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Low Intensity Beam Extraction Mode on the Protom Synchrotron for Proton Radiography Implementation

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Low Intensity Beam Extraction Mode on the Protom Synchrotron for Proton Radiography Implementation

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Abstract. Proton radiography is one of the most important and actual areas of research that can significantly improve the quality and accuracy of proton therapy. Currently, the calculation of the proton range in patients receiving proton therapy is based on the conversion of Hounsfield CT units of the patient's tissues into the relative stopping power of protons. Proton radiography is able to reduce these uncertainties by directly measuring proton stopping power. The study demonstrates the possibility of Protom synchrotron-based proton therapy facilities to operate in a special mode which makes it possible to implement proton radiography. This work presents the status of the new low beam intensity extraction mode. The paper describes algorithms of low flux beam control, calibration procedures and experimental measurements. Measurements and calibration procedures were performed with certified Protom Faraday Cup, PTW Bragg Peak Chamber and specially designed experimental external.

1. Introduction

Proton therapy is rapidly expanding worldwide [1]. Contemporary, the calculation of the proton range in patients receiving proton therapy is based on the conversion of Hounsfield CT units of the patient's tissues into the relative stopping power of protons [2]. Uncertainties in this conversion necessitate larger proximal and distal planned target volume margins [3]. These larger margins increase the dose to nearby healthy tissues, causing unwanted and avoidable toxicities [4].

Proton radiography avoids these uncertainties by directly measuring proton stopping power, and this can drastically reduce the planned target volume, thus directly reducing toxicity [5]. It has the capability to accurately align the patient to the proton beam and quantify anatomical consistency and proton range in the treatment position just prior to treatment, which will lead to more consistent target coverage, yielding improved patient outcomes [6].

Protom Synchrotron [7-9] is a medical accelerator specially designed for proton therapy. The accelerator complex based on the Protom synchrotron is shown in fig. 1. The synchrotron is able to accelerate protons up to 330 MeV. This fact makes proton imaging of the entire human body available without any restrictions. The use of proton imaging will allow us to avoid the uncertainty of the proton range in the patient's body and will make the treatment process more accurate. Moreover, proton radiography can be used as a tool for verification of patient position instead of standard cone beam computed tomography systems [10-11]. The proton imaging system has a lower equivalent dose to the patient than comparable X-ray imaging systems. However, proton imaging systems cannot handle the proton beam intensities used in standard proton therapy. This means that for implementation of proton radiography it is necessary to reduce the intensity of the protons significantly.

Fig. 1 Protom synchrotron-based accelerator complex

2. Requirements from the pCT Scanner

This work was focused on a proton detector prototype being developed by ProtonVDA [12-14]. ProtonVDA has developed a highly efficient and inexpensive proton radiography system based on solid state photomultipliers and fiber detectors. One of the main advantages of this system is the lower, compared to similar X-ray imaging systems, equivalent dose received by the patient. A key feature of this detector is its operation with single proton events. Which implies the development of a special mode of beam extraction from the accelerator, which is fundamentally different from the therapeutic mode required the maximum intensity of extracted beam.

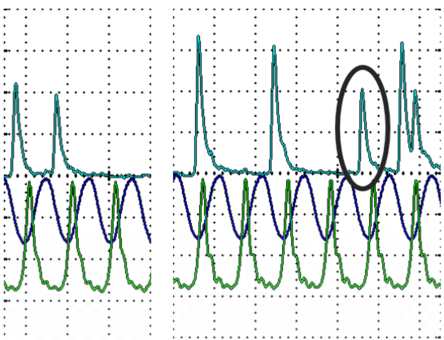

Fig. 2 Oscillograms from the external detector: Light blue line (the upper one) is signal from external detector 2 divisions – single proton events, 3 divisions – double protons event; dark blue line (the middle one) is accelerator RF; green line (the bottom one) – beam current inside the synchrotron

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Fig. 2 demonstrates good (single protons) and bad (other) events for the detector systems. The left oscillogram consists only single proton events, the right one has 2 double proton events, one single (in the ellipse) and one combined (double + single from the same revolution).

3. Low Intensity Beam Extraction Control System Design and Accelerator Mode

During the development of the low intensity beam extraction control system, the main conditions were determined that it must satisfy: no effect on the therapeutic beam for proton therapy complexes that are already in clinical practice, a design for integration into existing vacuum system interfaces, an universal design for all proton therapy facilities based on Protom synchrotron. The principal design of the Low Intensity Beam Extraction Control System is shown in Fig. 3.

Therefore, it was decided to create a separate module based on the existing system for imaging the proton beam during the transportation through the gantry. This subsystem can be easily implemented in vacuum interfaces; it takes up little space and can be located between the elements of the magnetic optics of the extraction channel. In addition, the removable design makes it possible to avoid changing the beam parameters of already certified installations.

