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Narodowy Instytut Onkologii
im. Marii Skłodowskiej-Curie
Państwowy Instytut Badawczy
Oddział w Krakowie

System for Radiation Dose Distribution Monitoring in Radiotherapy Treatment Planning

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on behalf of **Dose3D-Future Collaboration**
AGH University of Krakow

16th Pisa Meeting on Advanced Detectors

PM2024, 28.05.2024

Outline

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- Project motivation
- System overview
  - DAQ
  - Reconfigurable phantom
  - System verification
- Software
- Measurement at cancer treatment plant
  - Thanks to Maria Sklodowska-Curie National Research Institute of Oncology Krakow Branch
- Conclusions and future
- Acknowledgements

Project motivation

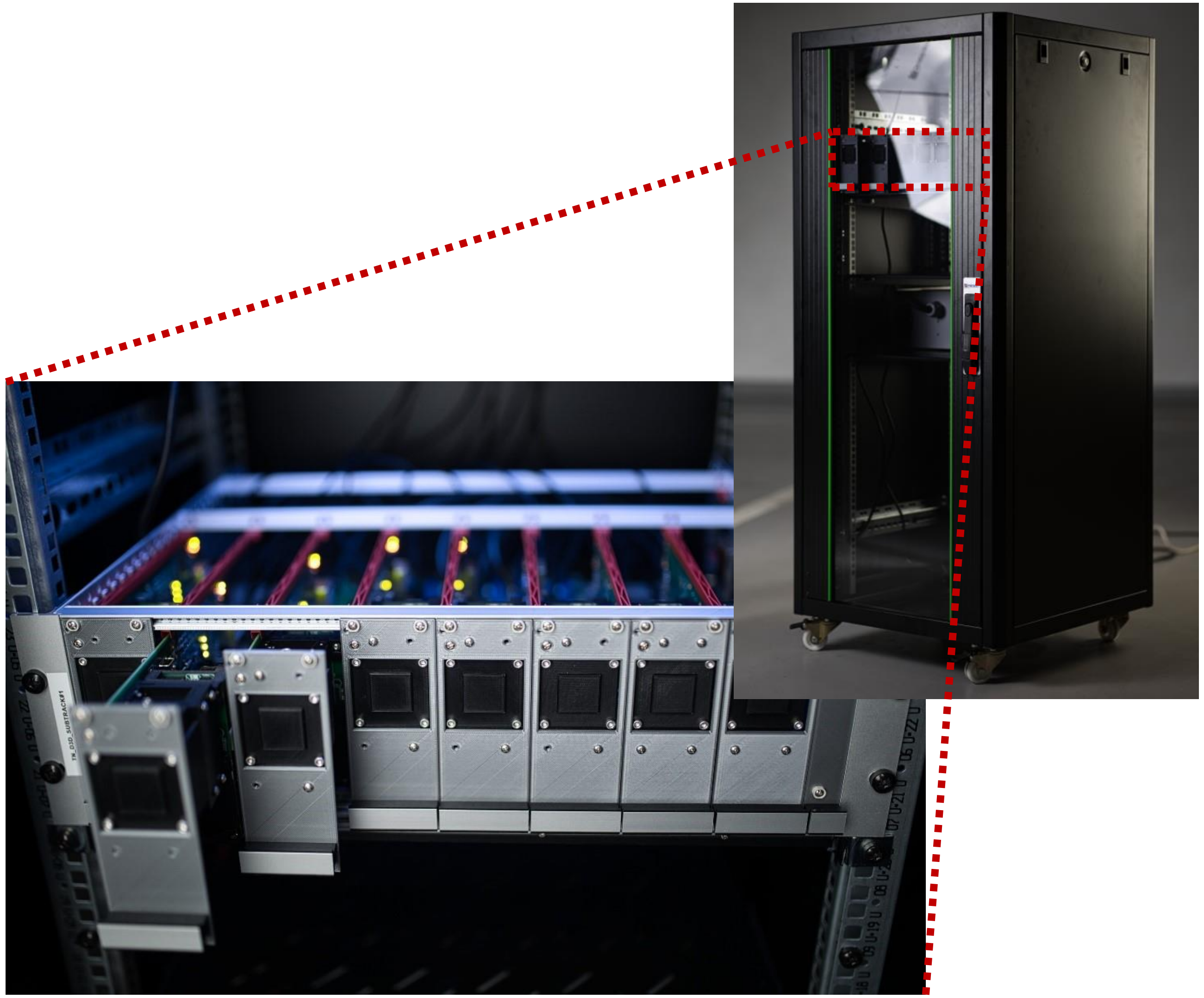
Project motivation

- According to World Health Organization (WHO) cancer is a leading cause of death worldwide, accounting for nearly 10 million deaths in 2020, or nearly one in six deaths
  - We need quick, efficient, reliable cancer therapy with as low as possible risk of developing long-term and late side effects
- The main goals of the project
  - Design and build a reconfigurable 3D detector for rapid and precise measurement of the radiation 3D dose distribution of therapeutic X-photons employing tissue-like active material
  - Improve individual treatment plans by developing new statistical tools and ML models for precise comparison of the delivered and planned doses

System overview

Scalable detection system

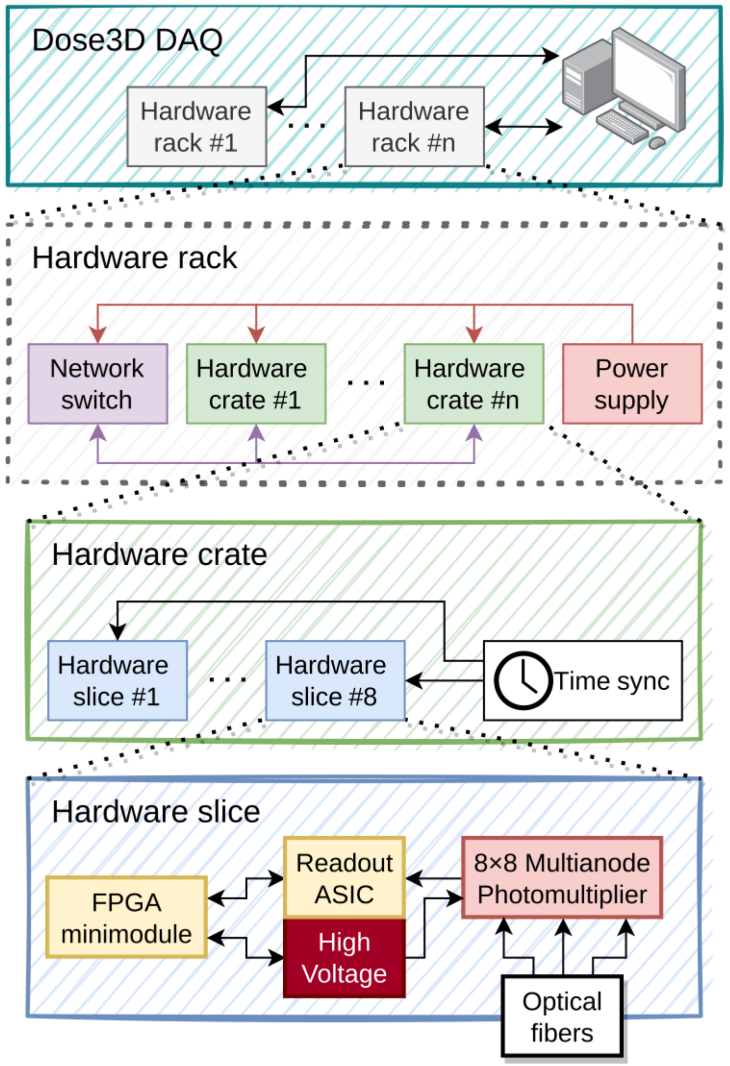
- Modular highly-scalable system
  - Rack mounted components
  - Fitted in standard 19’’ crates
  - Based on independent SLICEs
- SLICE – single readout unit
  - 64 channel – ASIC and PMT
  - Photon counting up to 20 MHz/channel
  - Signal amplitude with rate up to 30 kHz
  - Powering, calibration and monitoring included

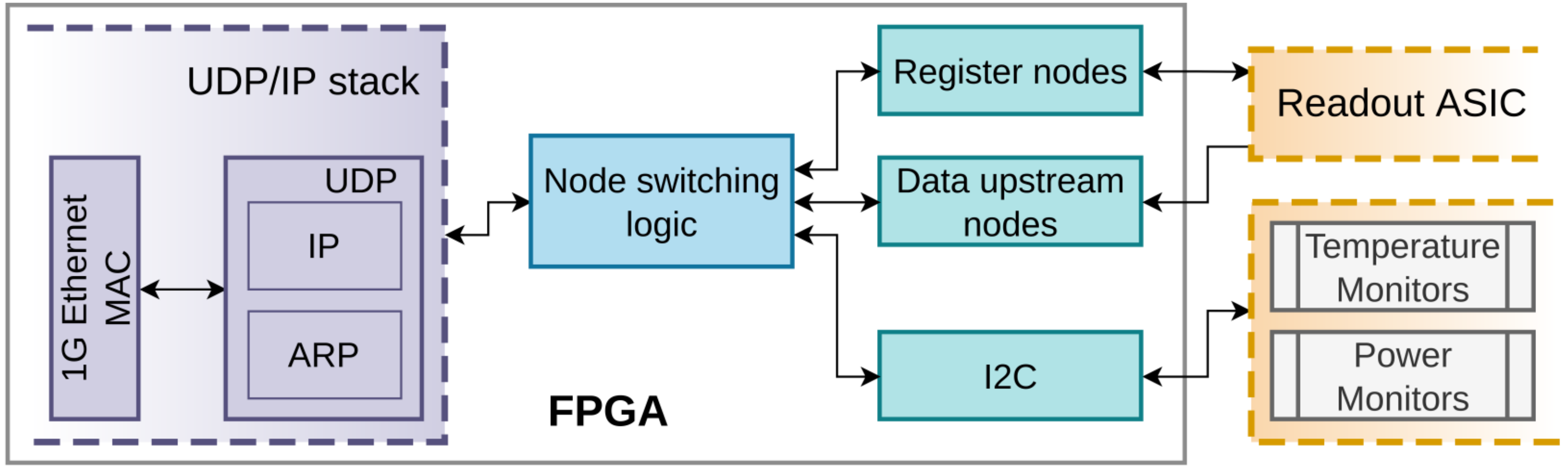


DAQ system

- Ethernet based communication
  - 1 Gbps throughput for single SLICE
  - Standard Ethernet IP solution
  - Modules interconnected using standard network switches – 10 Gbps
- Commercial components
  - FPGA mezzanine by Enclustra
    - Mars AX3
    - Standard SODIMM PCB format
  - ASIC by Weeroc – MAROC3A
    - 64-channel front-end ASIC for MaPMT
  - MaPMT by Hammamatsu
    - 64-channel H7546B
- Dedicate custom-made hardware system
  - Hosting FE ASIC and FPGA module
  - Providing HV for PMT and DC power for all components
  - Equipped with environment control units
  - Providing calibration circuitry
  - Patenting process in progress
- Mechanics and support
  - 3D printed custom-made components

