LAPPD performance from beam tests

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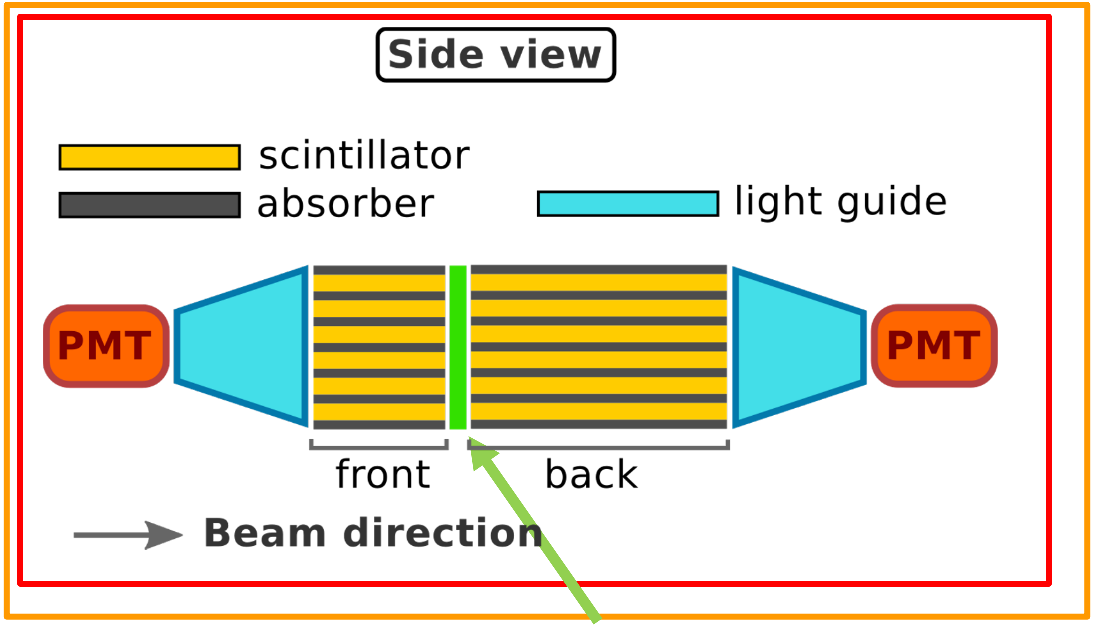
Outline

- Brief introduction on timing layer for ECAL Upgrade-2 and LAPPD technology
  - For more details see dedicated session on Wednesday
- Experimental setup at DESY and SPS beam tests
- Analysis of beam-test data and results
- Irradiation campaign at IRRAD
- Summary

A timing layer for the LHCb U2

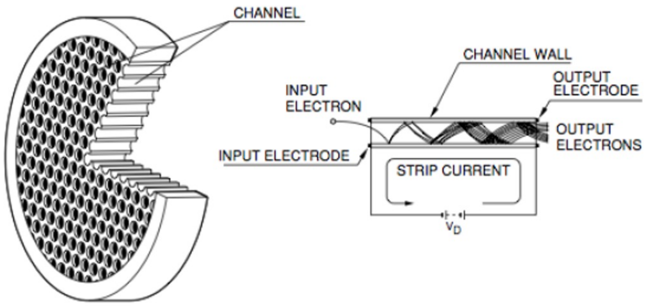


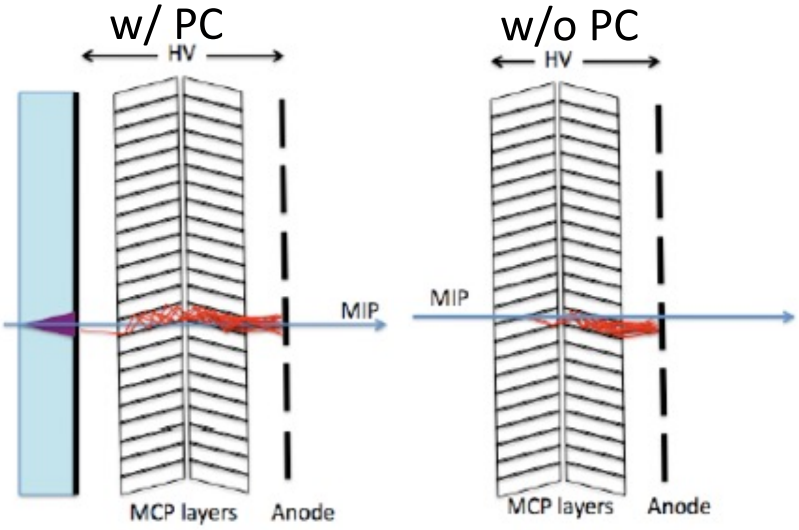
Timing layer based on microchannel plate detectors

