新型半導体光検出器PPDの液体キセノン中での基礎特性

東京大学素粒子物理国際研究センター、高エ研[A]

岩本敏幸、内山 雄祐、大谷 航、金子 大輔、澤田 龍、千葉 哲平、名取寛顕[A]、西口 創[A]、春山富義[A]、白 雪、藤井 祐樹、真木晶弘[A]、三原 智[A]、森 俊則

日本物理学会第67回年次大会　関西学院大学　西宮上ヶ原キャンパス

Introduction

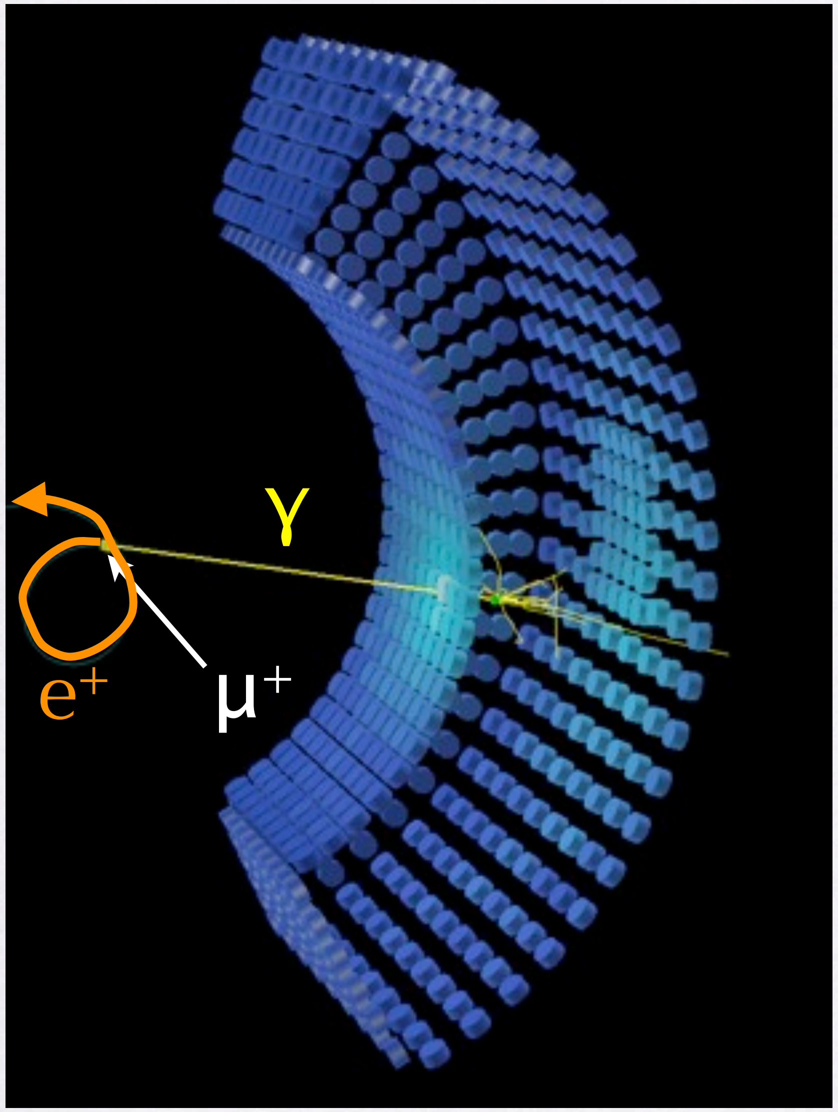
- MEG experiment utilizes PMTs in order to detect scintillation light in liquid xenon gamma-ray calorimeter. PMTs are one of the possible candidates for MEG detector upgrade.

- R&D of Pixelated Photon Detector (PPD) have been actively performed as a new novel silicon photon detector.

- Can the PPD be a candidate for MEG detector upgrade?

- Let's check basic characteristics of the PPD in liquid xenon, and develop new PPDs suitable for liquid xenon.

MEG experiment
Liquid xenon gamma-ray detector



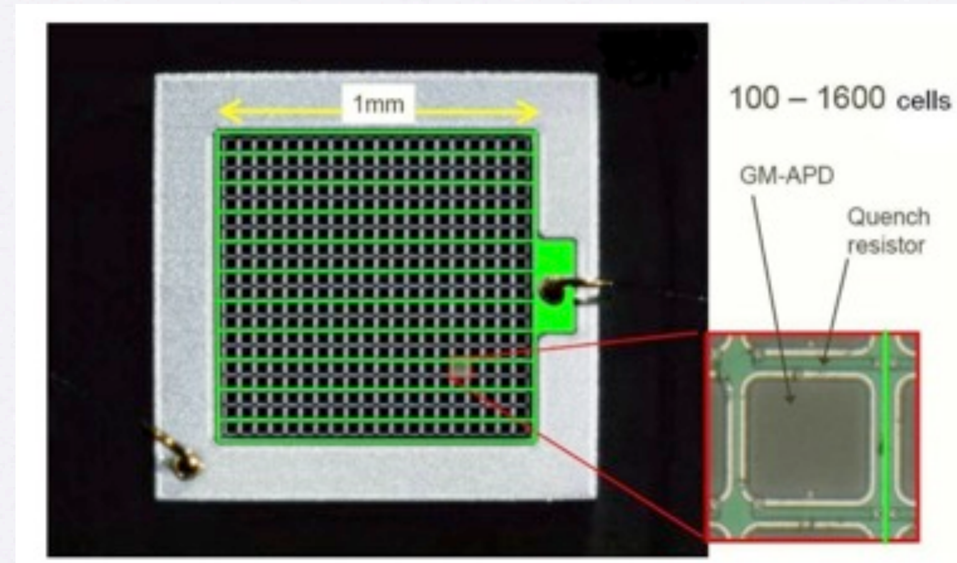
Performance in 2010 (for 52.8MeV γ)

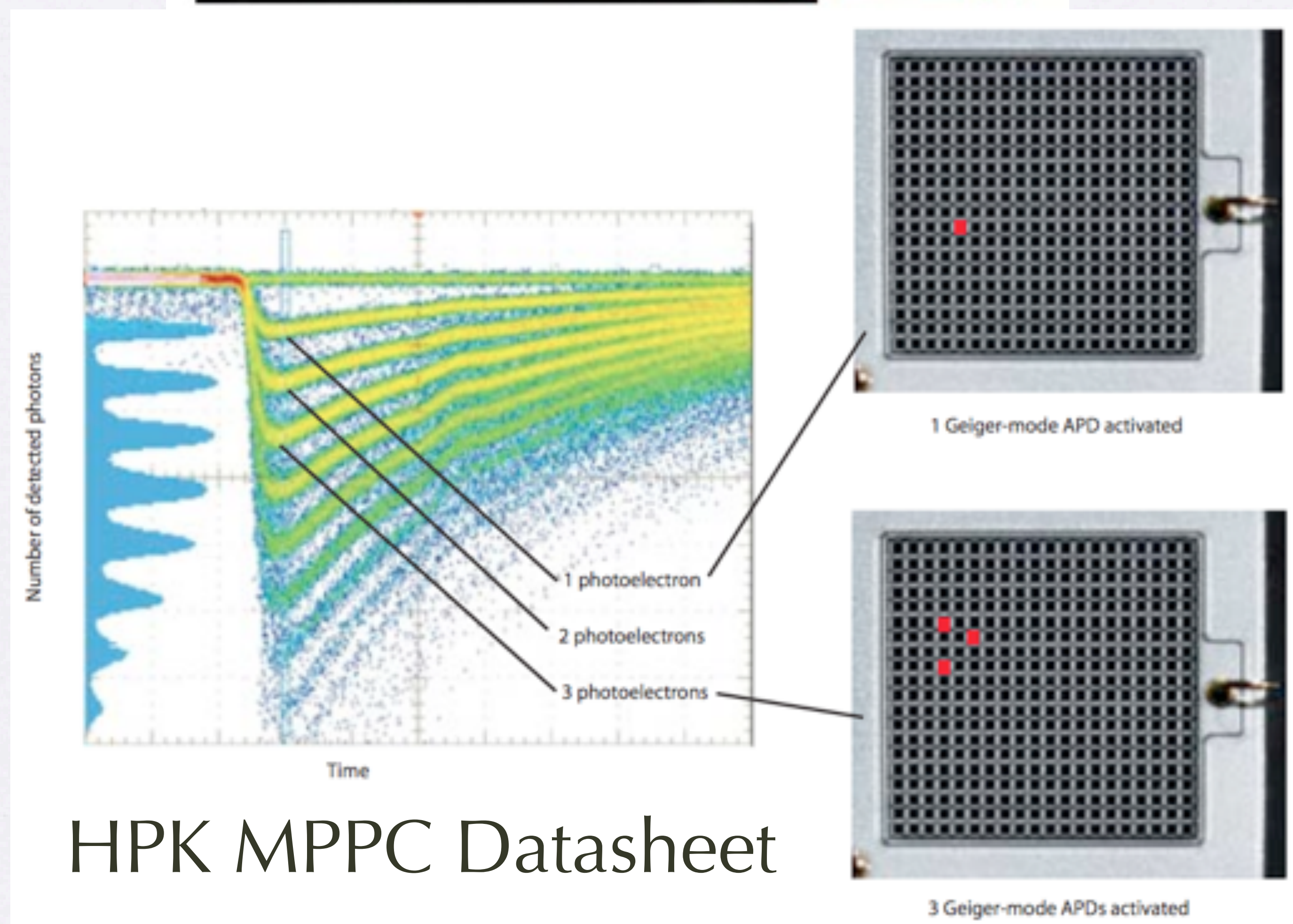
- Energy : 1.9% (depth>2cm, 64%), 2.4% (depth<2cm, 36%)
- Position : 5 mm
- Timing : 67 psec
- Efficiency 59%

- Liquid xenon 900L
- 846 x 2″ PMT (Hamamatsu R9288)
  - Submerged in liquid xenon (T=165K, p<3atm)
  - Sensitive to VUV, λ=175nm
  - QE~15% at 165K
- Performance evaluation in 2011 （金子大輔 25pFA9）
- MEG detector upgrade is seriously discussed among MEG collaborator to reach ultimate sensitivity (澤田龍 25pFA10)

What is PPD ?

- Pixelated Photon Detector (PPD)
  - solid state photon detector
  - multi-pixelated Geiger-mode APDs
  - possible to detect single photoelectron.
- MPPC is one of PPDs produced by Hamamatsu.
  - SiPM, Geiger Mode APD,...
  - pixel size ~10-100μm, active area ~ 1-several mm
  - 1 pixel = 1 photon at $N_{p.e.} << N_{pixel}$
  - Sum of pixel outputs is proportional to number of impinging photons



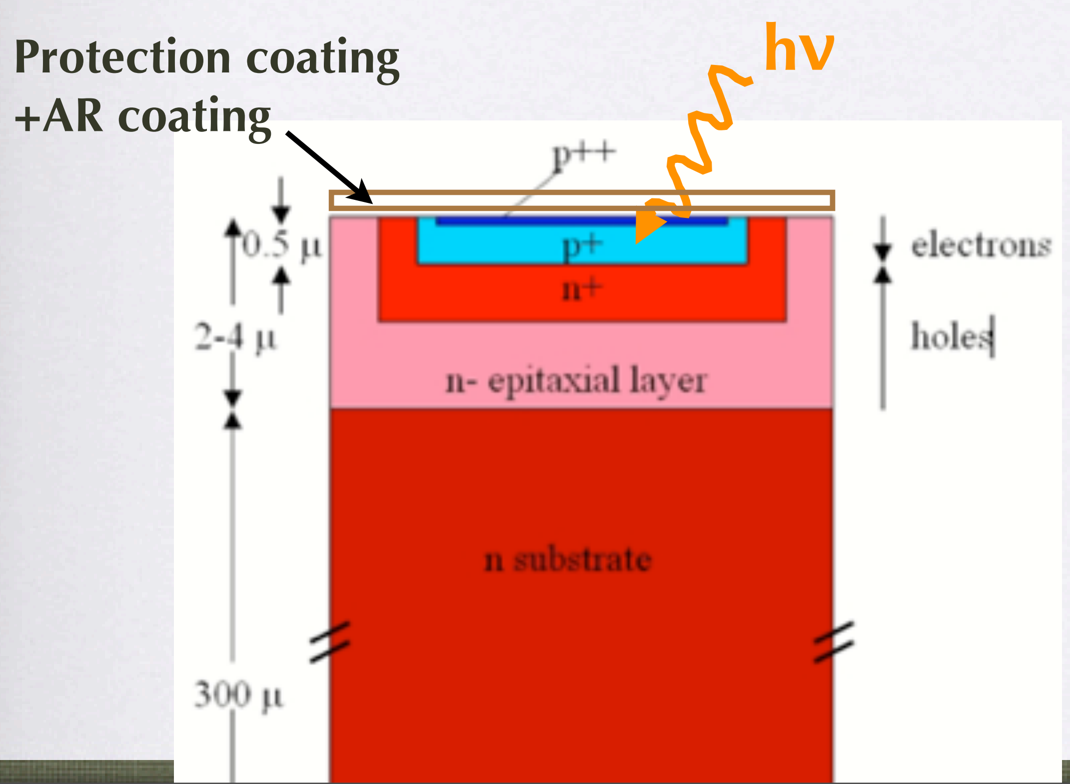


HPK MPPC Datasheet

PPD for MEG?