DAQ schema





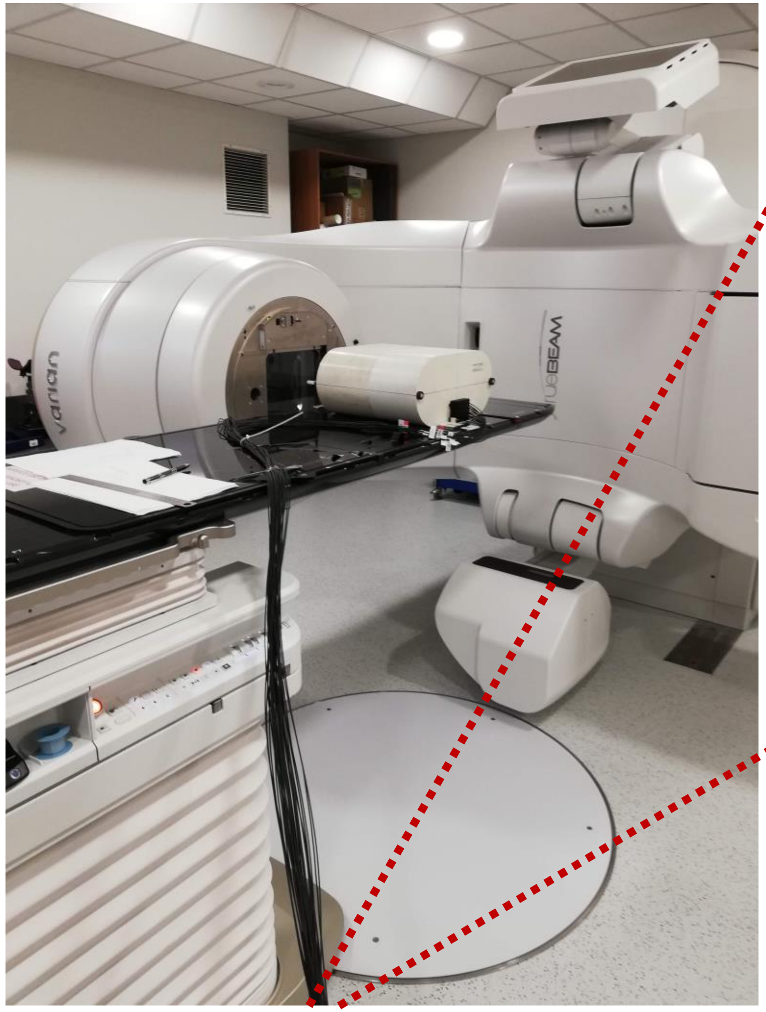
MARS AX3
https://www.enclustra.com/en/products/fpga-modules/mars-ax3/

MAROC3A
https://www.weeroc.com/products/photomultipliers-read-out/maroc-3a

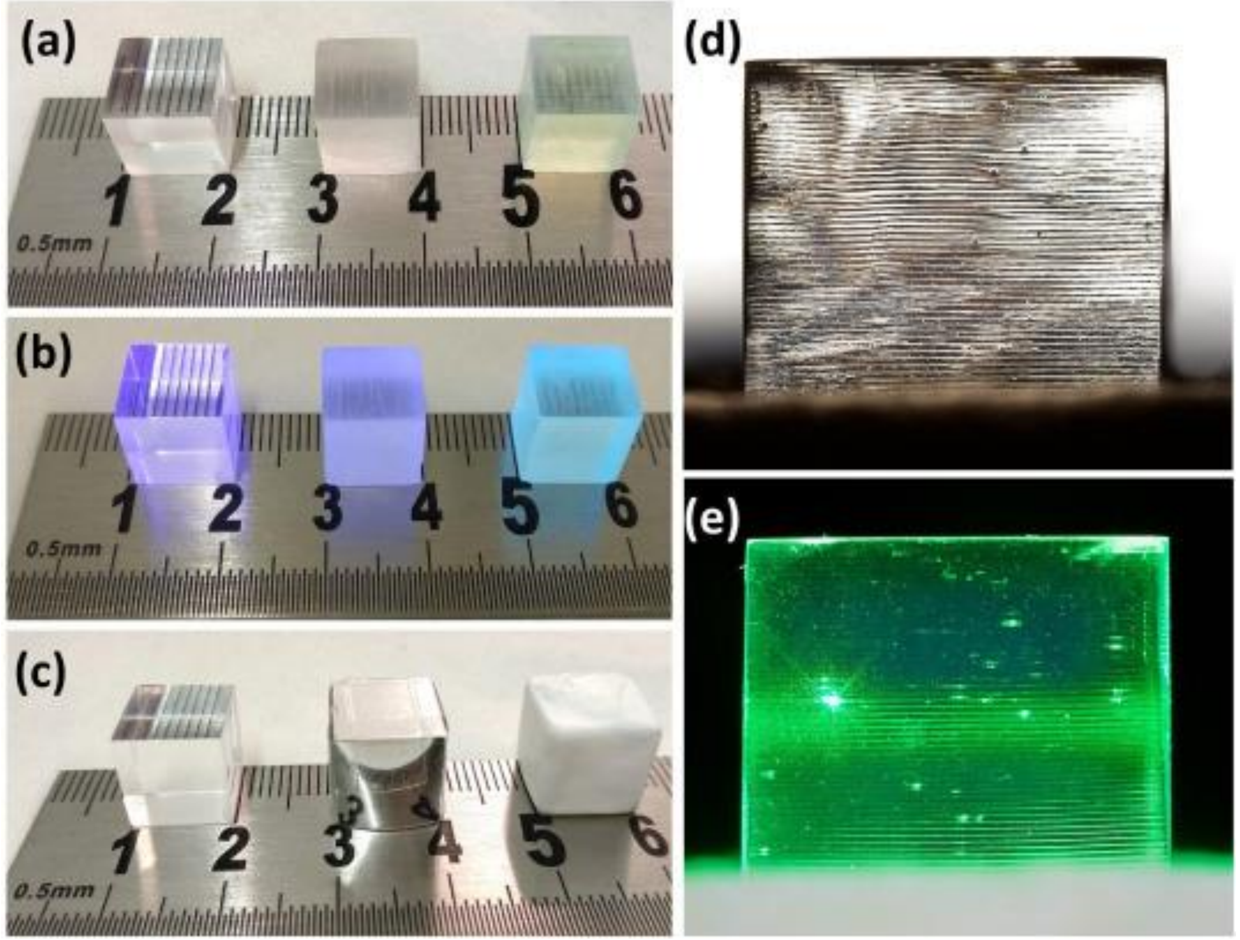
H7546B200
https://www.hamamatsu.com/eu/en/product/optical-sensors/pmt/pmt-assembly/metal-package-type/H7546B-200.html

Scintillation light readout

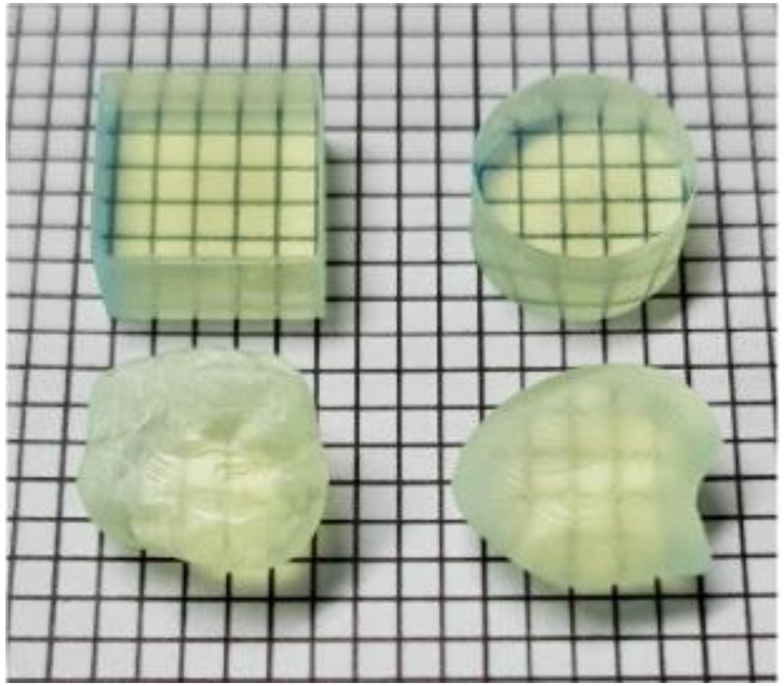
- Independent active components
  - Scintillating cubes with variable dimensions
- Fiber optic cables
  - Tunable connection to MaPMT
- Dedicated MaPMT coupling
  - Light tight 3D printed model developed @AGH
  - Configurable and easily handled
  - Patenting process in progress



