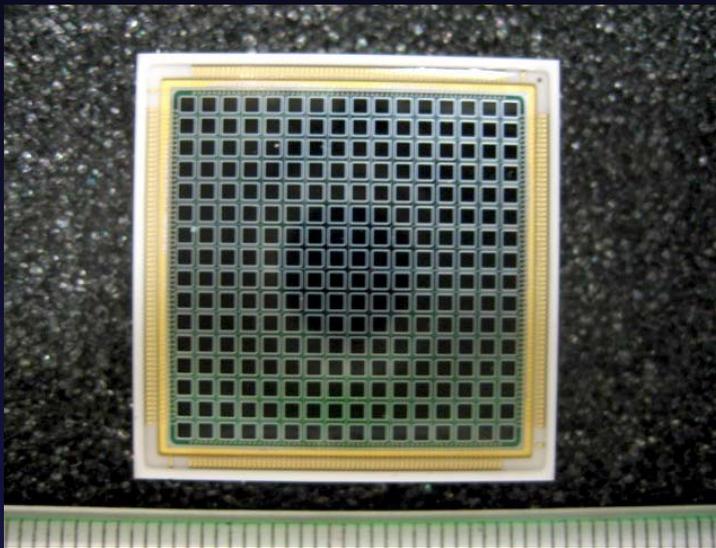


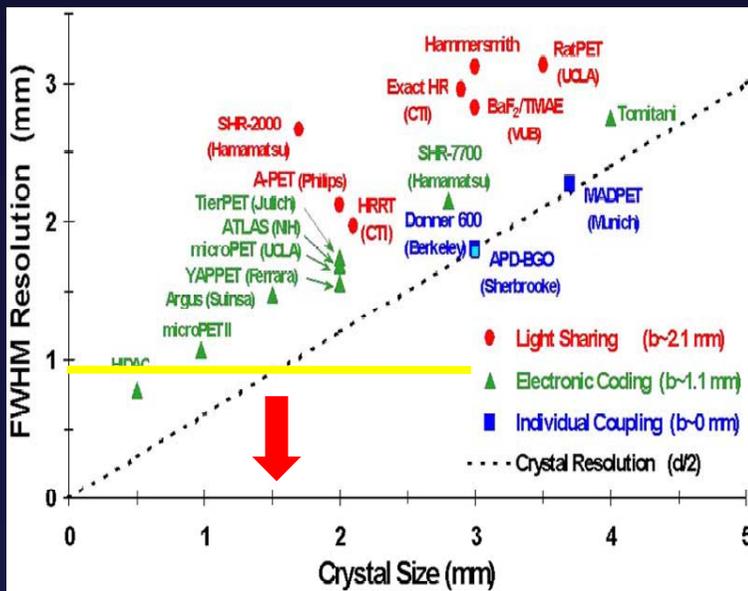
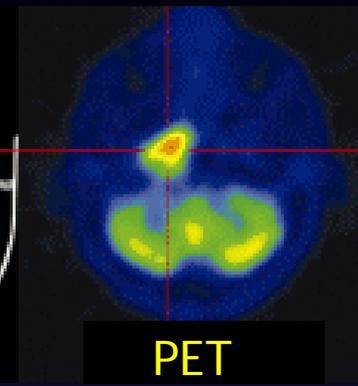
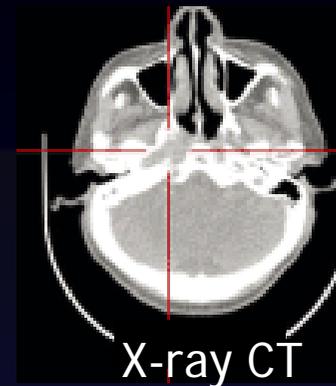
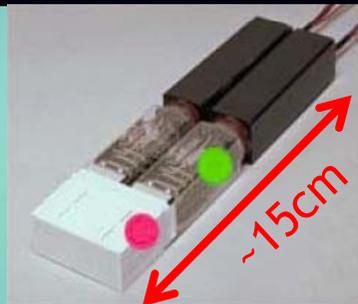
Development of large-area reverse-type APD arrays for high-resolution medical imaging



Jun KATAOKA (Tokyo Inst. of Tech.)

M.Koizumi, S.Tanaka (Tokyo Tech), H.Ikeda (JAXA/ISAS)
Y.Ishikawa, N.Kawabata, Y.Matsunaga (Hamamatsu Photonics),
S.Kishimoto (KEK) and H.Kubo (Kyoto U)

Learning from current PET scanner



Lecomte 04, NIM-A, 527, 157

■ PET scanner is a powerful tool, but...

- Very expensive, complex, bulky (~10M USD).
- Relatively poor image resolution (>5 mm vs ~5 μm for CT, MRI).

■ Theoretical limit: sub-mm

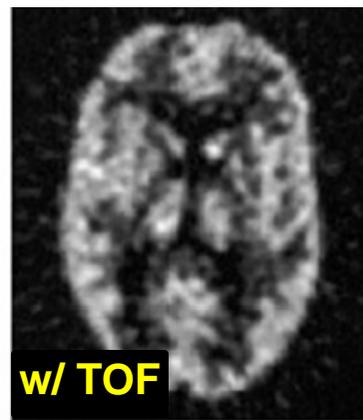
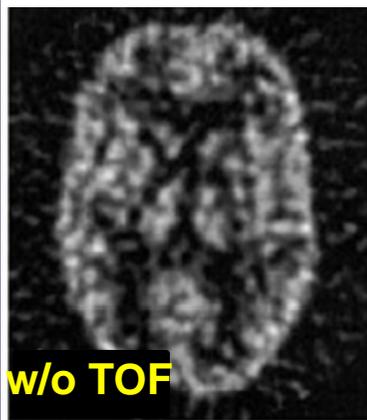
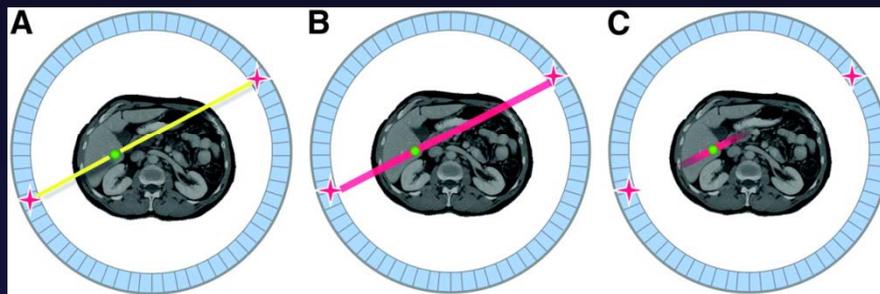
- Blurring effect due to noncollinearity: $\Delta_{nc} = 0.0022 \times D \sim 0.5 \text{ mm}$ (for small PET)
- To achieve sub-mm resolution we need to have a PSD w/ $d \approx 1.7 \text{ mm}$.

$$FWHM = a \times \{ (d/2)^2 + b^2 + r^2 + \Delta_{nc}^2 \}^{1/2}$$

Next step: MRI/PET, TOF-PET...



Judenhofer 08, Nature Medicine, 14, 459



Cherry+ 06, Shibuya+ 06

■ PET/CT scanner

- Advantage on clinical diagnosis, but **poor soft-tissue contrast**.
- Subjects the patient to significant radiation dose.

■ MRI/PET fusion

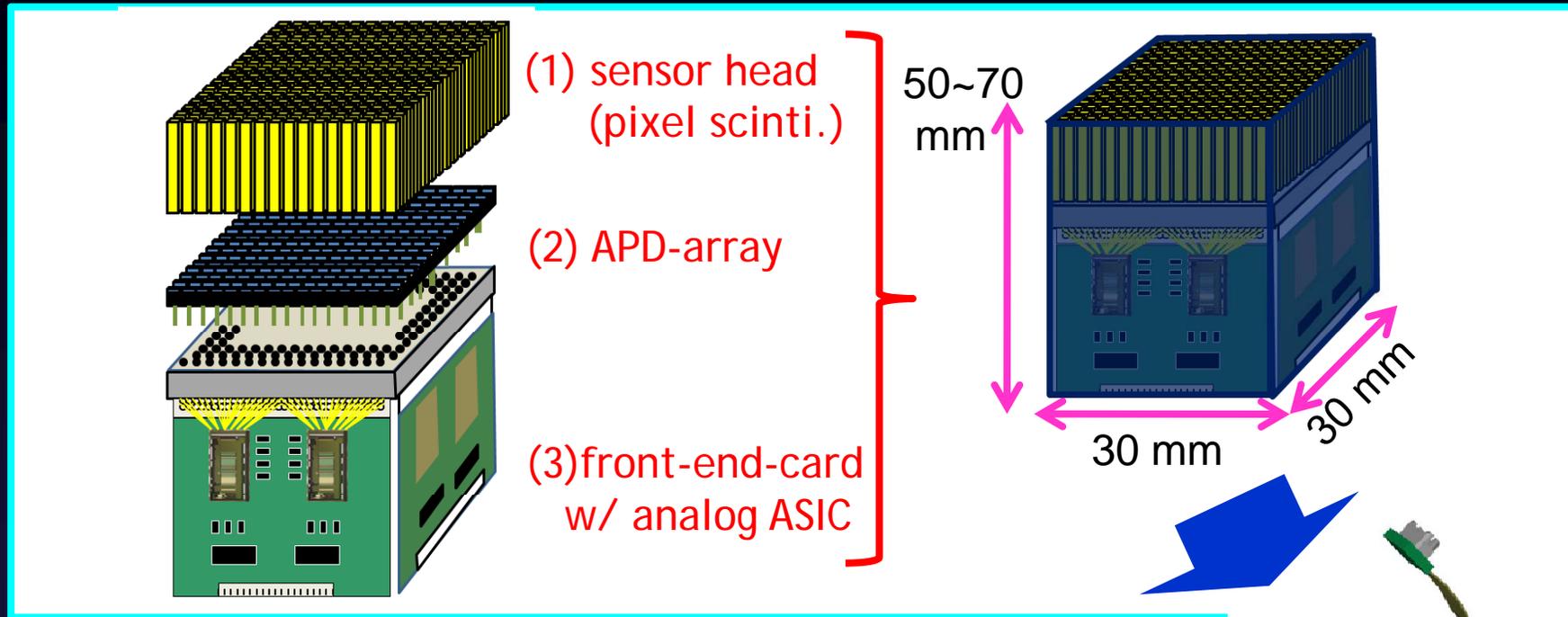
- Provides excellent soft-tissue contrast **w/o additional dose**.

