Plan of the ARICH upgrade

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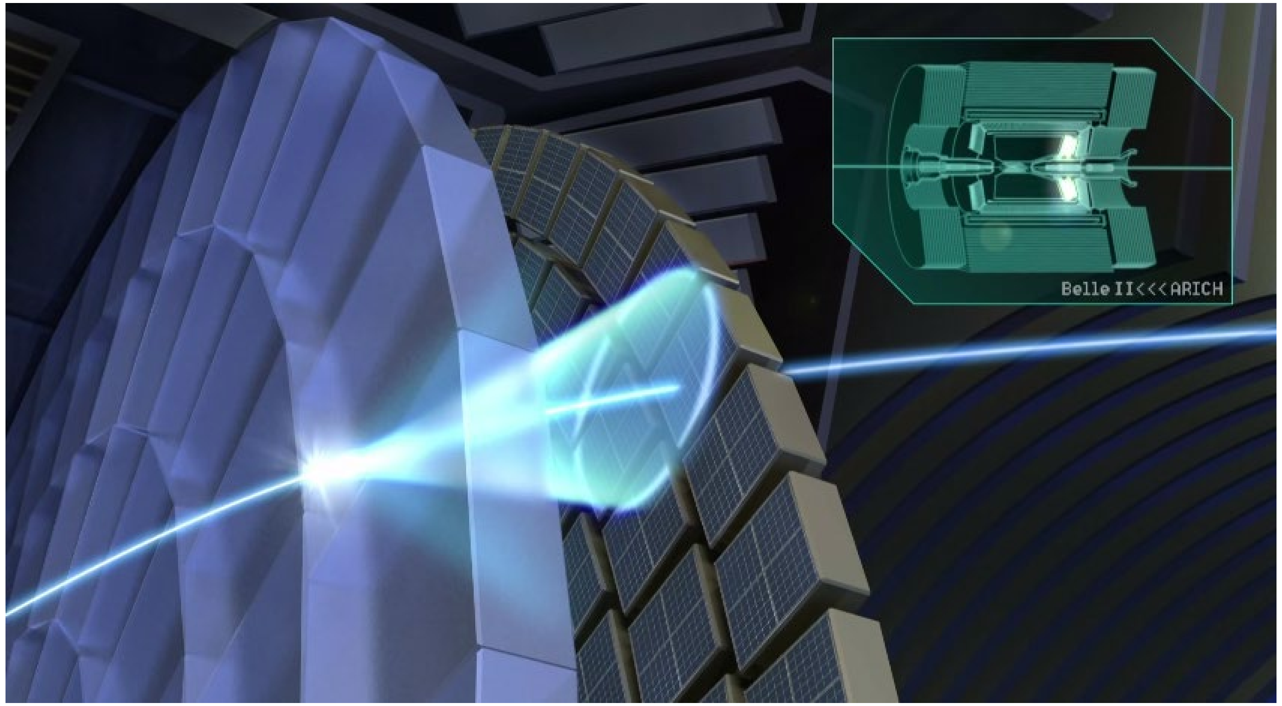
B1 Heavy Flavor and Dark Matter Joint Unit Symposium, 30 March 2023, Nagoya

Outline:

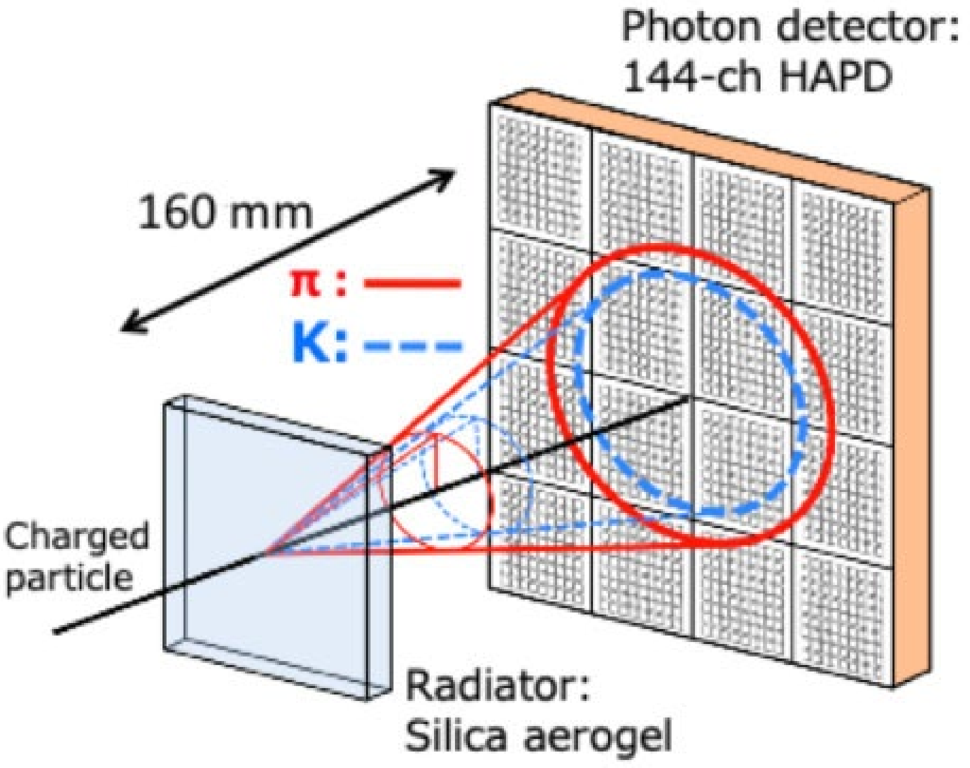
- Belle II ARICH:
  - operation status
  - upgrade considerations
    - aerogel radiator
    - photon sensor
      - LAPPD tests
    - electronics
      - LAPPD test with FastIC

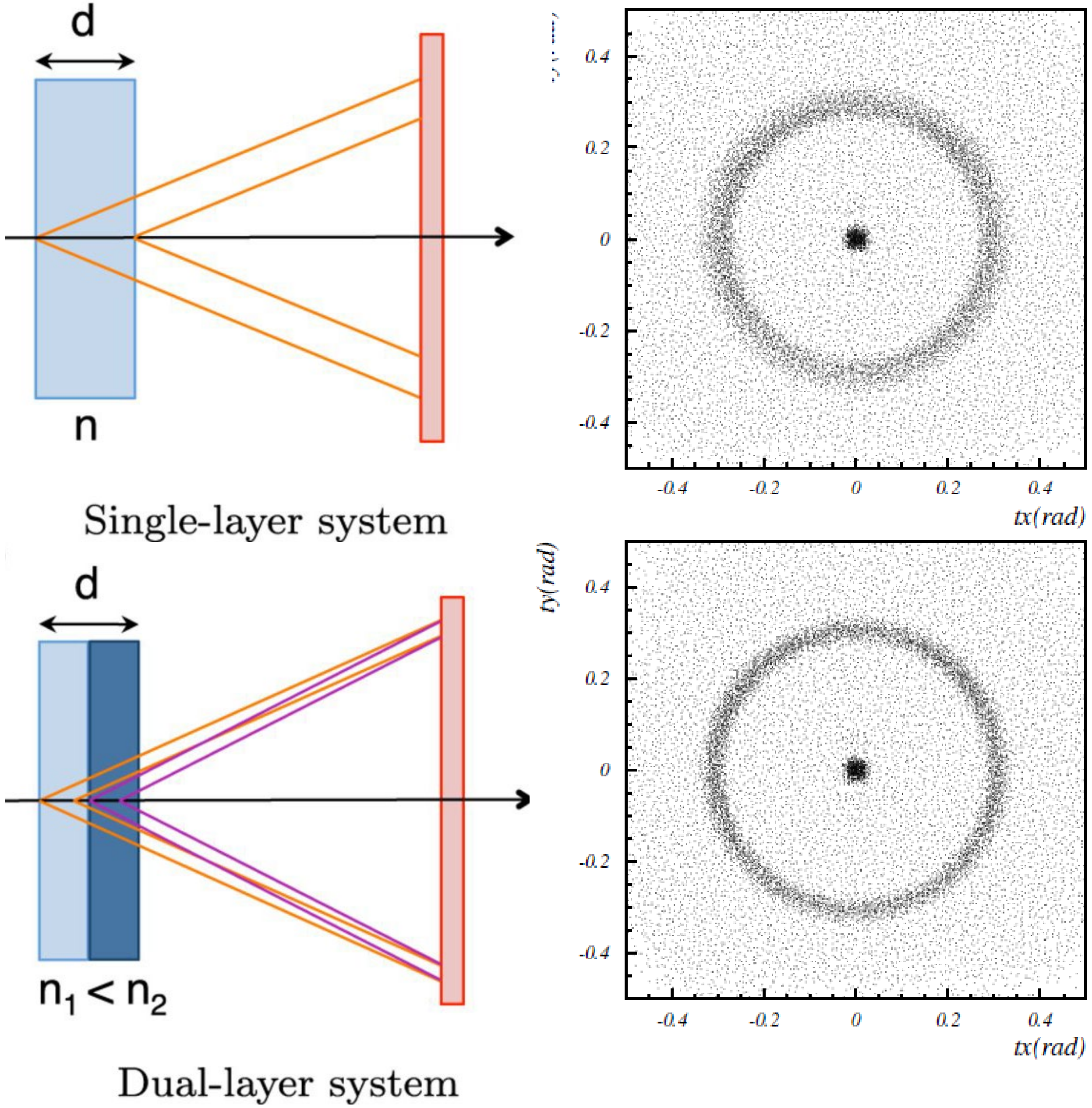


ARICH - basics

Proximity focusing Aerogel Ring Imaging CHerenkov detector (ARICH) components:

- double layer focusing aerogel radiator (20 mm + 20 mm)
- 160 mm expansion gap
- photon detector based on 420 Hybrid Avalanche Photo Detectors (HAPD)
- front-end electronics with dedicated ASICs and FPGAs

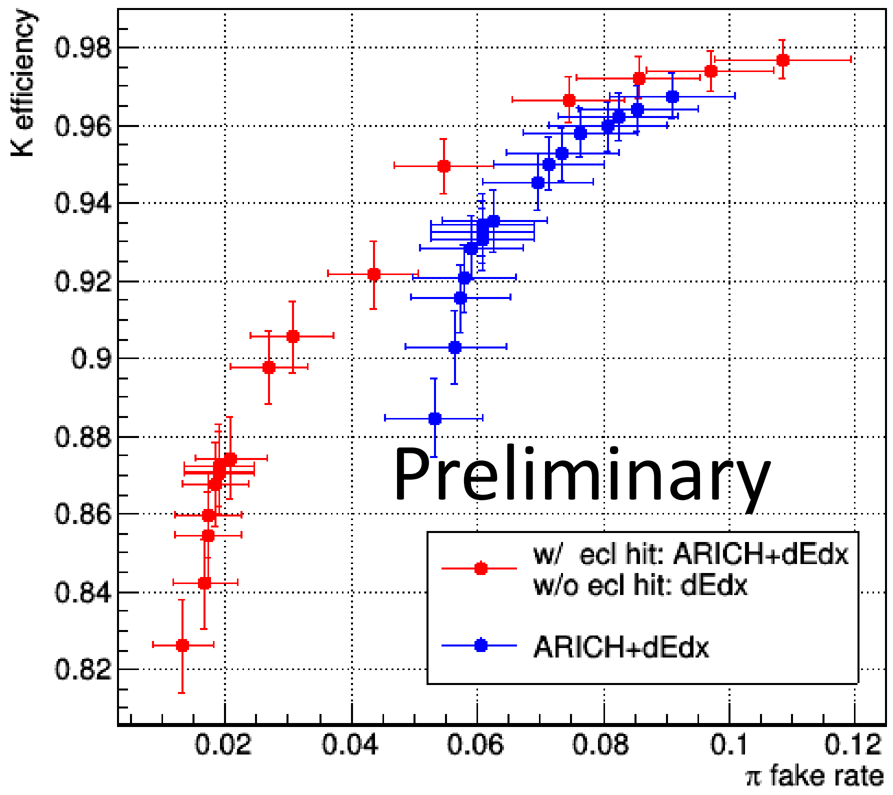


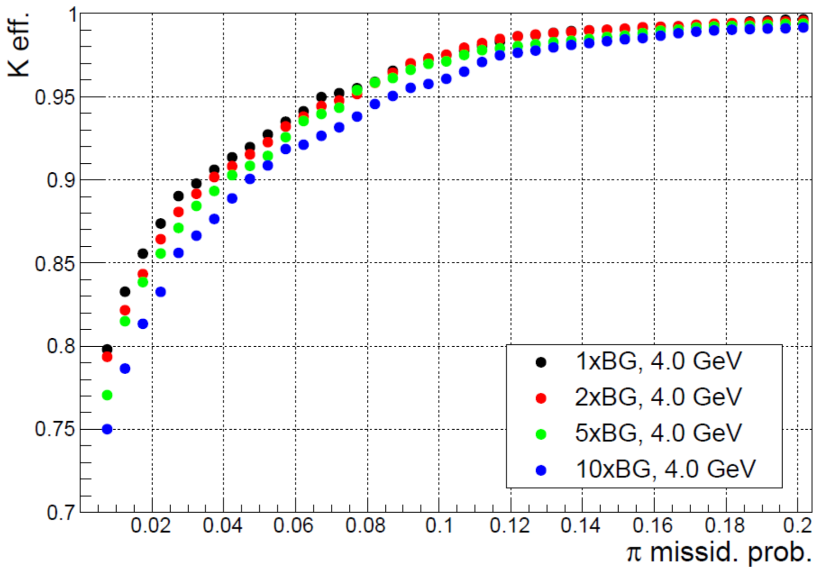


Combined PID – strong scattering/decay

- Large fraction of misidentified pions, especially at low momenta, are due to pions that are strongly scattered or decay on their way to ARICH detector.
- Due to missing photos around extrapolated track position such tracks are likely to be identified as kaons.
- Such tracks can be identified by missing ECL cluster and/or missing signal in case of tracks hit in HAPD window.
- Only minor loss of performance with 25% loss of HAPDs or 10 fold increase of nominal background

Combined CDC and ARICH PID

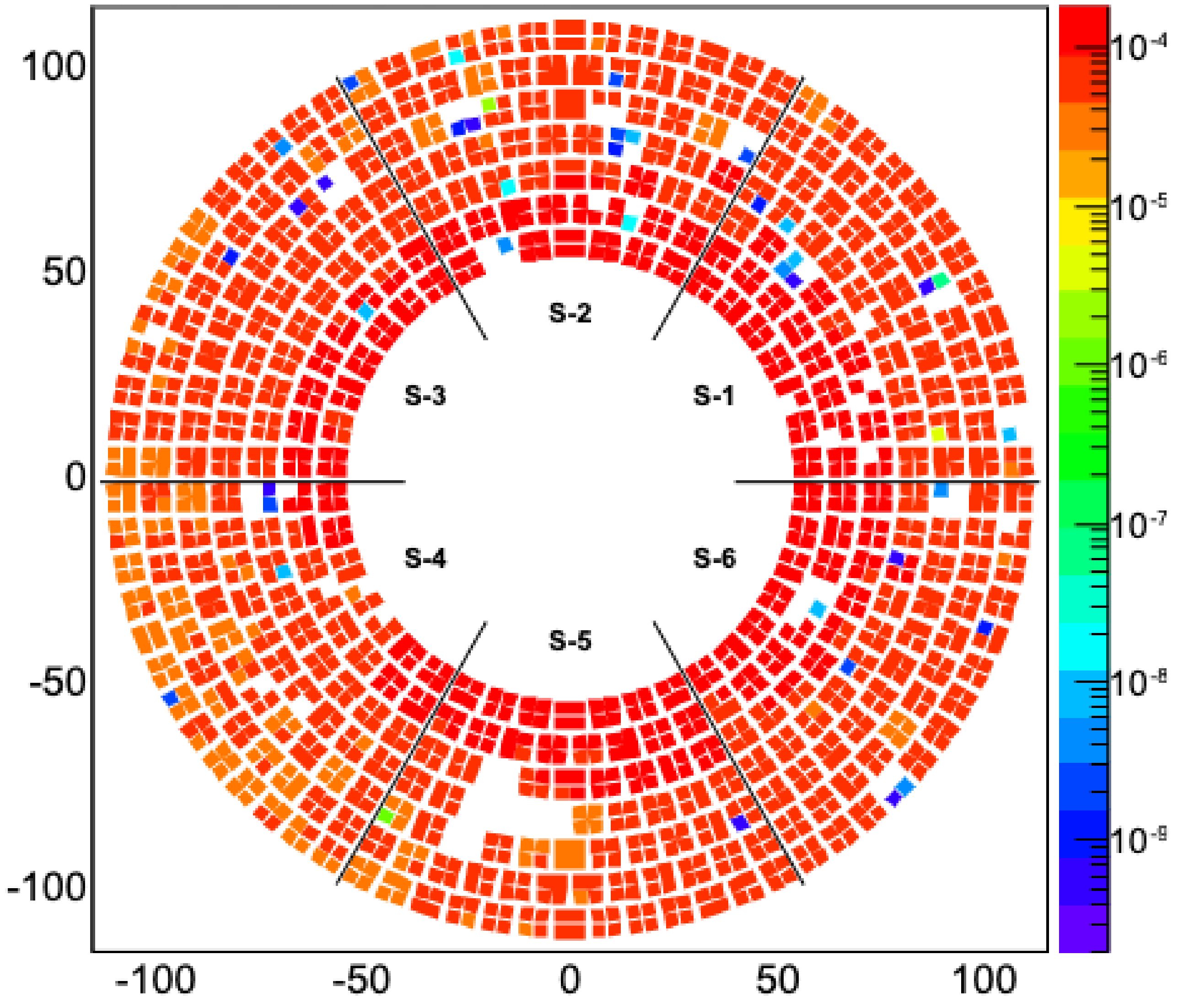




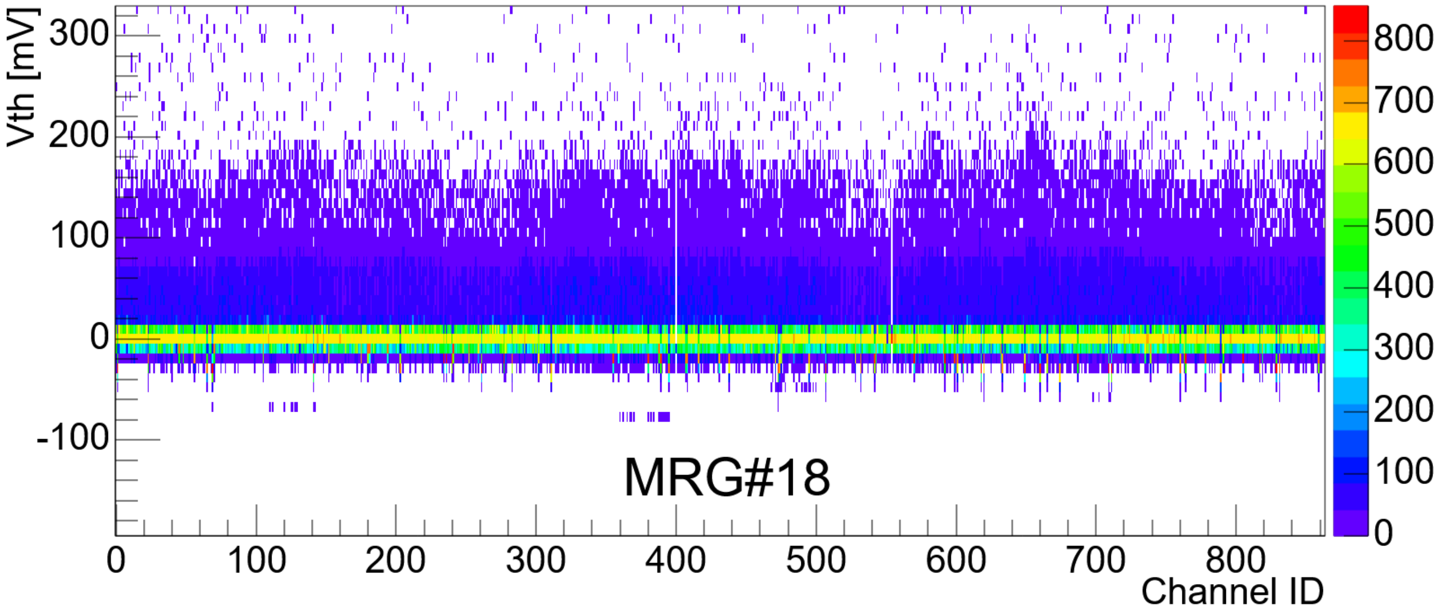
ARICH operation status before LS1

Since March 2019 ARICH is fully operational.

- Current status:
  - $\approx 94\ \%$ of ARICH channels operational
  - $\approx 1\ \%$, 1 merger group with 5 HAPD modules, off due to LV cable problem
  - $\approx 5\ \%$, off due to HV or bias problems – different reasons under study
- Electronics efficiency for single photon signals well above 90% – threshold set at $50\ \mathrm{mV}$.



- Average hits per APD per event – white, blue, green are inactive APDs



- Thershold scan for all the channels connected to merger 18 - LED illumination

ARICH upgrade considerations

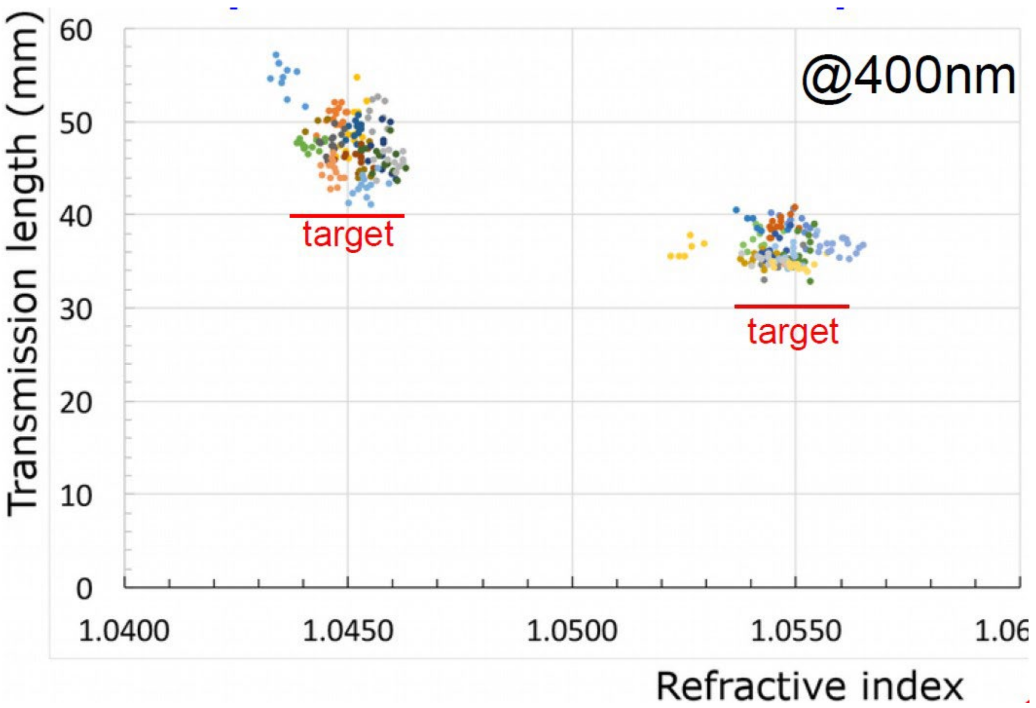
LS1 (in progress):
- LV cable repair – DONE!
- firmware upgrade – BRAM based pipeline

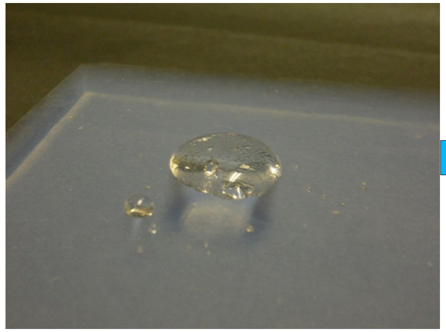
LS2:
- repair of HAPDs and replacement with available spares (order of 10)
- aerogel radiator upgrade - under consideration, to partially compensate for loss of HAPDs

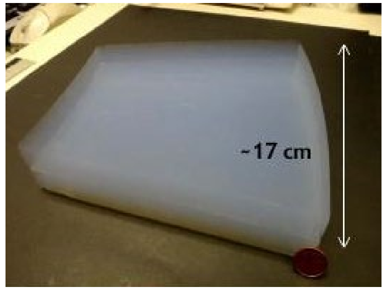
Beyond LS2 (long term):
- photon detector upgrade:
  - replacement of HAPDs with MCP-PMTs or SiPMS
  - new front-end electronics compatible with sensors
  - new mechanics, cooling …