Custom-made 3D printed scintillating cubes



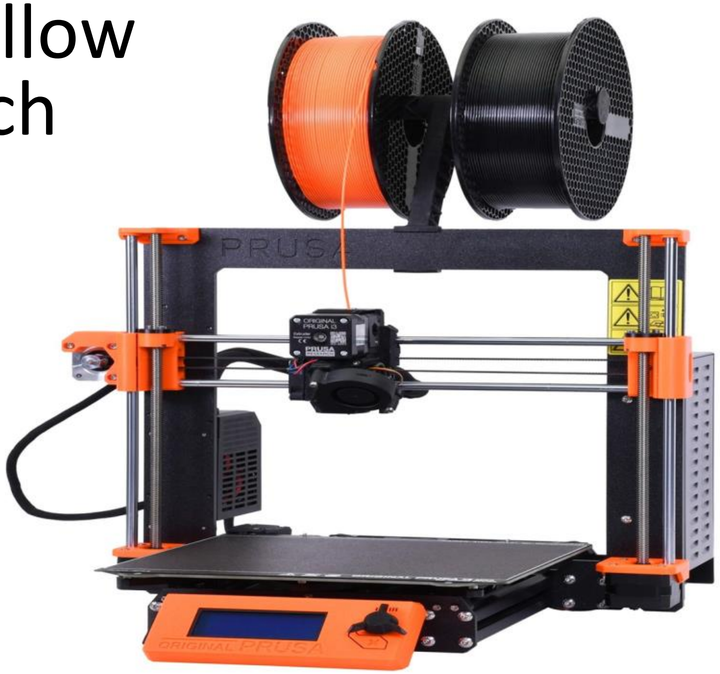
https://doi.org/10.1016/j.radmeas.2022.106864

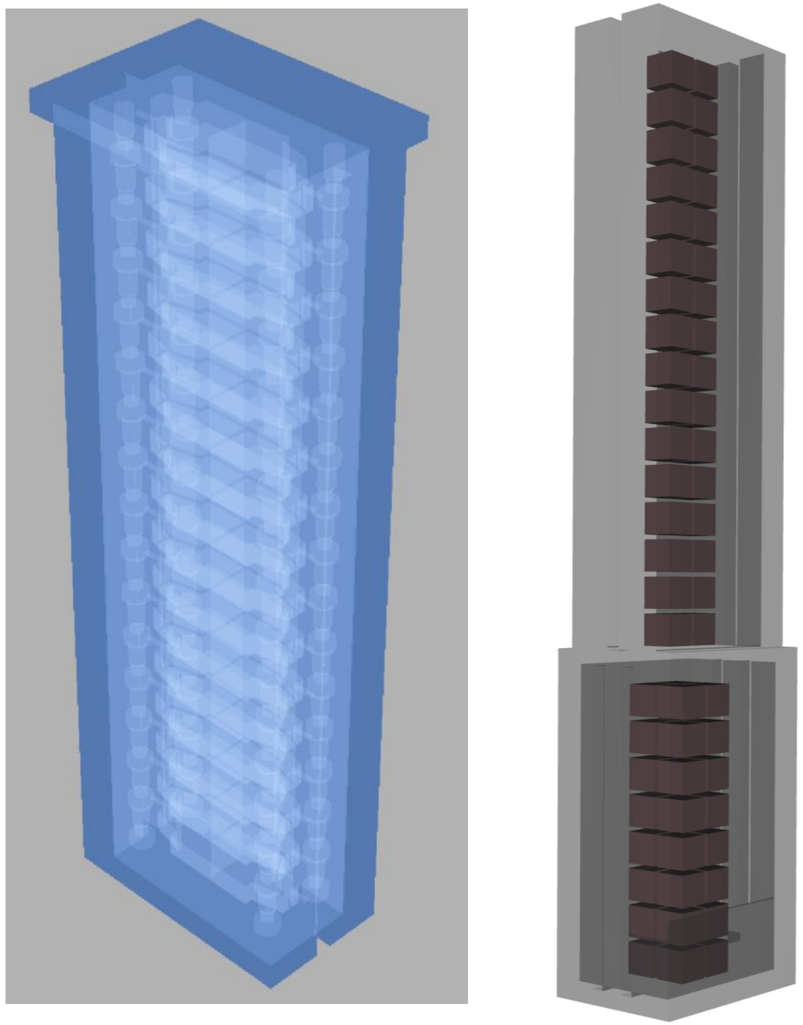


https://raymetrics.co.kr/customPrinted

Scalable and reconfigurable geometry

- Array of plastic scintillators
- Flexible phantom configurations are also possible
- The 3D-printed cases allow optical isolation for each cube
- Simple and fast (re-)configuration of the detector matrix to the required specification



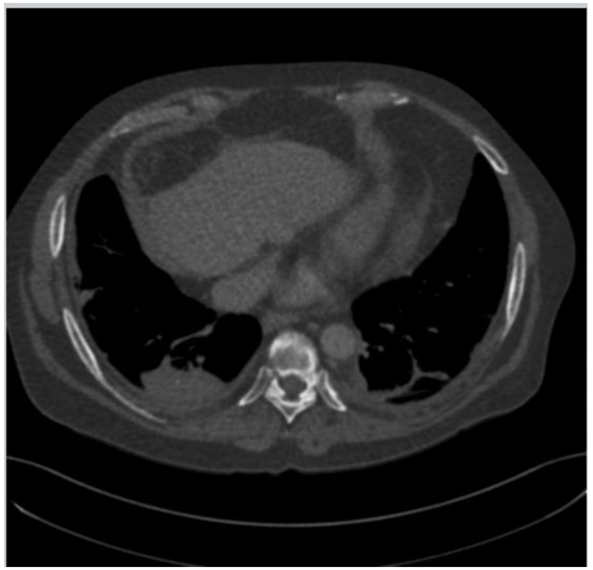


Software

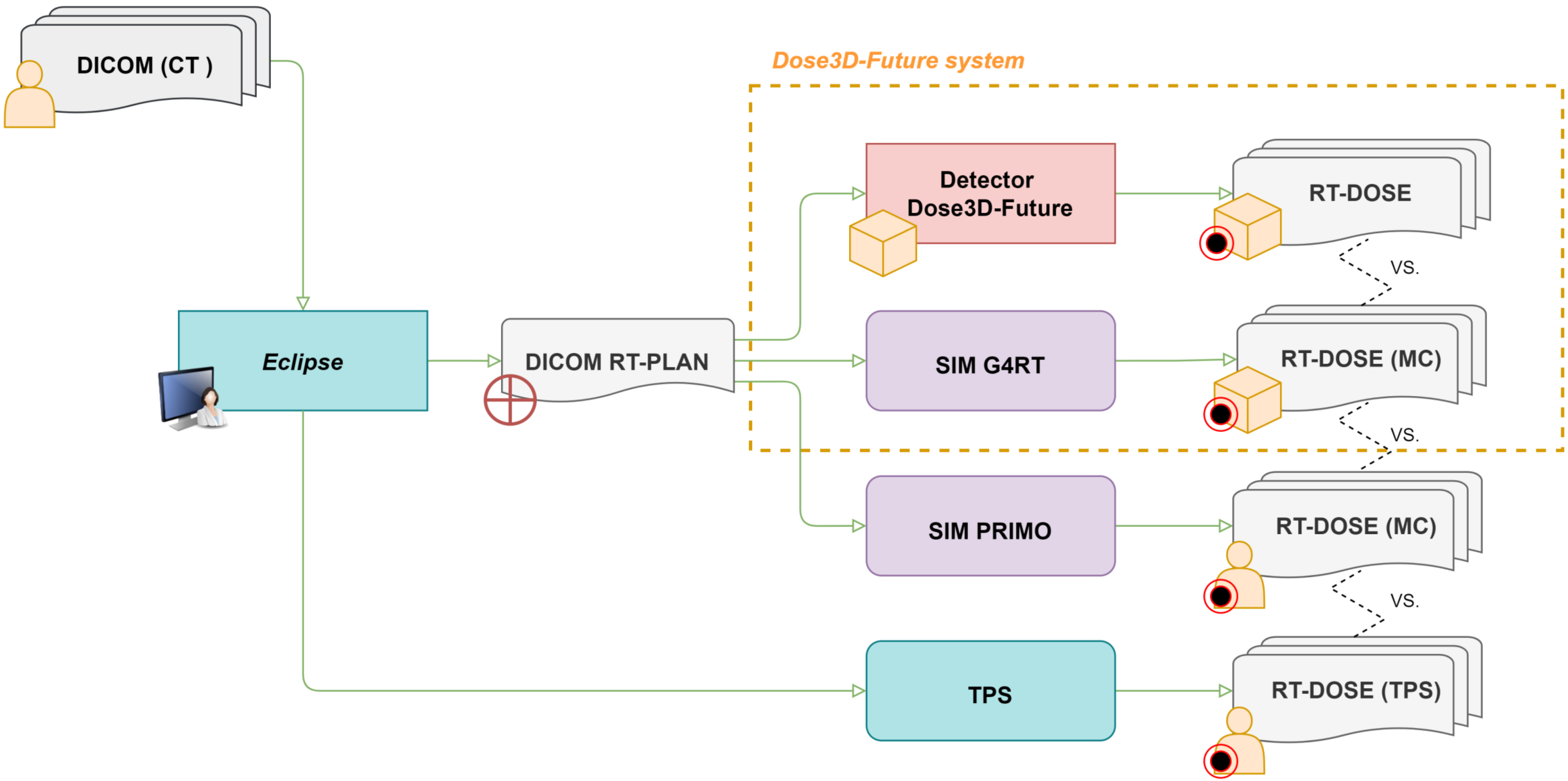
DICOM and HDF5 formats

- Digital Imaging and Communications in Medicine
  - Has been widely adopted by hospitals and the medical software industry
  - Standard way of data handling between devices and software
  - Variety of tools already exist
- Adopted by Dose3D-Future
  - High level software of simulated and reconstructed data

