Studies of large dynamic range silicon photomultipliers for the CMS HCAL upgrade

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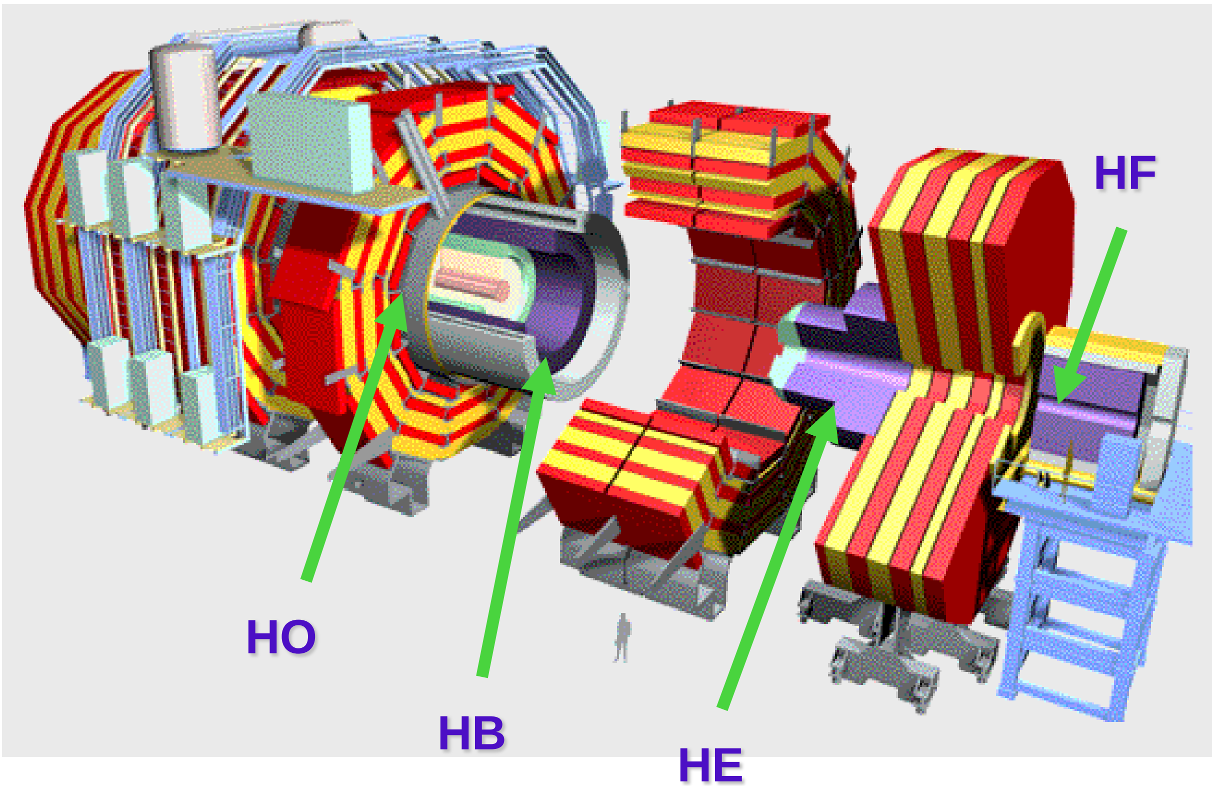
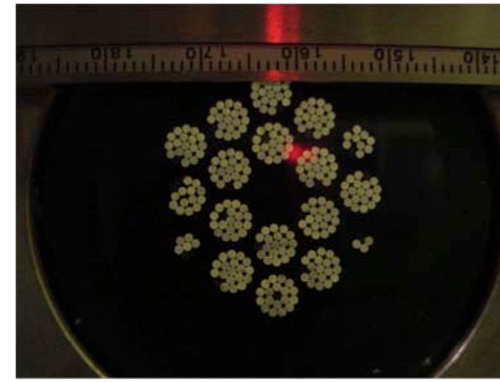
Outline

- CMS HCAL and motivation for its Upgrade
- HB&HE upgrade challenges
- Status of photo-sensor development for the HB&HE upgrade
- R&D plans for 2011-2012

CMS HCAL





HB, HE, HO similar technology: scintillator tiles with Y11 WLS fiber readout, brass (steel for HO) absorber. 19 ch. HPD was selected as the CMS HCAL photodetector.

Motivation for the HB/HE photo-detector upgrade

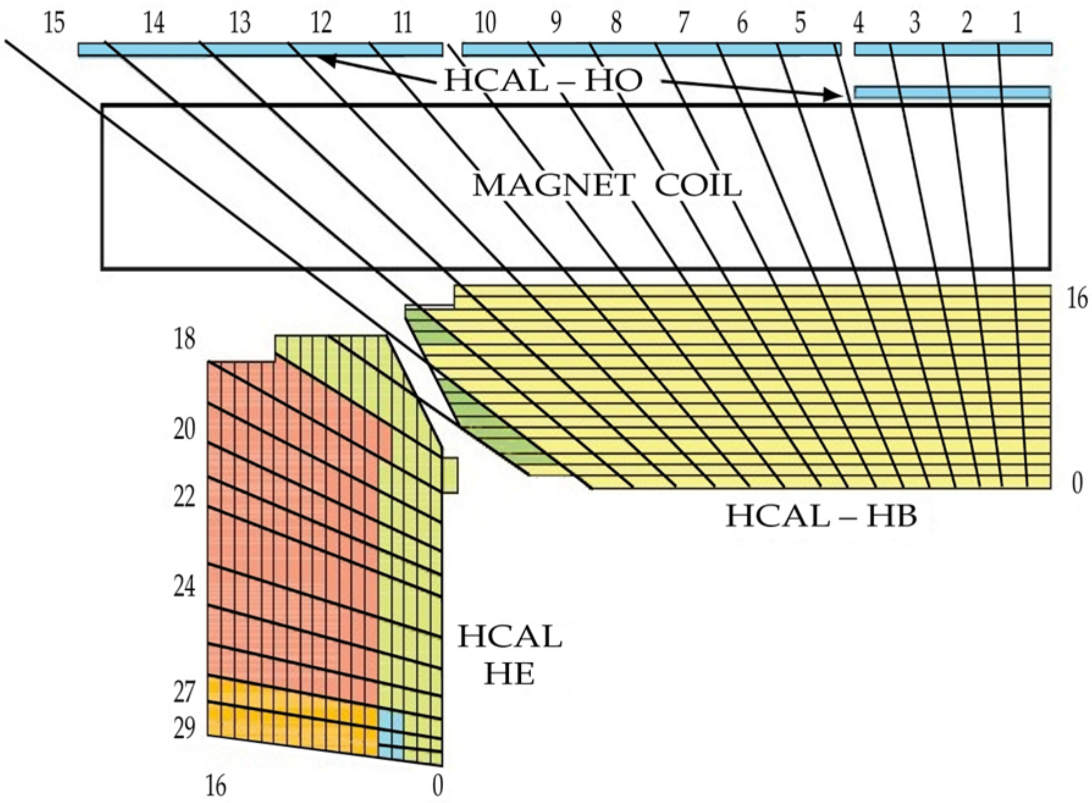
1. G-APDs/SiPMs have better quantum efficiency, higher gain, and better immunity to magnetic fields than HPDs. Since SiPMs operate at relatively low voltages, they do not produce large pulses from high voltage breakdown that mimic energetic showers like HPDs do. These features of the SiPMs together with their low cost and compact size compared to HPDs enable several major changes to the HCAL.

2. Implementation of depth segmentation which has advantages in coping with higher luminosities and compensating for radiation damage to the scintillators. This is made possible by the use of SiPMs.

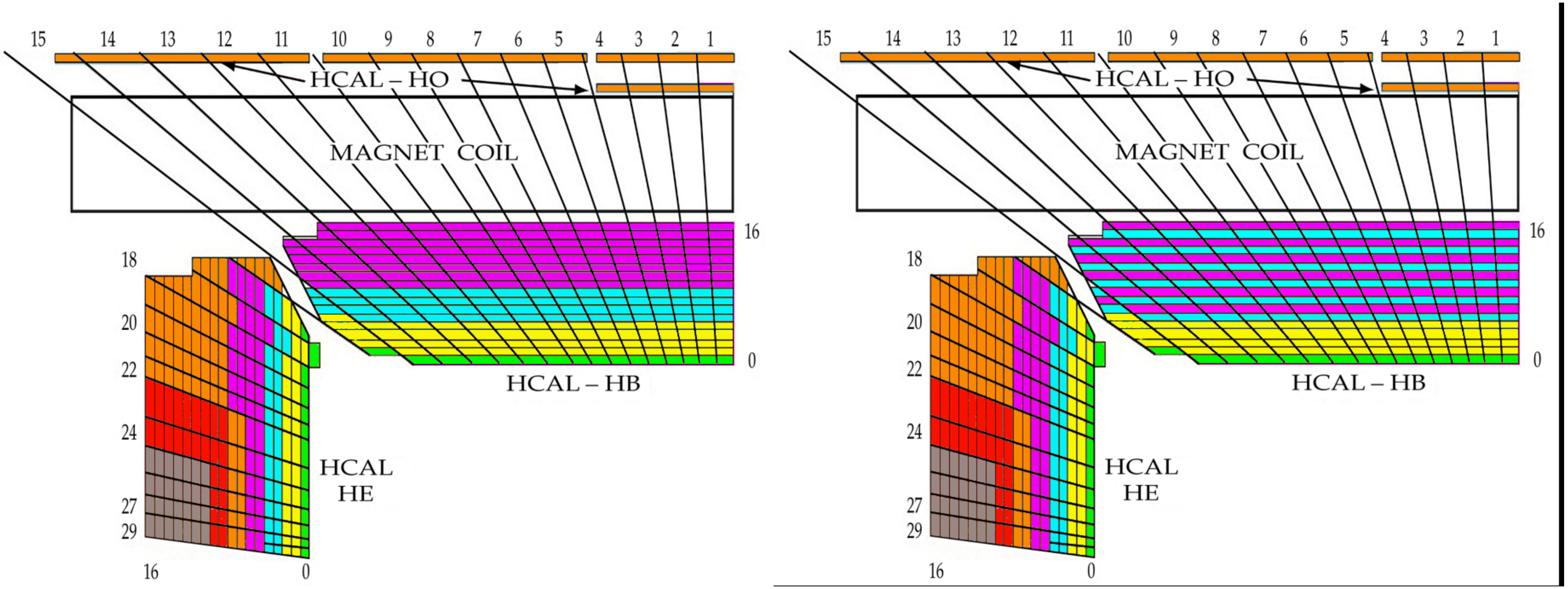
3. Use of timing to clean up backgrounds, made possible by the extra gain and better signal-to-noise of the SiPMs.

Status of the HO calorimeter upgrade is discussed in the NDIP-2011 poster (ID-101): J.Freeman "Progress on the SIPM Upgrade of the CMS Outer Hadron Calorimeter (HO)"

Longitudinal segmentation of the CMS HCAL



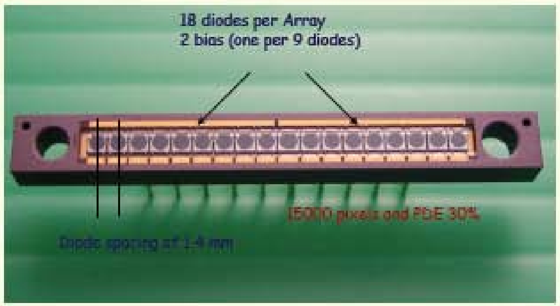
Segmentation schemes

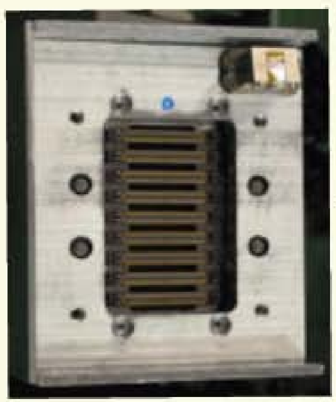


Color code represents the layers that are grouped into separate readout channels. The left scheme maximizes resolution by concentrating separate readout channels to groups of layers where the energy density is highest. The right scheme maximizes redundancy and robustness of the calorimeter by providing two rear readout channels with interleaving sampling of the hadronic showers.

