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DEVELOPMENT OF THE LOW INTENSITY EXTRACTION BEAM CONTROL SYSTEM AT PROTOM SYNCHROTRON FOR PROTON RADIOGRAPHY IMPLEMENTATION

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Abstract

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. 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.

This study demonstrates the current version of the new beam control system for low proton intensity extraction. 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 work 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 detector.

The development 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.

INTRODUCTION

Proton therapy is rapidly spreading throughout the world [1]. At present, 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. Uncertainties in this conversion necessitate larger proximal and distal planned target volume margins [2]. These larger margins increase the dose to nearby healthy tissues, causing unwanted and avoidable toxicities [3]. Proton radiography avoids these uncertainties by directly measuring the stopping power of protons, and this can significantly reduce the planned target volume, which directly reduces toxicity [4]. It has the ability to accurately target the patient to the proton beam and quantify anatomical consistency and proton range in the treatment position immediately prior to treatment, resulting in more consistent target coverage, leading to improved patient outcomes [5].

Figure 1: Protom synchrotron-based accelerator complex.

Protom Synchrotron [6-8] 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. 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.

REQUIREMENTS FOR BEAM EXTRACTION MODE

This work was focused on a proton detector prototype being developed by ProtonVDA [9-10]. ProtonVDA has developed a highly efficient and inexpensive proton radiography system based on solid state photomultipliers and fiber detectors. A key feature of this detector is its operation

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with single proton events. This implies the development of a special mode for the beam extraction, which is fundamentally different from the therapeutic mode, which requires the maximum intensity of the extracted beam.

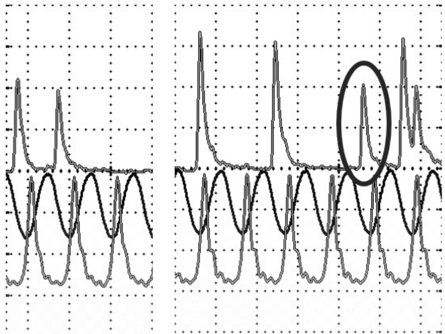

Figure 2: Oscillograms from the external detector: the upper line is a signal from external detector (2 divisions – single proton events, 3 divisions – double protons event); the middle line is an accelerator RF; the bottom line is a beam current inside the synchrotron.

Figure 2 shows low intensity extraction mode at Protom synchrotron. 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).

LOW INTENSITY BEAM EXTRACTION CONTROL SYSTEM

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.

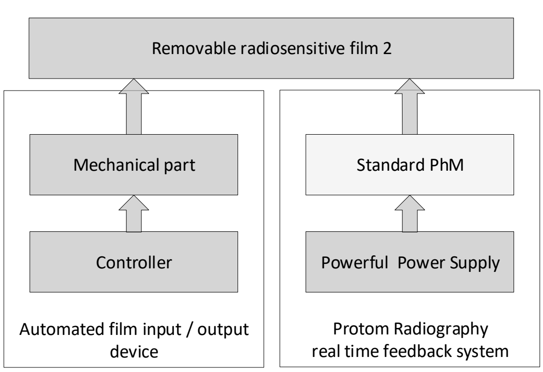

Figure 3: Low Intensity Beam Extraction Control System principle design.

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. The prototype of low intensity beam control unit is shown in Fig. 4.

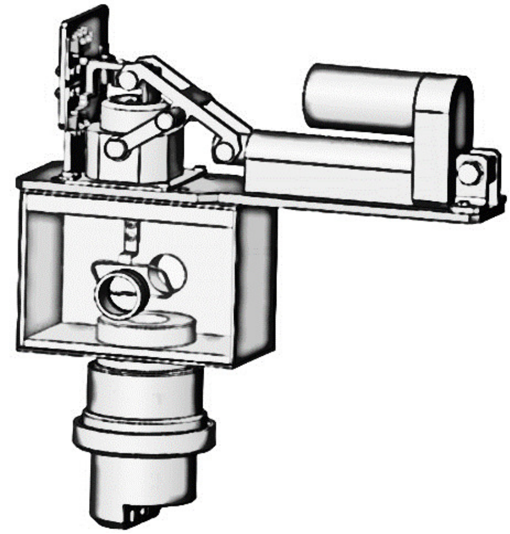

Figure 4: A prototype of low intensity beam control unit with removable film.

