Latest feasibility studies of LAPPD as a timing layer for the LHCb Upgrade-2 ECAL

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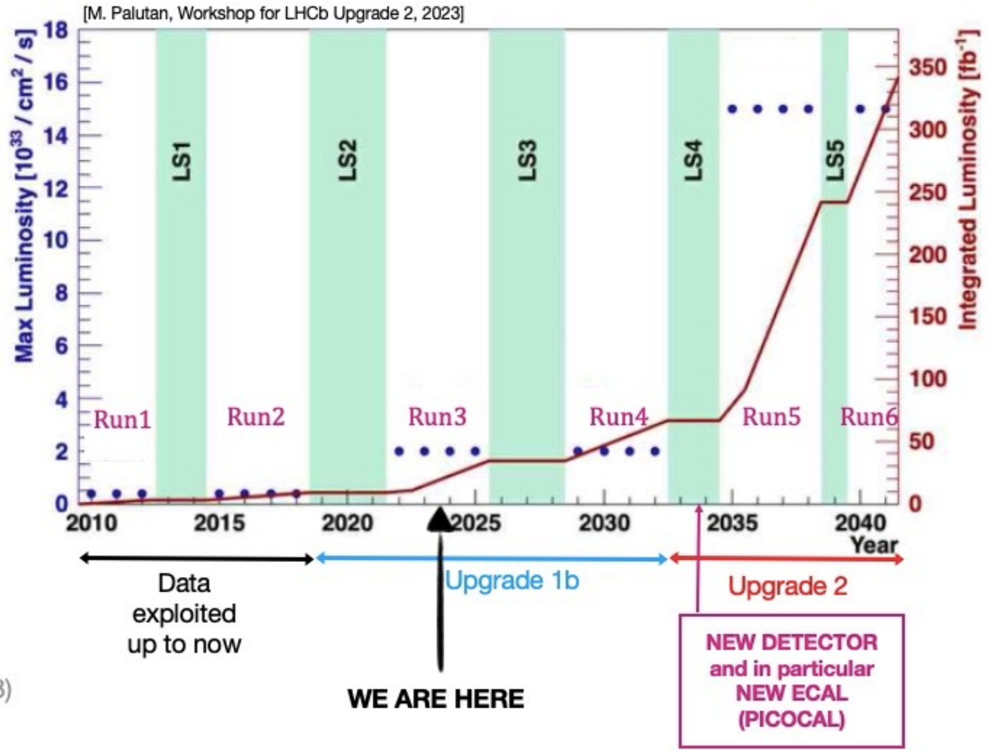
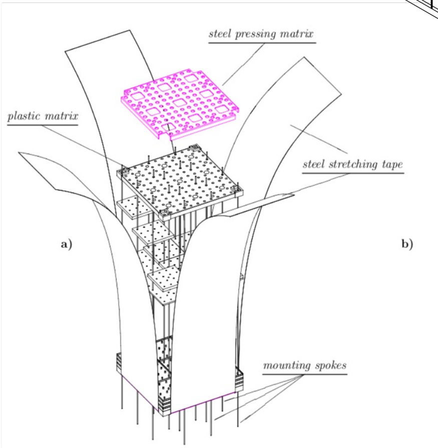
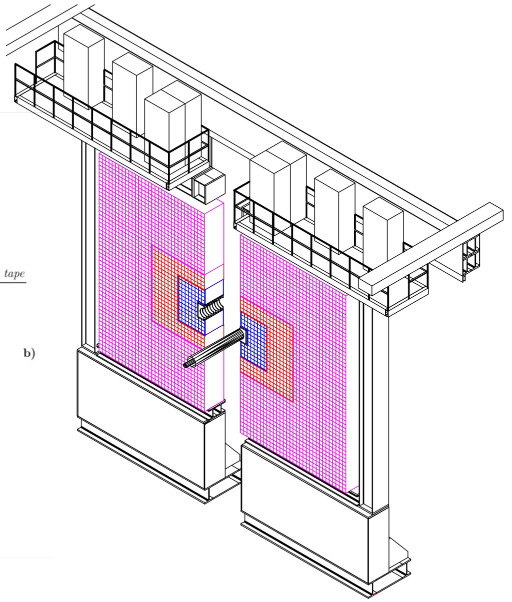
LHCb now and in the future

- The LHCb experiment is devoted to study beauty and charm hadron decays produced in pp collisions at the LHC
- Major upgrade of the whole detector foreseen in the LS4
  - Peak luminosity x7 compared to now
- New ECAL necessary to complete physics programme
  - CPV, FCNC, hadron spectroscopy, forward physics, fixed target, LFV, …
  - Details:
    - [Physics Case for an LHCb Upgrade 2 (2018)]
    - [FTDR for LHCb Upgrade 2 (2021)]



