ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPHA050

ONLINE SPILL INTENSITY MONITORING FOR IMPROVING EXTRACTION QUALITY AT CNAO

M. Caldara, Department of Engineering and Applied Sciences, University of Bergamo, Italy
E. Rojatti, Department of Physics, University of Pavia, Italy
J. Bosser, G. M. A. Calvi, L. Lanzavecchia, A. Parravicini, C.Viviani, CNAO Foundation, Pavia, Italy

Abstract

The CNAO Foundation is the first Italian center for deep hadrontherapy with Protons and Carbon Ions, performing treatments since September 2011. The extracted beam energy and intensity can vary over a wide range (60-250 MeV for Protons and 120-400 MeV/u for Carbon Ions, 4e6÷1e10 pps); the beam intensity uniformity during the slow extraction process is a fundamental requirement for achieving accurate and fast treatments. CNAO developed an online Fast Intensity Monitor (FIM), not perturbing the extracted beam, capable of measuring beam intensity with a bandwidth of 50kHz and a resolution of 1%. It consists of a thin (0.8 μm) metallic foil that emits secondary electrons when traversed by the beam. The electrons are multiplied by a Channeltron device, polarized at high voltage versus ground. The Channeltron output current is amplified and converted in a Pulse Width Modulated (PWM) signal, which is then decoupled and transmitted to the equipment room, where an FPGA implements a servo-spill. The work presents the detector, the floating electronics, the preliminary measurements with beam and the integration in a closed loop on the synchrotron air-core quadrupole obtaining promising results.

INTRODUCTION

CNAO is one of the four accelerators worldwide capable to perform hadrontherapy with both Protons and Carbon Ions; nowadays more than 400 patients completed the treatments, two third of them with carbon ions [1]. The active dose delivery treatment by rasterscan technique, presently used at CNAO, is the most advanced method in hadrontherapy machines for achieving accurate treatments of target volumes. The beam is directed to each tumor voxel by controlling fast magnets deflectors and the beam energy for transversal position and longitudinal penetration respectively. A uniform beam extracted intensity is favourable because it gives a higher intensity without risk of beam aborts, leading to faster treatments and thus more patients. In order to minimize the spill intensity ripple during the slow extraction, a feedback loop acting on the synchrotron fast quadrupoles [2] or on the RF Knock-Out exciter are the most diffused techniques [3-4]. A fast, accurate, high resolution and not-interceptive beam intensity measurement is essential in each servo-spill system.

MATERIALS AND METHOD

FIM Detector

In order not to perturb the beam, an ultra-thin metallic foil is the only material that can be traversed by the accelerated particles [5]; a secondary emission electrons principle is the signal origin, followed by electrons collection into a Channeltron (CEM) device [6], a single channel electron multiplier. The mechanical arrangement of the foil with respect to the beam path (Fig.1) is a compromise between secondaries yield maximization and beam perturbation minimization (α=45deg). By raising the angle between the foil and the beam trajectory, the foil thickness crossed by the beam and thus beam perturbation increases. Secondary emitted electrons angular distribution follows Lambert Law, namely it is proportional to cos(θ) (Fig.1). In consequence, if the CEM is installed on the foil perpendicular axis the number of collected electrons will be maximized. To be conservative, a foil input/output pneumatic actuator has been foreseen on the FIM instrument. The FIM monitor will be installed in the CNAO common extraction line; to get the results presented in this paper, the FIM has been installed at beam isocenter, in the treatment room.

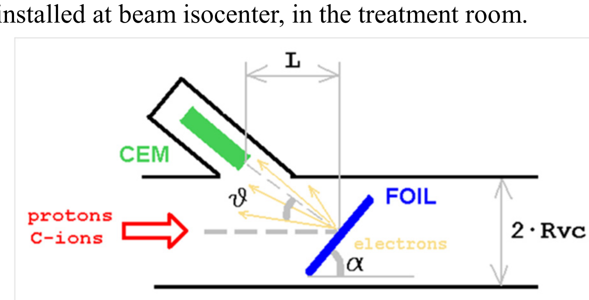

Figure 1: FIM detector mechanical layout; R_{vc} (33 mm) is vacuum chamber radius, L is 42mm.

Electronics and Processing

The CEM output electrons are attracted to an output collector, polarized to a higher voltage than the CEM output; being the beam-generated signal quasi-dc, the readout electronics cannot be AC coupled to the output collector, thus it needs to work at floating high potential with respect to ground. The system block diagram is depicted in Fig. 2. The electronics input signal is a current, thus the conversion into a voltage is implemented

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPHA050

with a sensing resistor. This voltage drop is then differentially amplified by a low-input bias, high bandwidth instrumentation amplifier and then low-pass filtered at 50 kHz. The analog signal is finally converted into a PWM; such technique brings several advantages, as an easy decoupling from high voltage to ground referred and more immunity to electromagnetic interference in the long cables transmission. In order to keep the system response fast, for implementation in the control loop, the PWM output frequency has been set to 1MHz, with an output dynamic ranging from 10% to 90%. As shown in Figure 3, the system demonstrated an outstanding linearity in the above mentioned range, which corresponds to a range of CEM output currents from 0 to 6.5 μA, leading to a sensitivity of 12.26%/μA for the amplifier high gain (obtained resolution 20 nA). Electronics local supply has been referred to the CEM high voltage supply. Due to that, the front-end electronics resulted to be floating at a few kV potential above ground; before bringing the signals to the long cable they have been properly decoupled.

