LAPPD R&D studies for the LHCb Upgrade-2 ECAL

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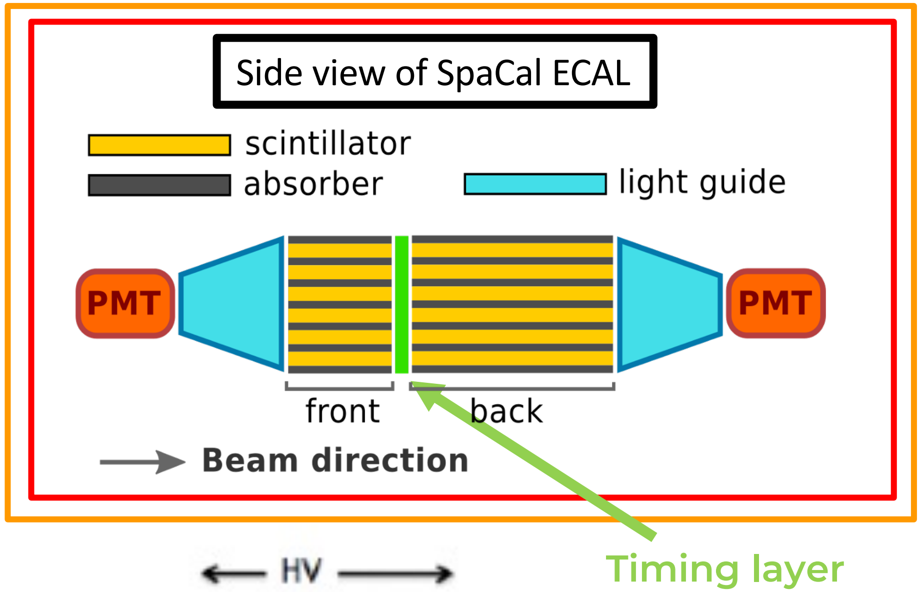
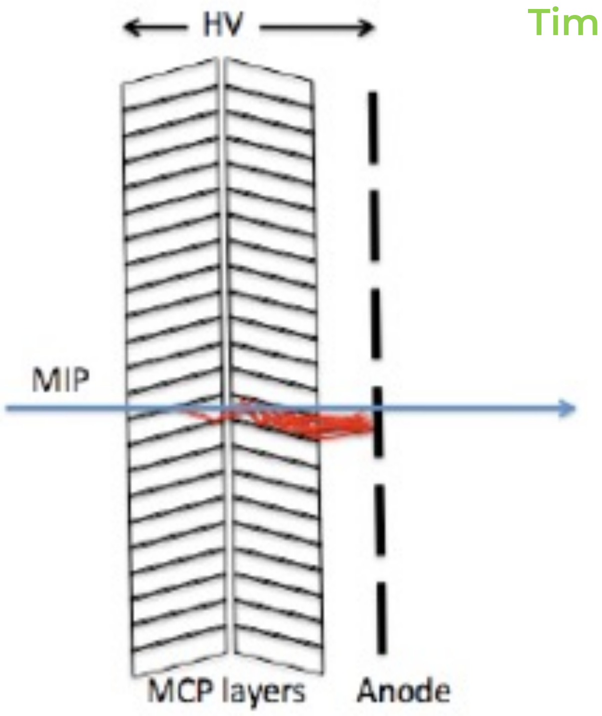
Outline

- First results with (first) z-stack 10 μm Gen-II LAPPD at CERN SPS
- First results with high-dose proton irradiation at CERN IRRAD
- Final results for MCP ageing tests with UV light in vacuum chamber

Reminder: timing layer for the LHCb Upgrade-2 ECAL

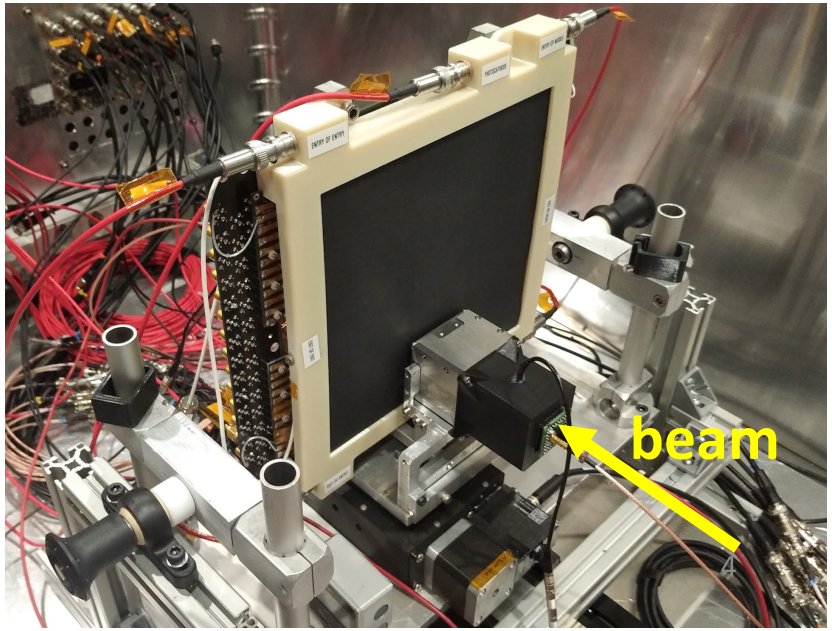
- The LHCb Upgrade-2 will operate in harsh hadronic environment
  - Instantaneous luminosity of proton-proton collisions up to 1.5 x 10^{34} $cm^{-2}s^{-1}$
  - High background in most central region
  - Measuring time of hits will be crucial to resolve pileup
    - Simulations indicate a time resolution of O(20) ps as necessary
- Insert a LAPPD-based detector between two sections of a sampling calorimeter
  - Detect charged component of EM showers by direct ionization within MCP wafers (no photocathode)
  - Exploit excellent time resolution of MCPs to determine the time of EM shower with O(10-20) ps precision



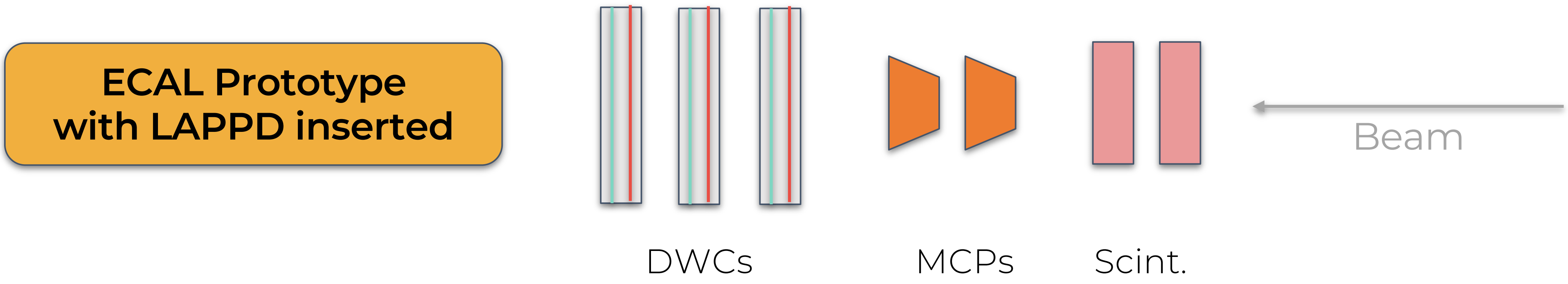


First z-stack LAPPD tested at SPS

- Custom LAPPD produced by Incom
  - First z-stack LAPPD: 3 MCPs instead of the usual 2
  - 10 μm pore size
  - Presence of the additional MCP give more flexibility in high-rate conditions and with lower energies with PC off
- This LAPPD came with an aluminum PC with extremely low QE, so no thorough characterization with laser pulses was made
- Beamtest conducted at CERN SPS at the end of June 2022
  - Electron beam from 20 to 100 GeV