- Hierarchical Data Format (HDF)
  - HDF5 a truly hierarchical, filesystem-like data format
  - Store all raw data produced by Dose3D-Future system (DAQ)



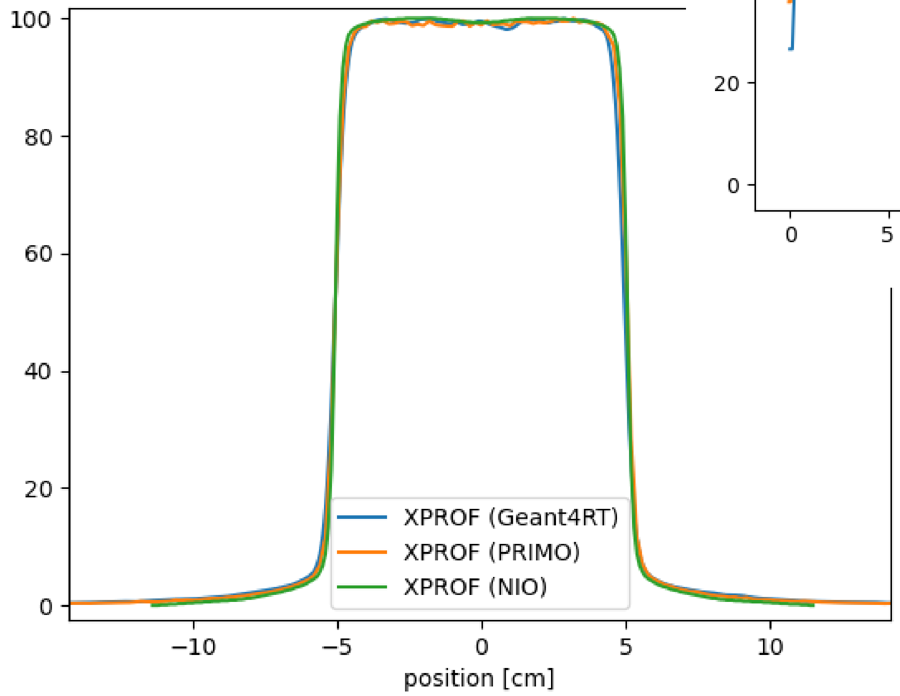
General overview of software

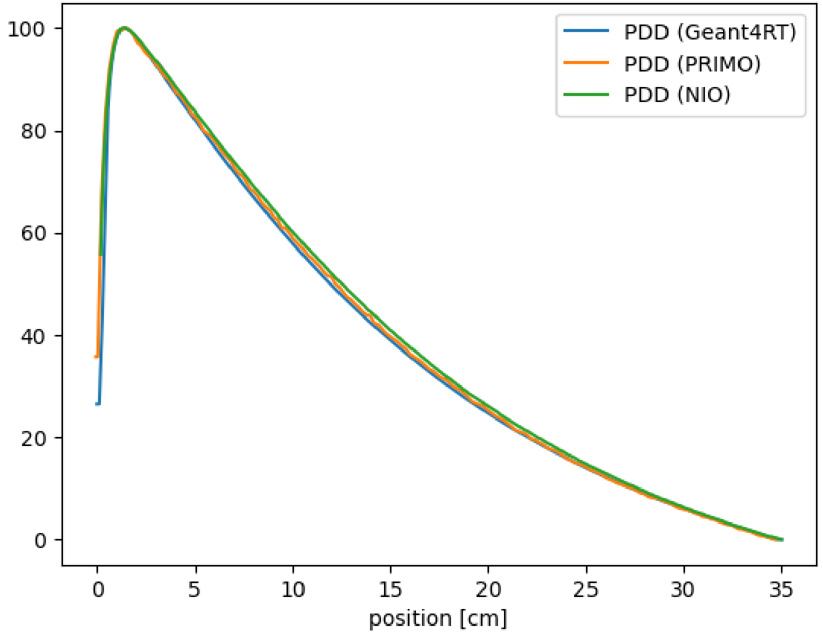


Geant4RT simulation platform

- Geant4 based simulator
  - Modular and dynamic detector/patient design
  - Handling geometric data from multiple sources in multiple formats
  - Support for DICOM-RT plan
  - Export geometry to DICOM-CT
  - Liniac machine beam model for Varian TrueBeam
  - Verified by measurements (NIO)

Beam profile

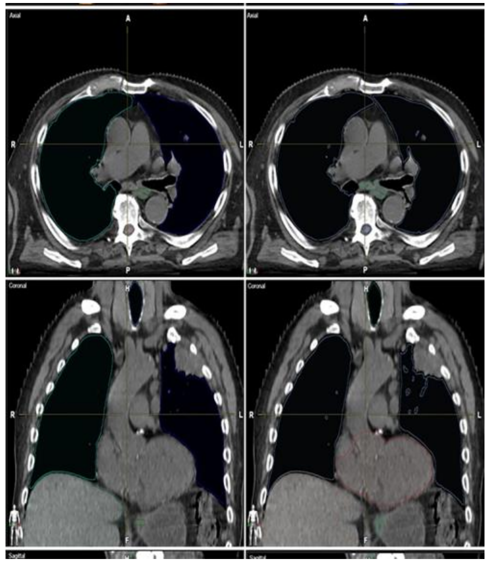




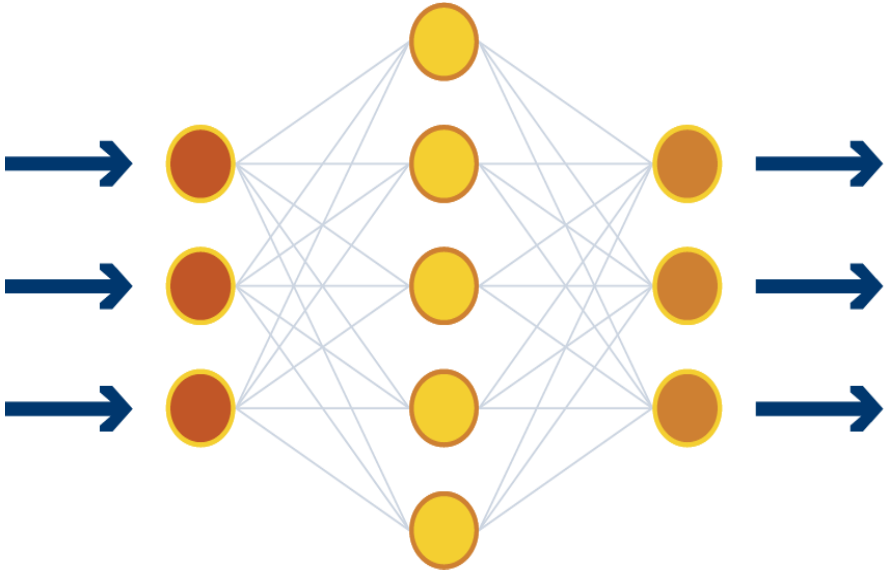
Dose depth profile

Machine learning activities

- Patient CT scans segmentation



Patient Data



Patient's Organs Geometry

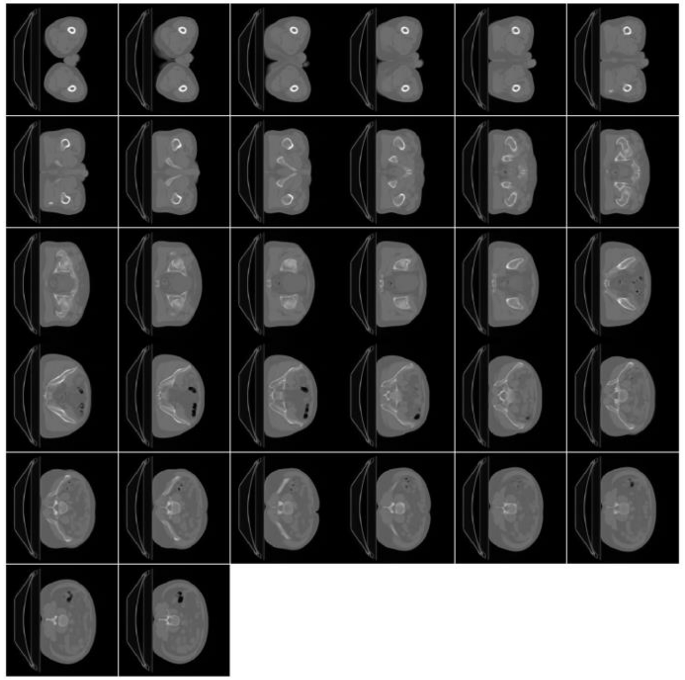
- Fully automatic segmentation tool based on Deep Learning models
  - Extract the volume patient's sensitive organs

https://doi.org/10.1016/j.nima.2022.167951

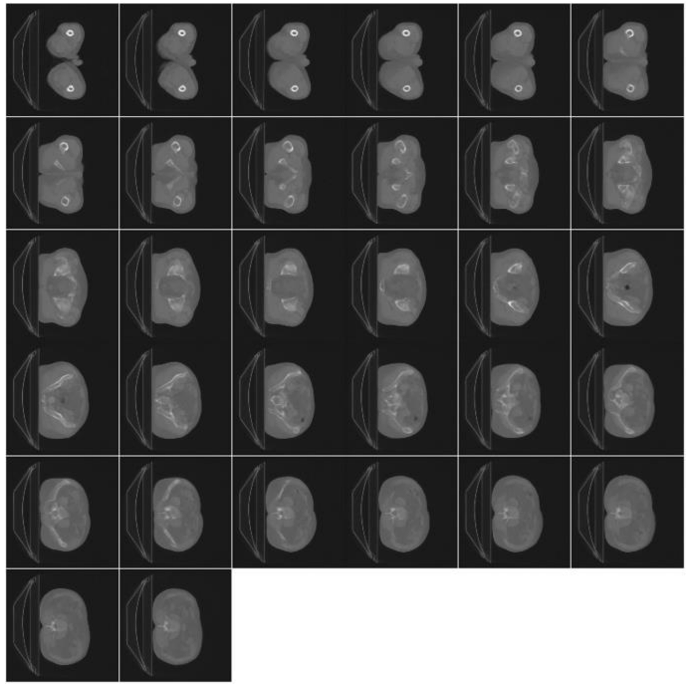
Patient data augmentation

- Artificial (generated) data are crucial
  - Provides fast and safe development (more data)
  - Allows for easy knowledge sharing
  - Ensure high level of security for very sensitive patient data

