波形シミュレーションを用いたMEG II陽電子タイミングカウンターの性能評価

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Overview

- **MEG II Overview**
- Waveform Simulation
- Afterpulse Measurement
- Application of Waveform Simulation
- Summary and Prospect

MEG II experiment

The most sensitive $\mu^+ \rightarrow e^+\gamma$ **search experiment** in the world with the most intense DC muon beam at PSI

✓**<u>In Standard Model</u>**

strongly suppressed and cannot be found by experiment

✓**<u>In Beyond Standard Model with SUSY-GUT, SUSY-seesaw model …</u>**

Br$(\mu^+ \rightarrow e^+\gamma)$ becomes larger and we can find by experiment !

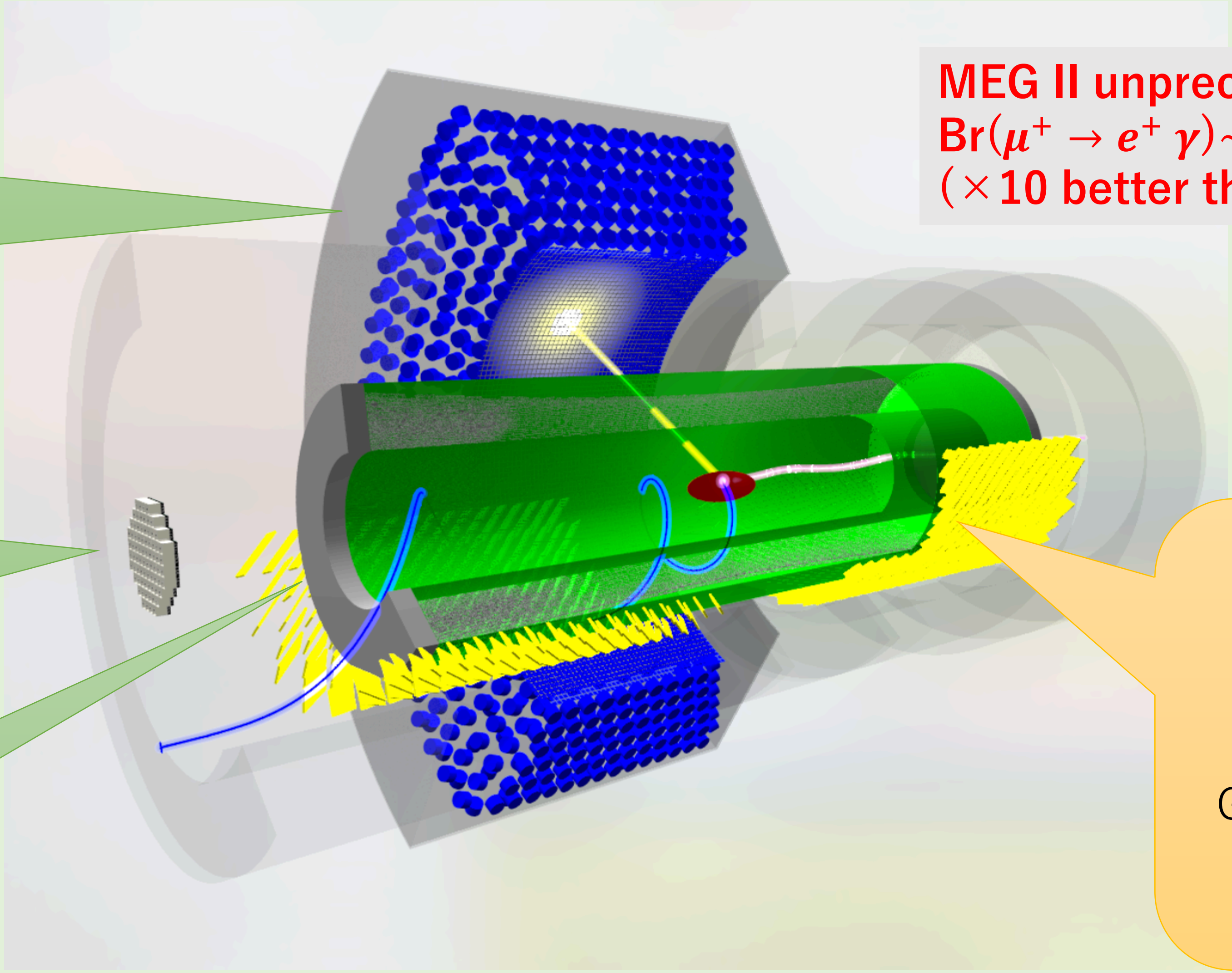
<u>To discover $\mu^+ \rightarrow e^+\gamma$ means to discover new physics !</u>

MEG II experiment-detectors-

Liquid Xe Detector
Detect gamma-rays with MPPCs and photomultiplier tibe

Radiative Decay Counter(RDC)
Detect low-energy positron
Tag BG event

Drift Chamber
Track positron



MEG II unprecedented sensitivity :
Br$(\mu^+ \rightarrow e^+ \gamma) \sim 4.0 \times 10^{-14}$
(×10 better than MEG experiment !)

positron Timing Counter(pTC)
Get the timing of positron

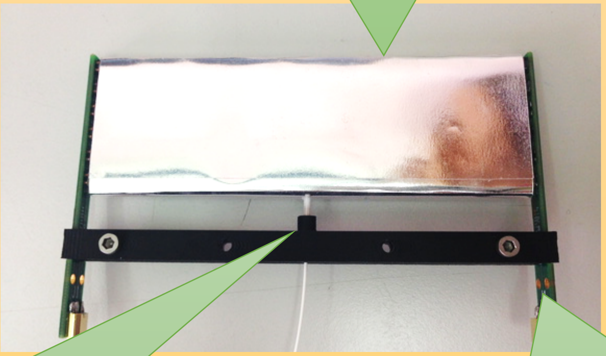
1 pixel counterとPCBの写真はhttps://meg.web.psi.ch/docs/talks/JPS/2015a/yoshida_jps2015a.pptxより引用

Positron Timing Counter

256 counters

Timing counter

1 pixel counter



PCB

ultra-fast plastic scintillator(BC422) + reflector
120mm x 40mm x 5mm
120mm x 50mm x 5mm

Support structure and laser fiber for calibration

6series SiPM on PCB
SiPM : ASD-NUV3S-P High-Gain(MEG)

Features :
- ✓ Small pixels(512 pixels)
- ✓ 6 series SiPM+fast scinti.
- ✓ Using multihit information
- ✓ Time resolution ~ 30ps

Analysis Flow of Timing Counter

DAQ → **Waveform analysis** → Hit reconstruction → Clustering → Positron Timing

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Waveform Simulation

Motivation
☆Deep understanding on detector
☆Evaluate the detector performance

Application
✓ Physics process in detector
✓ Noise effect on performance
✓ Pile up effect w/ actual MEG II physics run setup
✓ Radiation damage and current increase effect
etc…

1.Set up
Set detectors
Event generation

2.Photon Tracking
Record
hit pixel & time

3.Simulate Waveform
By using hit information &
SiPM's response

4. Waveform Analysis
Get the time resolution

Using **measured** parameters
Ex. Dark count rate,Recovery time,Prompt Cross Talk probability
Probability of afterpulse & delayed cross talk
Time const of afterpulse & delayed cross talk

Waveform Simulation Status

Already studied & included SiPM noises:

Cross talk, Dark noise, White noise, etc…

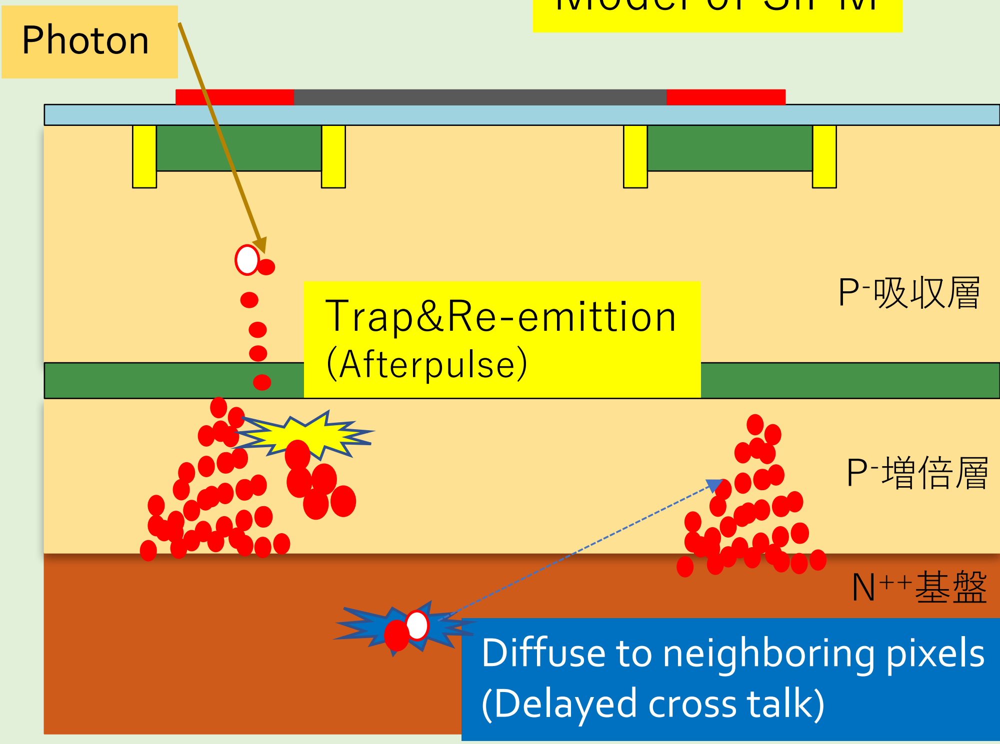
(Ref. JPS Slide {http://meg.icepp.s.u-tokyo.ac.jp/docs/talks/JPS/2016s/yoshida_jps2016s.pdf})

