Development of a fluorescence-based beam monitor and magnetic delivery studies for FLASH radiotherapy

Accelerator Physics PhD final seminar

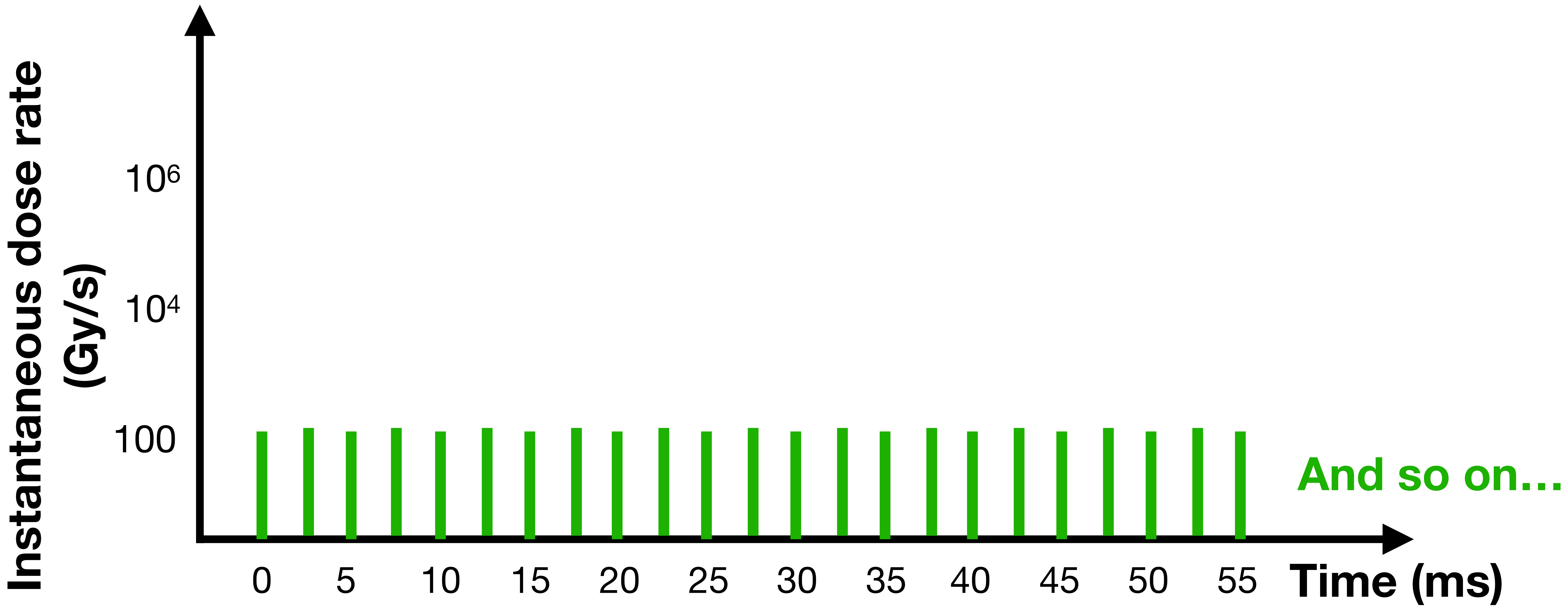
Antonio Trigilio

Supervisor: Prof. Alessio Sarti

FLASH Radiotherapy with hIgh Dose-rate particle beAms

FLASH effect

- The usual way a radiotherapy treatment is delivered is through a **pulsed** structure. The total dose is delivered in tens of **fractions** (~2 Gy, lasting some minutes), each made of a sequence of pulses (~1 μs) carrying a small amount of dose.

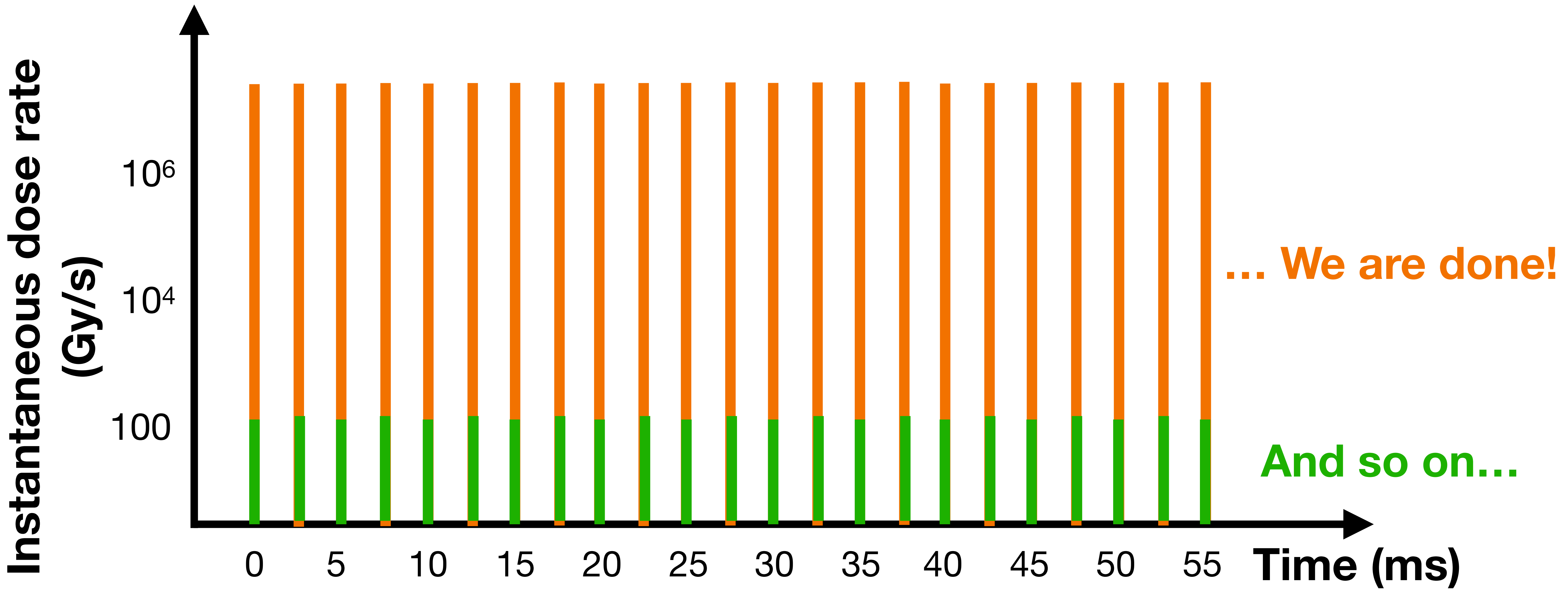


Beam characteristics	CONV
Dose per pulse	~ 0.4 mGy
Inst. dose rate (single pulse)	~ 100 Gy/s
Mean dose rate (single fraction)	~ 0.1 Gy/s
Total treatment time	~ minutes

FLASH effect

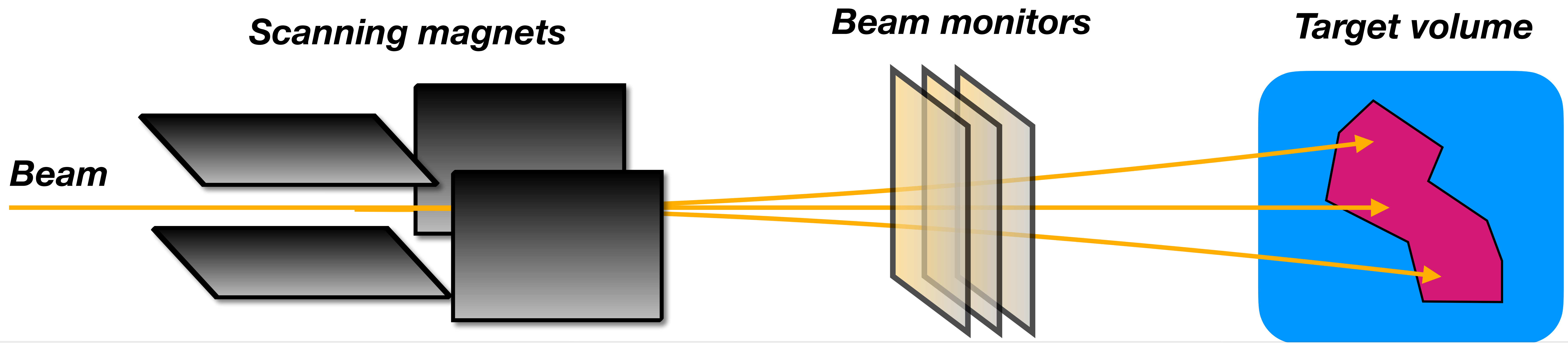
- The usual way a radiotherapy treatment is delivered is through a **pulsed** structure. The total dose is delivered in tens of **fractions** (~2 Gy, lasting some minutes), each made of a sequence of pulses (~1 μs) carrying a small amount of dose.
- An increased radio-resistance — **reduced toxicity** — is observed **in normal tissues** when delivering a single irradiation at ***ULTRAHIGH*** dose rates in a very short time (keeping anti-tumor efficacy).
- This has been named **FLASH** effect. Its biological mechanisms are not yet understood, and there is a lot of investigation going on.
- This opens up interesting possibilities for the treatment of radio-resistant tumours (overcoming safety constraints and under-dosage due to OARs sparing).

J. Wilson, et al., Ultra-high dose rate (FLASH) radiotherapy: Silver bullet or fool's gold?, Front. Oncol. 9:1563 (2020). doi:10.3389/fonc.2019.01563



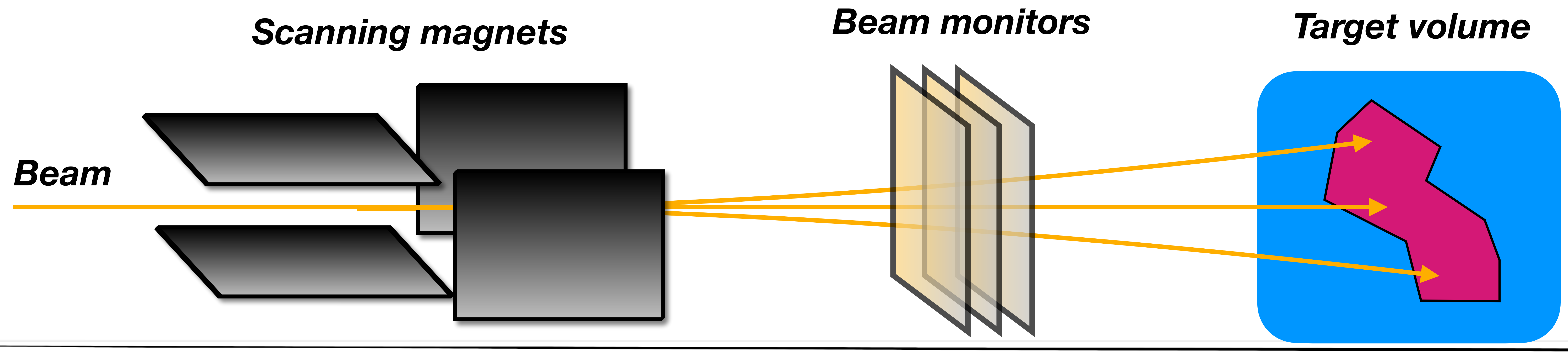
Beam characteristics	CONV	FLASH
Dose per pulse	~ 0.4 mGy	> 1 Gy
Inst. dose rate (single pulse)	~ 100 Gy/s	> 10^6 Gy/s
Mean dose rate (single fraction)	~ 0.1 Gy/s	> 100 Gy/s
Total treatment time	~ minutes	< 100 ms

My thesis work



Ultra-High Dose Rate irradiation is full of uncharted territories. The goal of my PhD thesis is to explore two innovative techniques and test their feasibility for future implementation of the FLASH effect in clinical practice.

My thesis work



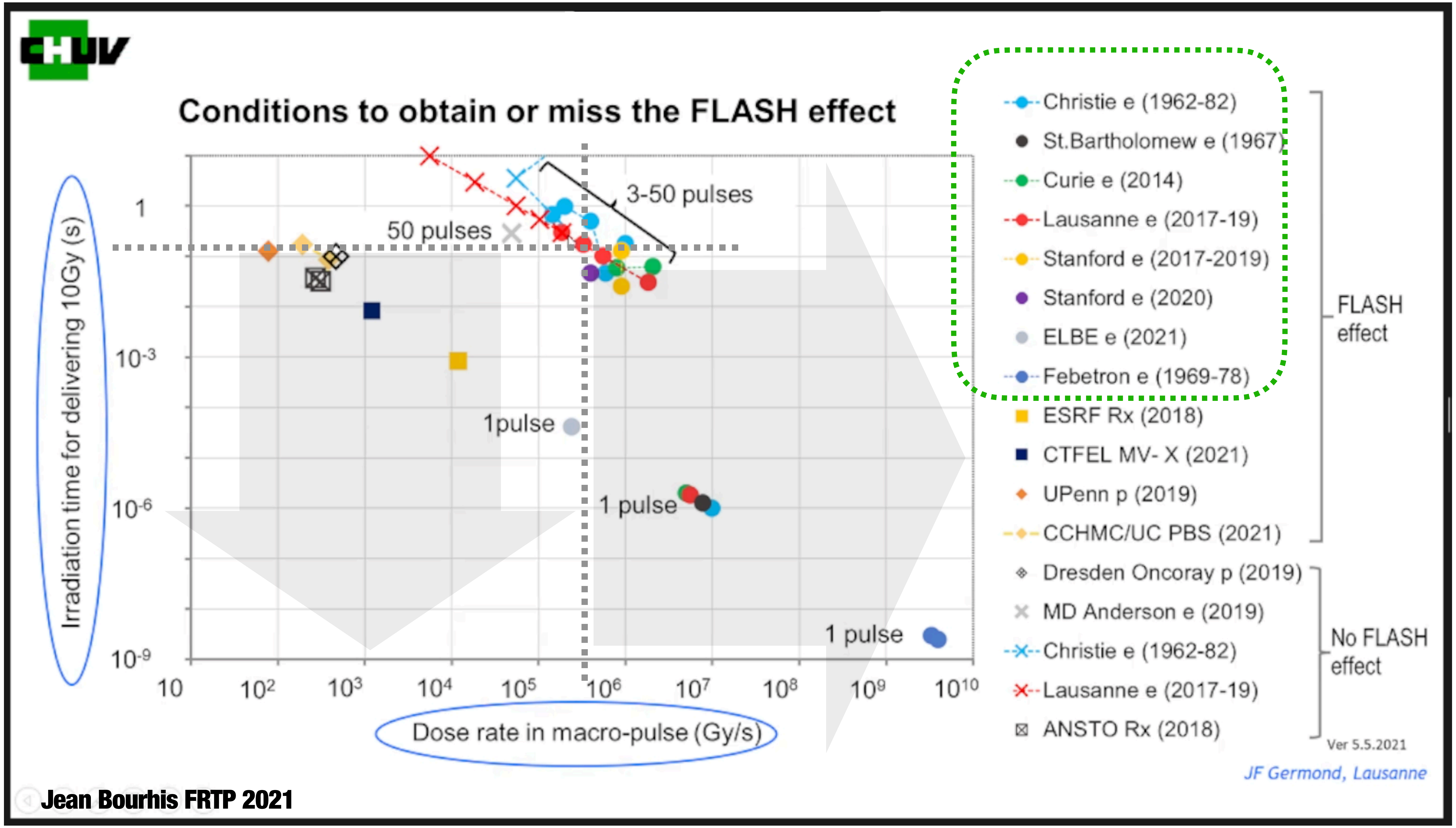
Ultra-High Dose Rate irradiation is full of uncharted territories. The goal of my PhD thesis is to explore two innovative techniques and test their feasibility for future implementation of the FLASH effect in clinical practice.

- How to safely deliver a FLASH beam? Is it possible to precisely target a solid tumor in such a short irradiation time? What are the technological challenges of an active scanning technique?

- How do we quantitatively characterize the FLASH effect parameters? Do we have a system that can provide the adequate set of measurements ensuring irradiation is being delivered according to the desired outcome?

FLASH beam monitoring

- Currently the experimental evidence points to the description of FLASH as a **threshold** effect. However, its characterization is complicated by fundamental uncertainties.
- It is difficult to deconvolve the role played by the **dose within each pulse** and the **time of irradiation**.
- Beam monitoring devices which are able to **follow the temporal evolution** of the beam while maintaining an **adequate response to the dose per pulse** are eagerly needed.
    - **Dose Rate Linearity** (up to 10^6 Gy/s)
    - **Spatial Resolution** (~ mm)
    - **Temporal Resolution** (< 1μs)

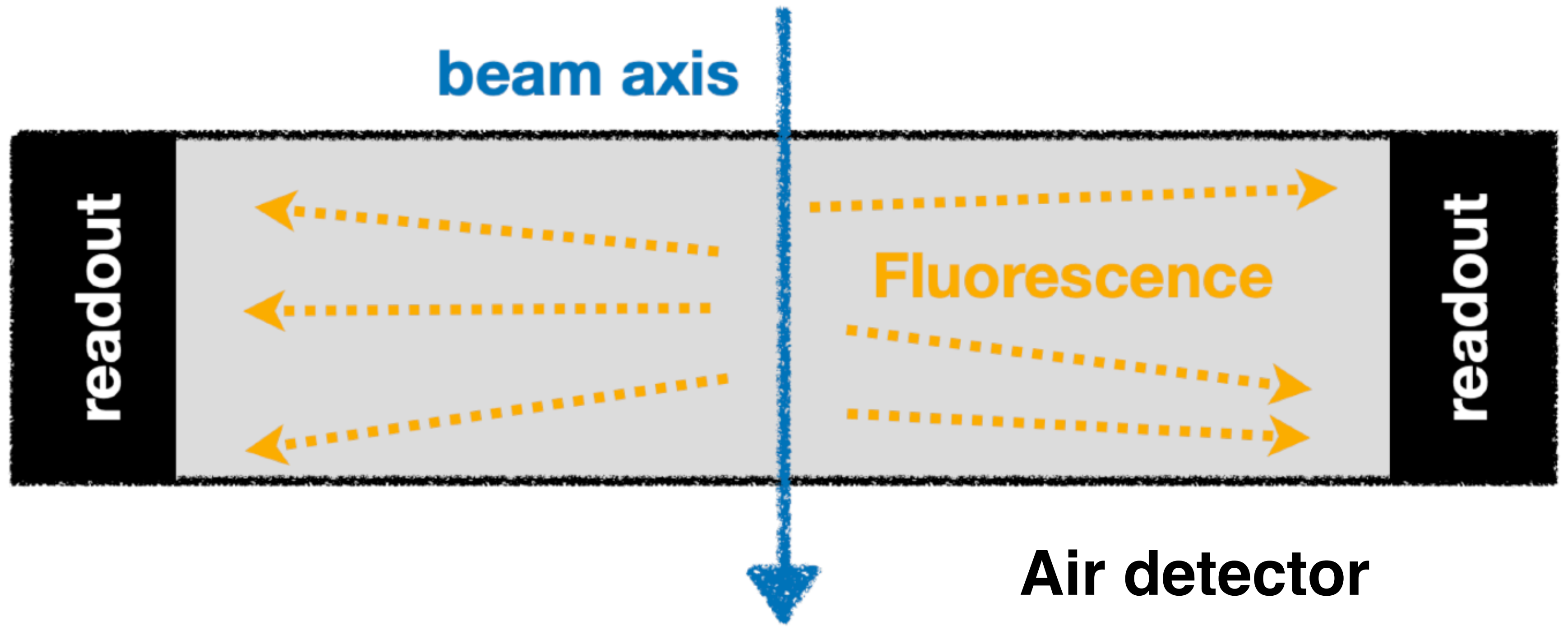


FLASH beam monitoring

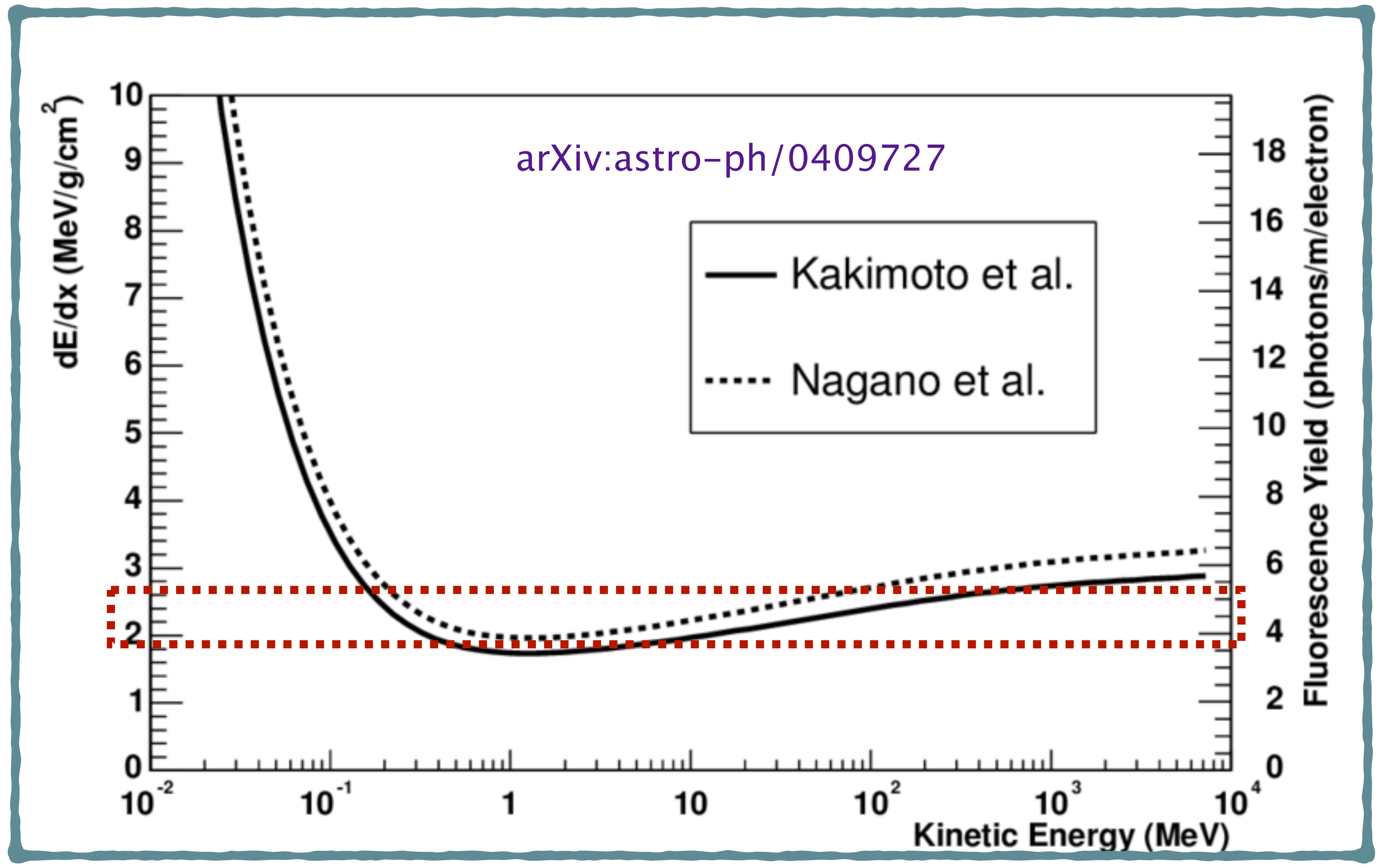
- At present, there is no standard device for beam monitoring in UHDR conditions. Detectors commonly used in clinics (standard ionization chambers) undergo substantial energy dependencies due to **volume recombination**.

- It is clear that we need *new monitoring devices* to precisely measure **the rate of impinging particles per pulse** (real-time, position by position). Promising results from **luminescence-based** detectors (thin scintillators, Cherenkov detectors…).

- According to data in literature, **air fluorescence** can do the job for us.



Photon emission	Isotropic (3D)
Excited state lifetime	10 ns
Wavelength spectrum	290-430 nm
Fluorescence yield	$\propto dE/dx$ (~ 4 ph./m)
Signal-to-#e⁻ relation	**LINEAR**
Transparency wrt ref. cond.	100%
Radiation hardness	Optimal



FLASH beam monitoring

Above all else, the philosophy of having a detector made out of air is to be as "invisible" to the beam as possible.

- At present, there is no standard device for beam monitoring in UHDR conditions. Detectors commonly used in clinics (standard ionization chambers) undergo substantial energy dependencies due to **volume recombination**.
- It is clear that we need *new monitoring devices* to precisely measure **the rate of impinging particles per pulse** (real-time, position by position). Promising results from **luminescence-based** detectors (thin scintillators, Cherenkov detectors…).
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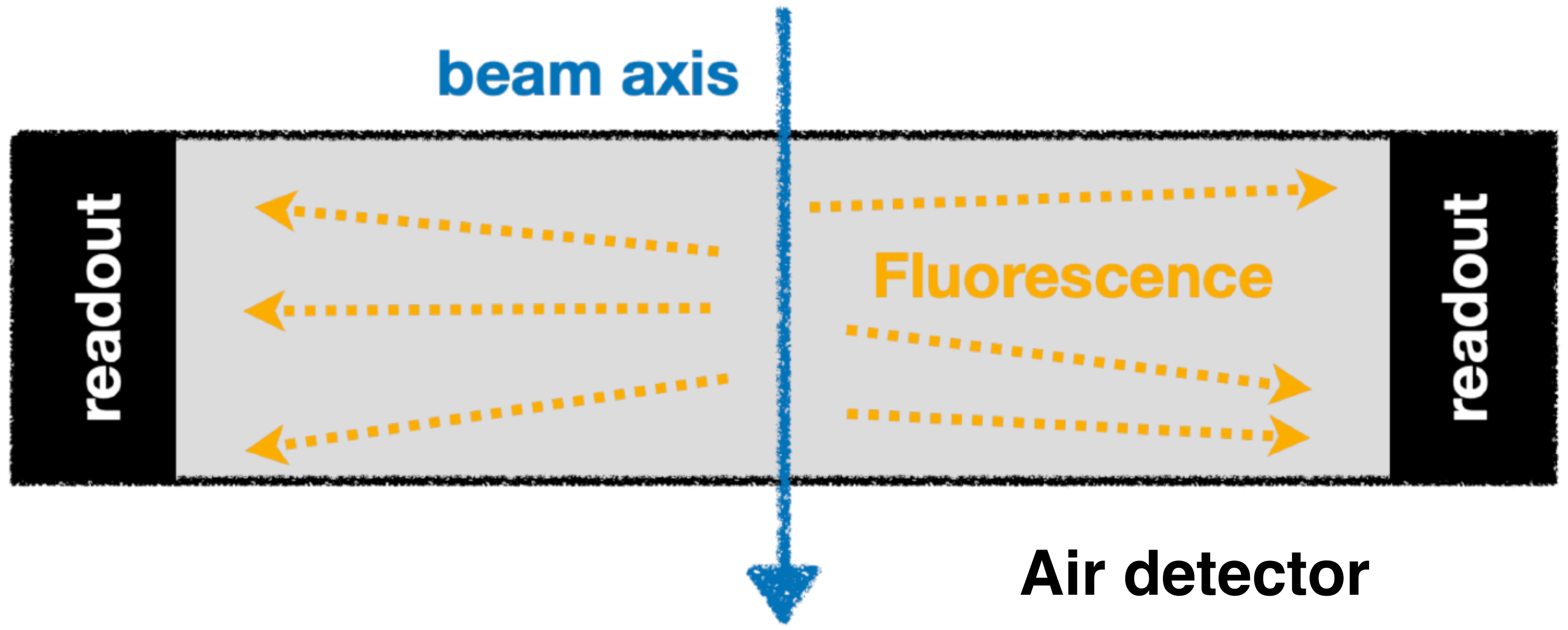

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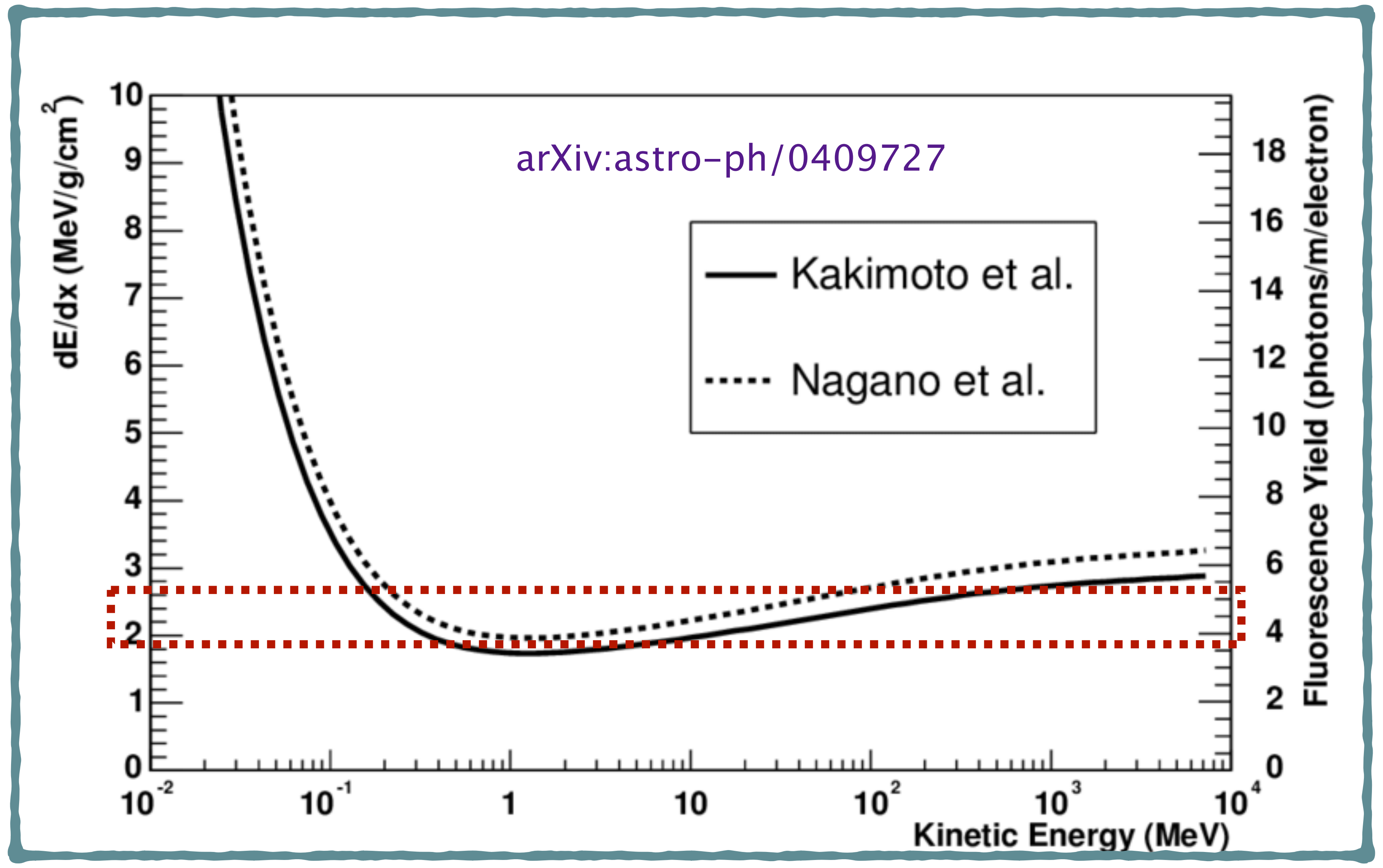


