LAPPD studies for ePIC

Testbeam 22, magnet 23

Jinky Agarwala[1], Deb Sankar Bhattacharya[1], Chandradoy Chatterjee[1], Silvia Dalla Torre[1], Mauro Gregori[1], Alexander Kiselev[2], Saverio Minutoli[3], Mikhail Osipenko[3], Richa Rai[1], Fulvio Tessarotto[1]

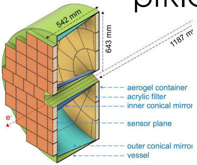
[1]INFN Trieste [2]BNL [3]INFN Genova

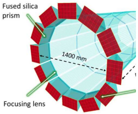
remote

Why studying LAPPDs/HRPPDs?

- HRPPDs are baseline photosensors in pfRICH (also hadron ToF),
- HRPPDs are alternative photosensors in hpDIRC,
- LAPPDs were considered as backup option for dRICH.

pfRICH





hpDIRC

Requirements to validate:

1. good SPE timing ($<$100 ps),
2. operation in B$<$1.5 T field,
3. low aeging ($>$10 C/cm^2).

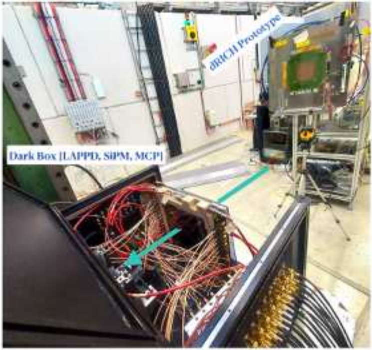
Pros:

- cost: 26 k\$/400 cm^2=65 \$/cm^2 (10 times less than SiPM),
- low DRC: few kHz/cm^2 (10 times less than SiPM),
- capable to high rates MHz/cm^2 (HRPPD), radiation hard, no cooling.

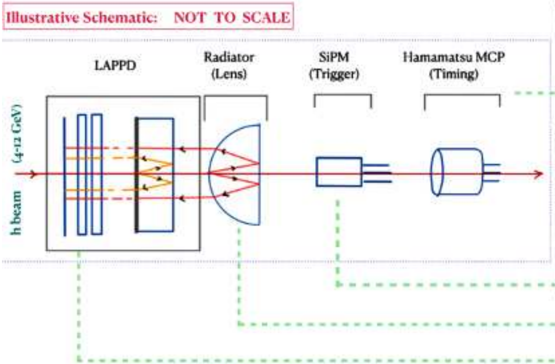
Experimental hall at T10 beamline Oct. 2022

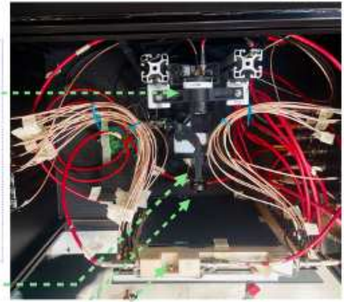
CERN PS, Hall T10

LAPPD installed downstream of dRICH prototype



Measurement setup

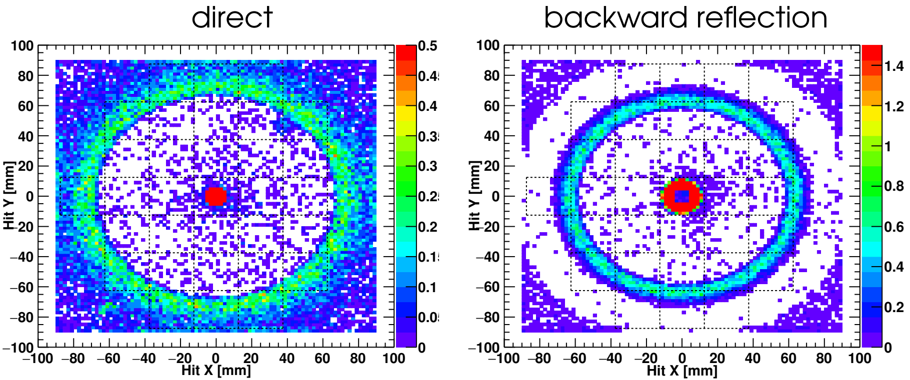




LAPPD window is covered by a protection card in this picture.

Geant4: direct vs. backward reflection

- direct configuration gives broad ring (11 p.e./pad),
- backward reflection gives narrow ring (12 p.e./pad),
- beam spot is larger for backward reflection,
- LAPPD 124 geometrical open area ratio 64%, but at 800 V PE collection efficiency of <50 % is expected.



Trigger SciFi+SiPM and reference MCP

Hamamatsu MPPC SiPM (S13360-6025CS)

Scintillating fibers
Kuraray 3HF(1500)MJ
diameter = 500 μm
array = 10×10

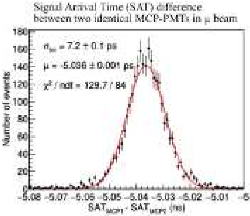
SiPM = 6×6 mm²
gain = 10 mV/p.e
risetime = 20 ns
falltime = 100 ns

The SiPM and the Lens mount

SiPM onboard amplifier

Hamamatsu MCP-PMT (R3809U-50)

Tube diameter = 45 mm

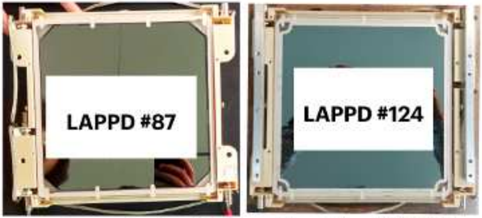


NIM A 969 (2020) 163592

Photocathode
Window = quartz, diameter = 11 mm 3.2 mm thick
Spectral response : 160 to 850 nm; peaks at 430 nm

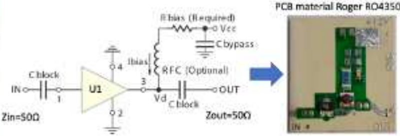
Typical Characteristics
Gain = 2 × 10⁵ ; Dark current = 10 nA
Rise time = 150 ps
Transit time = 550 ps
Transit time spread = 25 ps (RMS=10 ps)

LAPPD readout



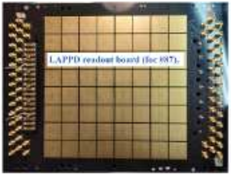
Can you spot an important difference between the two LAPPD tiles?

Custom made preamplifiers by INFN, Genova



Gain = 10 (20 dB), BW = 2 GHz, output = inverting

additional PCB for grounding anode

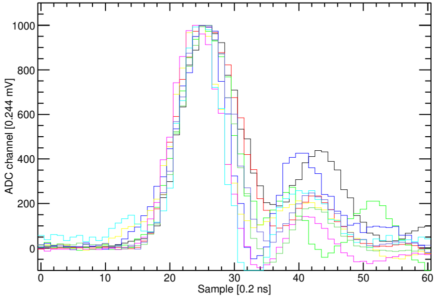


Present version comprises 8 input/output per unit

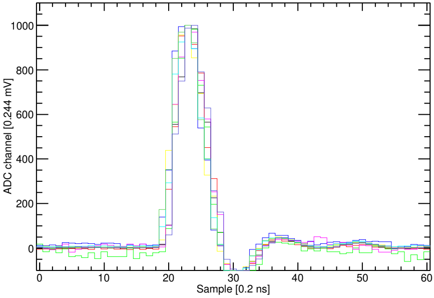
Measured LAPPD signals w.r.t. Hamamatsu MCP

- LAPPD risetime (20-80%) was about 0.75 ns,
- Hamamatsu MCP had 0.4 ns (intrinsic 0.16 ns),
- V1742 digitizer has BW=0.5 GHz →0.45 ns is its intrinsic limit on risetime (20-80%),
- LAPPD 1 inch pad has large capacitance 5 pF, assuming 50Ω load we expected 0.26 ns (coplanar parasitic capacitance 10 pF).

