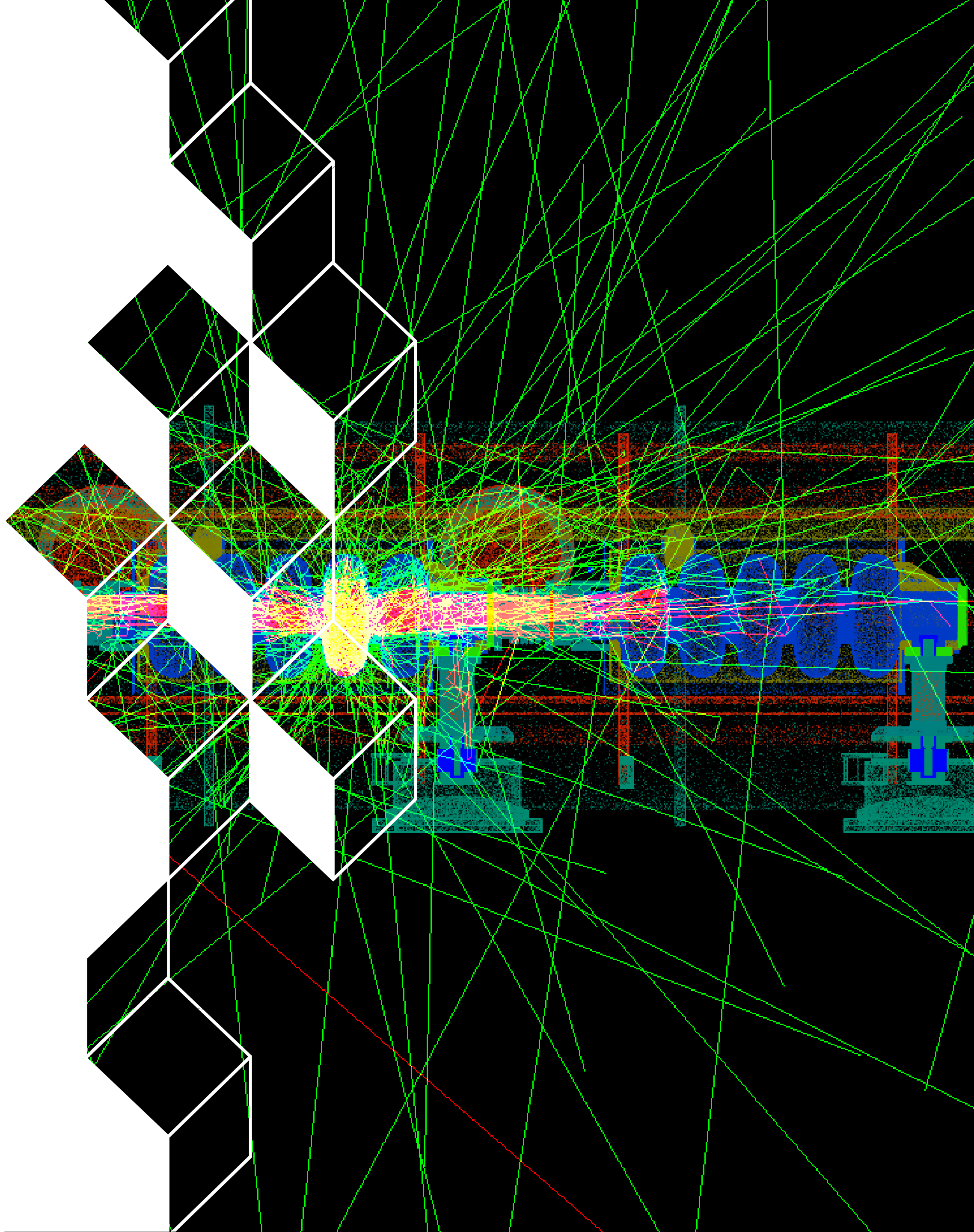
# Gamma diagnostics for SRF cavities and cryomodules

E. Cenni

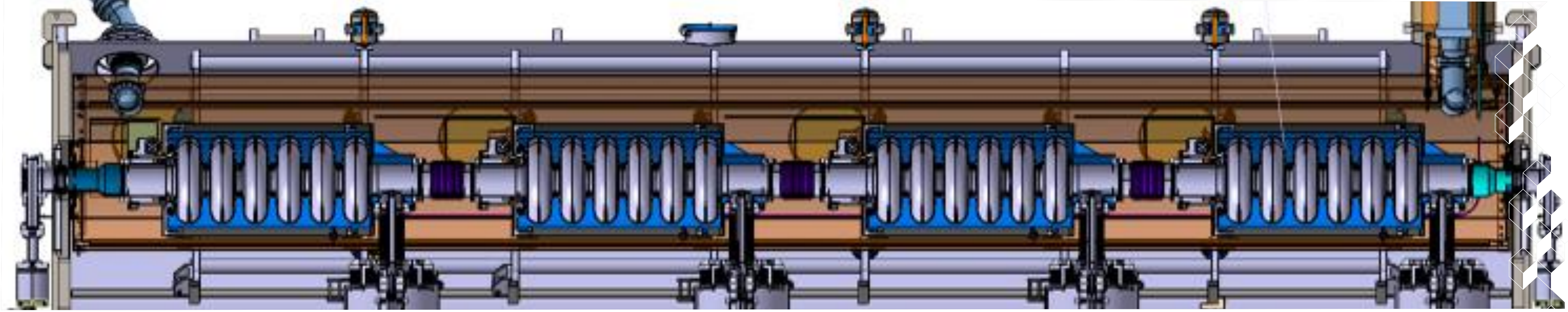
*On behalf of:*

*G. Devanz, O. Piquet, M. Baudrier, L. Maurice (DACM/LISAH), Paris-Saclay University*



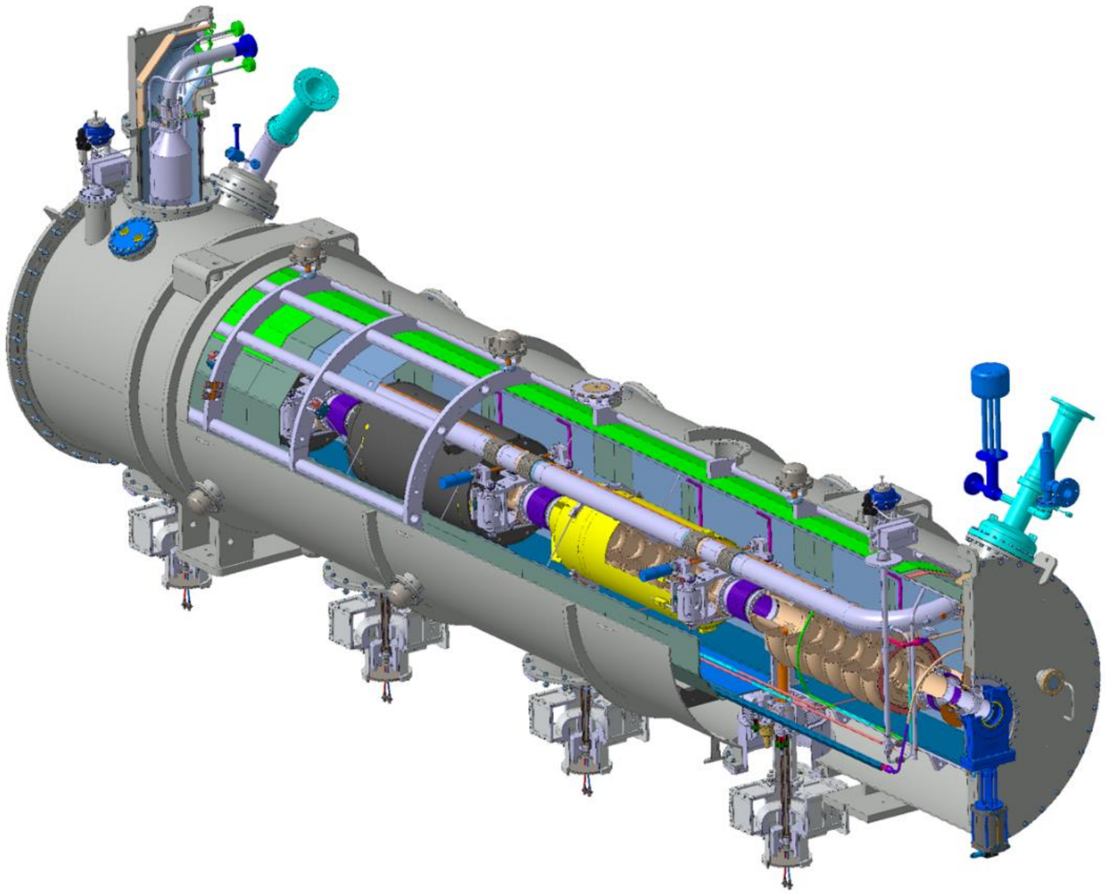
# OUTLINE

- ESS cryomodule and cavities specification in CEA
- Motivation
- Diagnostic development
  - Some results and simulations
- Outlook



# ESS CM and cavities parameters

| | MB | HB |
|---|---|---|
| β | 0.67 | 0.86 |
| Cell number | 6 | 5 |
| Eacc (MV/m) | 16.7 + *10%* | 19.9 + *10%* |
| Qo | > 5 $10^9$ | |
| Rep. rate (Hz) | 14 | |
| RF pulse length (ms) | 3.2 *3.6* | |
| italics = CM test values at Saclay | | |



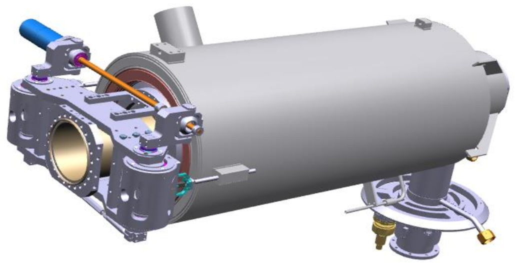
# Motivation and background

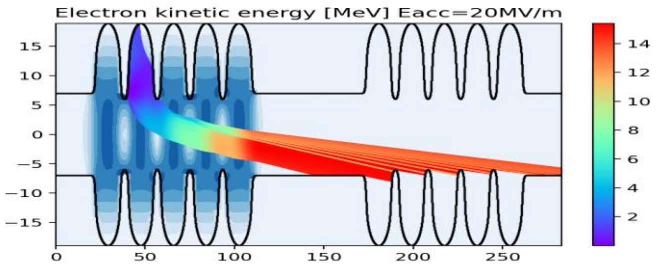
Field emission:
- One of the main causes for the degradation of superconducting cavity quality factor and machine final performance
- Mostly originates from “dust” particle contamination
- It can be enhanced by gas contamination (HC adsorption)

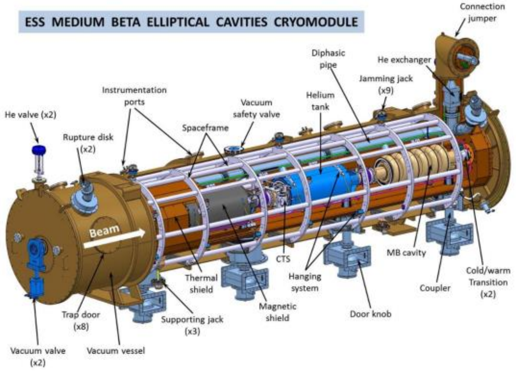

| Clean room | Diagnostics | Recovery/Mitigation |
| --- | --- | --- |
| **Cavity preparation**<br>*Clean environment is mandatory to preserve the cavity package high performance. Improvement in manipulation, pumping/venting procedures and automation can be valuable for high performance and mass production.* | **X-ray detection**<br>*X-ray pattern emerging from the cryomodule is an effective method to diagnose field emission and evaluate recovery or mitigation methods.* | **Surface treatment**<br>*Develop treatments capable to recover cavities performance or mitigate detrimental effects in the most cost effective way.* |

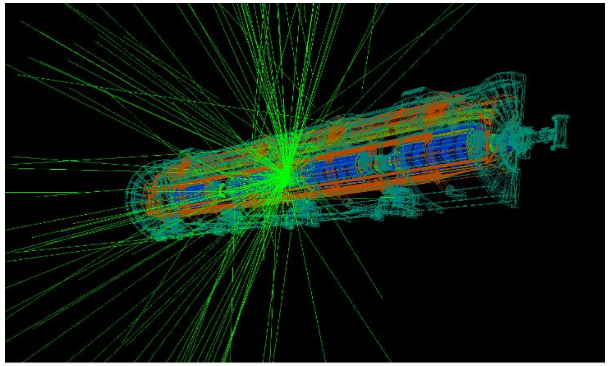
*Accelerator R&D Roadmap (European Strategy for Particle Physics )*

*Field emission will become even more relevant for future high gradient machine*



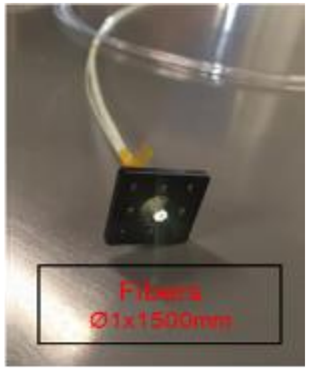


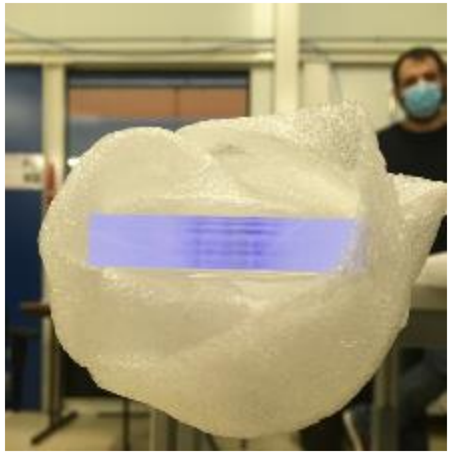



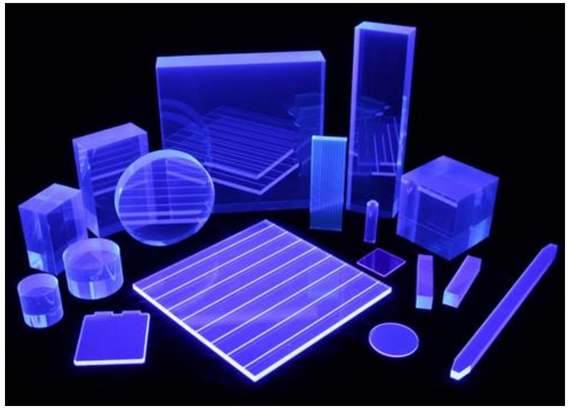
# γ–Diagnostic system for high performance cavities and cryomodule