- Merits
  - Insensitive to magnetic field
  - High granularity
  - less material before liquid xenon active region
  - single photon sensitive
  - low bias voltage (<100V)

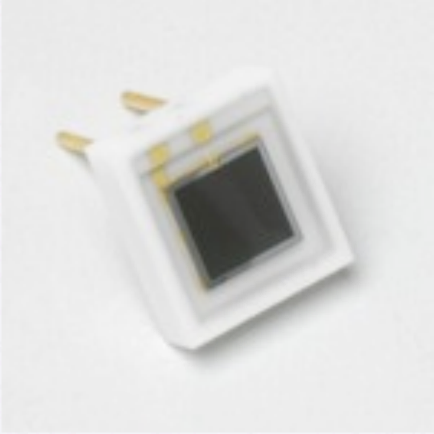
An example of PPD structure

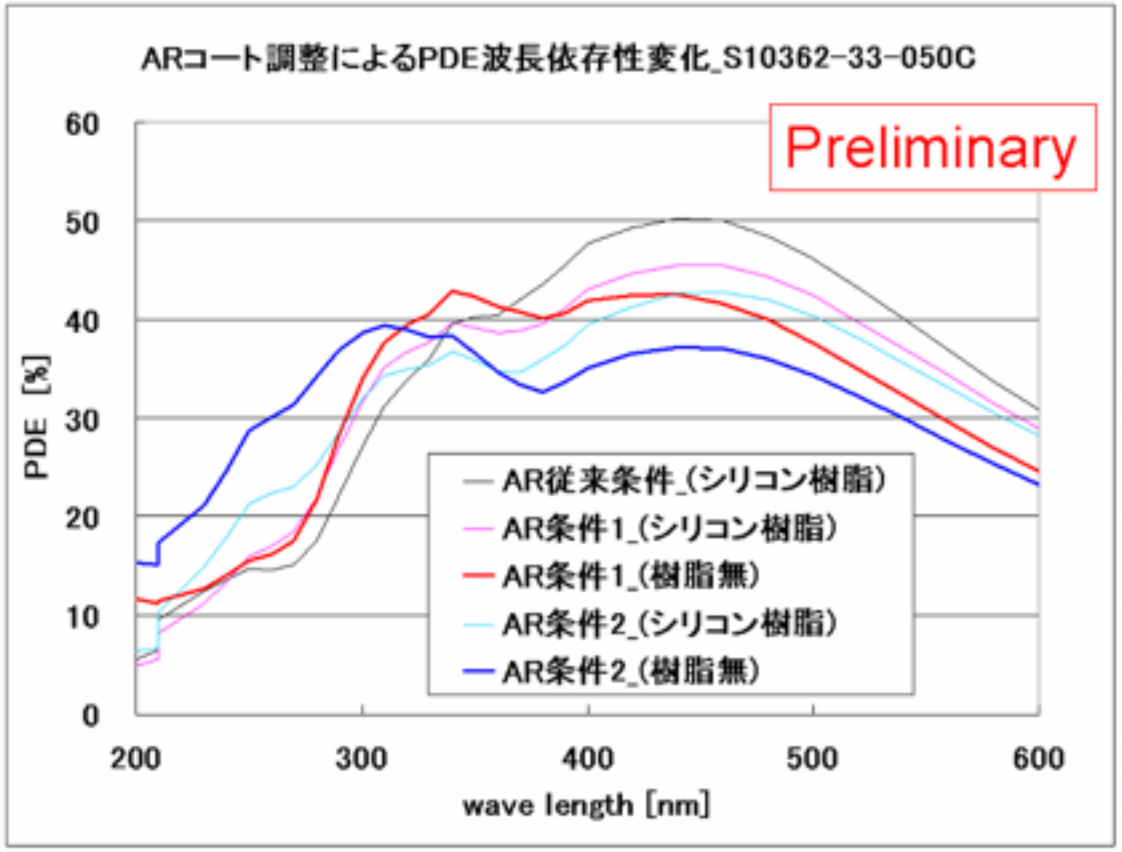


- Demerits
  - Less sensitive to VUV
    - protection coating (epoxy resin/silicon rubber)
    - Highly doped layer(p^{++}) with no electric field (Absorption length in Si for VUV photon =5nm)
    - Anti-Reflecting(AR) coating is not optimized to 175nm
  - Current largest sensor (~3x3mm^2) is still too small for MEG, at least 10x10mm^2
  - radiation hardness
  - after pulse, cross talk

PPD samples

- Several samples of PPDs provided by Hamamatsu
    - Commercial one, S10362-33-100C(**sample1**)
    - Remove protection coating + Optimize anti-reflection(AR) coating to suppress reflection (**2,3**)
    - Thinner p^{++} layer (**4,5,6**)
- Let's measure the basic properties!

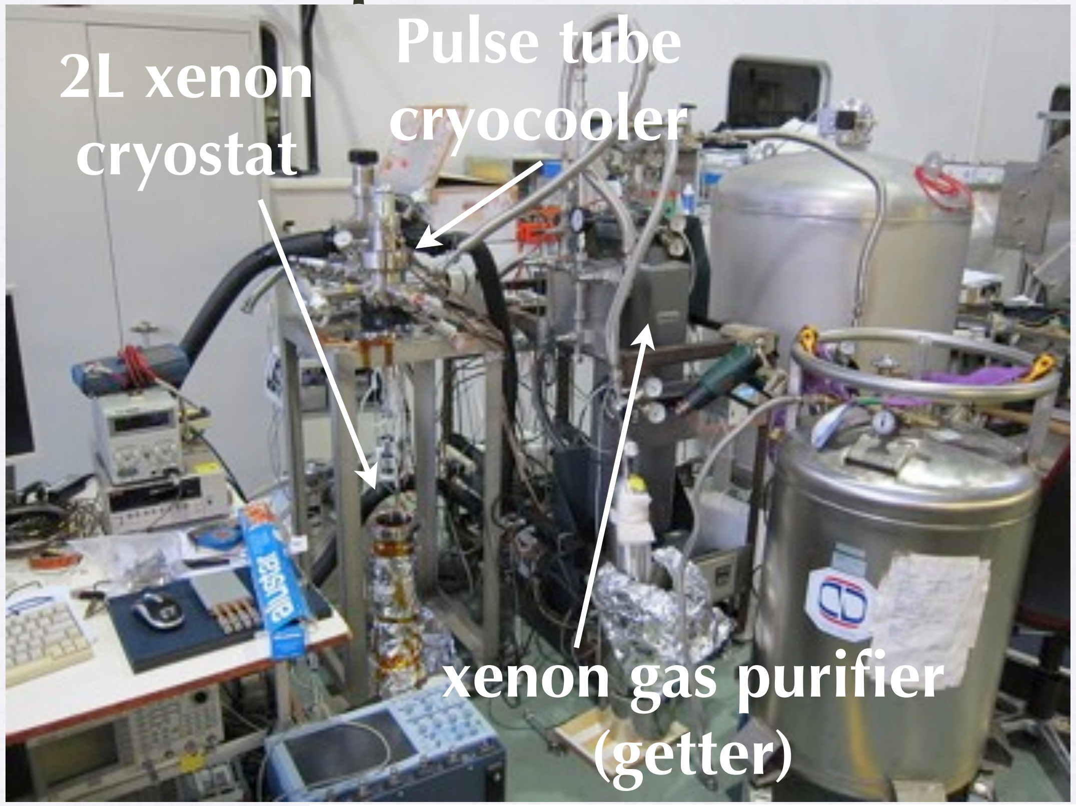


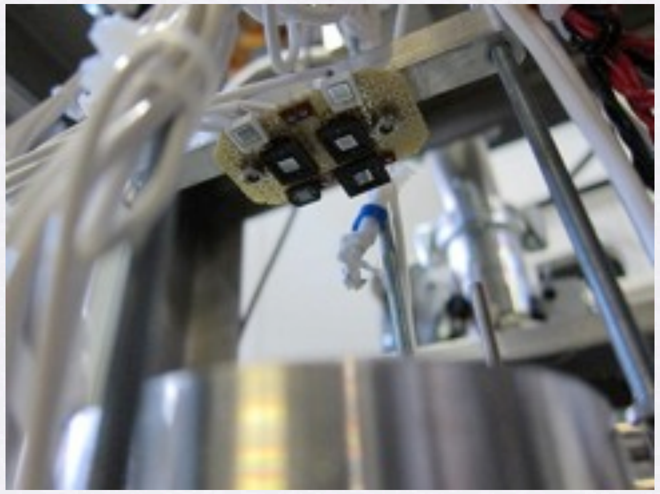


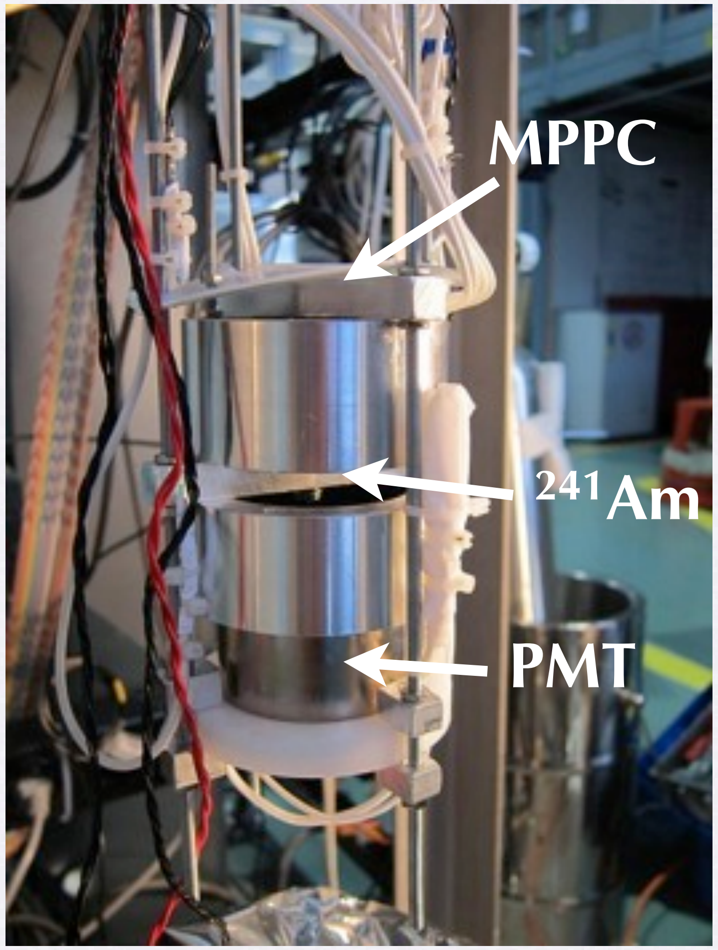
Hamamatsu Photonics K.K.

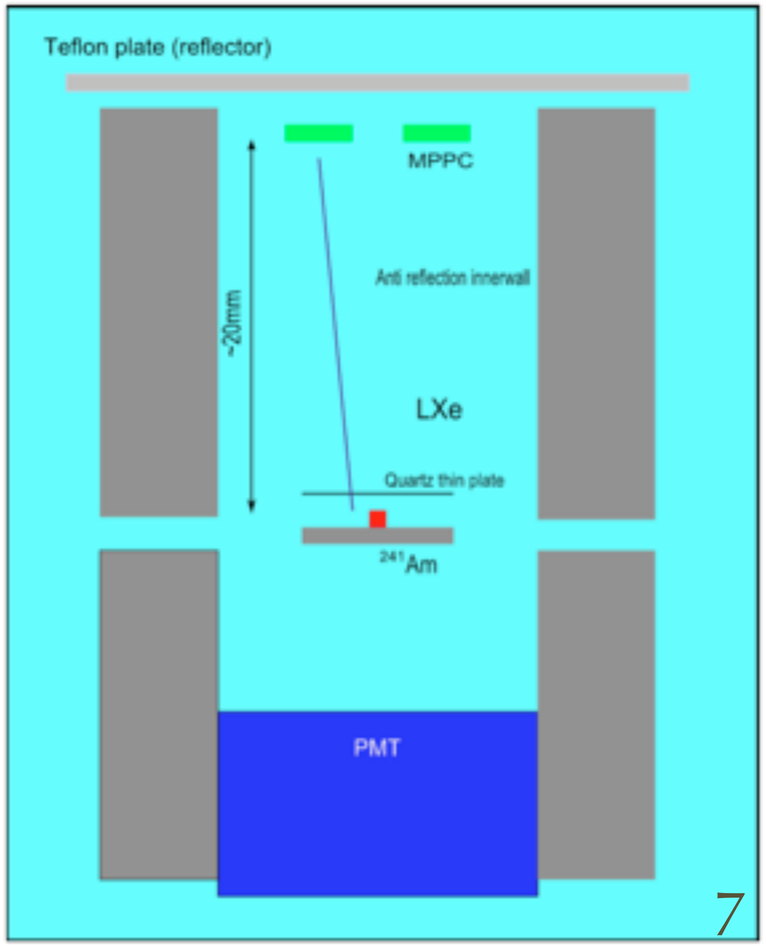
MPPC performance test in liquid xenon

- Liquid xenon test chamber @ Paul Scherrer Institute
- Setup
  - α source (^{241}Am) - Expected number of scintillation photons : 270-370
  - PMT(trigger)