LAPPD

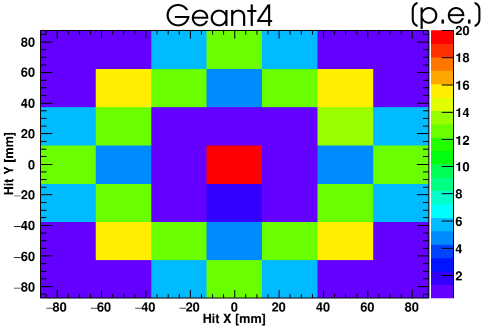


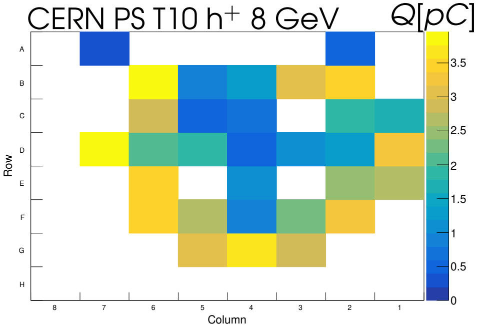
Hamamatsu MCP



Lens Cherenkov ring in UV

- in UV lens Cherenkov ring was observed at expected radius (60 mm), with expected shape,
- 3 p.e./pad were measured, Geant4: 12 p.e./pad,
- beam spot was suppressed by a factor of >100 (grease+black tape on the window),
- 32 channels were barely sufficient to cover entire ring.

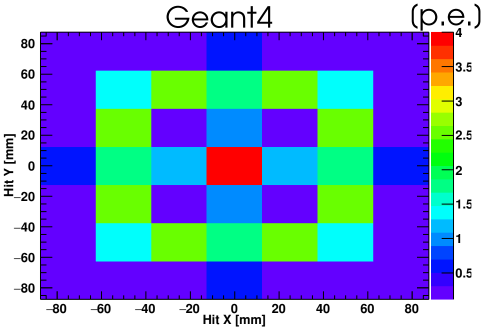




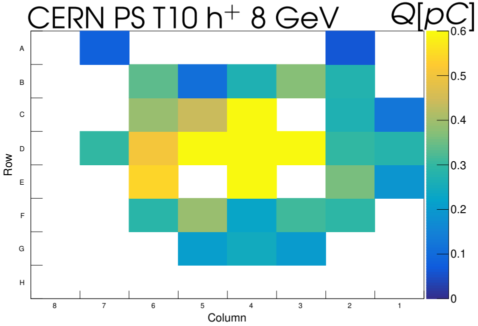
beam spot 180 p.e.

Lens Cherenkov ring in Visible

- in visible narrower lens Cherenkov ring was observed,
- 0.5 p.e./pad were measured, Geant4: 2 p.e./pad,
- beam spot suppression degraded by a factor of 10 (next day, after few opening of the box).
- signal delay in ring w.r.t. beam 0.5 ns, as expected.



beam spot 180 p.e.

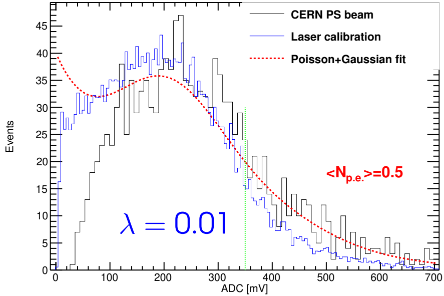


beam spot 6 p.e.

LAPPD SPE charge calibrations

- Laser SPE calibrations agree with beam-on spectra in Cherenkov ring pads,
- LAPPD N.124 at 800/900 V should have gain of 4×10^6, expected SPE at 1.28 pC,
- the observed SPE peak at 1.15 pC, in agreement,
- using laser calibration data estimated CERN $N_{p.e.}$=0.5 (80% at 1 p.e., 2 p.e. timing RMS broadening of 1.5%).

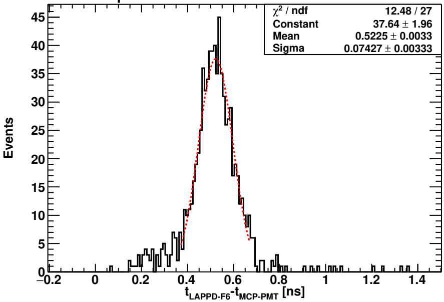
Laser SPE calibrations vs. testbeam data



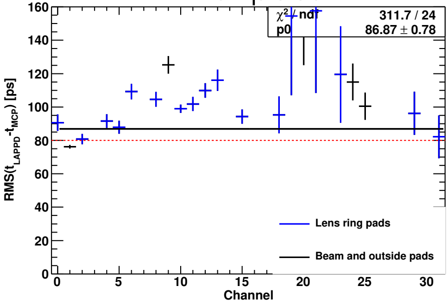
SPE timing results

- time difference distributions mostly appeared as a Gaussian-like peak,
- Gaussian fit was used to determine timing resolution,
- some pads showed significant background,
- pads on ch$>$ 7 received additional 11 ps (TR0)/33 ps (TR1) jitter between different DRS4 chips,
- best SPE timing was 75 ps (pad F6, ch2), mean 87 ps.

pad F6, ch2



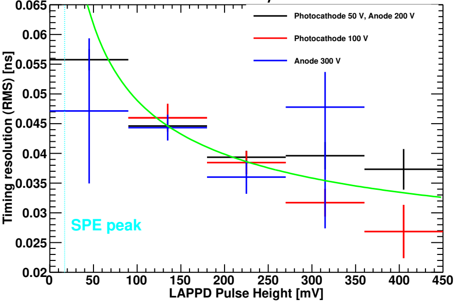
all pads



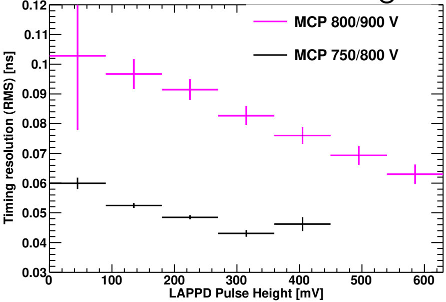
Bias voltage dependence

- timing resolution was insensitive to Anode voltage increase from 200 V to 300 V,
- increasing Photocatode voltage from 50 V to 100 V leads to improvement at high PH,
- there is no significant gain dependence of timing resolution (gain change by factor 10).

resolution vs. PC/Anode bias



resolution vs. LAPPD gain

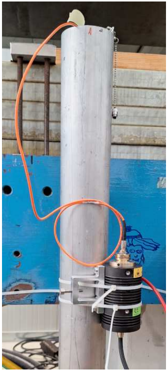


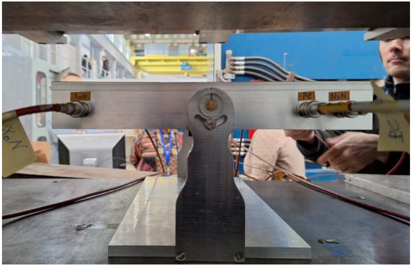
MNP-17 magnet, CERN Nov. 2023

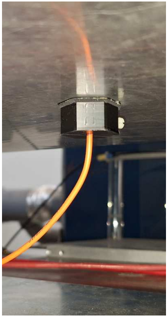
- 0.5 T dipole magnet with 30 cm gap height,
- current-to-magnetic field calibration, water cooling,
- 1D Hall-probe available.