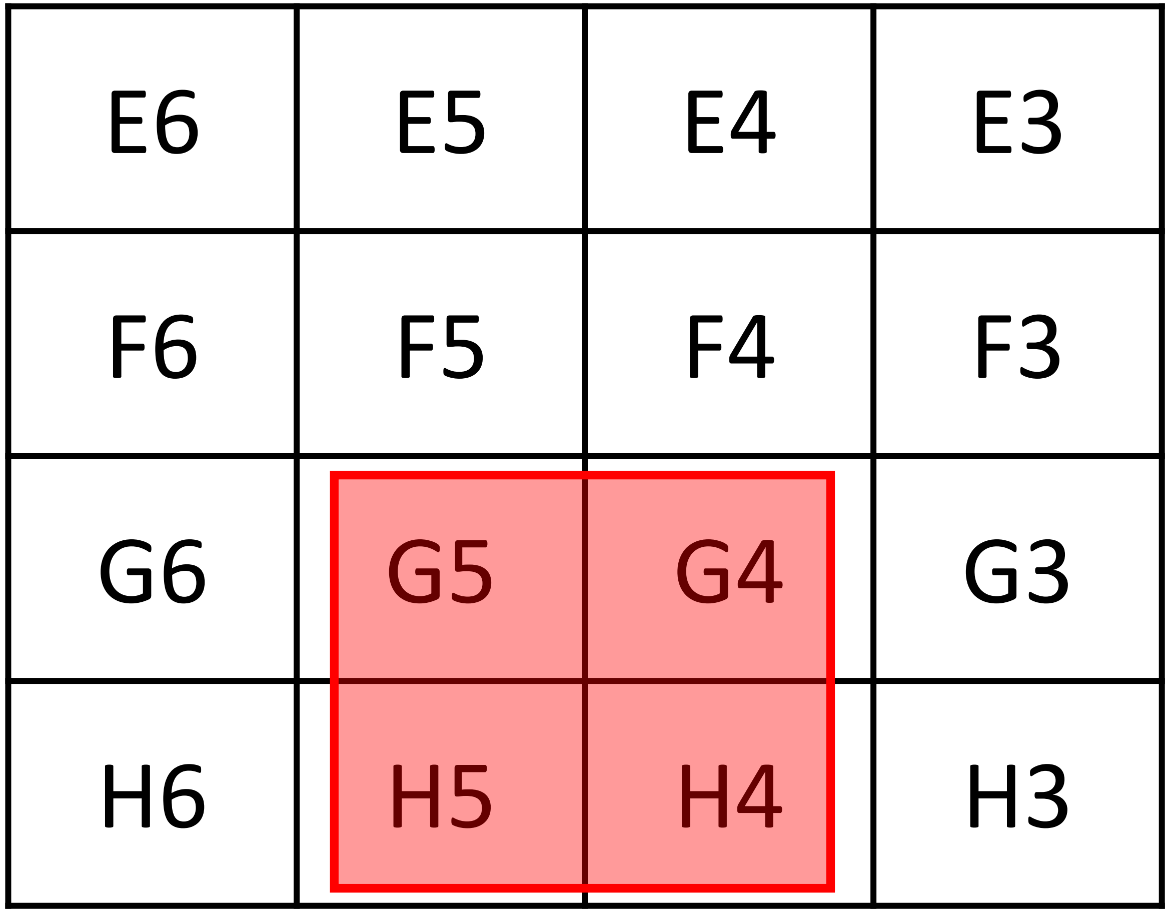


Beamtest setup



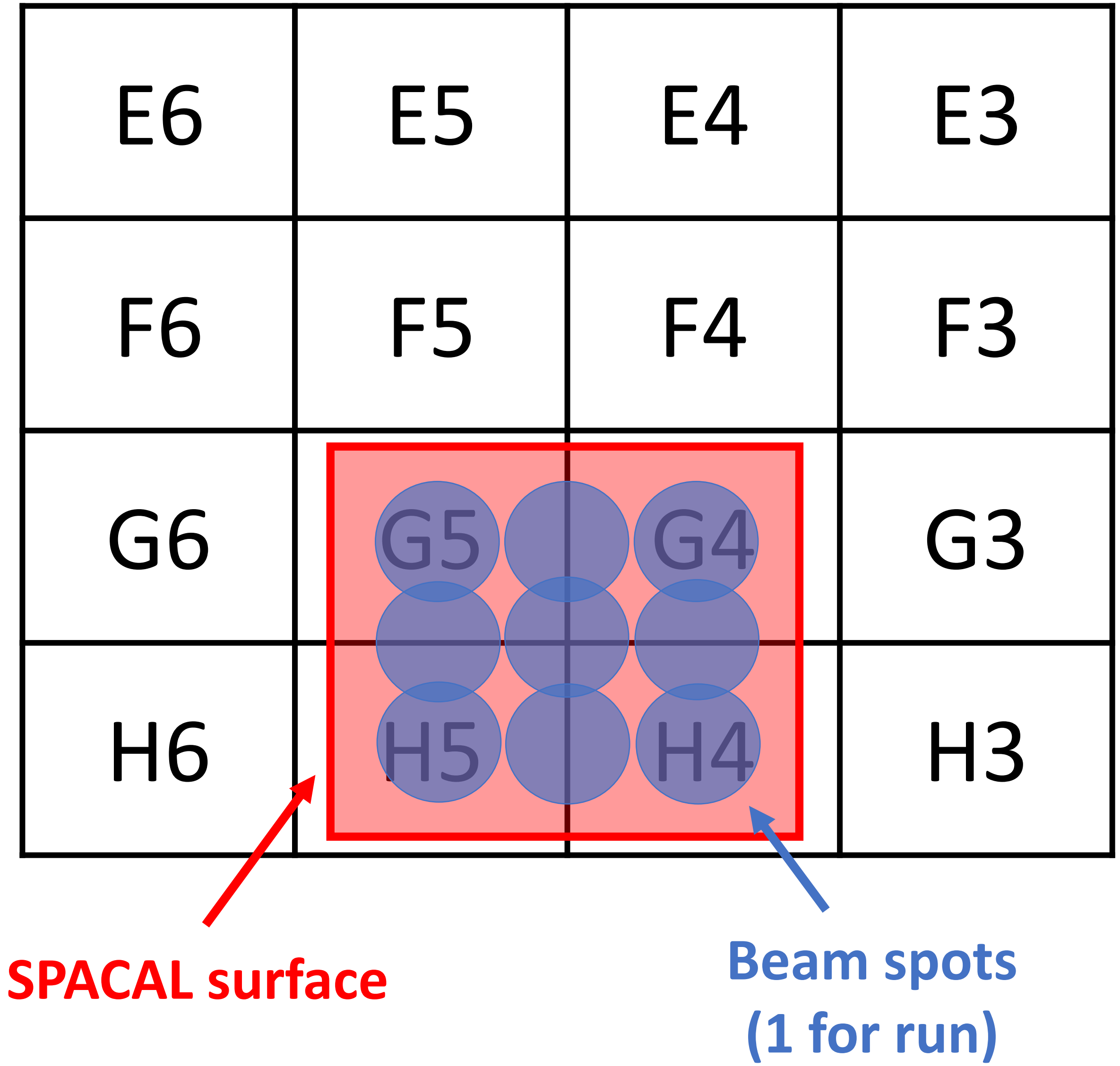
- Set-up from the beam
  - 2 scintillating pads for trigger
  - 2 MCP-PMTs used for time reference
  - 3 Delay Wire Chambers (DWC) for tracking
  - LAPPD sandwiched within two halves of a SPACAL module, enclosed in a dark box with motorized rotation axes
- Pulses recorded with V1742 CAEN digitiser (DRS4 chip), 5 GS/s, bandwidth 500 MHz

LAPPD front view (detail around SPACAL area, in red)



- Front SPACAL module is positioned to cover approximately 4 pixels of the LAPPD
  - Side of SPACAL module is about 4.5 cm while LAPPD pixel pitch is 2.5 cm
- Module is tilted by 3°+3° in the horizontal and vertical plane
  - SPACAL not well suited for measuring 0° particles due to longitudinal scintillating crystals (the spaghetti)

LAPPD front view (detail around SPACAL area, in red)



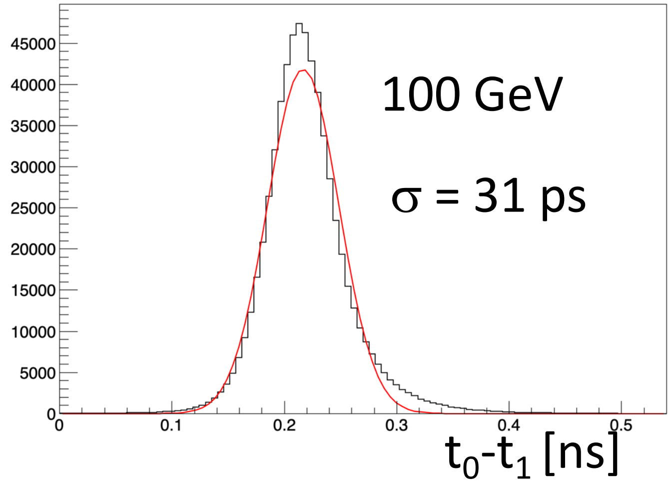
- Different runs are taken to scan the surface of the 4 pixels behind the front SPACAL half module

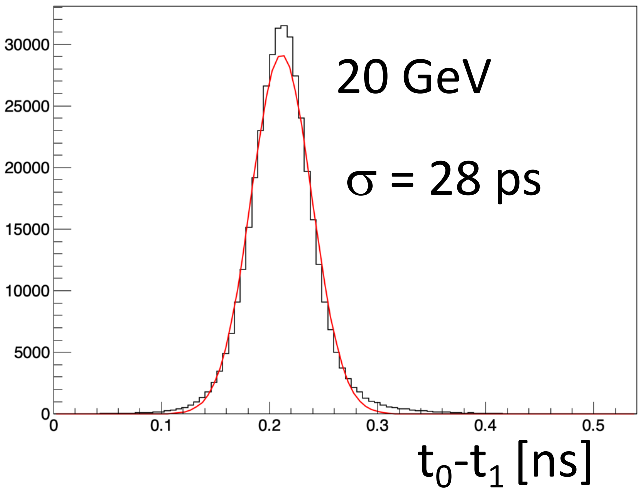
Voltage settings

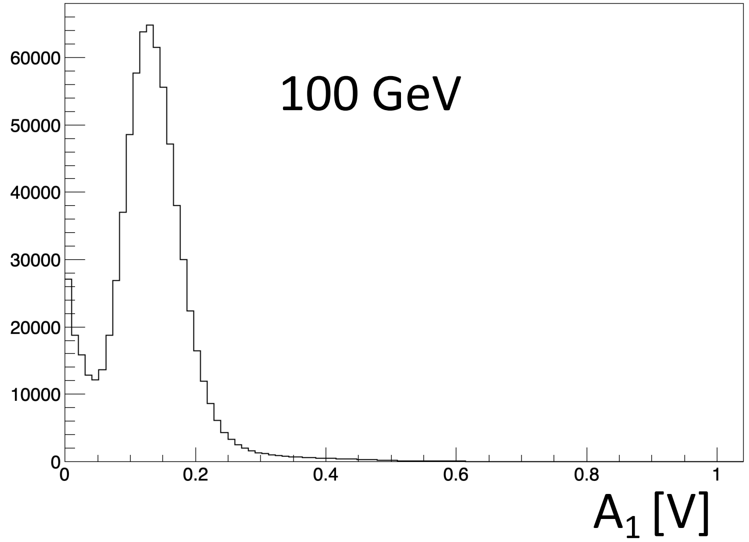
- All runs have been acquired with the following LAPPD voltage settings:
  - 500 V between internal anode and exit of bottom MCP
  - 400 V for bottom MCP (lower voltage due to instability of this MCP at higher voltage)
  - 200 V in the gap between bottom and middle MCP
  - 850 V for middle MCP
  - 200 V in the gap between middle and top MCP
  - 850 V for top MCP
  - Inverse bias of 10 V between PC and entry of top MCP, used to inhibit electrons to migrate from PC to the multiplication stage (although QE was extremely low anyway)

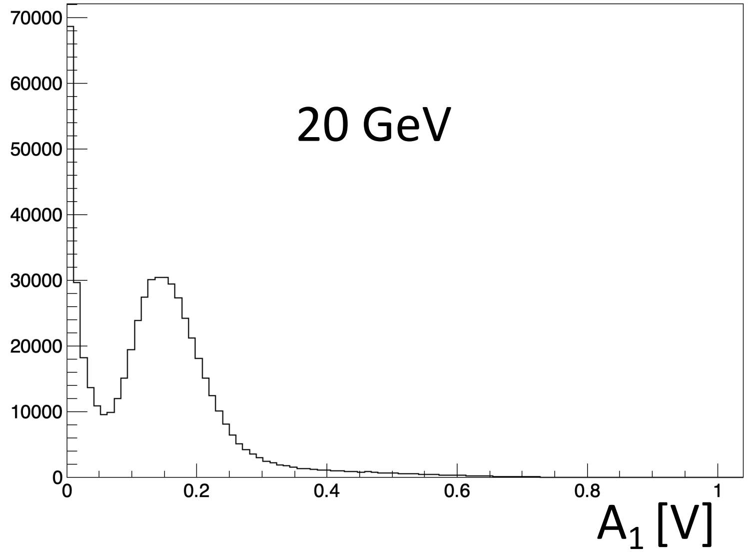
Time reference

- Two MCP-PMTs are used as time reference
  - Their amplitude is required to be between 50 and 800 mV, to ensure electrons produced good signals (beam spread) in the MCP-PMTs and to avoid saturating the digitiser dynamic range
  - The time average of the two is used as reference time
    - Resolution of reference time determined from the width of the distribution of time difference between the two MCP-PMTs







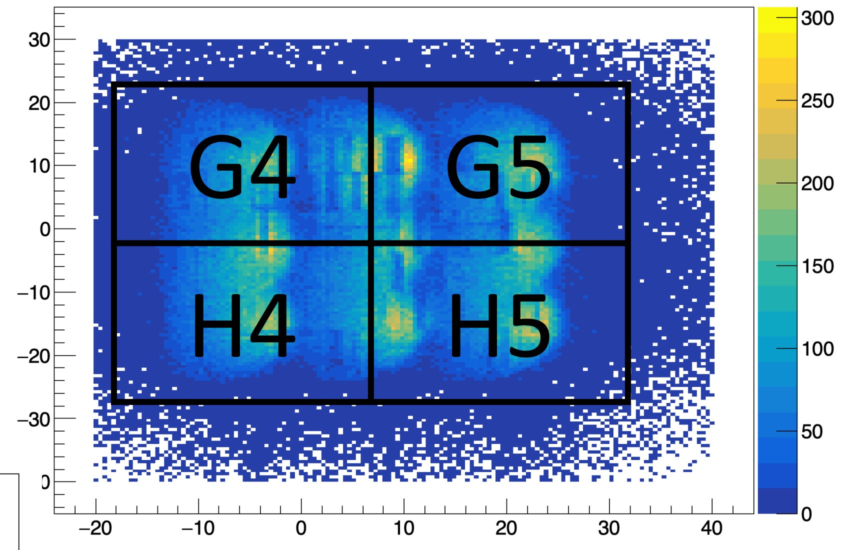


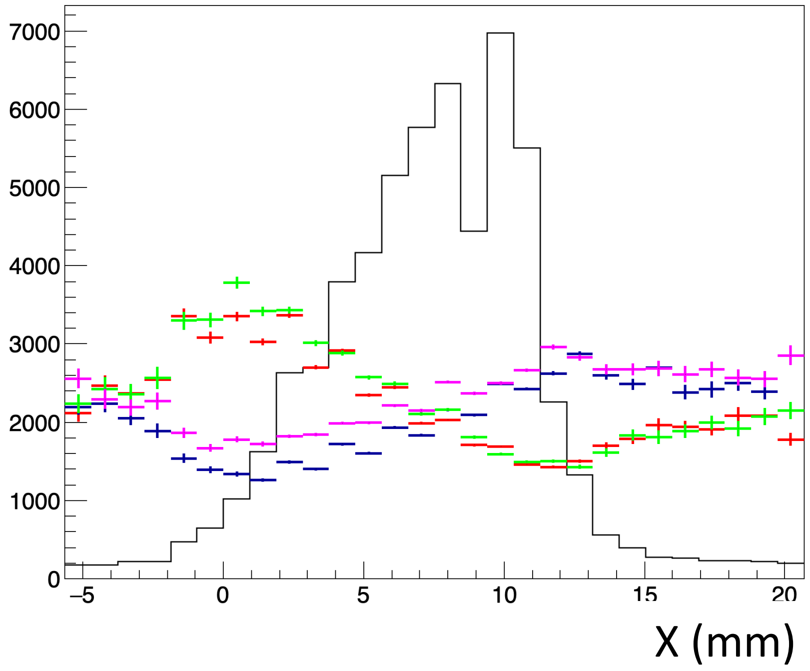
Resolution of reference time between 14 and 15 ps

