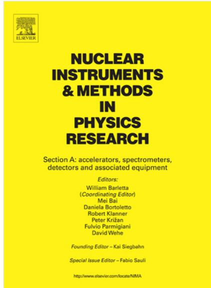
Accepted Manuscript

Real-time beam monitoring in scanned proton therapy

G. Klimpki, M. Eichin, C. Bula, U. Rechsteiner, S. Psoroulas, D.C. Weber, A. Lomax, D. Meer



PII: S0168-9002(18)30295-X
DOI: https://doi.org/10.1016/j.nima.2018.02.107
Reference: NIMA 60636

To appear in: *Nuclear Inst. and Methods in Physics Research, A*

Received date : 22 November 2017
Revised date : 3 February 2018
Accepted date : 23 February 2018

Real-time beam monitoring in scanned proton therapy

G. Klimpki[a,*], M. Eichin[a], C. Bula[a], U. Rechsteiner[a], S. Psoroulas[a], D.C. Weber[a,b], A. Lomax[a], D. Meer[a]

[a] *Paul Scherrer Institute (PSI), Center for Proton Therapy, 5232 Villigen PSI, Switzerland*
[b] *University Hospital Zurich, Department of Radiation Oncology, Rämistrasse 100, 8091 Zurich, Switzerland*

Abstract

When treating cancerous tissues with protons beams, many centers make use of a *step-and-shoot* irradiation technique, in which the beam is steered to discrete grid points in the tumor volume. For safety reasons, the irradiation is supervised by an independent monitoring system validating cyclically that the correct amount of protons has been delivered to the correct position in the patient. Whenever unacceptable inaccuracies are detected, the irradiation can be interrupted to reinforce a high degree of radiation protection. At the Paul Scherrer Institute, we plan to irradiate tumors continuously. By giving up the idea of discrete grid points, we aim to be faster and more flexible in the irradiation. But the increase in speed and dynamics necessitates a highly responsive monitoring system to guarantee the same level of patient safety as for conventional *step-and-shoot* irradiations. Hence, we developed and implemented real-time monitoring of the proton beam current and position. As such, we read out diagnostic devices with 100 kHz and compare their signals against safety tolerances in an FPGA. In this paper, we report on necessary software and firmware enhancements of our control system and test their functionality based on three exemplary error scenarios. We demonstrate successful implementation of real-time beam monitoring and, consequently, compliance with international patient safety regulations.

Keywords: beam monitoring, real-time controls, particle beam scanning, proton therapy, patient safety

PACS: 87.55.ne, 29.40.Cs, 29.40.Gx

1. Introduction

Almost every second proton therapy center around the world irradiates their patients using a *step-and-shoot* technique commonly referred to as pencil beam scanning [1, 2]: A proton beam of a few millimeter width in air is steered through the three-dimensional (3D) tumor volume by successively changing its penetration depth and transverse position. Scanning in depth (S-direction) can be achieved by adapting the proton beam energy and scanning in the transverse (T, U)-plane[1] is typically realized through a pair of beam-deflecting dipole magnets (see figure 1 for a graphical definition of the coordinate system). This state-of-the-art scanning process follows a 3D grid of thousands of discrete beam positions mapped onto the tumor volume.

To guarantee patient safety in case of machine-related errors, the number of delivered protons and the beam position are cyclically checked against expected values. For this purpose, the independent beam monitoring system reads out diagnostic devices (e.g. ionization chambers, position-sensitive monitors) distributed along the beamline. State-of-the-art monitoring systems perform cyclic safety checks every ~ 0.1 ms [3–5]. Due to the discrete nature of *step-and-shoot* irradiations, such measures are sufficient to comply with international patient safety regulations [6, 7].

The Center for Proton Therapy at the Paul Scherrer Institute treats cancer patients since 1996 using pencil beam scanning. To shorten irradiation times and gain flexibility in beam delivery, we aim to go beyond the conventional *step-and-shoot* approach. For this purpose, we discarded the idea of a fixed grid in one of the three dimensions and upgraded our beam delivery technology to support fully continuous scanning of the proton beam along one of the transverse axes (in the following referred to as the T-axis) [8, 9]. The dose deposition can be modulated by varying the beam current and transverse scan speed continuously along such T-lines. Consequently, the monitoring system needs to supervise these two quantities continuously, preferably in real-time, to guarantee short reaction times to errors in the irradiation. Restricted to discrete pencil beam scanning, our monitoring system fails to fulfill these tasks in its present form and needs to be upgraded accordingly. Hence, substantial enhancement had to be designed in order to guarantee safe patient treatments using continuous beam scanning [10].

In proton therapy, patient safety is of utmost importance calling for a highly reliable and responsive safety system. In this context, real-time monitoring of beam parameters represents a novelty despite being a standard method for many experimental beamlines. To our knowledge, no other

*Corresponding author
Email address: grischa.klimpki@psi.ch (G. Klimpki)

[1] For coplanar treatments with the beam in anterior-posterior direction, the T-axis coincides with the frontal axis of the patient and the U-axis coincides with the longitudinal axis of the patient.