TXePET

T.Tauchi, KEK, October 2006

General Property of Liquid Xenon

http://www.pd.infn.it/~conti/LXe.html

Rich detection media : Scintillation and Ionization

Scintillation	Ionization
energy	position
photomultipliers	ionization chamber with low noise amp. 300e
GEM/photocathod	GEM in 2 phase Xe
Avalanche Photodiodes	

22,000 VUV photons/511KeV with 3ns, 27ns and 45ns

30,000 electron-ion pairs/511KeV
electron drift at 2.3mm/us with 2kV/cm

At 511 keV, 22% photoelectric, 78% Compton with xenon
half a mm for 511 keV photoelectron

Primary ionization signal is weak: of the order of 1, 10, 100 and 500 keV for coherent neutrino, dark matter, solar neutrino and PET respectively.

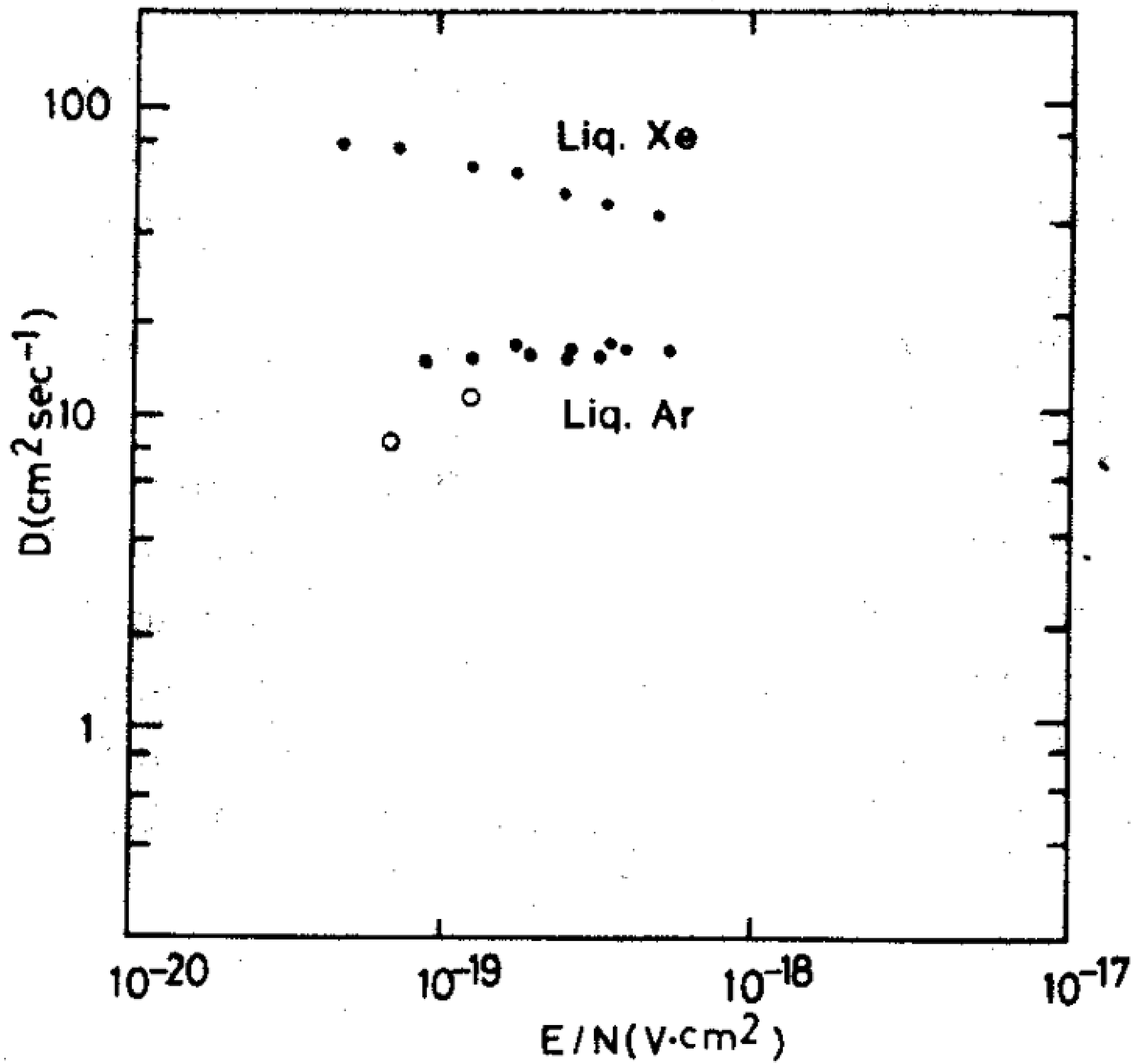

Fig. 1. Diffusion coefficients of electrons in liquid xenon and argon versus the density-normalized electric field. The full circles represent the authors' results and the open circles the results obtained by Derenzo [LBL, Group A Physics Note No. 786 (1974) unpublished]. T.Doke, NIM 196 (1982), 87

diffusion :

widening pulse shape

$$\sigma^2 = 2Dt = 2DL/v$$

$$C_D{}^2 = D/v$$

Example:
$t = 104\mu sec$
$D = 50 cm^2/sec$
$C_D = 145\mu m/SQRT(cm)$
$\sigma = 1mm$
note : $170\mu m/SQRT(cm)$

spatial resolution

$$\sigma_x = \sqrt{\sigma_x(0)^2 + C_D{}^2/N_{eff}Z}$$

N_{eff}=no. of electrons
if $N_{eff}=1000$ and $z=24cm$,
$C_D{}^2/N_{eff}Z = (20\mu m)^2$
with pad-analog readout

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North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Measurement of attenuation length of drifting electrons in liquid xenon

Masayuki Ichige [a], Elena Aprile [b], Tadayoshi Doke [a], Katsuhito Hasuike [a], Ken Itoh [a], Jun Kikuchi [a] and Kimiaki Masuda [c]

[a] *Science and Engineering Research Laboratory, Waseda University, 17 Kikui-cho, Shinjuku-ku, Tokyo 162, Japan*
[b] *Physics Department, Columbia University, New York, NY 10027, USA*
[c] *Saitama College of Health, 519 Kamiokubo, Urawa-shi, Saitama 338, Japan*

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To realize a long attenuation length of drifting electrons in liquid xenon, a purification system which consists of Oxisorb, molecular sieves and a Zr–V–Fe alloy getter has been constructed. A dual type gridded ionization chamber is used for the measurement of the attenuation length. An attenuation length longer than 2 m is achieved in the purified liquid xenon.

attenuation length > 2m !, –11% at 24cm drift

TXePET :分割の無い液体キセノンTPC

液体Xe：140ℓ,88cm内径,48cm FOV,9cm DOI (93%γ線検出)

光電子増倍管: 8x112x2=1792本

位置分解能(FWHM) = 2cm

同時計測時間 = 10 nsec

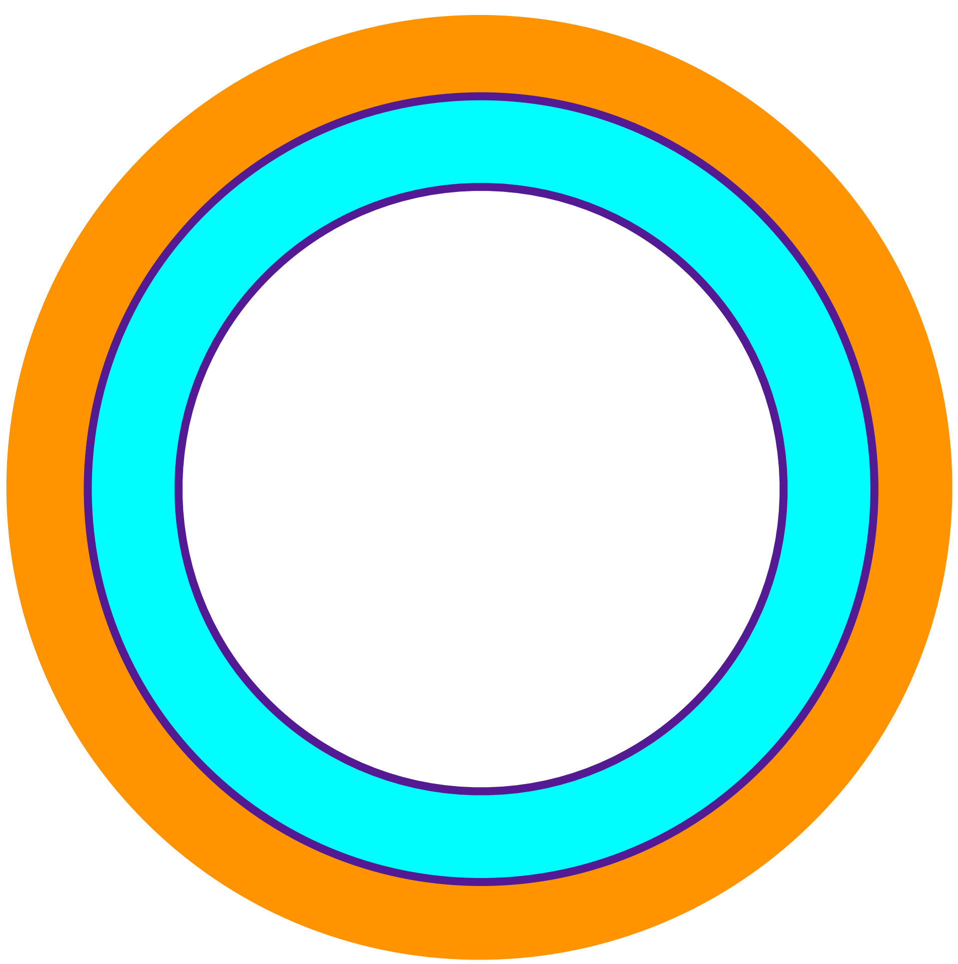
TPCへのタイムスタンプ

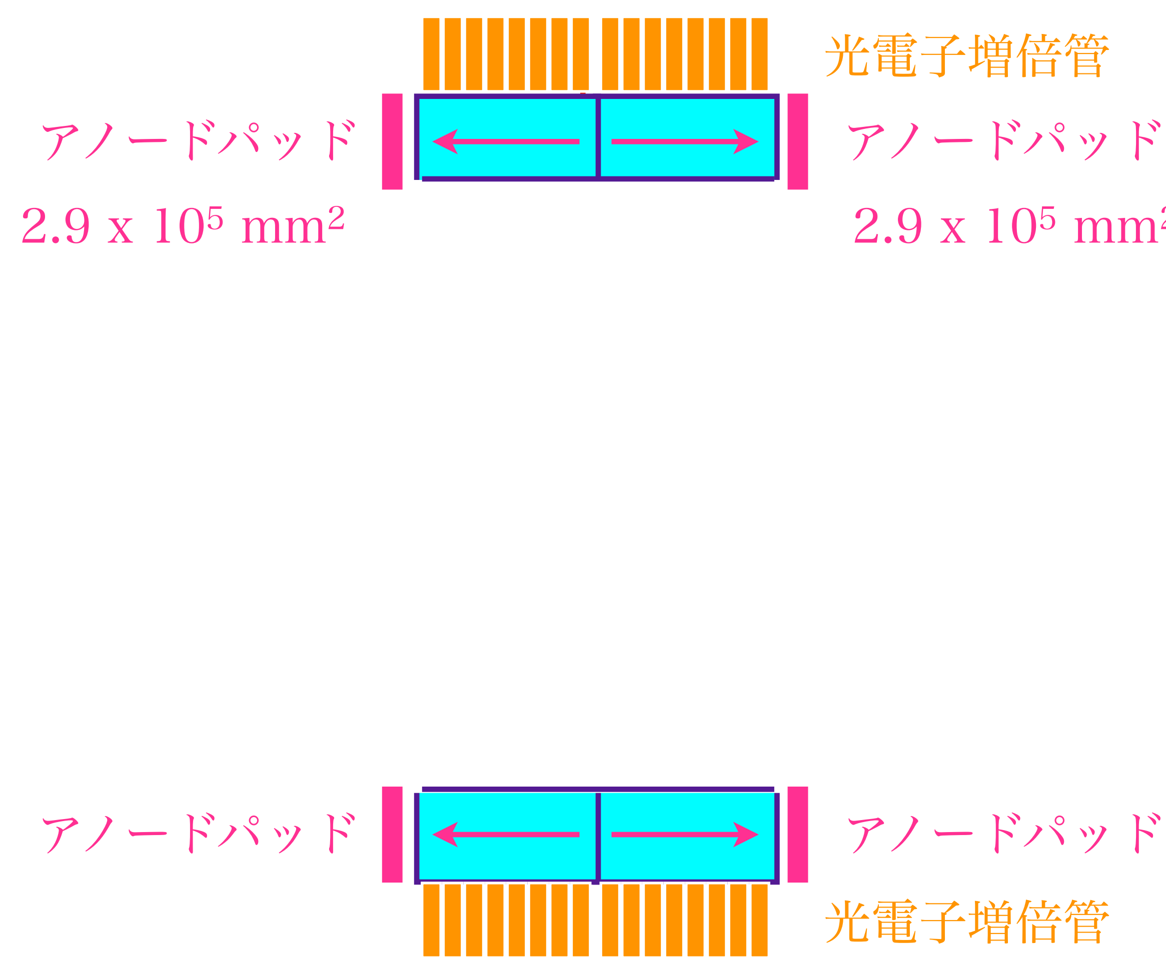
TPC：電場 48kV/24cm

ドリフト時間：104 μsec/±24cm

(ドリフト速度：2.3mm/μsec)