EDU vs. ODU concepts

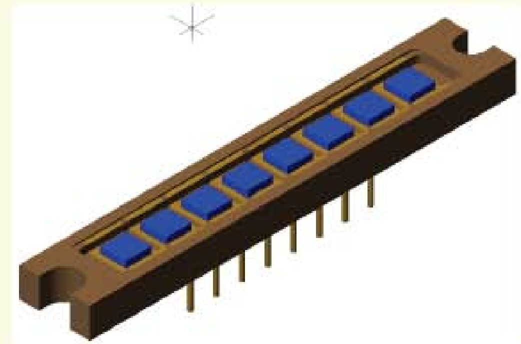
EDU Idea : direct readout of all 17 depth and sum electrically
L0,L1-4,L5-8,L9-16

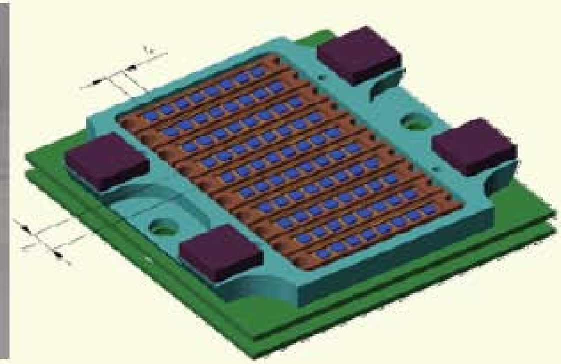




18x1 mm^2 G-APD array

ODU Idea : 4 depth optically summed
L0,L1-4,L5-8,L9-16





8x4.84 mm^2 G-APD array

The most important HB/HE G-APD/SiPM requirements

- High PDE(515 nm): 15 - 30%
- Number of pixels (effective pixels): >15 000 1/mm^2
- Fast pixel recovery time: 5 – 100 ns (depends on the pixel density)
- Good radiation hardness > 3*10^{12} n/cm^2 (10 years of SLHC)
  - Gain*PDE change < 20%
  - noise < 1 MIP at 50 ns integration time
- Low optical cross-talk between cells <10%
- Low sensitivity to neutrons < 10^{-5} 1/n at 30 p.e. threshold?
- Low temperature coefficient < 5%/C
- High reliability

HB/HE photo-sensor candidates (end of 2008)

MPPC S10362-050 (Hamamatsu)

- PDE(515nm)=25 - 30 %; Gain~7*10^5
- X-talk =10-15%
- dynamic range: 400 cells/mm^2 (1936 cell (for 4.84 mm^2) << 25 000)
- cell recovery time: τ~ 15-20 нсек

MPPC S10362-025 (Hamamatsu)

-PDE(515nm)~20 %; Gain~2.5*10^5
- X-talk <15%
- dynamic range: 1600 cells/mm^2 (7744 cell (for 4.84 mm^2) << 25 000)
- cell recovery time: τ~ 6 нсек

MAPD-A (Zecotek, Singapore):

- PDE(515нм)~14%; Gain~5*10^4
- X-talk <15%
- dynamic range: 15 000 cells/mm^2 (72 600 cells (for 4.84 mm^2))
- cell recovery time (95%): ~300 µs >> 1 µs

MAPD-A (Zecotek, Singapore):

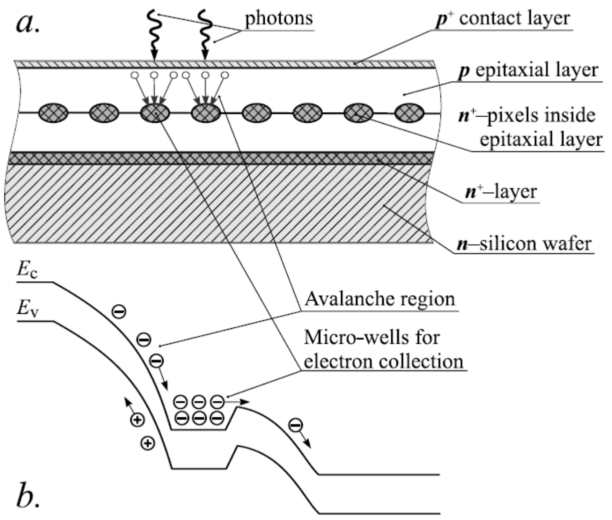
- PDE(515нм)~12%; Gain~2*10^4
- X-talk <15%
- dynamic range: 40 000 cells/mm^2 (193 600 cells (for 4.84 mm^2))
- cell recovery time (95%): ~300 µs >> 1 µs

We also studied devices from : FBK, CPTA , ST-Micro, Sens-L…
But all these SiPMs had low cell density <1000 cells/mm^2

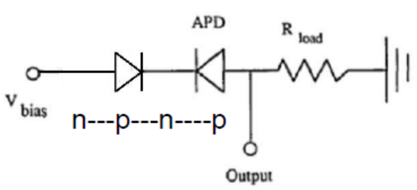
New candidate from Zecotek: MAPD-3N (2009)

Schematic structure (a) and zone diagram (b) of a Micro-pixel APD (MAPD)

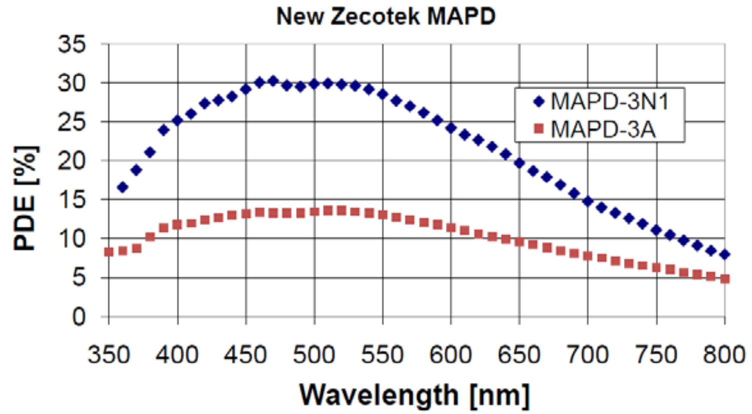
(Z. Sadygov et al, arXiv;1001.3050)



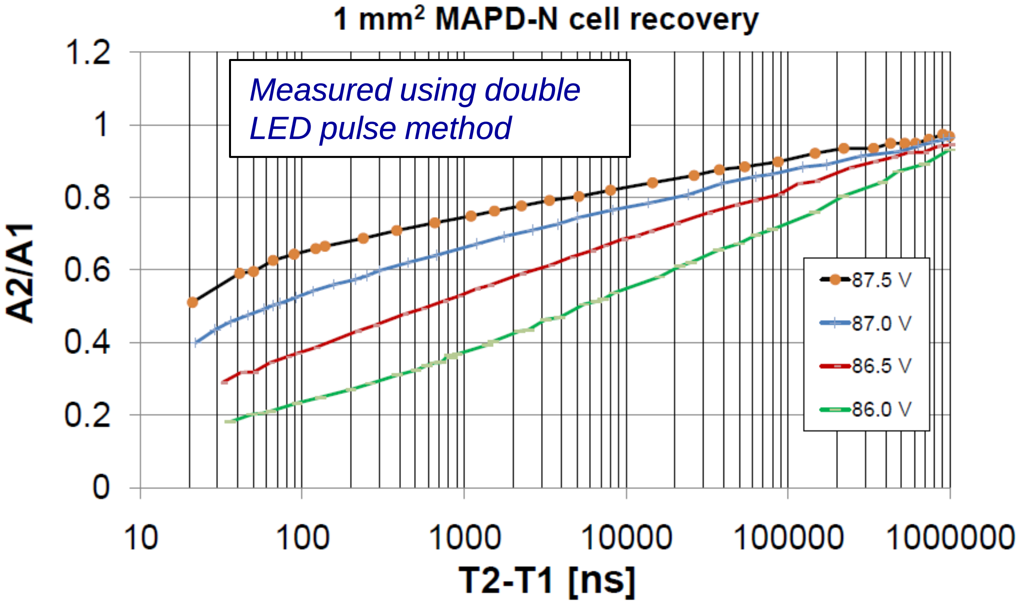
MAPD cell schematics



This structure doesn't contain quenching resistors. Specially designed potential barriers are used to quench the avalanches.



MAPD cell recovery



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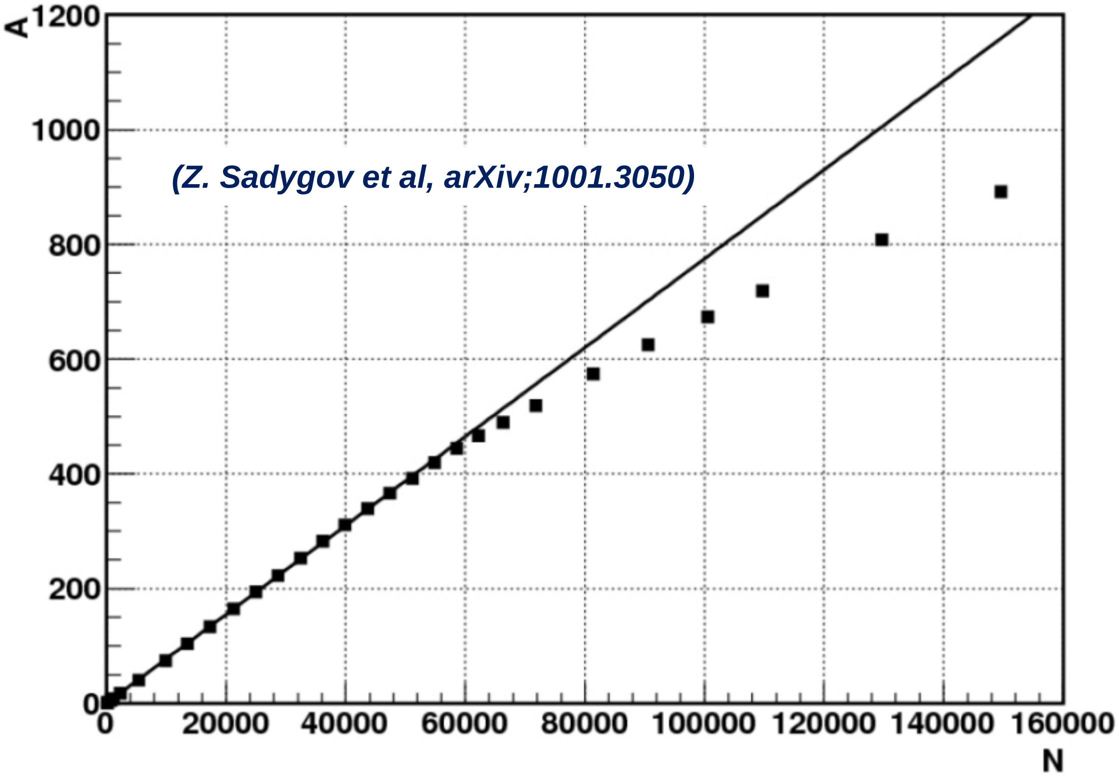
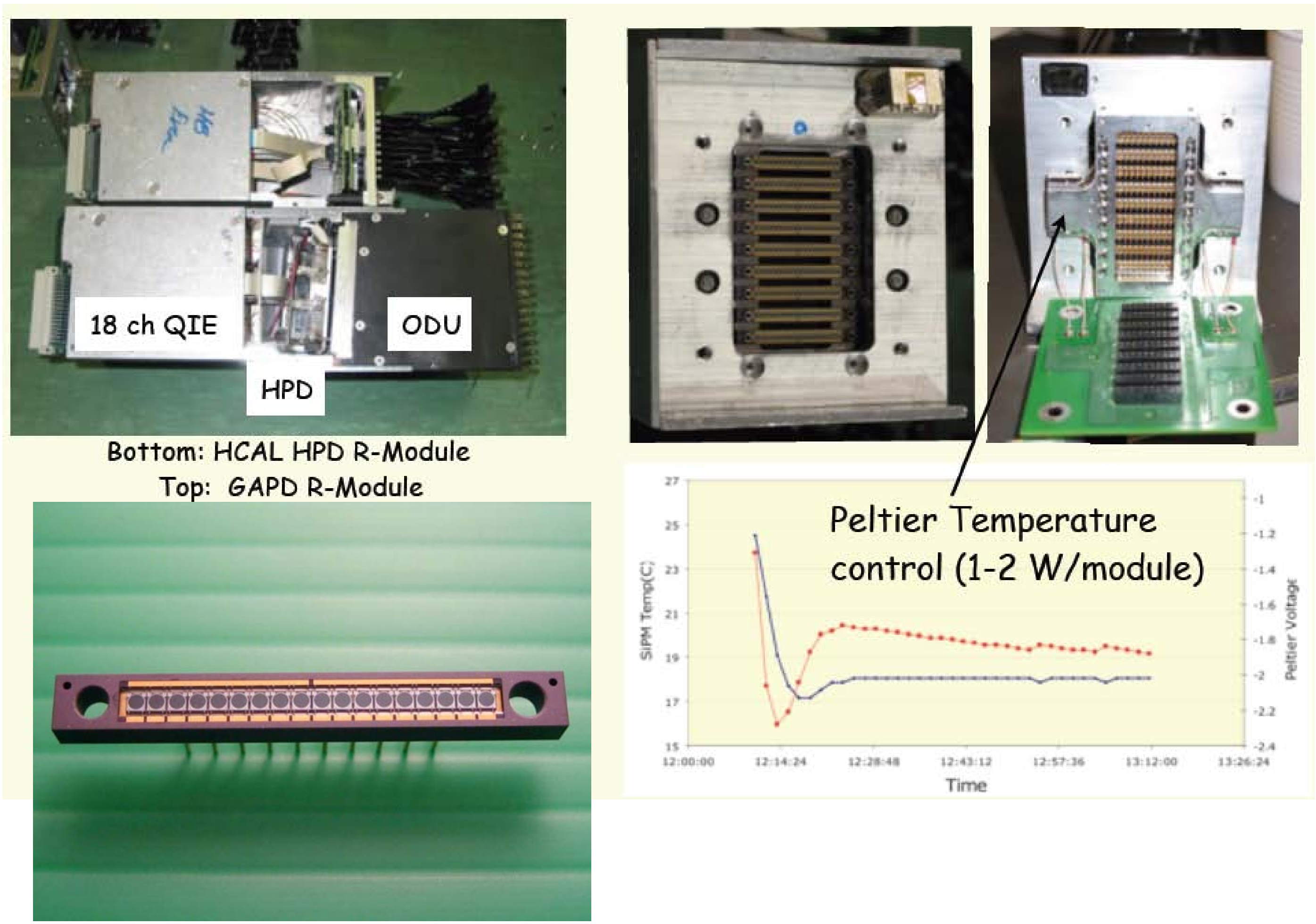
MAPD-N linearity