- We are interested in versatile and large-area coverage detectors:
  - Plastic scintillators can be shaped in different forms
  - Reasonably cheap with respect to the area coverage
  - Largely used in particle physics (e.g. Sci-Fi Tracker in LHCb)
- We started by testing a plastic block (10x50x1500mm) and fibers (Ø1x1500mm) as a proof of concept
- We are developing dedicated Geant4 applications for cryomodule and cavity testing allowing us to optimize detectors with respect to the radiation emerging from the cavities

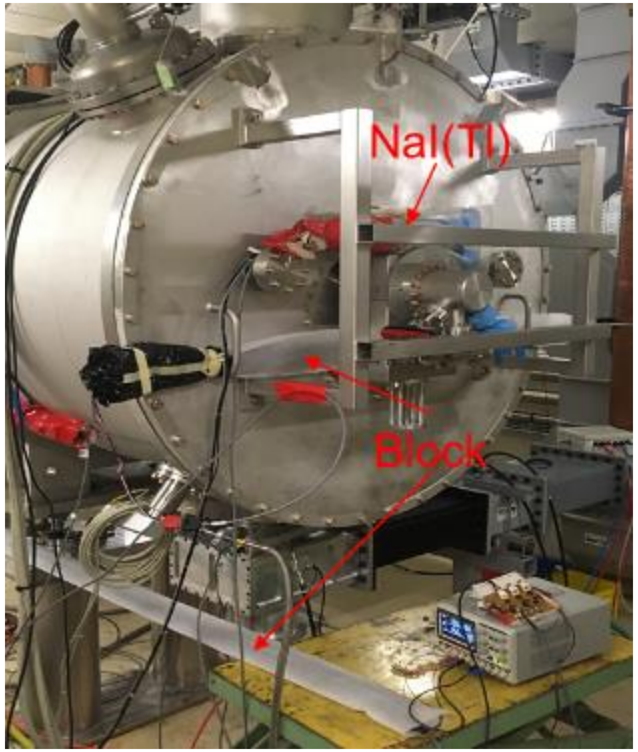






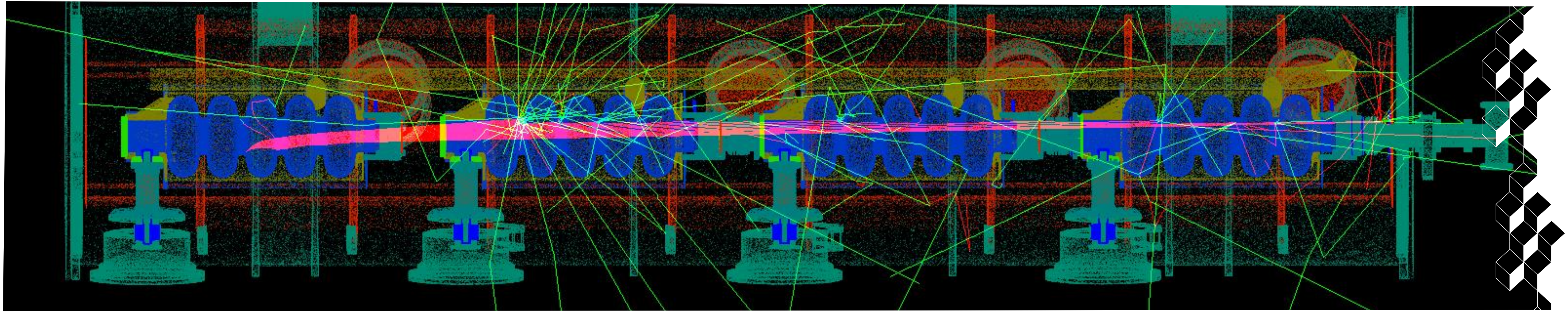
*Base plastic is Polyvinyl toluene (PVT)*

ESS cryomodule installed in the test stand at Saclay




Scintillator block installed on ESS cryomodule during power test in Saclay, close to a NaI(Tl) scintillator.

- <u>Detectors are at room temperature (easy to install and change configuration)</u>
- <u>Possibility to study field emission radiation pulse by pulse, with time resolution within the pulse</u>



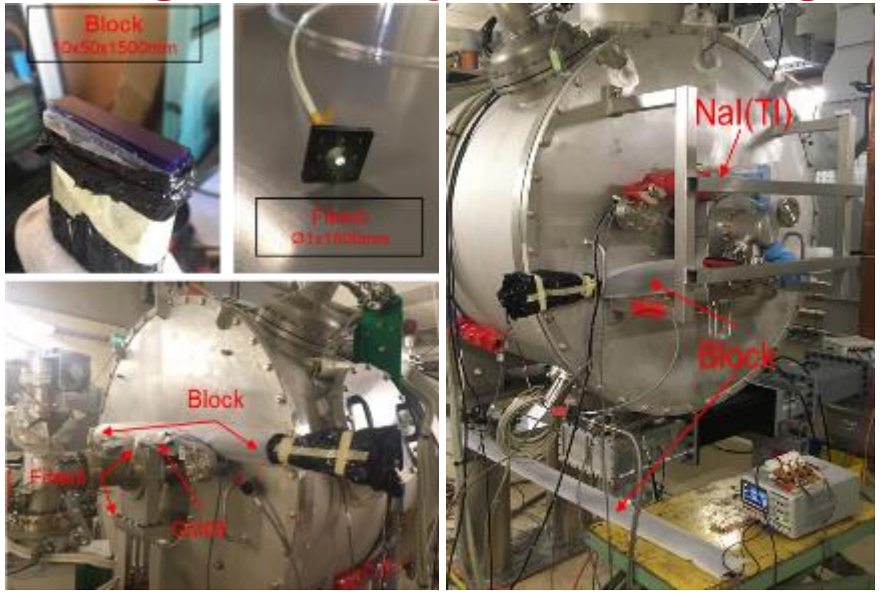
## Detector development (*generation*)

| Generation | Set up | Time resolution | Pros/Cons |
|---|---|---|---|
| I | Photomultiplier + LPS | ~10 µs | Implementation/ “slow” |
| II | Photomultiplier + fast amplifier | ~1ns | Response speed / cost per detector, read out speed (scope) |
| III | MPPC* + dedicated readout | ~1ns | Cheaper cost per detector, Fast acquisition/analysis / need dedicated ASIC |

We have collected data for Gen. I at CEA and ESS, Gen. II is ongoing, we have some preliminary data from ESS (TS2), Gen. III is under development (tested in mid-2024)

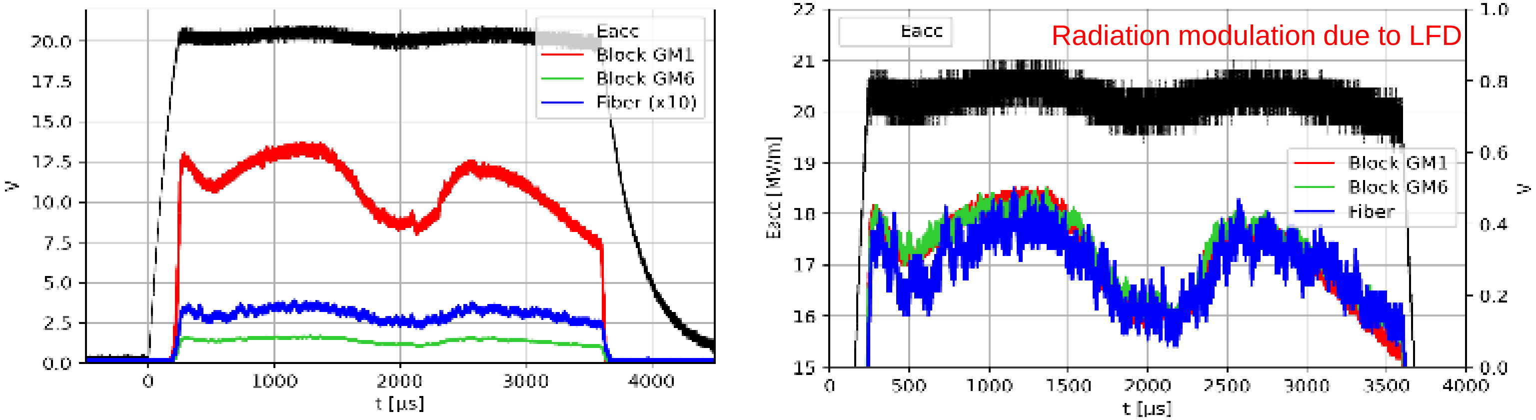
**Multi-Pixel Photon Counter, Silicon Photomultiplier*

# γ–Diagnostic system for high performance cavities and cryomodule




Proof of concept during ESS cryomodule test in CEA and Lund

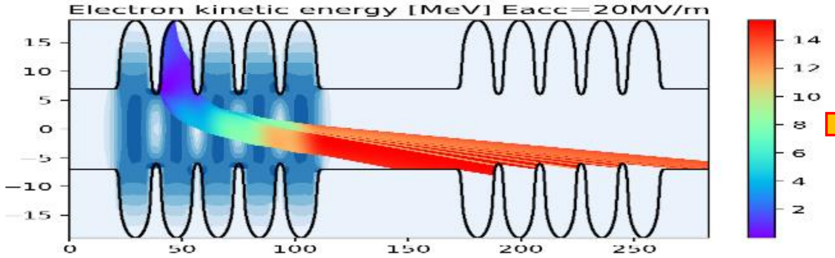
**DATA**



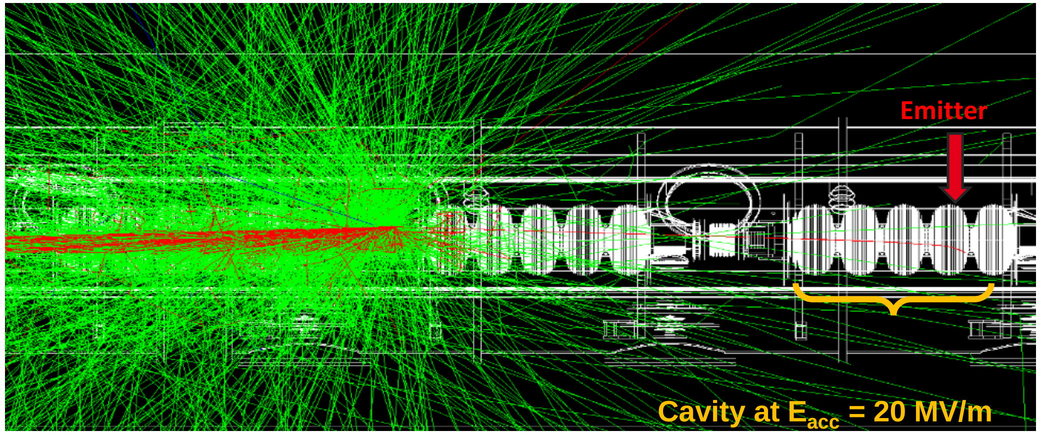

CAV1 excited with **nominal pulse**, the maximum Eacc is about 21.2MV/m (black), radiation detected by block at GM1 position, close to cavity (red), radiation detected by block (green) and from fiber (blue). *Right: zoomed and normalized view of the same pulse where it is possible to appreciate closely the change in the radiation amplitude due to Lorentz force detuning.*

✓ Time-resolved radiation detection pulse by pulse

## Particle tracking code




**Single emitter** trajectories calculation with one cavity powered (CAV4) while the adjacent is off (CAV3). Trajectory colours are determined with respect to the electrons kinetic energy. All the impact on the beam tubes and adjacent cavity have energies between 12 and 15MeV.