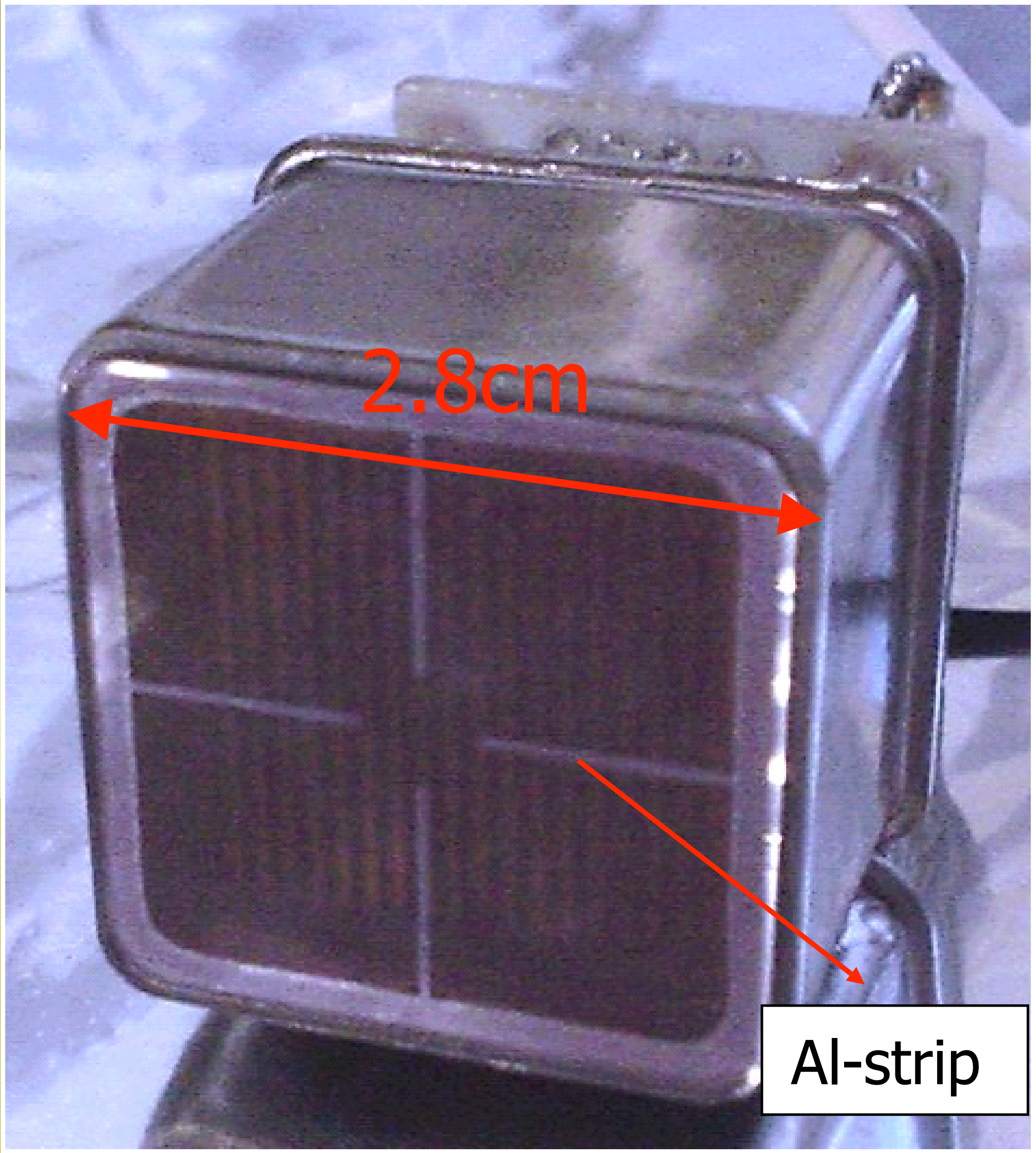
不感時間のない読み出し





LXeTOF PET, F. Nishikido

液体キセノン用 1” 光電子増倍管



R5900-06AL12S-ASSY

- 石英ウィンドウを用いることにより**Xe**波長に対しても十分な感度を得られる。
- 液体キセノン温度（**-110**℃）、3atmでも動作可能である。
- 光電面に**K-Cs-Sb**＋**Al**ストリップを用いることにより低温中でも高い量子効率を得ている（＞**20%**）。
- 高いゲイン（**>10^6**@800**V**）を持つ
- 表面不純物の発生が少ない。
- メタルチャンネル型ダイノードを採用

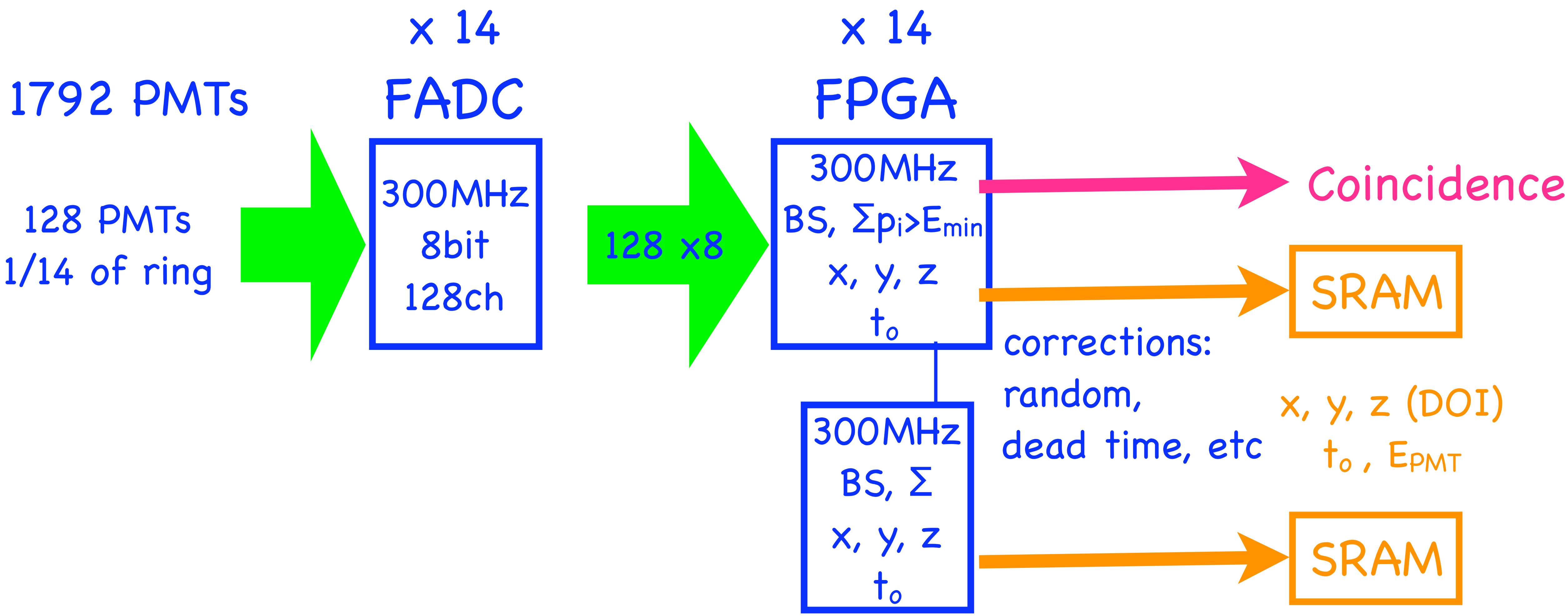
Quantum efficiency measured at room temperature	**21.6± 1.5%**
Gain (HV = 800V)	**$>10^6$**
Number of dynodes	**12 stages**
Material of photocathode	**K-Cs-Sb**
Size of photocathode	**18x18 mm^2**
Material of window	**Quartz**

MEG experiment

2” PMT Development Summary

1st generation R6041Q	2nd generation R9288TB	3rd generation R9869
		
228 in the LP (2003 CEX and TERAS) 127 in the LP (2004 CEX)	111 In the LP (2004 CEX)	Not used yet in the LP
Rb-Sc-Sb Mn layer to keep surface resistance at low temp.	K-Sc-Sb Al strip to fit with the dynode pattern to keep surface resistance at low temp.	K-Sc-Sb Al strip density is doubled. 4% loss of the effective area.
1st compact version QE~4-6% Under high rate background, PMT output reduced by 10 -20% with a time constant of order of 10min.	Higher QE ~12-14% Good performance in high rate BG Still slight reduction of output in very high BG	Higher QE~12-14% Much better performance in very high BG