FLASH beam monitoring

First round: November 2020-June 2021

Second round: July 2021-June 2022

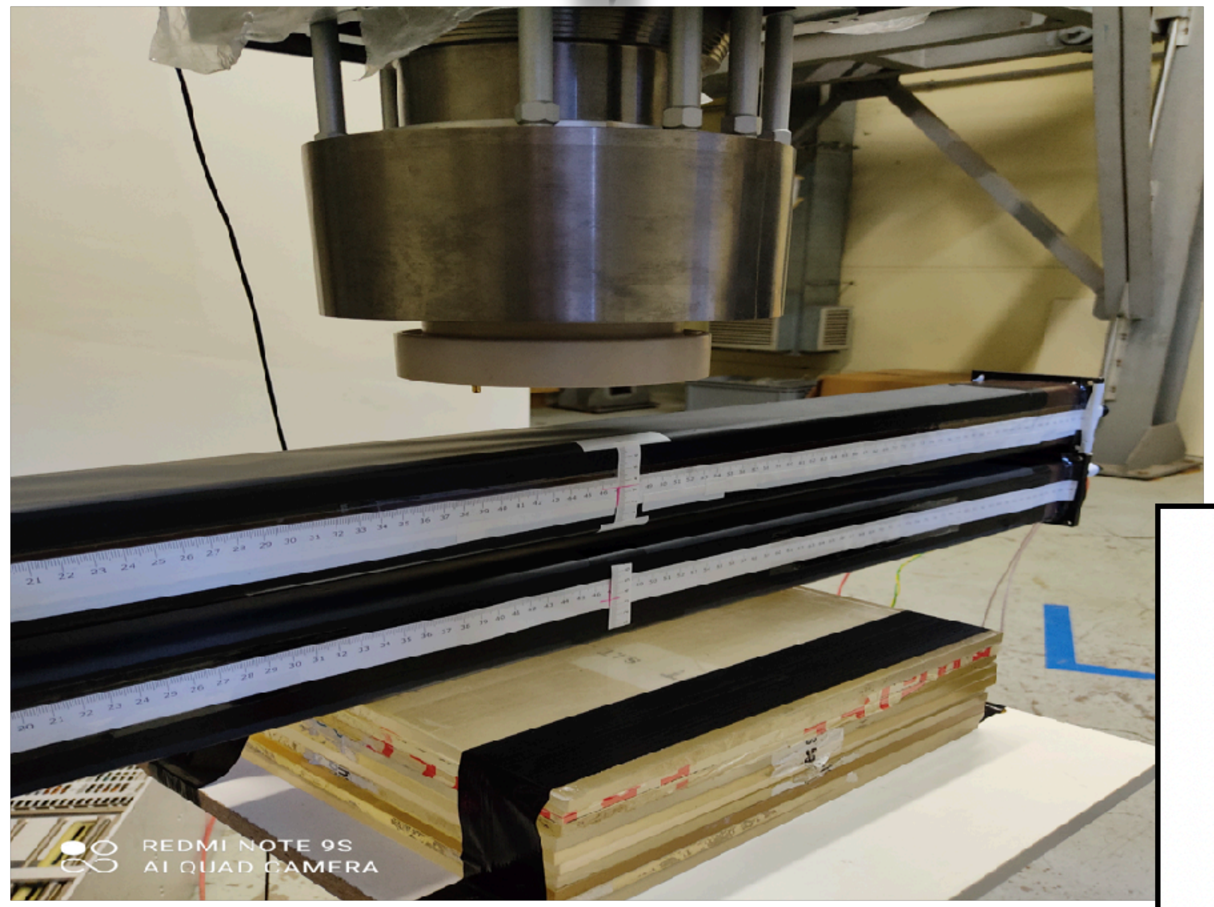
Third round: July 2022-June 2023

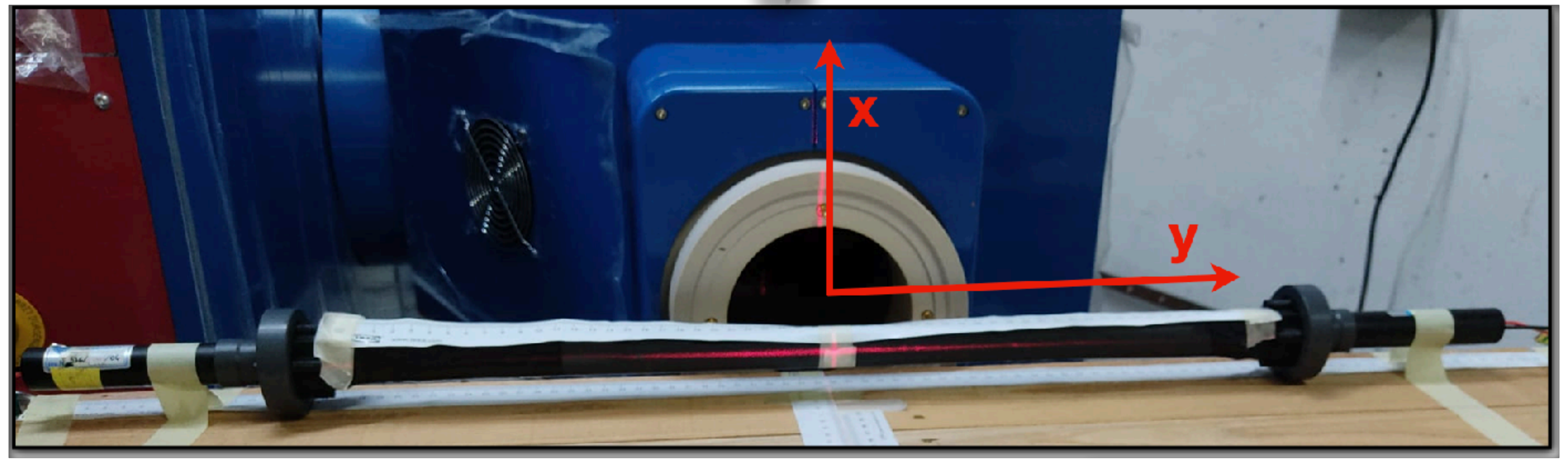
2021

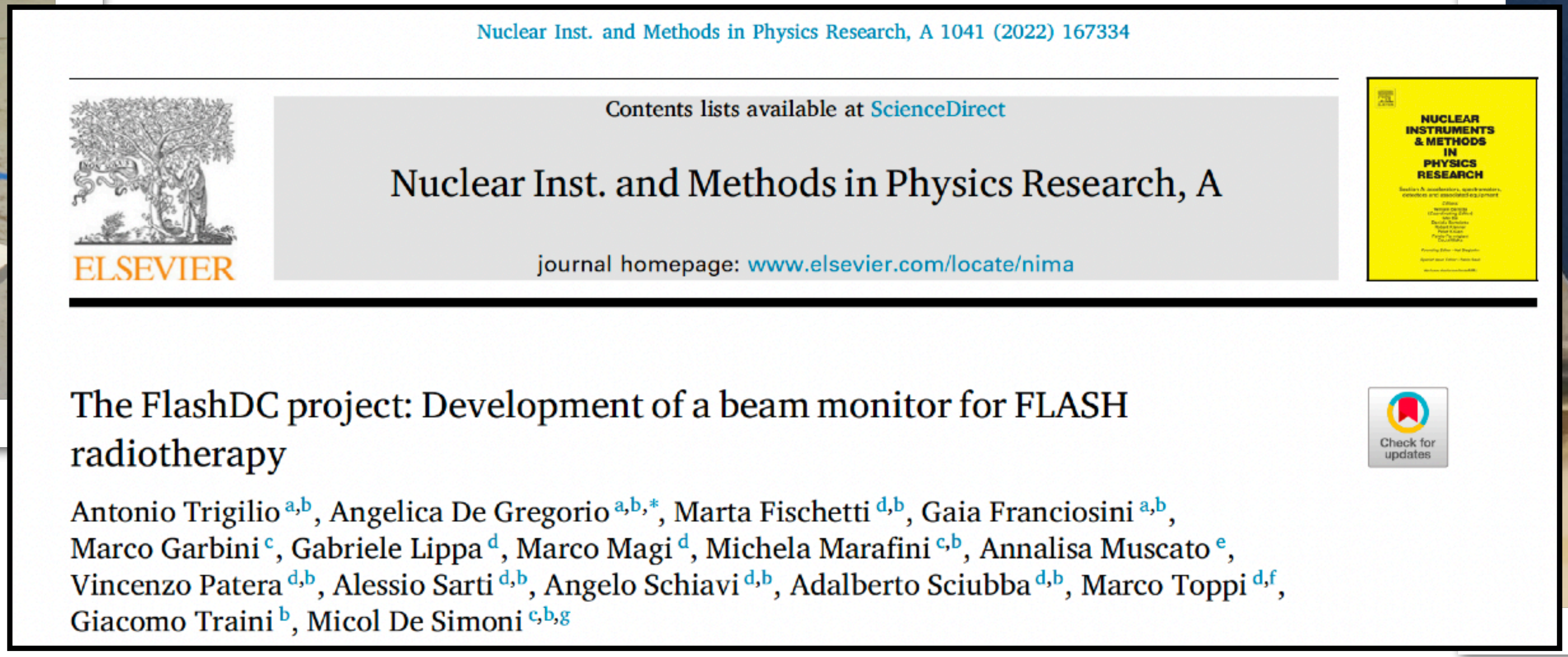
FLASH DC

2022

2023







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The FlashDC project: Development of a beam monitor for FLASH radiotherapy

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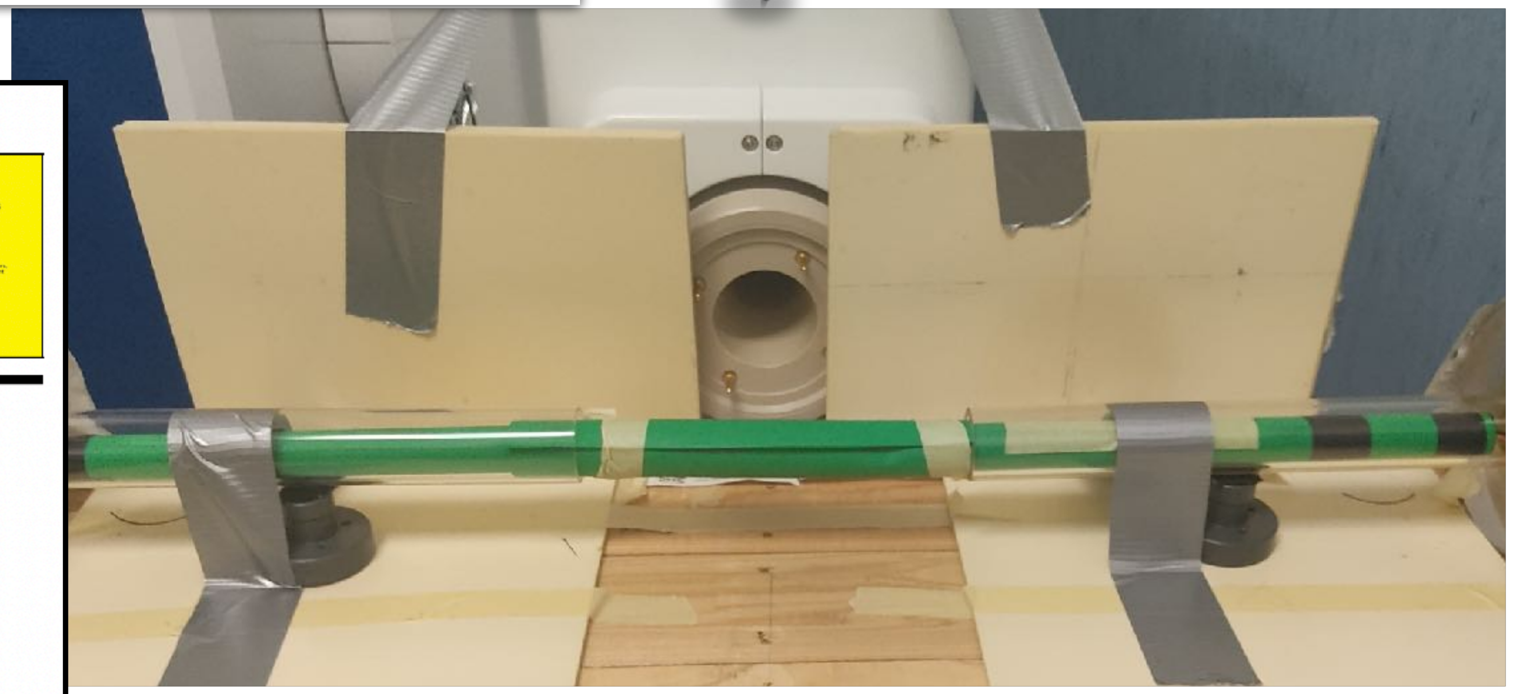
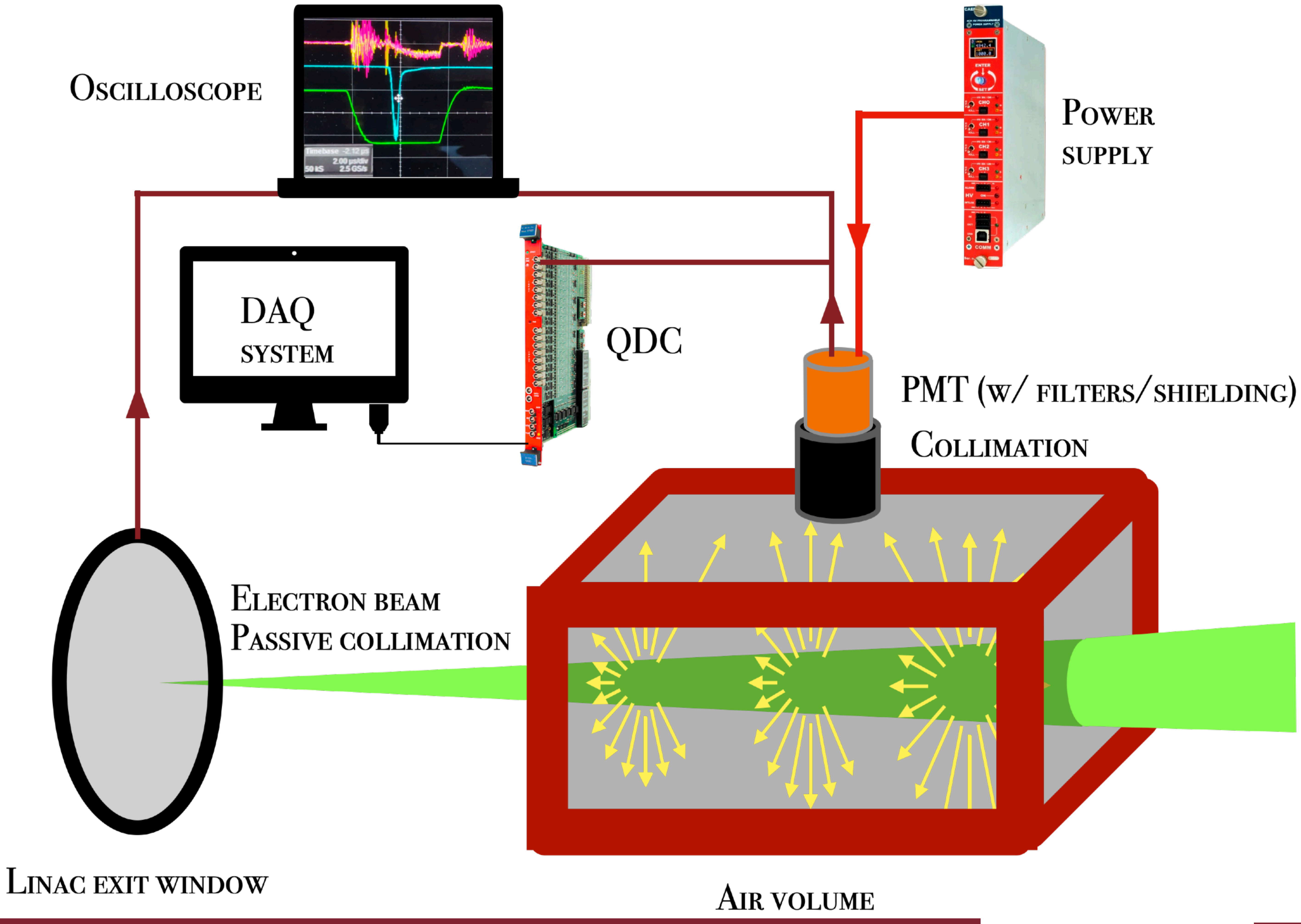


Article in writing...

FLASH beam monitoring

First round: November 2020-June 2021	Second round: July 2021-June 2022	Third round: July 2022-June 2023

- I worked with several prototypes testing the feasibility of a fluorescence-based beam monitor through different configurations and geometries.
- I have performed the design and testing focusing on the available sources of beams with FLASH intensities: low energy (6-12 MeV) electrons usually used for intra-operative applications.



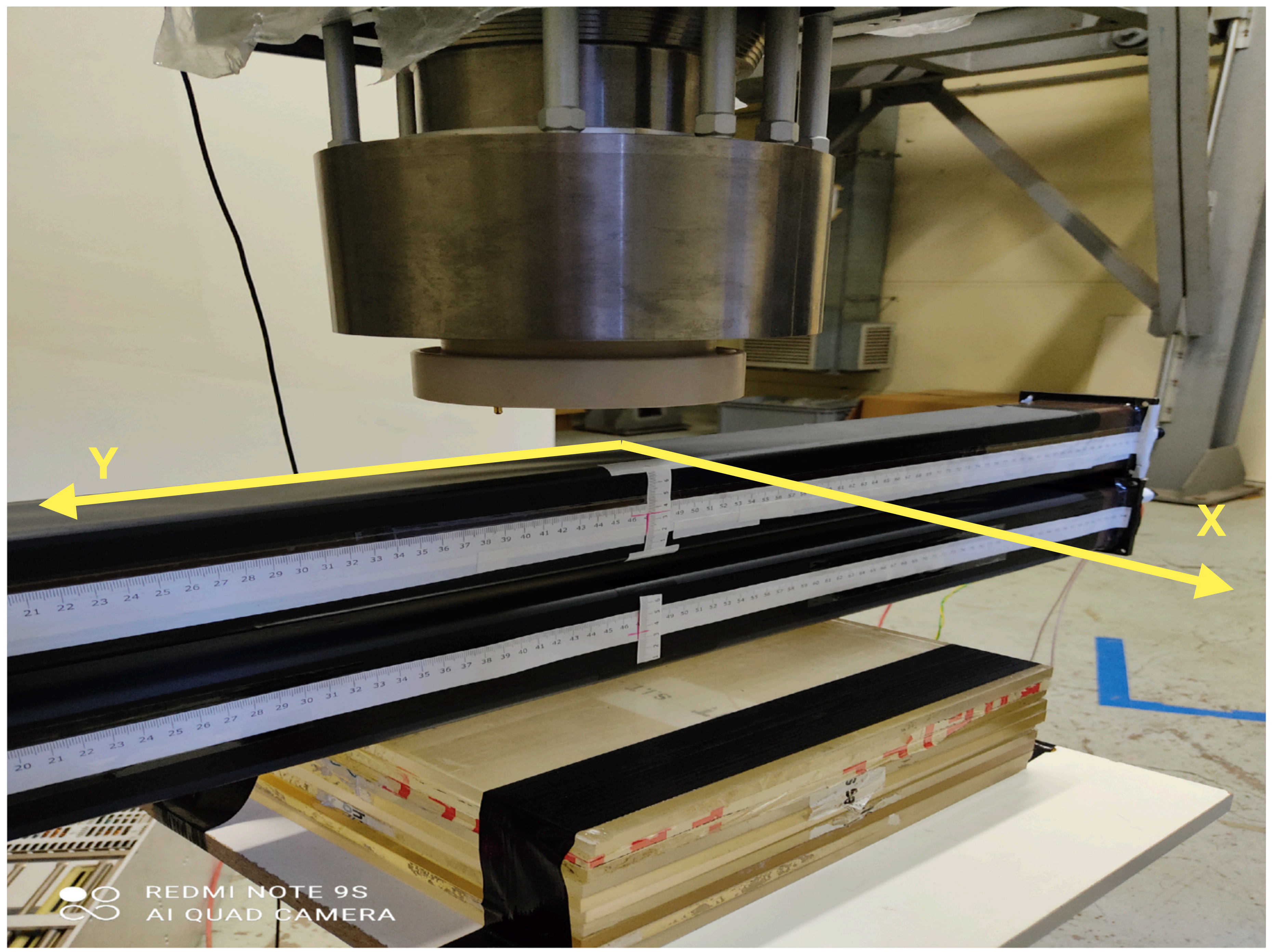
FLASH beam monitoring

First round:
November 2020-June 2021

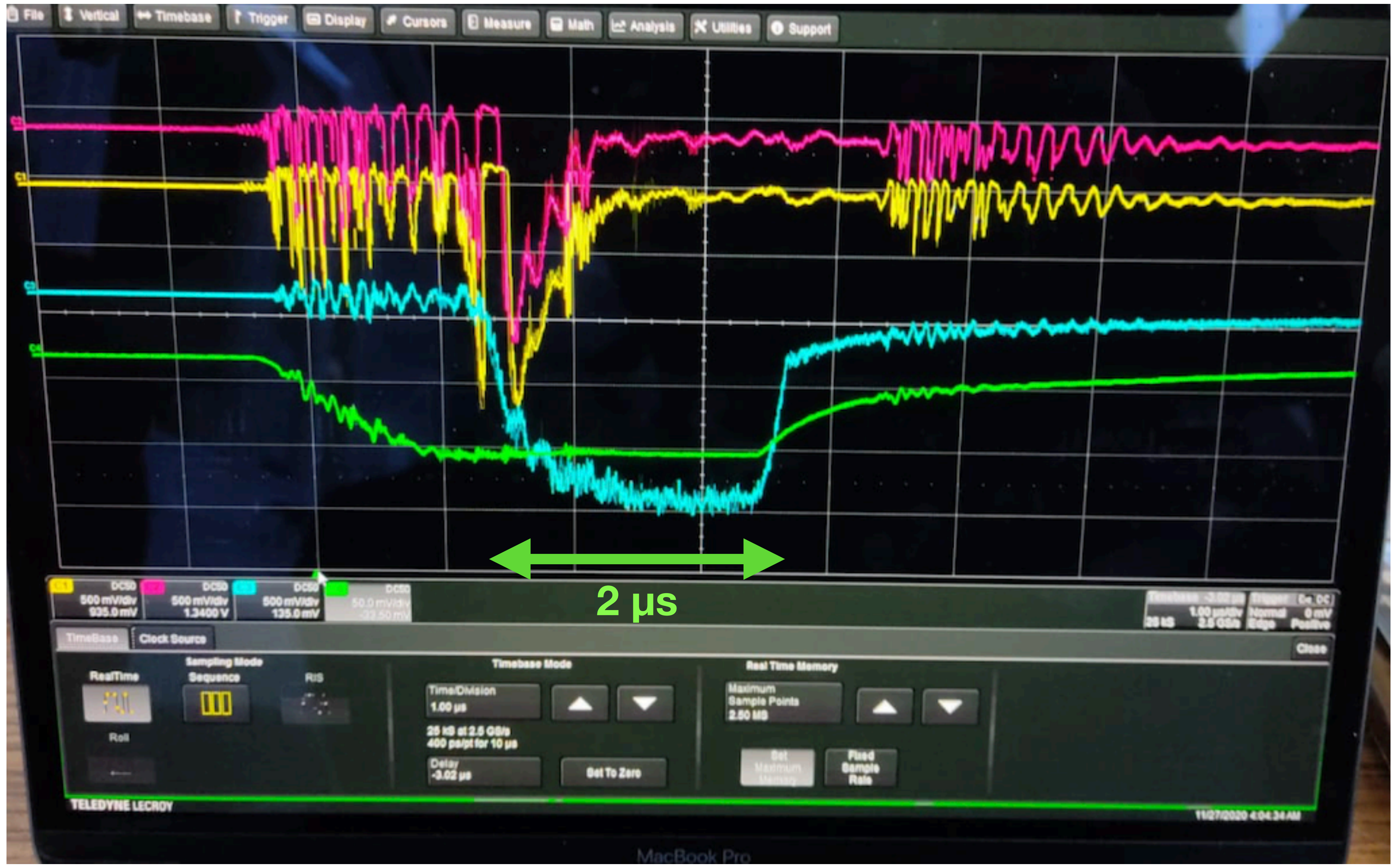
Second round:
July 2021-June 2022

Third round:
July 2022-June 2023

- The first objective is a successful **in-beam/off-beam** discrimination.
- The first prototype consisted in a volume of **7x7x90 cm³** of air, enclosed by a thin layer of Teflon sheet, with a PVC supporting structure and two PMTs on the opposite squared faces.

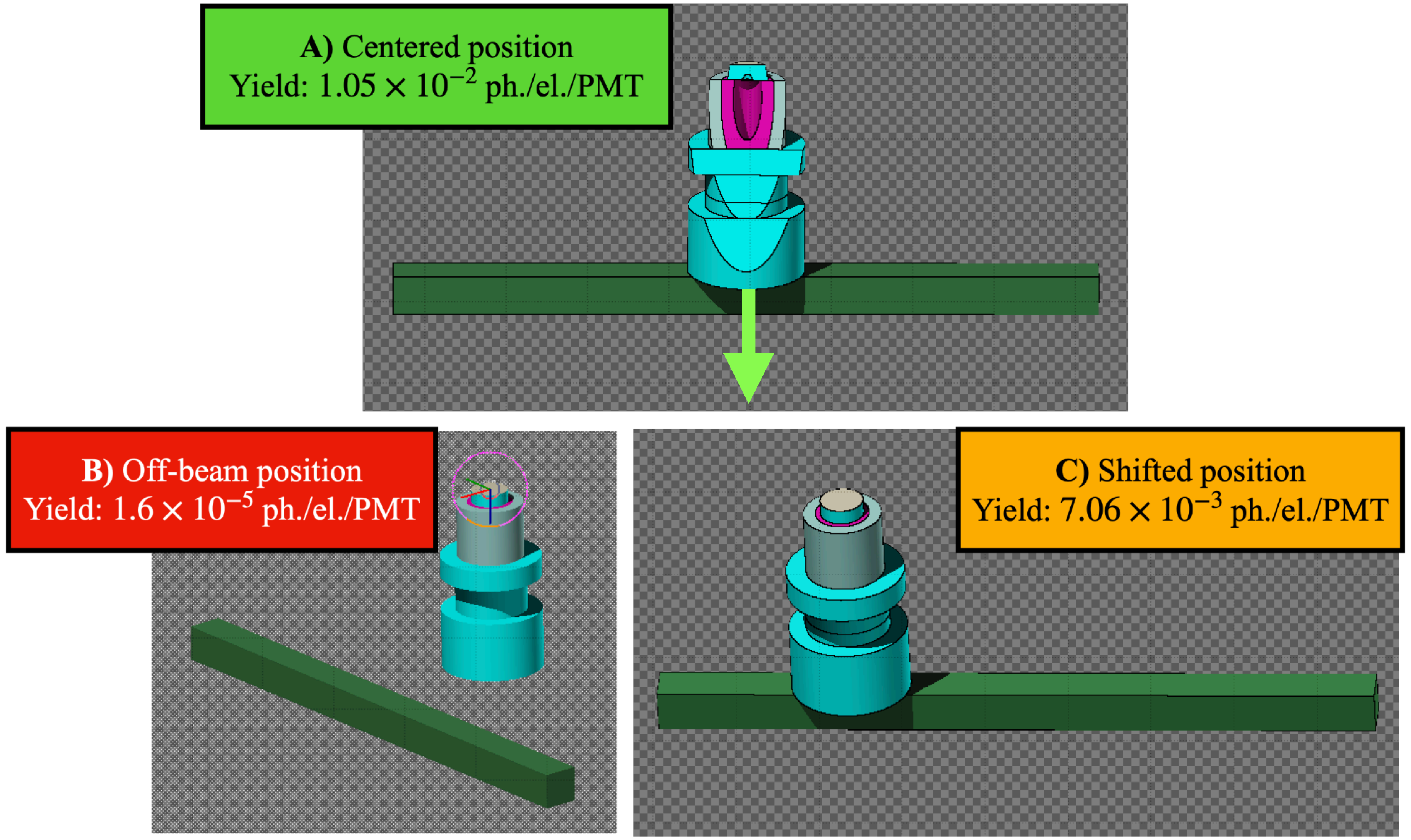


- The **signal** in charge is evaluated over the **pulse length**. Some PMTs saturate due to the oversized air volume. The gain had to be drastically lowered (down to 500 V).

