Development of photonic detector system for ultra-fast beam diagnostics in proton radiotherapy: the proof of concept

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Abstract. A concept of a photonic detector system for proton beam and Bragg peak position measurements in proton radiation therapy is presented. An approach of using scintillator plates with ultra-fast timing characteristics to detect the temporal fine structure of the beam is described. A detector module is made of a 10 × 10 cm² plastic scintillator plate with 1mm thickness. The light is collected on the corners of a plate by the optical fibers of pre-defined length, which introduce various known time delays. Using the Anger algorithm, the lateral position of the proton pencil beam traversing scintillator plate is reconstructed. We propose two applications of the system: thin single-plate beam position monitor and multi-plate stack quality control device to measure lateral beam position and relative position of the Bragg peak.

1. Introduction

Radiation therapy remains an important component of cancer treatment with approximately 50% of all cancer patients receiving radiation therapy during their course of illness [1]. Proton therapy is a rapidly growing modality that is used to treat certain types of cancers [2]. As of May 2021 there are 98 operational proton therapy centers, 83 of those became clinical in the last 10 years [3]. Key advantages of proton therapy, relative to conventional photon radiotherapy, is the specific dose distribution through the patient with low entrance dose and with majority of the dose deposited at the end of the proton track – at the depth of Bragg peak [4]. The commissioning and operation of these facilities require an extensive set of detectors for measuring various parameters of the treatment beam, in particular beam position monitors and detectors for beam range quality control are among key devices [2]. Given the complexity of proton therapy, a comprehensive quality assurance program is required, to maintain the best quality of treatment delivery for cancer patients.

Due to large dose gradients in the region of Bragg peak, its precise location is of critical importance [2]. Historically, reference percentage depth doses for proton pencil beam are measured with ionization chamber in the water at different depths and transverse positions [5]. Scanning Bragg curve with this method is time consuming, therefore many proton centers utilize Multi-Layer Ionization Chambers (MLIC), which provide considerably faster method for beam range measurements [6]. However, MLICs have some disadvantages: ionization chambers are not water-equivalent, finite size of charge-collecting electrode can complicate the measurement of integrated depth-dose curves [7] and system’s response exhibit dose-rate effects.

In the last decade, there has been an increase interest in scintillator-based detectors for quality assurance applications [2, 8-15], which can provide a competitive alternative to MLICs. A scintillator
is a material that emits light in response to the deposition of energy by ionizing radiation. Modern scintillator detectors have a combination of features advantageous for proton beam measurements, including excellent timing characteristics, high spatial resolution, radiation hardness, high degree of water-equivalence and can be produced in various geometries and dimensions [16, 17]. It was shown by Beddar et al. [18] that plastic scintillators exhibit high sensitivity, linear dose-response and excellent energy independence compared to other dosimeters used in radiotherapy. Main disadvantage of scintillators in their application in proton dosimetry is light quenching effects, which leads to a non-linear dependence between light output and dose deposition for heavy charged particles, such as protons [19].

Solid plastic scintillators were used to verify proton beam range [2, 20], and liquid-scintillator detectors were used to measure simultaneously and, almost in the real time, the range and lateral profiles of proton beams [21].

In this paper we present a concept of 2D and 3D monitoring systems for ultra-fast beam diagnostics that leverage the temporal fine (bunch-per-bunch) structure of the proton beam. Components of the systems were optimized to meet specific timing requirements and performance of the systems was evaluated in the Matlab simulations. Application of the 2D system focuses on beam position monitoring of the proton pencil beam; 3D system – on the range measurements (similar to MLICs) with simultaneous lateral beam position measurements. Scintillation light from each plate is collected at the corners by the optical fibers of various pre-defined length, creating known optical signal delays and consequently readout by a single photomultiplier tube. This configuration avoids optical artifacts, since fibers are directly coupled to the scintillator plate. Signal from the light pulse train is reconstructed to determine the lateral position of the beam in a single plate. Light quenching is accounted using method described by Tretyak [22]. Integrated photonic signals in each plate are associated with the total energy deposited by the proton beam and used to determine the position of Bragg peak.

2. Materials and Methods
There are two basic factors that need to be taken into consideration when using plastic scintillators for timing measurements: the total number of photons generated in the scintillator, i.e. light yield; and the de-excitation time of the scintillator molecules that defines how fast photons are emitted, i.e. rising time.