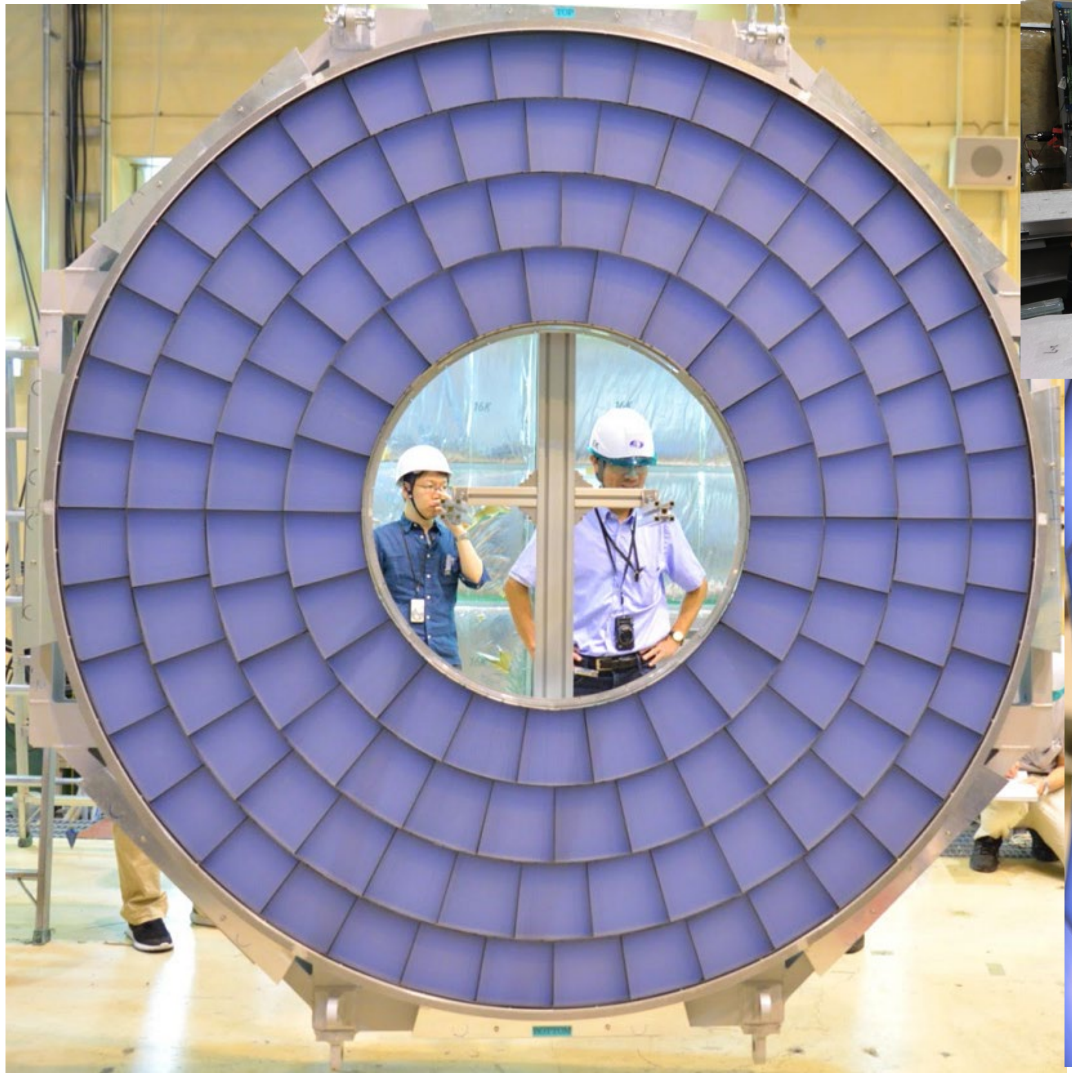
Aerogel radiator

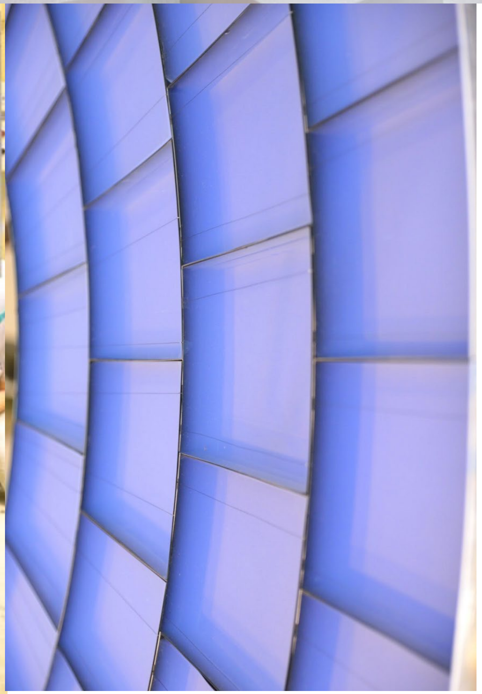
- two layers of $20\ mm$ thick hydrophobic aerogel :
  - upstream, $\mathrm{n} \approx 1.045, \lambda_{400\ nm} \approx 45\ \mathrm{mm}$
  - downstream, $n = 1.055\ , \lambda_{400nm} \approx 35\ \mathrm{mm}$
- 4 segmented rings, 2×124 tiles
- all but exit surface of each pair covered by black paper
- each pair fixed by two black strings running radially
- completed in December 2016









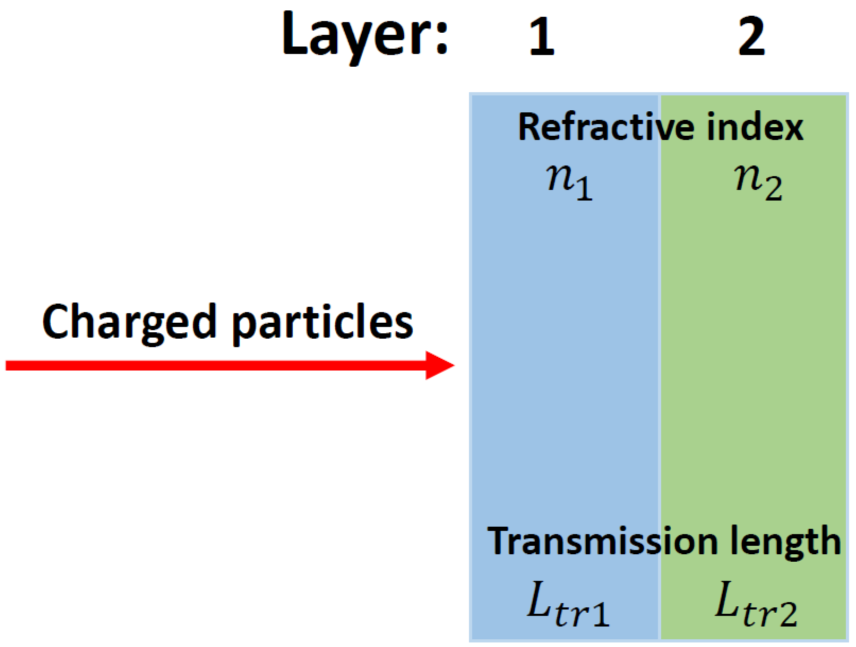


Aerogel radiator upgrade options

Aerogel radiator options under consideration if transmission length can be increased – retry pinhole dried aerogels?

- increase of downstream layer transmission length by factor1.5
- increase of transmission length of both layers by factor 1.5
- increase of refractive index of both layers provided that transmission length remains the same:
  - $n_1: 1.045 \rightarrow 1.055$
  - $n_2: 1.055 \rightarrow 1.065$
- possible introduction of acrylic filter to reduce detection of scattered photons (short λ)

Current Aerogel parameters



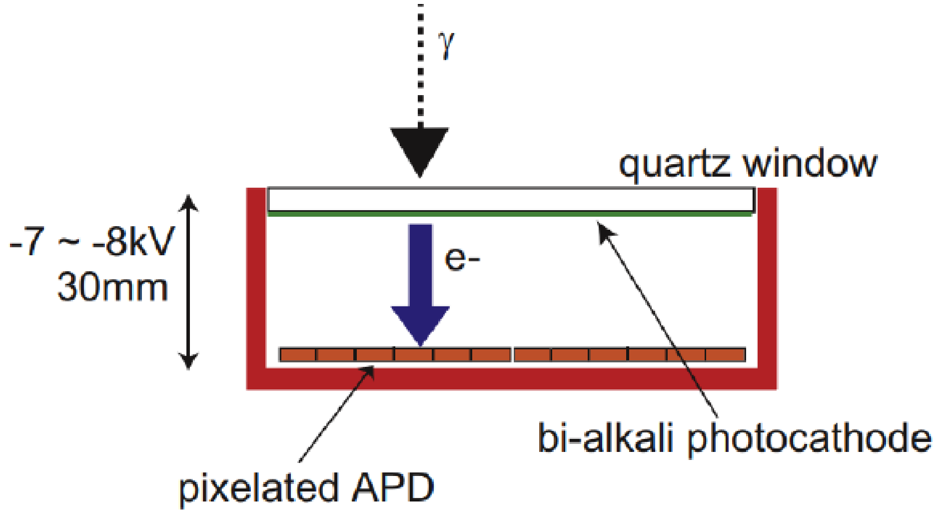
<Average parameters>

$$n_1 = 1.045$$
$$n_2 = 1.055$$

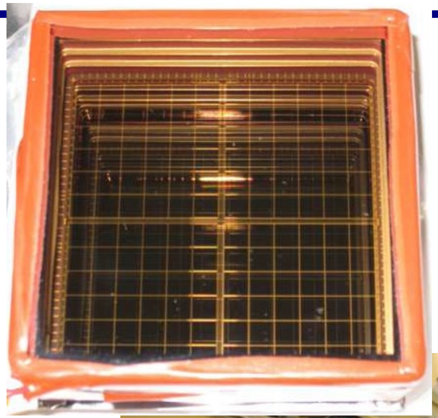
$$L_{tr1} = 45mm$$
$$L_{tr2} = 35mm$$

Preliminary studies show largest improvement for refractive index increase. Further studies needed in combination with loss of photon detector performance.

Photon detector - HAPD

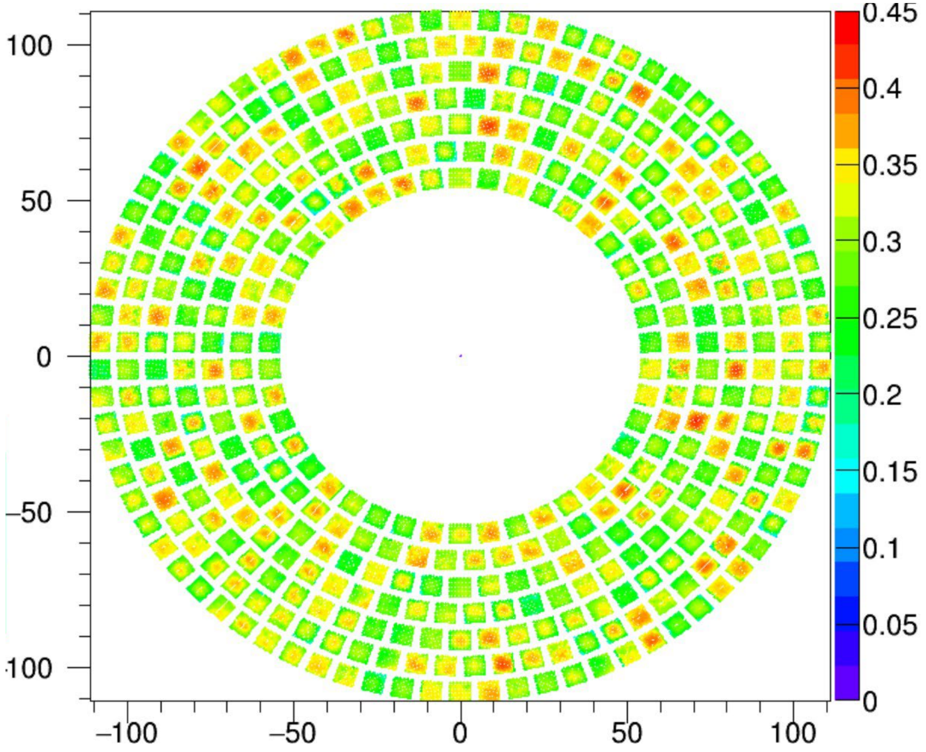


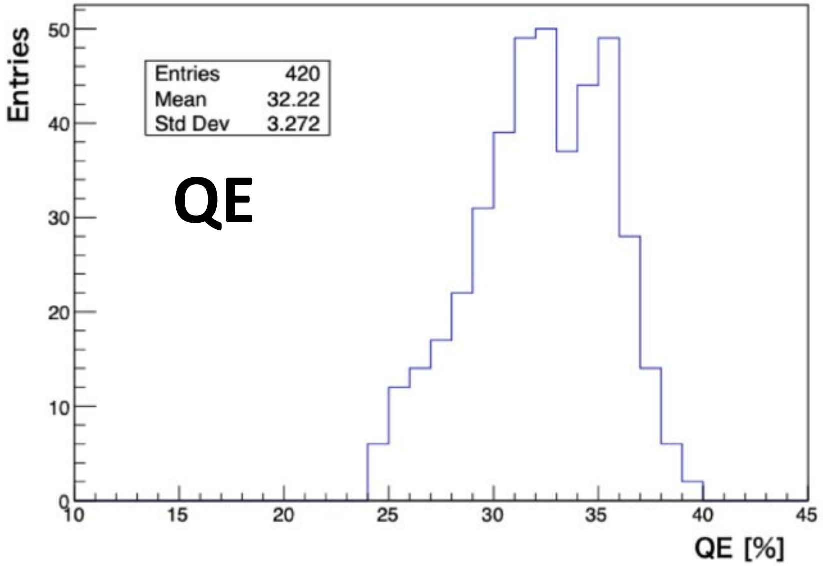
Photon detector is constructed from 420 HAPD modules.

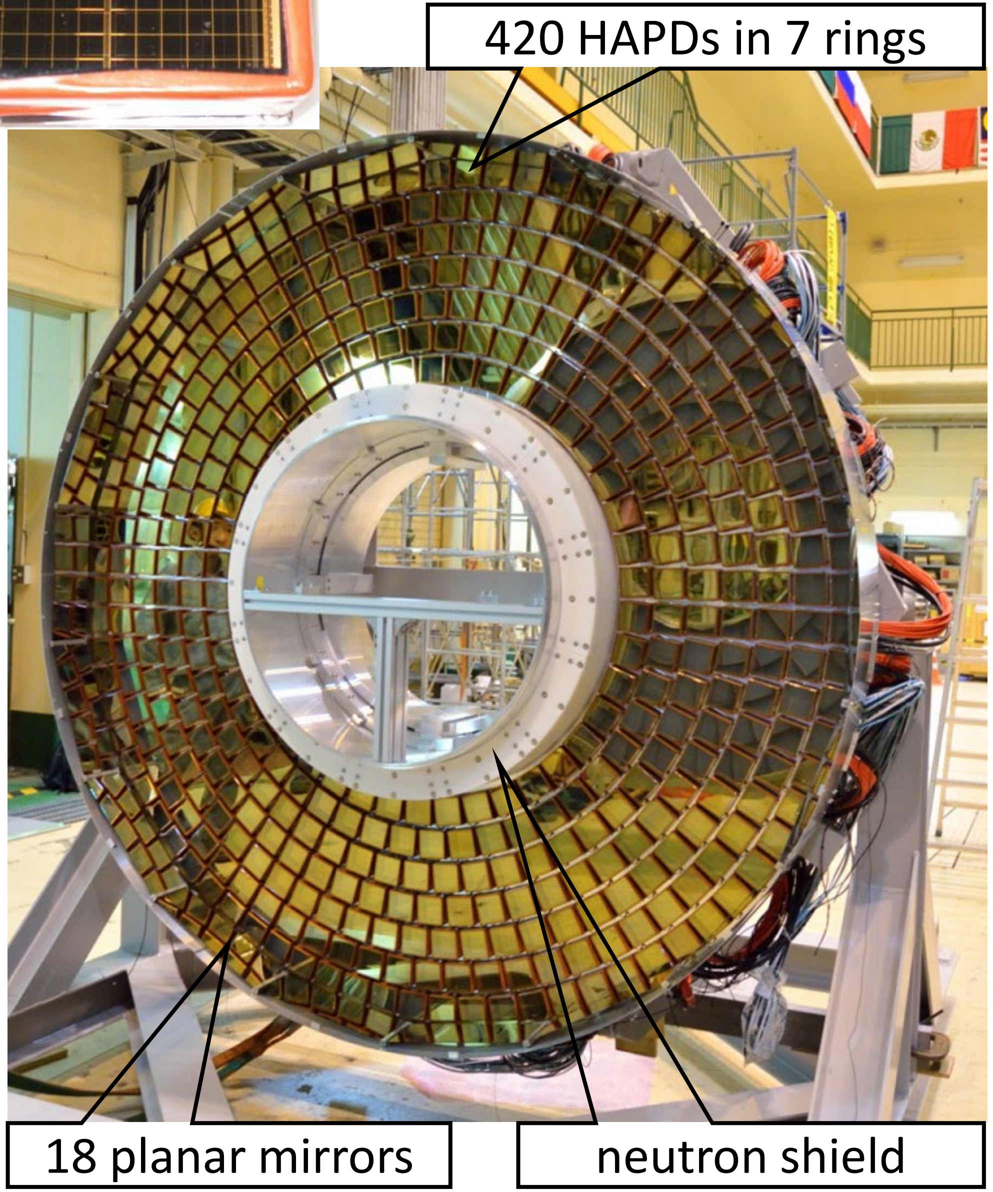


HAPD properties:

- size: $73 \times 73 \times 28\ \mathrm{mm}^3$
- 2×2 APDS with 6×6 channels, $4.9 \times 4.9\ \mathrm{mm}^2$ @ 5.1mm pitch
- $< QE_{400nm} > \approx 32\ \%$
- combined gain $\approx 70\mathrm{k}$
- channel capacitance $80\ \mathrm{pF}$
- operation in $\mathrm{B} = 1.5\ \mathrm{T}$
- radiation tolerance $\approx 10^{12}\ \frac{n_{1MeV}}{\mathrm{cm}^2}$



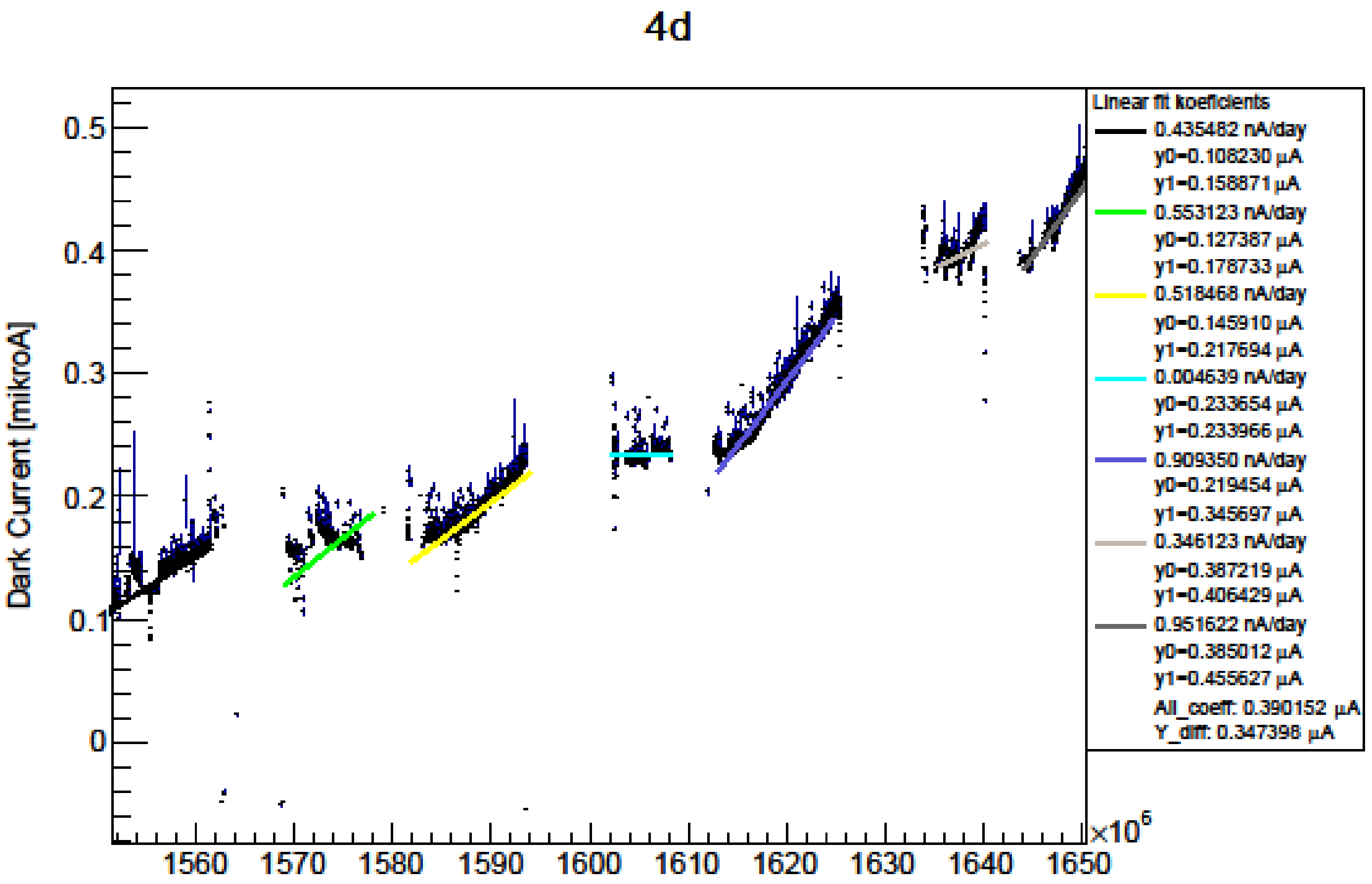


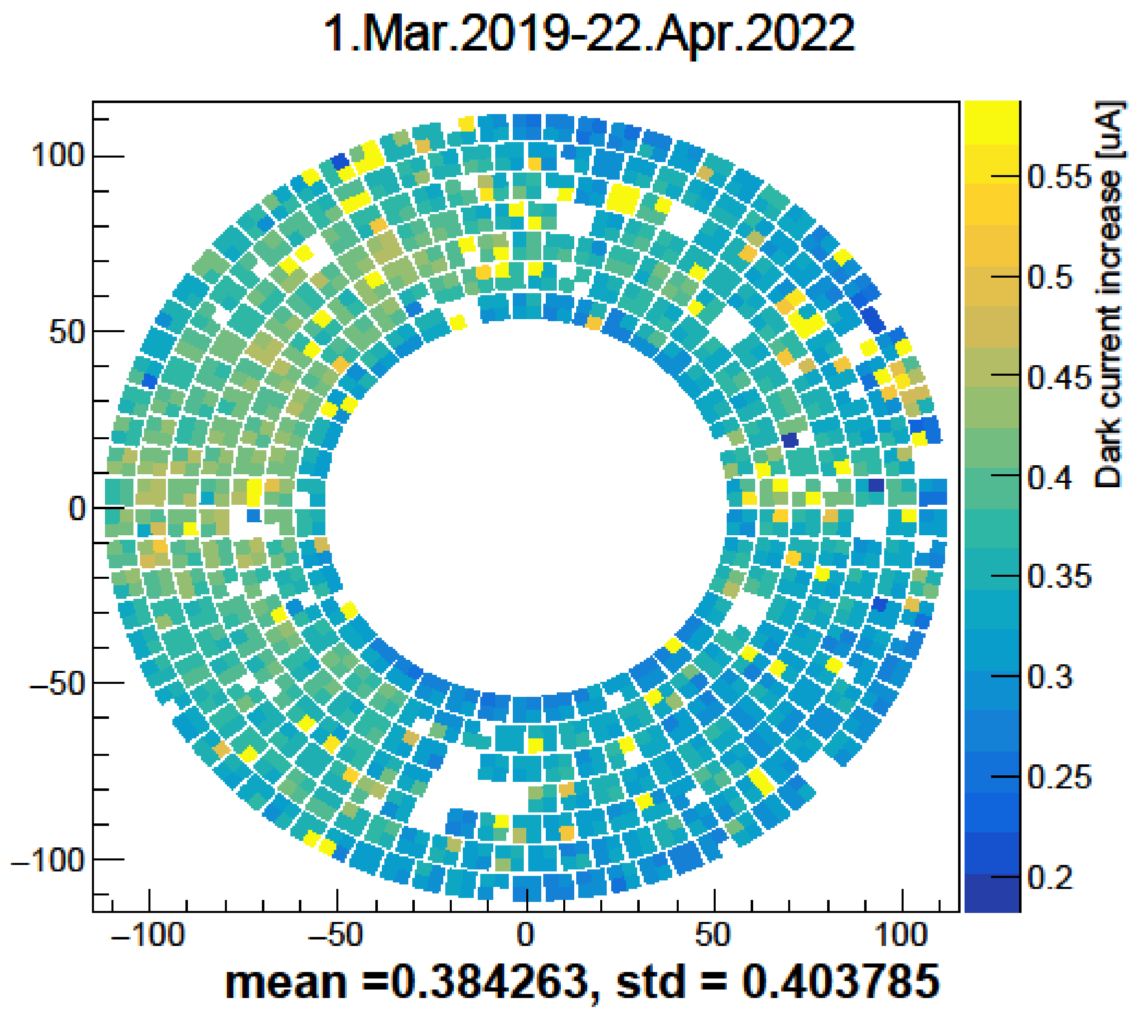


HAPD leakage current - fluence

Neutron fluence estimate:

- Average increase of leakage current $\approx 400\ nA/APD$ $(30\ nA \rightarrow \approx 10^{9}\frac{n_{eq}}{cm^2})$
- fluence estimate: $\Delta I_b \approx 400\ nA \rightarrow \approx 1.3 \cdot 10^{10}\frac{n_{eq}}{cm^2} \rightarrow$ more than one order below total expected from simulation
- expected to operate at least up to $10^{12}\frac{n_{eq}}{cm^2}$