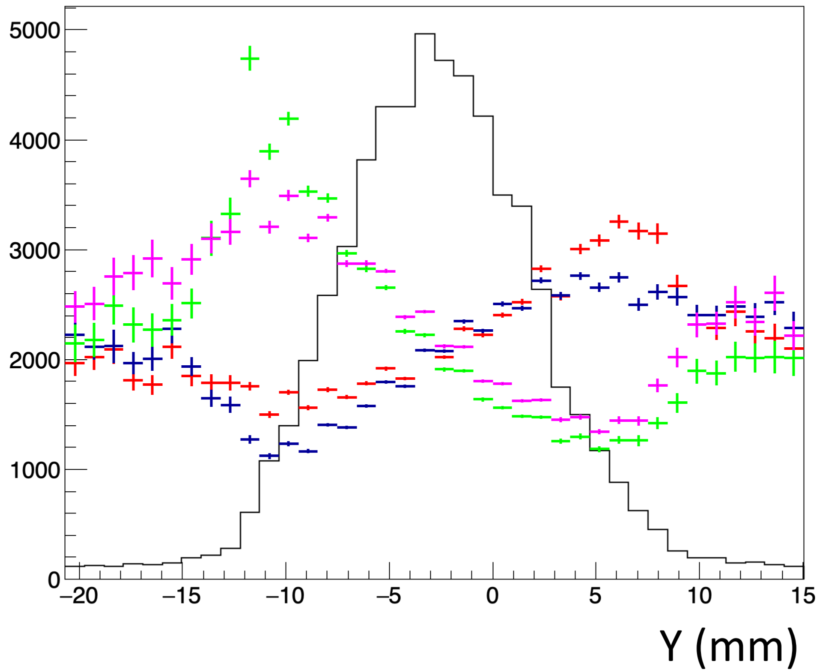
Alignment of beam with pixels

- Position of incoming electrons measured using the DWCs
- Correspondence of signal amplitude of the LAPPD pixels and beam position
  - E.g., plots below correspond to a run with beam towards the crossing of the four pixels
    - Average amplitude of the pixels is coherent with the beam position
    - G4 average amplitude increase toward lower X and higher Y

e$^-$ at 100 GeV/c







G4 average amplitude

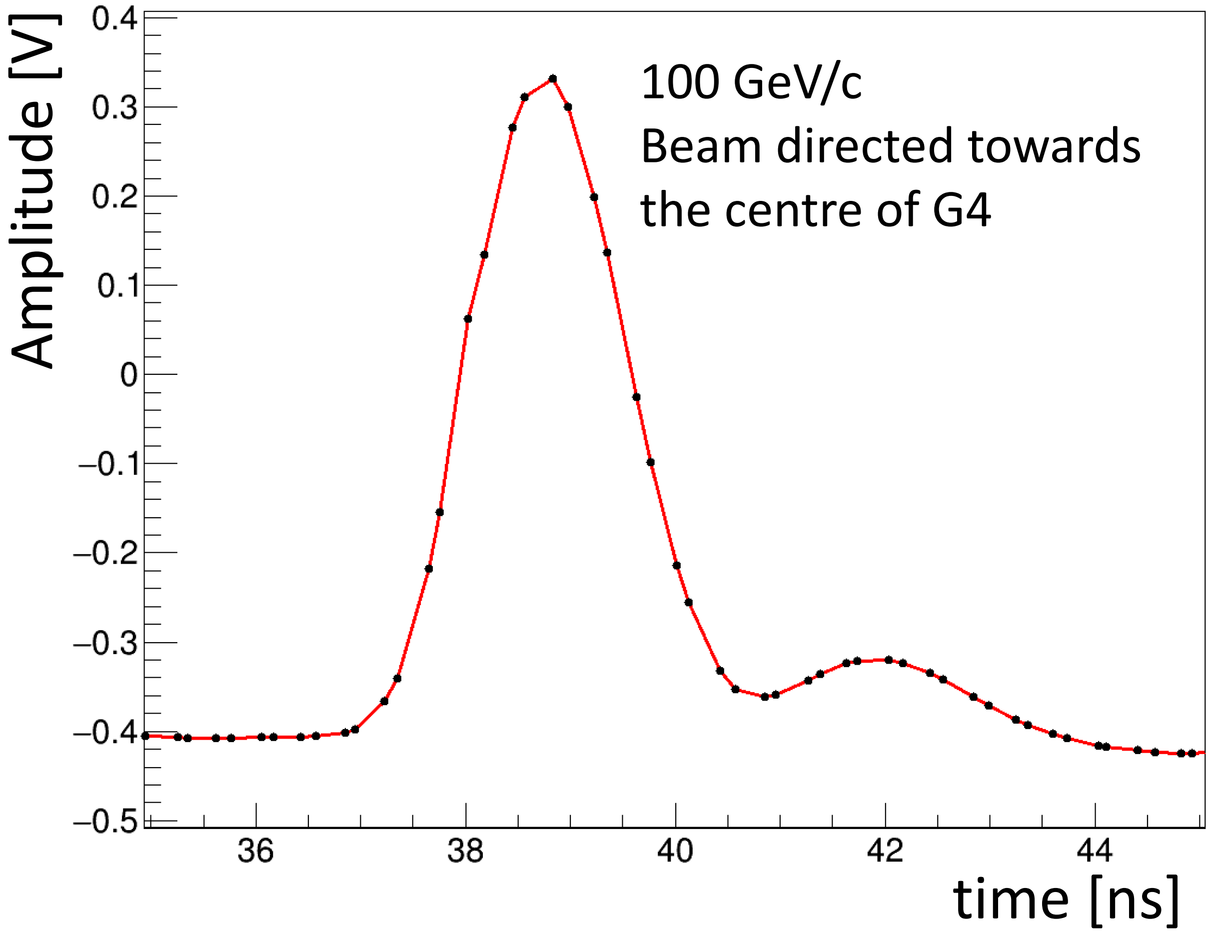
G5 average amplitude

H4 average amplitude

H5 average amplitude

Typical LAPPD signal

- Rise time between 10 and 90% measured in CERN SPS data to be about 1.1 ns
- Full width at half maximum of signal shape is about 1.7 ns

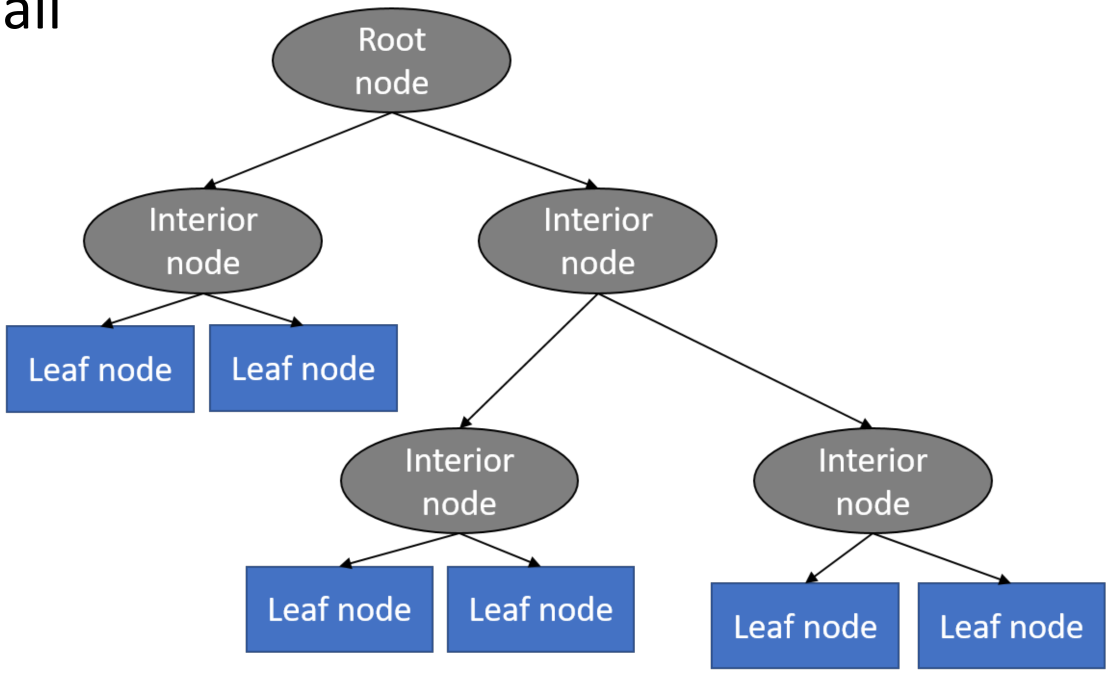


Problem: how to combine measurements of various pixels

- How to obtain optimal timing measurement if, as it is true in general, an electron can hit whatever point of the ECAL (and thus LAPPD) surface and release signals in multiple LAPPD pixels?
- Furthermore, LAPPD pixels are rather large in our case (2.5 cm pitch), so combination of multiple measurements can be important to achieve good uniformity, independent of how the charge wave develops on the internal anode
- In principle, one could try to model how the charge develops on the internal anode and thus how the signal is induced onto the pixels, but this is very complicated to do without a full-fledged simulation
- We thus tried with a multivariate approach for now

GBDT multivariate analysis

- Use gradient boosted regression trees to combine all information contained in the signals of the 4 pixels and the coordinates measured by the DWCs to obtain one “average” time-stamp
  - Easy to understand, do not require particular data cleaning, have a small number of parameters to tune
  - Prone to overtraining, but it can be easily checked

