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AN INTENSITY MEASUREMENT METHOD BASED ON INORGANIC SCINTILLATORS AND OPTOELECTRONIC SENSORS

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Abstract

The Heidelberg Ion Therapy Center (HIT) is a heavy ion accelerator facility located at the Heidelberg university hospital and intended for cancer treatment with heavy ions and protons. Currently ionisation chambers with highly sensitive charge amplifiers are regularly used for intensity measurements of the high-energy ion beams. The main subject of this paper is the examination of a new intensity measuring method based on the combination of fluorescent light from inorganic scintillators and an optoelectronic sensor with adjacent electronics as an alternative to the ionisation chambers. A special measurement set-up with a large-area Si PIN-diode and adapted optics was investigated with respect to signal dynamics, resolution and linearity and compared with the measured values of the ionisation chamber. In this paper the design and the experimental results with proton and carbon beams are presented in detail.

INTRODUCTION

The heavy ion accelerator at (HIT) is used for raster-scanning irradiation [1] of cancer patients with protons as well as carbon ions. It provides three fully operational therapy treatment rooms, two with horizontal fixed beam exit and one heavy ion gantry with rotatable beam exit, and a beam exit for experiments, see Fig. 1 [2].

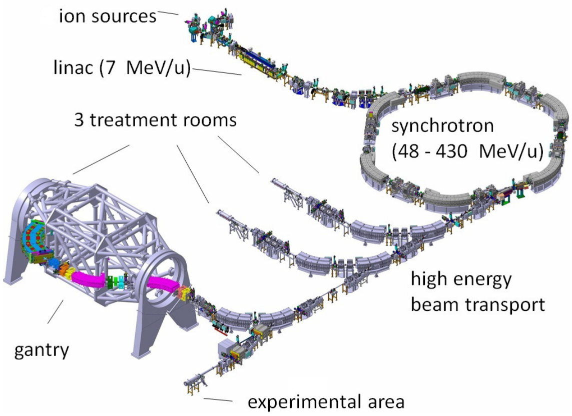

Figure 1: HIT accelerator facility with the ion sources, linear accelerator, synchrotron, two horizontal beam exits and a gantry for medical treatment and one experimental area.

The synchrotron and the high-energy beam transport lines are used to produce a library of highly focussed pencil-beams. For each ion species 255 energy values (88-430 MeV/u for carbon, 48-220 MeV/u for protons), 10 intensity levels (2×10^6 - 8×10^7 particles per second (pps) for carbon, 8×10^7 - 2×10^9 pps for protons) and 4 beam sizes are presently available. Regarding to the dose rate measurements ionisation chambers with highly sensitive charge amplifiers are used for particle rates of 10^6 up to 10^{10} pps. A new intensity measurement method based on inorganic scintillator and an optoelectronic sensor was developed as an alternative to the ionisation chambers. An optical system was built up to measure the fluorescent light emitted from a viewing screen (P 43 material) in the so-called isocentre position in the experimental test bench. The major advantage of the used material P 43 (Tab. 1) is the high light output, the sensitivity matching with the PIN-photodiode as well as a high radiation hardness. The P 43 material has a afterglow time of 1 ms. Therefore it can be used for exact measurements of the beam intensity in the millisecond region. Furthermore, a fast silicon PIN-photodiode is used as detector with a large sensitive area of 10 x 10 mm^2 and a high quantum efficiency at $\lambda = 540$ nm. The advantage of the new measurement method is the simple and inexpensive construction, whereas the technique and mechanics of ionisation chambers are very expensive and complicated to manufacture. One disadvantage is clearly that the ion beam is partially destroyed, mainly by straggling in the material.

Table 1: Viewing screen material characteristics. Efficiency η refers to 12 kV electron beams [3].

Mat.	Com-position	Maxim. Emis-sion	Decay Time (10 %)	Effi-ciency ph/el
P 43	Gd_2O_2S:Tb	545 nm	1 ms	550
P 46	$Y_3Al_5O_{12}$:Ce	530 nm	300 ns	256
P 47	Y_2SiO_5:Ce	400 nm	55 ns	630

DESIGN AND FUNCTION

The main function of the new measuring method is to transfer the emitted fluorescent light of a viewing screen P 43 onto a large-area PIN photodiode (10 x 10 mm^2) via a lens with $k = 1.2$ (aperture value), $f = 50$ mm and to deduce the beam intensity from the strength of the signal. Figure 2 illustrates the principle of the new method.

After leaving the exit window of the high energy beam transport the accelerated ions hit the viewing screen at an angle of 45° degrees with respect to the beam direction and lose a part of their kinetic energy ΔE in the scintillator.