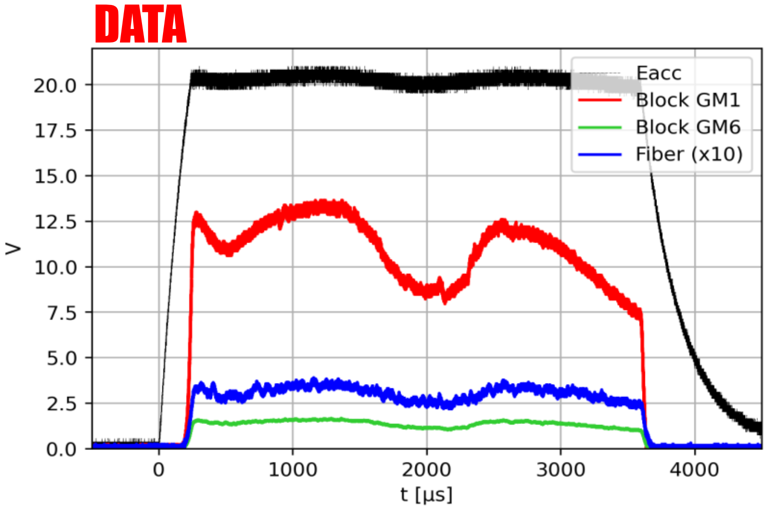

GEANT4

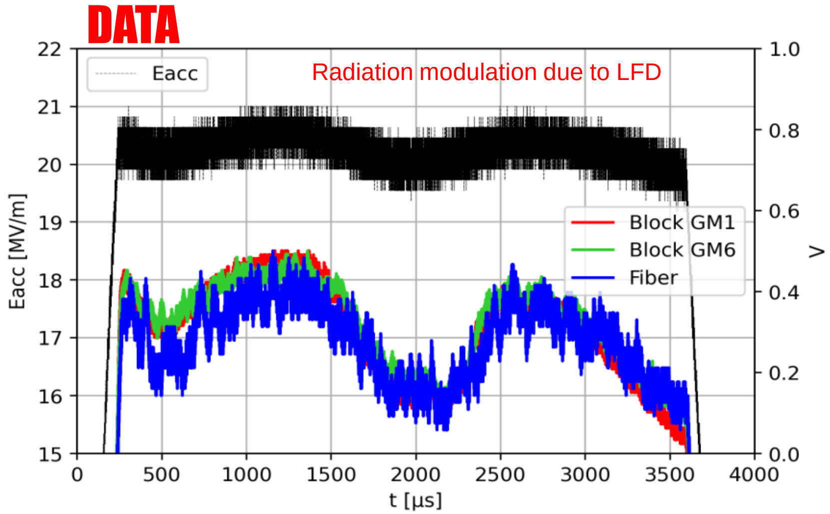
✓ 2D axial symmetry dedicated particle tracking code

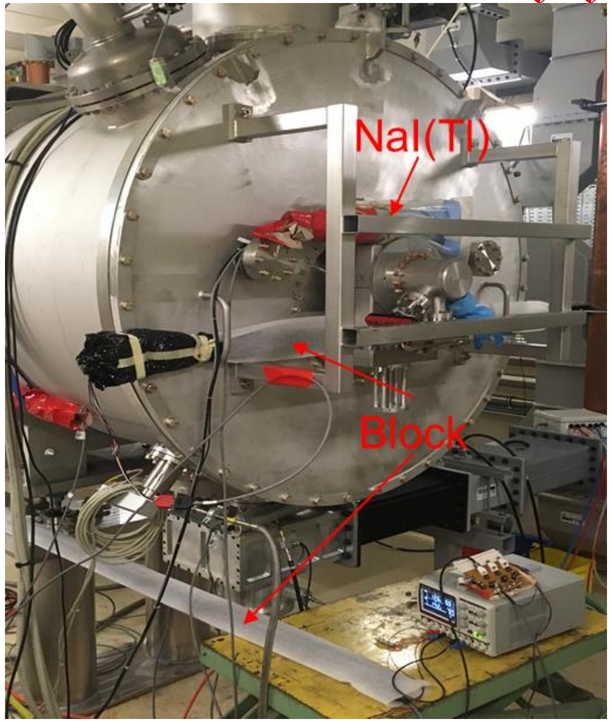
✓ Customizable particle-matter interaction application

cea

# γ–Diagnostic system for high performance cavities and cryomodule

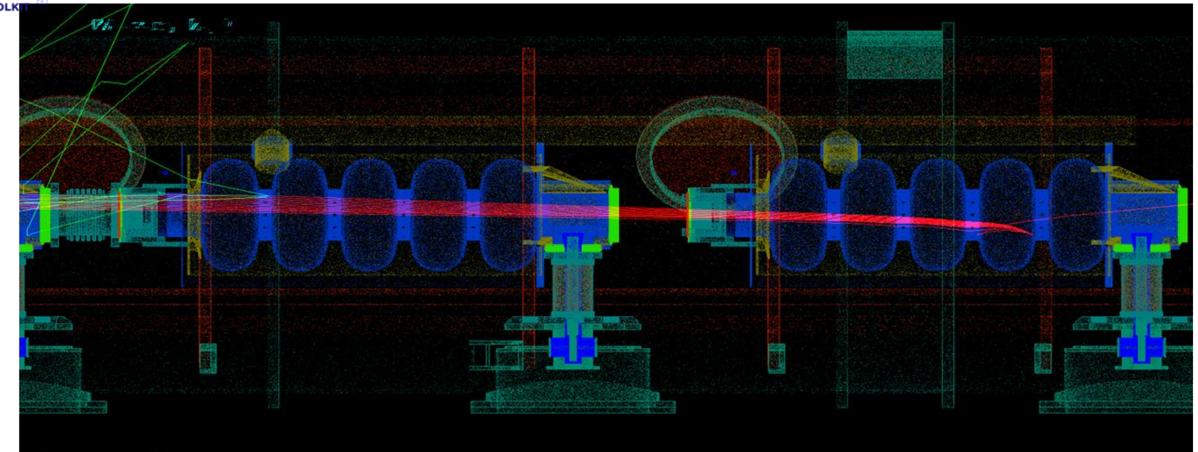


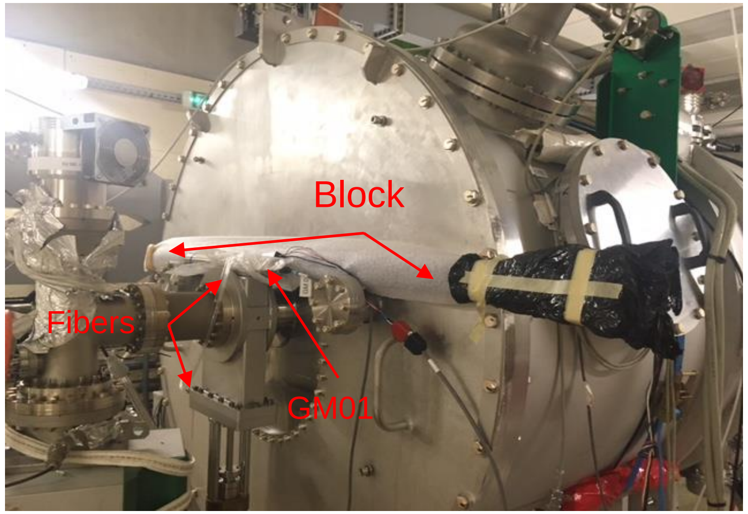




CAV1 excited with **nominal pulse**, the maximum Eacc is about 21.2MV/m (black), radiation detected by block at GM1 position, close to cavity (red), radiation detected by block at GM6 position (green) and from fiber (blue). Right: zoomed and normalized view of the same pulse where it is possible to appreciate closely the change in the radiation amplitude due to Lorentz force detuning.

Radiation is clearly detected during cavity pulse



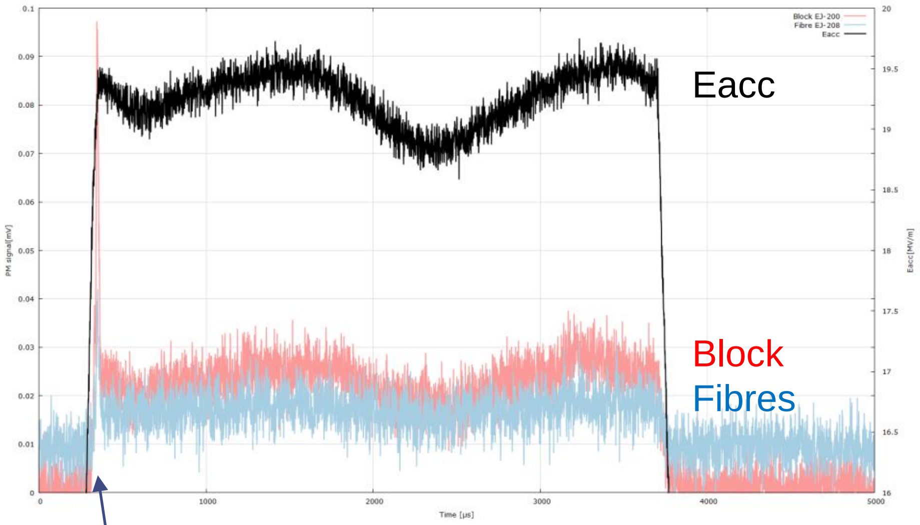
FE on CAV4 iris
Trajectory evolution while varying the phase around the typical 15 MeV, CAV3 impact case

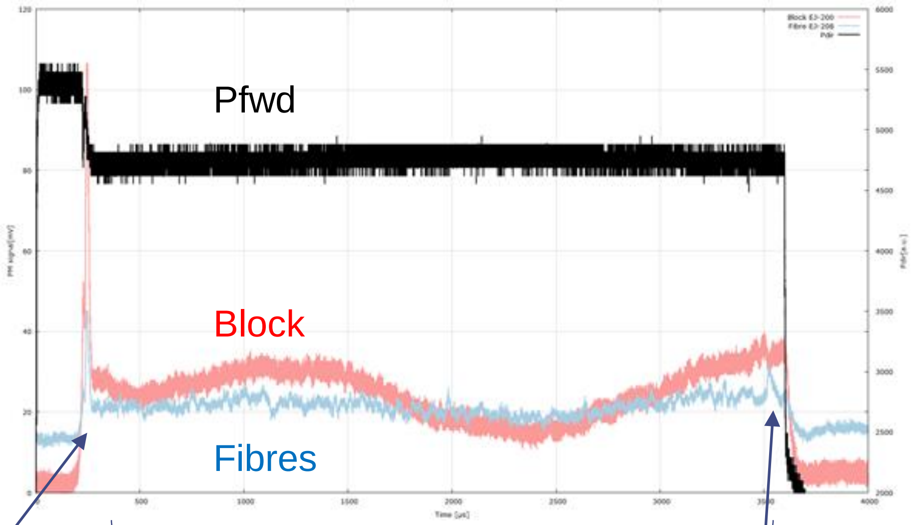


# Time-resolved radiation measurements (*details*)

## More details within the pulse structure

Using the plastic scintillators with PMTs (Gen I)




radiation from the cavity follows Eacc variations

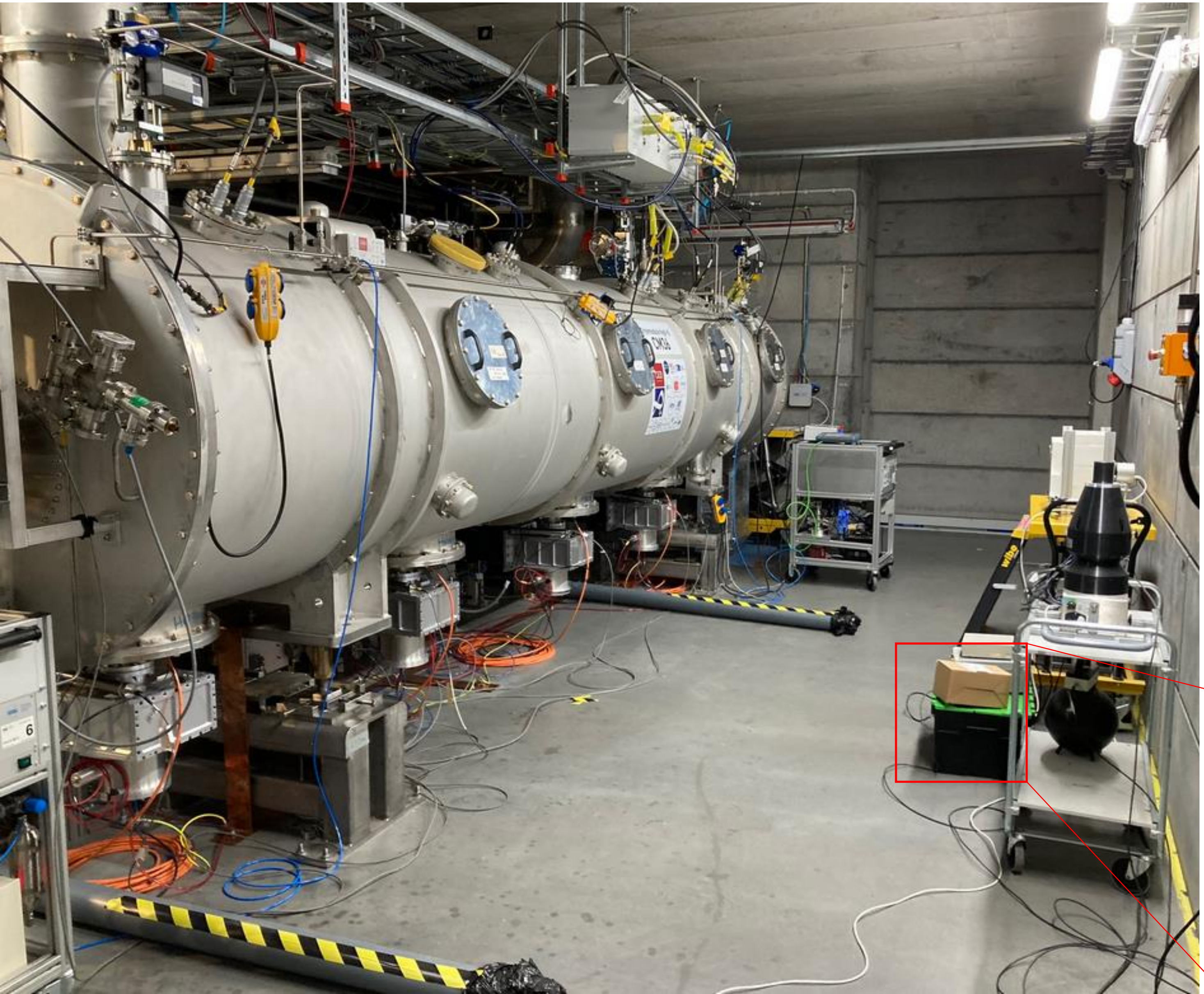
radiation from the cavity follows Eacc variations

