-line is indicated in the table 1. The particles losses are mainly in the injection and below 2 MeV. Additional losses are along the trajectory in the cyclotron (neutral particles at the level of 4.4% for protons) and along the beamlines (a few percentage).

MACHINE OPERATION STUDIES

The cyclotron is constituted of several internal magnets beside the main coil which provide the average magnetic field for the valley and hills. These are 3 compensation coils at 3 different radius (internal, medium and external) and paired harmonic coils. While in a dual-beamline run, the compensation ones are adjusted such that maximum current is obtained at both exit and the harmonic ones are set such that symmetry in intensity is observed. A scan of the intensity on faraday cups at the extraction exit was performed as a function of the compensation coils. The result is plotted in Fig. 3 for the intensity as a function of the external and medium coil and shows a region of maximum transmission with a large stability area (red). It also indicates some region to be avoided as a discontinuity on the magnet elements is present when passing 0A. This type of scan did show the need to perform regular check with newly constructed sets of magnet taking into account several multi-scan results. This type of scan with the help of dedicated beamline diagnostics can be used to track the status of the beam (eg resonances in the machine leading to beam blow-up, and modification of the beam shape) and stabilises overall runs. Taking into account these scans will have to be mitigated with the modification of the particles final kinetic energy.

BEAMLINE OPERATION STUDIES

Emittance measurements are important for check of the stability of the machine, determining focusing spots on the target and losses in the beamlines. This is addressed first though quadrupole scans in the beamlines.

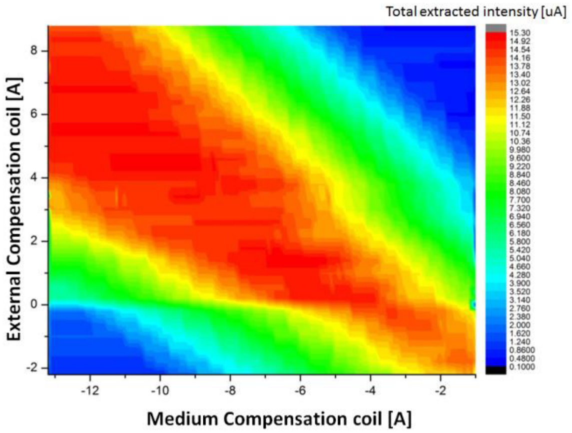

Figure 3: Total extracted intensity [uA] on both-side faraday cup as a function of compensation coils medium and external settings.

Quadrupole scan have been performed at intensities between 10 up to 30 μA. These scans have the goal to find the best setting for transmission rate in the beamline, for adequate beam size at the target location, emittance measurements studies and potential use in ballistic beam-based alignment to optimise the trajectory of the beam inside the beamline.

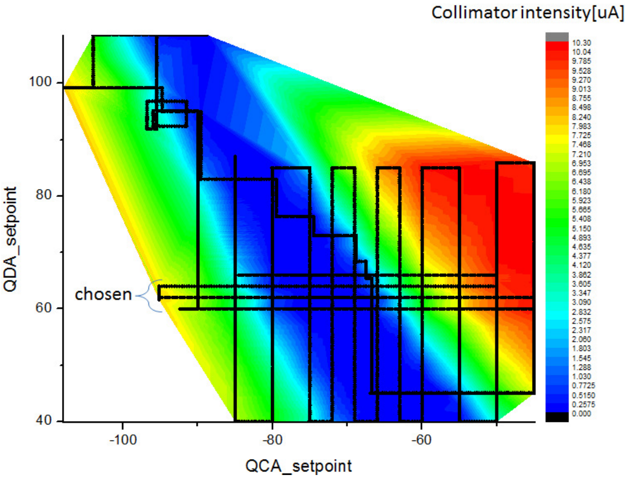

Figure 4: Quadrupole scan result with the 2 last consecutive magnets in the beamline. The coloring represents the interpreted intensity level on the collimators in the horizontal plane and the black dots the actual data points.

The scan of Fig. 4, was first obtained to select data that could be used to perform first preliminary emittance measurements. The criteria being two-fold: centered position of the beam and a full shape containing a deep in the scan. The chosen scan are indicated in Fig. 4. The technique uses first a transformation of the signal on the 10 mm aperture radius collimator into beam dimension. The fitted beam size is plotted as a function of strength in the quadrupole setting. The parabola obtained is then fitted to acquire the emittance according to:

$$\varepsilon_x = \sqrt{AC}\Big/_{d^2}$$

Where A and C are parameters of the fitting parabola [5] similar to single-wire scan and d is, a distance, here a fixed conversion factor from the simulation model in use.

