Proof-of-concept PRAGUE detection system: Monte Carlo simulation and first preliminary experimental results

A. Kurmanova[1,2], A. Amato[2], M. Guarrera[1, 2], D. Margarone[3,4], G. Messina[2], S. Passarello[2], G.A.P. Cirrone[2], S. Tudisco[2], E. Zappalà[2], G. Petringa[2, 3]

[1]Department of Physics and Astronomy “Ettore Majorana”, University of Catania, Catania, Italy
[2]INFN-Laboratori Nazionali del Sud, Catania, Italy
[3]ELI-Beamlines, Institute of Physics, Czech Academy of Sciences, Prague, Czechia
[4]Queen’s University of Belfast, Belfast, the United Kingdom

Introduction

Particle therapy is a viable alternative to conventional radiotherapy for treating deep-seated tumors on account of reduced radiation loading on the patient arising from more targeted dose deposition by charged particles along their tracks. In order to exploit proton therapy to the fullest, a robust quality assurance (QA) protocol and tools for reducing range uncertainties are essential [1]. To address the latter issue, the PRAGUE (Proton range measurement using silicon carbide) detection system was proposed by the medical physics group of INFN-LNS, aimed at developing a real-time solid-state detector in a stack configuration to measure percentage depth-dose distribution (PDDD) with μm-spatial resolution and perform routine proton therapy QA with the both conventional and high dose-rate beams.

