FlashDC, A fluorescence-based beam monitor for Ultra-High dose rates

International Workshop on
future research program with the high power
cyclotron of SPES-LNL

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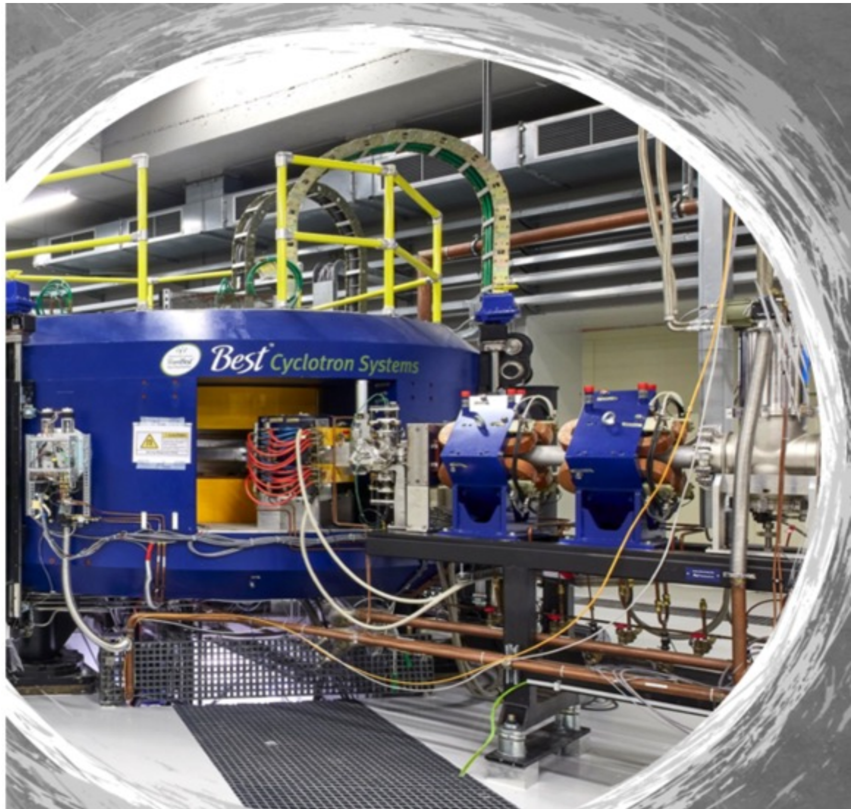


FLASH Radiotherapy with hIgh
Dose-rate particle beAms

FLASH therapy & beam monitoring

The FLASH effect is emerging as a new paradigm, with an increasing number of experiments underway, new machines being commissioned, and new theories developing.

Beam monitoring is a cornerstone of this research and must provide reliable assessment of beam parameters, which are sometimes extreme.

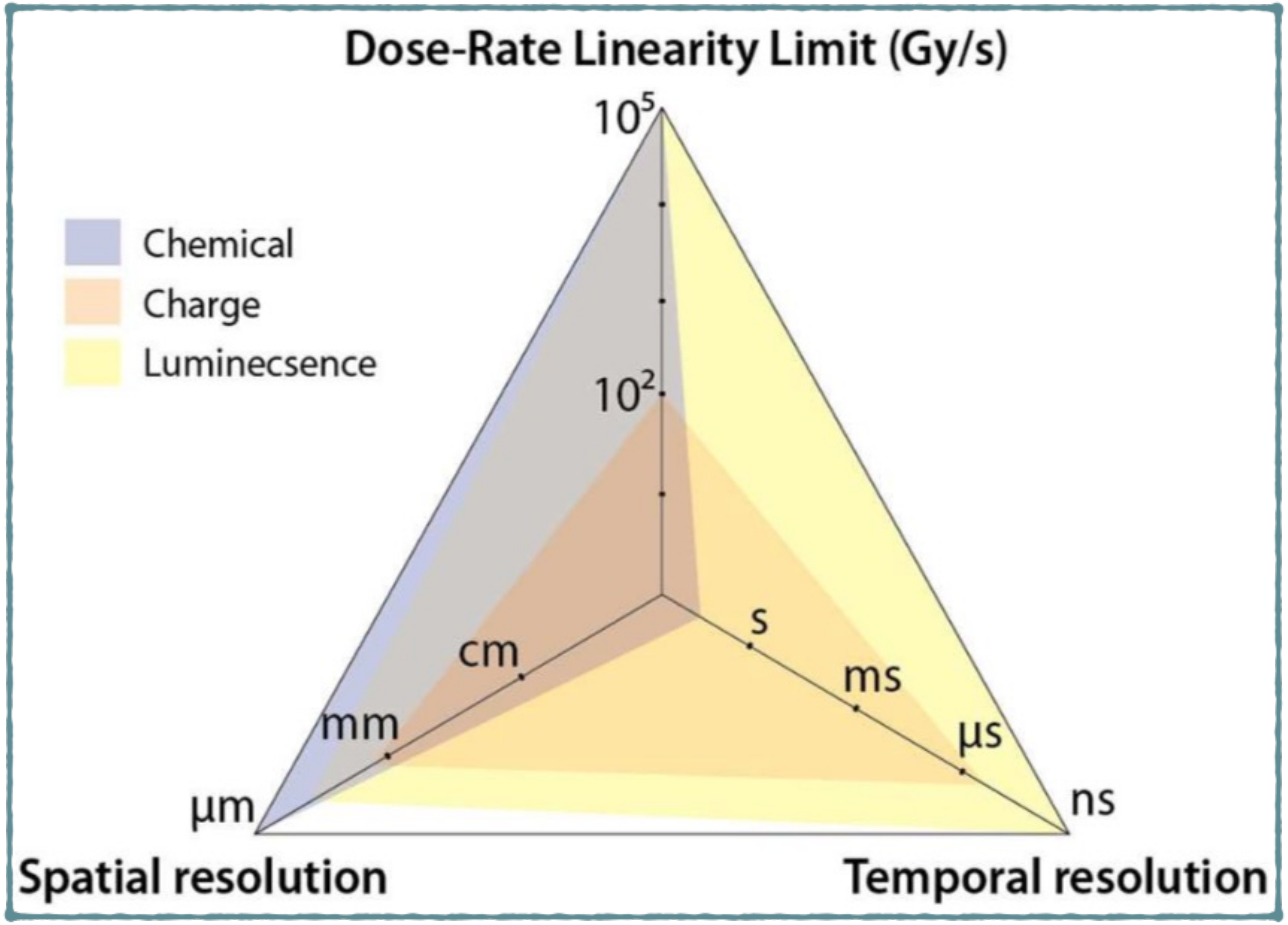
The FLASH radiotherapy environment poses significant challenges to beam monitoring detectors.. The activity in the field, both in the upgrade current technology or in the development of new detectors has been impressive in the last years.

FLASH beam monitoring

- At FLASH intensities, ***instantaneous dose-rate*** and ***dose per pulse*** can be orders of magnitude higher than in conventional radiotherapy, leading to issues of **saturation and/or non-linear response** of standard dosimeters.

The ideal device should feature:

- Dose rate linearity (up to 10^5 Gy/s)
- Real-time, in-beam monitoring
- No energy dependence
- No material obstructing the beam
- Spatial resolution on the millimeter scale

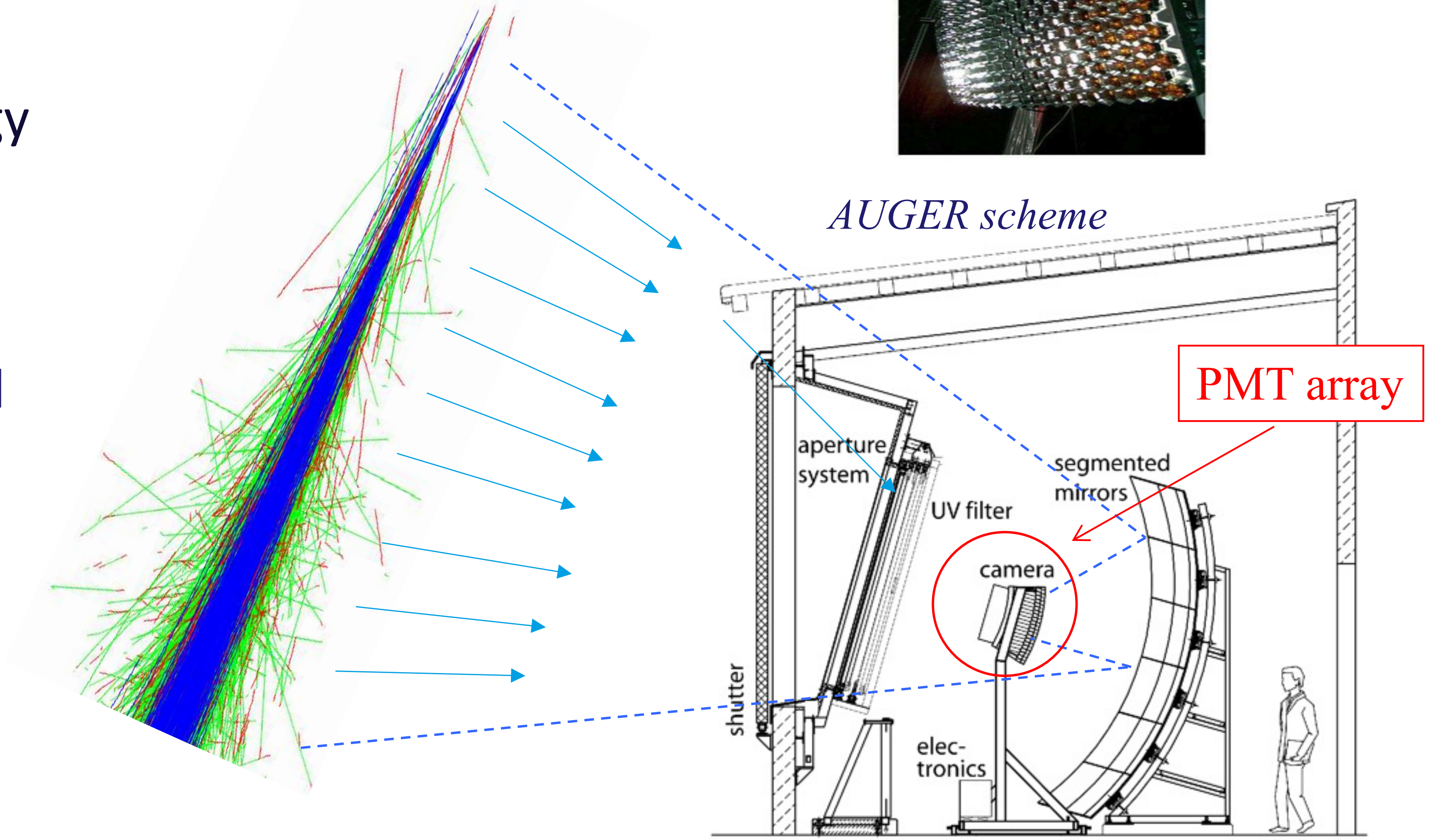


Ashraf MR et al, "Dosimetry for FLASH Radiotherapy" doi: 10.3389/fphy.2020.00328

Air fluorescence and .. EAS detector

The need of very low budget, low signal, high linearity made us look in other fields of physics (the best idea is always by someone else..)