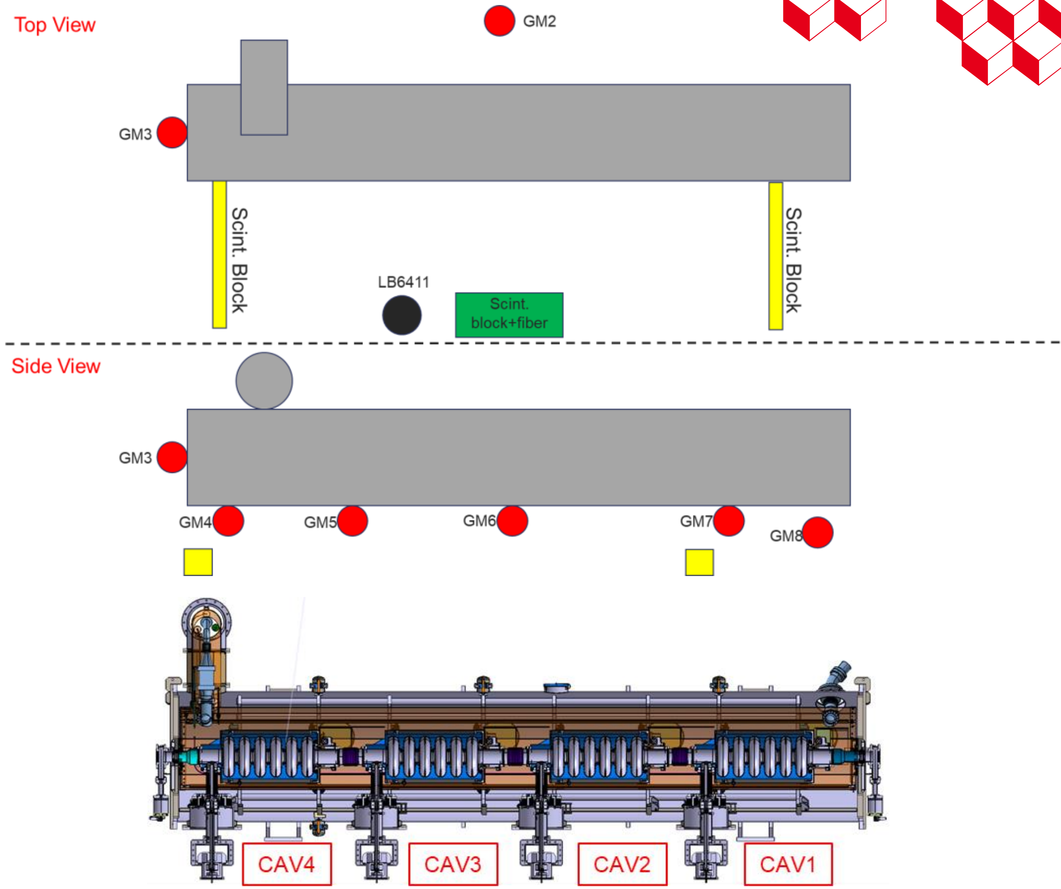
radiation spike at the end of filling time : coincides with e- detection in the coupler

*More on this in the next slides*

radiation spike during cavity decay: coincides with e- detection in the coupler, while crossing a MP band

# Test Stand 2 @ESS

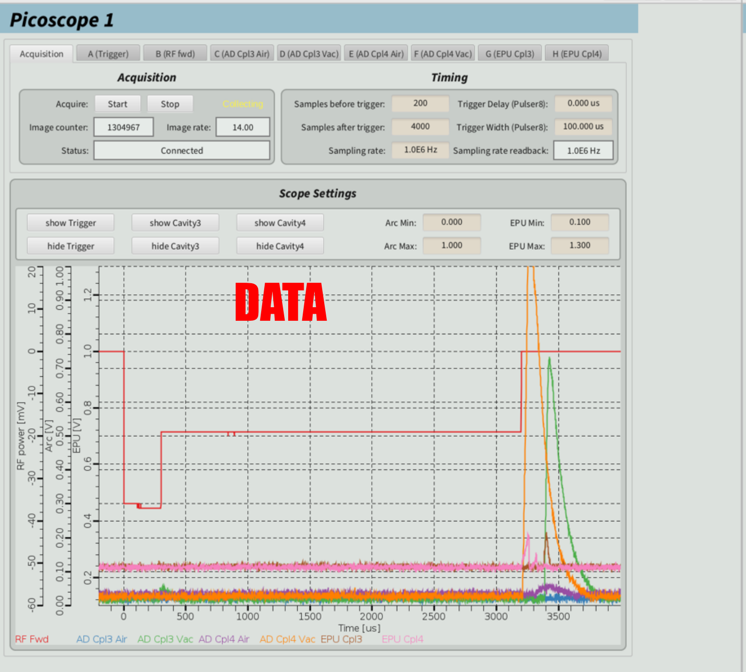


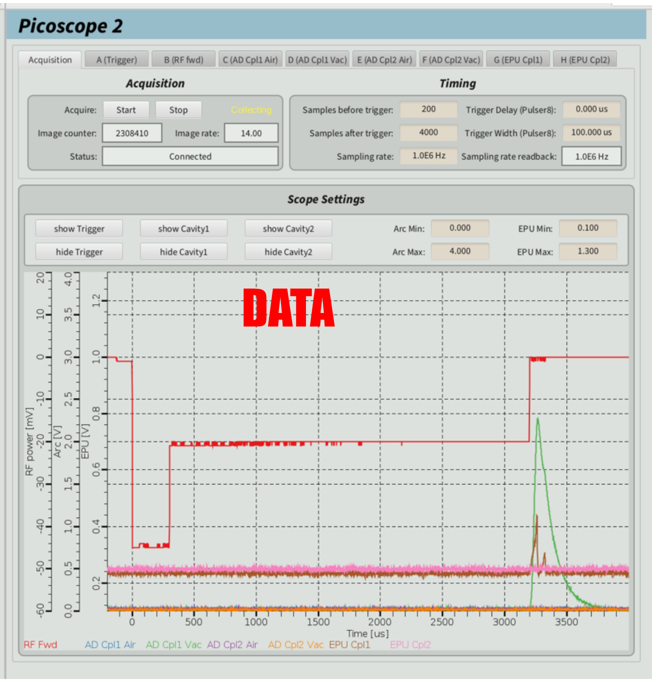



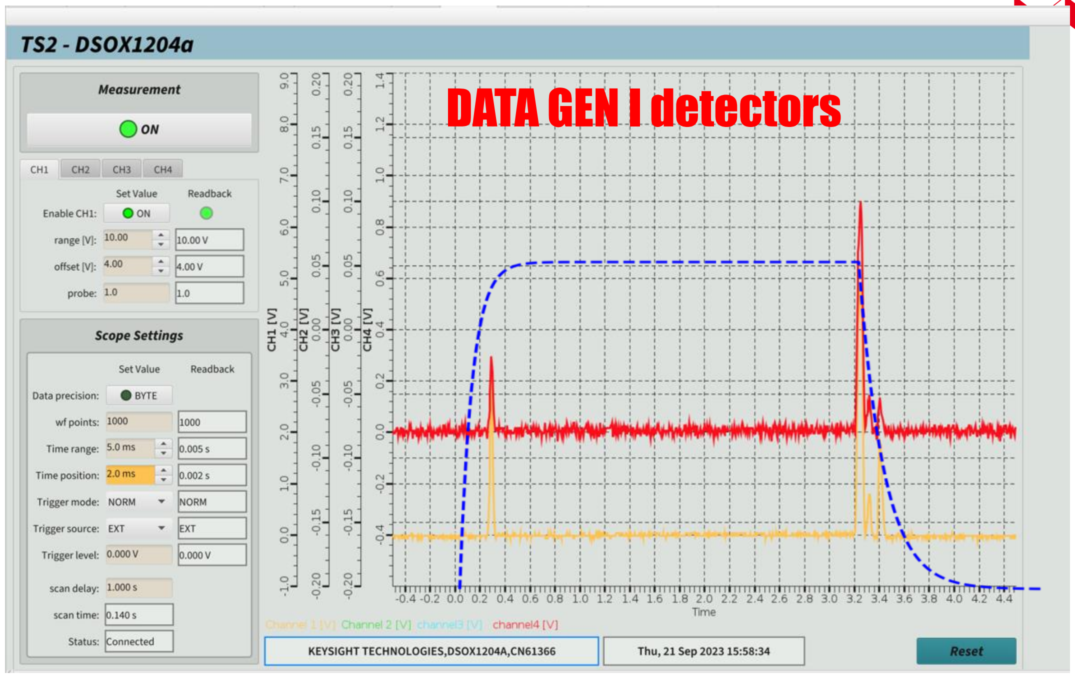

Saclay Gen II detector

"First time we can compare data from different detectors generation"

