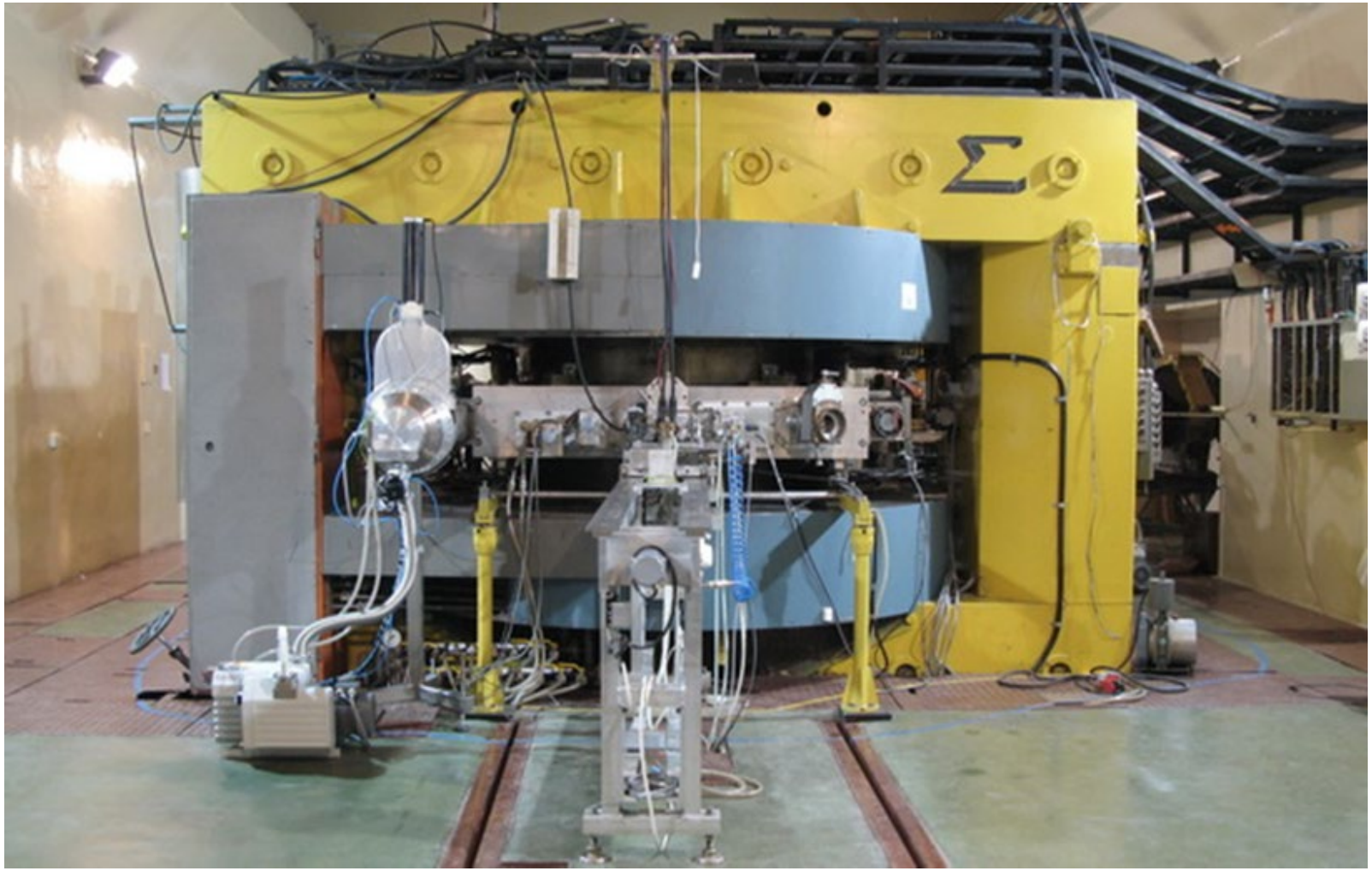
The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences, (IFJ PAN)

Research at AIC-144 Cyclotron

J. Swakoń

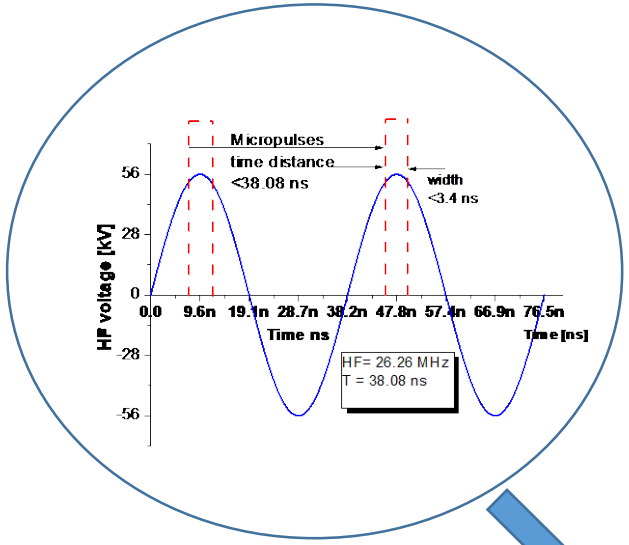
Department of Radiation Research
and Proton Radiotherapy (NZ62)
e-mail: jan.swakon@ifj.edu.pl

AIC-144 isochronous cyclotron



It has been used in research since 2006

Proton beam structure of AIC-144 cyclotron



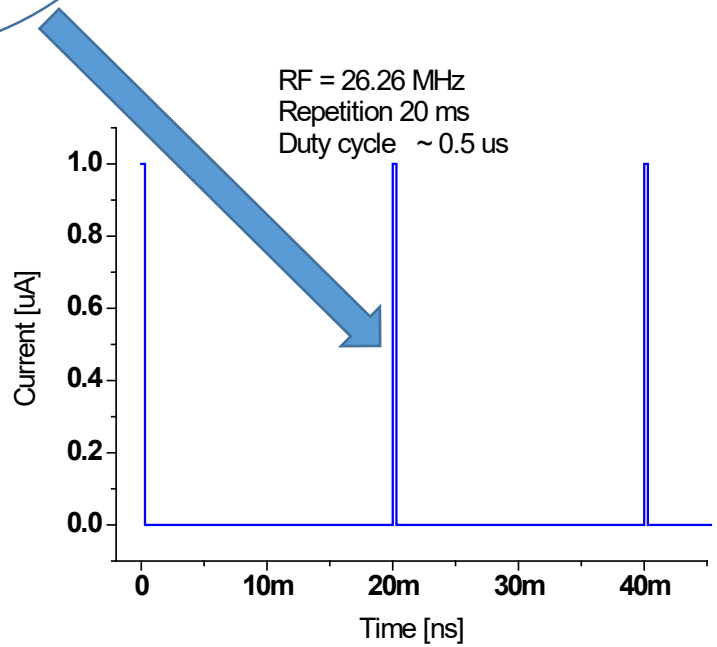
Energy 60 MeV

RF 26.26 MHz

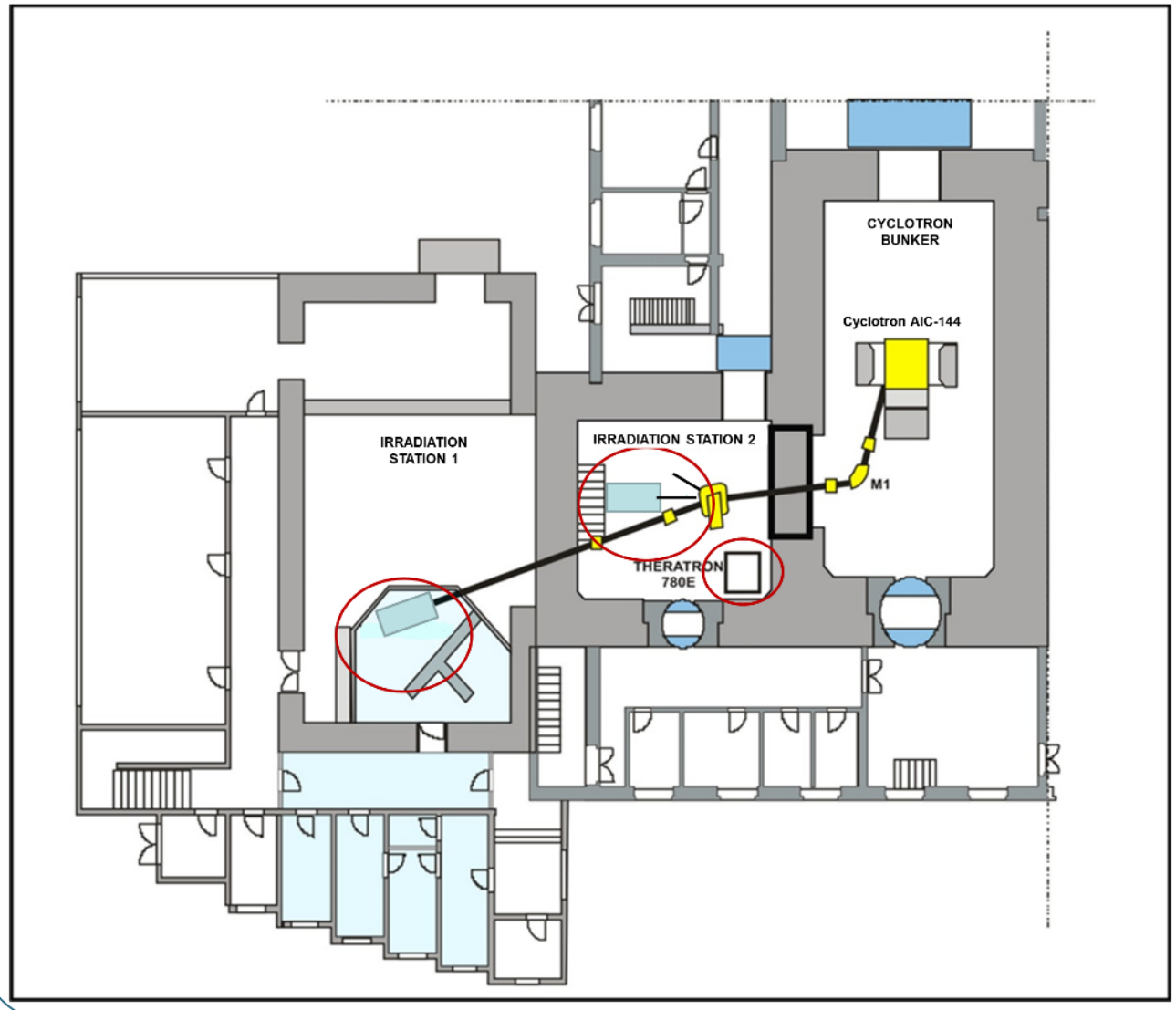
Beam macro structure 50 Hz,

Macro pulse length 0.5 ms,

Beam current 80 nA (110nA)