2.1 Scintillator
Five types of scintillators suitable for fast timing measurements were considered: Detec PS-91F [23] and Saint Gobain Crystals BC-422Q (quenched 0.5%), BC-418, BC-420, BC-422 [24]. Physical properties of these scintillator materials are presented in Table 1. Birks’ constant ($k_B = 9 \text{ mg/MeV/cm}^2$) to correct for quenching effect was obtained using semi-empirical method described by Tretyak [22].

| Scintillator       | Rise time, $\tau_r$ [ps] | Decay time, $\tau_d$ [ns] | Light output, $L_{\text{yield}}$ [% anthracene] | Attenuation length (bulk), [cm] | $\lambda_{\text{MAX}}$ emission, [nm] |
|--------------------|--------------------------|---------------------------|-----------------------------------------------|---------------------------------|--------------------------------------|
| PS-91F             | 700                      | 1.8                       | 45                                            | ----                            | 390                                  |
| BC-422Q (0.5%)     | 110                      | 0.7                       | 19                                            | $\leq 8$                        | 385                                  |
| BC-418             | 500                      | 1.4                       | 67                                            | 100                             | 391                                  |
| BC-420             | 500                      | 1.5                       | 64                                            | 110                             | 391                                  |
| BC-422             | 350                      | 1.6                       | 55                                            | 8                               | 370                                  |

For the purpose of simulations performed in this work, scintillator with the fastest rising time (110 ps) – BC-422Q (0.5%) was selected.
2.2 Timing requirements
We have analysed the beam micro-structures of the TRIUMF cyclotron and synchrotron at Heidelberg Heavy-Ion Therapy Centre to estimate the scope of the timing requirements for proposed photonic detectors. Fine structure of the beam is defined by the accelerator’s radiofrequency system (RF) that operates at about 23 MHz for TRIUMF cyclotron and 5 MHz for HIT synchrotron. This dictates the requirement for using scintillator with sub-nanosecond rising time and for system’s readout timing performance from 40 ns to 200 ns, necessary to prevent overlapping of the photonic signal trains between the neighbouring bunches.

2.3 Photomultiplier tube (PMT), digitizer and optical fibers
The most important features for the timing measurements with PMT are rise-time, transit time spread (TTS), quantum efficiency (Q.E.), photocathode size and gain. A lower TTS and higher photocathode efficiency are essential for the timing measurements. Three typical PMTs used for ultra-fast timing measurements were considered with their characteristics listed in Table 2.

Table 2. Characteristics of PMTs suitable for ultra-fast timing measurements.

| Hamamatsu PMT | Rise time, [ps] | TTS, [ps] | Q.E., [%] | Gain | Photocathode size, [mm] | Peak sensitivity, $\lambda_{\text{MAX}},$ [nm] |
|---------------|----------------|----------|-----------|------|------------------------|----------------------------------|
| R7400U-04 [25] | 780           | 230      | 26        | $5 \times 10^5$ | 8                     | 400 |
| R7400U-01 [25] | 780           | 230      | 26        | $5 \times 10^5$ | 8                     | 400 |
| R3890U-52 [26] | 150           | 25       | 22        | $2 \times 10^5$ | 11                    | 385 |

To fulfill our timing requirement, we selected MCP-PMT R3890U-52 with the rise time 150 ps, TTS-25 ps and gain $2 \times 10^5$.

For the combination of BC-422Q (0.5%) scintillator and MCP-PMT R3890U-52 the readout system should be capable of collecting the data with at least 5 GS/s sample rate. To satisfy this requirement, in our simulation we have selected a high-speed digitizer from National Instruments - PXIe-5186 with the sample rate 12.5 GS/s and 8 bit resolution.

The light from the corners of scintillator plate to PMT is delivered by multimode quartz optical fiber (FiberTech® UV-SIV) that is designed to transmit UV light of 350 – 390 nm. Attenuation length of the fiber $\Lambda = 0.05 \text{ dB/m}$ and aperture 0.22.

The photonic signal is delayed in the optical fiber. Some value of fiber lengths and introduce optical delays are presented on Table 3.

