ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB276

INVESTIGATION ON THE INJECTION OF THE ARRONAX CYCLOTRON 70XP

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Abstract

A 70 MeV cyclotron is being used at the Arronax GIP (Interest Public Group), France, for various types of R&D on nuclear, biological and chemical reactions with beams and radioisotopes production. In order to adapt its usage for experiments and users demands of high peak intensity, above an equivalent average of a few µA, the injection is being adapted. Several studies are thus being performed in this section. These include the newly installed chopper-based system and the injection collimator. This paper details the various studies, specifically the signal purity obtained in the pulsed mode. A mode particularly adapted for flash irradiation.

INTRODUCTION

The C70XP cyclotron of the Arronax GIP (Public Interest Group) has a wide range of intensity capacities [1] to provide concurrently multi-ions to several beamlines. Developments are being realised on the injection section of the accelerator. They include experimental explorations of the beam intensity capacities within this section and measurements of the emittance [2]. They also concentrate on the chopper system which ejects bunches to form trains of bunches sent to the users. This system allows to deliver high intensity beam during a short time for experiments requiring high dose rates, such as flash proton therapy [3]. For this, the adequate time definition of the trains for the end-of-line users is crucial. The main timing definition of interest have been defined in terms of train time length (i.e. number of bunches in a train), train time interspace (i.e. the rest time), repetition of the train (i.e. the number of train within a second) and the rise/fall time of the trains. As an example for the users, the time length, that have been most regularly used at Arronax, are of the order of hundreds of µs up to a few ms for flash irradiation and radiolysis studies. Another key characteristic of the beam pulsing scheme is the signal purity, which corresponds to the ratio of the intensity during the train and the intensity during the rest time. For the users, this ratio has to be as high as possible, and ideally no beam should be sent to the users during the resting time. This characteristic is being particularly investigated as it is dependent on how well the chopper system is efficient. It can be conditioned by the beam longitudinal and transverse emittance in front of the chopper, the operation settings of the magnets and chopper and also the cyclotron ability to accelerate unwanted ions from the background if the RF is on. All of this can constitute a noise for the users.

IRRADIATIONS AT THE C70XP CYCLOTRON

Routine irradiations occur at Arronax with beam extraction at high intensity and high energy. These irradiations have the goal to generate sufficient amount of medical oriented radioisotopes, for example: ^{82}Sr, ^{68}Ge, which necessitate 70 MeV protons irradiations over several days, ^{64}Cu with 16 MeV D^+, and ^{211}At with 67 MeV He^{2+}. The runs generate continuously 32.84 ns time-separated bunches, to the targets, i.e. 9.36×10^{17} protons/s at 150 µA. The machine has also shown its capacity to reach regularly 2.18×10^{18} protons/s for dedicated runs.

For time dependent irradiation experiments such as proton radiolysis and flash proton therapy studies, the machine has shown its capacity to deliver over 300 kGy/s at the user's location.

BEAM INTENSITY IN INJECTION

The injection beamline, located downstream the source and above the cyclotron at Arronax is constituted of a water cooled copper faraday cup (FI). For the above irradiation at 150 µA on target, the source arc current (S1C) is set often below 2 A and attains 350 µA on FI although beam intensity, with specific settings and same S1C, have been measured up to 450 µA. Also tests of the source have shown capacities to deliver up 2.4 mA if S1C is increased (see Fig. 1). It is expected that additional source optimisation could lead to higher intensity.

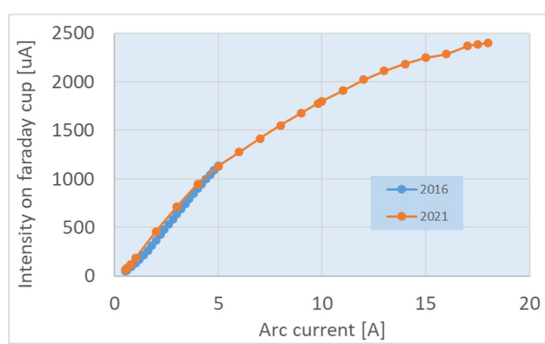

Figure 1: Intensity on the injection faraday cup vs the arc current of the multicusp source for two different tests in 2016 and 2021.