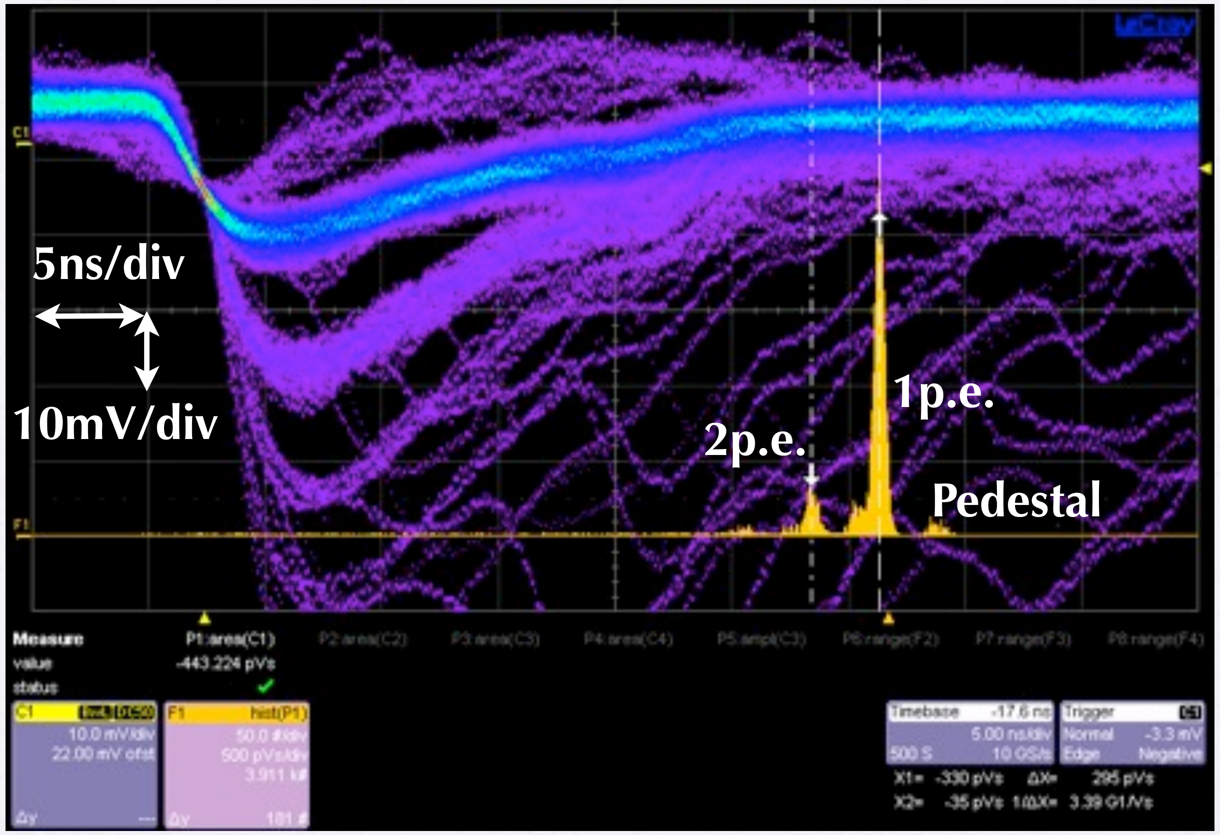




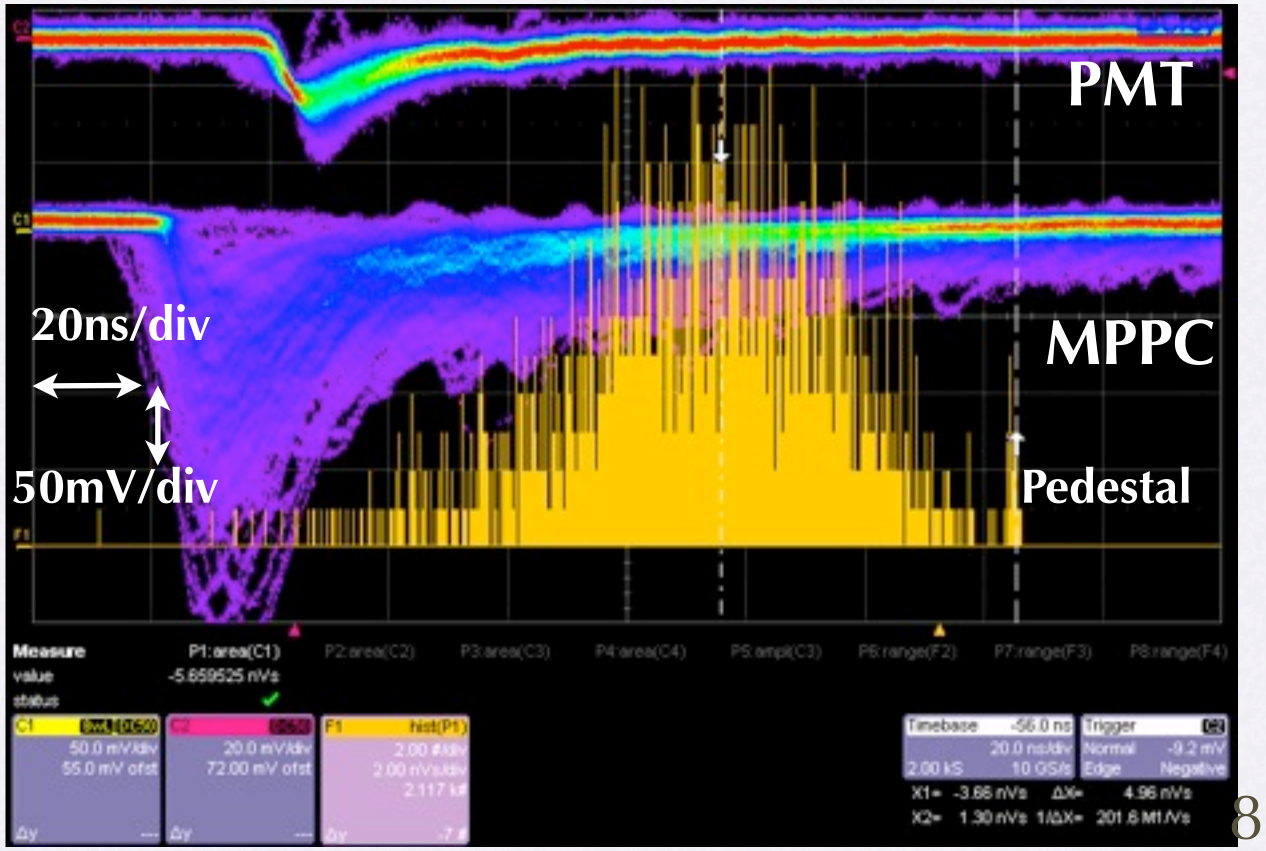
Gain/PDE measurements

PPD self trigger (for gain) :
by single photoelectron peak

MPPC
+ pre-amp(x4.3)
(+ PM-amp, x10.6)
--> Oscilloscope (20MHz filter, x0.38)



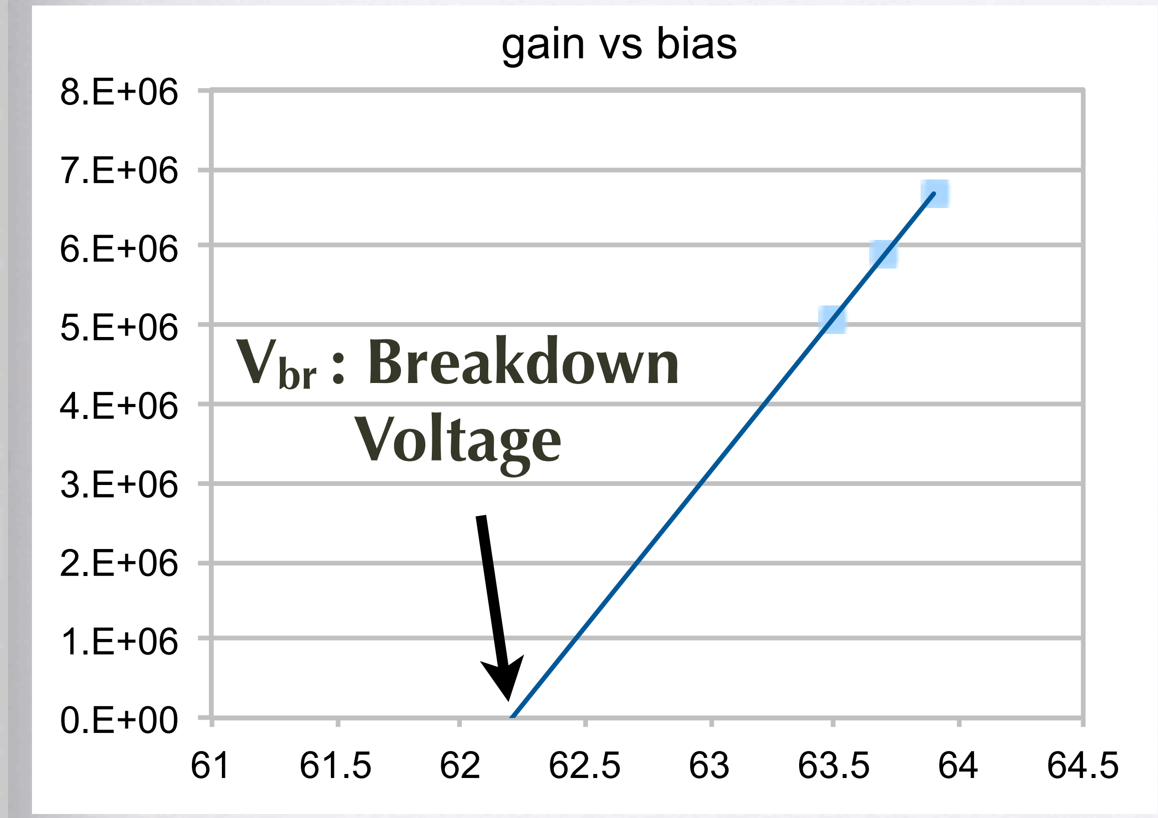
PMT trigger for alpha events (for PDE) :
by detected # p.e./expected # p.e.



Example of AR coating(3)

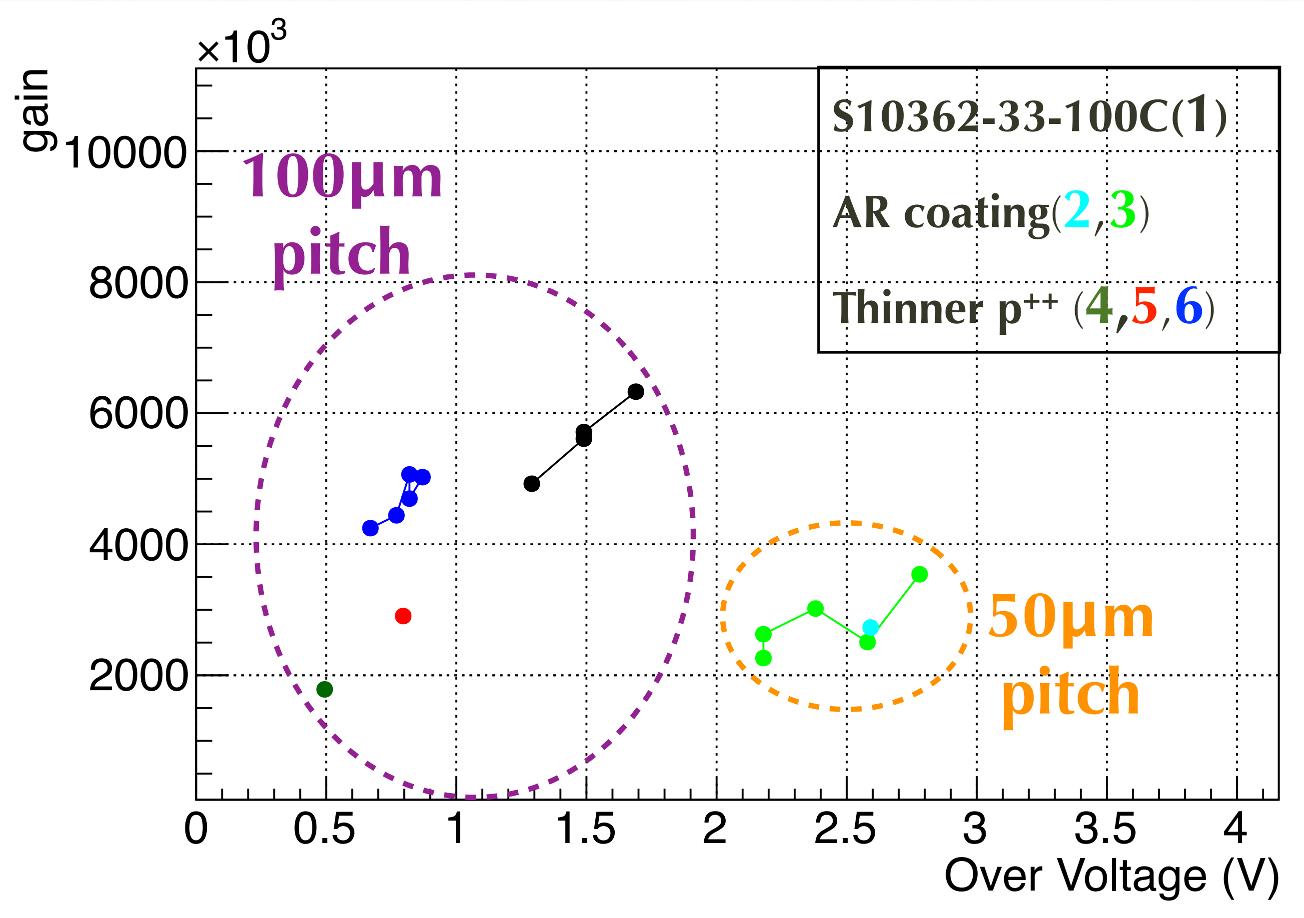
Gain measurements

Gain@170K (S10362-33-100C)



Bias Voltage (V)

Gain = $C(V_{op} - V_{br})/e$



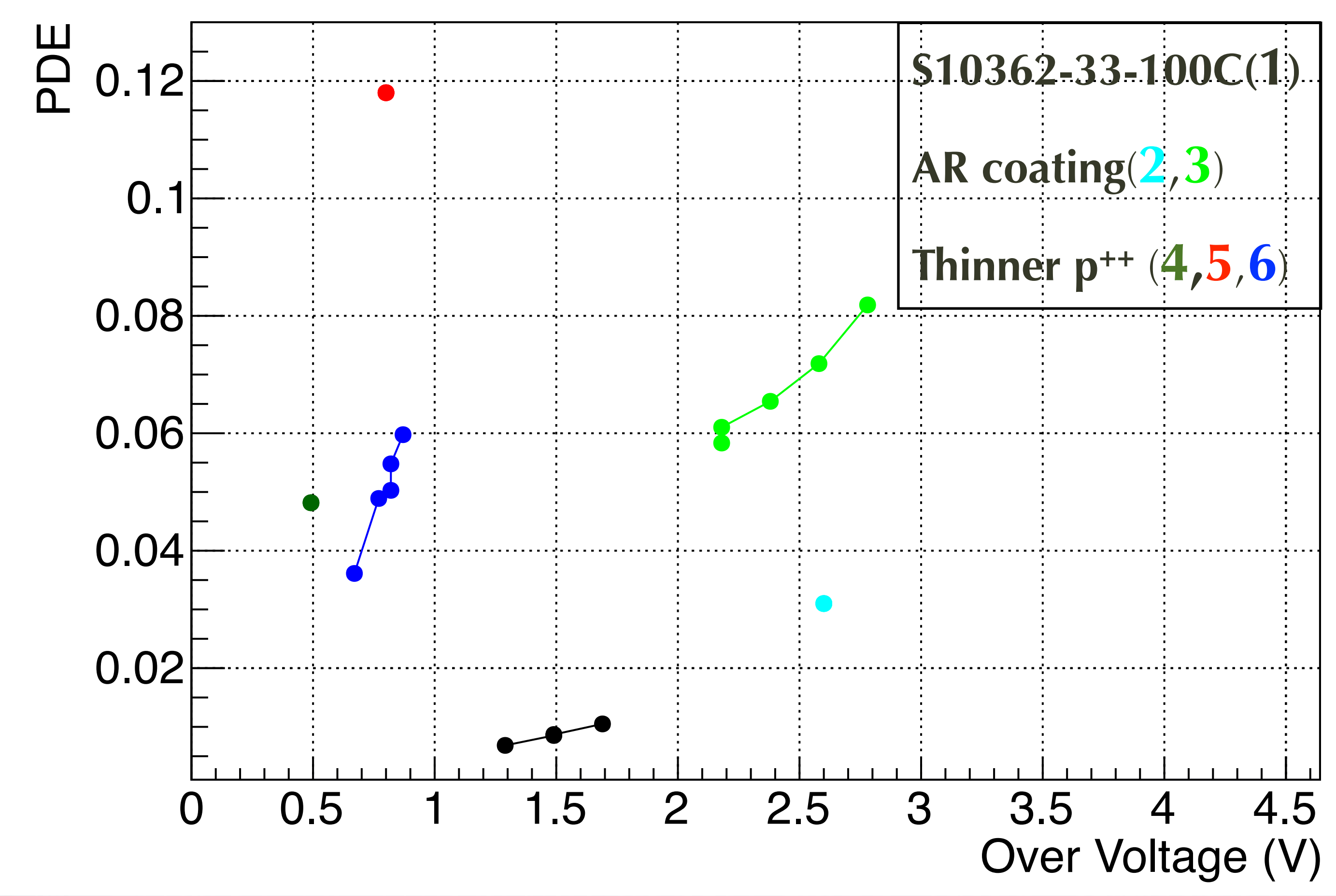
Pixel capacitance depends on the pixel pitch size

Gain>10^6 is measured. (Sufficient for MEG)

PDE measurements

- PDE (Photon Detection Efficiency) = ε_{geom} x Q.E. x ε_{geiger}
  - ε_{geom} : geometrical efficiency of active region (fill factor)
  - ε_{geiger} : probability for e-h pair to induce geiger avalanche
  - Measured #p.e. / Calculated #p.e.(270-370p.e.)

PDE measurement in liquid xenon



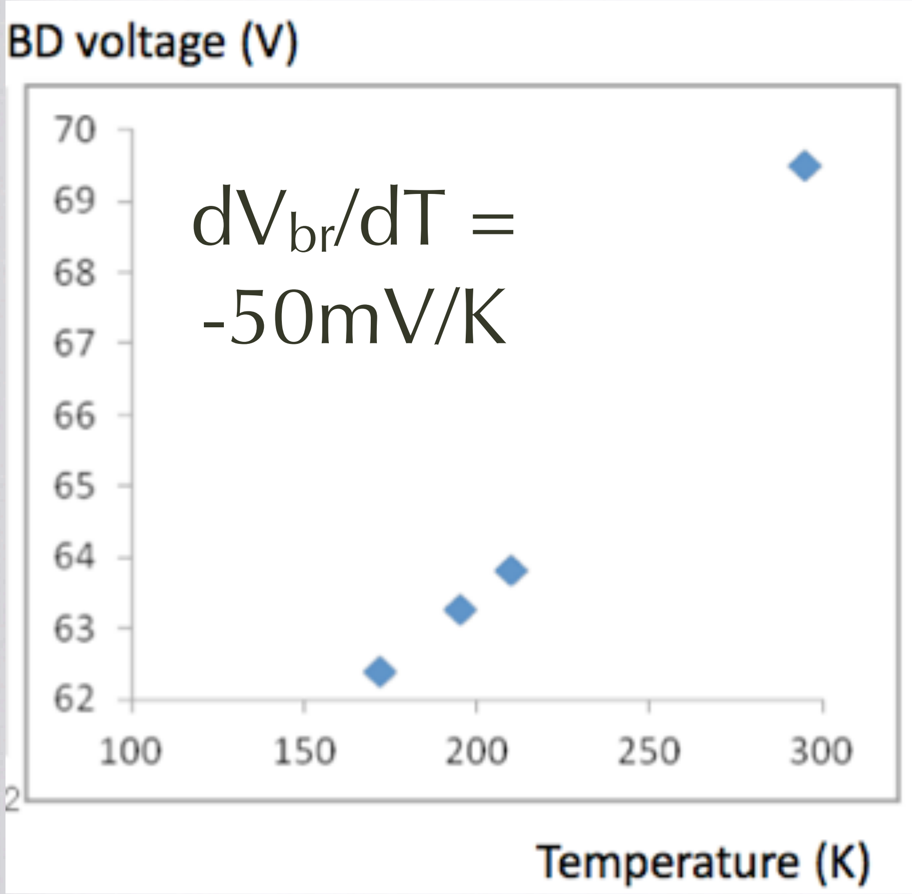
Note: This PDE contains cross talk, after pulse.