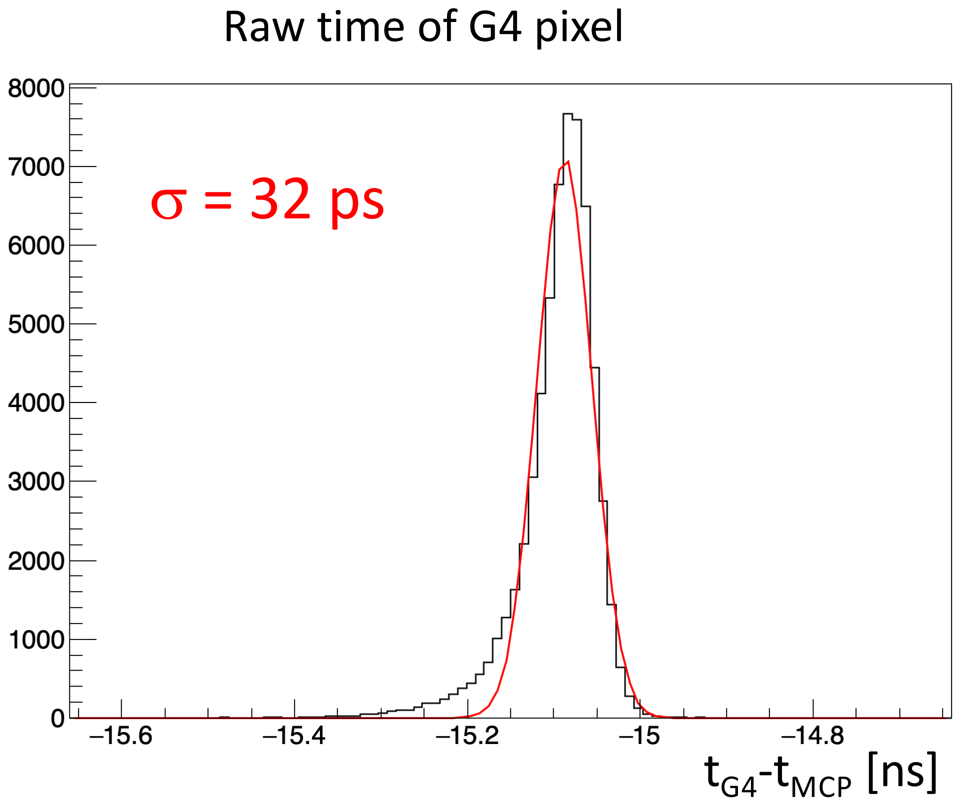


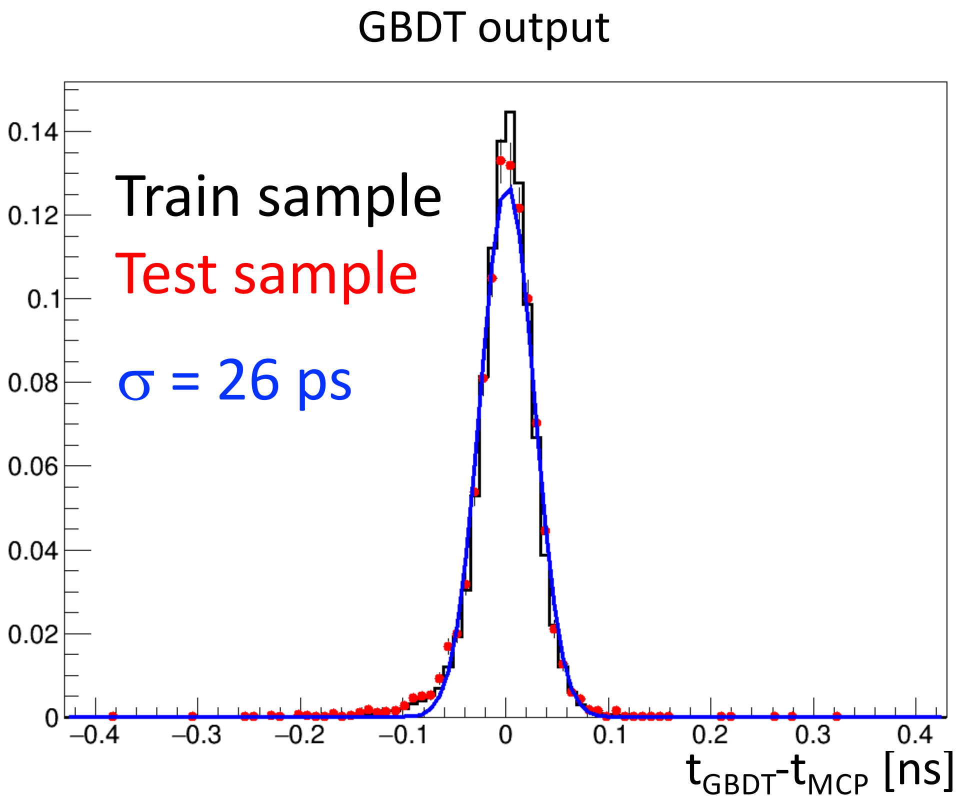
- Basic functioning
  - The training sample is split in two (nodes) in order to minimise the variance of the target variable (time stamp) in each subsample
  - Splitting is repeated until no further improvement is observed for the variance, defining a set of ”leaves”
  - To any event falling into the hypercube defined by a leaf, the average of the target variable inside that leaf is associated

Application to our case

- Training of regression tree on a training sample
  - Input variables: timestamps, amplitudes, rise times and FWHM of the four pixels plus the coordinates provided by the DWCs
  - Target variable: reference time of MCP-PMTs
  - Training sample and test samples kept separate to estimate possible overtraining effects
- Preliminary study presented in the following slides for 20 and 100 GeV electrons only
  - All timestamps calculated by two-point interpolation at 50% constant fraction

Example: 100 GeV beam towards centre of G4

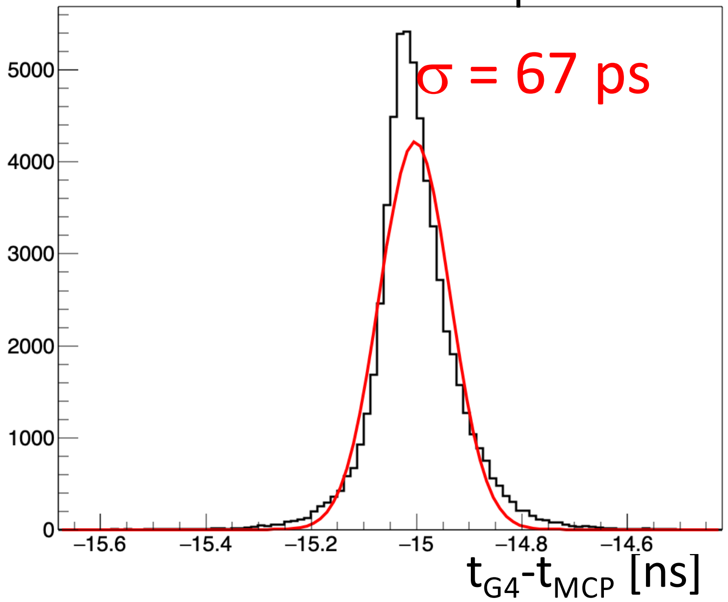




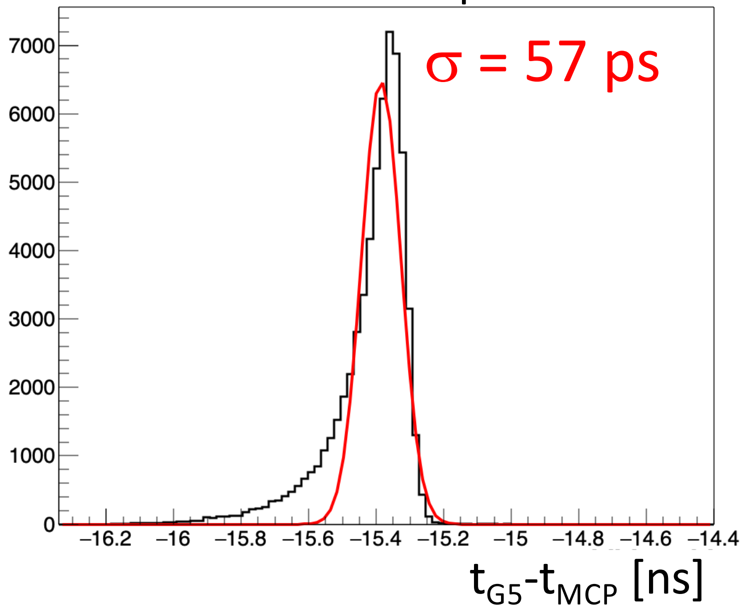
- Asymmetric raw time measurement by single pixel mostly due to beam spatial distribution
- Action of the GBDT is able to symmetrise and improve the resolution
- Once the resolution of reference MCPs is subtracted, the final time resolution from the GBDT in this example is about 20 ps

