THE PULSING CHOPPER-BASED SYSTEM OF THE ARRONAX C70XP CYCLOTRON

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Abstract

The Arronax Public Interest Group (GIP) uses a multi-particle cyclotron to perform irradiation from a few pA up to hundreds of µA on various experiments and targets [1]. To support further low intensity usage and extend the beam time structure required for experiments such as pulsed experiments studies (radiolysis, proton therapeutic irradiation) and high intensity impact studies, it has been devised a pulsing system in the injection of the cyclotron. This system combines the use of a chopper, low frequency switch, and a control system based on the new extended EPICS network. This paper details the pulsing system adopted at Arronax, the last results in terms of time structure, various low intensity experimental studies performed with alpha and proton beams and the dedicated photon diagnostics.

INTRODUCTION

The cyclotron of Arronax provides bunches interspaced by 32.84 ns (RF frequency=30.45MHz) at average intensities at least up to 375 µA for proton and 50 µA for alpha. This translates respectively into 7.8 10^7 and 5.1 10^6 particles per bunch. These features are the base for delivering a high number of particles to users. Additionally, the need from users at Arronax for short time structure have been addressed through the usage of a chopper system that can get rid of bunches at low energy before they are accelerated and sent to the end-of-beamline. This philosophy, associated to a variable frequency high voltage (HV) switch, controlled by a dedicated electronics, allows a versatile system applicable to any particles at Arronax, provided that the deviation voltage is high enough and performed sufficiently fast. The prototype version of the chopper relies on the switch located close to the injection. With the regular high intensity runs of Arronax, it has been decided to build a system that can be removed and installed only when needed at least during a year-long period of tests.

BASIC CONCEPT

The pulsing chopper based system is designed to provide a variable number of trains of bunches to users from an initial continuous bunch structure, typical of cyclotrons. The present prototype design and functioning system allows thus, as illustrated in Fig. 1, to modify the *dt* train duration and repetition (=$^{1}/_{dit}$ with *dit* the inter ending-train duration). Based on the electronics, at the fastest, the system can provide trains of 164 ns length at 50 kHz repetition i.e. 5 bunches every 200 µs. This time structure can be modified online by the operators via the specifically devised EPICS interface.

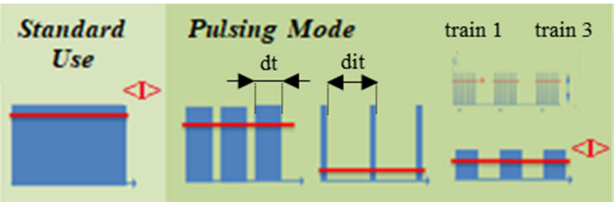

Figure 1: Examples of variable time structure with the new pulsing chopper-based system. 3 trains of bunches are represented. <I> is the average intensity.

OVERALL LAYOUT AND INTEGRATION

The system is based on a chopper located in the injection above the accelerator, and deflects particles which are around 40 keV for H- or 20 keV for the other particles (alpha, D-). Their energy depends on the setting of the source puller which is in accordance to the tuning of the downstream buncher. The main objective for the tuning in the injection is to maximize the number of particles. The overall system has been simplified compared to the one described in [2]. Thus the 50kV beamline deflection is not used and triggers are coming from the cyclotron RF generator directly and selected by the controller to mirror train presence. This signal is dispatched to the user's acquisition room and can serve as experimental triggers.

The chopper is based on two copper plates mounted vertically in the beam-pipe with HV pass-through connectors. Each plate is 100 mm long by 50 mm of width. They are separated by 47 mm within a vacuum of 1.5e-5 mbar. Proton and alpha particles take respectively 36 and 102 ns to travel between the plates.

General Layout

The power supply room hosts the control electronics, a 3.3 kV High power supply and a Raspberry Pi3 [3]. The cyclotron vault houses the switch box as shown in Fig. 2.

The switch is a Behlke FSWP 51-02 [4]. It is encapsulated in a dedicated removable box as pictured in Fig. 3, with specifically designed short ground lines.

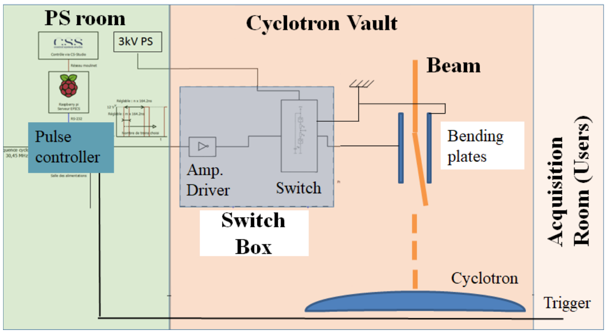

Figure 2: General layout of the pulsing system.