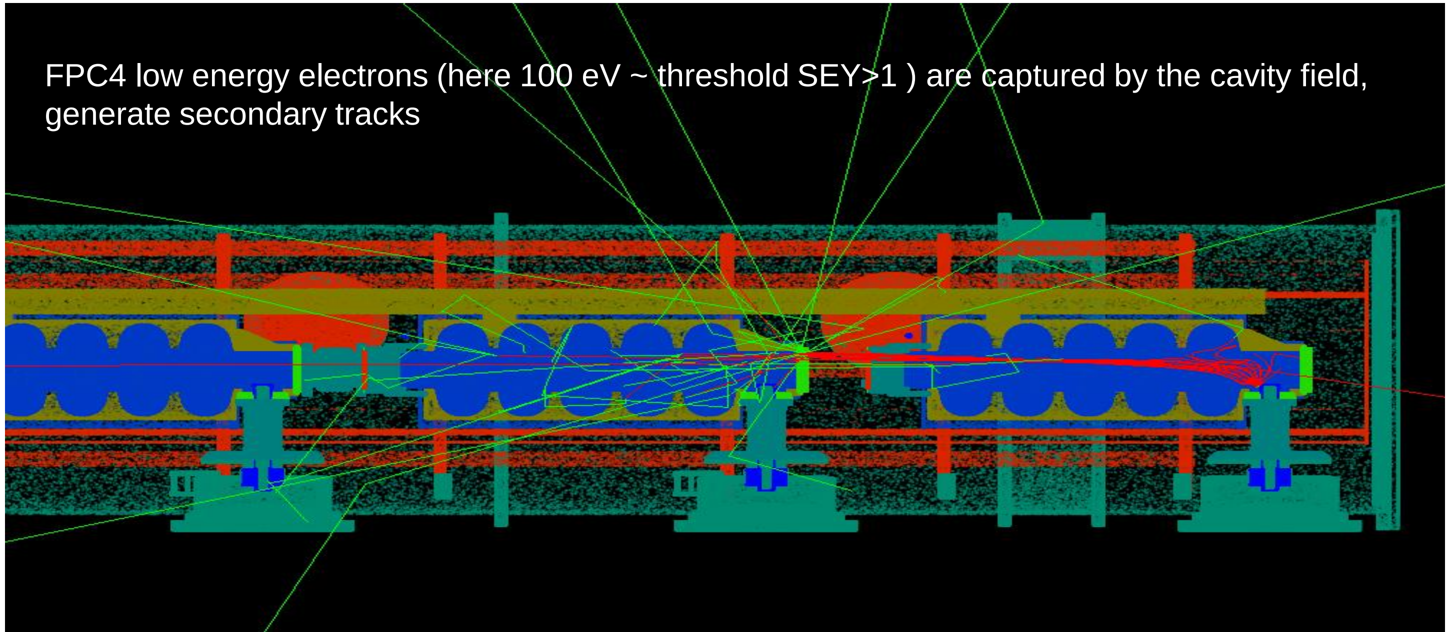
# FPC electron emission



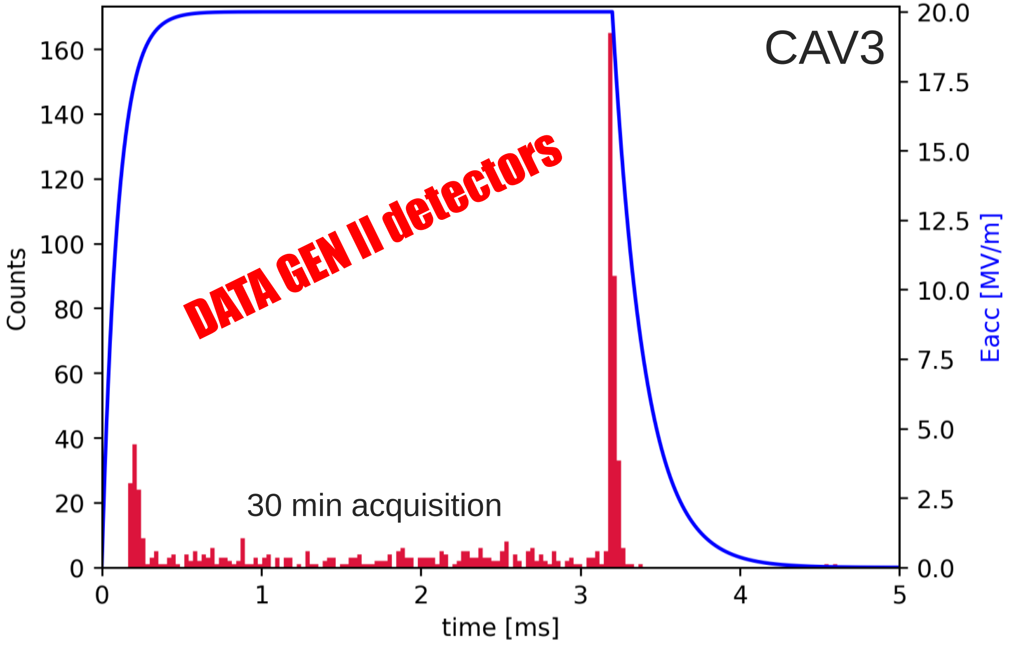



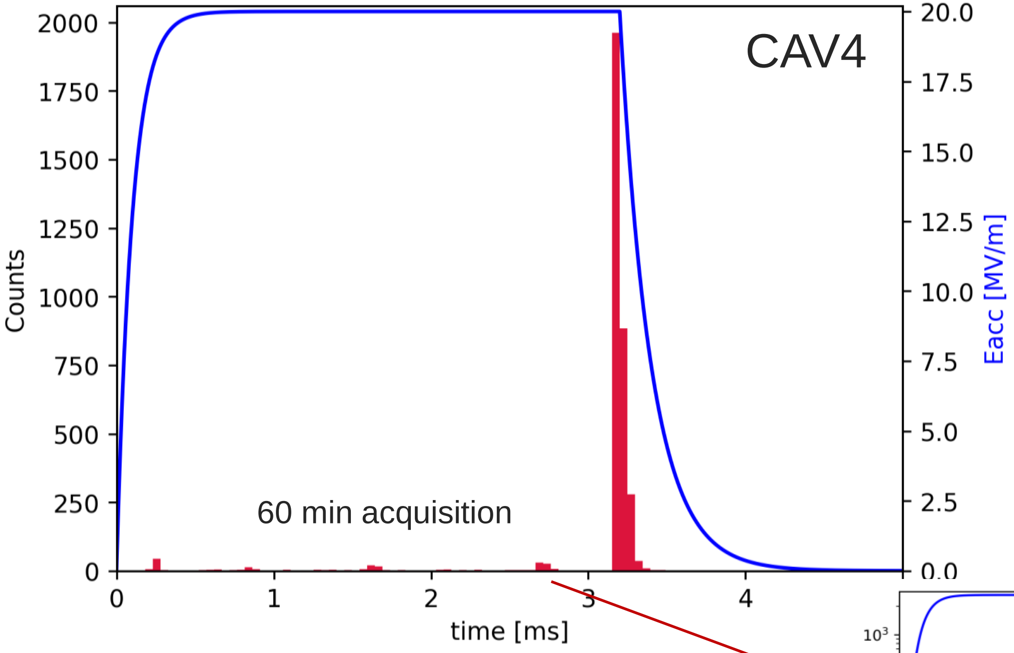

*Dashed line= cavity field as reference*



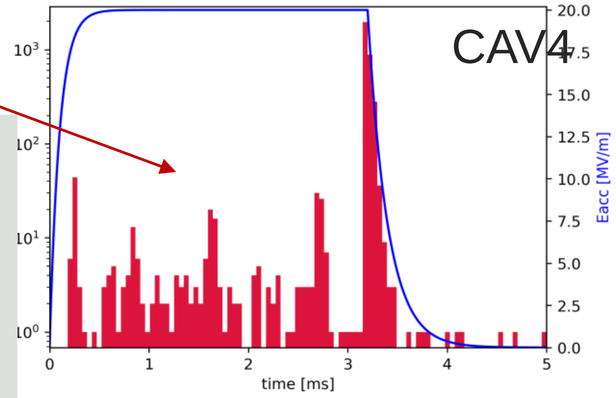

"thanks to 10µs time resolution, we can distinguish between FE and FPC electron emission"

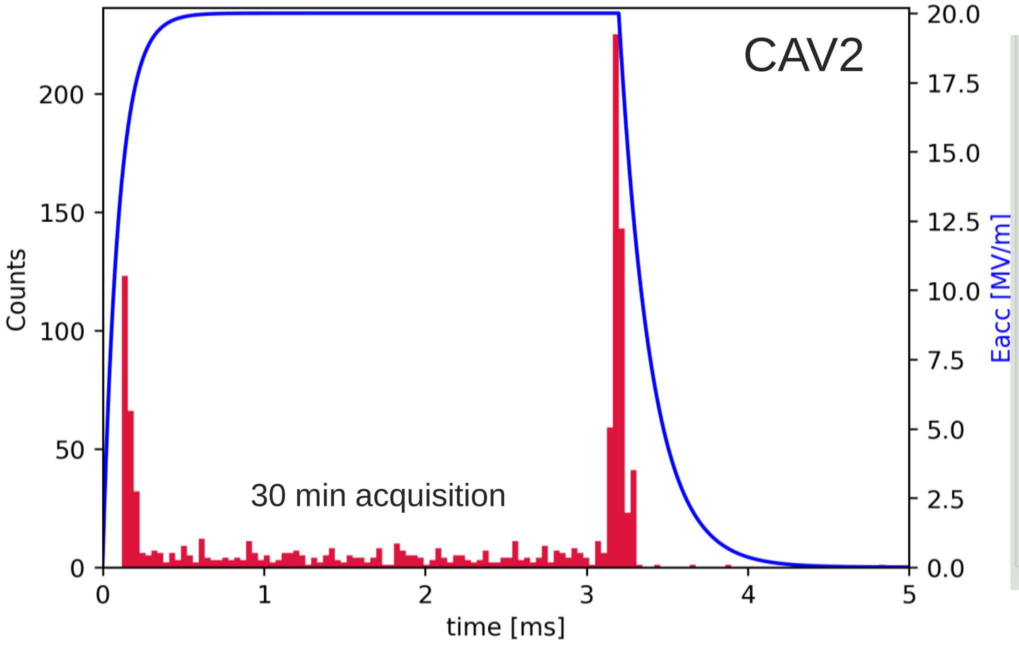
# Data taken during CM36 test @ESS (light pulse count wrt time)

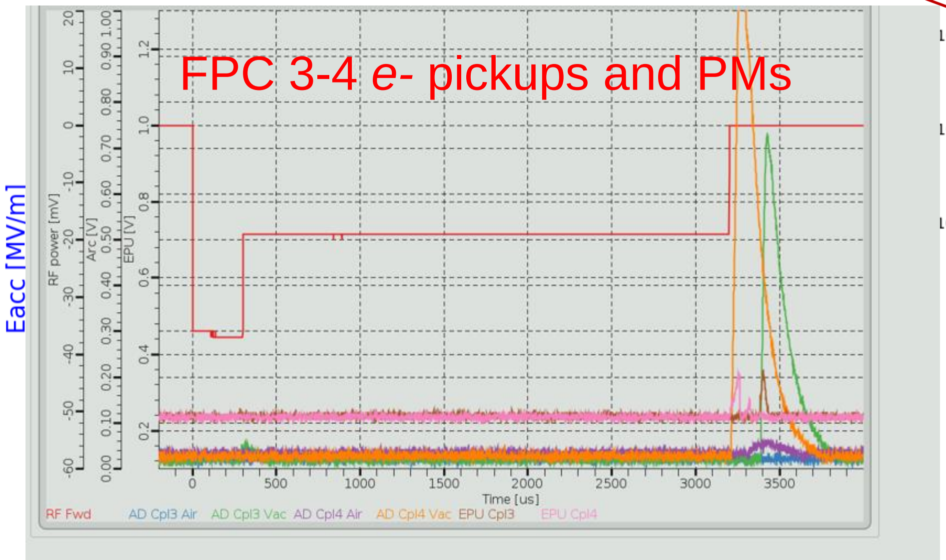


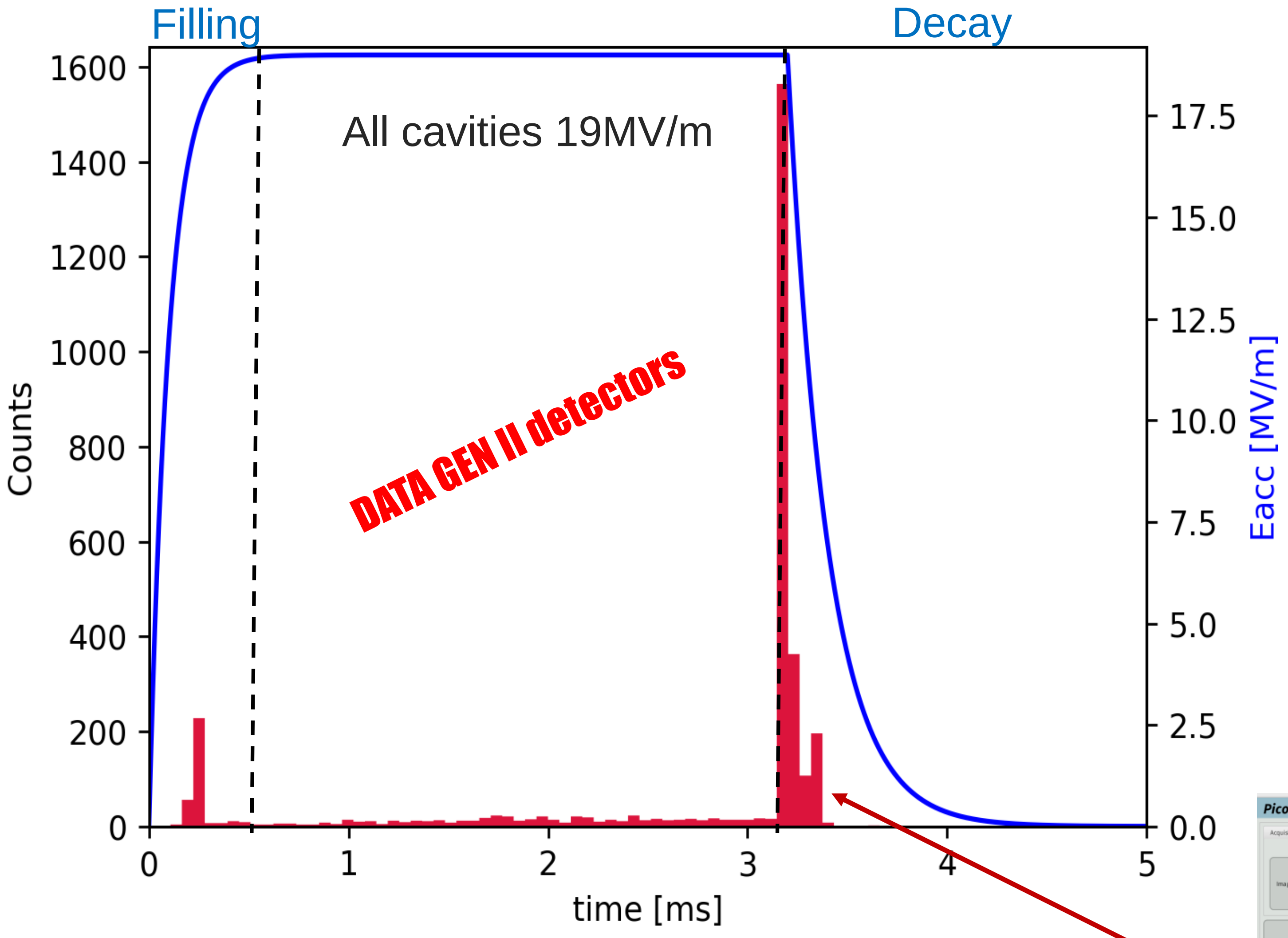




log scale



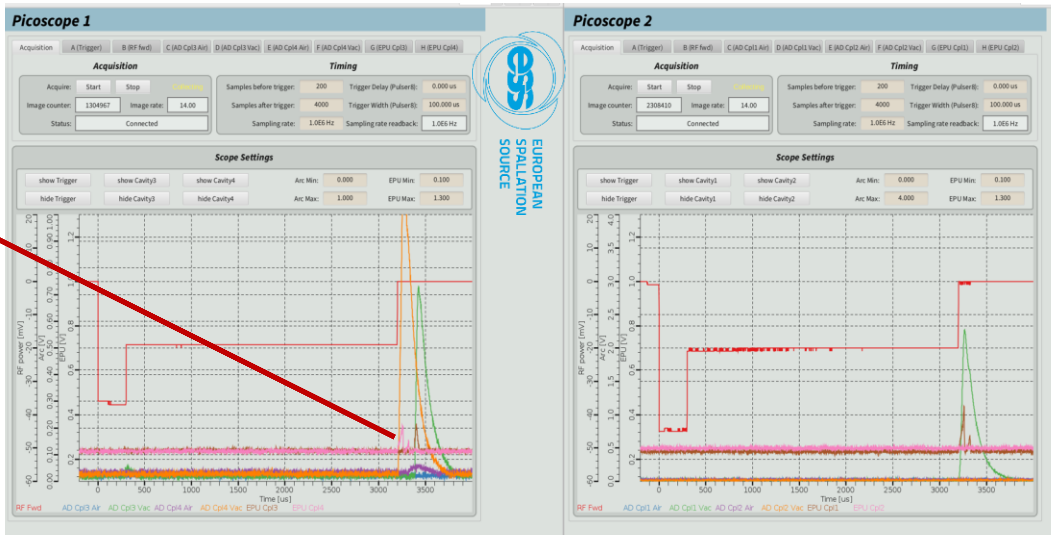





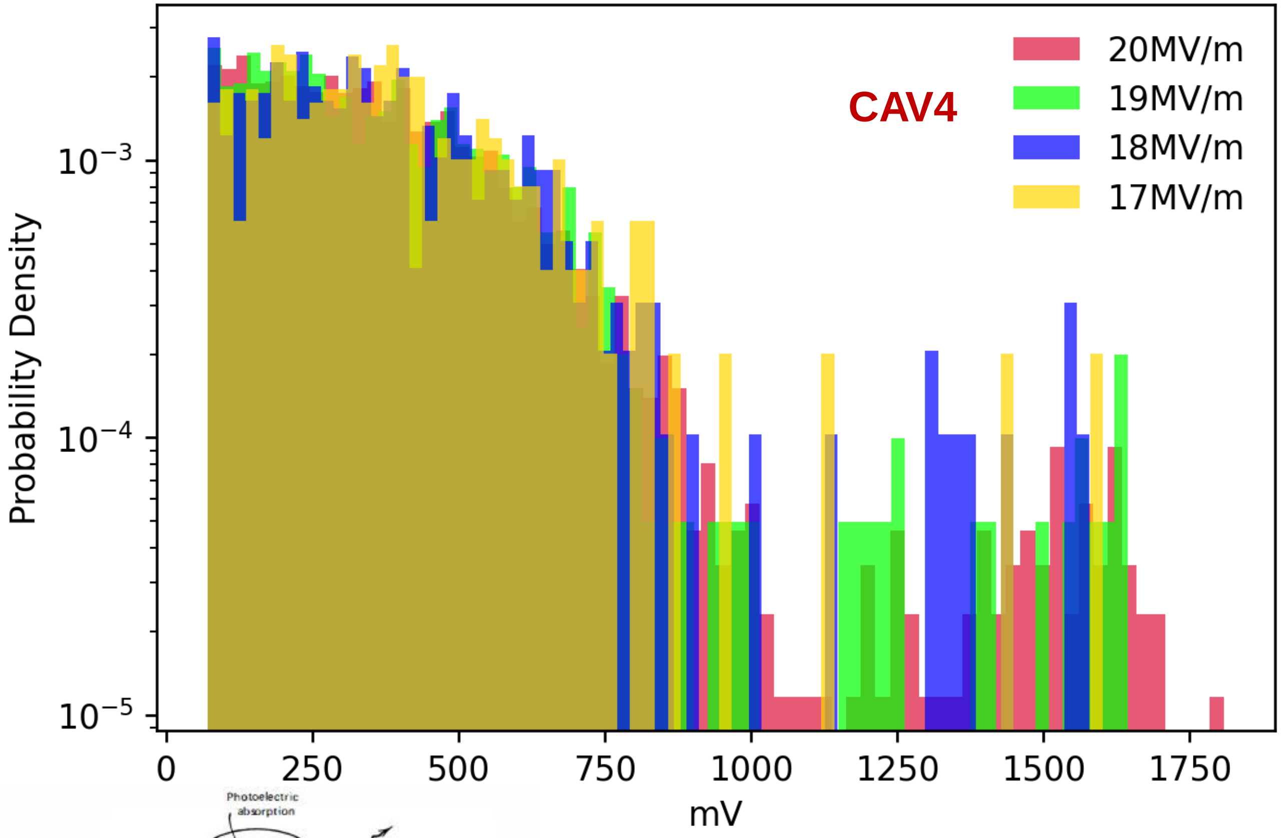

※ We observed a clear correlation between light pulse counting and activity in the fundamental power couplers