Table 3. Length of the fibers selected for every corner (Figure 1) and related time delays.

| Corner # | Length (m) | Time delays (ns) |
|----------|------------|------------------|
| 1        | 0.1        | 0.5              |
| 2        | 1.6        | 8.4              |
| 3        | 3.6        | 18.9             |
| 4        | 6.1        | 32.1             |

Ultrashort pulses propagating though the fiber can undergo substantial temporal and spectral changes, mostly due to chromatic dispersion. In high-bit-rate systems chromatic dispersion has a significant influence on the broadening of the pulse. Taking into account the dispersion of scintillator emission spectra $\sigma_\lambda = 60 \text{ nm}$ and the sample rate at 5GS/s, we have estimated the broadening of 97 ps per 1 m of the optical fiber.

3. Results and Discussion
The light emitted from the scintillator volume is collected on the corners of the scintillator plate, transmitted by optical fibers and readout with a single PMT (Figure 1). The collected light carries information about the beam’s lateral position and energy. We propose creating optical delays with
optical fibers of pre-defined lengths to distinguish corners of the plate and use that information to reconstruct the position of a proton beam from the photonic signal pulse train.

### 3.1.1. Single-Plate Design

We designed the detector in a form of a square scintillator plate with dimensions 10×10 cm² and thickness 0.1 cm (Figure 1). Traversing the plate, proton beam creates a photonic signal in the scintillator (Figure 2). The light from the interaction point beam-plate travels to the plate corners, which are coupled to the optical fibers. In Matlab we have simulated a transport of the photonic signal train as it is formed and delayed by the optical fibers of pre-defined length. Only prompt photons from the interaction point that are in the acceptance angle of each corner are detected. The length of the fibers was optimized to be sufficient to contain and transmit the total photonic signal generated by a single proton bunch before the arrival of the consecutive bunch, i.e. within one RF period (200 ns for HIT synchrotron). Since the length of each fiber, attenuation length and signal behavior inside fiber, as well as amount of light lost due to quenching are known, it is possible to reconstruct the true signal generated in the scintillator plate at every corner. Total amount of light produced per bunch and temporal structure of the signal is used to evaluate the energy of the impacting proton beam. To define the position of interaction point, an Anger algorithm was utilized [27]. Proton beam interaction point was deliberately simulated off plate’s centre (Figure 2) to study the capabilities of the system to identify off-axis lateral beam position.

![Figure 1. Design of the beam position monitor. Scintillator plate is readout on the corners by optical fibers of different length, herewith \( L_1 < L_2 < L_3 < L_4 \). Bunch per bunch photonic signal arrives to the PMT in a form of signal pulse train.](image)

The standard Anger algorithm can be expressed by the following equation:

\[
x = \frac{(N_1 + N_2) - (N_3 + N_4)}{N_1 + N_2 + N_3 + N_4}, \quad y = \frac{(N_1 + N_4) - (N_2 + N_3)}{N_1 + N_2 + N_3 + N_4},
\]

(1)

where \( N_1, N_2, N_3, N_4 \) are the reconstructed true number of photons at corners 1, 2, 3 and 4 respectively (Figure 1). \( x, y \) are the coordinates of the proton beam entering the plate (Figure 2). For the scintillation light originating directly from the interaction point in rotated by \( \pi/4 \) plane, the position \( x^* \) and \( y^* \) can be defined using a positioning algorithm described by Zhang et al. [28], which also reduces the ‘pin-cushion’ distortion. The new algorithm can be expressed as an asymmetry functions in \( (x^*, y^*) \) coordinates:

\[
x^* = \frac{N_1 - N_3}{N_1 + N_3}, \quad y^* = \frac{N_2 - N_4}{N_2 + N_4}
\]

(2)

Original \( x, y \) coordinates can then be calculated as:
\[ x = x^* \cos \left( \frac{\pi}{4} \right) + y^* \sin \left( \frac{\pi}{4} \right), y = y^* \cos \left( \frac{\pi}{4} \right) + x^* \sin \left( \frac{\pi}{4} \right). \] (3)

Resolution of the system to identify the centroid of the proton beam lateral position is determined by two factors: variation in the amount of scintillation light entering optical fibers as proton beam traverses the plate off-centre and resulting in solid angle variation at each corner of the plate; and shift of photonic pulses on the temporal scale of uncentered beam relative to its central temporal signal response. Our simulations suggest that utilizing of these two mechanisms < 5 mm resolution can be achieved.