Not studied & included SiPM noises :

Afterpulse, Delayed cross talk

Including all noises properly must be done to simulate pulse & understand detector

Model of SiPM



右図引用)hep-www.px.tsukuba.ac.jp/~hontaku/MPPCSchool/slides/MPPCshibata.pptx
23Pの図を引用、一部変更

Afterpulse measurement

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Model & Measurement

There are some previous studies on afterpulse measurement

The number of component

2 afterpulse component & 0 delayed cross talk component

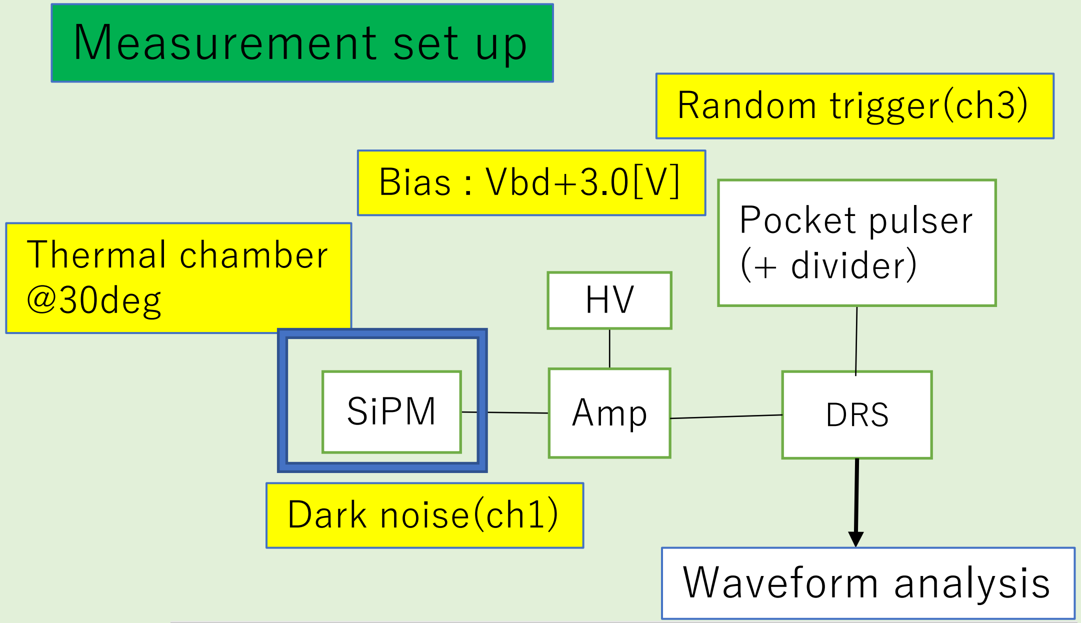
1 afterpulse component & 1 delayed cross talk component

Measurement method

Many of afterpulse measurement uses :

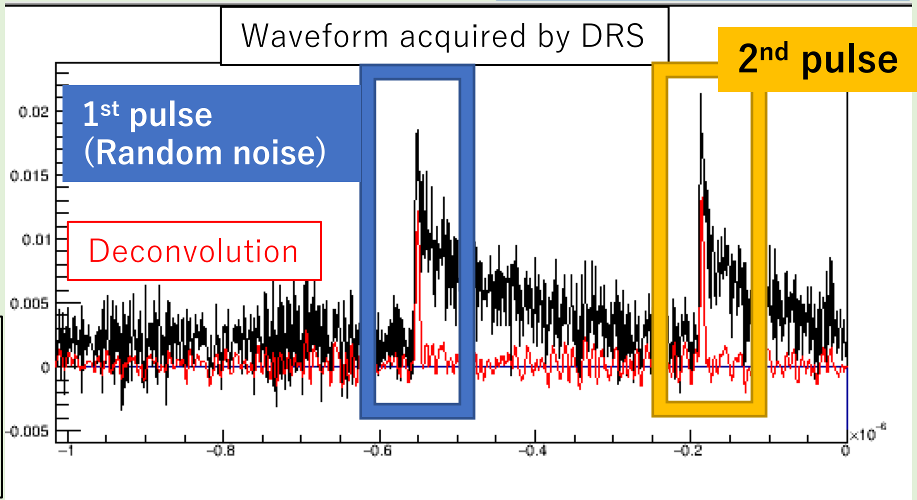
waveform analysis & **deconvolution**

->to suppress the tail of pulse



Domino **R**ing **S**ampling chip : **DRS**

Waveform digitizer used in MEG



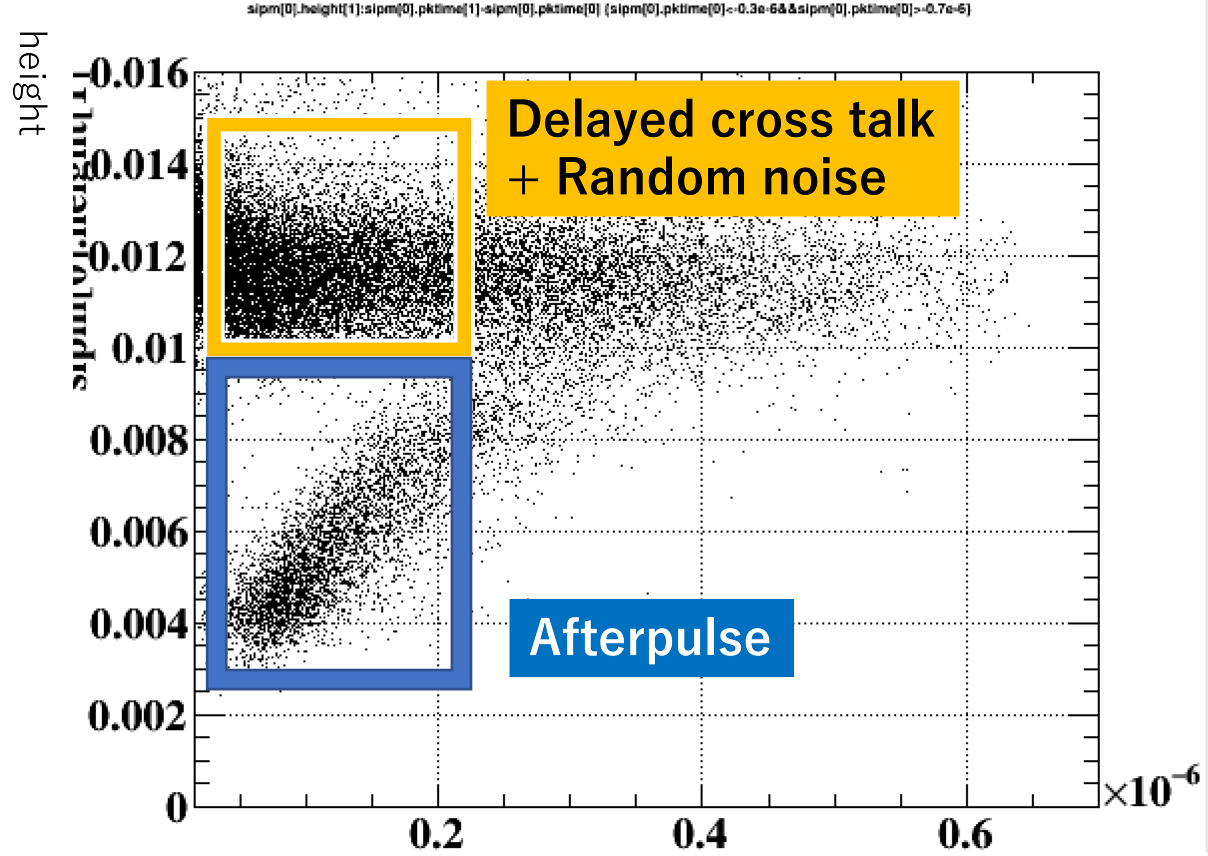
【ref:修士論文 半導体光検出器 PPD の基本特性の解明と, 実践的開発に向けた研究研究 (生出 秀行、平成21年1月8日）】AP 2 comp.

【ref2:Afterpulse and delayed crosstalk analysis on a STMicroelectronics silicon photomultiplier(Ferenc Nagy et al., Nuclear Instruments and Methods in Physics Research A 759 (2014) 44–49)】AP1 comp+DCT 1 comp.

【ref3 : Characterisation studies of silicon photomultipliers(Patrick Eckert et al. Nuclear Instruments and Methods in Physics Research A 620 (2010) 217–226)】AP2 comp.