However, PMT is highly sensitive to B-field used in the MRI (~5T)!

■ Time of Flight (TOF) PET

- Effectively reduce the statistical noise in the reconstructed image.
- Need **extremely FAST detector** system ($\Delta t \approx 100$ ps yields 1.5 cm resol).

APD-PET project; starting!



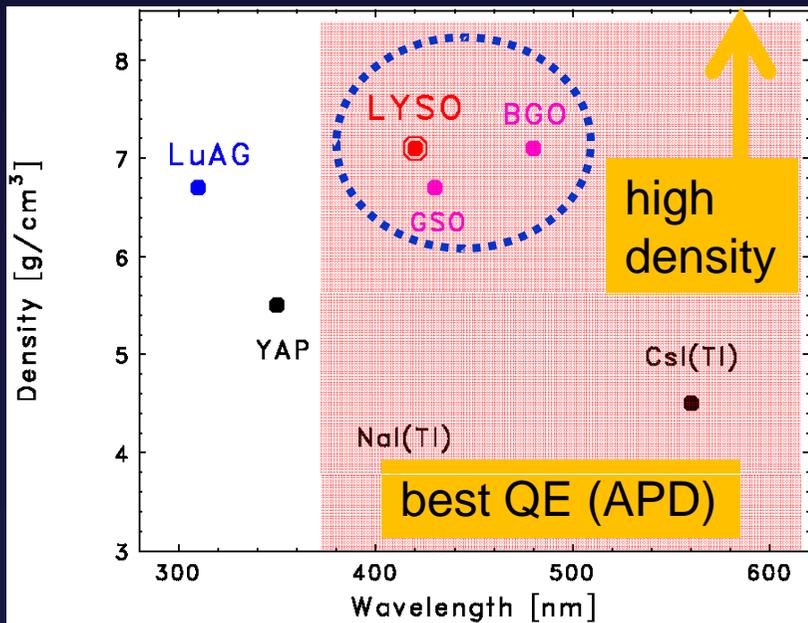
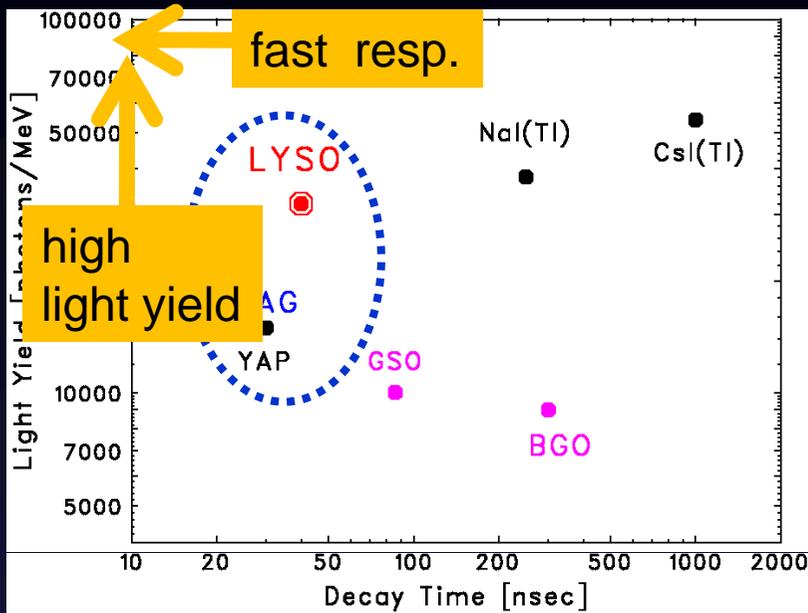
■ Fabrication of a simple PET device

- Fine-pixel APD (Avalanche Photo-Diode) arrays to achieve **sub-mm resolution**.
- γ -ray **pixel scintillator** to match w/ the APD.
- Multi-channel front-end ASIC for APD. (**next talk**)

- ✓ Flexible, low-cost mobile PET w/ sub-mm resol.
- ✓ Application to MRI/PET and TOF-PET.



γ -ray detector (sensor head)



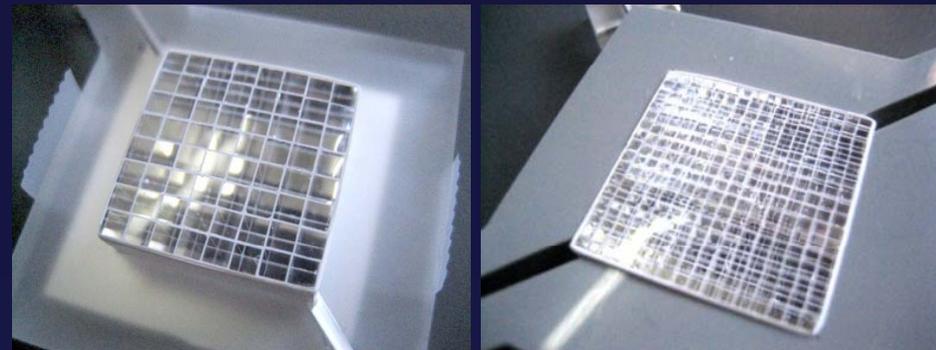
■ Bench mark for APD-PET

- **light yield** \Rightarrow energy resol.
- **decay time** \Rightarrow Δt window, TOF
- **lumi. λ** \Rightarrow matching w/ APD
- **density (Z)** \Rightarrow stopping power
- **others:** mechanical stiffness, deliquescence, T-dep...

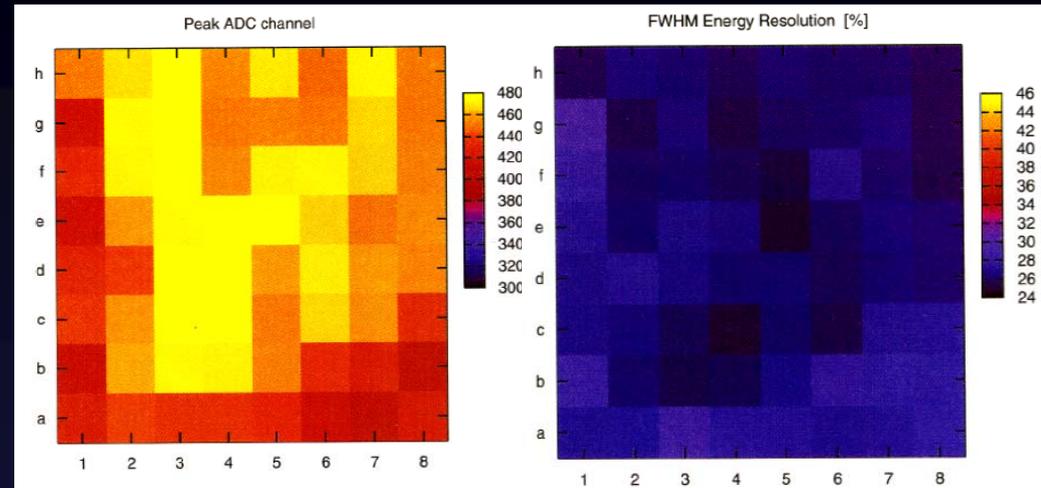
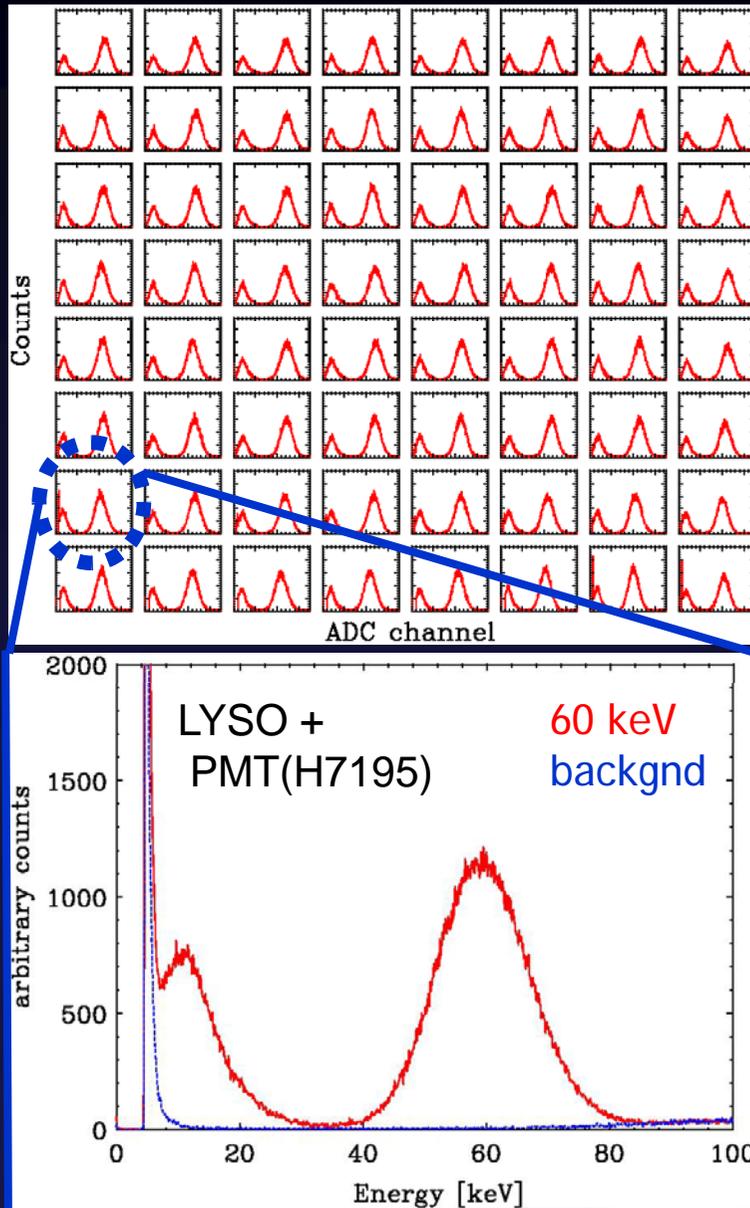
■ LYSO was particularly selected so as to couple w/ the APD-array.