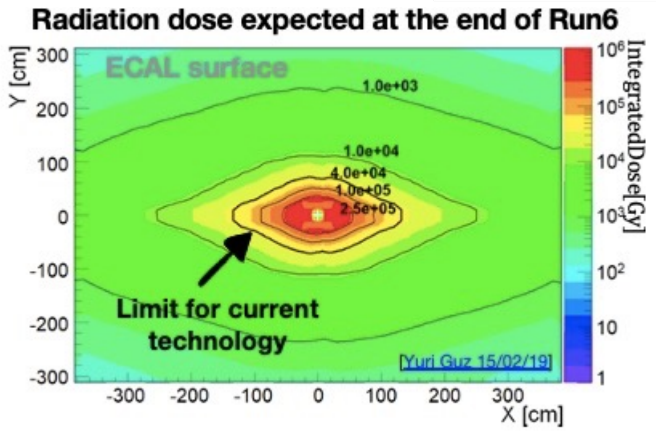
Current ECAL and challanges

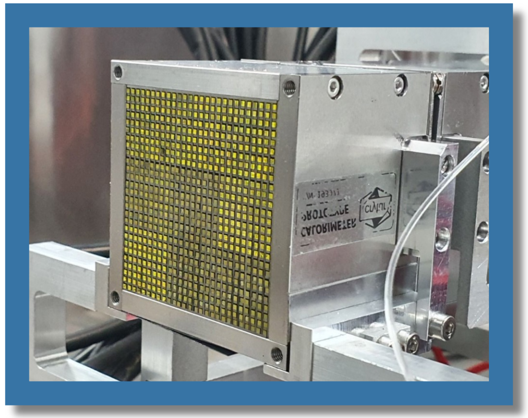


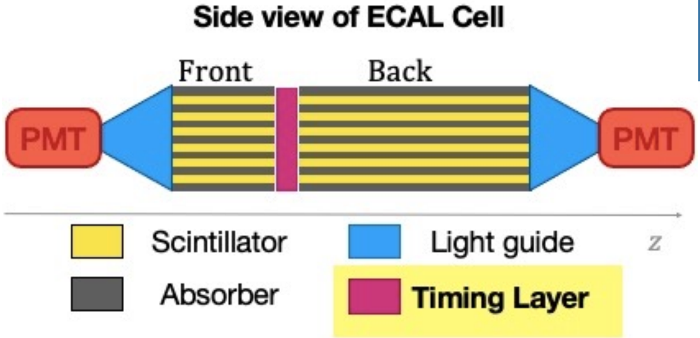


3 regions with different cell sizes

- Large array of shashlik cells
  - Radiation tolerance up to 40 kGy
  - γ, π^0, $e^\pm$ from few-GeV up to 100-GeV
- Main problems in future runs
  - Radiation hardness → SPACAL
  - Occupancy → time information
- Time information effective to suppress combinatorial and resolve pile-up: insert timing layer within a SPACAL module
  - Required time resolution: < 20 ps

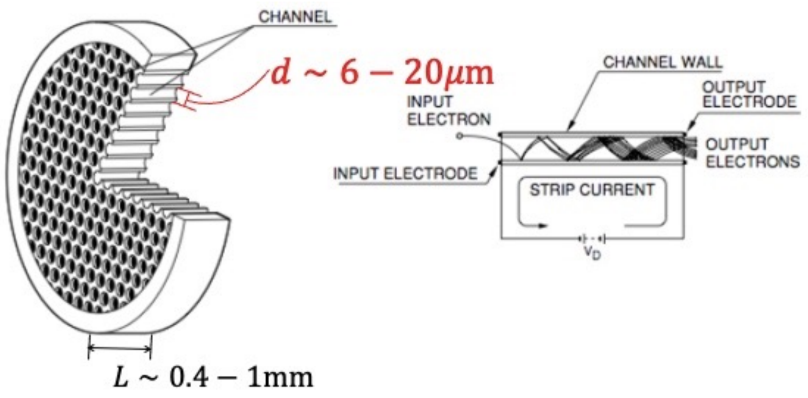


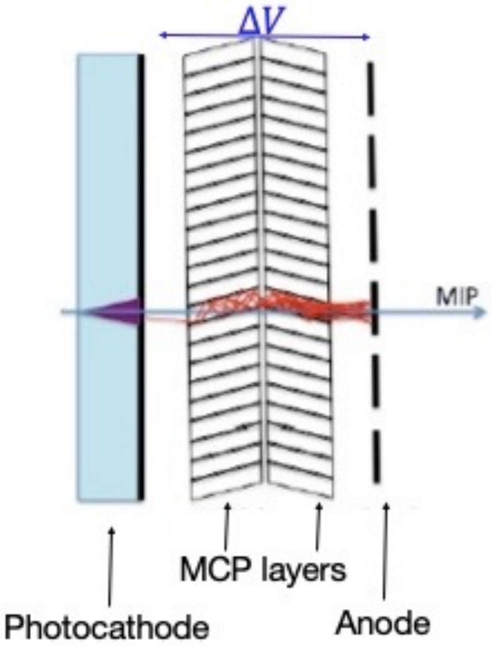




MCP-PMTs

- An MCP is a matrix of **micrometrical channels** able to multiply electrons
  - Traditionally produced from stacks of optical fibres with lead-glass cladding
- Gain: 10^6-10^7 with a stack of two MCPs
- Time resolution: 30 ps for single photoelectrons
- Original idea from the '90
  - [A. Ronzhin et al., IFVE 90-99, Protvino, 1990]
- More recent work for HL-HLC
  - [A. Ronzhin et al.], [A. Barnyakov et al.]



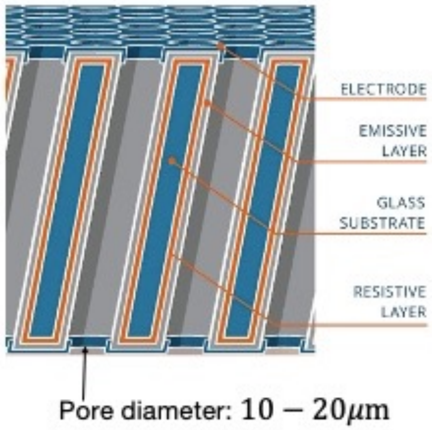


Limitations of MCP-PMTs

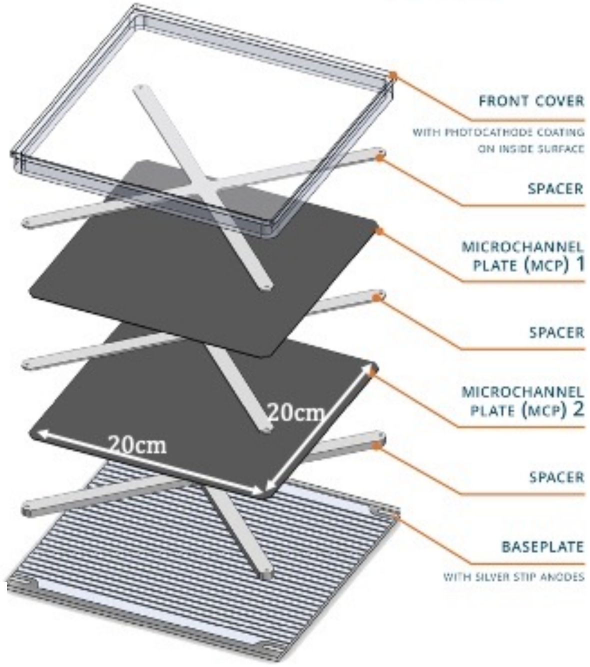
- Cost
  - Need to instrument large area (47 m^2)