Measurement Result

2D plot of 2^{nd} pulse distribution



Time difference b/w 1^{st} pulse and 2^{nd} pulse[s]

Model assumption

- ✓ Delayed cross talk occurs at only neighboring pixel
- ✓ Afterpulse occurs at only the same pixel
- ✓ Only 1 delayed cross talk & afterpulse can occur from 1 avalanche
- ✓ The time distribution of 2^{nd} pulse obeys to:

$$\frac{1}{\tau_{DCT}} e^{-\frac{t}{\tau_{DCT}}} \text{ or } \frac{1}{\tau_{AP}} e^{-\frac{t}{\tau_{AP}}}$$

Model case	Delayed Cross Talk	After-pulse
a	○ p_{DCT}	× $(1-p_{AP})$
b	○ p_{DCT}	○ p_{AP}
c	× $(1-p_{DCT})$	○ p_{AP}
d	× $(1-p_{DCT})$	× $(1-p_{AP})$

Model and Fitting

$$P_1\left(p_{DCT},p_{AP},\tau_{AP},\tau_{DCT}\right) = P_{1a}+P_{1b}+P_{1c}+P_{1d}$$
$$P_2\left(p_{DCT},p_{AP},\tau_{AP},\tau_{DCT}\right) = P_{2b}+P_{2c}$$

Fitting function is

$$N_1\left(p_{DCT},p_{AP},\tau_{AP},\tau_{DCT}\right) = N_{trigger\ window} Bin_{width} P_1 / I_{dead\ time\ cor.}$$
$$N_2\left(p_{DCT},p_{AP},\tau_{AP},\tau_{DCT}\right) = N_{trigger\ window} Bin_{width} P_2 / I_{dead\ time\ cor.}$$

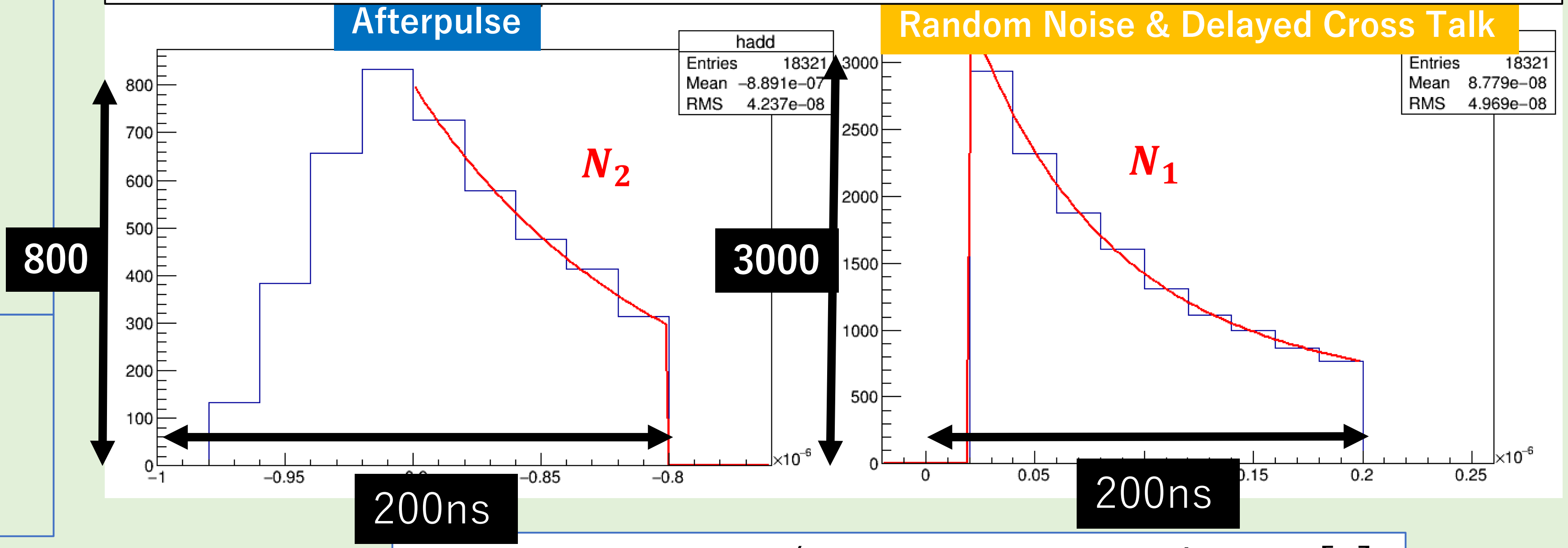
At this model we can get 4 parameters(**common** to P_1 & P_2) only by fitting.

	p_{DCT}	p_{AP}	τ_{DCT}	τ_{AP}
Average	22.3%	31.6%	78.5ns	107ns
Individual difference	±1.2%	±0.6%	±4.7ns	±12ns
Error of each fitting	~3%	~3%	~5%	~10%

$$P_1\left(p_{DCT},p_{AP},\tau_{AP},\tau_{DCT}\right)$$
$$= p_{DCT}(1-p_{AP})\frac{\tau_{DCT}+\tau_{RN}}{\tau_{DCT}\tau_{RN}} e^{-\frac{\tau_{DCT}+\tau_{RN}}{\tau_{DCT}\tau_{RN}}t}$$
$$+p_{DCT}p_{AP}\frac{\tau_{RN}+\tau_{DCT}}{\tau_{DCT}\tau_{RN}} e^{-\frac{\tau_{DCT}\tau_{RN}+\tau_{RN}\tau_{AP}+\tau_{AP}\tau_{DCT}}{\tau_{DCT}\tau_{AP}\tau_{RN}}t}$$
$$+p_{AP}(1-p_{DCT})\left(\frac{1}{\tau_{RN}} e^{-\frac{t}{\tau_{RN}}} e^{-\frac{t}{\tau_{AP}}}\right)$$
$$+(1-p_{AP})(1-p_{DCT})\frac{1}{\tau_{RN}} e^{-\frac{t}{\tau_{RN}}}$$
$$= P_{1a}+P_{1b}+P_{1c}+P_{1d}$$

$$P_2\left(p_{DCT},p_{AP},\tau_{AP},\tau_{DCT}\right)$$
$$= p_{DCT}\, p_{AP}\frac{1}{\tau_{AP}} e^{-\frac{\tau_{DCT}\tau_{RN}+\tau_{RN}\tau_{AP}+\tau_{AP}\tau_{DCT}}{\tau_{DCT}\tau_{AP}\tau_{RN}}t}$$
$$+p_{AP}(1-p_{DCT})\frac{1}{\tau_{AP}} e^{-\frac{\tau_{AP}+\tau_{RN}}{\tau_{AP}\tau_{RN}}t}$$
$$= P_{2b}+P_{2c}$$

1D Plot of Time difference



Time difference b/w 1st and 2nd pulse[s]