LYSO: 8x8 array
(2.2x2.2x10 mm³)

LYSO: 16x16 array
(1.3x1.3x10 mm³)



Performance of LYSO-array



(a) light yield

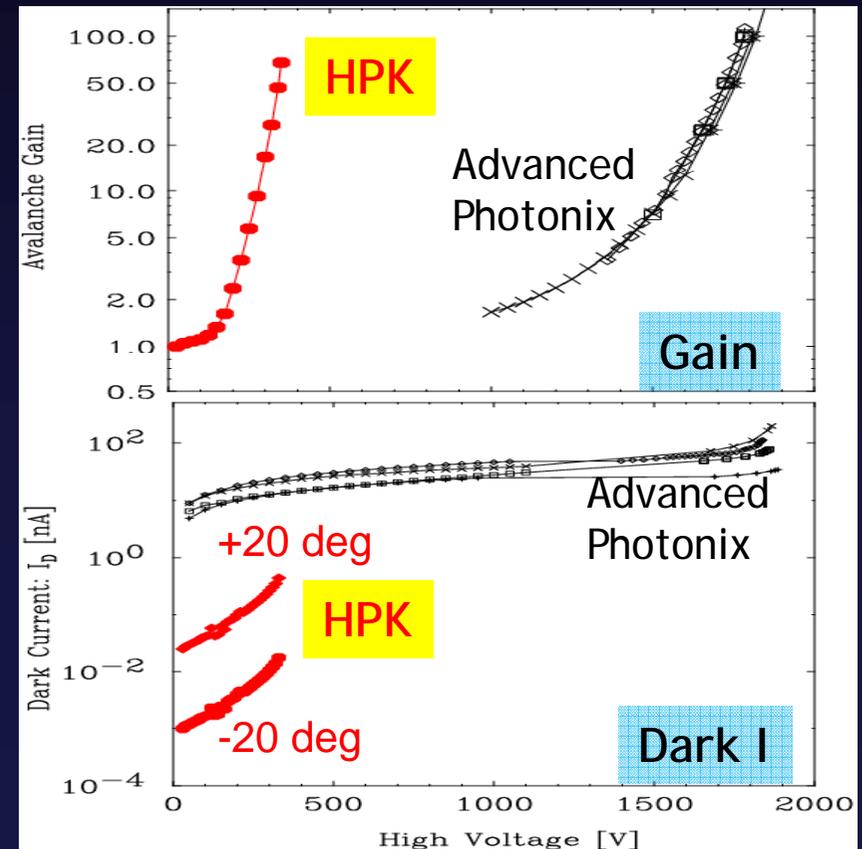
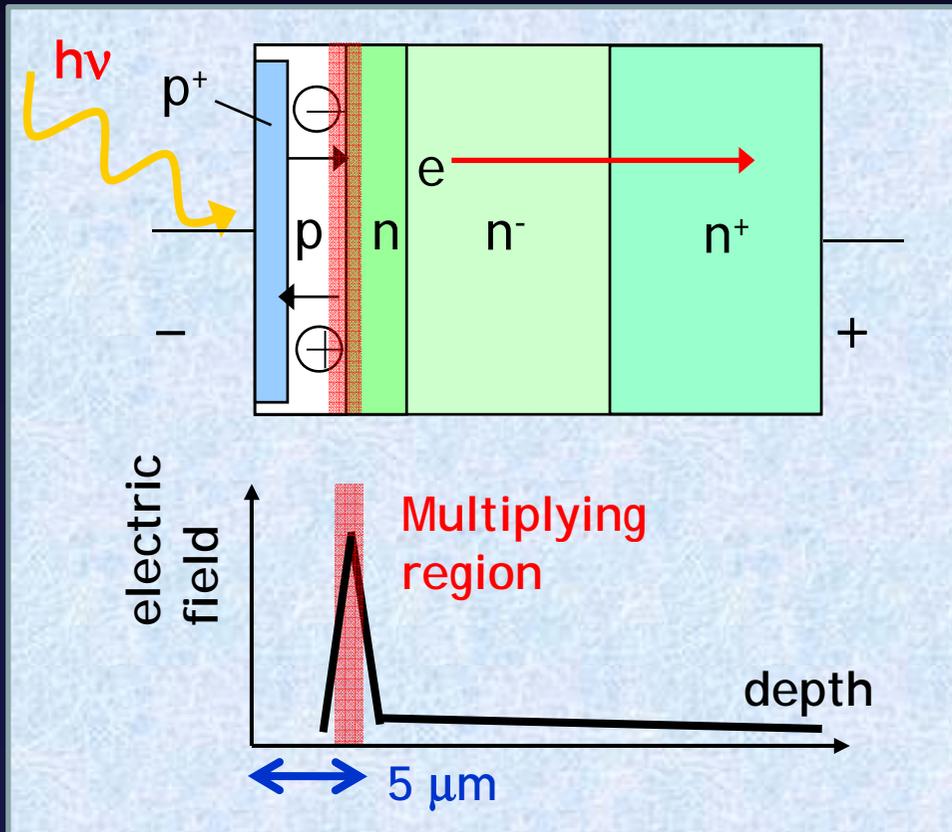
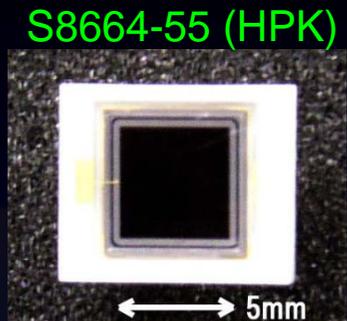
(b) energy resol.

- 60 keV γ -ray scan w/ PMT read-out.
- E-threshold as low as 10 keV.
- Extremely uniform - only <10 % variations in light yield and resolution.

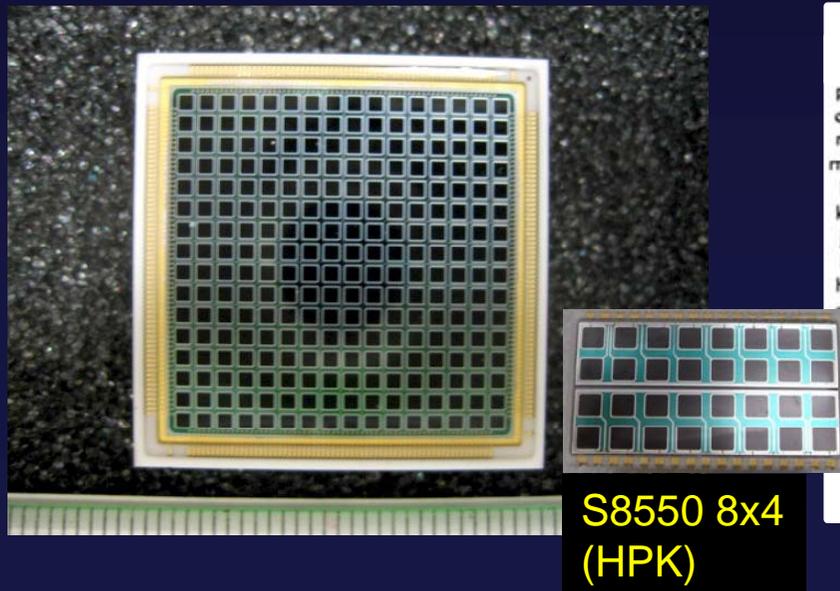
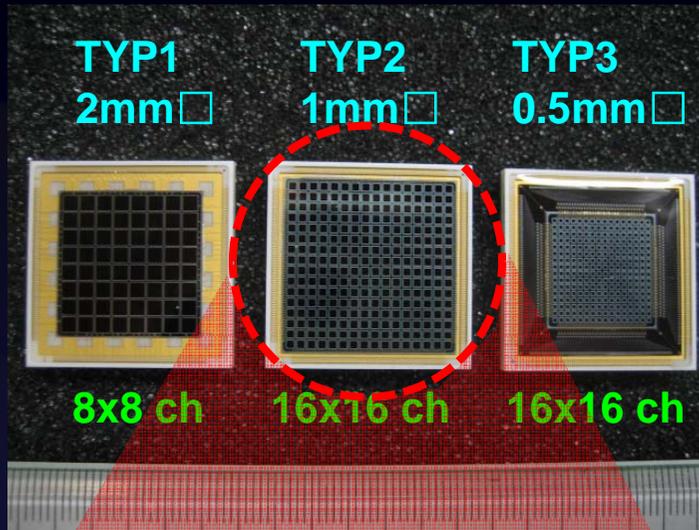
Excellent performance as sensor-head for the APD-array.

Advantage of "Reverse-type" APD

- Narrow high-field multiplying region close to the surface.
 - Low bias operation.
 - Low dark noise (only hole multiplication).
- High QE (> 80%) at $\lambda \sim 500$ nm.
 - Best to be coupled w/ scinti., but only small area available so far.