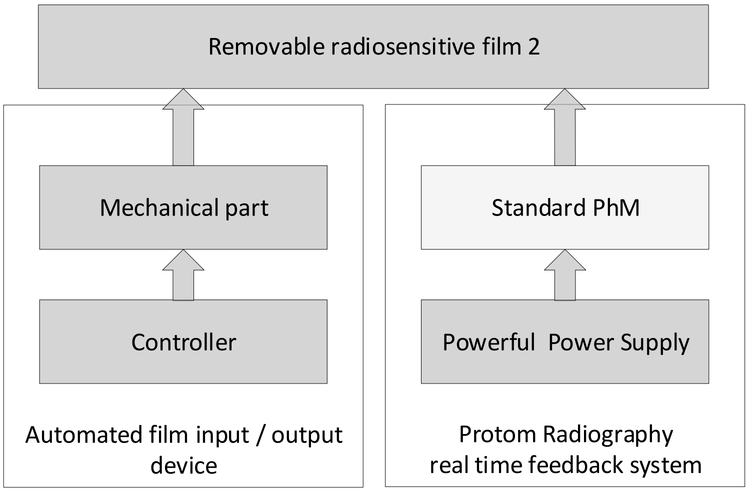

Fig. 3. Schematic diagram of Low Intensity Beam Extraction Control System

The low intensity beam extraction control unit is based on the photomultiplier Hamamatsu R6094 (which is used in standard extraction mode) with an upgraded power supply, as well as films based on the SC-307 scintillator or on gadolinium-terbium oxysulfide.

The standard operating modes of the accelerator were substantially revised to reduce the extraction intensity of the proton beam. Firstly, the number of particles injected into the accelerator was reduced. For this, built-in beam visualization systems consisting of ceramic plates inserted into the vacuum chamber of the injector were used, which significantly reduces the aperture of the vacuum chamber. It was necessary to change the extraction orbit using 16 horizontal electromagnetic correctors operating in a dynamic mode. The values of the acceleration and excitation frequencies were also changed to achieve optimal controllability parameters and beam sizes at the extraction point. The results of experimental measurements are presented in the next chapter.

4. Experimental Verification of Low Intensity Extraction

This chapter presents the results of experimental measurements of a special operating mode of the accelerator for a low intensity beam extraction. Below are the results of two experiments testing the low intensity extraction mode of the proton radiography implementation on the Protom synchrotron. A static experimental version Low Intensity Beam Extraction Control System was used for these experiments.

4.1. Experimental measurements of extracted particles number via external self-made detector

As part of this experiment, it was necessary to be convinced of two things. First of all, there was a need to demonstrate the correspondence of the calculated values of the extracted protons with real ones. Second thing that should be demonstrated is the presence of single proton events in the structure of the beam extraction, which can be effectively registered by the proton radiography detector system. For these purposes, a detector was assembled based on SC-307 scintillation unit 50 mm thick, photomultiplier PhM-84, power supply Spellman MP5N24 and oscilloscope Aktakom ADS-2114T. Two series of measurement with different timescale was performed. The results of measurements of low intensity proton beam extraction using this external detector are presented below in Fig. 4 and Fig. 5. Table 1 consists of data comparison expected (calculated) and measured number of extracted protons.

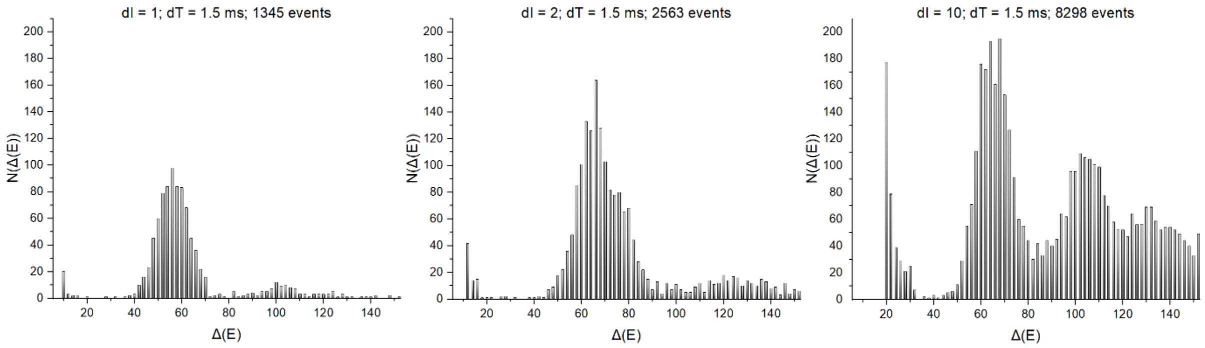

Fig. 4 The first series of experimental measurements of low intensity beam extraction using external detector; the measured extraction time (dT) was 1.52 ms.