PMT Readout



$x_{PMT} = \Sigma x_i p_i / \Sigma p_i$

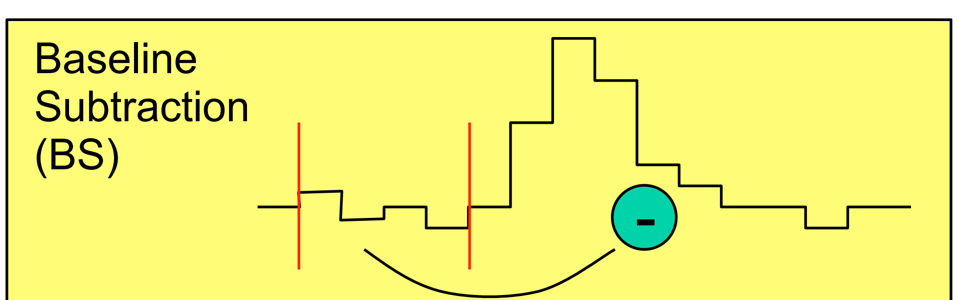
$y_{PMT} = \Sigma y_i p_i / \Sigma p_i$

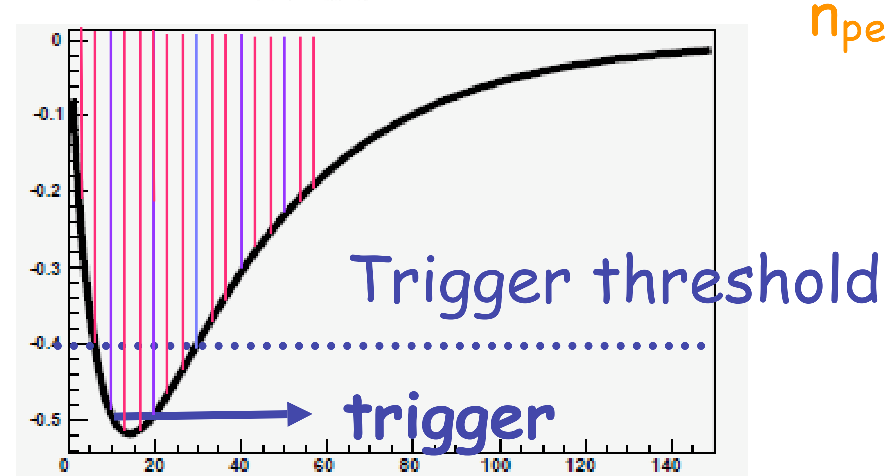
$z_{PMT} = Z(D)$

$n_{pe} = p_i$

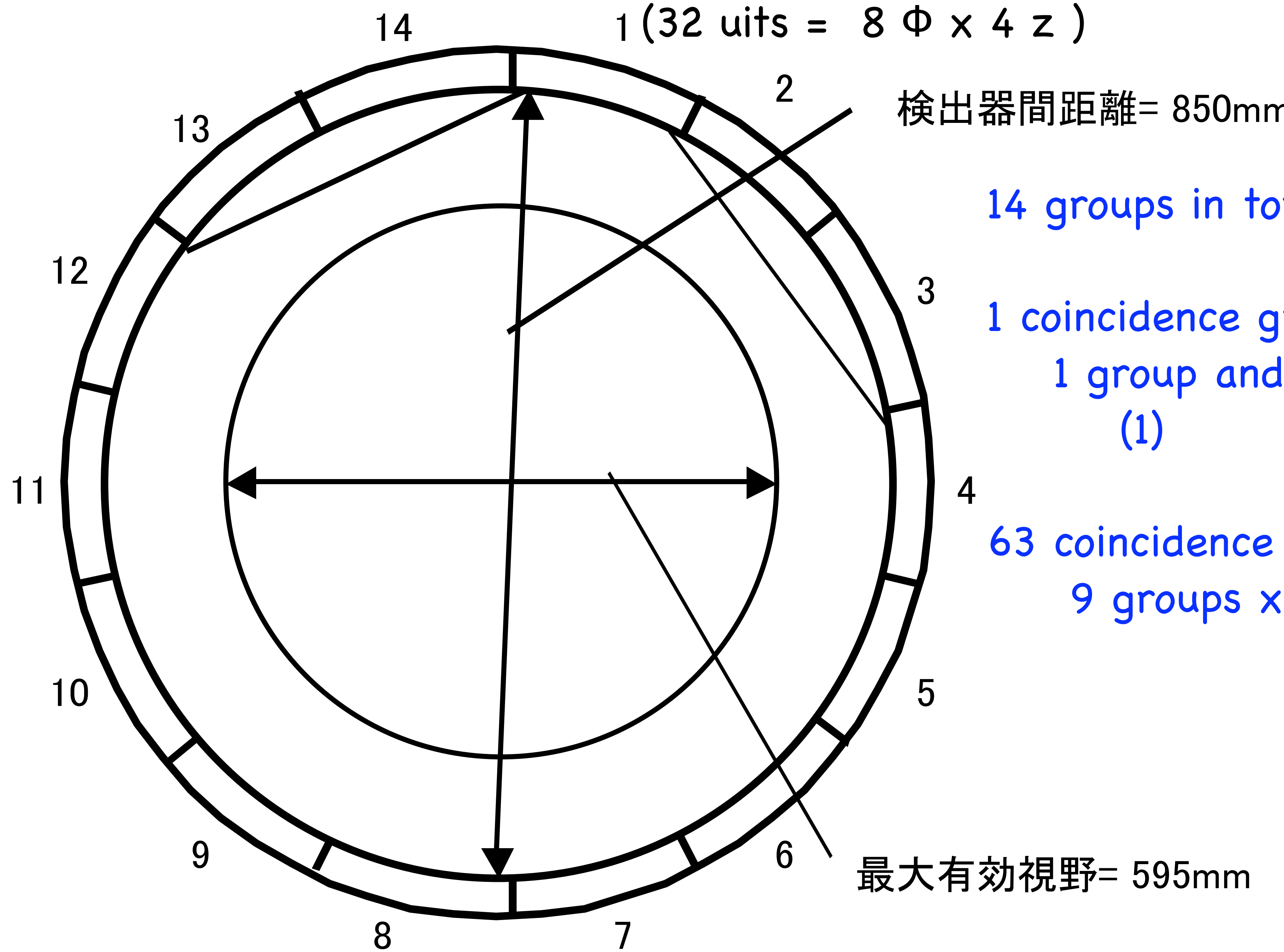
$$D = \frac{\sum n_{pe}(i)x(i)^2 + n_{pe}(i)y(i)^2}{\sum n_{pe}(i)} - \left(\frac{\sum n_{pe}(i)x(i) + n_{pe}(i)y(i)}{\sum n_{pe}(i)}\right)^2$$

MEG experiment





Coincidence processor (SET-2400W)



14 groups in total

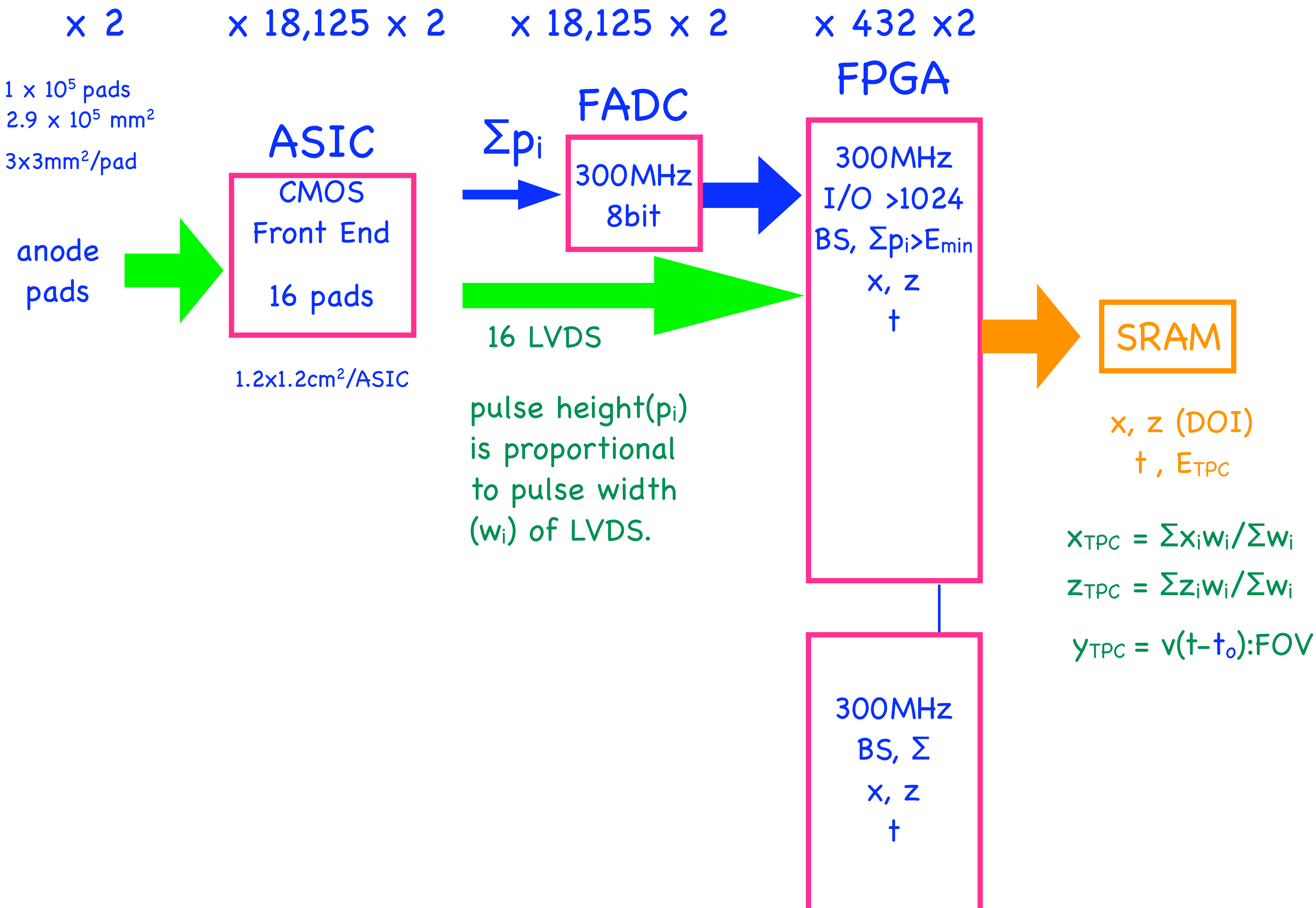
1 coincidence group (15ns) :
1 group and 9 groups
(1) (4-12)

63 coincidence circuits
9 groups x 7 (angles)