Measurement setup

- PicoQuant 405 nm laser connected by optical fiber,
- laser synch signal used as the start time,
- 10 μm pore LAPPD N.153 in inclinable dark box,
- LAPPD signals amplified by custom amplifiers,
- 3D Hall-probe for precise monitoring.

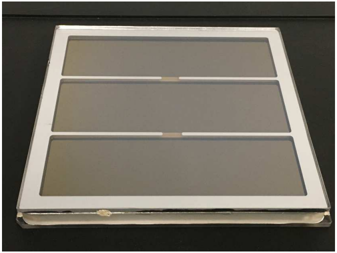


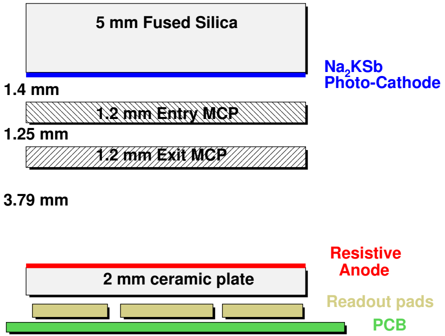




LAPPD N.153 (small pores, small gaps)

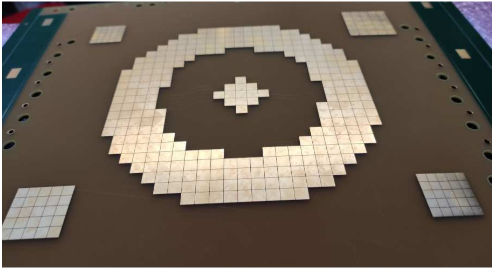
- Gen II, 10 μm capillary, short stack, Multi-Alkali,
- ROP 50/875/200/875/200, gain 7.45×10^6, TTS SPE 68 ps,
- MCP maximum bias 900 V, 5.5 MΩ/MCP,
- Dark Count Rate (th. 4 mV) 2.1 kHz/cm^2 over 373 cm^2, means 0.76 kHz/6 mm pad,
- QE(405 nm)$\simeq$18% (max. at 365 nm 25%).

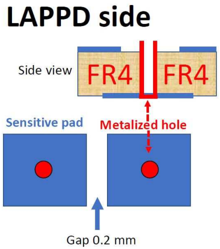


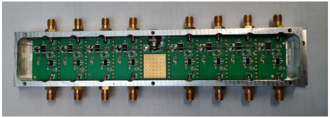


Developed LAPPD readout (traceless)

- LAPPD is capacitively coupled to PCB pads,
- PCB pads are directly connected to amplifiers,
- 1 GHz amplifiers have 20 dB gain, 0.22 mV noise and $<$0.2% cross-talk.

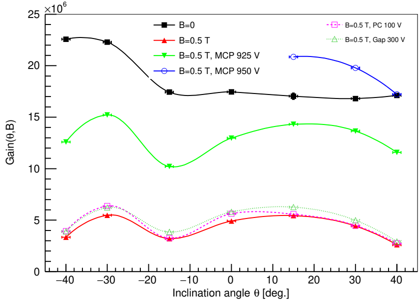


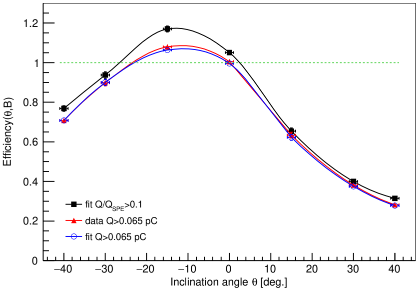




LAPPD gain and efficiency at 0.5 T

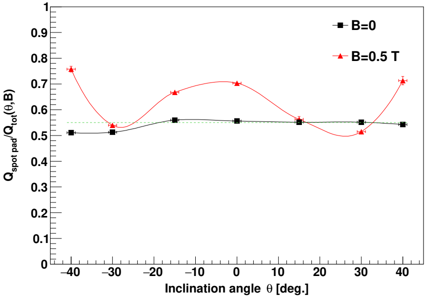
- in 0.5 T field the gain was reduced by factor 0.25,
- in 0.5 T at ±40 deg. & -15 deg. gain drops by -40%,
- gain recovery is limited by LAPPD insulation,
- efficiency: ratio of data or fit: B=0.5 T/B=0 with pC or PE thresholds,
- all efficiency estimates are similar: factor 3 drop at +40°, high at -15° (in B-filed better PE collection).

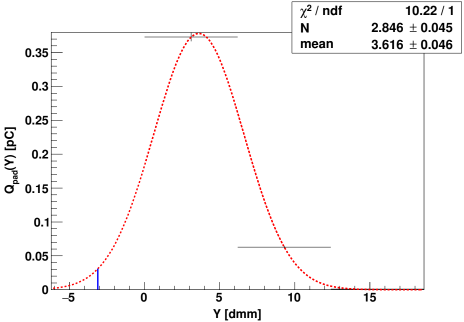




Charge fraction collected on the spot pad

- at B=0 spot pad collects about 0.55 of total charge;
- at B=0.5 T this fraction increases up to 0.7 (smaller width), but varies with angle;
- at ±40 deg. the extrapolation into missing pad indicates that we are loosing about 5-7% of charge, insufficient to recover -40% gain loss;
- instead the peak position from the fixed width fit comes on the expected $\tan\theta$-line.





Summary

- measured timing of 20 μm pore LAPPD N.124, capacitively coupled to the Incom readout board with 1 inch pads, published in:
  Nucl. Instrum. Methods A1058, 168937 (2024). ,
  - observed SPE timing RMS of about 80 ps ✓,
- 10 μm pore LAPPD N.153, capacitively coupled to custom readout board with 6 mm pads, tested in magnetic field of 0.5 T,
  - in 0.5 T field gain was reduced by factor 0.25,
  - gain reduction in 0.5 T field can be compensated by about 60 V increase of MCP bias voltage, but LAPPD dark current might become unstable ✓,
  - efficiency loss up to factor 3 observed at +40^o field inclination ✗,
  - test in 1.5 T field are running right now at CERN.
- LAPPD aeging setup in development at TS.