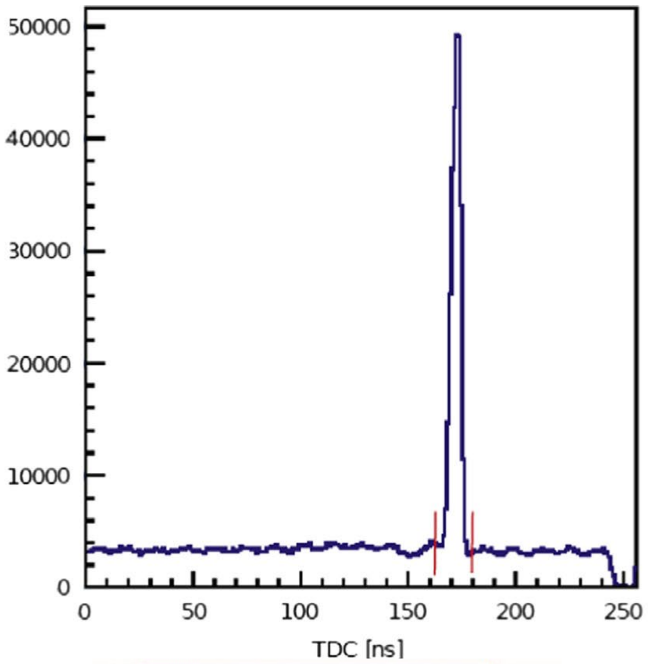


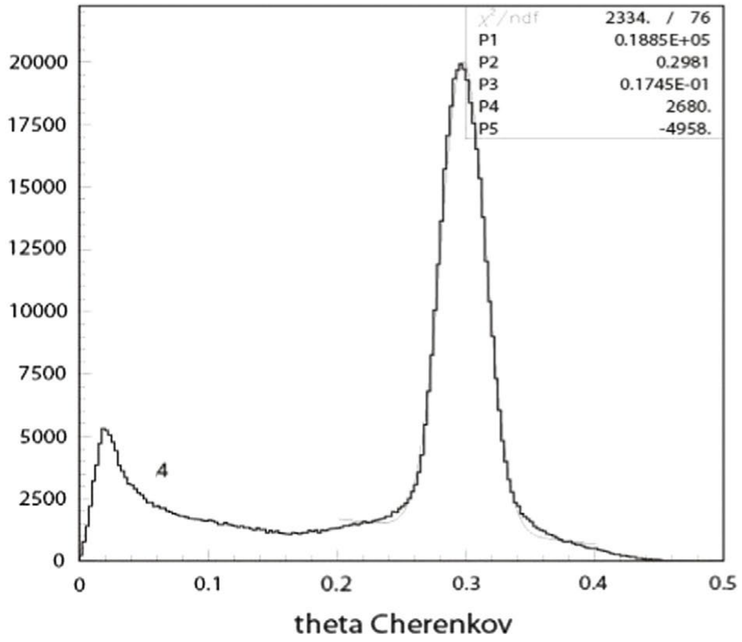
SiPM for ARICH: early tests

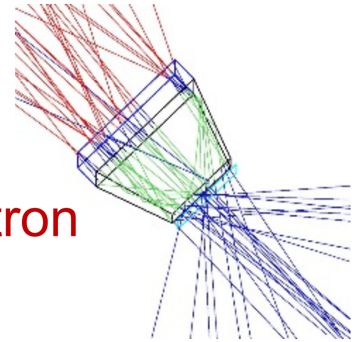
ARICH photon detector module prototype:

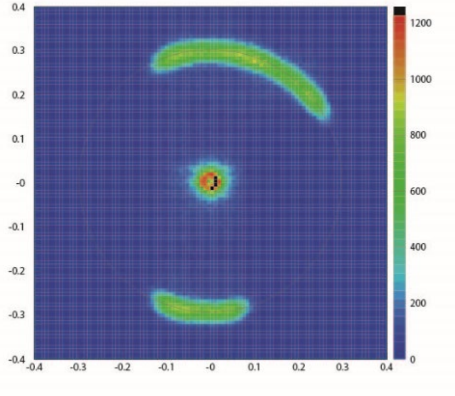
- Hamamatsu 64 channel MPPC module S11834-3388DF, 8×8 array of $3 \times 3\ mm^2$ SiPMs @ $5\ mm$ pitch
- matching array of quartz light concentrators used
- two $20\ mm$ thick aerogel tiles in focusing configuration $(\mathrm{n} = 1.045, 1.055)$
- tested in $5\ GeV$ electron beam at DESY
- estimated 36 hits on full ring

- electronics with < 1 ns resolution
- radiation hardness – DCR increase by neutron irradiation?
- cooling

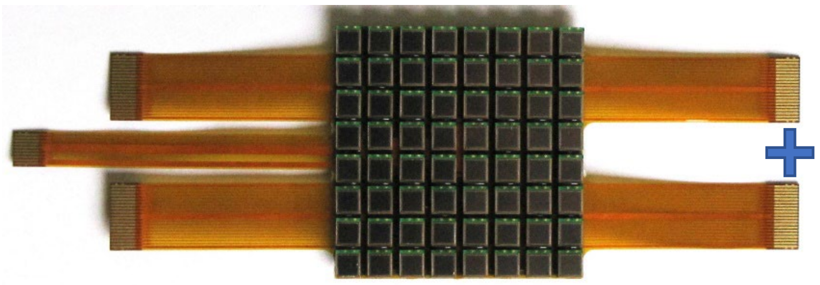


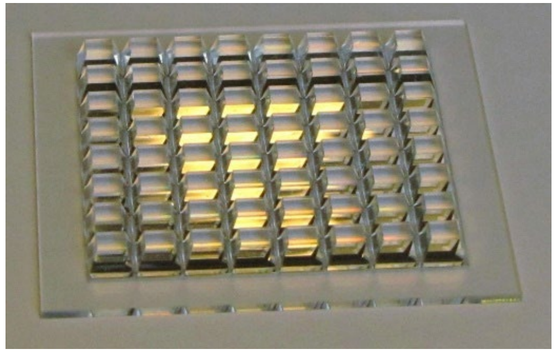


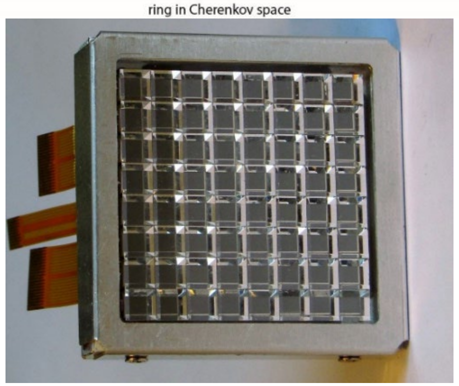




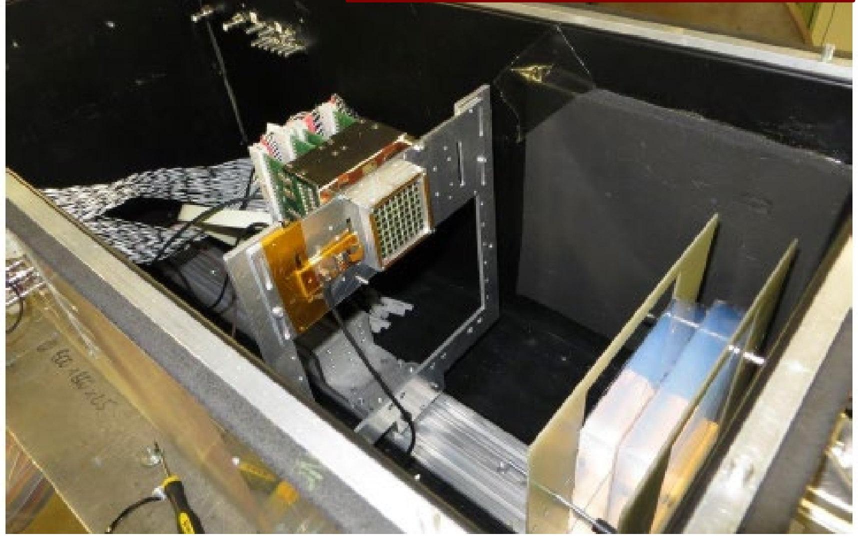
ring in Cherenkov space







S. Korpar et al. NIM A766(2014)107



SiPM irradiation tests @JSI

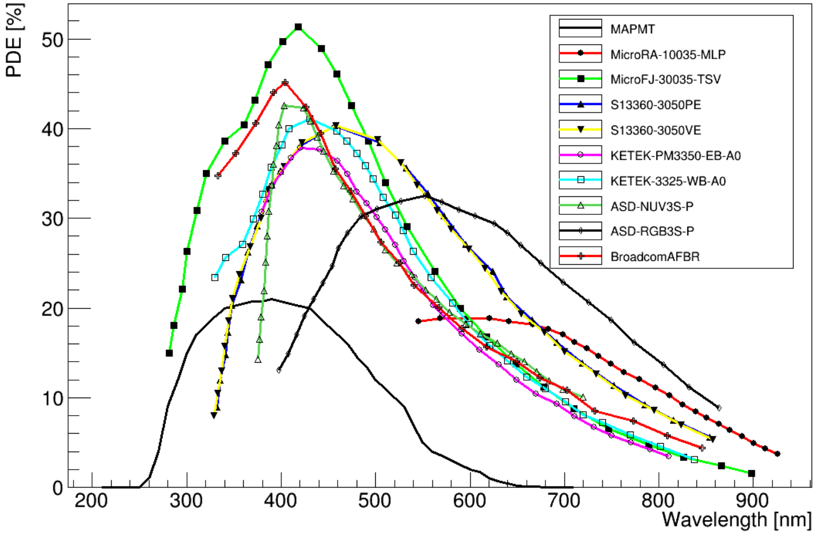
Producer	Type	Size (mm²)	Cell size (μm)	V_{br} (V)
Sensl	MicroRA-100XX-MLP	1x1	35	28
Sensl	MicroFJ-300XX-TSV	3x3	35	24.5
Ketek	PM3325-WB	3x3	25	27
Ketek	PM3350-EB	3x3	50	24.5
Hamamatsu	S13360-3050PE	3x3	50	51
Hamamatsu	S13360-3050VE	3x3	50	51
Advansid	ASD-NUV3S-P	3x3	40	26
Advansid	ASD-RGB3S-P	3x3	40	28
Broadcom	AFBR-S4N44C013	3.8x3.8	30	27

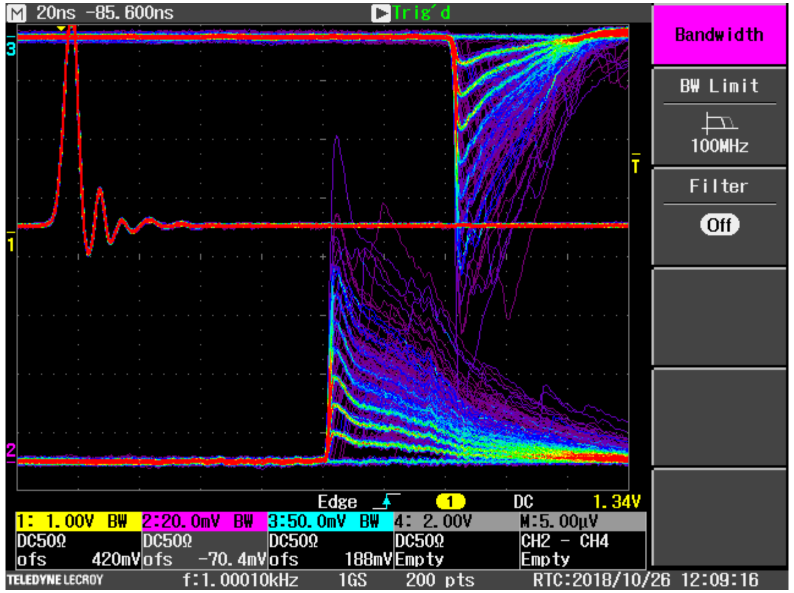
5 different samples of each type have been tested

Irradiation @ TRIGA nuclear reactor at Jožef Stefan Institute, Ljubljana

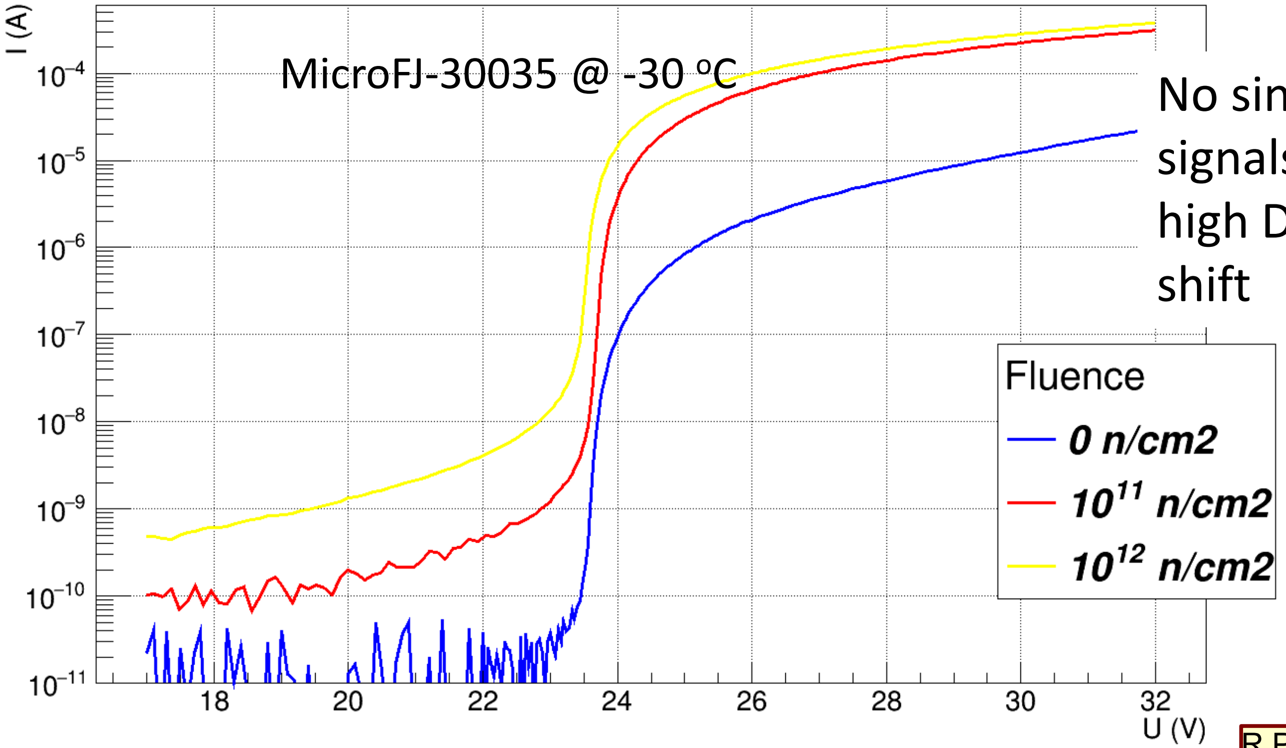
Fluence 10^{11}n/cm² 10^{12}n/cm²

Photon detection eff @ 3V overvoltage





Laser triggered response to low light

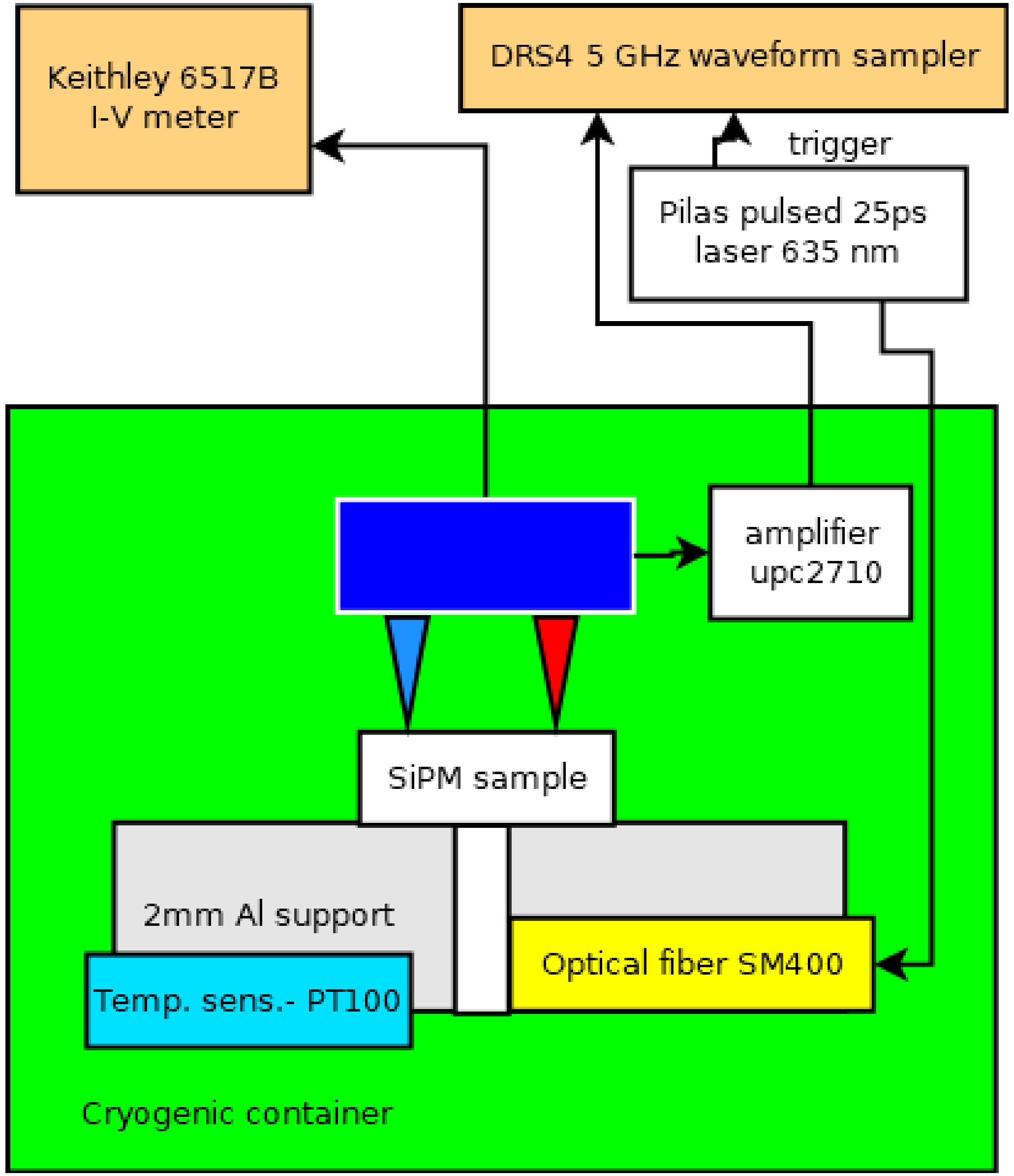


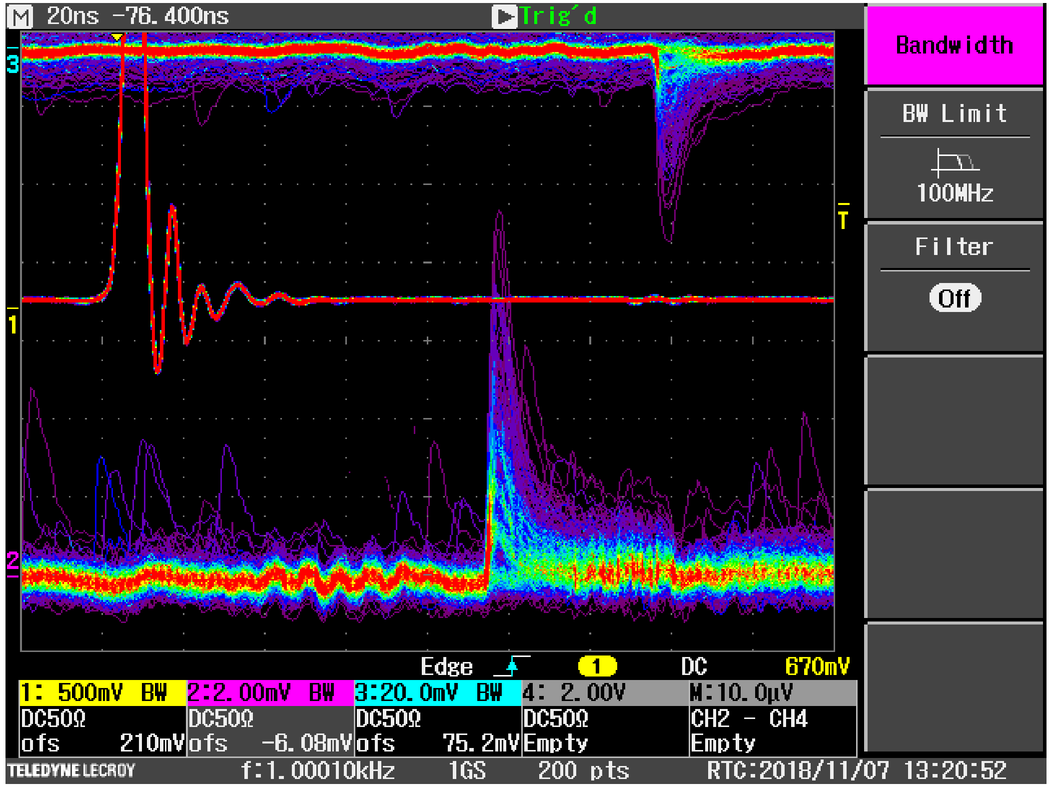
No single photelectron signals observed due to high DCR and baseline shift

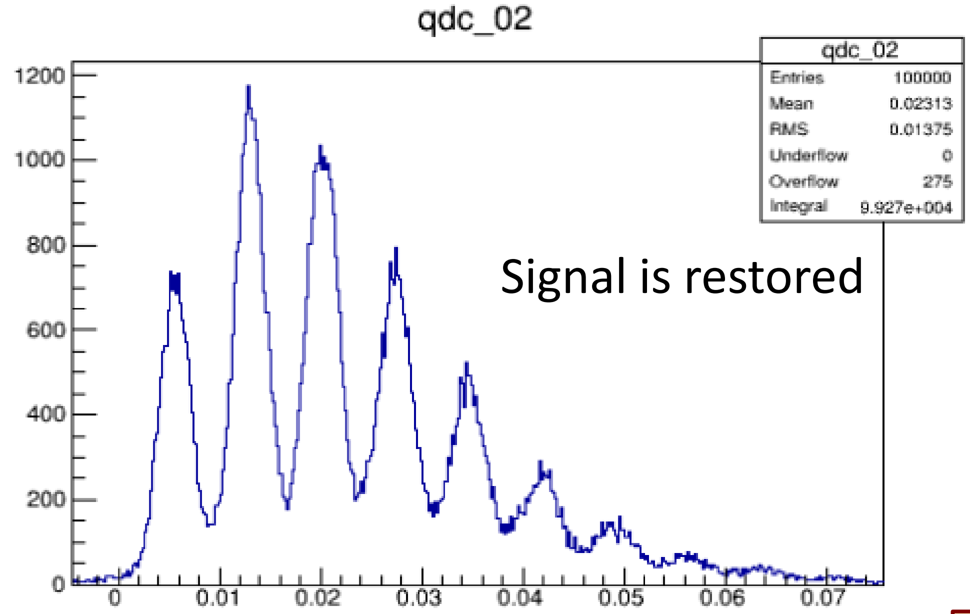
R.Pestotnik @ IEEE NSS 2018

Tests at LN2, T=-196°C

Dry Cryogenic container







Signal is restored

R.Pestotnik @ IEEE NSS 2018

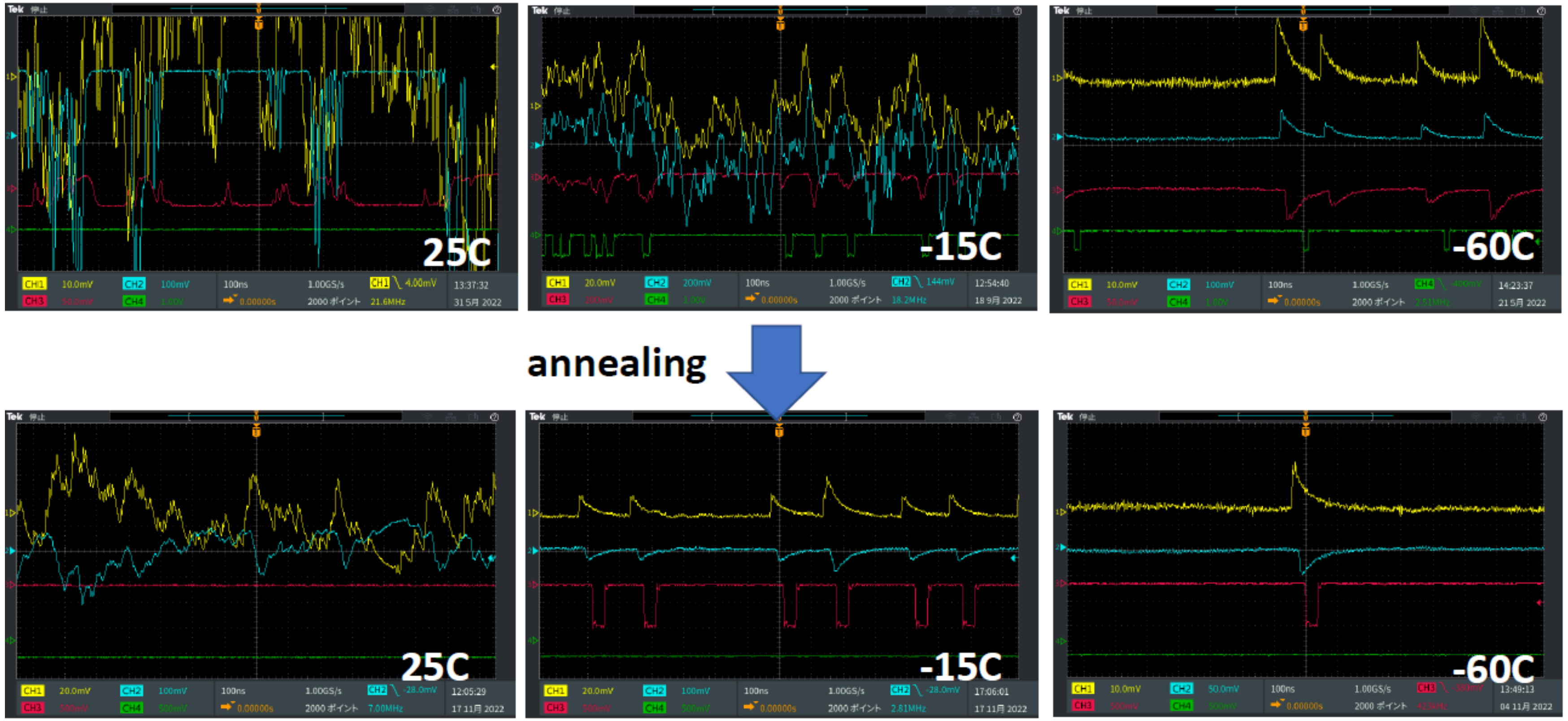
Tests of irradiated samples after annealing for several days at $170°C$ (Motohashi-san at 44th B2GM):

- Tests show that SiPMs could possibly be used if cooled, regularly annealed and replaced each year.