total PMTs =32 x 14 x 4= 1792

図 3-14 有効視野と同時計数グループの関係

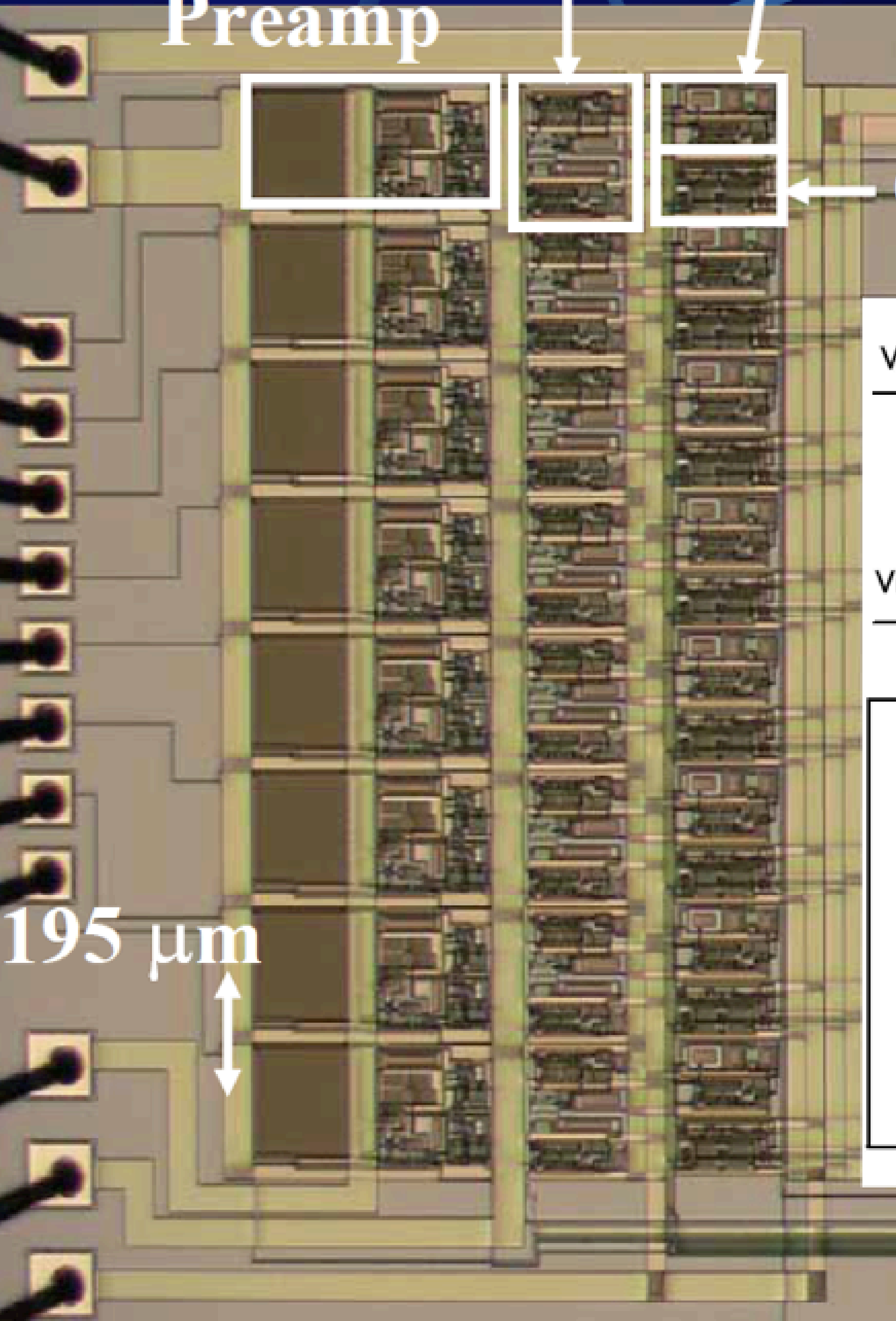
TPC Readout

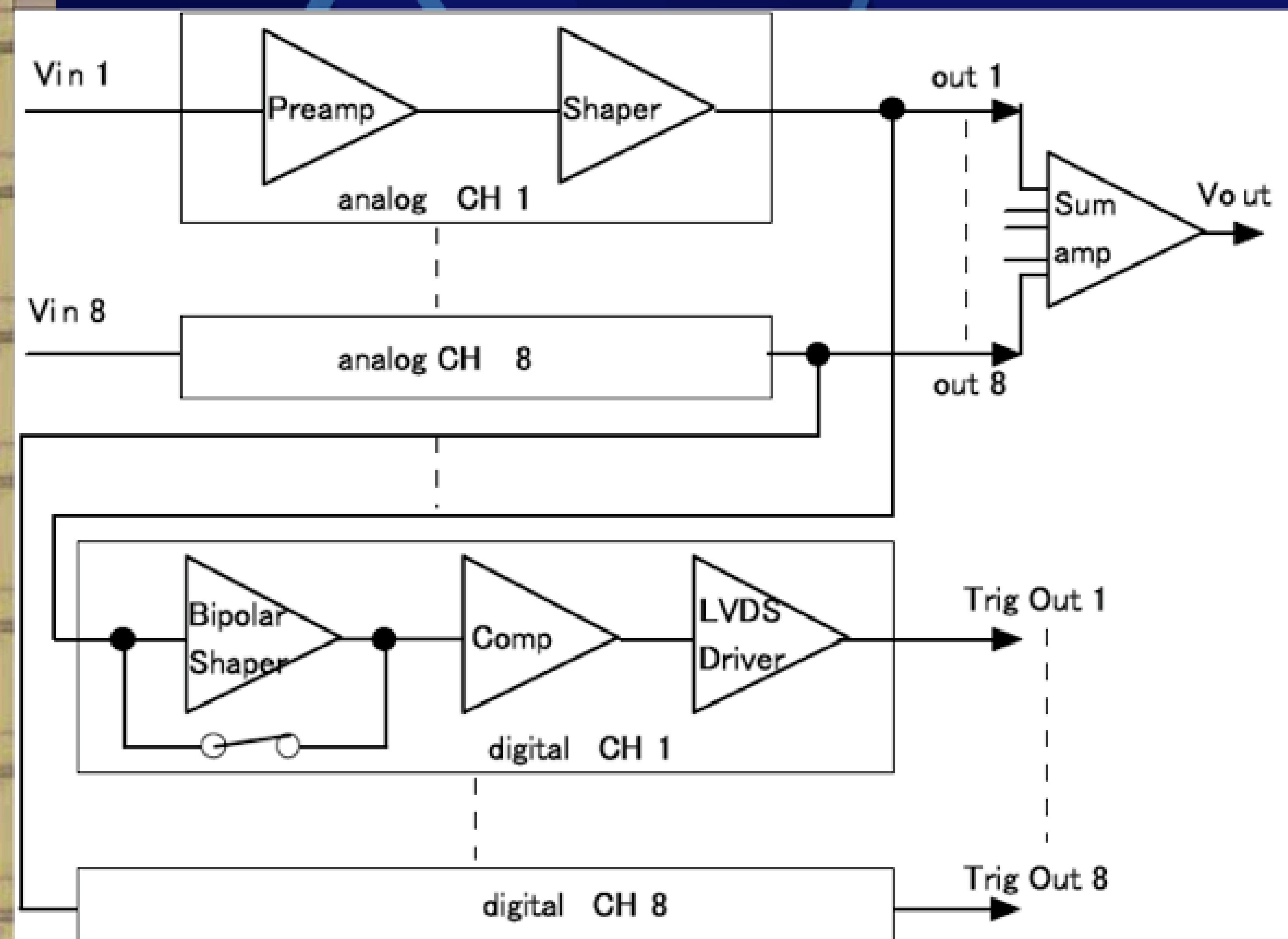


x 2
x 18,125 x 2
x 18,125 x 2
x 432 x2
1 x 10^5 pads
2.9 x 10^5 mm^2
3x3mm^2/pad
anode pads
ASIC
CMOS
Front End
16 pads
1.2x1.2cm^2/ASIC
Σpi
FADC
300MHz
8bit
16 LVDS
pulse height(pi) is proportional to pulse width (wi) of LVDS.
FPGA
300MHz
I/O >1024
BS, Σpi>Emin
x, z
t
300MHz
BS, Σ
x, z
t
SRAM
x, z (DOI)
t , ETPC
xTPC = ΣxiWi/ΣWi
zTPC = ΣziWi/ΣWi
yTPC = v(t-to):FOV