Place a thin detector based on MCP-PMT between two sections of sampling calorimeter split at the shower maximum to sample the secondary particles produced in EM showers and reach time resolution of the order of 10-20 ps

Direct ionisation inside microchannel plates

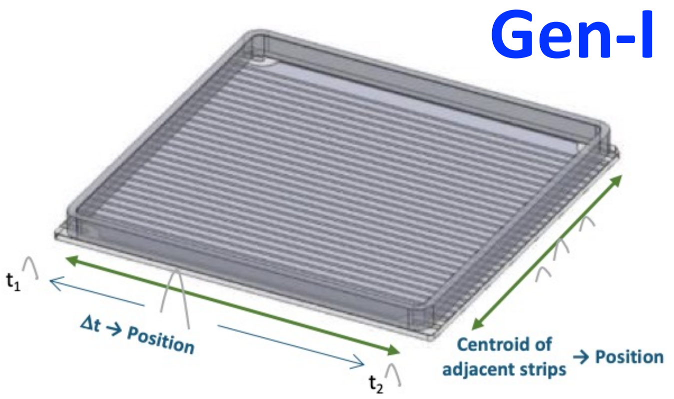
- Large number of secondary particles in the shower allows the usage of a photocathode to be avoided
  ➔ electrons produced by direct ionisation inside the MCP wafers
- Photocathode is by far the most fragile part of MCP-based PMTs due to large rate of ion feedback
  – Robustness greatly improved without a photocathode, along with significant reduction of complexity and costs

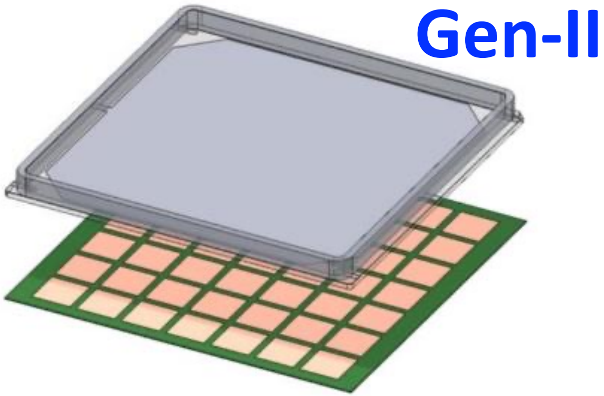




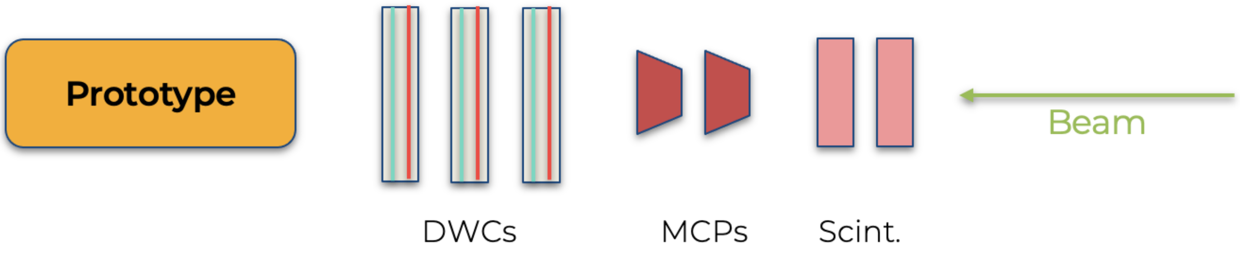
LAPPD versions

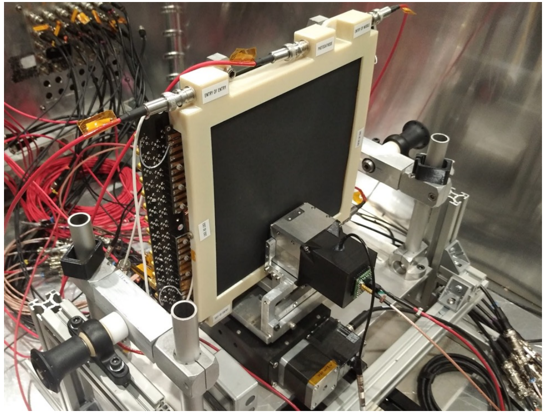
- LAPPD comes in two main readout versions
  - **Gen-I with delay-line anode**
  - **Gen-II with capacitively coupled pixelated anode**
- During last two years, several beam tests at DESY and SPS with both Gen-I and Gen-II detectors, with different pore sizes, with two- and three-MCP stacks, along with pulsed-laser characterizations, have been carried out to study basic performances of the devices
- In today's presentation
  - Latest results from Gen-II LAPPD prototype with **10 μm pore size**
  - **Beam tests** performed at **DESY** with **1-5.8 GeV electrons** and **SPS** with **20-100 GeV electrons**