※-1μs is offset for combined fitting

Waveform Simulation

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Radiation damage

✓**Current increase** by radiation damage @ past pilot run

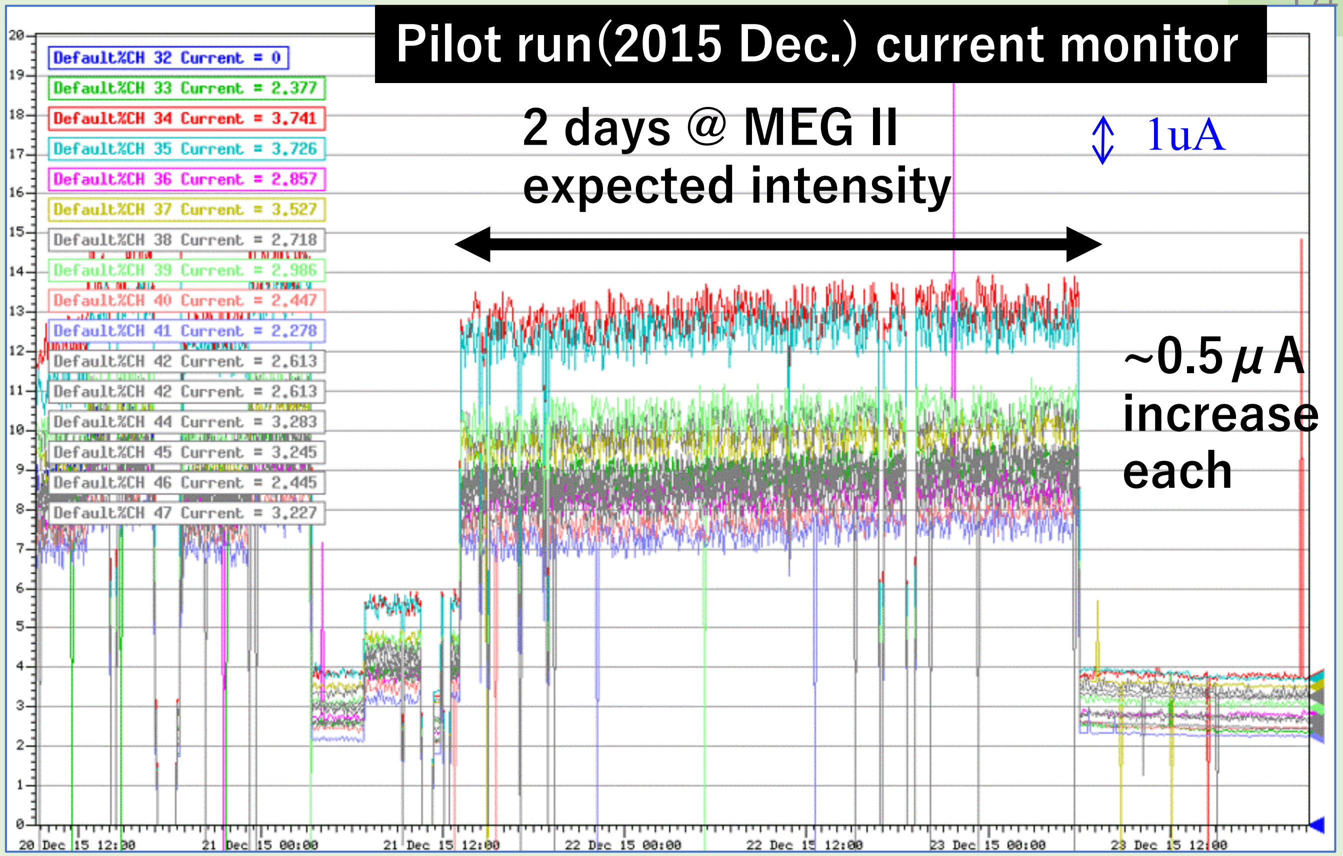
✓**Expected current increase :**

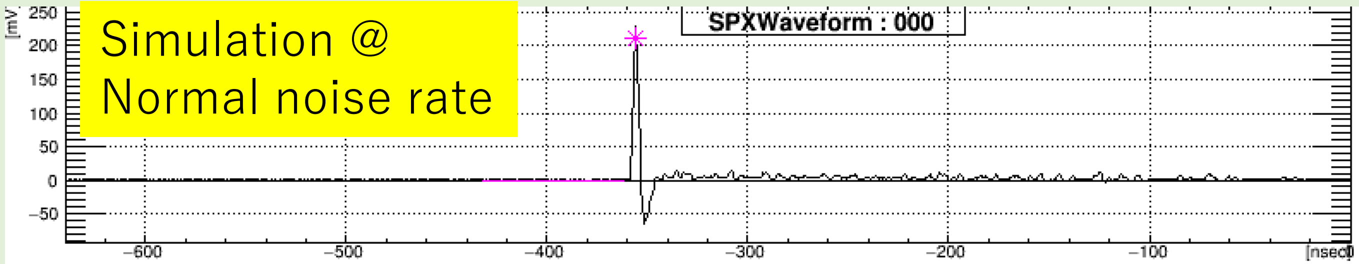
100~200μA

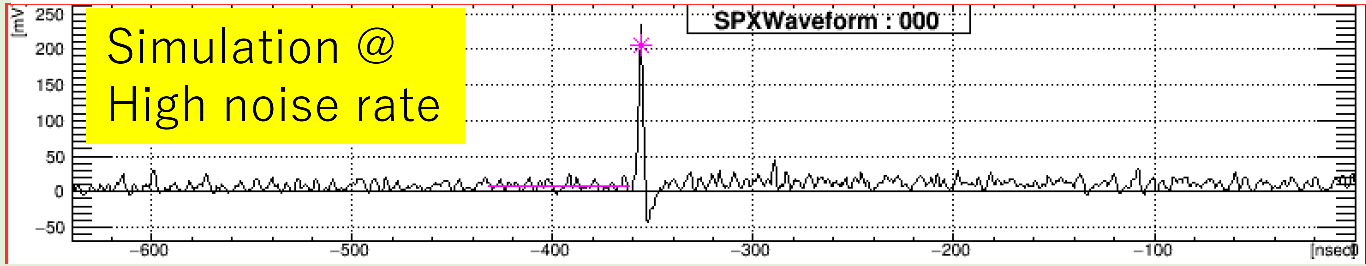
(25week × 3 year physics run)

At this current level, time resolution may be deteriorated

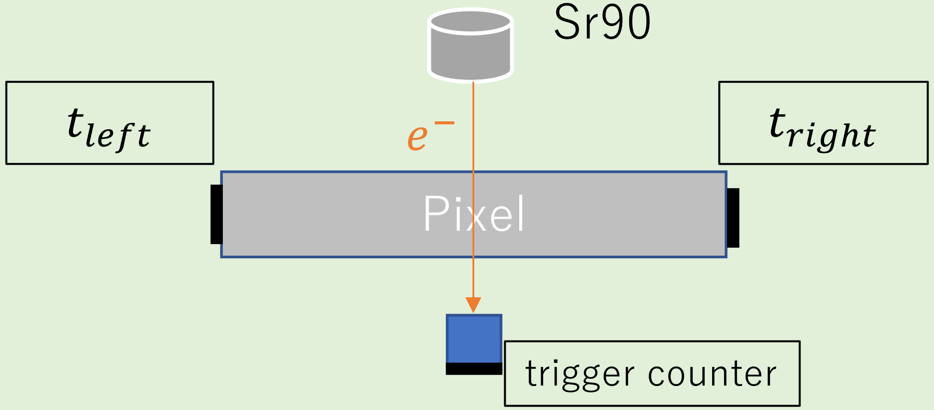
Check the effect from simulation by changing dark count rate







Simulation Result

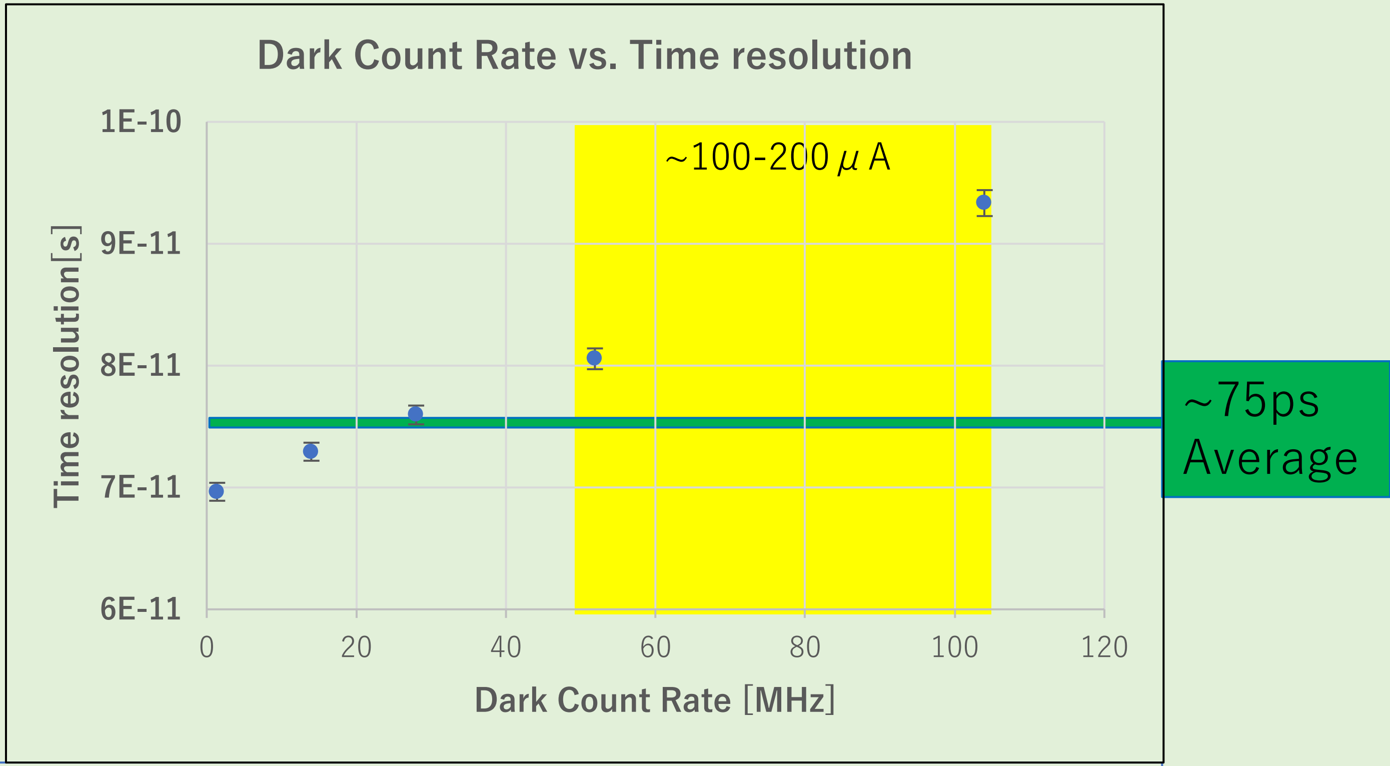


Time resolution is defined as:

$$\sigma\left(\frac{t_{right} + t_{left}}{2}\right)$$

t_{left} & t_{right}

The time when height becomes 20% of peak height



The effect on gain : no significant deterioration

The effect on time resolution : **~16%-34%**

The deterioration level is not so serious : Estimated ~few % for overall sensitivity

But we have to check operation of Timing Counter @ high current level

Summary and prospect

- **<u>Waveform simulation</u>**

For deep understanding on detector, we are developing the simulation scheme

- **<u>Afterpulse measurement for waveform simulation</u>**

Calculation of simple & intuitive afterpulse + delayed cross talk model

Fitting and analysis to get :

Probability of afterpulse(31.6%) & delayed cross talk(22.3%)

Time const of afterpulse(107ns) & delayed cross talk(78.5ns)

Model comparison w/ previous studies & more systematic study will be done

- **<u>Application of waveform simulation</u>**

One example of application :Radiation damage effect on time resolution

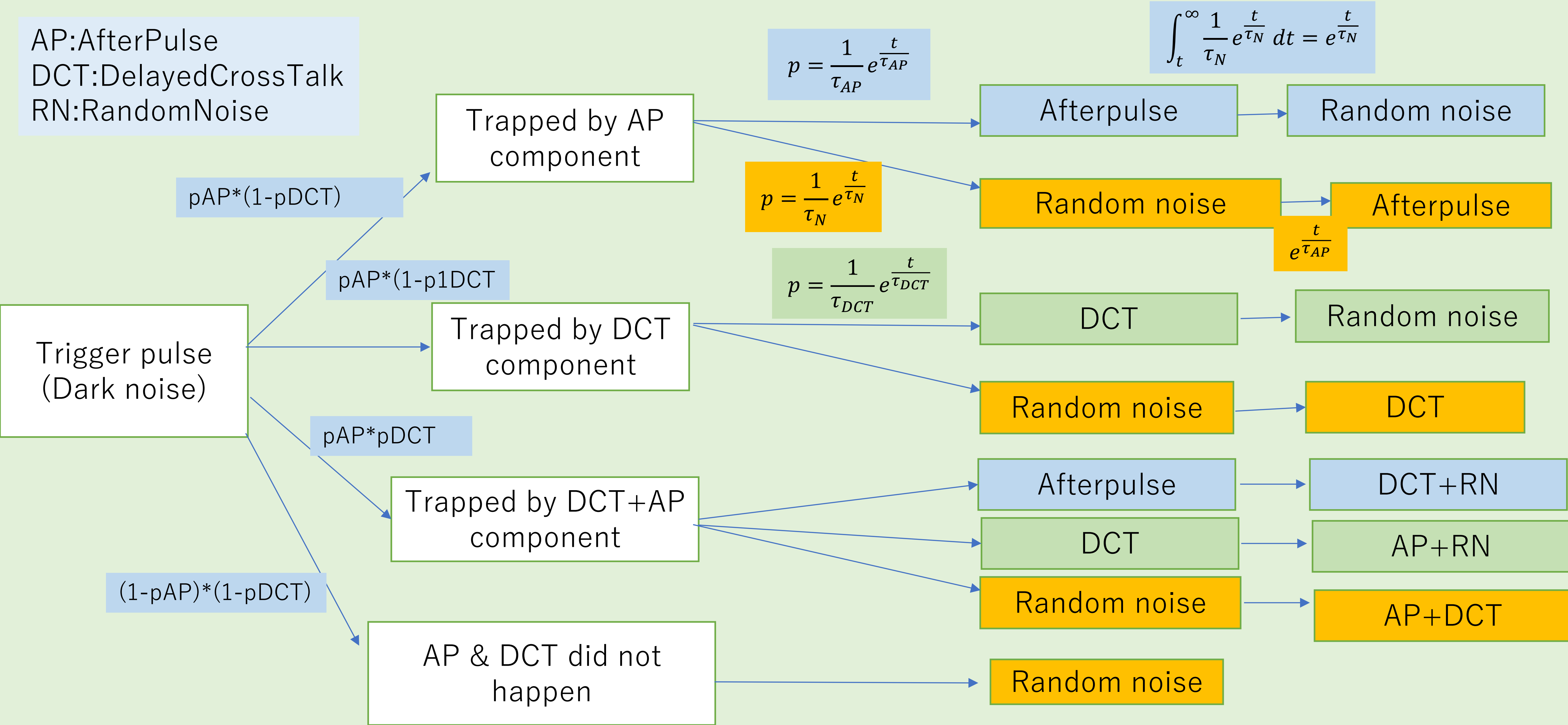
~16-34% deterioration on time resolution