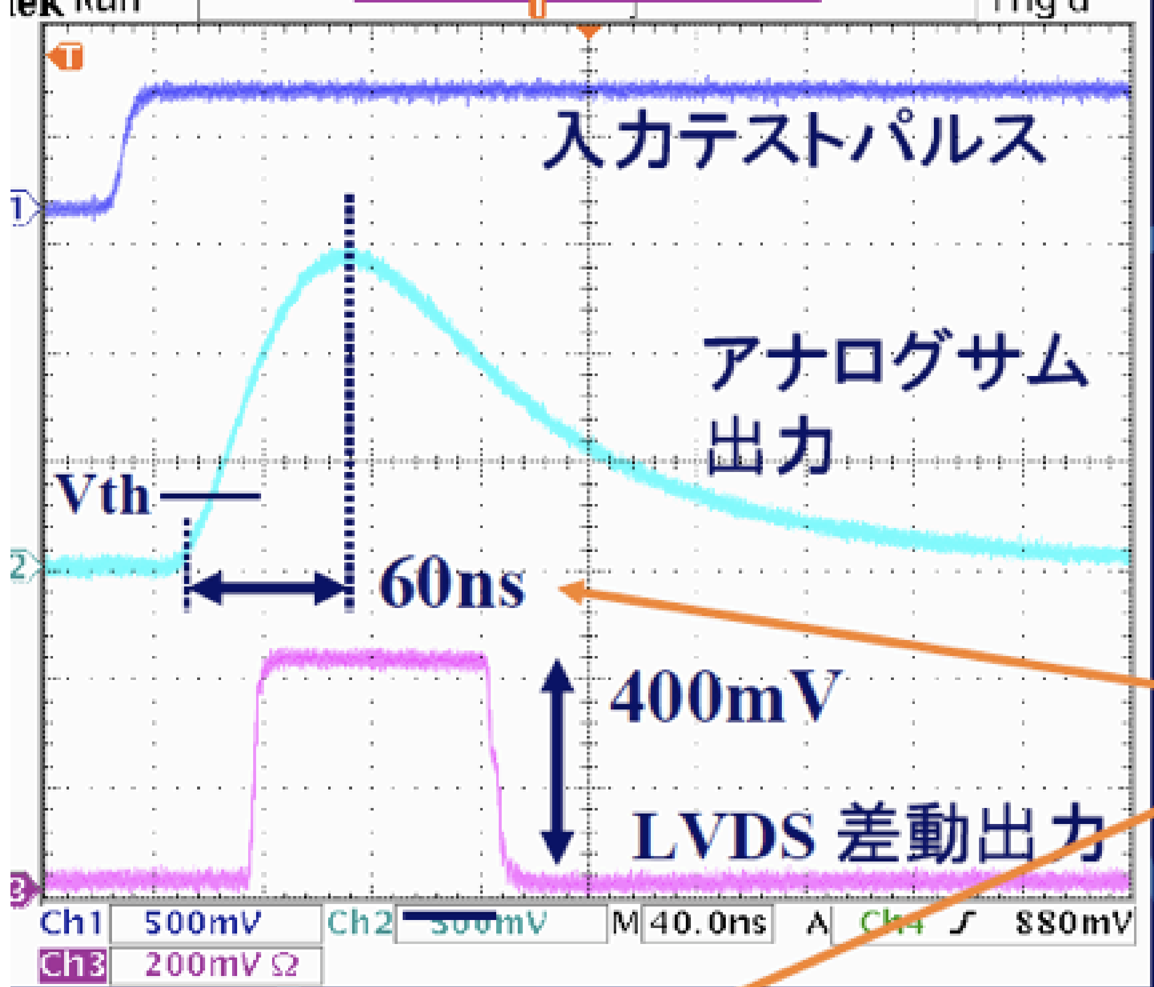
CMOS Front End レイアウト

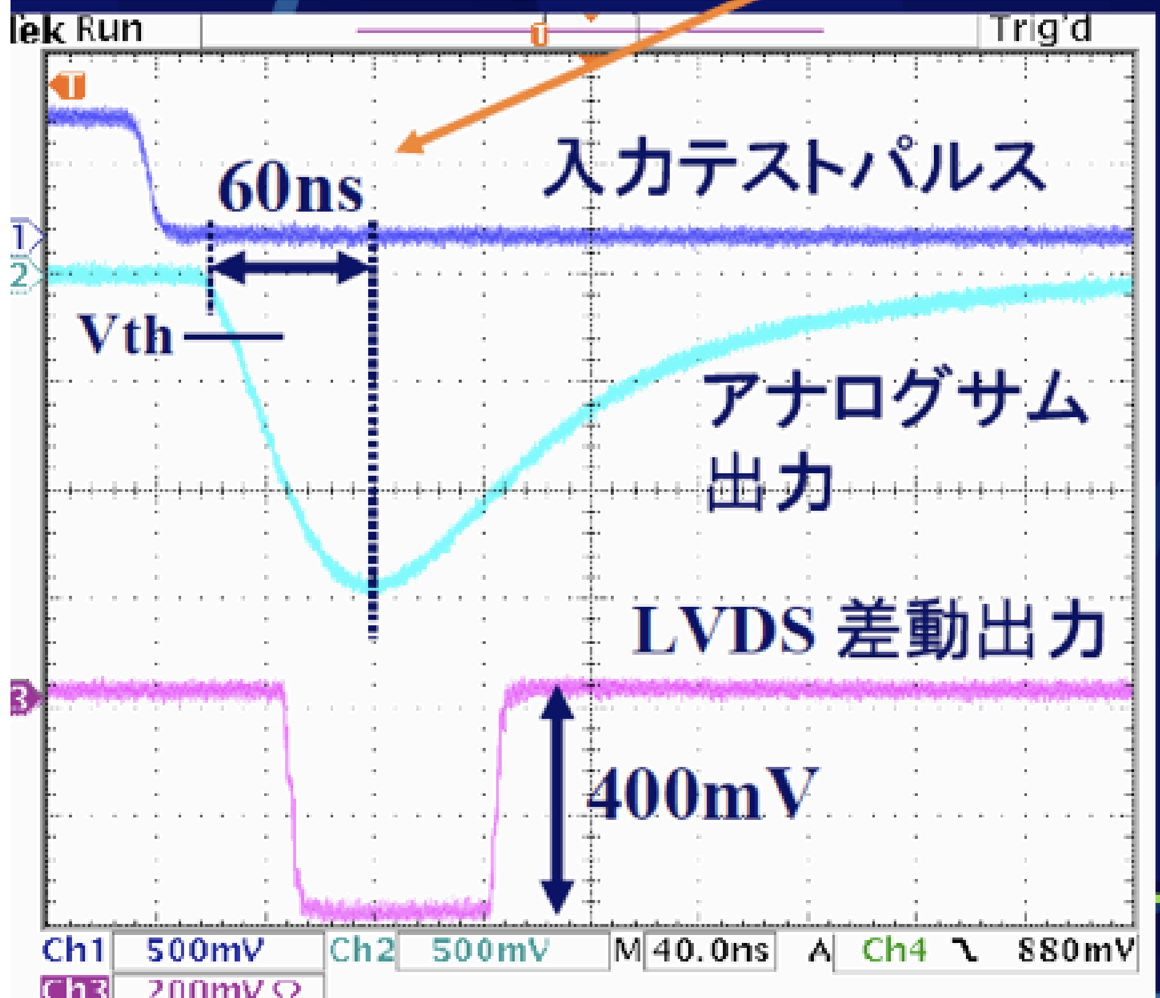
藤田陽一





パルス応答





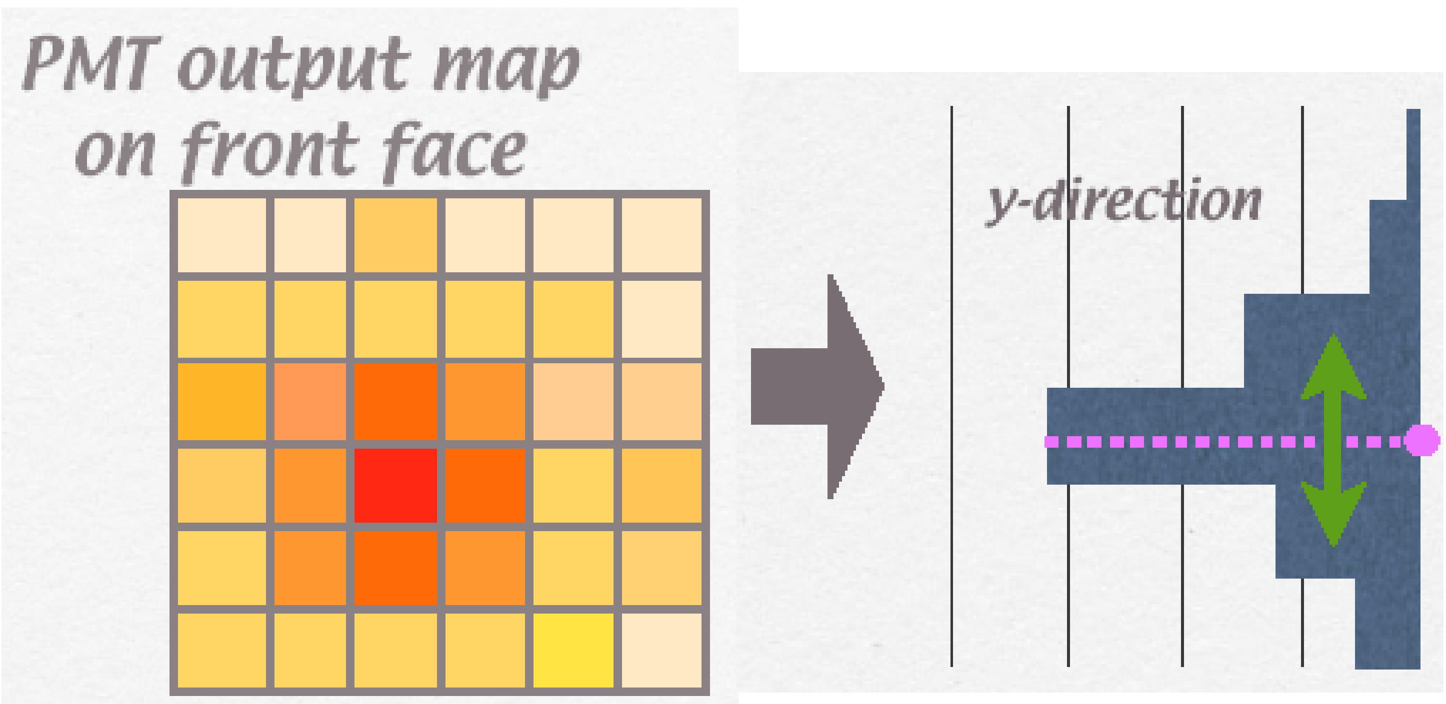
目標仕様

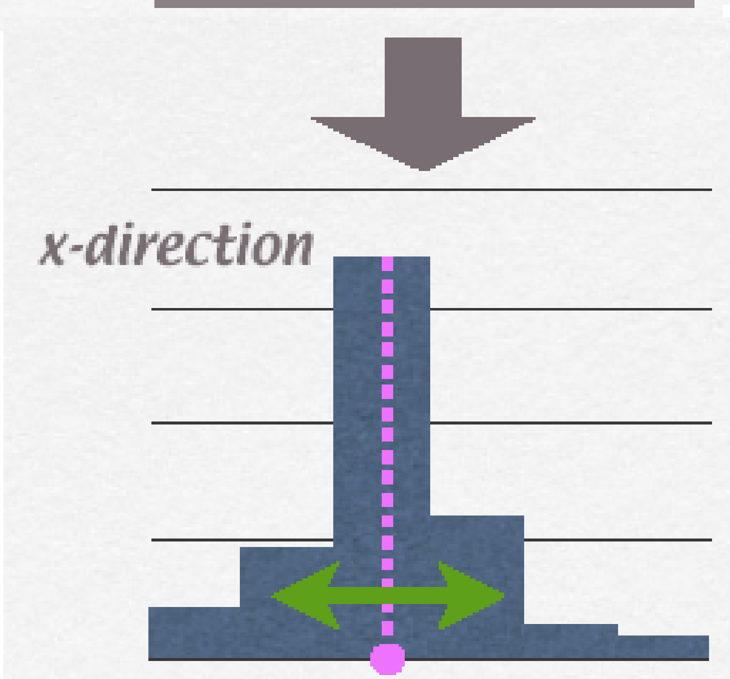
- ピーキングタイム 30ns
- 出力
  - LVDS（チャネル毎）
  - アナログサム（全チャネル）