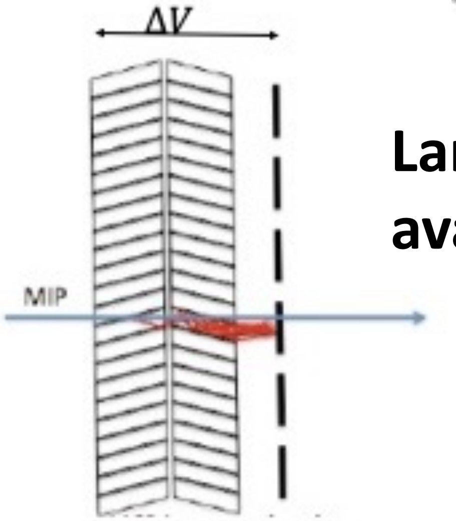
  → LAPPD by INCOM: porous structure of the MCP made of common borosilicate, then activated through deposition of resistive and emissive layers (Atomic Layer Deposition)
- Photocathode lifetime
  - Ion-feedback ruins the photocathode and spoils the quantum efficiency
  - Max integrated charge in literature: 35 C/cm^2 (10 times lower than LHCb ECAL)

  → Remove photocathode (reduced complexity and cost) and exploit primary ionisation at shower maximum



Exploded view of LAPPD, Gen I





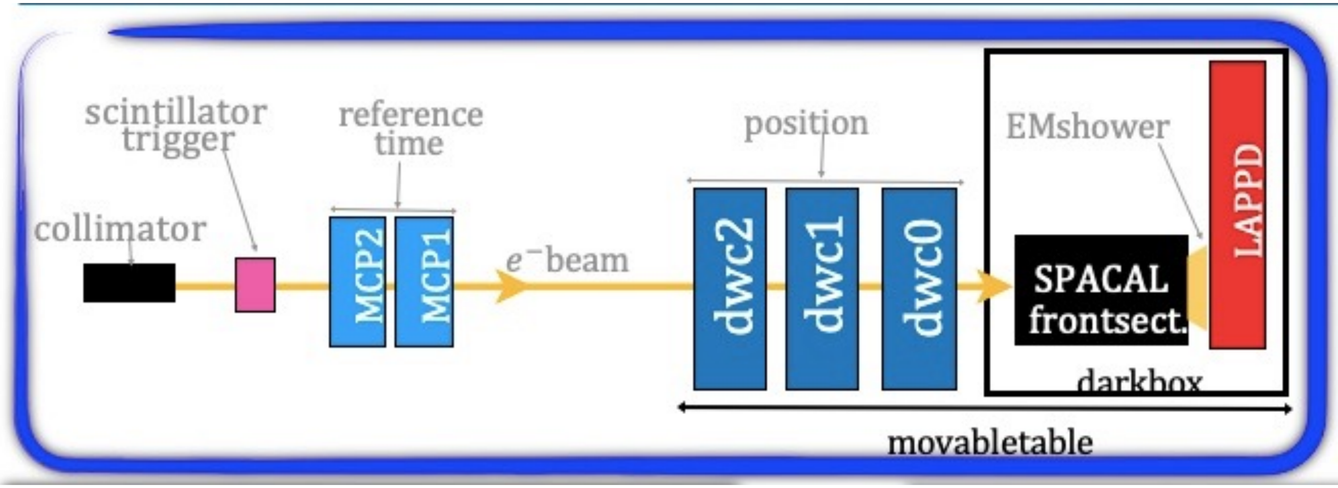
Largest area MCP-PMT available on the market

Gen I: resistive strips
Gen II: capacitavely coupled anode (square pixels)

List of tests performed

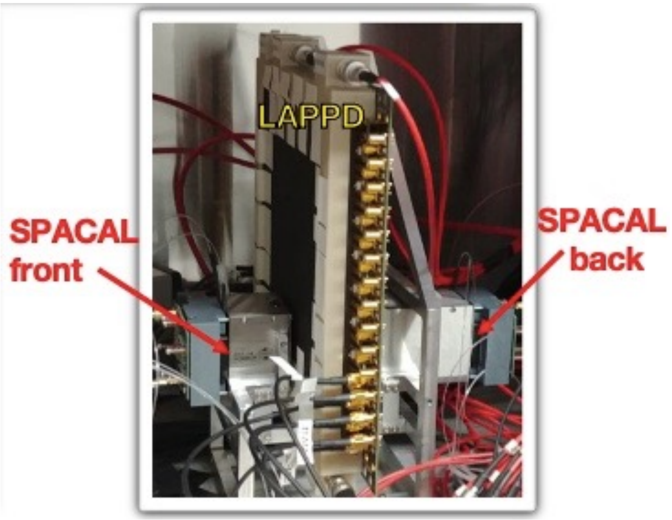
- At accelerators
  - Electrons (time and spatial resolution, efficiency)
    - DESY: 1-5.8 GeV
    - CERN SPS: 20-100 GeV
  - Protons (radiation hardness)
    - IRRAD: 24 GeV
- In the laboratory
  - UV lamp (ageing)
  - Laser (operation under high-flux)

Test beam setup

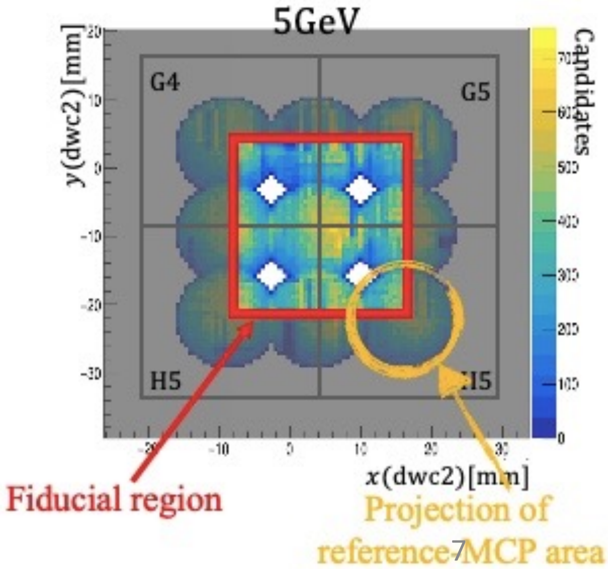


- LAPPD z-stack (3 MCPs)
  - d = 10 μm, photocathode: inhibited, anode with square pixels: 2.5x2.5cm^2
- Signal digitised with CAEN v1742 (5 GS/s)
- Reference MCPs resolution: 12 ps