Beam-test setup

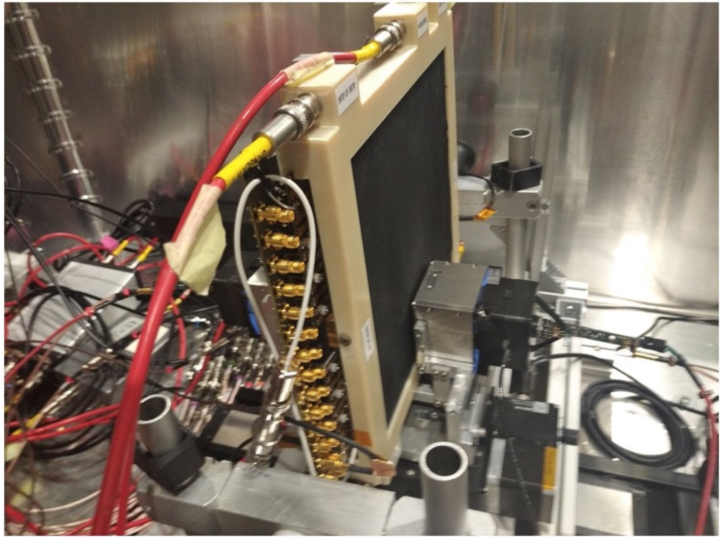


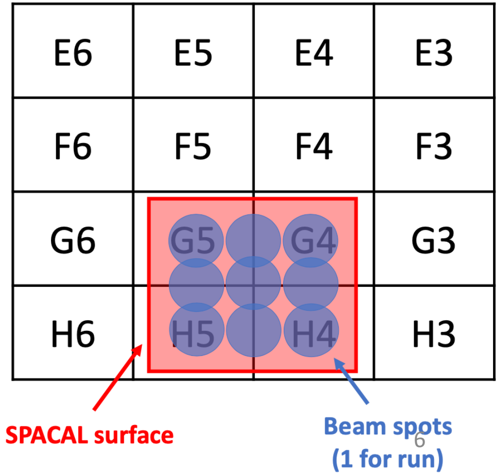


- Set-up from the beam
  - 2 scintillating pads for trigger
  - 2 MCP-PMTs used for time reference
  - 3 Delay Wire Chambers for tracking
  - Prototype enclosed in a dark box with 2 rotating axes (azimuth and altitude)
- Pulses recorded with V1742 CAEN digitiser (DRS4 chip), 5 GS/s, bandwidth 500 MHz

SPS beam test: October 2022

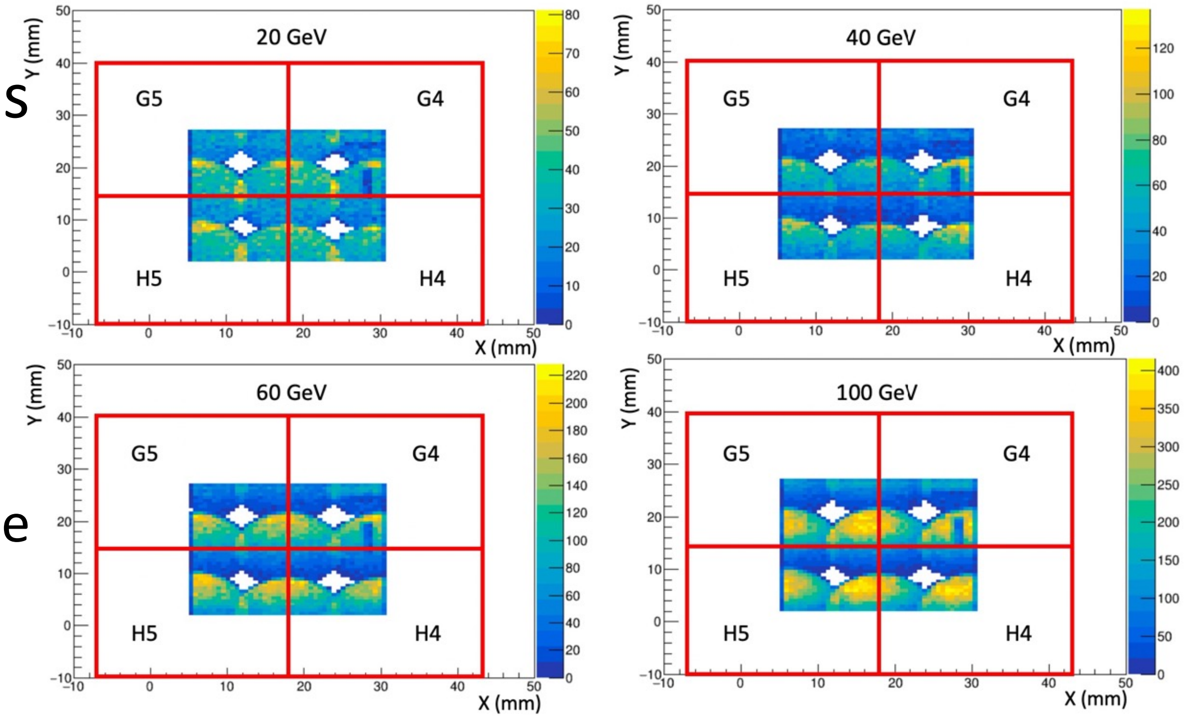
- SPACAL covering four pixels (2.5 cm pitch)
  - G4, G5, H4, H5 in the sketch below
- LAPPD operated with three MCPs in z-stack configuration
- LAPPD voltage settings
  - 200 V / gap, 685 V / MCP, -10 V / PC (reverse bias)
- Data taken with electrons at **20, 40, 60 and 100 GeV**
  - Several runs at different positions to **scan the SPACAL and hence the LAPPD surface covered by the SPACAL**
- LAPPD time resolution determined using multivariate regressors which combine the information of the four pixels under study