The technique is at the present time being tested for robustness. It relies on simulations model with G4Beamline [6] for the transformation of the signal on the collimator to a beam size. The first measurements indicated variation in the emittance by a factor of 4 for runs separated by a few weeks.

MACHINE AND BEAMLINES ADAPTATION

End-of-beamline users require inter-bunch time which can modified from the initial 30.45 MHz. Using a technology composed of a 3.3 kV chopper in the injection and a 60kV sinusoidal deflector in the experimental beamlines, that is already in place, a new control system on the chopper was devised. This system allows a "start-stop" mode with a fixed number of bunches and various settings for the inter-bunch time. Figure 5 shows the results with 1282000 bunches on the end-of-beamline intensity. Implementations include an EPICS (Experimental physics and industrial control system) software and PIC18 microcontrolers.

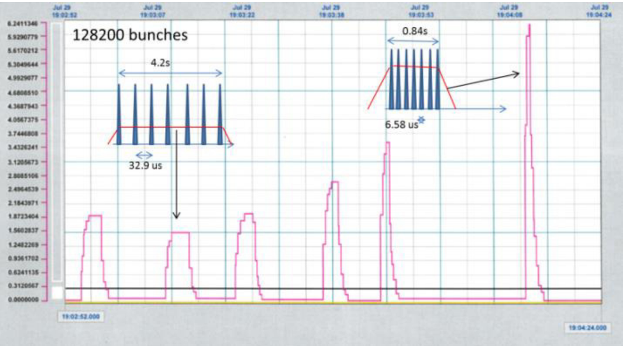

Figure 5: Intensity at the end of the beamline for the "start-stop" pulsation system.

The cyclotron computing environment has as well evolved. An EPICS system has been installed, initially developed with Cosylab, first as a core to retrieve data coming from the simantec S7 Siemens PLC of the accelerator and second as the possible foundation for the extension of the local network. Using a parallel CP-443 Ethernet card, it allows to access the accelerator data without impacting the main control system provided by IBA.

This network (Fig. 6) is foreseen to be the base for several beam diagnostics and technical environment measurements (eg water, gaz). An EPICS software, developed by Ithemba, for Beam Loss monitors is also being tested to later help the extension of beam diagnostics on beamlines and the cyclotron vault. Additionally, various upgrades are being performed on the beamlines, the irradiation stations, and the cyclotron environments (eg collimators, water cooling).

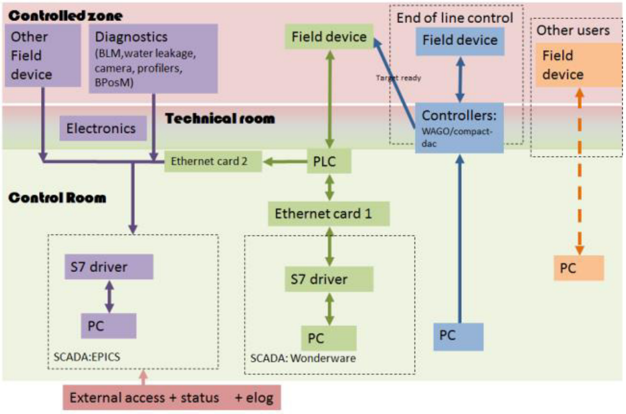

Figure 6: The intermediary planned phase for the computing environment of the cyclotron.

CONCLUSION

The use of the C70 arronax has increased over the years and several operational investigations are being carried out through magnet settings studies. Also a first emittance measurement with collimators at high intensity is being addressed with a model dependant methodology. Operation requirements have lead the need to develop a pulsation system that will extend to a pulsed train system in the injection and also, being part of a long term plan, the computing environment of Arronax is broadening through installation of new EPICS control systems.

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REFERENCES

[1] F. Haddad *et al.*, "Arronax, a high-energy and high-intensity cyclotron for nuclear medicine", Eur J Nucl Med Mol Imaging. 2008, 35, 1377-1387.

[2] F. Poirier *et al.*, "The C70 ARRONAX in the hands-on phase", IPAC12, May 2012, MOPPD024.

[3] F. Poirier *et al.*, "The C70 ARRONAX and Beamline Status", IPAC11, Sept. 2011, WEPS069.

[4] C. Duchemin, "Étude de voies alternatives pour la production de radionucléides innovants pour les applications médicales", Ph.D. thesis, Subatech, 2015.

[5] M.G. Minty, F.Zimmermann, "Measurement and control of Charged Particle Beams", p.103, Springer, 2003.

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