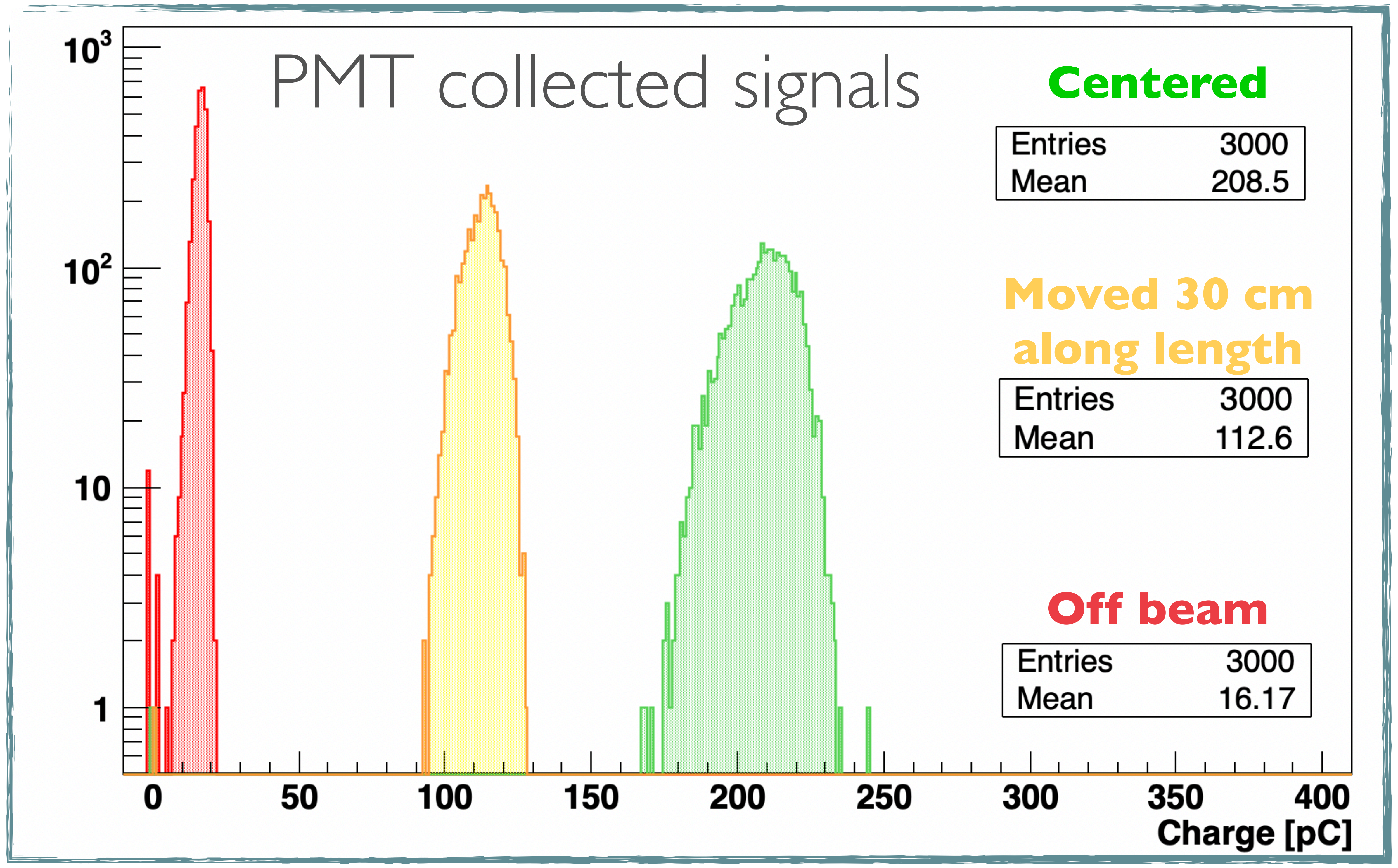


FLASH beam monitoring

First round: November 2020-June 2021 → Second round: July 2021-June 2022 → Third round: July 2022-June 2023



- I took part in the first data taking and performed the subsequent analysis.
- The results confirmed the expected signal sensitivity to the detector position with respect to the beam.

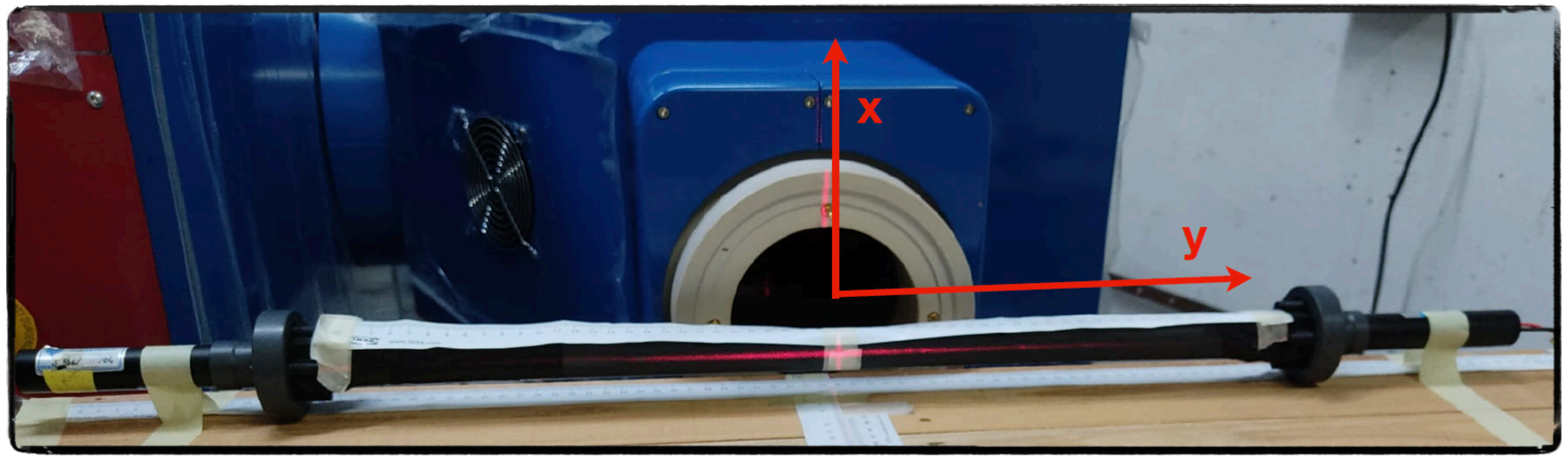


- I performed several runs of MC simulations to evaluate the expected signal (and background) in different configurations, and the **ratio** of optical photons reaching the PMTs when:
  - **Off-beam/In-beam** ($\approx 10^{-3}$)
  - **Absorbing/Reflecting** ($\approx 10^{-2}$)

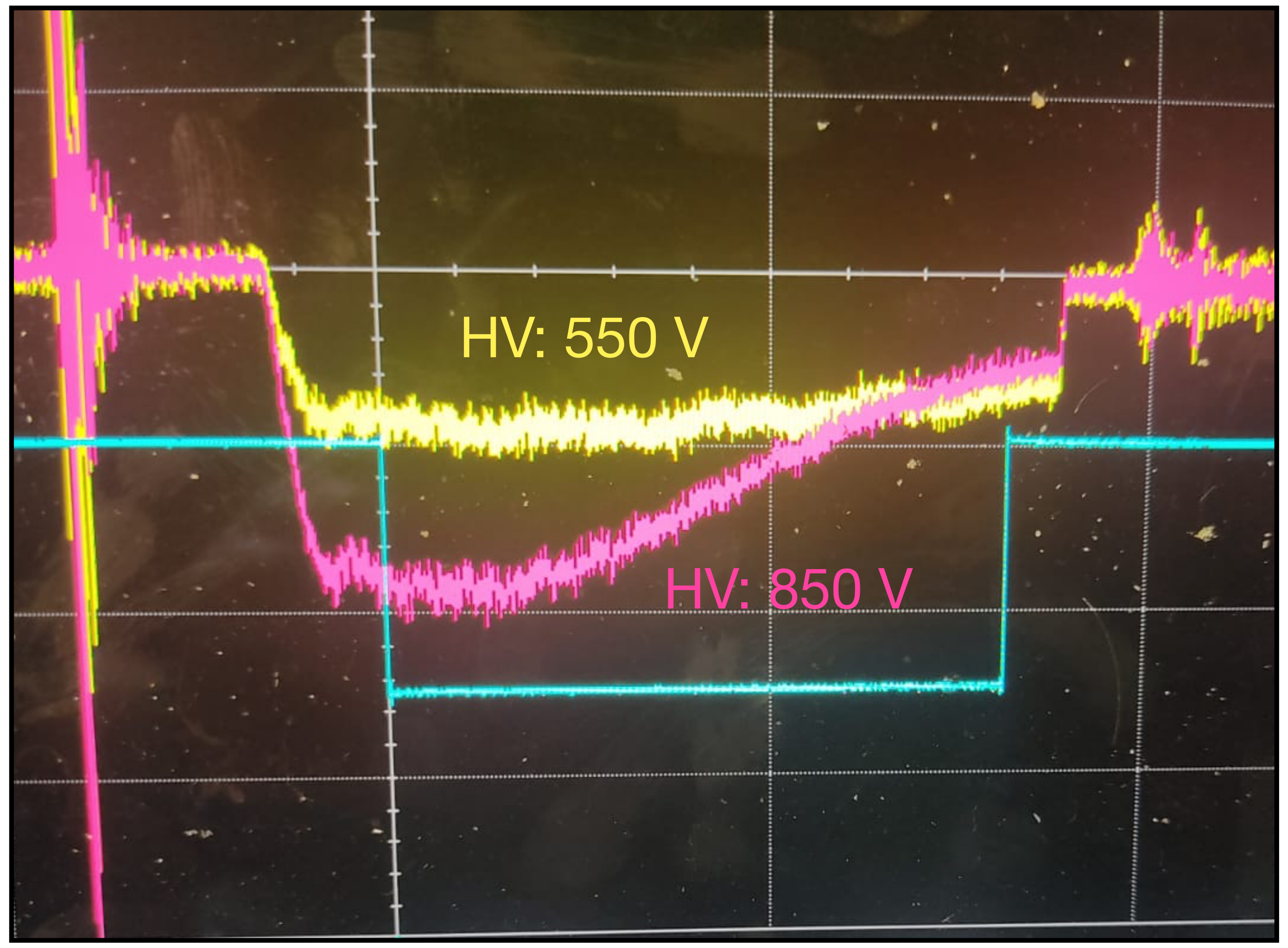
Indeed we should be able to tell the difference between positions.

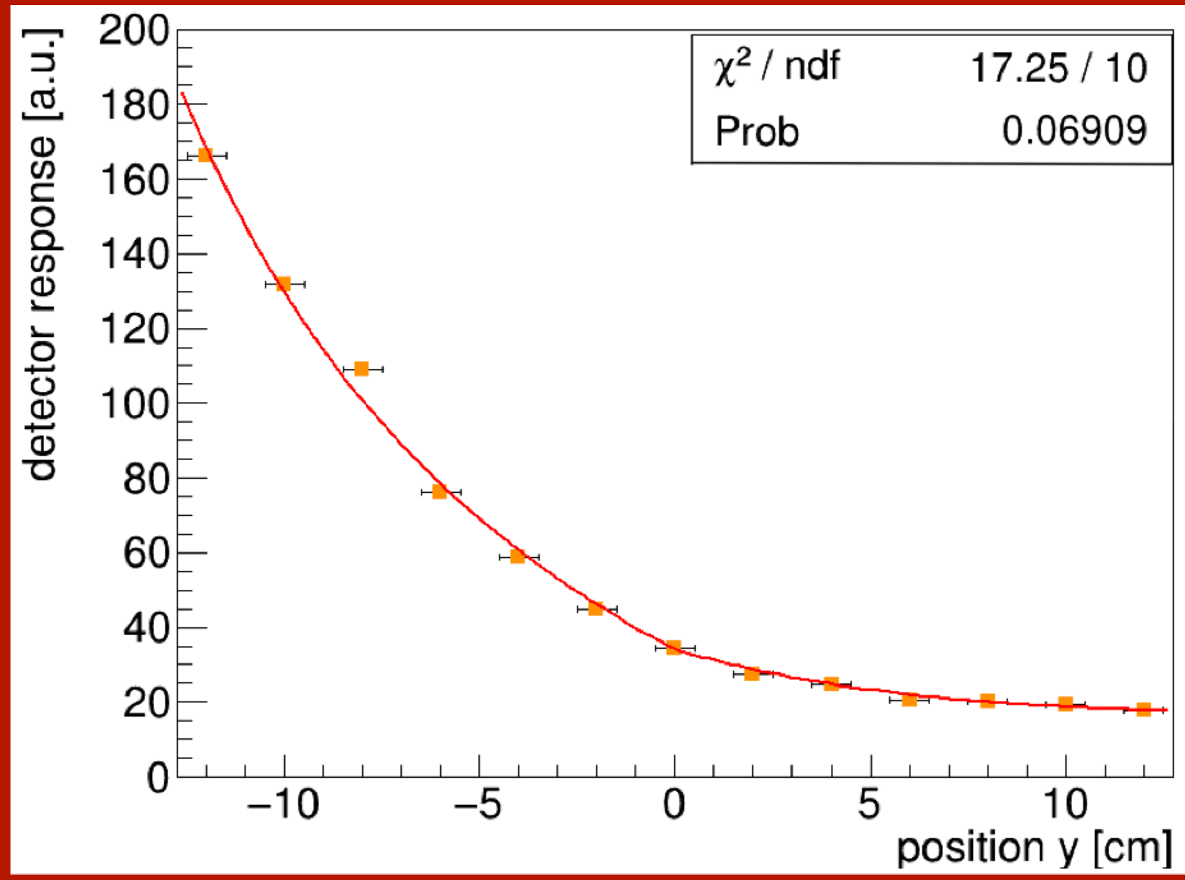
FLASH beam monitoring

First round: November 2020-June 2021 → **Second round:** July 2021-June 2022 → **Third round:** July 2022-June 2023



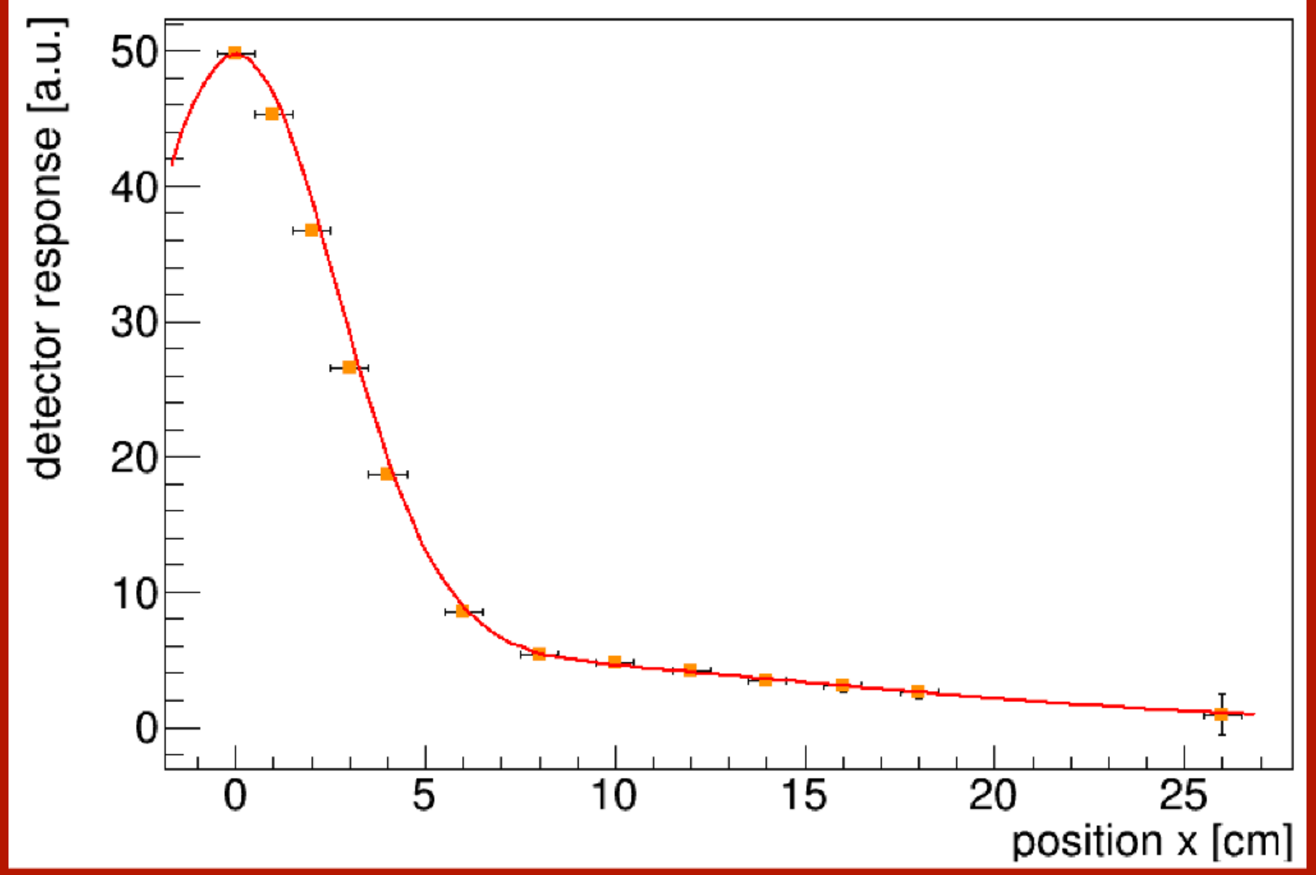
- These pieces of information were useful to design the new prototype, with a smaller volume (**2x2x60** cm³).
- Equipped with **UV filters**.
- Meant for studies on both position and ***charge*** sensitivity.





- I performed the analysis verifying the expected geometry dependencies of the detector response in different positions.
- Further indication that the signal is indeed due to the production of optical photons **inside** the active volume.

- Plot obtained gradually moving the detector off the beam to reconstruct the transverse shape.
- The in-beam/off-beam difference is observed.



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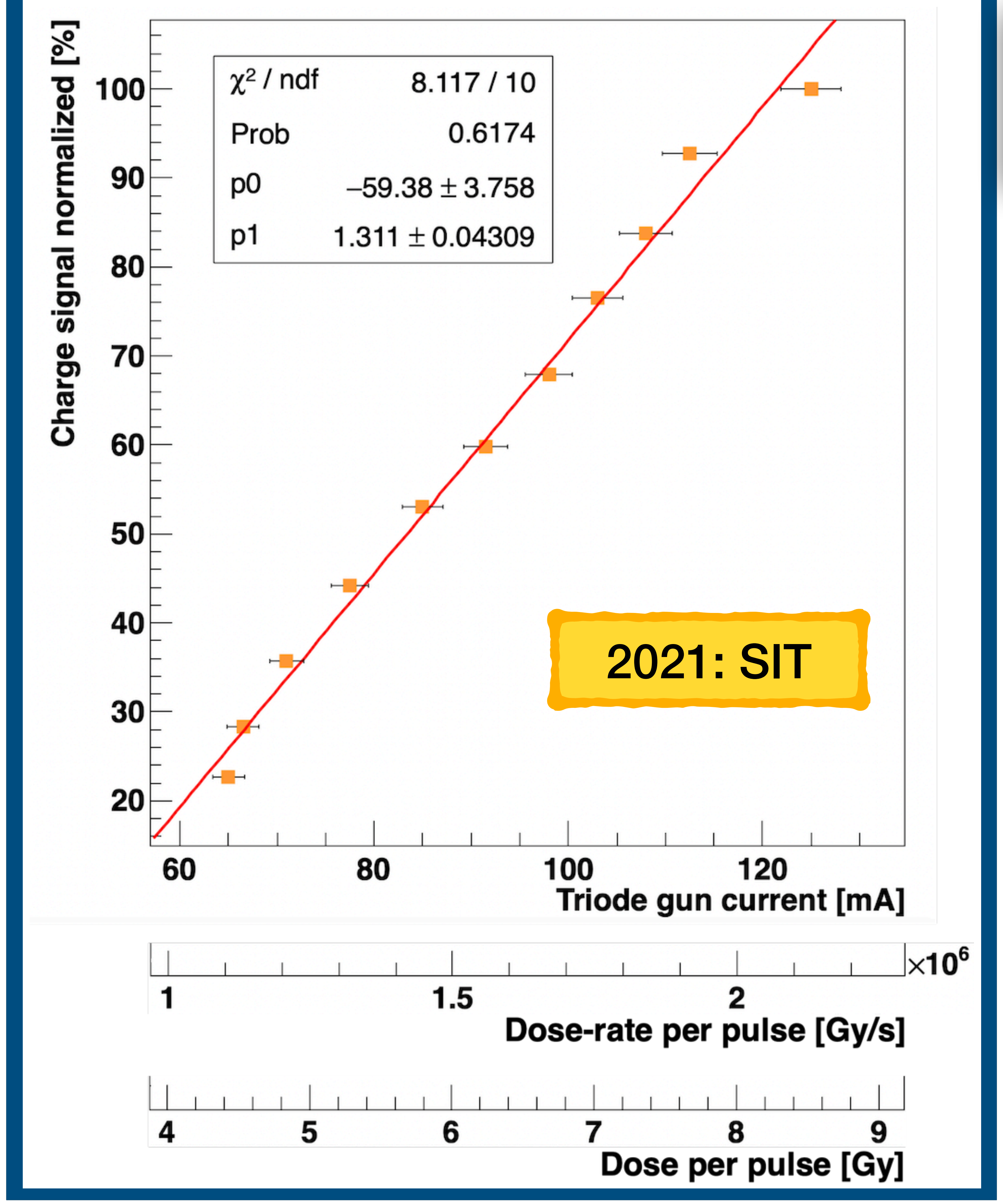
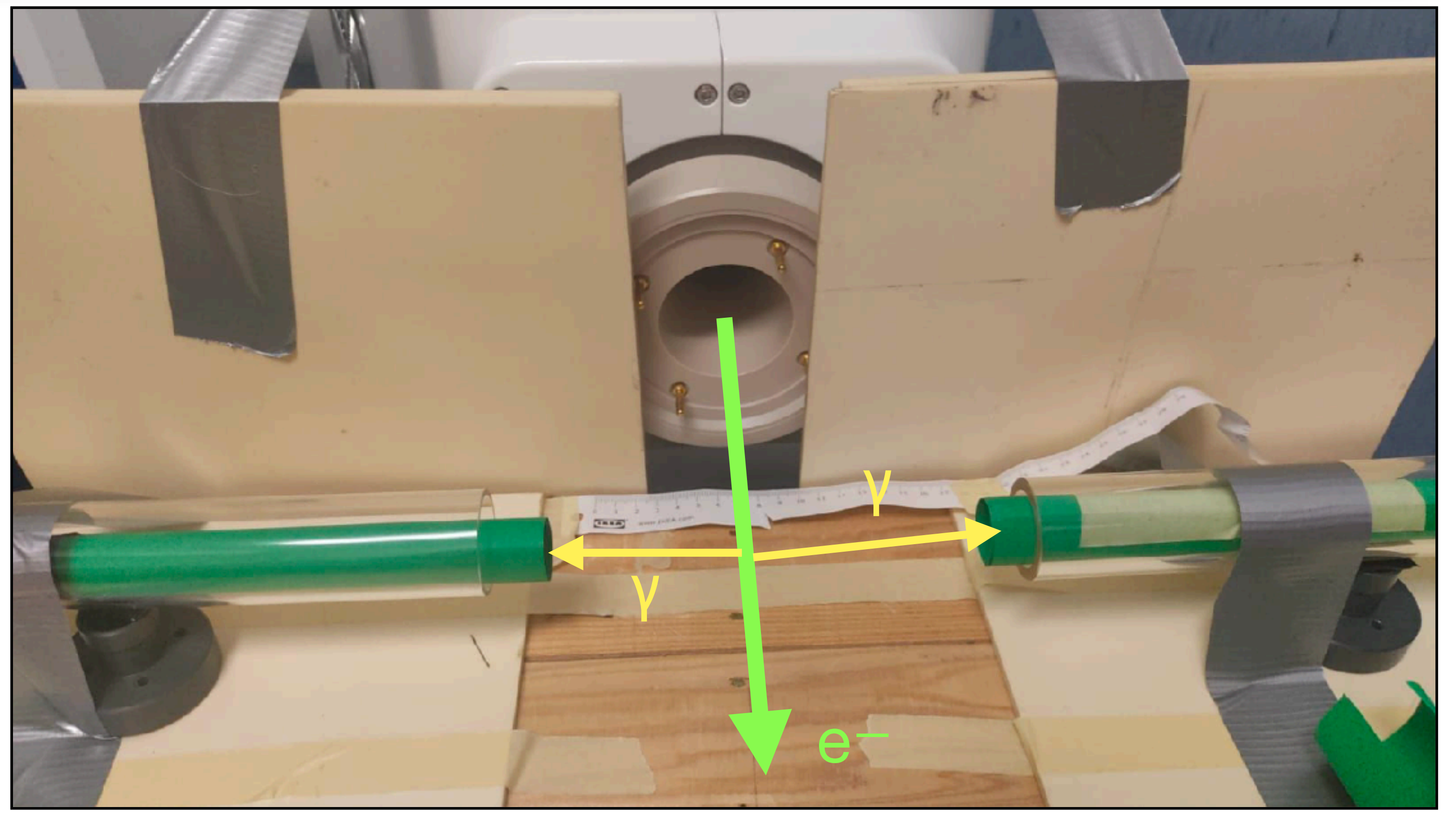
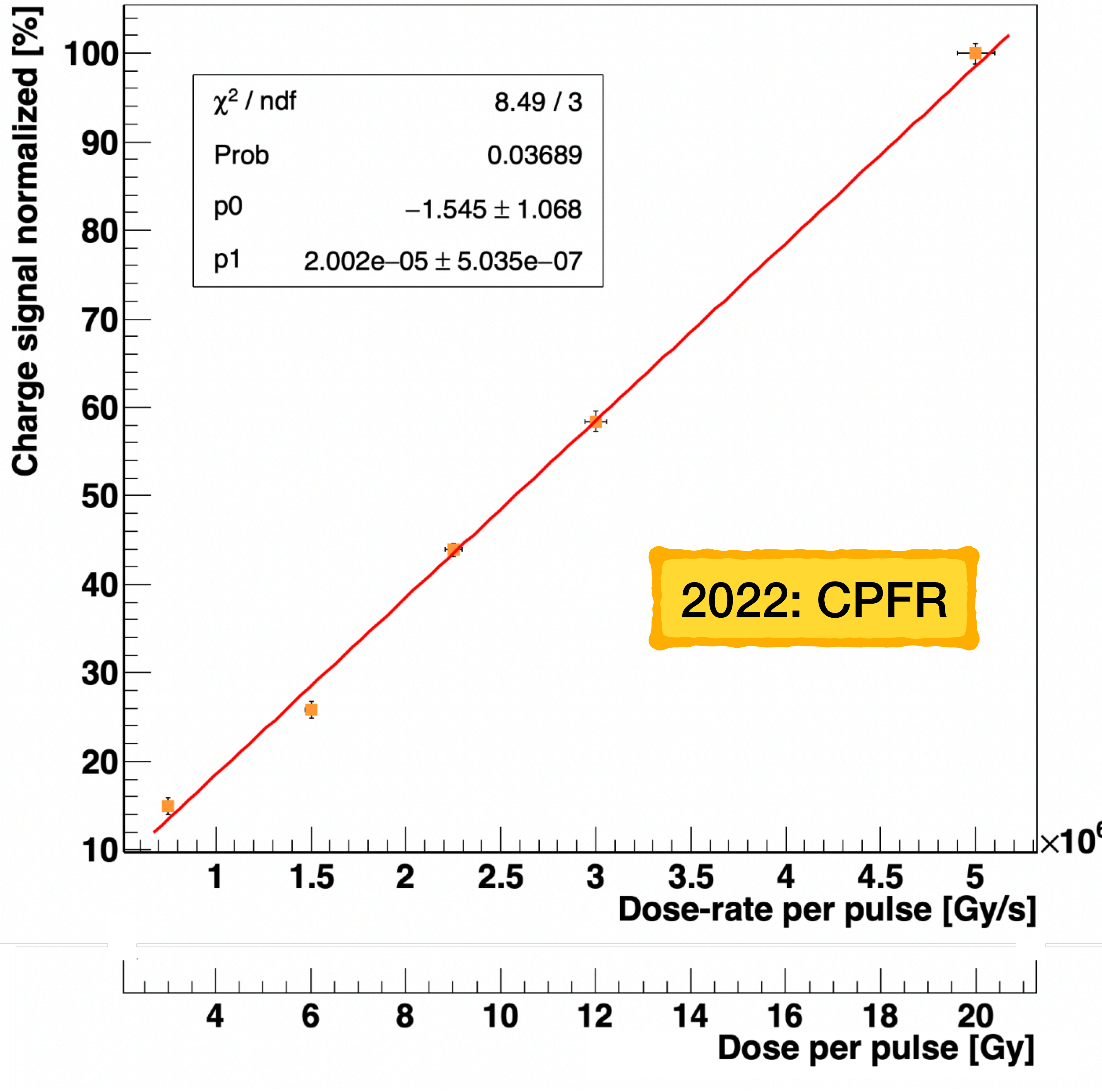


A linear response is observed over the full range of intensities explored.