Example: 100 GeV beam towards crossing of four pixels

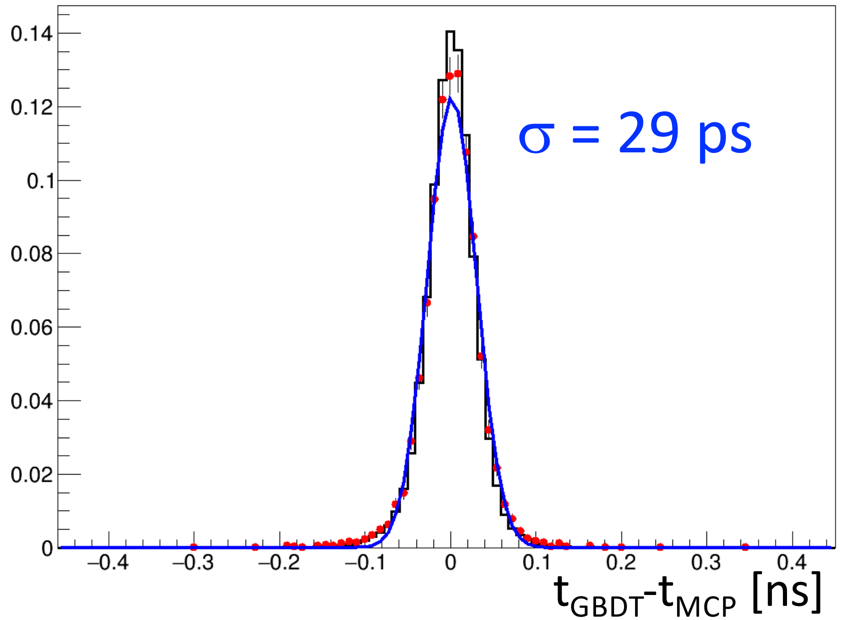
Raw time of G4 pixel



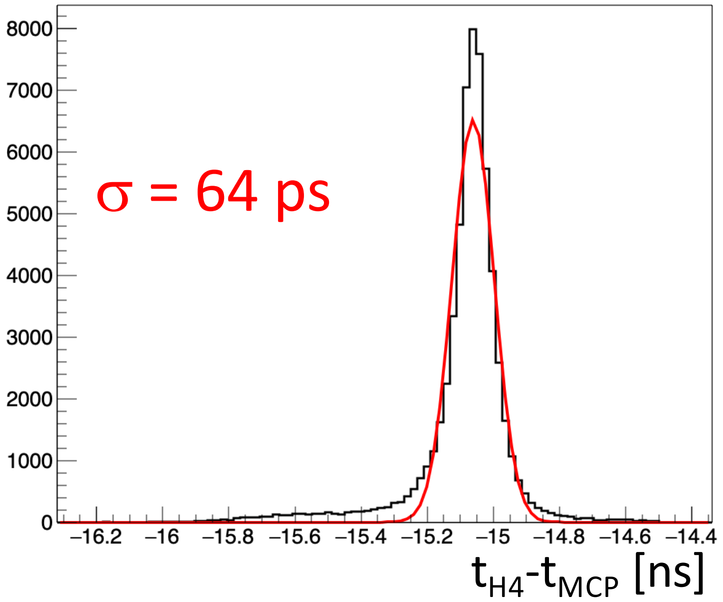
Raw time of G5 pixel



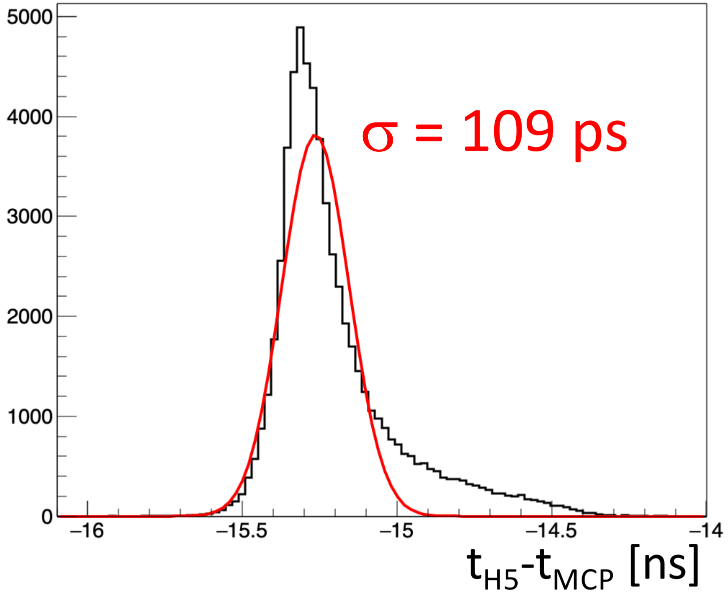
GBDT output



Raw time of H4 pixel

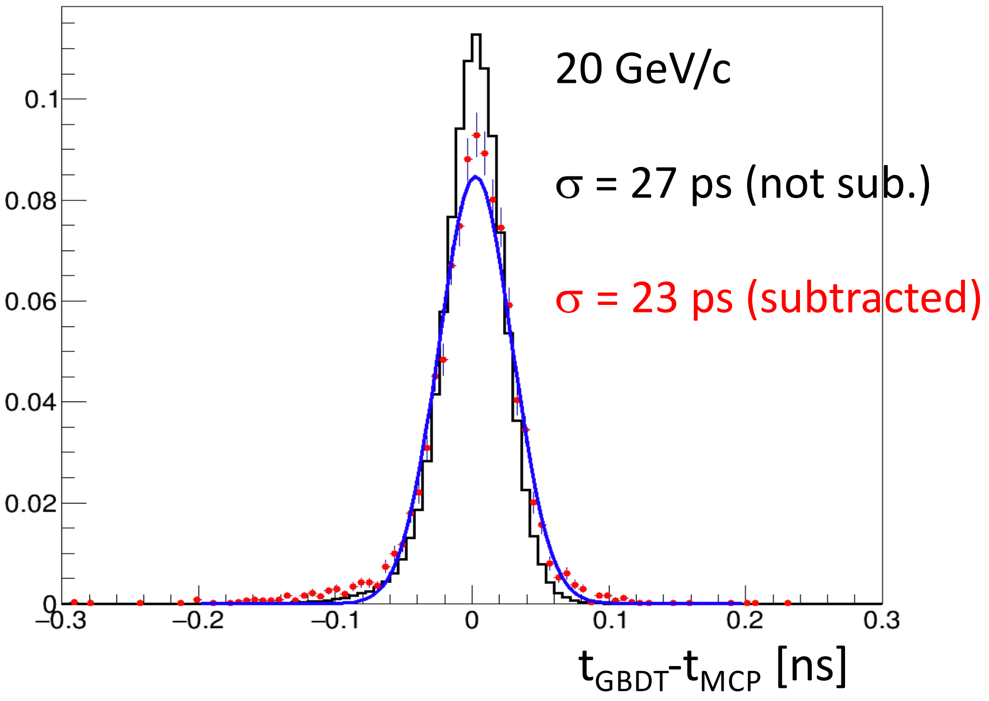


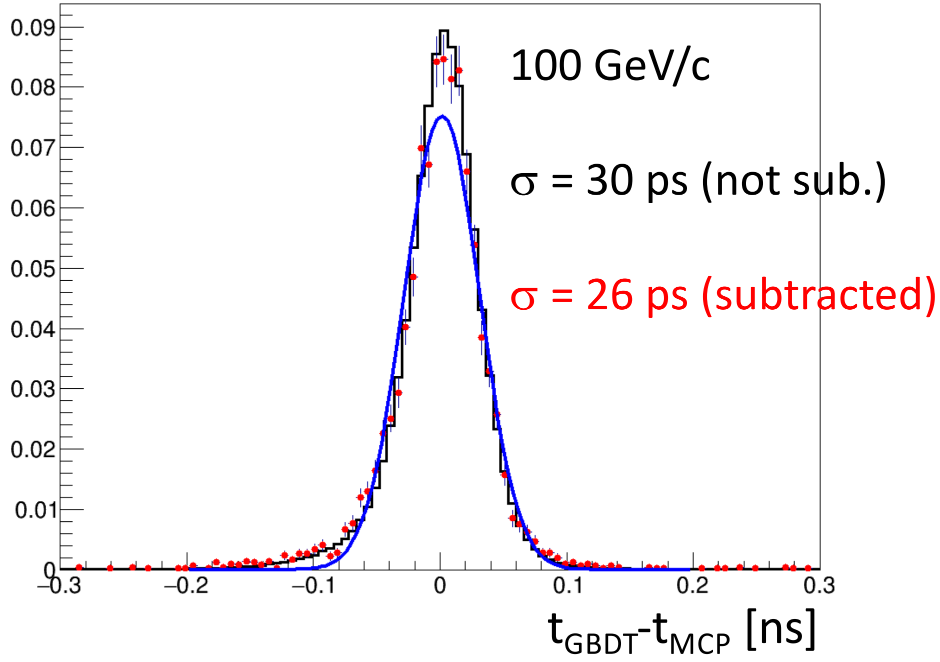
Raw time of H5 pixel



- GBDT result symmetric and much better than single pixels
- Once the resolution of reference time is subtracted, the final time resolution is about 24 ps

Training the BDT on all runs together



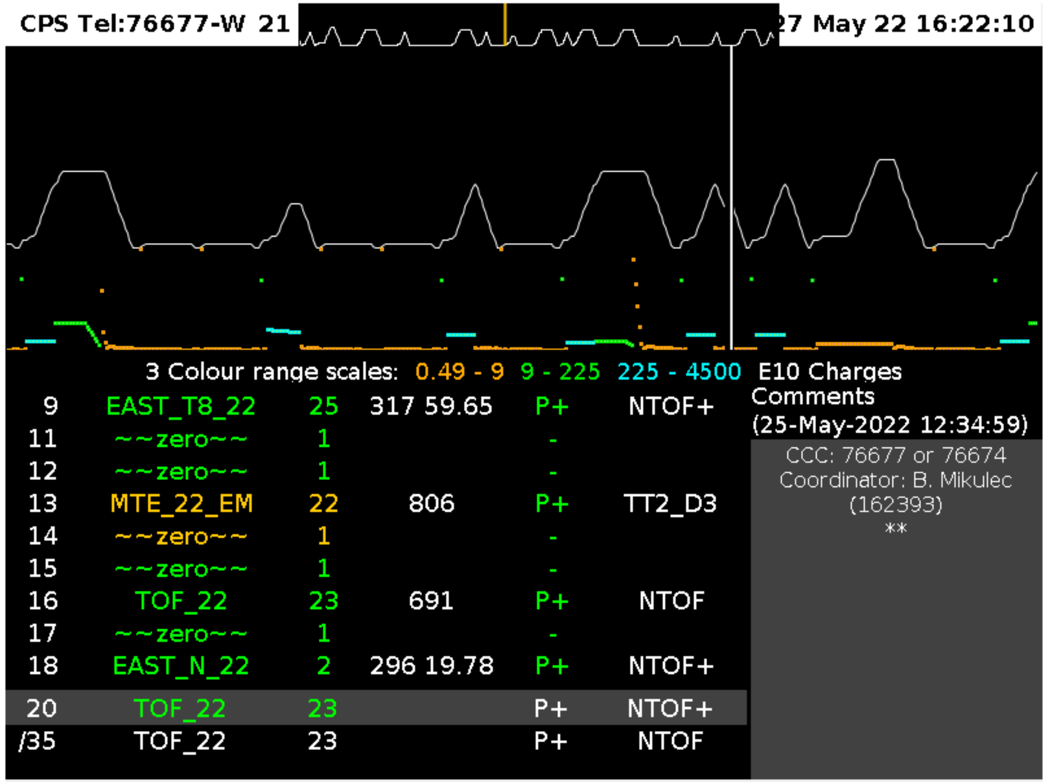


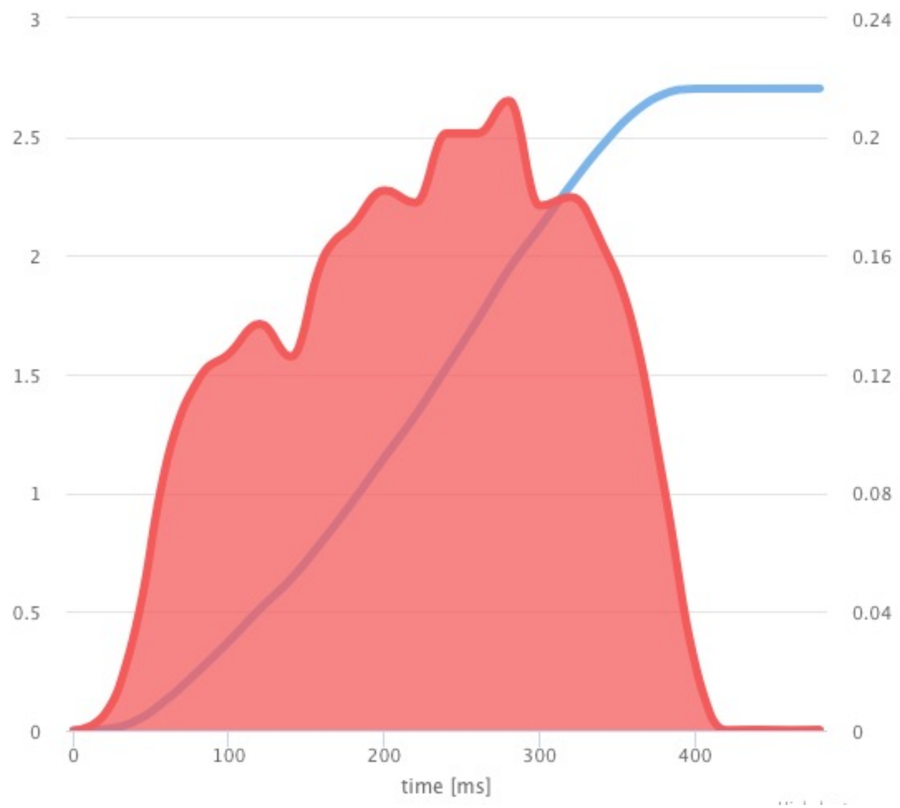
- Little amount of overtraining in 20 GeV data (larger beam spread and lower statistics of training sample)
- In either case, by the use of the GBDT we are able to combine all measurements and obtain an improved (with respect to single LAPPD pixels) and symmetric time resolution
- Although pixels are rather large in our case, the combination of information from the various pixels allow a good timing resolution to be achieved
- Work still very preliminary → room for further improvements

Irradiation tests at CERN IRRAD

IRRAD parameters

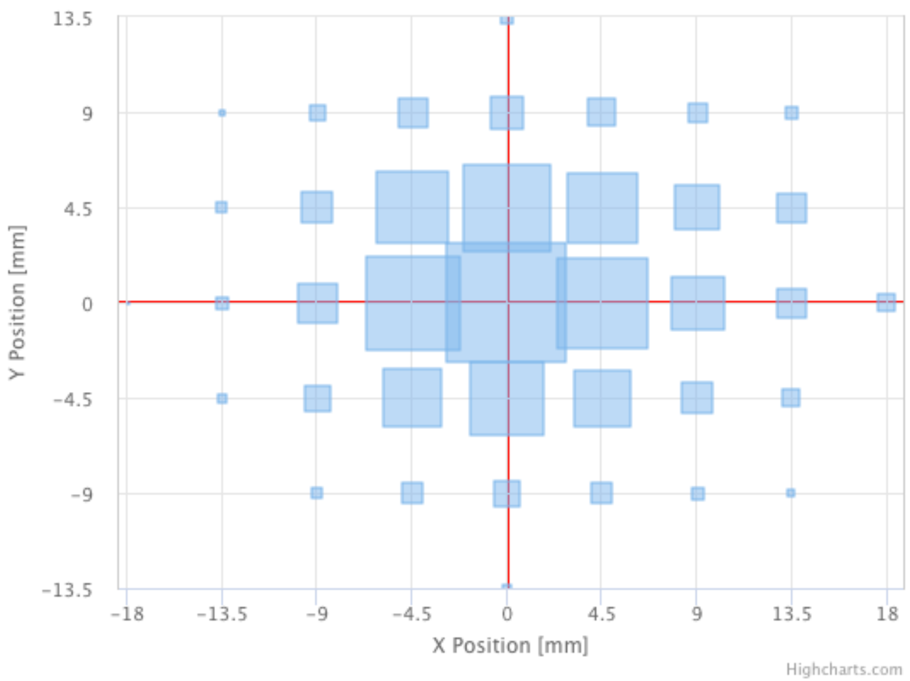
- The facility provides a beam of 24 GeV protons extracted from the CERN protosynchrotron (PS)
- Protons are organized in spills, about 5×10^{11} protons per spill, each spill lasting about 400 ms, with one spill every 12 s (on average)