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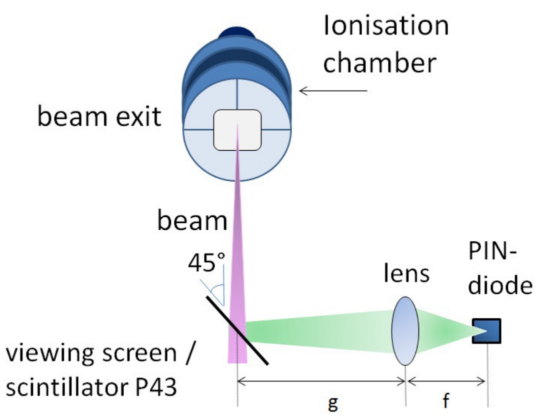

Figure 2: Measurement principle of the new measurement method. The scintillator P 43 is under 45° degrees to the beam direction. The emitted fluorescent light is imaged with a lens to the PIN-photodiode; $f = 50$ mm is the focal length of the lens and g the optical distance from the viewing screen.

The emitted radiant flux Φ of the viewing screen P 43 is proportional to the fluence (number of particles N per area A) [4] and thus proportional to the intensity I (pps):

$$\Phi = \frac{1}{2} \cdot \eta \cdot I \cdot \Delta E \;, \; \Delta E = s \cdot \frac{dE}{dx} \;. \tag{1}$$

Here, dE/dx is the energy loss per distance (Bethe-Bloch equation), s is the path length of the beam in the scintillator, and η is the efficiency of the scintillator material. For inorganic scintillators it is known that the light yield of heavy charged ions amounts to approx. 50 % to 70 % when compared to electrons [5].
Since the medical accelerator is very flexible, the beam width and the beam position can varied from spill to spill. The measuring system was designed in a way that the area projected from the viewing screen to the sensor is as large as possible. For this purpose experiments were performed in the laboratory with a test light source. The photoelectric signal response versus light spot position above the PIN active area was analysed in depending on the distance g between the viewing screen and the lens (Fig. 3). The measurements with the light spot position has shown that the field of view depends on the distance g, but also on the size of the sensor surface and the focal length f. The maximum reached light spot position shift, see Fig. 3, is ≈ 72 mm (for $g = 50$ cm) with a maximum deviation within the measured values of about 13 %. For the measurements in the experimental cave a distance of $g = 40$ cm was chosen to increase the output signal of the PIN-photodiode.

RESULTS AND DISCUSSION

During irradiation the emitted radiant flux Φ of the viewing screen is subsequently measured with the PIN-photodiode and converted into a photo current linear to the radiant flux. The photo current is amplified with a highly sensitive charge amplifier.

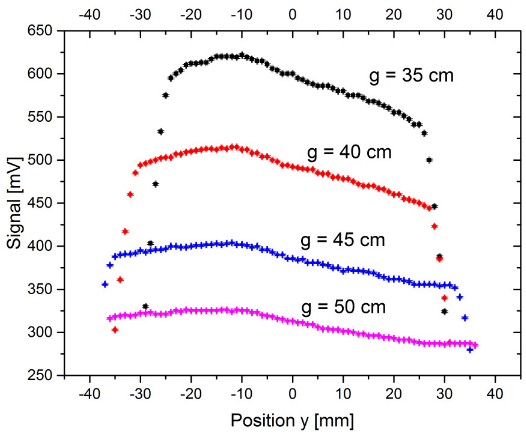

Figure 3: Scanning response of an PIN photoelectric signal versus light spot (diameter 1 cm) vertical position on the screen in dependence of the distance between the viewing screen and the lens g.

General Signal Waveform

In order to illustrate the good reproducibility of the intensity measurements, Figure 4 shows a comparison of the measurement data for six consecutive intensity levels for both the ionisation chamber and the output voltage of the measurement system for carbon beams. The measured spill shape of the intensity has a 5-second cycle due to the selected extraction time.

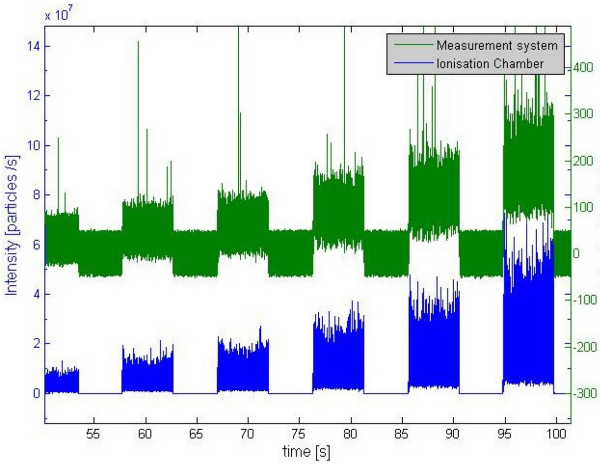

Figure 4: Comparison of measurement data of the ionisation chamber (blue) with the output voltage of the measurement system (green) for carbon beams with the energy $E = 93.42$ MeV/u and the intensity levels 3 (5.0×10^6 pps) to 8 (3.0×10^7 pps). All measurements were performed with a beam width (FWHM) of 9.5 mm (focus level 1). The distance between the viewing screen and the lens is $g = 40$ cm.