- Scan performed over 4 pixels and 9 positions
- Information from different pixels combined with a random forest regressor



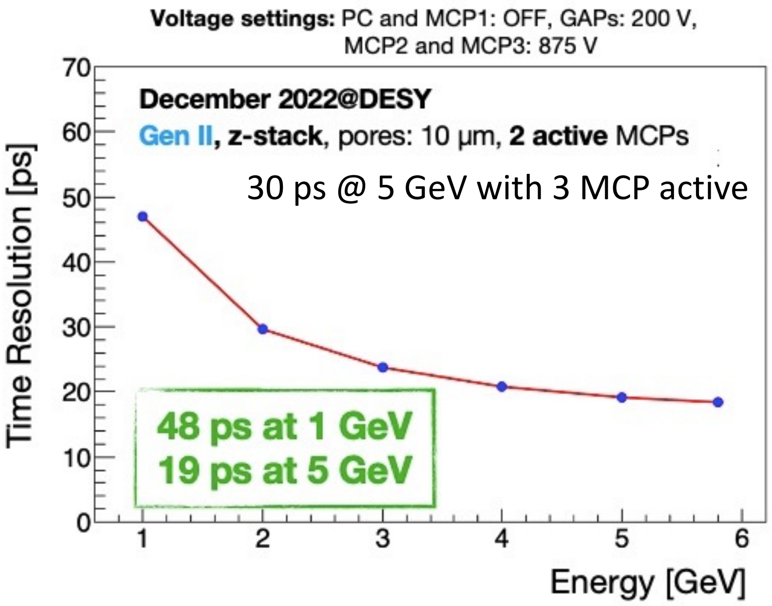
~7 X_0 in front of LAPPD

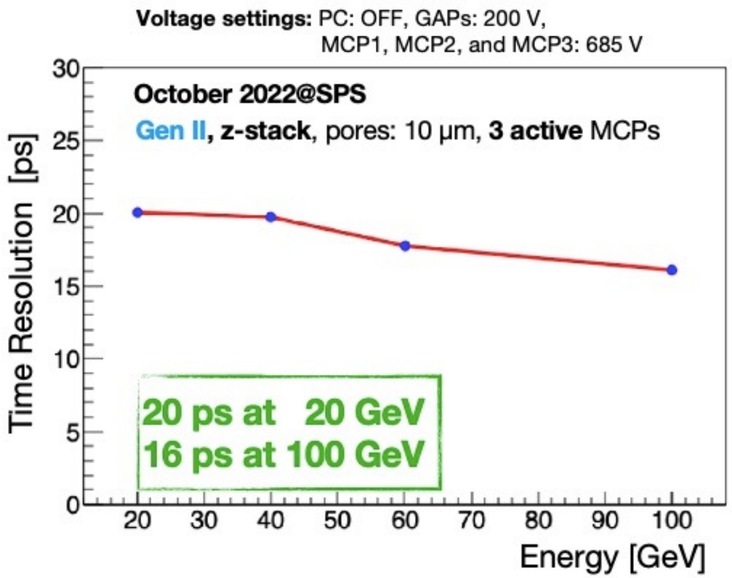


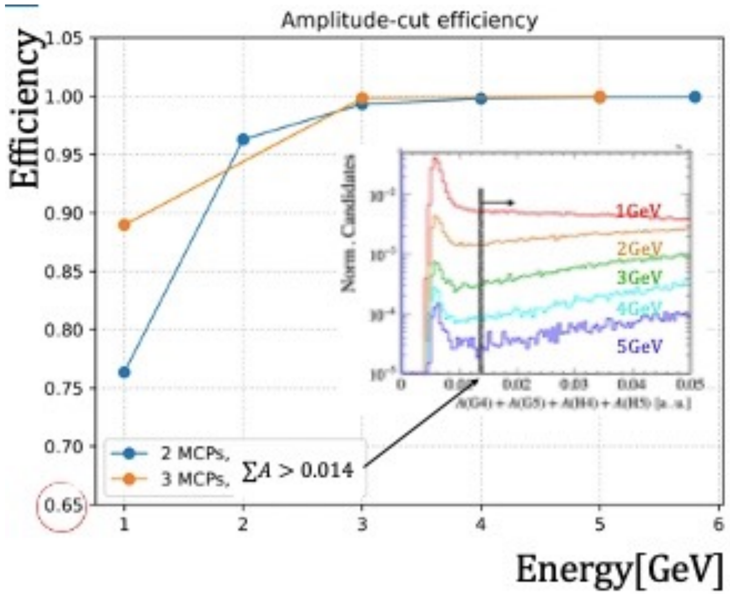
Resolution of reference MCPs already subtracted in this slide

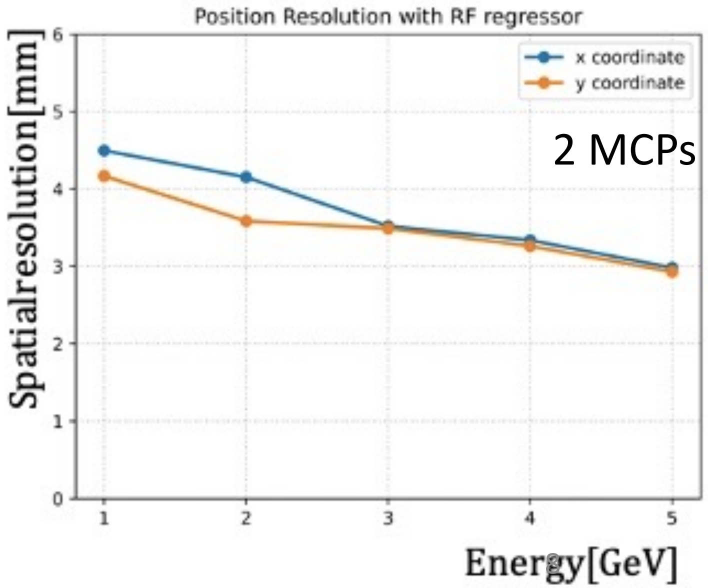
Results

- Time resolution in line with ECAL requirements for energies above 5 GeV
- Efficiency 99% for E > 3 GeV with two MCPs, 89% for E > 1 GeV with three MCPs
- Spatial resolution between 5 and 3 mm for energies below 5 GeV