Original dataset

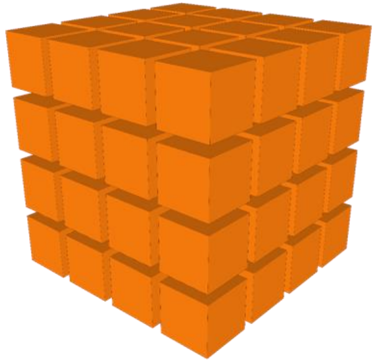


Generated dataset



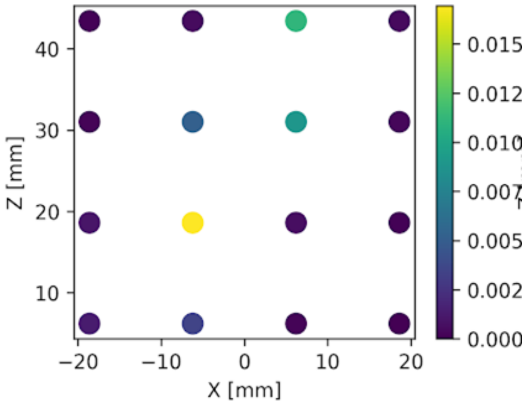
Up-scaling for measuring the spatial distribution of radiation dose

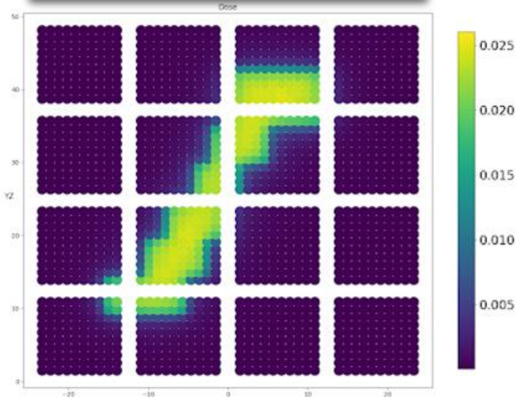
- The fine spatial resolution of the dose in patients is vital for
  - Delivering precise and effective treatment
  - Enhancing patient safety
  - Improving diagnostic image quality
- Deep Learning model for enhancing resolution
  - Up-scaling 3D results to the level of CT image



Input 4x4x4

Output 4x4x4 x 10x10x10

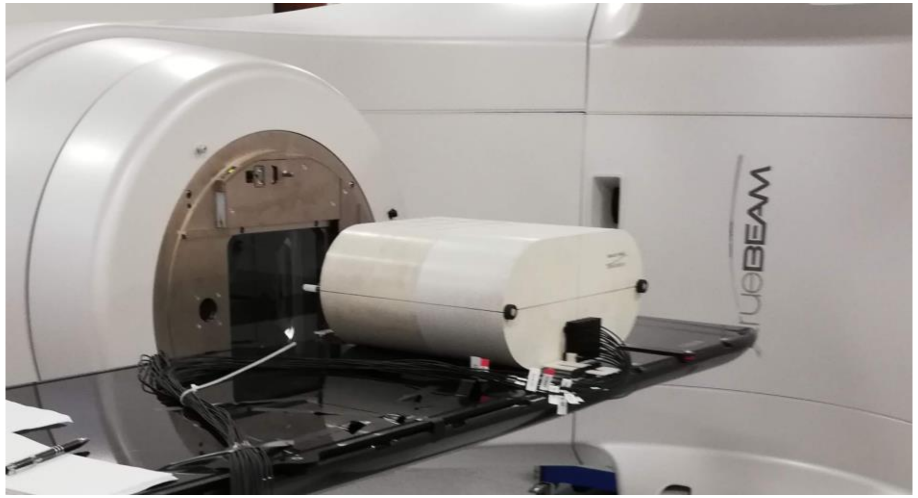




Based on: https://doi.org/10.48550/arXiv.1911.09428

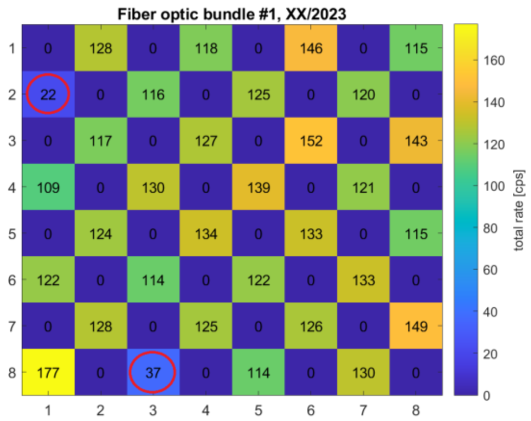
Test beam at cancer treatment plant

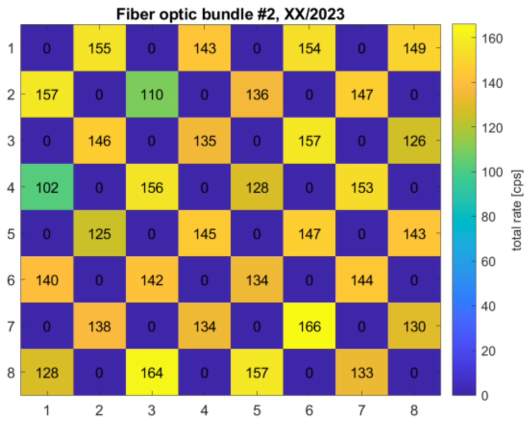
National Research Institute of Oncology

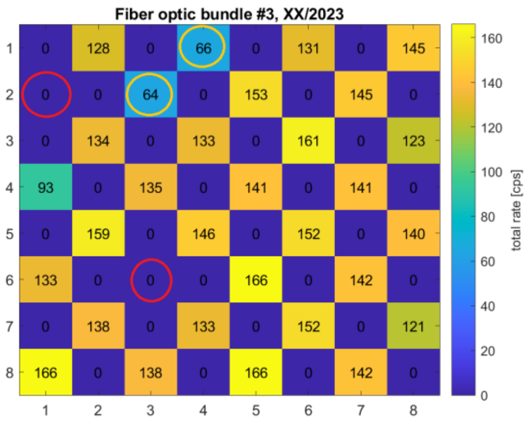


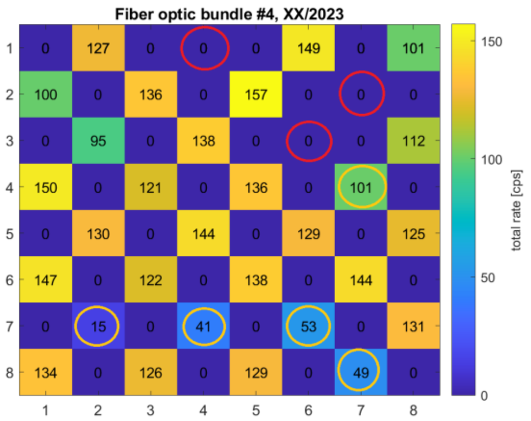
https://www.varian.com/products/radiotherapy/treatment-delivery/truebeam