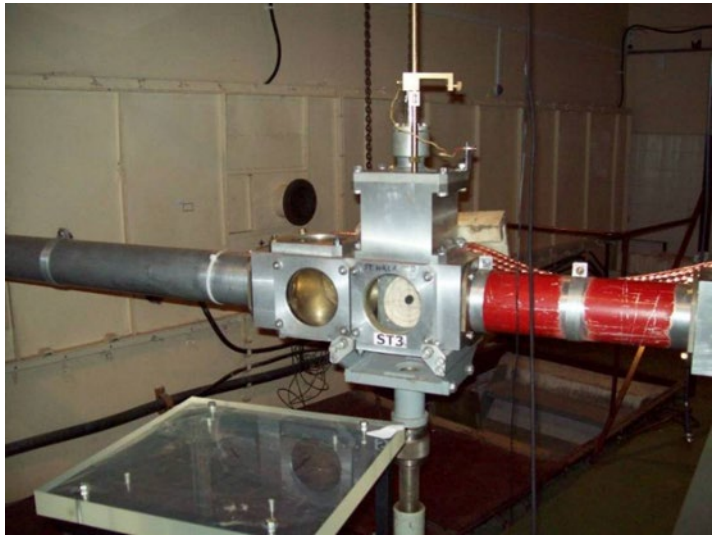


AIC-144 cyclotron facility





Beam lines

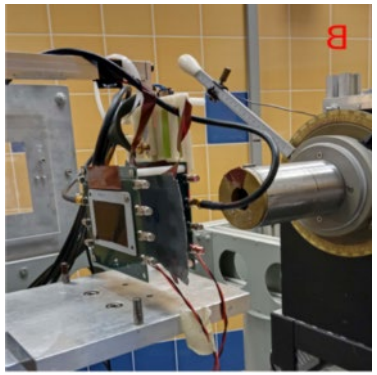


Scattering foil *(tantalum 25um)*

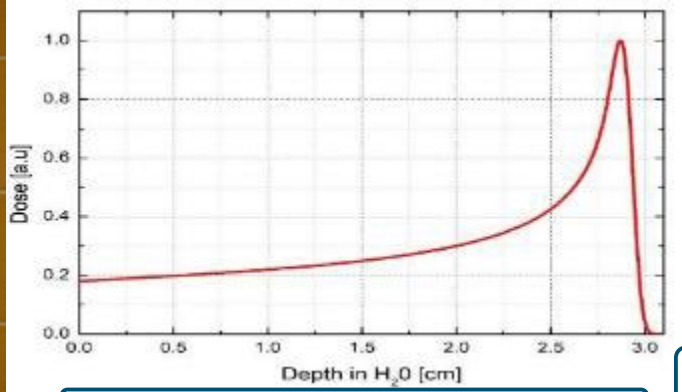
Irradiation station 1



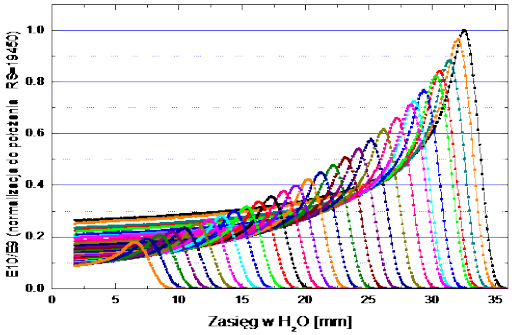
Beam parameters:
Energy: 10 - 58 MeV;
Dose rate 0,001 – 1 Gy/s;
Flux 5e5-1e9 p/cm2s;
Max dose < 1kGy;



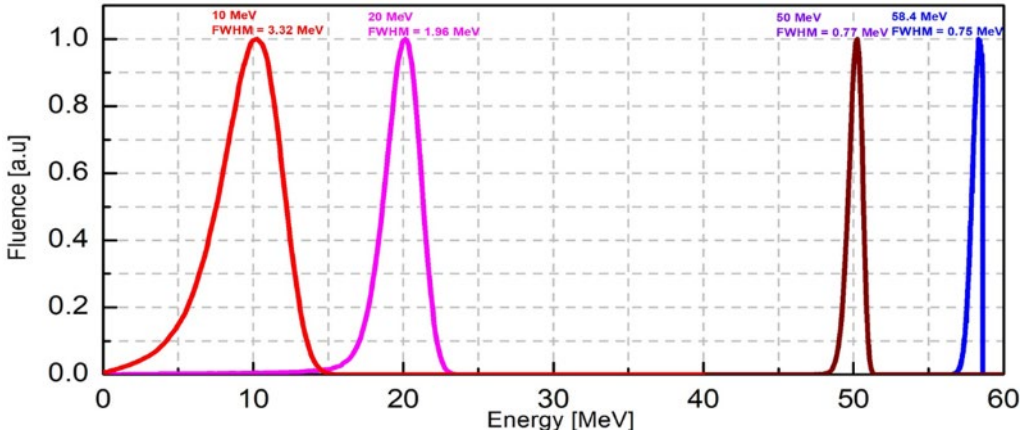
Irradiated sample



Dose depth distribution

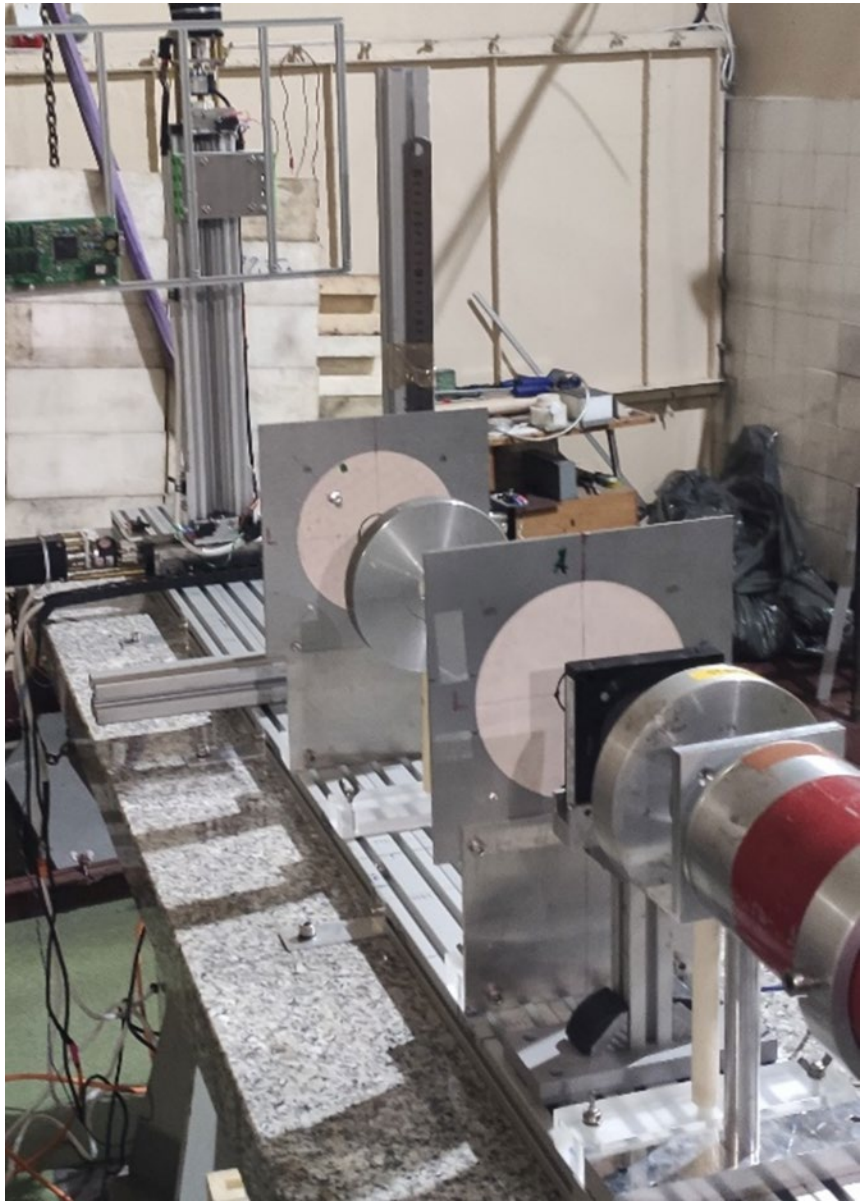


Dose depth distribution for different energies

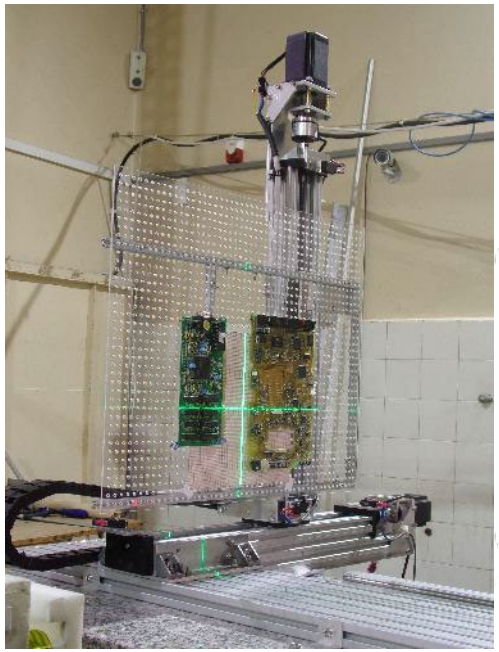


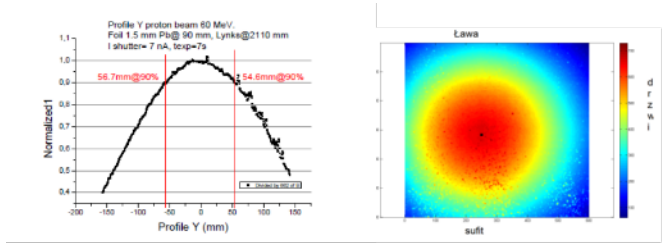
Fluence distributions after degradation

Irradiation station 2

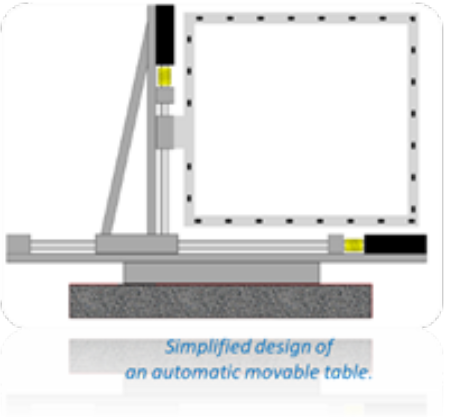


Proton Beam parameters:
Energy: 10 - 60 MeV;
Flux 1e6-1e13 p/cm²s;
Single spot diameter – up to 12 cm;

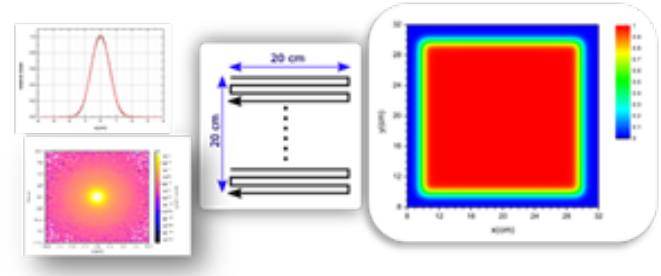




IBA Lyn XPT beam profile measurements



Simplified design of an automatic movable table.