Backup slides

Known timing uncertainties

Sources of timing uncertainties related to the experimental setup, which should appear as a contribution to the constant term p_0:

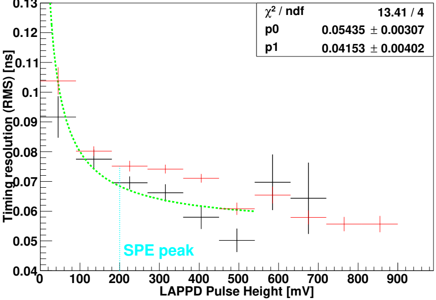
Source	Estimate
Hamamatsu MCP-PMT	10 ps
Geant4 detector geometry and chromatic dispersion	8.3 ps
Readout pad size	12 ps
Total	18 ps

Best resolution at very large $N_{p.e.} \simeq 23$ measured in this test was 27 ps, fairly close to expected.

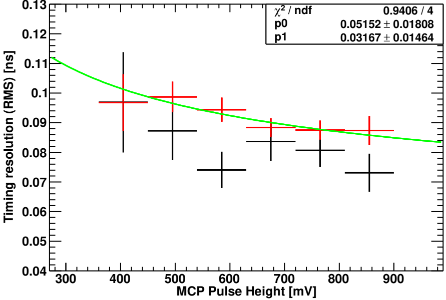
PH-dependence of timing resolution

- the resolution is $\sqrt{p_0^2 + \frac{p_1^2}{V/V_{SPE}}}$ function of LAPPD PH,
- constant term was 50 ps, expected 18 ps,
- $N_{p.e.}$ term is approximately $= 40\ ps/\sqrt{N_{p.e.}}$,
- no significant dependence on Hamamatsu MCP PH.

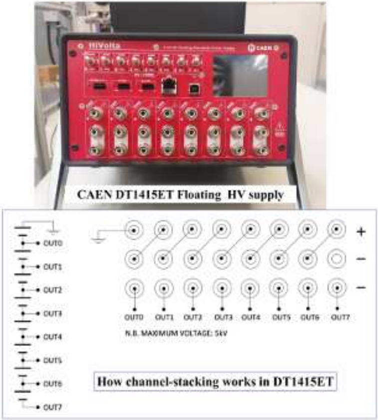
resolution vs. LAPPD PH

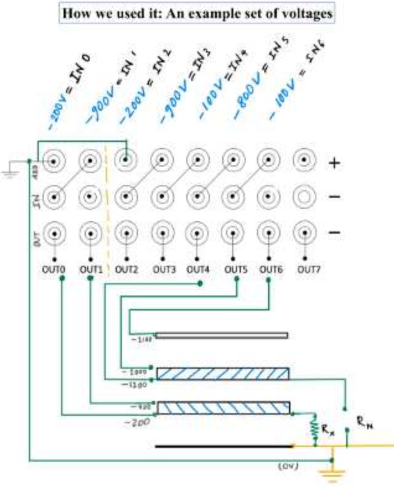


resolution vs. MCP PH



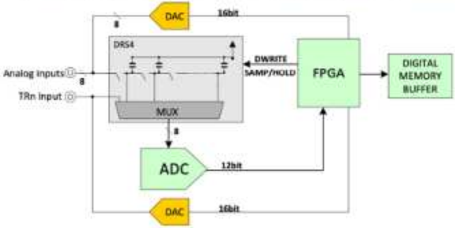
LAPPD bias voltages

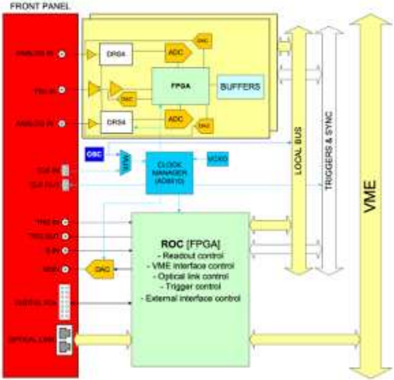




DAQ system

WEINER VME crate:
CAEN V1718 controller board
CAEN V1742 Digitizer board with 32 readout channels





V1742 Board:

> 4 DRS chips
> 5 GS/s -> 200 ps
> 32 Analog channels
> 2 fast triggers (1 global trigger)
> each channel has 1024 SCA (Cells)
> one 12 bit ADC in each chip

Number of Cherenkov photons

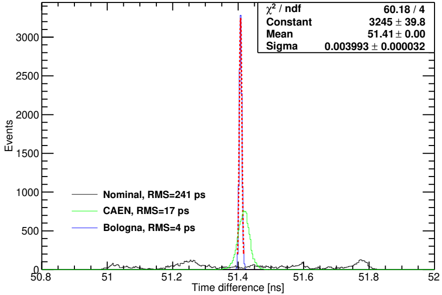
- assume proton beam with P=12 GeV/c, β_p=0.9969589 and $\theta_C = 48.4^\circ$ in fused silica (n=1.51 at 250 nm),
- the number of Cherenkov photons (in range of LAPPD photocathode sensitivity) produced in 1 mm of quartz:

$$N_\gamma = 0.0256 * \left\{ \frac{1}{160nm} - \frac{1}{560nm} \right\} = 114 \, \frac{photons}{mm} \, ,$$

- thus in 5 mm thick LAPPD window we produce 570 photons,
- in 14 mm thick aspheric lens we produce 1600 photons,
- assuming 30% mean QE of Na_2KSb photocathode we estimate: 170 p.e. from LAPPD window and 480 p.e. from aspheric lens,
- Geant4 simulation gives 180 p.e. from LAPPD window and 300 p.e. from aspheric lens.

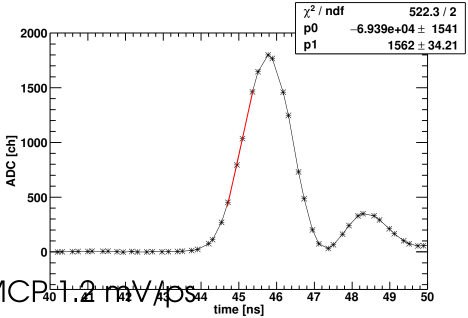
DRS4 timing calibrations

- we used timing calibration procedure developed by Vincenzo Vagnoni (INFN Bologna),
- validation of calibration gave 4 ps residual resolution,
- calibrated delays between cells are around 150/250 ps for even/odd cells,
- timing corrections are significant: 50 ps broadening.

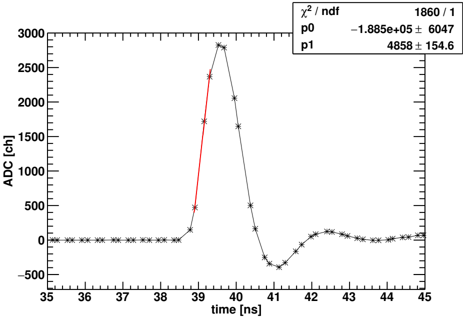


LAPPD and MCP time measurements

- acquired raw waveforms (no CAEN on-line corrections) were converted in TGraphs with variable delays between samples (using Bologna calibrations),
- to measure time we fitted pulse rising edge in the region of 50% height with a linear function,
- time was determined as the crossing point of 50% height by the linear fit function.