Fibre optics with scintillator cubes

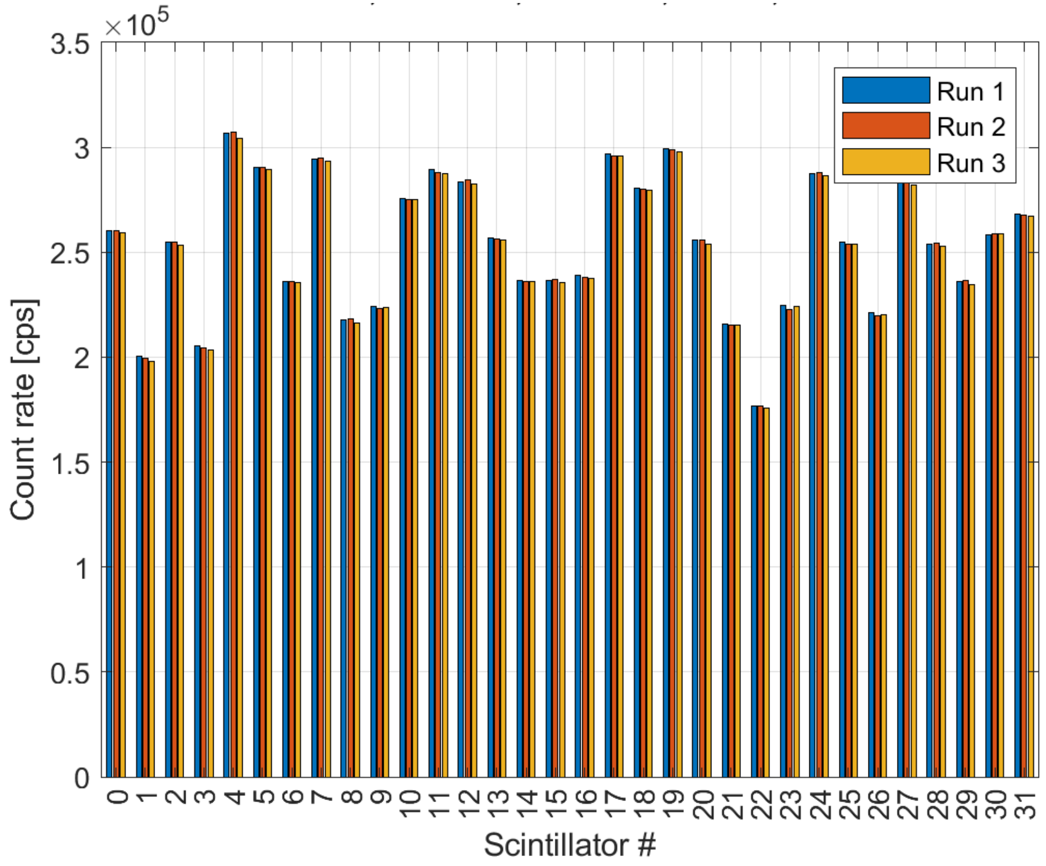






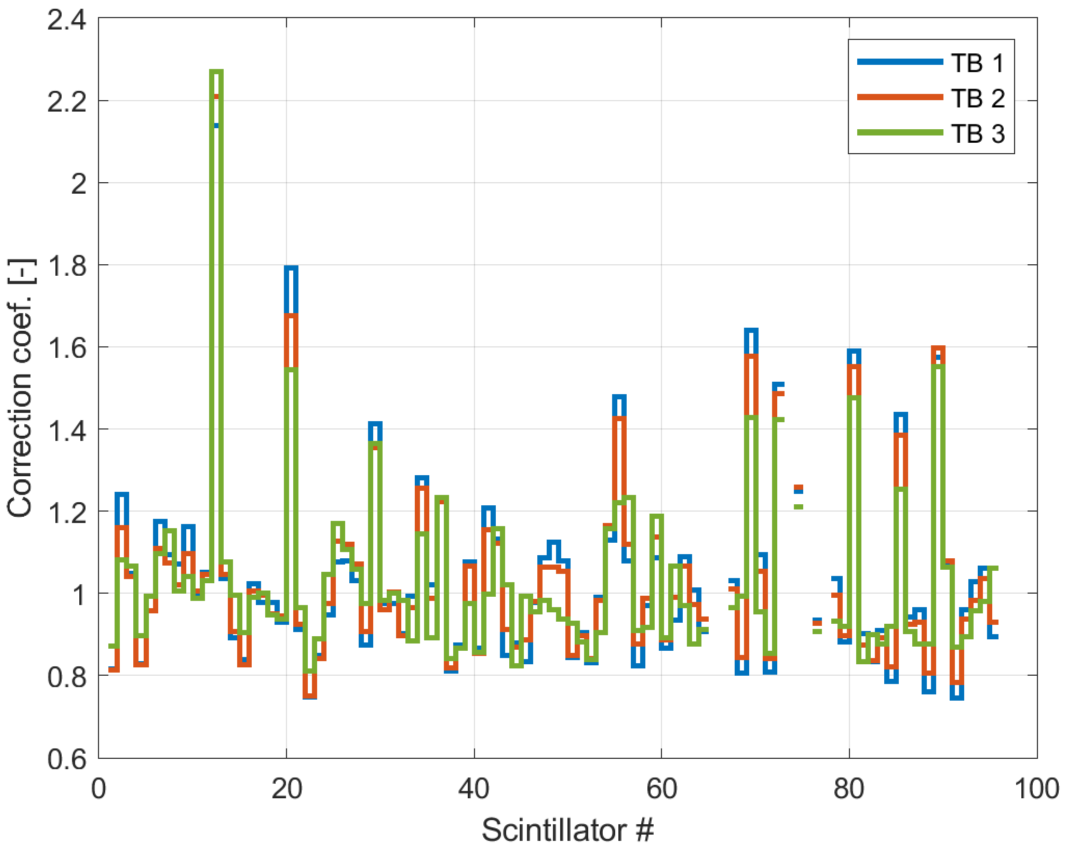


System calibration stability



Repeatability of dose measurement

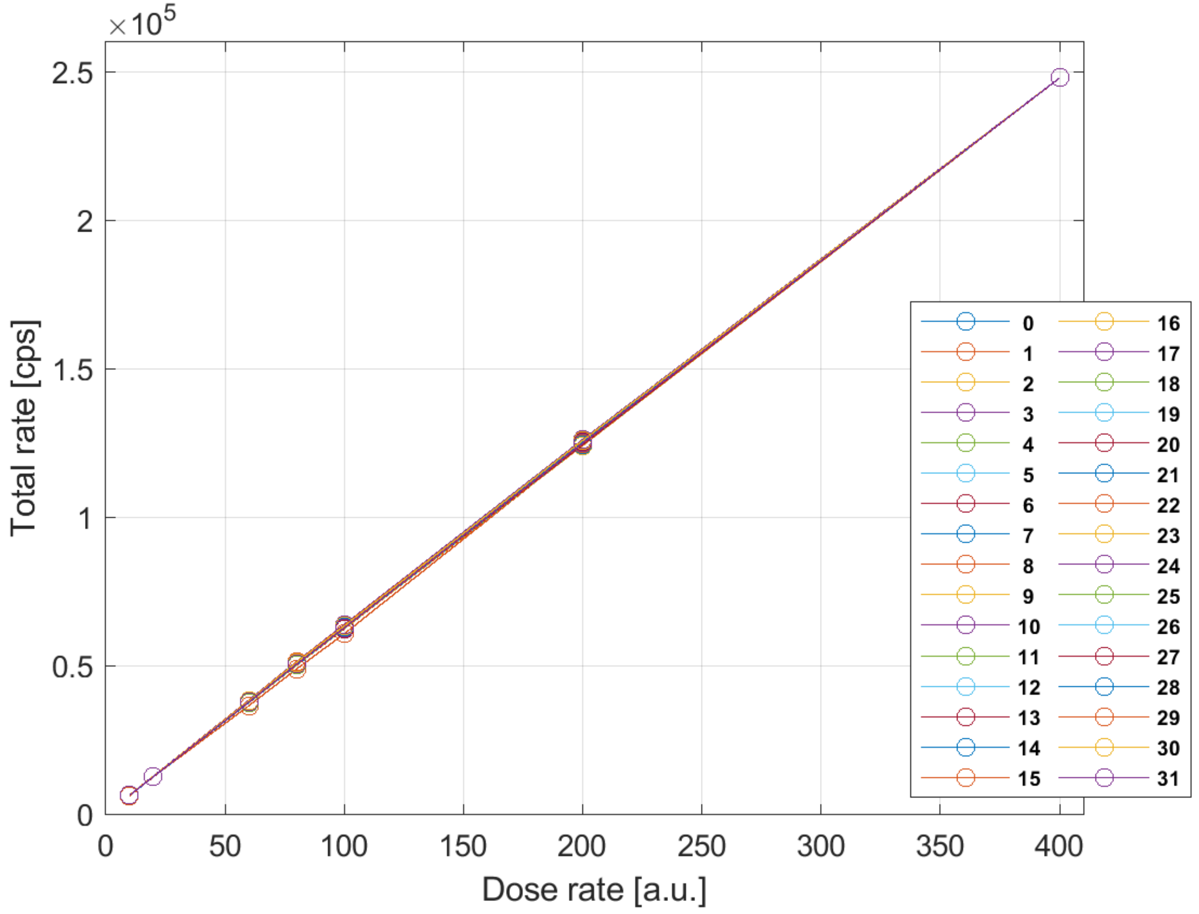
PRELIMINARY RESULTS



Calibration stability over time

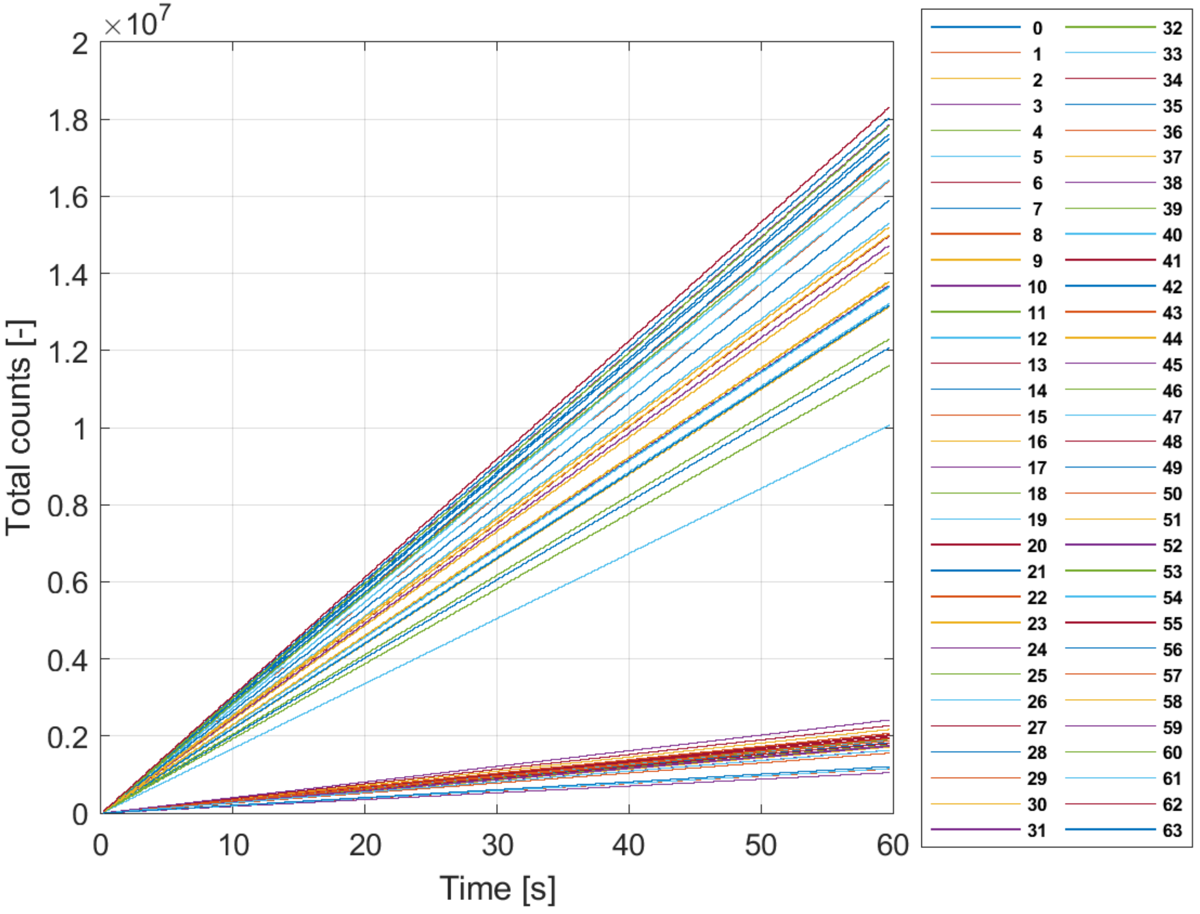
PRELIMINARY RESULTS

System linearity



Counting rate vs dose rate

PRELIMINARY RESULTS



Total counts vs time (delivered dose)