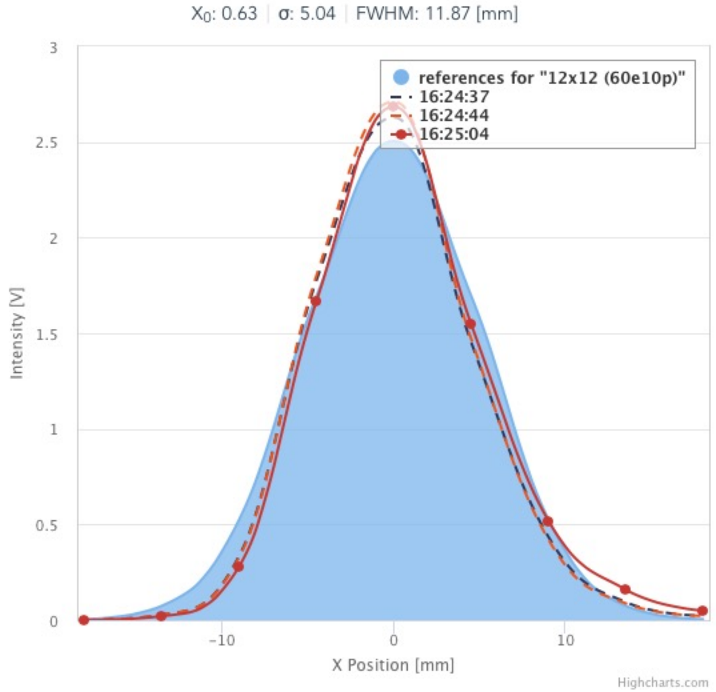


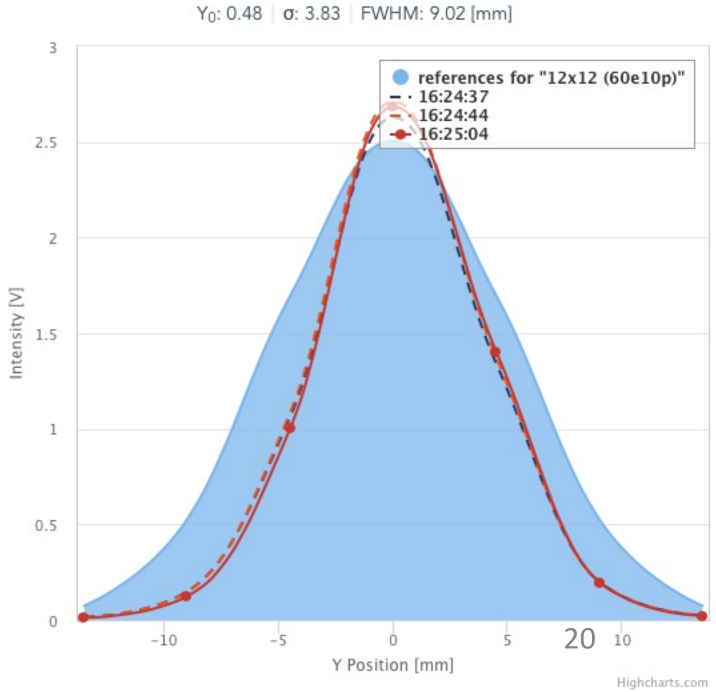


IRRAD parameters

- The proton beam has a spread of about 1 cm (FWHM) in both X and Y
- With 5 spills per minute, the total number of protons in one day is approximately
  $5 \times 5 \times 10^{11} \times 60 \times 24 = 3.6 \times 10^{15}$
- Accounting for machine dead time, 10^{16} protons could be integrated in about one week of run
  - June/July 2022
  - Roughly corresponding to 5×10^{15} 1MeV neq.

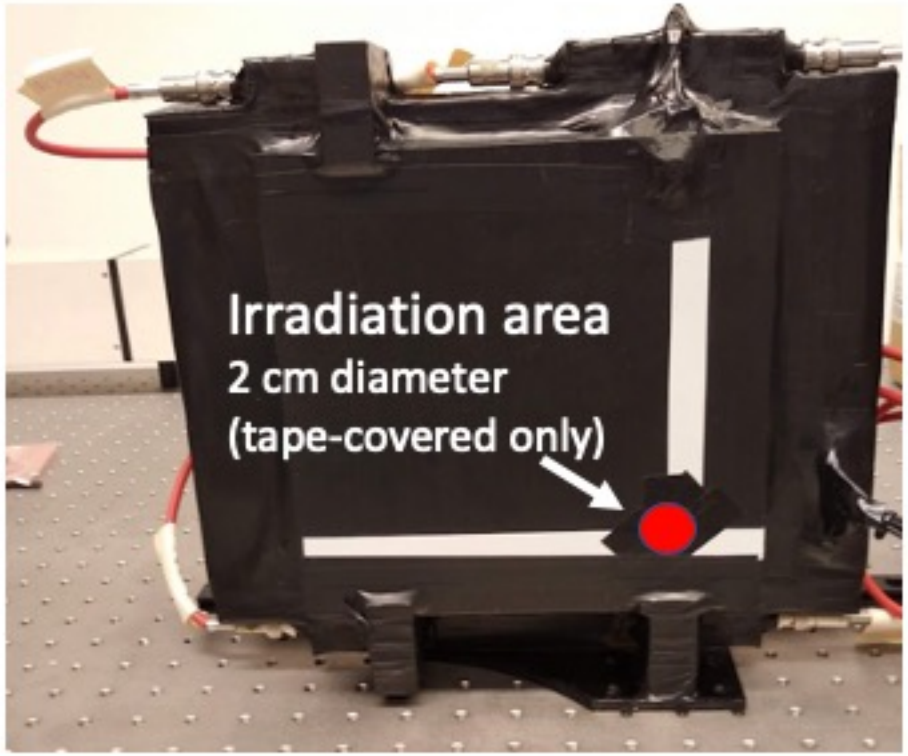


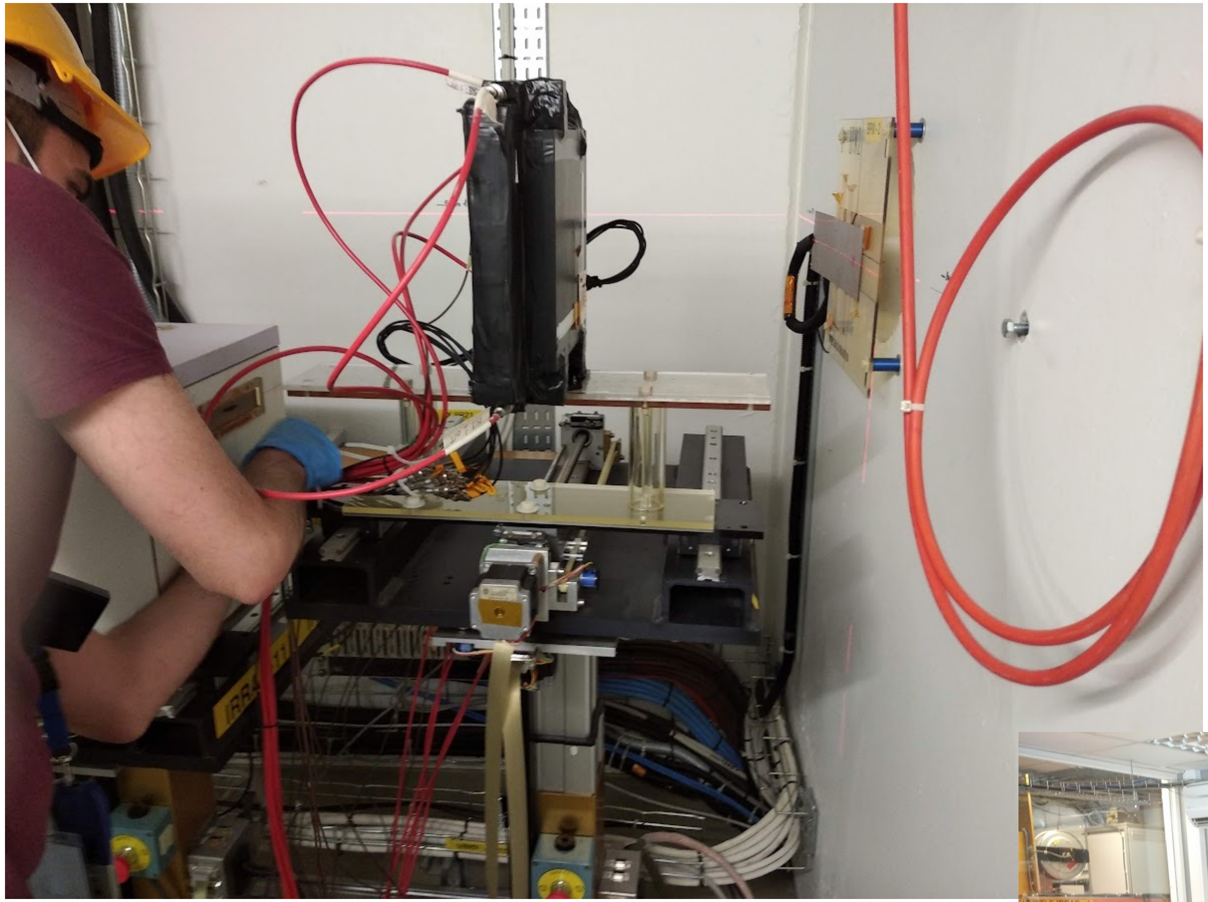




LAPPD #119 irradiation setup

- 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
- 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

