LAPPD magnetic field test results

CERN MNP-17, Nov. 2023

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remote

Why measuring LAPPD response in magnetic field

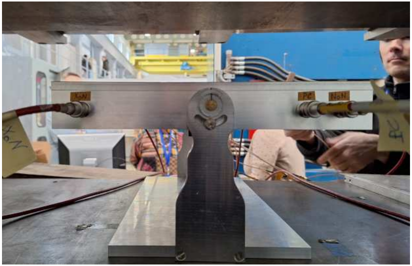
- Large Area Picosecond Photodetectors were expected to operate in magnetic fields,
- smaller MCPs from other brands ???,
- RICH and PET applications require detector tolerance to about 1 T magnetic fields,
- it is already established that LAPPD gain drops in magnetic field, but can be recovered by higher bias voltage,
- it is yet not clear whether efficiency, timing and spacial resolutions are also affected,
- we decided to verify it on MNP-17 magnet at CERN.

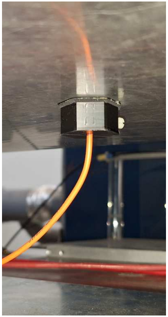
MNP-17 magnet in B-168 at CERN

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

Measurement setup

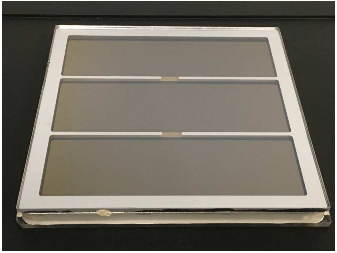
- PicoQuant 405 nm laser connected by optical fiber,
- 10 μm pore LAPPD N.153 in inclinable dark box,
- 3D Hall-probe.

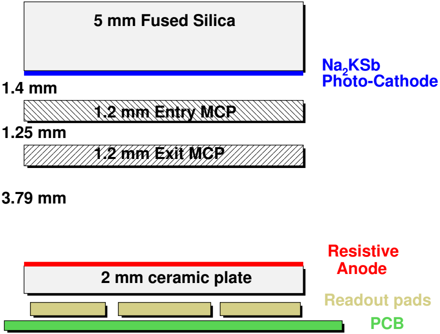




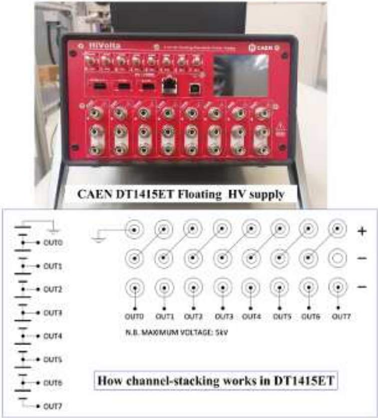
LAPPD N.153

- 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%).





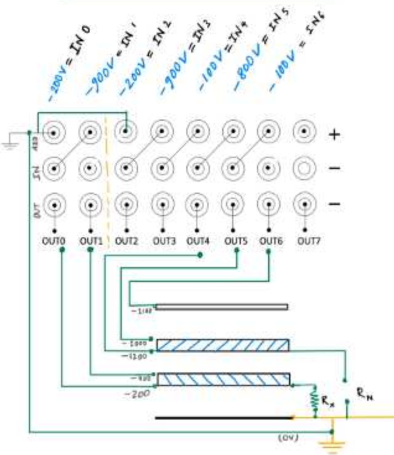
LAPPD bias voltages



CAEN DT1415ET Floating HV supply

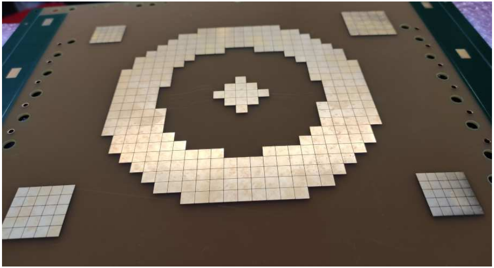
How channel-stacking works in DT1415ET

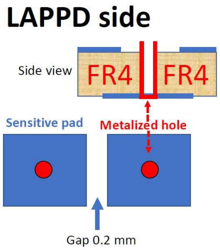
How we used it: An example set of voltages

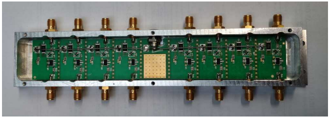


LAPPD readout

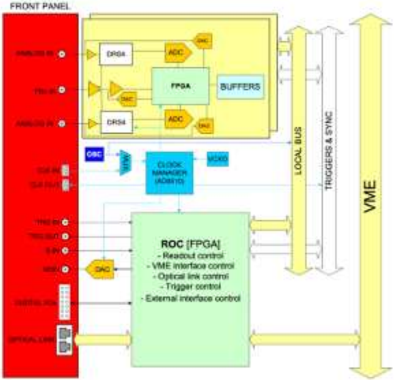
- LAPPD is capacitively coupled to PCB pads,
- PCB pads are directly connected to amplifiers,
- 1 GHz amplifiers have 20 dB gain, 0.22 mV noise and <0.2% cross-talk.

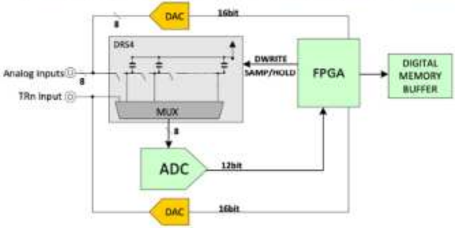






DAQ system



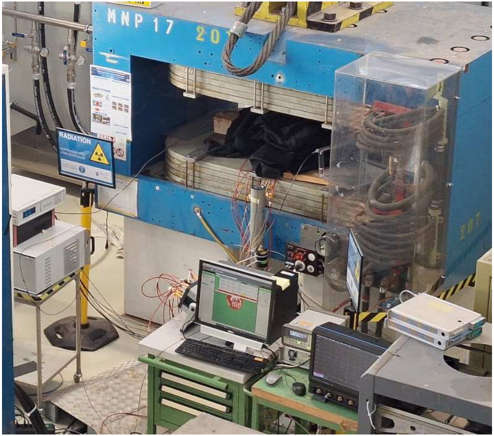


V1742 Board:

> 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

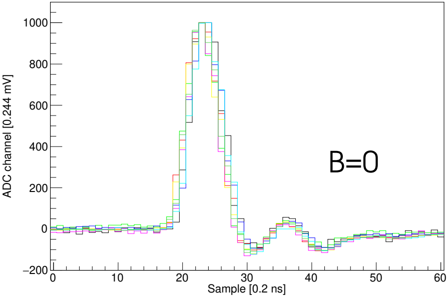
Entire setup

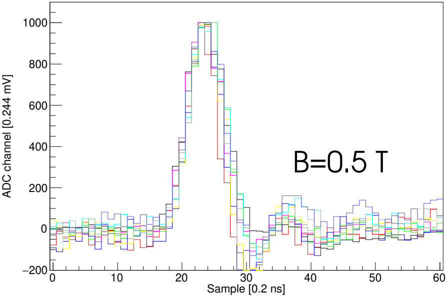
- LAPPD and dark box were covered with black clothes to reduce further ambient light background,
- electronics was installed at about 2 m from the magnet.



Measured LAPPD signals

- LAPPD risetime (20-80%) was about 0.45 ns,
- V1742 digitizer has BW=0.5 GHz →0.45 ns is its intrinsic limit on risetime (20-80%),
- LAPPD 6 mm pad has capacitance 1.6 pF, assuming 50Ω load we expected 80 ps,
- B=0.5 T field increased signal risetime on 25%.

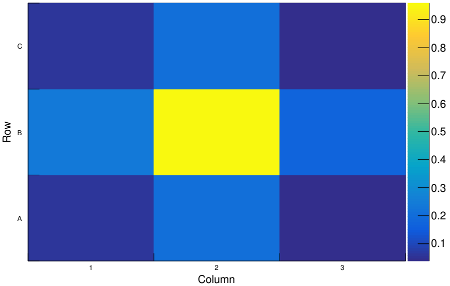




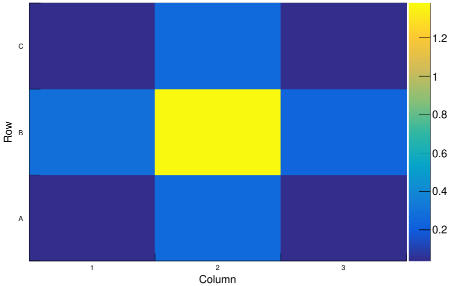
2D maps of collected charge at B=0

- 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



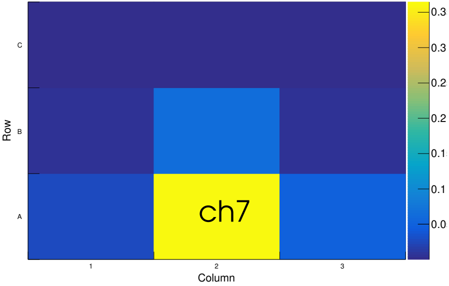
inclination -40 deg.