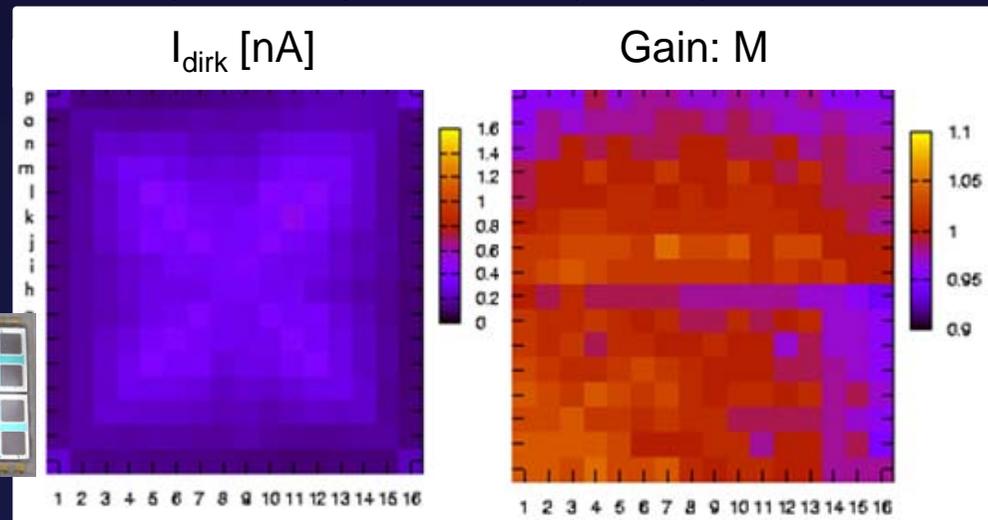
Development of "NEW" APD-arrays



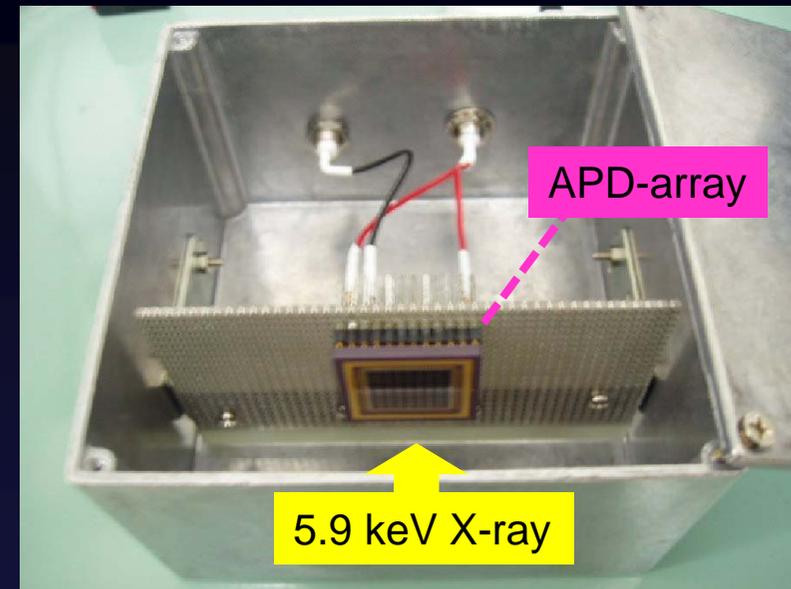
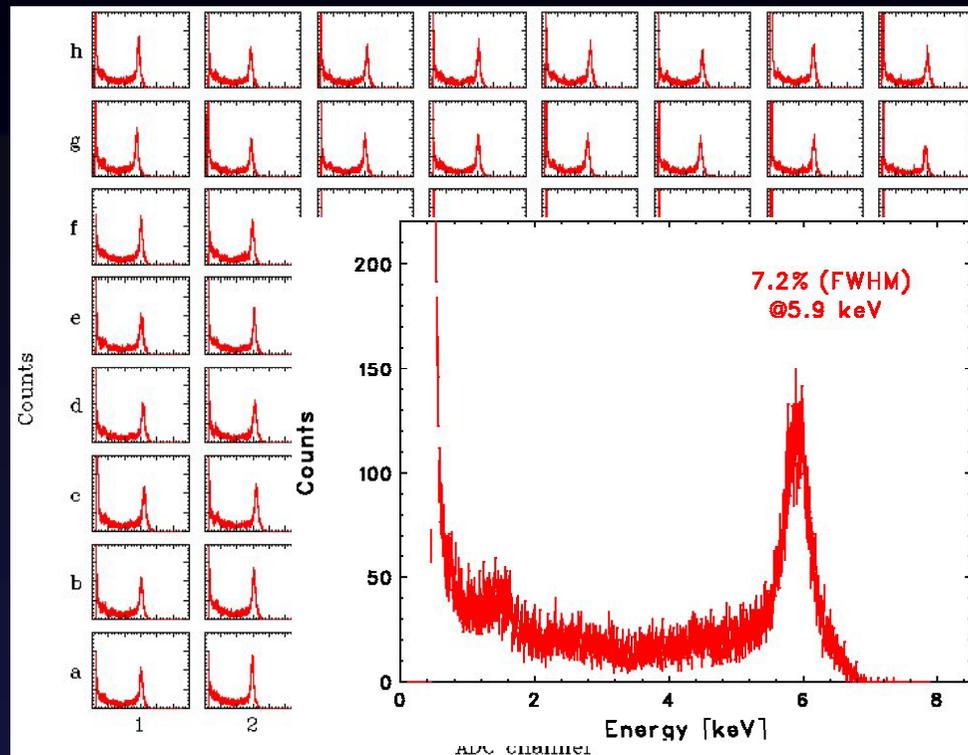
■ New line-up of Hamamatsu APD-arrays;

- low V_{bias} $\Rightarrow M = 50 @ 300\sim 400V$
- low C_{det} $\Rightarrow 4pF/mm^2$
- low I_{dirk} $\Rightarrow < 1nA$
- ΔM (gain) $\Rightarrow < 10\%$

■ Significantly Improve the effective area by reducing the gap: 48 % (S88550) \Rightarrow 76 % (TYP1)

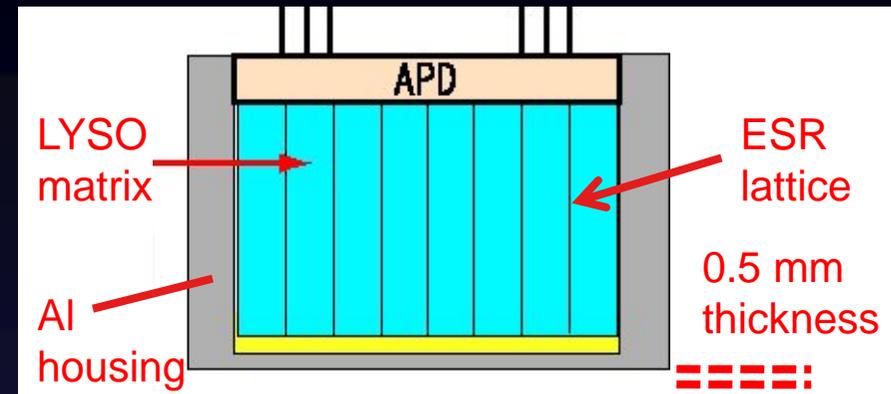
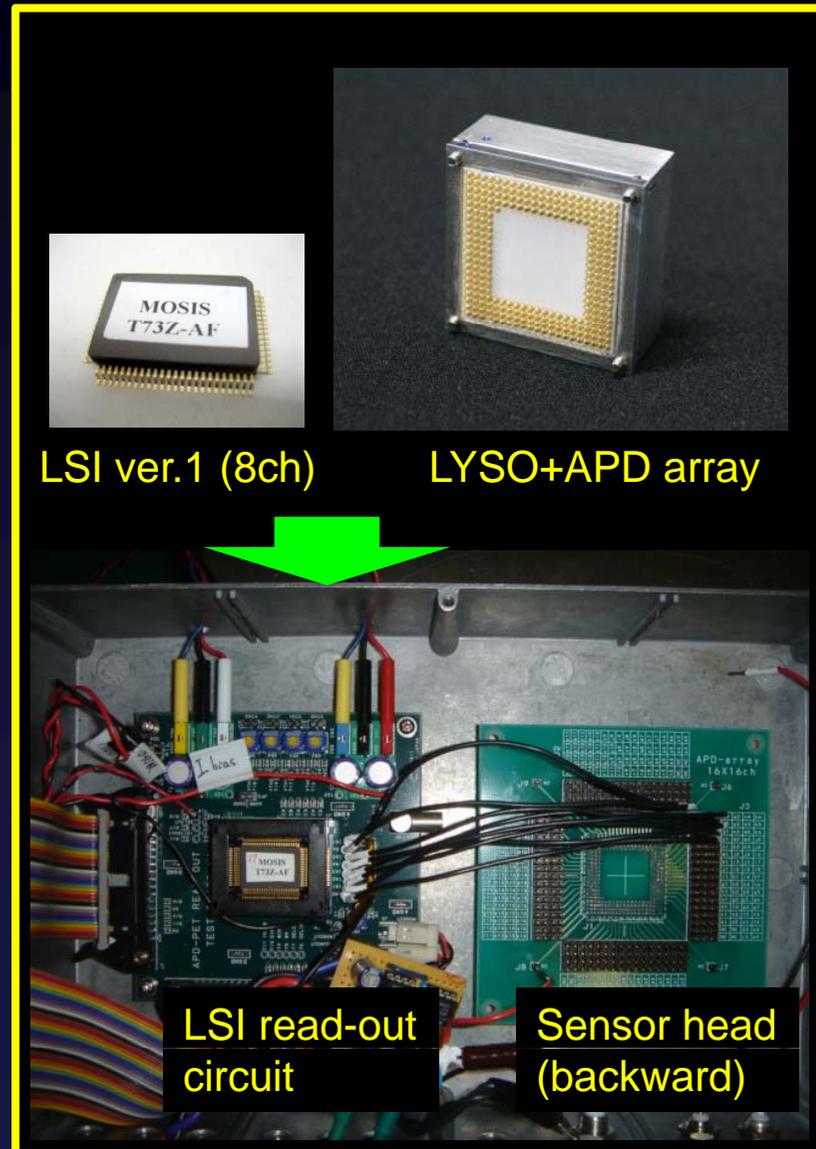