We confirmed PPD can be sensitive to VUV by removing protection layer and by making thinner p^{++} layer.

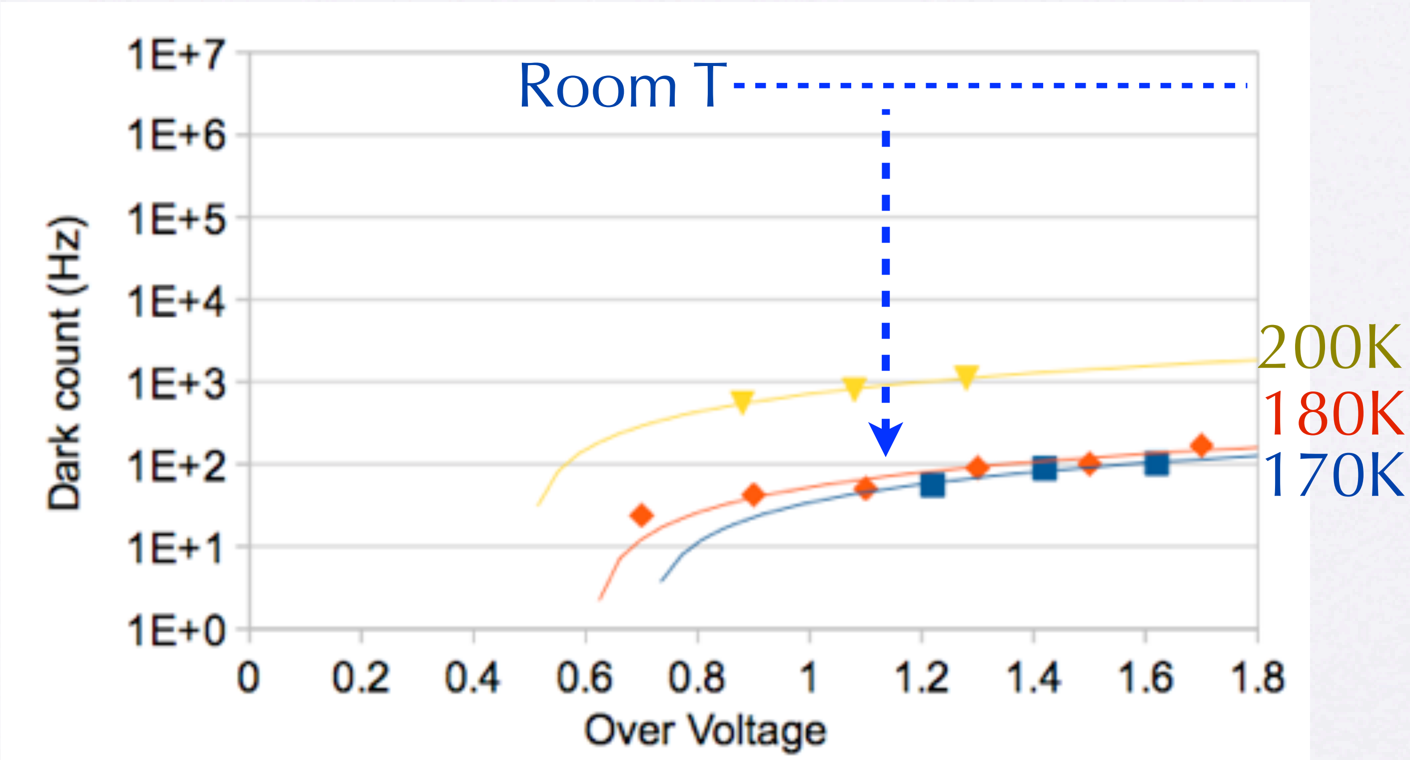
PDE ~ 10%

Temperature dependence

V_{br} vs T (S10362-33-100C)



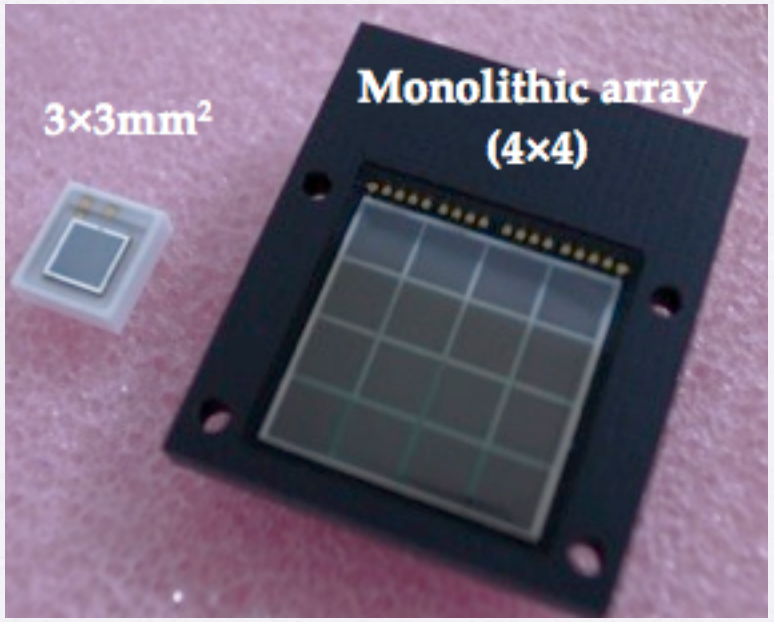
Dark count rate (S10362-33-100C)



Noise rate becomes half every 8 degreeC decrease
= 5 orders decrease at 165K

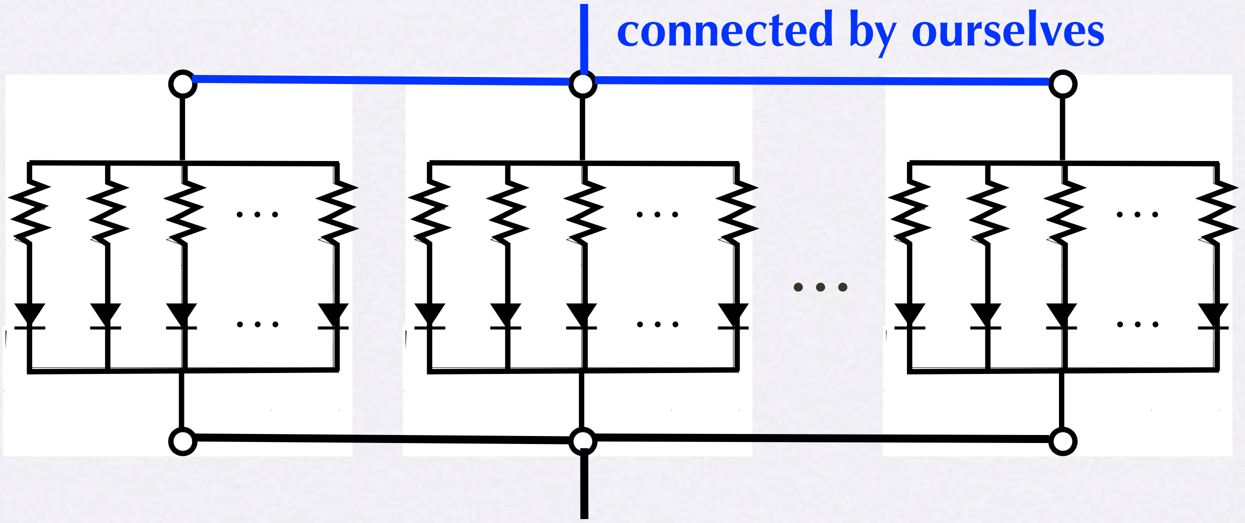
- At low temperature
  - Breakdown voltage will go down
  - Dark count rate will go down
  - Resistance of quenching resistor (Poly-Si) will go up

Sensor size



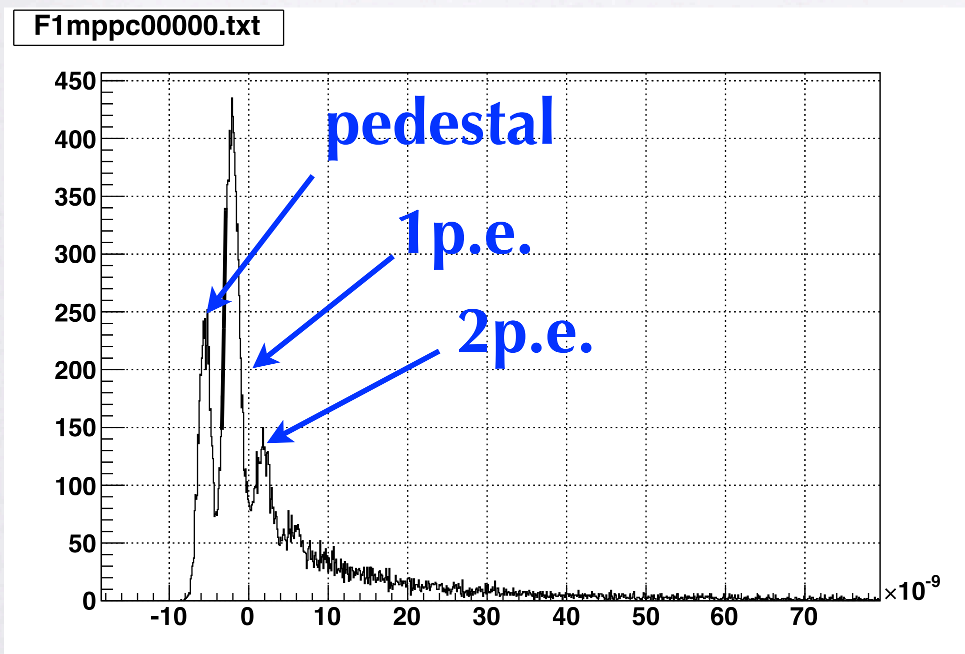
- Current largest PPD ~ $3x3mm^2$
- MEG experiment requirement ~ $>10x10mm^2$
- Possible issues
  - dark count increase
  - non-uniformity of gain
  - larger capacitance.
  - ...
- There are already such products with 4x4 monolithic array MPPC (although those are not sensitive to UV yet).
  - Independent bias voltage can be supplied for 16 MPPCs
  - Good gain uniformity is expected

- Outputs of 4x4 monolithic array MPPC are summed in parallel to make one "pseudo" large MPPC
  - Sum of 9ch and 16ch
  - $3x3mm^2$ --> $9x9mm^2/12x12mm^2$ single MPPC