Dependence of the MAPD (135 000 cells, 3x3 mm^2 area) signal amplitude A (in relative units) on the number of incident photons N

2009 prototype module

We decided to perform BT-2009 to understand challenges using G-APDs in HCAL.
Separate read-out of HCAL layers (1-2-2-12 segmentation)



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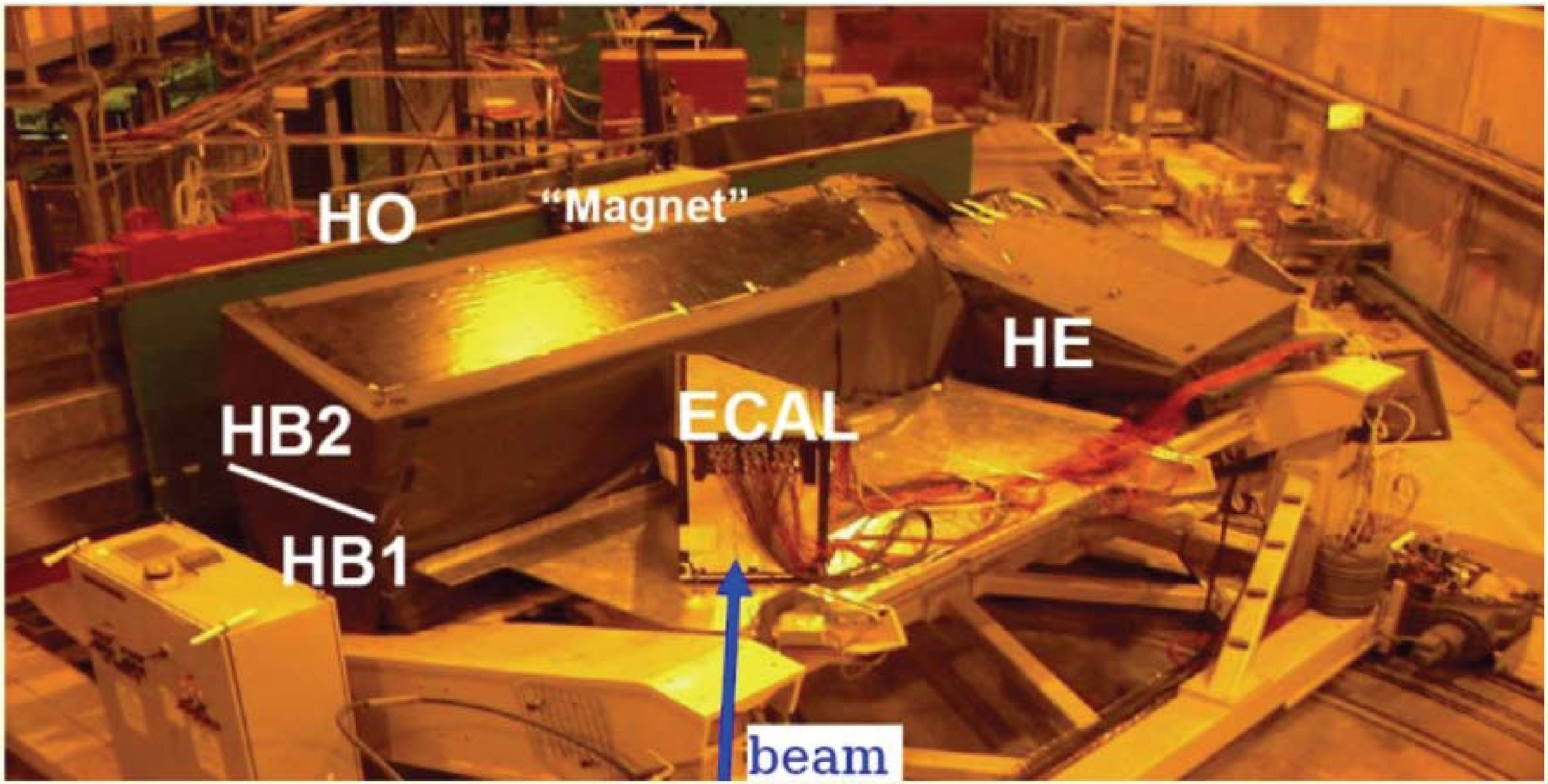
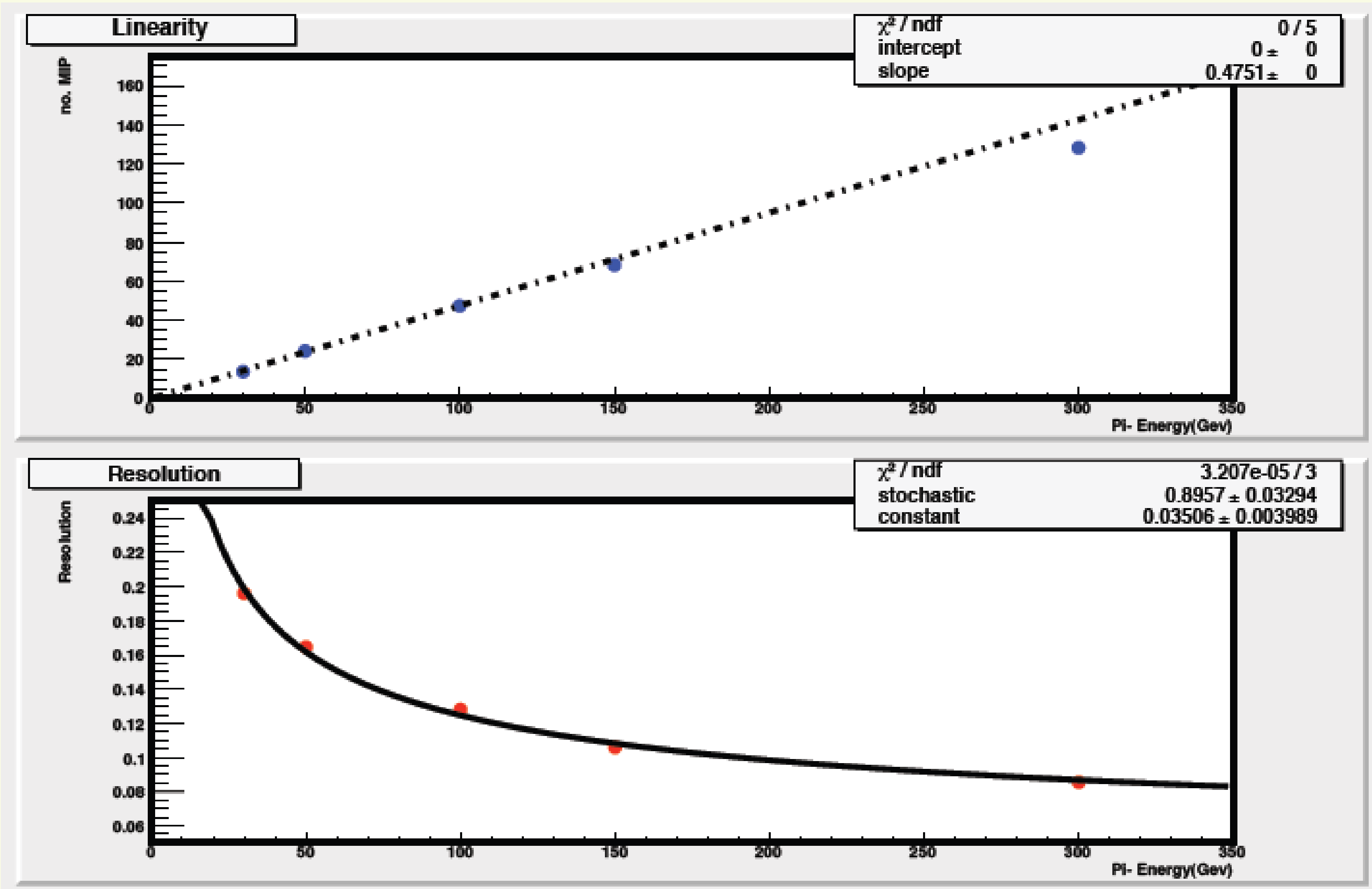
CERN H2 TB-2009 setup



This year we expect real ECAL Supermodule and good data on the advantages of the depth segmentation.

TB-2009 with 15K/mm² MAPDs

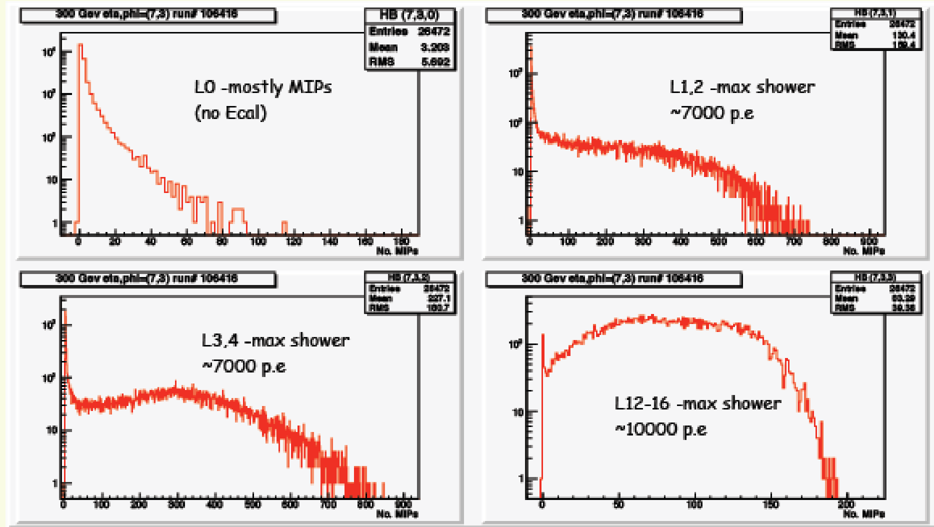


Challenges using G-APD in HCAL

1) Very large dynamic range
   A few p.e. /MIP/layer =2 GeV up to 500 GeV in a few layer from Jet events

2) High occupancy in front layers in SLHC
   Fast recovery time

300 GeV pion distributions vs depth in CMS HCAL tower (No ECAL)



3) Radiation hard up to 3E12 1 MeV neutrons/cm2 for 3000 fb-1 (SLHC)

5/11/2011 *A.H Heering, May 2011 upgrade week* 7

Our candidates didn't complelly satisfy the requirements of the CMS HB/HE upgrade
→ R&D to develop G-APD for HB/HE started in 2009

R&D goals for Zecotek

Zecotek can produce MAPDs with >15 000 cells/mm^2 keeping high PDE >25% at the same time. However the existing MAPDs have slow cell recovery time (~300 μs for 95% recovery). It has to be reduced a factor of ~100 to satisfy the CMS HCAL upgrade requirements. We set the following main R&D goals for Zecotek

- PDE(515nm): >20 %;
- number of cells: ~27 000/mm^2 (MAPD-EDU concept), 50-70K cells for 2.2x2.2 mm^2 MAPD-ODU solution
- cell recovery time (95% cell recovery): ~ 1-10 μs
- gain ~30 000 – 60 000
- optical cross-talk: <10%
- radiation hardness: up to ~10^{13} n/cm^2
- low sensitivity to neutrons: 10^{-5} 1/n at 1 MIP threshold (?)