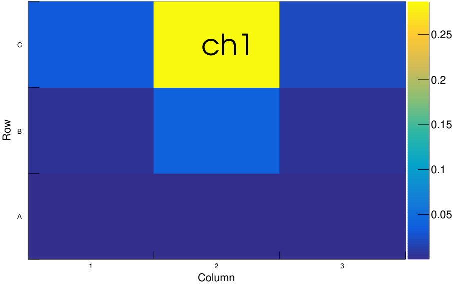
2D maps of collected charge at B=0.5 T

- 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.



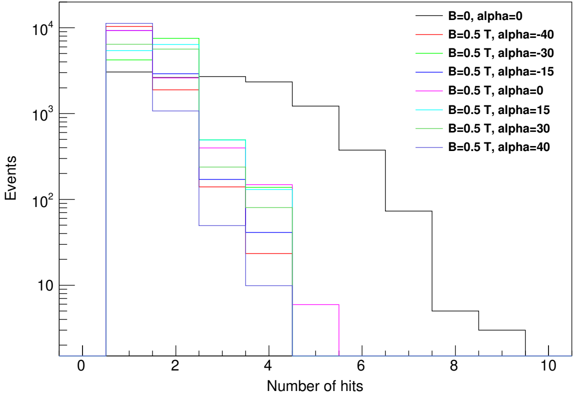
inclination +40 deg.



LAPPD hit multiplicity

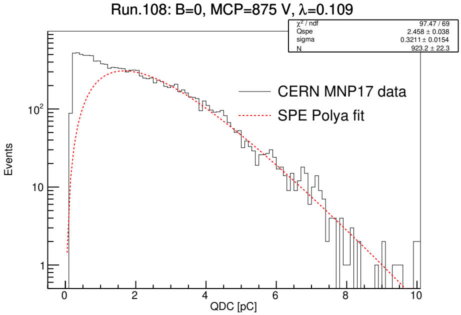
- at B=0 charge distribution is 2 times broader and pad hit multiplicity is larger (mean 2.8),
- at B=0.5 T all multiplicities are similar and the mean varies from 1.1 to 1.7.

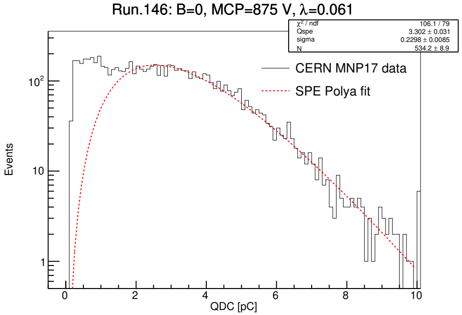
Standard bias voltages



LAPPD collected charge at B=0

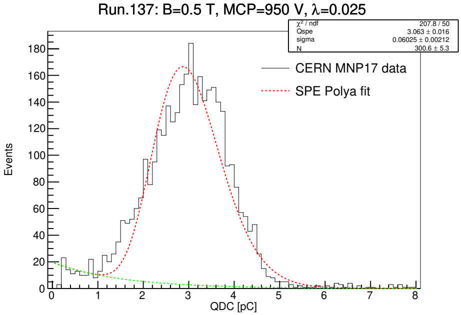
- datasheets of LAPPD N.153 at 875 V (50 V PC) gives gain of 8×10^6, we expected SPE peak at 2.56 pC,
- the observed SPE peak at 2.46±0.04 pC, $\sigma/\mu \sim$0.32,
- $\theta =$-30 and -40 deg. peak at 3.3 pC (+34%),
- fit requires exponential component.

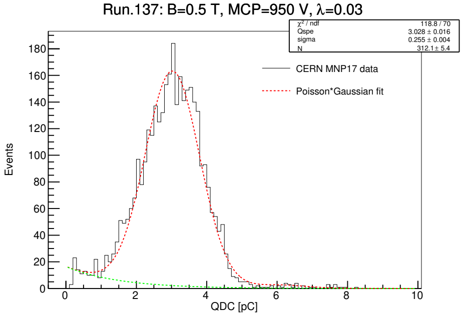




LAPPD collected charge at B=0.5 T MCP=950 V

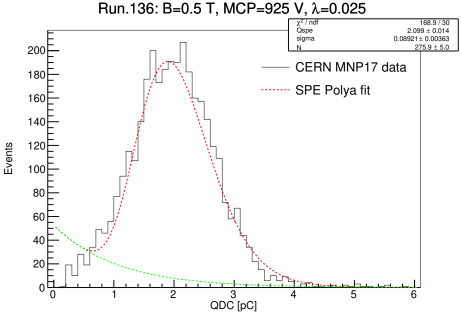
- exponential tail is 10 times smaller (w.r.t. B=0),
- Polya shape gives 2 times larger χ^2 (w.r.t. Gaussian),
- σ/μ ~0.26 (Gaussian) or 0.06 (Polya), number of secondaries $N_e \sim (\mu/\sigma)^2$: 15 or 278,
- SPE charge is compatible within uncertainties.

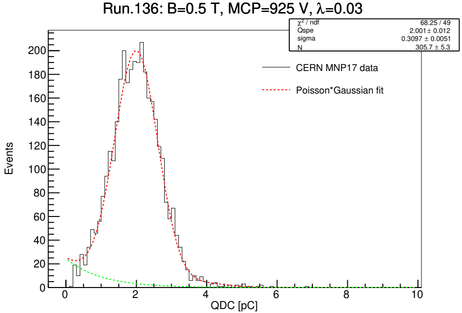




LAPPD collected charge at B=0.5 T MCP=925 V

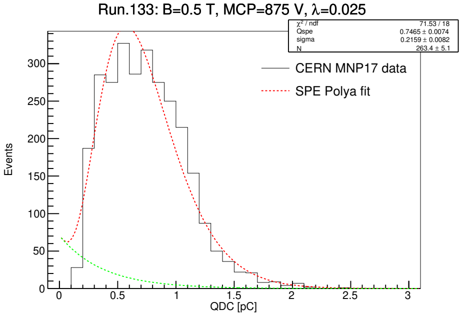
- exponential tail is 10 times smaller (w.r.t. B=0),
- Polya shape gives 2 times larger χ^2 (w.r.t. Gaussian),
- $\sigma/\mu \sim$0.31 (Gaussian) or 0.09 (Polya), number of secondaries $N_e \sim (\mu/\sigma)^2$: 10 or 123,
- SPE charge is compatible within uncertainties.

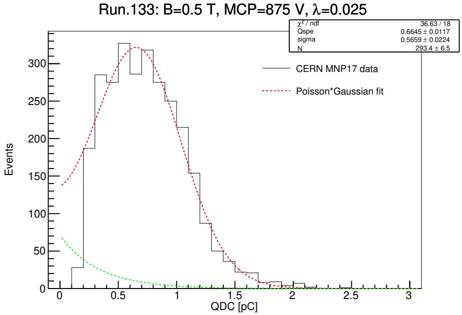




LAPPD collected charge at B=0.5 T MCP=875 V

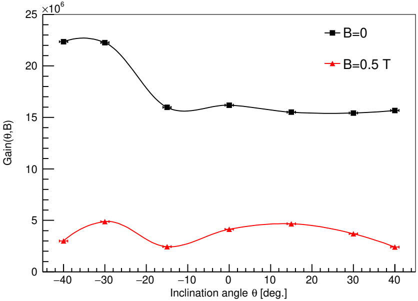
- exponential tail is 10 times smaller (w.r.t. B=0),
- Polya shape gives 2 times larger χ^2 (w.r.t. Gaussian),
- σ/μ ~0.57 (Gaussian) or 0.22 (Polya), number of secondaries $N_e \sim (\mu/\sigma)^2$: 3 or 21,
- Polya gives 13% larger SPE charge.

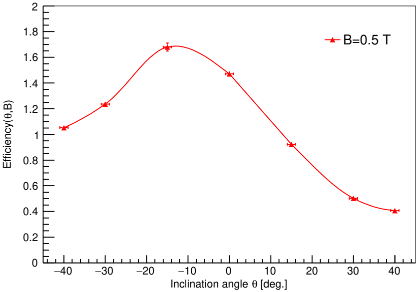




LAPPD gain and efficiency at 875 V

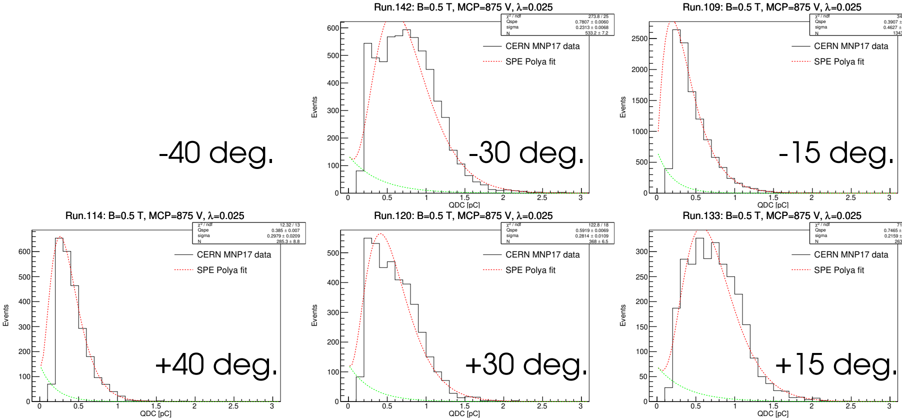
- gain estimated from Polya fit (Qspe parameter/e),
- $\theta =$-30, -40 deg. peaks are higher, -15 deg. 40% lower,
- at $\pm$40 deg. gain drops by 35%,
- efficiency: ratio of Polya normalizations B=0.5 T/B=0,
- at B=0.5 T Polya fits are not always good.