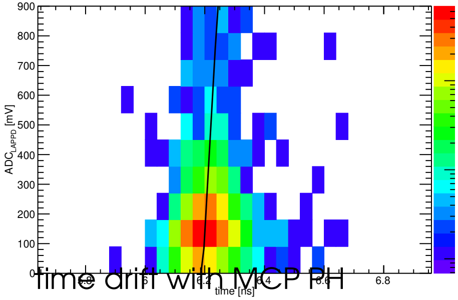


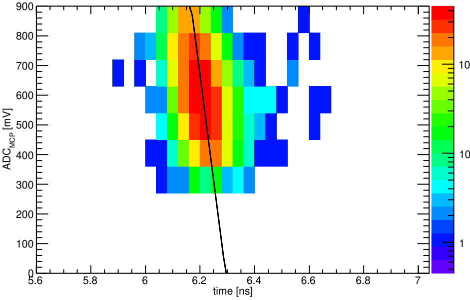
MCP 1.2 mV/ps



LAPPD and MCP PH-corrections on time

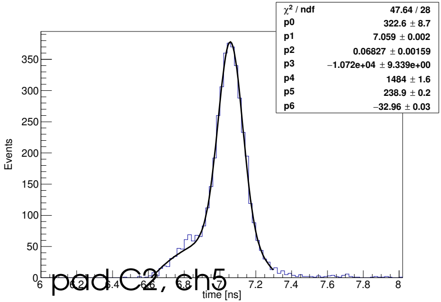
- linear function approximation in the fit leads to systematic effects on the time difference,
- time difference depends on signal Pulse Heights,
- in LAPPD time drift is about 0.1 ps/mV,
- in Hamamatsu MCP time drift is about 0.2 ps/mV,
- after correction the residual PH-dependence is <5 ps.

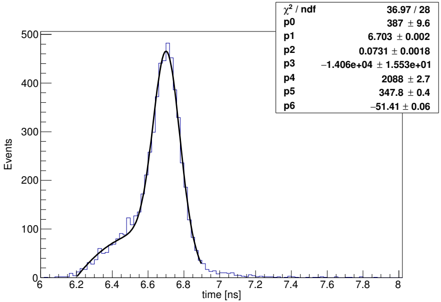




SPE timing background

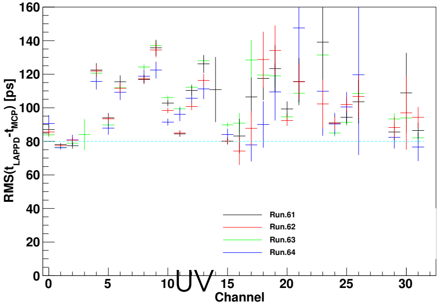
- most common background - l.h.s. tail or a peak anticipated by about 0.3 ns,
- background is higher in pads near horizontal and vertical beam spot pads,
- perhaps due to Cherenkov in LAPPD window followed by multiple internal reflections,
- in affected pads 20% improvement fitting Gaus+pol,
- best SPE timing 68 ps (pad F5, ch0), mean 86 ps.

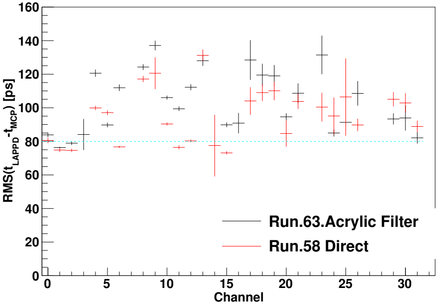




SPE timing consistency

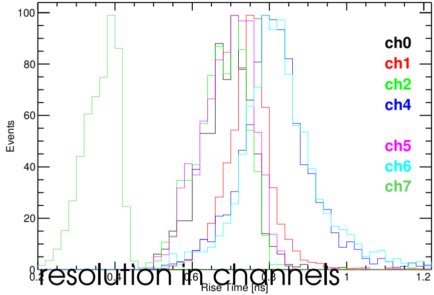
- we took four different runs with acrylic filter,
- the results from these four runs agree within statistical uncertainties,
- run taken with UV photons gives better resolution because of 3 times larger mean number of p.e., but also limited to about 75 ps.

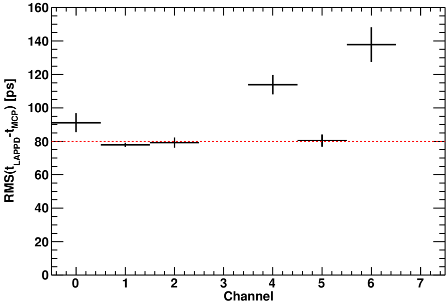




LAPPD signal risetime variations

- 15% variations of risetime channel-to-channel, not seen during the calibrations,
- some correlation with timing resolution observed,
- large risetime in nearby pads: B6+C6 and F3+G3,

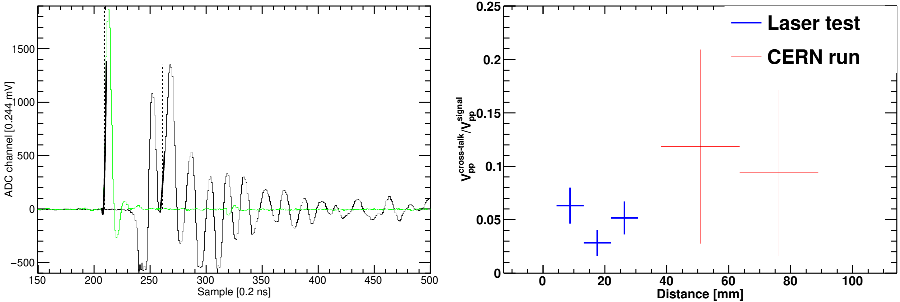




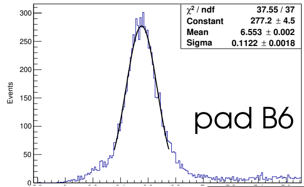
resolution in channels

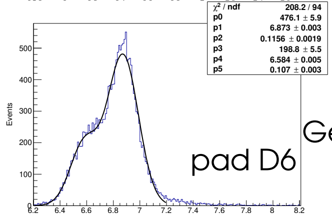
Resistive anode cross-talk in LAPPD

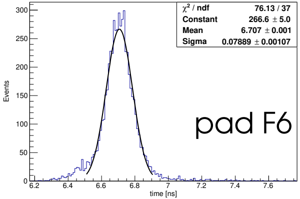
- strong cross-talk between pads was observed at testbeam and in the lab,
- cross-talk appears as a dumped oscillator,
- the amplitude of oscillation is about 5÷10% of the primary signal,
- cross-talk amplitude seems to be independent from the pad location.