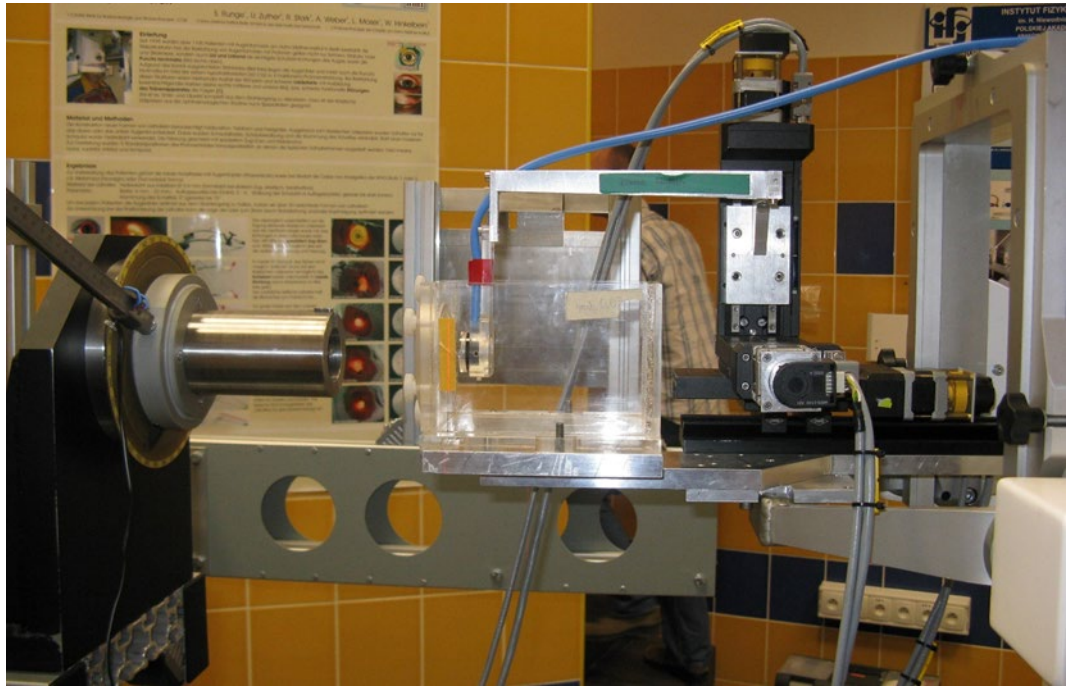
Simulation of radiation field with moving table:
a) 2D single beam dose distribution,
b) example of moving table scanning trajectory,
c) simulation of dose distribution with moving table

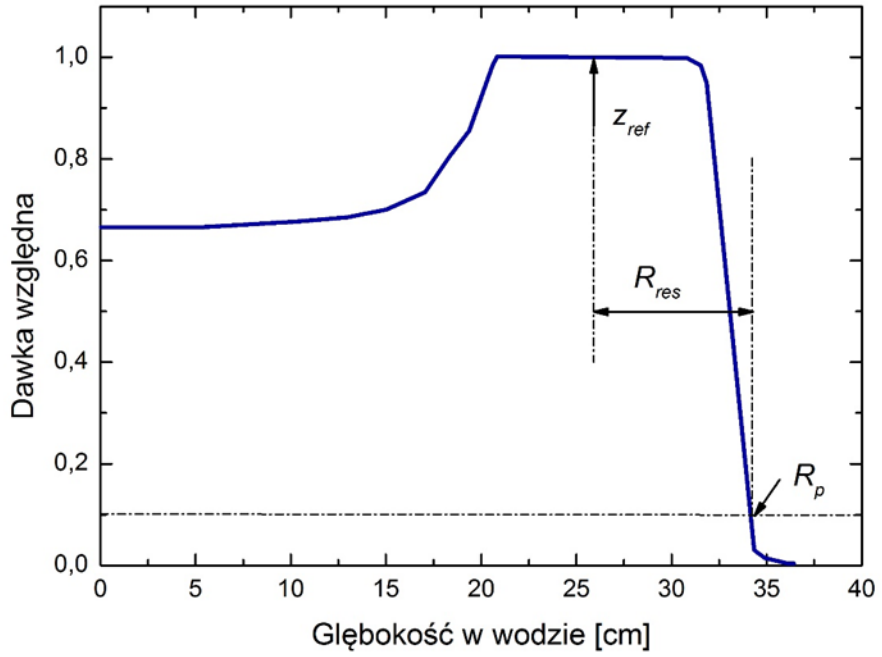
The automatic, remote controlled 2D moving table has been constructed to enable moving the probes perpendicular to beam's axis.

Reference dosimetry

Proton beam reference dosimetry based on the recommendations of the IAEA TRS-398 Code of Practice protocol

dose measurement with ionization chambers calibrated in the Co-60 radiation field, dose measurement performed in a water phantom





$$D_{w,Q} = M_Q \cdot N_{D,wQ_0} \cdot k_{Q,Q_0}$$

Applied dosimetry methods

Active methods:

Dose determination

- Ionization chambers (PTW Markus IC) with reference class electrometers
- Faraday cup with Keithley 6517A electrometer

Spatial dose distribution

- ProBImS active system equipped with thin plastic scintillator and CCD camera

Dose determination and beam structure measurements

- RL/OSL PORTOS dosimetry system with LiF:Mg,Cu,P (MCP-N) crystal

Passive methods:

Dose determination/spatial dose distribution

- Thermoluminescent detectors
- Alanine pellets

- 2D TLD foils
- Gafchromic EBT3, EBT4 films

Collaboration

Cooperation with international organizations and networks:

EURADOS

PTCOG /Ocular Subcommity/

International collaboration (examples):

Paul Scherrer Institute PSI Switzerland */MEMORANDUM OF UNDERSTANDING/ W. Hajdas*

University of Geneva/NCBJ/ L. Burmistrov – Polar2, continued at EURO-LABS

University of Luxembourg at EURO-LABS

University College Dublin/CERN R. McNulty / N. Minafra EURO-LABS

Nuclear Physics Institute of the Czech Academy of Sciences, dr I. Ambrožová

…

National partnerships (examples):

Jagiellonian University, WFAiIS, prof. E. Stępień /radiobiology for FLASH/

Jagiellonian University, WBBiB, prof. M. Elas /research involving animals/

AGH University of Krakow, WFiIS, prof. A. Jung /TLD's for high dose rate proton beams/

University of Warsaw, WF, prof. T. Matulewicz /cross-sections, activation of biological materials/

Warsaw University of Technology, Faculty of Mechatronics, prof. P. Tulik /recombination chambers/

National Centre for Nuclear Research, dr A. Bancer /Jetcounter tests/

Gdańsk University of Technology, dr. M. Maryański /gel detectors for protons/

University of Silesia (University of Pisa), prof. B. Kozlowska /plant radiobiological models/

…..

Cooperation within the IFJ PAN: PCA, NZ61, NZ63, NZ56, CCB, etc.

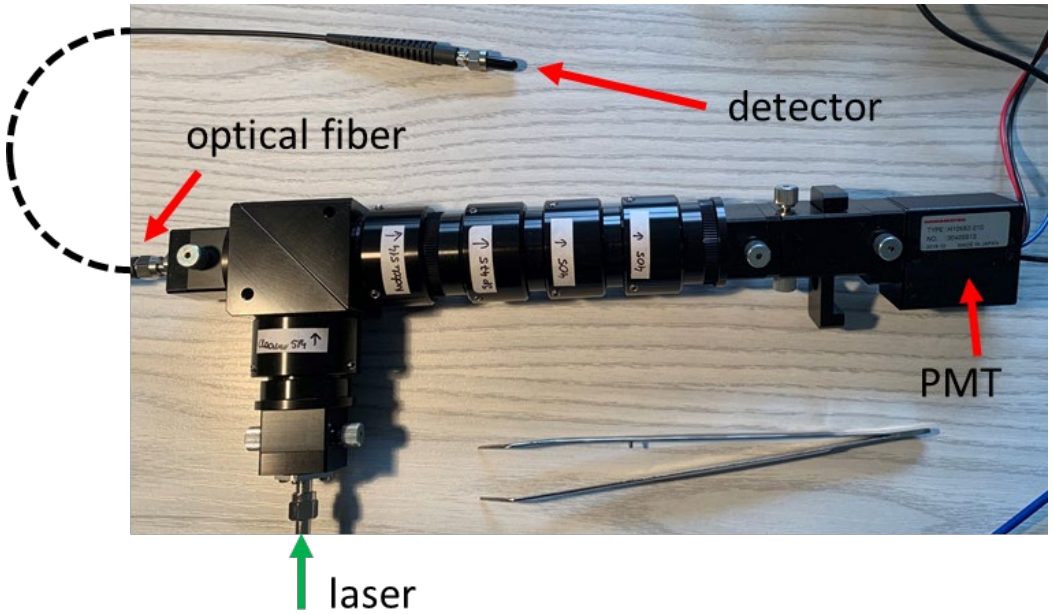
Proton beam for: EURO-LABS, RADNEXT 2030, EUROFUSION

Main research areas

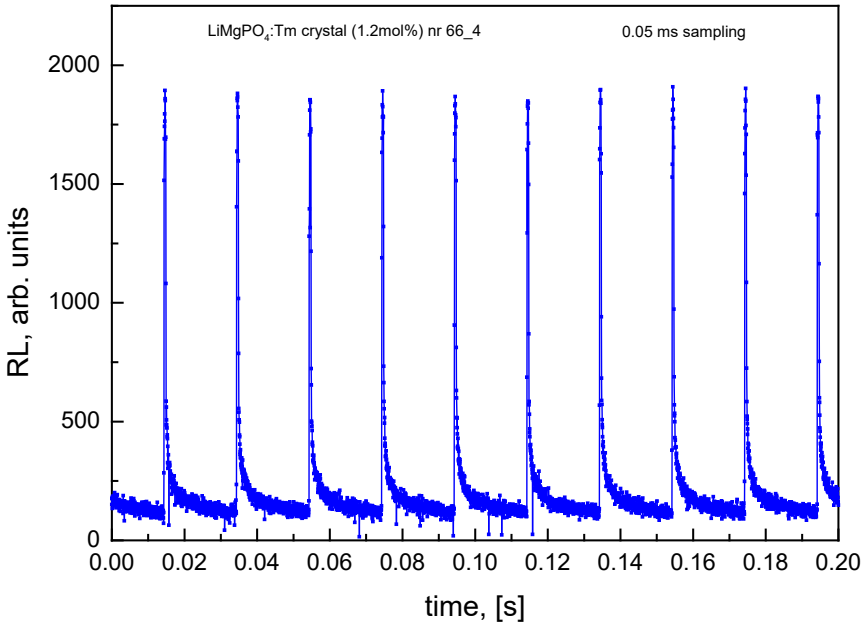
- Radiobiology;
- Radiotherapy;
- Methods of dosimetry for radiotherapy;
- Radiobiology and dosimetry for space applications;
- Radiation hardness of electronics for space research;
- Radiation hardness of electronics and construction materials for high energy physics infrastructure