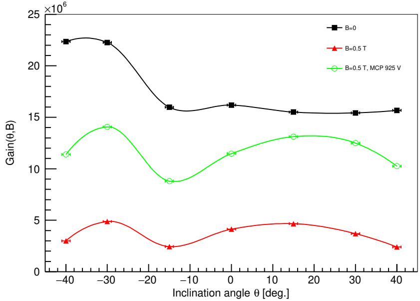
Fits at B=0.5 T, MCP=875 V

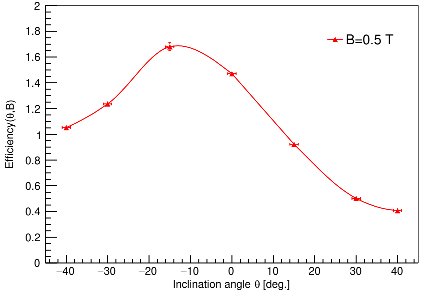
- at -30 deg. higher peak and large exponential,
- at -15 deg. lower peak and large exponential,
- fits ambiguous due to overlap with exponential.



LAPPD gain and efficiency at 925 V

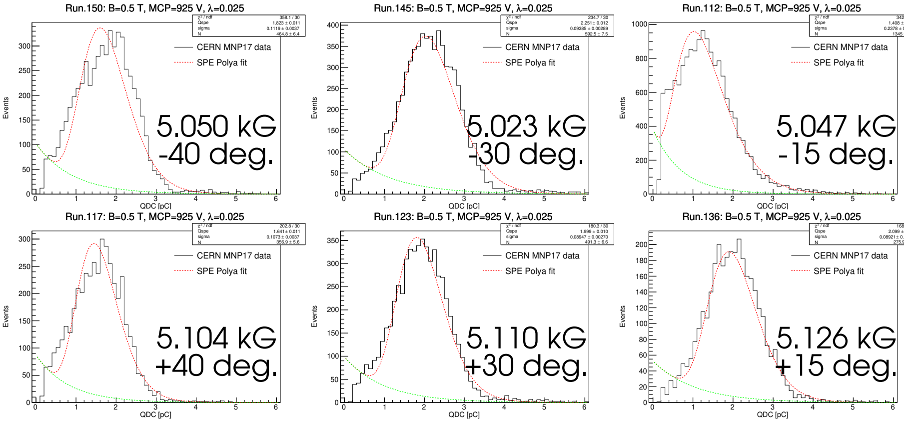
- confirm that at ±40 deg. gain drops by 18%,
- θ =-15 peak 30% lower (consistent with 875 V),
- gain variations of 20%,
- efficiency: ratio of Polya normalizations B=0.5 T/B=0,
- at B=0.5 T Polya fits are not always good.





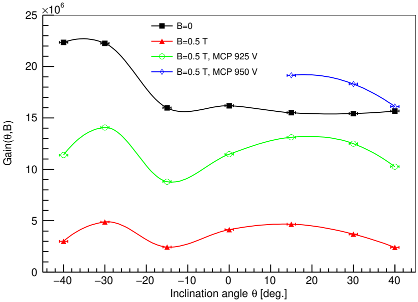
Fits at B=0.5 T, MCP=925 V

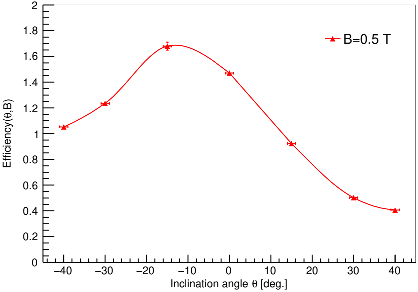
- peak positions are unambiguous,
- magnetic field variations $\leq 2\%$.



LAPPD gain and efficiency at 950 V

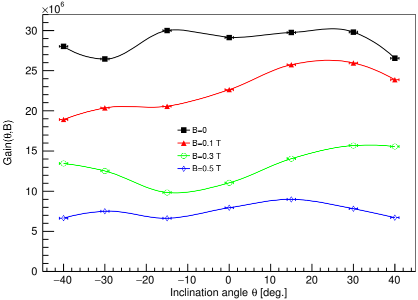
- confirm that at +40 deg. gain drops by 13%,
- efficiency: ratio of Polya normalizations B=0.5 T/B=0,
- at B=0.5 T Polya fits are not always good.

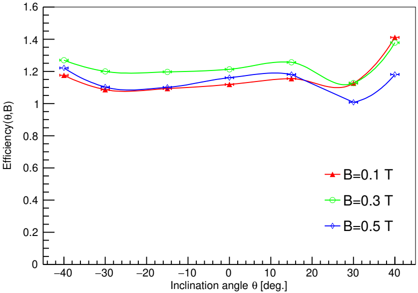




LAPPD gain and efficiency at 900 V, Photo-Cathode disconnected

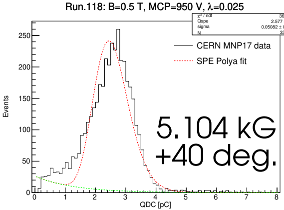
- 1.7 times higher gain than at 875 V (both B=0 and B=0.5 T), datasheets suggest factor 2,
- efficiency independent of angle and B-field,
- minimum at -15 deg. the same as with Photo-Cathode.

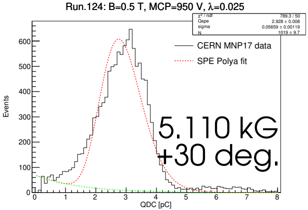


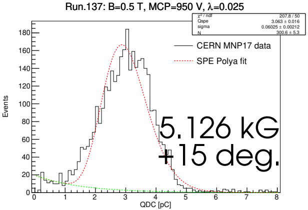


Fits at B=0.5 T, MCP=950 V

- peak positions are unambiguous,
- magnetic field variations $\leq$0.4%.

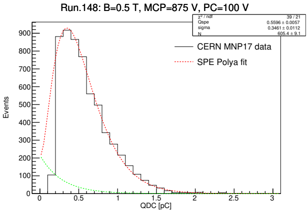


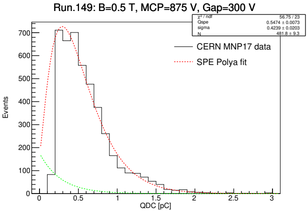




Fits at B=0.5 T, MCP=875 V, $\theta = -40$ deg.

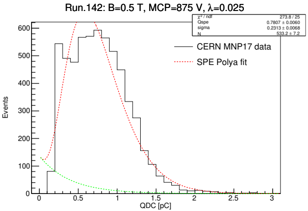
- PC=100 V: gain +17%,
- Gap=300 V: gain +14%.

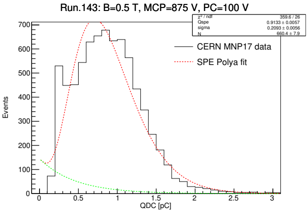


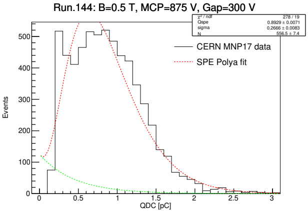


Fits at B=0.5 T, MCP=875 V, $\theta = -30$ deg.

- PC=100 V: gain +17%,
- Gap=300 V: gain +14%.

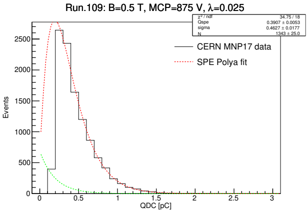


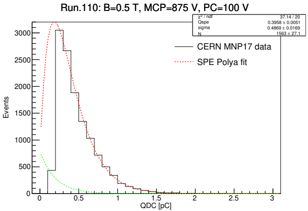


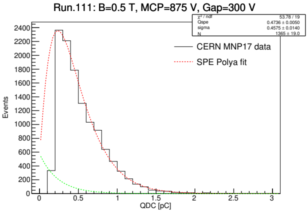


Fits at B=0.5 T, MCP=875 V, $\theta = -15$ deg.

- PC=100 V: gain +2%,
- Gap=300 V: gain +21%.

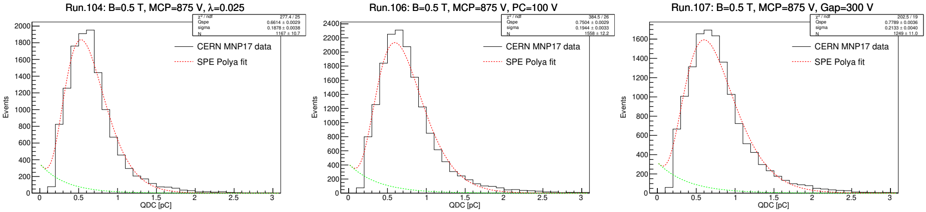






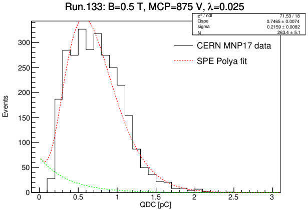
Fits at B=0.5 T, MCP=875 V, $\theta = 0$ deg.