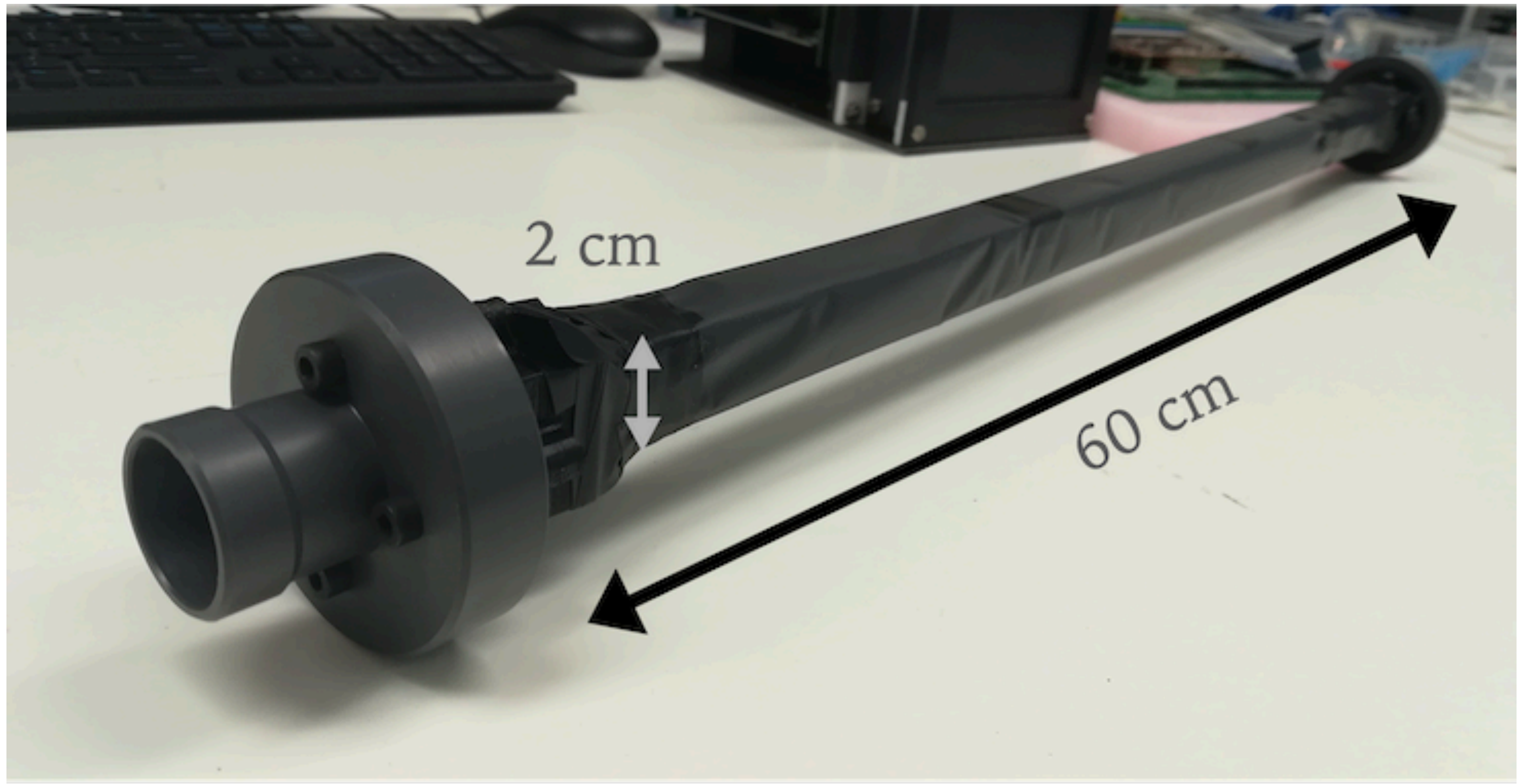
- The ElectronFlash, now available at CPFR in Pisa, is the first electron beam accelerator that can provide different beam currents: it is the best place to verify the detector linearity!
- I repeated the measurement, also starting to modify the geometry in order to perform background subtraction studies.

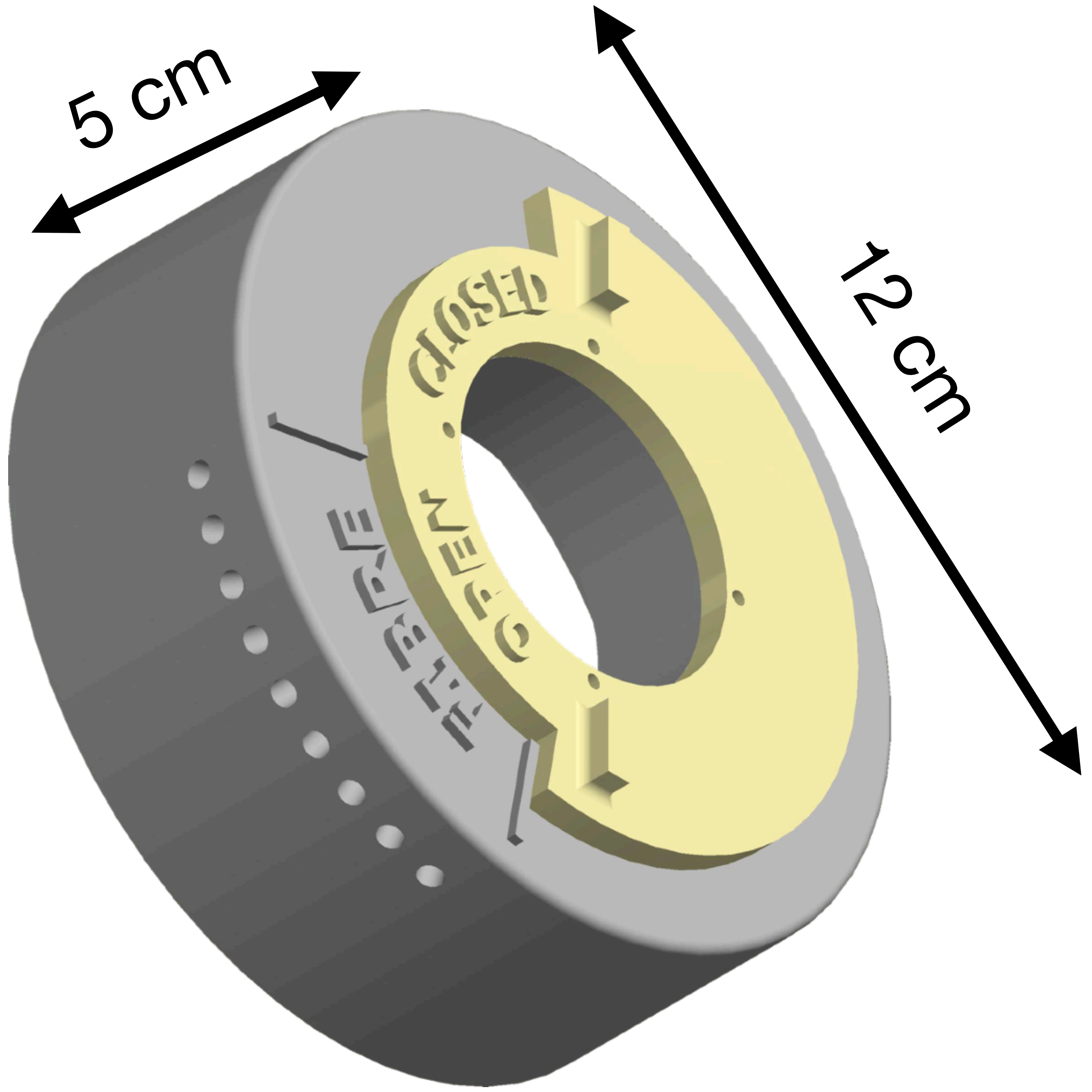


FLASH beam monitoring

First round: November 2020-June 2021	Second round: July 2021-June 2022	Third round: July 2022-June 2023

- Next step is to prove that the expected linearity of signal *vs* beam current is really due to fluorescence => subtract background.
- The active volume is the air immediately after the beam exit window, enclosed in this cylindrical case. A sliding leaf on the external face can be closed and opened for background measurement.





FLASH beam monitoring

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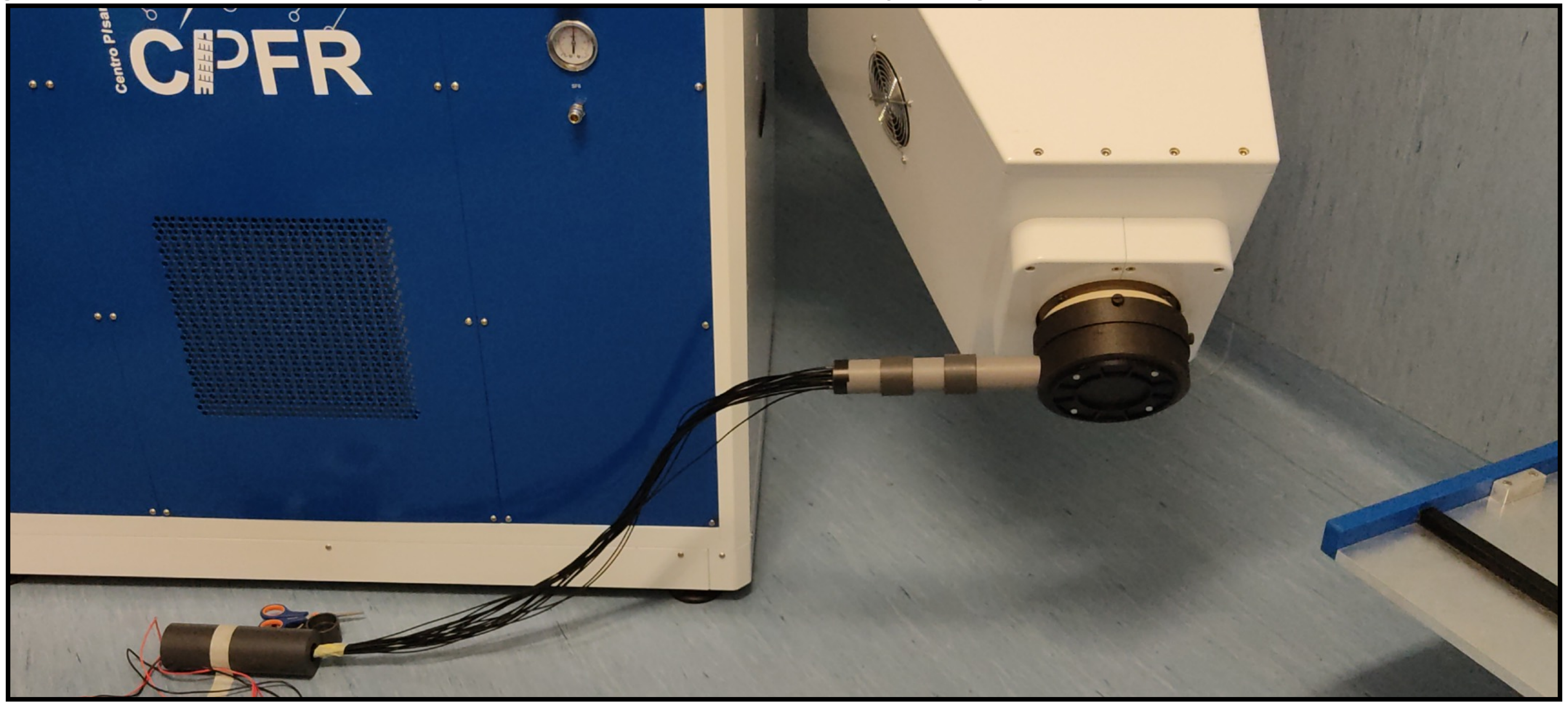
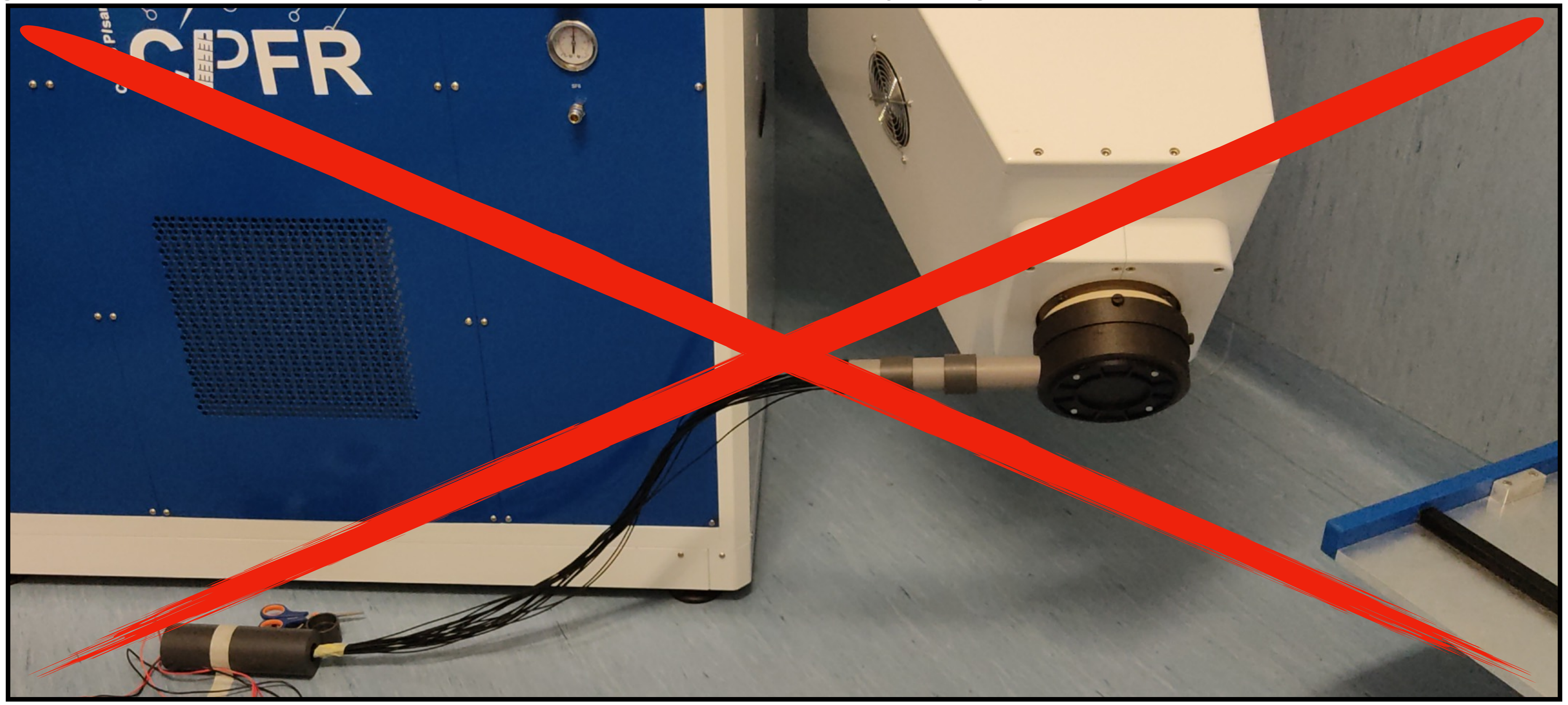


- The detector is directly attached to the linac.
- In this configuration, the active volume is too close to the Beam Exit Window: I need to carry the signal away towards the PMT (wrapped in a plastic shield with thickness of 2 cm.
- I performed preliminary measurements in order to verify whether optical fibers could be used to transmit fluorescence photons, distancing them from the machine by means of a hollow pipe.

FLASH beam monitoring

First round: November 2020-June 2021 → Second round: July 2021-June 2022 → Third round: July 2022-June 2023



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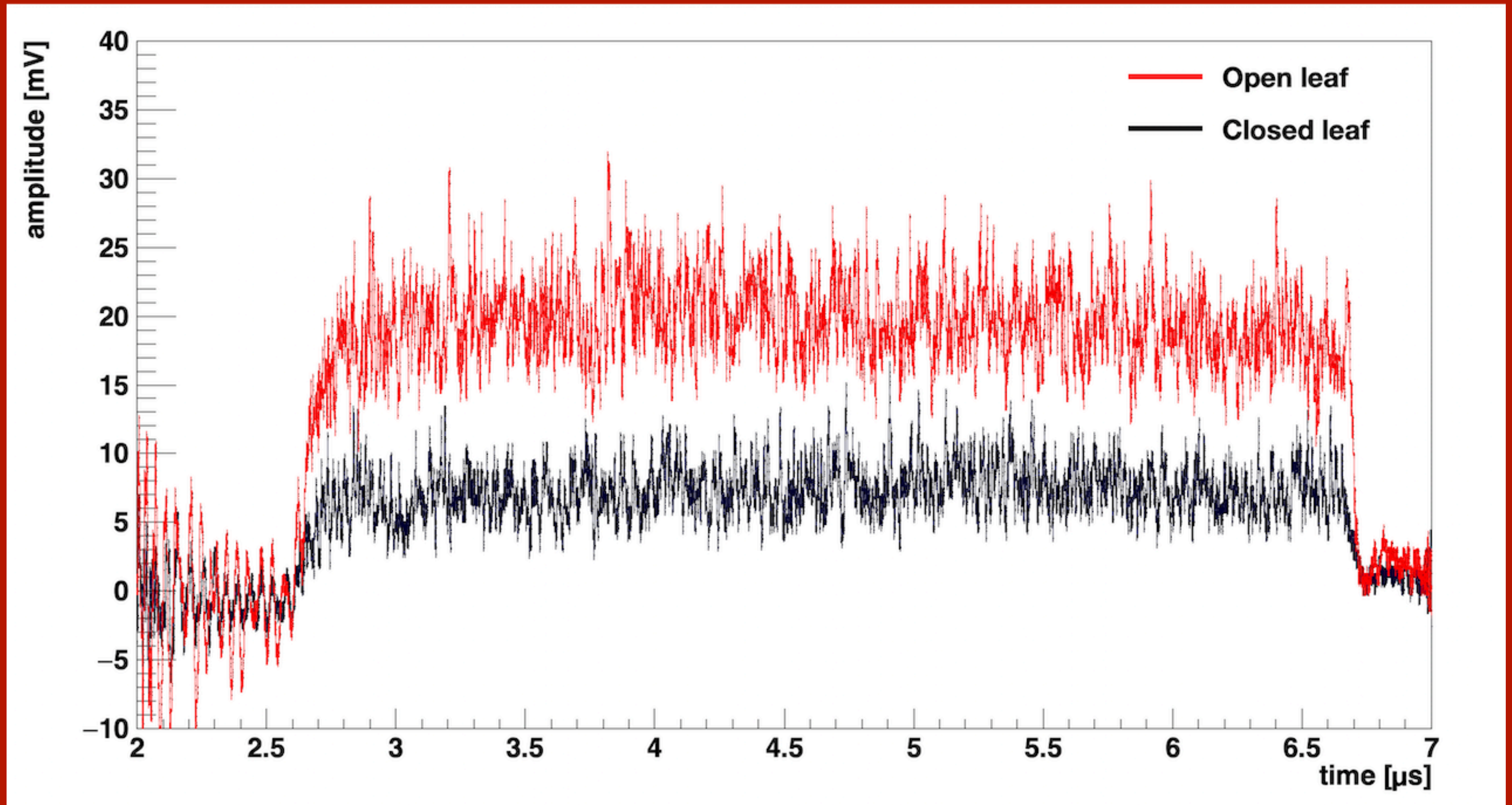
- I performed preliminary measurements in order to verify whether optical fibers could be used to transmit fluorescence photons, distancing them from the machine by means of a hollow pipe.

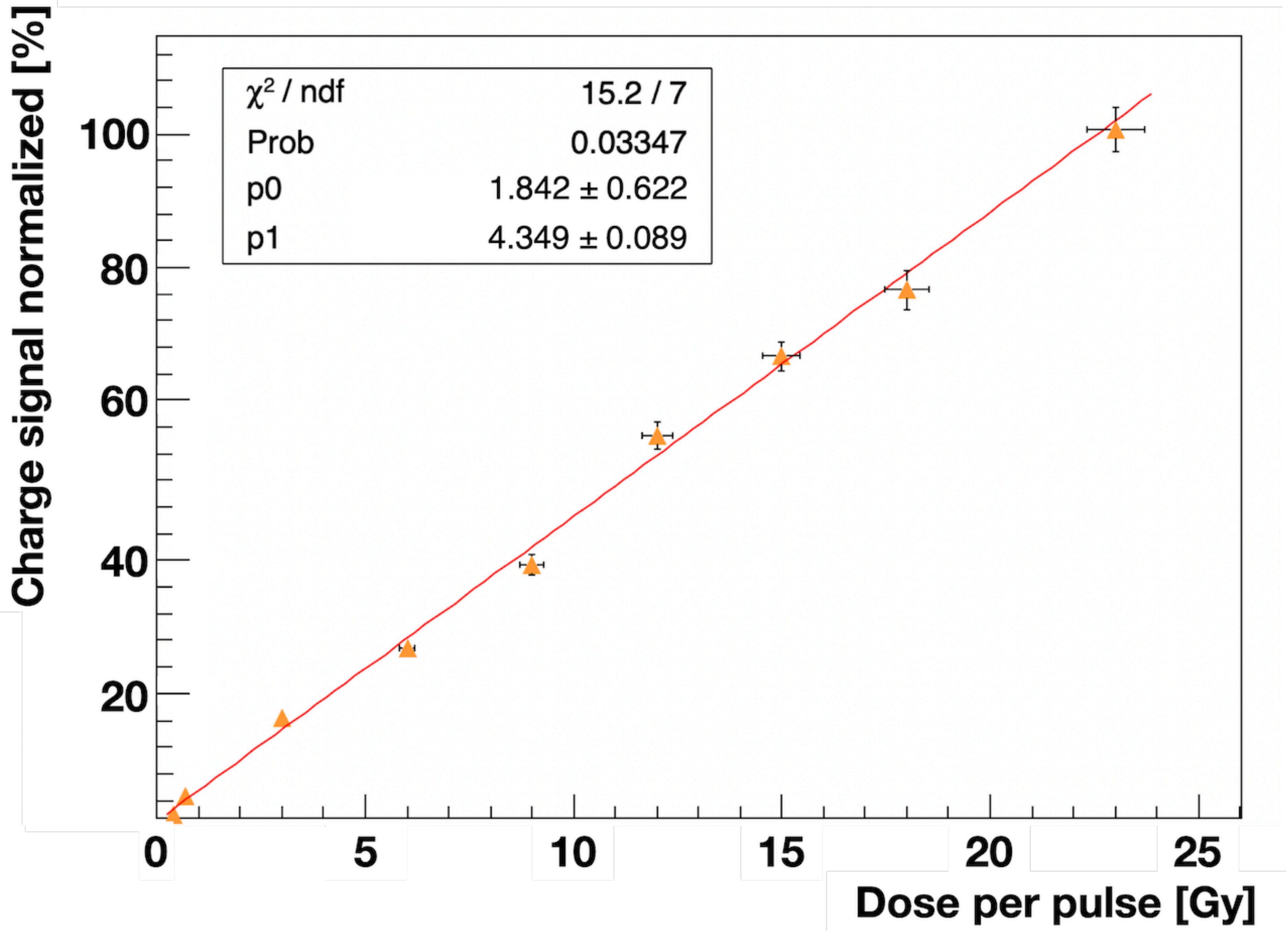
- No difference observed between signals with closing window switched-on/off. Cherenkov is too important, even at 2 m away from the machine.
- For the second round of testing at Pisa, I removed the fibers and put the PMT at 1.2 m from the beam exit window.

FLASH beam monitoring

First round: November 2020-June 2021	Second round: July 2021-June 2022	Third round: July 2022-June 2023

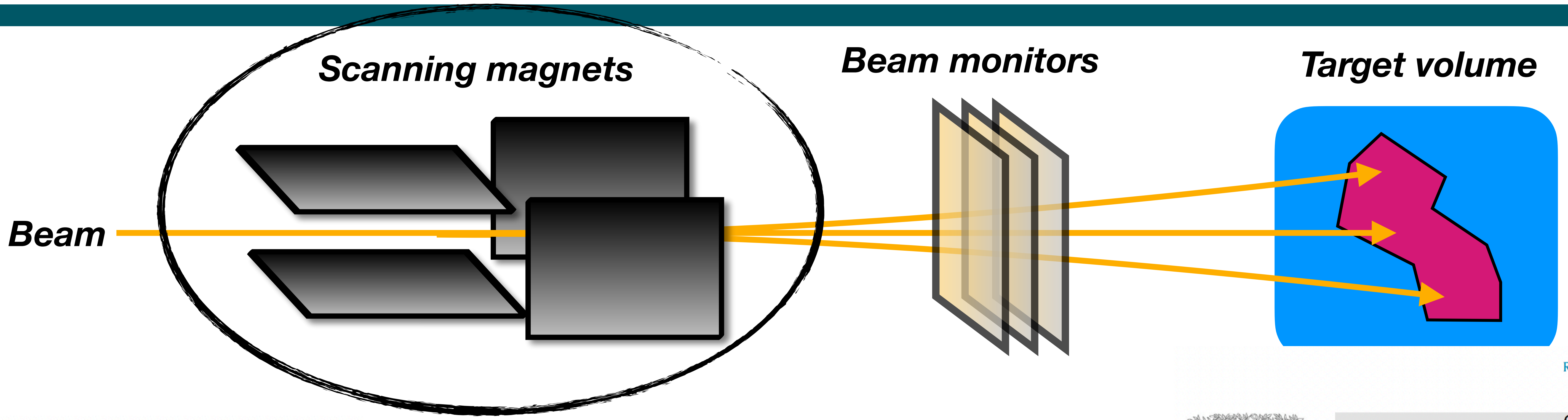
- Background can be successfully subtracted, although with this setup it is a sizable portion (~35%) of the total signal. Moreover, the gain of the PMT is still non-optimal for the fluctuations of the signal amplitude.
- The readout system and the geometry need to be optimized to increase the signal-to-noise ratio.





- The statistics is quite low (30 events per point), and the uncertainty has been put to 3% considering a systematic uncertainty on the D_p value.
- Linearity plot obtained with signal background-subtracted. **Fluorescence linearity is verified.**

VHEE + FLASH: natural partners?



Description	value
Beam energy	> 130 MeV
RF frequency	5.712 GHz
Pulse repetition frequency	100 Hz
Pulse duration	< 3 μs
Max charge per pulse	600 nC
Max pulse current	200 mA
In-pulse dose-rate	> 10^7 Gy/s
Dose per pulse	>> 1Gy
Total treatment time	<100 ms
Average dose rate	>100 Gy/s

Parameter list of the VHEE LINAC.

- As of today, only electrons of **low-to-intermediate** energy (<20 MeV) are used to treat **superficial tumors** or for IOeRT applications.
- The idea to use electron beams with E > 50 MeV (***Very High Energy Electrons - VHEE***) to cure deep seated tumors has gained interest.
- A VHEE linac has been proposed as a collaboration between Sapienza and INFN, the ***SAFEST*** project.
- Beam delivery is an issue: FLASH does not allow for the loss of spatial conformity.

Radiotherapy and Oncology 175 (2022) 210–221

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Radiotherapy and Oncology

journal homepage: www.thegreenjournal.com

Review Article

FLASH radiotherapy treatment planning and models for electron beams

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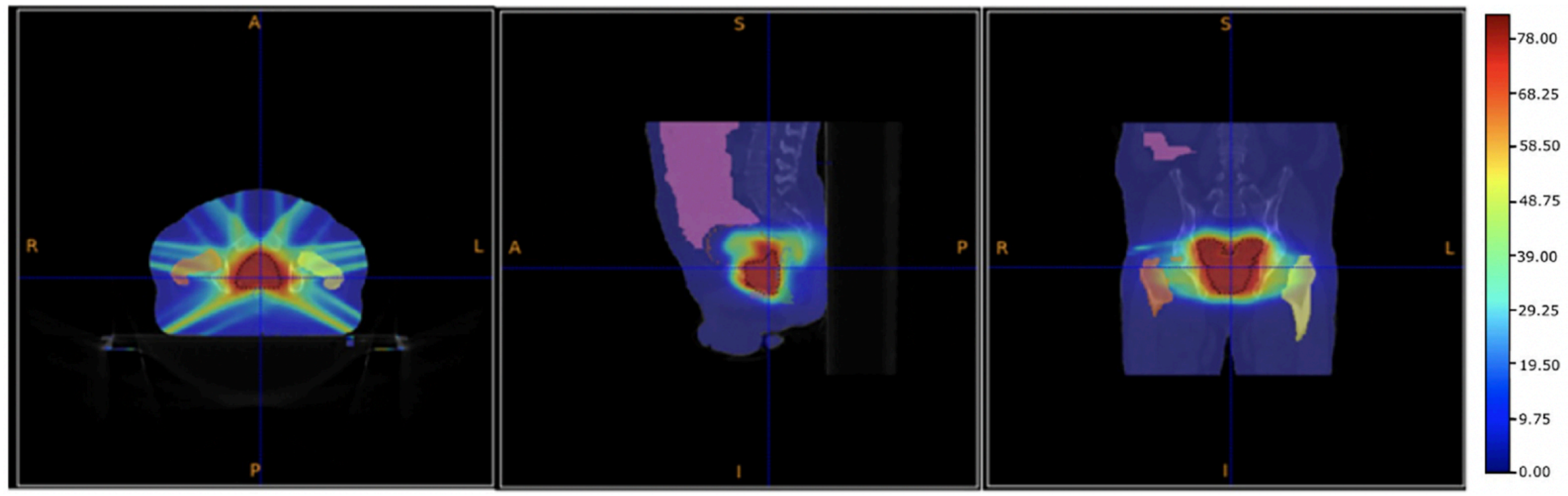
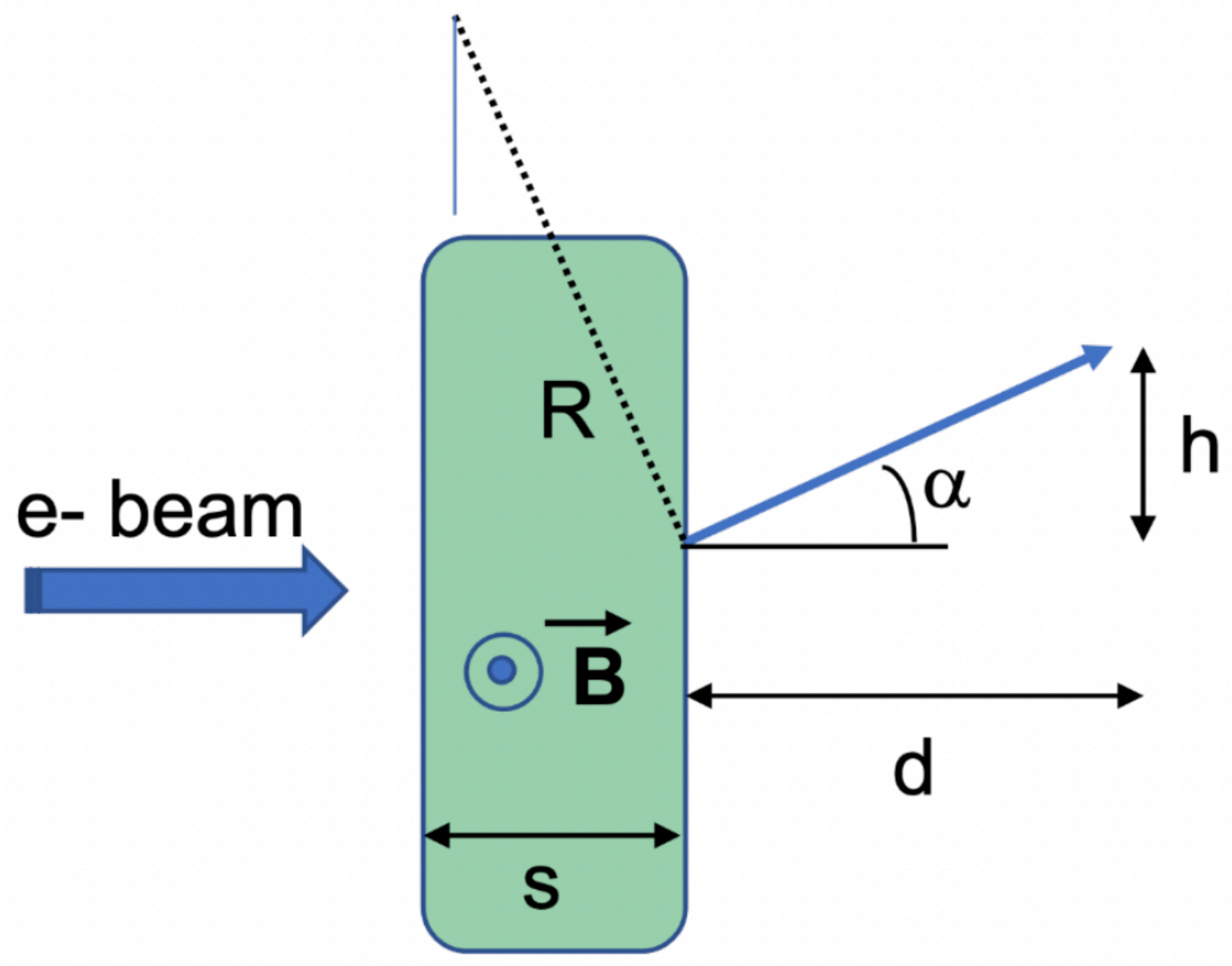


Sarti A et al (2021) Deep Seated Tumour Treatments With Electrons of High Energy Delivered at FLASH Rates: The Example of Prostate Cancer. Front. Oncol. 11:777852. doi: 10.3389/fonc.2021.777852

Magnetic scanning system

- Due to the intrinsic technological features of a compact VHEE-LINAC, the resulting beam is a collimated, narrow "**pencil beam**".
- Requires either passive or **active** scanning system to cover the full target volume.
- Option: Two-dimensional dipole shifting the beam direction at each pulse changing the current, to be evaluated for a 100 MeV electron.