It is not so serious but we **have to check the operation** @ high current level

Back up

AfterPulse + Delayed Cross Talk Model

AP:AfterPulse
DCT:DelayedCrossTalk
RN:RandomNoise



Calculation of fit function –RN + DCT–

RNが先に来て
その後DCTが来る

DCTが先に来る

-1-Detected at DCT+RN region

-1a-Trapped by only DCT component

$$P_{1a} = p_{DCT}(1-p_{AP})\left(\frac{1}{\tau_{DCT}}e^{-\frac{t}{\tau_{DCT}}} \times \int_t^\infty \frac{1}{\tau_{RN}}e^{-\frac{t}{\tau_{RN}}}dt + \frac{1}{\tau_{RN}}e^{-\frac{t}{\tau_{RN}}}\int_t^\infty \frac{1}{\tau_{DCT}}e^{-\frac{t}{\tau_{DCT}}}dt\right)$$

$$= p_{DCT}(1-p_{AP})\frac{\tau_{DCT}+\tau_{RN}}{\tau_{DCT}\tau_{RN}}e^{-\frac{\tau_{DCT}+\tau_{RN}}{\tau_{DCT}\tau_{RN}}t}$$

-1b-Trapped by AP and DCT component

$$P_{1b} = p_{DCT}p_{AP}\left(\frac{1}{\tau_{DCT}}e^{-\frac{t}{\tau_{DCT}}} \times \int_t^\infty \frac{1}{\tau_{RN}}e^{-\frac{t}{\tau_{RN}}}dt\int_t^\infty \frac{1}{\tau_{AP}}e^{-\frac{t}{\tau_{AP}}}dt + \frac{1}{\tau_{RN}}e^{-\frac{t}{\tau_{RN}}}\int_t^\infty \frac{1}{\tau_{DCT}}e^{-\frac{t}{\tau_{DCT}}}dt\int_t^\infty \frac{1}{\tau_{AP}}e^{-\frac{t}{\tau_{AP}}}dt\right)$$

$$= \frac{\tau_{RN}+\tau_{DCT}}{\tau_{DCT}\tau_{RN}}e^{-\frac{\tau_{DCT}\tau_{RN}+\tau_{RN}\tau_{AP}+\tau_{AP}\tau_{DCT}}{\tau_{DCT}\tau_{AP}\tau_{RN}}t}$$

-1c-Trapped by AP component (and RN is detected)

$$P_{1c} = p_{AP}(1-p_{DCT})\left(\frac{1}{\tau_{RN}}e^{-\frac{t}{\tau_{RN}}} \times \int_t^\infty \frac{1}{\tau_{AP}}e^{-\frac{t}{\tau_{AP}}}dt\right) = p_{AP}(1-p_{DCT})\left(\frac{1}{\tau_{RN}}e^{-\frac{t}{\tau_{RN}}}e^{-\frac{t}{\tau_{AP}}}\right)$$

-1d-No trap

$$P_{1d} = (1-p_{AP})(1-p_{DCT})\frac{1}{\tau_{RN}}e^{-\frac{t}{\tau_{RN}}}$$

Calculation of Fit Func. -AP-

-2- Detected in AP region

-1b-Trapped by AP and DCT component

$$P_{2b} = p_{DCT} p_{AP} \left(\frac{1}{\tau_{AP}} e^{-\frac{t}{\tau_{AP}}} \times \int_t^\infty \frac{1}{\tau_{RN}} e^{-\frac{t}{\tau_{RN}}} dt \int_t^\infty \frac{1}{\tau_{DCT}} e^{-\frac{t}{\tau_{DCT}}} dt \right)$$
$$= p_{DCT} p_{AP} \frac{1}{\tau_{AP}} e^{-\frac{\tau_{DCT}\tau_{RN}+\tau_{RN}\tau_{AP}+\tau_{AP}\tau_{DCT}}{\tau_{DCT}\tau_{AP}\tau_{RN}} t}$$

-1c-Trapped by AP component

$$P_{2c} = p_{AP}(1-p_{DCT}) \left(\frac{1}{\tau_{AP}} e^{-\frac{t}{\tau_{AP}}} \times \int_t^\infty \frac{1}{\tau_{RN}} e^{-\frac{t}{\tau_{RN}}} dt \right)$$
$$= p_{AP}(1-p_{DCT}) \frac{1}{\tau_{AP}} e^{-\frac{\tau_{AP}+\tau_{RN}}{\tau_{AP}\tau_{RN}} t}$$

case	DCT	AP
a	trap	-
b	trap	trap
c	-	trap
d	-	-

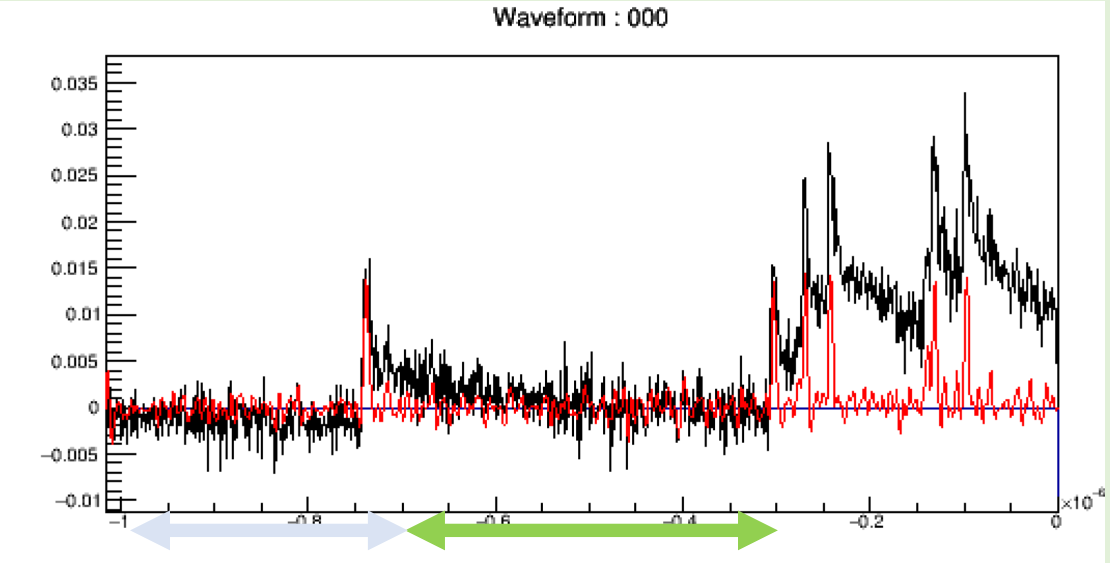
So, Fit Func. is

$$\boldsymbol{P_1 (p_{DCT}, p_{AP}, \tau_{AP}, \tau_{DCT}) = P_{1a} + P_{1b} + P_{1c} + P_{1d}}$$
$$\boldsymbol{P_2 (p_{DCT}, p_{AP}, \tau_{AP}, \tau_{DCT}) = P_{2b} + P_{2c}}$$