R&D goals for Hamamatsu

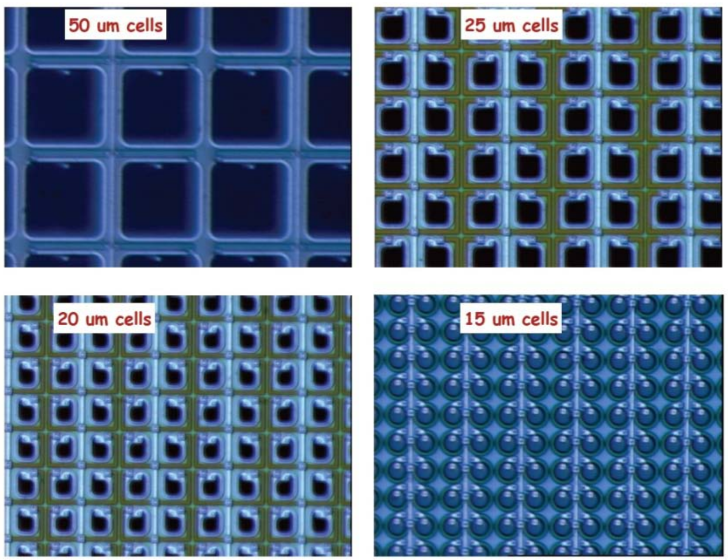
Hamamatsu can't produce MPPCs with >5 000 cells/mm^2 keeping high PDE >15% at the same time. However it can produce devices with very fast cell recovery time (<6 ns). The emission time of Y11 WLS is ~10 ns. MPPCs with fast cell recovery time <5 ns should have a factor 2-3 larger dynamic range in comparison to the MPPCs with slow cell recovery time. We set the following main R&D goals for Hamamatsu:

- PDE(515nm)>15 %;
- number of cells: 4 489 cells/mm^2 (or ~20 000 cells for 2.2x2.2 mm^2 MPPC-ODU solution)
- cell recovery time: τ~ 5 ns (the maximum dynamic range of such MPPCs should be extended to ~11 000-12000 p.e/mm^2)
- gain ~200 000
- optical cross-talk: <10%
- radiation hardness: up to ~10^{13} n/cm^2
- low sensitivity to neutrons: 10^{-5} 1/n at 1 MIP threshold (?)

MPPCs with increased dynamic range

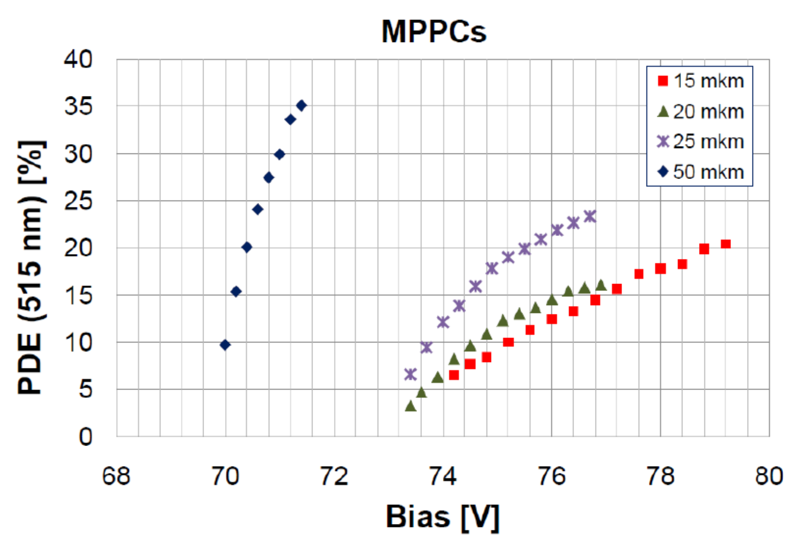
In June 2010 Hamamatsu developed for CMS new large dynamic range MPPCs

MPPCs' photos taken using microscope

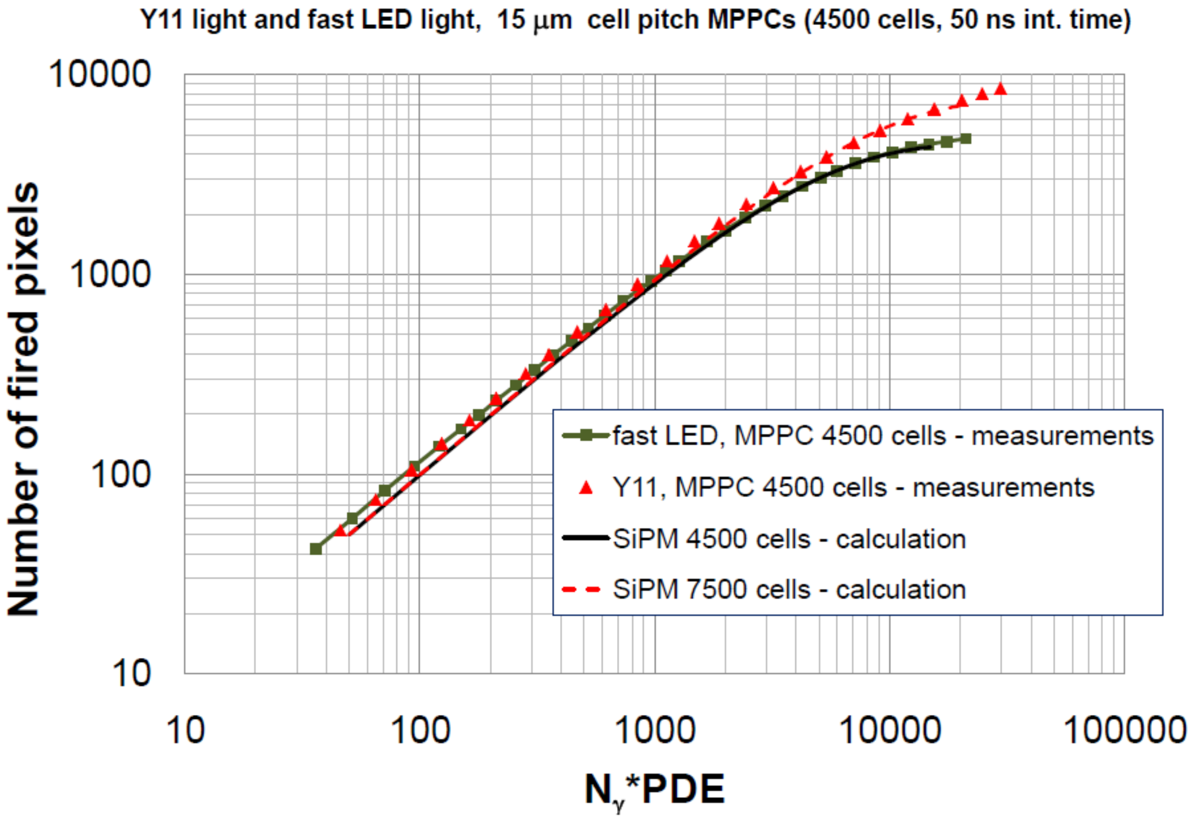


Main MPPC parameters

MPPC type	# cells 1/mm²	C, pF	R_{cell}, kOhm	C_{cell}, fF	$\tau = R_c x C_c$, ns	VB, V T=23 C	V_{op}, V T=23 C	Gain(at V_{op}), $X10^5$
15 μm pitch	4489	30	1690	6.75	11.4	72.75	76.4	2.0
20 μm pitch	2500	31	305	12.4	3.8	73.05	75.0	2.0
25 μm pitch	1600	32	301	20	6.0	72.95	74.75	2.75
50 μm pitch	400	36	141	90	12.7	69.6	70.75	7.5



Linearity for Y11 and fast LED light (R_q=1.67 MOhm, 15 μm MPPCs)



Fast LED light: the MPPC with 4 500 cells is equivalent to a SiPM with 4 500 cells.
Y11 light (emission time ~10 ns): the same MPPC works as a SiPM with 7 500 cells. Pixel recovery time constant: τ~11 ns.

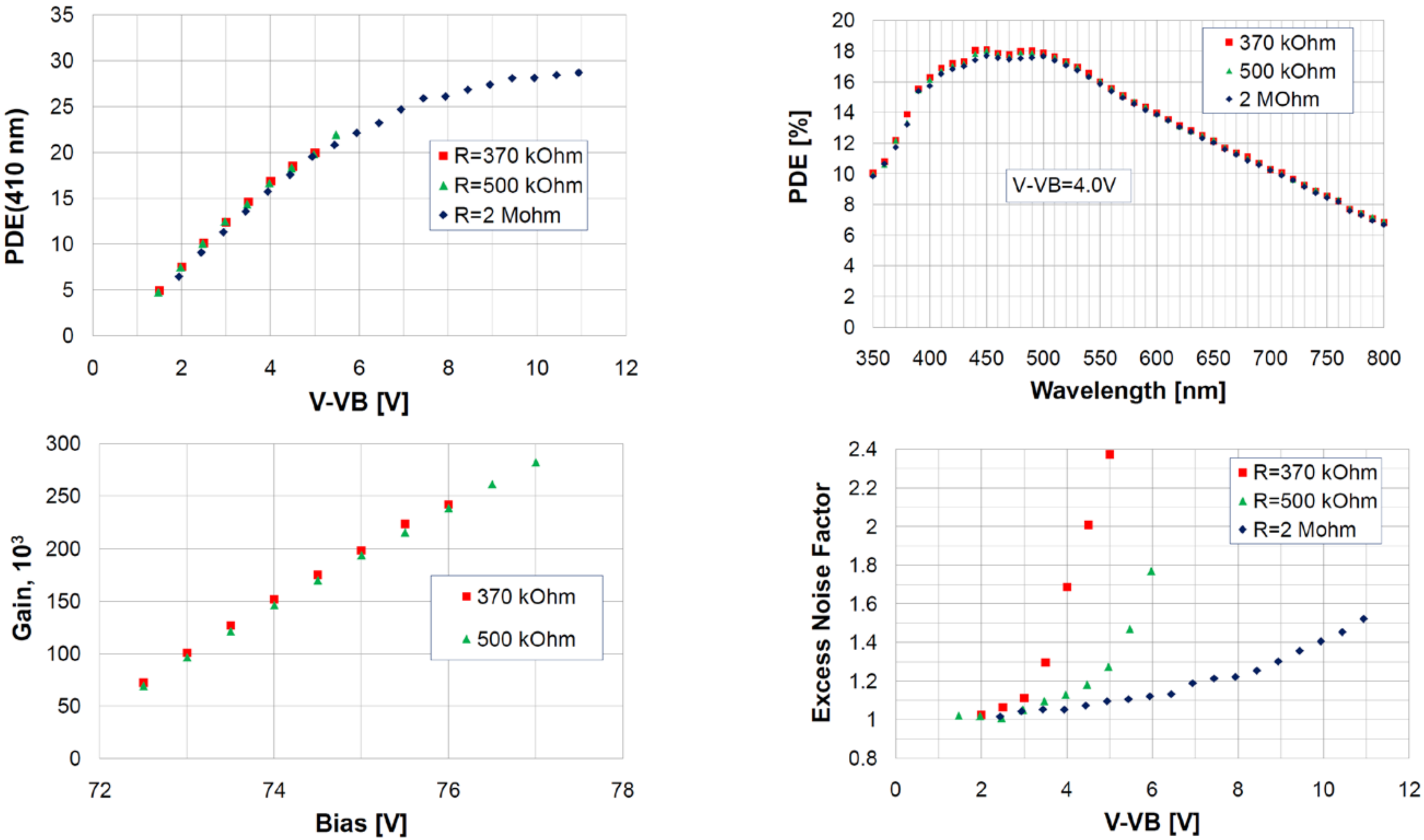
Fast 15 μm MPPCs

- In March 2011 we received 3 new typs of 1 mm^2 15 μm cell pitch MPPCs from Hamamatsu (free samples):