- **Time factor:** The magnetic sweeping should not introduce any delay in the dose delivery to keep the high dose rate needed in the FLASH modality.
- The beam sweeping must take less time than the inverse of the pulse repetition frequency of the LINAC.
- Using the scanning system for the CNAO center of oncological hadron therapy as reference, the upper limit is ~5 kHz.

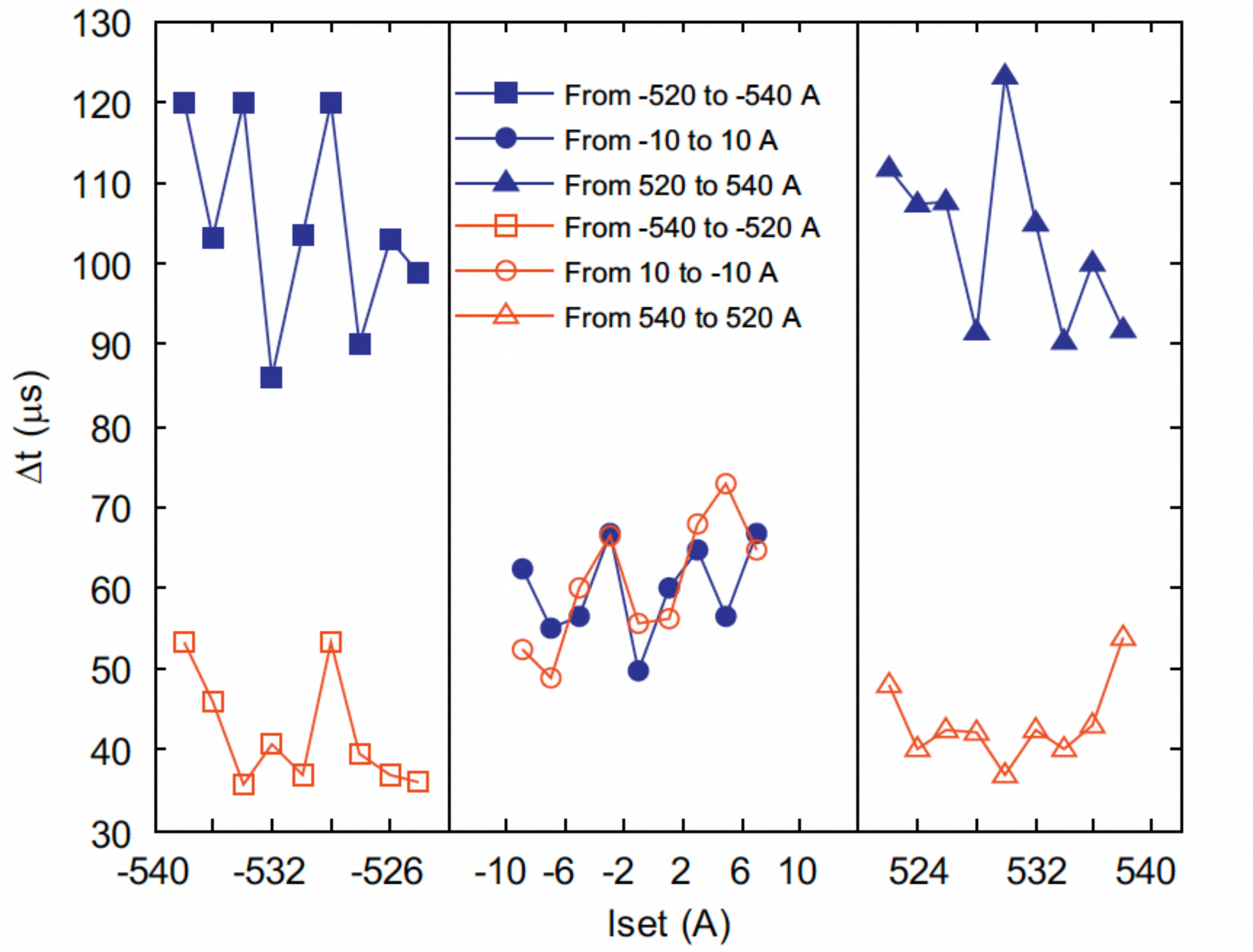


Fig. 10. Transient time (Δt) between 20% and 80% of 2 A steps as a function of I_{set} for increasing and decreasing currents.

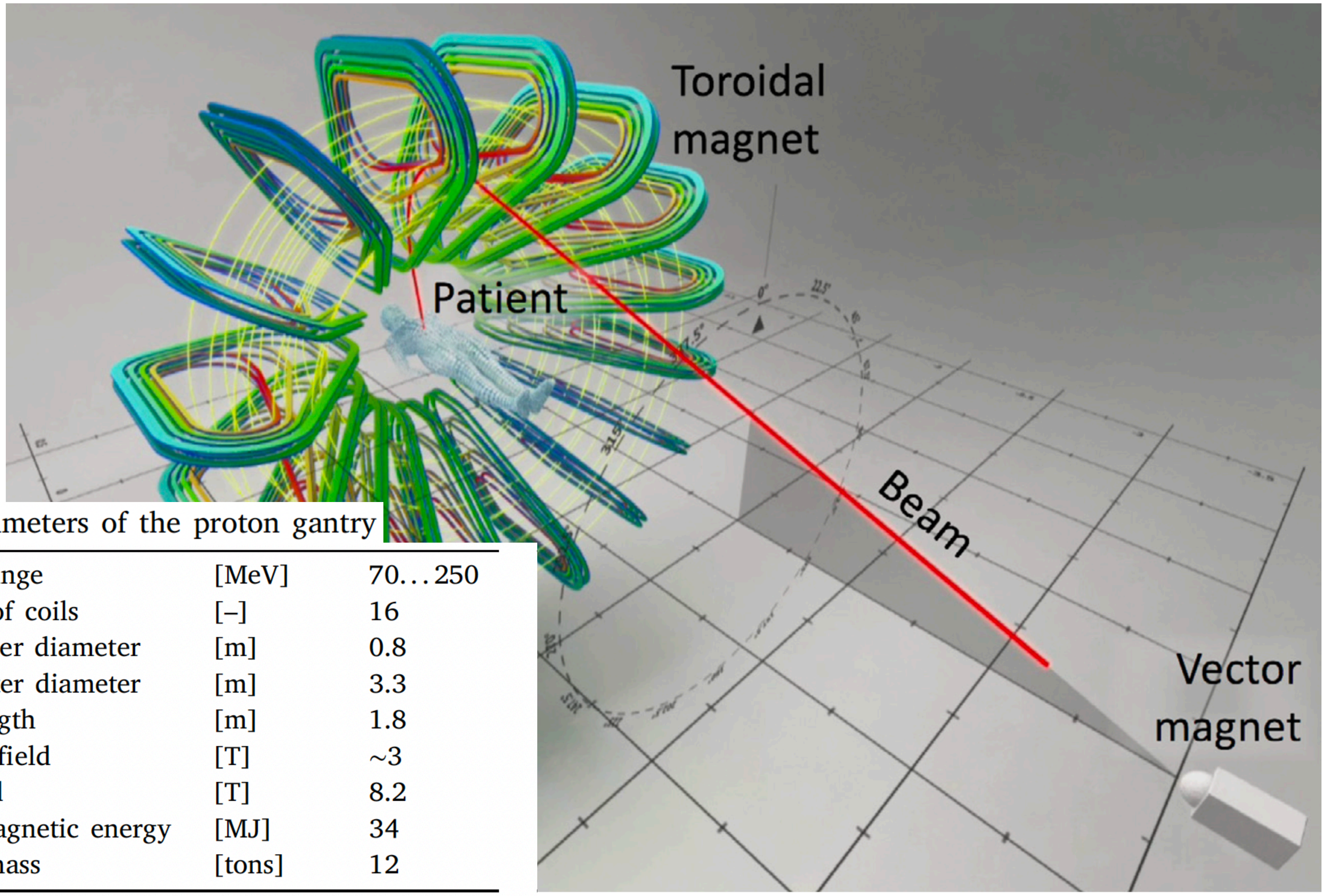
S. Giordanengo et al., Nucl. Instrum. Methods Phys. Res. A 613 (2010) 317–322

Considering a $2h \times 2h$ field of view ($h = 10$ cm) and a distance $d = 0.5$ m between the magnet and the patient, with a $B_{max} = 0.3$ T the result will be $R = 1.7$ m and $s = 20$ cm.

Magnetic scanning system

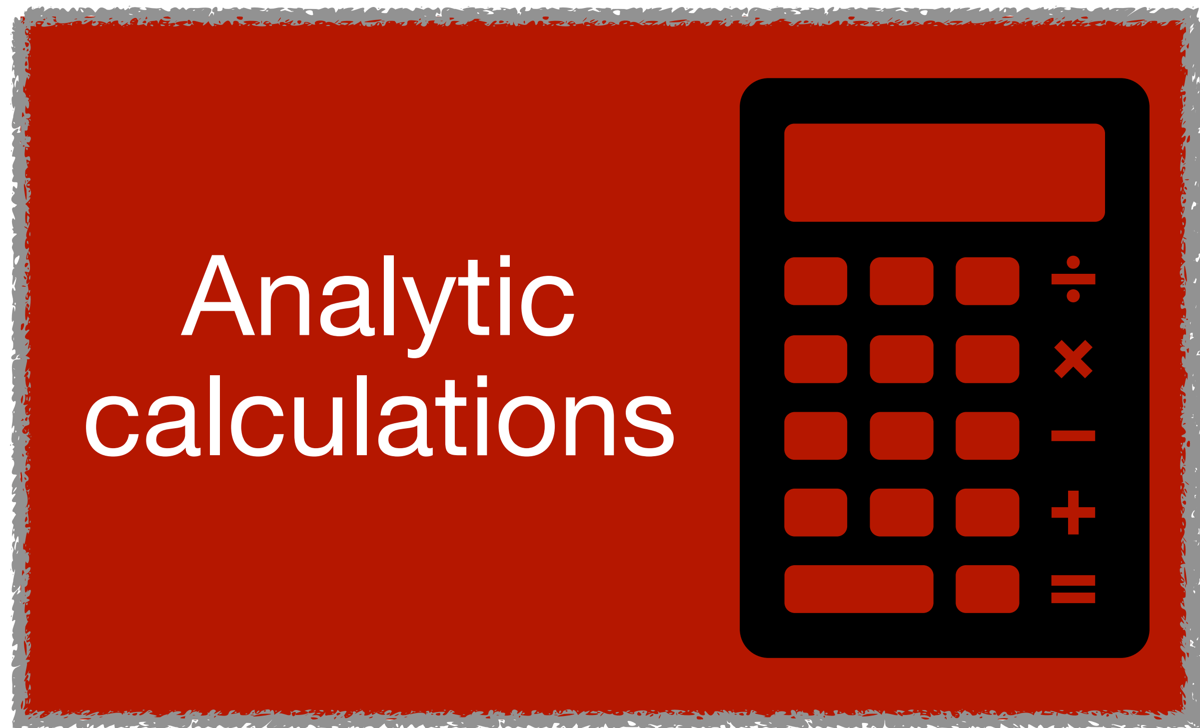
- In the larger perspective of a clinical implementation of VHEE-FLASH to treat deep seated tumors, there is the issue of **multi-directional treatments**.
- The idea is to use a **static gantry**, bending the beam towards the patient with a toroidal system, located after the initial kicker magnet.
- **<u>Not new</u>**: GaToroid concept for PT. Requires superconducting, **large** and **heavy** structure.
- I studied the possibility to scale down GaToroid and have a *<u>lightweight</u>* gantry that, on top of the field transversal scanning, will bend magnetically the electron beam to reach the patient from **<u>different directions</u>**, providing the field entrances chosen in the TPS.

L. Bottura, E. Felcini, G. De Rijk et al., Nucl. Inst. Methods Phys. Res. A 983 (2020) 164588



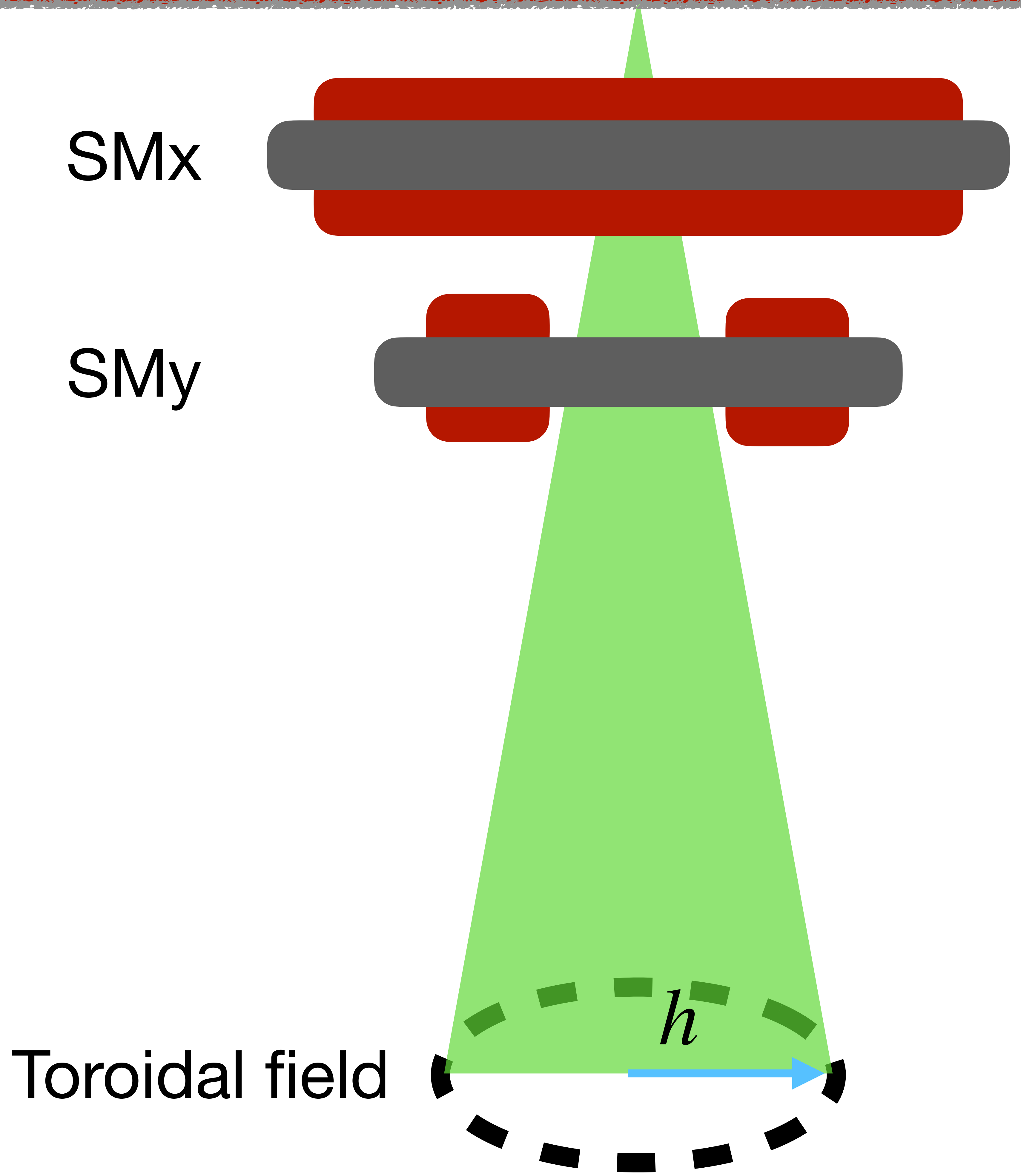
Main parameters of the proton gantry

Energy range	[MeV]	70...250
Number of coils	[–]	16
Torus inner diameter	[m]	0.8
Torus outer diameter	[m]	3.3
Torus length	[m]	1.8
Effective field	[T]	~3
Peak field	[T]	8.2
Stored magnetic energy	[MJ]	34
Magnet mass	[tons]	12



Magnetic scanning system

Analytic calculations



- For the scanning dipoles, I computed the magnet current and geometric features based on data similar to what already in use at CNAO.
- Based on the existing cross-section of the coils, the power converter would need to operate at about **12%** its maximum value.
- The existing dipoles are **oversized**: an active scanning of the beam at UHDR is achievable.

Electron Energy	100 MeV
Mag. Rigidity	0.33 Tm
Dipole Peak field	0.31 T
Field rate	6.6 T/s
Vector magnets length	0.55 m
Gap between poles	0.05 m
Distance source/toroid	1.5 m
Deflection angle	28.34°
Beam distance w/ toroid center (h)	0.81 m

Effective cross-section	79.5 mm^2
Length	123.04 m
Ampereturns NI per coil	17’603.5 A
Inductance	4.4 mH
Max. current ramp	121256 A/s
Current density	7.38 A/mm^2
Power	42.6 kW (maximum 335 kW)

Magnetic scanning system

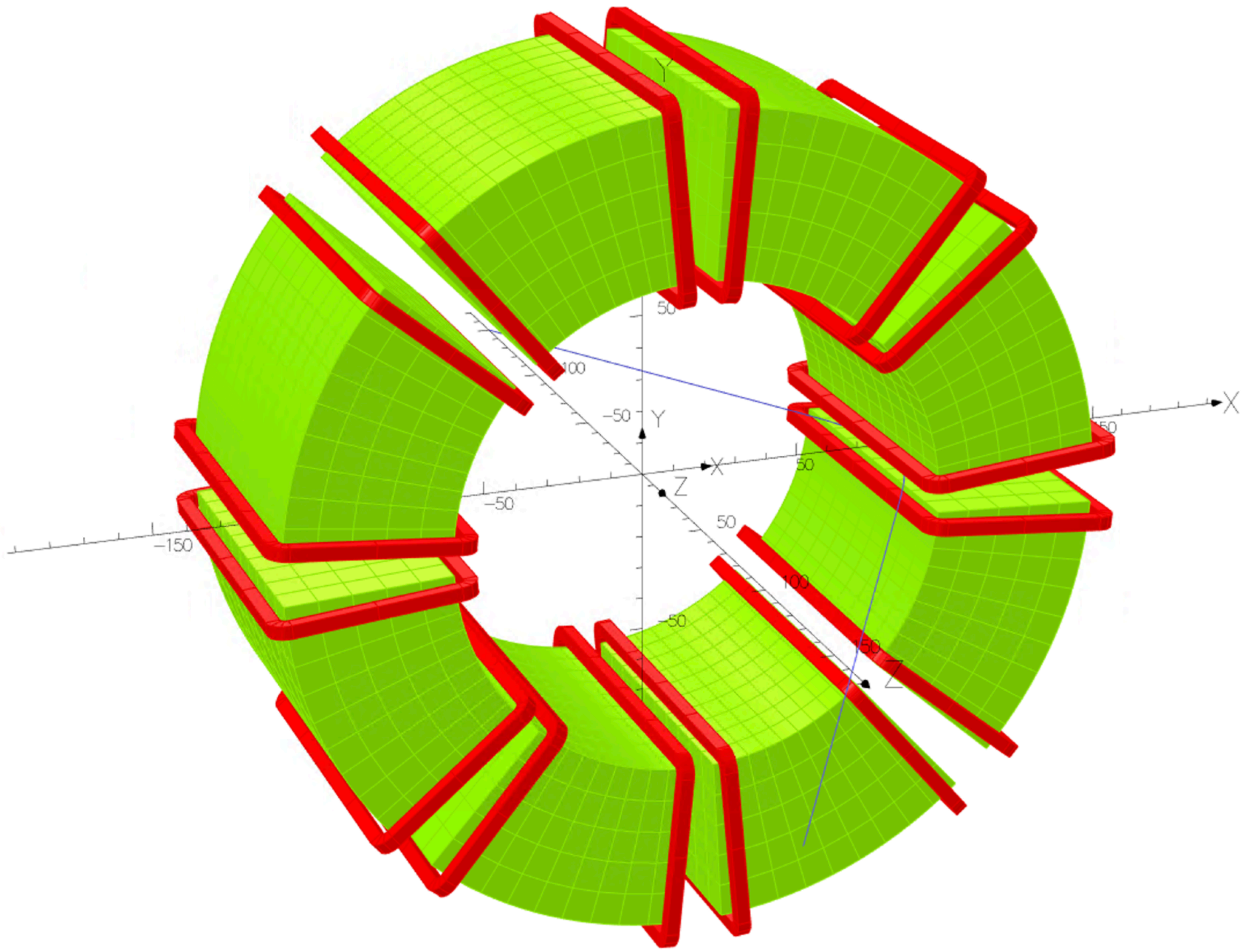
Analytic calculations	OPERA 3D simulation

- The values of the number of coils have been taken from the original Gatoroid optimization, but they could be reduced.
- Parameters to be analyzed for future optimization: magnet length and cooling circuits (work in progress).
- The field computed can be passed as input to FLUKA => dosimetric validation.

Deflection angle	90° (test)
Effective length	1 m
Torus outer radius	1.5 m
Number of directions	8
Number of coils	16 (test)
Ampereturns NI per coil	45’863.9 A
Effective field	0.524 T
Air aperture	0.11 m

Effective cross-section	60 mm²
Current per coil	327.6 A
Length per turn	3 m
N of turns per coil	140
Current density	5.34 A/mm²
Resistance	0.15 Ω
Power loss	16.16 kW

- **Bending of the particle track: OK**



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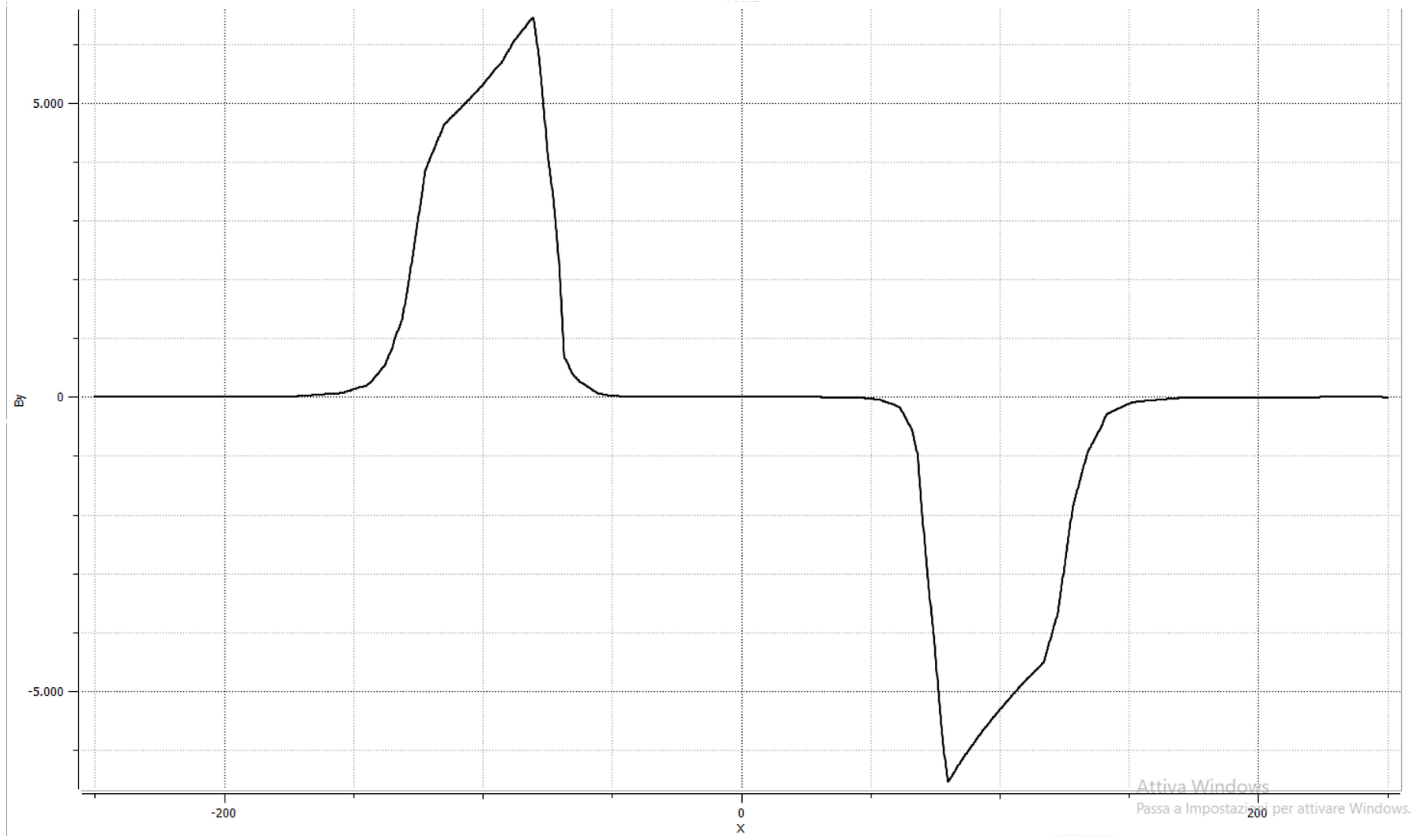

- Graph of B_y (vertical field) calculated over the horizontal direction.
- Peak value of 0.65 T (slightly above prediction, but this is due to simplified geometry in the analytical model)

Summary and Conclusions

- I dedicated my PhD research to the investigation of major topical issues in FLASH effect and UHDR studies.
- I actively explored air fluorescence as a beam monitoring technique, verifying the linear response with respect to the dose-rate per pulse and obtaining promising results.
- With FLUKA-MC simulation, I have started the design and development of a 2D BM device. New detector and first round of tests are foreseen at BTF in Frascati in 2024.
- I performed a preliminary evaluation on the feasibility for a beam delivery to the target exploiting both scanning dipole magnets and a static toroidal magnetic field.
- The OPERA 3D simulation has been validated. I will perform a geometry optimization and detailed description of technical requirements.
- **Acknowledgements to the FlashDC team:** Michela Marafini, Angelica De Gregorio, Gaia Franciosini, Marco Garbini, Vincenzo Patera, Alessio Sarti, Adalberto Sciubba, Marco Toppi, Giacomo Traini.

Thank you for your attention!