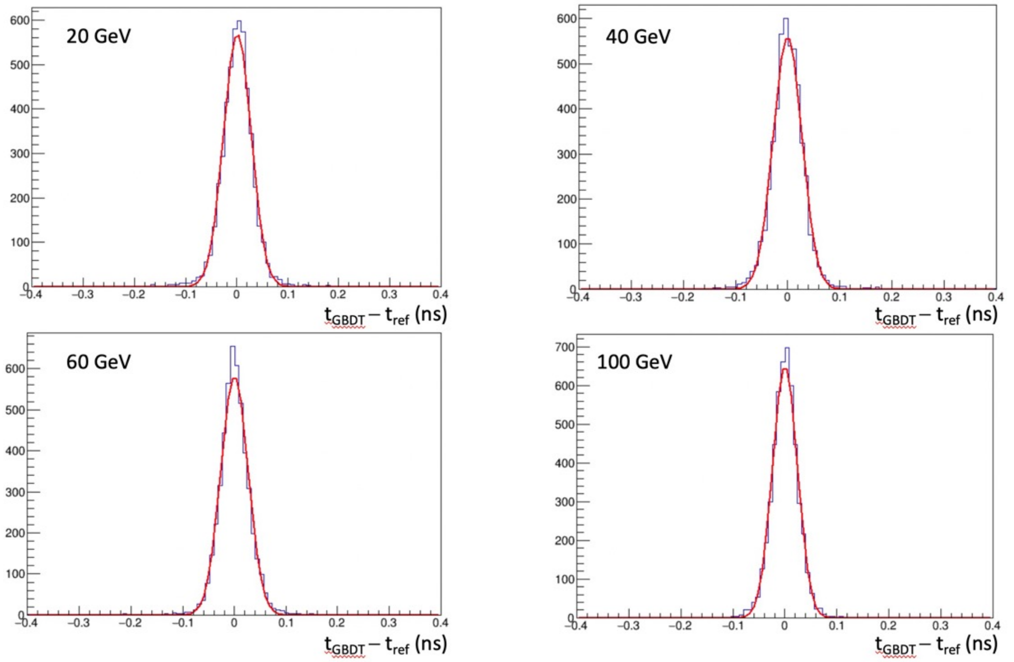
Spatial distribution of events

- Fiducial region defined as a rectangle with vertices at pixels centres
- Beam position scanned to cover entire region
  - Not perfect, but decent coverage was achieved
  - The four little holes visible in the plots are due to small uncovered regions due to some fiducial cuts



Time resolution from multivariate regressors

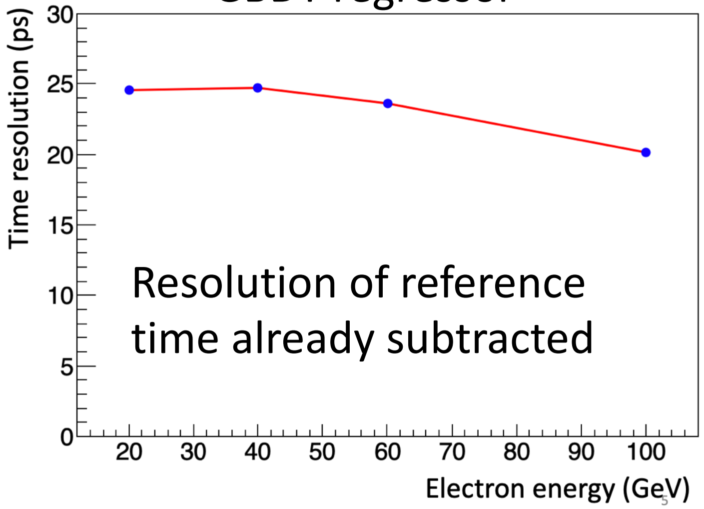
- Input variables: **amplitudes** of pixels, **timestamps** of pixels (at 10, 50 and 90% of signal amplitude), coordinates provided by the DWCs
- Target variable: **reference time of MCP-PMTs**
- Training sample and test samples kept separate to avoid overtraining effects on performance estimate
- Output shows a very good Gaussianity for all energies