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.

ACCELERATOR MODE

The standard operating modes of the accelerator have been substantially revised in order to reduce the intensity of the proton beam extraction. 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.

LOW INTENSITY EXTRACTION VERIFICATION

The results of two experiments testing the low intensity extraction mode of the proton radiography implementation on the Protom synchrotron are demonstrated below. A static experimental version Low Intensity Beam Extraction Control System was used for these experiments.

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

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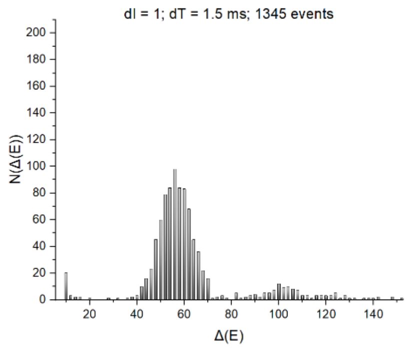
demonstrate the correspondence of the calculated values of the extracted protons with real ones. Second thing that should be demonstrated is the presence of single proton events in the structure of the beam extraction, which can be effectively registered by the proton radiography detector system. For 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.



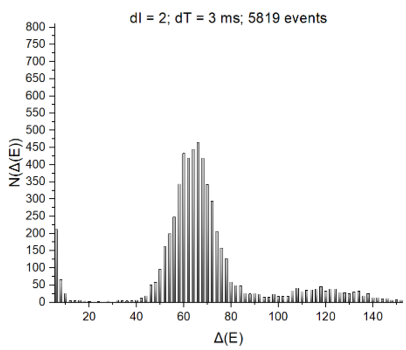


Figure 5: Samples of experimental measurements: the top diagram corresponds the first experimental series, the bottom one – the second series; these diagrams show the total number of detected events (including single protons, from 40 to 80 a.u. dE).

Table 1: Comparison of the Expected and Measured Number of Extracted Protons

Value dI, internal calibration	Expected protons number	Measured protons number
	dT = 1.52 ms	
1	1924	1703
2	3848	4653
10	19242	16167
	dT = 3.04 ms	
1	3848	3536
2	7697	6761
10	38485	37946

Two series of measurement with different timescale was performed. The results of these measurements are presented in Figure 5 and Table 1. The obtained results are in satisfactory agreement with the expected events. The experimental results were used for calibration using an internal Protom Faraday Cup.

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 previous experiment). Table 2 presents the experimental data comparing the PTW Bragg peak chamber readings and the Faraday-calibrated readings of the low-intensity beam extraction control system. The obtained PTW Bragg Peak Chamber data agree with the calibration data of the Protom Faraday Cup up to statistical and instrumental errors.

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

CONCLUSION

Within the framework of this study, the basic concept of a low-intensity beam extraction control system is proposed. The system is based on an automatic removable unit with a special luminescent film and a photosensor. The use of a removable module allows us to keep the original parameters of the therapy beam. Remote automatic control of this device will ensure switching between therapy and imaging modes between synchrotron cycles.

A static prototype of a low-intensity beam extraction control unit for the use of the radiographic mode has been developed and manufactured. The performance of this prototype, together with a specially designed low-intensity beam extraction mode, was experimentally confirmed by two series of verification tests. Measurements 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 a special operating mode of the accelerator can be implemented in any proton therapy complexes based on the Protom synchrotron. This allows us to use the original synchrotron beam as a tool to check the patient's position and eliminate the proton range uncertainties.

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