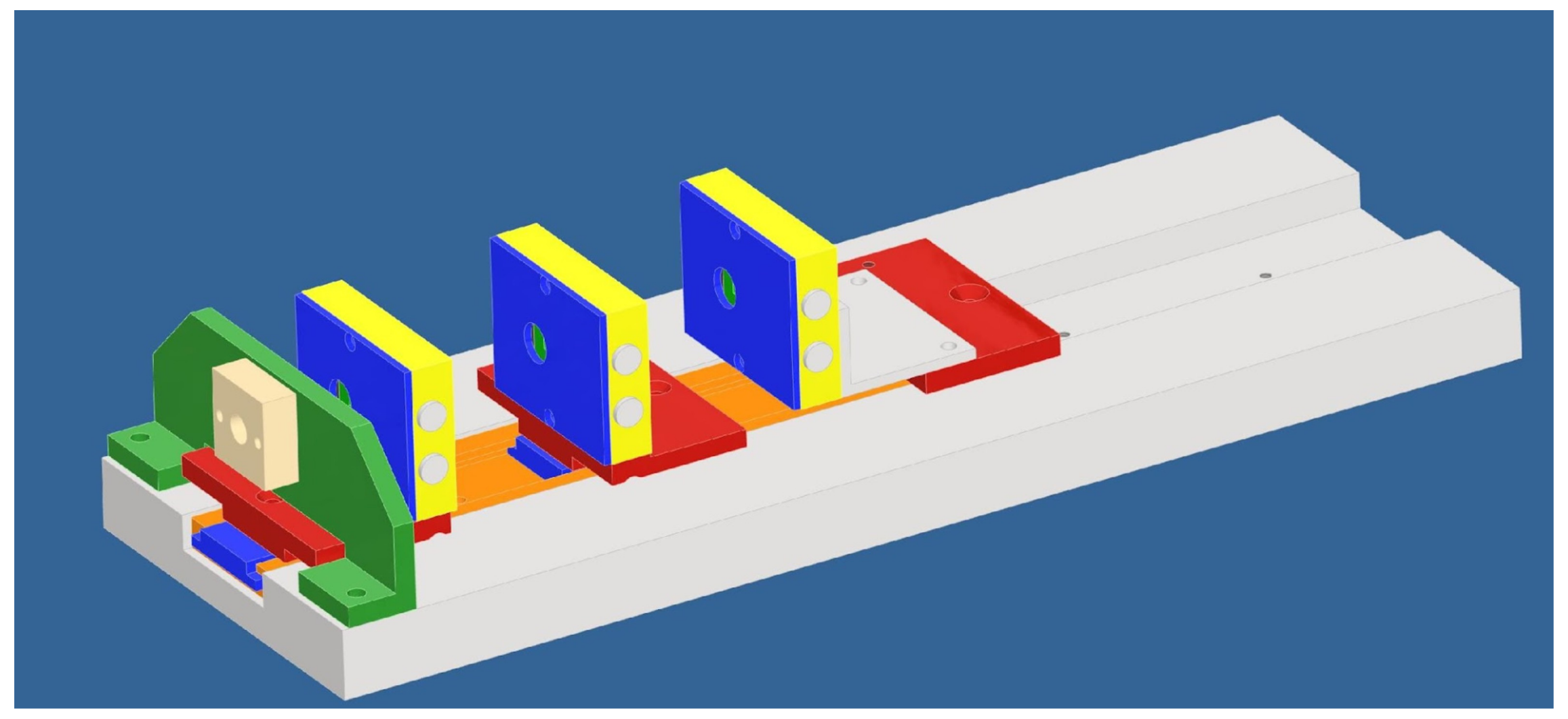
Methodology

Simulation

The TOPAS (TOol for PArticle Simulation) simulation toolkit [2], a packaged and enhanced version of GEANT4 for particle simulation, was used to create a proof-of-concept PRAGUE detection system. The proton simulation platform was used to perform a Monte Carlo analysis of the predicted PDDD, and the results were experimentally verified by measurements at the Trento Proton Therapy Center.

Experiment

To fulfill the aim of this work, an experimental campaign composed of three measurements was performed at the Trento Proton Therapy Center. The first measurement was devoted to checking the SiC detectors’ response and beam quality, and this was followed by experiments intended for range assessment using a stack of Gafchromic EBT films. The final set of experimental measurements was focused on dose curve reconstruction.