- Air fluorescence detector are largely used in very high energy EAS obstervation
- The air is excited by the EAS and the fluorescence is collected by a large mirror and then focused on a light detector composed by PMTs
- This mechanism, which uses AIR as active medium, can in principle be applied also to FLASH beam monitoring…

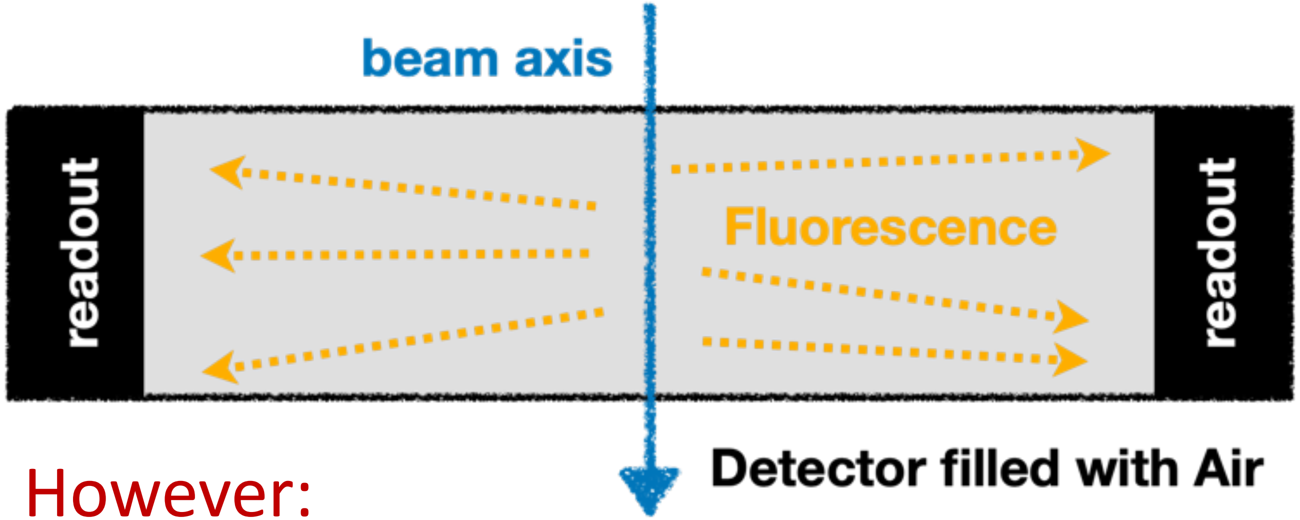


Fluorescence & FLASH beam monitor

What about the air (nitrogen) fluorescence as radiation detection mechanism?
Conceptually, a fluo-based BM is an empty box filled of air, with walls of thin black mylar with a light read-out at the end (maybe PMT?)
The beam excites the air that produces light collected by the readout (PMT)

Appealing features:

- ☑No energy threshold
- ☑Photons emitted isotropically
- ☑Signal emitted within ~ns
- ☑Simple and cheap to produce
- ☑Minimal impact on the beam
- ☑Range limitation by UV filter



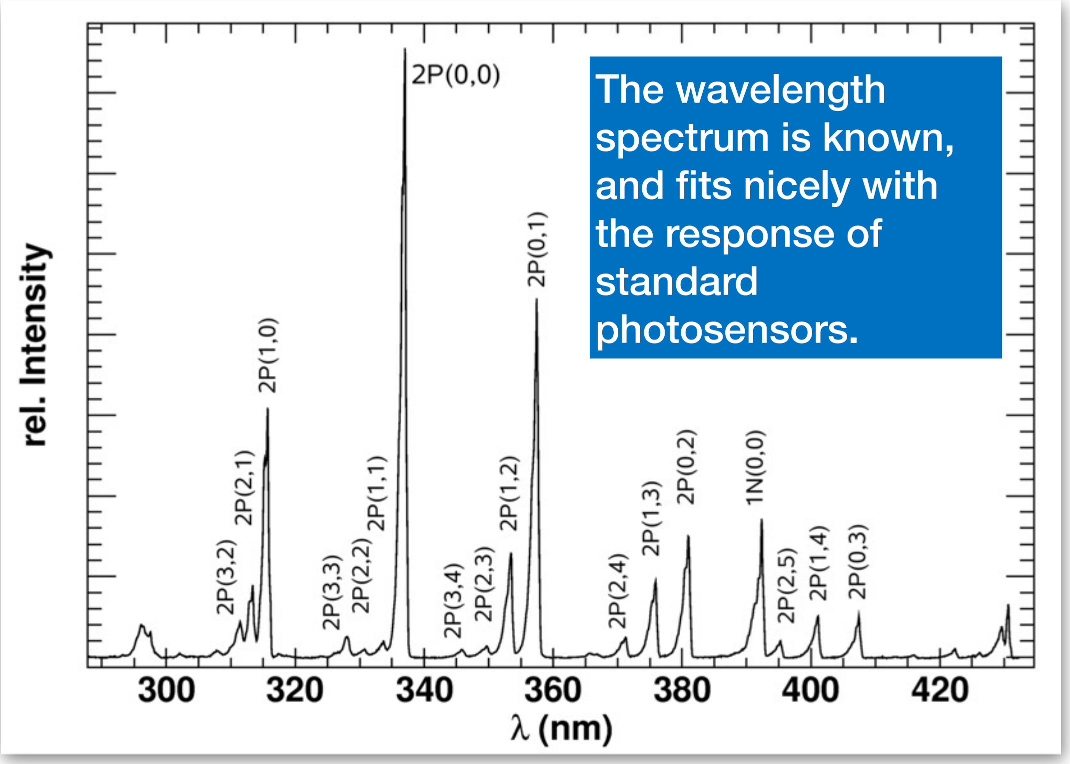
However:

- ☑Not yet well measured
- ☑.... Does it work???

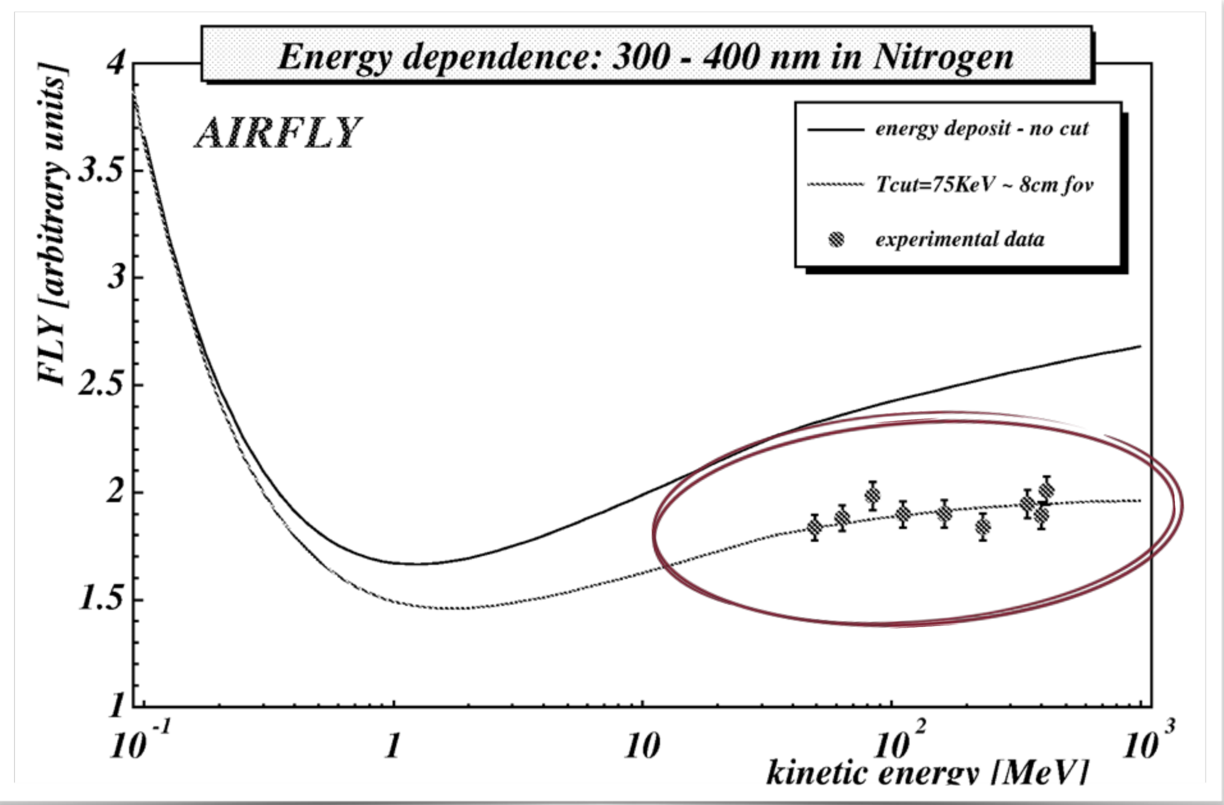
Fluorescence and FLASH BM

✓ In air, fluorescence occurs mainly on the nitrogen molecule.

✓ Nitrogen fluorescence has a lifetime of around 10^{-8} s, with emission spectrum that nicely fits in a standard photo-sensor response window (es: PMT)



The wavelength spectrum is known, and fits nicely with the response of standard photosensors.



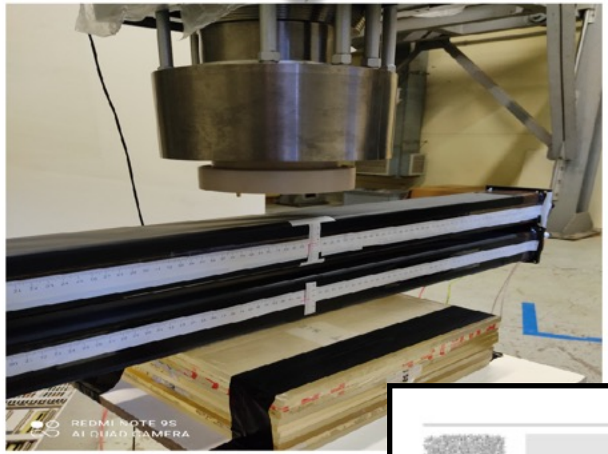
Fluo for FLASH monitoring.. a journey!

First round: LIAC-HWL
November 2020-June 2021

Second round: EF Antwerp
July 2021-June 2022

Third round: EF Pisa
July 2022-June 2023

2022



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

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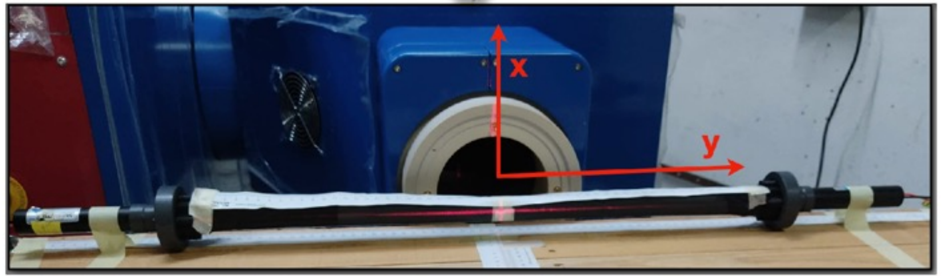
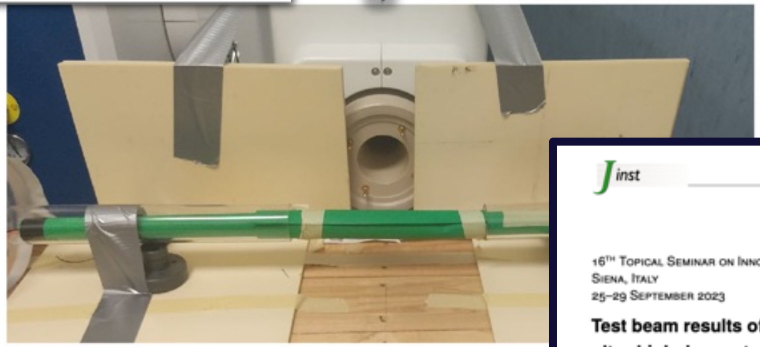
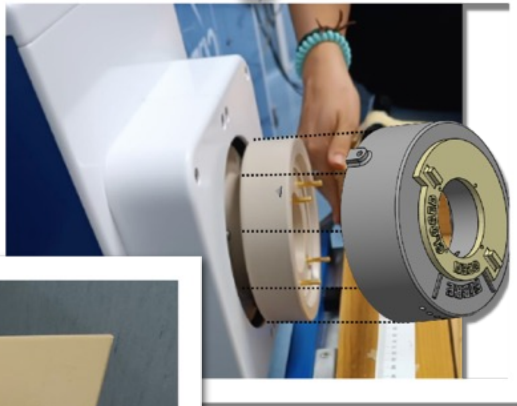
2023



2024



2025



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Test beam results of a fluorescence-based monitor for ultra-high dose rates