※ It is possible to correlate the light pulse arrival time to the cavity pulse

※ It is possible to measure the pulse amplitude (next slide) for “spectroscopy” analysis



# Light pulse amplitude wrt Eacc

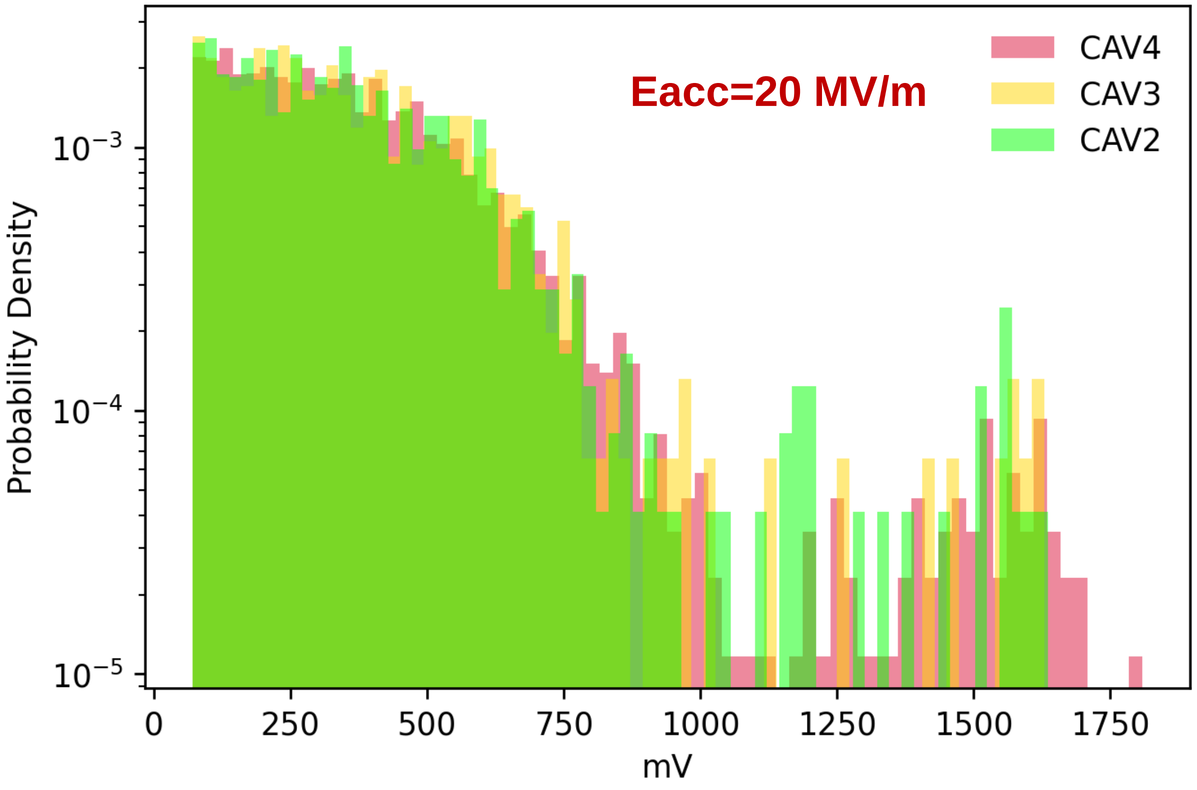



※ We are in a “small detector” approximation, only primary interactions are responsible for energy deposit *(scheme below)*

※ More *statistic is needed, to estimate the full-energy peak

※ Calibration with known gamma sources is planned

**more detectors/coverage and more acquisition time*



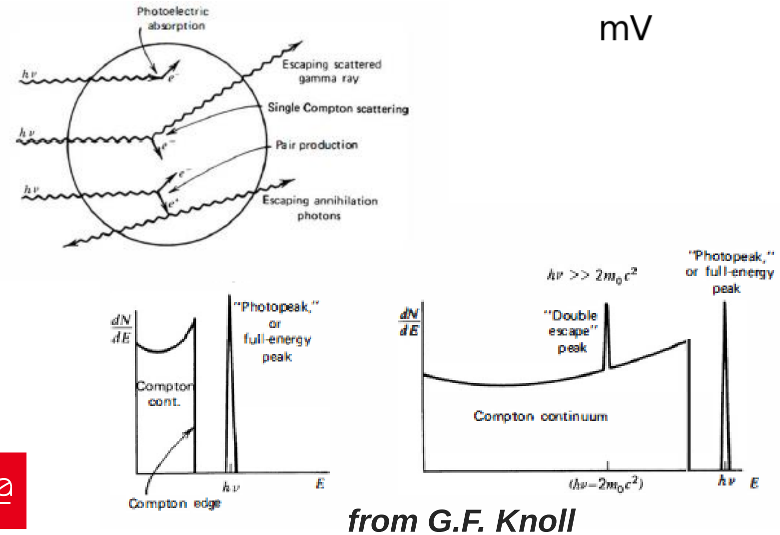
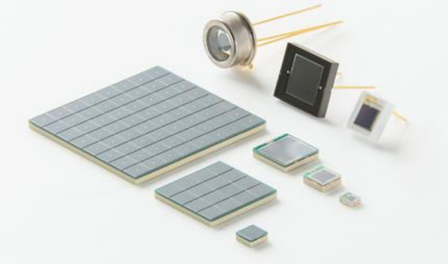



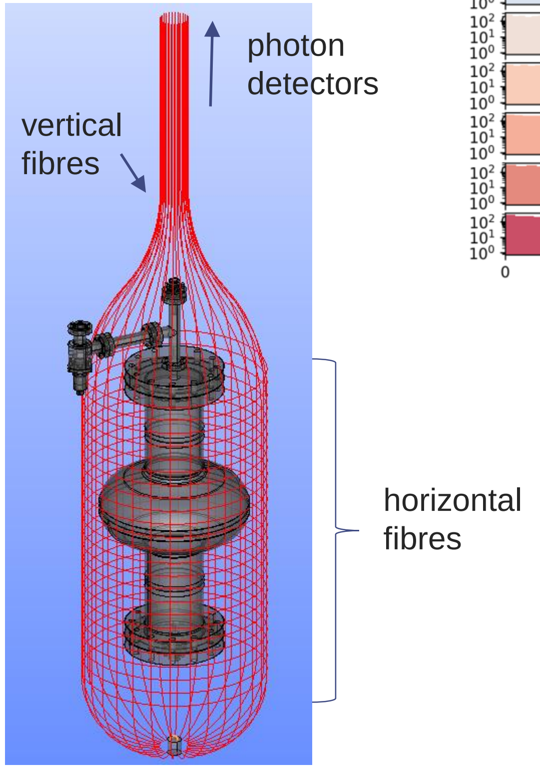

**Figure 10.2** The “small detector” extreme in gamma-ray spectroscopy. The processes of photoelectric absorption and single Compton scattering give rise to the low-energy spectrum at the left. At higher energies, the pair production process adds a double escape peak shown in the spectrum at the right.

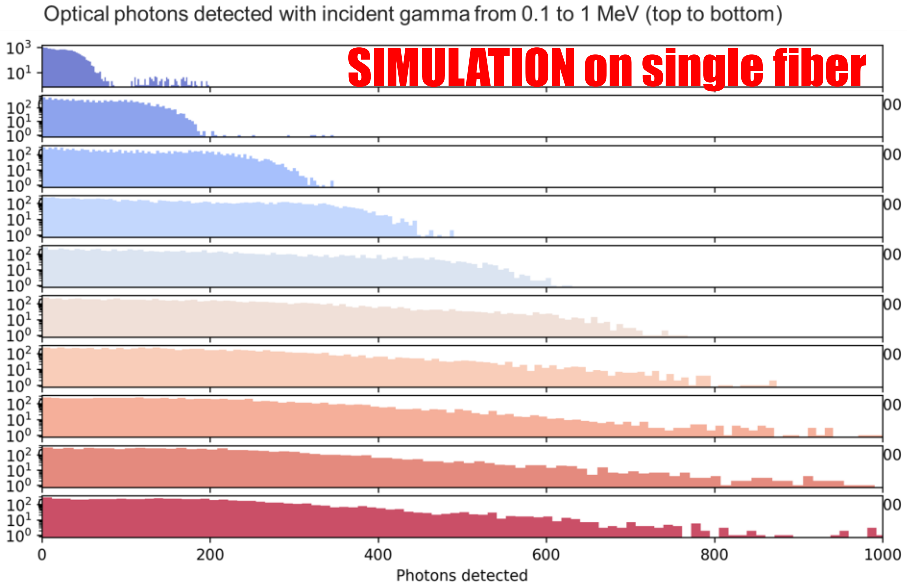
***from G.F. Knoll***

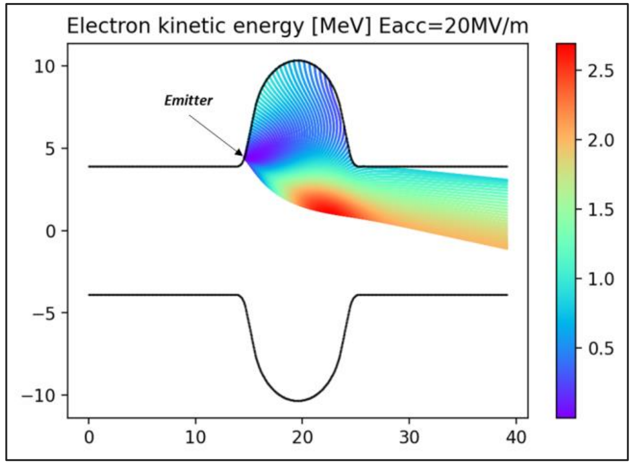
# Outlook

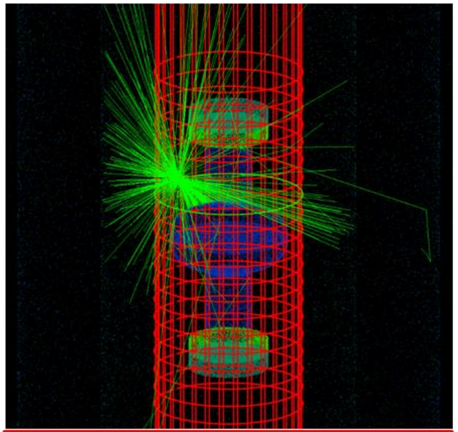
Along with current data acquisition at ESS (TS2), we are developing a detection system based on Saclay_gen III to be equipped in our vertical cryostat.