The signal waveform of the measurement system, as shown in Figure 4, illustrates its feasibility. The measurement shows an increase of the output voltage for each spill depending on the intensity levels. Thus, a corresponding value of the output voltage can be clearly assigned to each level of intensity. The scattered peaks in the signal are caused by electromagnetic interference in the sensor signal of the test set-up.

Signal Dynamics

To analyze the output signal of the PIN-photodiode for one intensity level, Figure 5 shows a measured spill shape for carbon beams for the intensity level 8 (3.0 x 10^7 pps).

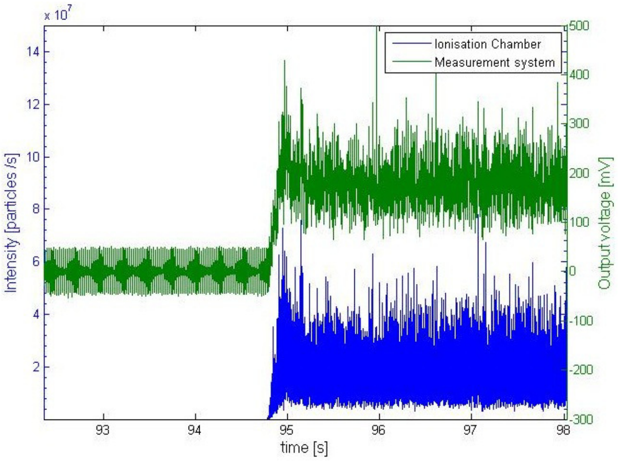

Figure 5: Comparison of measurement data of the ionisation chamber (blue) with the output voltage of the measurement system (green) for carbon beams with the energy $E = 93.42$ MeV/u for the intensity level 8 (3.0 x 10^7 pps).

When comparing the recorded measurement data in Figure 5 it can be observed that the signal of the PIN-photodiode approximately reflects the existing spill shape. Looking at the signal waveform at the beginning of the spill, the output voltage of the measurement system shows a signal increase which simultaneously also occurs in the ionisation chamber. The reason for the periodical output signal during the background measurement is the very low terminal capacitance and the resistance of the PIN-photodiode resulting in an RC resonant circuit.

Temporal Resolution

Figure 6 shows an example of a detailed resolved representation of the proton spill shape for the intensity level 10 (2.0 x 10^9 pps). Looking at the microscopic spill shape in Figure 6 it can be observed that the output voltage provides a good reproduction of the spill structure in comparison with the measurement of the ionisation chamber. Thereby, the temporal resolution of the measurement system depends on two factors: on the one hand it is determined by the afterglow time of the scintillator P 43; on the other, by the bandwidth of the amplifier operating in the chosen sensitivity level (2 nA/V). P 43 has an afterglow time of 1 ms for a reduction in light intensity from 90% to 10 %, the afterglow time for a reduction in light intensity from 10% to 1% is 1.6 ms. Thus, due to the scintillator's afterglow time the measuring system cannot measure light pulses with a frequency of more than 1 kHz. For the selected sensitivity level of the amplifier the bandwidth lies between 500 Hz and 1 kHz. However, the cut-off frequency of the PIN-photodiode is 40 MHz - at this frequency the light pulses can still be separated. For this reason, the overall temporal resolution of the measuring system is estimated to be 500 Hz to 1 kHz. In comparison, the time resolution of the ionisation chamber is about 10 kHz.

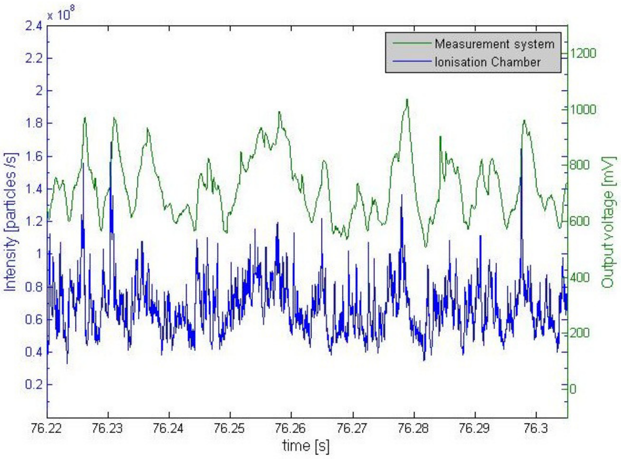

Figure 6: Comparison of measurement data of the ionisation chamber (blue) with the output voltage of the measurement system (green) for proton beams with the energy $E = 50.60$ MeV/u for the intensity level 10 (2.0 x 10^9 pps). The measurement was performed with a beam width (FWHM) of 31.3 mm (focus level 1).

CONCLUSION

By using a well adapted optics the output voltage of the measuring system consisting of a scintillator and a PIN-photodiode was able to reproduce the temporal microscopic spill shape of the beam intensity for all beam parameters of the HIT accelerator in comparison to the measured values of an ionisation chamber. In summary, the first prototype shows that the new optoelectronic measuring method based on the P 43 material and a large-area PIN-photodiode provides a good basis for characterizing the intensity of high-energy ion beams.

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