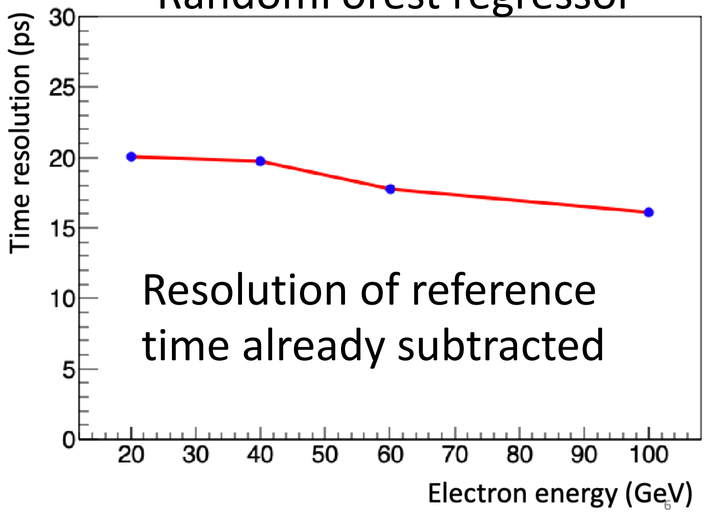
Numerical results in next slides

Time resolution from multivariate regressors

GBDT regressor



RandomForest regressor



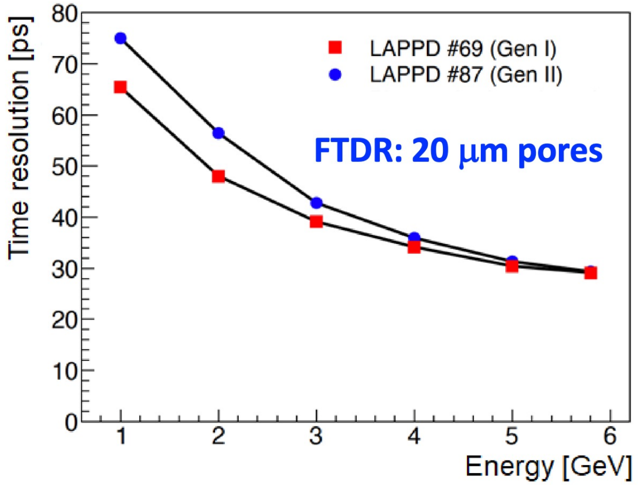
- After subtraction of reference time spread
  - GBDT: **24 ps @ 20 GeV**, **20 ps @ 100 GeV**
  - RandomForest: **20 ps @ 20 GeV**, **16 ps @ 100 GeV**
- Precision below 20 ps achieved by combining information from the four pixels despite their large size (~2.5 cm in side)

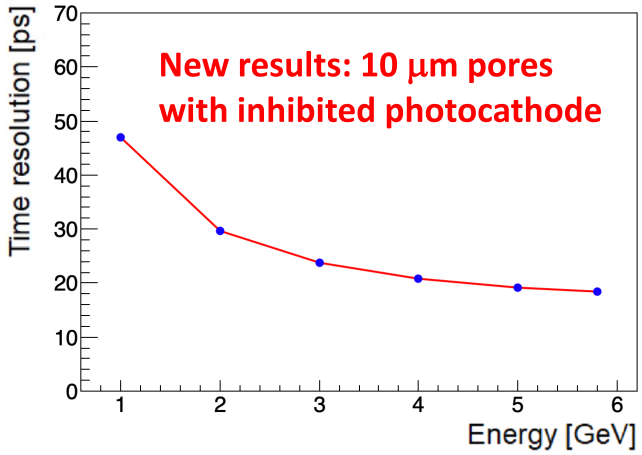
DESY beam test: November 2022

- **Similar strategy as that used at SPS**
  - SPACAL covering four pixels: G4, G5, H4, H5
  - Fiducial region corresponding to square with vertices in the centres of pixels
  - Information from pixels combined with RandomForest regressor
- All 3 MCPs activated
  - 200 V / gaps, 700 V / MCP, -10 V / PC (reverse bias) → **25 ps @ 5 GeV**
- Then top MCP inhibited with reverse bias to compare with LAPPD with two-MCP Chevron configuration
  - 200 V / gaps, 875 V / MCP, -10 V / PC (reverse bias) → **19 ps @ 5 GeV**
  - 200 V / gaps, 685 V / MCP, -10 V / PC (reverse bias) → **32 ps @ 5 GeV**, same voltage settings used at SPS