- ピーキングタイムが予定より大きいのは、抵抗が一律に 70%増で製造されたことによると考えられる

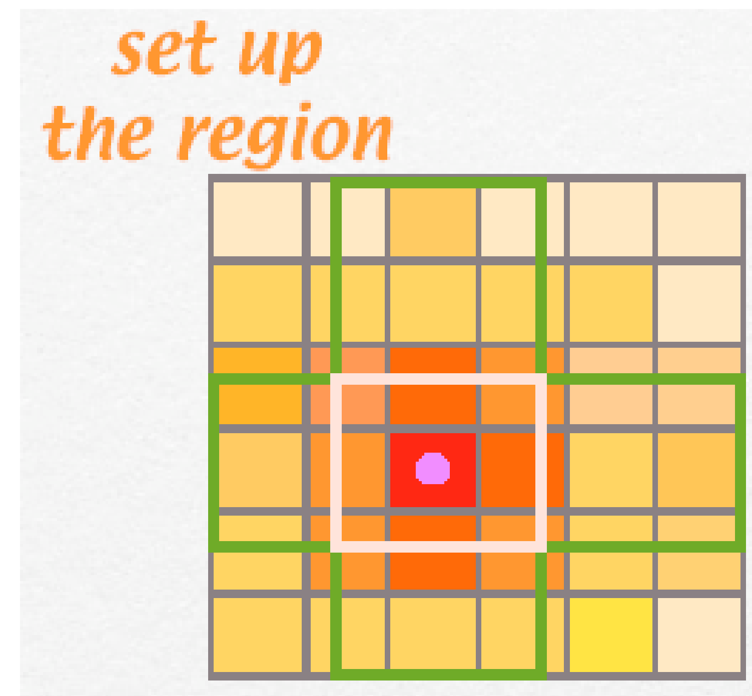
Position Reconstruction

- Localized Weight Method





- Projection to x and y directions.
- Peak point and distribution spread

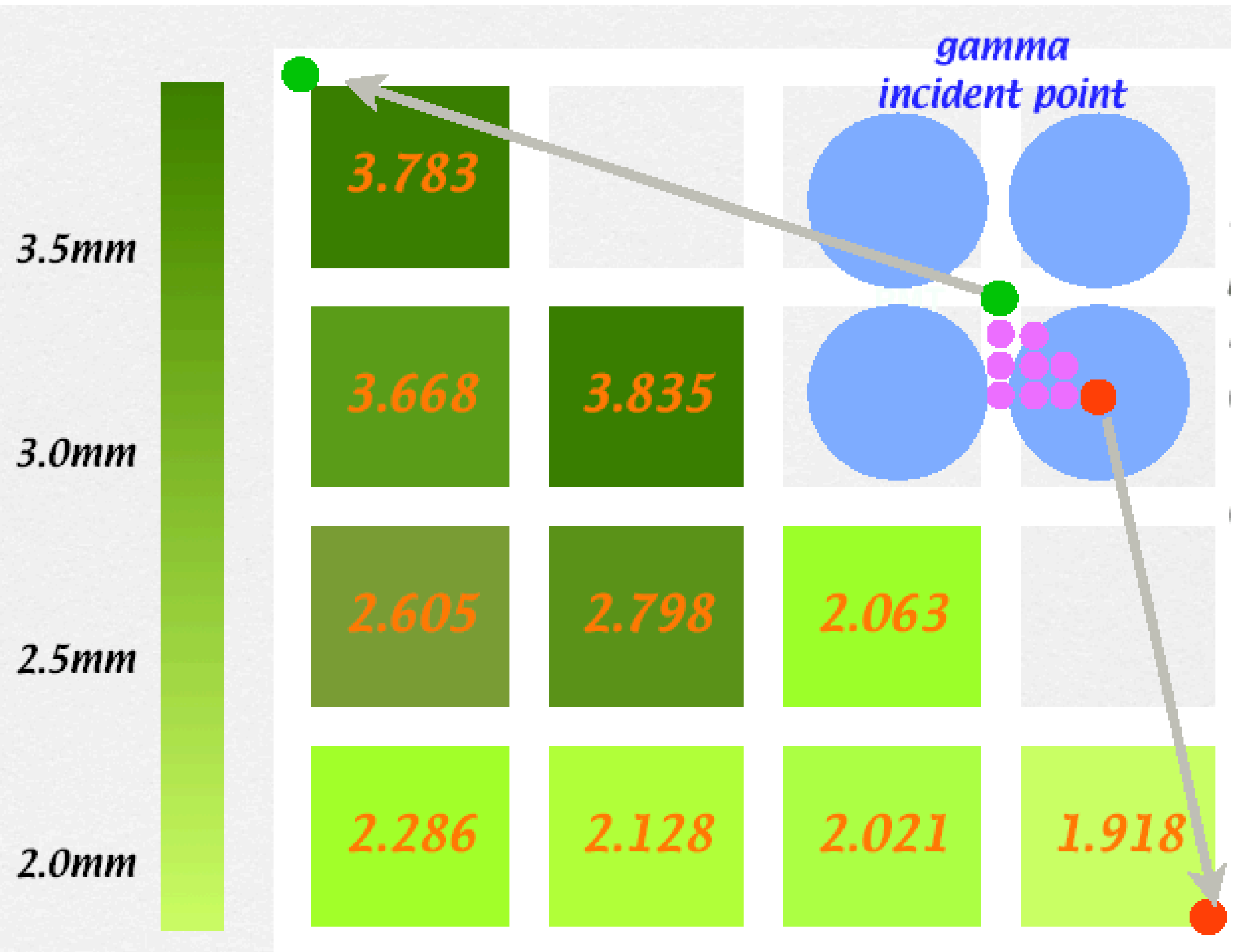


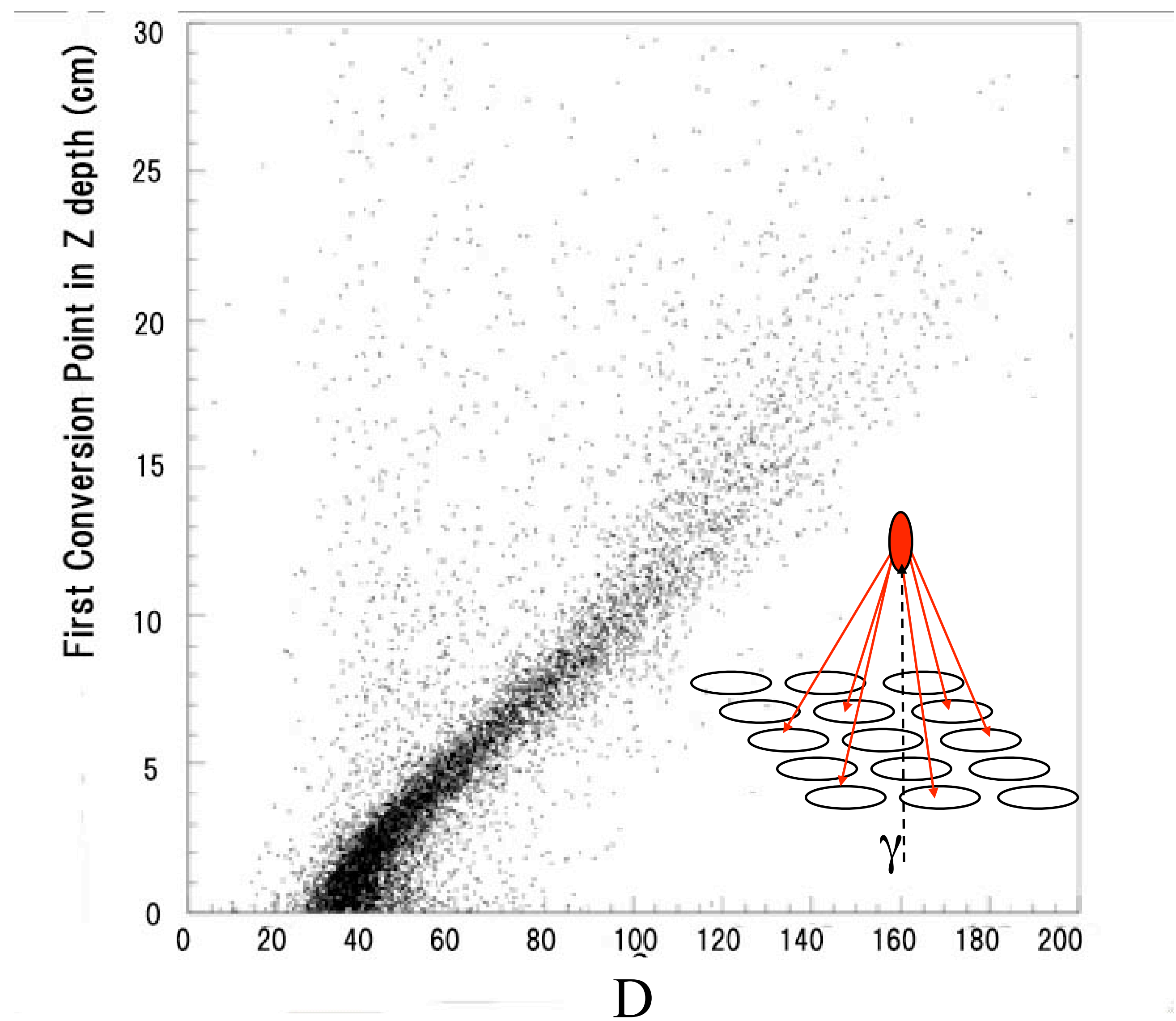
•Position reconstruction using the selected PMT

$$X_{reconst.} = \frac{\sum_i w_i\, Q_i\, x_i}{\sum_i w_i\, Q_i}$$

Position Reconstruction

Resolution (σ, FWHM=2.35σ)



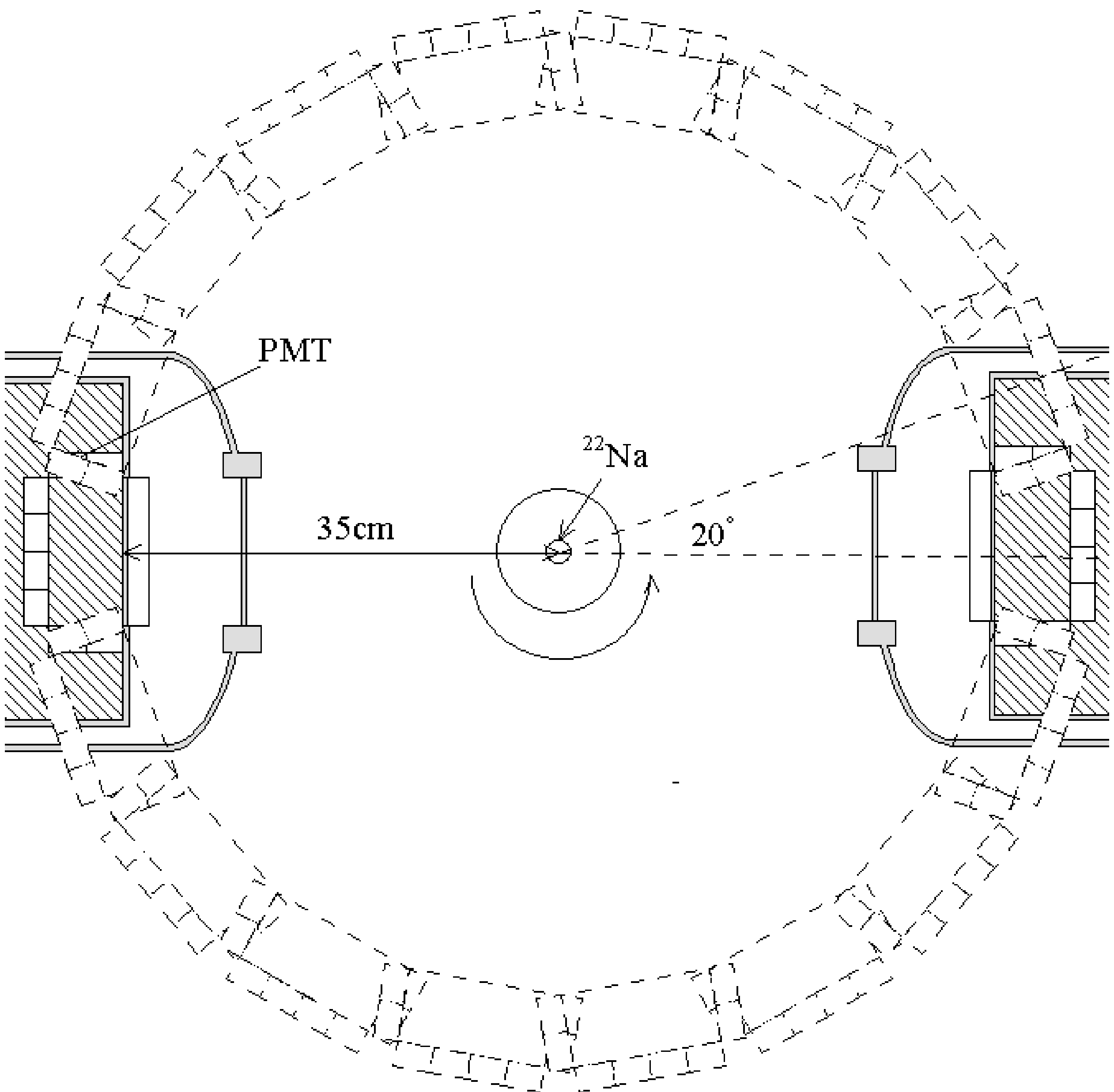


FWHM = ~ 4.7mm

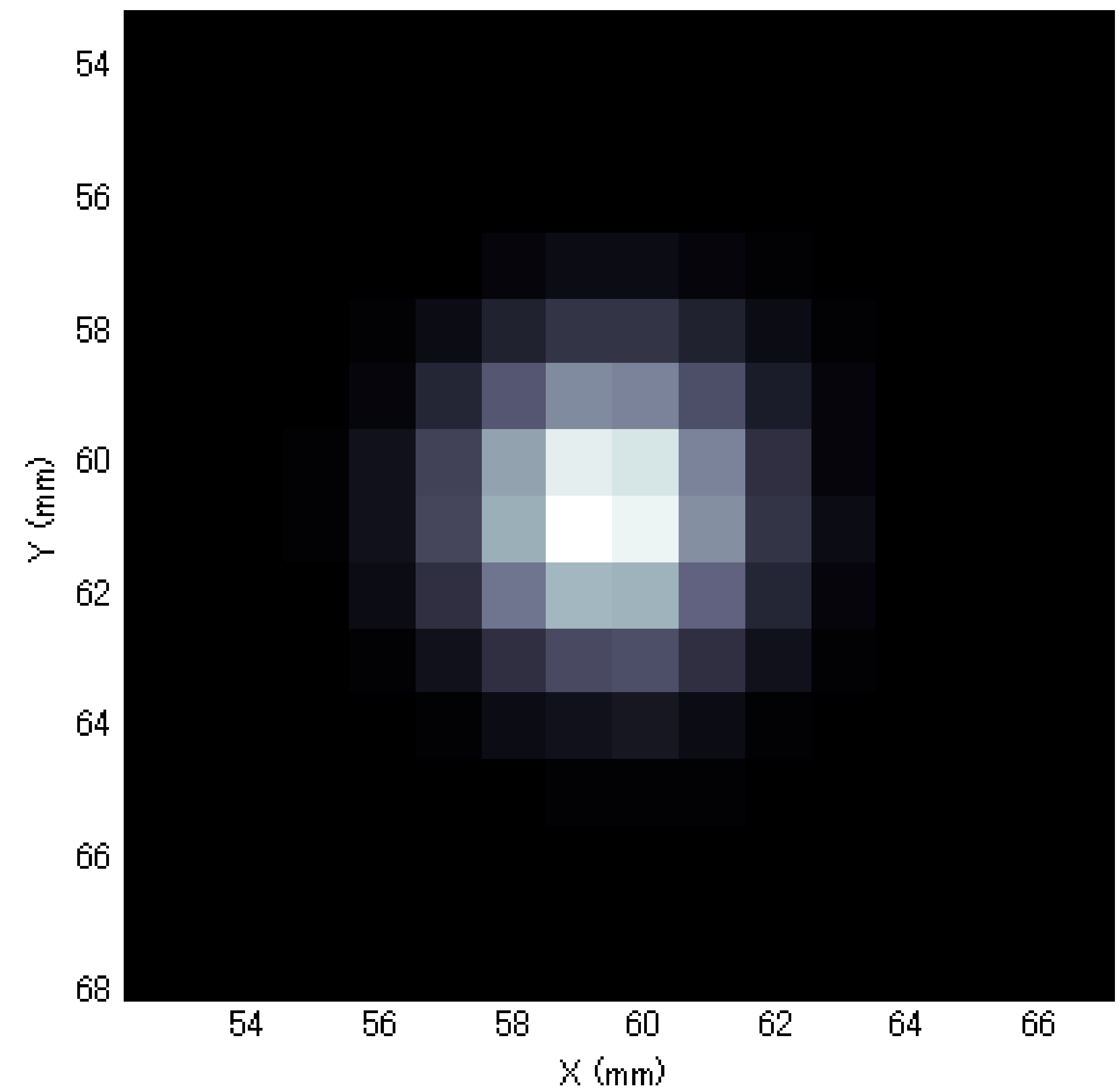
FWHM(D) = ~ 2cm

$$D = \frac{\sum n_{pe}(i)x(i)^2 + n_{pe}(i)y(i)^2}{\sum n_{pe}(i)} - \left(\frac{\sum n_{pe}(i)x(i) + n_{pe}(i)y(i)}{\sum n_{pe}(i)}\right)^2$$

画像再構成



^{22}Na点線源の再構成画像



再構成条件：ML-EM法

反復回数100回

-5<Y<5の範囲を用いる　→2Dモードを仮定

空間分解能：3.3mm
(FWHM)