- MPPC with R_q=2 MOhm
- MPPC with R_q=500 kOhm
- MPPC with R_q=370 kOhm

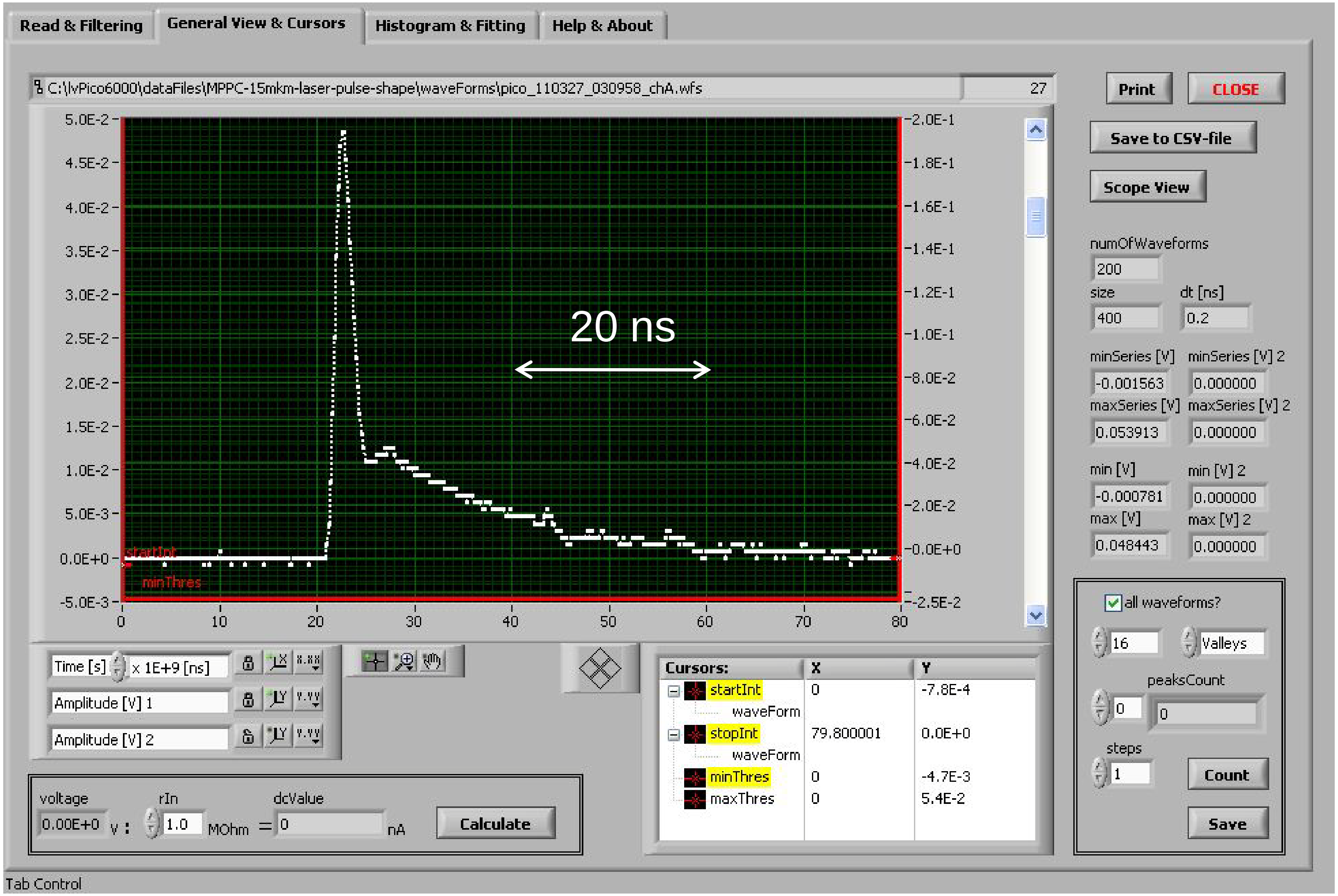
- Such parameters of MPPCs as VB, Gain, Capacitance, Cell resistor, 35 ps laser response, PDE(515 nm) were measured at CERN APD Lab.
- Set-ups for cell recovery time and linearity measurements were improved (the LED was replaced with much faster and brighter one)
- Cell recovery was measured for new 15 mm cell pitch MPPCs (500k Ohm and 2 MOhm quenching resistors)
- MPPC linearity of 15 μm (500 kOhm) for Y11 WLS light was measured