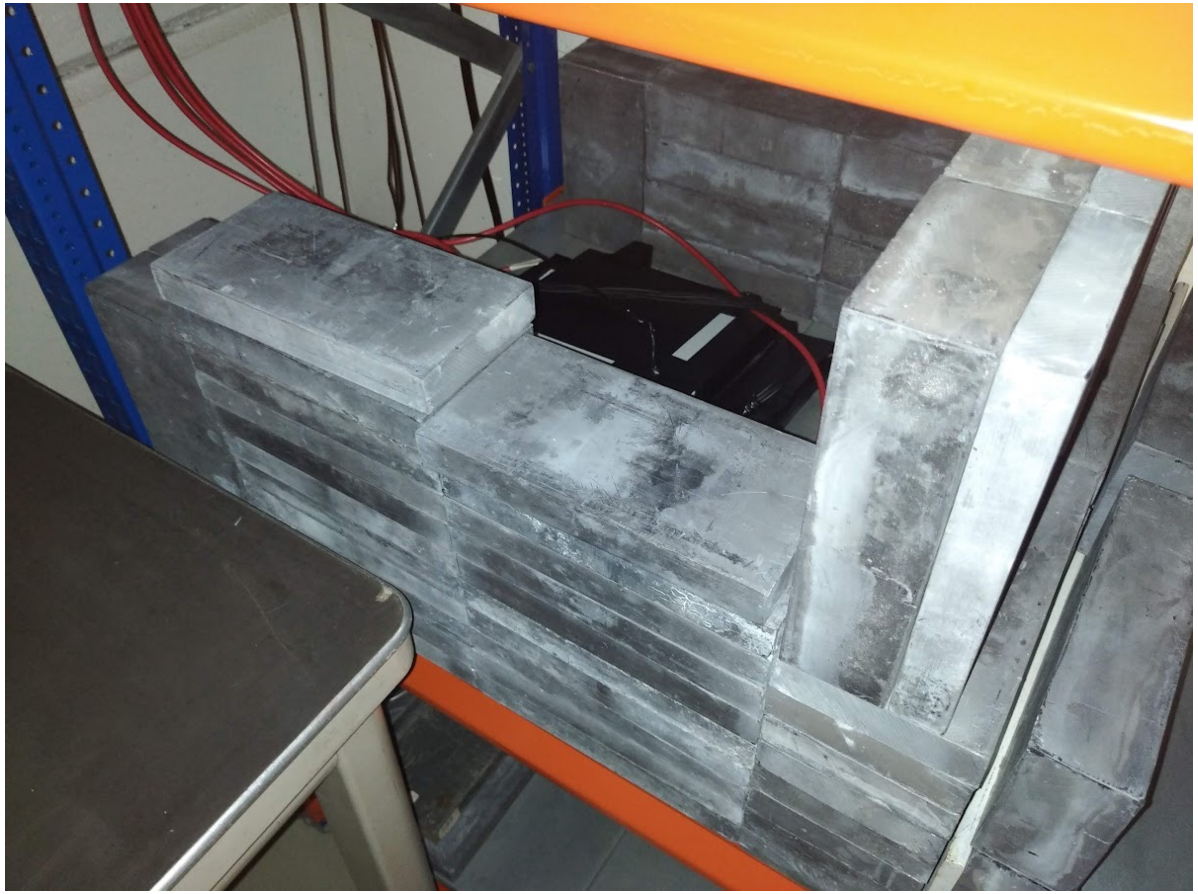




Shift crew not dramatically motivated while waiting for dose accumulation…

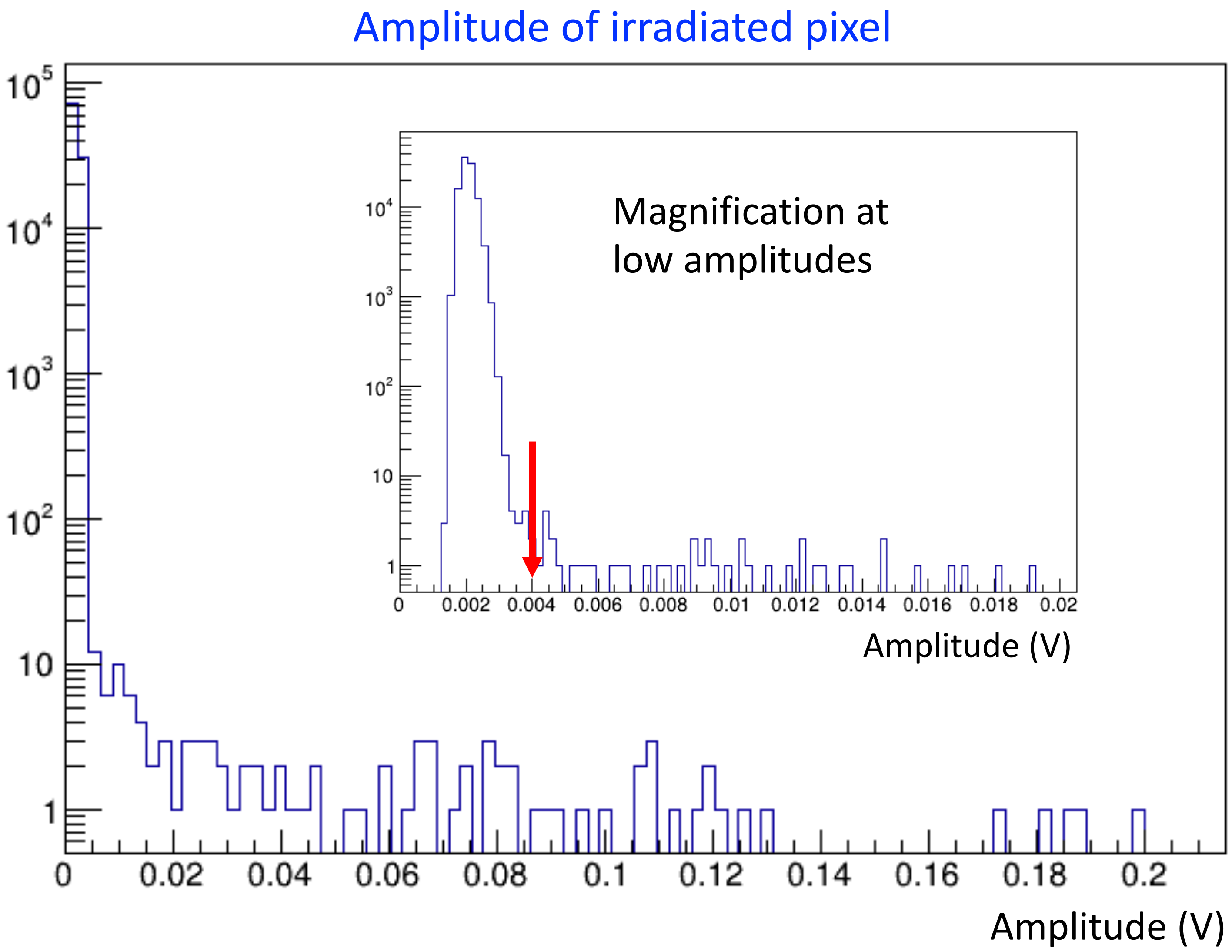
Bad boss

Then LAPPD moved to storage area to cool down and measure dark rate and gain over the summer



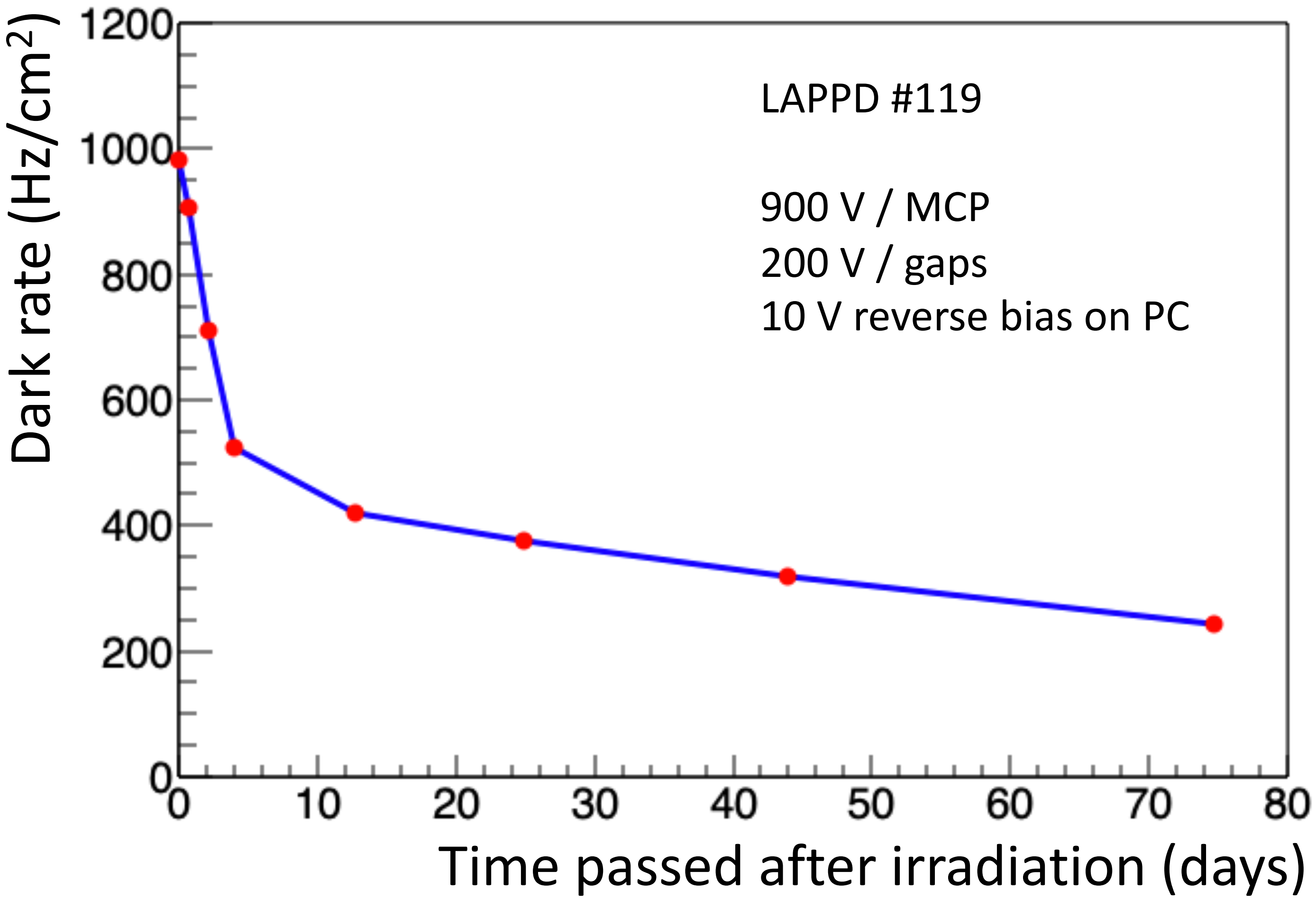
Dark counts right after irradiation

- Settings
  - 900 V/MCP
  - 200 V/gaps
  - 10 V reverse bias on PC
- A cut at 4 mV enough to get rid of empty events and measure dark rate



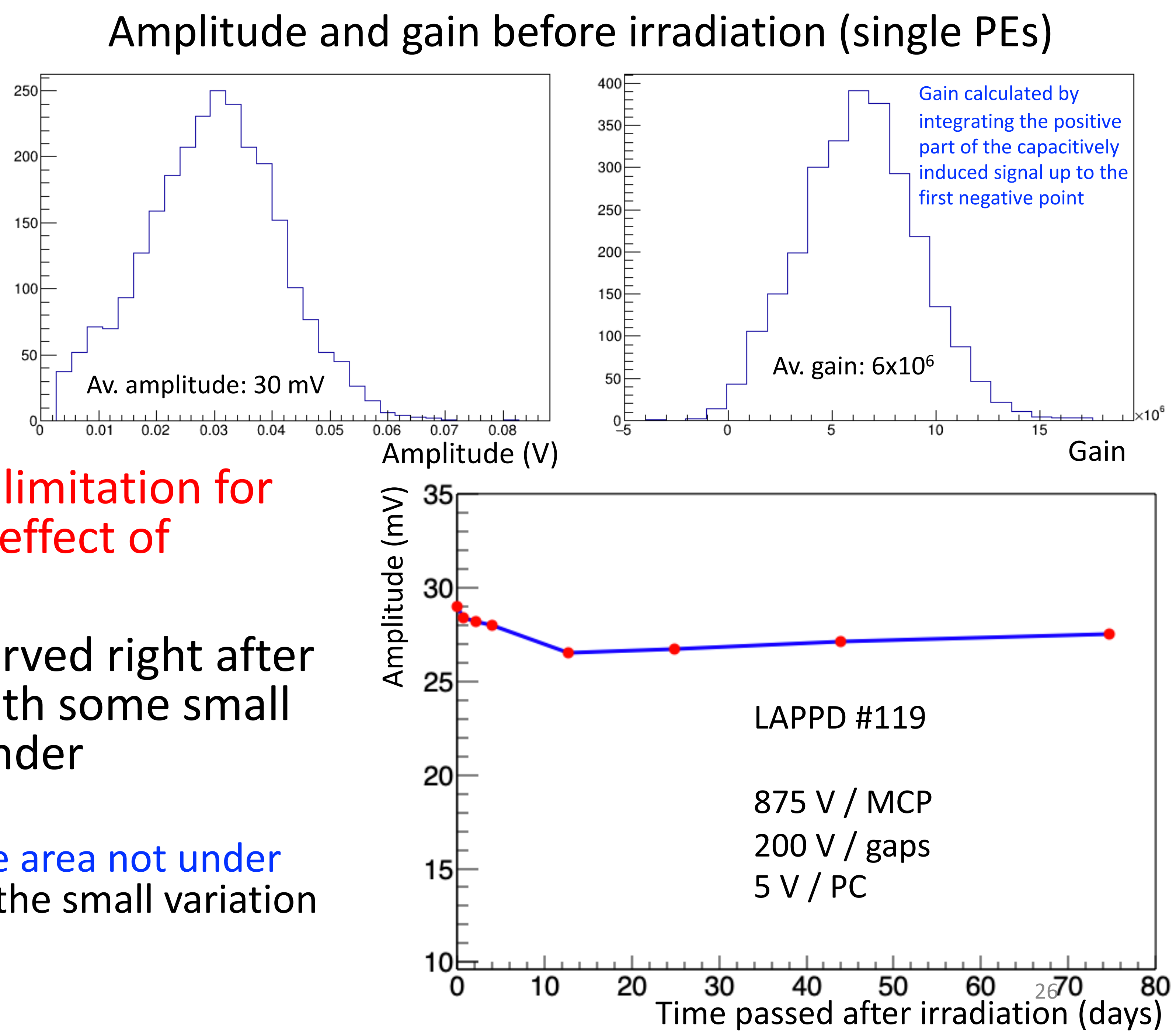
Dark counts: results

- 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



Gain variation

- LAPPD #119, used for such a destructive test, was unstable for high PC voltages, so gain was measured with low PC voltage
- However, qualitatively not a limitation for the purpose of studying the effect of irradiation
- Slight reduction of gain observed right after irradiation (30 → 29 mV), with some small variation over the 75 days under observation
  - Temperature in IRRAD storage area not under control → our best guess for the small variation observed over time