EXAMPLES OF APPLICATIONS

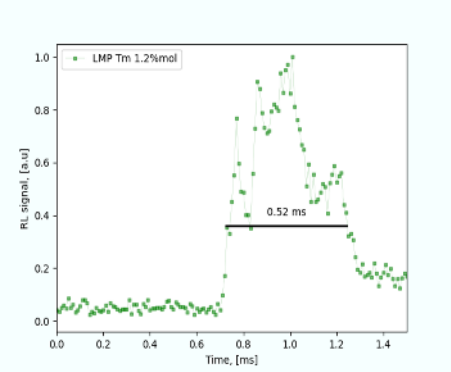
The measurements of the dose rate in the beam macro pulse



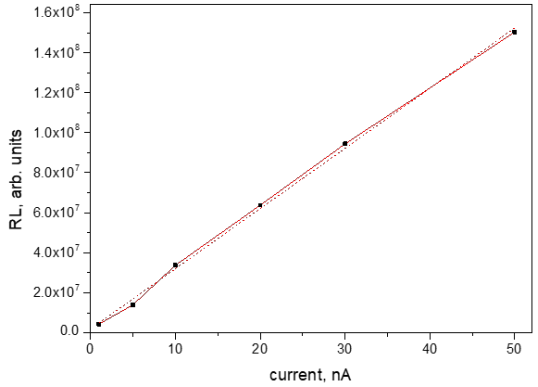
RL/OSL PORTOS dosimetry system with
LiF:$MgPO_4$ (LMP) crystal



Macro structure of AIC-144 Proton Beam



Structure of single macro pulse



RL signal linearity

EURO-LABS TA Experiments: LGAD *Low Gain Avalanche Detectors*

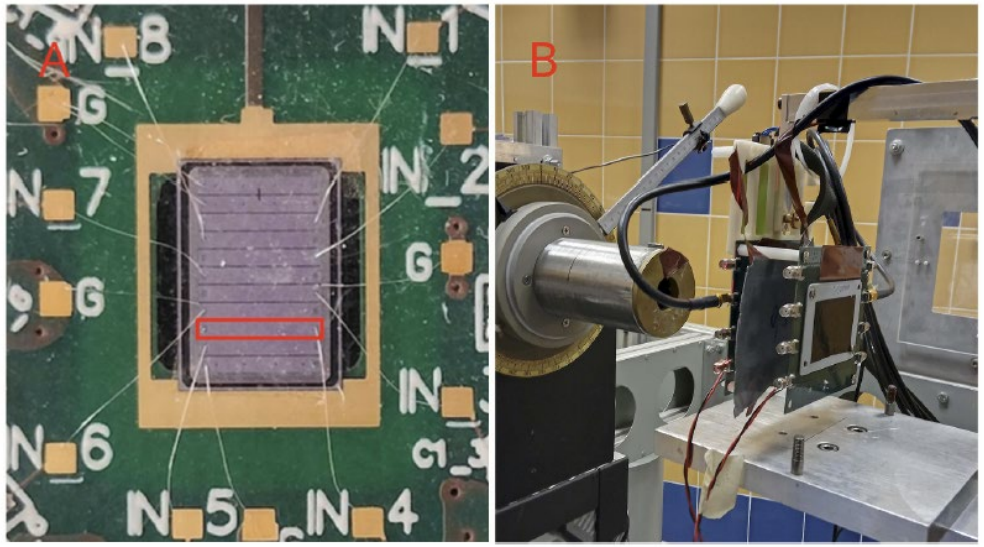


Figure 2. Panel A (left): the LGAD sensor mounted on the readout board. The strip used in this study is highlighted in red. Panel B (right): two sensors mounted one behind the other in the cyclotron beamline. The first board is positioned in the isocentre.

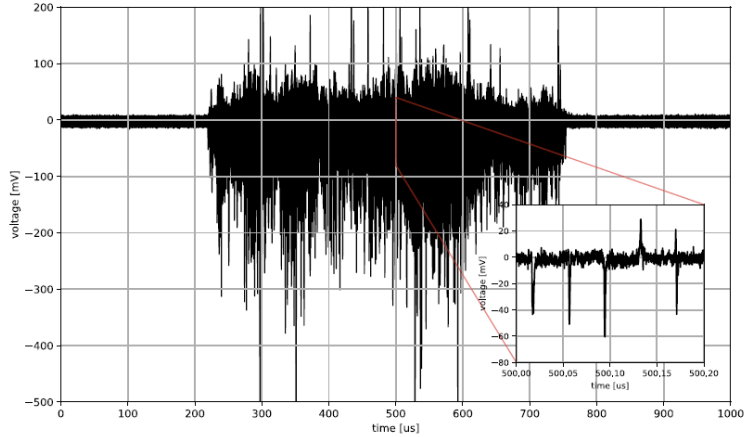


Figure 3. A macropulse as recorded by the data acquisition system during a 1 ms time window in the 4 nA dataset. The inset is a magnified view showing the micropulse structure with a 200 ns time window. Signals appear in the negative vertical direction: the pulses in the positive direction are due to electronic induced effects.

Macro pulse of the proton beam from AIC-144

IOP Publishing Phys. Med. Biol. 70 (2025) 235004 https://doi.org/10.1088/1361-6560/ae19c8

Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

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PAPER

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Fast silicon detectors as proton therapy beam monitors

A Bellora[1], L Grzanka[1,2,*], R McNulty[3], N Minafra[4], K Misan[1], M Nessel[1], T Nowak[2], P Rzeznik[1], J Swakon[2] and T Szollosova[5]

1 AGH University of Krakow, Krakow, Poland
2 Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
3 School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
4 Department of Physics & Astronomy, University of Kansas, Lawrence, KS 66045, United States of America
5 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
* Author to whom any correspondence should be addressed.

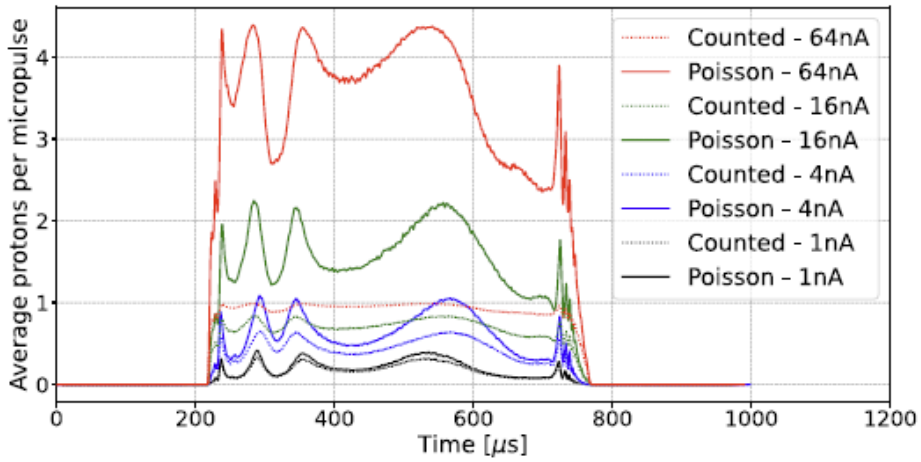
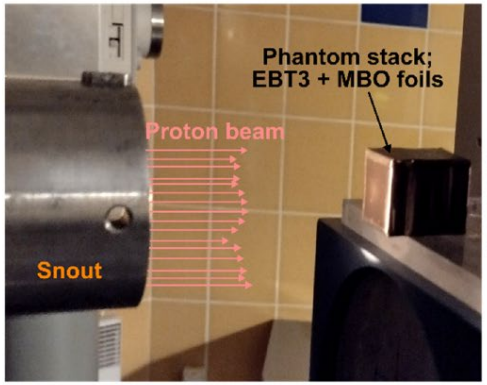
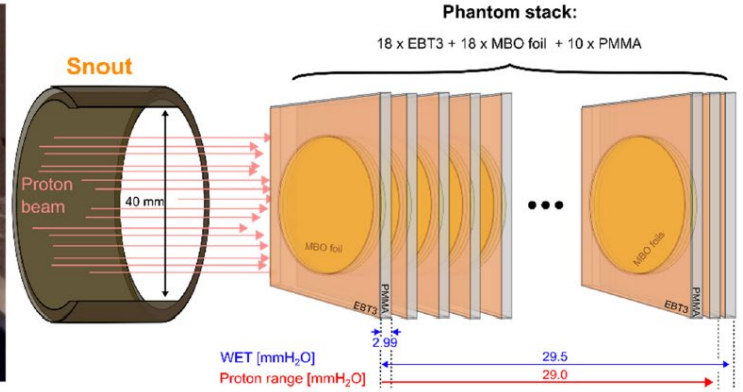


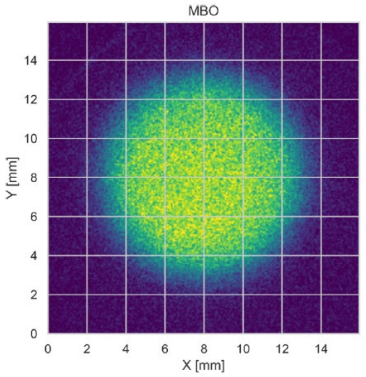
Figure 7. Measured number of protons per micropulse as measured using the simple counting method (dashed lines) and with the Poisson-counting method (solid lines), as a function of time within the macropulse, for four of the data-sets summarised in table 1.