New 15 μm MPPCs parameters

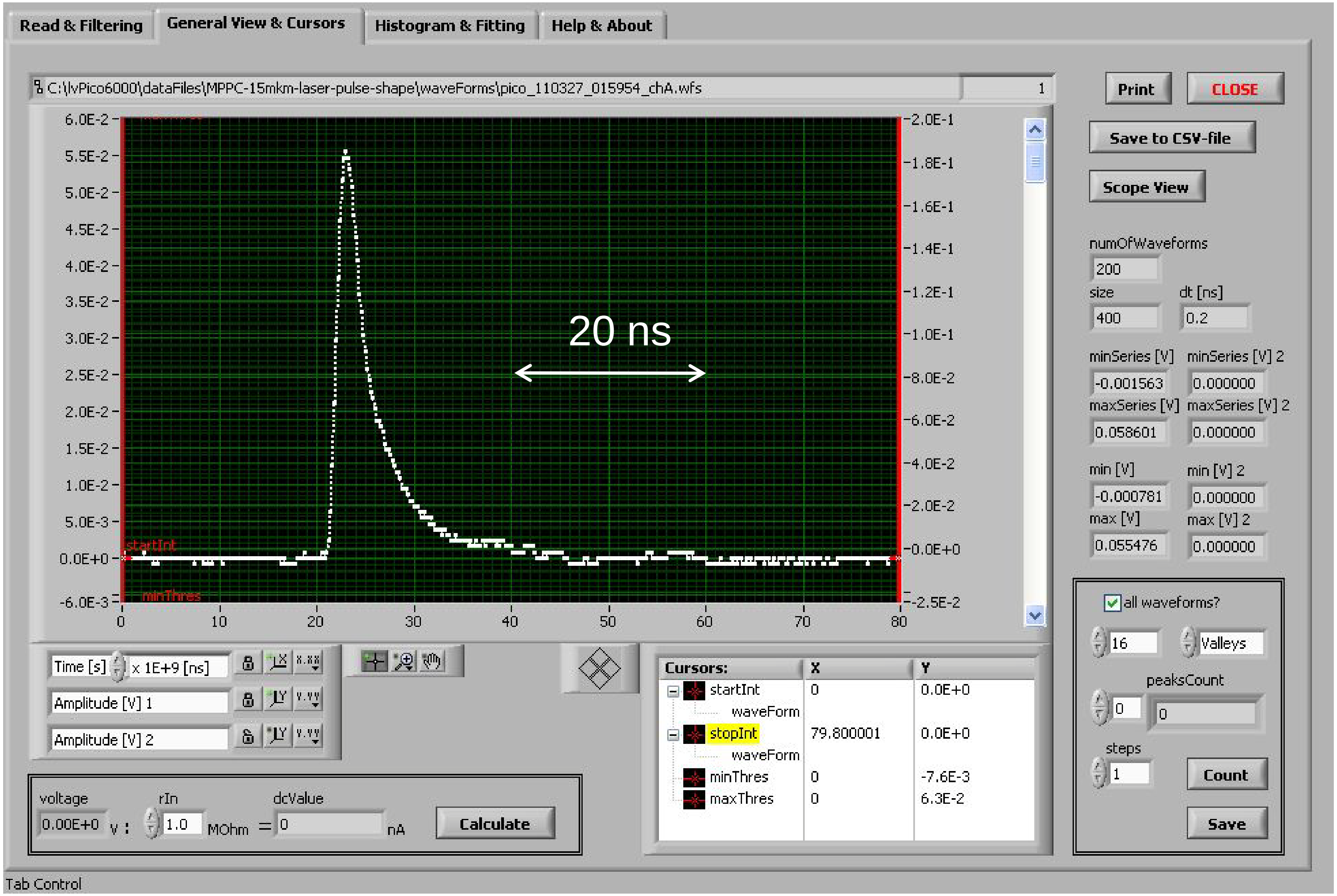


C_{cell}~8 fF, for R_q~500 kOhm → τ~4 ns

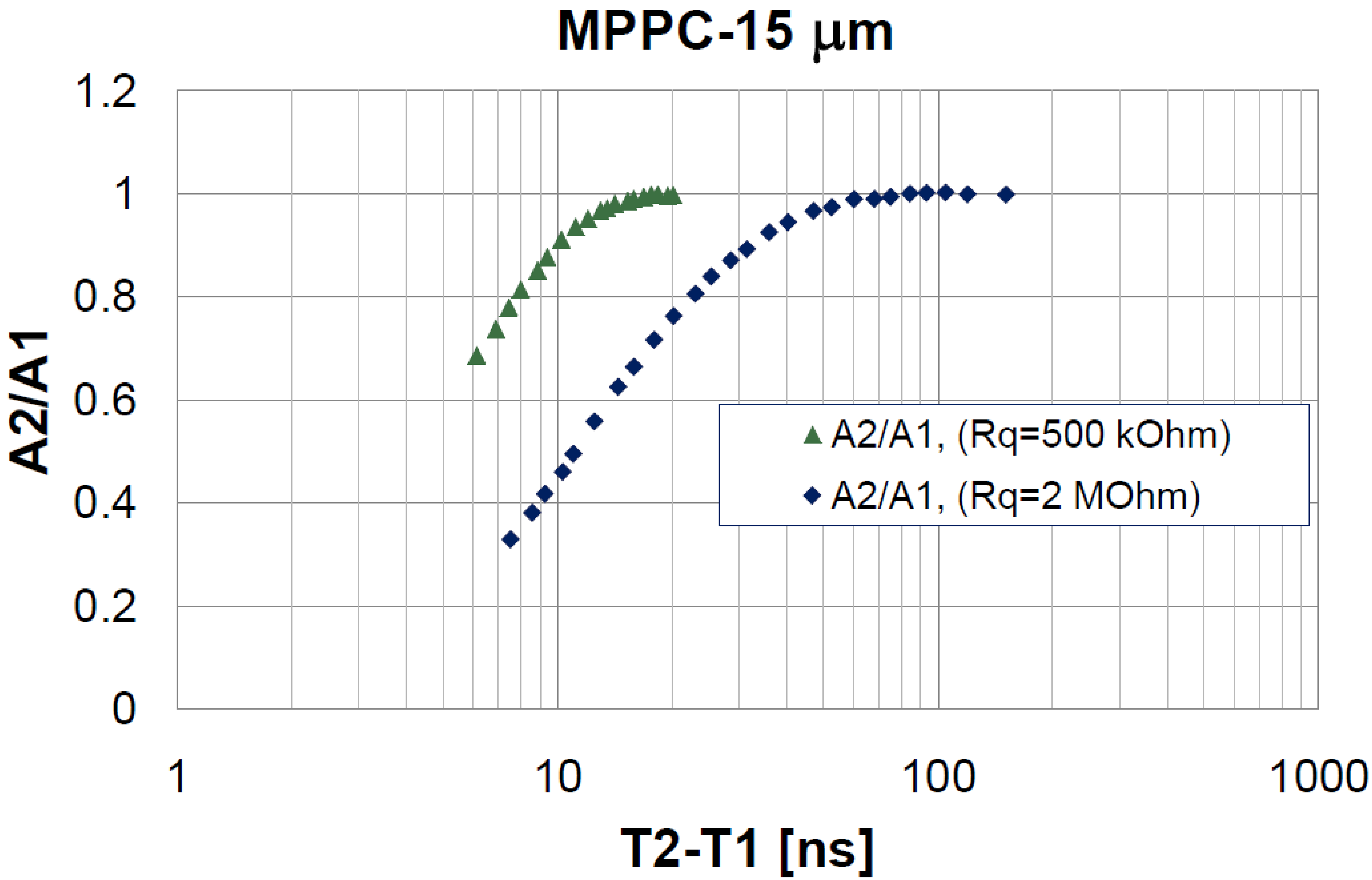
2 MOhm MPPC: 35 ps laser response



500 kOhm MPPC: 35 ps laser response

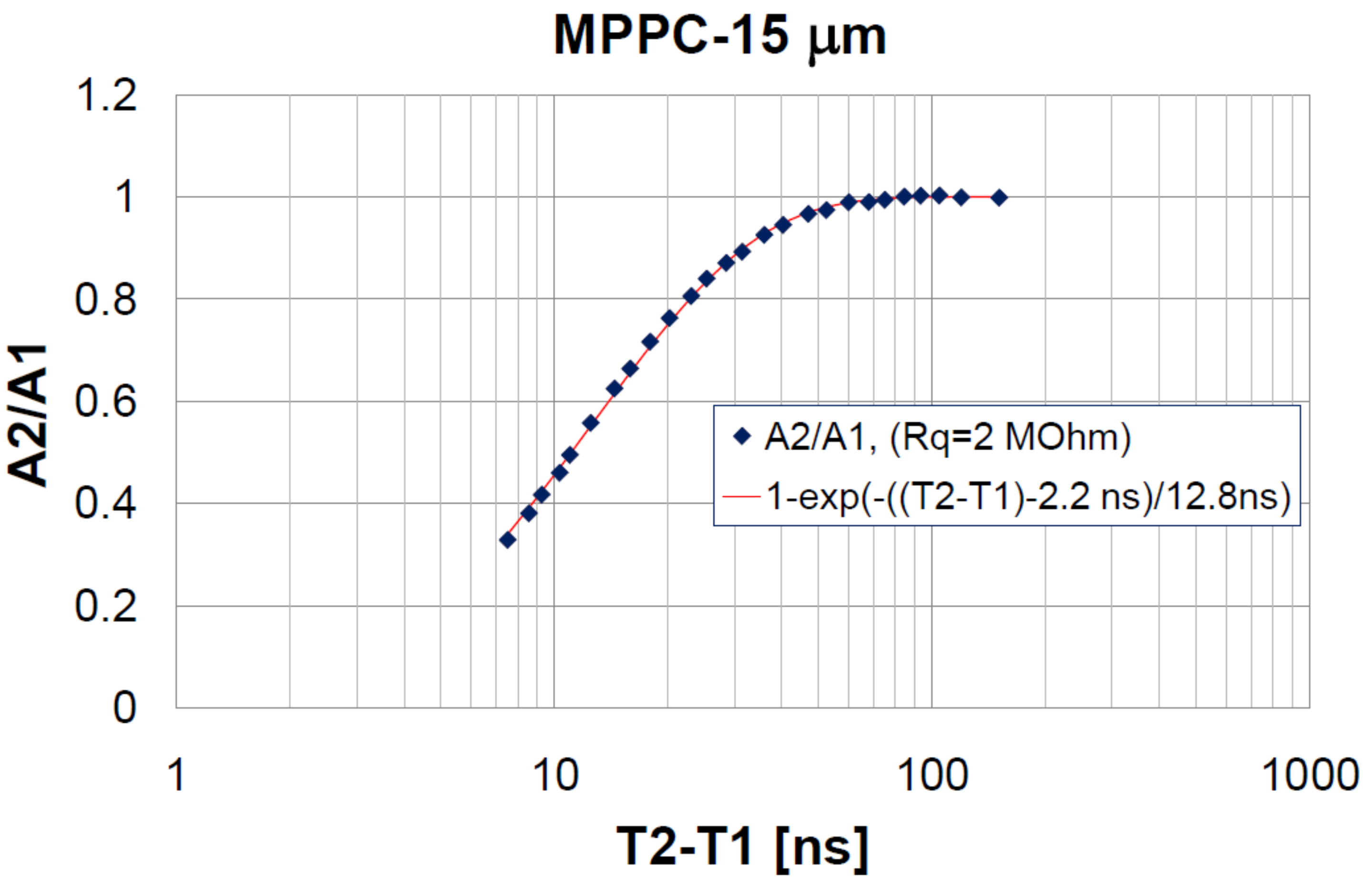


Cell recovery studies with fast UV LED



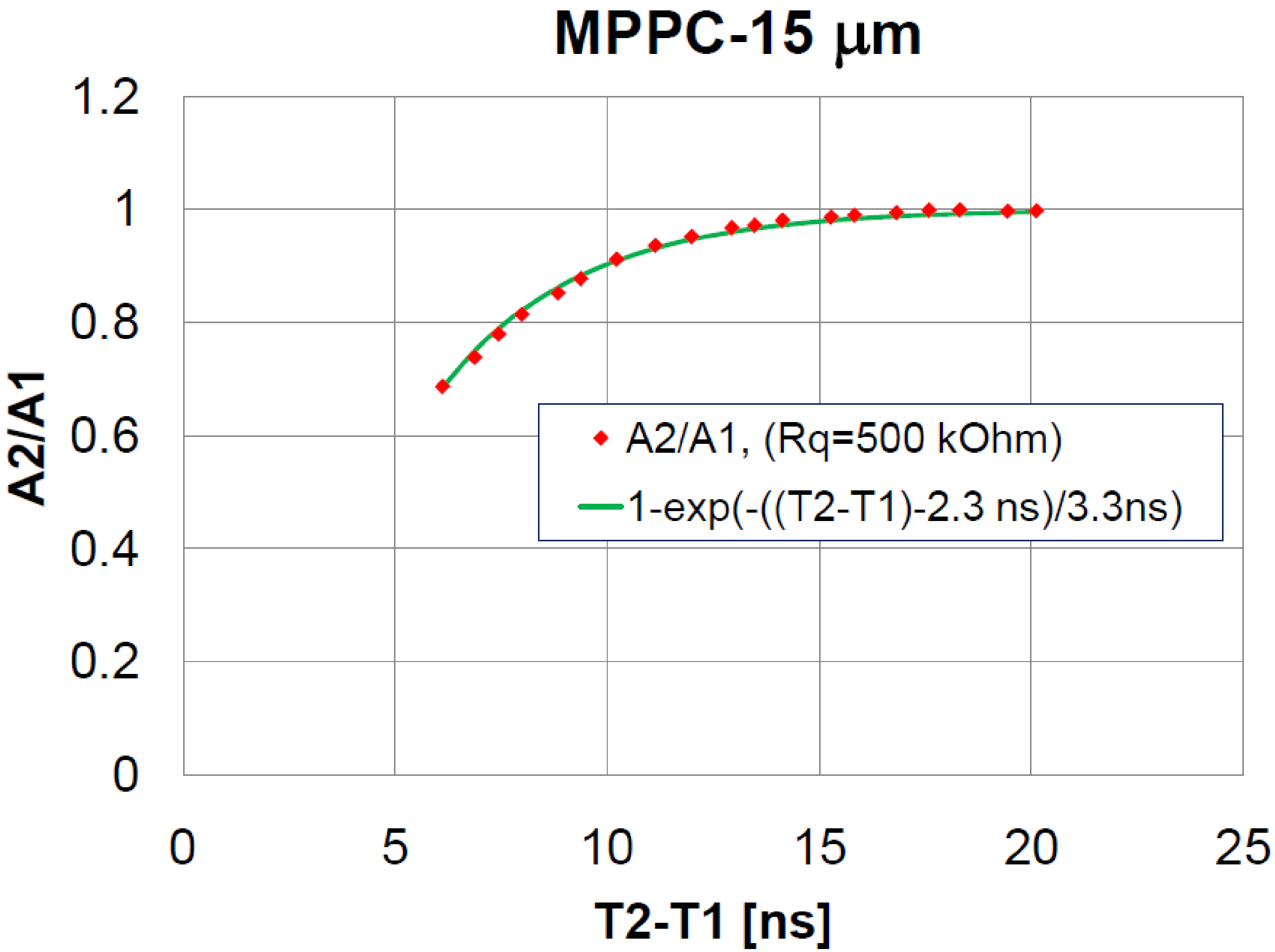
Measured using double LED pulse method

R_q= 2MOhm cell recovery



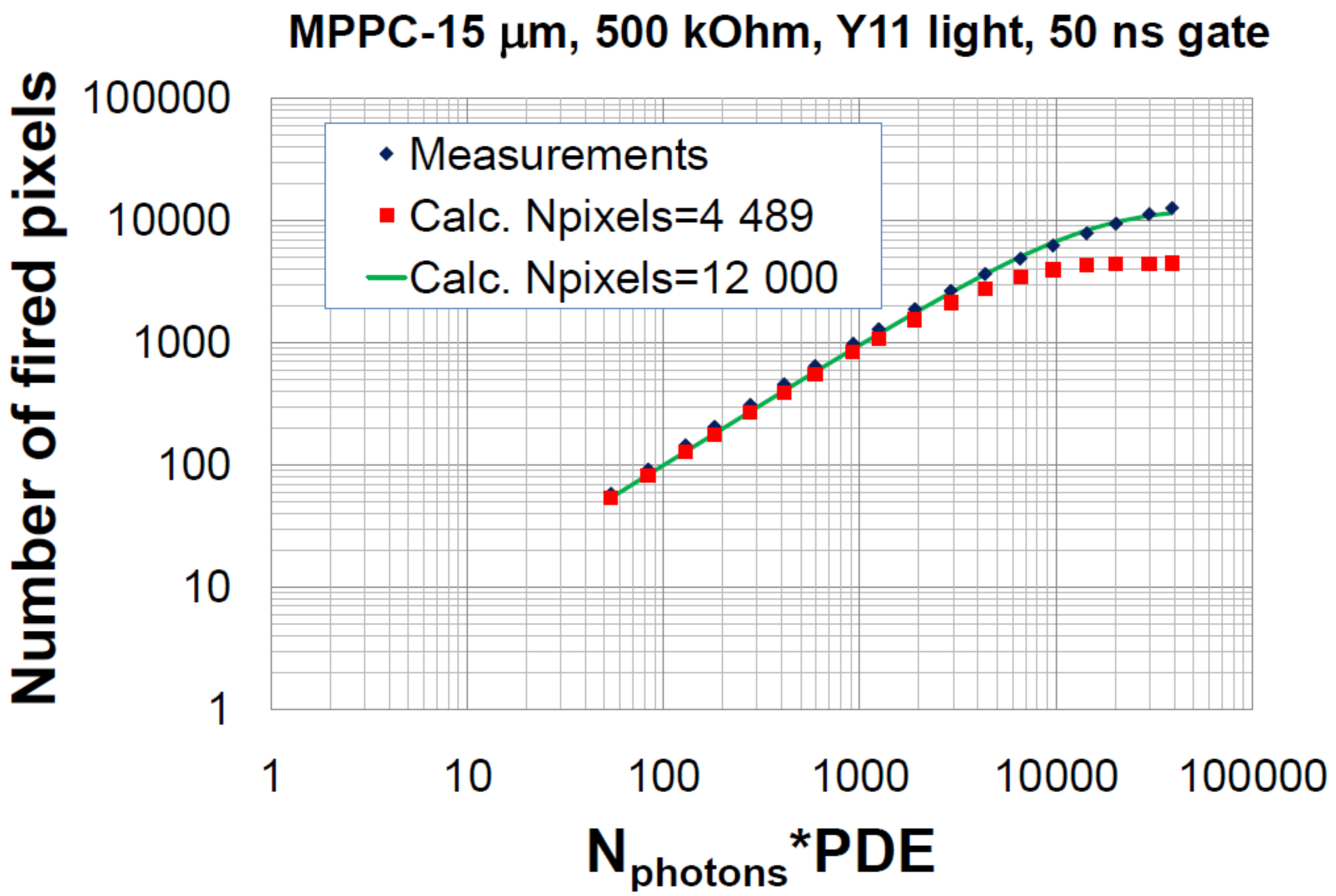
99% cell recovery after ~60 ns

R_q= 500 kOhm cell recovery



99% cell recovery after ~15 ns. 2.3 ns pixel dead time?