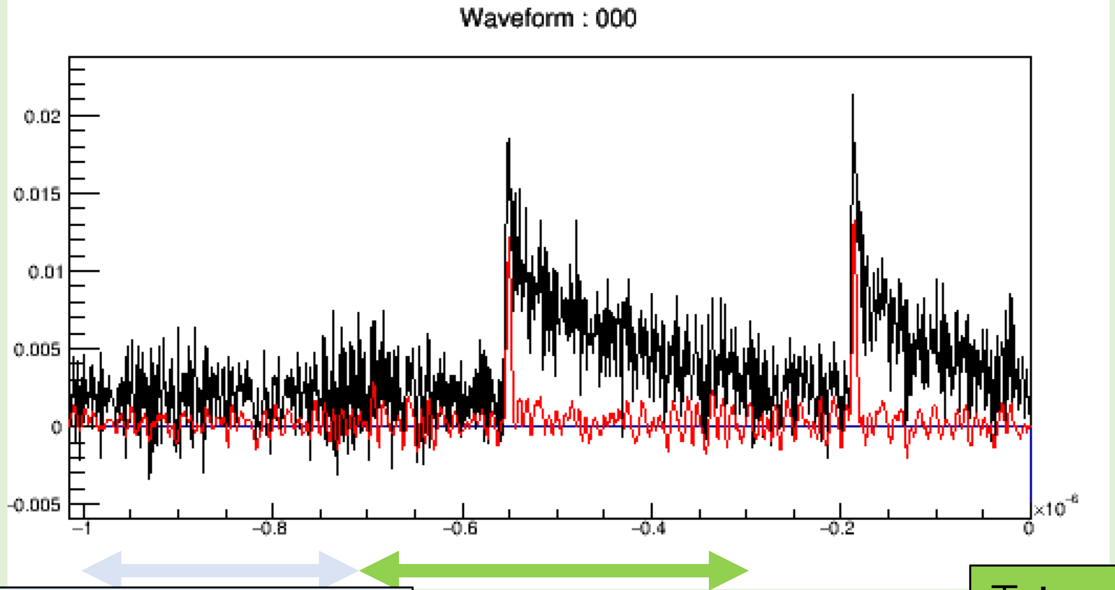
Analysis

パルス高が畳み込みの後で分解能が落ちる可能性あり

Deconvolutionのパルス幅や移動平均点数、パルス高については要調査・調整



First pulse is in VETO
->not used



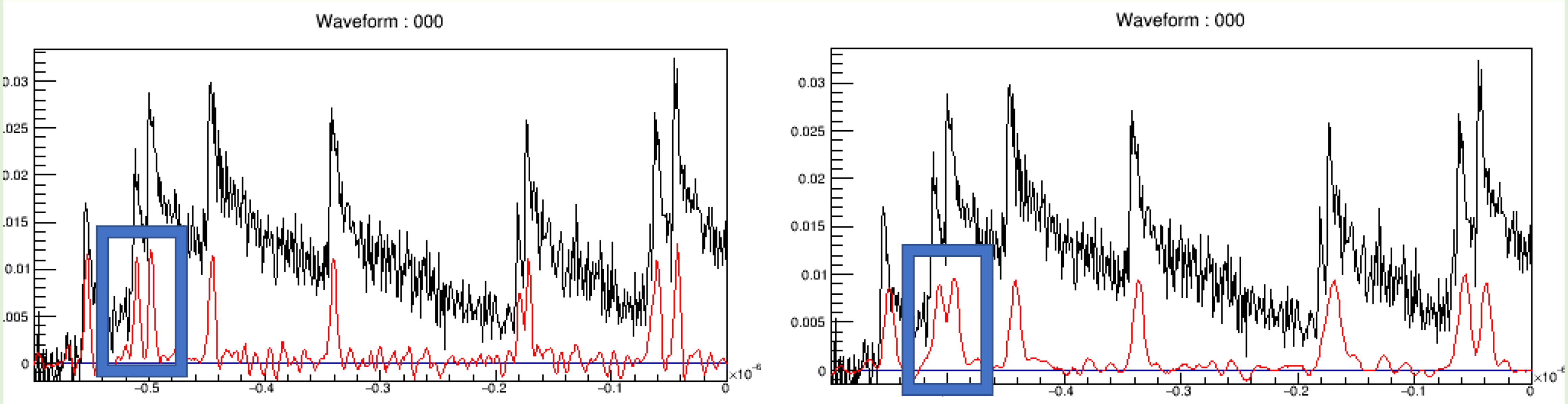
First pulse is in trigger region
->used

VETO region(300ns)
If 1st pulse comes to this region,
we do not use that event for analysis
to get primary random noise

Trigger region(400ns)
If 1st pulse comes in this region,
it is efficient event and search for
2nd pulse after 1st pulse

発表後追記

Example of Deconvolution



bad resolution

pulse widthが細すぎる：エレキのノイズを拾う可能性がある
pulse widthが太すぎる：dark noiseを分離できない

Pulse width should be optimized to distingush the pulse properly
Parameter optimization & improvement will be studied.

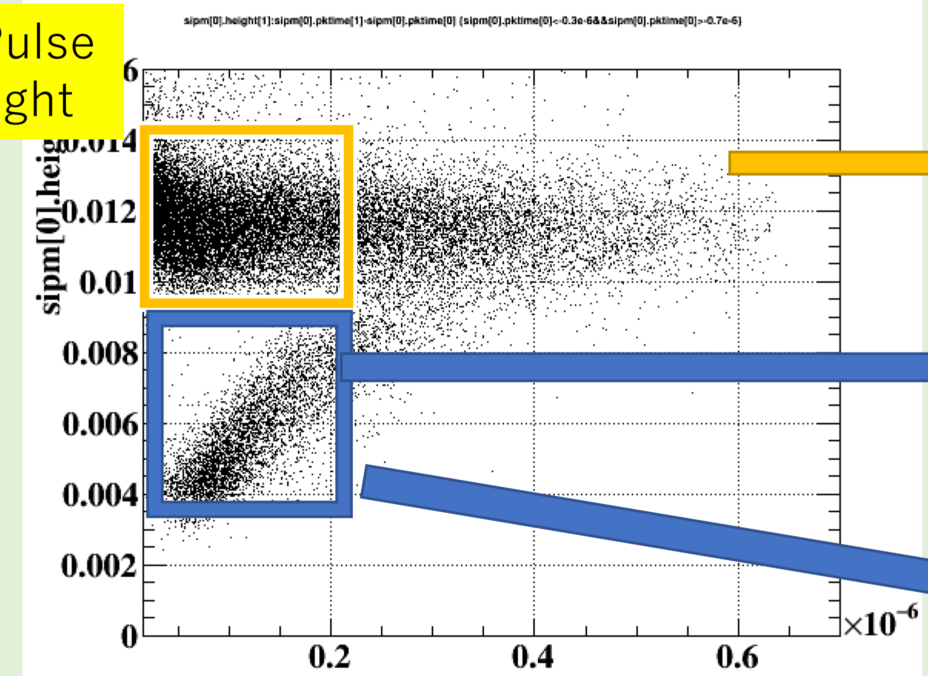
発表後追記

Delayed Cross Talk and Afterpulse

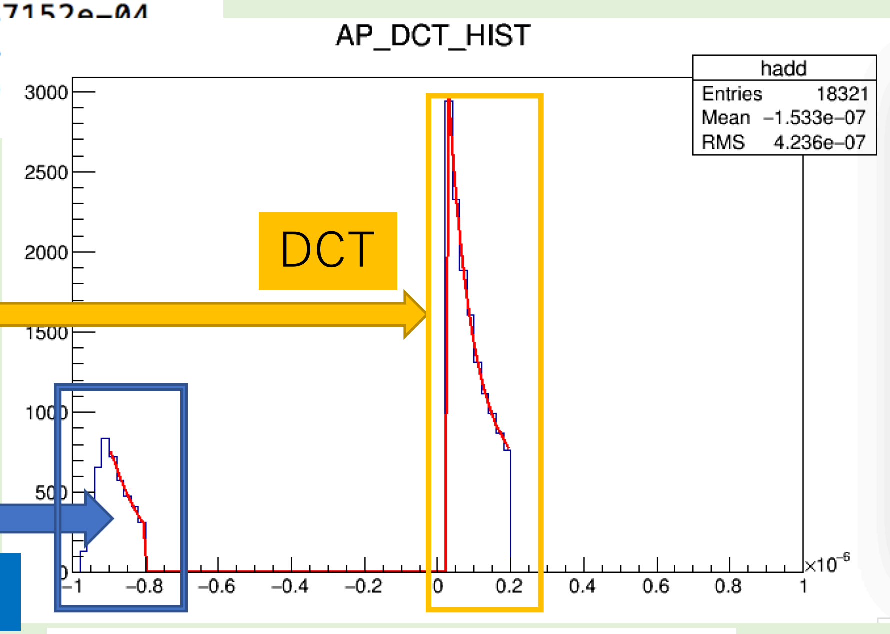
NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	Prob_DCT	2.18888e-01	5.07251e-03	5.36147e-06	-4.44711e-04
2	Prob_AP	3.07108e-01	5.50071e-03	6.57516e-06	2.47152e-04
3	TimeConst_DCT	7.44914e-08	3.16120e-09	3.24969e-12	-
4	TimeConst_AP	1.24313e-07	1.10581e-08	1.31117e-11	-9

ERR DEF= 0.5

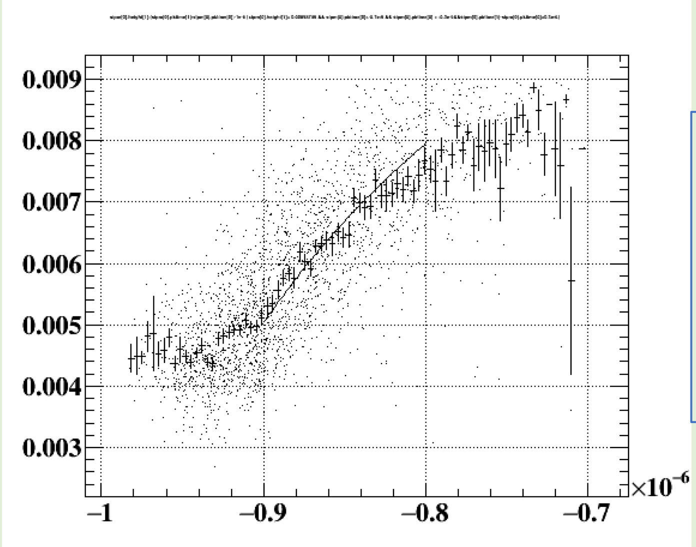
y:Pulse height



Time difference b/w 1st pulse and 2nd pulse[s]