PRELIMINARY RESULTS

AGH

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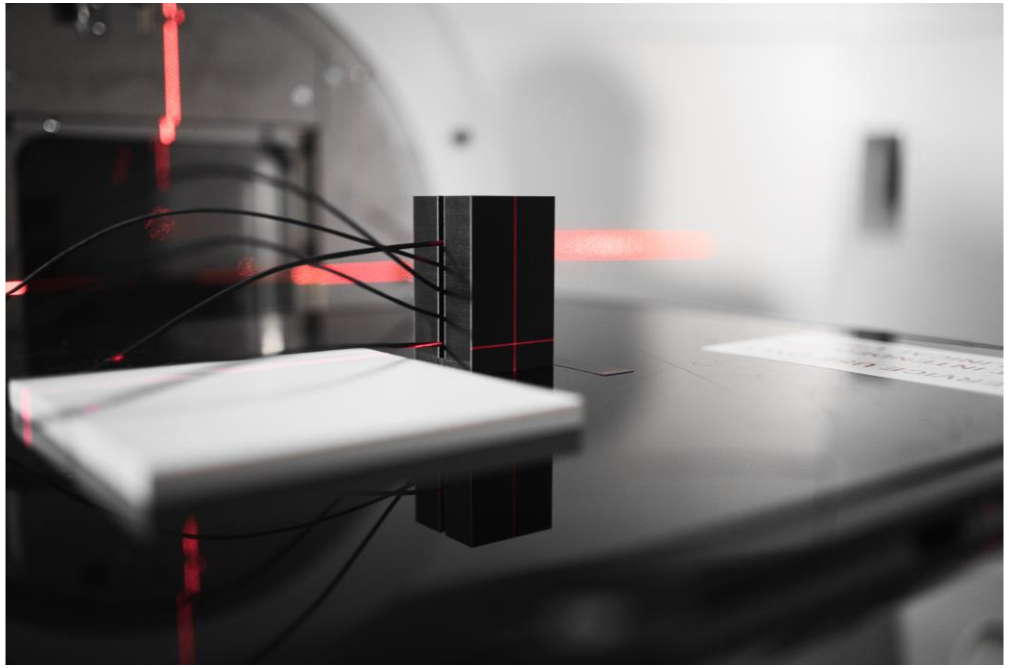
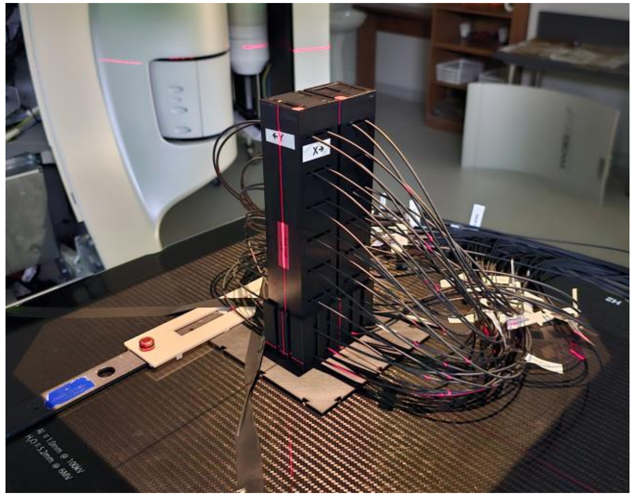
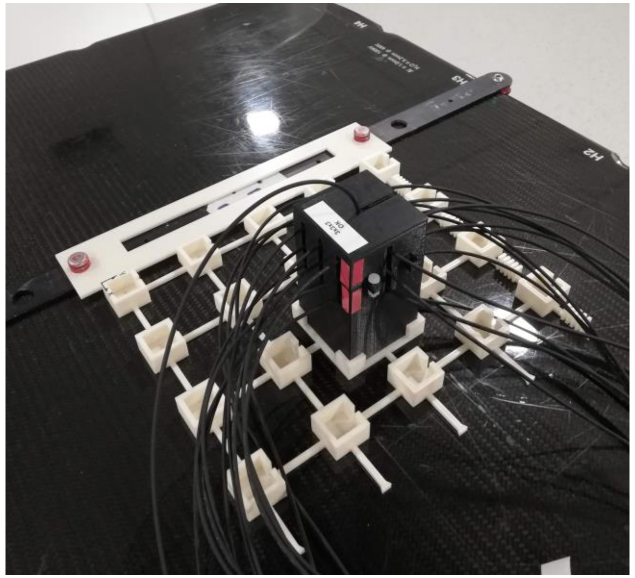
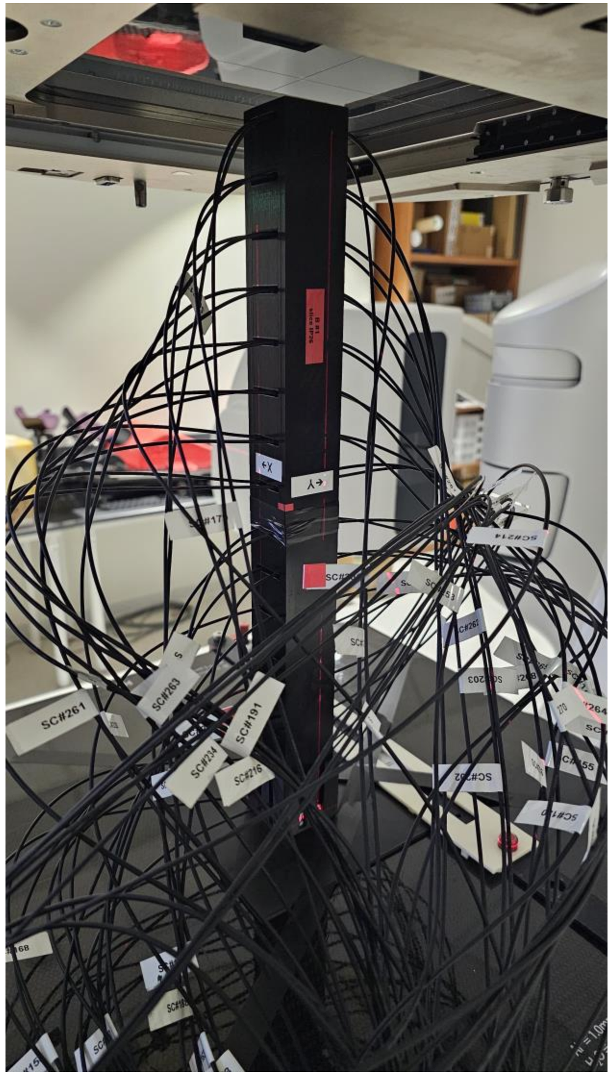
Reconfigurable phantoms