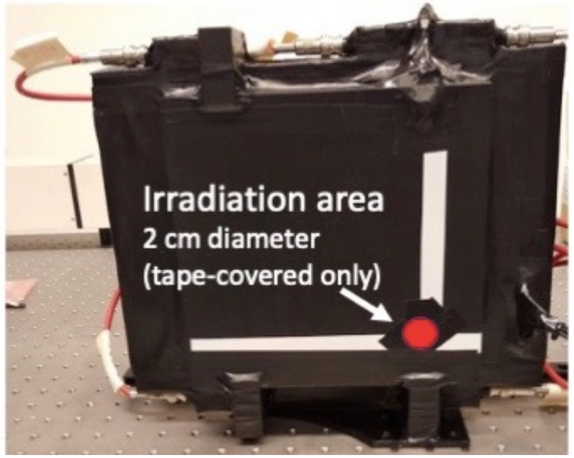


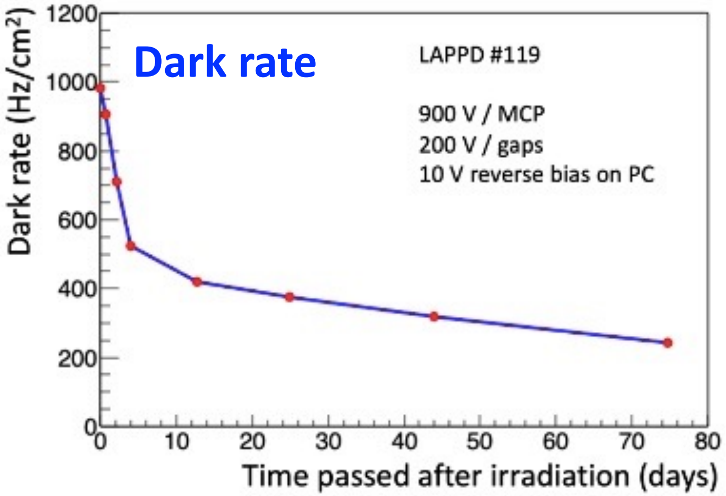


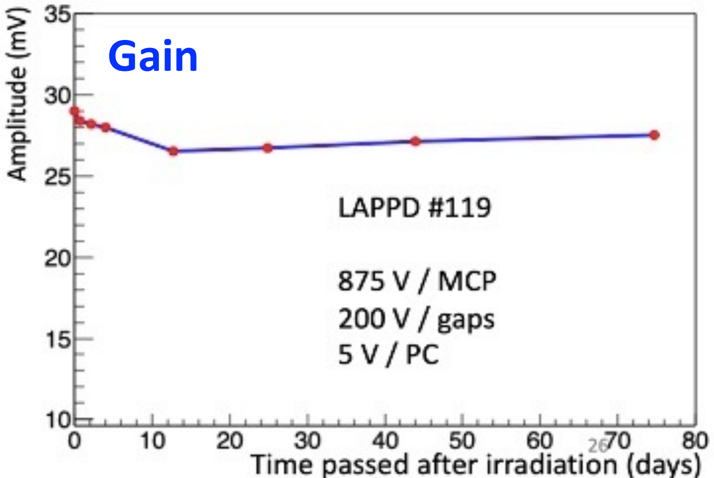


Radiation hardness

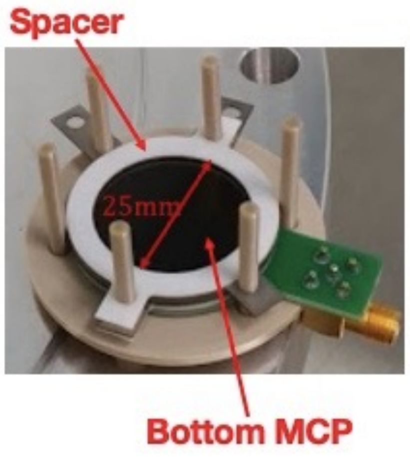
- LAPPD-#119, Gen-II, 10 µm pores, light tight with black paper sheets, plastic, and tape
- 10^{16} protons integrated in about 1 week, corresponding to ~ $5\text{x}10^{15}$ 1MeV neq / cm^2
- After irradiation, a blue LED was inserted in front of the irradiated area, tuned to produce single isolated photoelectrons → gain monitoring
- Prior to irradiation, dark rate ~ 10 Hz/cm^2 → increase of 2 orders of magnitude just after irradiation, decaying to ~ 200 Hz/cm^2
  - Such dark rate is by far not problematic for our use
- Slight reduction of gain observed, with fluctuations → could be due to IRRAD storage area not stable temperature