PULSING SYSTEM

The chopper system is located in the injection beamlines [4] and uses two vertical parallel plates inserted between a buncher and the faraday cup. Also above the

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buncher are installed several solenoids that can be used to modify the beam size at the plates position. The chopper is controlled by a Behlke switch located outside the beampipe, a few cm away of the plates. The switch, itself, connected to a positive Glassman 10 kV power supply, is commuted according to an in-house made DLL based electronics. The electronics is assigned statuses, low and high, with a raspberry Pi3 connected to an EPICS dedicated network. The low status let the beam go through while the high status applies the high voltage (HV), which bends the ions away. The electronics is compatible with 100 ns rise time changes as shown in [3] although the switch, without a specific power supply, reveals its limitation around 50 kHz. At the same time, overall rise and fall time of the train of bunches in the experimental vault has been measured to be approximately 3 µs with the above configuration.

The interlock system has been mechanically implemented such that the power supply switches off when the personal enters the cyclotron vault. Included in the interlock, are the machine protection systems encompassing, at the present time, the various fault signals that could come from the errors of the switch, the vacuum pressure and failure of the power supply.

COMPUTING ENVIRONMENT

The control and computing environment of the cyclotron has been suited to synchronise and simplify the use of several systems. For example, an EPICS network has been used and serve as a central core for the data exchange from the additional diagnostics and systems that are being added to the cyclotron over the years, as shown in Fig 2.

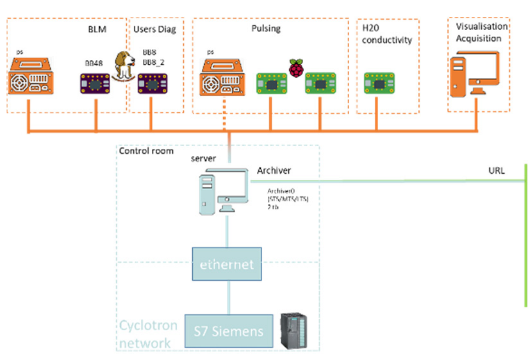

Figure 2: The EPICS network at Arronax.

The raspberry, the high voltage power supply, and the various error messages have also been included in the network and a graphic users interface, based on CS-Studio, has been developed for the machine operators.

MEASUREMENTS OF THE SIGNAL

With the chopper system letting the beam goes through, the intensity of the beam can be up to the maximum capacity of the accelerator. For the purpose of the study here, the beam intensity was limited to a few tens of µA. This is referred later on in this paper as the continuous mode and prefigures the intensity when trains are let through (signal). To avoid activation in the user's vault, the beam is stopped in the cyclotron vault and measurements are performed on a faraday cup with a linear voltage amplifier. The transmission from the faraday down to the users has been measured to be 100% without collimators. The source solenoid can be used to execute scans of the beam and improve the beam intensity as described in [4]. The highest beam intensity was found with the present machine settings at approximately 125 A, with a beam fixed at 10 µA.

Background Scan Measurements

With the HV continuously applied to the chopper, i.e. simulating a steady rest time or stop mode, the remaining beam intensity is measured with an in-house ionisation chamber installed at the exit of the beamline. The voltage is modified while performing the measurements and scans of the solenoid, ~2 m upstream the chopper, is applied as shown in Fig. 3. The results indicate a region with a high background level (20 pA) at a solenoid value below 120 A. This region reduces as the voltage increases but the number of breakdowns (electric discharges) increases also. A second region appears which does not depend on the applied chopper HV but only on the solenoid settings and is at 9 pA maximum for ~125 A. For this the arc current was fixed at 0.5 A. The study also pointed out that the buncher voltage, when optimized for best transmission in the continuous mode, has to be set at its lowest value in the available range to minimize the background noise in the stop mode.

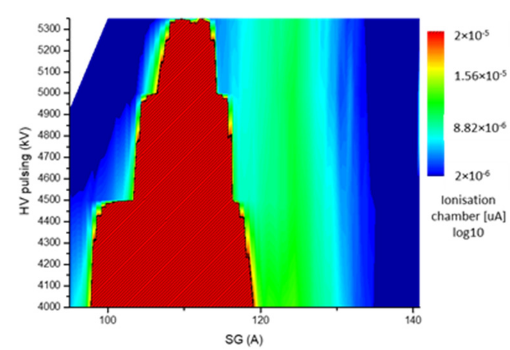

Figure 3: The background noise intensity measured by the ionisation chamber vs the solenoid settings and HV on the chopper.

IMPROVEMENT AND PURITY OF THE SIGNAL

In order to improve transmission several scans versus the parameters settings of the injection magnets have been performed and also included the modification of the vacuum in the beamline (from 3.2 to 2.6×10^{-5} mbar) and H2 gaz pressure in the multicusp source providing the H- ions. It led with the same-as-above arc current to attain a maximum intensity of 23 µA and also helped to decrease the maximum background intensity of the second region. It has to be noticed that this maximum is directly proportional to the vacuum level in the source. The Purity of the signal, defined here as the ratio of the signal^2 over the back-

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ground, can then be shown with respect to the solenoid settings as given in Fig. 4. Compared to earlier optimization, the purity has increased from 6×10^6 to slightly below 5×10^7 at 120 A.