OSL Silicone Foils for QA Proton Eye Radiotherapy

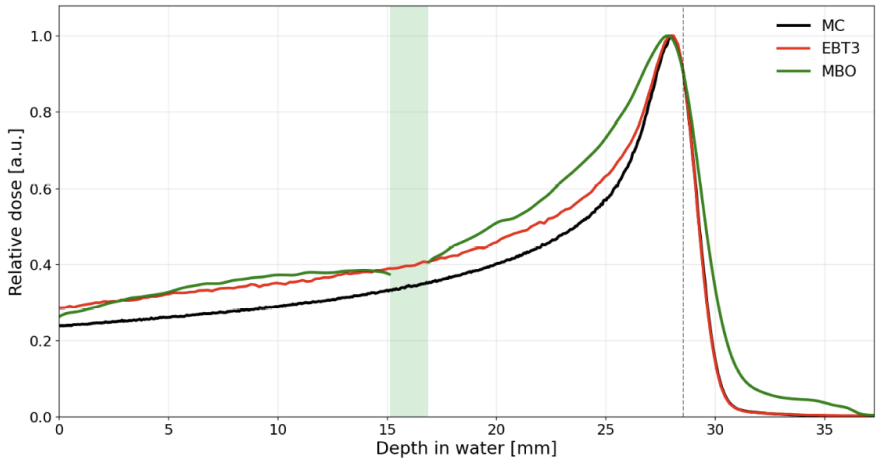




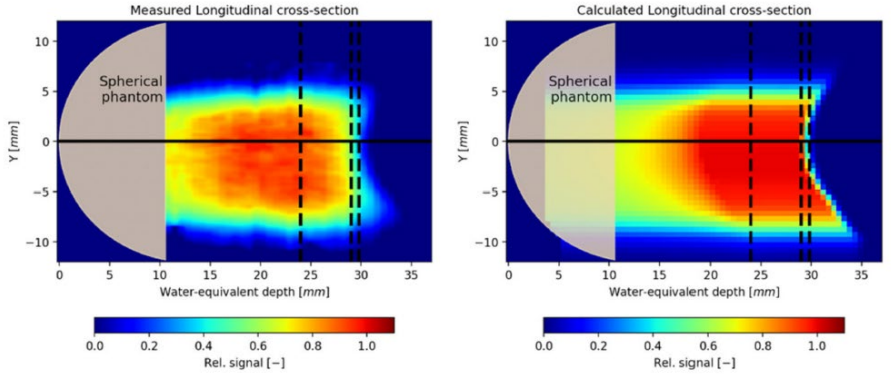
The experimental phantom used to measure the radial profile dose distribution for the EBT3 film and MBO foils



MBO foil readout



Comparison of Bragg curve profiles measured perpendicular to the beam direction for the AIC-144 beam (58.8 MeV) using MBO foils (green), EBT3 films (red), and MC simulations (black)



The 3D dose distributions longitudinal cross-section reconstructed from the stack of forty 2D LMP foils

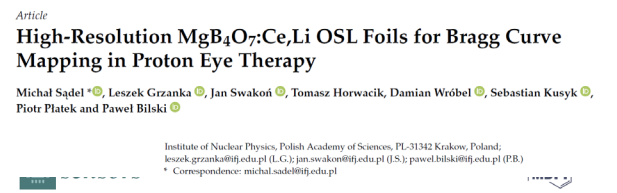

materials

Article

Optically Stimulated Luminescence Silicone Foils for 2D Dose Mapping in Proton Radiotherapy

Michał Sądel [1,*], Leszek Grzanka [1], Jan Swakoń [1], Damian Wróbel [1], Sebastian Kusyk [1], Lily Bossin [2] and Paweł Bilski [1]

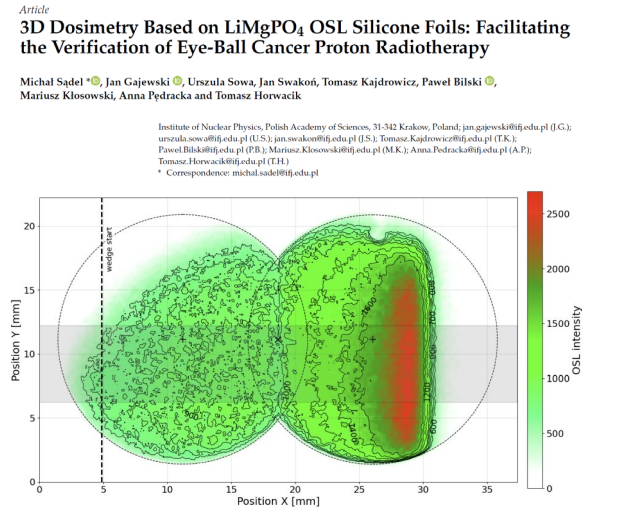
[1] Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland
[2] Department of Radiation Safety and Security, Paul Scherrer Institute, Forschungsstrasse 111, 5232 Villigen, Switzerland
* Correspondence: michal.sadel@ifj.edu.pl


Article

High-Resolution MgB_4O_7:Ce,Li OSL Foils for Bragg Curve Mapping in Proton Eye Therapy

Michał Sądel *, Leszek Grzanka, Jan Swakoń, Tomasz Horwacik, Damian Wróbel, Sebastian Kusyk, Piotr Płatek and Paweł Bilski

Institute of Nuclear Physics, Polish Academy of Sciences, PL-31342 Krakow, Poland; leszek.grzanka@ifj.edu.pl (L.G.); jan.swakon@ifj.edu.pl (J.S.); pawel.bilski@ifj.edu.pl (P.B.)
* Correspondence: michal.sadel@ifj.edu.pl


Article

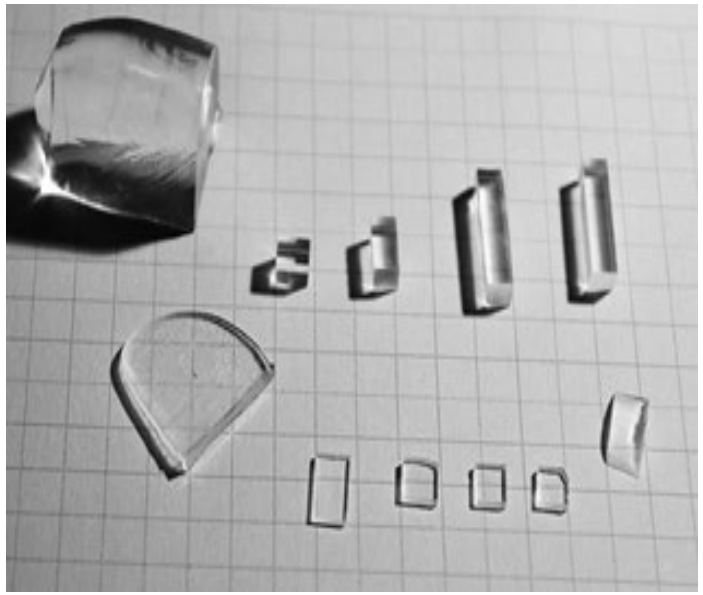
3D Dosimetry Based on $LiMgPO_4$ OSL Silicone Foils: Facilitating the Verification of Eye-Ball Cancer Proton Radiotherapy

Michał Sądel *, Jan Gajewski, Urszula Sowa, Jan Swakoń, Tomasz Kajdrowicz, Paweł Bilski, Mariusz Kłosowski, Anna Pędracka and Tomasz Horwacik

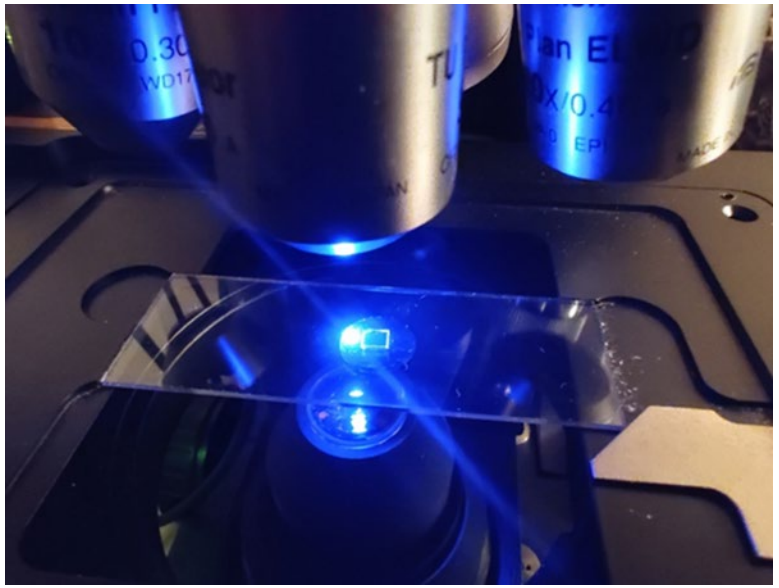
Institute of Nuclear Physics, Polish Academy of Sciences, 31-342 Krakow, Poland; jan.gajewski@ifj.edu.pl (J.G.); urszula.sowa@ifj.edu.pl (U.S.); jan.swakon@ifj.edu.pl (J.S.); Tomasz.Kajdrowicz@ifj.edu.pl (T.K.); Pawel.Bilski@ifj.edu.pl (P.B.); Mariusz.Klosowski@ifj.edu.pl (M.K.); Anna.Pedracka@ifj.edu.pl (A.P.); Tomasz.Horwacik@ifj.edu.pl (T.H.)
* Correspondence: michal.sadel@ifj.edu.pl

Comparison of the 2D OSL intensity obtained for the MBO foils irradiated at the AIC-144 (58.8 MeV)

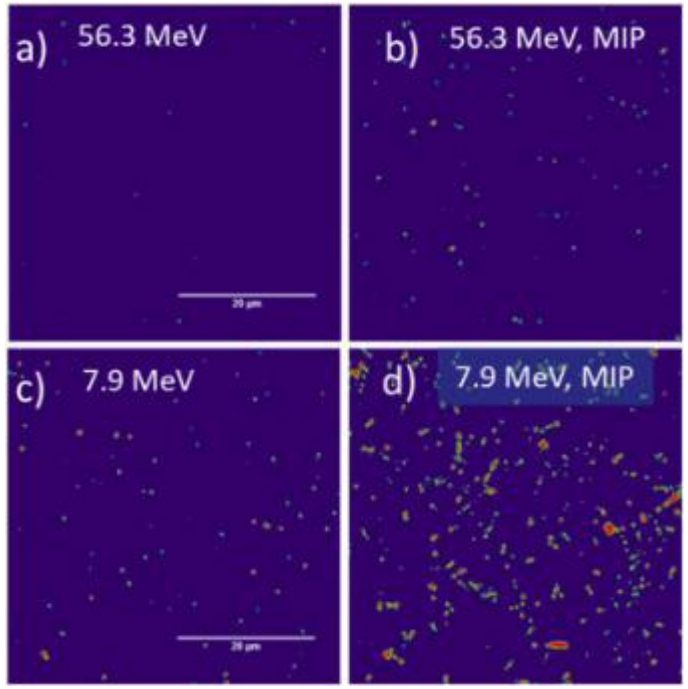
Detection of proton tracks with LiF fluorescent nuclear track detectors (FNTD)



LiF crystals grown at IFJ PAN with Czochralski method



Irradiated crystals analysed under fluorescence microscope – flashed with blue diod