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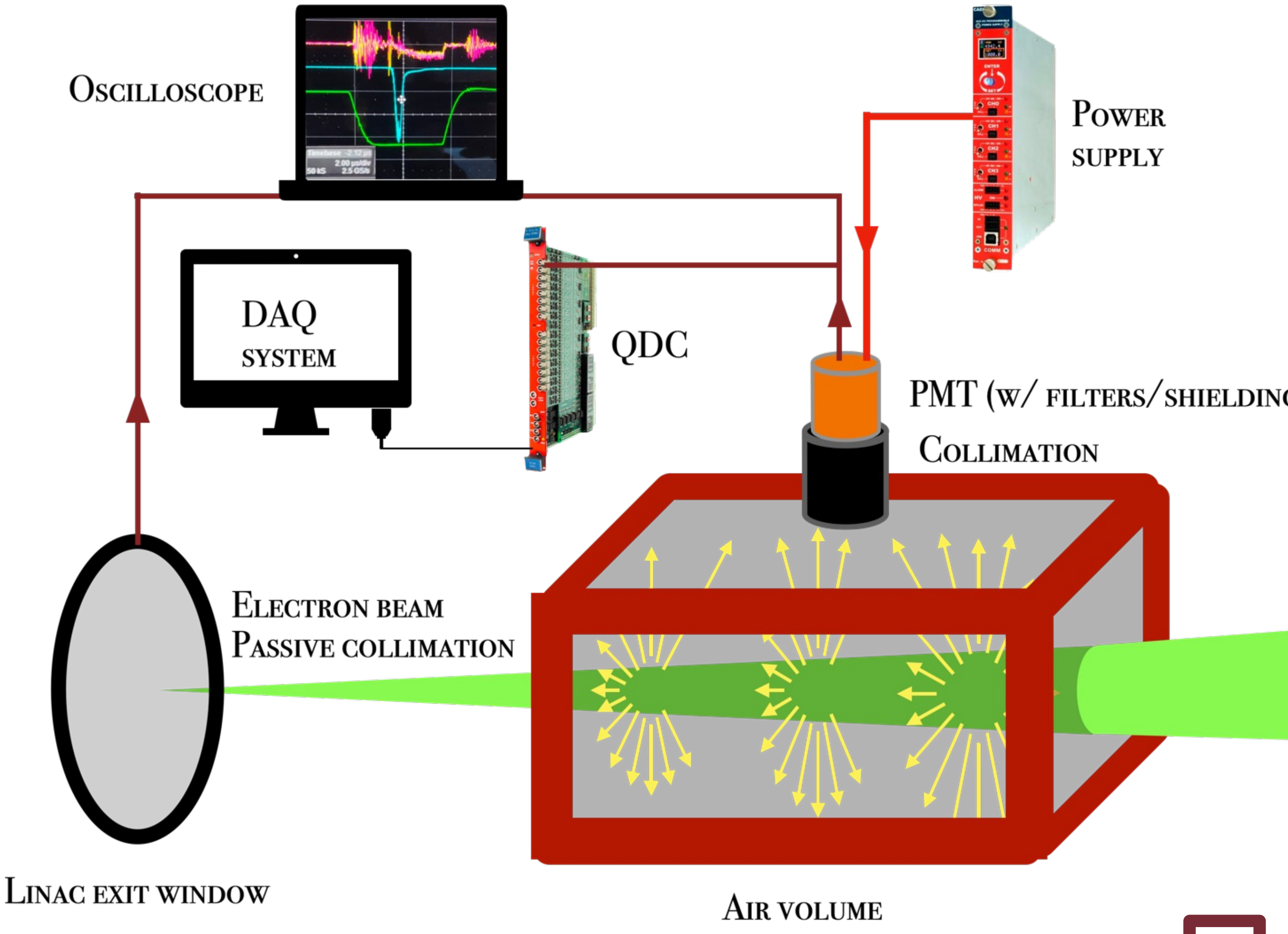
2024 JI

FLASH DC

First assesment @FLASH beam

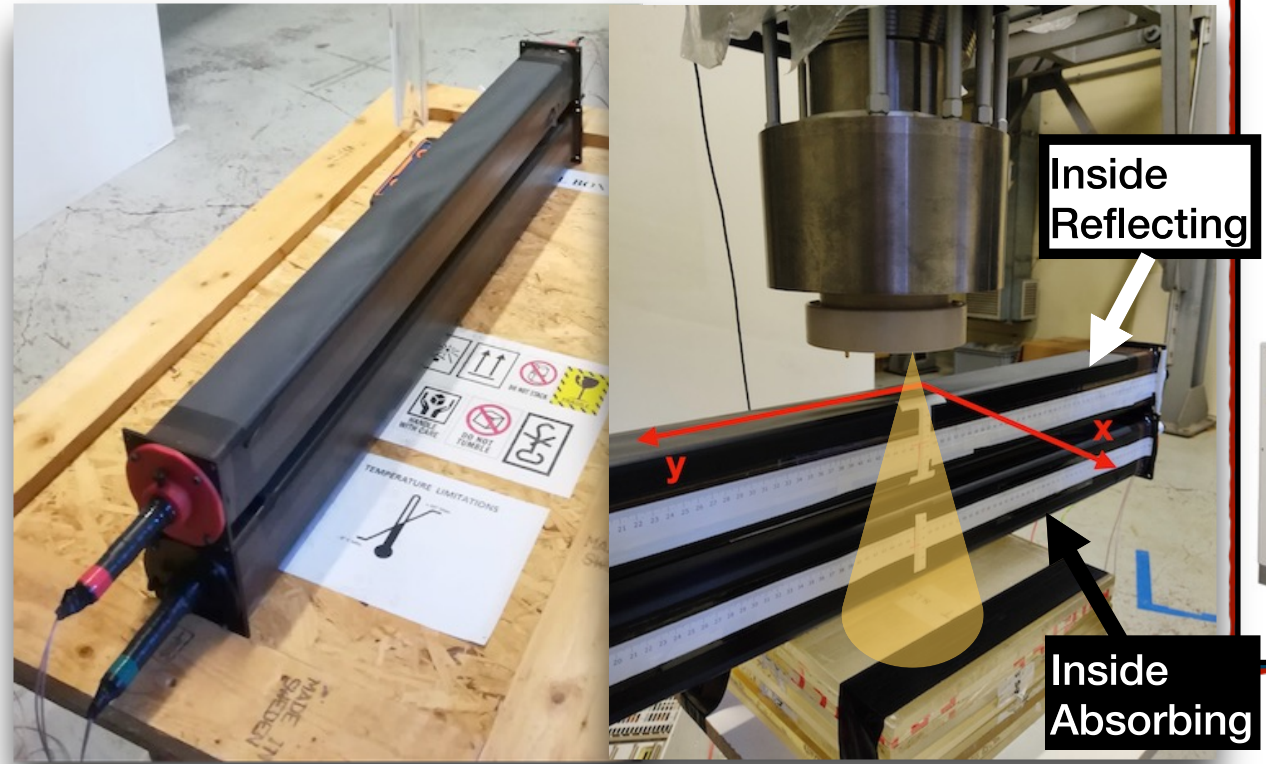
We started with very basic exp setup….

Testing has been done on the (easily) available sources of beams with UHDR intensities: low energy (6-12 MeV) electrons usually used for intra-operative applications or dedicated to FLASH study



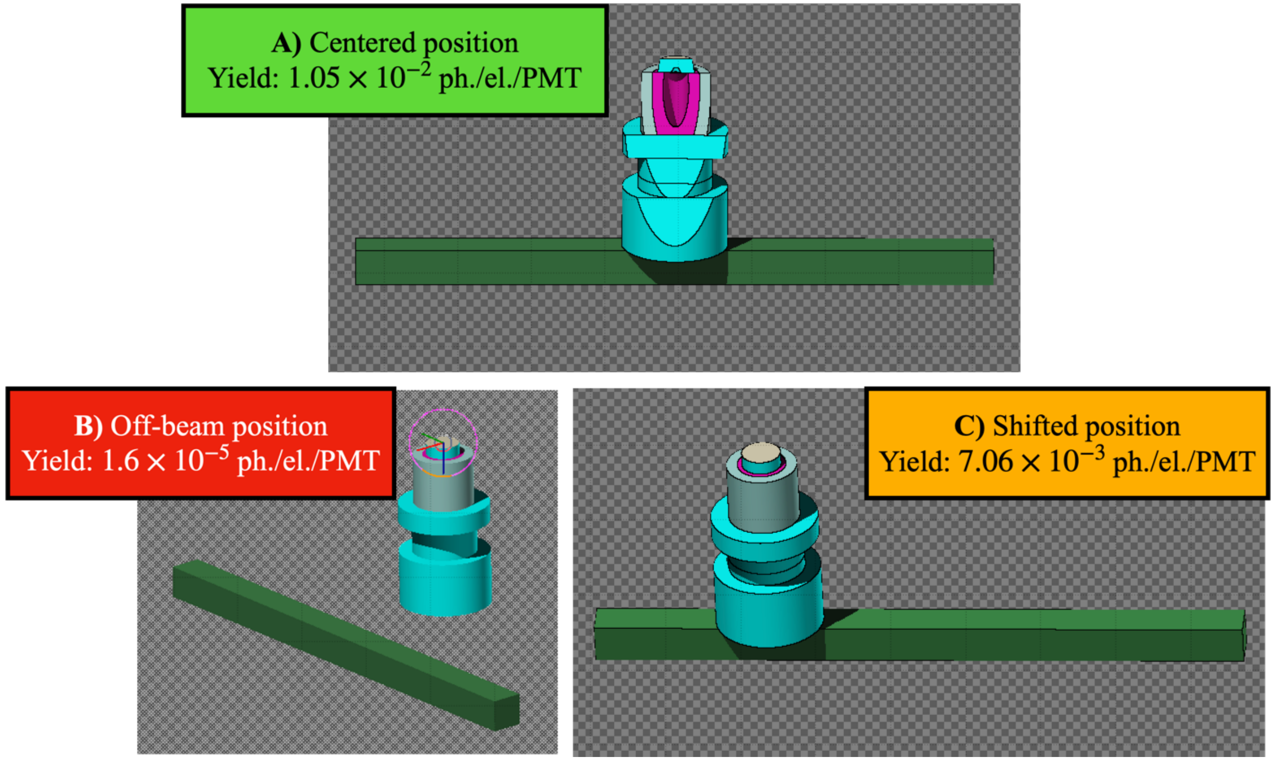
First: proof of principle..

First prototype: 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.

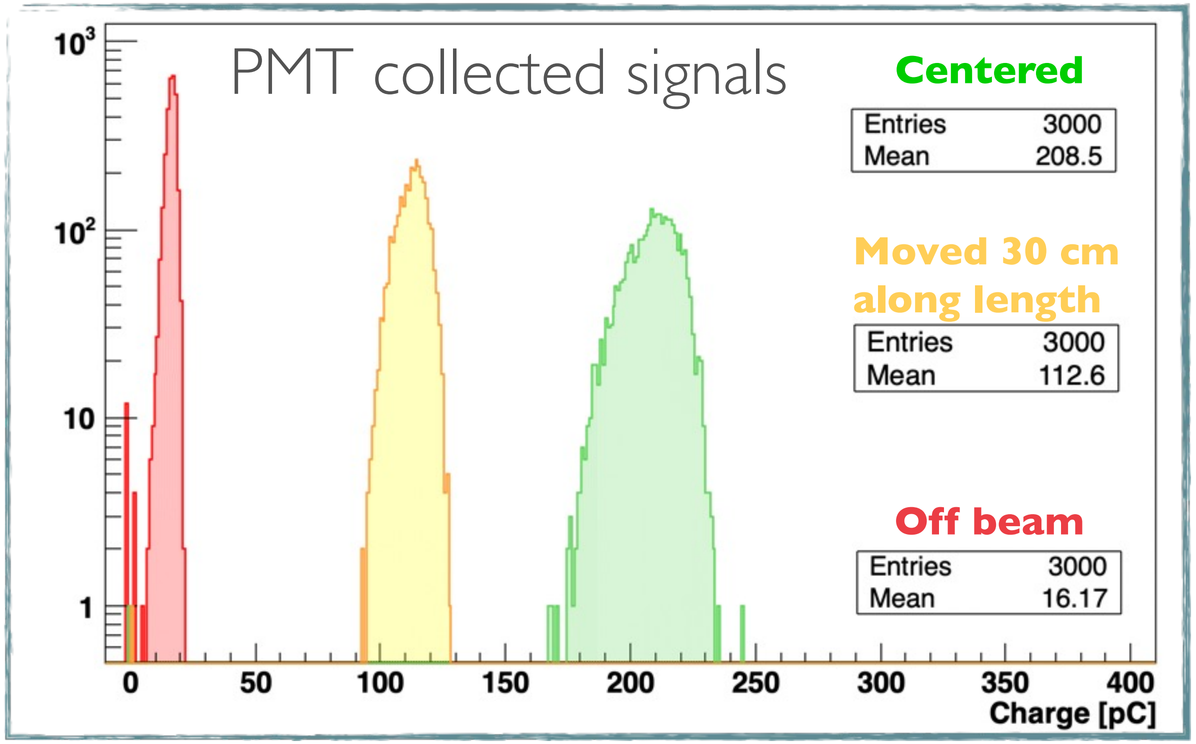


- **LIAC HWL**: linac for intra-operative electron RT **modified** to reach 10^{10} electrons/pulse.
- Electron energy: 6MeV.
- Pulse duration: 2 μs.
- Dose per pulse ~ 0.3 Gy.
- Large area beam (5-10 cm diameter)
- **FLUKA MC simulation** of accelerator delivery and the detector

Looking for the fluorescence signal



- The results confirmed the expected signal sensitivity to the detector position with respect to the beam.



MC simulations (FLUKA 2021) used to evaluate **signal and background** and **ratio of optical photons** on the PMTs when the beam moves along the bar.