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Pulse Control Electronics

The control electronics for the switch includes a circuit with a 10-bit programmable interrupt controller (PIC) 18F connected to D flip-flop electronics, three 32 bit CMOS counters LS7366R and fast drive amplifiers MOSFET IXRFD630 to level the voltage.

The CMOSs are used to count the number of pulses from the RF clock. The PIC which drives the fast switch receives the various state information from the raspberry board. This information, high or low state, let the switch drive the HV to the plates, and defines the length of a train (low state), and the period of the train. The raspberry Pi3 is used as a local server linked to the Arronax global EPICS [5] network [1].

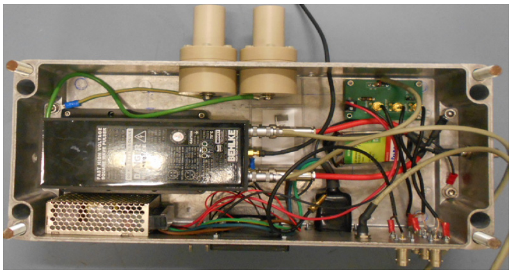

Figure 3: The switch, low power voltage supply, cooling fan and pass-through connectors on top of the box.

PRELIMINARY STUDIES

Measurements have been done to check the shape of the voltage on the plates, in air with electronics similar to the final installation. To trigger the switch, a well-defined square signal from a low frequency generator HP8116A, located 30 cm away has been used. The plates were connected with a one-thousand divider voltage probe N2771B 50 MHz, to a Rhode & Schwarz 2 MHz oscilloscope. Up to 20 kHz, the global shape of the voltage increase is similar i.e. an overshoot of a peak occurs, then the voltage drops down to its operation level as shown in Fig. 4. The peaks' amplitude of the signals have been measured at 10.4 µs, show a decrease with the repetition frequency of the trigger as expected, and point to a 54 kHz limit (-3dB). At one kHz, the rise time (10 to 90%) for the voltage on the plates with a 3 kV has been measured to be below 40 ns.

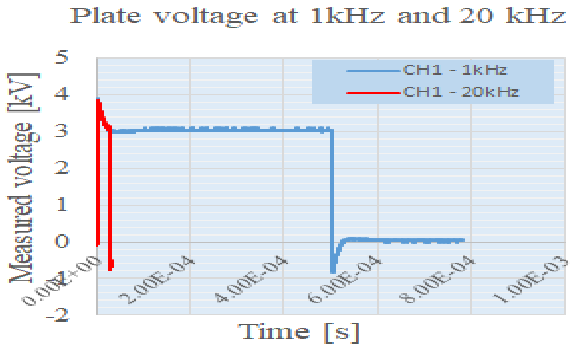

Figure 4: The plate voltage measured in air vs time for 1 kHz and 20 kHz.

OPERATIONAL STUDIES

The control system of the chopper allows to choose several modes: A "sequence mode", the beam has the time structure according to the setting of the control system; a "stop-mode", with the plates at the maximum available voltage, the beam is bent away; and a "continuous-mode" where the plates are at ground level and the beam goes through the injection.

The chopper plates are located downstream a solenoid. This latter is tuned to ensure that the beam is first passing well between the plates. Solenoid scans are performed and the beam intensity is measured with the Faraday cup available in the beamline.

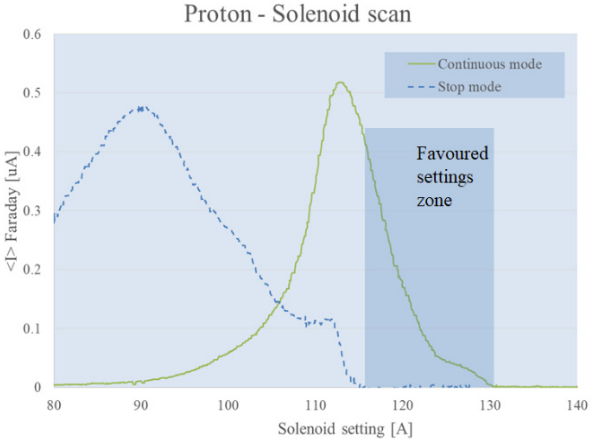

Figure 5: 2 Solenoid scans results for the "stop-mode" and the "continuous mode".

Figure 5 shows the results of the scan and indicates that below a certain set-point of the solenoid, the "stop-mode" let some particles go through. This is potentially due to the transverse dynamics of the beam, that is: its large emittance and/or its angle upstream the plates. Ongoing simulation has pointed out the compatibility of the results with a large emittance and an under-focused beam setting. This study encourages towards more understanding of the beam dynamics in the injection as the under-focused beam scenario would mean particles travel outside the plates.

This operational method has also lead to a protocol such that transmission is first maximised with the source setting. The solenoid, within a favoured settings zone, can then serve to degrade the beam to lower down the intensity at the end-of-line.