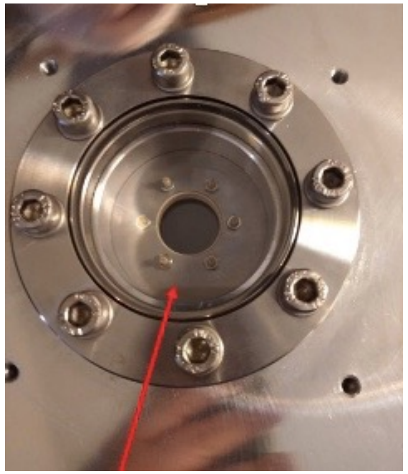






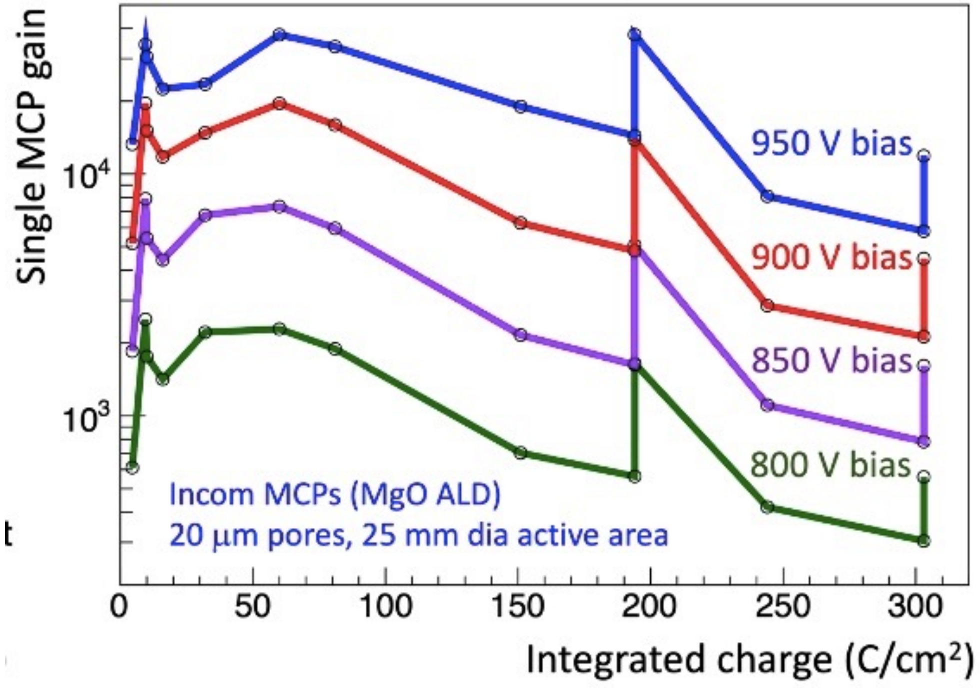
MCP lifetime measurement





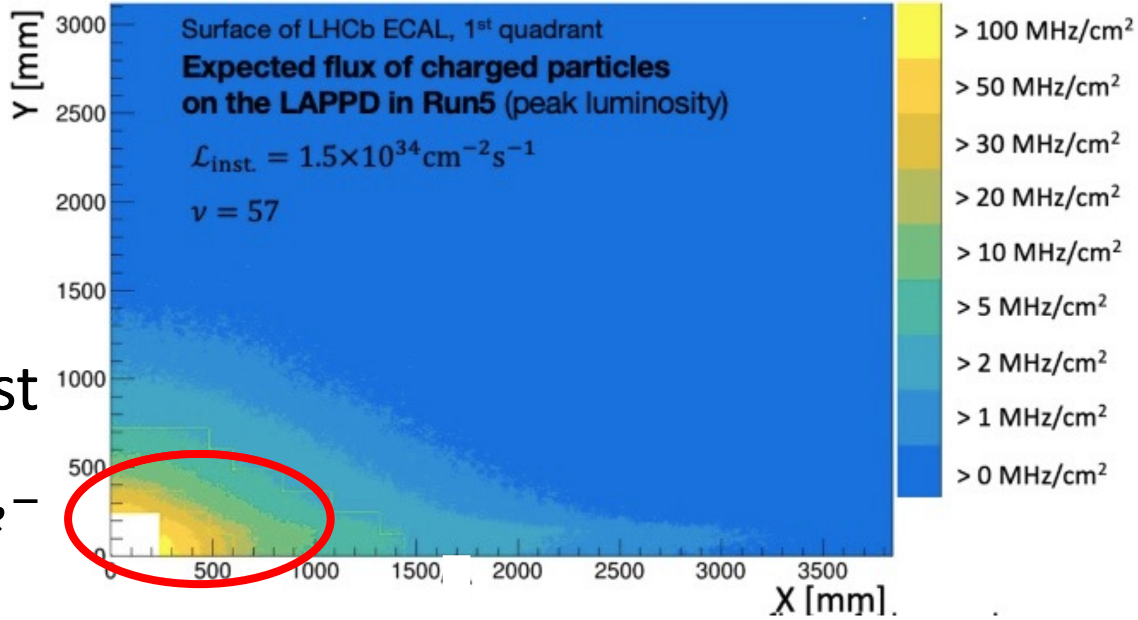
Top view of installed stack below the viewport

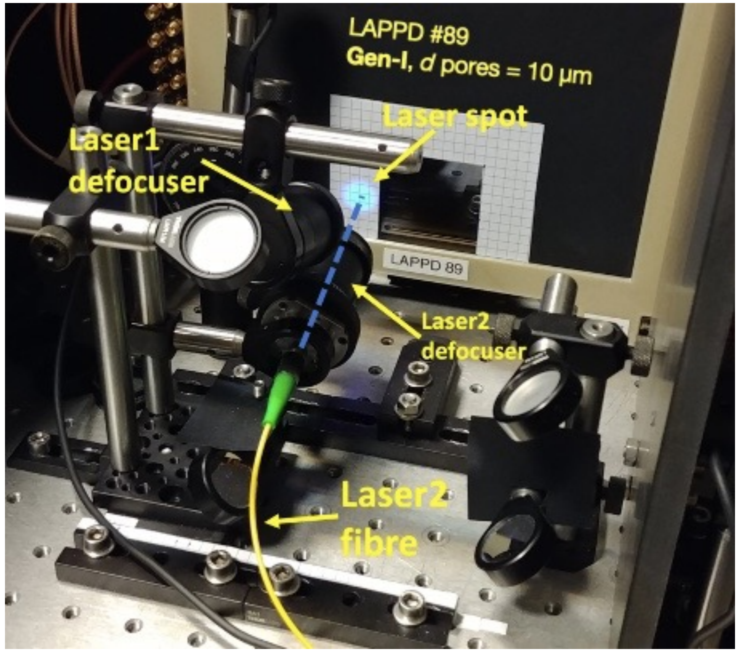
- Chevron stack of 2 round MCPs placed in a vacuum chamber with viewport
- **Mercury lamp** (one line at 185 nm) placed on top of the viewport, to extract e^- from top MCP
- Electrons are multiplied by the MCP stack and charge is collected by a metallic anode
- Integrated charge: 300 C/cm² → gain reduction of factor 7 recoverable with + 100 V
  - Recovered gain after 1 week of rest (jump at 200 C/cm²), then went back to previous trend