18/ring

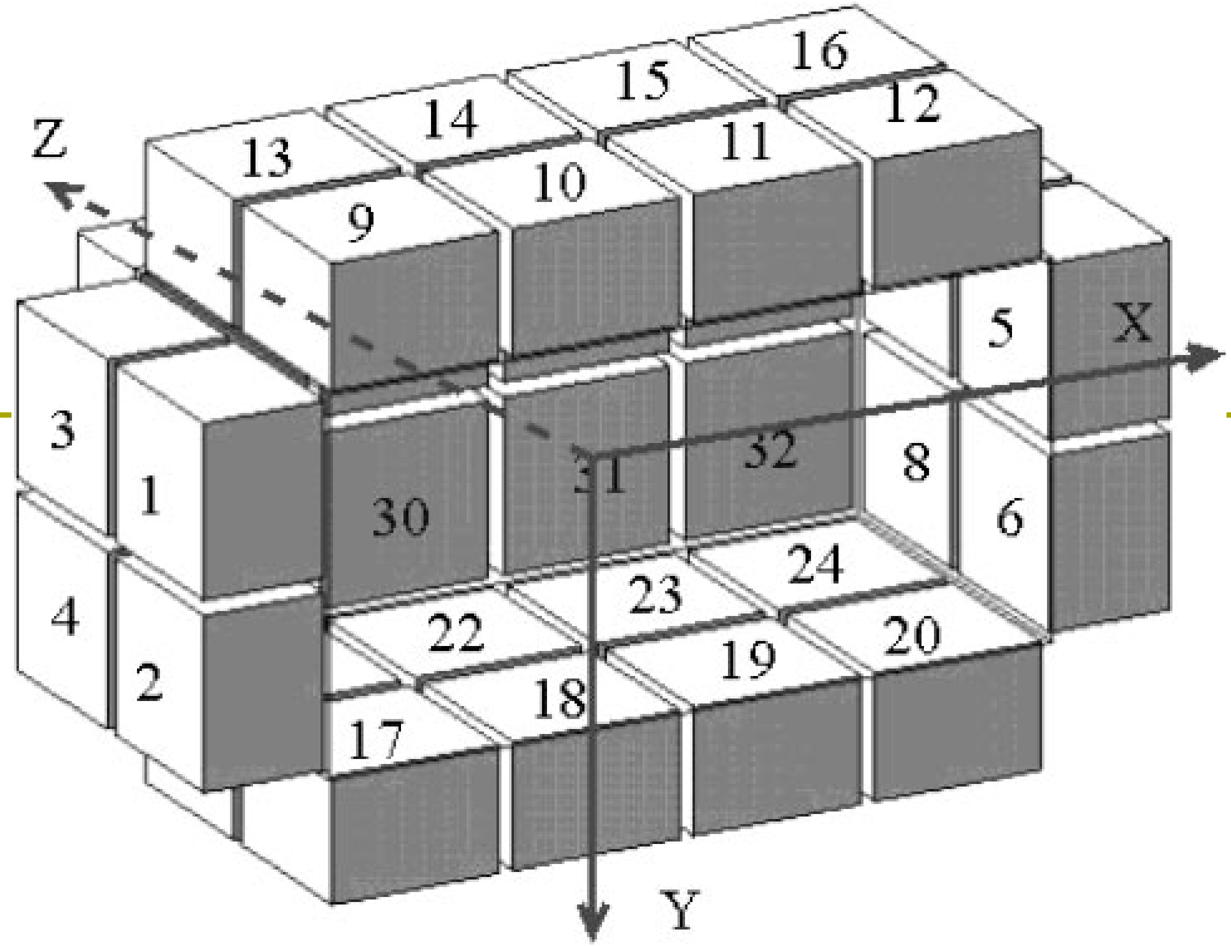


Fig. 2. Arrangement of 32 PMTs.

$$N = \sum_{j=1}^{32} N_j,$$

$$X = \frac{1}{N} \sum_{j=1}^{32} X_j \cdot N_j,$$

$$Y = \frac{1}{N} \sum_{j=1}^{32} Y_j \cdot N_j,$$

$$Z = \frac{1}{N} \sum_{j=1}^{32} Z_j \cdot N_j,$$

where N is the total number of photoelectrons, N_j is the number of photoelectrons in each PMT, and X_j, Y_j, and Z_j are the positions of the PMTs. The position distributions of

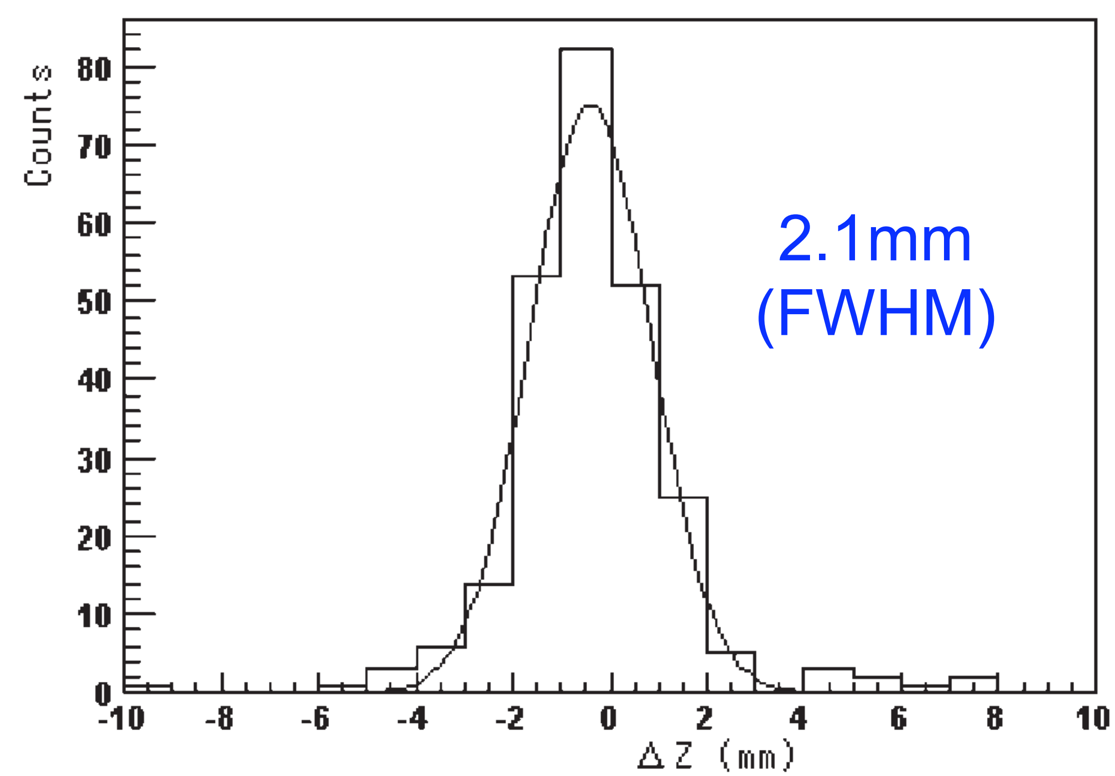


Fig. 9. Spectrum of ΔZ for events in central volume ($-2.5 < X < 2.5$ mm, $-2.5 < Y < 2.5$ mm, and $-2.5 < Z < 2.5$ mm in Fig. 6).

jPET-D4

平成17年度 次世代PET装置開発研究報告書、(7) jPET-D4システム性能評価 、吉田英治, 放医研

同時計数：10nsec

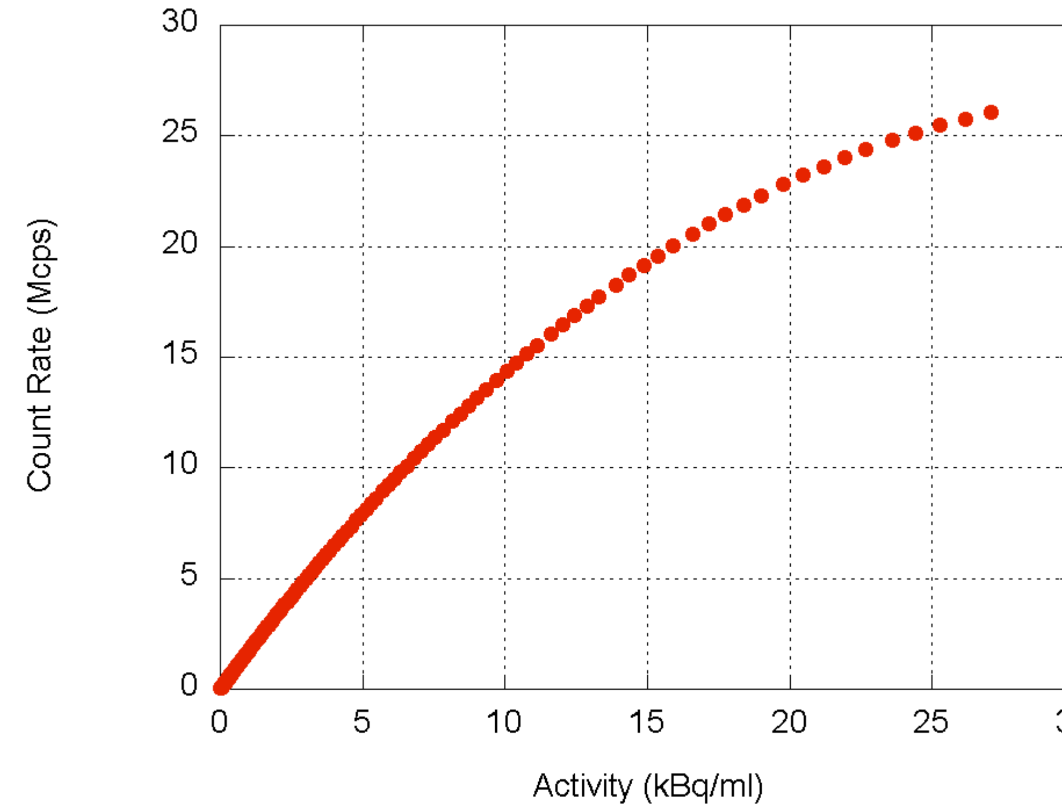


図６　シングル計数率

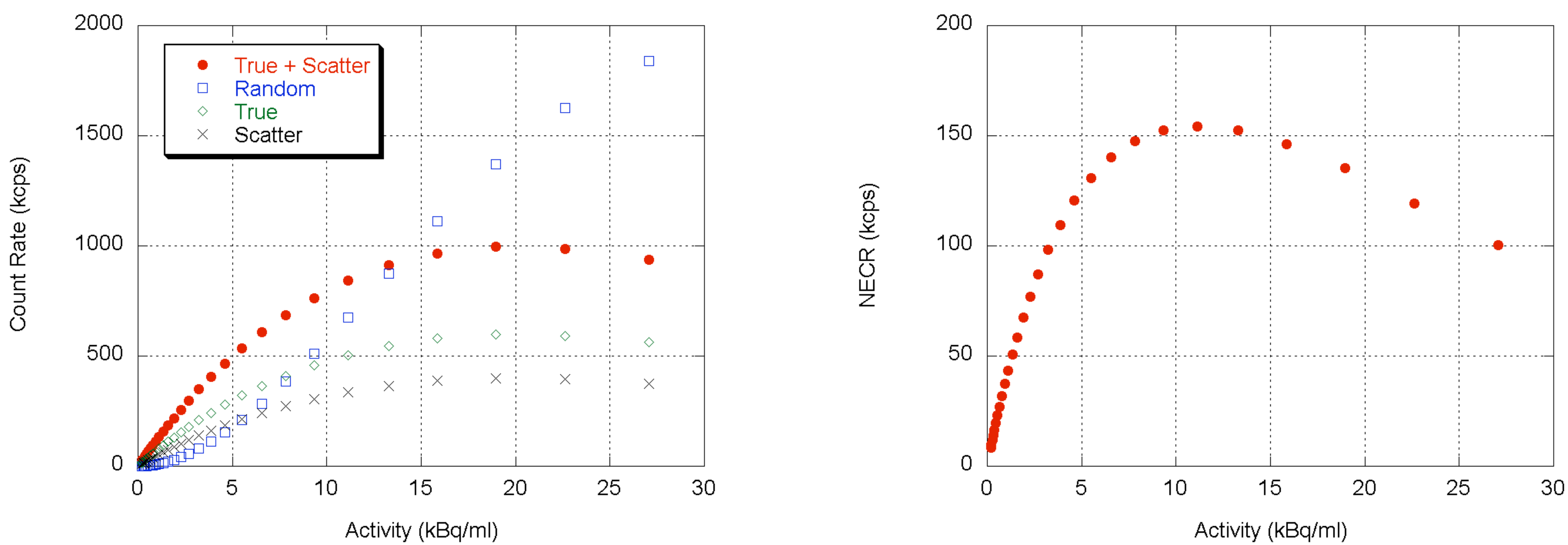
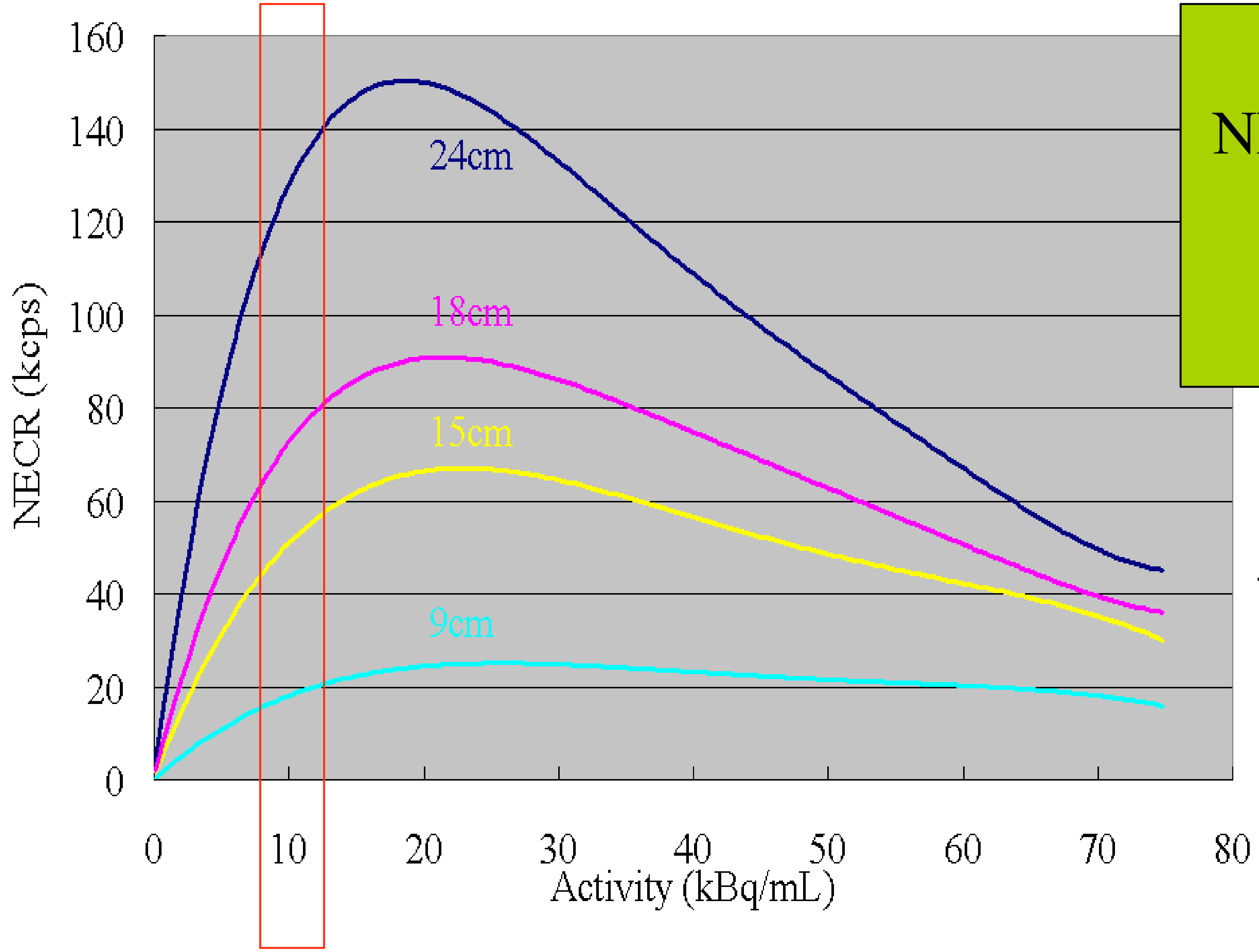