**Figure 2.** Schematic signal flow in the single-plate detector. Proton beam transverses scintillator plate off-centre producing light. Photonic signal from the shortest optical fiber is used to trigger the system. Photonic signal from the plate corners is used to reconstruct interaction point position \((x^*, y^*)\) and energy deposited in the plate by the proton bunch, which can be associated with proton beam energy.

**Figure 3.** Simulated photonic signal train of an uncentered proton beam. Thick line represents the corrected for quenching signal registered by the PMT, while dotted line – simulated signal corrected for quenching in scintillator plate and signal modifications during the transport in the optical fibers.
Time delay ($\tau_d$), created by the longest fiber guiding light from the scintillator plate corner to the PMT plus the bunch length ($t_b$) should be less than the time between bunches ($T$): $\tau_d + t_b < T$. This requirement prevents overlapping of the signals from the neighboring bunches. By the time the signal from the next coming bunch arrives through the shortest fiber to the PMT, all light generated by the first bunch in all fibers would already be detected.

### 3.1.2. Multi-Plate Design

An array of a single-plate detector modules stacked together in the direction of the proton beam can extend the application of the system by enabling beam range measurement (Figure 4). In our design multi-layer structure is immersed in water-filed rectangular cuboid vessel with the length sufficient to cover the range of proton beam. Longitudinal resolution of detector system depends on the thickness of scintillator plate and longitudinal spatial granularity of plates in the beam’s direction. Scintillator plate thickness of each module is 1 mm, while granularity can vary depending on requirements: it can be sparse in the plateau region of Bragg curve or can be stacked back-to-back as implemented by Kelleter et al. [2]. In the latter, optical decoupling between modules should be maintained. The position of the plate with maximum integral photonic signal, i.e. maximum amount of energy deposited in the plate, can be associated with the Bragg peak position with 1 mm accuracy. Calibrated system with the known proton energy can be utilized for daily quality control.

![Schematic signal flow in the three-plate detector system](image)

**Figure 4.** Schematic signal flow in the three-plate detector system. 200 MeV proton beam traversing the water phantom deposits increasing amount of energy with increasing depth. System readout is triggered by every proton bunch crossing entrance phantom window at $z = 0$ cm. Each module is readout by a single PMT.

We have simulated a water phantom with the three scintillator plates at depths of 10 cm, 20 cm and 24 cm in the 30 cm length water phantom (Figure 4). Our simulations suggest that system can readout every 150 ns. In Figure 5, we have simulated the response of a 28-plate system in 200 MeV proton beam with modules positioned at 1 cm increments. Transformation of photonic signal in the optical fibers is known from the section 2.1.3 and can be utilized to reconstruct the original signal in each scintillator plate and reconstruct the Bragg curve, position of Bragg peak with 1 mm resolution and lateral position of the beam with 5 mm resolution.
Proposed system is flexible, scalable and provides opportunity to quantitatively examine typically unknown fine structure of the particle beam. In addition, the system do not exhibit dose-rate effects, which is an important feature for FLASH proton therapy when action may be required on the nanosecond temporal scale to provide safe and effective treatment.

4. Conclusion
The results of our simulation suggest the possibility of using a proton fine beam structure for diagnostics of proton beam. Single-plate design of proposed detector system can be applied as a beam monitor for high intensity proton pencil beams, capable to measure simultaneously lateral position of the beam’s lateral centroid position with < 5 mm accuracy and energy of the beam by utilizing temporal structure of the light signal. Multi-plate design can be applied as a quality control device for Bragg peak position verification with ~1 mm accuracy defined by spatial frequency of the plates in the system and by the scintillator plate thickness. Our future steps are focused on the prototyping of these devices to validate our simulations.

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Figure 5. Bragg curve from a 28-layer detector system simulated for 200 MeV proton beam. In red — uncorrected (except for quenching) simulated integral PMT signal, blue — simulated integral signal corrected for quenching in scintillator plates and for attenuation, broadening in the optical fibers, representing true photonic signal emitted from the scintillator plate.
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