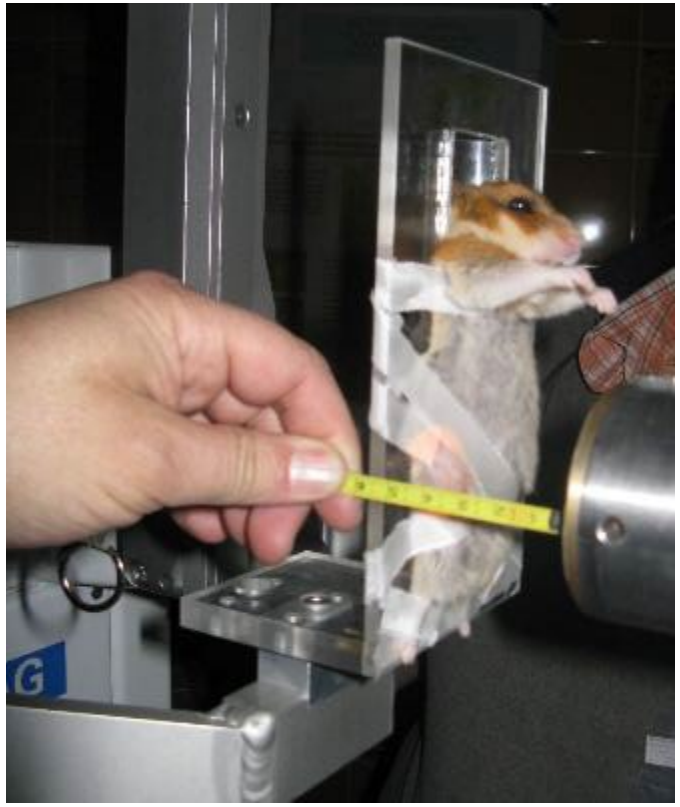


Proton tracks registered with LiF
MIP: Maximum Intensity Projection

Chemically etched FNTD (CR-39) can detect only protons E < 10 MeV

With LiF FNTD it is now possible to identify proton tracks for 60 MeV protons

Irradiation of biological material



Irradiation of tumors located on the leg of a Chinese hamster

Jagiellonian University, Faculty of Biochemistry, Biophysics and Biotechnology



Tests of a radiobiological model based on Japanese quail embryos for the purpose of an experiment on the ISS

Nuclear Physics Institute of the Czech Academy of Sciences



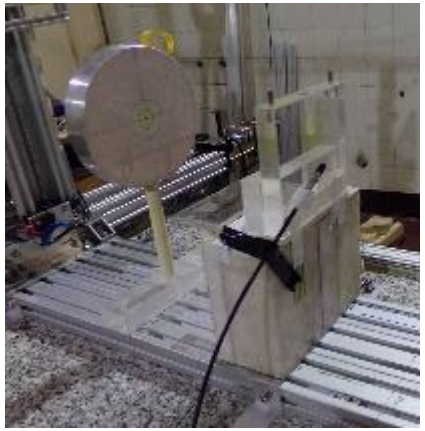
Irradiation of onion seeds - tests of a plant-based radiobiological model

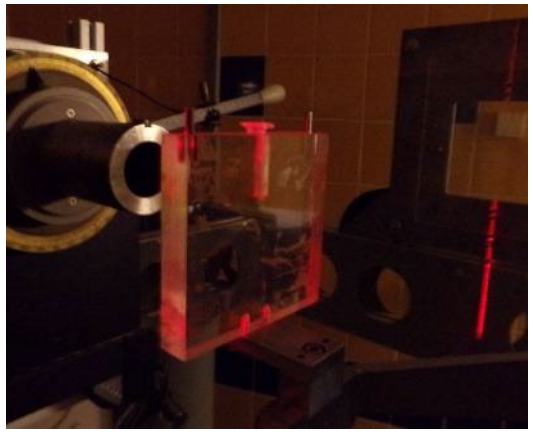
University of Silesia (University of Pisa)

Radiobiological studies

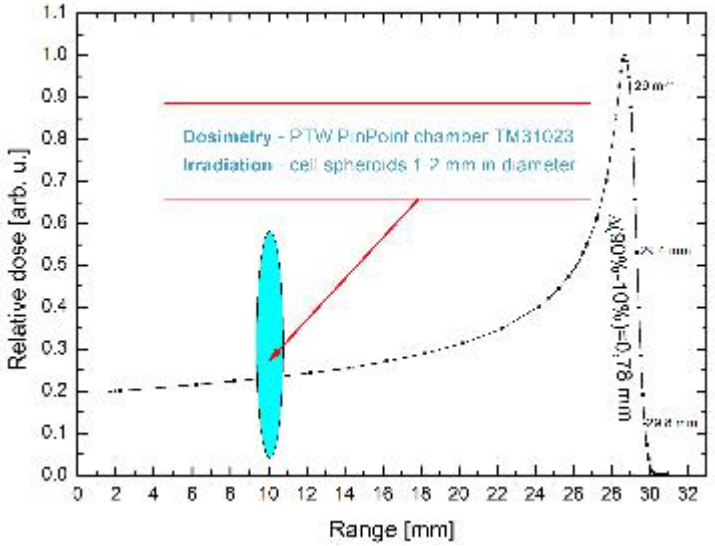
(collaboration with Department of Medical Physics, Jagiellonian University in Kraków

- Comparison of the proton FLASH irradiation method with a conventional radiation method applied to determine effects on the biochemical structure of the tumour (3D model – spheroids) and the secretion of extracellular vesicles (EVs) and their cargo.
- Short-term response of melanoma cells (Wm-266-4) and normal skin cells (melanocytes- HEMA-Lp) to FLASH proton radiotherapy (60 Gy/s) with a final dose of 3 Gy.

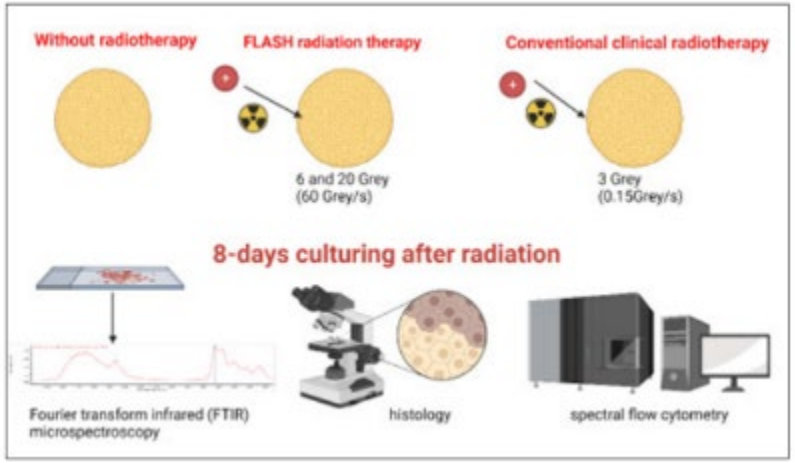




Irradiation setups for Flash and normal dose rate



Sample positition



Methodology of experiment

(Durak-Kozica et al. 2023)

The first radiobiological results using the 3D spheroid model are very promising

Examples of application for space

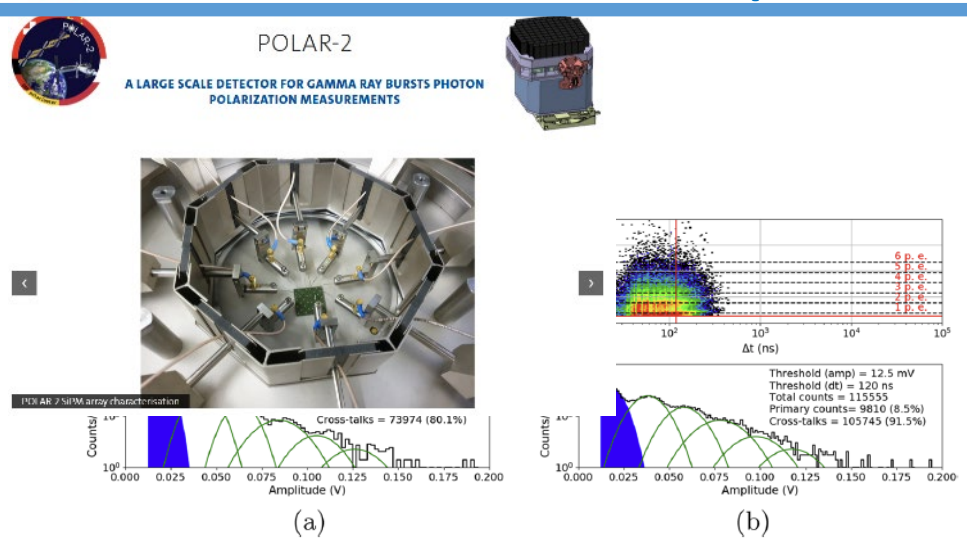


Fig. 19 An example of waveform analysis for data taken two months after S13361 irradiation with doses **a)** 2.19Gy and **b)** 4.96Gy at temperature $-20°C$. The Z-axis is represented here by a colour scale. The

Experimental Astronomy (2023) 55:343–371
https://doi.org/10.1007/s10686-022-09873-6

For industry

Satellite components:

- Electronic boards;
- Components:
  - memories;
  - microprocessors;
  - cameras;
  - data transmission systems;
  - antennas;
  - power supplies;
  - radiation shielding;

Commercial use

For research

ORIGINAL ARTICLE

Proton irradiation of SiPM arrays for POLAR-2

Slawomir Mianowski[1] · Nicolas De Angelis[2] · Johannes Hulsman[2] · Merlin Kole[2] · Tomasz Kowalski[3] · Sebastian Kusyk[3], et al. *[full author details at the end of the article]*

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Temperature dependence of radiation damage annealing of Silicon Photomultipliers

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[b] Institute of Nuclear Physics, Polish Academy of Sciences, Pl. 31342 Krakow, Poland
[c] National Centre for Nuclear Research, ul. A. Soltana 7, 05-400 Otwock, Swierk, Poland

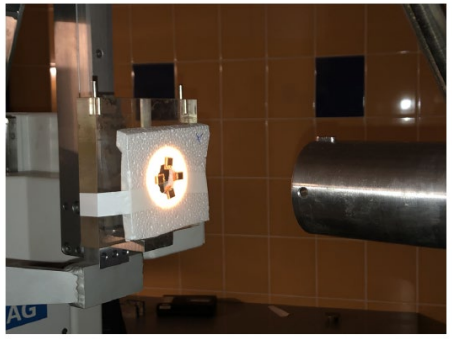


Fig. 2. Four single channel SiPMs placed on the beam axis at IFJ-PAN.