DESY beam test: November 2022

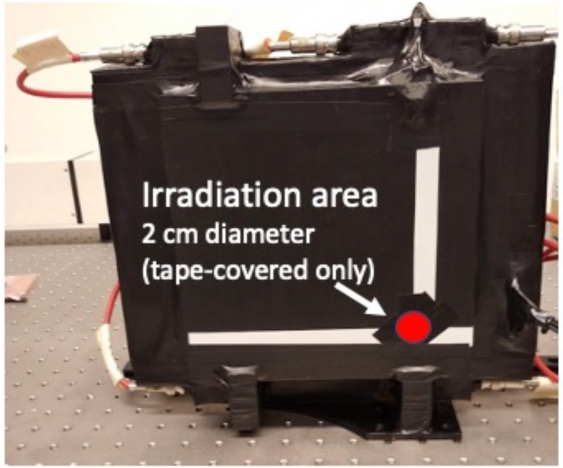
- Once the resolution of time reference is subtracted, the resolution of z-stack LAPPD with **top MCP inhibited** ranges from **47 ps @ 1 GeV** to **19 ps @ 5 GeV**
  - Great improvement with respect to old Gen-II with 20 μm pores
- **Using all 3 MCPs** time resolution worsens to **25 ps @ 5 GeV**
  - **Larger transit time with 3 MCPs, implying also larger transit time spread**
- Not yet clear whether there could be real advantages to use stacks of three MCPs instead of two
- In any case, with 10 μm pores we can achieve sub-20 ps resolution from about 4 GeV onwards
  - Probably something better can be done with reduced pixel size, and certainly better by reducing even further the pore size

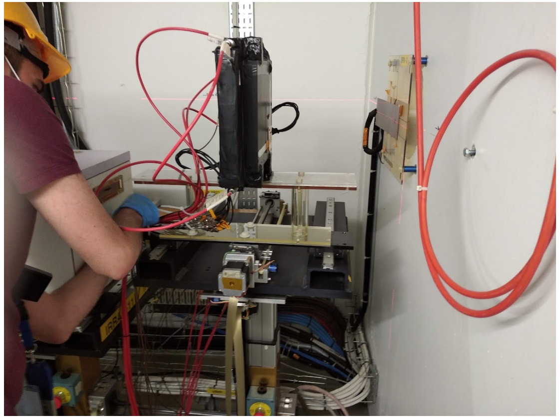




LAPPD irradiation at CERN IRRAD

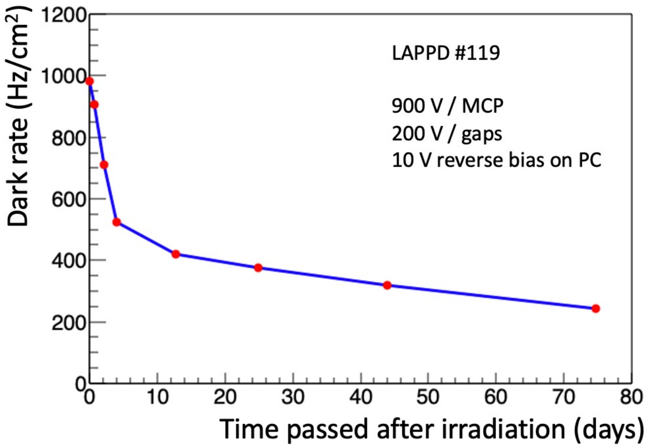
- The LAPPD was mounted on plastic holders, and made light tight with a combination of black paper sheets, black tape and black plastic covering the window
  - No heavy materials allowed on beam and surroundings
- 10^{16} protons were integrated in about one cm^2 over a week of run in June/July 2022
  - Roughly corresponding to 5 x 10^{15} 1MeV neq.
- During irradiation, the LAPPD was kept under high voltage
  - 900 V/MCP, 200 V/gaps
  - PC inhibited with 10 V reverse bias
- After irradiation, a blue LED was inserted in front of the irradiated area to send light to a square of 1 cm^2 centered at one LAPPD pixel
  - LAPPD Gen-II with 2.5 cm pads in pitch
  - The LED was powered by a short pulse from a waveform generator, with pulse width and amplitude tuned to produce single isolated photoelectrons