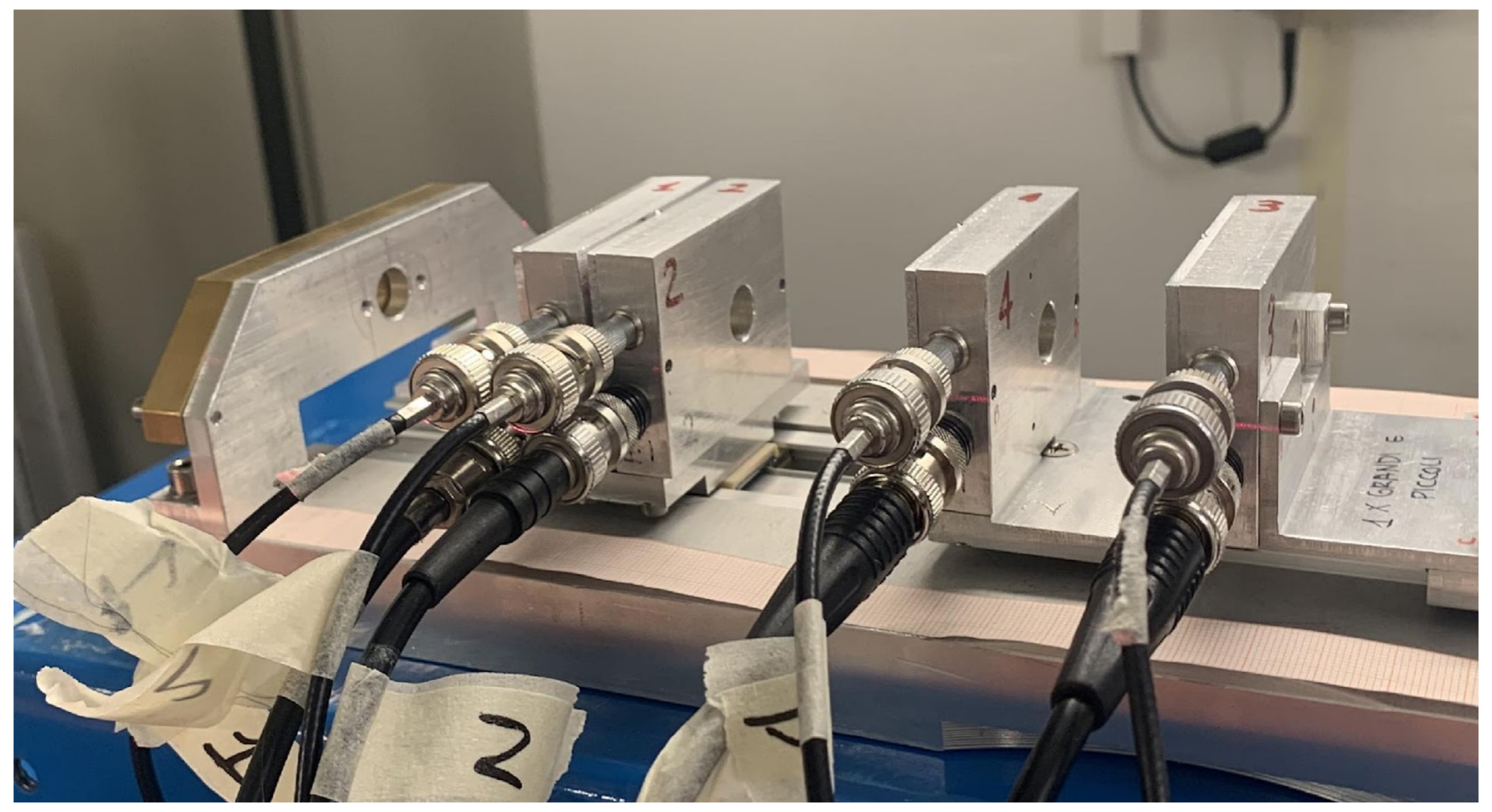


Figure 1. Schematic of simulation and experimental setup (top) and real image from measurement campaign (right)

Data Analysis

Dose and uncertainty calculation for Gafchromic EBT Film

Gafchromic EBT film is a 2D passive chemical-based dosimeter whose optical density changes upon exposure to ionizing radiation, triggering a permanent color change to occur. Since the structural characteristics of the film evolve over time, scanning and analysis were performed a day after measurement to allow color permanence, in accordance with protocol [3].
Mean absorbed dose and standard deviation were calculated as

$$OD = -log10\frac{I}{I_0} \qquad (1)$$

where I_0 and I are average pixels’ values for the background and region of interest, respectively.

$$D = p_1OD^3 + p_2OD^2 + p_3OD - p_4 \qquad (2)$$

where p_1, p_2, p_3, p_4 are coefficients are taken from the evaluation of samples with known parameters.

$$\sigma_D = \left(A\left(ln\frac{I}{I_0}\right)^2 + Bln\frac{I}{I_0} + C\right)\frac{0.4343}{I}\sigma_I \qquad (3)$$

where A, B,C are parameters derived from Eq. 2 using the standard error propagation algorithm.

Dose and uncertainty calculation for SiC detector

The signal from the SiC detector is a time dependent voltage processed with I-V converter. Using Ohm’s law and I-V converter resistance of R=10 GΩ, the dose can be computed directly:

$$D = \frac{W}{e}\frac{Q}{m} = \frac{W}{em}\int_0^T V dt \qquad (4)$$

where *Q* is the total charge produced, *m* is a mass of the detector in which the energy is deposited, and *W* and *e* are the mean energy required to create an electron-hole pair and electron charge, respectively.
Subsequently, the standard deviation in the voltage signal can be propagated into uncertainty in dose, given as

$$\sigma_D = \frac{W}{me}\frac{1}{R}\sigma_V T \qquad (5)$$

Results

The result of the PRAGUE detection system simulation modeled using TOPAS was the dose curve predicted for the Trento proton therapy center beamline. Simulated PDDD was compared with the analyzed experimental data, showing a good degree of match (χ^2 test with 99.5% confidence) (Fig 2) .