IRRAD summary

- Irradiation of 10^{16} protons (24 GeV) in about 1 cm^2
  - Equivalent to roughly $5x10^{15}$ 1MeV neq.
- Increase in dark rate from MCPs significant, but not to worrying levels
  - E.g., still below average dark counts from PC, when activated
- Decrease in single PE gain almost insignificant
- Note: we didn’t measure the QE loss, as not very significant for this kind of test, and not relevant for our purposes
  - i.e., PC-less MCPs for electromagnetic showers timing
- Warm thanks to the CERN IRRAD staff, in particular Federico Ravotti and Giuseppe Pezzullo for their invaluable support

Lifetime tests in vacuum chamber

Reminder: MCP lifetime tests in vacuum chamber

- A stack of MCPs is placed inside a vacuum chamber whose upper flange is equipped with a viewport
  - High quality fused silica with cut off well below 200 nm
- A mercury lamp is placed on top of the viewport and its light is used to trigger the extraction of primary electrons from the MCPs
  - UV light (in particular a line at 185 nm) leads to low but nonzero quantum efficiency for electron emission from MCP surface
- Electrons are then multiplied by the MCP stack and the charge is collected by a metallic anode placed below the stack, which is read out
  - Very high currents can be reached this way, thus allowing for large emitted charge to be accumulated
- A Chevron stack of two round MCPs is used, each of 33 mm diameter
  - 25 mm active area once electrodes and separators are put in place
- See also LAPPD workshop on March 2022 → showing final results today

Experimental setup

Mercury lamp inserted in top hat

Top flange with viewport

Vacuum chamber

Heating tape

HV flange

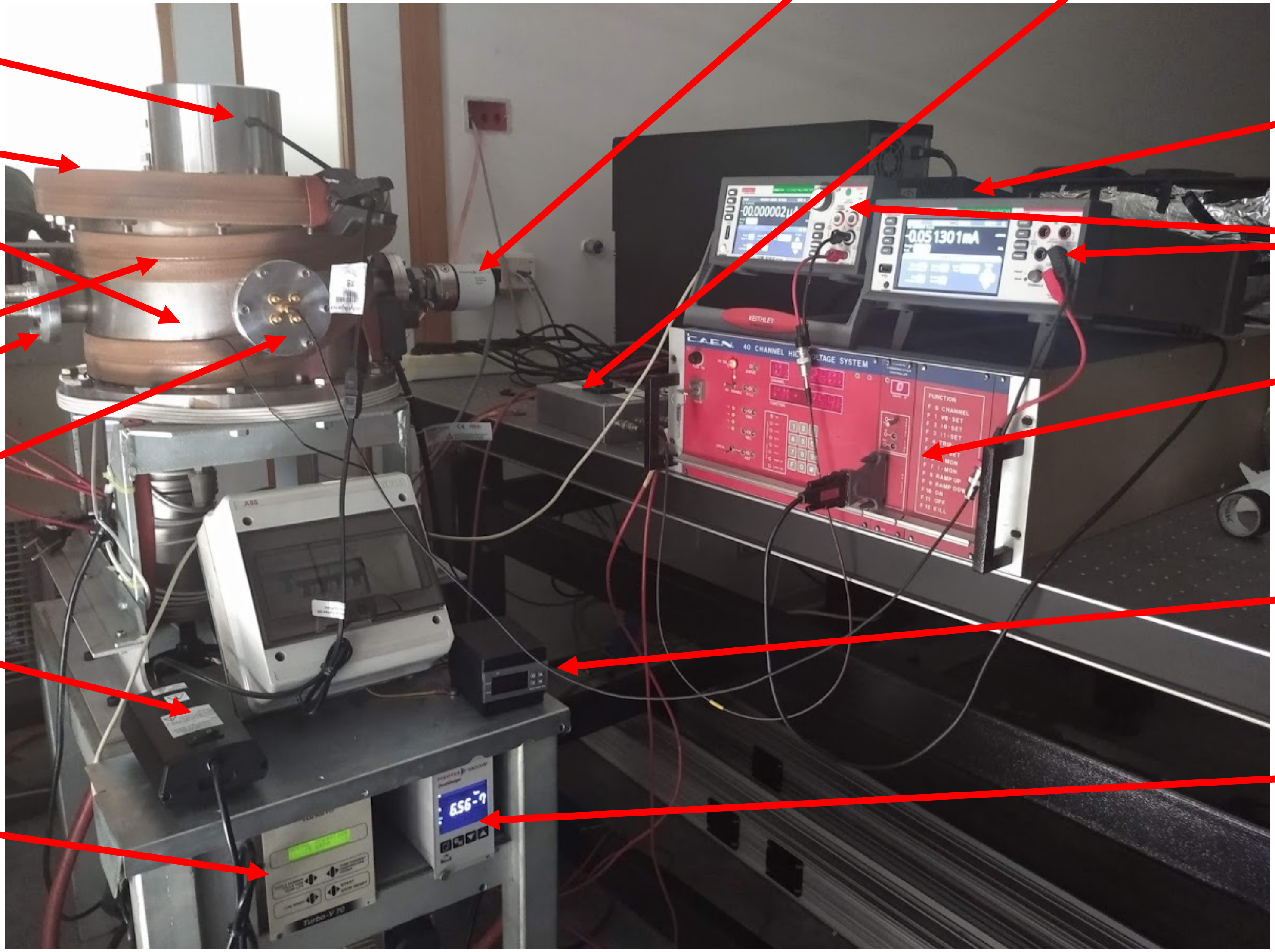
Signal flange

Mercury lamp power supply

Turbo pump controller

Vacuum gauge

Selector to switch between gain measurements and high-current settings



Mini PC for data acquisition and control

Multimeters

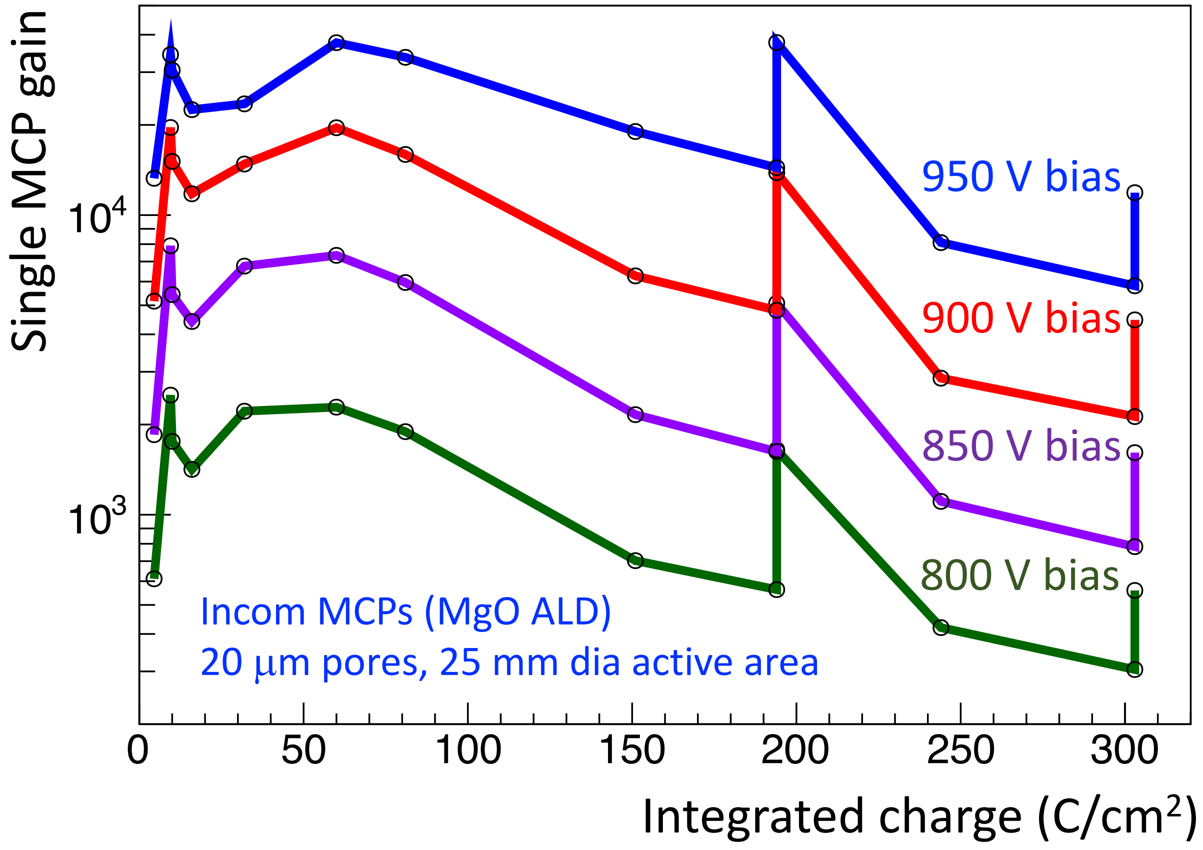
HV power supply

Thermostat for heating tape

Vacuum gauge controller

Results of lifetime campaign

- Measurements are represented by circles
  - Continuous lines are just joining the data points
- Discrete jumps at 200 and 300 C/cm^2 are because for those two points we repeated the gain measurement after turning off the UV light for about a week
  - Leaving the MCPs at rest they recover part of the lost gain, but then as apparent from the point at 250 C/cm^2, the gain goes back to the previous trend after some time
    - Looking at the anodic current plot, not shown here, it appears to happen within about the subsequent 30 C/cm^2
- Note that the MCPs were not pre-conditioned before being inserted into the vacuum chamber for the measurements
  - E.g., no preheating to remove water film and other impurities
  - Used as they were out of the factory and after delivery



Conclusions

- Preliminary results from first Gen-II z-stack presented
  - Very encouraging, expect some improvements wrt what shown today
  - New z-stack just delivered → will be tested at SPS commencing next weekend
- Irradiation measurement with 24 GeV IRRAD protons of Gen-II LAPPD
  - Reached 10^{16} protons in one cm^2
  - Some (non worrisome for us) increase of dark rates and basically no impact on gain
- Final results of MCP lifetime campaign with UV light
  - Reached 300 C/cm^2
- Support from Incom staff is always greatly appreciated!