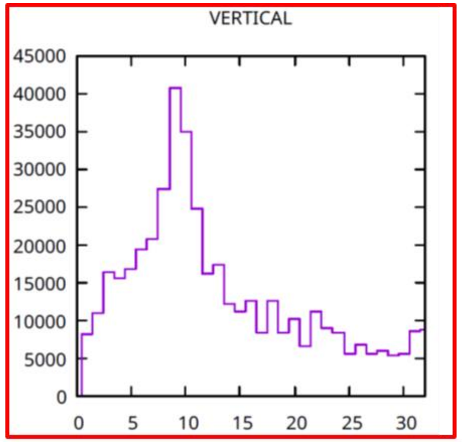


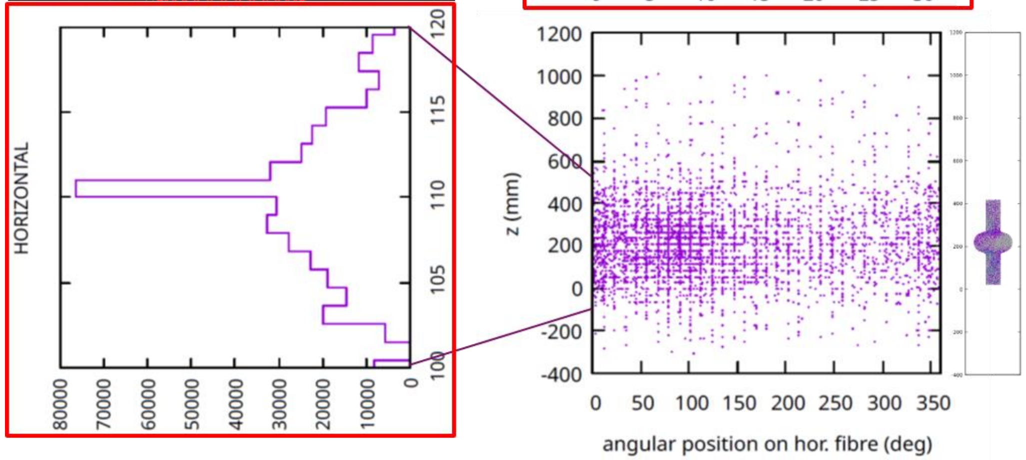





*Please check the talk and paper at SRF2023 for more details* doi:10.18429/JACoW-SRF2023-FRIBA02

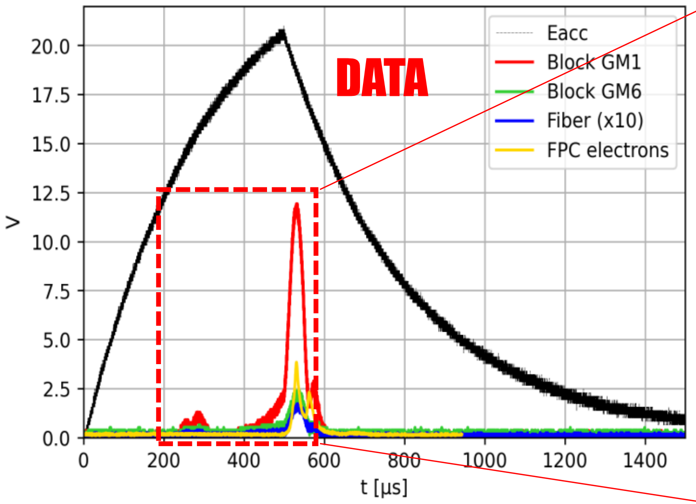
# Thank you for your attention

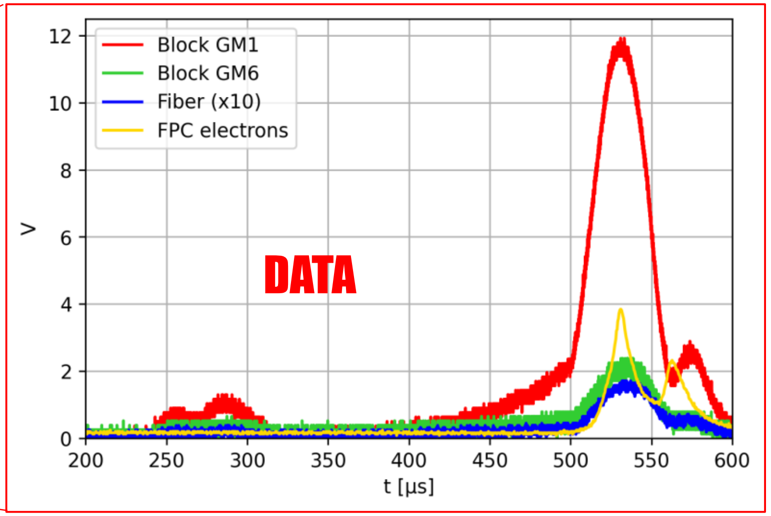
## A big thank you to all the TS2 team at ESS

EUROPEAN SPALLATION SOURCE

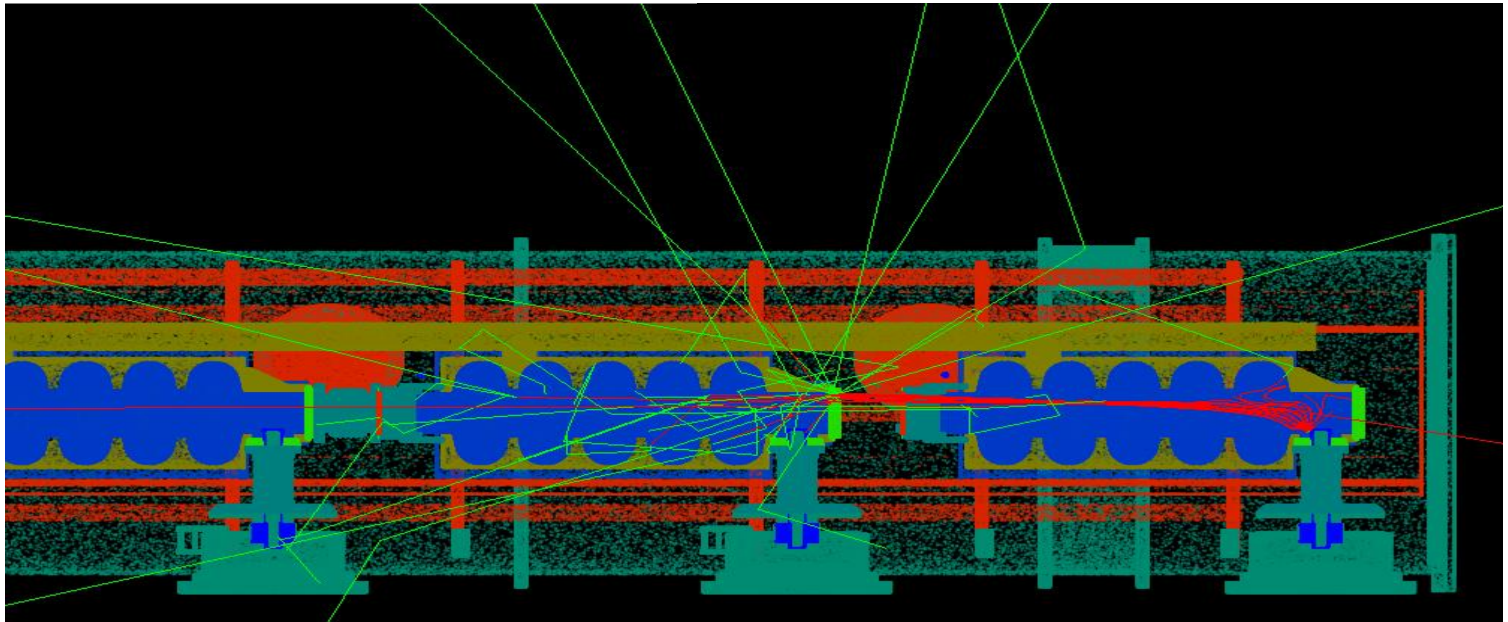
# Back up slides

# Case 2: FPC electron emission (CEA TEST)



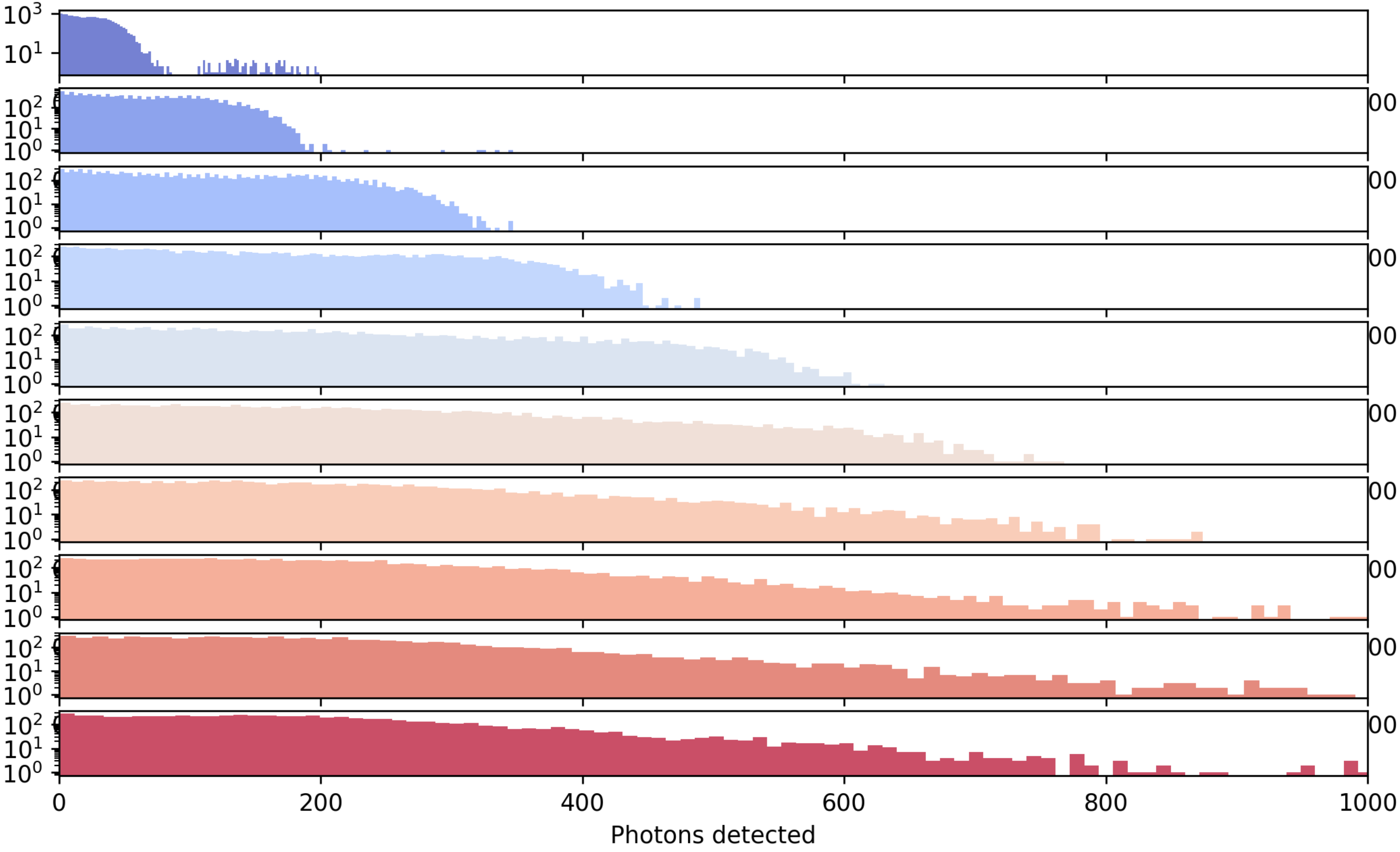

CAV4 excited with **500µs square pulse**, the maximum Eacc is about 20MV/m (black). It is possible to appreciate the **electron current detected by the pick up in the fundamental power coupler (gold)** and the radiation detected by the plastic scintillator at the cryomodule ends, block at GM1 position (red) block at GM6 position (green) and fiber (blue).