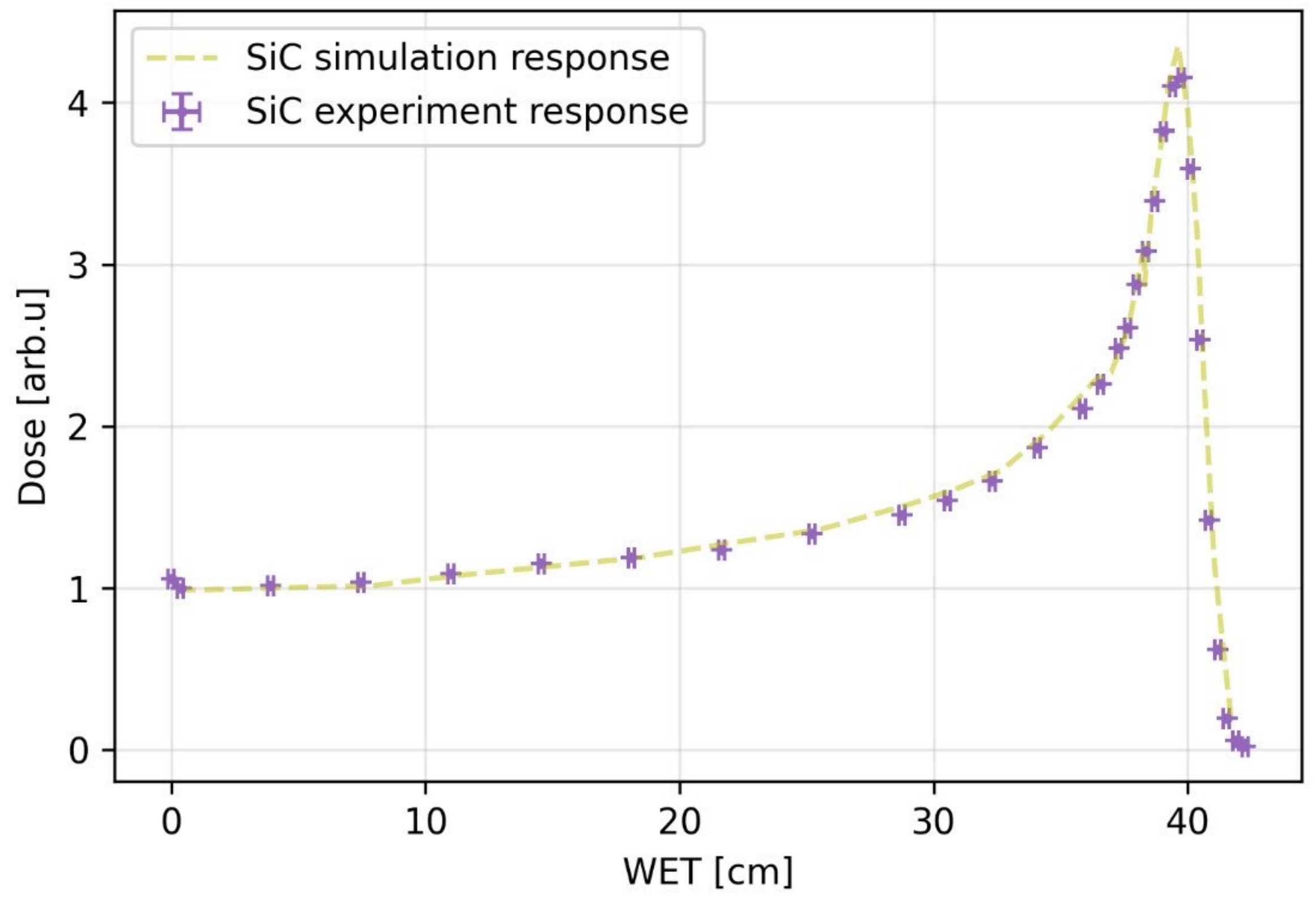


Figure 2. Experimental and simulated PDDD reconstructed with the PRAGUE detection system

The analysis of the experimental data on Gafchromic films and SiC detector responses illustrates widespread agreement (Fig. 3). This indication makes the PRAGUE detection system a potential device for many applications of radiation physics, since gafchromic films are considered as a reliable technique for accurate dose assessment and quality checks.