The signal acquisition and processing have been implemented with a PXI platform FPGA, capable to acquire the PWM signal coming from front-end electronics with a fixed 100 MHz sampling rate. The signal is processed by counting at 100MHz the high level duration of the PWM, implying a reading resolution of 10ns. In order to reduce the noise, the software makes it possible to select a time window and performs an average over the processed pulses. A maximum of ten PWM periods can be averaged (10 μs added delay), in order to maintain an effective loop correction on the beam. The control panel, developed using Labview RT, implements the computation of the beam current, a relative FFT power spectrum dedicated to see the main harmonics of the extracted beam, and the PID parameters needed to set the servo-loop. The dedicated PXI system is in charge of generating the signals for the synchrotron air-core quadrupole power supply, capable to correct the beam with a 5 kHz bandwidth.

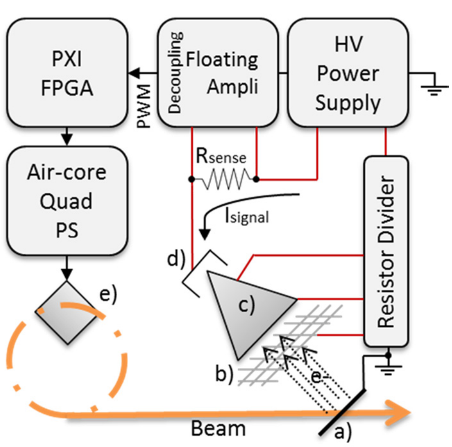

Figure 2: FIM servo-spill block diagram; a) is the thin foil, b) the grid, c) the CEM, d) the electrons collector, e) the fast quadrupole.

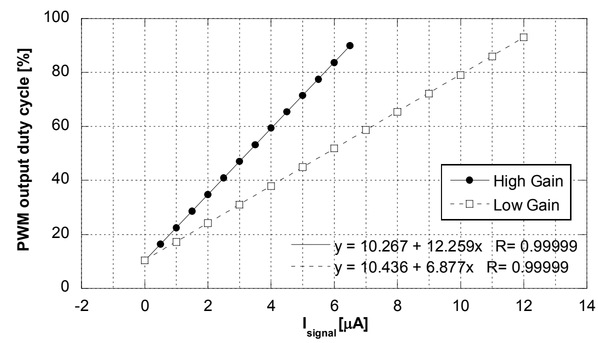

Figure 3: Dynamic and linearity of the amplifier for the two available gains.

RESULTS AND DISCUSSION

The FIM instrument has been first commissioned with beam, in order to test its functionalities and also to find the optimal settings in terms of CEM elements polarization. Figure 4 depicts the installation of the standalone FIM, in its vacuum chamber, on the patient bed, just after the nozzle. CEM, which operates only in vacuum, is inside the chamber, while the floating electronics is placed aside the detector. Due to the limited total charge that can be provided by the CEM (~30 C), and due to its dependence on the polarization voltage, it has been decided to set the CEM voltage to its minimum (~1300V), since it maximizes the device lifetime and thus the instrument robustness. The FIM commissioning with beam showed that a grid voltage higher than 50-60V does not improve the signal at the output, as expected since secondaries energy is not larger than 50eV. Moreover CEM gain, as expected, is strongly affected by its polarization voltage, thus a stable supply is mandatory for high reading resolution. Finally, depending on beam energy, 30÷60 Carbon Ions and 700÷2000 Protons resulted to be needed for collecting one pC at CEM output; the expected CEM lifetime is thus 5 years, considering CNAO beam parameters.

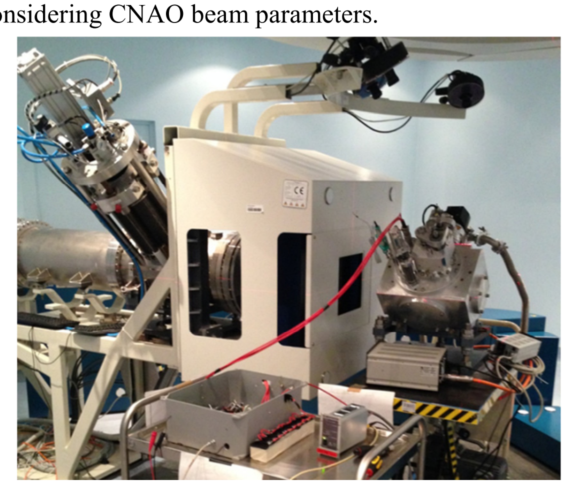

Figure 4: FIM installation after the dose delivery system, for its commissioning with beam.