Links:
arpg-serv.ing2.uniroma1.it/arpg-site/index.php/research-projects/current-project/flashdc
web.infn.it/FRIDA/


Nuclear Inst. and Methods in Physics Research, A 1041 (2022) 167334
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Nuclear Inst. and Methods in Physics Research, A
journal homepage: www.elsevier.com/locate/nima

The FlashDC project: Development of a beam monitor for FLASH radiotherapy

Antonio Trigilio [a,b], Angelic
Marco Garbini [c], Gabriele I
Vincenzo Patera [d,b], Alessio
Giacomo Traini [b], Micol De

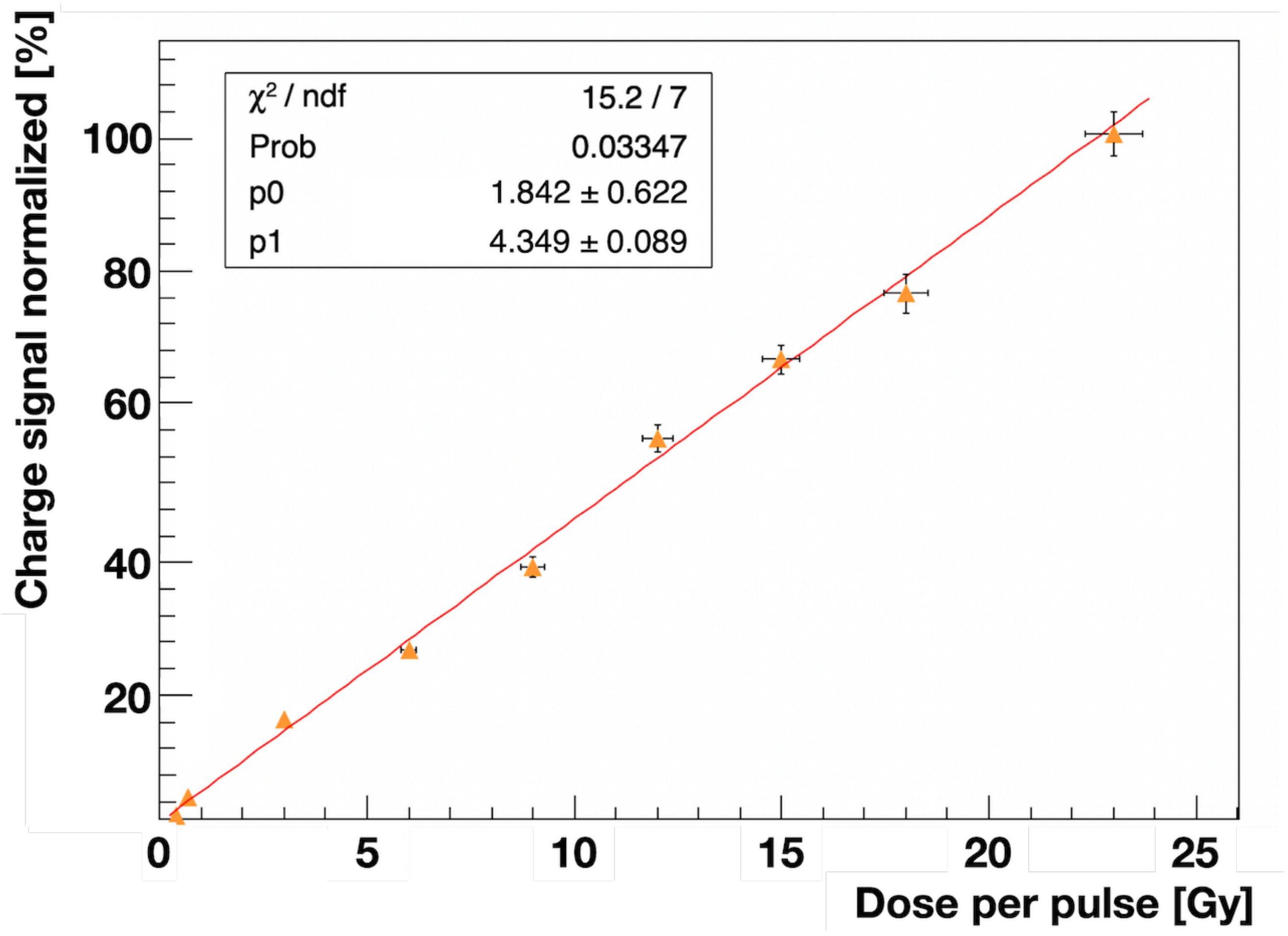

Radiotherapy and Oncology 175 (2022) 210–221
ELSEVIER
Contents lists available at ScienceDirect
Radiotherapy and Oncology
journal homepage: www.thegreenjournal.com

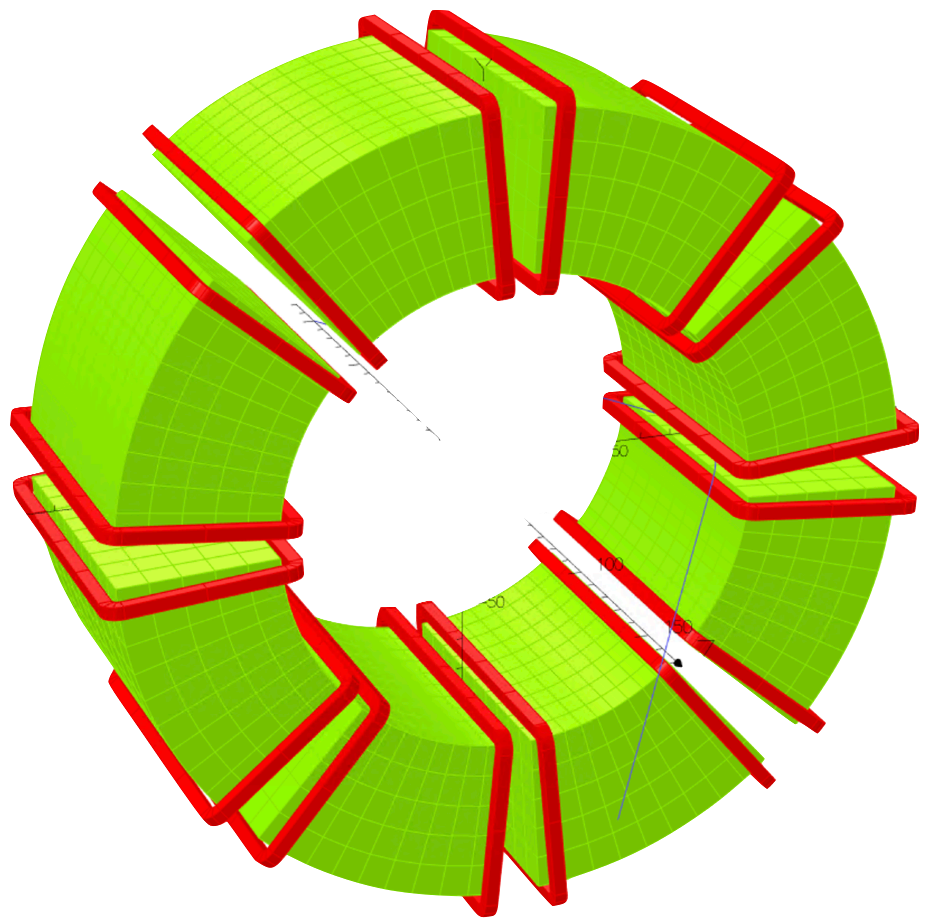
Review Article

FLASH radiotherapy treatment planning and models for electron beams

Mahbubur Rahman [a,1], Antonio Trigilio [b,c,1], Gaia Franciosini [b,c], Raphaël Moeckli [d,*], Rongxiao Zhang [a,e], Till Tobias Böhlen [d]

[a] Thayer School of Engineering, Dartmouth College, Hanover, NH, USA; [b] Physics Department, "La Sapienza" University of Rome; [c] INFN National Institute of Nuclear Physics, Rome Section, Rome, Italy; [d] Institute of Radiation Physics, Lausanne University Hospital and Lausanne University, Lausanne, Switzerland; [e] Dartmouth Hitchcock Medical Center, Lebanon, NH, USA





Backup

Beam delivery studies

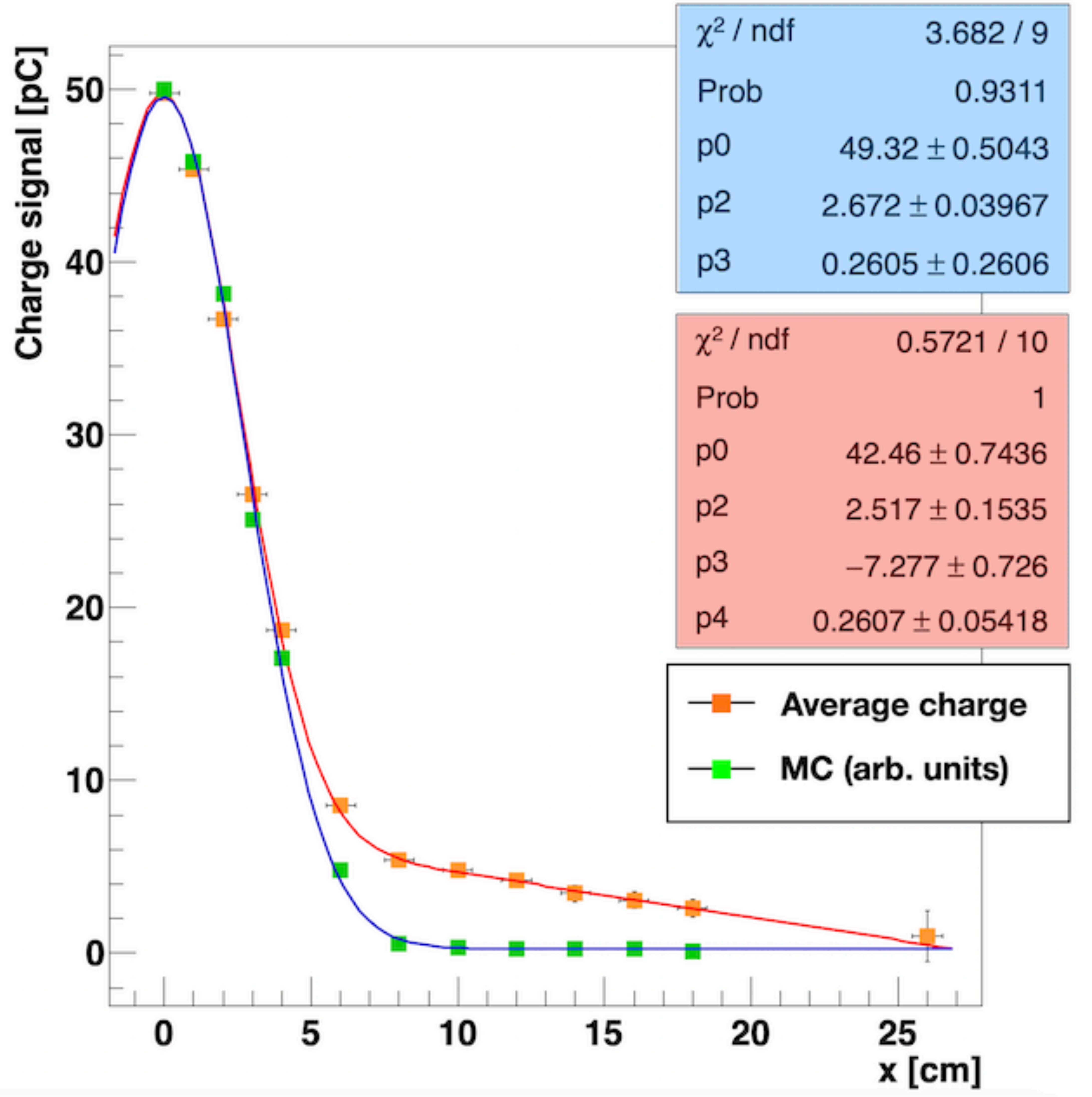
- **LIAC HWL**: modified to reach 10^{10} electrons/pulse.
- Electron energy at the linac exit: 6MeV.
- Pulse duration: 2 μs.
- Dose per pulse ~ 0.3 Gy.
- Mobile head: useful to test sensitivity to beam position.

- The accelerator delivery section and the detector geometries are implemented in a **FLUKA MC simulation**.
- The fluorescence production is activated using experimental data found in literature.

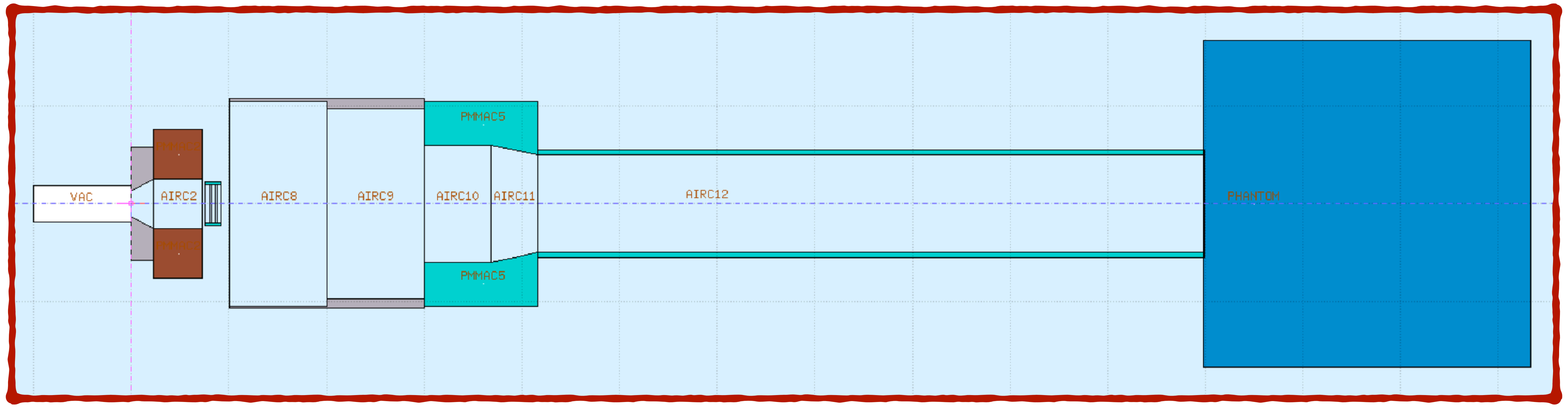
- **ElectronFlash**: 10^{12} electrons/pulse.
- Electron energy at the linac exit: 7MeV.
- **Dose(-rate) per pulse: up to 20 Gy ($5*10^6$ Gy/s).**
- Field spread: 5-6 cm at BEW (uncollimated).

Beam delivery studies

- The MC simulation was used to estimate the amount of missing background produced at the beam edges.
- In order to study this spurious signal, we need a new system with a better repeatability that can further minimize the impact of the material along the beam line and measure the **signal-to-noise** ratio.



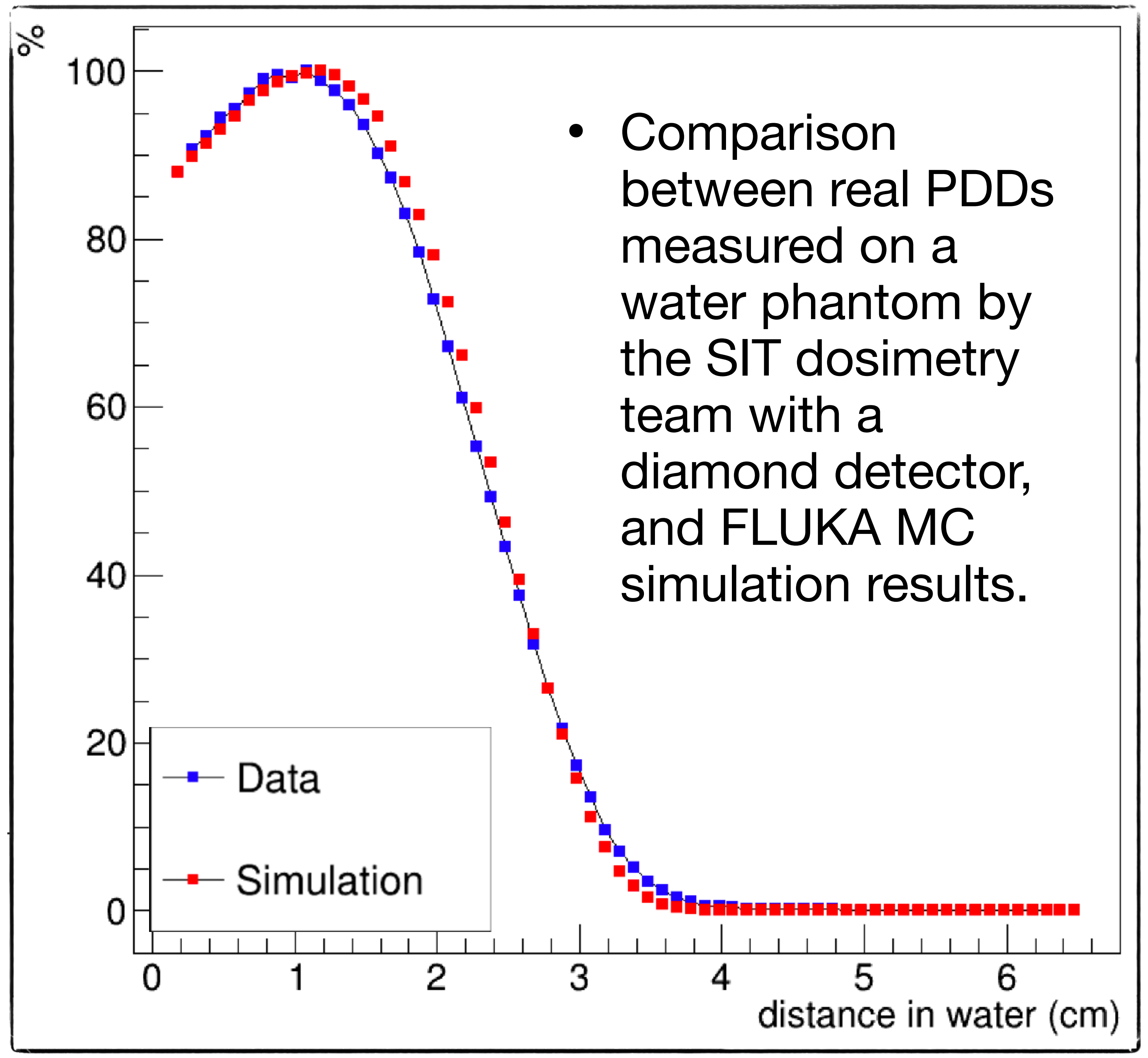
Beam delivery studies



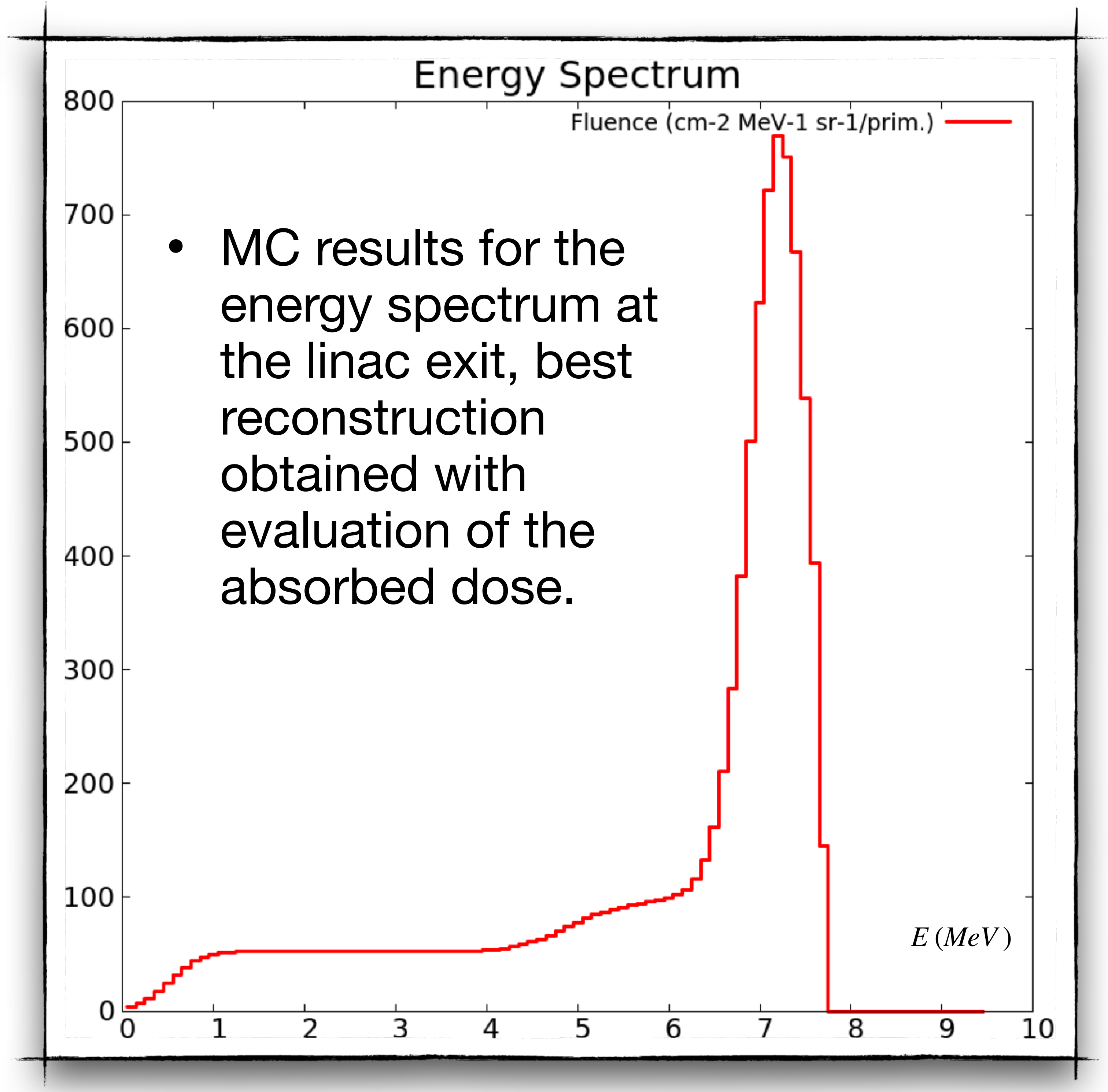
- Monte Carlo simulation provide a solid base to estimate the accuracy of the beam delivery system and the expected dosimetric qualities. It can also be a useful tool for the **optimization** of the hardware apparatus.
- I performed several validations with different applicator geometries comparing **Percentage Dose Depth** and dose profile measurements.

- **ElectronFlash**: ~10^{12} electrons/pulse.
- Electron energy at the linac exit: 7MeV.
- **Dose rate (single pulse): up to $5*10^6$ Gy/s.**
- Field spread: 4-5 cm at BEW (uncollimated).

soiort.com/flash-rt-technology/



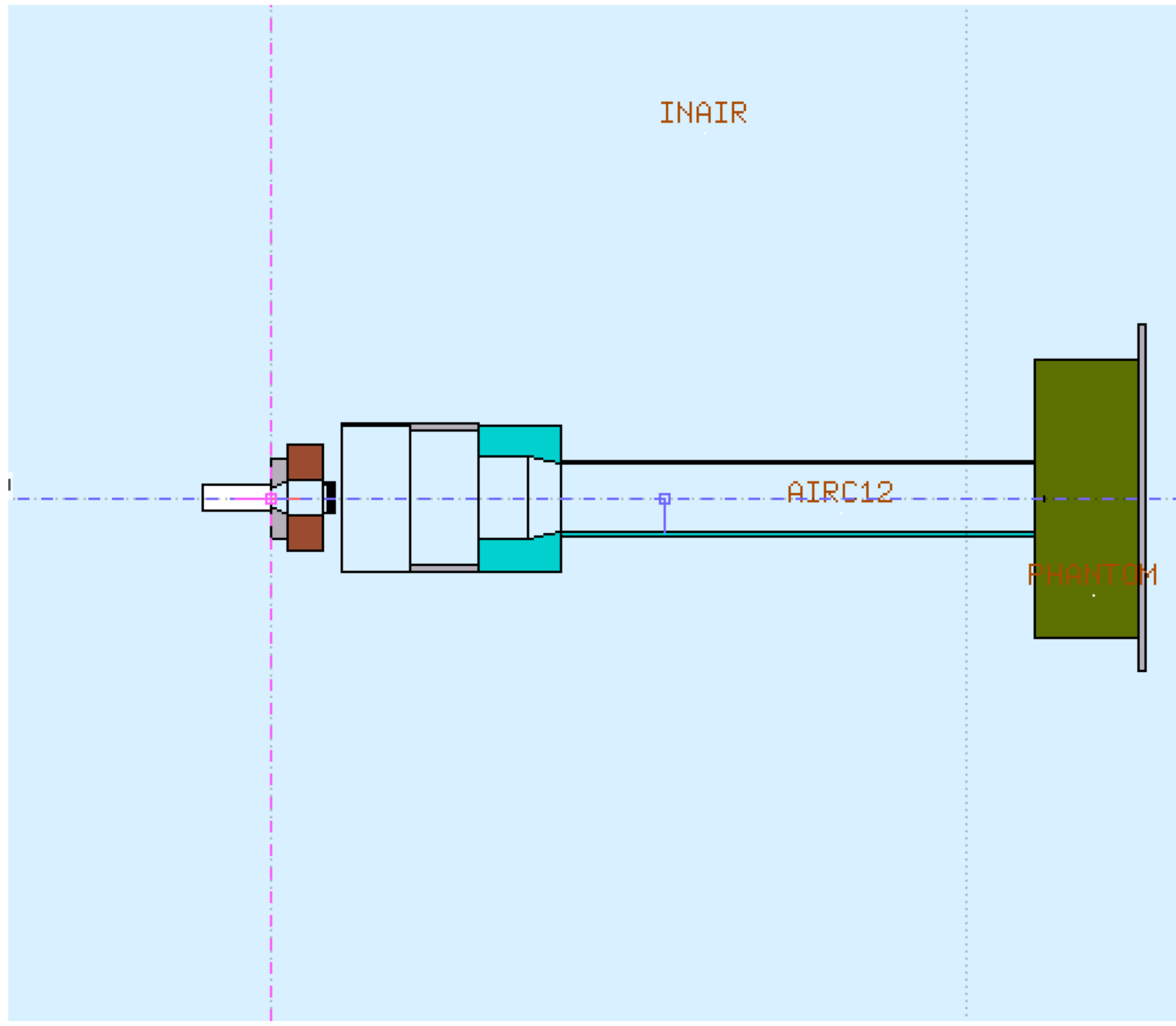
- Comparison between real PDDs measured on a water phantom by the SIT dosimetry team with a diamond detector, and FLUKA MC simulation results.



- MC results for the energy spectrum at the linac exit, best reconstruction obtained with evaluation of the absorbed dose.

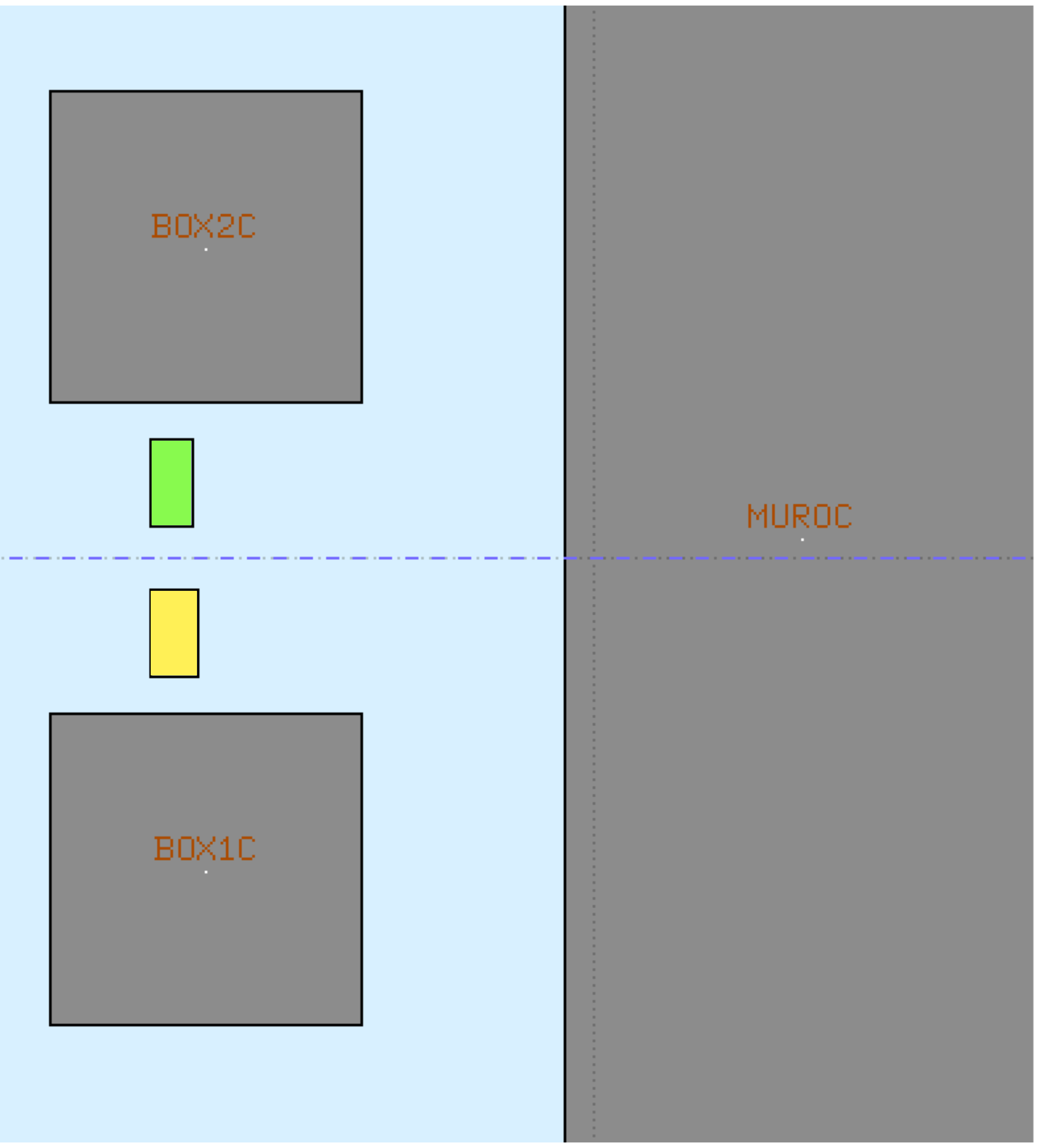
Beam delivery studies

- Concerning **radio-protection** studies, I was asked to assess the adequacy of a set of ambient survey meters used to measure **stray radiation** inside the bunker where the ElectronFlash was installed in **University of Antwerp, Belgium**.
- It is one of the few facilities in the world where FLASH pre-clinical studies are performed with dedicated machines.
- In this case, no optimization required. Instead, a careful modeling of the **geometry** of the bunker / **scoring** of the particle fluences.



- The beam hits a target of RW3. Secondary radiation is stopped by a lead block. The walls are concrete and show no significant leakage.
- At FLASH intensities, the simulation was found in reasonable agreement with the experimental results.