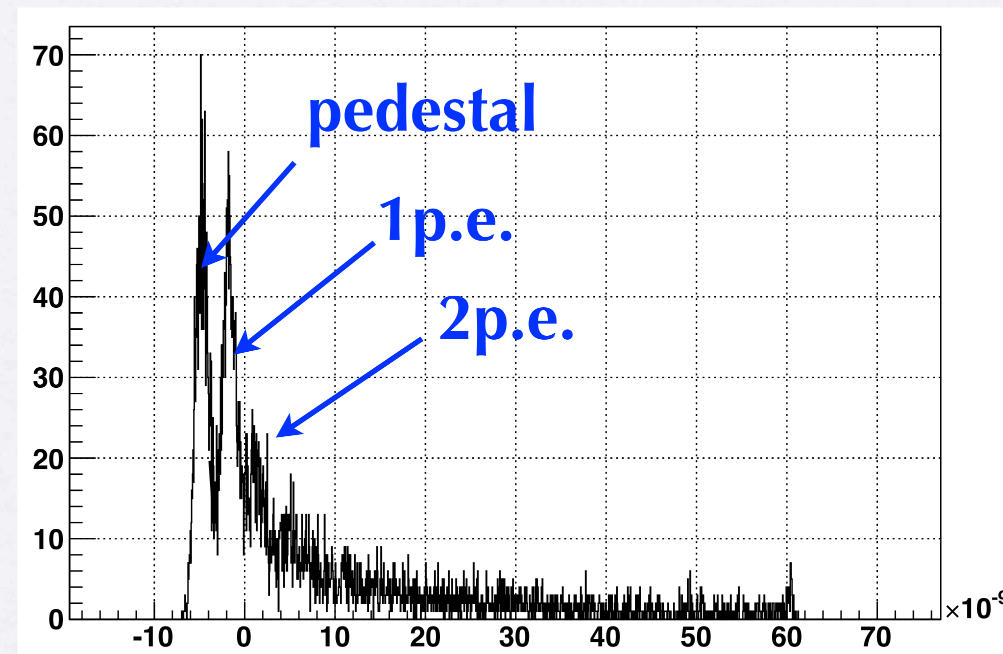


Monolithic array MPPC

3x3 monolithic MPPC



4x4 monolithic MPPC

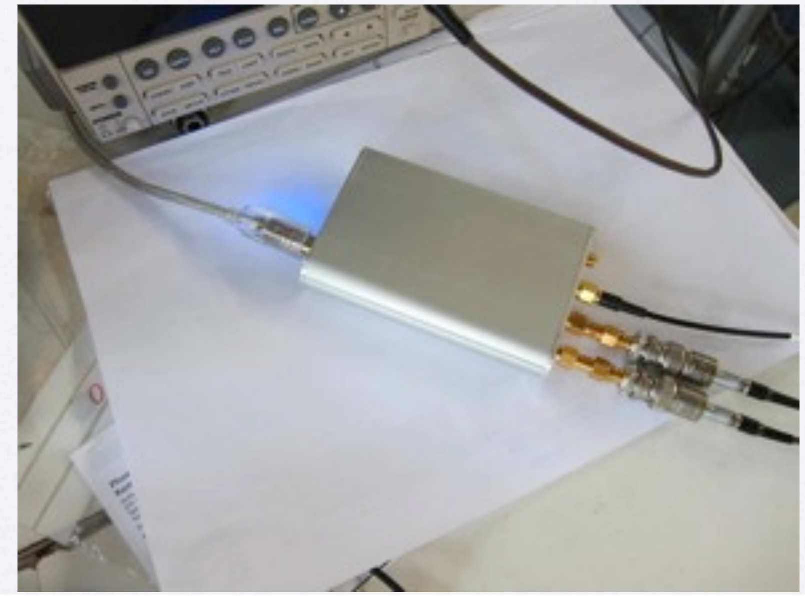


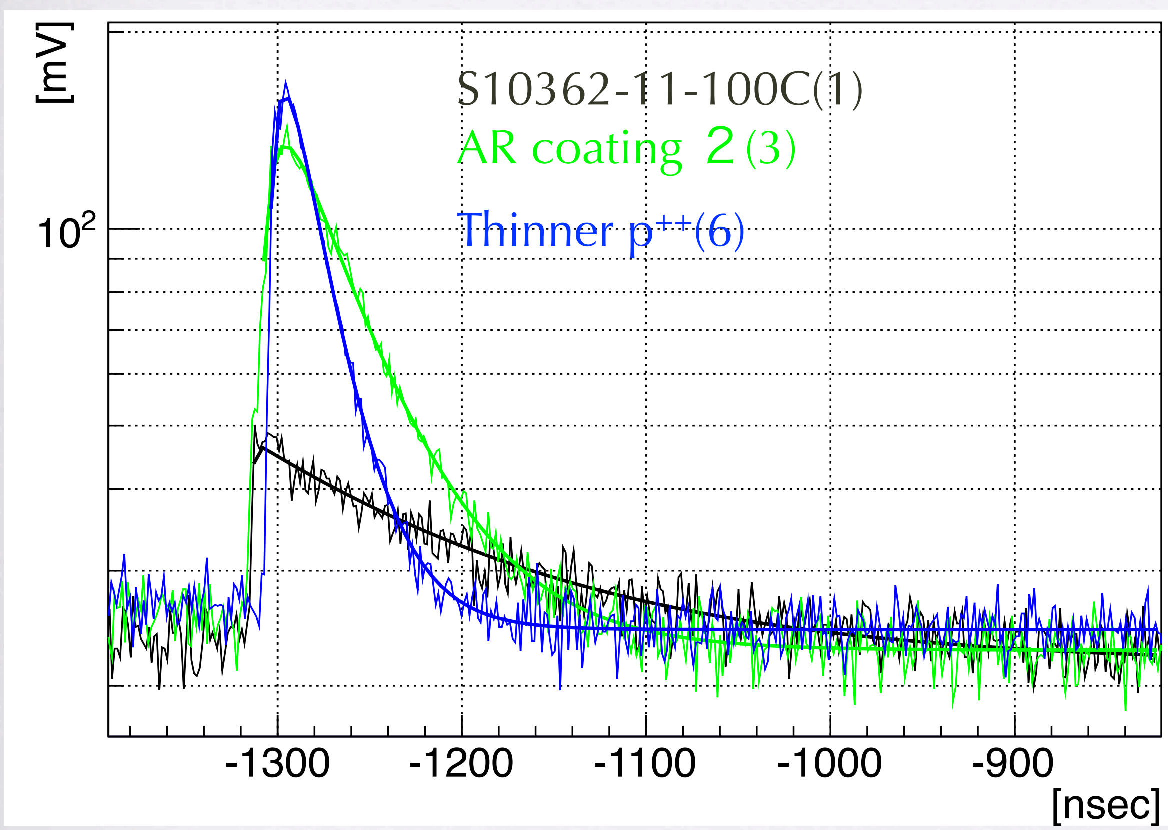
- 1p.e., 2p.e.,...peaks were observed. It clearly shows that monolithic array MPPC has a good gain uniformity.
- This is the first step to realize 12x12mm^2 single MPPC

	Dark rate	Pitch size	ε_{geom}(Fill factor)	Dark rate/area
S10362-33-100C	60-100 Hz	100 μm	0.785	8-14 Hz/mm^2
3x3 monolithic	300-600 Hz	50 μm	0.615	6-12 Hz/mm^2
4x4 monolithic	720 Hz	50 μm	0.615	8 Hz/mm^2

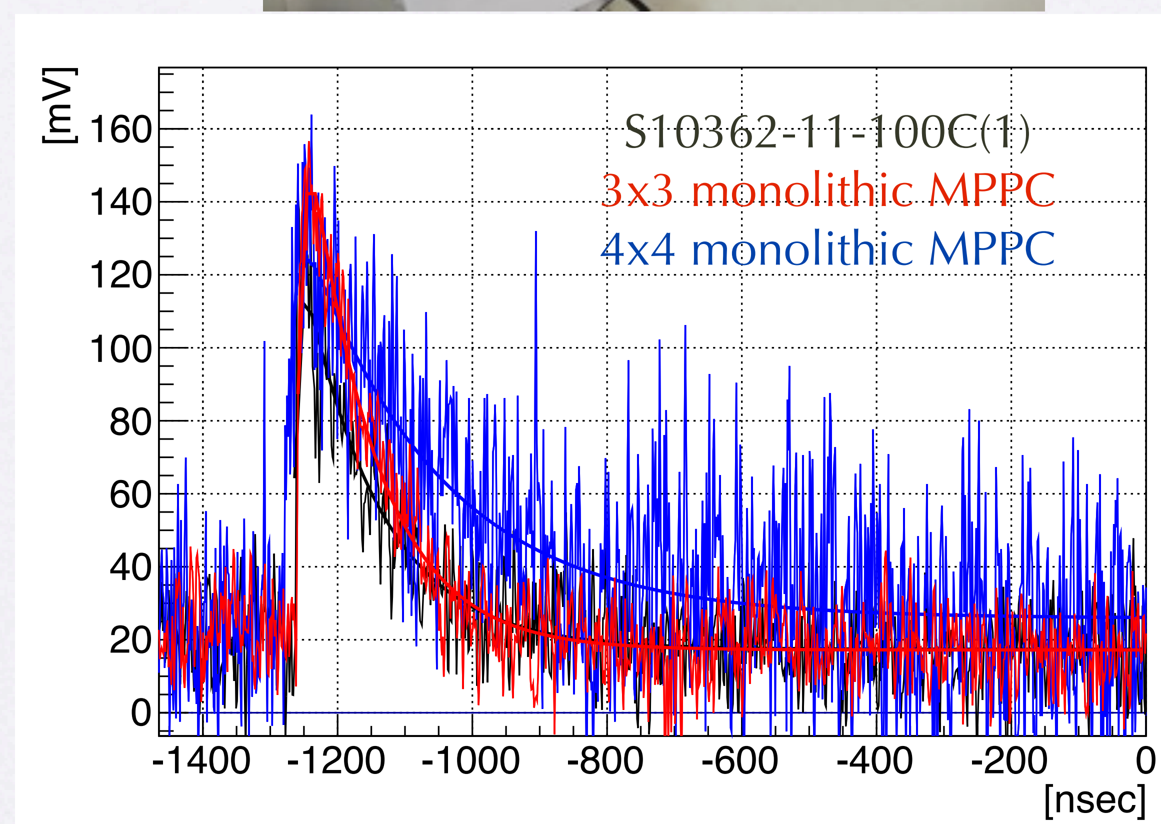
Waveform analysis

- Waveform digitizer is installed to study waveform leading/trailing edge, after pulse etc.
- DRS4 evaluation board: developed by PSI researchers. USB connection. 4ch inputs, 700MHz-5GHz sampling rate





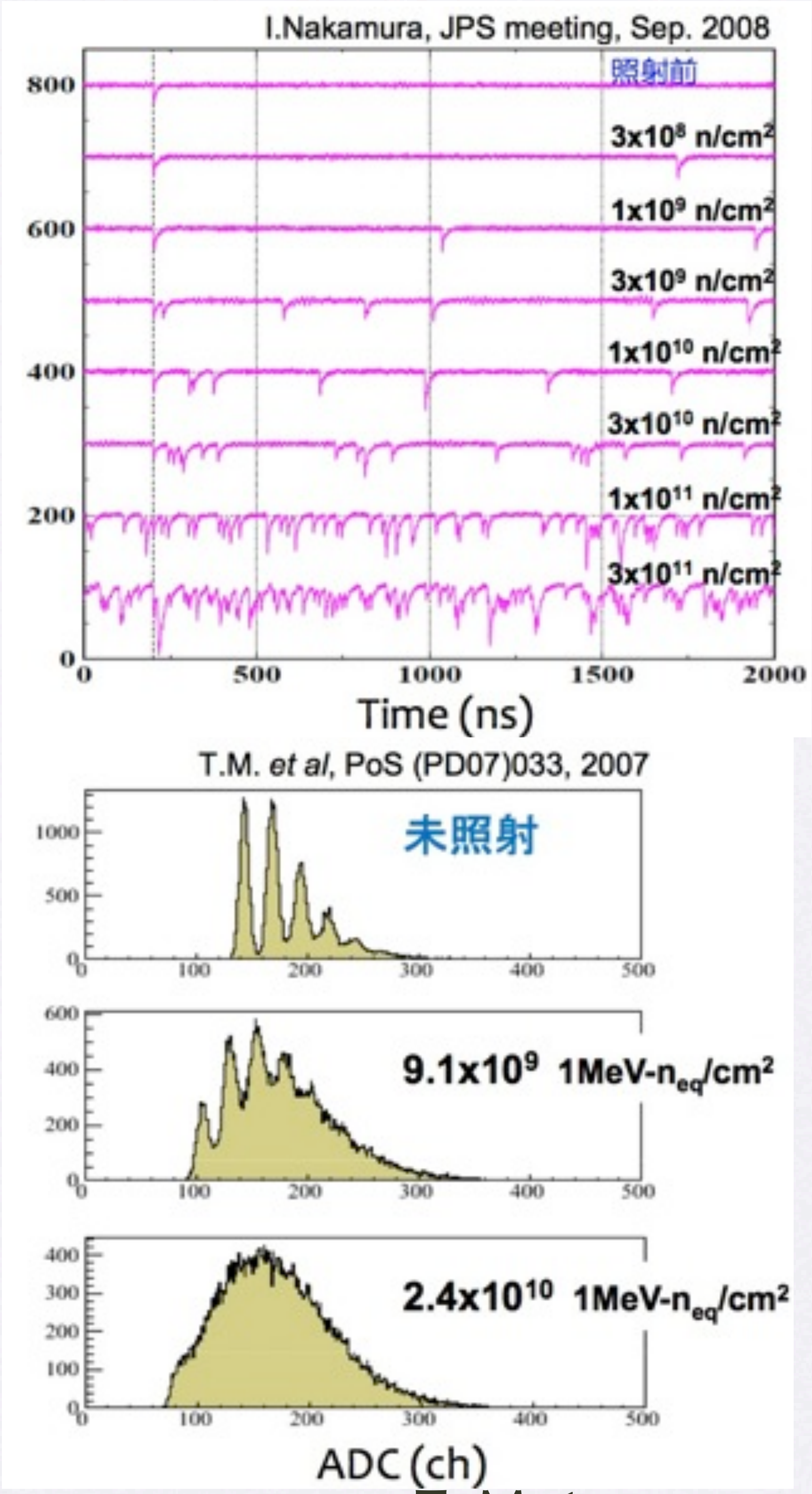
S10362-33-100C : long tail by 100μm pitch (large C)
Thinner p++ : short tail even by 100μm pitch (small quench R, will be optimized)



4x4 monolithic MPPC has longest tail due to increased C

Radiation hardness

- Radiation produces defect in silicon bulk or Si/SiO_2 interface
  - Dark count rate, leakage current, PDE, ...
- Fast neutron
  - $>10^8$ n/cm^2 Increase of dark count rate
  - $>10^{10}$ n/cm^2 Loss of single p.e. detection capability
  - <1 n/s/cm^2($>$0.1MeV) ~ $<1.6\times10^8$ n/cm^2 for full 5-years operation in πE5 area in PSI
  - ~3.5n/s/cm^2 ~ 10^7 n/cm^2 for one week CEX run per year for 5-years
- γ-ray
  - 200Gy Increase of leak current
  - MC: 0.58Gy with 10^8 μ/s for 5-years for MEG
- Radiation damage might not be an issue for MEG.



T. Matsumura et al.

Summary

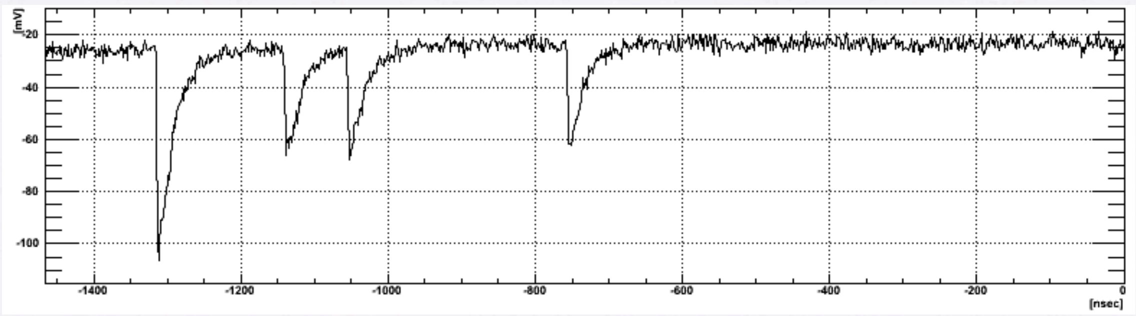
- PPD could be a good candidate for MEG LXe detector upgrade.
- We have started a development of UV-sensitive PPD, and some samples show PDE almost comparable to that of PMT for VUV.
- We succeeded in detecting S.P.E. peak from the sum of 16 channels in parallel of 4x4 monolithic array MPPC (still not sensitive to UV) in liquid xenon.
- Radiation hardness might not be a problem for MEG.
- The basic idea looks promising, but still lots of issues to be addressed,
  - Further optimization of PDE for VUV
  - Sensor size, quench resistor, package design optimization
  - Readout scheme (effect of long cable, feedthrough, ...)
  - performance check by prototype detector
- Realistic MC study including cross talk, after pulse (澤田龍 25pFA10)