Direct X-ray Detection w/ APD-array



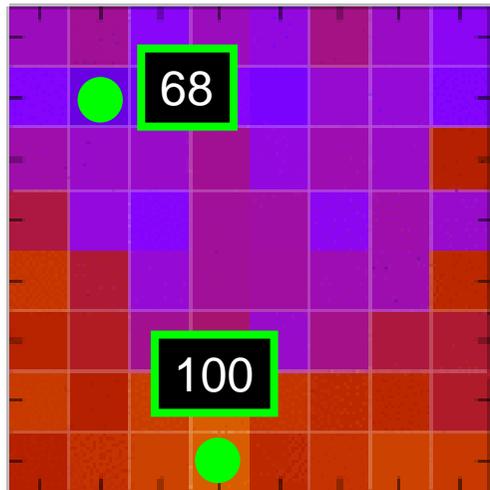
- APD-array was irradiated by a ^{55}Fe source (5.9 keV X-ray).
 - Excellent uniformity over the entire pixel.
 - Energy resolution $7.2 \pm 0.6 \%$ (FWHM) with $E_{\text{th}} \approx 0.6 \text{ keV}$.
- **One drawback** : the device does not allow efficient X-ray detection due to its thin depletion layer ($\sim 10 \mu\text{m}$)
 - other types of APDs preferable (e.g., Moszynski+ 02, Yatsu et al+ 06)

Fabrication of Prototype γ -ray camera

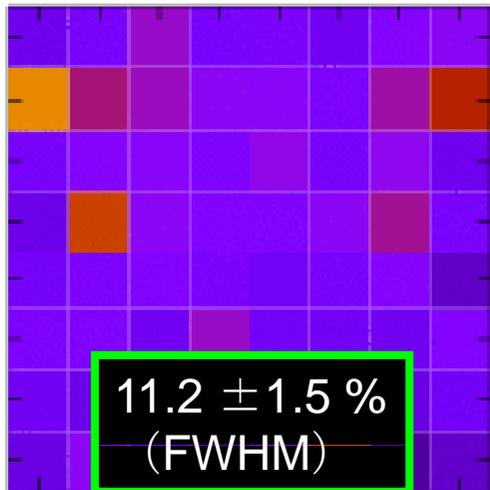


- A prototype gamma-ray camera consists of an **APD-array optically coupled w/ a LYSO matrix**.
 - Divided w/ the lattice of a thin reflective layer (ESR, 65 μm).
 - Signal read-out by a low-noise analog front-end ASIC specifically designed for APD-PET. (next Koizumi talk)

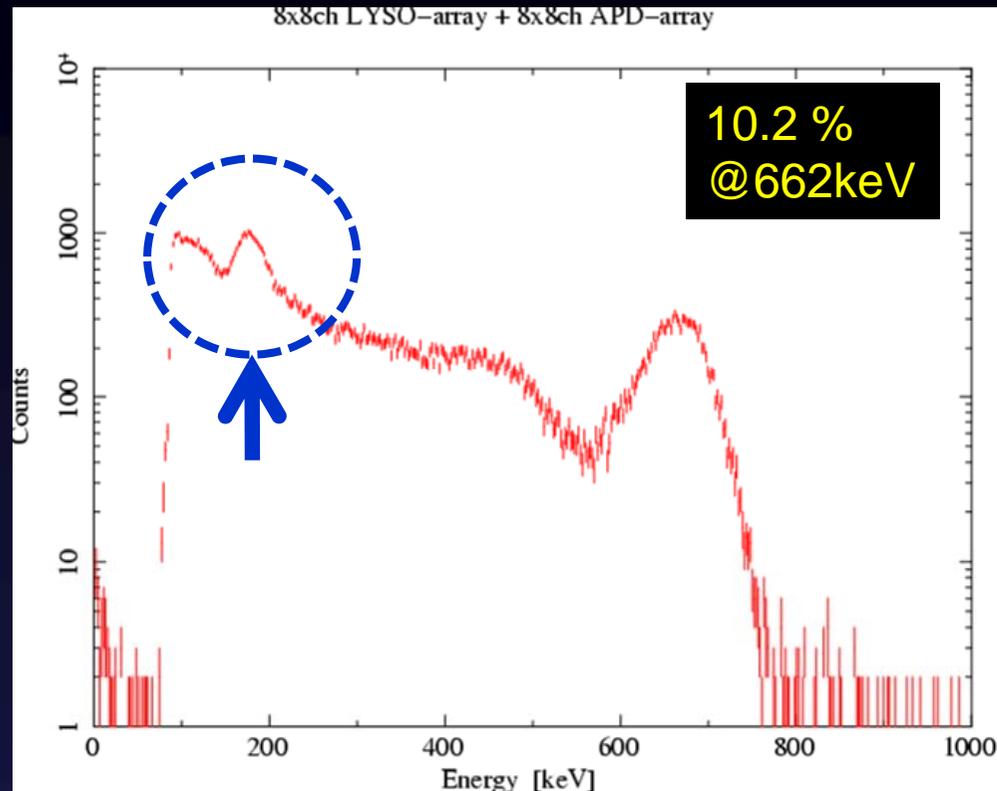
Results: 8x8 γ -ray Camera



Signal amp (APD+LYSO)

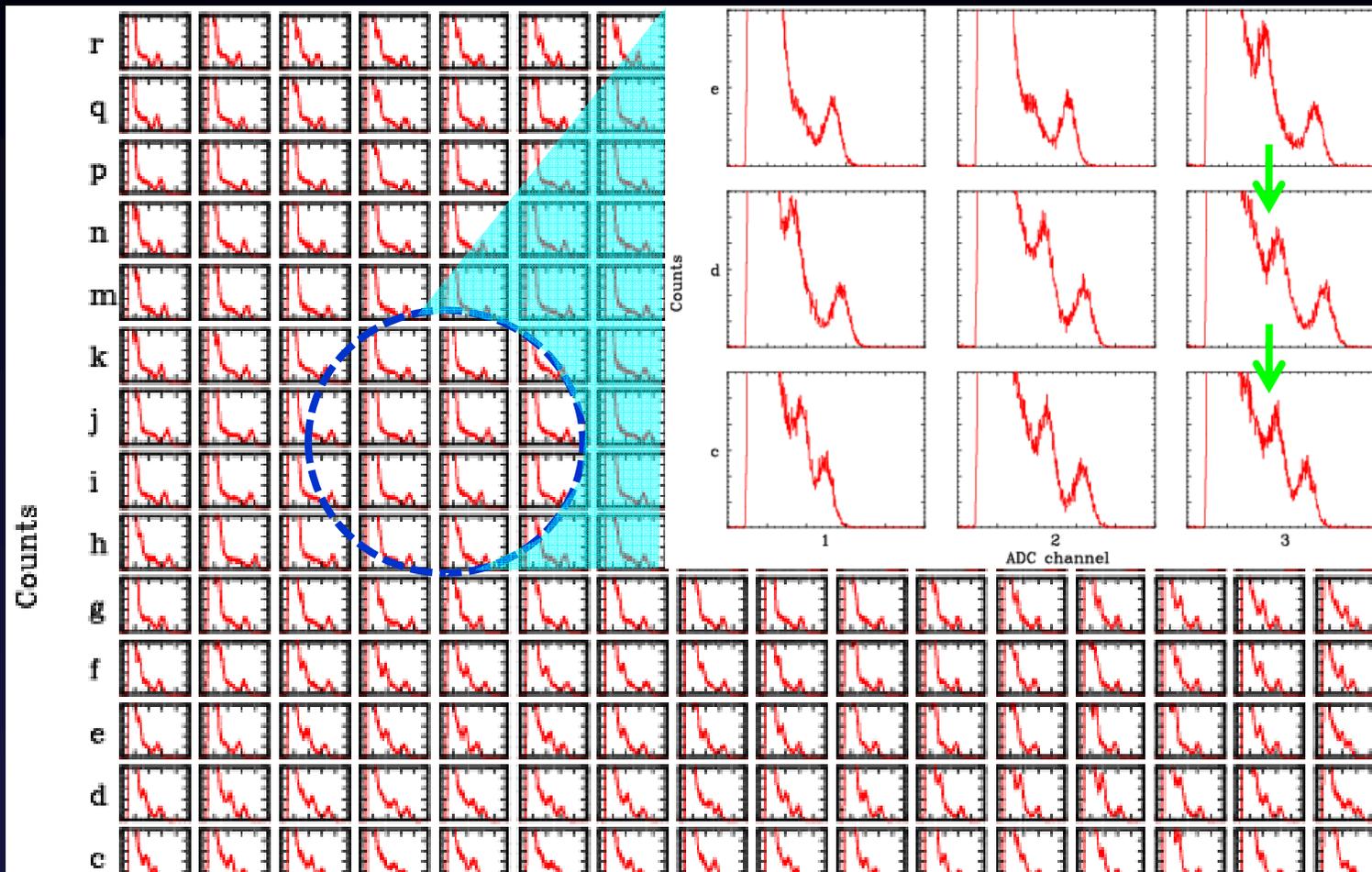


Energy resolution



- The variation in signal amp. is $\pm 16\%$.
 - Inhomog. of APD gain, LYSO light yield.
- A small peak in the spectrum.
 - Cross-talk from neighboring pixel.
 - Actually acceptable for PET imaging.