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPHA050

The FIM on-beam validation has been performed with a reference instrument installed along the extraction line. After that the FIM-based servo-spill has been activated and tested on both particles, for different energies and intensities. Figs. 5-6 show the visible improvements in beam spill uniformity for protons and carbon ions respectively. The beam intensity is hereafter indicated as CEM collected electrons current (I_{signal} of Fig. 2).

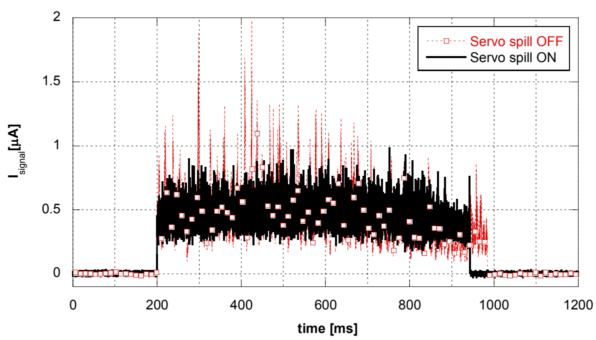

Figure 5: Servo-Spill intensity time profile for Protons with energy 90 mm W.E. (110.96 MeV/u).

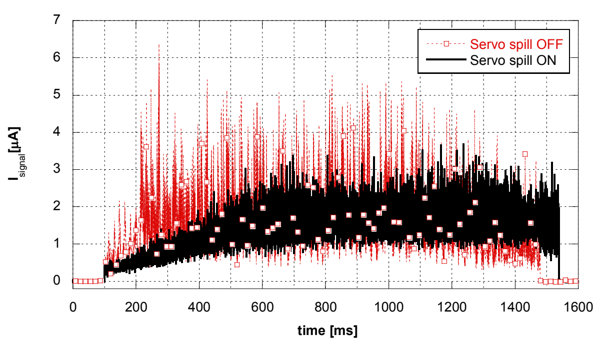

Figure 6: Servo-Spill intensity time profile for Carbon Ions with energy of 90 mm W.E. (208.57 MeV/u).

Table 1: Servo Spill Results with Protons at 110MeV

	N_{p_spill} = 3e8		N_{p_spill} = 9e8	
Correction	**OFF**	**ON**	**OFF**	**ON**
<I> [µA]	0.18	0.15	0.48	0.48
Irms [µA]	0.19	0.16	0.52	0.49
Imax [µA]	0.54	0.34	2	0.98
Imin [µA]	0.04	0.07	0.1	0.17
Imax/<I>	**3.1**	**2.2**	**4.1**	**2**

Table 2: Servo Spill Results with C^{6+} at 208 MeV/u

	N_{C_spill} = 5e7	
Correction	**OFF**	**ON**
<I> [µA]	1.67	1.52
Irms [µA]	1.85	1.69
Imax [µA]	6.38	5.19
Imin [µA]	0.29	0.1
Imax/<I>	**3.82**	**3.41**

As summarized in Tables 1-2, while the average beam current is held constant, the servo-spill improved the beam uniformity up to 48% for protons and 10% for carbon ions. Moreover the more homogeneous beam provided a significative reduction of dose delivery interlock, a beneficial impact for the whole CNAO operation.

CONCLUSION

This work focuses on the not-interceptive spill intensity monitoring introduced at CNAO for improving extracted beam quality. An ultra-thin foil based detector with 50kHz overall bandwidth and 1% resolution has been developed and its output has been fed to a loop control system on air-core quadrupoles in the synchrotron during extraction. The system has been characterized by placing the detector at the isocenter, obtaining a remarkable reduction in the beam intensity ripple up to 48% for protons and 10% for carbon ions. This demonstrates that the FIM instrument can be used as a non-perturbing stand-alone therapeutic beam intensity monitor.

REFERENCES

[1] S. Rossi, The National Centre for Oncological Hadrontherapy (CNAO): Status and perspectives, Physica Medica, Available online 31 March 2015, ISSN1120-1797, http://dx.doi.org/10.1016/j.ejmp.2015.03.001

[2] H. Caracciolo et al., "Beam Diagnostics Commissioning at CNAO", THOAA01, Proceedings of IPAC'11.

[3] C. Schömers et al., "Patient-specific Intensity-modulation of a Slowly Extracted Beam at the HIT Synchrotron", WEPME010, Proceedings of IPAC'13, Shanghai, China.

[4] K. Mizushima et al., "Extra Dose Reduction by Optimizing RF-KO Slow-Extraction at HIMAC", TU6PFP012, Proceedings of PAC09.

[5] J. Bosser, G. Ferioli, P. Lefevre, J. Mann, G. Molinari, "Profile Measurement in the LEAR Transfer Line", SPS/ABM/Note/87-06, LEAR Note 87-04.

[6] Channeltron CEM 4820 COA G datasheet, EC No. 10-6360, Photonis USA Inc. Specification.