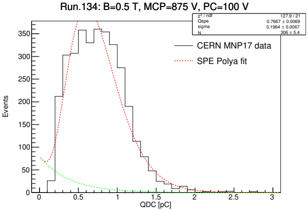
- PC=100 V: gain +14%,
- Gap=300 V: gain +18%.

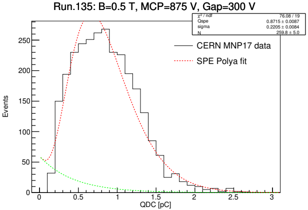


Fits at B=0.5 T, MCP=875 V, $\theta = 15$ deg.

- PC=100 V: gain +3%,
- Gap=300 V: gain +17%.

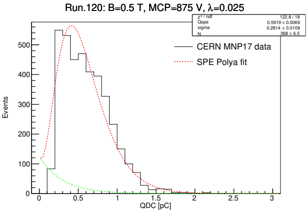


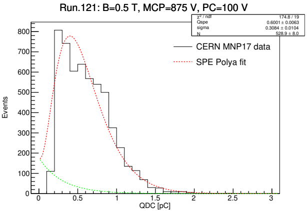


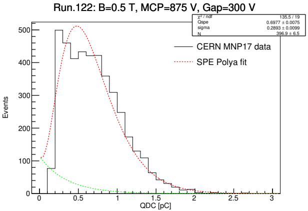


Fits at B=0.5 T, MCP=875 V, $\theta = 30$ deg.

- PC=100 V: gain +2%,
- Gap=300 V: gain +18%.

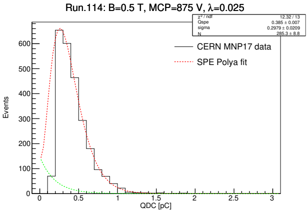


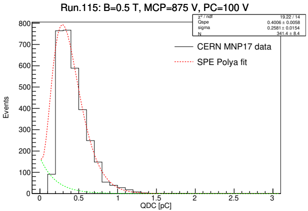


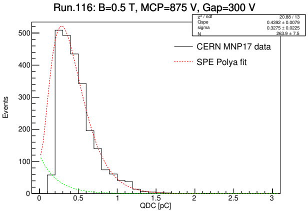


Fits at B=0.5 T, MCP=875 V, $\theta = 40$ deg.

- PC=100 V: gain +4%,
- Gap=300 V: gain +14%.

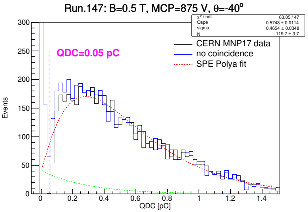


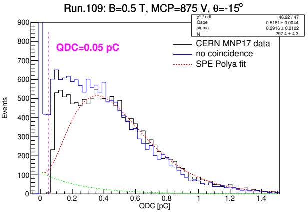


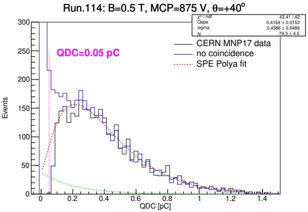


Lowest feasible threshold

- integrating 3 ns interval 20 ns after the laser synch gives an idea of S/N,
- for θ <+30 noise rises <0.025 pC, corresponding to 5 mV threshold,
- for $\theta \geq$+30 noise rises <0.05 pC, corresponding to 10 mV threshold,
- for the reference the baseline RMS is about 2 mV,
- $\theta =$-15 deg. has second peak at low QDC$\simeq$0.13 pC.

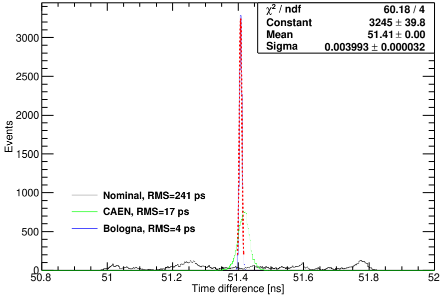






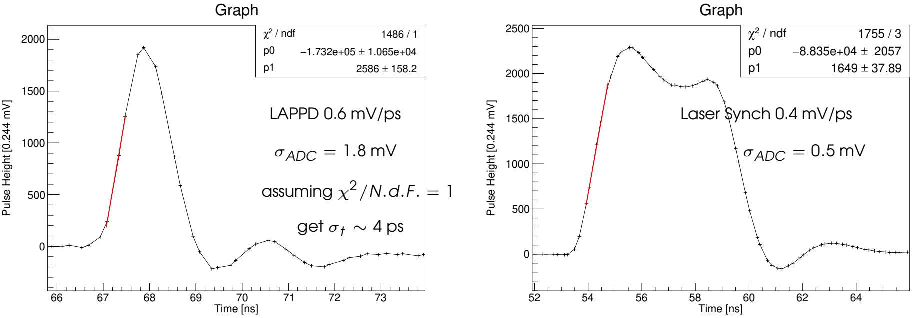
DRS4 timing calibrations

- 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.



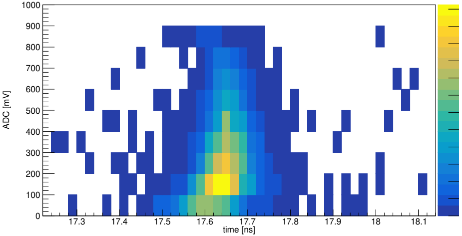
LAPPD time measurements

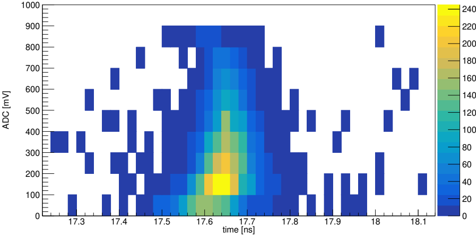
- acquired raw waveforms (no CAEN on-line corrections) were converted in TGraphs with variable delays between samples (using Bologna calibrations),
- to measure time we fitted pulse rising edge in the region of 50% height with a linear function,
- time was determined as the crossing point of 50% height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



LAPPD 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 0.2 ps/mV, mostly <100 mV,
- but this correction is visible only in runs without Photo-cathode.

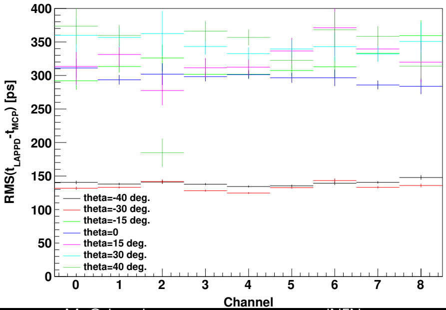




SPE timing results

- time difference distributions mostly appeared as a Gaussian-like peak,
- Gaussian fit was used to determine timing resolution,
- movement of optical fiber reduced resolution by a factor of 2, and shifted mean by -1.6 ns (34 cm),
- for $\theta =$-40 and -30 deg. SPE timing was 135 ps at B=0, and 145 ps at B=0.5 T (datasheets 70 ps),
- for other angles varies in range 300-400 ps.

B=0



B=0.5 T

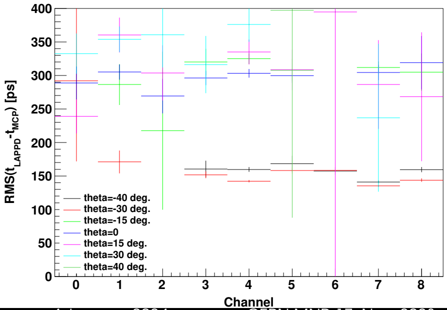
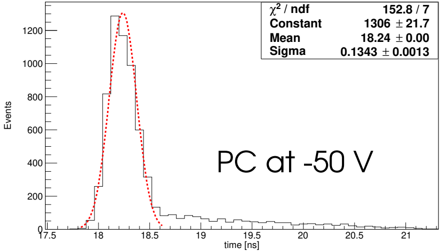
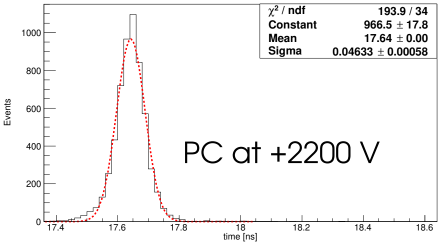


Photo-cathode bias effect

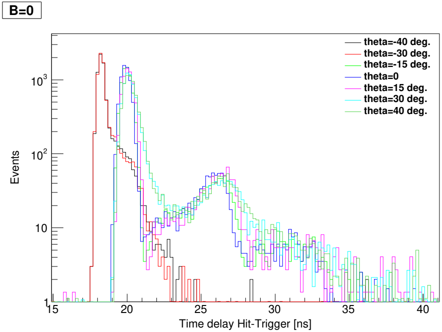
- data taken with disconnected Photo-cathode (+2200 V w.r.t. entry MCP) show 50 ps RMS,
- with Photo-cathode RMS is at least factor 3 worse, and mean shifted by +0.6 ns (time electron travels in 50 V/1.4 mm electric field is 0.58 ns),
- PicoQuant LDH-P-C-405 laser head has 44 ps FWHM pulse (19 ps RMS), thus fiber uncertainty 40 ps,
- initial electron energy 7 times lower than acceleration term, why RMS different?