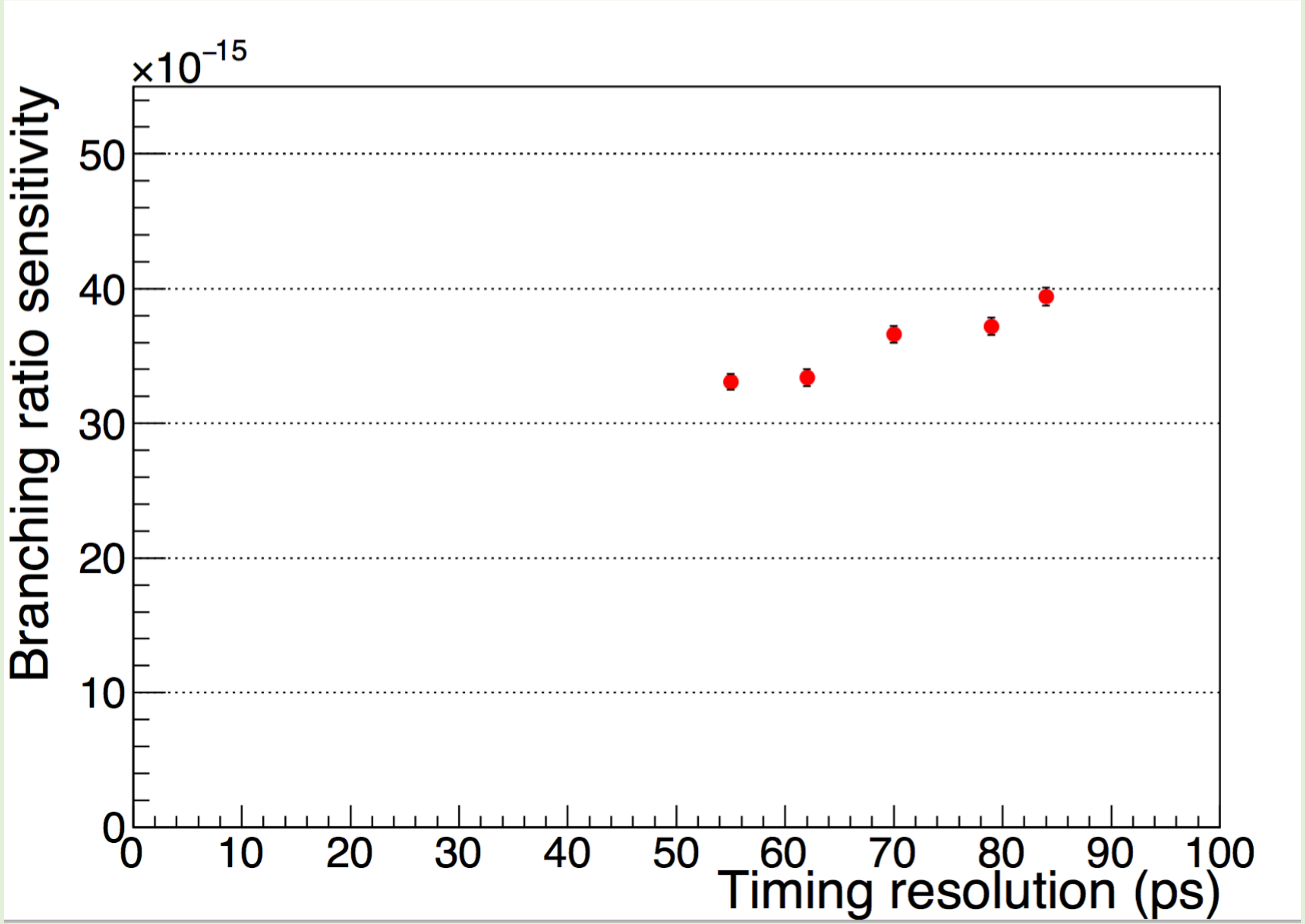
By fitting, we got the parameters for simulation
- AP prob.
- AP time const
- DCT prob.
- DCT time const



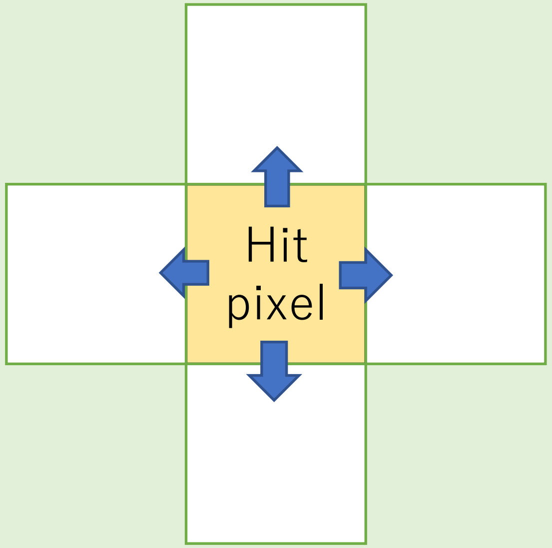
Also by using the 2D histgram AP region, we can get
- recovery time

the result was : **185** ± 2ns

MEG II Sensitivity vs. Tegamma



Algorithms of simulation



After pulse and DCT time difference is reproduced by MC method :

$$\xi = \int_0^t \frac{1}{\tau_{DCT}} e^{-\frac{t}{\tau_{DCT}}}\, dt = 1 - e^{-\frac{t}{\tau_{DCT}}}$$

-> $t = -\tau_{DCT} \ln(1-\xi)$

where $0 < \xi < 1$ (random number)