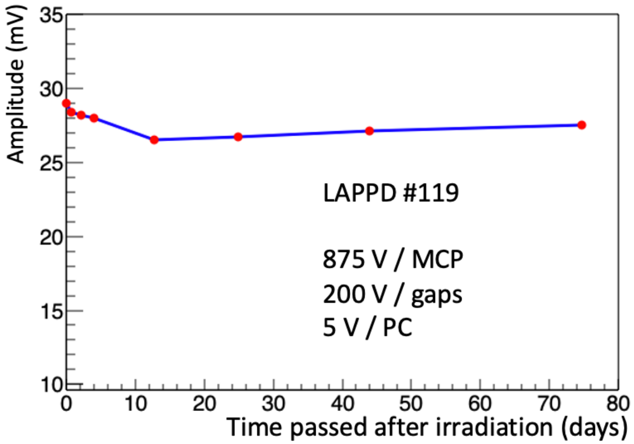




LAPPD irradiation at CERN IRRAD

- Prior to irradiation, dark rate was about 10 Hz/cm^2
  - Right after irradiation, increased by 2 orders of magnitude
  - Then decreased steeply in the first few days, with a much slower long-term trend
  - Although remaining significantly higher than prior to irradiation, such a level of dark rate is (by far) not problematic for our purposes
- Signal amplitude from single photoelectrons was instead basically unaffected
  - Decrease of a few percent only caused by irradiation





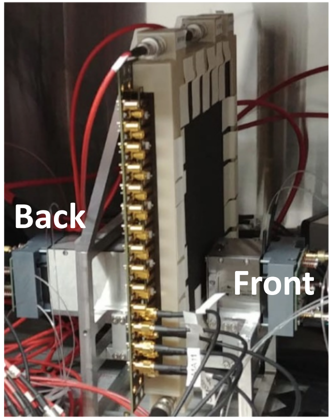
Summary

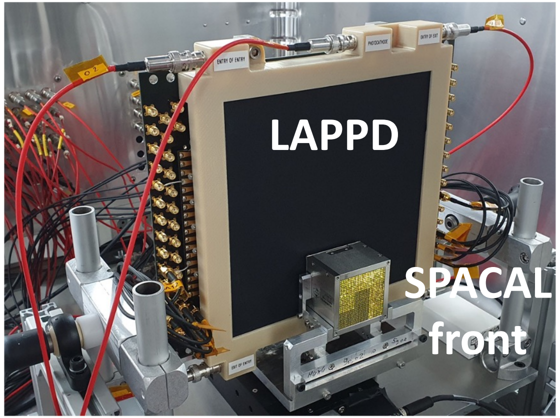
- New Gen-II LAPPD with with 10 μm pore size has been tested at DESY and SPS with electrons from 1 to 100 GeV
- Good time resolutions, below 20 ps, for all energies from 4 to 100 GeV
  - Some room for improvements with reduced pixel size and with possible future tiles with smaller pores
  - Combination of information from different pixels using multivariate regressors allows good uniformity of response
- High-dose irradiation performed at IRRAD does not show significant degradation of performances
- Basic performances at low rates established → now need to focus on operation at high rate

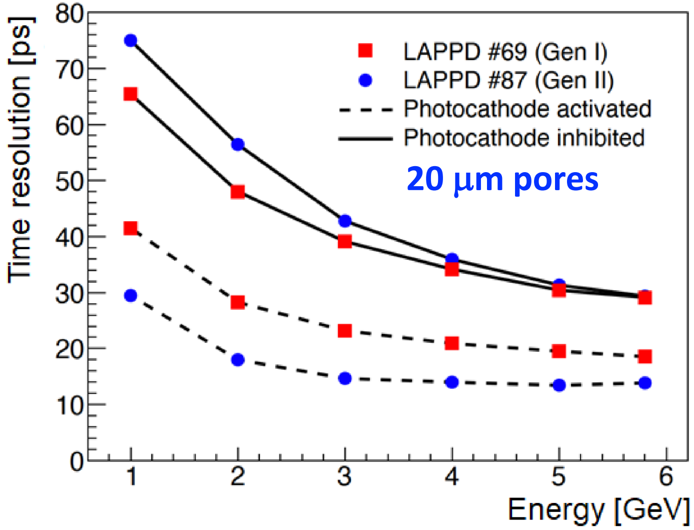
BACKUP

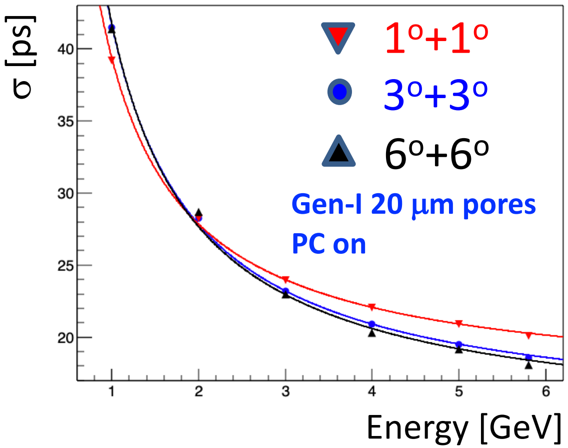
Beamtest at DESY (Nov 2020, May 2021)

