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# STUDY OF INJECTION LINE OF THE CYCLOTRON C70XP OF ARRONAX

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### *Abstract*

The cyclotron C70XP is an accelerator built for the production of non-conventional radionuclides for nuclear medicine, research in physics, radio-chemistry and biology. Its injection section has been designed for 4 types of ions (HH+, D-, He2+ & H-), 3 types of ions reach the end of the beamline (H+, He2+ & D+) at the maximum energy of 70 MeV (H- & He2+). It is important that regular and standard runs provide similar beam features with a good emittance quality. An investigation, focused on the beam in the injection, cover beam measurements and potential beam geometry constraints. The beam transverse characteristics in the injection line has been studied with an Allison-type emittance meter and a simple instrumented collimator installed inside the injection line. With these 2 devices, it is scrutinized how the beam emittance evolves as a function of settings of the injection magnets and the source parameters. Dependencies found between the emittance, beam hotspots and tunings are discussed, as well as the protection performed by the collimator. Future of this work with a potential collimator design is introduced.

## INTRODUCTION

The Arronax Public Interest Group (GIP Arronax) aims at providing well-defined transverse ion-beam dimensions. This, to secure reliable production of radio-isotopes at high intensity and deliver an adequate beam as-homogeneous-as-possible at low intensity for research and detector studies. A study program of the beam in the various sections of the accelerator, mainly transport beamlines and injection section, has been put in place. The study includes first emittance measurements performed in the injection section [1]. The installation of the emittance-meter and the outcomes of the measurements are described in the paper, including the code devised to analyze the data. The observations have pointed out that several high-density spots could be obtained, depending on the machine parameter settings. To check the rejection capacity of these spots, a slit was mounted in the injection section. Measurements of the beam dimensions at the end of two beamlines were performed. The results trigger the need to explore the design of a new collimator system adapted to low energy and high intensity beams.

## MEASUREMENTS WITH THE EMITTANCE-METER

### *Installation*

A 2D (x,x') Alison type emittance meter built in the frame of the EmitM collaboration [2] was installed in the injection line of the C70XP for a measurement campaign [3].

The injection line is composed of two ion-sources (a multicusp for H-/D- ions and an ECR for He2+ ions), a first solenoid, a first steerer, a 90° selection dipole, a quadrupoles triplet, a second steerer, a second solenoid, and a buncher.

A flange on the injection line was modified to allow the insertion device, i.e. a lengthened dedicated flange was built, the penning IKR050 gauge was deported as well as the PV AL25PK pipeline vacuum valve, and the Faraday-cup of the injection line was removed.

Due to the limited space available for the installation 30 cm downstream the buncher, the emittance-meter was positioned in a single plane measurement mode only.

The emittance-meter was aligned by a vertical laser at the geometrical center of the line to define the reference point of the displacements of the head of the emittance-meter.

### *Experimental Preparation*

To ensure the comparability of the measurements, each morning at the start of the day, series of measurements are carried out with the low energy beam (~40keV). For this, systematic emittance measurements are achieved while increasing the arc current of the multicusp source.

Also every morning, the source and magnetic elements were set for low and high beam intensity, and emittance measurements were performed for later comparison.

For the measurement, we start with the optimization for high beam current, each parameter of the injection line was studied systematically and in defined step before returning to the starting value.

During the whole manipulation, no parameter that could affect the acquisition of the signal was changed. All these precautions have been taken in order to make the measurements as comparable as possible.

Prior to the emittance measurements, the reference beam intensity is measured on a radial probe inside the cyclotron at 150 mm of the center of the cyclotron, downstream the spiral inflector.

## EMITTANCE MEASUREMENTS RESULTS

Emittance measurements have shown three major features. First, emittance measurements, combined with the intensity measurements, show a higher transmission rate with an off-axis beam.

Second, beam hotspots, performed with the H- beam, are present within the majority of-the measurements (Fig. 1), The beam hotspots are high density regions of current measurements on the emittance plots.

Third, a 4mm slit, helps to mitigate the number of hotspots. The slit is installed upstream the emittance-meter, on the top of the buncher, and positioned 90° compared to the slits of the emittance-meter.

### *Analysis Code*

For the analysis of the results, a C++ code using the open-source data analysis ROOT framework [4] was developed. This code is based on a matrix for signal background separation and data fitting by a 2D Gaussian as described below.

The matrix cleaning routine is based on two experimental observations, at first a constant mean of back ground noise (BGN) during all experimentation following a Gaussian distribution, at second the signal is positive and reunite in spot inside the emittance measurement.