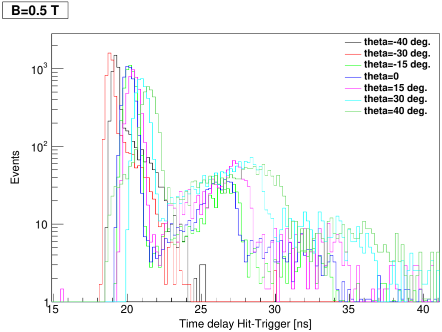




Coincidence time

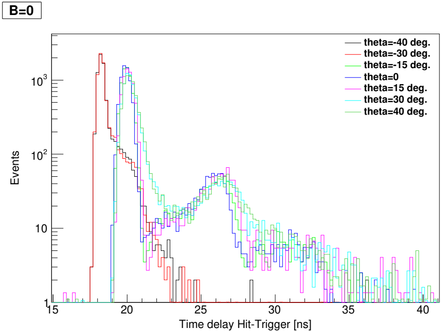
- before fiber movement we had secondary peak at +6.5 ns (and small one at +13 ns),
- after fiber movement it disappeared,
- the main peak has r.h.s. tail up to about 3 ns.

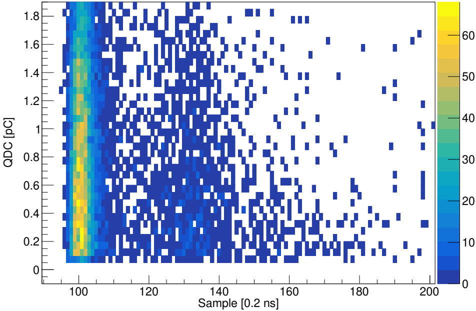




Coincidence time vs QDC

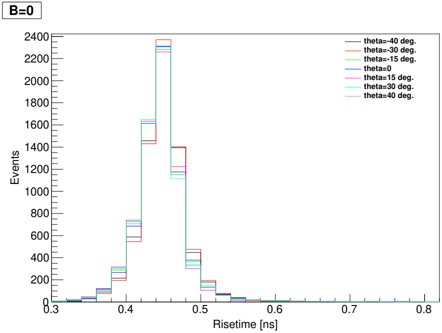
- the secondary peak appears for all charge values,
- it is not for small signals only.

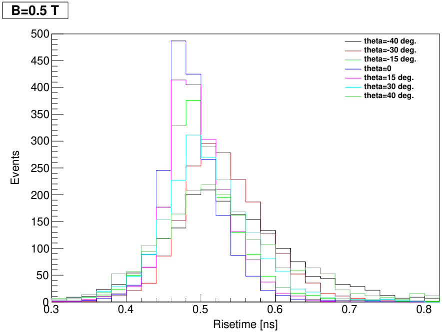




Rise-time vs B

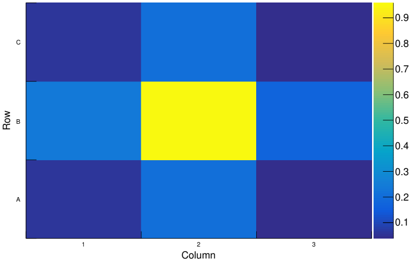
- at B=0 all risetimes are about 0.45 ns (V1742 limit),
- at B=0.5 T risetime depends on angle:
  0.48 ns at 0 deg.,
  0.52 ns at 40 deg.

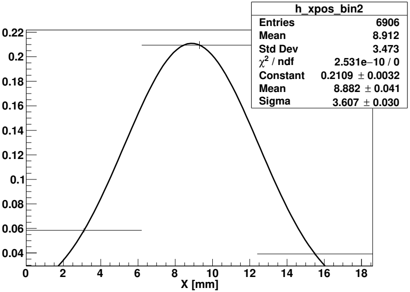


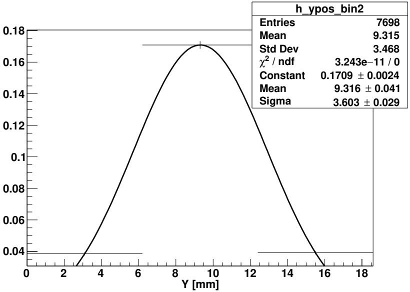


Spacial charge distribution B=0, $\theta = 0$ deg.

- spot in central pad (ch4),
- all angles in agreement,
- RMS about 3.6 mm.

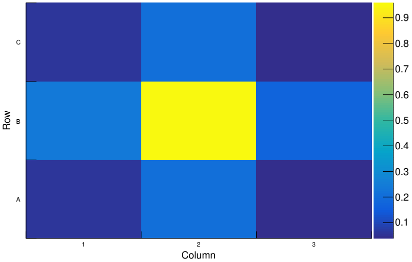


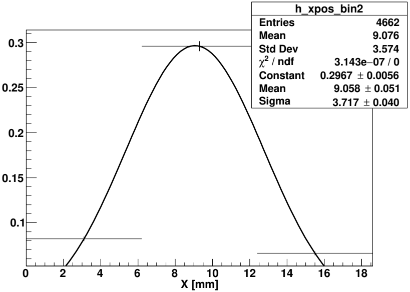


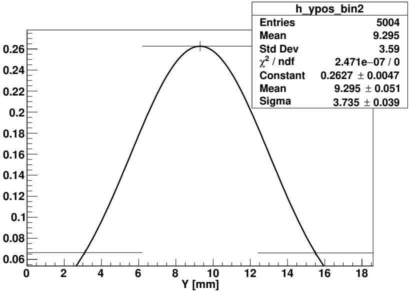


Spacial charge distribution B=0, $\theta = -40$ deg.

- offset in X: +0.2±0.05 mm,
- offset in Y: -0.02±0.05 mm,
- within uncertainties same position.

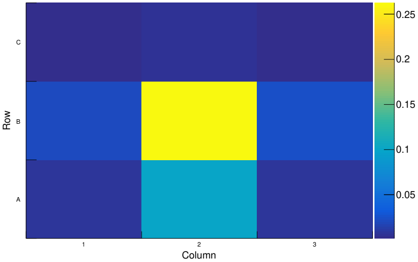


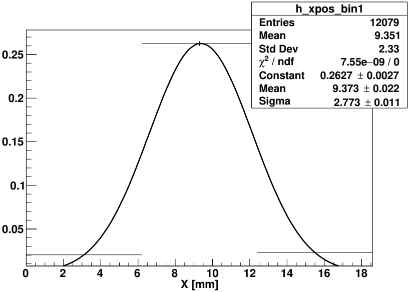


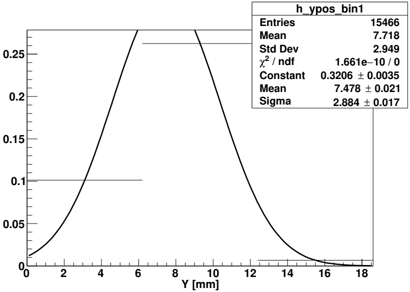


Spacial charge distribution B=0.5 T, $\theta = -15$ deg.

- offset in X: +0.3±0.2 mm,
- offset in Y: -1.8±0.05 mm,
- peak still in central pad.

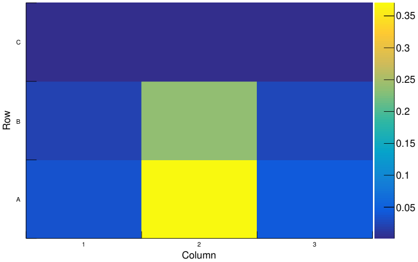


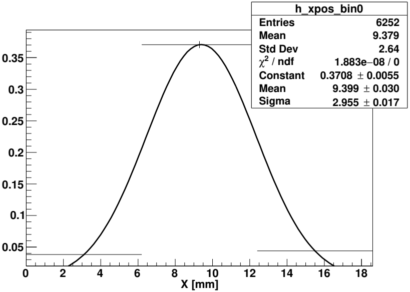


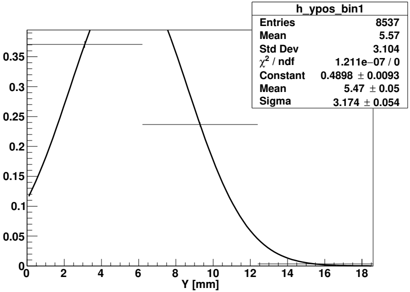


Spacial charge distribution B=0.5 T, $\theta = -30$ deg.

- offset in X: +0.5±0.05 mm,
- offset in Y: -3.8±0.05 mm,
- peak in first pad - need one pad more!