Cosmic Challenges: Unmasking Soft Error Vulnerabilities in COTS SoCs and FPGAs under Accelerated Proton Radiation and Linux

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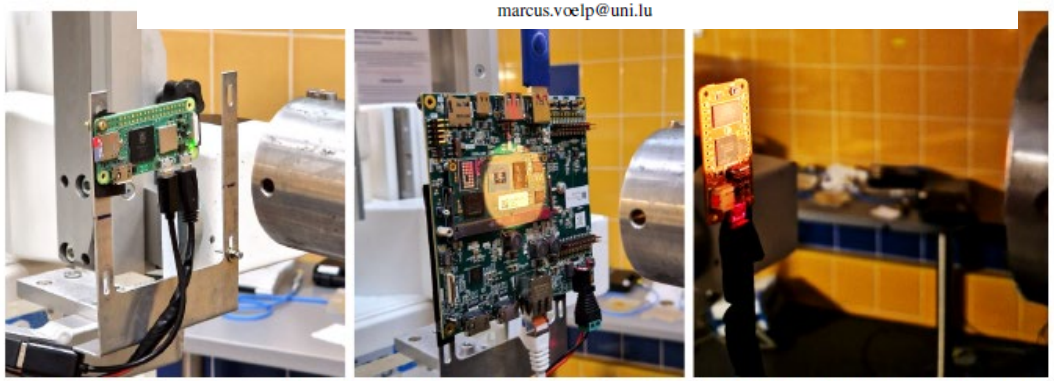
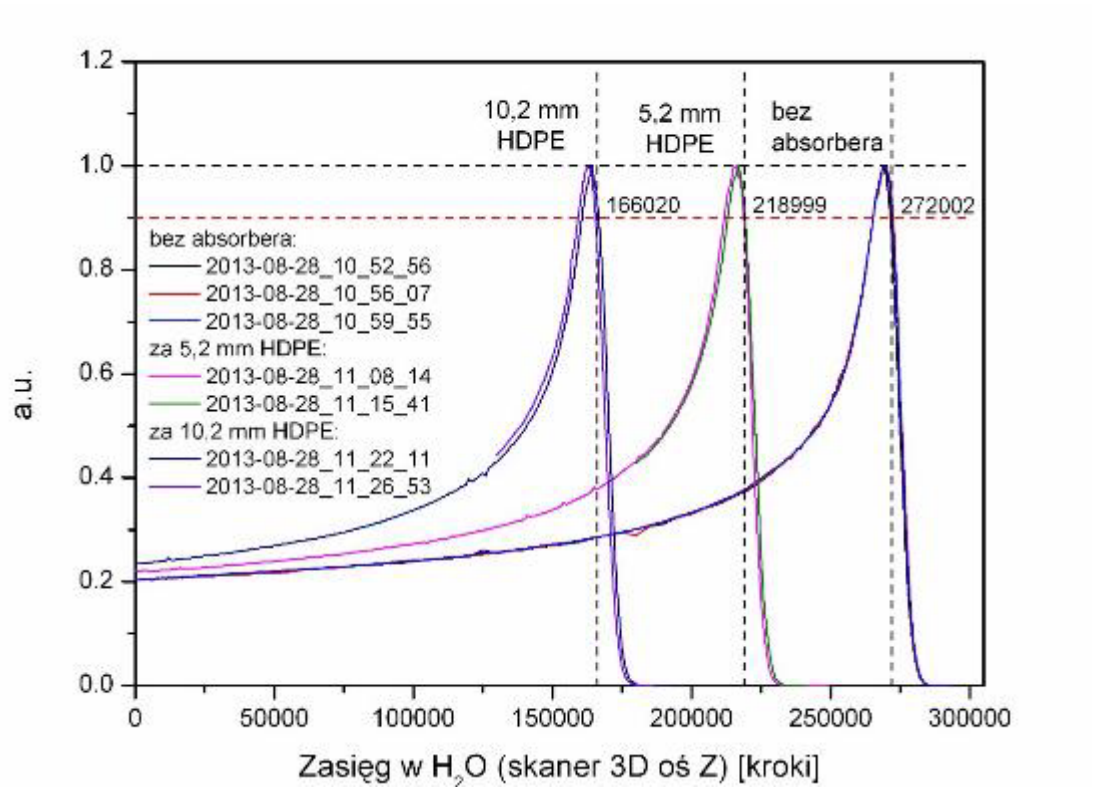


Fig. 3: Proton Irradiation Effects on Heterogeneous DUTs: (Left) SBC: Raspberry Pi Zero 2W, (Center) SoM: NXP i.MX 8M Plus, and (Right) FPGA: OrangeCrab ECP5 Lattice v2

Testing electronic systems for the Space Research Centre (LEM – the first Polish satellite)

Testing of CCD arrays at the AIC-144 beamline using a proton beam
with energies of 58 MeV and 27.2 MeV;
Determination of the density (WET) of high-density polyethylene (HDPE) samples doped with boron compounds, intended for the construction of shielding for electronic systems (such as the CCD arrays of satellite cameras)

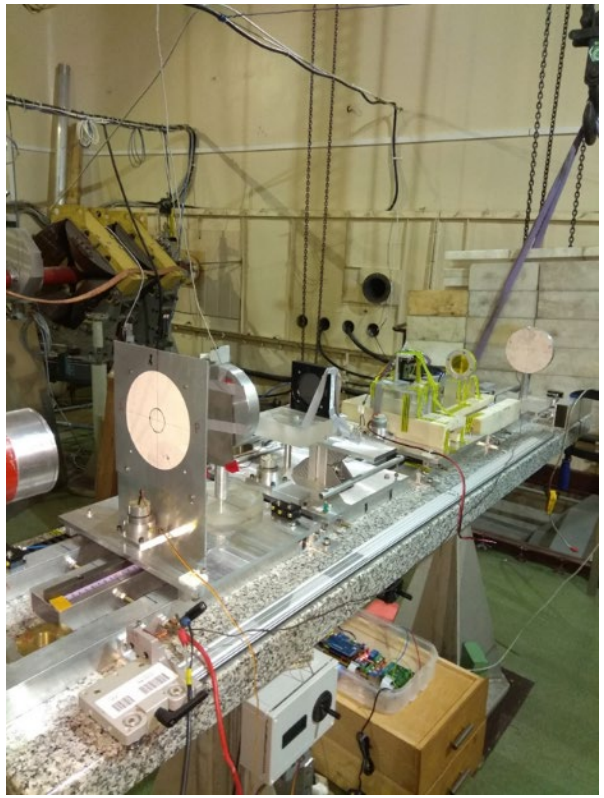




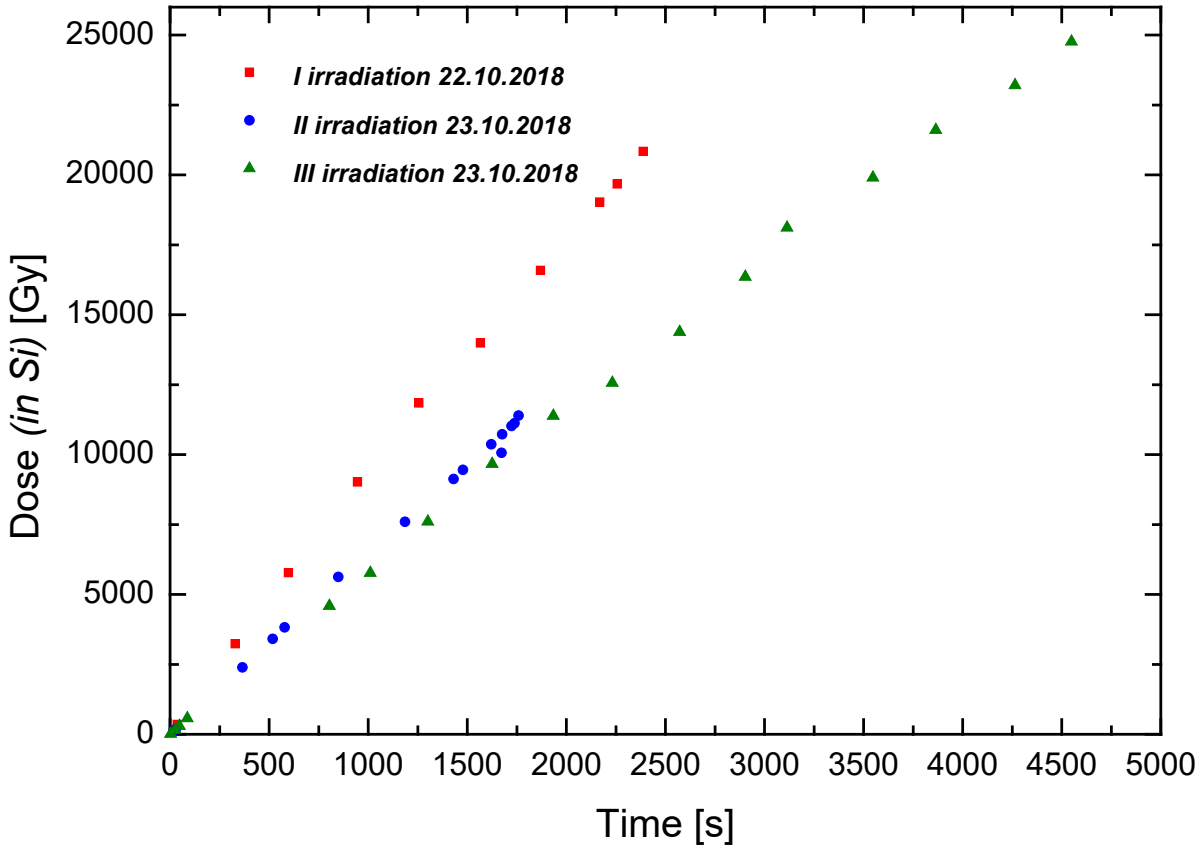


Radiation-hardness testing of electronics under an agreement with CBM (FAIR GSI)





Radiation hardness testing of analog and digital electronics and construction materials



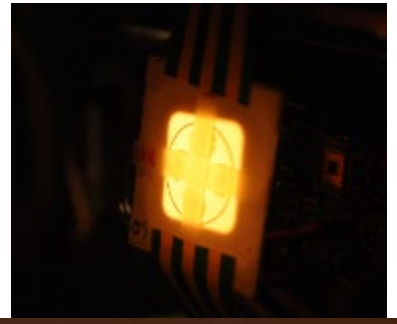
Monitoring of the delivered dose

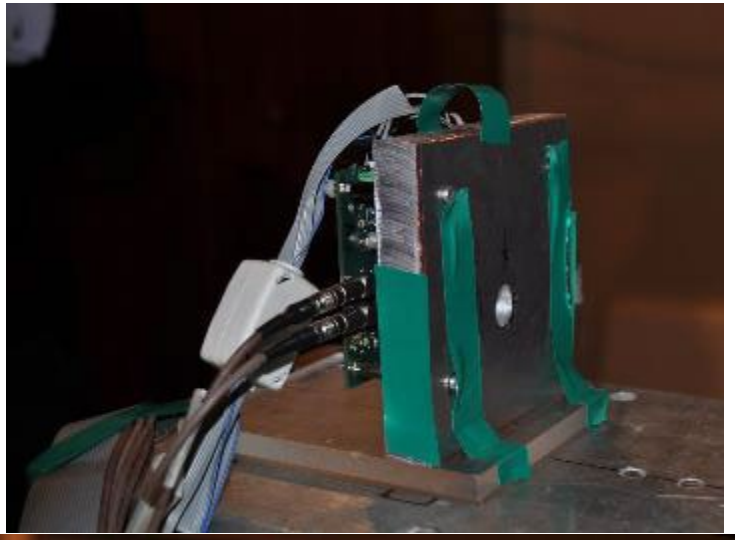
Single irradiation with a dose of up to 70 kGy