Next step: intensity sensitivity

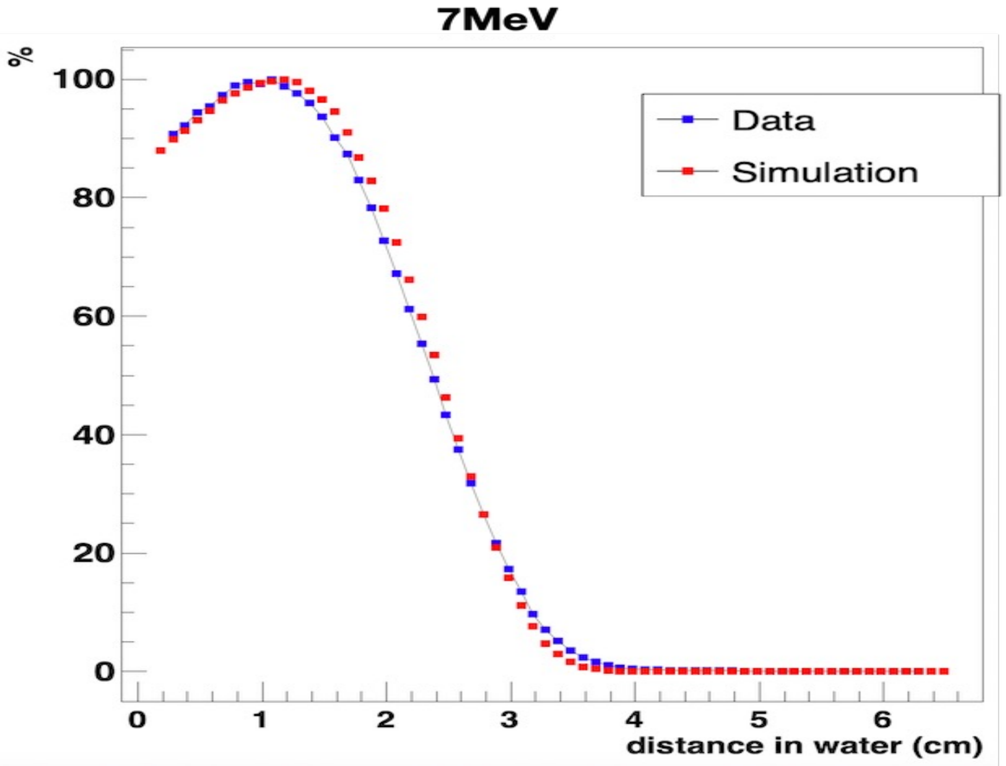
- The linearity of the fluorescence VS beam intensity has been tested @ ElectronFlash by S.I.T., an electron LINAC developed specifically to perform FLASH studies

- **ElectronFlash**: up to **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 diameter: **5-6 cm at BEW**

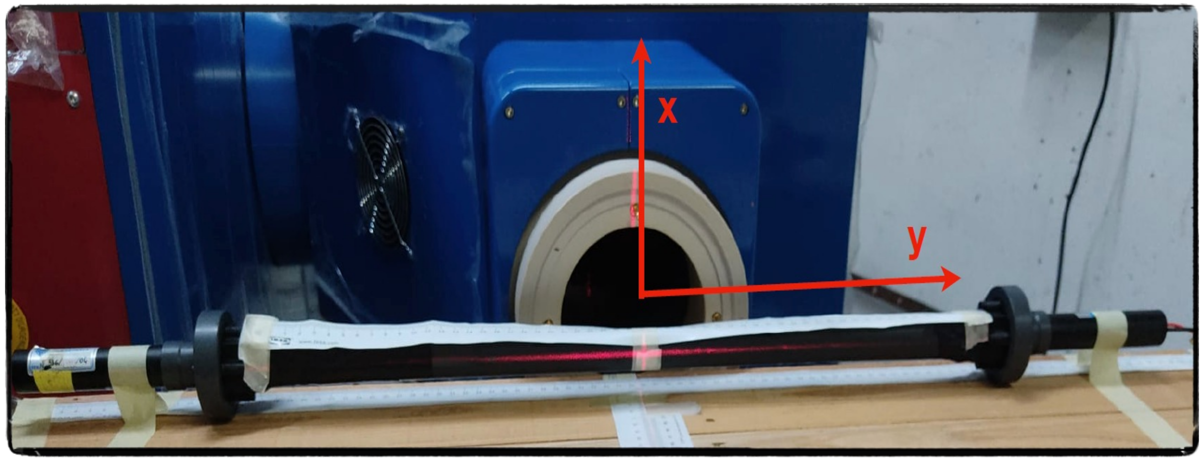
SO

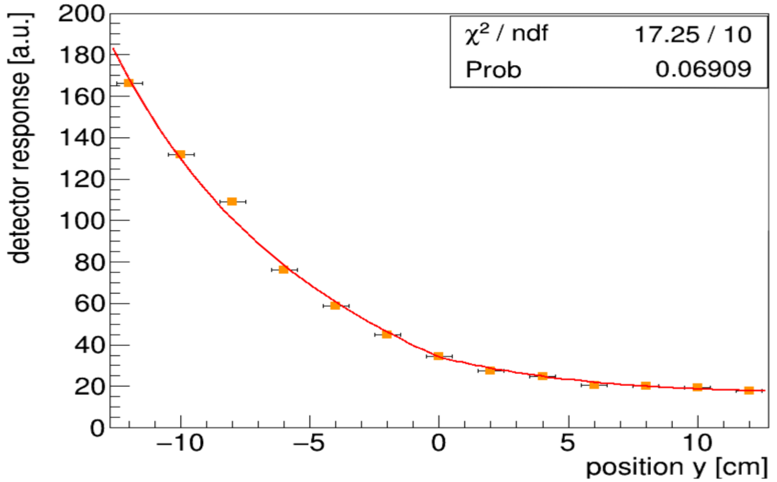
soiort.com/flash-rt-technology/

PDDs of electrons delivered were measured using **flash Diamond** detector and compared to **FLUKA MC simulation**).



Moving around the detector

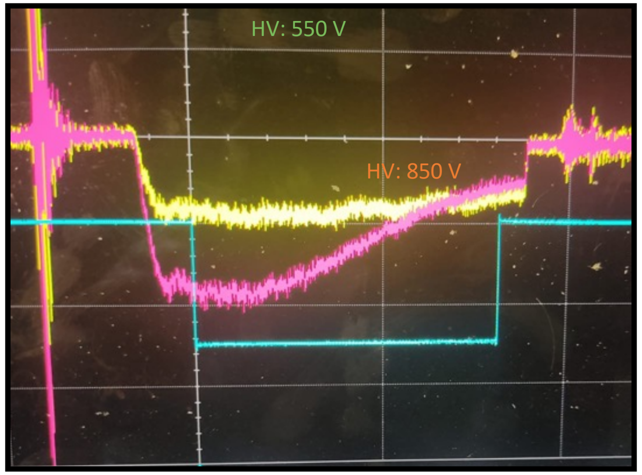




Moving along Y
Near-far inside the beam

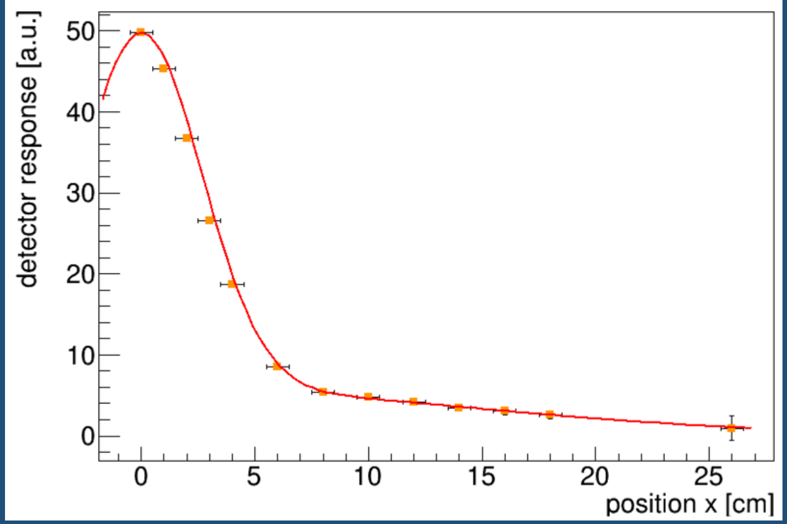
The active media of the prototypes was an air volume, with dimensions : **2x2x60** cm^3

Two PMTs on both ends equipped with **UV filters**



studied both position and ***charge*** sensitivity.

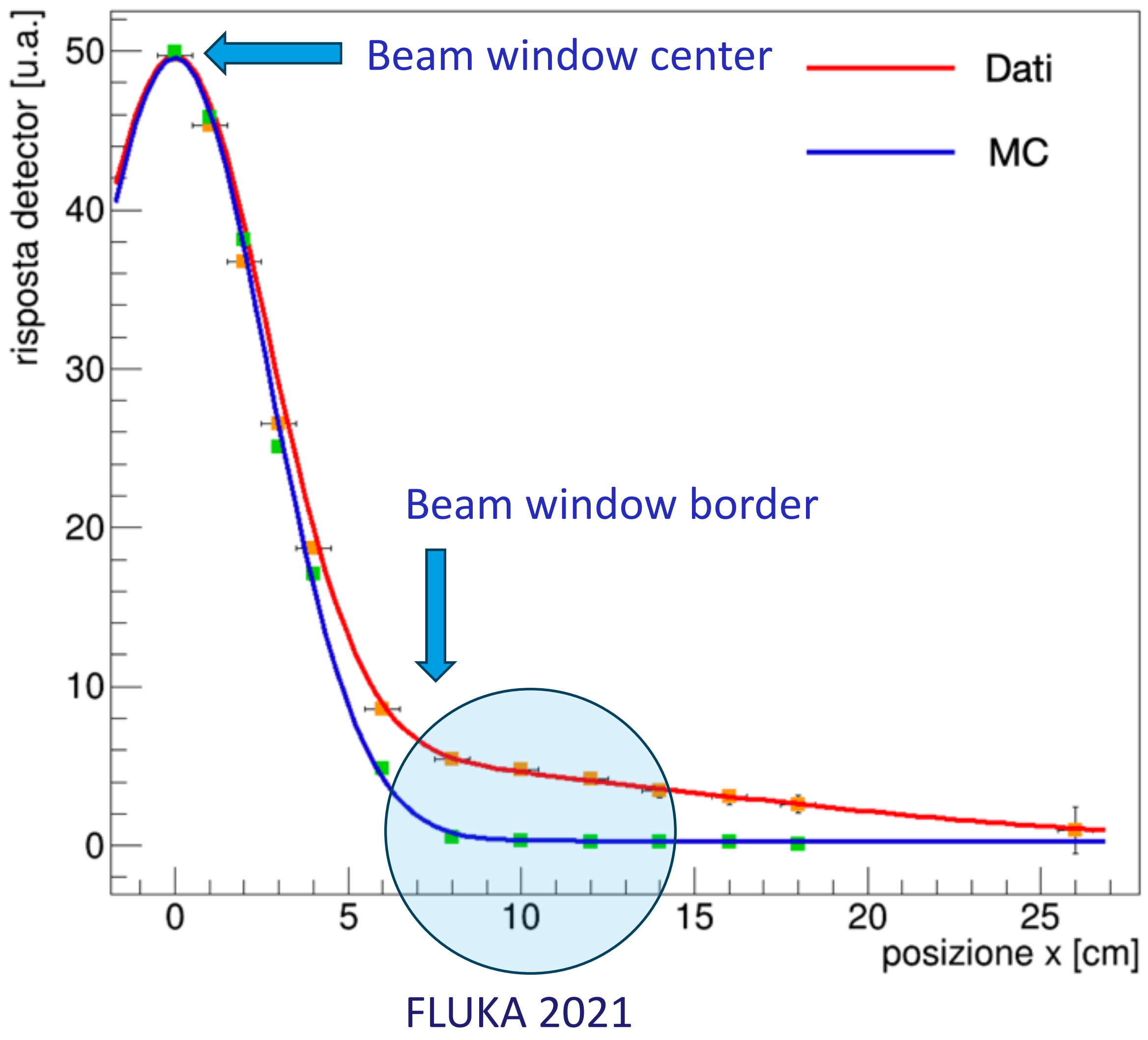
Moving along X (inside-outside the beam)



Data vs MC simulation

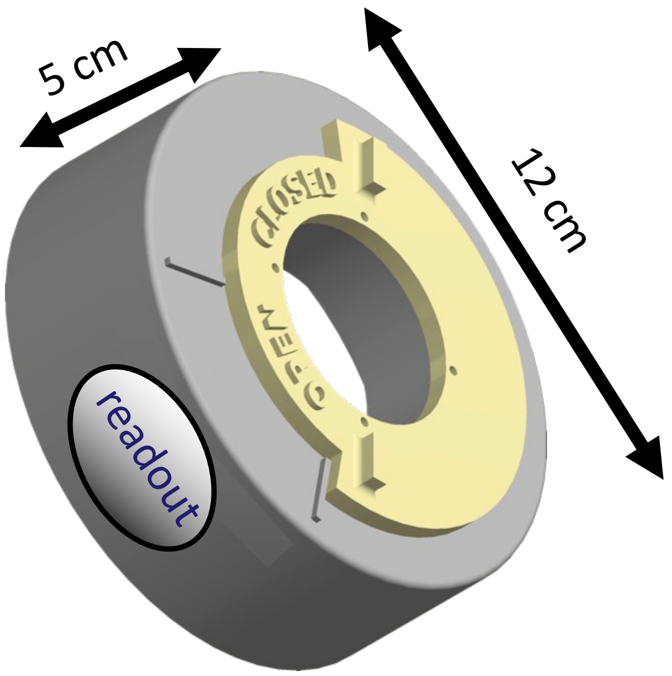
MC simulation has been developed to model the detector response.