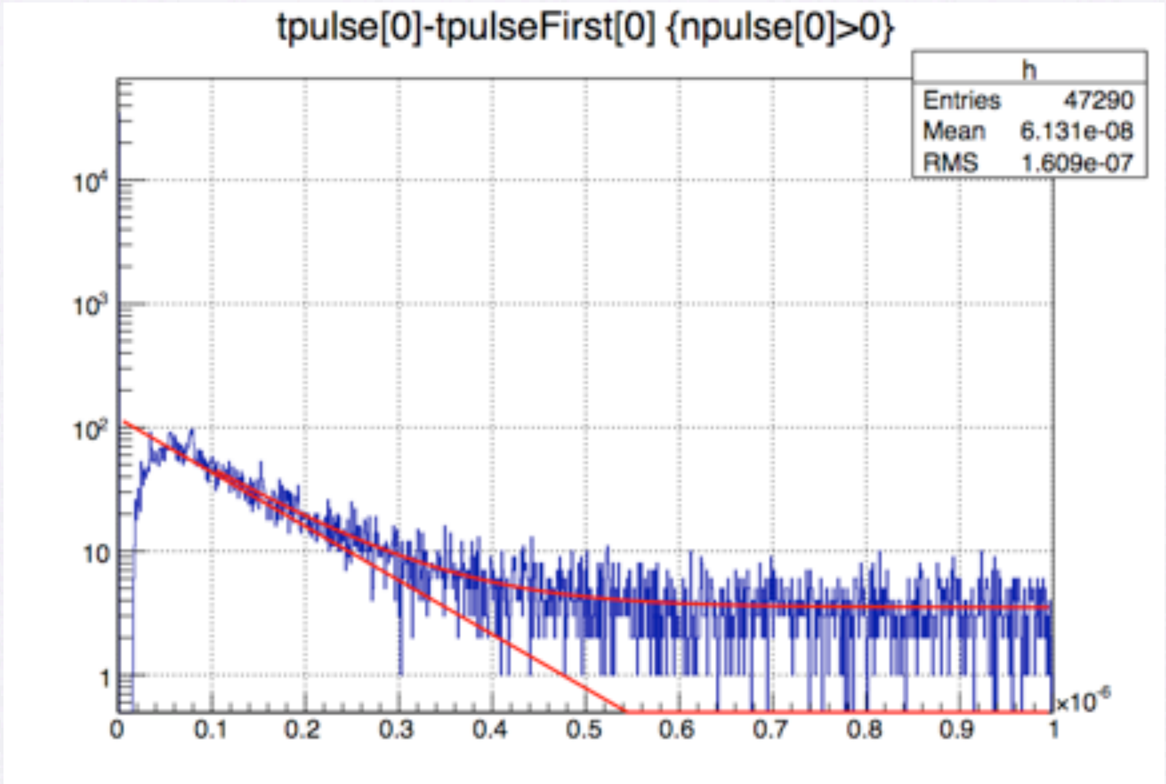
Backup

After pulse

- キャリアがアバランシェ中格子欠陥にトラップされ、しばらくしてから解放され、アバランシェを再び起こす過程。

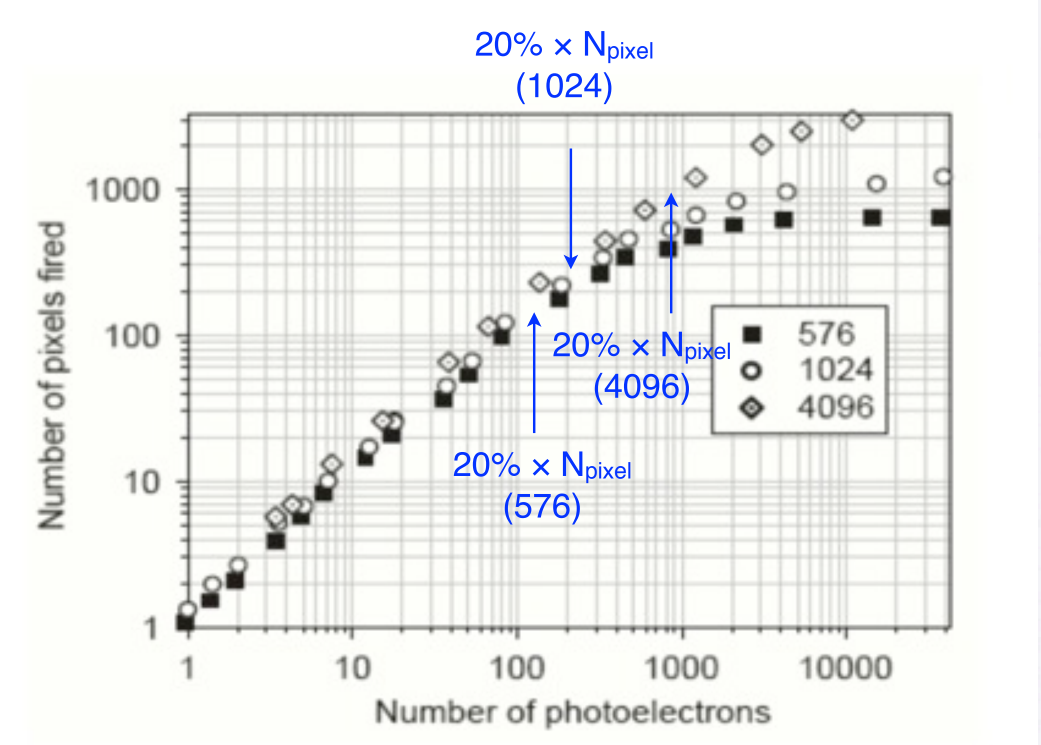
- パルスの発生時間とトリガーされたパルスの時間との差をプロットし、アフターパルスの減衰時間、発生確率等を求める。

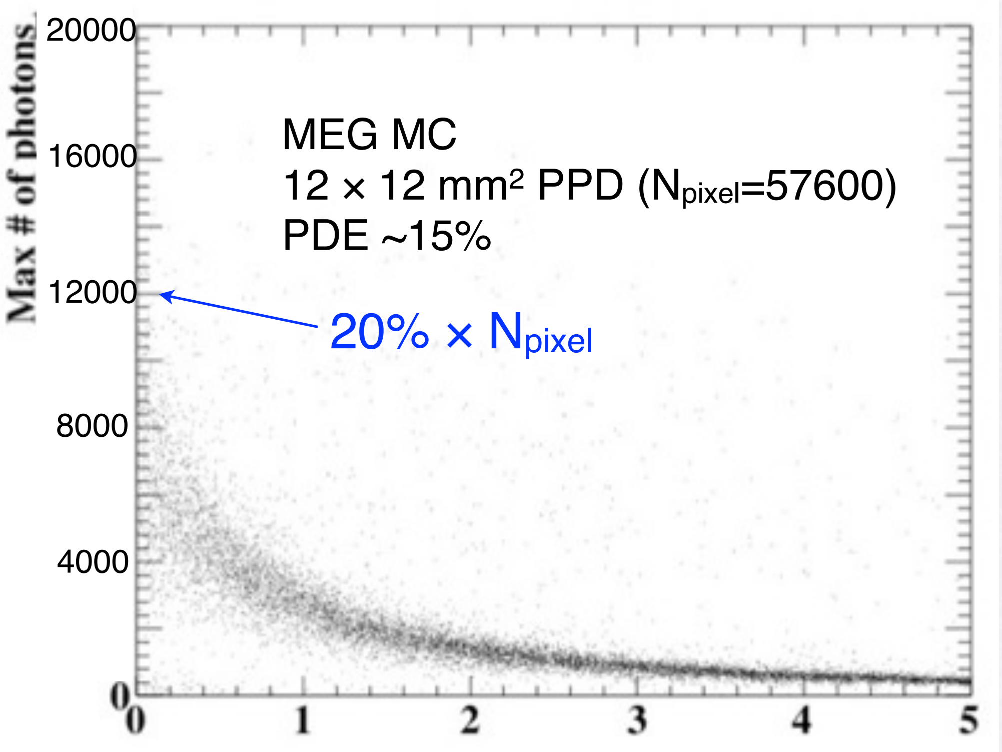




Dynamic range

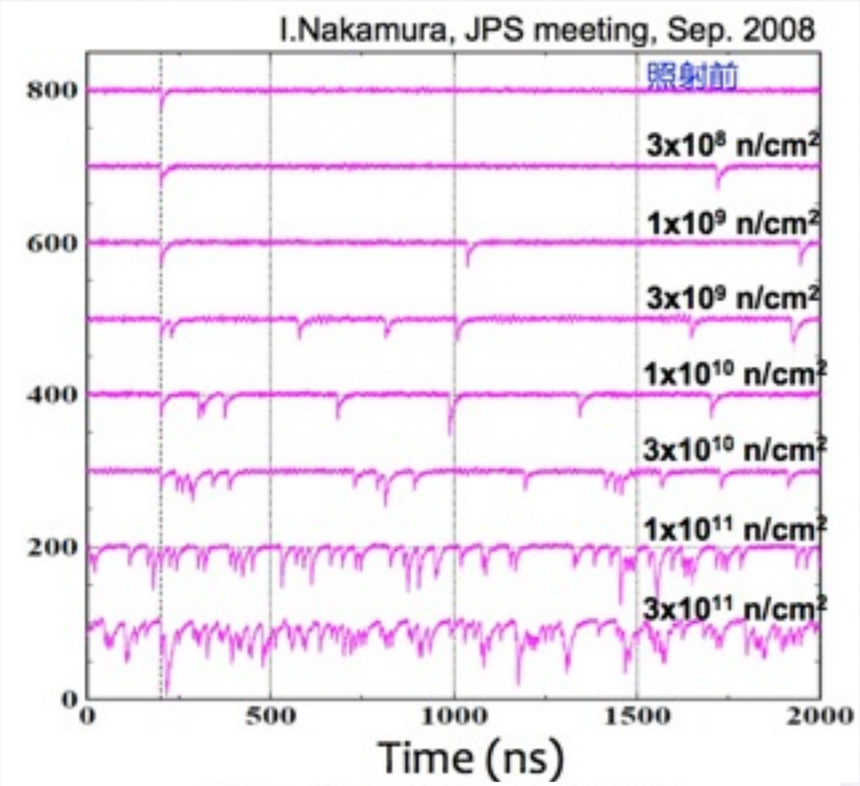
- PPD response shows a non-linearity if the number of detected photons is large relative to total number of pixels
- Optimal condition $N_{p.e.} < N_{pixel}$
- Might be an issue for very shallow events for MEG LXe detector.

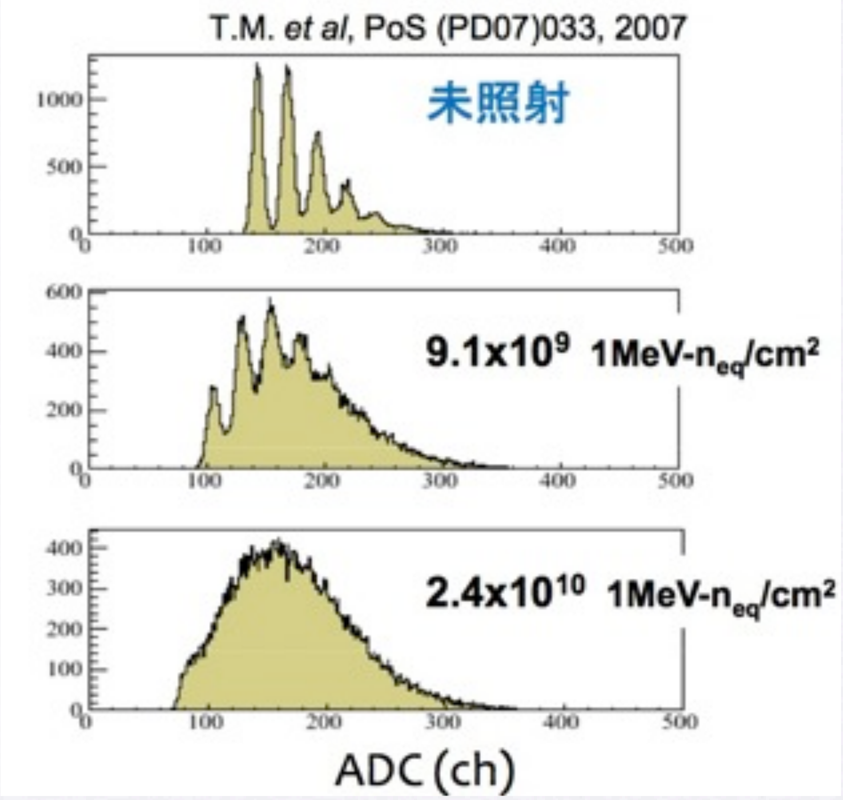




Radiation damage

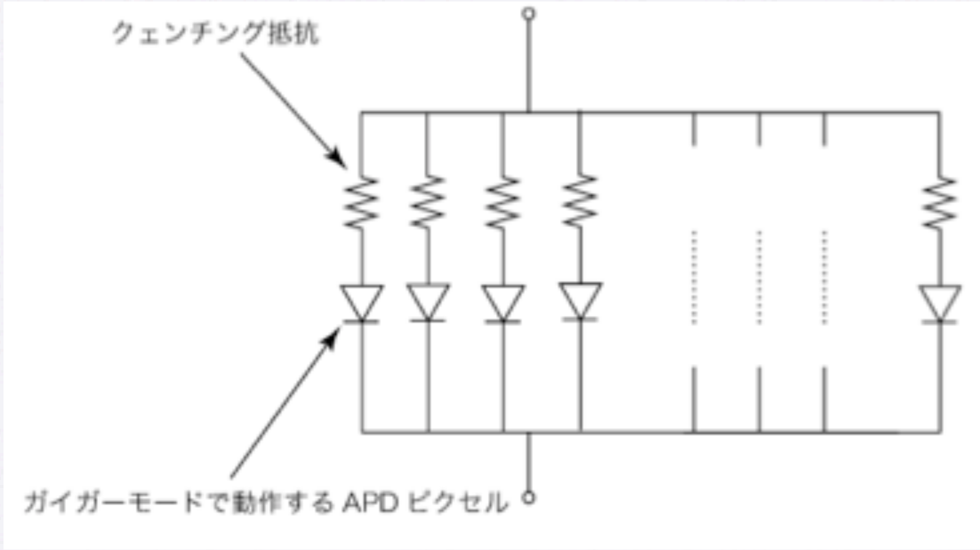
- Radiation produces defect in silicon bulk or Si/SiO_2 interface which may deteriorate PPD performance.
    - Dark count rate, leakage current, PDE, ...
- Radiation damage of PPD
    - Fast neutron
        - >10^8 n/cm^2 Increase of dark count rate
        - >10^{10} n/cm^2 Loss of single p.e. detection capability
    - γ-ray
        - 200Gy Increase of leak current
- Neutron flux in πE5 area in PSI
    - ~10n/s/cm^2(<0.1MeV) ~ <1.6x10^8 n/cm^2 for full 5-years operation
- Fast neutron in CEX run
    - ~3.5n/s/cm^2 ~ 10^7 n/cm^2 for one week CEX run per year for 5-years
- Gamma dose
    - MC: 0.58Gy with 10^8 μ/s for 5-years.