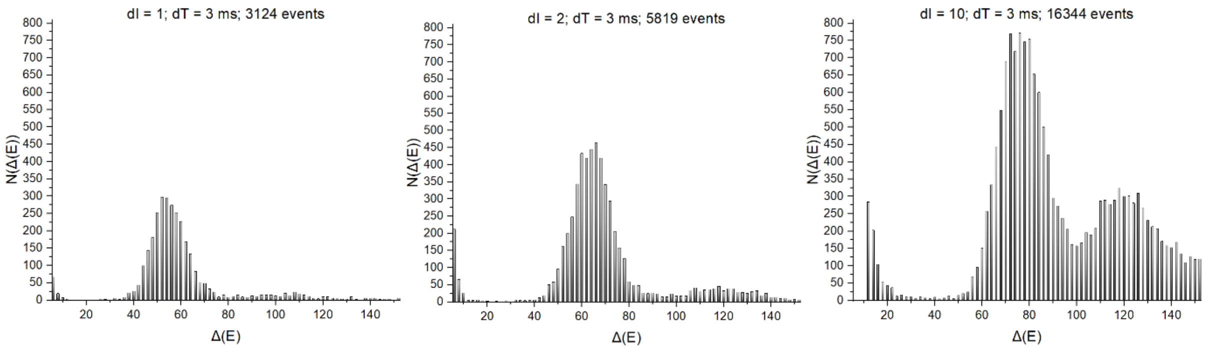

Fig. 5 The second series of experimental measurements of low intensity beam extraction using external detector; the measured extraction time (dT) was 3.04 ms.

The diagrams shown in Fig. 4 and Fig. 5 correspond to the energy of the extracted proton beam equal to 200 MeV. Events in the dE range from 40 to 80 correspond to a single proton, 100 - 140 - to a double proton. An example of a sample of an extraction structure is demonstrated in Fig. 2. The presented diagrams have a rather extended distribution along the abscissa axis, which corresponds to the presence of events with several protons. These can be triple or more protons, or single + double or triple protons extracted in one revolution. For convenience, only the first two distributions are shown, corresponding to single-proton and double proton events.

The obtained results are in satisfactory agreement with the expected events. The experimental results were used for calibration using an internal Protom Faraday Cup. The calibration was done for long beam extraction time (more than 1 second). The relative units (*dI*) of this calibration are presented in the Table 1, the first column. Typical dI values for therapy mode is in the range of 300-1000, for standard feedback system that is 10 times less sensitive.

Table 1. Comparison expected and measured number of extracted protons

Value dI, internal calibration	**Expected protons number**	**Measured protons number**	**Error**
	dT = 1.52 ms		
1	1924	1703	0.11
2	3848	4653	0.17
10	19242	16167	0.16
	dT = 3.04 ms		
1	3848	3536	0.08
2	7697	6761	0.12
10	38485	37946	0.01

4.2. Internal calibration linearity check

The purpose of the following experimental measurements is to show the linearity of the Protom Faraday Cup calibrations using an independent detector (*dI* values in the Fig. 4 and Fig. 5). Table 2 presents the data about an experiment comparing the PTW Bragg peak chamber readings and the Faraday calibrated readings of a low intensity beam extraction control system. The data are presented for two energies 220 and 250 MeV, examples of energies of interest for proton radiography.

Table 2. Comparison of Protom Faraday Cup Calibration and PTW Bragg Peak Chamber Readings

Energy, MeV	**PTW Bragg Peak Chamber readings, pC**	**Protom Faraday Cup Calibration number, protons**
220	20±2	5×10^{6}
220	3.8±0.4	1×10^{6}
220	2.1±0.2	5×10^{5}
250	19±2	5×10^{6}
250	3.9±0.4	1×10^{6}
250	1.9±0.2	5×10^{5}

A series of PTW Bragg Peak Chamber irradiations was carried out, consisting of 5 shots for each point, consisting of a certain energy and intensity in accordance with internal calibrations (the right column of table 2). The obtained PTW Bragg Peak Chamber data agree with the calibration data of the Protom Faraday Cup up to statistical and instrumental errors.

5. Conclusion

The study made it possible to achieve the values of the extracted beam intensity required for the implementation of proton radiography mode. A special operating mode of the accelerator for low intensity beam extraction has been developed and tested. This will increase the percentage of registration of useful for radiography, which are used for further reconstruction of proton tracks. This mode will increase the efficiency of the proton radiography system and reduce the dose.

The principal concept of Low Intensity Beam Extraction Control System has been proposed. The system is based on automatic removable unit with special luminescence film and sensitive photoreceptor. Using of the removable module allows us to save initial parameters of the therapy beam. Remote automatic control of this unit will provide switch therapy and imaging modes between synchrotron cycles. The static prototype of this system has been made and used in the series of experimental measurements. The algorithms of low flux beam control, calibration procedures and experimental measurements have been described. Measurements and calibration procedures were performed with certified Protom Faraday Cup, PTW Bragg Peak Chamber and specially designed experimental self-made external detector.

The developed Low Intensity Beam Extraction Control System and special operating mode of accelerator can be implemented in any proton therapy complexes based on the Protom synchrotron. This allow us to use initial synchrotron beam as a tool for patient verification and to eliminate proton range uncertainties.

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