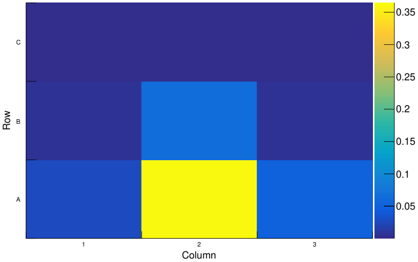


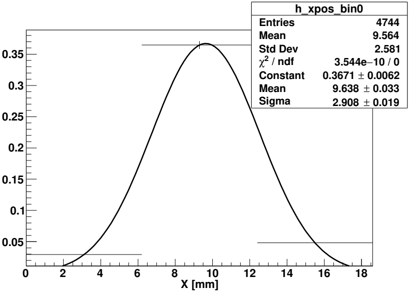


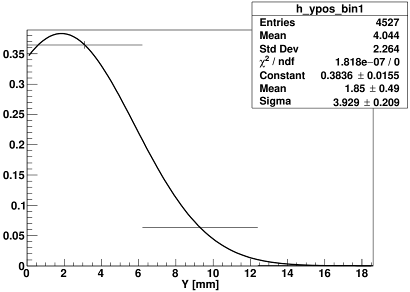


Spacial charge distribution B=0.5 T, $\theta = -40$ deg.

- offset in X: +0.55±0.1 mm,
- offset in Y: -7.4±2 mm,
- peak in first pad - need one pad more!

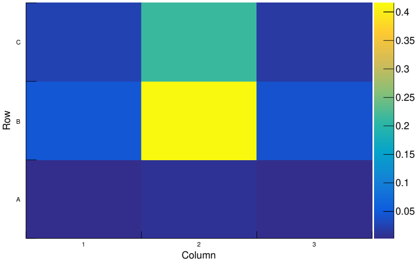


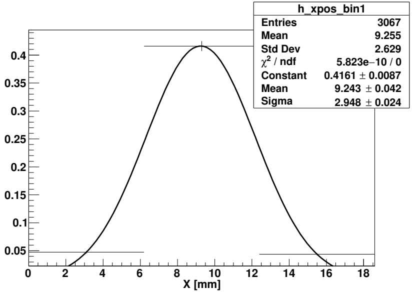


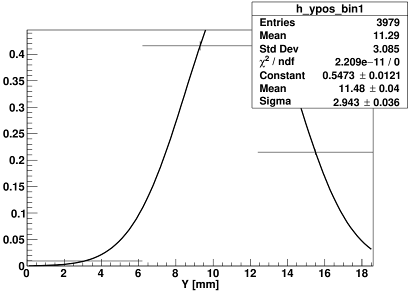


Spacial charge distribution B=0.5 T, $\theta = 15$ deg.

- offset in X: $+0.3 \pm 0.2$ mm,
- offset in Y: $+2.2 \pm 0.05$ mm,
- peak still in central pad.

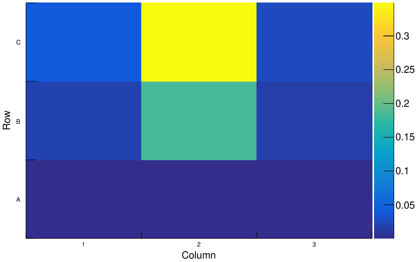


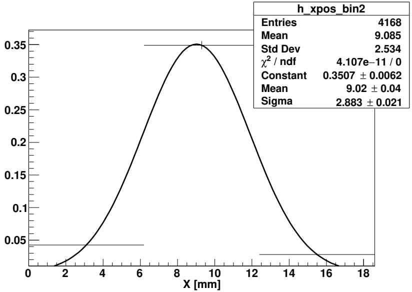


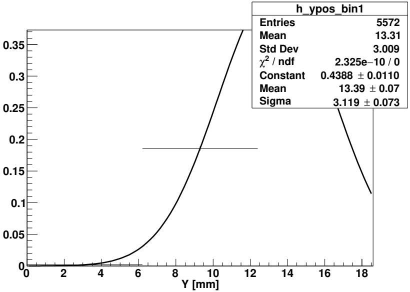


Spacial charge distribution B=0.5 T, $\theta = 30$ deg.

- offset in X: +0.5±0.05 mm,
- offset in Y: +4.1±0.05 mm,
- peak in first pad - need one pad more!

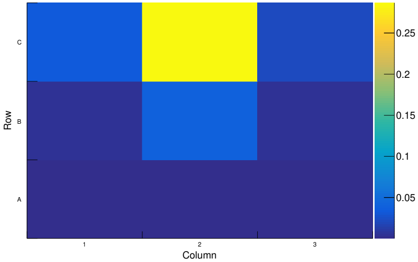


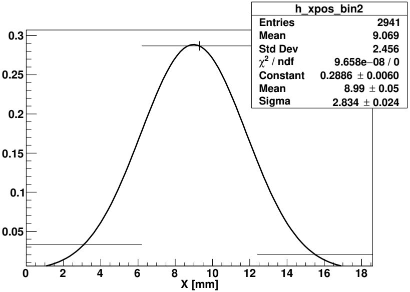


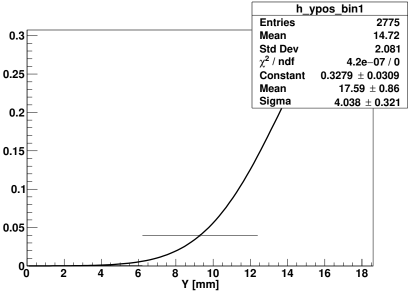


Spacial charge distribution B=0.5 T, $\theta = 40$ deg.

- offset in X: +0.55$\pm$0.1 mm,
- offset in Y: +8.3$\pm$2 mm,
- peak in first pad - need one pad more!

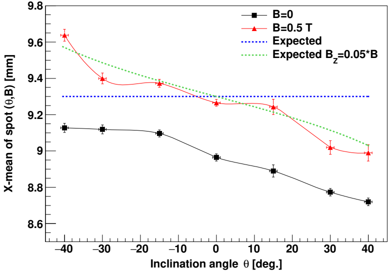


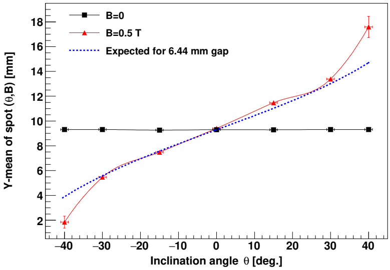




Collected charge spot position in B-field

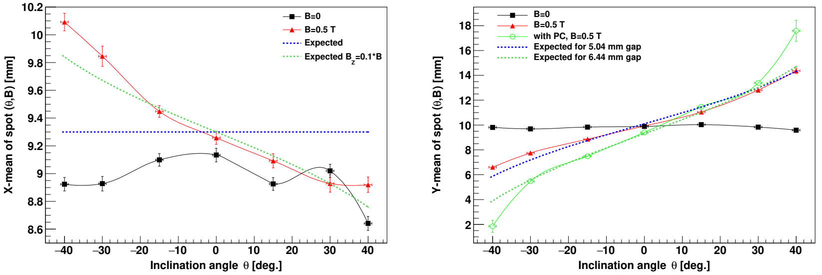
- X-positon is offset by -0.3 mm and moves with angle on 0.6 mm, at B=0.5 T it jumps by +0.2 mm;
- Y-position is well centered at expected 9.3 mm, at B=0.5 T it follows the expected 6.44*tan(θ) distribution except $\pm$40 deg. which are highly uncertain;
- -40 and -30 deg. are consistent with others;
- at $\pm$20 deg. offset =2.4 mm, spot will be almost equally shared between central and nearby pads.





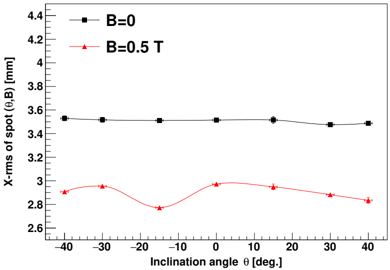
Collected charge spot position without PC

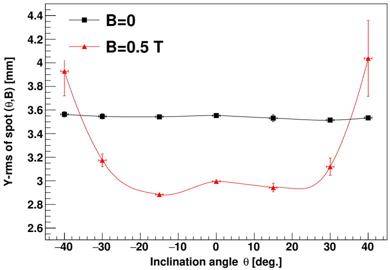
- X-positon is offset by -0.3 mm and 10% B-filed effect;
- Y-position is offset by +0.5 mm, at B=0.5 T it follows the expected 5.04*tan(θ) distribution;
- 1.4 mm difference in total gap height (with and without PC) is clearly visible.



Collected charge spot RMS in B-field

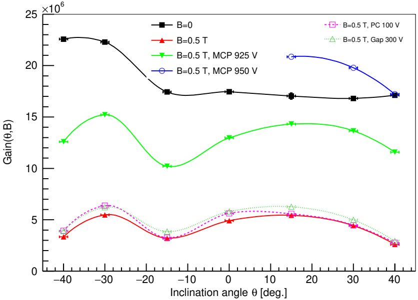
- X-resolution is 3.5 mm at B=0,
  at B=0.5 T it reduces to 2.9 mm (-17%);
- Y-resolution is consistently 3.5 mm at B=0,
  at B=0.5 T it reduces consistently to 2.9 mm (-17%),
  except uncertain edges ±40 deg.;
- -40 and -30 deg. are consistent with others.