- The comparison is quite fair, but some beam parameters are not correctly modeled in the simulation, like beam secondaries and uncertainties in the energy and angular divergence
- The background modeling is the culprit of the MC simulation in the low signal region.
- The presence of this background not under control triggered an optimization of the geometry.



Towards a true FLASH beam monitor

- Next step is to prove that the linearity of signal *vs* beam current is really due to fluorescence => subtract background.
- The detector design has been **directly tailored** to the Beam Exit Window dimensions. is



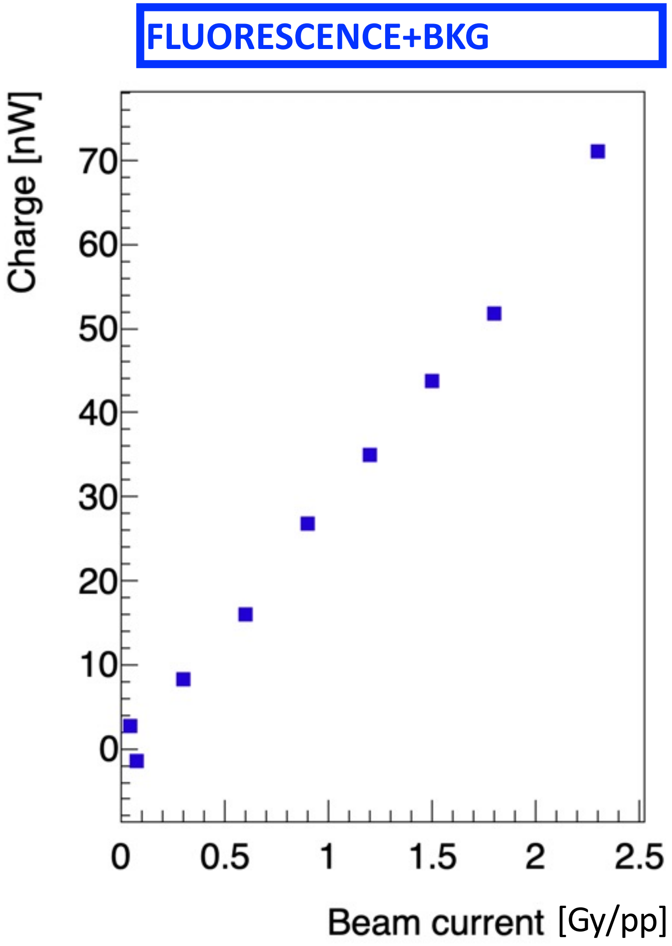
Towards a true FLASH beam monitor

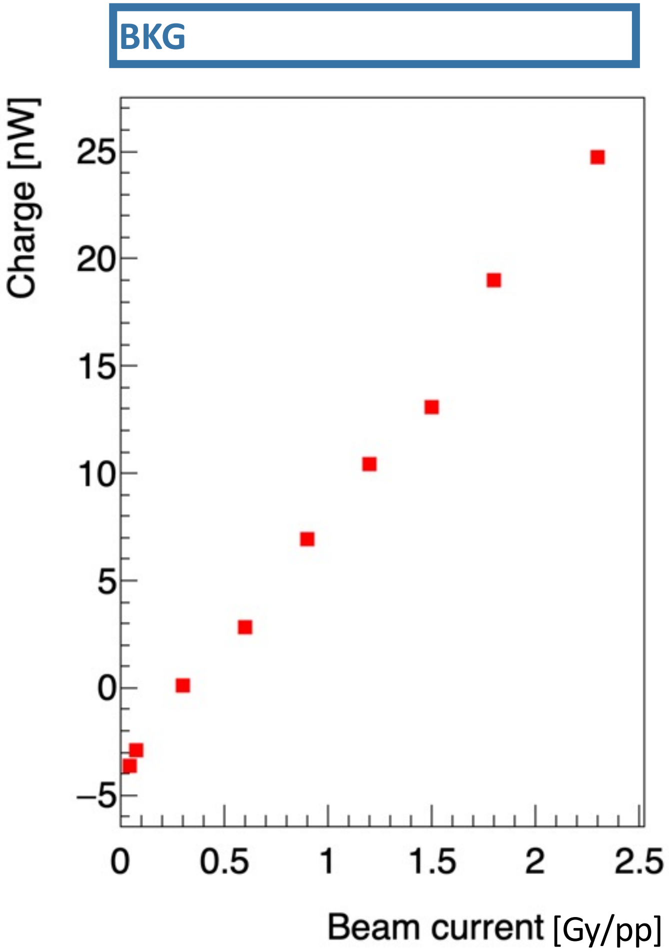
- Next step is to prove that the linearity of signal *vs* beam current is really due to fluorescence => subtract background.
- The detector design has been **directly tailored** to the Beam Exit Window dimensions. is
- The active volume is the air immediately after the BEW, enclosed in a cylindrical case. A sliding leaf on the external face can be closed and opened for background measurement.

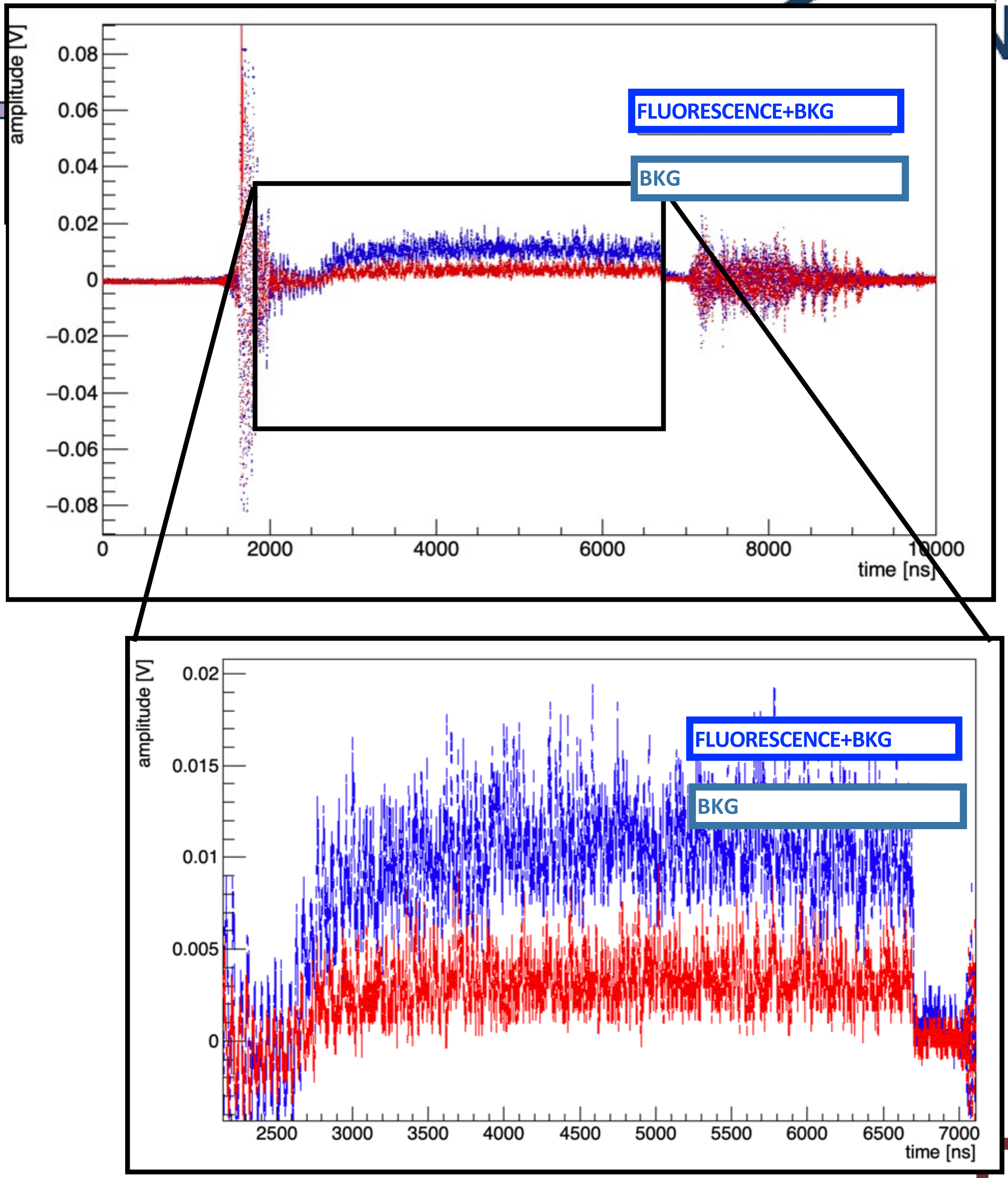
active volume mounted on the beam exit window.
N.B.: **<u>no material on the beam line!</u>** Just air…

PMT is wrapped in a plastic shield with thickness of 2 cm, at 1.2 m from the beam exit window