EXPERIMENTAL STUDIES

Settings

Several experimental tests have been performed with alpha and proton at average intensity respectively up to 2 and 1 µA with various settings of the repetition frequency and length of trains as shown below.

A photomultiplier Hamamatsu R928 with a quantum efficiency above 20% at 400 nm and a pulse rise time of 2.2 ns, collected the 337 nm emitted light from the interaction of the nitrogen from the air and the beam. It is located 5 cm downstream the exit window. A beam dump positioned 1 m away and connected to an electrometer was used to measure the average intensity. The trigger was provided by the control electronics of the chopper. Figure 6 illustrates an example of the measurements performed with 2000 trains of 100 µs length at a repetition frequency of 10 and 100 Hz. In both example the rising and fall time of the signal have been measured to be $\tau \leq 2$us. Here a fitting of the data was applied with A the amplitude of the signal, t the time base, y_0 the pedestal of the signal $y = A \times e^{-t/\tau} + y_0$.

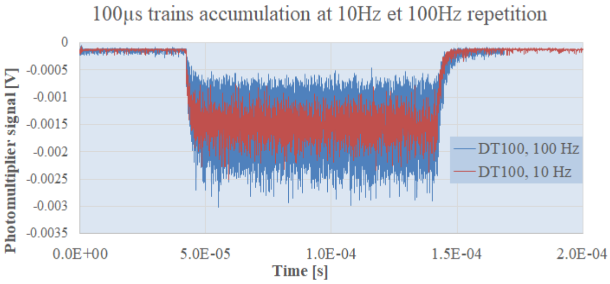

Figure 6: Measurements with the light detector for 100 µs trains of proton at two repetition frequency.

Overall Measurements

An extended scan over the repetition frequency and train length has been performed and is shown in Fig. 7. It indicates the average intensity measurements for the range from 10 Hz to 50 KHz and with trains from 164 ns to the continuous scenario. It first indicates the full range usable with the switch. The measured intensity has shown good linearity except for trains which are short and repetition above 10 kHz (i.e. dominated by rise/fall time).

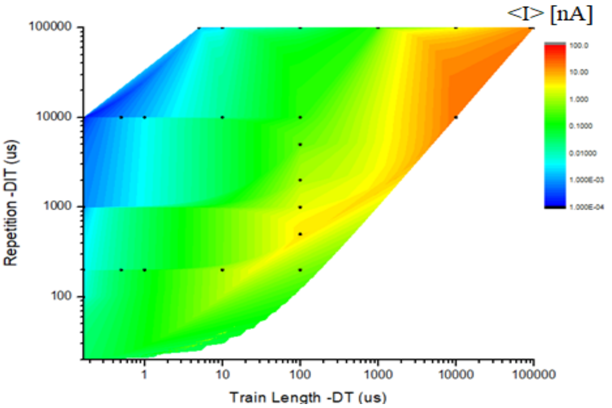

Figure 7: Mapping from the data points (dots) of the detector signal [nA] vs the repetition and train length.

Discussion

The precise time definition of trains is being scrutinised particularly in accordance with the settings of the magnet elements in the injection. Thus with an under-setting of the solenoid, the pedestal of the signal, as shown in Fig. 6, increases in amplitude and beam between the trains then rises. This, as pointed in section operation studies, can be mitigated by the solenoid set-point. Although the HV polarity is positive and thus not adapted to all particles charges, no-damages has been observed or measured in the internal pipe of the injection. Dose integration follow-up of neutron and gamma/beta with Landaeur "Neutrak-J 1M AMB" and "Iplus+Neut-T 3M" [6] dosimeters have shown that the switch has accumulated more 500 mSv without major operational failure.

CONCLUSION

The system is being used, as defined in this paper for short duration and precisely defined irradiations for example for alpha and proton particles induced material and medium reactions that require time studies. Preliminary work is being addressed for these studies, including end-of-line dedicated diagnostics similar to the one described here.

Though several possible optimisation can be foreseen e.g. to ease operations, a collimator in the source could be built to mitigate the solenoid tuning; protection from HV malfunction should be also considered; the integration of a variable HV power supply, possibly negative [7], can help to understand and further develop adapted methods; as well adaptation of the plates geometry to enhance the time structure.

The possibility to use and reduce trains time duration for machine studies and use the solenoid scan for potential emittance characterisation is a long term plan.

Combining the capacity of the machine for high intensities and the new possibility of the train time structure indicates that proton integrated dosimetry up to 33 Gy could be theoretically obtained in less than 10 µs and that any other less drastic, i.e. longer, train structure is achievable at Arronax for the same dosimetry. This result leads the way to open strategies for time resolved radiolysis studies and various scenarios of flash proton-therapy.

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