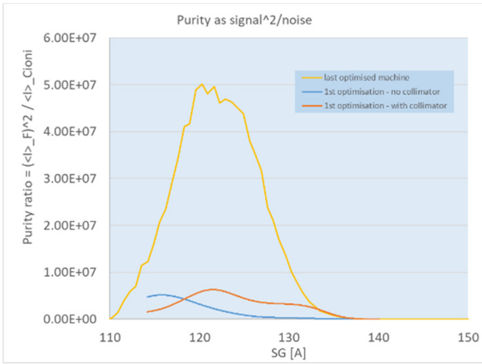

Figure 4: Purity of the signal after optimisation with respect to the solenoid settings.

USE OF A COLLIMATOR

A 25 mm circular aperture collimator has been installed above the buncher in the injection line for further tests. This is done, as a preliminary stage of possible future emittance constrains, to check the compatibility of such elements with the chopper system. It is grounded and cooled by conduction with the beampipe wall. In order to optimise the transmission, the steerers of the injection have been readjusted and, as above, scans have been performed and are shown in Fig. 5. The impact of the collimator can be seen as a cut-off of the background noise at low solenoid value (<117 A). Also background noise, in the second region, at solenoid values close to 128 A shows a higher intensity of the order of 16 pA. This value is slightly above the previous value without the collimator. Though it remains to be check that it is due to the collimator or a degraded vacuum upstream the instrument.

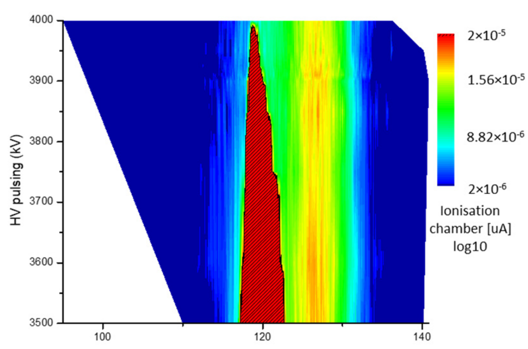

Figure 5: Scan versus the solenoid settings of the background signal with an HV below 4000 V.

Additional studies have included verifications of a use of a single instrumented collimator and also the impact of the injection collimator at the end-of-line users, mostly for operation ease-of-use. Here no major effects were measured with the quadrupole scans technique at the target location.

FURTHER WORK AND DISCUSSION

For the above study, the Behlke switch was located close to the beampipe. This requires that it is dismantled for high intensity runs for radioisotope production to avoid electronics damages and reinstalled for the pulsing usage. It has also been shown that the use of the switch for tuning the magnets with low intensity extracted ions (and a low pulsing duty cycle) can be of great convenience [4].

As a preliminary study, the Behlke switch has been tested with a 20 m cable connected to the plates. The results show rise and fall time of the order of a few us making it compatible with present operational usage and adaptable to high intensity long runs. Though the cable was not adapted for AC high voltage and several recurrent breakdowns of the voltage manifested after a few hours of run.

Tuning the injection for best transmission with minimum background noise depends on the beam characteristics and magnets settings. A great care has to be taken for the beam optimisation when the chopper system is used. A specifically designed set of scrappers might be of help to limit the setting range and ease the operation. With this configuration, background will have to be studied. In effect, the background, which is measured in the 2nd region, is not affected by the chopper system, but by the solenoid only. This points to potential neutral particles created in the injection.

CONCLUSION

Further studies of the use of the chopper system at Arronax are being performed. They show the capacity to reach high intensity for the train with a high purity of the signal, i.e. low background noise. Though these are dependent on the many settings in the injection and source, of which some are presented here.

Beyond the optimisation protocol that has been used to improve the beam transmission and purity, scan techniques applied here can be used to characterise the beam with respect to the settings in the source and injection as several other magnets settings can be favoured for the users. Nonetheless, the technique is being used for flash proton therapy such as zebra fish embryos and radiolysis irradiations.

In Addition, in the last years, at the demand of the users, a set of magnet settings has been found which help to switch the machine from a pulsation mode above 20 µA to a low intensity continuous mode. To help further the investigation in the injection, an emittance-meter has been used and analysis are on-going.

ACKNOWLEDGEMENTS

This work has been, in part, supported by grants from the French National Agency for Research, Arronax-Plus n°ANR-11-EQPX-0004, IRON n°ANR-11-LABX-18-01 and Next n°ANR-16-IDE-0007.

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