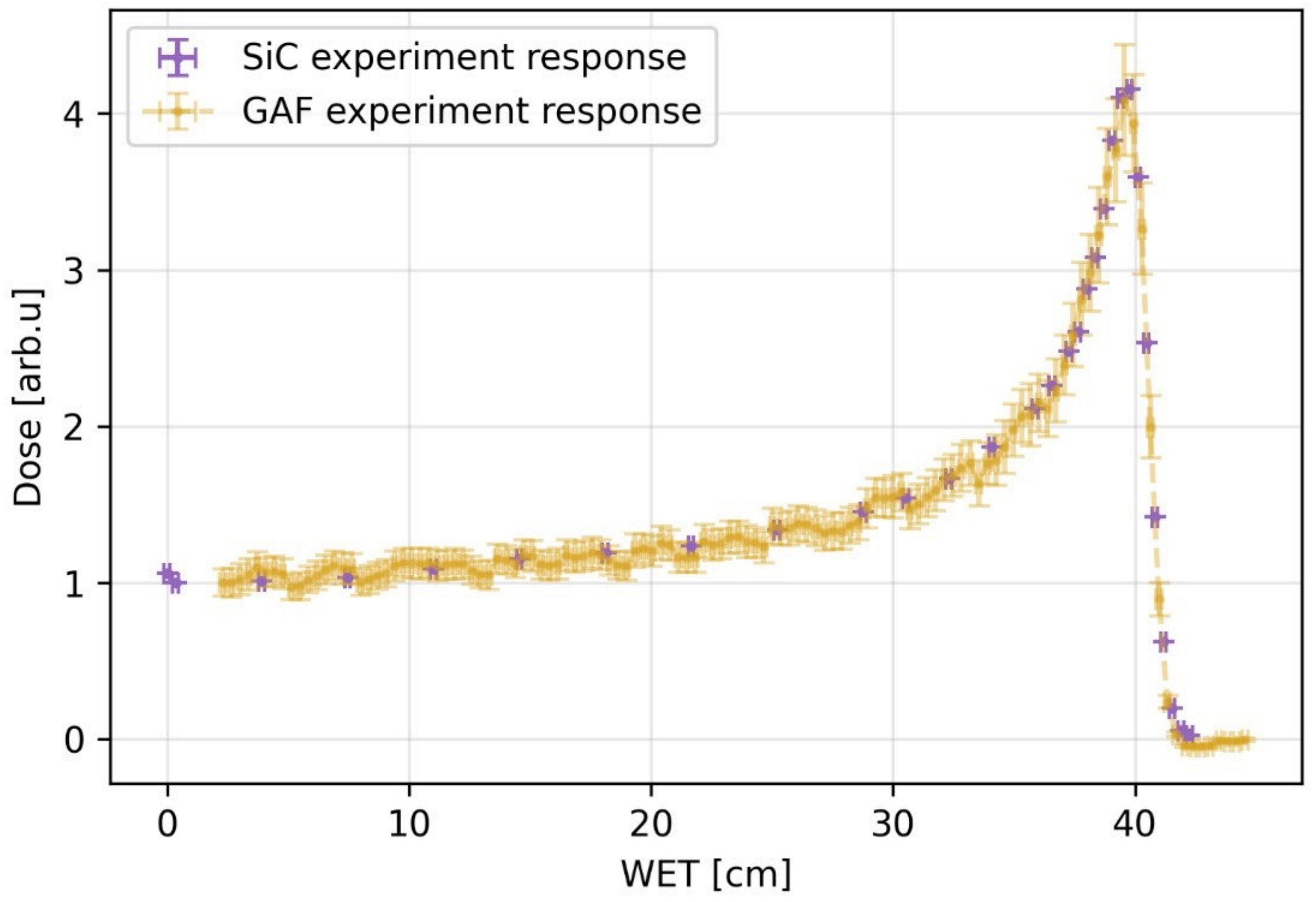


Figure 3. Experimental data for gafchromic and the PRAGUE detection system prototype

In addition, the analyzed experimental data were compared with the experimental data obtained with a multi-layer ionization chamber placed in a water phantom, which demonstrated disagreement in the WET range (Fig. 4). This difference could be explained by the lack of the detailed source information and difficulties to define correct stopping power. However, the depth-dose profiles of the above-mentioned experimental data still repeat the shape.