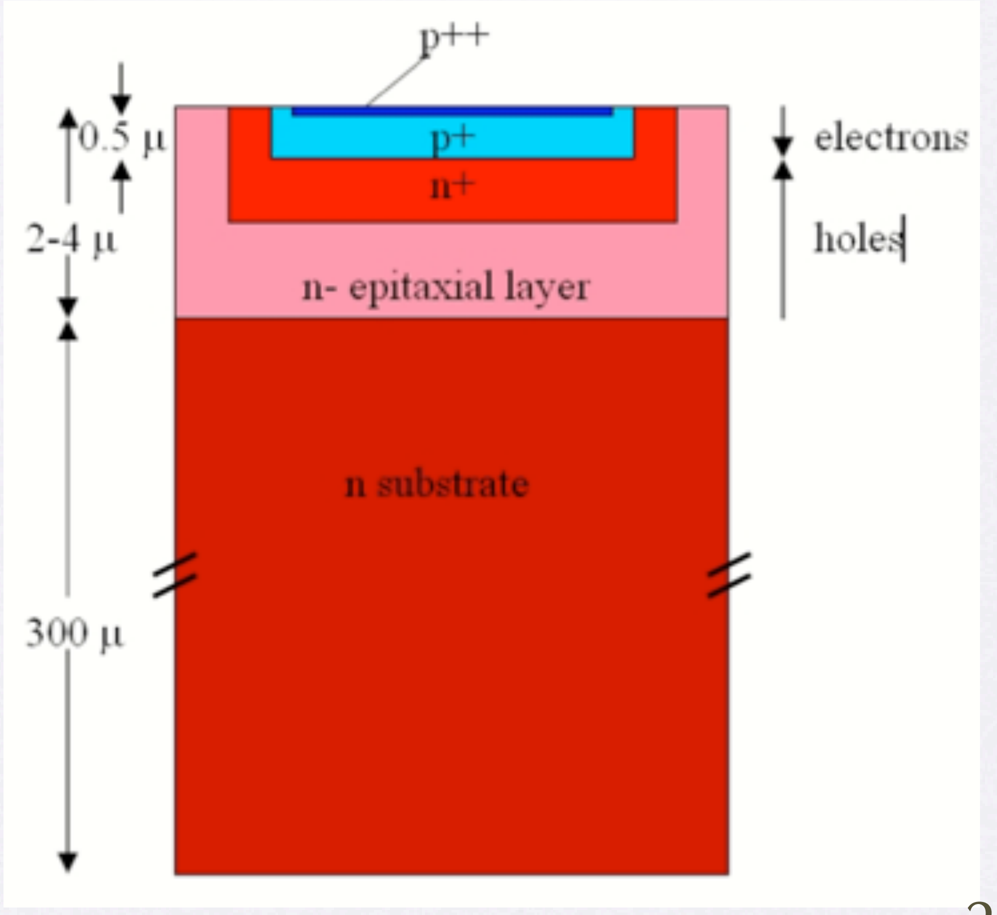




PPDの動作

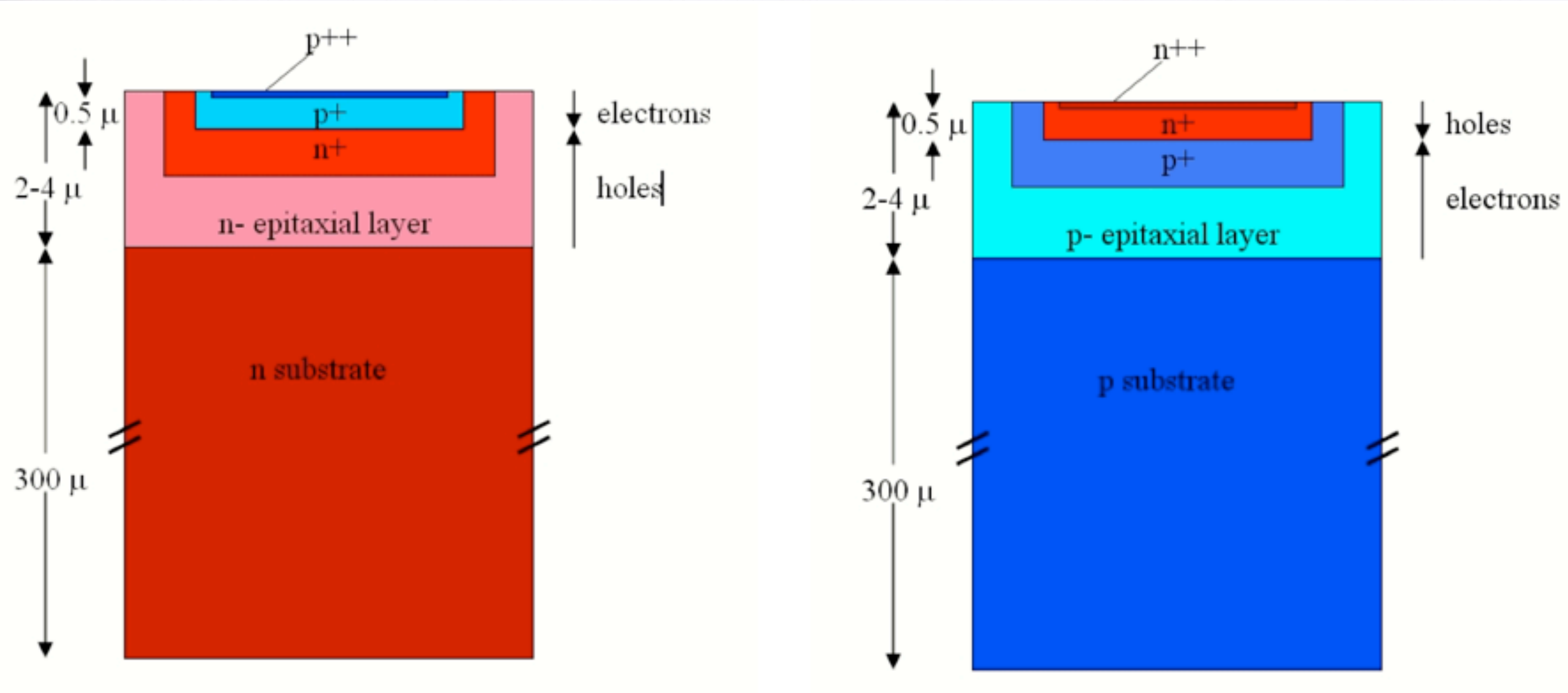
- An array of Geiger-mode APDs connected in parallel
  - incident photon, e-h pair creation, Geiger mode avalanche multiplication, voltage drop by quench resister, Geiger mode stops.
  - each pixel works as a binary device
- 1 pixel = 1 photon at $N_{p.e.} << N_{pixel}$
- Sum of pixel outputs is proportional to number of impinging photons





G-APD

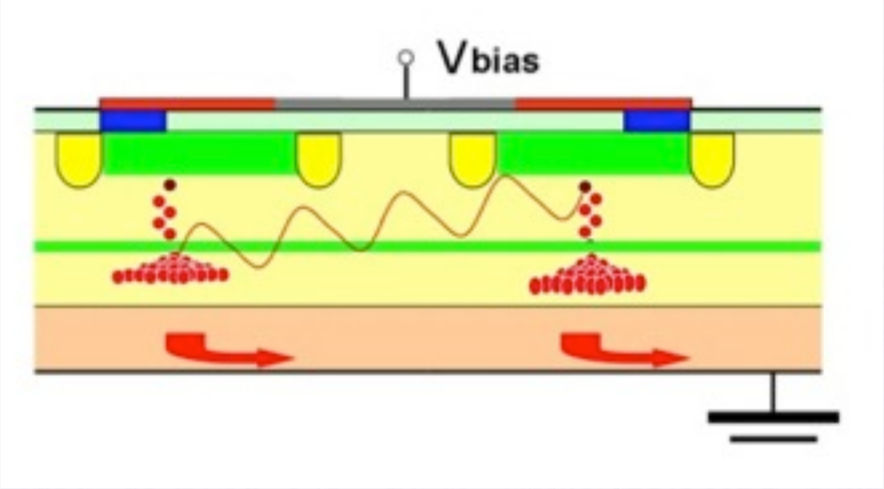
blue-sensitive | red-sensitive

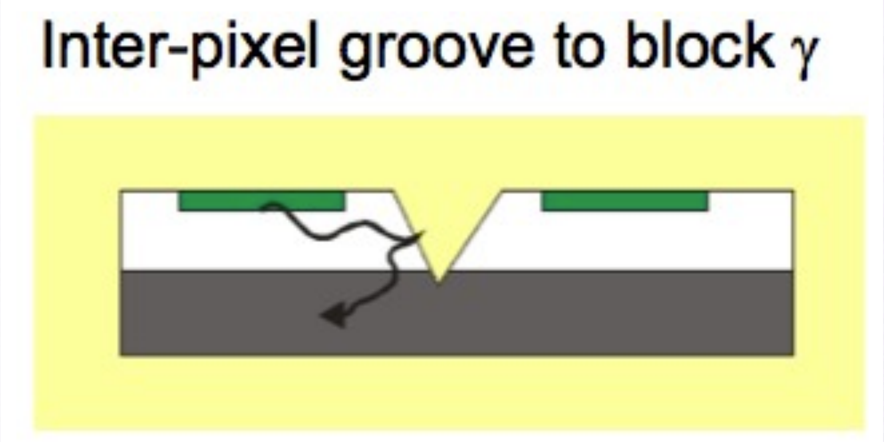


- D. Renker and E. Lorenz, JINST 4 P04004 (2009)
  - Not shown are the passivation layers, the quenching resistors and the Al connection lines. Left is the so-called p-on-n structure (blue-sensitive) and right the n-on-p (red-sensitive) structure.

Cross talk

- Hot-carrier luminescence generate signal in adjacent pixels
  - 10-20% probability
- How to suppress optical crosstalk
  - Optical isolation between pixels with a groove
  - Lowering bias voltage





MPPC parameters

項目	記号	S10362-33			S10931			単位
		-025C	-050C	-100C	-025P	-050P	-100P	
有効受光面サイズ	-	3 × 3			3 × 3			mm
ピクセル数	-	14400	3600	900	14400	3600	900	-
ピクセルサイズ	-	25 × 25	50 × 50	100 × 100	25 × 25	50 × 50	100 × 100	μm

電気的および光学的特性 (指定のない場合はTyp. Ta=25 °C)

項目		記号	S10362-33			S10931			単位
			-025C	-050C	-100C	-025P	-050P	-100P	
開口率 *1		-	30.8	61.5	78.5	30.8	61.5	78.5	%
感度波長範囲		λ	320 ～ 900			320 ～ 900			nm
最大感度波長		λp	440			440			nm
動作電圧範囲		-	70 ± 10 *2			70 ± 10 *2			V
ダークカウント *3	Typ.	-	4	6	8	4	6	8	Mcps
	Max.		8	10	12	8	10	12	
端子間容量		Ct	320			320			pF
時間分解能 (FWHM) *4		-	500 ～ 600			500 ～ 600			ps
逆電圧の温度係数		-	56			56			mV/°C
増倍率		M	2.75×10^5	7.5×10^5	2.4×10^6	2.75×10^5	7.5×10^5	2.4×10^6	-

*1: 1ピクセル中で受光部の占める割合
*2: 個別製品の推奨動作電圧については、製品に添付されたデータを参照してください。
*3: 0.5 p.e. (閾値レベル)
*4: シングルフォトンレベル
注) 各値は推奨動作電圧時における値です。
型名の最後の記号は、パッケージを表します (C: セラミック、P: SMD)。

Monolithic array data sheet

S11827-3344MG(X) data sheet 2011/11/17

TEST DATA

Ta = 25°C

Serial No.	17		18		Element No.
FPC Pin No.	Vop (V)	dark @Vop (uA)	Vop (V)	dark @Vop (uA)	
1	72.10	0.05	71.67	0.05	D1
2	72.10	0.05	71.59	0.05	D2
3	72.08	0.05	71.54	0.06	D3
4	72.06	0.05	71.51	0.07	D4
5	72.15	0.05	71.71	0.05	C1
6	72.14	0.05	71.64	0.05	C2
7	72.13	0.05	71.59	0.05	C3
8	72.11	0.05	71.57	0.06	C4
9	72.18	0.05	71.65	0.06	B4
10	72.19	0.05	71.67	0.05	B3
11	72.21	0.05	71.73	0.05	B2
12	72.21	0.05	71.79	0.05	B1
13	72.25	0.05	71.74	0.05	A4
14	72.25	0.05	71.76	0.05	A3
15	72.28	0.05	71.82	0.05	A2
16	72.29	0.06	71.88	0.05	A1

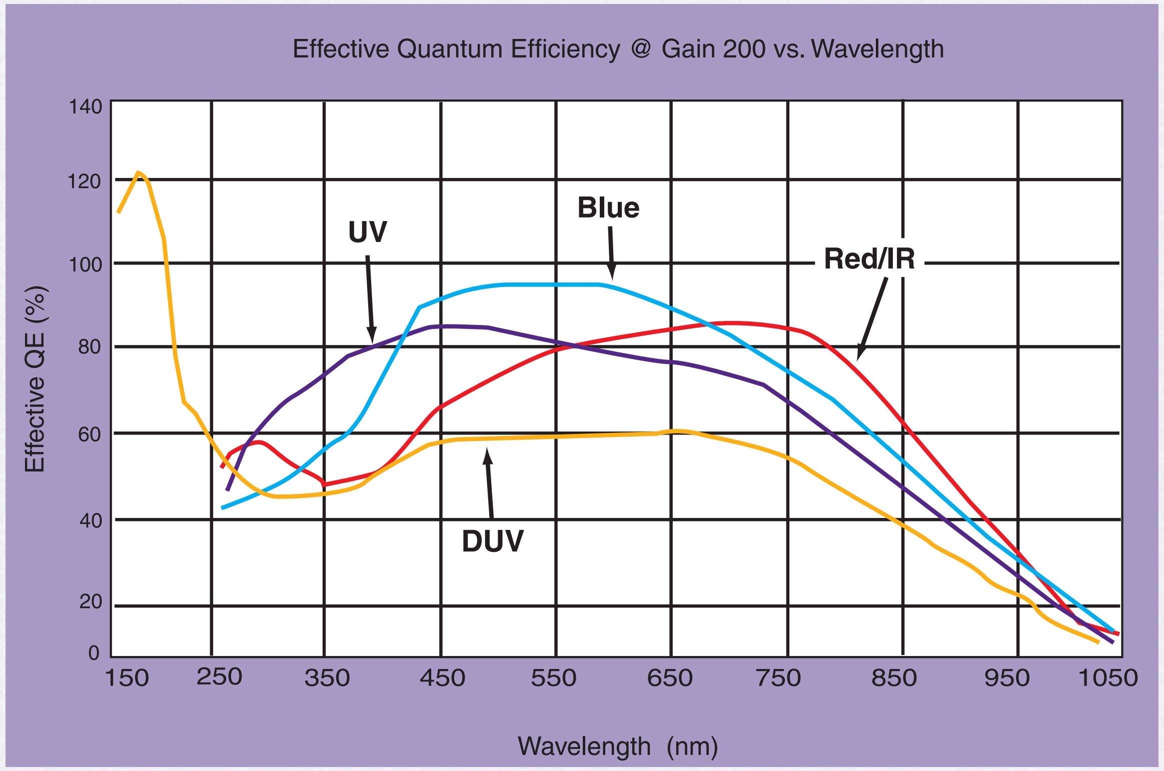
Vop : Recommended operation bias voltage for each elements.
We estimated the gain at Vop as $M = 6.5 – 8.5 \times 10^5$.