High-rate tests

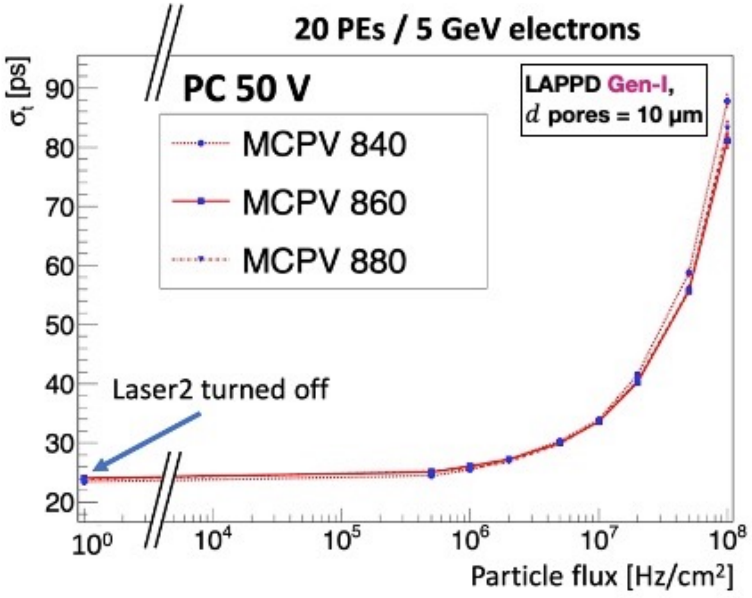
- 30-100 MHz/cm^2 expected in the hottest region of ECAL
  - Each multiplication depletes the pores of e^- → dead time per pore that leads to lower signal amplitude and thus worse time resolution
- Two lasers operated simultaneously
  - First laser to mimic signal EM showers (15 mm spot) with different energies
  - Second laser to mimic background flux, with same spot size
- Study time resolution for the signals produced by the first laser as a function of the pulse rate of the second laser

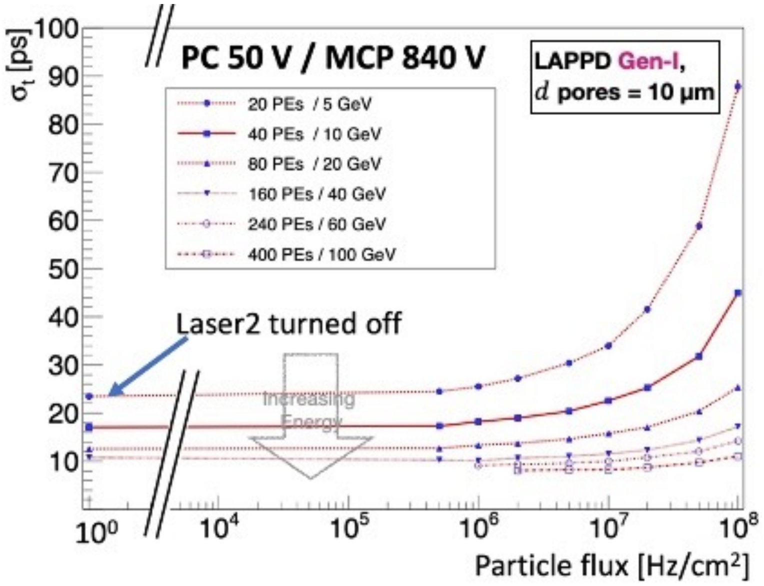


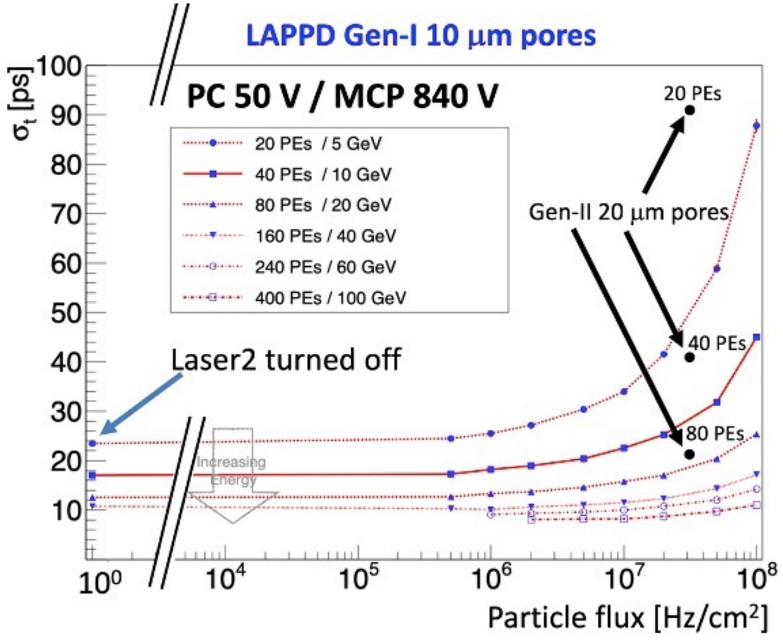


Performances at high rate

- Time resolution degrades with increasing incident flux
- Study repeated as function of signal EM shower energy → reduced degradation for higher energy showers
- As expected, reduced pore size helps in recovering performance → still R&D to do, especially at low enegies







Conclusions

- A LAPPD-based timing layer is currently one of the candidate components for the Upgrade-2 of the LHCb ECAL
  - Cost reduction compared to traditional MCPs
  - Several test already done both in the laboratory and at beam facilities
  - Effective radiation hardness for the LAPPD
  - Lifetime of MCP wafers tested and found to meet the requirement of 300 C/cm^2 of integrated charge
  - Good time resolution, even without the photocathode
- Intense R&D is ongoing, with a particular focus for performance at high incident flux
  - Smaller pore size, z stack, …
- Simultaneous effort with LLMCP project for R&D on robust and cheap photocathodes activated by INFN

Spares

Lab equipment

- Laser system
  - PICOPOWER™-LD by ALPHALS
  - Class 3B with 405 nm wavelength
  - Repetition rate tunable
    from 1Hz to 50 MHz (in steps of 1 Hz)
  - Pulse width with optimal settings
    measured at the factory before shipment 11.7 ps (RMS)
  - Trigger jitter measured in the lab to be 3.4 ps
- Digitiser CAEN v1742
  - VME board with 32 channels based on DRS4 chip
  - Maximum sampling rate is 5GS/s with 1024 cells per channel
    (full acquisition window of 204.8 ns), and 500 MHz bandwidth
  - Calibration performed in the lab based on [D. Stricker-Shaver et al., IEEE Trans. Nucl. Sci. 61 (2014) 3607]
  -