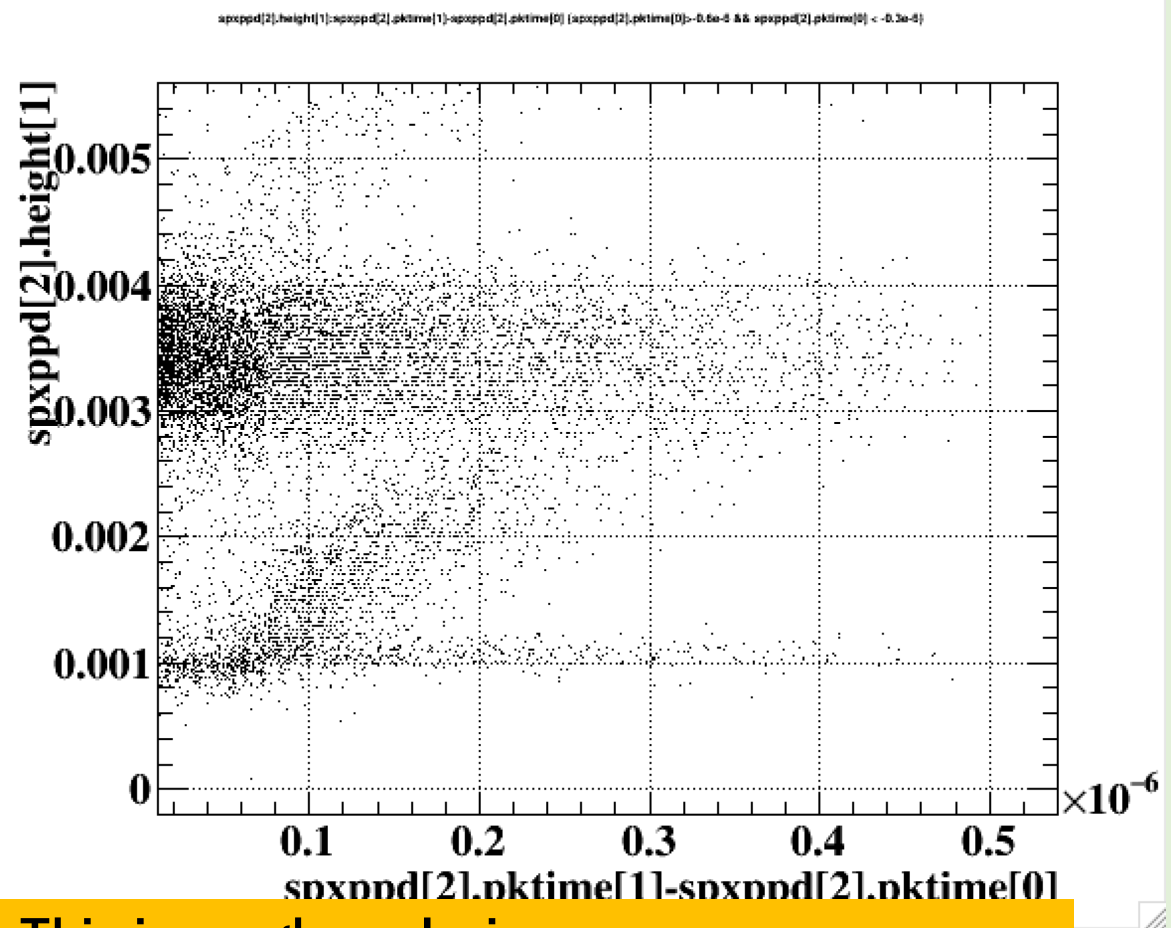
<u>DCT algorithm</u>

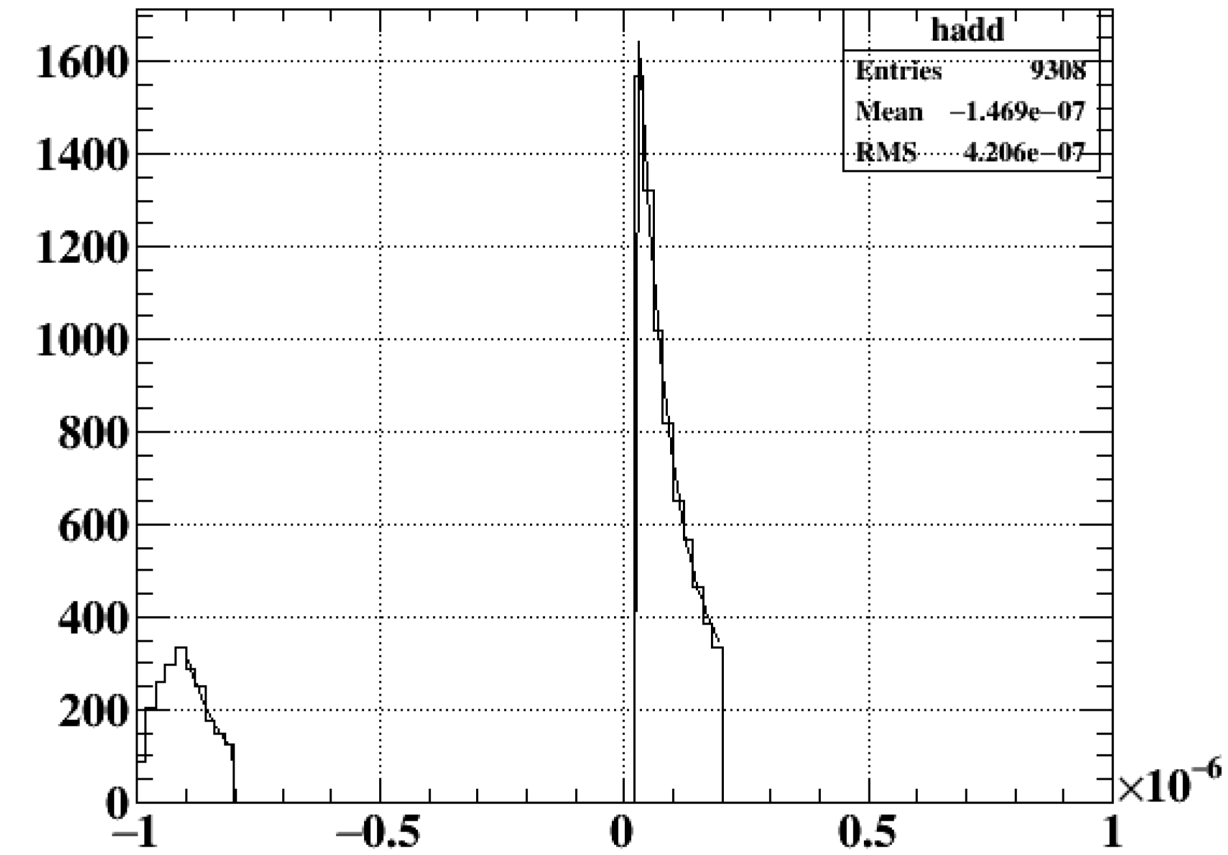
DCT occurs at only neighboring pixel

The time difference (t) b/w first pulse and second pulse obeys $\sim \frac{1}{\tau_{DCT}} e^{\frac{t}{\tau_{DCT}}}$

Reconstruction from simulation

Input:
AP prob. 30%
DCT prob. 26%
AP time const. 110ns
DCT time const. 84ns
recovery time. 185 ns



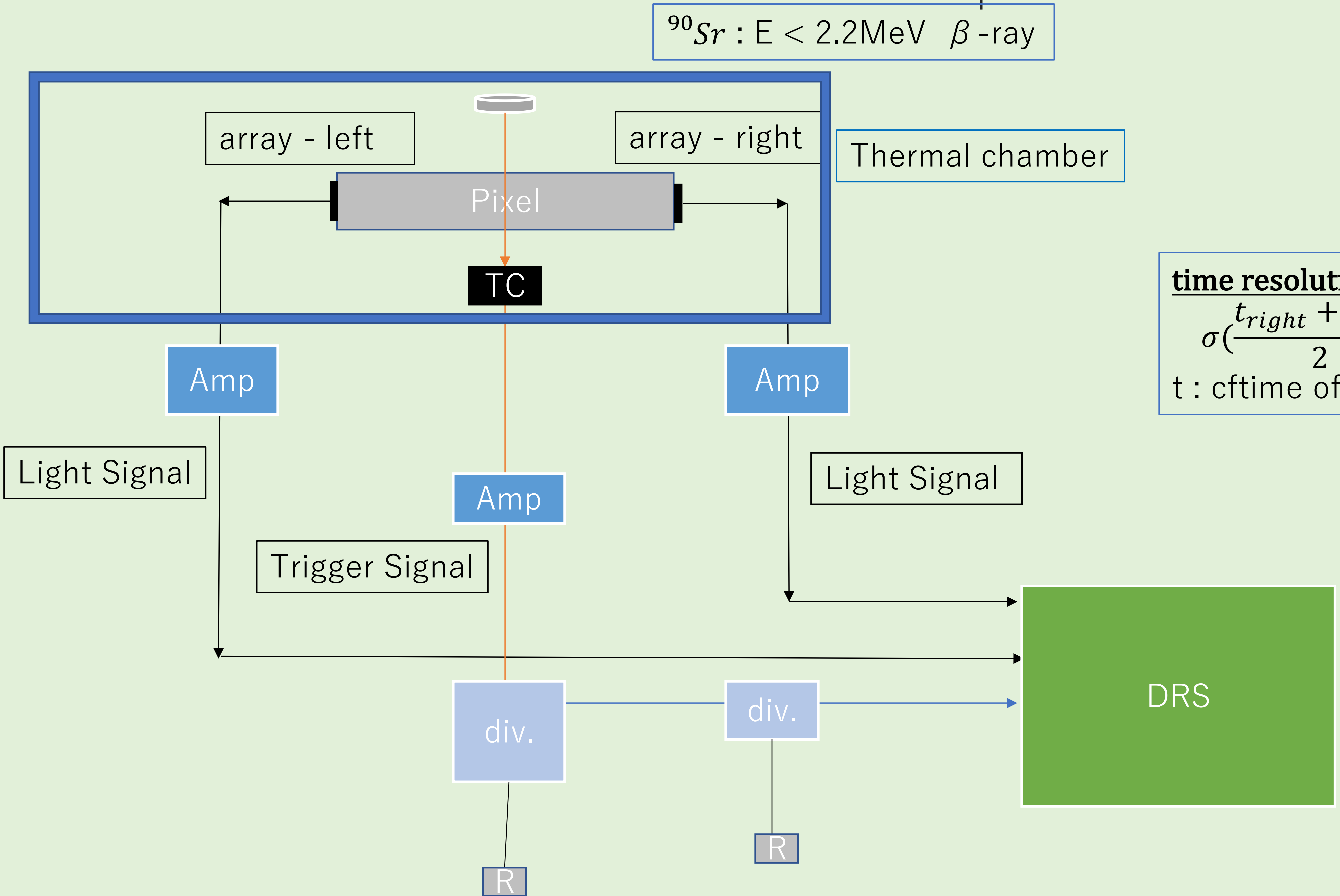


NO.	NAME	VALUE	ERROR	SIZE	DERIVATIVE
1	Prob_DCT	3.24031e-01	7.84217e-03	1.14880e-05	1.88715e-03
2	Prob_AP	2.84324e-01	8.72343e-03	1.31057e-05	-2.67125e-03
3	TimeConst_DCT	8.06186e-08	3.43598e-09	4.92327e-12	1.55593e+04
4	TimeConst_AP	1.15248e-07	1.49950e-08	2.22373e-11	-4.21476e+03

ERR DEF= 0.5

<u>This is rough analysis</u>
We could not set 1 μ s window,
so analysis was not the same to measurement
Parameter is not optimized yet

Time resolution measurement set up



time resolution

$$\sigma\left(\frac{t_{right} + t_{left}}{2} - t_{ref}\right)$$

t : cftime of each channel

参考論文について（Model & Measurement）

P9-12で参考にしたafterpulseやdelayed cross talk のモデル。今後これらのモデルとの比較も検討中。

- 修士論文 半導体光検出器 PPD の基本特性の解明と, 実践的開発に向けた研究 (生出 秀行、平成21年1月8日)(http://www.icepp.s.u-tokyo.ac.jp/yamashita/archives/oide/oide_mthesis.pdf)

Afterpulse 2成分でのモデルを組み立てたもの。Fittingから確率を求めるモデルの組み立て方、ランダムノイズの切り分け、測定におけるDeconvolutionの手法等を参考にした。Recovery timeを考慮していない。

- Afterpulse and delayed crosstalk analysis on a STMicroelectronics silicon photomultiplier (Ferenc Nagy et al., Nuclear Instruments and Methods in Physics Research A 759 (2014) 44–49)

(http://www.sciencedirect.com/science/article/pii/S0168900214004501)

Delayed Cross Talk 1成分、Afterpulse1成分のモデル。Delayed Cross Talk 現象についての記述や、時間差が指数関数に従うこと等を参考にした。

- Characterisation studies of silicon photomultipliers(Patrick Eckert et al. Nuclear Instruments and Methods in Physics Research A 620 (2010) 217–226)

(http://www.sciencedirect.com/science/article/pii/S0168900210008156)

Afterpulse2成分の比較的シンプルなモデル。積分から確率を求める。

その他引用など

- P8Model of SiPMの引用

(hep-www.px.tsukuba.ac.jp/~hontaku/MPPCSchool/slides/MPPCshibata.pptx)

23Pの図を引用、基盤部を厚くし、クロストークの発生機構を省略し、Delayed Cross Talk,Afterpulseの発生機構を追加するなどの一部追記

- P8のステータス

2015年秋季大会(https://meg.web.psi.ch/docs/talks/JPS/2015a/yoshida_jps2015a.pptx)

第71回年次大会(https://meg.web.psi.ch/docs/talks/JPS/2016s/yoshida_jps2016s.pdf)

K. Yoshida “MEG II 実験のための SiPM を用いた陽電子タイミングカウンターのシミュレーションによる性能評価”で報告

- P5の写真

1 pixel counterとPCBの写真は2015年秋季大会のスライドより引用