Result of waveform on 3050VE @ $V_{bd}+3[V]$

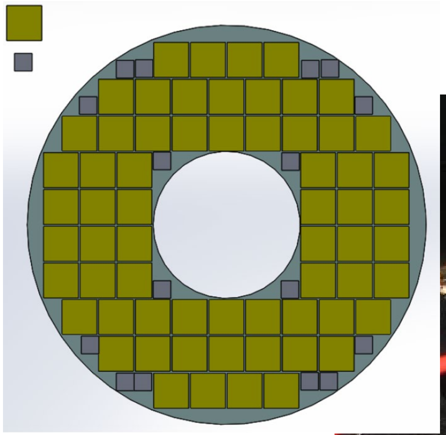
MPPC sample	Pixel pitch[µm]	Gain($\times 10^5$)	PDE[%]	Size[mm^2]	Dark count rate[kcps]	Capacity [pF]	Geometrical fill factor[%]
3050VE	50	17	40	3×3	500	320	74

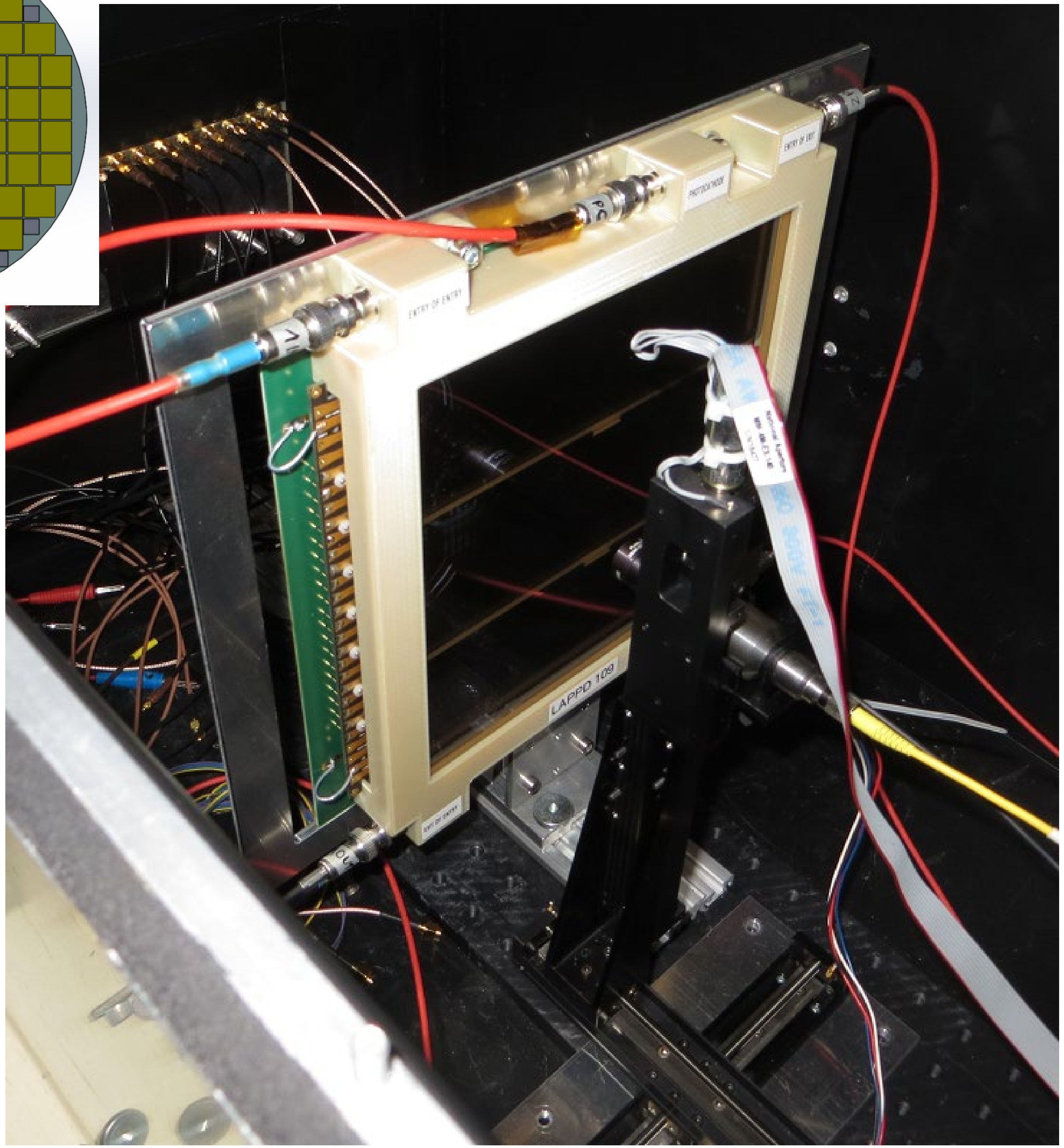
Irradiation 10^{11} ⇒ means use for annual on Belle II



2023/2/7 B2GM 44th 15

LAPPD (or HRPPD) for ARICH





Tested sample - LAPPD #109:

- $\approx 200 \times 200\ mm^2$
- 20 μm pores @ 25 μm pitch
- resistive anode plane, capacitive coupled readout
- 5 mm thick glass backplate
- 5 HV levels: PC, MCP1in, MCP1out, MCP2in, MCP2out and resistive anode at ground potential

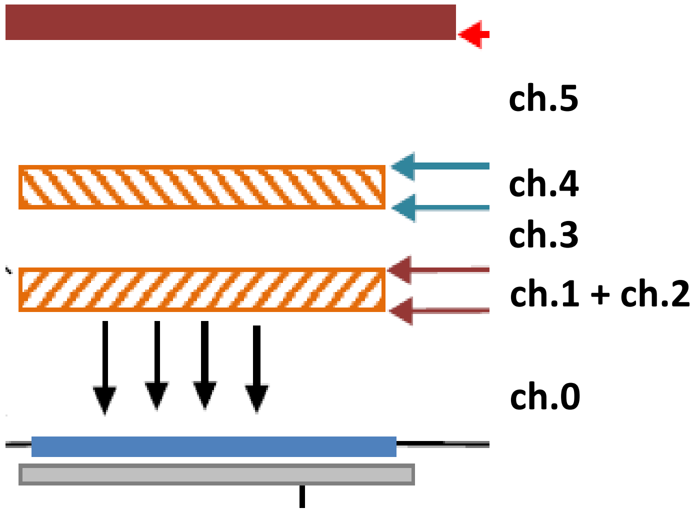
- Standard setup with QDC, TDC, 3D stage ...
- TDC value corrected for time-walk

- ALPHALAS PICOPOWER™-LD Series of Picosecond Diode Lasers – 405 nm
- FWHM $\approx$ 20 ps
- light spot diameter on the order of 100 μm

LAPPD - HV supply

CAEN HiVolta (DT1415ET), 8 Ch Reversible 1 kV/1 mA Desktop HV Power Supply – floating channels

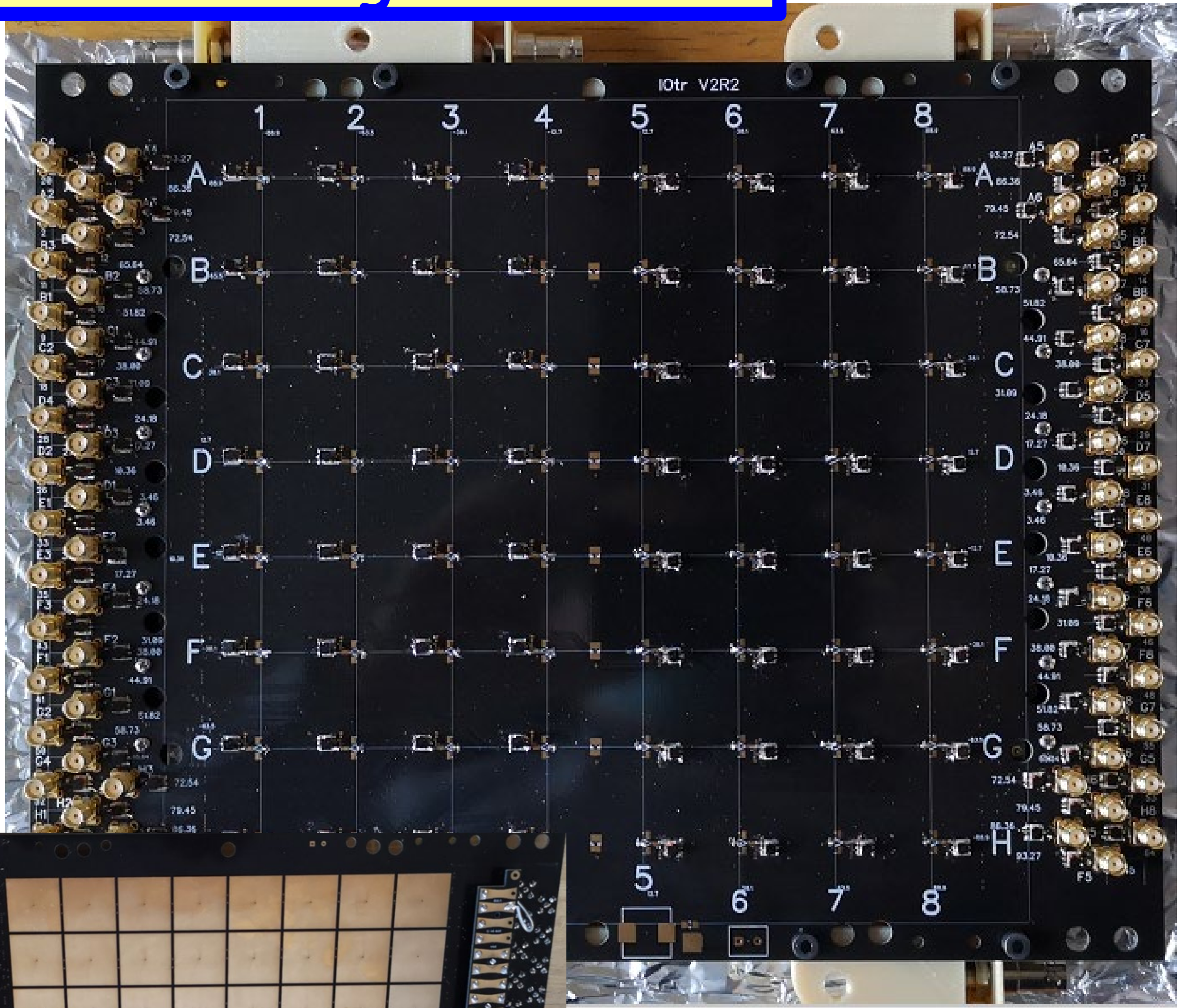
- 1 kV/1 mA and 0.6 W(!) per channel
- ch.0 MCP2out – AN
- ch.1+ch.2 MCP2in – MCP2out (2 ch. due to power limit per channel)
- ch.3 MCP1out – MCP2in
- ch.4 MCP1in – MCP1out
- ch.5 PC – MCP1in

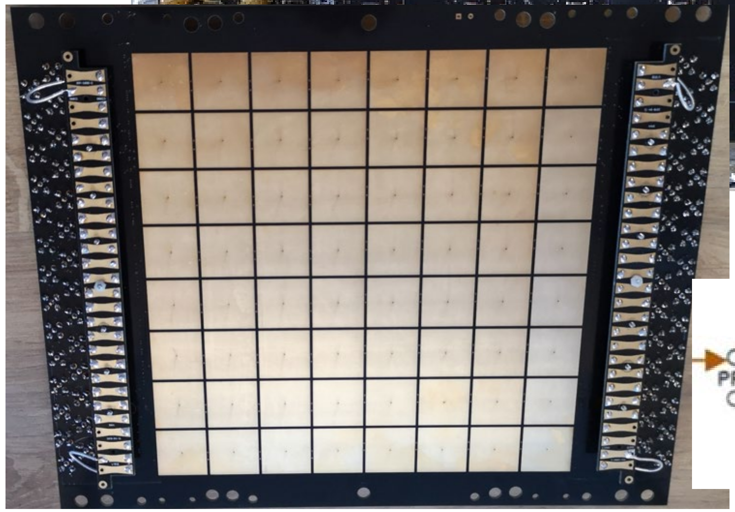


ROP voltages A-PC: 500/825(400+425)/200/825/100 V

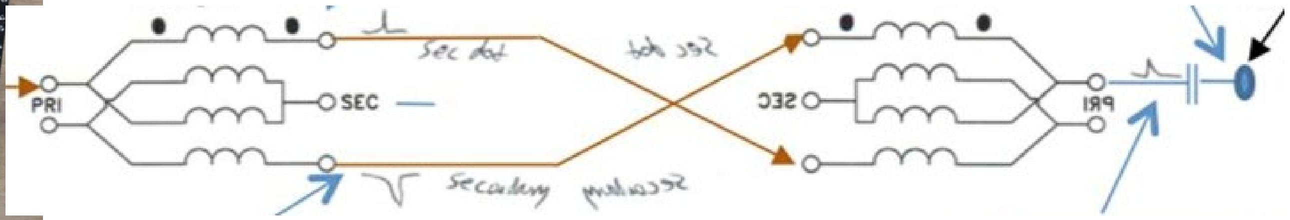
Custom	VSet	VMon	IMon	ISet	Pw	Status	SWVmax
00.000	500.00	500.06	3.8730	50.00	On		500
00.001	400.00	400.16	791.5960	900.00	On		400
00.002	425.00	425.30	791.7310	900.00	On		450
00.003	200.00	200.22	15.7010	50.00	On		200
00.004	825.00	825.46	345.5840	450.00	On		850
00.005	100.00	100.20	0.0680	5.00	On		150

LAPPD - sensing electrodes



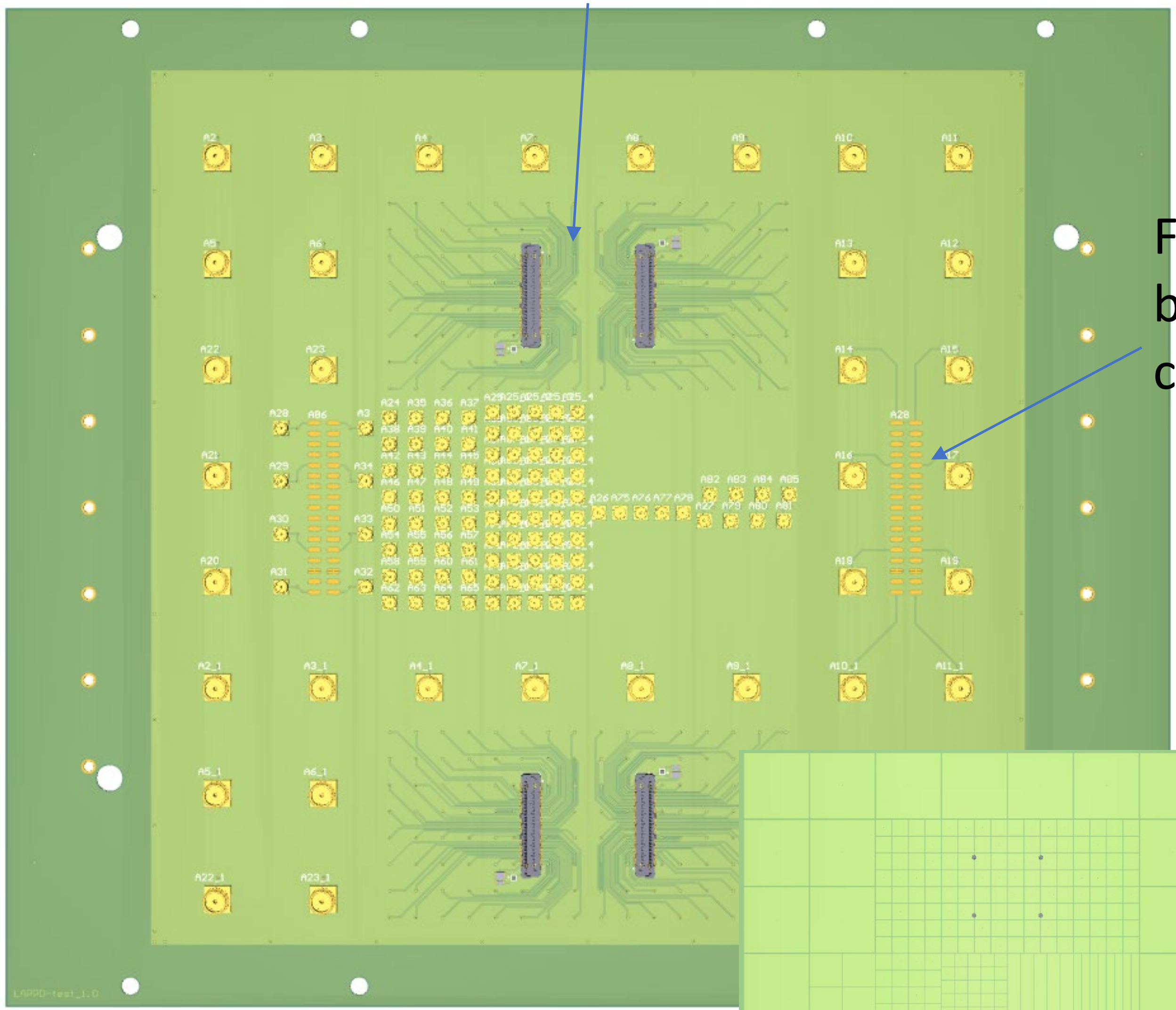


INCOM

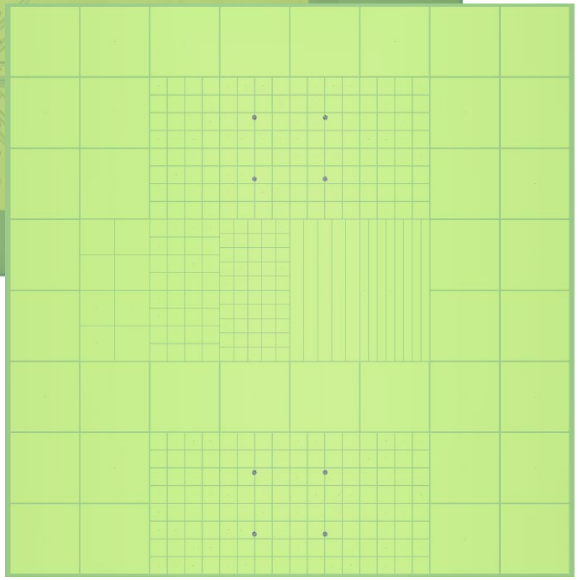


PETSYS conn.

FastIC board conn.