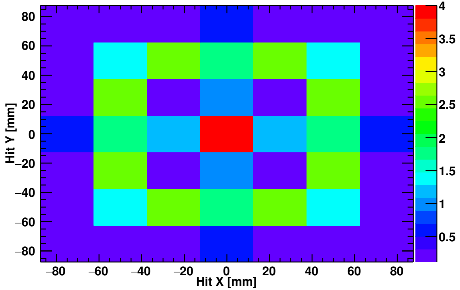


Beam spot background - left side

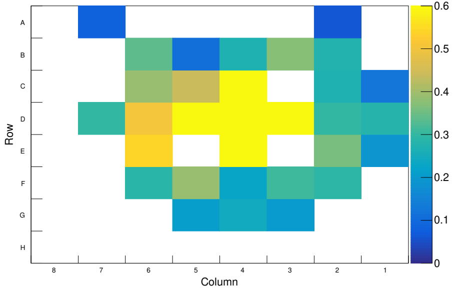




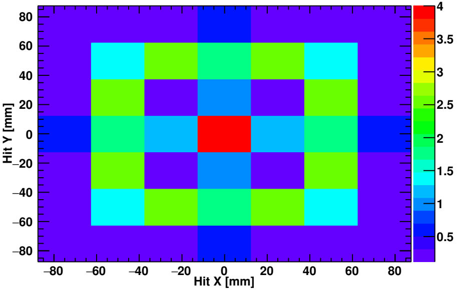


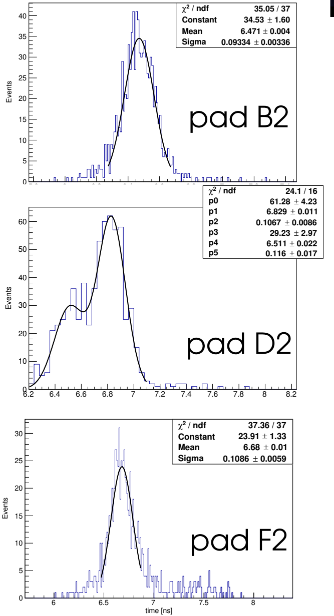


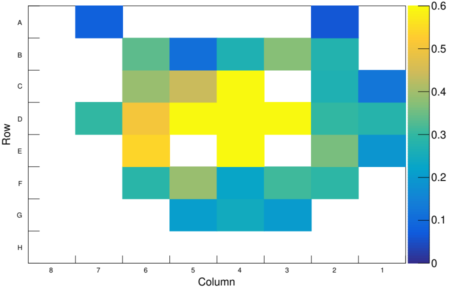
Geant4



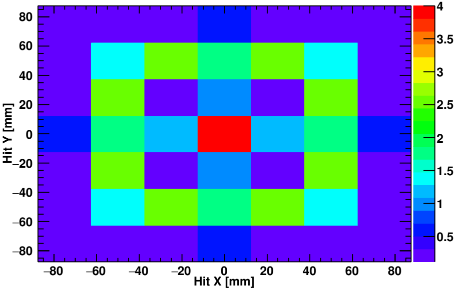
Beam spot background - right side

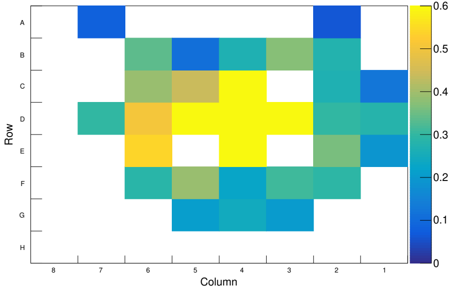


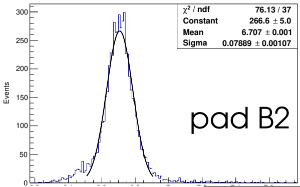


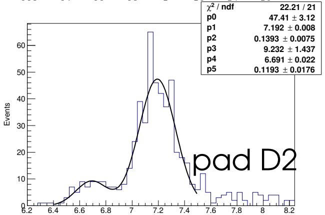


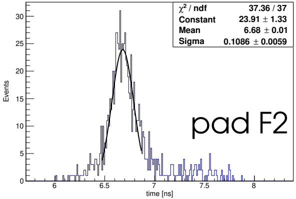
Beam spot background - bottom side





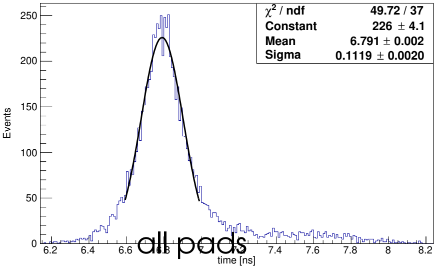


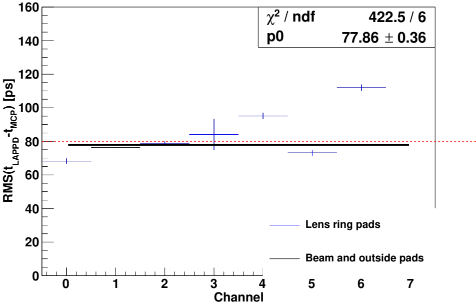




SPE timing results chip.0

- best resolution is achieved on chip0, where Hamamatsu MCP-PMT is connected to ch7,
- best SPE timing was 68 ps (pad F5, ch0), mean 78±0.4 ps,
- ch4 (pad C6) and especially ch6 (pad G3) deviate from the mean, these pads have larger risetime.

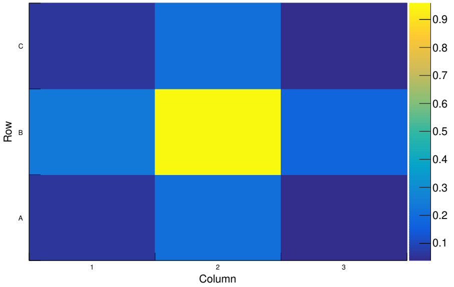




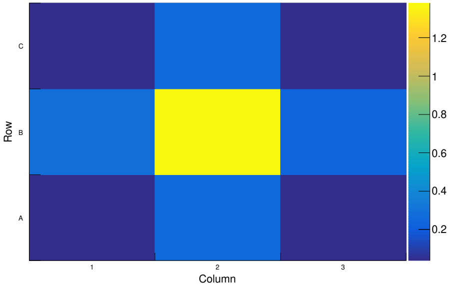
2D maps of collected charge at B=0

- 55% of charge is collected on the pad under fiber,
- different LAPPD inclinations at B=0 preserve the same charge map,
- after fiber movement the charge collection in all pads increased on 34%, 0.2 mm gap area fraction is just 6.35%, requiring main peak to be located at the edge of central pad, but the observed distribution is symmetric.

normal



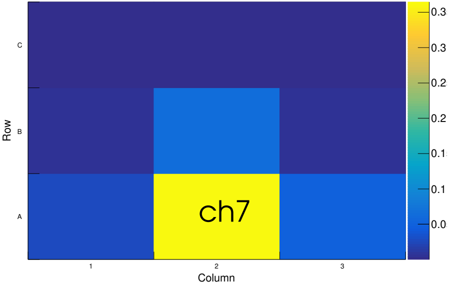
inclination -40 deg.