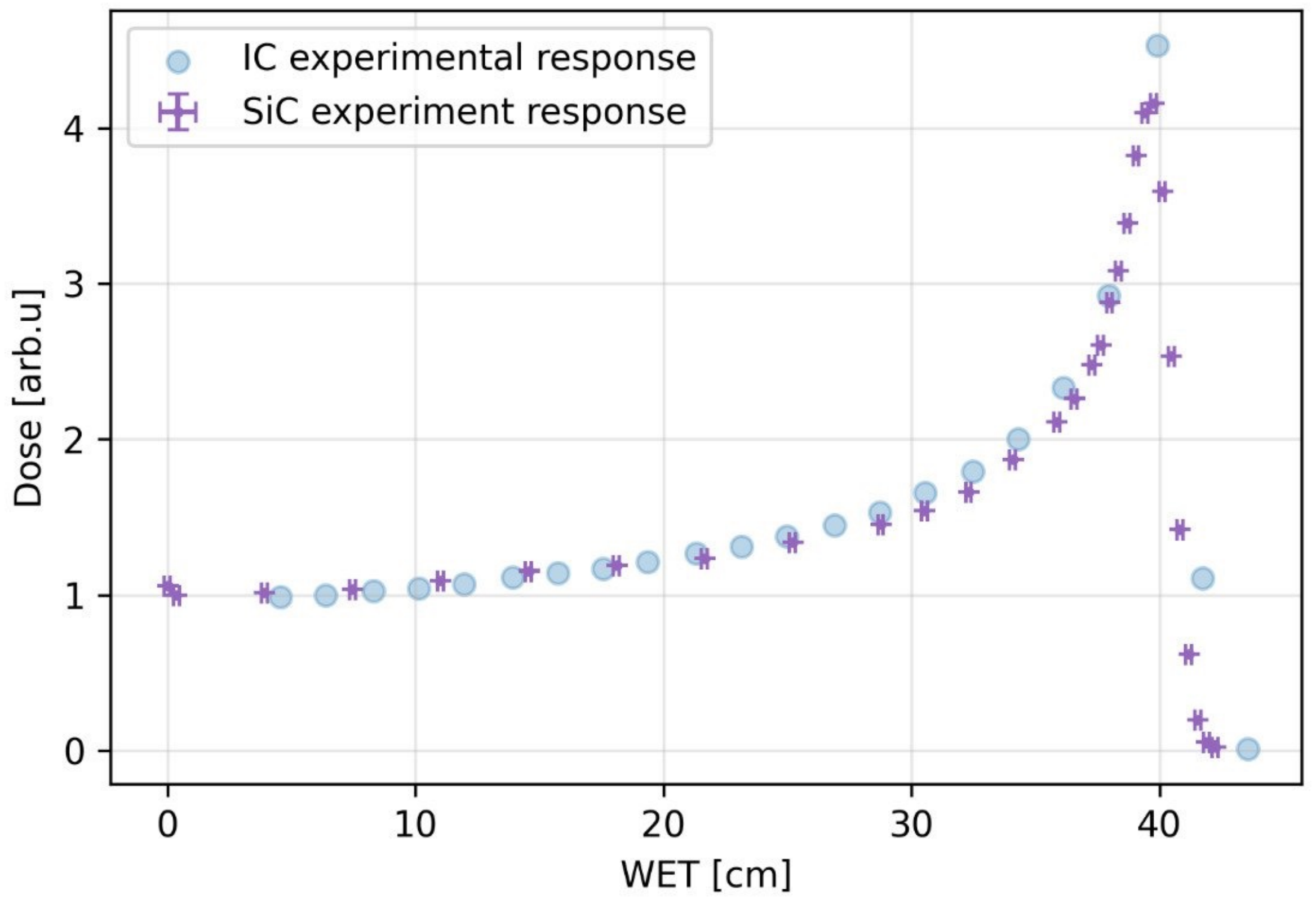


Figure 4. Comparison between experimental PDDD reconstructed with the PRAGUE detection system and the approved dosimetric system

Conclusions

Positive match between simulated and measured data provides proof-of-concept support to the application of the proposed detection system to conventional proton therapy, paving the way for PRAGUE to potentially become a standard in dosimetry for clinical treatment.

References

[1]H. Paganetti, Range uncertainties in proton therapy and the role of Monte Carlo simulations, Physics in Medicine & Biology 57 (11) (2012)
[2] J. Perl, J. Shin, J. Schumann, B. Faddegon, H. Paganetti, TOPAS: An innovative proton Monte Carlo platform for research and clinical applications, Medical Physics 39 (2012)
[3], B. Cagni, G. Cuttone, G. Fustaino, M. Guarrera, R. Khanna, R. Catalano, Use of radiochromic films for the absolute dose evaluation in high dose-rate proton beams, Journal of Instrumentation 15 (04) (2020) C040