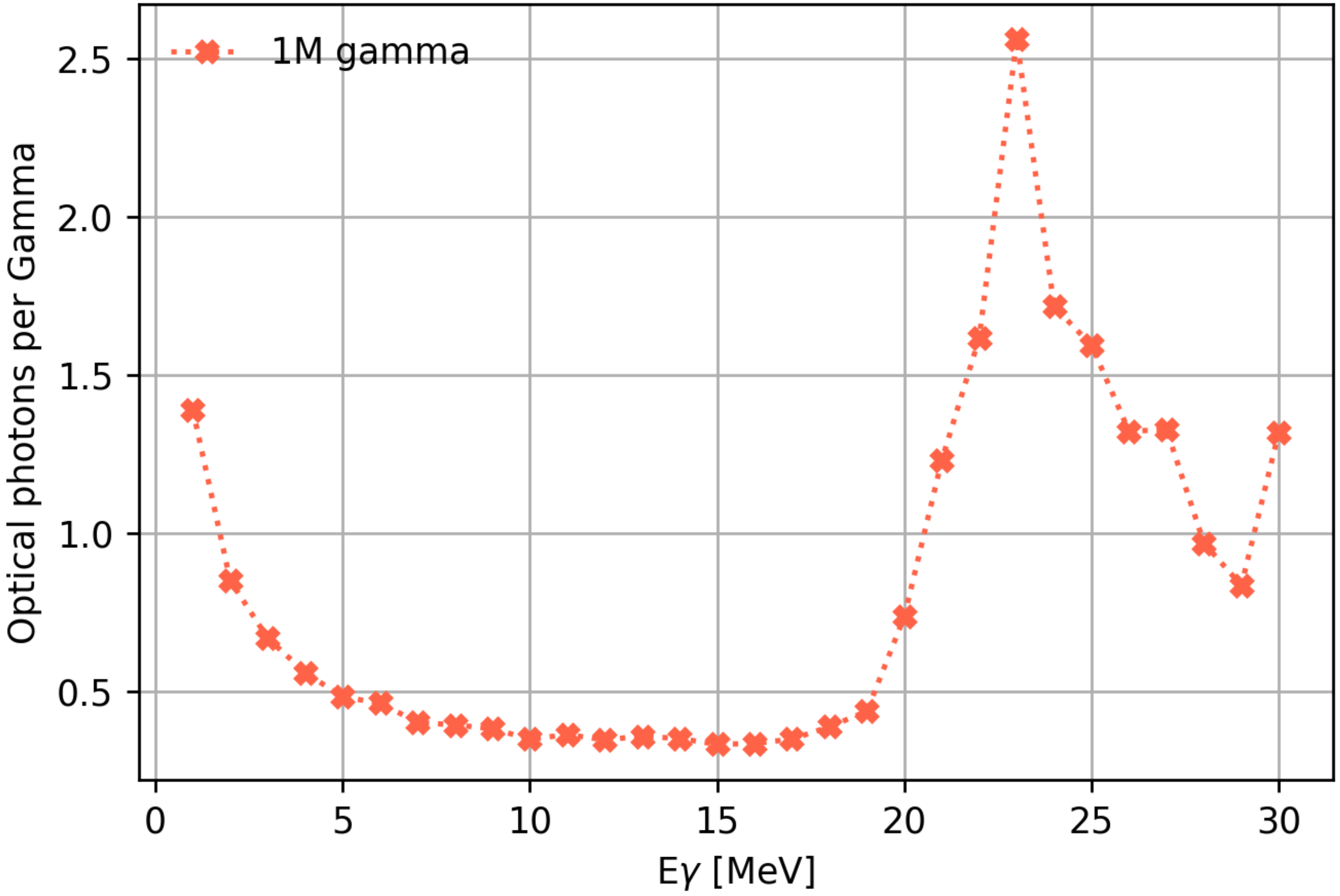


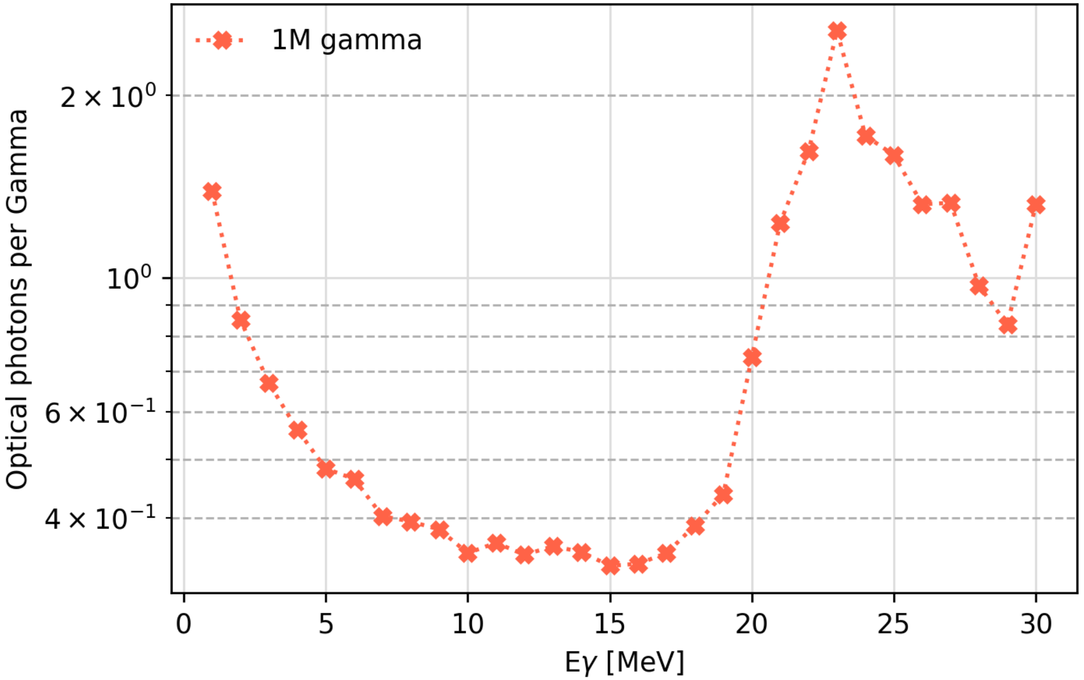
FPC4 low energy electrons (here 100 eV ~ threshold SEY>1 ) are captured by the cavity field, generate secondary tracks

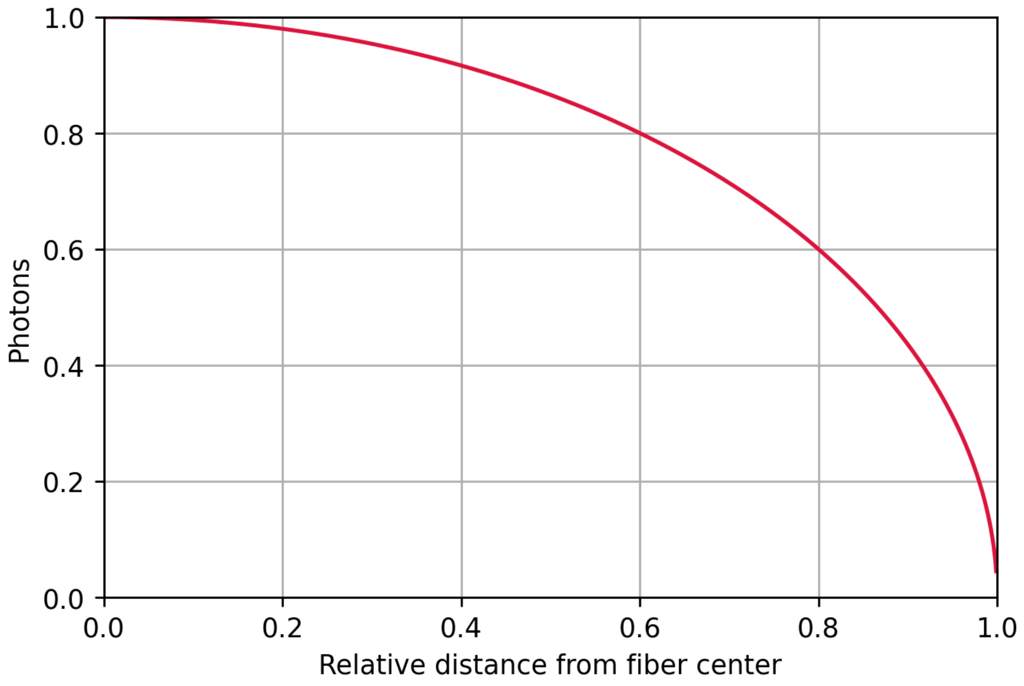
"thanks to 10µs time resolution, we are able to distinguish between FE and FPC electron emission"

# Optical photons detected with incident gamma from 0.1 to 1 MeV (top to bottom)




1M gamma
Optical photons per Gamma
Eγ [MeV]


1M gamma
Optical photons per Gamma
Eγ [MeV]



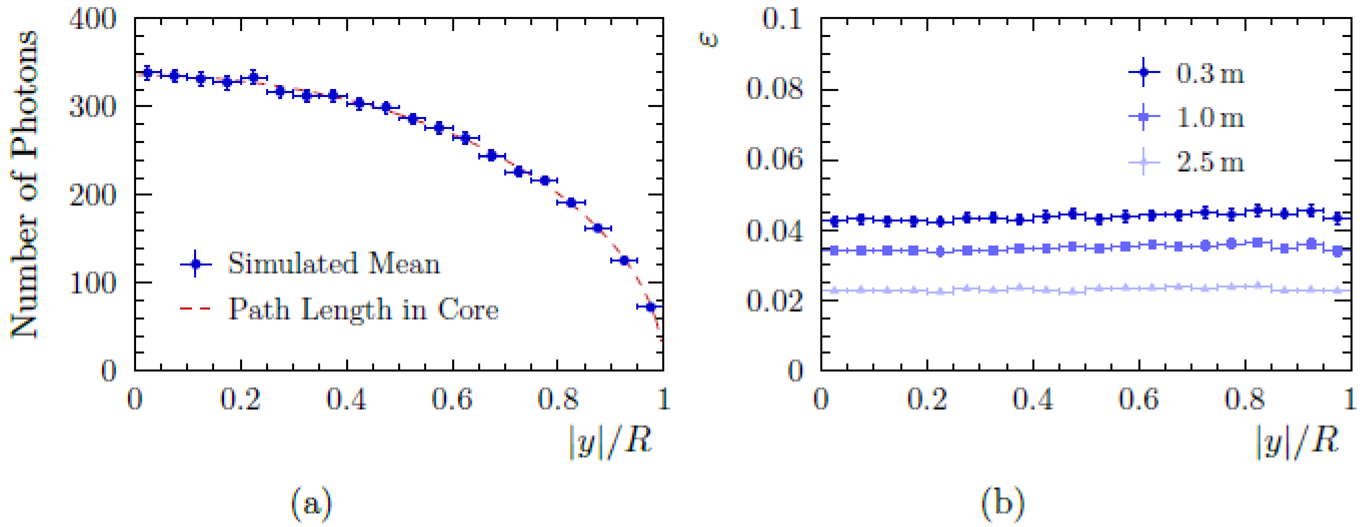




Figure 3.36: Dependencies of mean number of produced photons per MIP (a) and ratio of photons reaching one fibre end $\varepsilon$ (b) on distance $|y|$ of the MIP's trajectory from fibre axis. The dashed line in (a) shows a trend proportional to the MIP's path length in the fibre core. Values in (b) are obtained at three distances $x$ of the excitation from the fibre end.

# Scintillation process

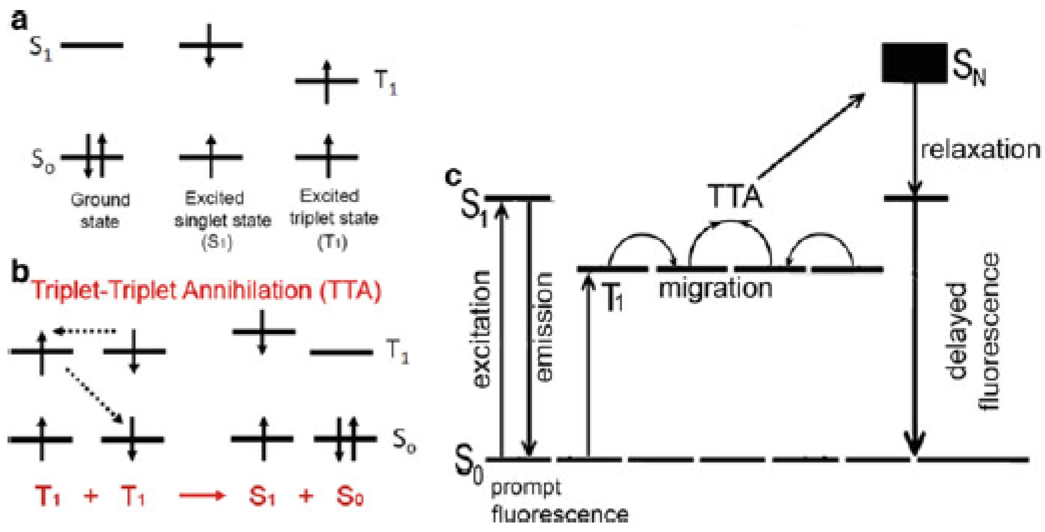
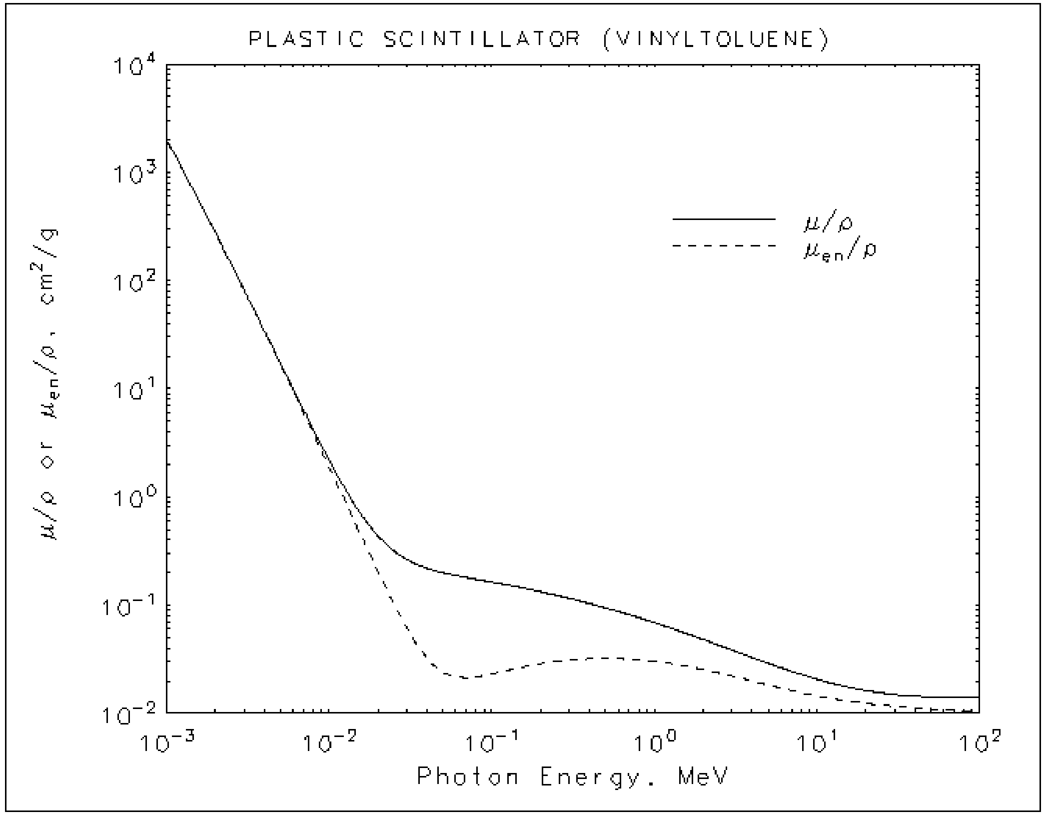



**Fig. 2.1** a—Simple molecular orbital representation of singlet and triplet excited states; b—Triplet–triplet annihilation (TTA), and c—Energy level diagram illustrating basic processes leading to the formation of the prompt and delayed light emission




| Parameters | Block | Fibers | PM |
|---|---|---|---|
| Rise time [ns] | 0.9 | 1.0 | 0.57 |
| Decay time [ns] | 2.1 | 3.3 | / |
| Att. Length [m] | 3.8 | 4.0 | / |

# Why investigate radiation induced by FE

Many projects/machines report concerns about FE and degradation with beam operation

Within projects with many contributors, comparison between radiation measurements on a given cavity

- at different test facilities
- at different stages of testing (VT, CM test bunker)

is not straightforward, unless they have the exact same setup

Need for quantitative measurements of the radiation source(s) especially in the development phase of prototypes, to qualify preparation and assembly tooling and procedures

Characterization has more value (emitter(s) position and electronic current) but is probably very challenging

A combination of dedicated instrumentation and simulation models can improve the situation

# Some options for radiation measurement

## Area monitors:

Our area monitors measure H*(10) equivalent dose rate

- GM tubes
  - are not calibrated above ~1.3 MeV
  - saturate earlier than spec when radiation is pulsed (dead time)
- ionization chambers are more suited
- neutron detector (rem type,...)

cannot be placed close to the cavity, the environment is always interfering.
usable in a cryomodule test environment as long as a set of reproducible placements is defined and applied

## Scintillator based detectors:

Scintillating medium coupled to a photodetector

- Inorganic scintillators are widely used i.e. NaI (spectrometry)
- plastic (PS, PVT,...) is a good candidate (low cost, any shape)
  - in the form of fibres, provide the transport of the scintillation photons
  - fast scintillators : extra functionnality based on coincidence can be added