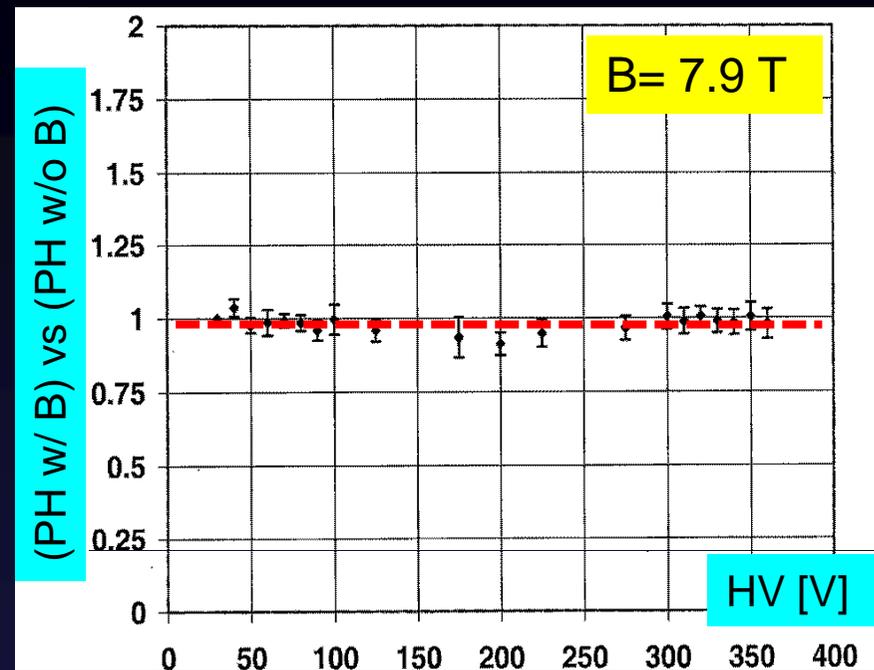
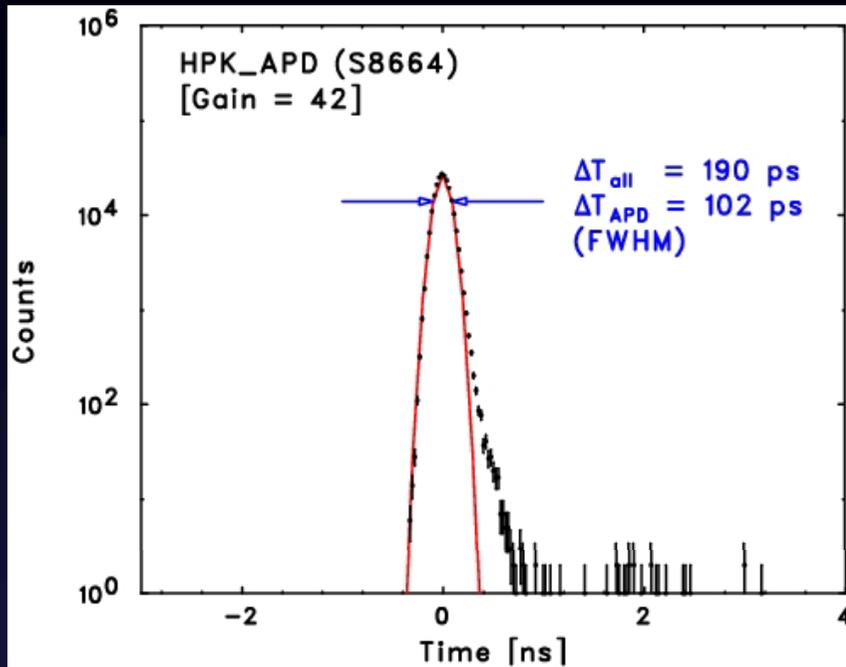
Results: 16x16 γ -ray Camera



- The cross-talk being more serious, due to smaller pixel size.
 - Revised version of APD-arrays w/ a **thin epoxy coating**.
 - Improvement of **mechanical housing** etc.

TOF, MRI-PET...future

Marler et al. 00, Woody et al. 07



- **Timing experiment** on the reverse-type APD at KEK-PF.
 - The direct detection of 16 keV X-rays in single bunch (SB) mode.
 - An excellent time resolution: **102 ps (FWHM)** for a 3mm ϕ pixel.
 - ➔ TOF resolution of **~1.5 cm!**
- Reverse-APD was also exposed to strong B-field at CMS in LHC, Cern.
 - The APD gain is unaffected by the presence of **7.9T B-field**.
 - Similar results reported for APD-array **S8550 (HPK 8x4 array)**.

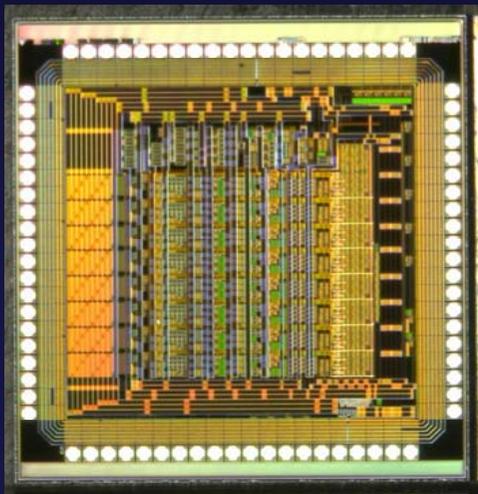
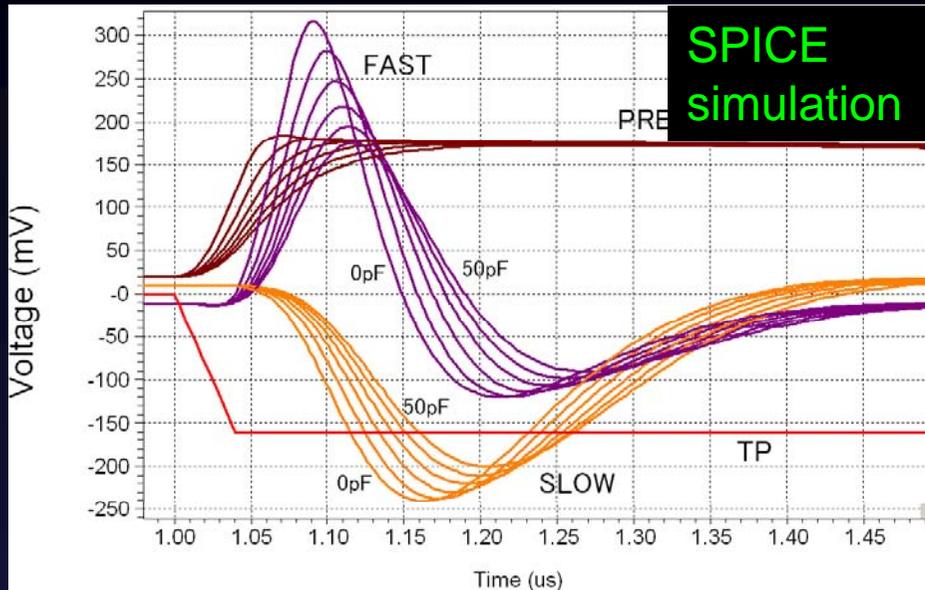
Summary

We have briefly overviewed the designs and performance of large-area APD-arrays recently developed with Hamamatsu Photonics K.K.

- Excellent gain uniformity ($< 10\%$) and low dark-noise ($< 0.3\text{nA}$).
- Energy resolution of 7.2% (FWHM) was obtained for the direct detection of 5.9 keV X-rays, while 10.2% (FWHM) was obtained for 662 keV gamma-rays, when coupled with a LYSO-array.
 - ✓ still a problem on cross-talk due to extremely small pixel size.
- Excellent time resolution of 102 ps (FWHM) and insensitivity to B-field suggests that newly developed APD-arrays offer a promising device for future application in MRI/PET and TOF-PET.

Back-up slides

Analog Front-end ASIC



Development Schedule

R&D (2006.Oct)

- Circuit design
- Detailed simulation

3-month

Layout

- Layout on Si,
TSMC 0.35 μm

2-month

Production/TSMC

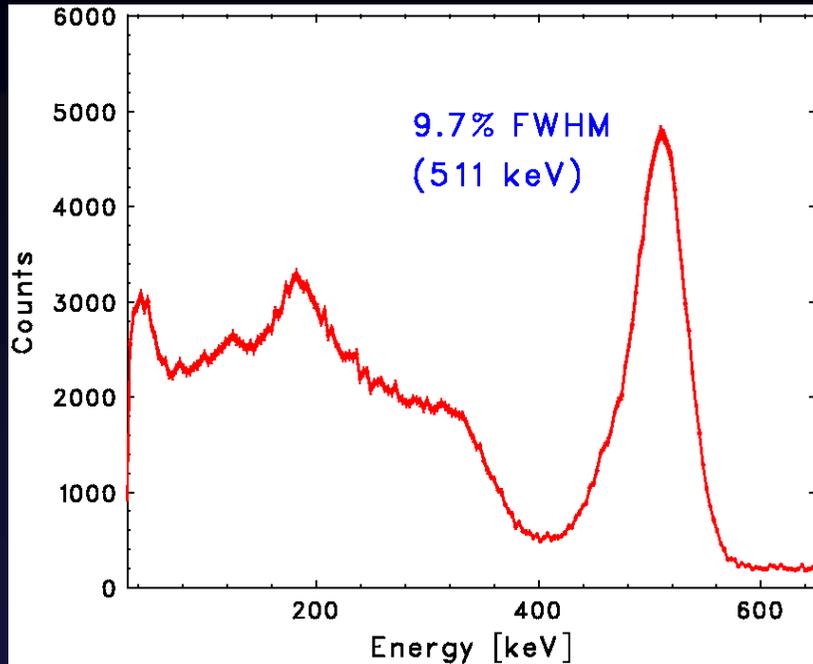
- packaging
- bonding

3-month

Ready! (2007.May)