Survey meter	Exp.	MC
Babyline	18.3 ± 0.3 μSv/Gy	16.8 ± 0.2 μSv/Gy
STEP OD-02	12.2 ± 0.3 μSv/Gy	13.1 ± 0.2 μSv/Gy



FLASH RADIOTHERAPY & PARTICLE THERAPY 2022
BARCELONA & ONLINE
30 NOVEMBER - 2 DECEMBER 2022

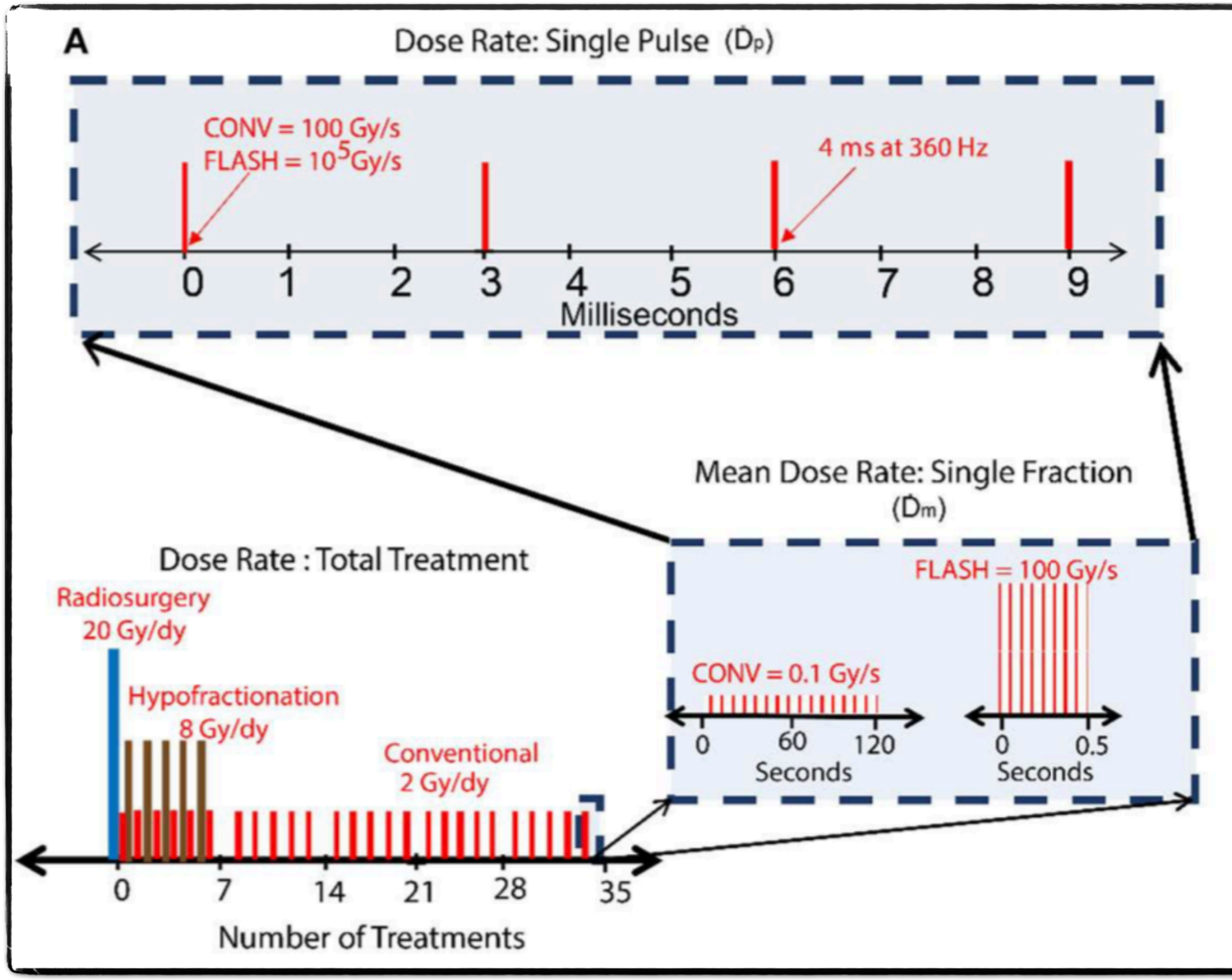
Radiation protection and other stories on the installation of ultra-high dose rate electron beam systems

A. Gasparini[1,2], A. Trigilio[3], F. Di Martino[4], S. Heinrich[5], G. Felici[6], G. Mariani[6], M. Pacitti[6], R. Pain[5], V. Vanreusel[1,7], V. Patera[3], D. Verellen[1,2]

[1]University of Antwerp, AReRO, Belgium; [2]Iridium Netwerk, Physics, Belgium; [3]Sapienza University of Rome, Italy; [4]CPRF, Italy; [5]Institut Curie, France; [6]S.I.T., R&D, Italy; [7]SCK CEN, RDA, Belgium

Backup

Ashraf MR, Rahman M, Zhang R, Williams BB, Gladstone DJ, Pogue BW and Bruza P (2020) Dosimetry for FLASH Radiotherapy: A Review of Tools and the Role of Radioluminescence and Cherenkov Emission. Front. Phys. 8:328. doi: 10.3389/fphy.2020.00328



B

Beam Characteristics	CONV	FLASH
Dose Per Pulse D_p	~0.4 mGy	~1 Gy
Dose Rate: Single Pulse $\dot{D}_p$	~100 Gy/s	~10^5 Gy/s
Mean Dose Rate: Single Fraction $\dot{D}_m$	~0.1 Gy/s	~ 100 Gy/s
Total Treatment Time T	~days/minutes	< 500 ms

Backup

Response	Detectors	Measurement type	FLASH study	Instantaneous dose-rate/dose per pulse (D_p) dependence	Spatial resolution	Time-resolution	Energy dependence
Luminescence	TLD/OSLD	**1D,** 2D	e [15, 37, 71]	Independent (~10^9 Gy/s) [80, 137]	~ 1 mm	Passive	Tissue-equivalent
	Scintillators	1D, **2D**, 3D	p [13, 18]	Independent (~10^6 Gy/s) [29]	~ 1 mm	~ns	Tissue-equivalent
	Cherenkov	**1D**, 2D, 3D	e [29]	Independent (~10^6 Gy/s) [29]	~ 1 mm	~ps	Energy dependent
	FNTD	2D	NA	Independent (~10^8 Gy/s) [85]	~ 1 μm	Passive	Energy dependent
Charge	Ionization chambers	**1D**, **2D**	p [13, 18, 19] e [15, 37, 71] ph [16, 17]	Dependent on D_p [48, 52] (>1 Gy/pulse),	~3–5 mm	~ms	Energy dependence shows up > 2 MeV
	Diamonds	**1D**	p [18]	Dependent on D_p (>1 mGy/pulse) [49]	~ 1 mm	~μs	Tissue-equivalent
	Si diode	**1D**, 2D	NA	Dependent on D_p [54] (Independent ~0.2 Gy/s) [138]	~ 1 mm	~ms	Energy dependent
Chemical	Alanine pellets	**1D**	e [12, 15, 37, 139]	Independent (10^8 Gy/s) [69]	~ 5 mm	Passive	Tissue-equivalent
	Methyl viologen/fricke	**1D**	e [29, 48]	Depends on the decay rate and diffusion of radiation induced species	~ 2 mm	~ns	Tissue-equivalent
	Radiochromic film	**2D**	p [18, 19] e [10–12, 15, 30, 37, 71, 140] ph [16]	Independent (10^9 Gy/s) [70, 71]	~1 μm	Passive	Tissue-equivalent
	Gel dosimeters	3D	NA	Strong dependence below 0.001 Gy/s [141] and above 0.10 Gy/s [142]	~1 mm	Passive	Tissue-equivalent

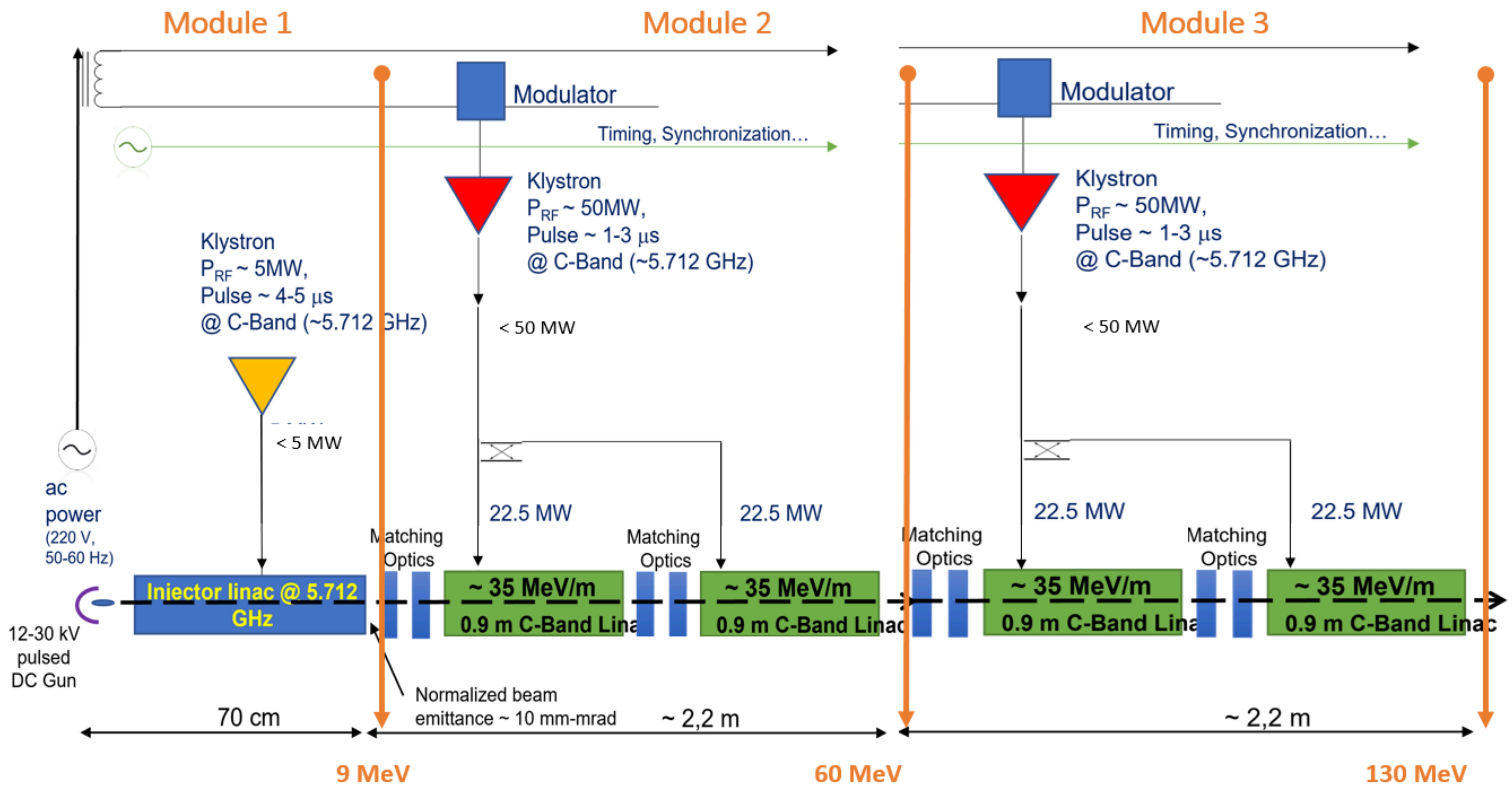
Devices using FLASH irradiation modalities

Devices	Dose rate [Gy/s]	Pulse width [μs]	Energy [MeV]	Particle
Oriatron e6, CHUV (Losanne)	10^{-2} - 10^{7}	0.05 - 2.7	4.9 - 6	Electrons
Modified Elekta SL75 (Oxford UK)	200	3.4	6	Electrons
Modified Elekta Precise (Sweden)	220	1	8	Electrons
Varian Clinac 21EX, Cancer Institute (Stanford)	280	5	16	Electrons
ElectronFlash, Institut Curie (Orsay), Pisa University and Antwerp University	0.05 - 10^{6}	0.5 - 4	5 - 9	Electrons
Modified proton cyclotron (IBA), Institut Curie (Orsay)	40	/	230	Protons
Proton-Therapy Centers with PBS	Inst. up to 200 Mean dose rate ~0.05	/	TBD	Protons

SAFEST

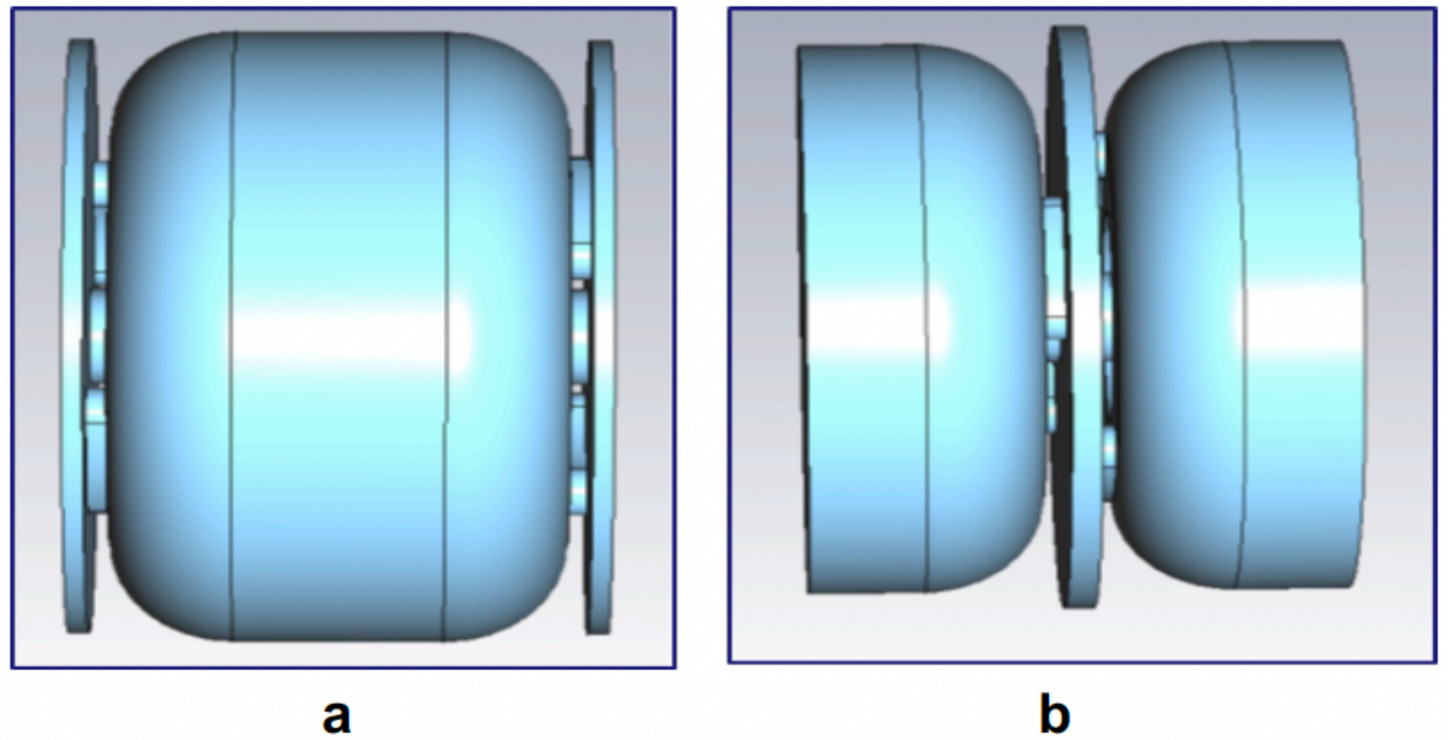
- **Proposal:** Research Facility based on an innovative VHEE LINAC operating in C-band (5.712 GHz), able to deliver the high current required by the FLASH irradiation regime, with a higher accelerating gradient which, compared with the existing traditional machines in the word, is more compact in terms of weight and size. The length of accelerating cells is approximately half of those of S-band (2.998 GHz).
- The electron source for the VHEE LINAC is a thermionic DC gun operated at a maximum voltage of 30 kV. The VHEE LINAC system comprises one standing wave (SW) injector and four traveling wave (TW) high-gradient accelerating structures. It is divided into 3 main modules:

- In Module 1 we can distinguish, on the left, the first accelerating SW injector capable of accelerating a current exiting from a pulsed DC gun up to 200 mA at an energy of 9-12 MeV.
- In Module 2 the beam is matched by means of quadrupoles (matching optics) and injected into a compact linear TW accelerating structure characterized by a high accelerating gradient (up to about 40 MeV/m) able to bring the energy of the electron beam up to about 60 MeV.
- In Module 3 the beam energy is finally brought up to 130 MeV by means of a total of four 90 cm long accelerating structures, each one followed by quadrupoles for matching conditions. Solenoids around the accelerating structures guarantee the necessary focusing to the beam.



SAFEST

- **Module 1:** In the gun, electrons are generated by producing a potential difference between the thermionic emitter (cathode) and a plate (anode) with an hole to permit the electron beam to exit.
- For this project we used a commercial Electron Gun triode, in which the emission of the electrons from the cathode are tuned by utilizing a grid between the cathode and anode. The optimal distance between cathode and the LINAC entry plate is 0.5 cm for a maximum beam capture larger than 40%.



celerating cell with two half coupling cells (b) and coupling cell with two half accelerating cells.

- The injector is a standing-wave (SW), biperiodic, magnetic coupling structure. The accelerating mode is the π/2 mode, it has an electric null field in the coupling cavities and alternating field in the accelerating cells.
- For the magnetic coupling, holes off axis are used to connect the accelerating cells with the coupling ones. The first and last cell has only one pair of slots, while other cells have two pairs of slots on both ends.

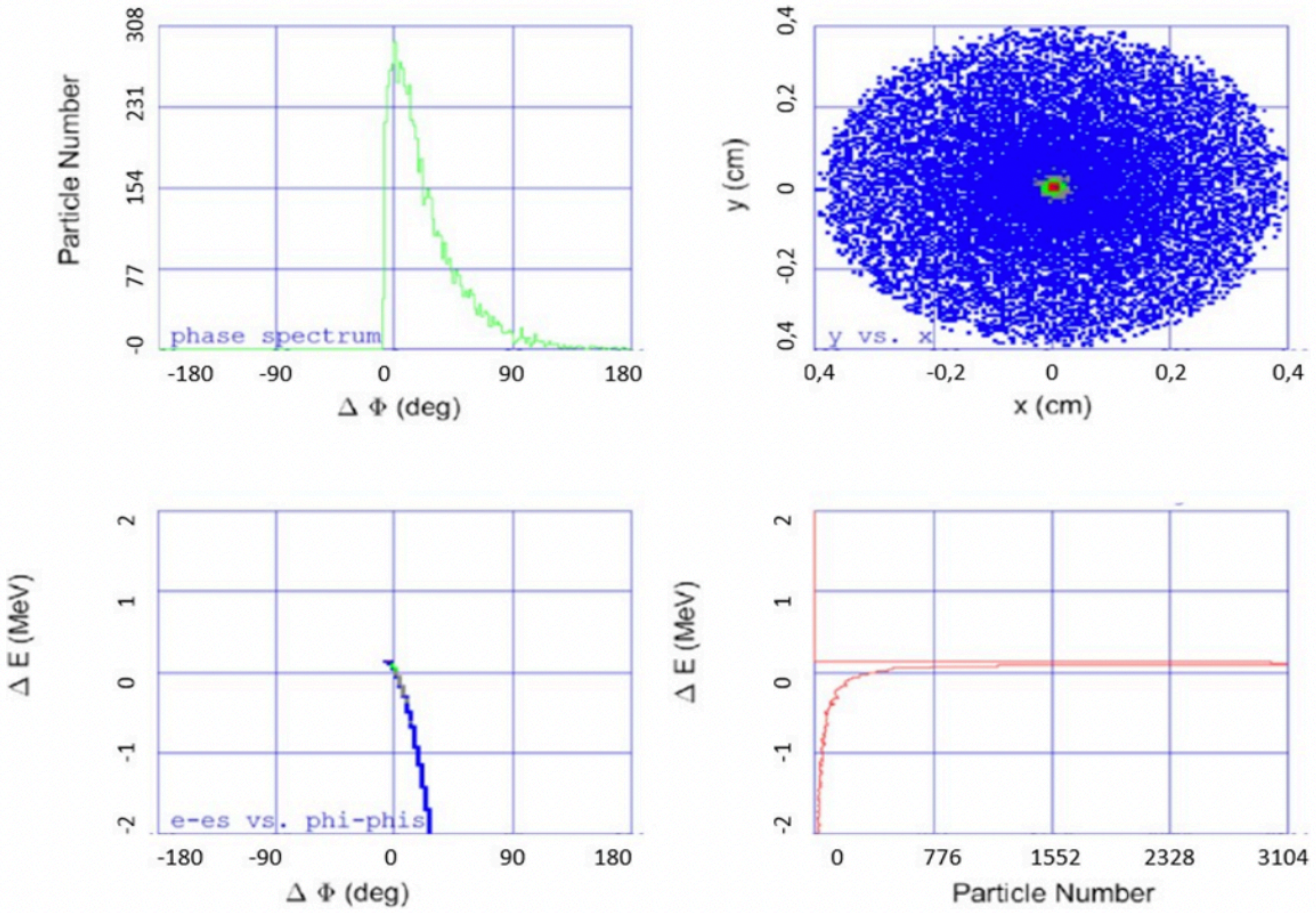


Figure 5.5: TSTEP output electron beam parameters at the exit of the Module 1.

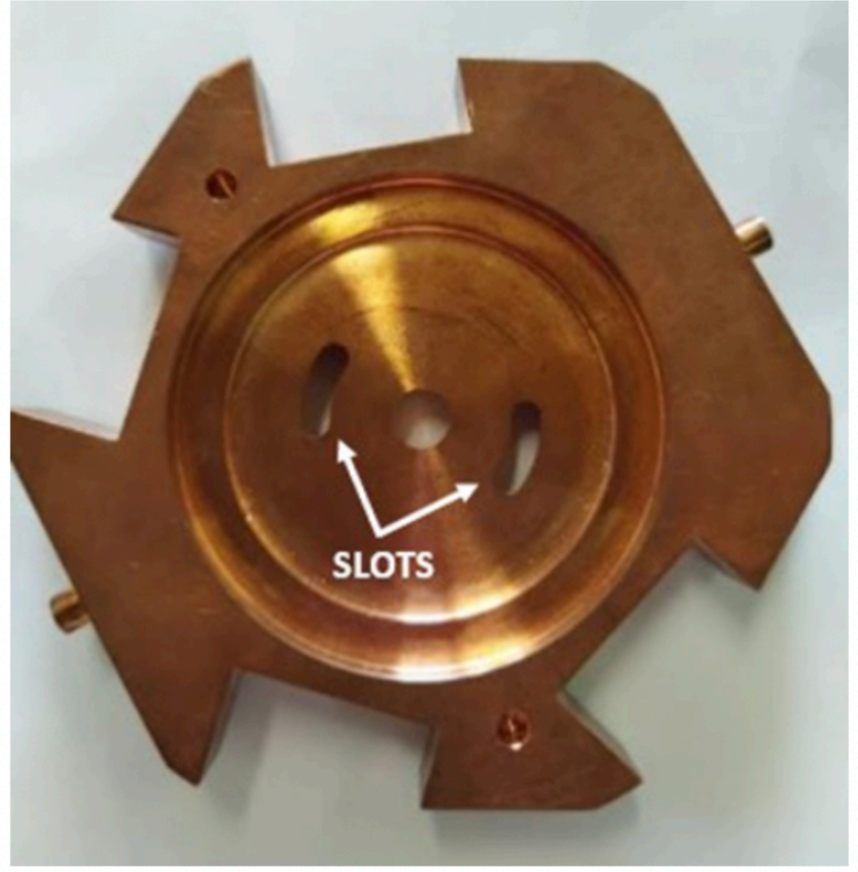
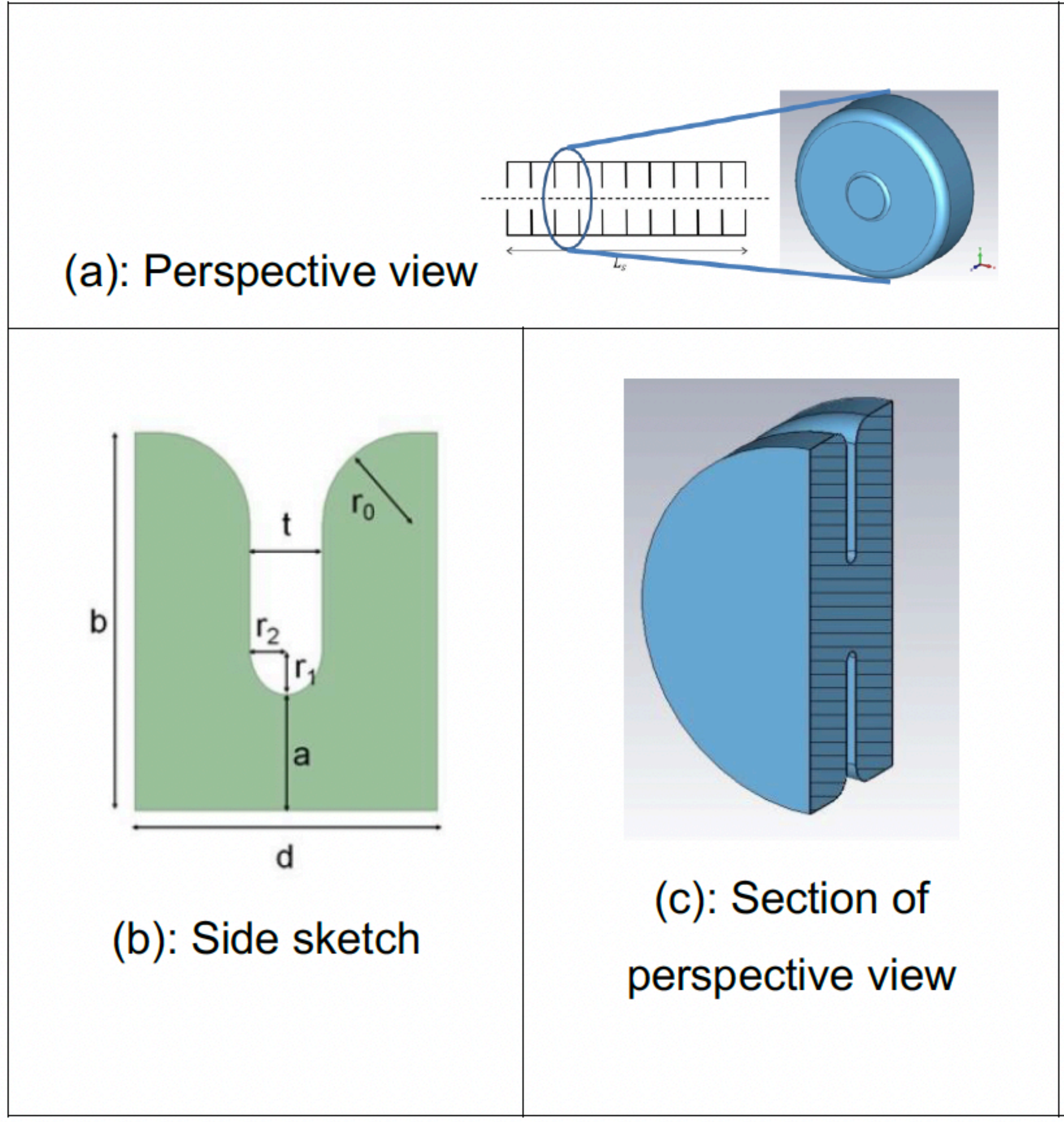


Figure 5.3: Off axis slots for the magnetic coupling.

SAFEST

- **Modules 2 and 3:** The C-band high gradient TW accelerating structures (Modules 2 and 3) operate in the TM_{01}-like mode with a phase advance per cell (ϕ") of $2\pi/3$ which guarantees the best efficiency for this type of accelerating cavities.
- A single RF structure increases the beam energy up to about 35 MeV in a space of about 90 cm, thus respecting the available space constraints.
- The electron beam transverse size exiting from the LINAC can be easily modified. For the case of operation with a fixed field, a magnet quadrupole duplet can be located after 50 cm from the LINAC exit.
- The beam size is enlarged by one order of magnitude, from 4 mm to 4 cm, by utilizing a normal conducting magnet quadrupole with 47 T/m gradients. In alternative to quadrupoles, it is also possible to use scattering materials.