- Time resolution
  - PC on → **23 ps (Gen-I)** and **14 ps (Gen-II) @ 5 GeV** (Q.E. higher for Gen-II)
  - PC off → **~30 ps @ 5 GeV**
- No relevant difference depending on the rotation with respect to the beam axis
  - Configuration with 1°+1° slightly worse



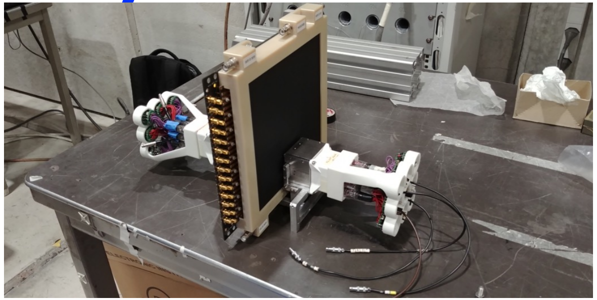


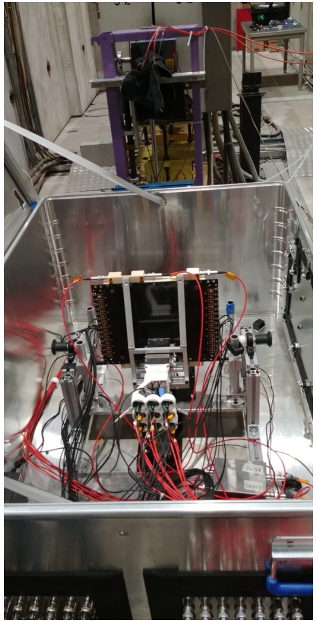


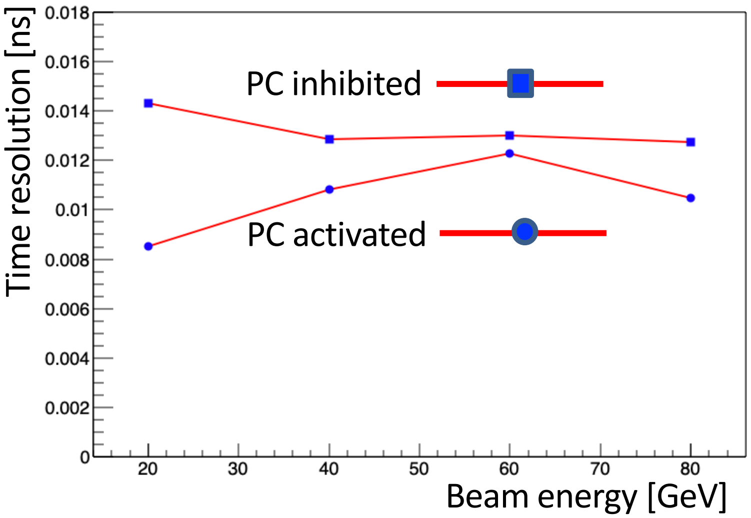


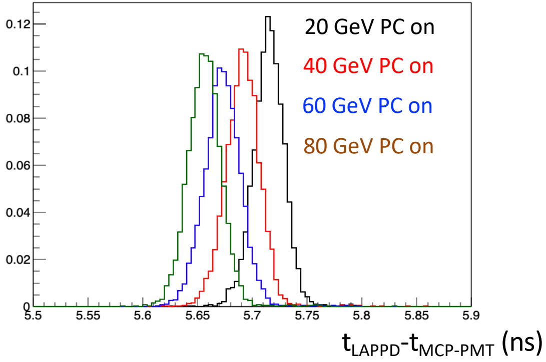
Beamtest at SPS (Nov 2021)

- First LAPPD Gen-I tile with 10 μm pores characterised with electron beams between 20 and 80 GeV
- Time resolutions with inhibited PC comparable to those with activated PC
  - Between **8 and 12 ps with PC on**
  - About **13-14 ps with PC off**
  - According to laser data, with this 10 μm LAPPD model, we think that a resolution **around 20 ps is at reach with PC off even at 5 GeV**









- A shift in LAPPD timestamp is observed as a function of energy, most likely due to different electron rates at different energies
- Must be understood in depth in order to envisage a proper time calibration strategy