- ver.1 (8ch ASIC) done!
- ver.2 (32ch w/ improved performance)
now under testing (Koizumi talk)

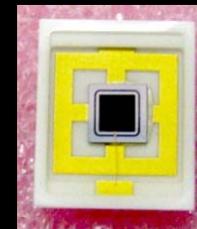
Performance verification



LYSO : 2x2x10 mm³ pixel
APD : 2x2 mm² pixel
LSI : ver.1 (No.30_#2)



LYSO
2mm□



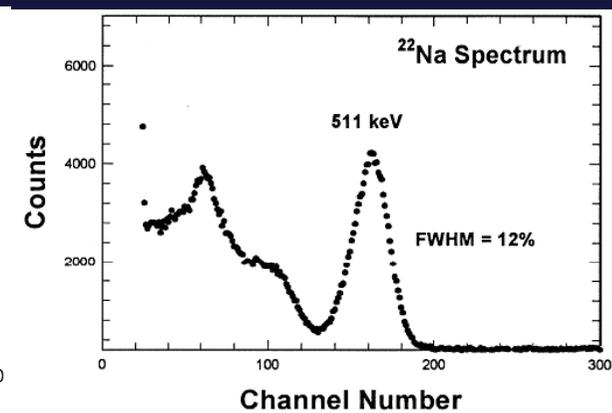
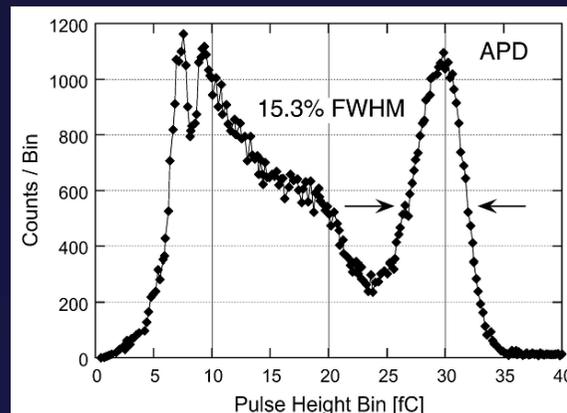
APD
2mm□



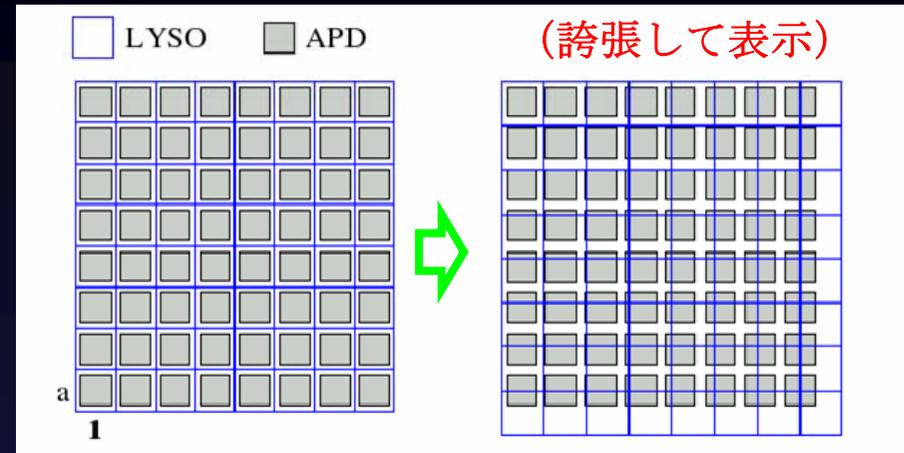
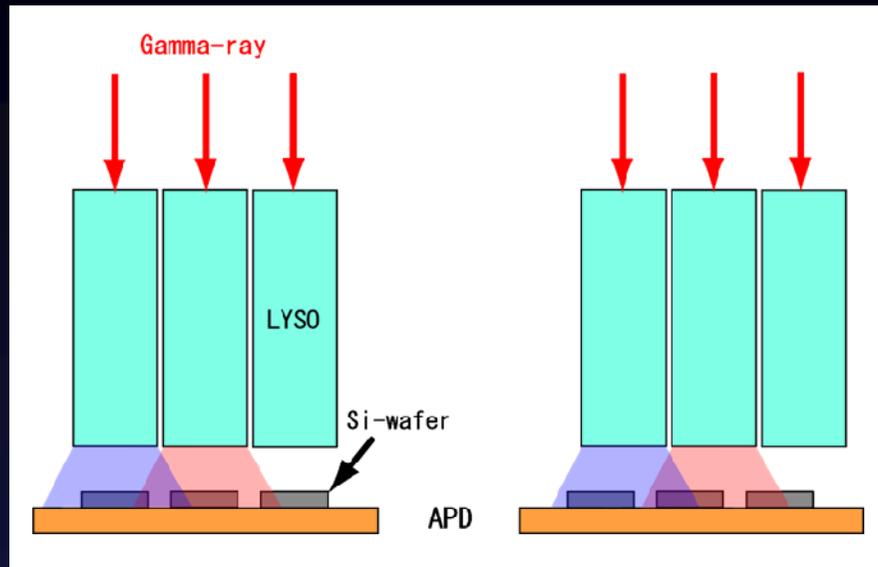
APD-LSI
No.30_#2

■ 9.7% FWHM (@511keV): better than previous tests in literature.

Farrell et al. 00
Pratte et al. 04
Oo et al. 07 ...
12% (@511 keV)



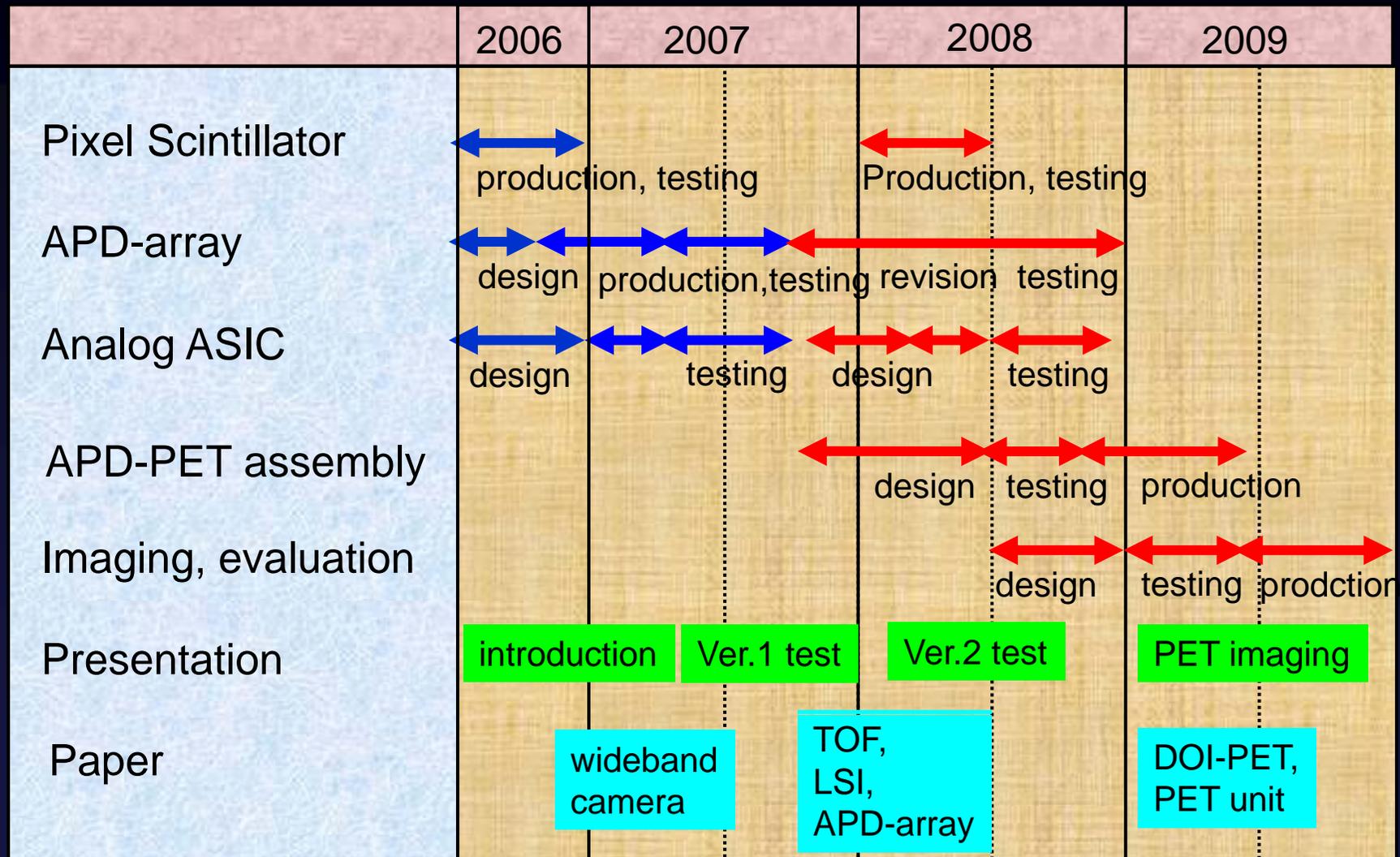
What happens?



- A subtle mismatch between the position of LYSO pixel and corresponding APD pixel.
- The gap/mismatch is only ~ 0.8 mm even at the worst case.
- Since we have 16 pixel arrays, only 0.8 mm/16pix ~50 μm difference for each pixel could account for this problem!

Improved accuracy in fabrication process, as well as very careful assembling necessary in the revised version.