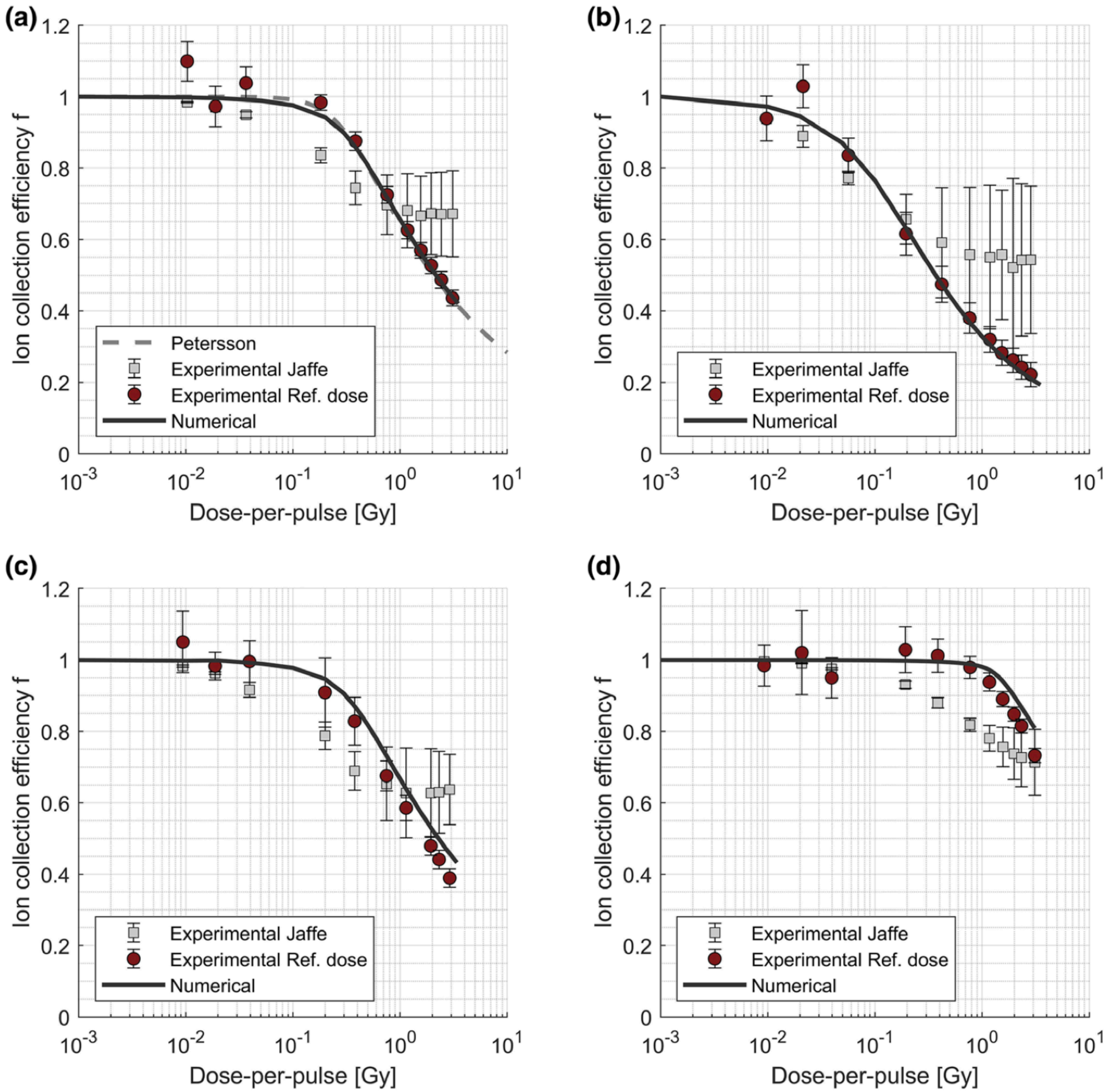


Cell geometric parameter

- a: iris radius ($a \in [3,7] mm$)
- t: iris thickness (2 mm)
- r_1: iris rounding radius (1 mm)
- r_0: edge rounding radius (2.5 mm)
- d: cell length (function of ϕ_0, $d = \frac{c}{\omega}\phi_0 = 17.5\ mm$)
- b: outer radius (function of a and frequency f)
- ϕ_0: phase advance per cell ($\frac{2}{3}\pi$)

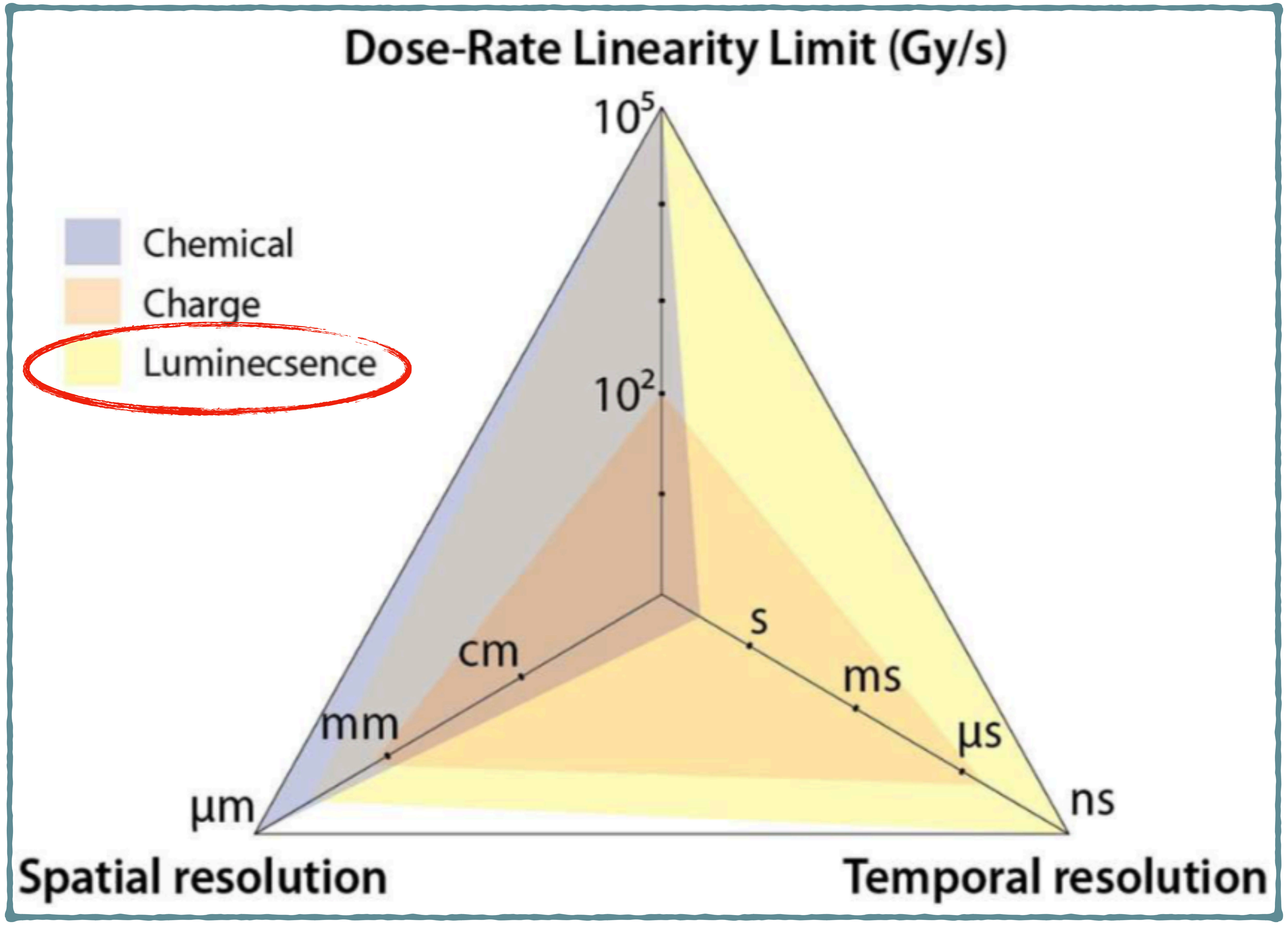
Figure 5.6: TW cell and its geometric parameters. (a): Perspective view; (b): Side sketch with main dimensions; (c): Section of perspective view.

Beam Monitoring vs FLASH effect



Ion collection efficiency for the ionization chambers with a polarizing voltage of 300 V.
(a) Advanced Markus, **(b)** EWC2, **(c)** EWC1, **(d)** EWC05. doi: 10.1002/mp.14620

FLASH beam monitoring

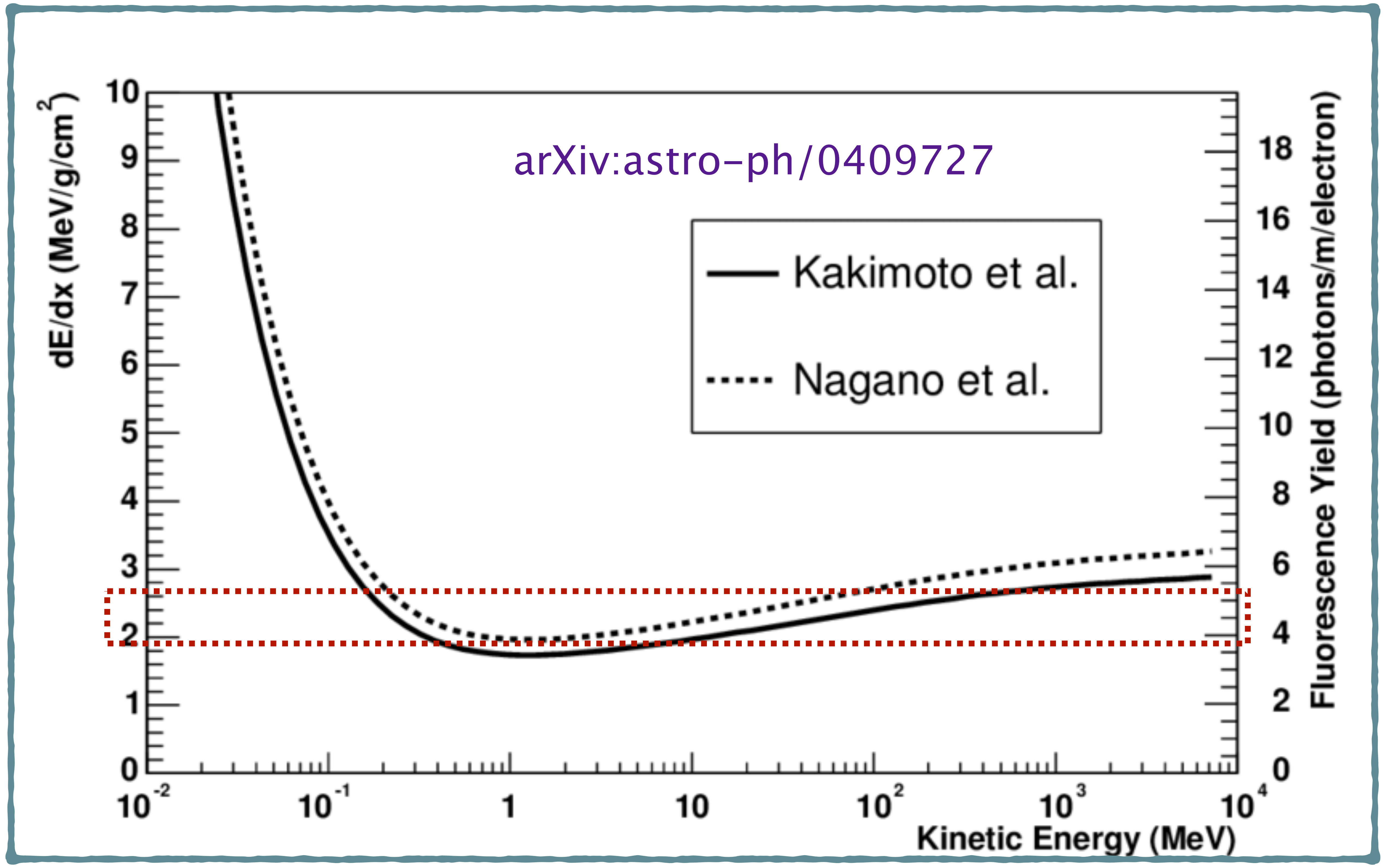


Ashraf MR et al, Dosimetry for FLASH Radiotherapy
doi: 10.3389/fphy.2020.00328

Backup

- How many photons we expect at typical IOeRT and VHEE energies?

E_K	ph./m (Fluor.)	ph./m (Ch.)
10 MeV	4 (@4π)	Under thr.
20 MeV	4 (@4π)	6 (@0.1°)
130 MeV	5 (@4π)	70 (@1.4°)



Backup

M. Ave et al. / Astroparticle Physics 28 (2007) 41–57

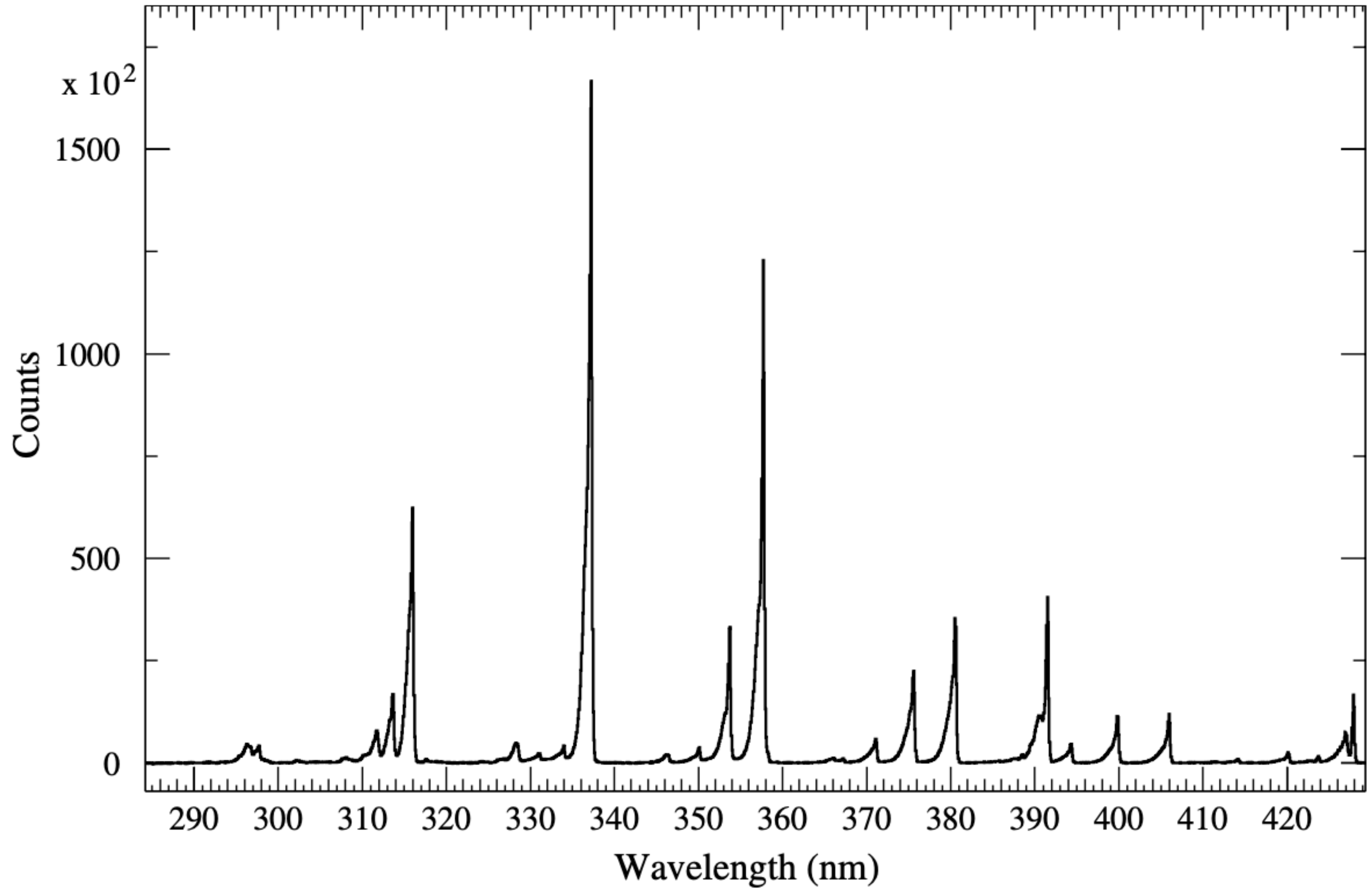
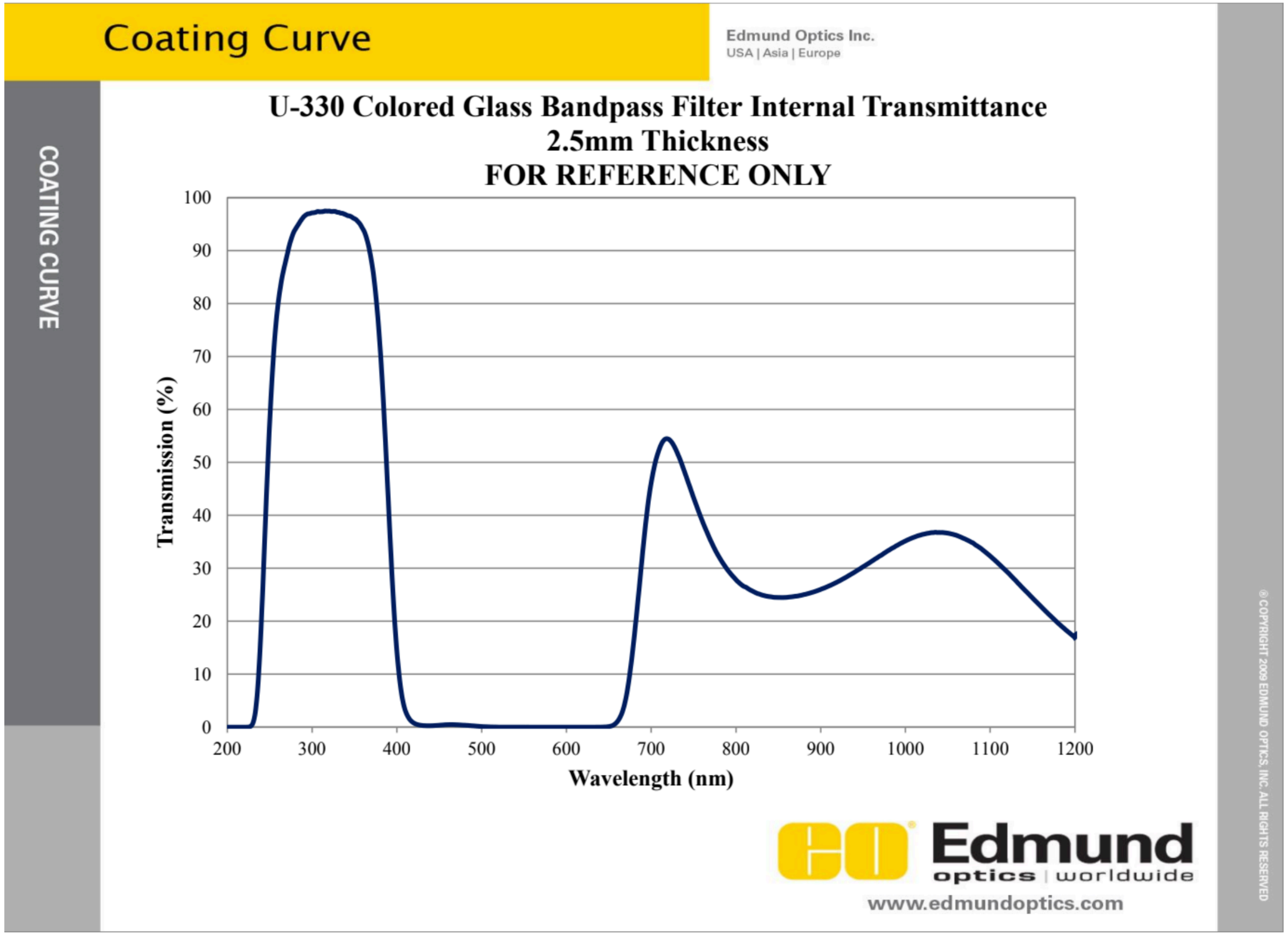


Fig. 4. Measured fluorescence spectrum in dry air at 800 hPa and 293 K.

Backup


Coating Curve
Edmund Optics Inc.
USA | Asia | Europe
COATING CURVE
U-330 Colored Glass Bandpass Filter Internal Transmittance
2.5mm Thickness
FOR REFERENCE ONLY
Transmission (%)
100
90
80
70
60
50
40
30
20
10
0
200
300
400
500
600
700
800
900
1000
1100
1200
Wavelength (nm)
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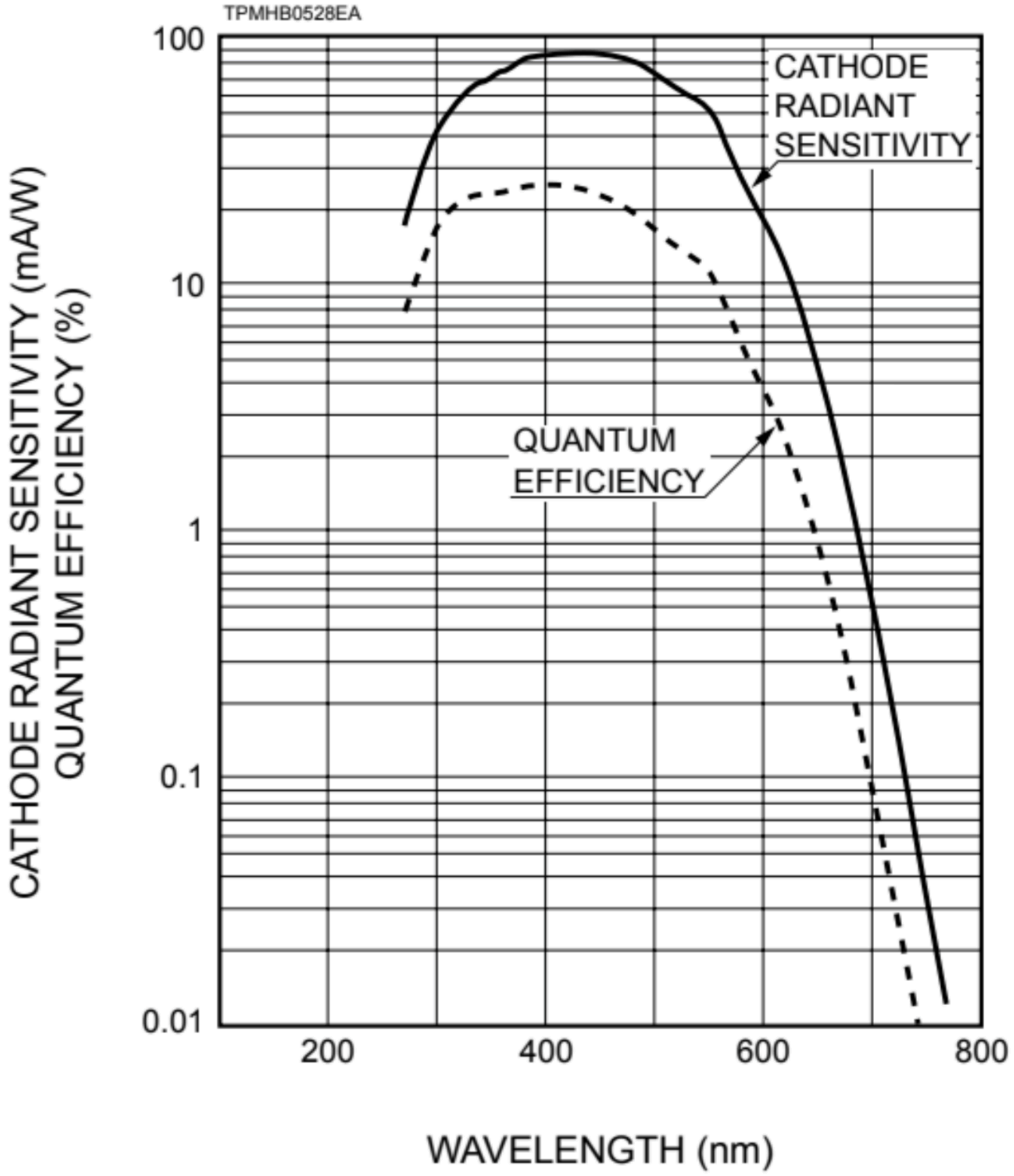
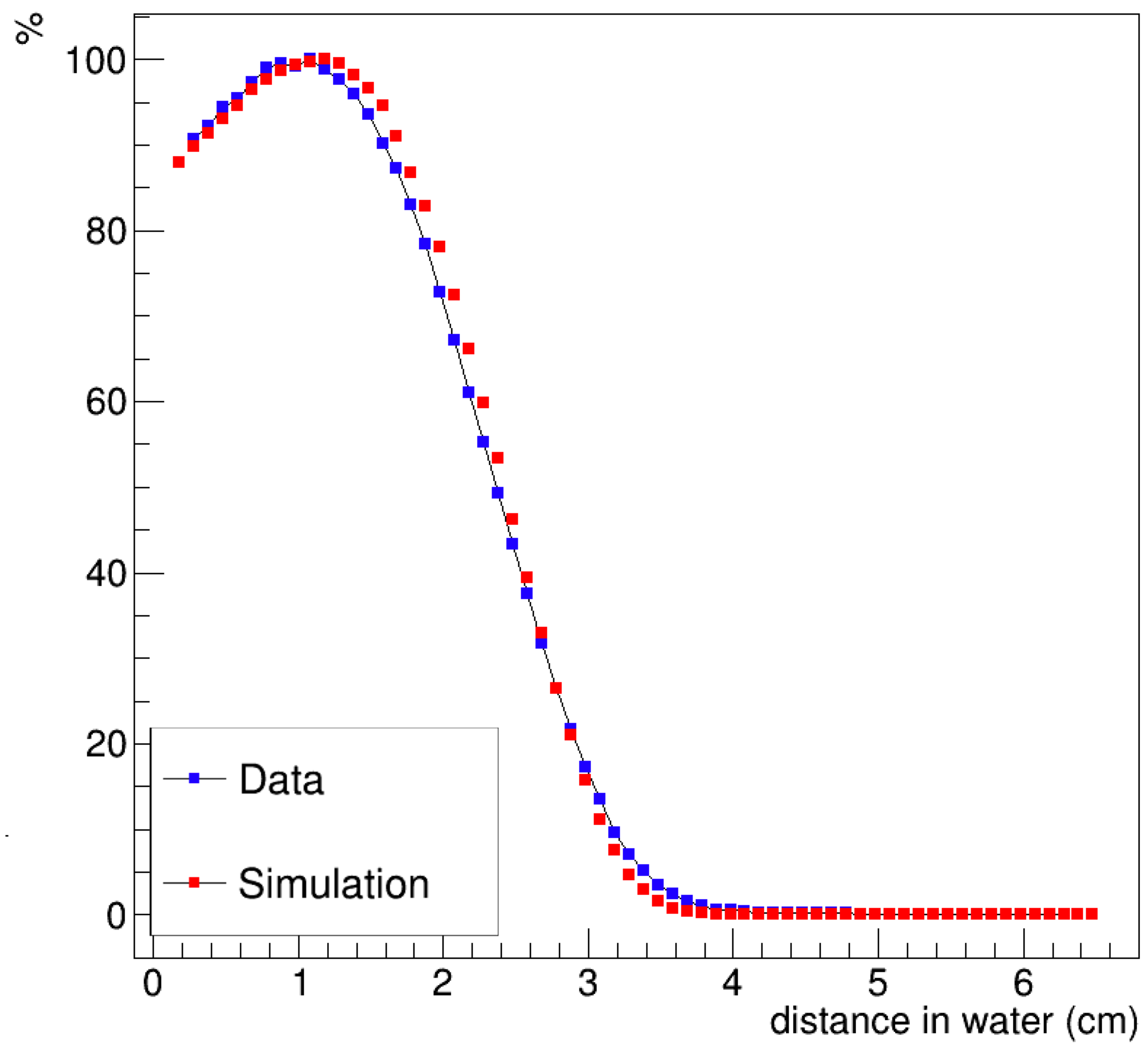
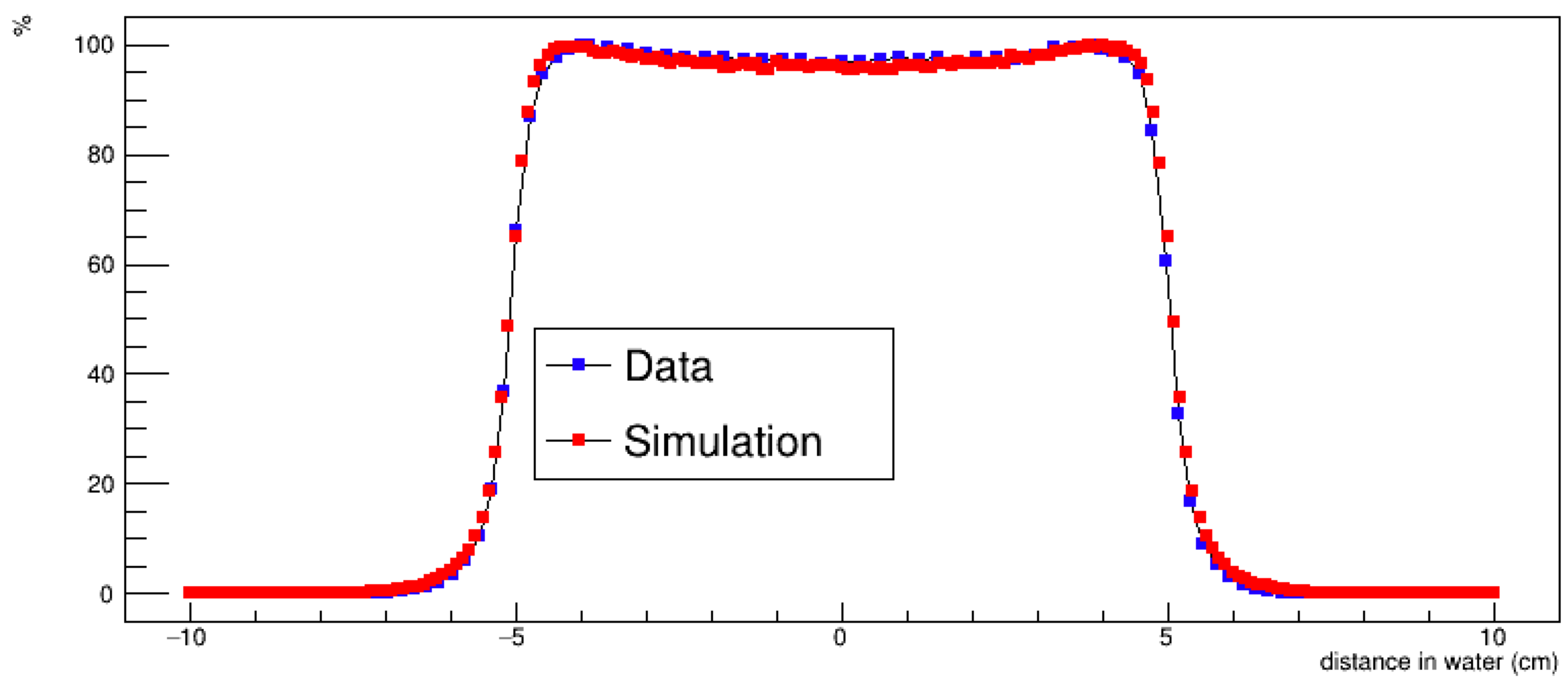

TPMHB0528EA
CATHODE RADIANT SENSITIVITY (mA/W)
QUANTUM EFFICIENCY (%)
100
10
1
0.1
0.01
CATHODE
RADIANT
SENSITIVITY
QUANTUM
EFFICIENCY
200
400
600
800
WAVELENGTH (nm)

Best results - 7 MeV



Profile X 7MeV



Profile Y 7MeV