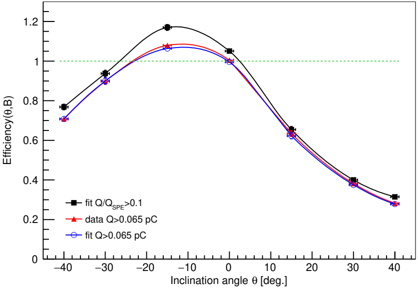




new LAPPD gain and efficiency at 875 V

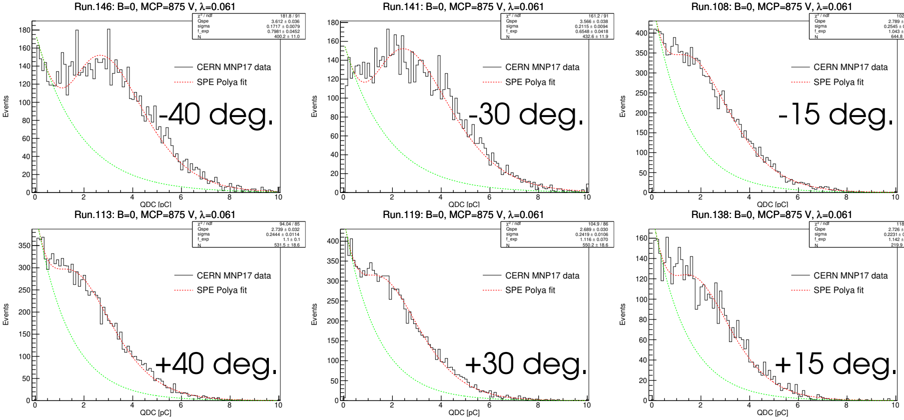
- confirm that at ±40 deg. and -15 deg. gain drops by -40%,
- efficiency: ratio of data or fit B=0.5 T/B=0 with pC or PE thresholds,
- all efficiency estimates are similar.





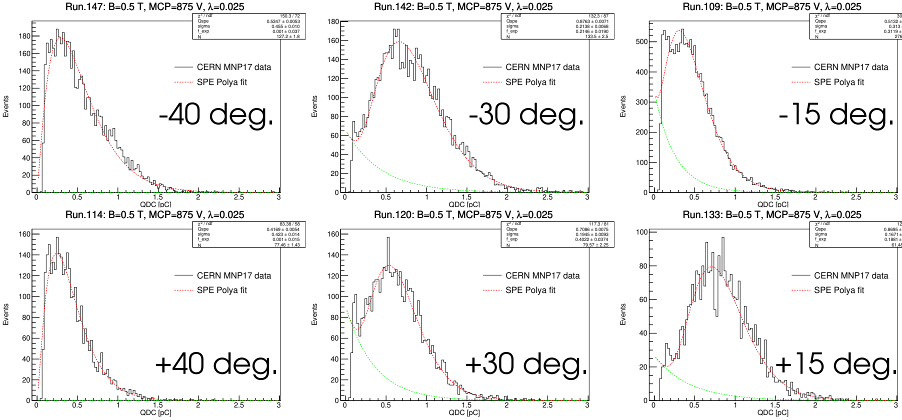
B=0 fits used in gain

- large exponential contribution;
- peak position is model-dependent (exponent shape), except for -40 and -30 deg.



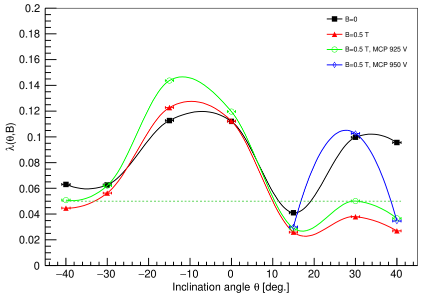
B=0.5 T fits used in gain

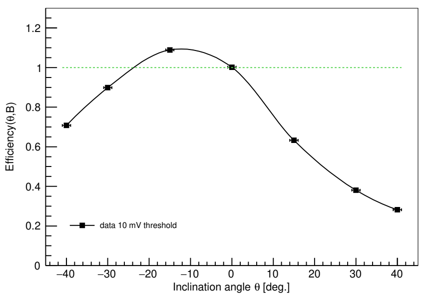
- at ±40 deg. threshold rise in data too steep;
- at -15 deg. double Polya (also very steep threshold rise).



Simple LAPPD gain and efficiency at 875 V

- our goal was to take data at $\lambda = 0.05$, but some runs were taken at $\lambda \simeq 0.10$;
- at $\lambda \simeq 0.10$ the probability to observe 2 PE events is =0.05 (at $\lambda = 0.05$ it is 2 times smaller =0.025);
- efficiency obtained simply from the ratio of coincidence events at B=0.5 T/B=0 in good agreement with more sophisticated estimates.





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 $\pm$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 positon from the fixed width fit comes on the expected $\tan\theta$-line.

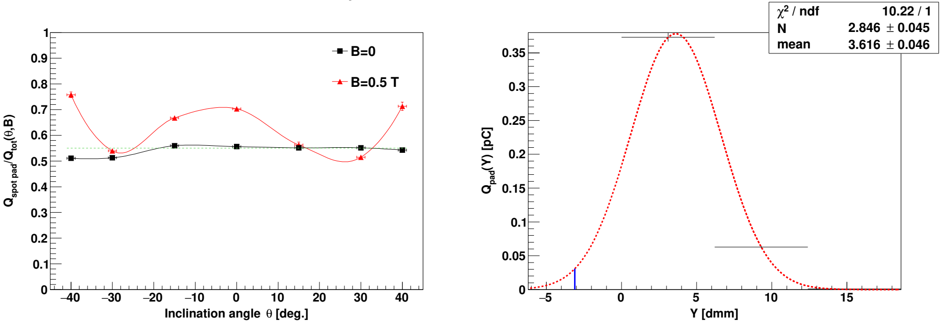
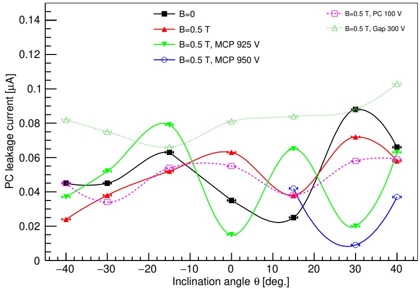


Photo-Cathode leakage current

- for 50 kHz/cm^2 DCR expected: 2×10^7 e/s=3.2 pA,
- observed current around 50 nA, four orders of magnitude larger,
- variations by factor of 2, high for 300 V gaps,
- almost no difference between 50 and 100 V at PC,
- PC isolation leakage:
  PC-Entry MCP =1 GΩ (depend on PC V) - excluded,
  PC-GND =44 GΩ - most likely.

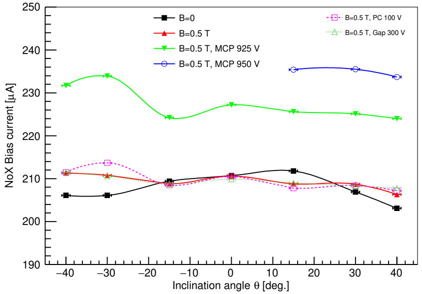


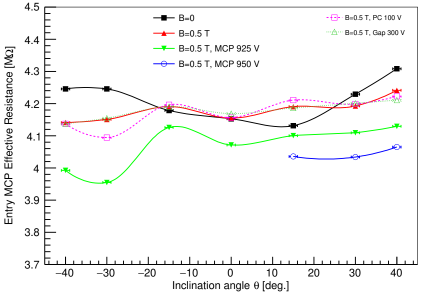
Entry MCP leakage current and resistance

- effective resistance of Entry MCP was $R_0 = 4.2\ \mathrm{M\Omega}$,

$$R_{eff}(V, I) = \frac{V_{set}}{I_{leakage}}$$

- resistance decreases with High Voltage,
- B-field had small effect.



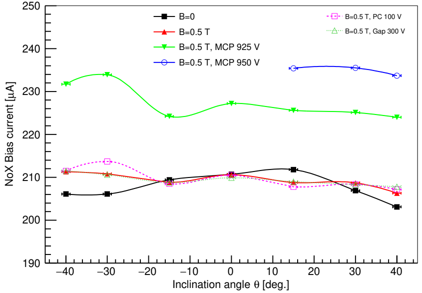


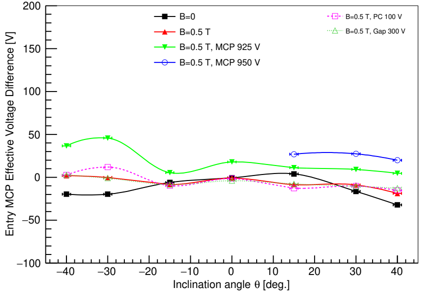
Entry MCP leakage current and voltage

- effective voltage deviation of Entry MCP was estimated assuming series connection:

$$\Delta V_{eff}(V, I) = I_{leakage} \times R_0 - V_{set}$$

- 5 μA deviation gives 20 V voltage offset,
- at higher MCP bias resistance changes.