UHDR beam monitoring

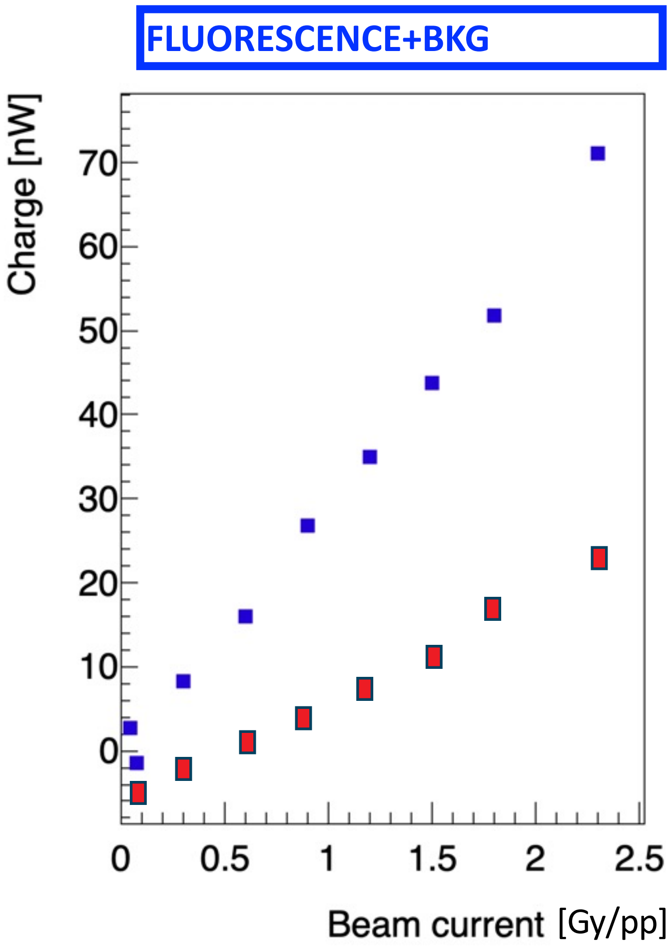


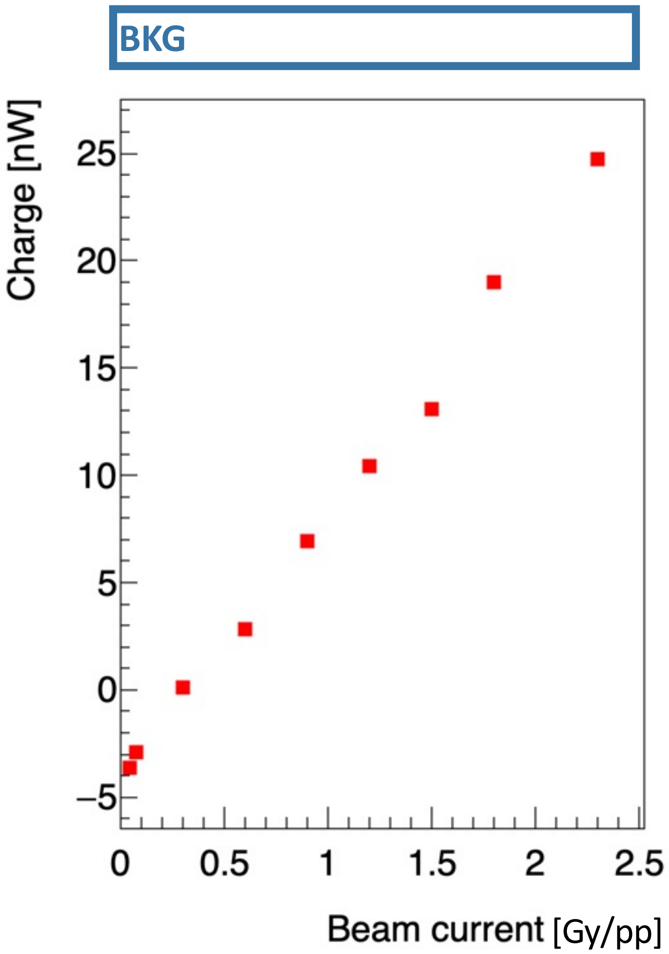


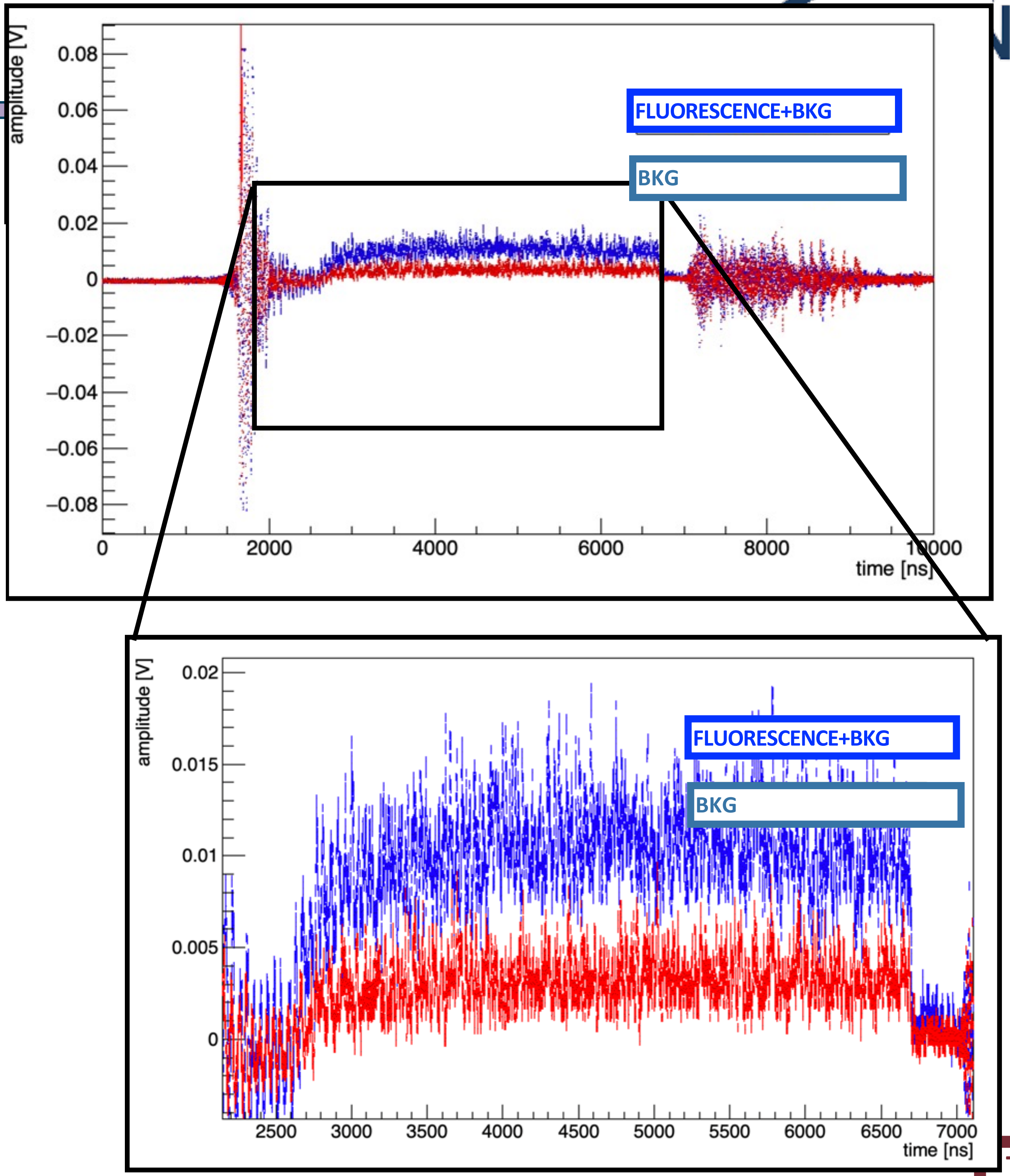


S/N can be largely optimized → dedicated readout system in development!!!

UHDR beam monitoring



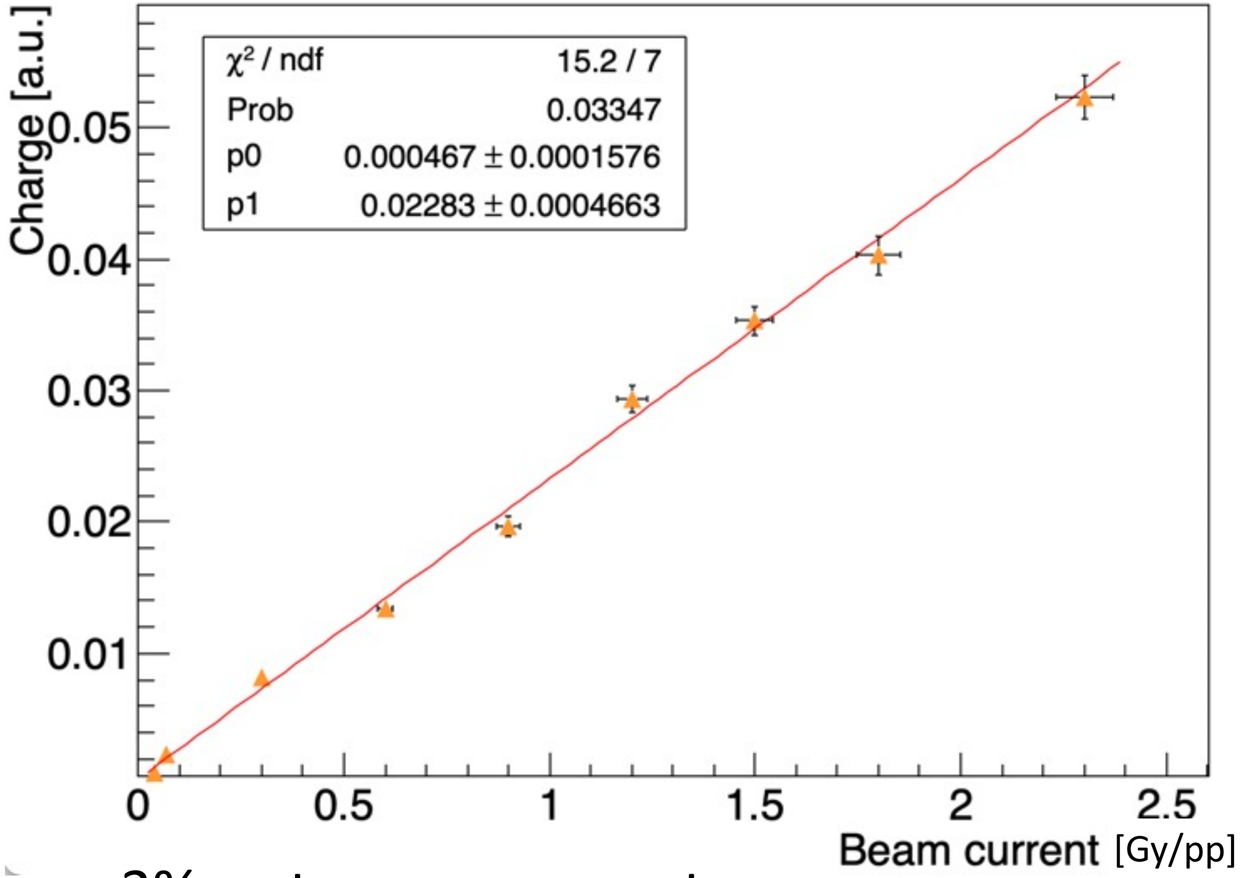


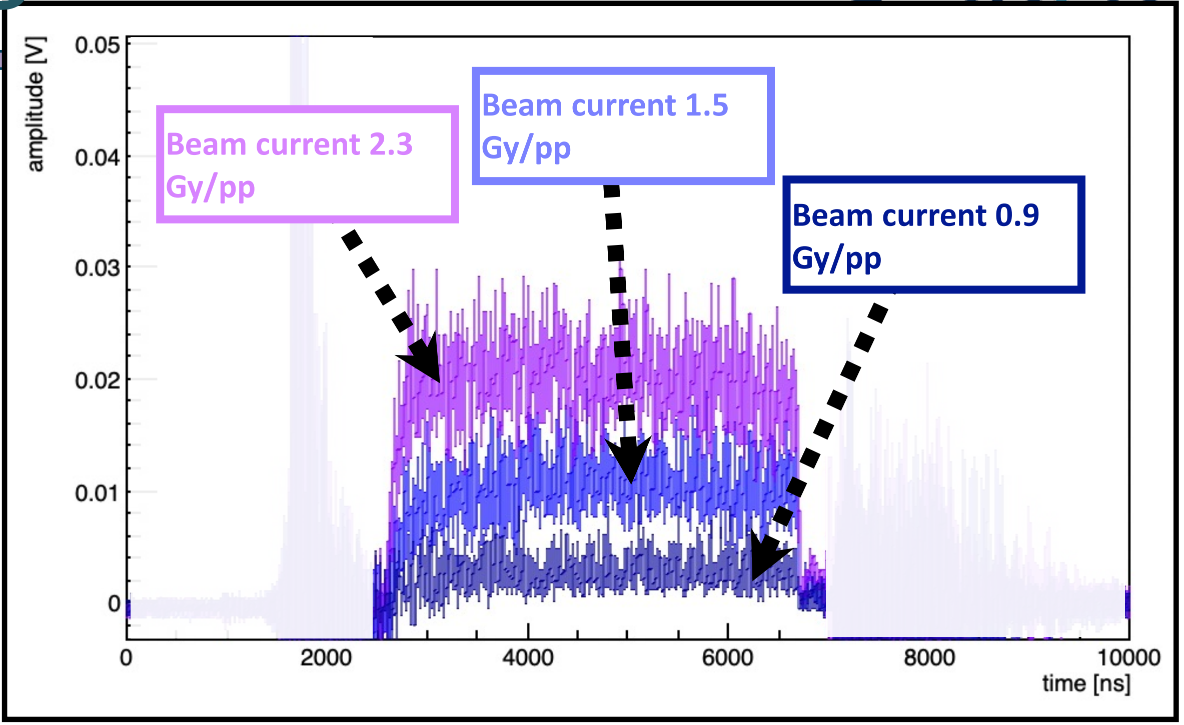


S/N can be largely optimized → dedicated readout system in development!!!

FLASH beam monitoring

FLUORESCENCE-bck





- 3% syst. err on current
- 3% syst.err ⊕ stat.err on charge

- ☑ Fluorescence signal linearity as a function of the beam current is confirmed!
- ☑ The statistics is very low… only 30 pulses have been acquired (for each current).