Linearity for Y11 light (R_q=500 kOhm, 15 μm MPPCs)



Performances of new Hamamatsu MPPCs

• new MPPCs (15 μm cell pitch, R_q=500 kOhm) have a factor of 2.7 increased dynamic range for Y11 light due to very fast cell recovery time (~4 ns)

• at 4V over-voltage they have:

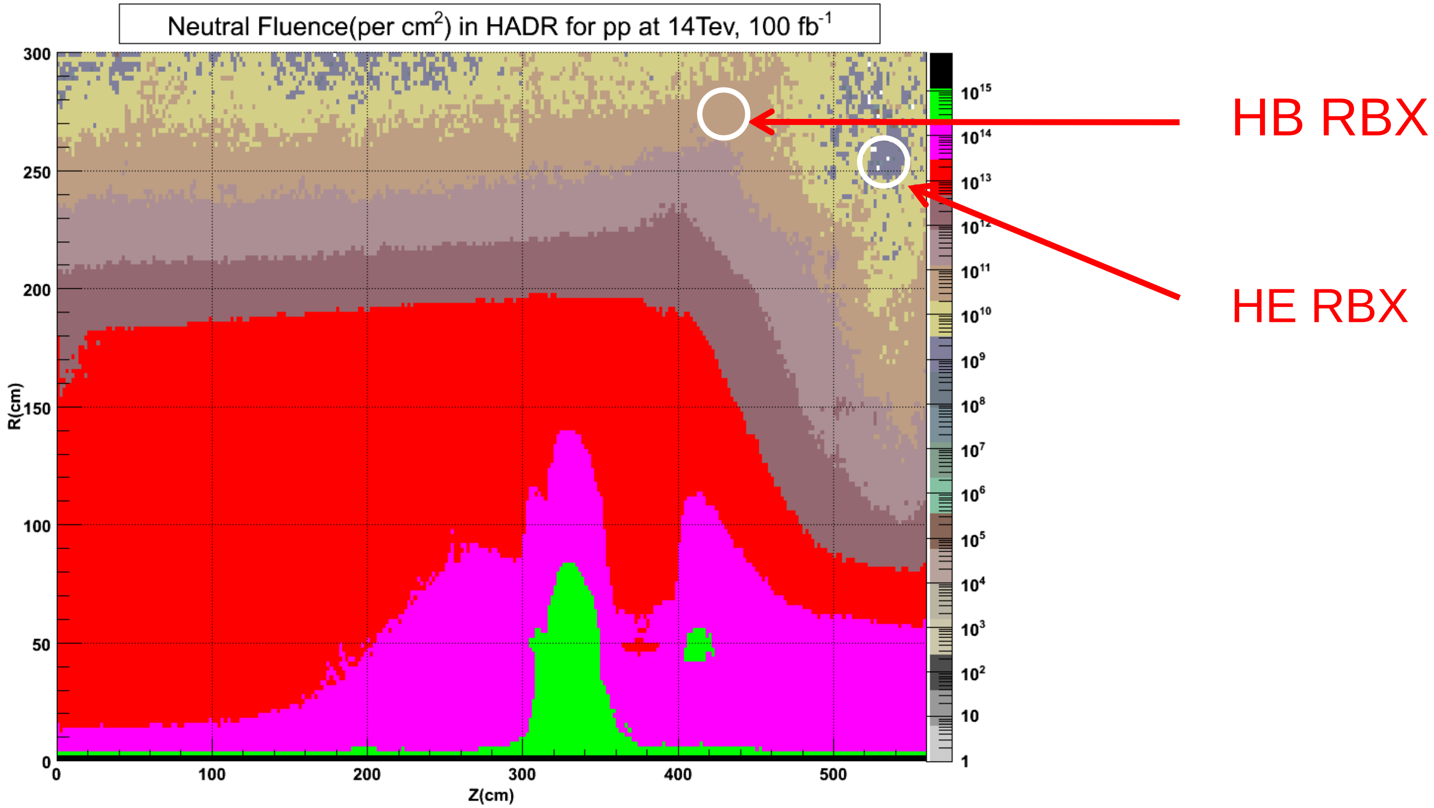
- Gain=2*10^5
- PDE(515 nm)~17 %
- ENF~1.1

• linearity for Y11 light of 4489 cells/mm^2 MPPC (R_q=500 kOhm) corresponds to a G-APD with ~12 000 cells/mm^2

Neutron fluxes in CMS

For 3000 fb^{-1}:

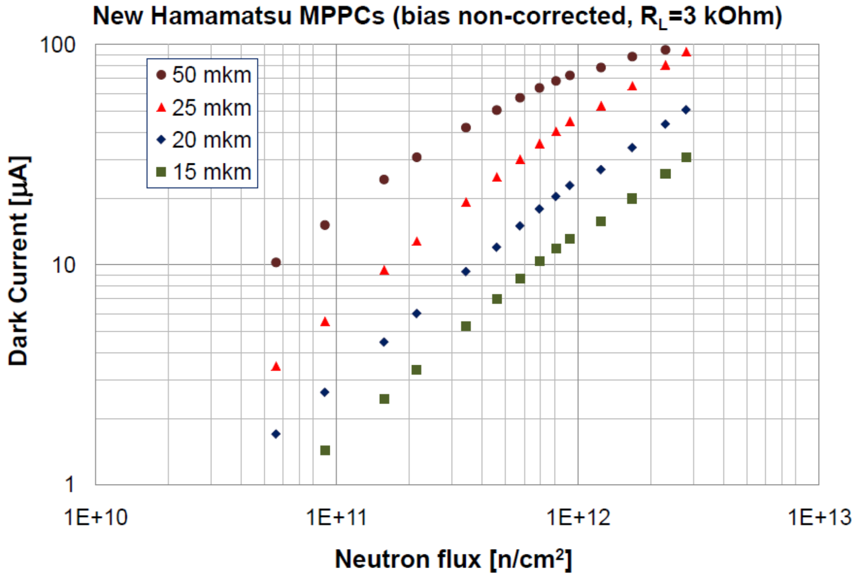
RBX HO: ~1-2*10^{11} 1 MeV n/cm^2 , RBX HB&HE: ~1-2*10^{12} 1 MeV n/cm^2

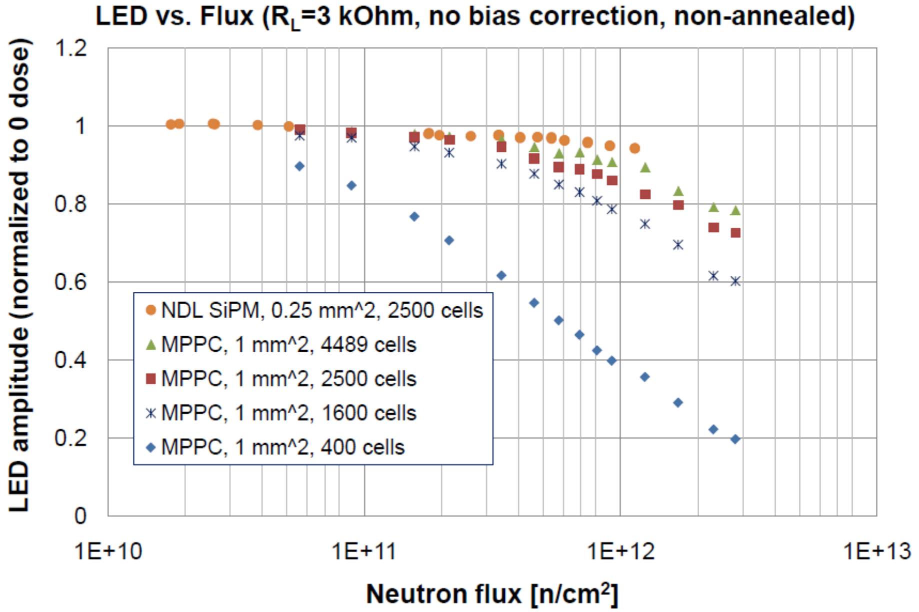


Calculated using MARS code (http://cmstrk.fnal.gov/radsim/NFluenceG.php)

Neutron irradiation tests

We performed SiPMs' radiation hardness tests using neutrons (E~1 MeV) at CERN IRRAD-6 facility (see NDIP-2011 talk A. Heering et all. " Radiation damage studies of silicon photomultipliers at SLHC at CERN PS")

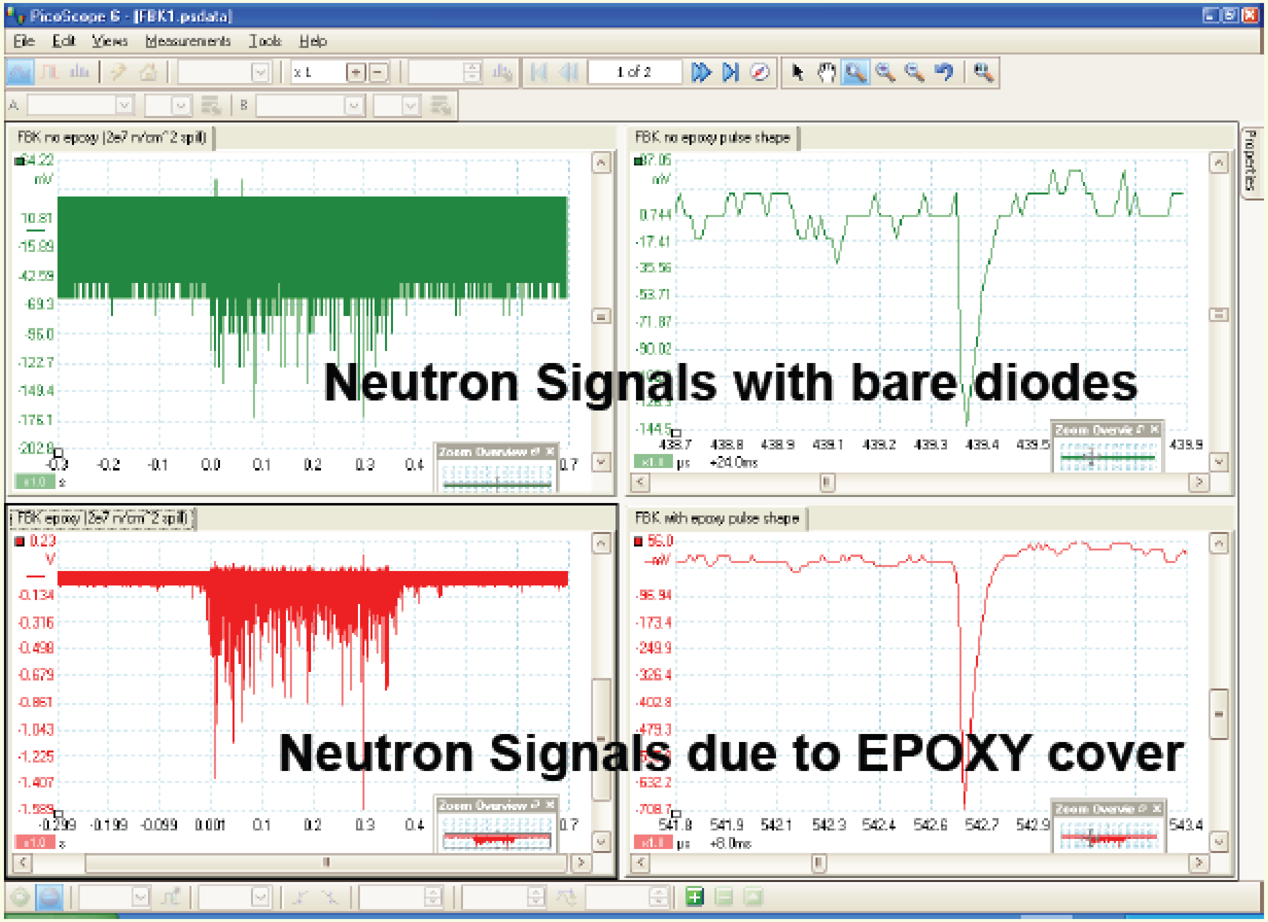




G-APDs with high cell density and fast recovery time can operate up to $3*10^{12}$ neutrons/cm^2 (gain change is< 25%).