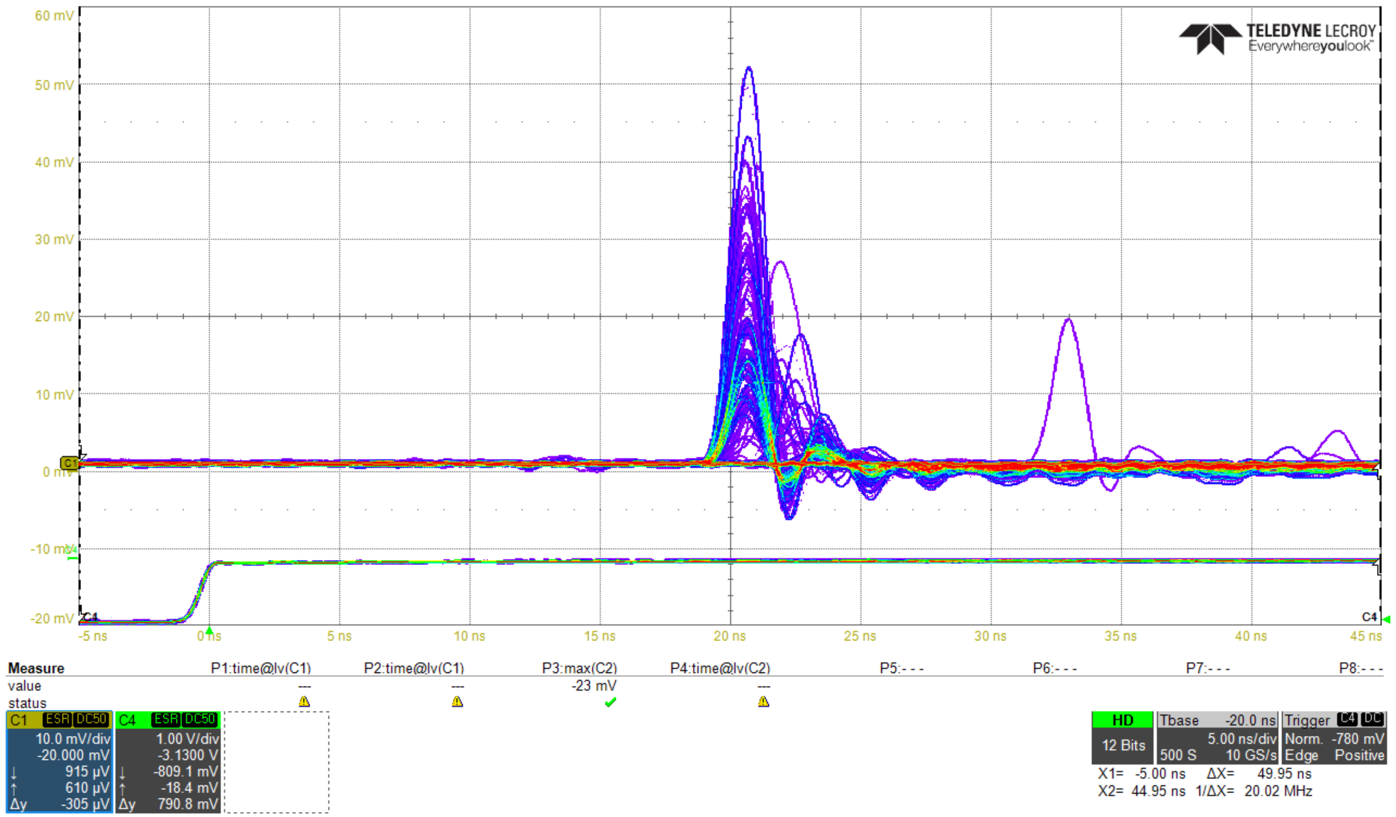


IJS

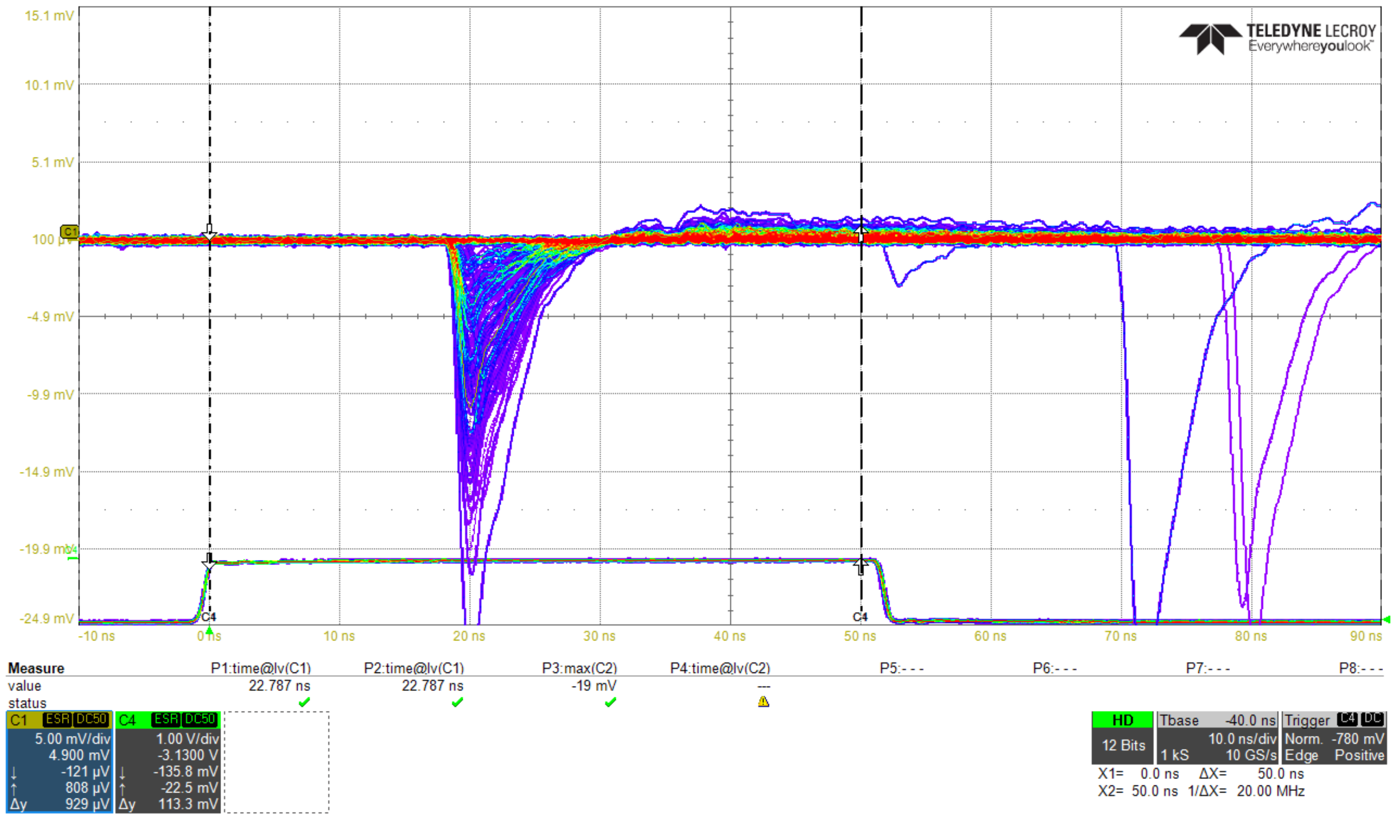


LAPPD – raw signals

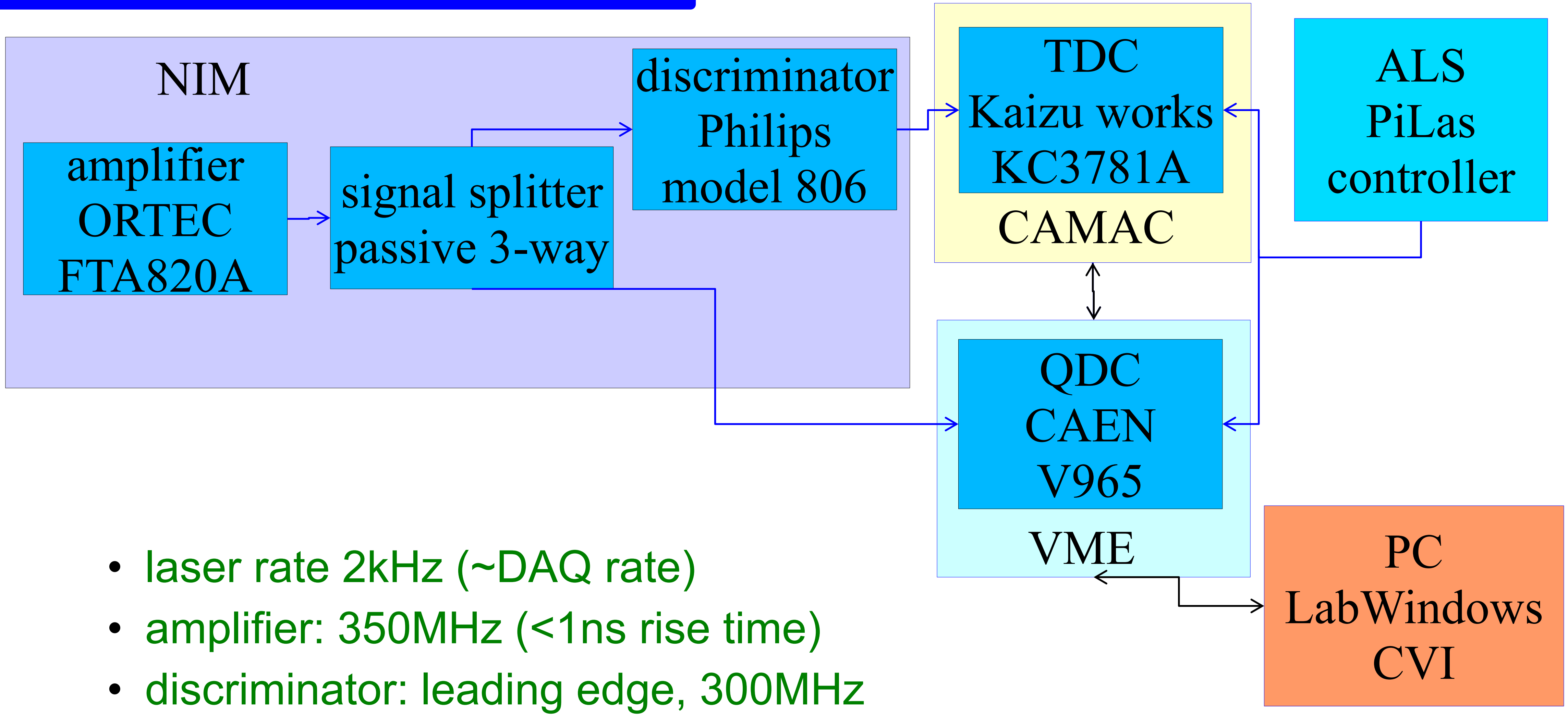
- transformed signal



- direct signal (gain $\approx 2 \cdot 10^6$)



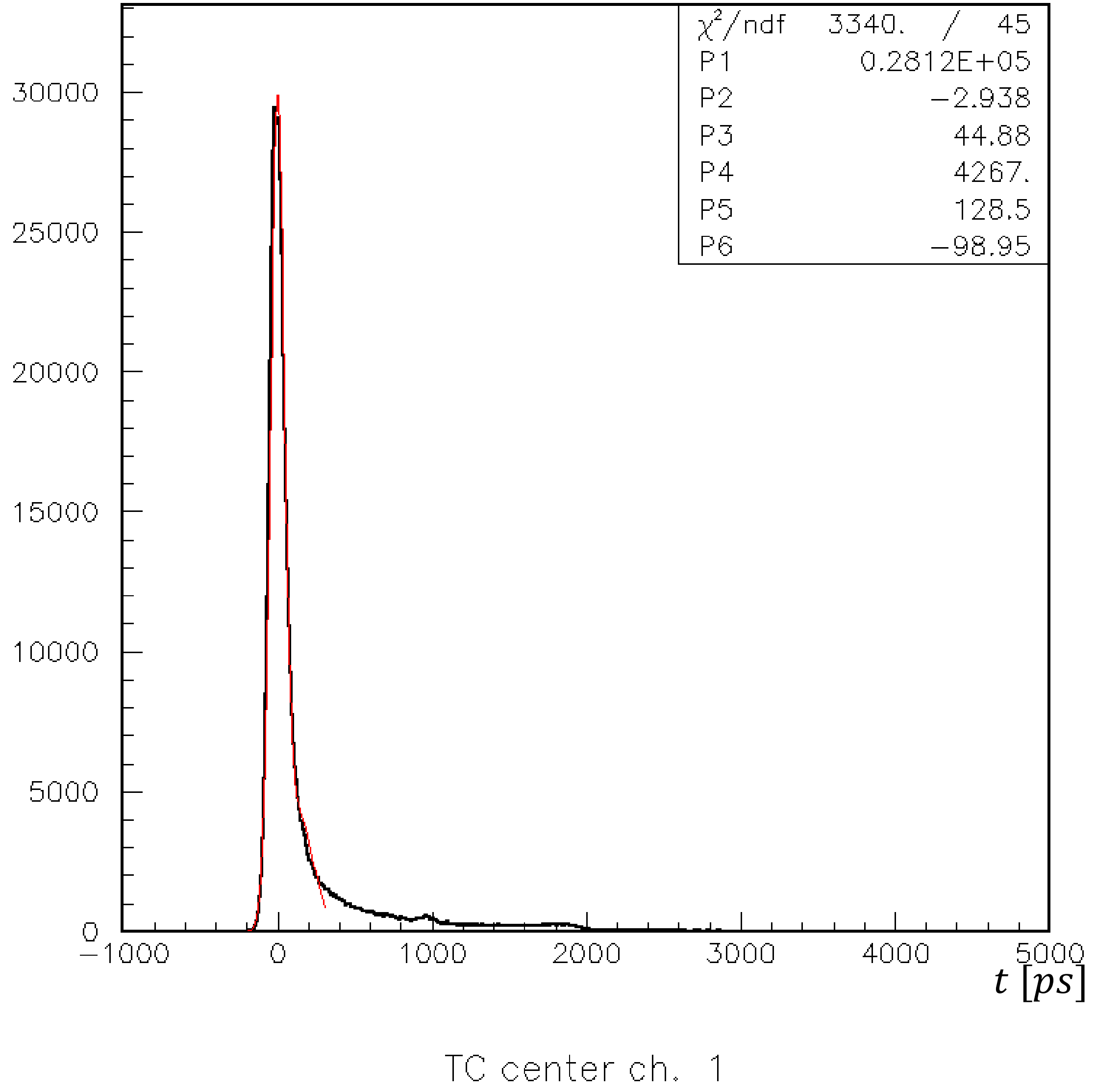
Modular readout system for tests

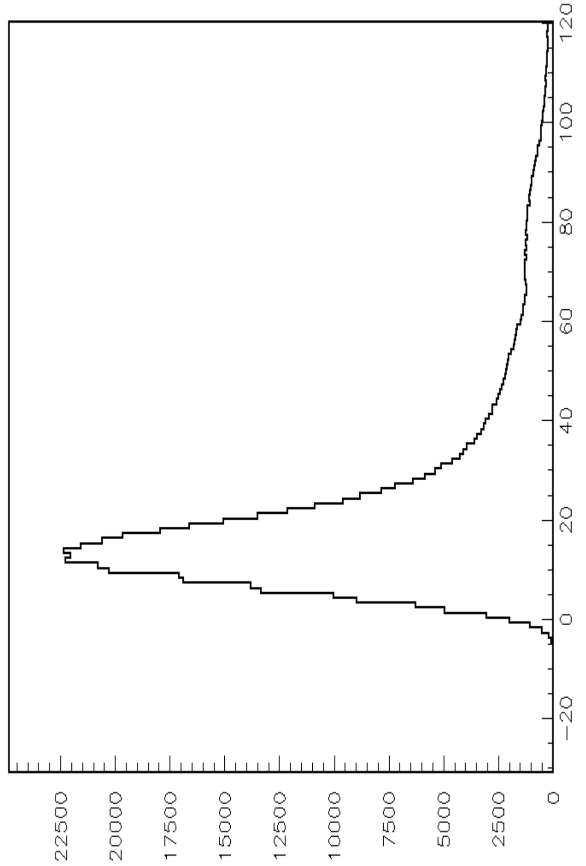


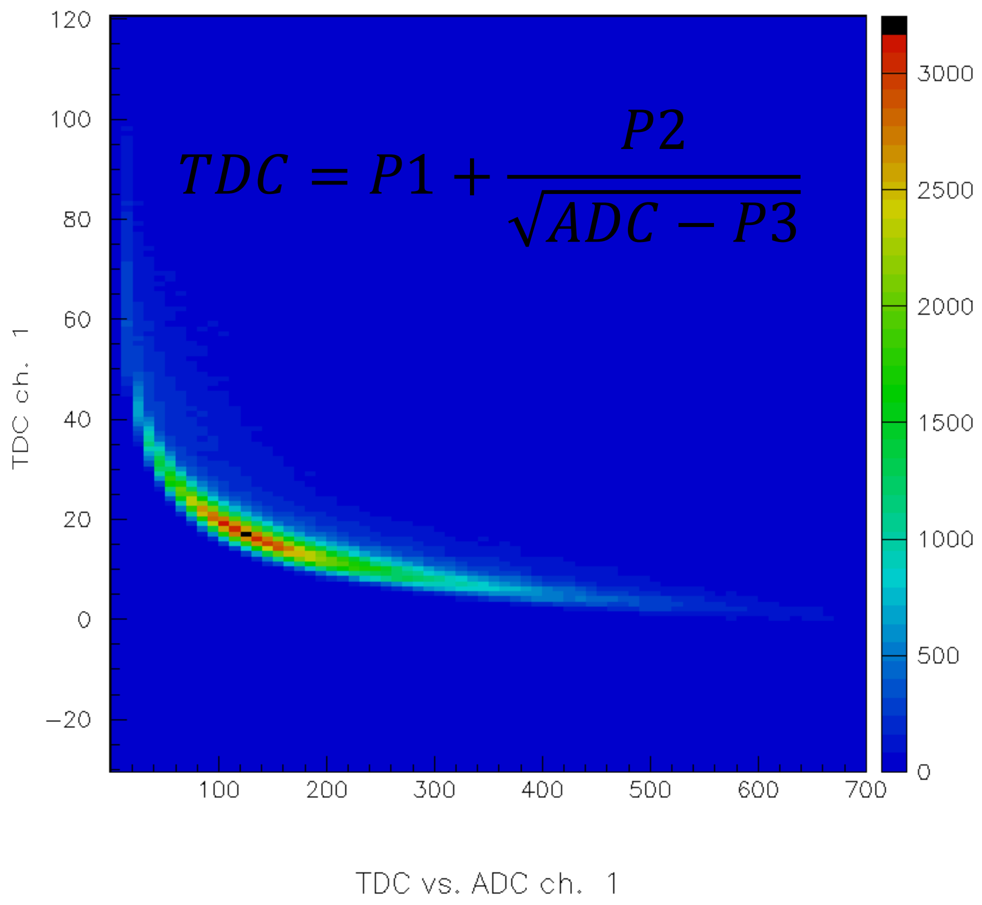
- laser rate 2kHz (~DAQ rate)
- amplifier: 350MHz (<1ns rise time)
- discriminator: leading edge, 300MHz
- TDC: 25ps LSB(σ~11ps)
- QDC: dual range 800pC, 200pC

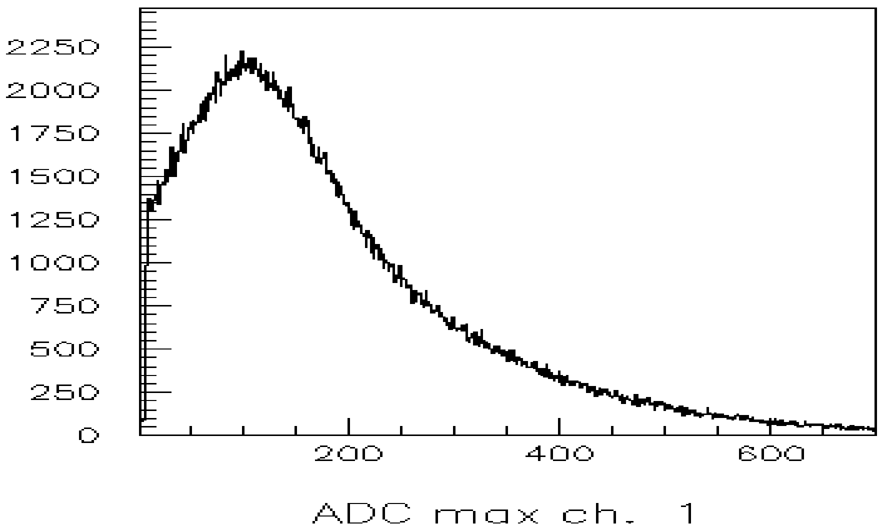
LAPPD – time-walk correction

- TDC corrected for time-walk
- timing resolution (prompt peak) $\sigma \approx 40$ ps after time-walk correction







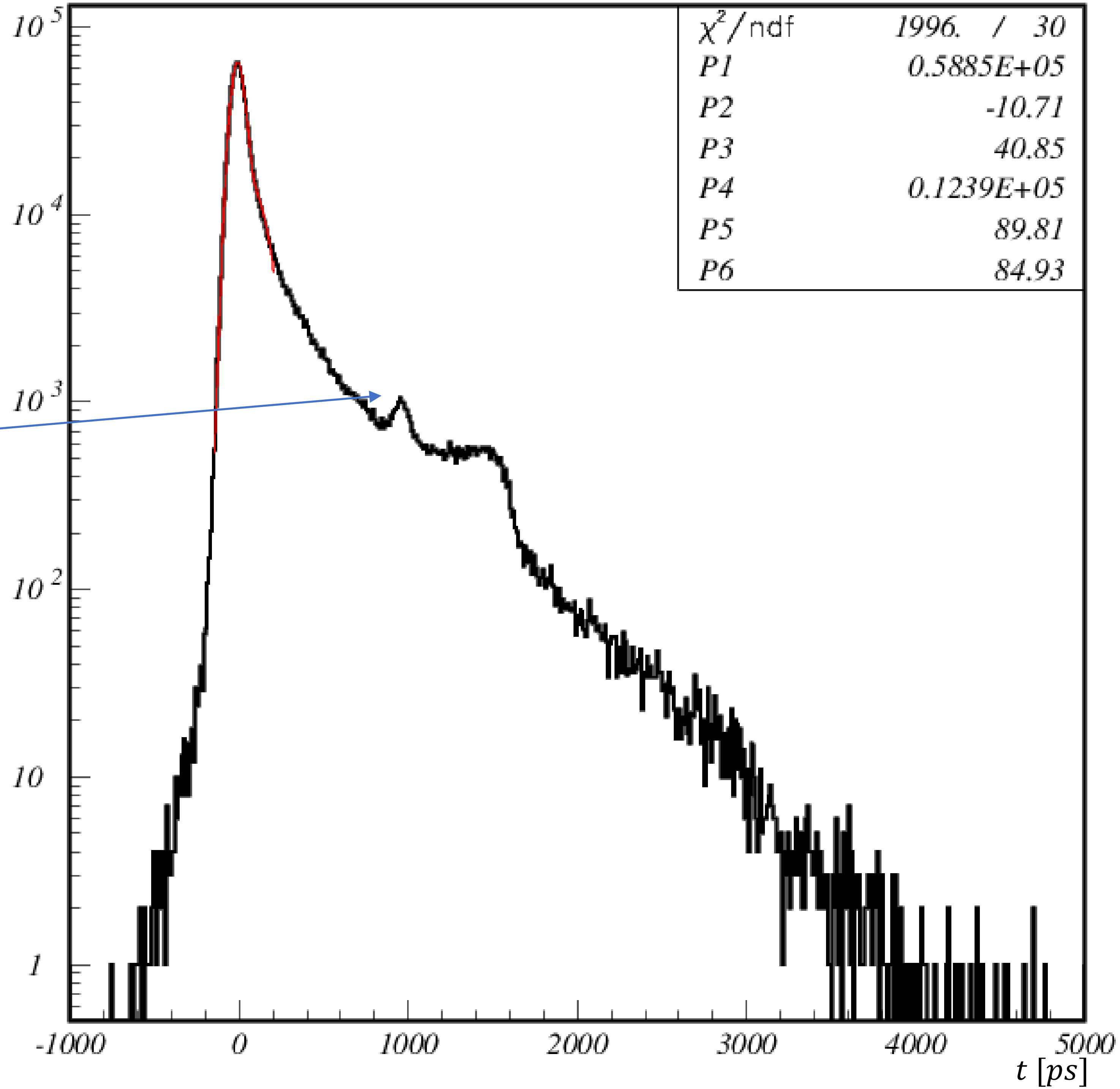


LAPPD – timing disdribution

- measured timing distribution typical for MCP-PMT
- main prompt peak with some inelastic and elastic backscattering contribution

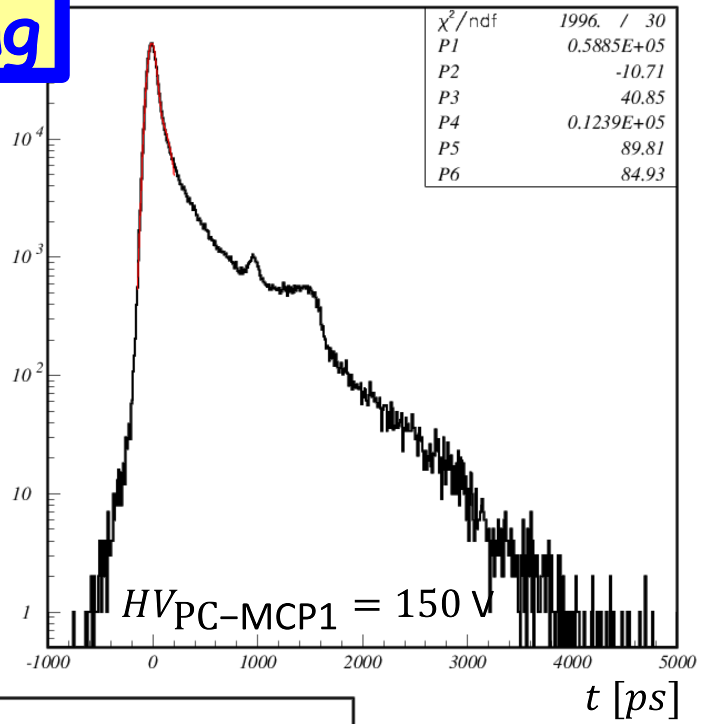
- additional small peak at about 1 ns delay probably due to some reflection (light?), delay not affected by PC-MCP1 voltage

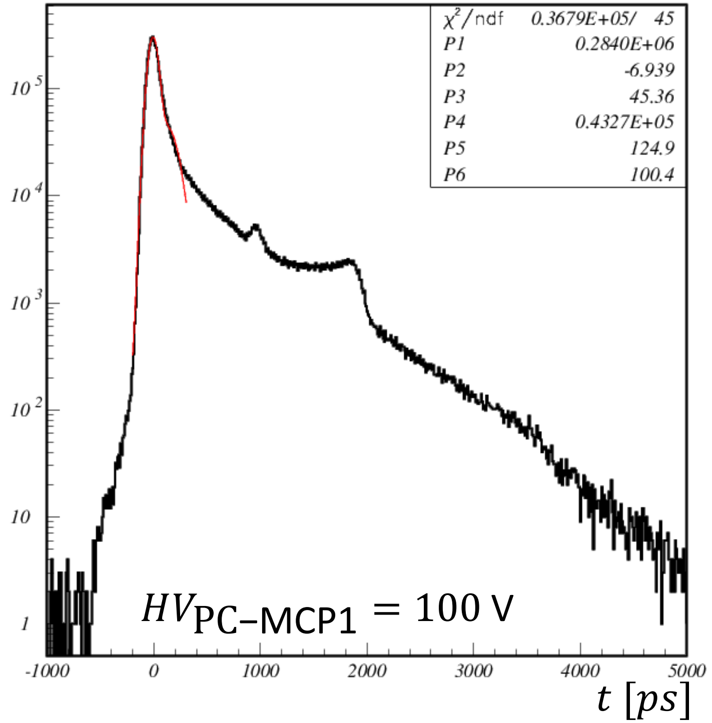
- plot is for the PC-MCP1 voltage of 150 V and ROP for others

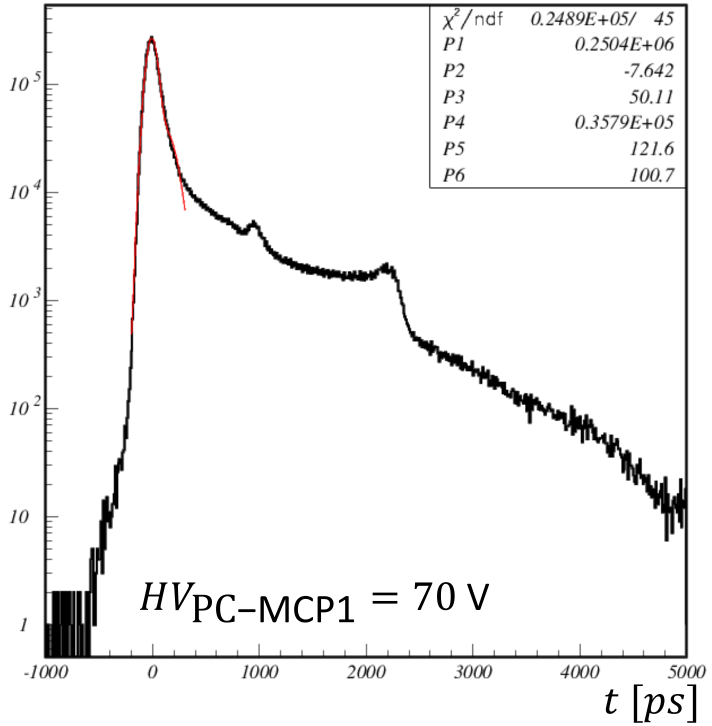


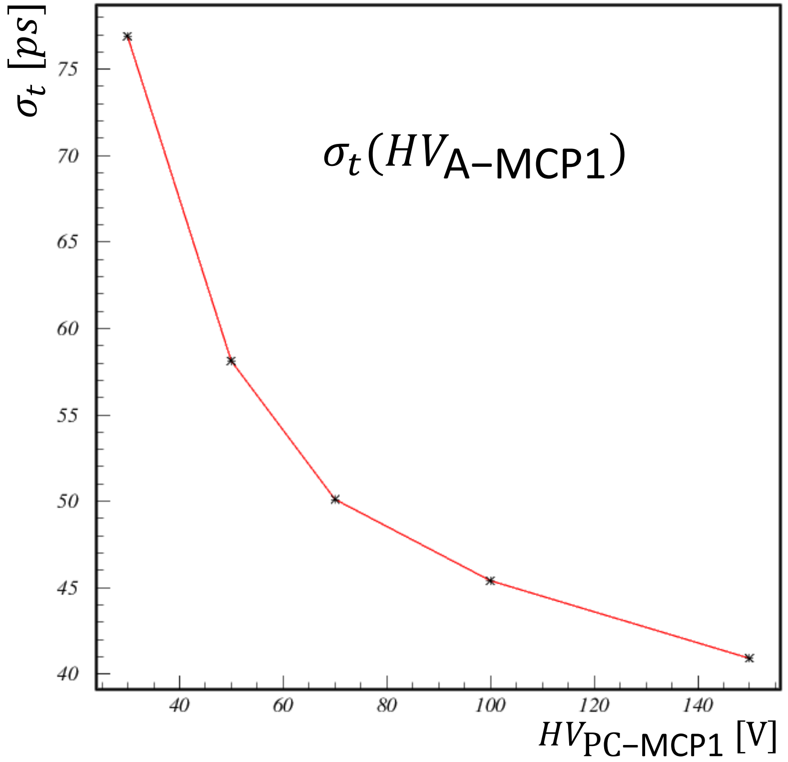
LAPPD – timing

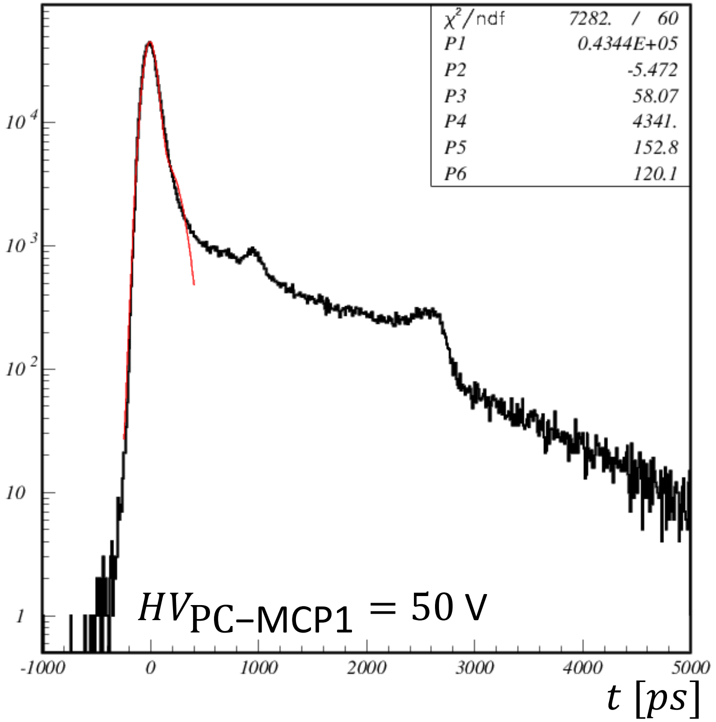
- corrected TDCs for several PC-MCP1 voltages
- time resolution vs PC-MCP1 voltage