To separate the signal from the noise, a part of the emittance measurement data is extracted in the form of a matrix (order: N*M) around a point of study. The order need to be chosen carefully, the higher is the order of the matrix, the more side effects will appear, and at lower order of the matrix falser positive data will appear.

The number of points above the average BGN is counted inside the extract matrix. If the number of points counted outrun the number Nc [Eq. (1)], the study point inside the matrix are considerated like a part of the signal and be kept, see Fig. 1

The number Nc is 50% of the number of entries of matrix extracted data multiplyed by the factor of convergence of the random normal law function.

$$N_c = 0.5 * N * M * \left(1 + \frac{1}{\sqrt{N*M}}\right) \qquad (1)$$

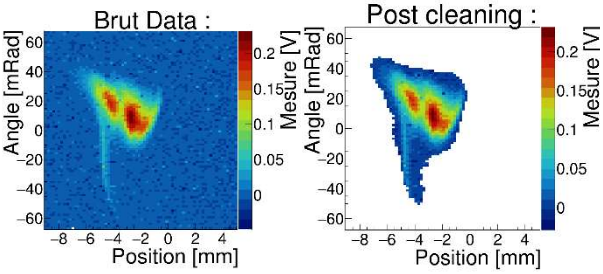

Figure 1: Before and after the matrix cleaning, with beam hotspots and tail, the extraction order is 9*9 in this case.

The matrix cleaning, in the present case, is more effective than the simple 2D Gaussian fitting. We estimated the emittance (not normalized value) for a high beam current optimized with the filament of the source at 4 A. The radial probe measurement indicating the total beam current inside the cyclotron is 283 µA and the emittance is 20.3 mm.mrad. With a particular optimization of the source, the radial probe measurement becomes 361 µA and the emittance 7.6 mm.mrad. This optimization concerns the puller, the electron suppressor and the high tension of the ion-source.

## IMPACT OF THE SLIT

Experiments were performed to determine the impact of the same 4 mm slit located in the injection section on the transverse geometry of the beam of a beamline after the cyclotron compatible with high intensity runs (i.e. >10µA) and another beamline which accommodates an exit window. This latter is particularly adapted to host dedicated in-air beam diagnostics for low intensity beams such as industrial radiographic films. We noticed that, the beam dimensions and the operation methodology is dependent on the type of beamline in use. At the low current beamline, a shape of the beam with beam hotspots is investigated, and on the high current line, the emittance is studied with a scan of the last quadrupole of the beamline.

### *High Intensity Beamline Experiment*

On the high current beamline, the beam was optimized to maximize the intensity on the target. To perform a scan of the transverse dimensions of the beam, the current of the quadrupole upstream a four-finger collimator was swept from 40A down to -20A. The intensity deposition on the collimator's isolated left and right fingers were added up and normalized by the total intensity, measured on the collimator and target. A parabola-like curve was obtained, with a beam waist inversely proportional to the emittance i.e. a lower emittance corresponds to a larger width [5]. With the slit in operation a reduction of the emittance was visible, which is as shown in Fig. 2.

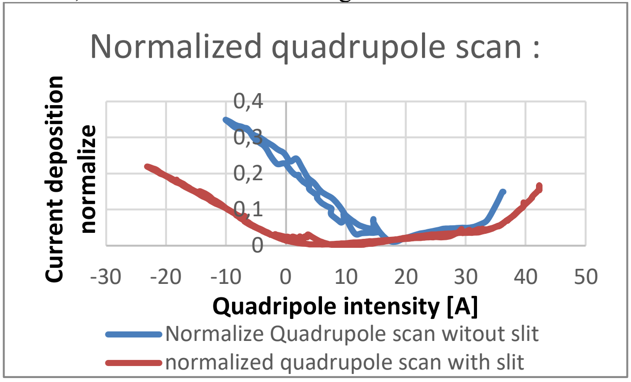

Figure 2: Quadrupole scan on the high intensity beamline with and without the injection slit.

### *Low Intensity Beamline*

On the low current line, the measurements were made on two consecutive Gafchromic™ HD-V2 films, respectively located 130 mm and 630 mm downstream of the exit of the beamline.

The first film was installed to study the beam geometry and the second film to check the alignment of the beam. The beam was stopped inside an aluminum block located 2 m away.