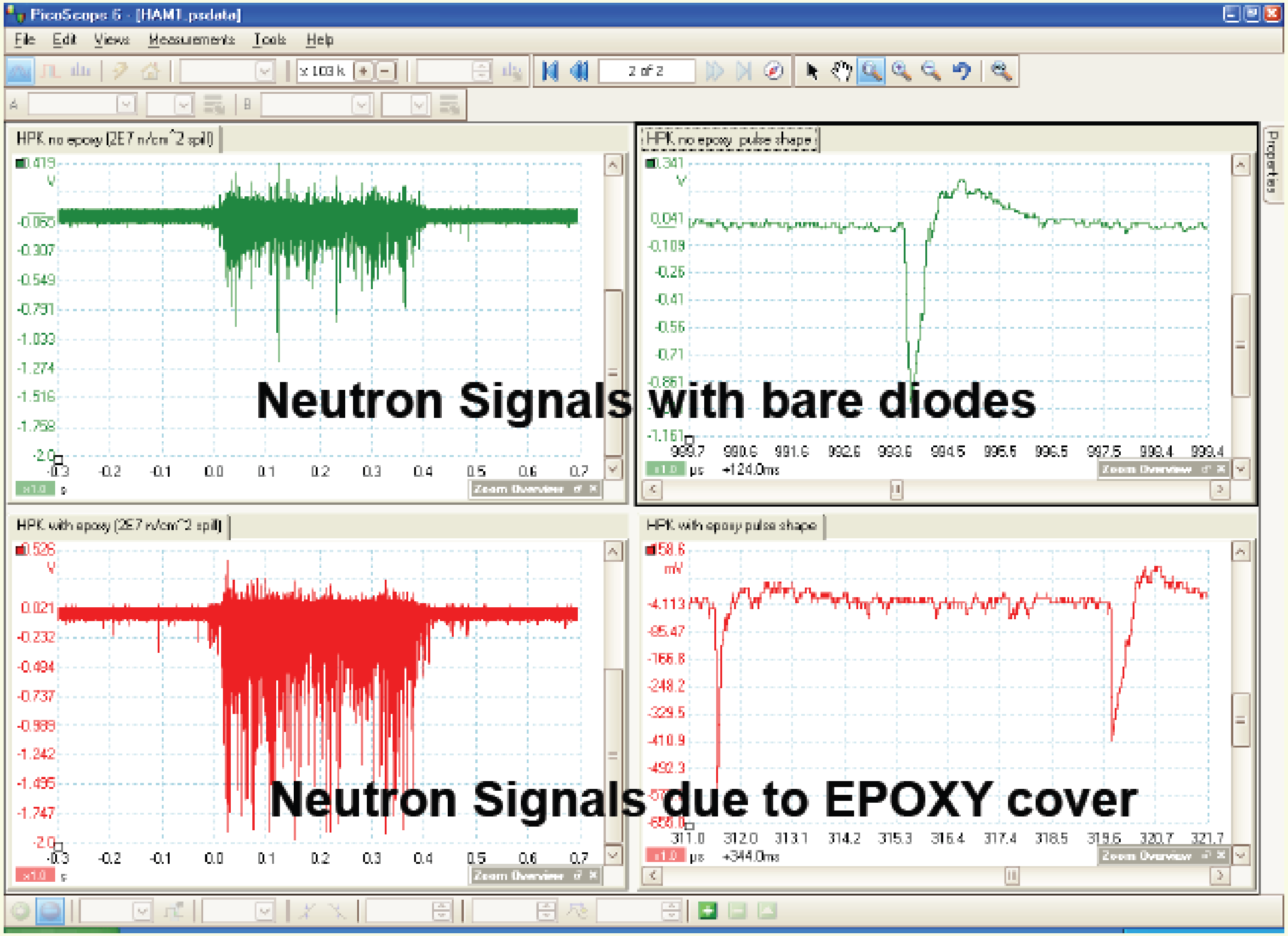
Neutron signals in FBK, KETEK and Zecotek G-APDs

We expect other than ECAL APD only few cells fired



We will try barrier SiO2 layer and quarts window on package

Neutron signals in Hamamtsu MPPCs



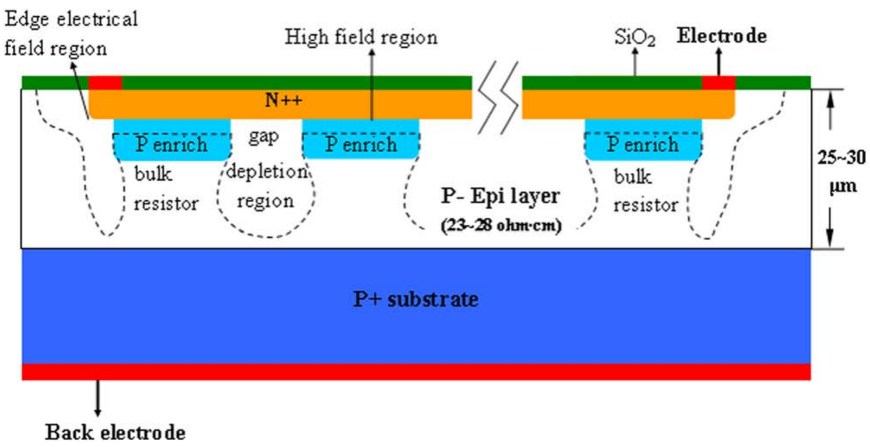
Signals from Bulk? We will try Boron-11 and thinner diode

“Third party” vendors in the Game

Large dynamic range SiPMs with bulk integrated quenching resistors from NDL(Beijing)

(see NDIP-2011 presentation of Han Dejun “Progress on SiPM with bulk quenching resistor”)

Schematic structure of the SiPM with bulk integrated resistors (S=0.5x0.5 mm^2, 10 000 cells/mm^2)



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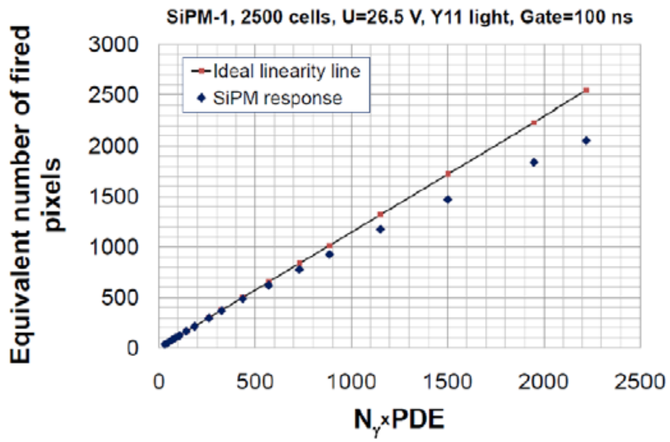
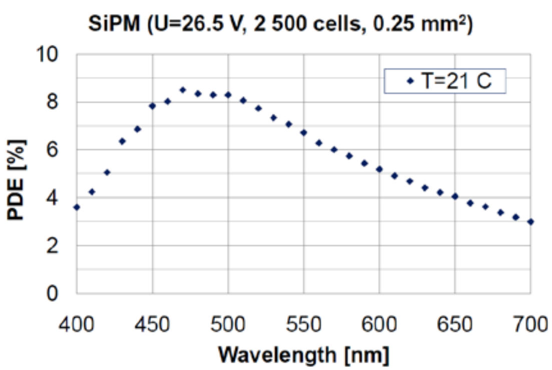
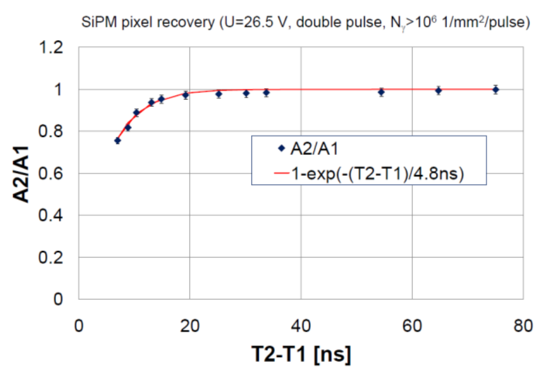
SiPM non-linearity



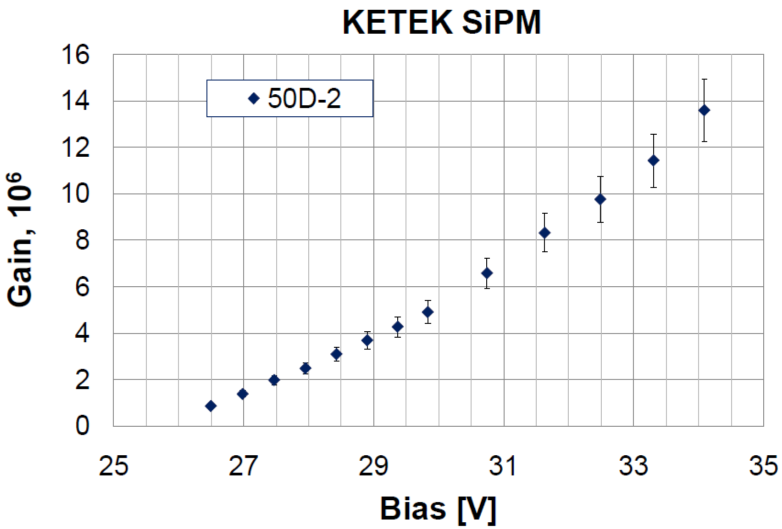
- n on p (structure for green light)
- sensitive area - 0.25 мм^2
- number of cells - 2 500
- operating voltage- 26.5 V
- quenching resistor value - 200-300 кОм

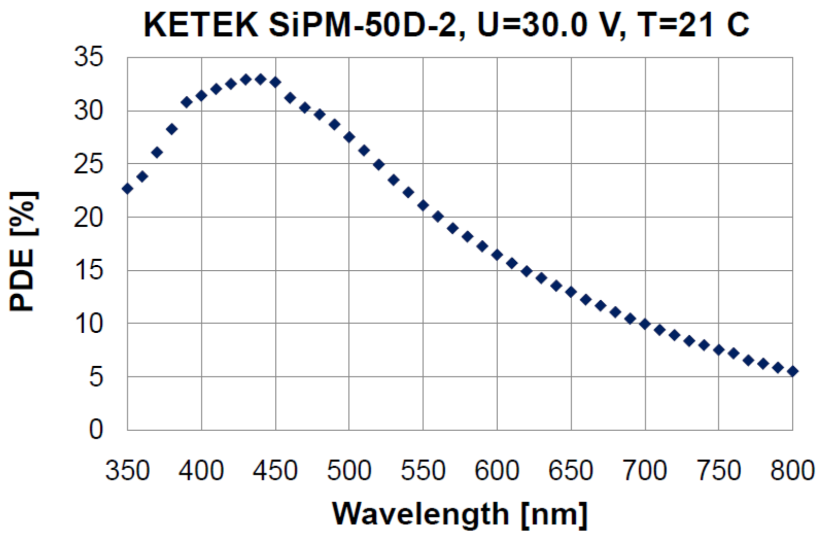


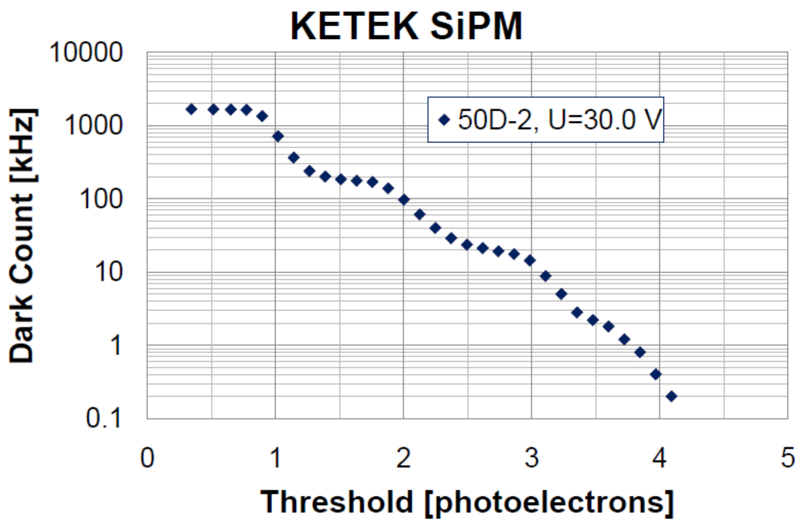


SiPM from KETEK (Germany)

- Sensitive area: 1 mm^2
- Number of cells: 400
- PDE(515 nm)~25 %
- Gain (dVB~4V): $5*10^6$
- Dark Count (0.5 ph.e.): ~$1.5*10^6$
- Opt. cross-talk (dVB~4V): 10%







Specs for photo-sensors

EDU

Zecotek:
- 15k cells/mm PDE ~30%
- Trec < 1 µs

HPK:
- 4.5k cells/mm PDE ~15%
- Trec < 6ns

KETEK:
- 4.5k cells/mm PDE ~10%
- Trec < 6ns

ODU

Zecotek and HPK

FBK:
- 2.5k cells/mm PDE ~10%
- Trec < 6ns

KETEK:
- 2.5k cells/mm PDE ~15%
- Trec < 8ns

CPTA:
- 7k cells/mm PDE ~12%
- Trec < 10ns

NDL:
- 10k cells/mm PDE ~8%
- Trec < 5ns

Summary

• We are in the middle of the R&D stage to develop photo-sensors for the CMS HCAL Phase-I Upgrade.

• Significant progress on the development of large dynamic range, fast, radiation hard G-APD/SiPM photosensors was achieved over the last year.

• Currently we are working with 6 G-APD/SiPMs producers: Hamamatsu, Zecotek, CPTA, KETEK, FBK, NDL.

• We received very promising devices from Hamamatsu and Zecotek. New devices are expected from all the G-APD/SiPM producers at the end of this summer. In July and October we plan to have beam tests at CERN to check the EDU/ODE concepts.

• At the end of 2011 we expect to have at least one candidate which satisfy most of requirements of the CMS HCAL Phase-I Upgrade.

We should select 1-2 producers to continue R&D in 2012 with the goal to improve parameters of the selected G-APDs-candidates and finally select the best photosensor for the CMS HB/HE Phase-I Upgrade.