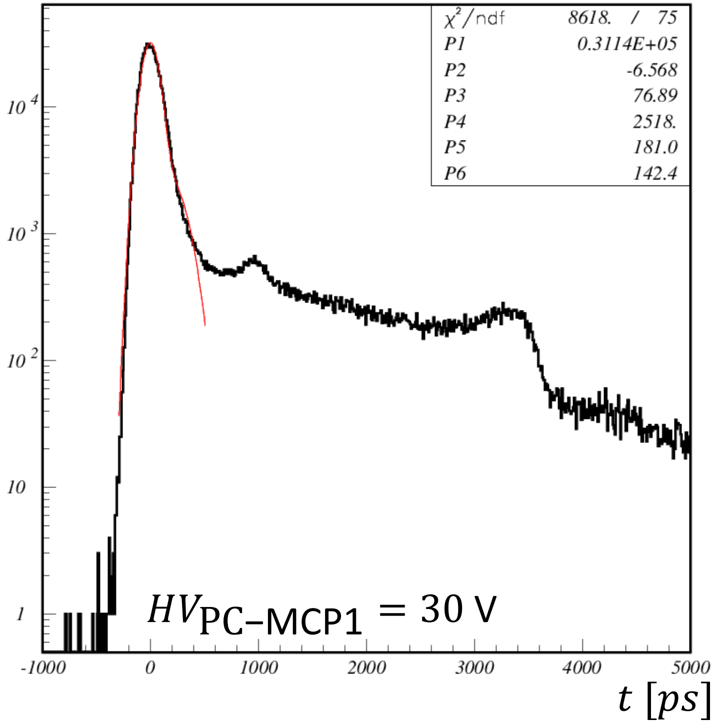






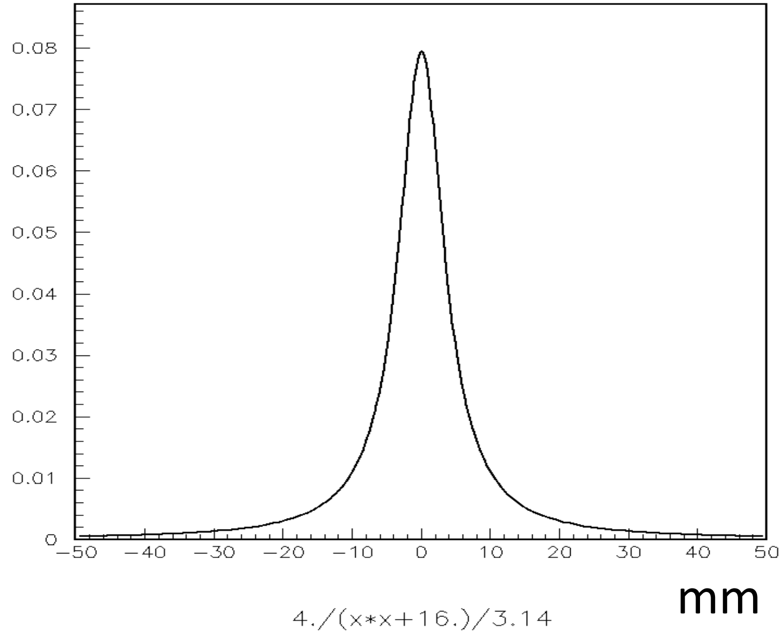


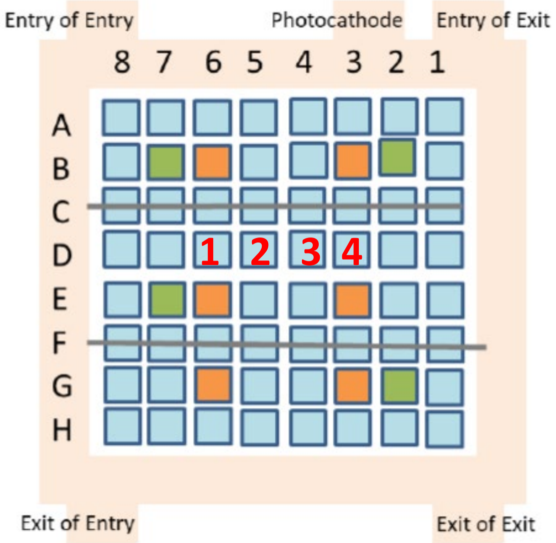


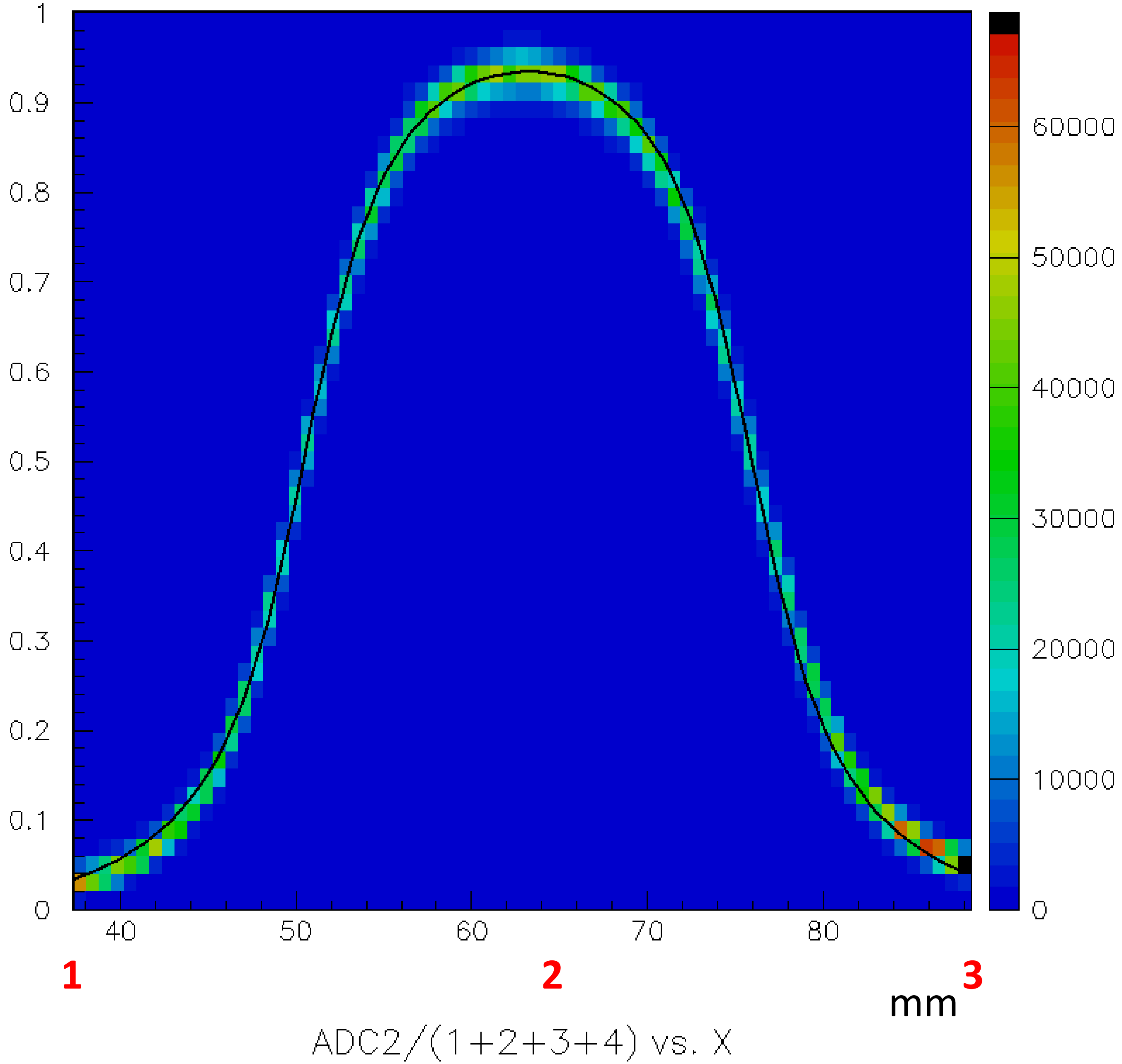


LAPPD – induced charge

- fraction of the signal on ch. 2 vs laser spot x position: $f(x) = \frac{q_2}{\sum_i q_i}$
- first approximation of expected fraction $f(x)$ ‚fitted' by hand (weighting potential of a strip in an infinite conductive plane)
- induced charge distribution FWHM ≈ 8 mm (below)
- further tests with smaller pads, narrower strips
- for pad sizes of few mm a thinner back-plate will be needed





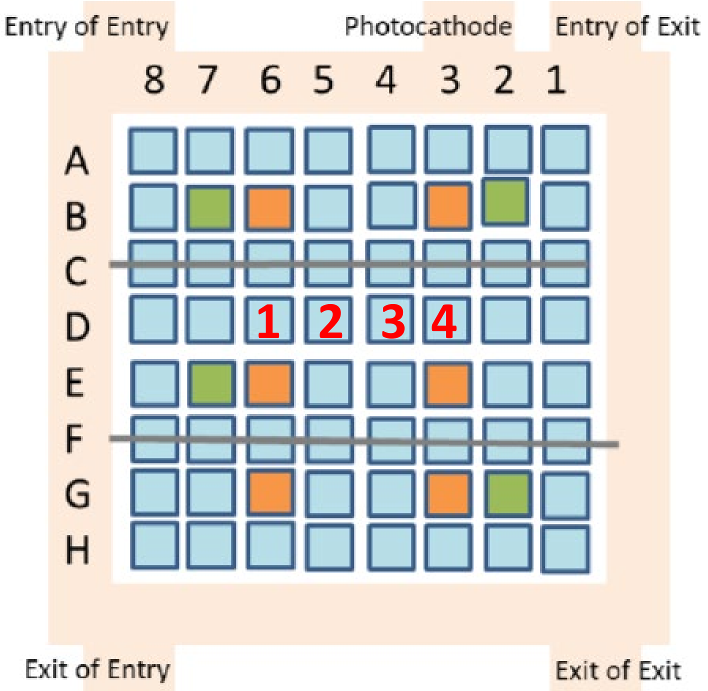


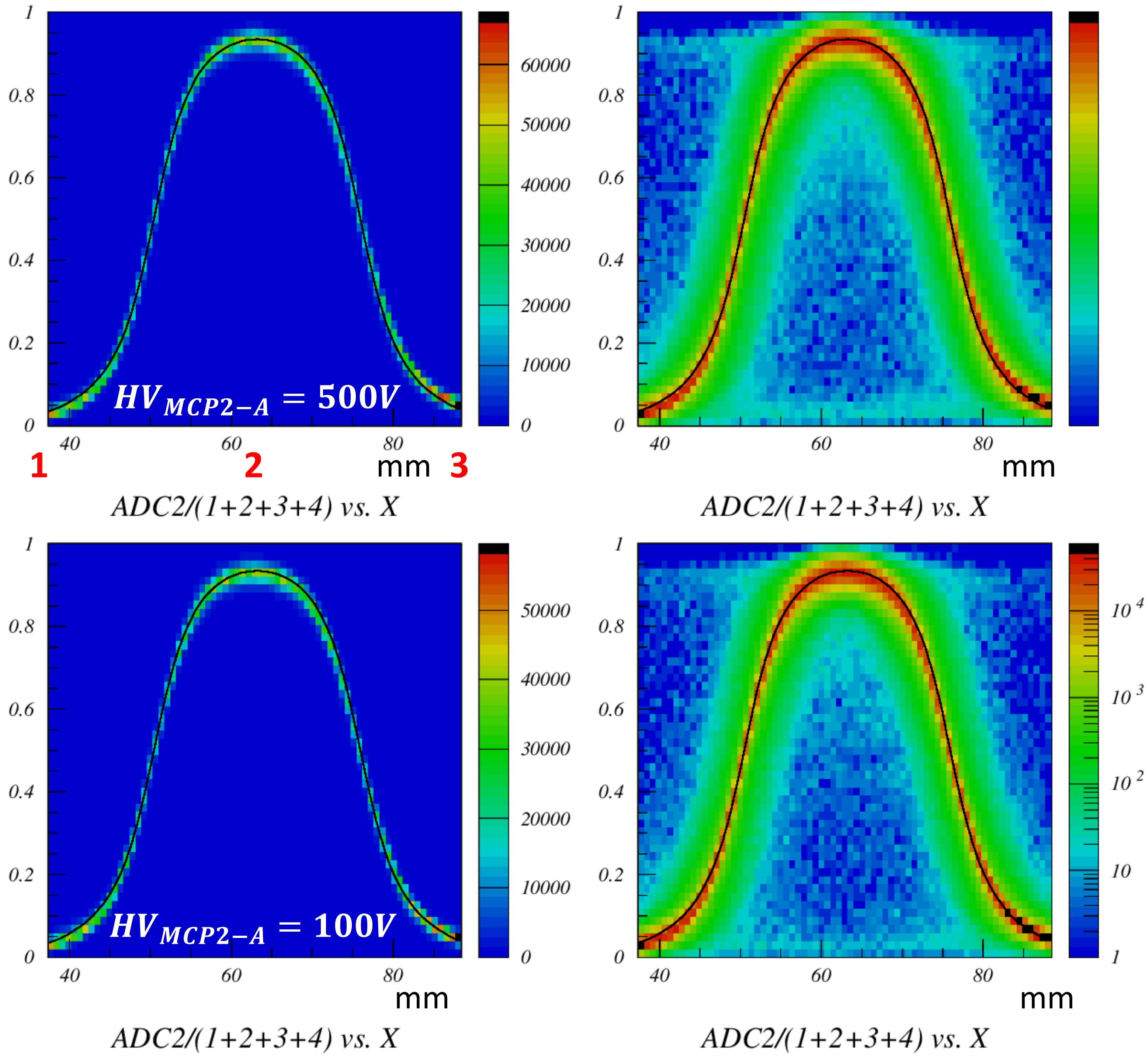
function: $0.385\left(\operatorname{atan}\left(\frac{x-50.5}{4}\right) - \operatorname{atan}\left(\frac{(50.5+25.4)-x}{4}\right)\right) - 0.04$

Samo Korpar
Univ. of Maribor and J. Stefan Institute

LAPPD – induced charge fraction

- fraction of the signal on ch. 2 vs laser spot x position: $f(x) = \frac{q_2}{\sum_i q_i}$
- green band (log scale) indicates the range of a backscattered photoelectrons – twice the PC-MC1 distance (on each side)
- ROP for upper plots and 100 V between MCP2 and A for lower ones
- Signal spread not mainly from electron spread but induced charge spread on coupled electrode

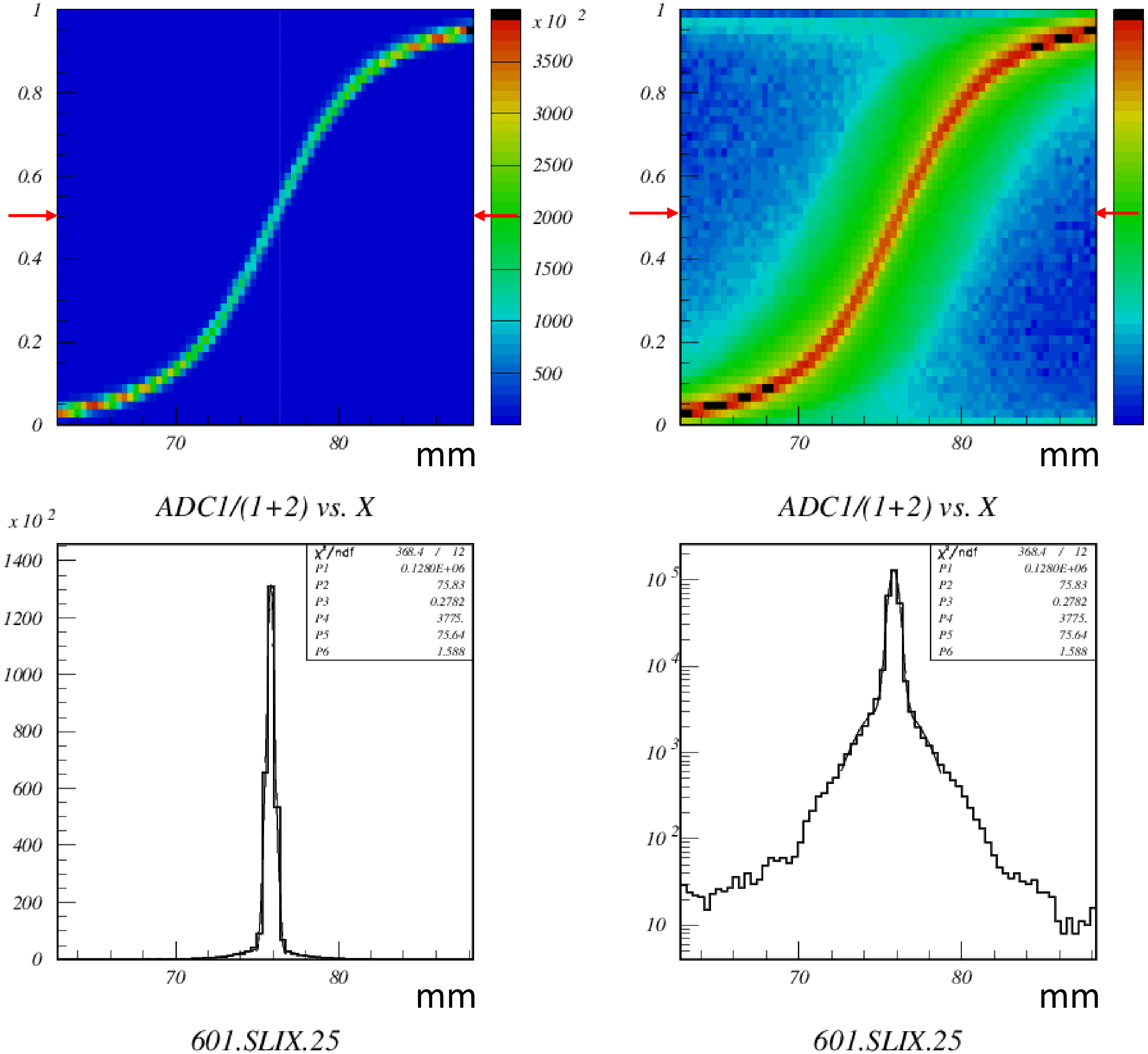




LAPPD – charge sharing

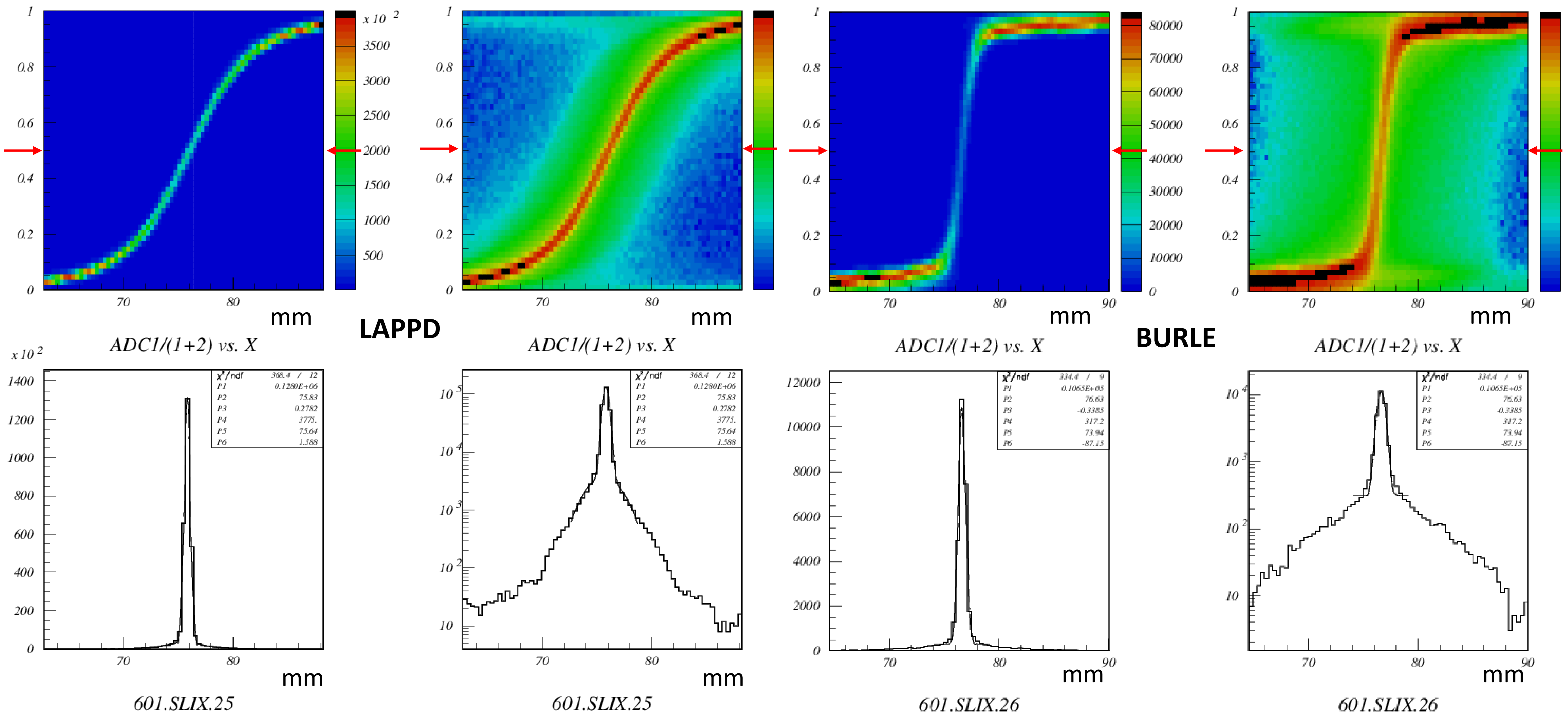
- more detailed scan between the centres of adjacent pads (top)

- central slice where signal is equally split between the pads (bottom)
- narrow peak is due to the light spot size and photoelectron spread
- longer tail from photoelectron backscattering - ≈ 6 mm on each side
→ ≈ 3 mm PC – MCP1 distance