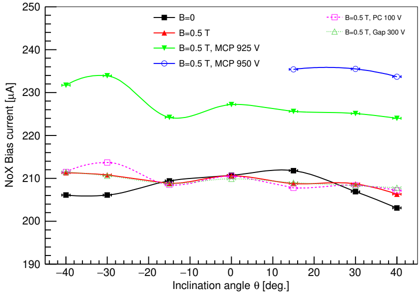


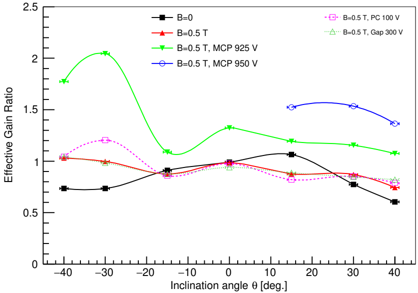
Entry MCP leakage current and gain

- effective gain ratio of Entry MCP was estimated:

$$\frac{G_{eff}(V,I)}{G_0} = \exp\left\{\frac{d\ln G}{dV}\frac{(I_{leakage}\times R_0 - V_0)}{2}\right\}$$

- 5 μA deviation gives 30% gain offset,
- B-field had small effect.



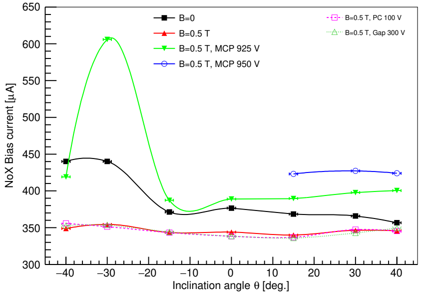


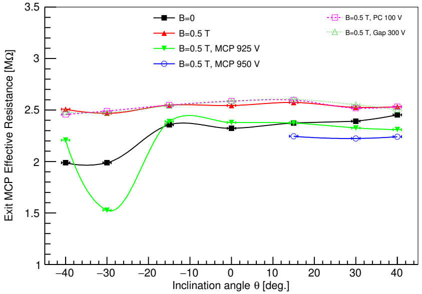
Exit MCP leakage current and resistance

- effective resistance of Exit MCP was $R_0 = 2.2\ \mathrm{M}\Omega$,

$$R_{eff}(V, I) = \frac{V_{set}}{I_{leakage}}$$

- resistance decreases with High Voltage,
- +10% B-field effect, not seen in Entry MCP.



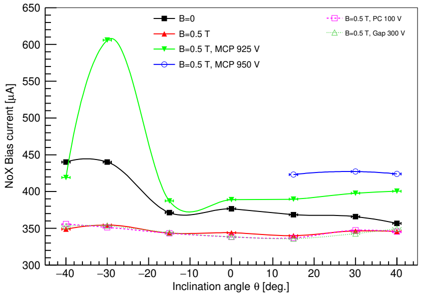


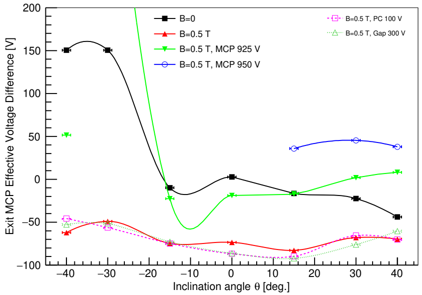
Exit MCP leakage current and voltage

- effective voltage deviation of Exit MCP was estimated assuming series connection:

$$\Delta V_{eff}(V, I) = I_{leakage} \times R_0 - V_{set}$$

- 20 μA deviation gives 50 V voltage offset,
- at higher MCP bias resistance changes.



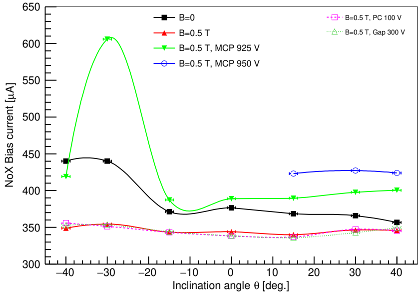


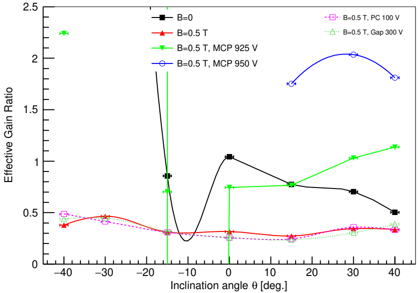
Exit MCP leakage current and gain

- effective gain ratio of Exit MCP was estimated:

$$\frac{G_{eff}(V,I)}{G_0} = \exp\left\{\frac{d\ln G}{dV}\frac{(I_{leakage}\times R_0 - V_0)}{2}\right\}$$

- 20 μA deviation gives 50% gain offset,
- 0.5 T B-field gives -50% effect, not seen in Entry MCP.





Lessons learned I

1. avoid touching optical fiber: 35% variation of gain,
2. at low gain ambiguous SPE-charge reconstruction: higher MCP voltage in B-field? But it is unstable at B=0.
3. extrapolating to B=1.5 T expect $<$2% gain (at B=0.5 T was 25%), QDC shoulder will shrink from 0.7-1 pC (B=0.5 T) to 0.04-0.06 pC. This is below actual threshold of 0.2 pC. Can we measure at much lower threshold? Or shall we increase laser intensity and measure 10 PE peak?
4. at $\pm$30 deg. charge spot moves to the edge of instrumented 3x3 pad array: solder remaining 4 pads and add SMA connectors!
5. angular gain variations are seen only around $\theta = -13$ deg. and $|\theta| > 40$ deg.: enough measure at 0, $\pm$13 deg., $\pm$40 deg. and higher.

Lessons learned II

1. bad timing resolution with PC not understood,
2. does it depend on the laser intensity?
3. for NA=0.22, 200 μm core straight fiber TIR every $\geq$1.3 mm, corresponding to $\geq$6.4 ps,
4. RMS$\sim$40 ps residual (observed without PC) suggests 6.3 TIRs FWHM, or 8 mm of fiber length,
5. test (in Trieste) fibers of different length and different core sizes,
6. test (in Trieste) time resolution as a function of fiber bending,
7. test (in Trieste) time resolution as a laser intensity,
8. test (in Trieste) charge collection as a function of fiber bending.

Summary

- tested 10 μm pore LAPPD N.153 capacitively coupled to custom readout board with 6 mm pads,
- tests performed at CERN MNP-17 magnet at 0.5 T,
- in 0.5 T field gain was reduced by factor 0.25,
- gain reduction was almost independent of angle, except $\theta = -13$ deg. and $|\theta| \geq 40$ deg.,
- 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,
- timing resolution was not understood (but B=0.5 T effect is relatively small),
- spacial resolution improves in B=0.5 T field.

References

1. M. Amarian *et al.*, "The CLAS forward electromagnetic calorimeter", *Nucl. Instr. and Meth.* **A460**, 239 (2001).
2. M. Guillo, "EC Time Calibration Procedure for photon runs in CLAS", CLAS-Note-2001-014, 2001.
3. M. Osipenko, "Geometrical alignment of CLAS DCs using tracks with constrained vertex", CLAS-Note-2019-001, 2019.

Backup slides

Polya approximation

- Polya distribution approximates events following a sequence of Poisson processes proceeding with slightly different rate parameters,
- For a large number of multiplied electrons, the Polya distribution approaches a Gamma distribution:

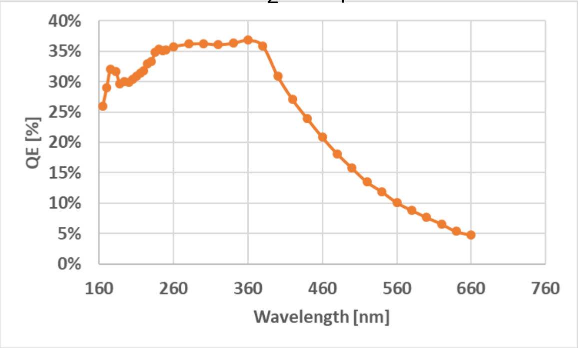
$$Polya(q;\mu,b) = \frac{1}{b\mu\Gamma(\frac{1}{b})}\left(\frac{q}{b\mu}\right)^{\frac{1}{b}-1} e^{-\frac{q}{b\mu}}$$

μ is the distribution mean, and b is unitless relative gain variance.

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



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

Optical fiber propagation time variance

- laser head LDH-P-C-405 operates at 405 nm,
- quartz refractive index $n(405\ nm) = 1.4698$, light group velocity $v_g \simeq 21$ cm/ns,
- optical fiber NA=0.22 maximum photon angle inside core:
$$\theta_{core}^{max} = asin\left(\frac{NA}{n_{core}}\right) = 8.6^o\ ,$$
- fiber length traveled by a photon between TIRs in $D = 200\ \mu$m fiber:
$$l_{TIR} \geq \frac{D}{\tan\theta_{core}^{max}} = 1.3\ mm\ ,$$
- photon path length variation (inclined-straight):
$$\frac{\frac{l_{TIR}}{\cos\theta_{core}^{max}} - l_{TIR}}{l_{TIR}} = 0.0114\ ,$$
- assuming flat angular distribution (for SM NA=0.12 fiber 3.4 times smaller): $RMS = \frac{0.0114}{\sqrt{12}} \frac{1\ m}{21\ cm/ns} = 16$ ps.