図７　計数率特性（左）と NECR（右）

NECR



$$NECR = \frac{T^2}{T+S+R}$$

T：真の同時計数イベント
S：散乱同時計数イベント
R：偶発同時計数イベント

<u>NEC simulation</u>

System dead time:200ns

Coincidence window:4ns

Energy window:450-550keV

Counting Rates

jPET-D4

solid angle = 0.713

segmentation 24 (ring) x 5 (axis) = 120

maximum NECR = 150kcps / 10kBq/ml

single count = 15Mcps / 10kBq/ml

total count = 2Mcps / 10kBq/ml

true+scatter = 1Mcps / 10kBq/ml

random = 1Mcps / 10kBq/ml

Nishikido LXeTOF PET

solid angle = 0.287

segmentation of "PMT" 103 (ring) x (8 (axis) +2 (DOI)) = 1030

maximum NECR = 150kcps / 20kBq/ml , 100kcps / 10kBq/ml

TXePET

solid angle = 0.514

segmentation of "PMT" 112 (ring) x 16 (axis) = 1792

General PET (Shimizu SET 3000GCT)

solid angle = 0.352

segmentation of "PMT" 88 (ring) x 10 (axis) = 880

maximum NECR = 60kcps / 9.8kBq/ml

Assume single count is one of jPET-D4;

single count/total PMTs =15MHz/total PMTs
=15MHz/1792 PMTs
= 8370Hz/PMT

1/8370= 119μsec/PMT

PETYA : segmented drift chamber with PMT 1x5x6cm^3 cell (LXe 6cm long)

Table 1. Comparison of the liquid xenon detector with scintillation crystal systems

	PETYA	BGO block detector [20]	LSO block detector (CTI) [21]
Time resolution	1.3 ns	2 ns	1.5 ns
Position resolution	0.8×0.8 mm^2(*)	5×5 mm^2	2×2 mm^2
Interaction depth resolution	2 to 5 mm	None	7.5 mm
Energy resolution	15% to 17%	20%	14% to 20% (**)
Efficiency	60%	80%	not quoted
Dead time	50 μs·cm^2	25 μs·cm^2	not quoted

* $\Delta x\times\Delta y$; Δx - from the drift time measurement; Δy – obtained with the center of gravity method with the mini-strip plate (extrapolated from the measurements with α-source and convoluted with the photoelectron range)

** for a single crystal

LXe-TPC PET 1x1x9 cm^3 cell ; a module of 24x60x9cm^3 9cm drift

24x60cm^2 anode place segmented by 0.5x0.5mm^2 pads

PET camera at NECR = 30kHz	Activity (kBq/ml)	Sensitivity – Net Trues (cps/Bq/ml)	Spatial cut (spatial resolution FWHM) (mm)	Energy resolution (FWHM)
BGO 80cmΦ, 15cm	3	30 8,4,30mm^3	10 (~7)	26.7
LXe 60cmΦ, 60cm	0.4	190	3 (~1.7)	13.8

Table 1: Performances of the proposed LXe-TPC PET compared to a standard BGO PET camera.

Product		Cryscal/Radiation material		fiducial volume		position resolution			Slice pitch	energy res.	sensitivity		NECR by NEMA NU 2-2001			Solid angle
designer	name		size	inner diameter	field of view	tangentially	radially DOI	axial (z)	z	511 keV	NEMA NU2-2001		NECR	at radiation dose (20Φ x70(20)L	scatter fraction	point source
PET/CT			x, z, y in mm	cm	cm	mm	mm	mm	mm	%	cps/kBq	%	kcps	kBq/ml	%	
GE	ADVANCE	BGO	4, 8.1, 30	67.2	15.2	7	30	7.3, 8.4		33		0	37.6	10	44.8	0.221
GE	Discovery ST Elite	BGO	6, 6, 30	55	15.2	4.25	30	4.8	3.27		8.5	0.85	80	12	36	0.266
Siemens	ECAT EXACT HR+	BGO	4.39, 4.05, 30	65.3	15.5	4.3	30	4.1			8.98	0.898	27.3(79.2	6.3(12.5)	37	0.231
Siemens	biograph 16 HI-REZ	LSO	4, 4, 20	58.5	16.2	3.5	20	3.12	2	10	4.92	0.492	84.77	28.73	34.1	0.267
Philips	Gemini GXL (-TF)	GSO(+Zr)	4, 6, 20 (30)	56	18	4.9-5.5	20	5.0-6.1	4	8.5	8	0.8	70	11	35	0.306
Shimazu	SET-3000GCT	GSO	2.45, 5.1, 30	66.4	25	2.45	30	5.1	2.6		19	1.9	60	9.8	50	0.352
Toshiba	Aquiduo PCA-7000B	LSO	4, 4, 20	58.5	16.2	3.5	20	3.12	2	10	4.92	0.492	84.77	28.73	34.1	0.267
PET																
Hamamatsu	SHR-92000	BGO	2.9, 6.3, 20	60	68.5						9.72	0.972	113.6	10.5	31.4	0.752
Nantes univ.	LXeTPC PET	Liq.Xe	10, 10, 90 (93%)	60	60	0.25	0.14	0.25		13.8			70	1.5	54.5	0.707
Coimbra univ.	PETYA	Liq.Xe	10, 50, 60 (73%)			0.8	2.0-5.0	0.8		15-17						
NIRS	LXeTOF PET	Liq.Xe	segmentation?	80	24	3.7		3.7		16	35	3.5	150	10		0.287
KEK-NIRS	**TXePET**	**Liq.Xe**	**no segmentation**	**88**	**48**	**1.64**	**1.64**	**1.2**		**16**	**70**	**7**	**300**	**10**		**0.479**
Brain PET													20Φ x20L cm^2			
CERN	brain HPD-PET	LSO	3.2, 3.2, 200(z)	35	10	1.9	1.9	4.5		7.5	4	0.4	130		30.4*	0.275
NIRS	jPET-D4	GSO	2.9, 2.9, 7.5x4	25.6	26	2.5	7.5	2.5		16	7.1	0.71	154	11	39.7	0.713
CPS	HRRT	LSO-LYSO	2.1, 2.1, 7.6x2	31.2	25	2.4-2.9	2.4-2.9	3.0-4.0		17	4.5	0.45	140	13	40	0.625
Univ. Pennsylvania	G-PET	Anger-logic GSO	4, 4, 10	30	25.6	4	10	5		18	4.79	0.479	60	7.4	39	0.649
Hamamatsu	SHR-1200(2400)	BGO	2.8(1.4), 6.55, 30	33	16.3	2.9	30	2.9								0.443
Hamamatsu	SHR-12000	BGO	2.8, 6.55, 30	50.8	16.3	2.9	30	2.9								0.306
Small Animal PET														(2.5Φ x7L cm^2),MBq/		
UVP BioImaging	microPET II	LSO	0.975,0.975,12.5	16	4.9	1.17	1.47	1.42			22.6	2.26	235	2.35		0.293
SCETI, Univ. of Ferrara	YAP-PET	YAP	2, 2, 30	4	4	1.8	1.8	1.8		14.5	18	1.8	90	16.6MBq		0.707
Oxford Positron System	Quad HIDAC	HIDAC		17	28	1	1	1			18	1.8	100	0.2	30-40	0.855
raytest	ClearPET	LYSO-LuYAP	2, 2, 10x2	22.5	11	1.25-2	1.25-2.4	1.25-2		30	38	3.8				0.439
LIP	RPC-PET	RPC		6	10	0.5		0.5			21	2.1	318	2.63		0.857
Philips	MOSAIC	GSO		12.8	11.9	2.1-2.5					5.7	0.57				0.681
GE	eXplore Vista	GSO/LYSO	1.55, 1.55,	6.7	4.7	1.56	1.45	1.74			41.4	4.14				0.574
Siemens	FOCUS 220	LSO	1.5, 1.5, 10	19	7.6	1.3-2.5				18	40	4				0.371
Advanced MI	LabPET7.2	LYSO/HPD	1, 1, 10	11	7.2	1.1										0.548
Gamma Medica	X-PET	BGO		10	11.6	2	2	2			83	8.3				0.757
Joseph Fourier univ.		Liq.Xe	2, 2, 50(z)	8	5	1	1	8								0.53

TXe プロトタイプ

(1) TPCの大きさ（ fiducial volume ）

9cm x 24 cm x ±24cm = 5.2 x 2 ℓ（ PETの14分の1 , トリガーセクター）

- Central membraneを挟んで両側にそれぞれ24cmのドリフト空間があるもの
- PMT (R5900) は24cm x 24cm x 2の上に有り、64x2 本あります。
- anodeの全体の大きさは、9cm x 24cm x 2で、3mm x 3mmのpadでできています。

(2) 液体キセノンの量

5.2x2ℓ(fiducial volume)+ 純化•液化に必要な量

(3) 純化•液化装置一式

(4) pad readout system

約2,400x2個のpad （ 150x2 CMOS-FE16chチップ ）

概算

TPC容器＋電極など　－ ？ 700万円

Endplate with anode pads
TPC HV (48kV) ？

Anode pad readout electronics ? 2400x2 pads, 1000円/ch, 240万円

- 150x2 CMOS-FE16chチップ, FADC (300MHz,8bit)x150, FPGA(300MHz)

PMT 64x2本+2本予備 = (64x2+2)x17.8= 1175万円

PMT readout electronics 64x2 PMTs, 22400円／ch, 144万円

- FADC(300MHz,8bit)x64x2, FPGA(300MHz)

PMT power supply (10^6gain/800V) ?

- 海津製作所製KH6506A divider-16ch, 235000円/台, 141万円
- HV power supply, KH6600 3kV, 370000円/台, 74万円

液体キセノン - 5.2x30x2=156万円x2＋more = 300万円？

純化•液化装置一式 ? 300万円