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The total beam current at the exit of the line was measured with a photomultiplier (PM), measuring the ionization of nitrogen in the air. The PM was calibrated at the start of the experiment [6]. The dose of the film was calculated according to the total beam current measured on the PM, and thus by the measurement of the density of gray deposit inside the film.

On the image below (Fig. 3) the density distribution (spot) of the beam, on the *y*-vertical and *x*-horizontal plane of the first film, is visible in term of dose deposition.

The coordinates of the beam are between 2 and 10 mm on the *x*-horizontal plane and -5 and 7 mm one the *y*-vertical plane.

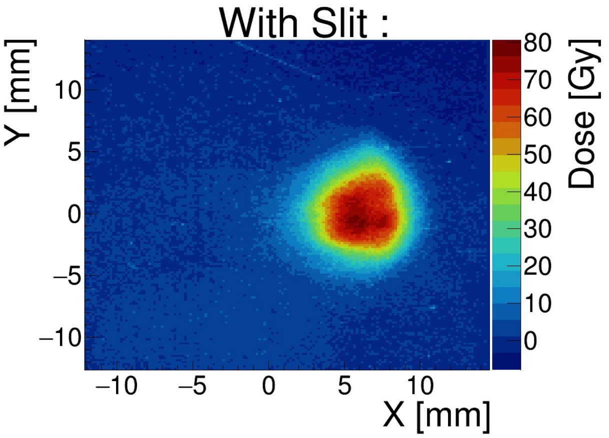

Figure 3: Beam shape on the Gafchromic™ HD-V2 film, 130 mm downstream the exit of the beamline, case with the slit.

Without the slit and with the same optimization it is possible to find other beam hotspots and the beam current increases by 20 – 25 %, see Fig. 4.

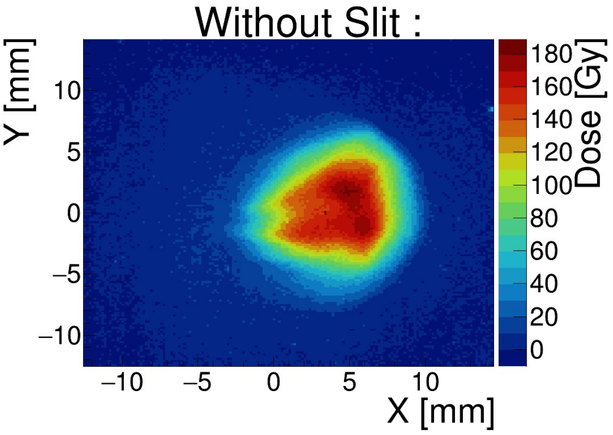

Figure 4: Beam shape on Gafchromic™ HD-V2 130 mm downstream of the exit of the beamline, case without the slit.

When is compare the two images (Fig. 3, Fig. 4), an increase of the transverse dimensions is visible without the slit

Two experimental outcomes were observed: the slit reduce the beam size and the emittance is reduced at the end of the beamline.

## FUTURE COLLIMATOR

It is necessary to determine the maximum aperture of the collimator with the least possible impact on the beam. A circular collimator of 42 mm aperture diameter has been installed on the top of the buncher to validate the design. Initial measurements with the collimator indicated a beam current collection of a few nA.

Following previous emittance measurements, specifications for the future collimator were partly determined: the collimator aperture has to be offset by a few mm. In order to allow positioning indication, the collimator requires at least 4 individual instrumented markers (so called fingers). Each finger should ideally be able to move freely for the adjustment of the aperture. The specifications of the collimator should include the reduction of the emittance i.e. they should define the longitudinal extension. They should also define the safety role for the sensitive elements in the accelerator e.g. the spiral inflector.

The variable aperture of the collimator is mandatory because it is important for the operations to be able to adjust the beam cross-section, especially in the Y-vertical plane.

The future design is foreseen to be modelled with a G4beamline [7] simulation to investigate the potential geometry of the collimator.

## CONCLUSION

Emittance measurements have been performed in the injection section of the C70XP cyclotron and highlight several hotspots in the beam. With the adequate tuning of the source parameters, these hotspots have been mitigated and allows now high transmission in the injection section. To deepen the exploration, a slit has been installed in the injection section. in order to modulate the transverse beam dimensions downstream the cyclotron in two different beam lines. Although the hotspots have not totally disappeared, the measurements indicate an increase of the transmission. It can be noticed that with the use of a slit, the operation tunings converge faster and the beam shows a more homogenous density. This advocates the ongoing studies for a future adjustable collimator in the injection section.

## ACKNOWLEDGEMENTS

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