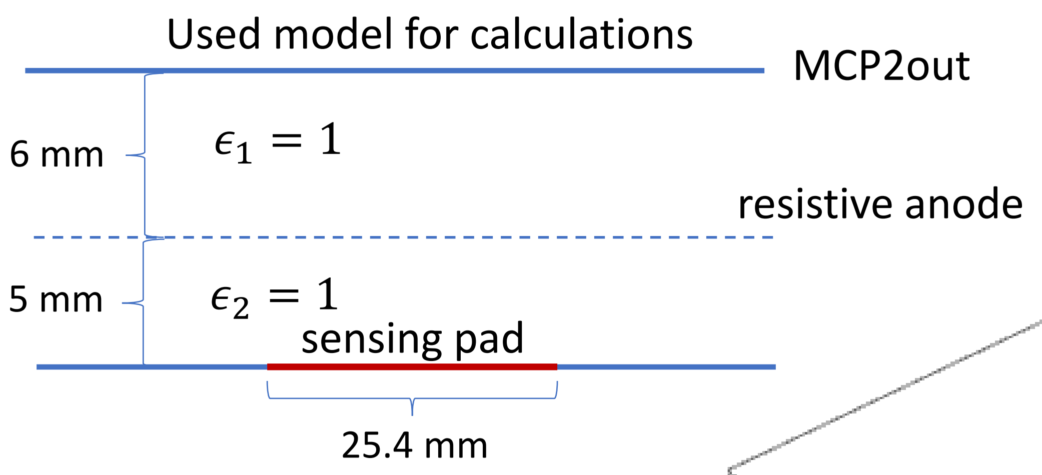


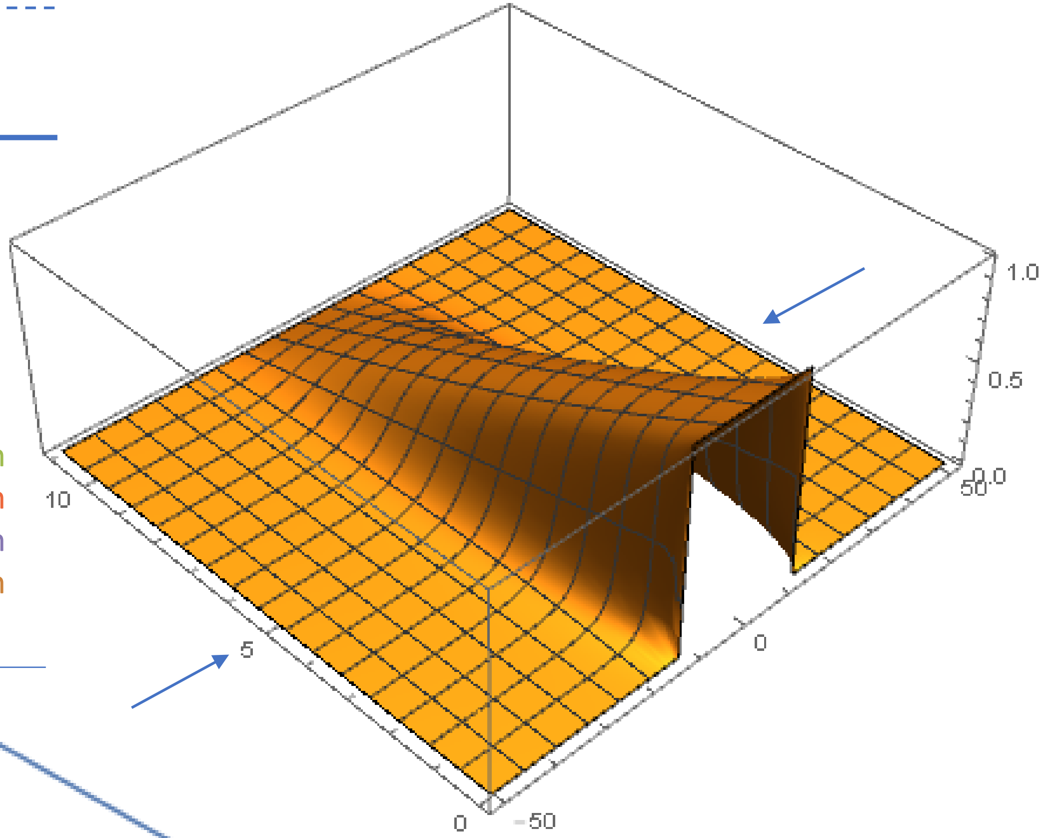
LAPPD vs. BURLE PLANACON

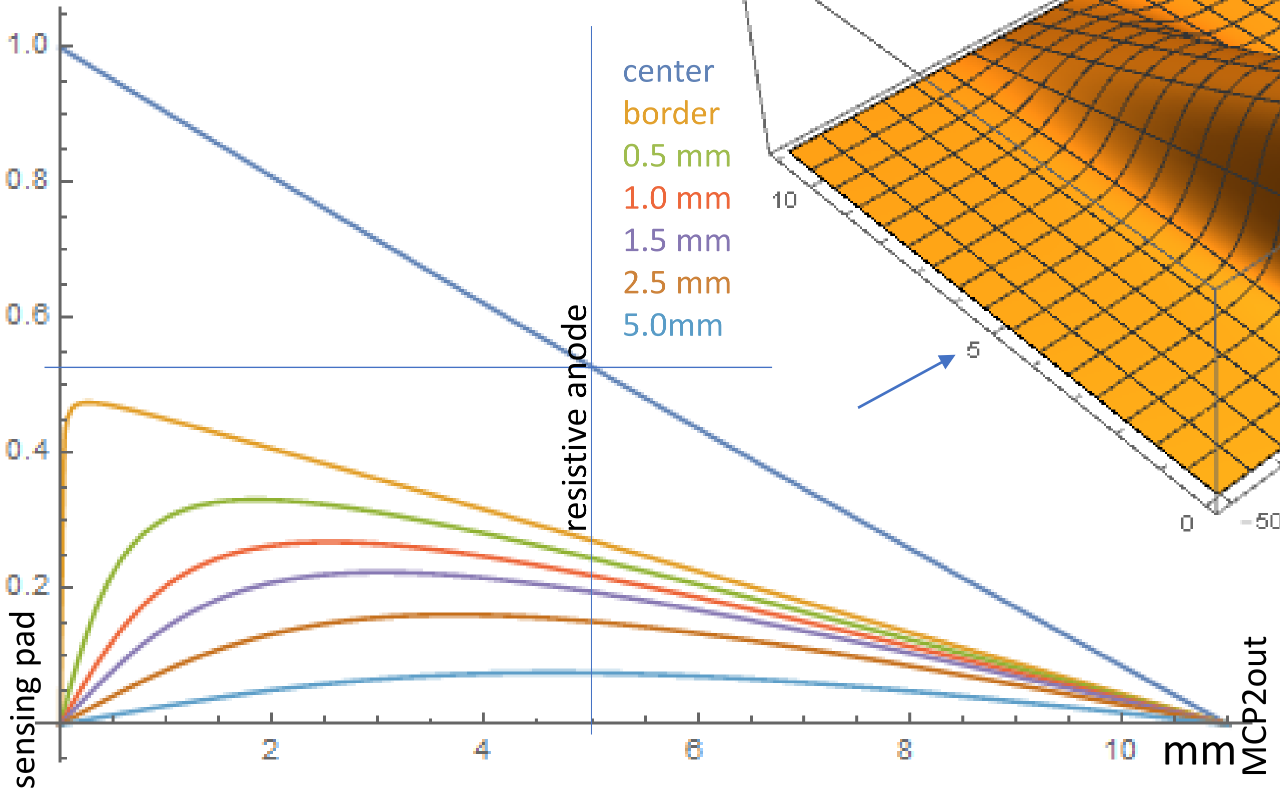
LAPPD (capacitive coupling) – BURLE PLANACON (internal anodes) signal spread comparison – same pad size, same range

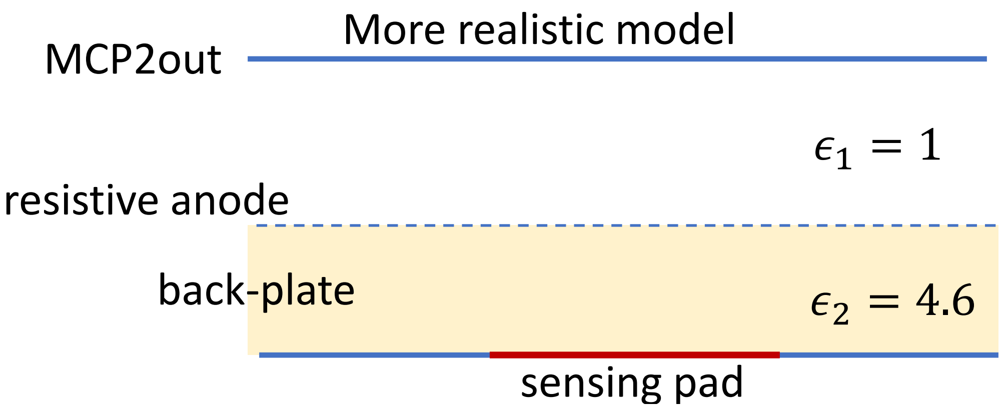


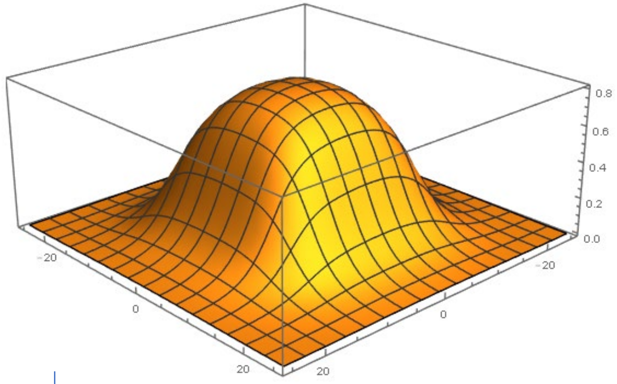
LAPPD – induced charge calculations

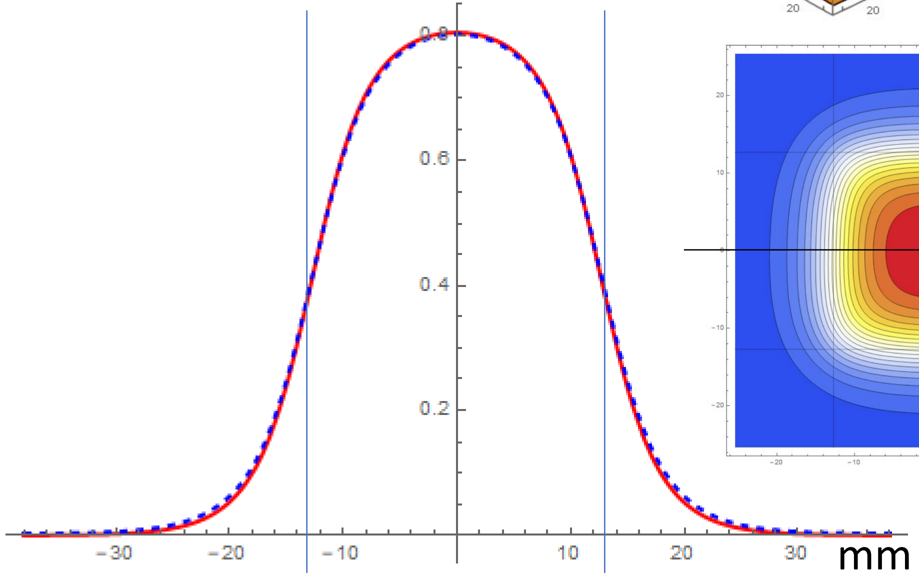


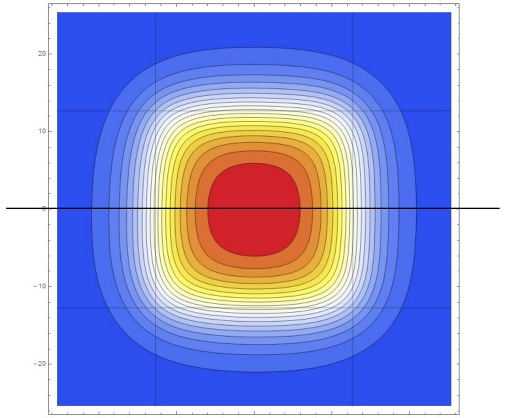






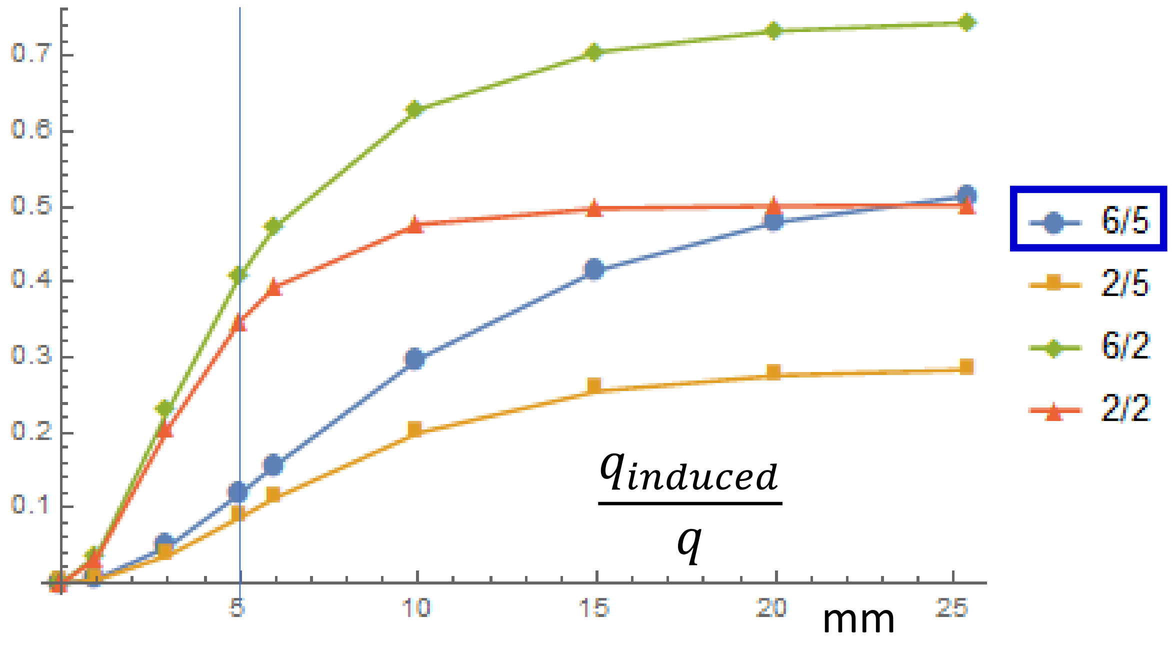


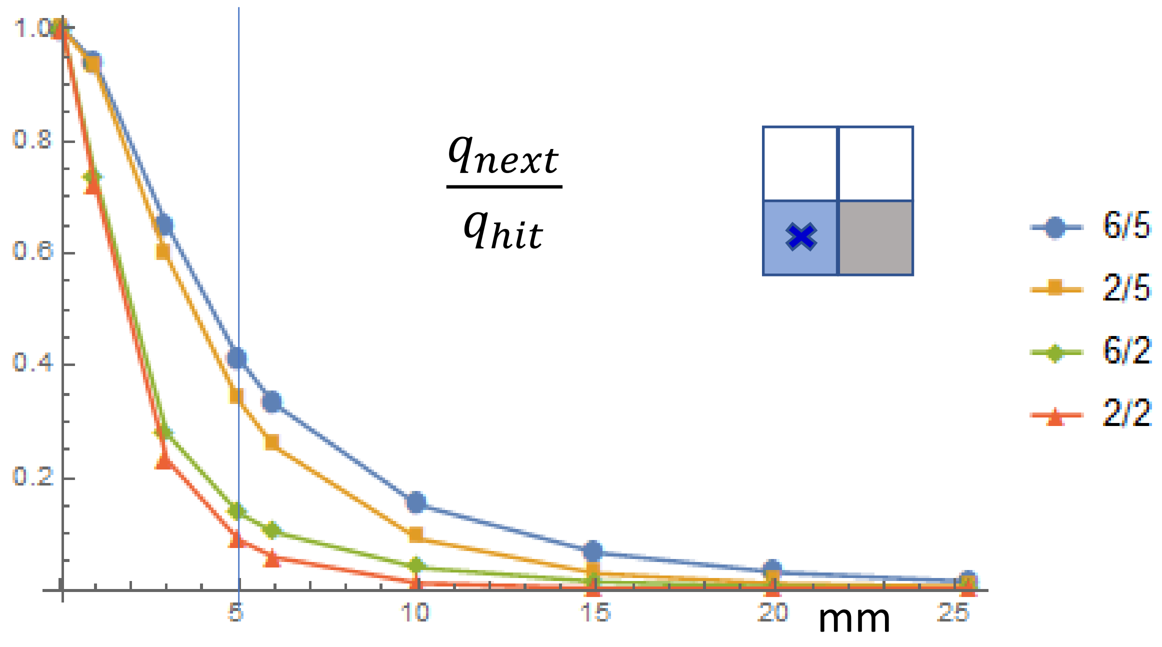


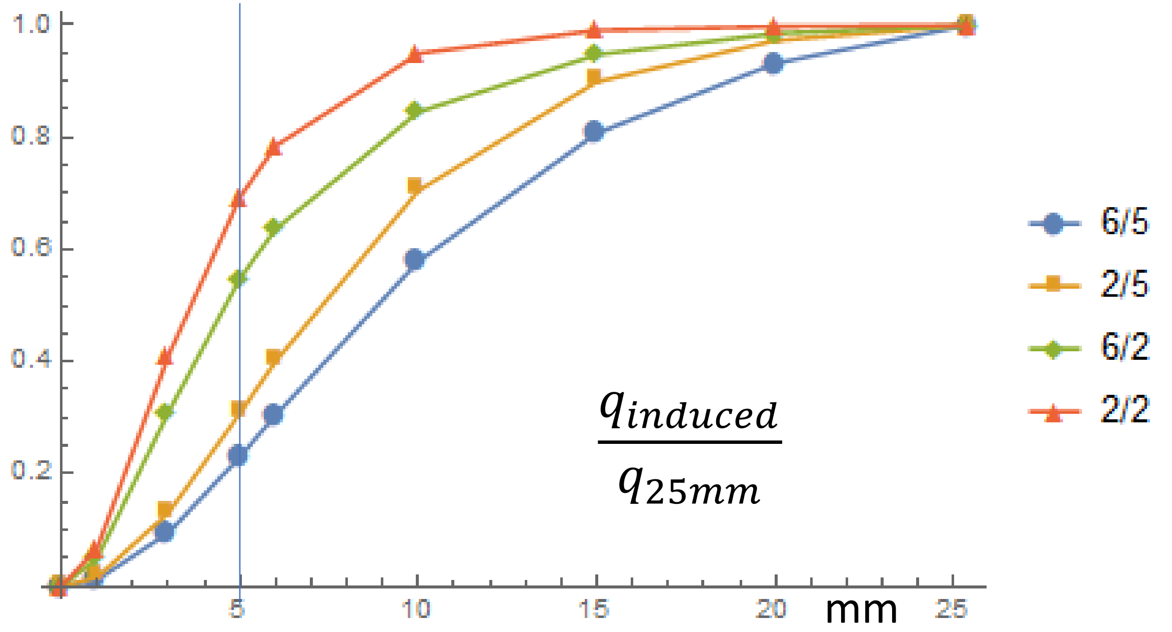


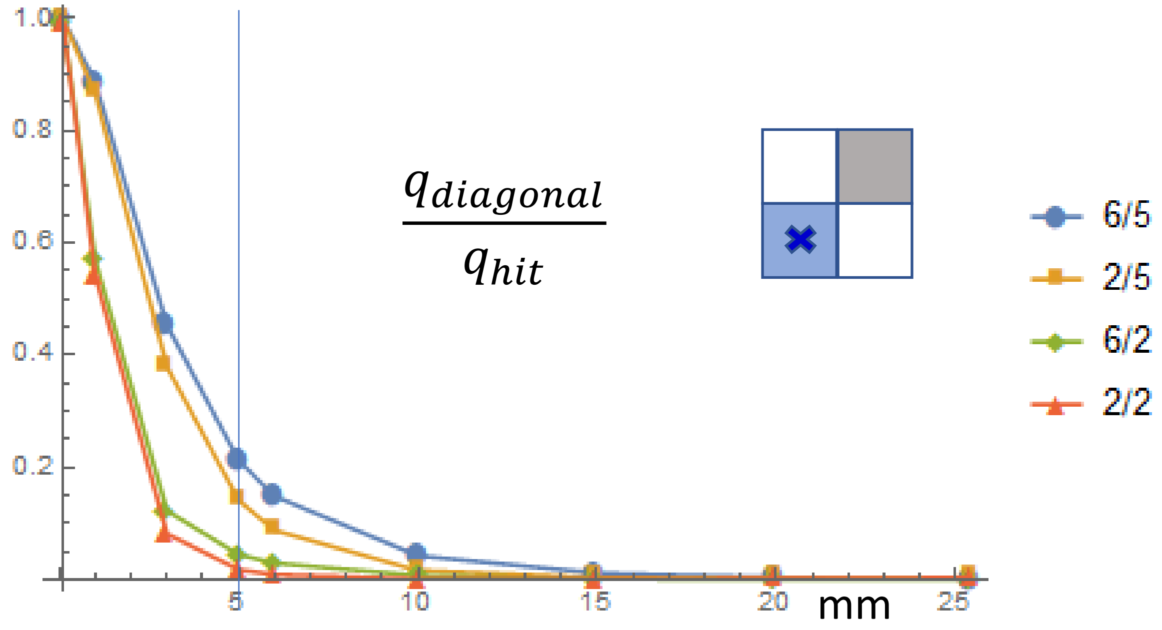
LAPPD – induced charge estimates

Collected charge by pads of different size and for different (MCP2out-A)/(A-pad) distances. ϵ not included.

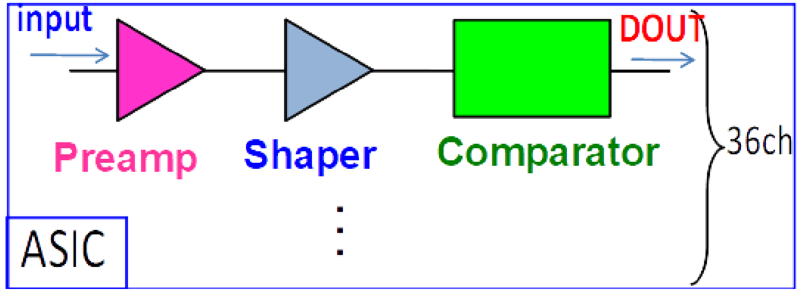


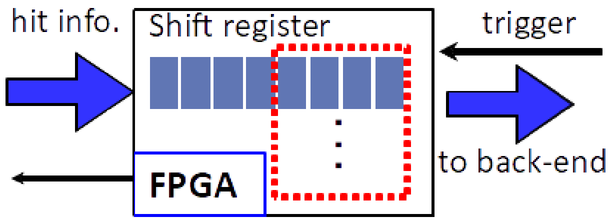






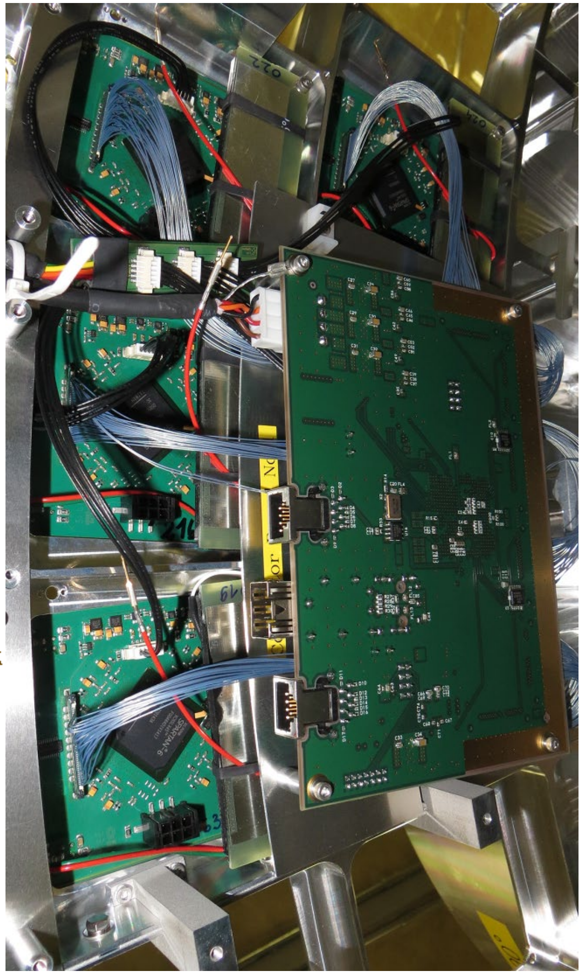
Front-end electronics

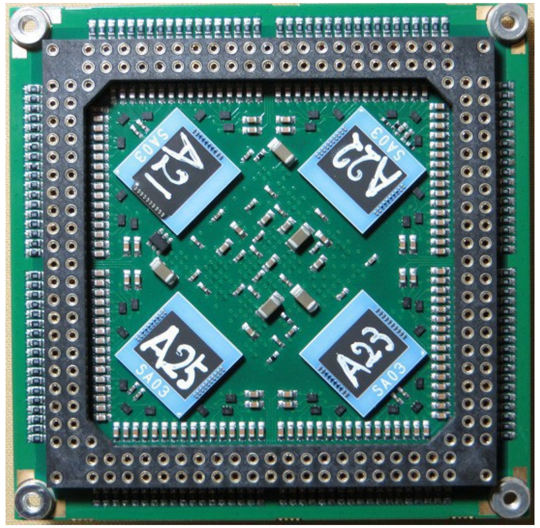


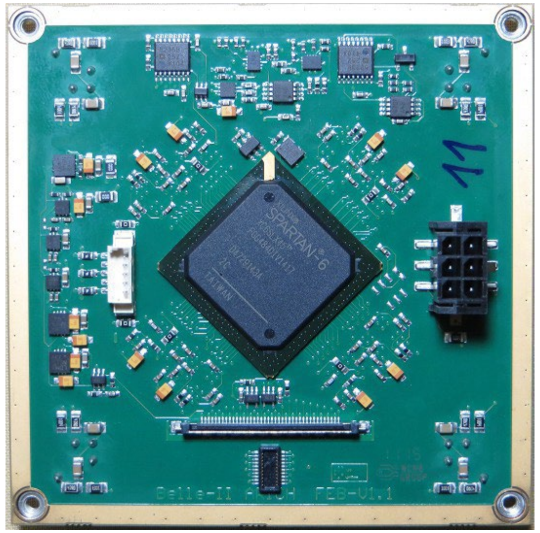


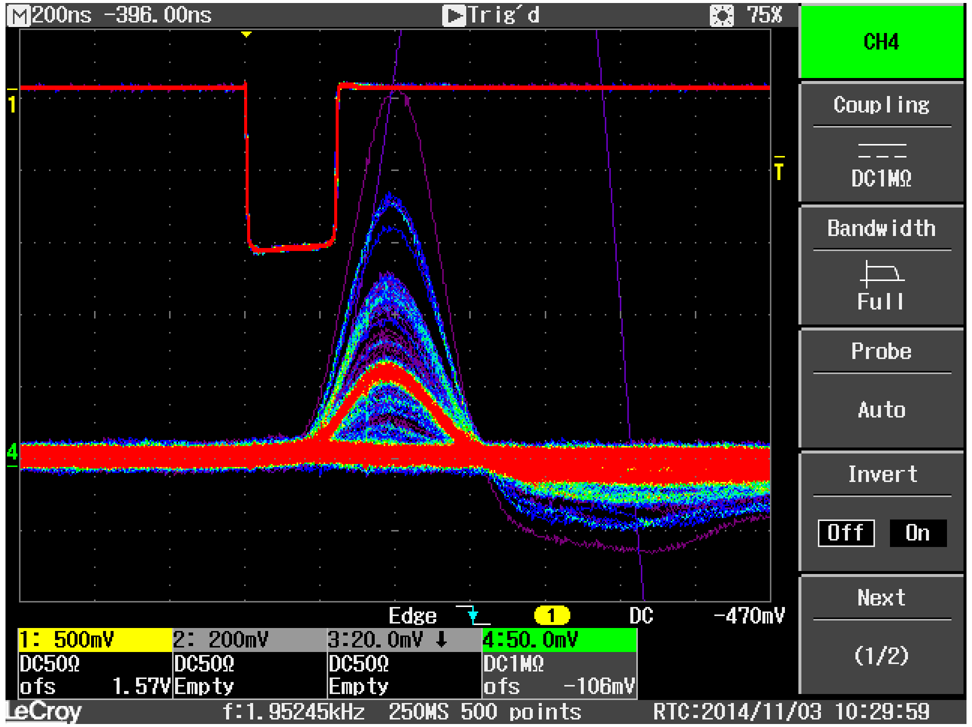
Front-end electronics is organized in units of one merger board (MB) controlling 6 (or 5) front-end boards (FEB)