PPD in liquid xenon

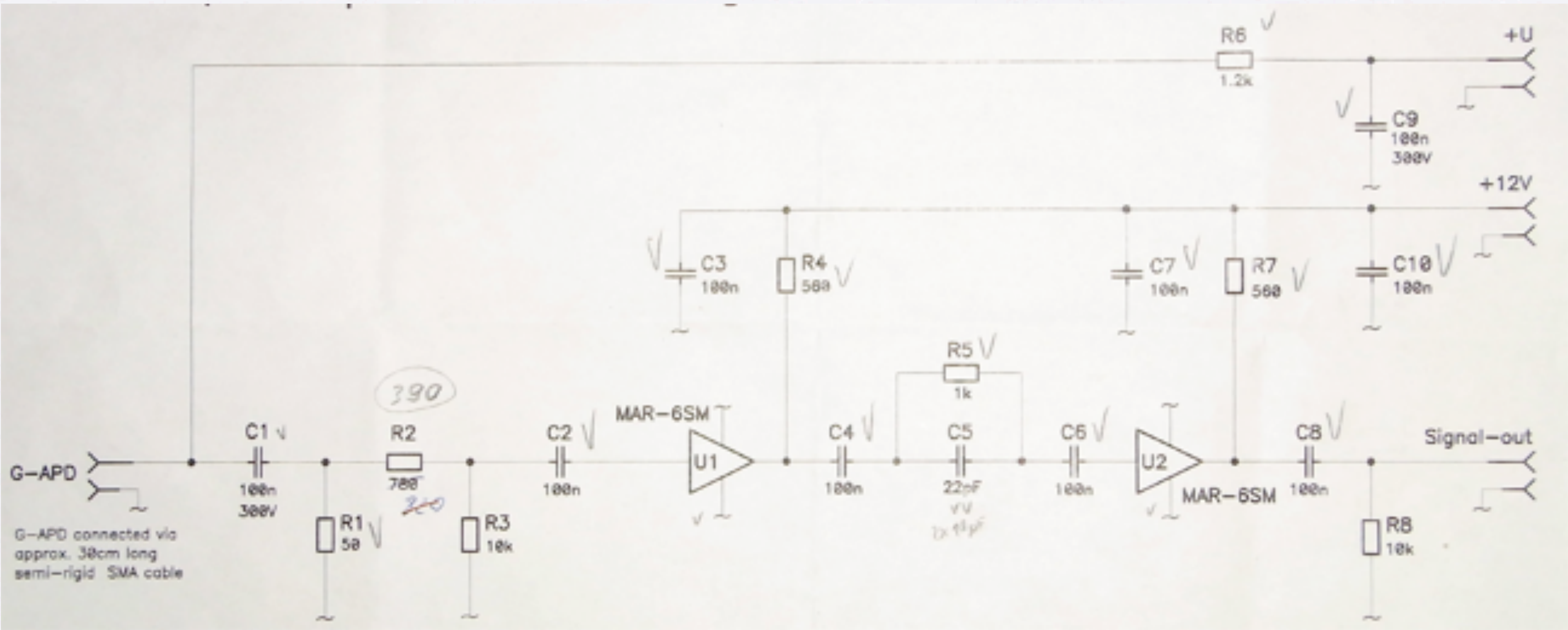
- Need to be tested
  - PDE against VUV light
    - 通常のMPPCはUV光に対して殆ど感度がない(保護用樹脂膜）。シリコン中での真空紫外光の吸収長(5.5nm@rambda=175nm)有感層まで到達できない。保護膜がない場合PDE 10-15%@r=200nm
  - dark count
    - これはどちらかというとメリットあり。165Kでは5桁くらいノイズは落ちる。
  - cross talk
  - quench resistor
    - 抵抗値が常温の2倍程度になってしまう。波形のテイルはRCで決まっていて、Cはほぼ温度依存はないがRが大きくなるため、波形のテイルも長くなる。液体キセノン温度で最適化すると常温での抵抗値が小さくなりすぎる可能性があり、難しいかも。高抵抗金属合金などは？
  - after pulse
  - sensor size
    - サイズが大きくなると容量が大きくなり、またcross talk, after pulseが多く、saturationしやすい。また波形の立ち上がり、立ち下がりも長い。fill factor は30%ほどロスするが、50μmあたりが最適か。
  - radiation hardness
  - dynamic range
  - reflection on sensor surface

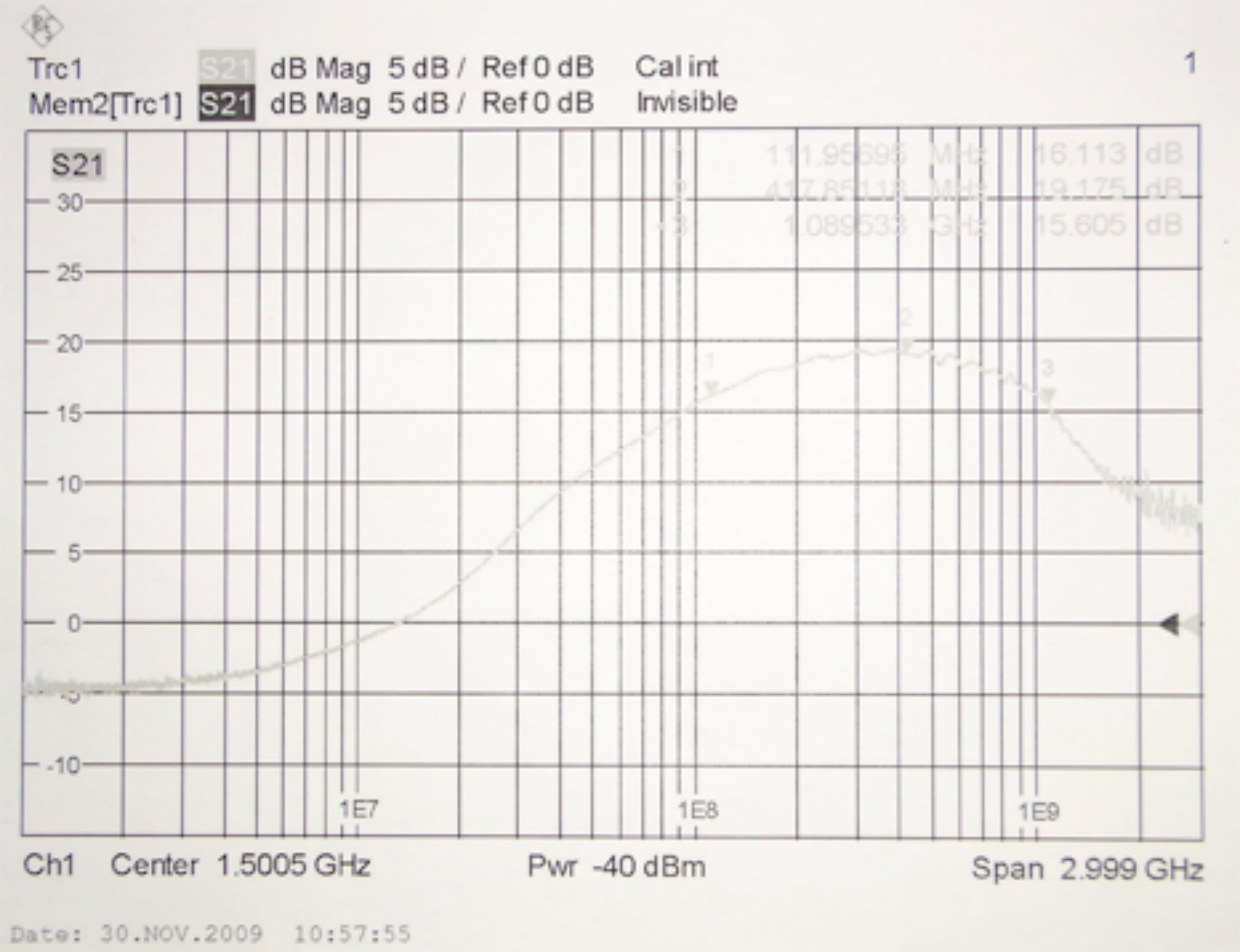
UV sensitive APD

- LAAPD from Advanced Photonix Inc.
  - QE = 120% @ 170nm
  - QE = transmission eff. (50%) x $N_{e\text{-}h}$ pair (2-3)
  - R. Chandrasekharan et al., NIMA 546(2005) 426
  - Low gain(~200)...



Pre amplifier

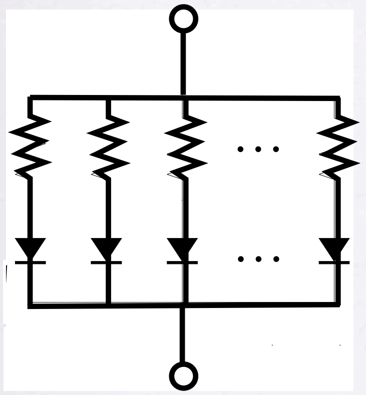




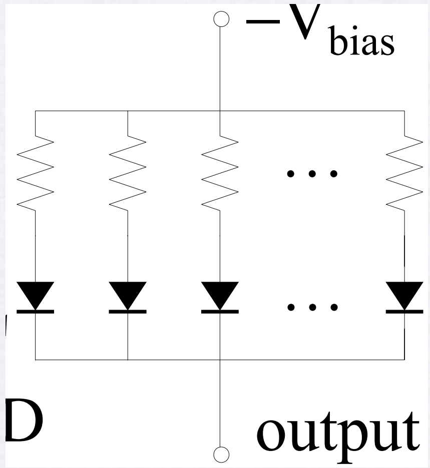
Other experiments

Schedule of PPD development

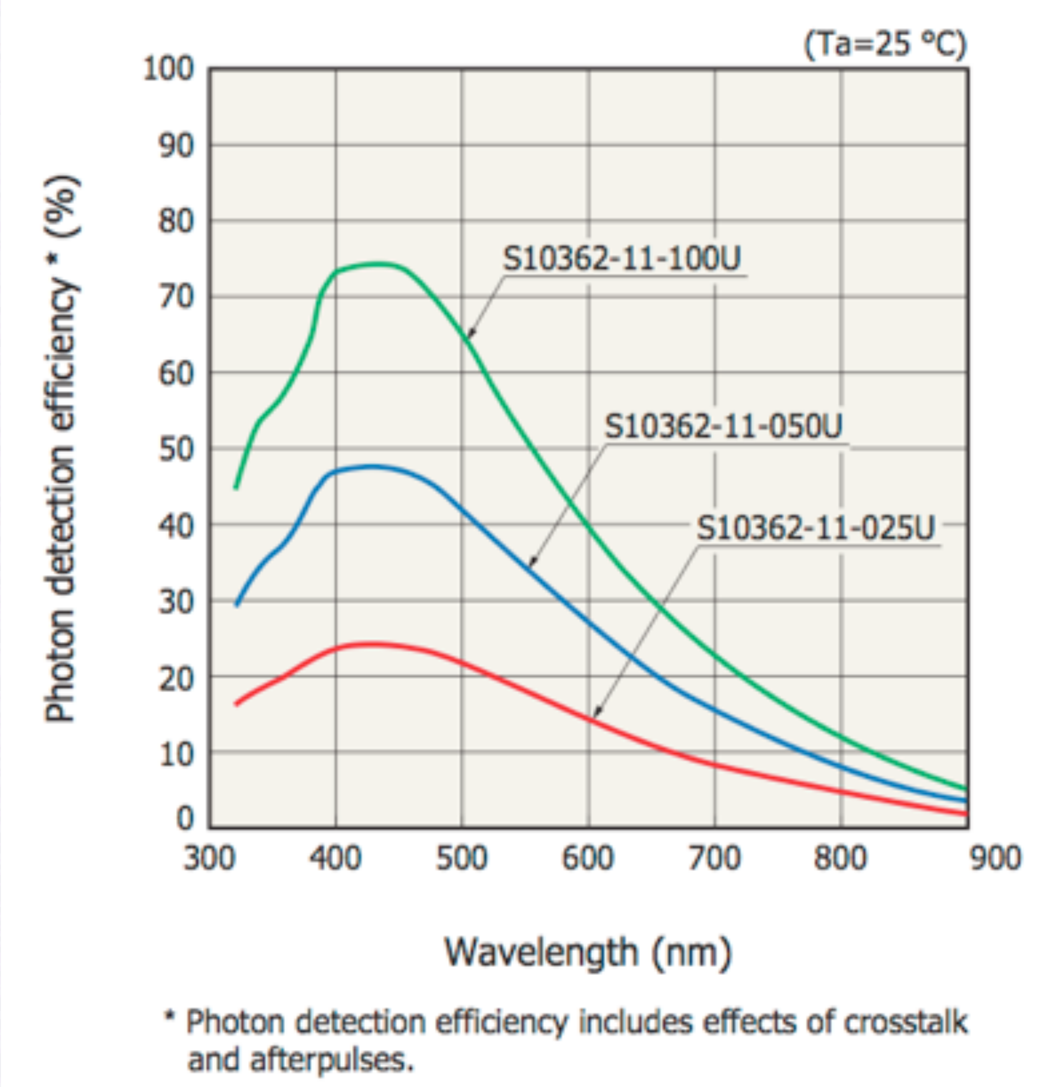
- Summer 2012
  - Development of PPD sensitive to VUV
- End of 2012
  - Construction of prototype detector with ~100 L liquid xenon and ~500 PPDs
- 2013
  - Test beam with prototype detector
  - Construction of the final detector



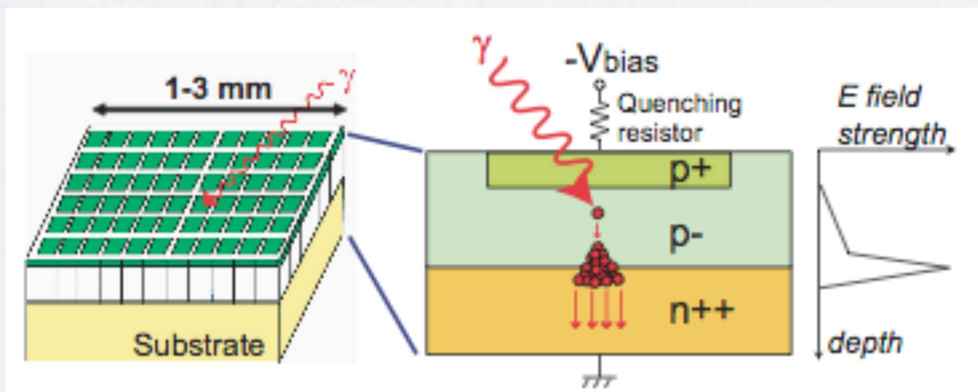
PDE



−V bias
D
output



(Ta=25 °C)
Photon detection efficiency * (%)
Wavelength (nm)
S10362-11-100U
S10362-11-050U
S10362-11-025U
* Photon detection efficiency includes effects of crosstalk and afterpulses.



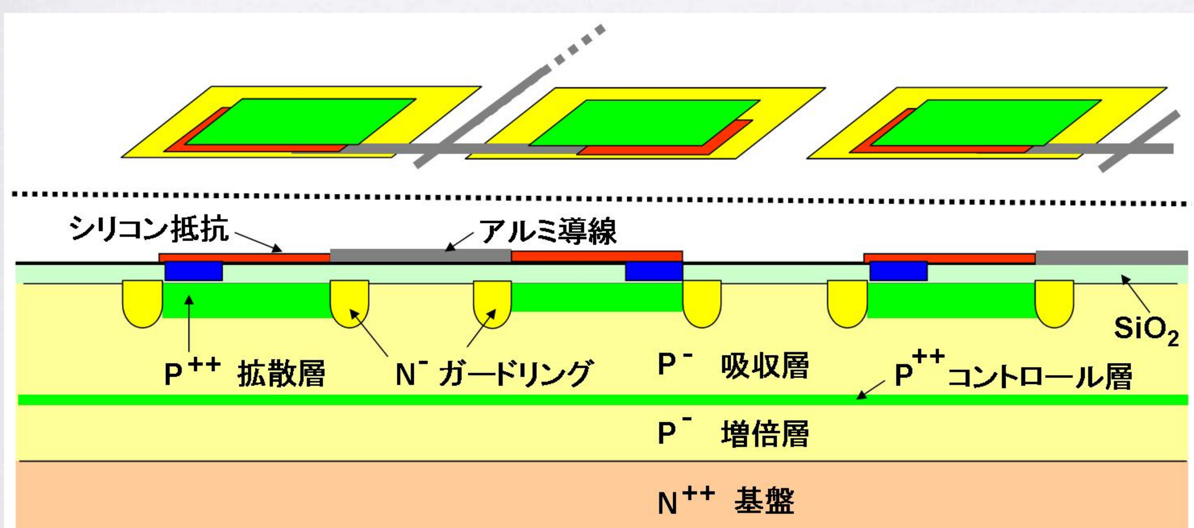


図 2.7: MPPC の断面図

	半導体の型 (不純物)	不純物濃度	厚さ
拡散層	P^{++}(B)	$1.0^{18} \times cm^{-3}$	$0.5\mu m$
吸収層	P^{-}(B)	$1.0^{15} \times cm^{-3}$	$1.5\mu m$
コントロール層	P^{++}(B)	$2.0^{17} \times cm^{-3}$	$0.02\mu m$
増倍層	P^{-}(B)	$1.0^{15} \times cm^{-3}$	$1.0\mu m$
基盤	N^{++}(As)	$1.0^{18} \times cm^{-3}$	$0.5\mu m$

表 2.2: MPPC 各部の不純物濃度及び厚さ