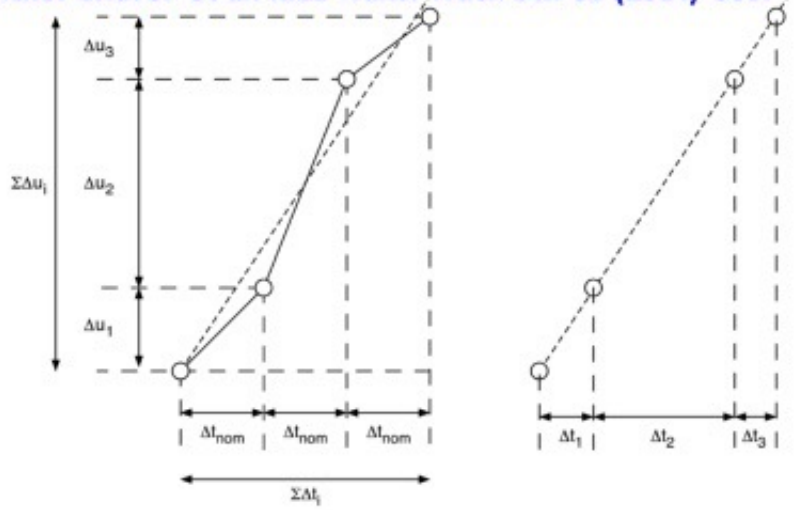
Digitizer calibration

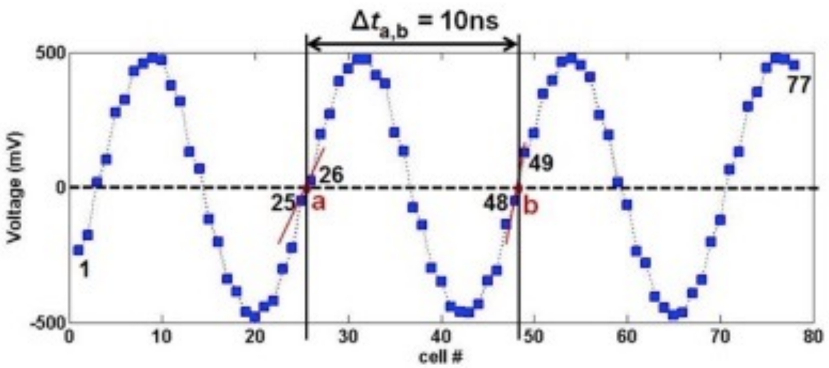
- Voltage offsets calibration
  - Injected into each channel a set of **constant voltages**
  - Use a **linear fit** to parameterise the correspondence between voltage and the average or registered ADC counts for each cell of each channel

- Local calibration of cells time widths
  - Injected into each channel **50 MHz saw-tooth waveform**
  - Exploit **linear correlation between voltage difference and time difference of two adjacent cells**

- Global calibration of cells time widths
  - Injected into each channel a **100 MHz sinusoid waveform**
  - Measure the time **difference between zero crossings** for one or multiple periods, and use this difference to correct the time widths of all intermediate cells

D. Stricker-Shaver et al. IEEE Trans. Nucl. Sci. 61 (2014) 3607

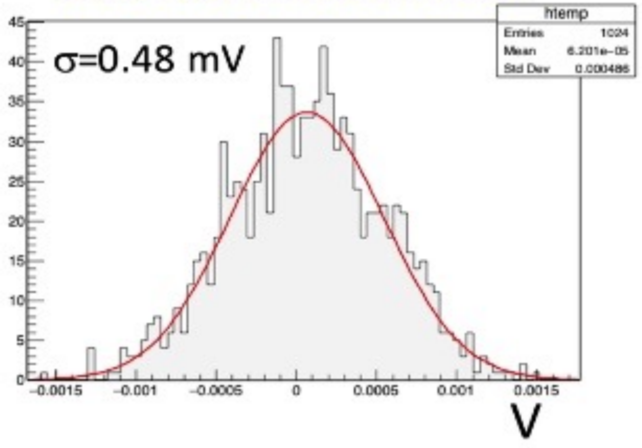


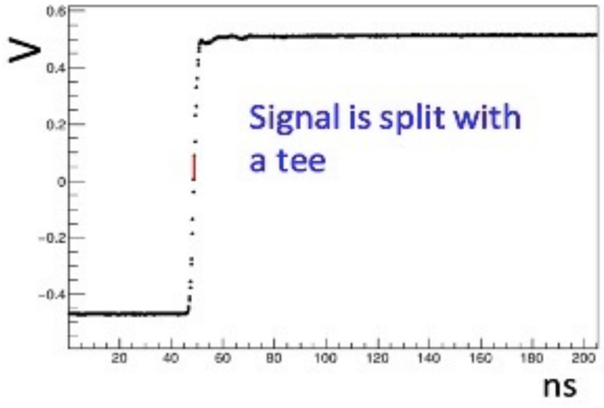


Calibration results

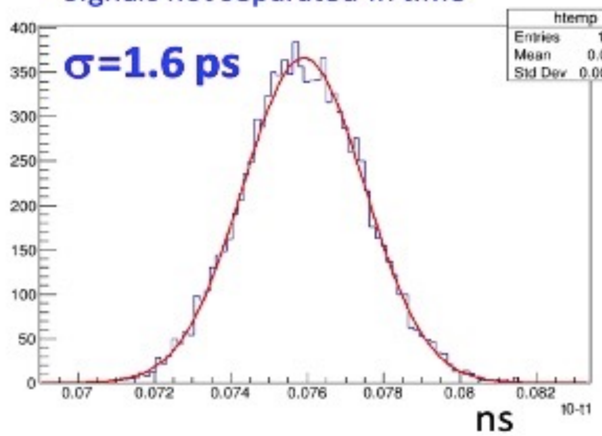
- Calibration check is performed with a **signal split test**
  - A rising edge is generated via waveform generator, split in two and sent to two distinct channels of the board
  - One of the two signals is also delayed wrt the other via a longer cable
    - Effect of small miscalibrations of cells widths adds up for signals separated in time
  - Difference between the two signals is used to determine time resolution

Residual noise after calibration





Signals not separated in time



Signals separated by ~100 ns