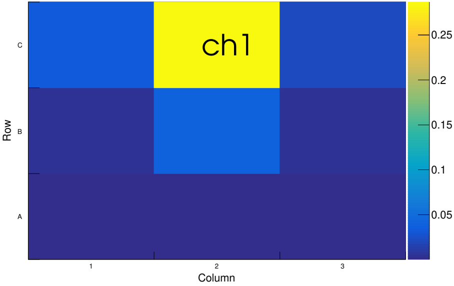
2D maps of collected charge at B=0.5 T

- at normal field the peak is still in central pad, but it collects 79%,
- inclination of field shifts the peak by about one pad and increases peak pad fraction to 85%.

inclination -40 deg.



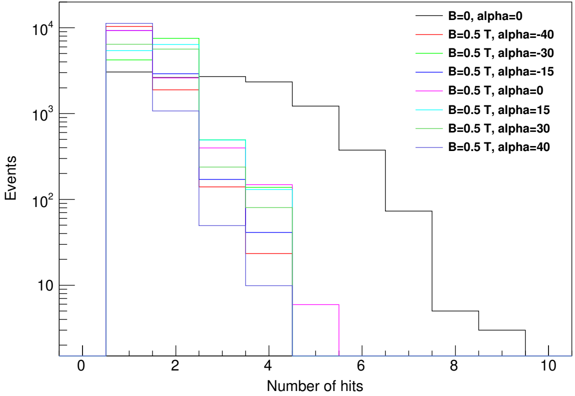
inclination +40 deg.



LAPPD hit multiplicity

- at B=0 charge distribution is 2 times broader and pad hit multiplicity is larger (mean 2.8),
- at B=0.5 T all multiplicities are similar and the mean varies from 1.1 to 1.7.

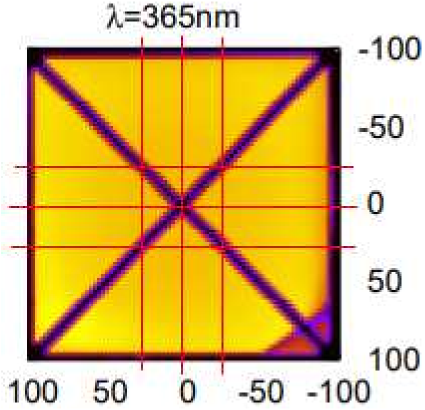
Standard bias voltages



LAPPD cross shadow

- LAPPD pads are large: 25$\times$25 mm^2,
- MCP cross-shaped support shadow affects 4 central pads,
- but their geometrical efficiency remains $>$ 50%.

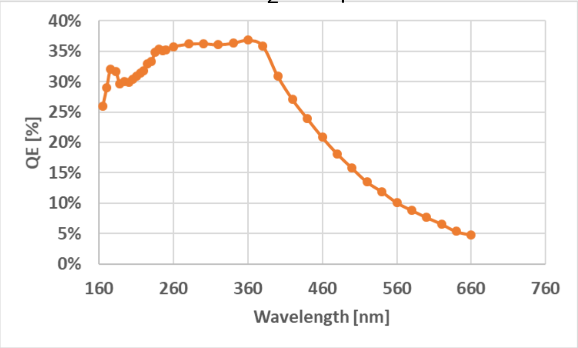
LAPPD.87 with Na_2KSb photocathode



LAPPD Quantum Efficiency

- in wavelength range 180-400 nm QE of LAPPD is $> 30\%$,
- numerical convolution $dN/d\lambda(\lambda)$ and $QE(\lambda)$: 33.6 p.e./mm.
- analytic estimate of Cherenkov p.e. yield assuming average QE=30%:

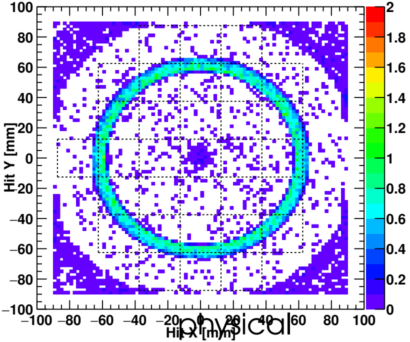
LAPPD.12 with Na_2KSb photocathode



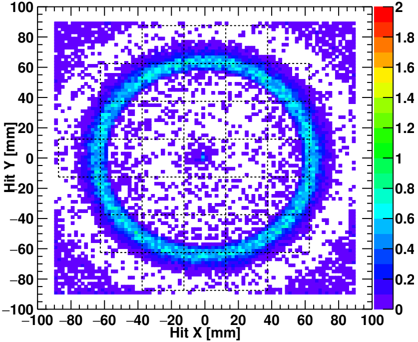
$$N_\gamma = 0.0256 * \left\{ \frac{1}{160nm} - \frac{1}{560nm} \right\} * 0.30 = 34 \frac{p.e.}{mm},$$

60 mm backward, chromatic dispersion - ring

- Cherenkov ring is wide even without chromatic dispersion,
- chromatic dispersion adds more width to the ring.

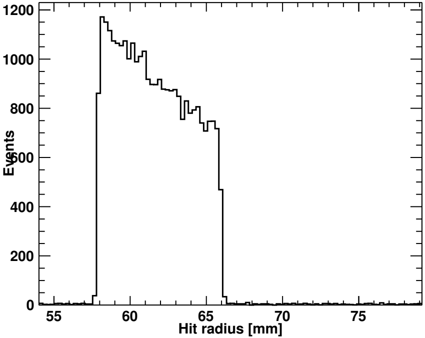


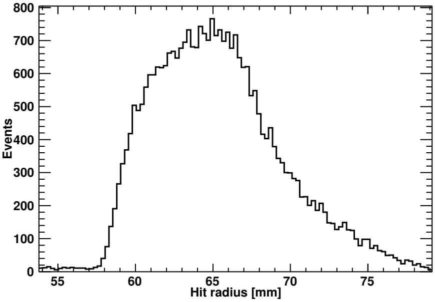
physical



60 mm backward, chromatic dispersion - radius

- Cherenkov ring is 8 mm wide even without chromatic dispersion,
- the width is related to emission point uncertainty: it varies from 4.3 mm to 13.8 mm (from lens face - first 4.3 mm is blind).
- chromatic dispersion doubles the width of the ring.

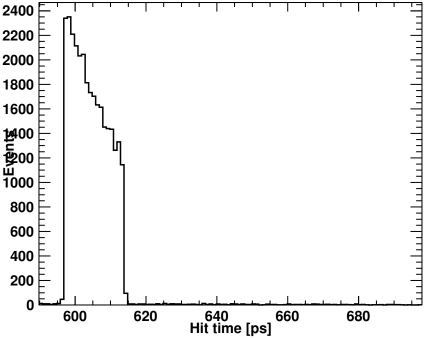




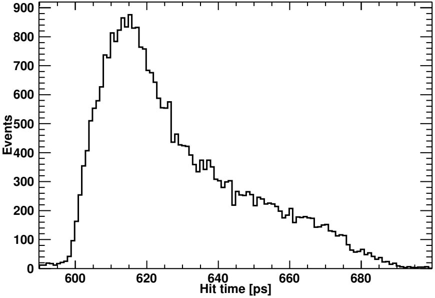
physical

60 mm backward, chromatic dispersion - time

- without chromatic dispersion total width of Cherenkov photon timing distribution is 17 ps,
- chromatic dispersion delay fraction of photons increasing the width by 5 times.