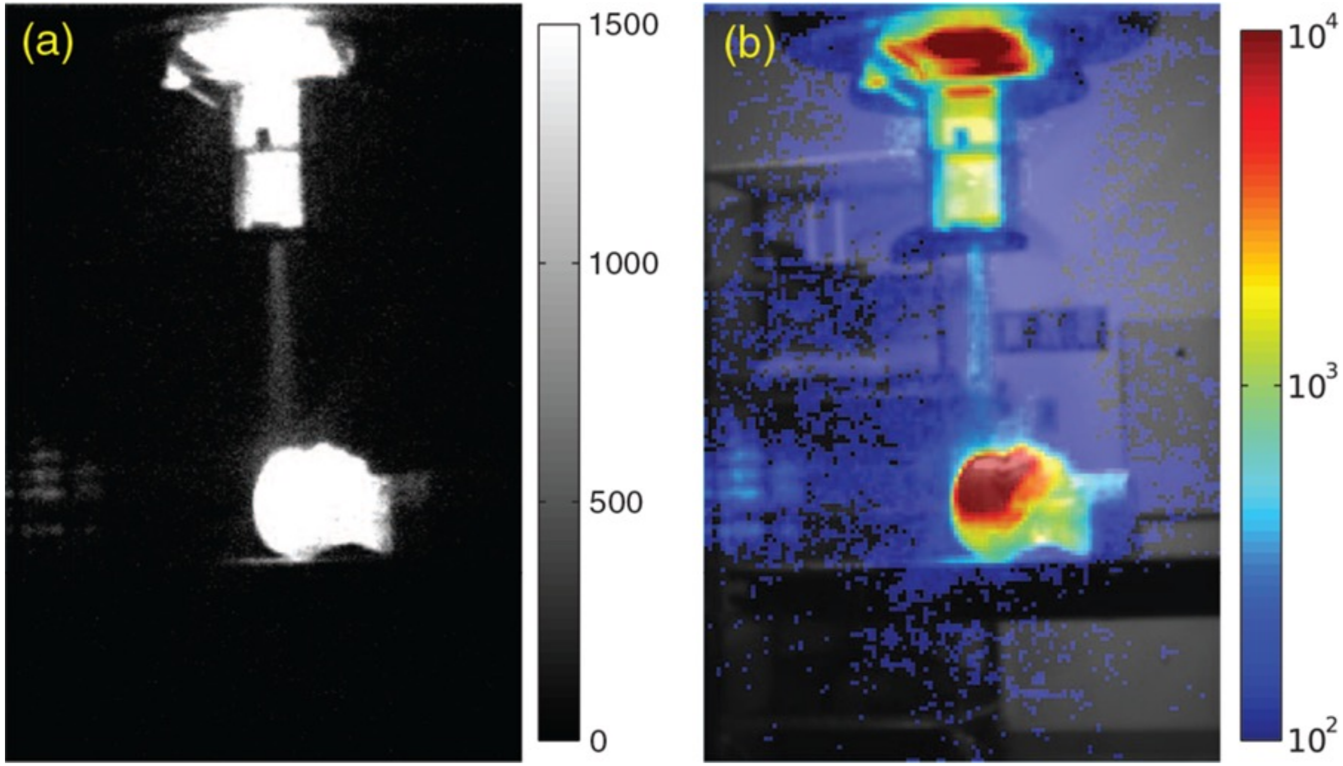
Beam monitoring @SPES intensity…?

Fluorescence technique could be safely applied to the low end of the intensity range of SPES… application to high end is uncertain

- FlashDC showed no saturation at the maximum intensity/energy available at electron FLASH machine→ higher intensity can be explored 👍
- FlashDC prototype seems to suffer from low signals with respect to bck→ could gain S/N at higher intensities 👍
- Proton beam with reduced transverse size opens to transverse position accuracy measurement using dedicated readout 👍
- However, several unknown need to be explored:
  - Fluorescence saturation?
  - Background effect? 🤷‍♂️ ? 🤷‍♂️ ? 🤷‍♂️ ? HIC SUNT LEONES…
  - ….?

BTW, good ideas have a lot of fathers…

Of course we discovered the the effect was already observed in 2013 not only in EAS physics, but also in radiotherapy!!!



Seeing the invisible: Direct visualization of therapeutic radiation beams using air scintillation

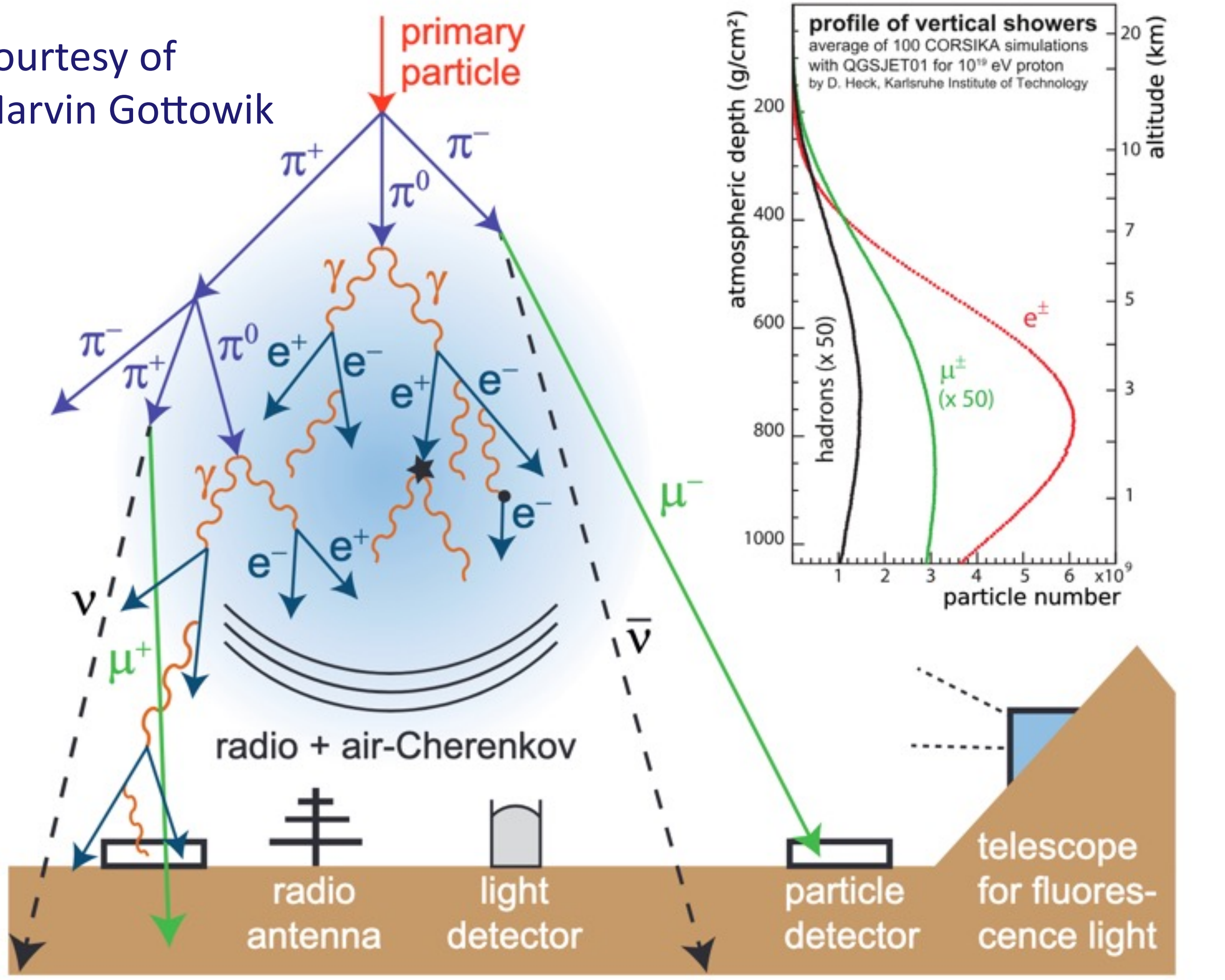
Benjamin Fahimian et al Medical Physics, Volume: 41, Issue: 1, 2013, DOI: (10.1118/1.4851595)

And now, back from FLASH to EAS…

- SPES can have a charged particle density that can mimic the highest EAS energy (10^{21} Ev)
- A tailored FLASH-DC detector can measure the Fluorescence Yeld induced by very high Energy EAS

Extensive air shower (EAS)

Courtesy of Marvin Gottowik



Fluorescence Yeld experiments

AIRFLY is the **current standard** for most major UHE EAS observatories

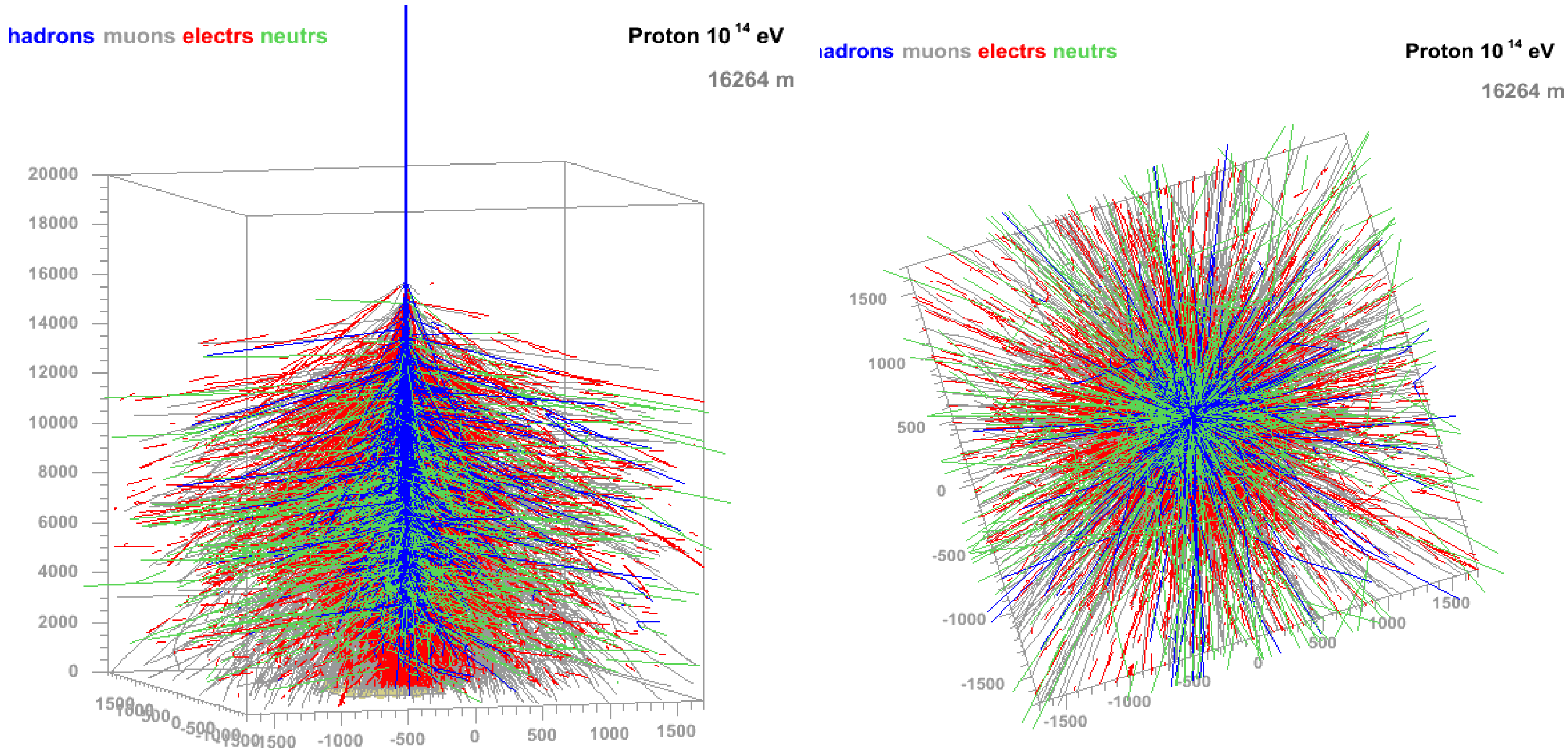
Experiment	Technique	Achievements
AIRFLY (Fermilab)	High-energy electron beam in controlled air	Measured absolute FY to ~3% precision
FLASH (SLAC)	Electron beam + ultra-pure air target	Focused on high-energy particle induced fluorescence
Nagano et al. (Japan)	Sr-90 β-source	Pressure/temperature dependence

No hadron beam!!

Today, the overall FY uncertainty propagates to about **7–8% energy uncertainty**

Improving it to **3–5% total** would require new experiment carefully simulating **atmospheric conditions all along the shower**.

EAS structure



The EAS shower is not made only by electron but has a hadron core contributing to the fluorescence

Exp@SPES could Improve FY meas?

Peculiar @SPES??