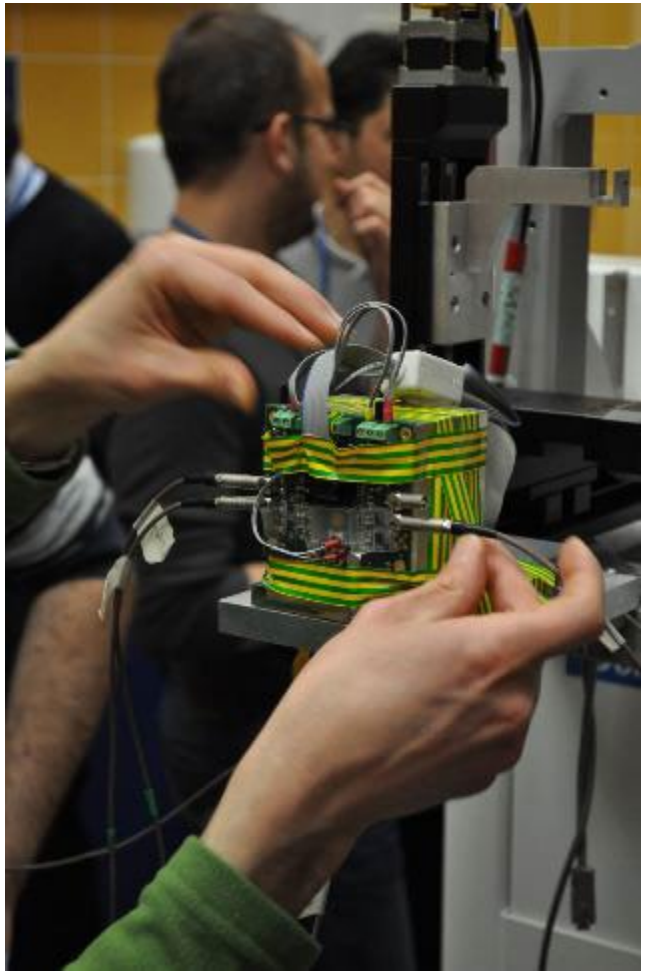
Irradiation of electronic system for LHCb detector:

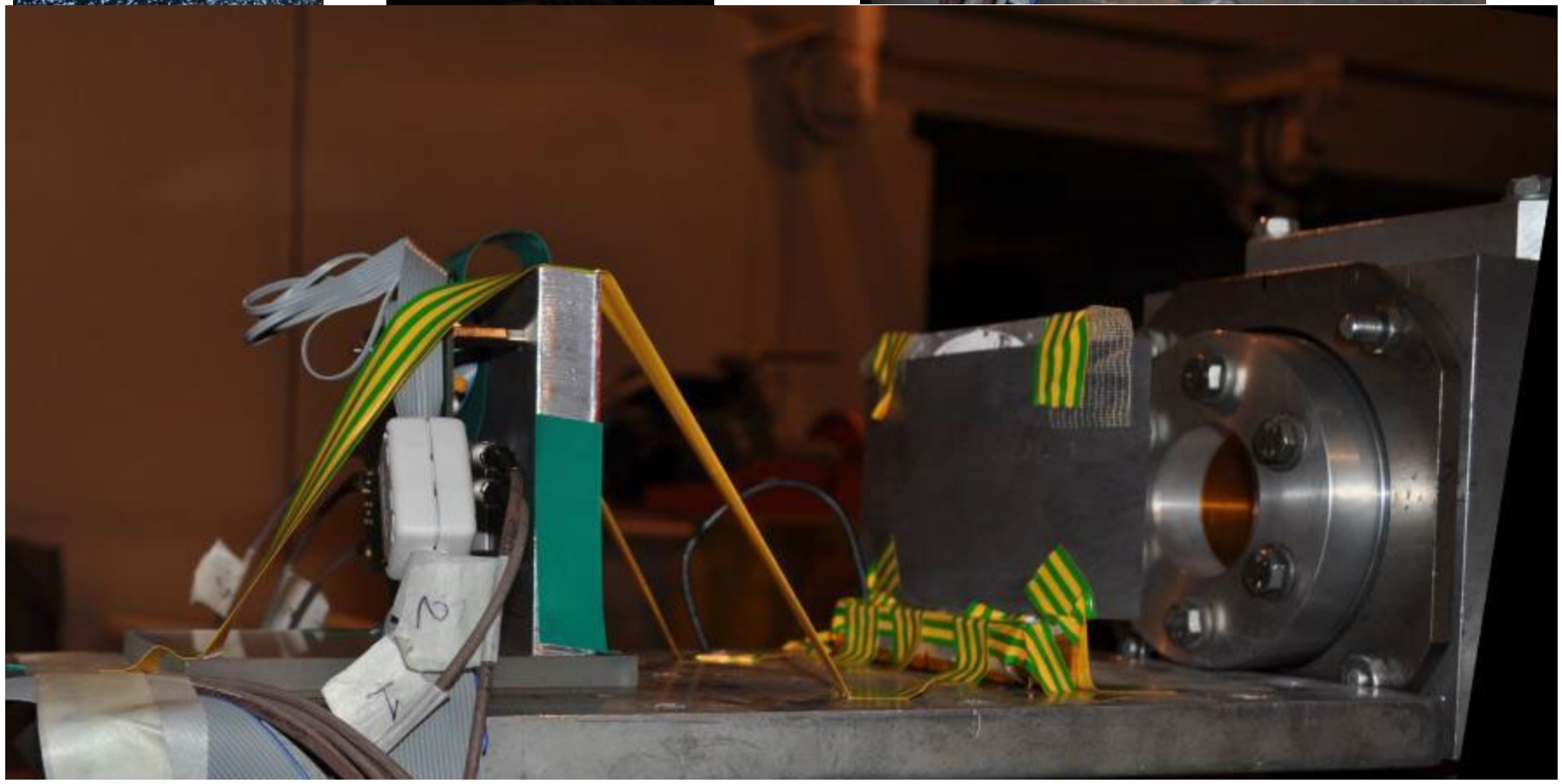
CLARO - the 4 channel, 0.35um CMOS prototype detector





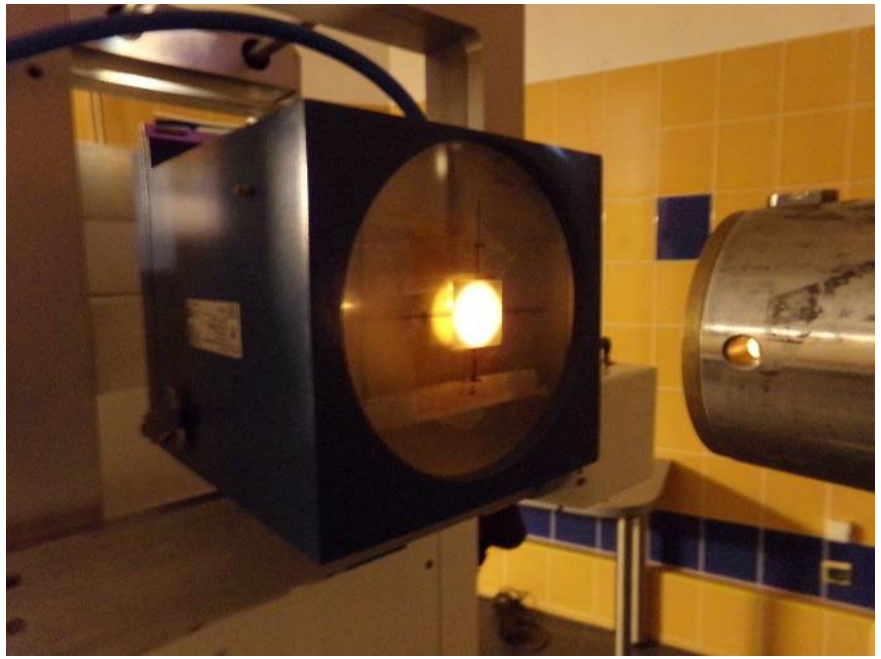




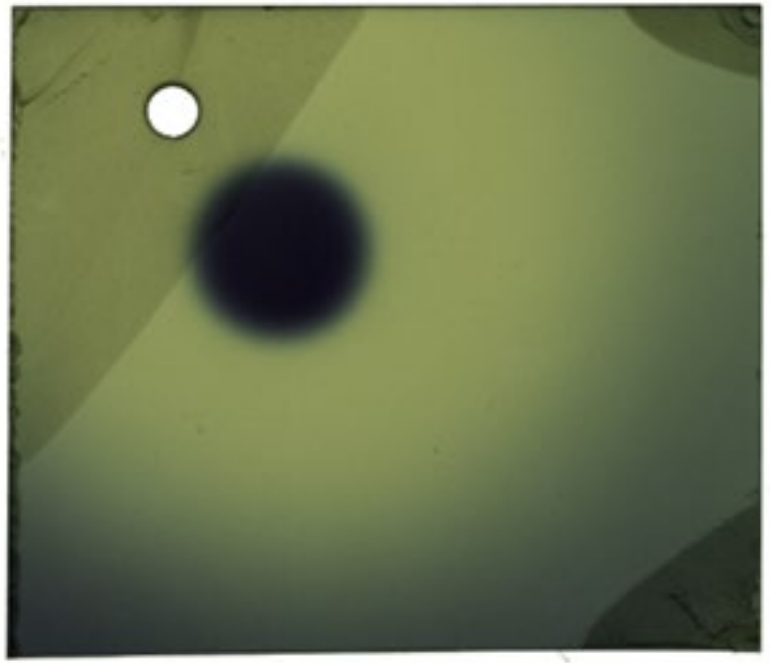


EURO-LABS: Calibration of stack detectors for ELI-NP (K. Spohr)

	Layer material	Thickness (mm)
	Aluminium	0,012
1	HD-V2 (1)	0,109
	Fe (1)	0,1
2	HD-V2 (2)	0,109
	Fe (2)	0,2
3	HD-V2 (3)	0,109
	Fe (3)	0,3
4	HD-V2 (4)	0,109
	Fe (4)	0,3
5	HD-V2 (5)	0,109
	Fe (5)	0,5
6	HD-V2 (6)	0,109
	Fe (6)	0,5
7	HD-V2 (7)	0,109
	Fe (7)	0,5
8	HD-V2 (8)	0,109
	Fe (8)	0,7



Stack of Gafchromic detectors irradiated with high proton doses (up to 100 kGy) for calibration for ELI-NP 10 PW laser experiment



Optical density of the Gafchromic film depends on the absorbed dose

Current possibilities:

- Irradiation of electronic components using a proton beam with energies ranging from 10 MeV to 60 MeV for the purposes of radiation resistance testing (a wide range of available fluxes and fluences);
- Radiation resistance testing of structural materials used in radiation-related applications;
- Detector testing in a proton beam;
- A proton beam ready for radiobiological research across a wide range of intensities, including dose rates suitable for FLASH radiotherapy;

In the future:

- Construction and commissioning of a facility for neutron beam irradiation generated by a 60 MeV proton beam

Summary and conclusions

Research using a proton beam from the AIC-144 cyclotron has been conducted for 20 years;

There is great interest in using the proton beam from the AIC-144 cyclotron for research on the part of numerous teams from Poland and around the world;

There is a growing demand for access to the proton beam from the AIC-144 cyclotron from commercial companies in the space sector, both in Poland and internationally