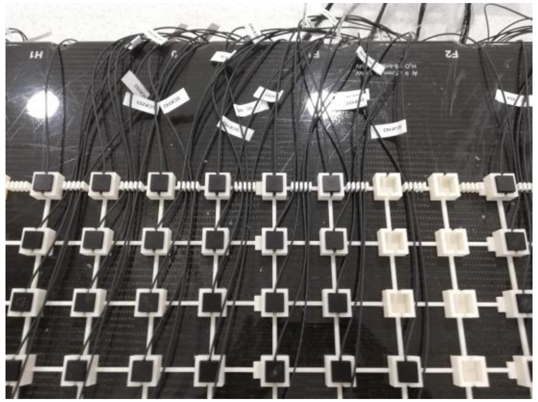






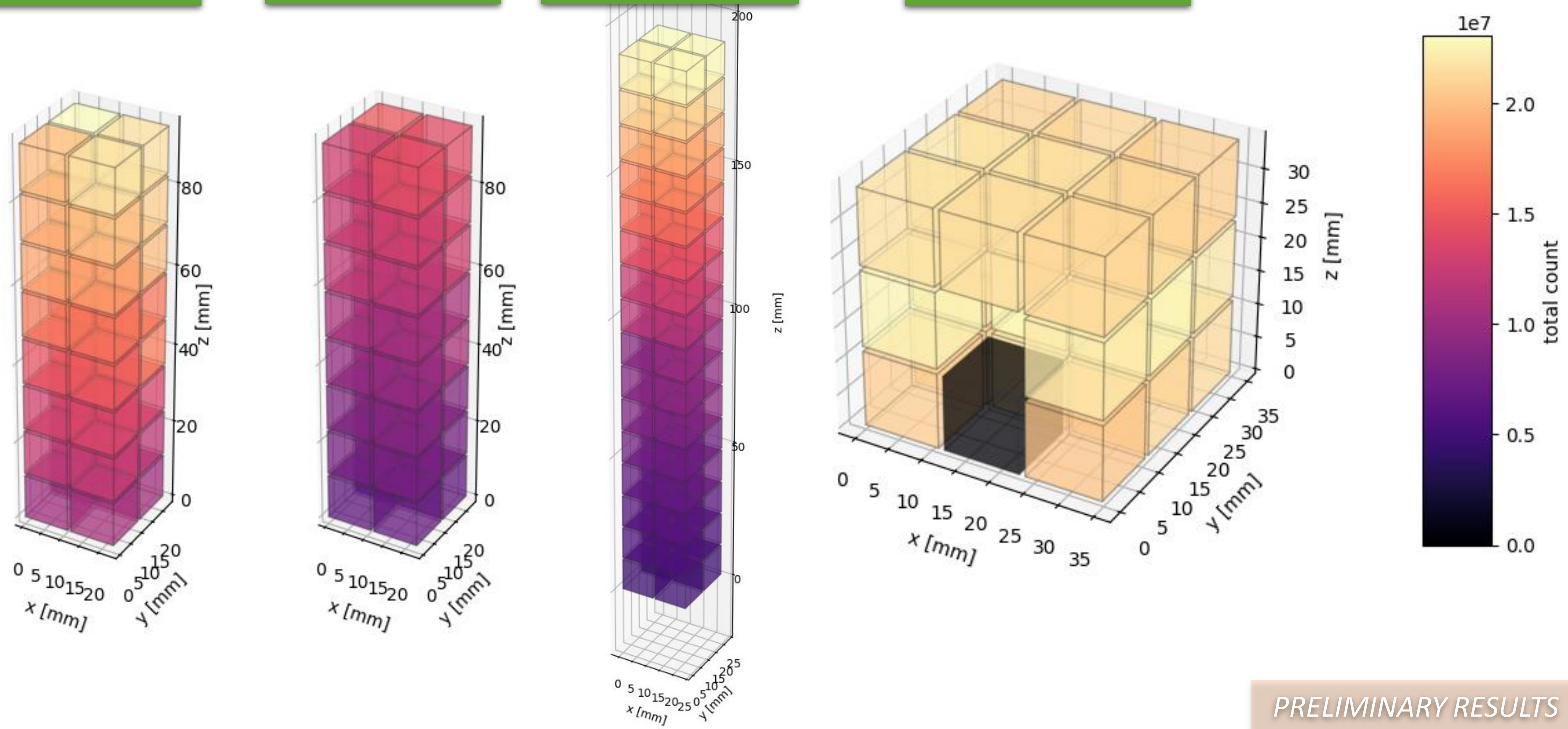


3D printed models



Phantom response visualisation

Tower 2x2x8 | Tower 2x2x8 | Tower 2x2x16 | Cube 3x3x3 (-1)

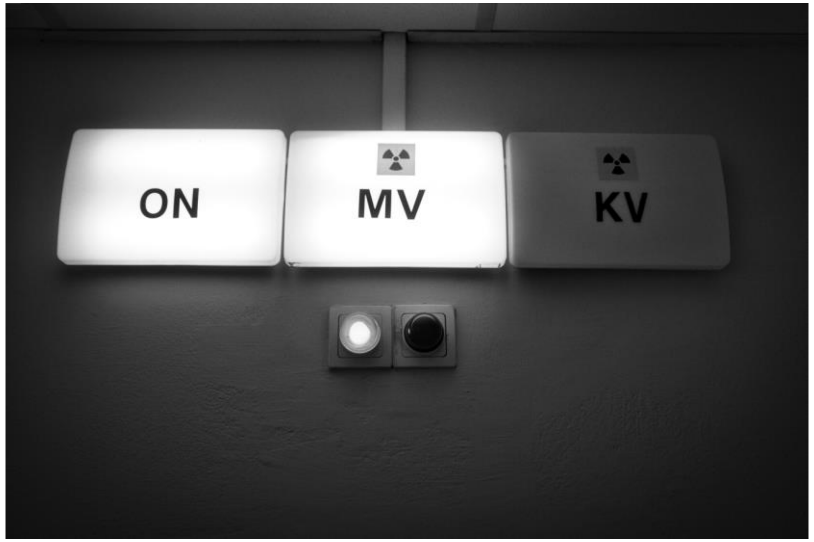


PRELIMINARY RESULTS

Conclusions & Future

Conclusions

- We successfully build a versatile detection system for radiation dose monitoring
  - Scalable hardware architecture to handle even thousands of readout channels
  - Equipped with re-configurable phantoms for 3D dose distribution measurement
  - Supported by sophisticated dedicated software capable of simulation and reconstruction of delivered dose in 3D
    - Enhanced by the ability to data augmentation and segmentation using ML and DL models



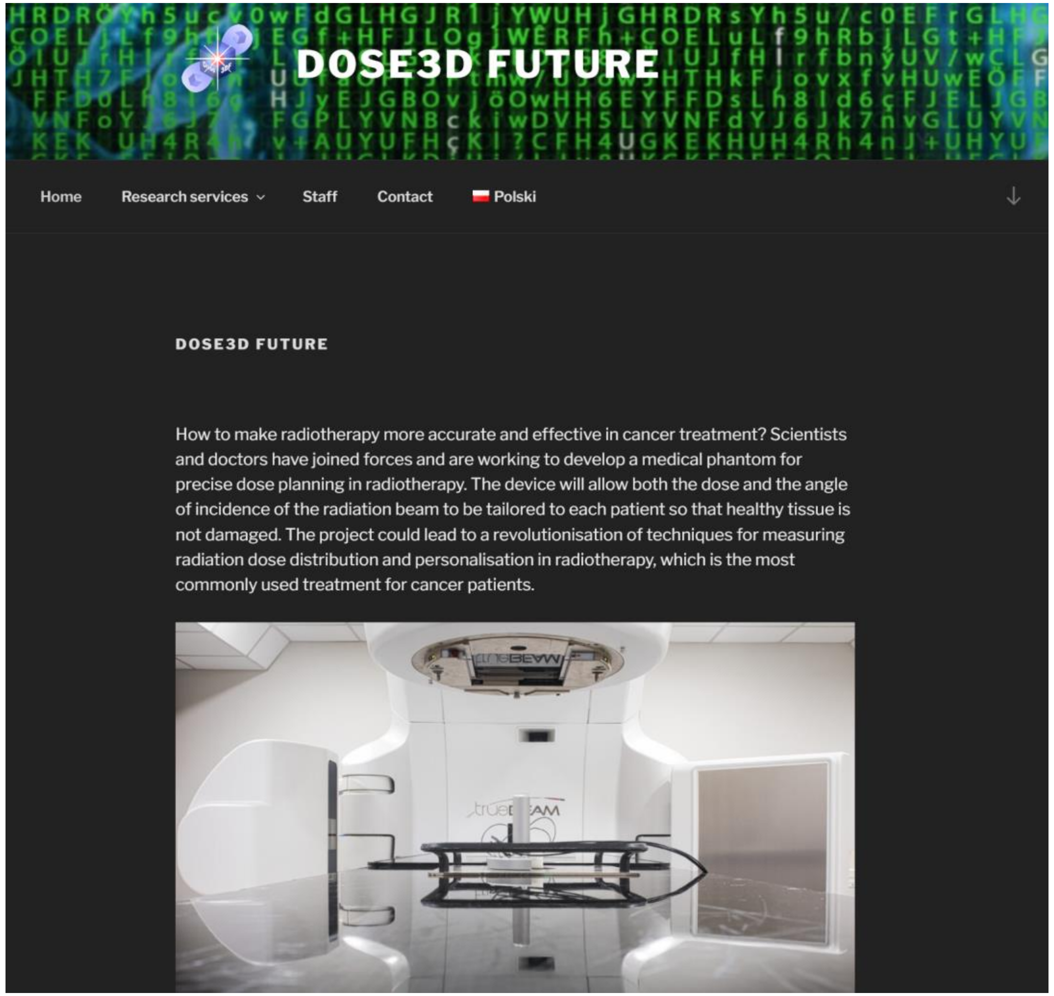
Plans for (near) future

- Broad test and optimization of light coupling to scintillation cubes
- Comprehensive tests in the treatment plant
  - Absolute dose measurements
  - Full system verification during actual radiation treatment plan application to the organ-like phantom
  - Background studies
- Long term stability tests of light yield generated by scintillation cubes
- Test and verification of a set of different scintillation plastic materials
- Software enhancements
  - System control
  - ML organ segmentation and data augmentation
  - Interface to/from commercially available treatment software

Acknowledgements

Dose3D-Future Collaboration

- AGH University of Krakow
  - Faculty of Physics and Applied Computer Science
    - Department of Interactions and Detection Techniques (KOiDC) AGH
- Maria Sklodowska-Curie National Research Institute of Oncology Krakow Branch
- Foundation for Polish Science
  - Continuation of grant no.: POIR.04.04.00-00-15E5/18



https://dose3d-future.fis.agh.edu.pl/

Our team (almost complete)

Thank you

Q&A

Backup slides

Abstract

- According to World Health Organization (WHO) cancer is a leading cause of death worldwide, accounting for nearly 10 million deaths in 2020, or nearly one in six deaths. Each year, an estimated half a million children and adolescents develop cancer. A correct cancer diagnosis is essential for appropriate and effective treatment. Often treatment includes radiotherapy, especially when other options like surgery are limited due to the cancer type or location of the tumor. Therefore under a research project “A reconfigurable detector for measuring the spatial distribution of radiation dose for applications in the preparation of individual patient treatment plans” we developed a scalable detection system for evaluation of the dose distributions in 3D phantom during the preparation of the treatment plans under the photon radiotherapy procedure. Having a fast, efficient, and safe treatment is essential for every patient. Therefore, the development of a system capable of monitoring the real-time dose deposition in 3D can significantly improve the procedure, resulting in safer and faster treatment. This, in turn, enables hospitals to assist more patients effectively.

- The system consists of a configurable 3D phantom that is based on tissue-equivalent printed scintillator cubes. It also includes a dedicated data acquisition (DAQ) system. The phantom can be fully customized to allow for setting arbitrary 3D configurations, with a granularity of 1 cm3 (possibly shrunken to 0.125 cm3). The measurement system is based on multichannel photomultiplier tubes, which are readout by a dedicated application-specific integrated circuit (ASIC). This ASIC is controlled by a field programmable gate array (FPGA) and managed by specialized software. During the conference, we will present the design and performance of the system, along with the results obtained during test-beams in the treatment plant using a therapeutic accelerator.