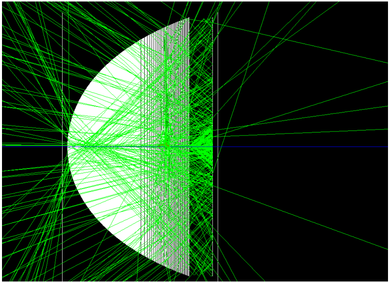


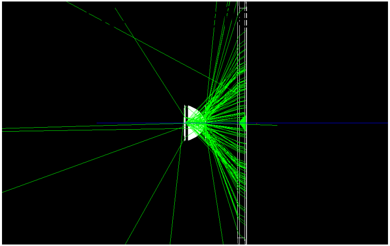
physical

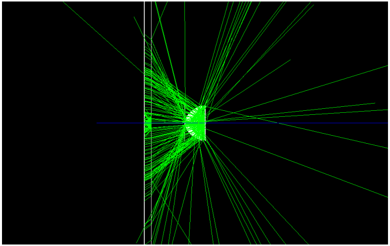


Setup for testbeam

1. beam - protons 5-12 GeV/c,
2. aspheric lens radiator,
3. LAPPD with 32 ch readout by V1742 digitizer.

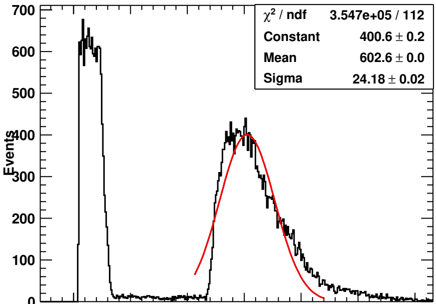




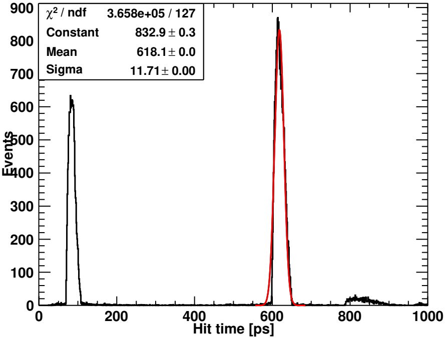


60 mm Direct vs. backward reflection - time

- direct configuration gives photon timing RMS of 24 ps, and 0.07 ns offset from proton impact,
- backward reflection gives photon timing RMS of 12 ps, and 0.31 ns offset from proton impact,
- backward reflection gives better time separations from beam hit.

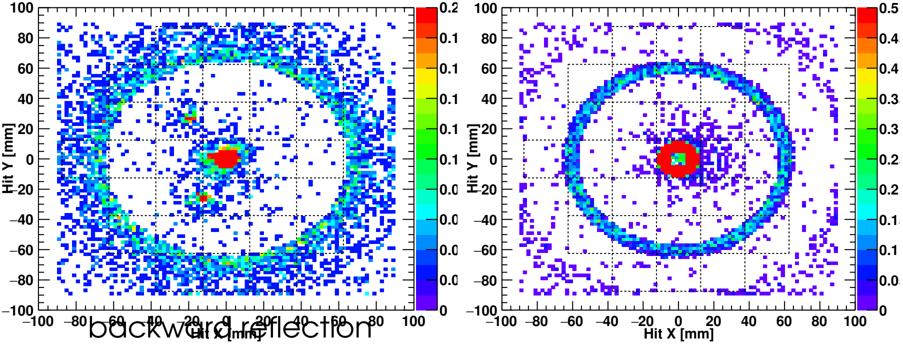


backward reflection



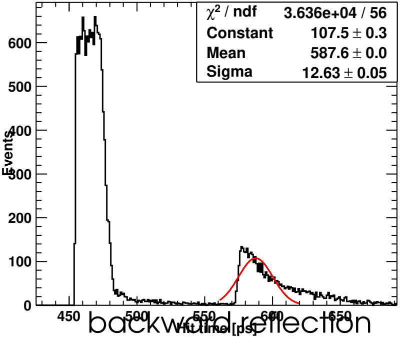
AF 60 mm Direct vs. backward reflection - ring

- direct configuration gives broad ring (2 p.e./pad),
- backward reflection gives narrow ring (3 p.e./pad),
- why?
- beam spot is larger for backward reflection.
- direct gives better spacial separations from beam hit.

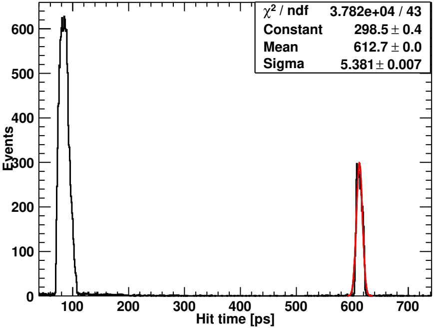


AF 60 mm Direct vs. backward reflection - time

- direct configuration gives photon timing RMS of 10-13 ps, and 0.07 ns offset from proton impact,
- backward reflection gives photon timing RMS of 3.5-5 ps, and 0.31 ns offset from proton impact,
- backward reflection gives better time separations from beam hit.

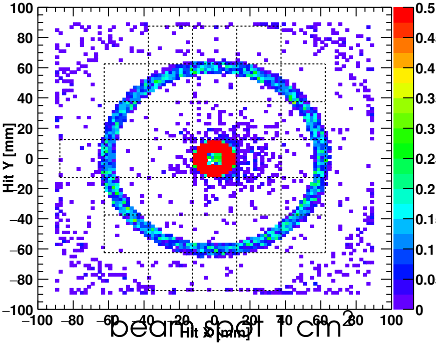


backward reflection

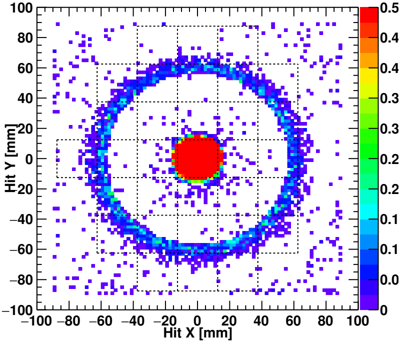


AF 60 mm backward reflection BS 1 cm^2 - ring

- beam spot 0 (3 p.e./pad),
- beam spot 1 cm^2 (3 p.e./pad),
- LAPPD beam spot is larger for BS 1 cm^2, entering in nearby pads (5 p.e./pad).

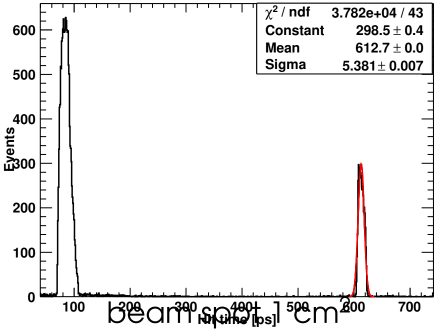


beam spot 1 cm^2



AF 60 mm backward reflection BS 1 cm^2 - time

- beam spot 0 timing RMS of 3.5-5 ps,
- beam spot 1 cm^2 timing RMS of 14-15 ps,
- beam spot 1 cm^2 is too large.



beam spot 1 cm^2