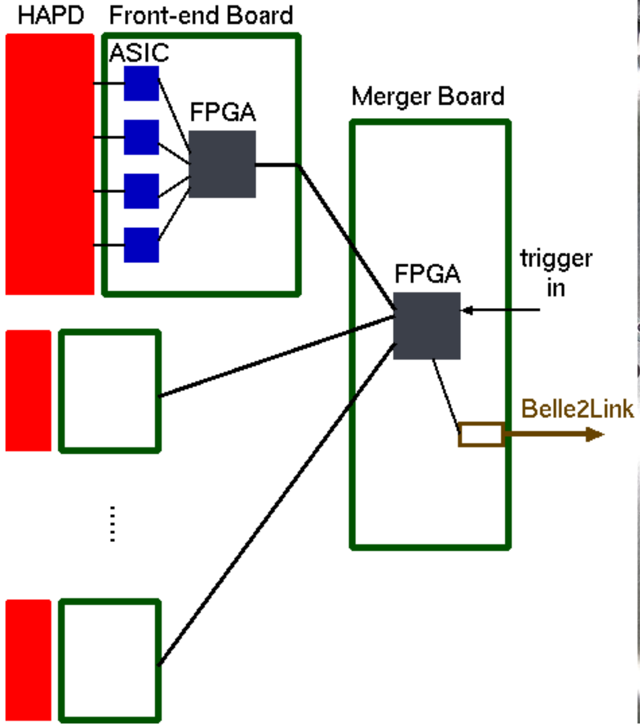
- FEB is based on 4 36 ch. ASICs each covering one APD, and Spartan-6 FPGA
- MB controls FEB slow control parameters, and collects and transfers data to back-end DAQ





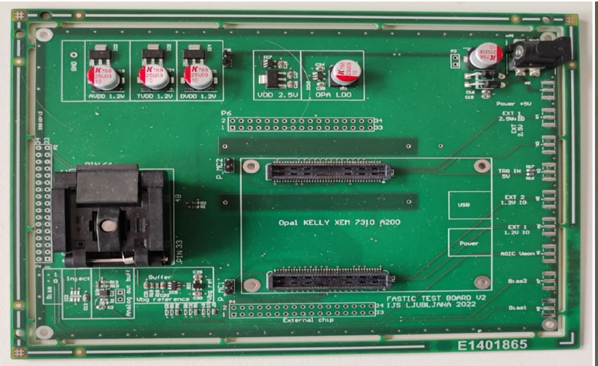


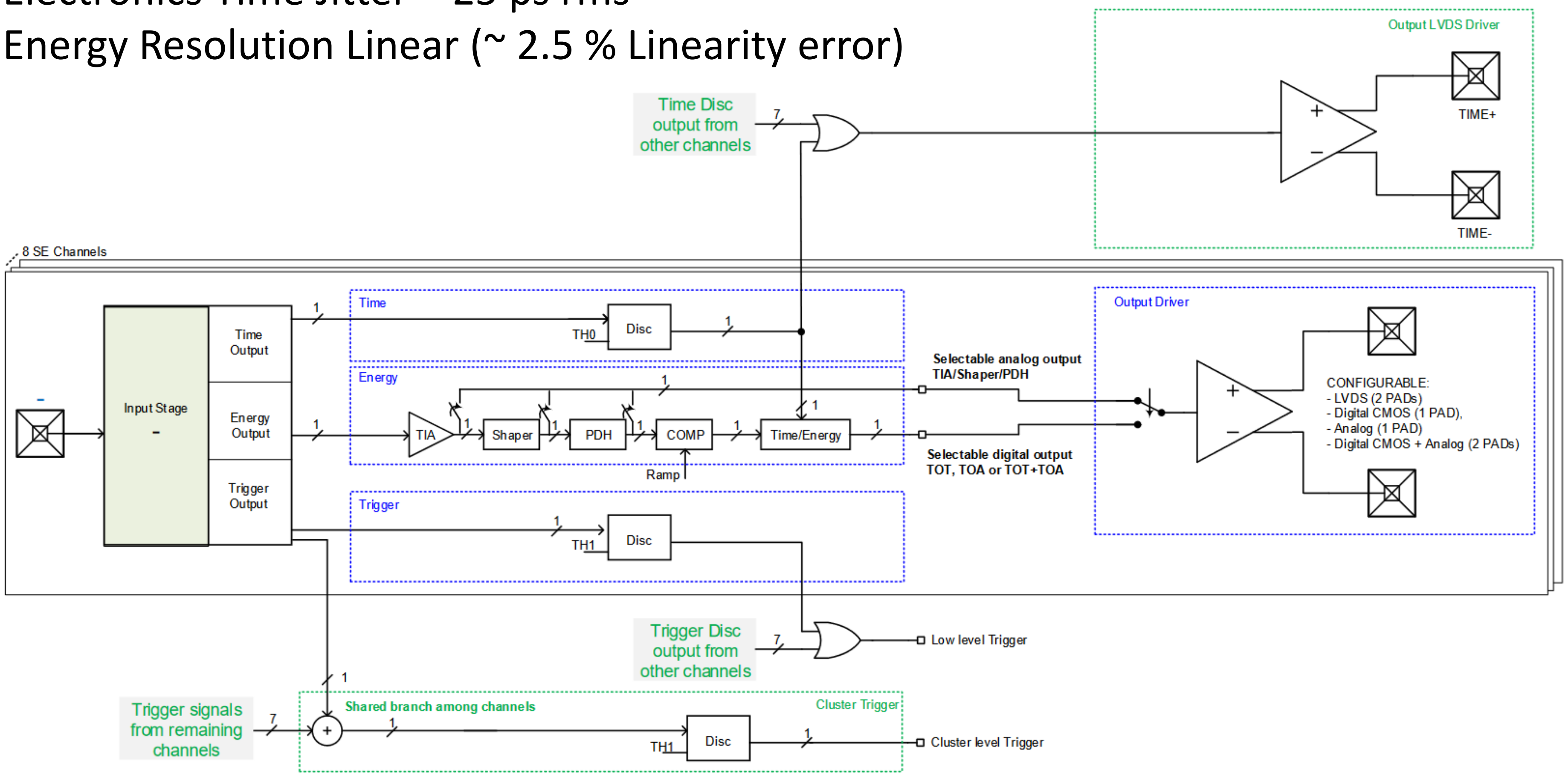


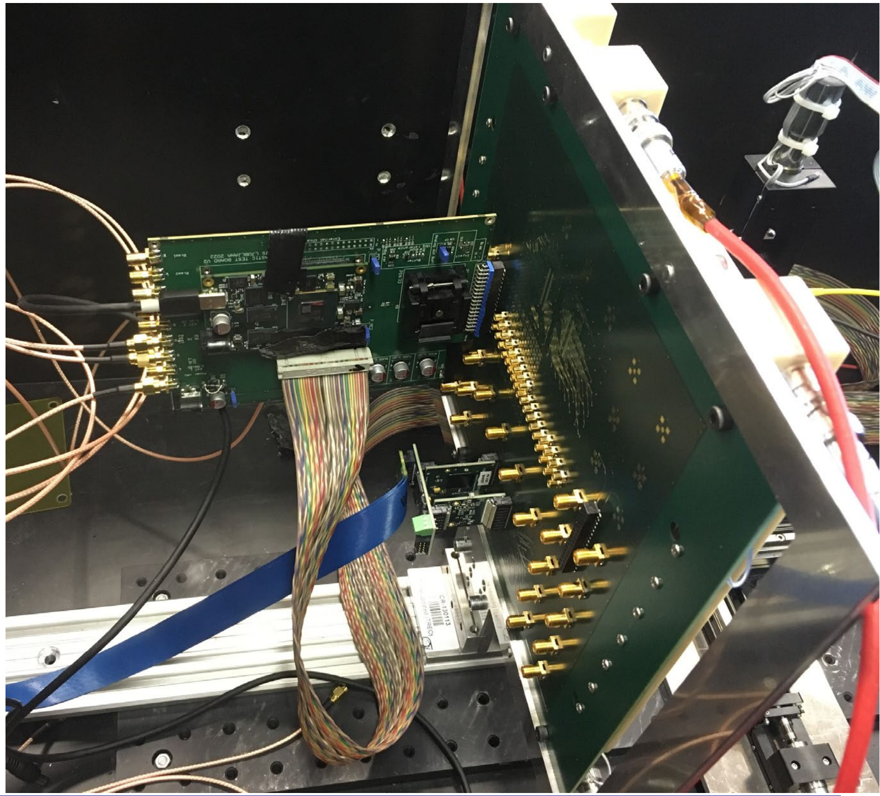


LAPPD + FastIC

- 8 CH ASIC
- Technology 65 nm CMOS
- ~ 6 mW/ch
- Number of channels: 8 SE / 4 DIFF
- Connection Type Configurable SE (Pos/Neg polarity) DIFF, Sum of 4 (Pos/Neg polarity)
- Electronics Time Jitter ~ 25 ps rms
- Energy Resolution Linear (~ 2.5 % Linearity error)

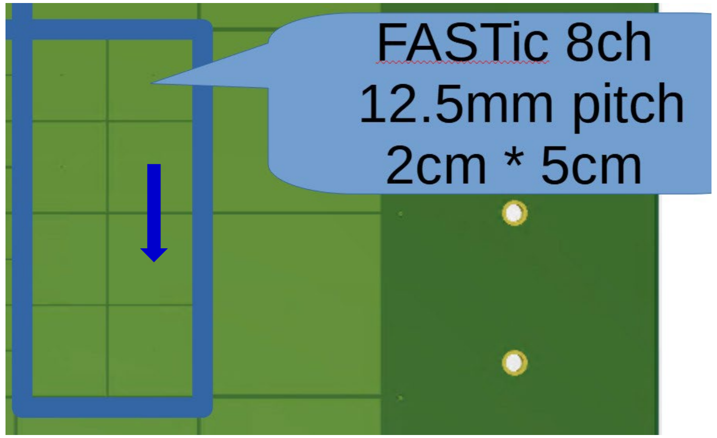


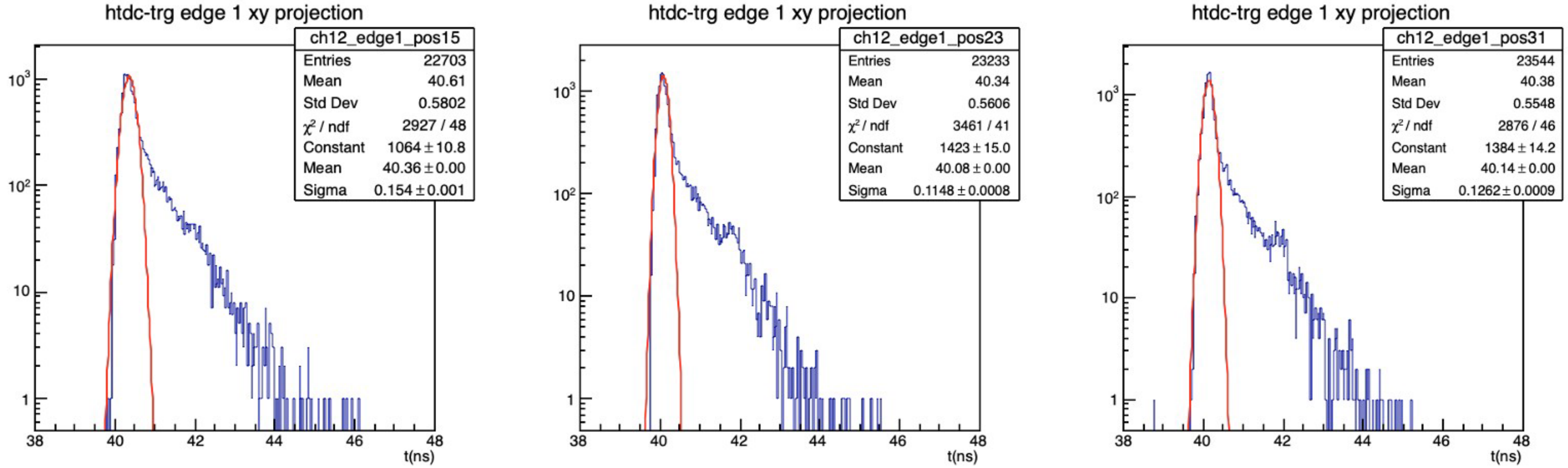




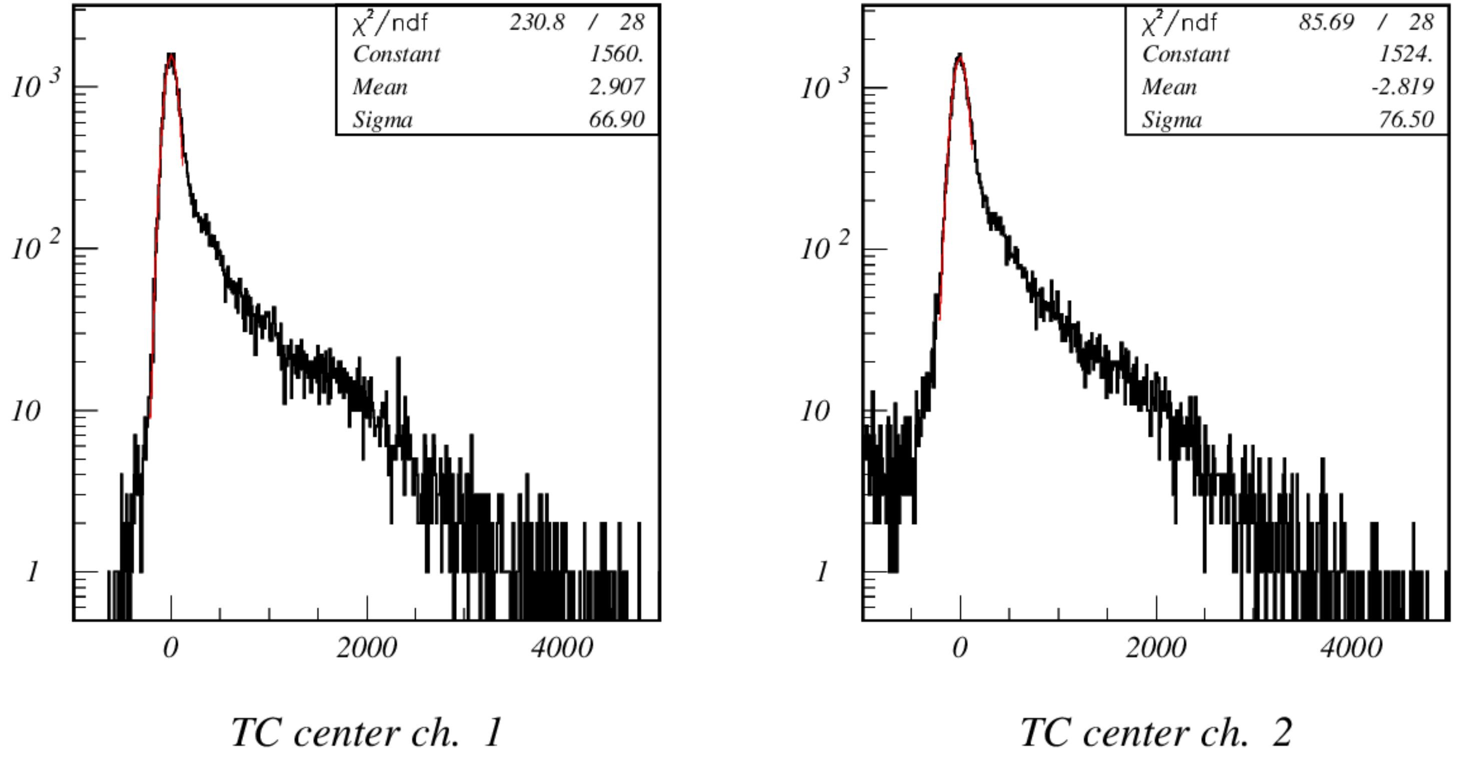
LAPPD + FastIC

- Timing resolution at different positions of laser spot $\approx 115\ ps$ – no time-walk correction





- Timing resolution $\approx 70\ ps$ with time-walk correction, ADC from shared signal on the neighbouring pad used



Summary & Plan

Operation of ARICH is stable with good PID performance

- detector is expected to work without upgrade throughout the Belle II operation

- LV connectors fixed during LS1 – no changes to the detector

- repair and replacement of some HAPDs planed for LS2
- possible aerogel radiator upgrade is considered for LS2 or beyond

- photodetector upgrade foreseen beyond LS2 – possible candidates:
  - MCP-PMTs (LAPPD, HRPPD …)
  - SiPMS

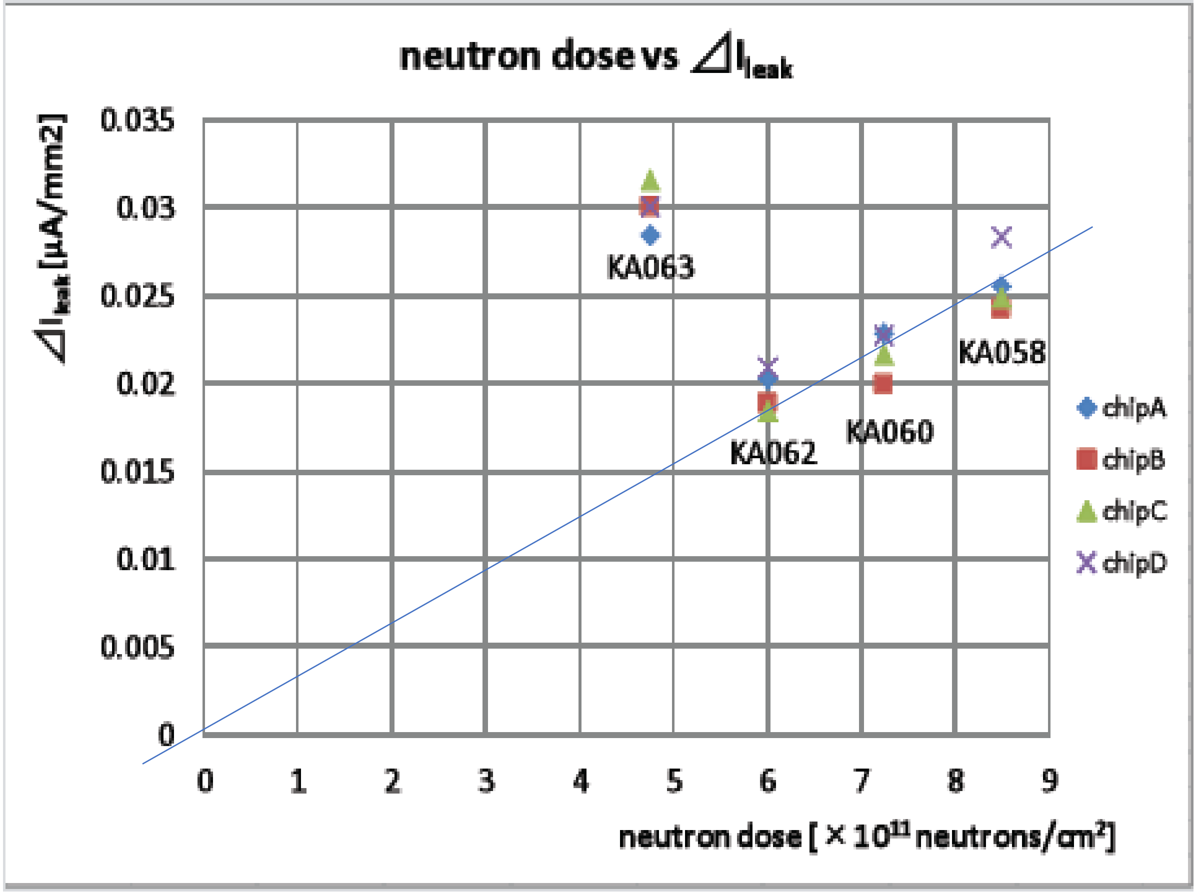
- simulations and tests of hardware are in progress …

BACKUP SLIDES

From irradiation tests

Neutron irradiation tests:

- $S_{APD} \approx 1000\ mm^2$
- fluence $10^{12}\ \frac{n_{eq}}{cm^2} \rightarrow \approx 30\ \mu A/APD$
- $30\ nA \rightarrow \approx 10^9\ \frac{n_{eq}}{cm^2}$

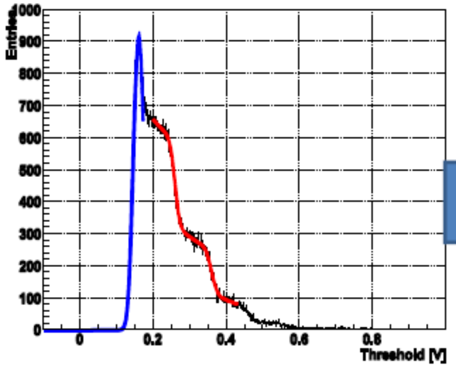


After measurement
(threshold scan@SA03)

KA058
Film A
Electrode ○
P+ thin
Neutron
8.5*10^11

*measured by SA03(X-FAB,QFP) (shaping time 100ns)

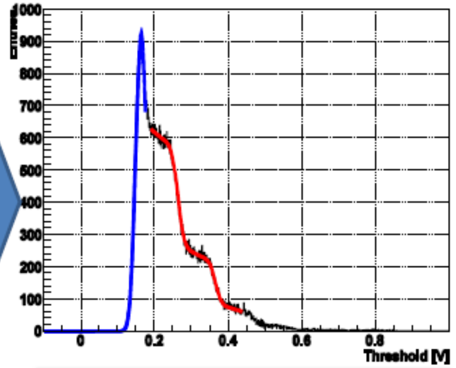
Before Gamma Irradiation



chip A-34ch:326.5V(17.26μA)
HV:-8.5kV

noise(gaus0) = 5464.03[e-]
2pe - 1pe = 39137.45[e-]
S/N(2pe-1pe/sigma0) = 7.16

After Gamma Irradiation

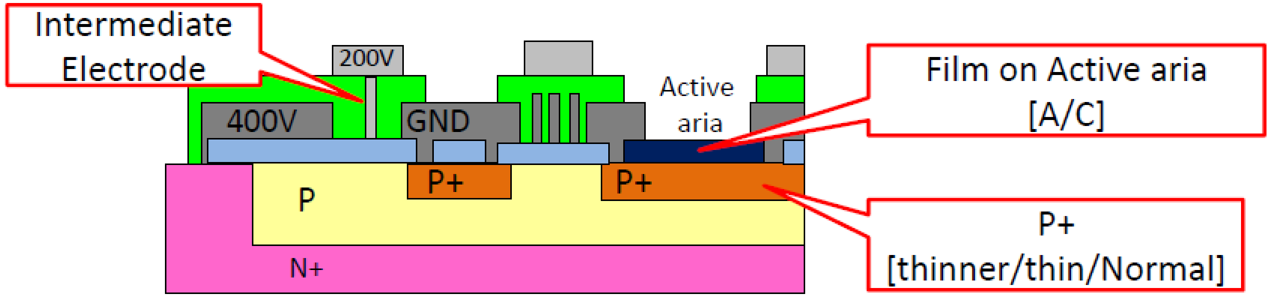


chip A-34ch: 326.5V(17.02μA)
HV:-8.5kV

noise(gaus0) = 5665.96[e-]
2pe - 1pe = 39763.47[e-]
S/N(2pe-1pe/sigma0) = 7.02

・Noise Level & Total Gain dose not change before and after irradiation.
・If HAPD dose not Break down, we can use it.

Film A type APD with intermediate electrode selected for production



LAPPD – 5mm strips

- charge sharing for 5 mm strips