A FD measurement useful for High Energy EAS the measurement could:

- **Extend pressure and humidity range**:
  Test very low pressure and very dry/wet air to simulate full EAS altitudes realistically (down to 100 hPa).
- **Measure heavier gas admixtures**:
  Air is not 100% N2 and O2 — minor gases (Ar, CO_2) could slightly affect fluorescence.
- **Wavelength-resolved FY at all conditions**:
  Some detectors are sensitive across 300–400 nm. Better mapping of spectrum vs conditions would reduce systematic error.
- **Direct ion beam excitation**:
  Instead of secondary electrons, use **light ion beams** (p, He) to study more realistic energy deposition profiles of the inner hadronic core.
- **Nonlinear effects at high ionization densities**:
  Study whether high particle densities (core of showers) suppress FY

Summary and conclusions

- Air fluorescence can be used as detection principle for FLASH beam monitoring
- Careful geometry and readout optimization needed to deal with background of FLASH beams
- The functionality of such a technique could be explored at SPES with UHDR proton beams

- A FlashDC could be used @SPES to refine the measurement of the air fluorescence for UHE EAS

Thanks!!!

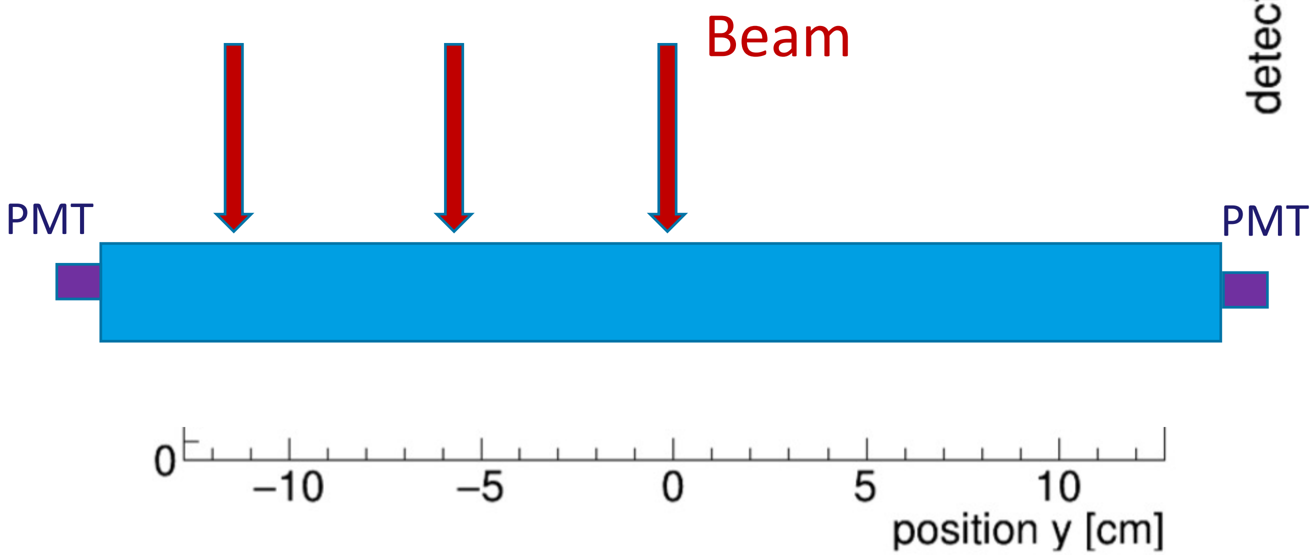
FLASH Radiotherapy with hIgh Dose-rate particle beAms

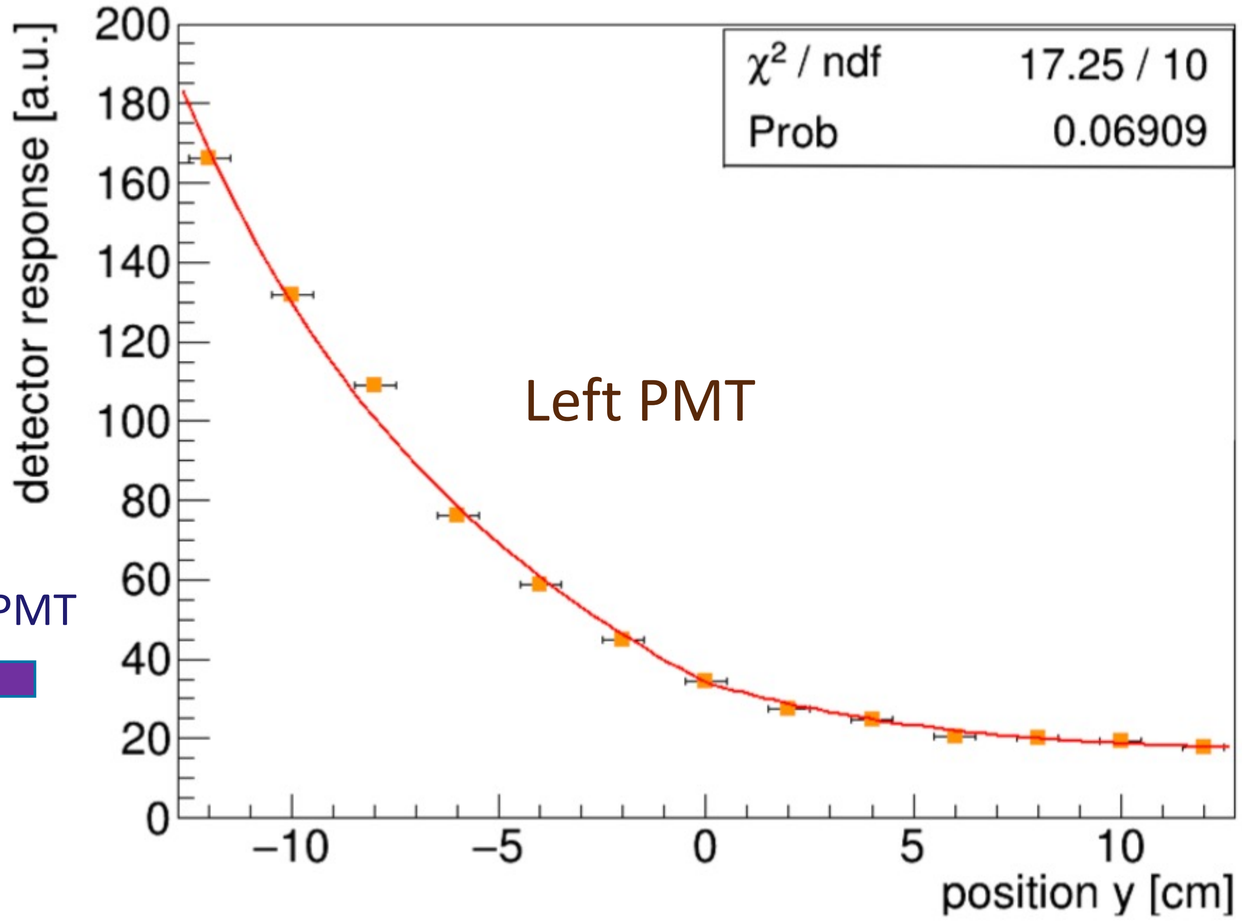
CENTRO RICERCHE
ENRICO FERMI

SIT
Sordina IORT Technologies

Position sensitivity test

For this test we positioned the BM near the LINAC nozzle so to have a beam size of the order of ~cm. Then we moved the beam position along the detector

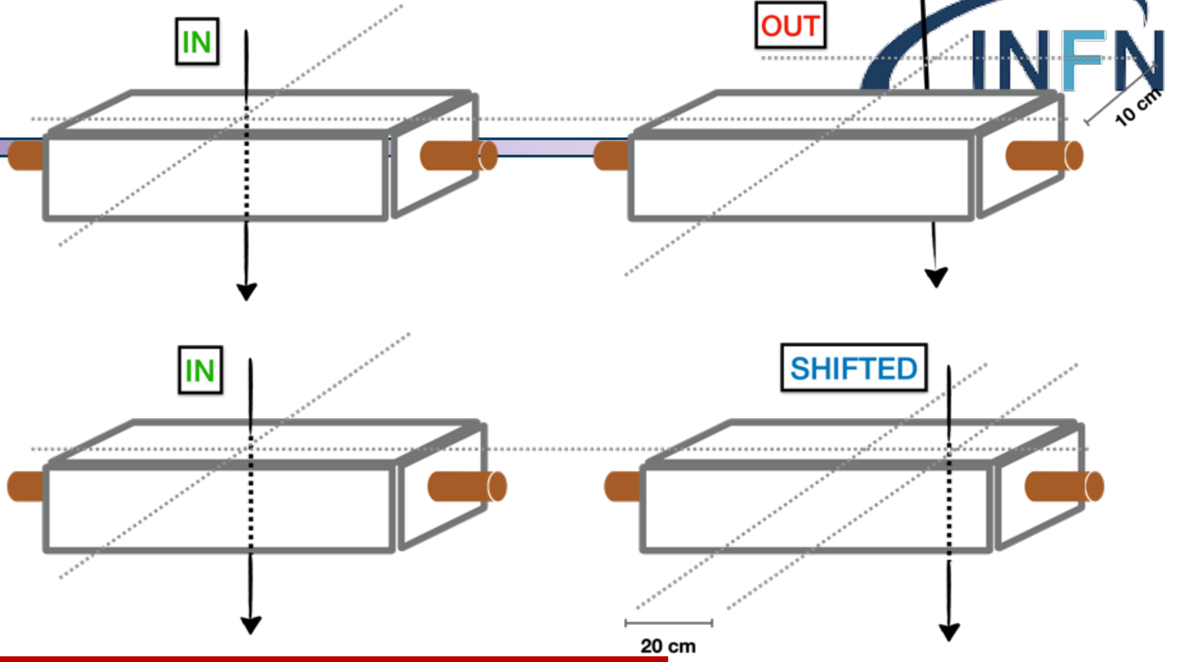


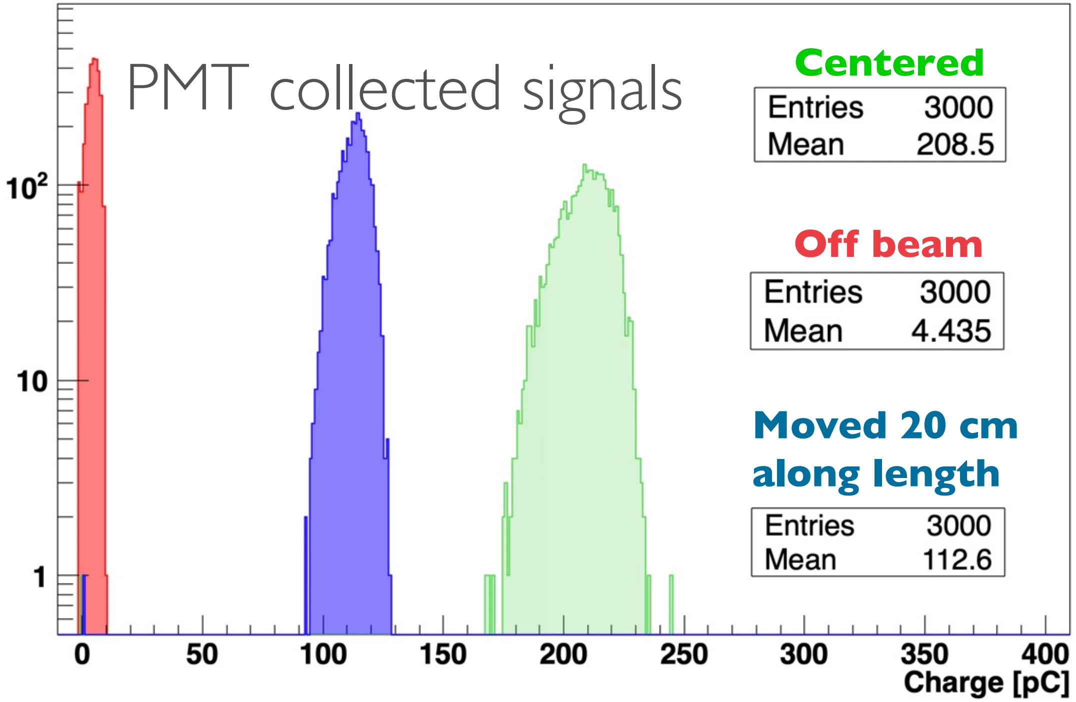


The PMT charge has a nice sensitivity with respect to the beam position…

Preliminary tests

- ✓ **1st question**: can we observe in-beam/off-beam difference?
- ✓ Experimentally, we move the device <u>10 cm away</u> from the beam axis.
- ✓ A FLUKA* MC simulation estimates a reduction of optical photons of a factor 10^3.





- **2nd question**: what if one of the PMTs is farther from the aperture?
- With a <u>20 cm shift</u>, FLUKA* estimates a reduction of optical photons of a factor 2 with respect to the configuration with the beam shooting at the center of the device.