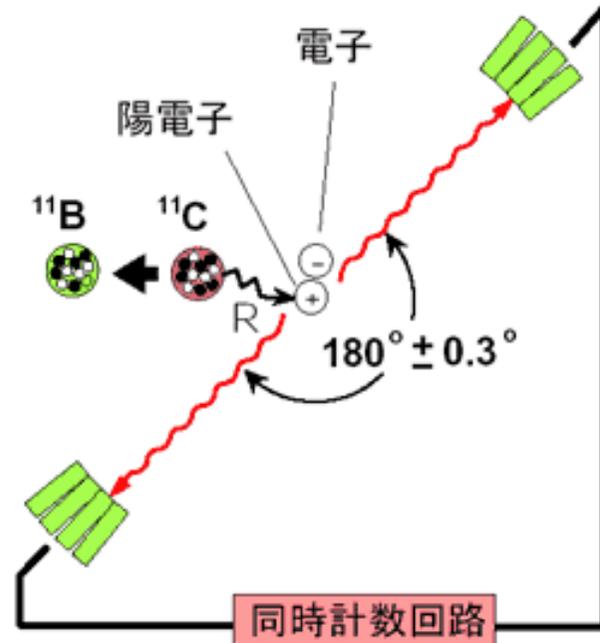
Schedule



Limit for PET imaging

Range of e⁺ in body

核種	陽電子の最大エネルギー (MeV)	誤差 R
¹¹ C	0.961	0.28 mm
¹³ N	1.20	0.60 mm
¹⁵ O	1.73	1.1 mm
¹⁸ F	0.634	0.22 mm
⁶⁸ Ga	1.90	1.4 mm



■ Range of e⁺.



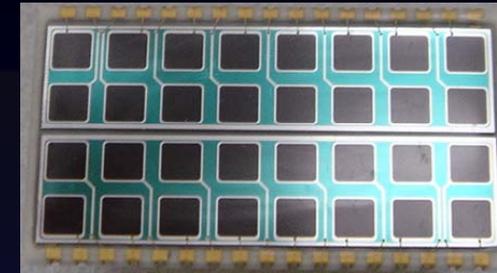
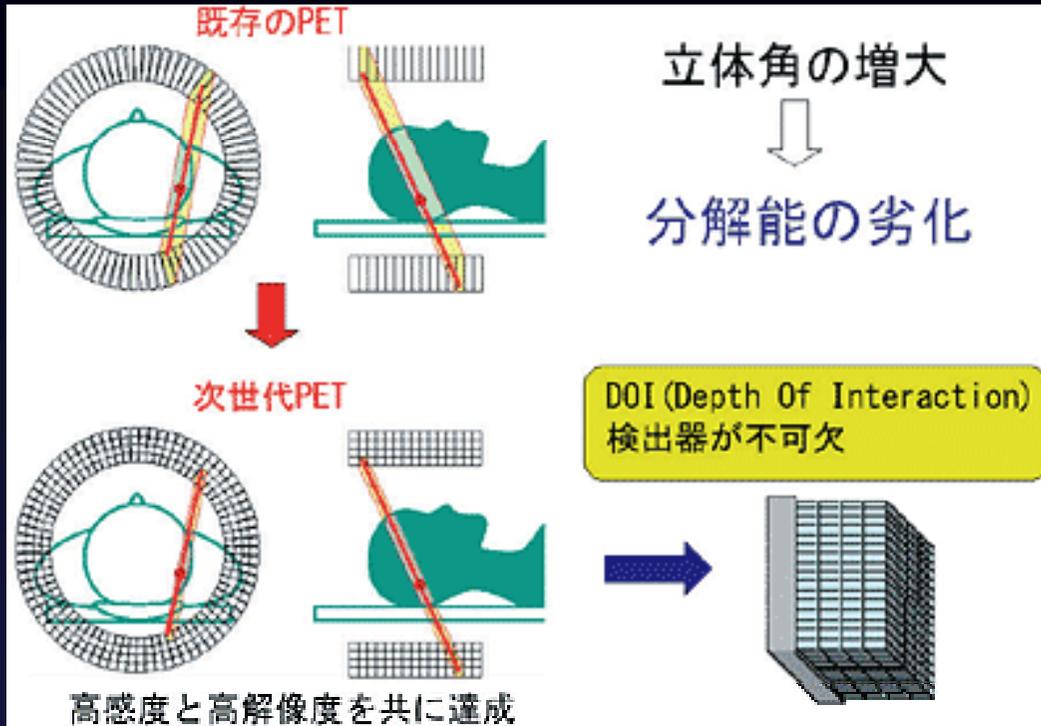
■ Noncollinearity of 511 keV directions.



■ Theoretical limit on image w/ PET.

model	Diameter	Resolution (FWHM)
animal	10 cm	0.3 mm
head	30 cm	0.9 mm
body	60 cm	1.8 mm

DOI application? (1)

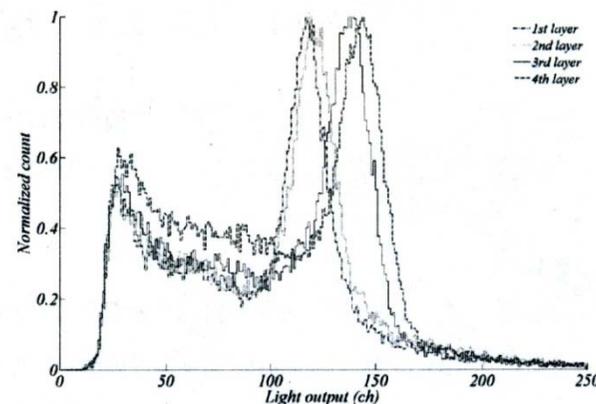
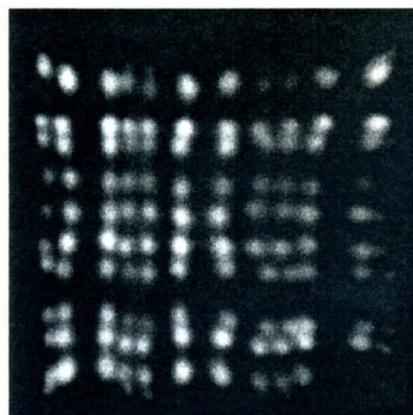


APD-array S8550 (32ch array)

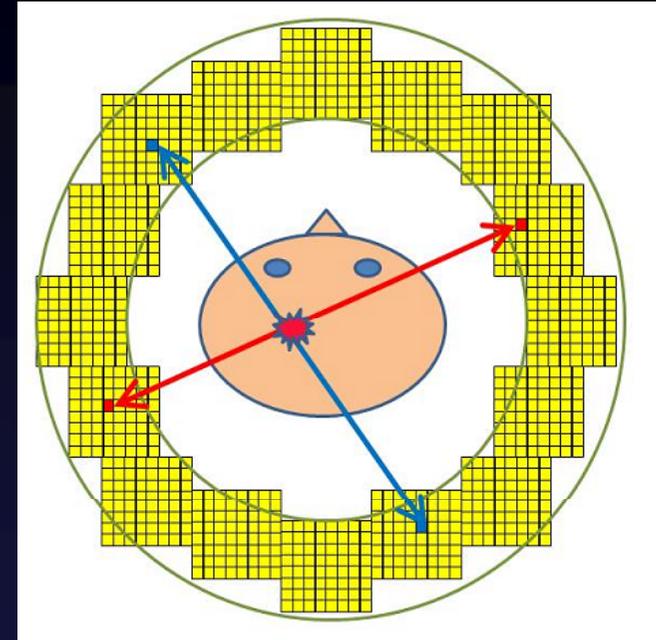
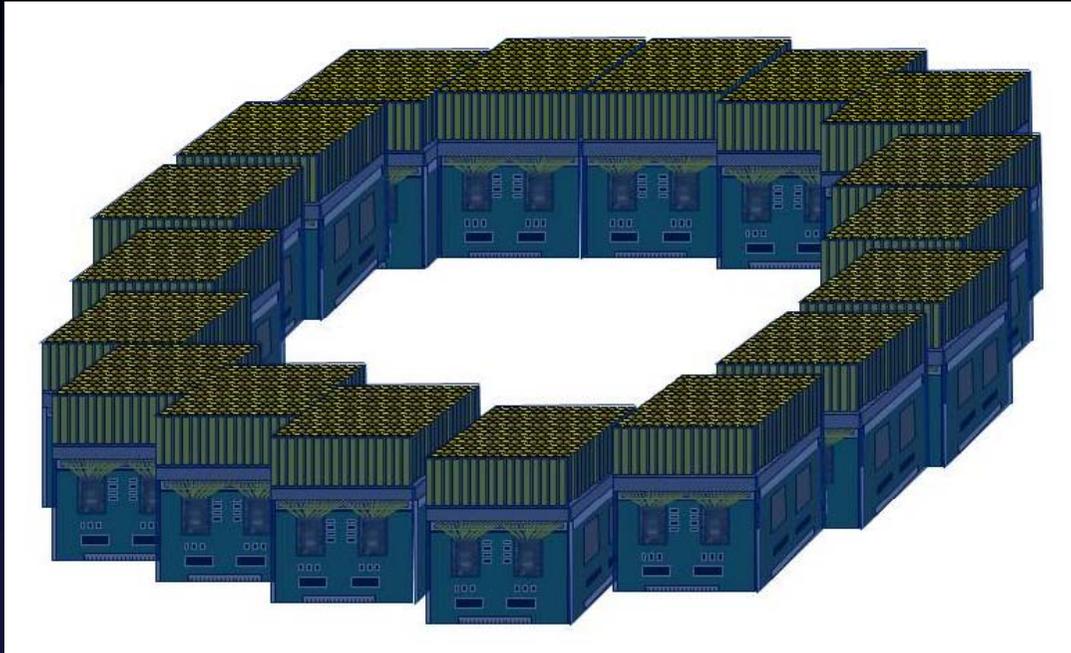
- A prototype was tested by jPET-D4 team at National Inst. of Radiological Sci, using APD-array S8550.



Four-layer DOI detector was successfully operated, which provides excellent image as those obtained with MAPMT.



DOI application? (2)



- make a ring of APD-PET unit, but in “vertical direction”.



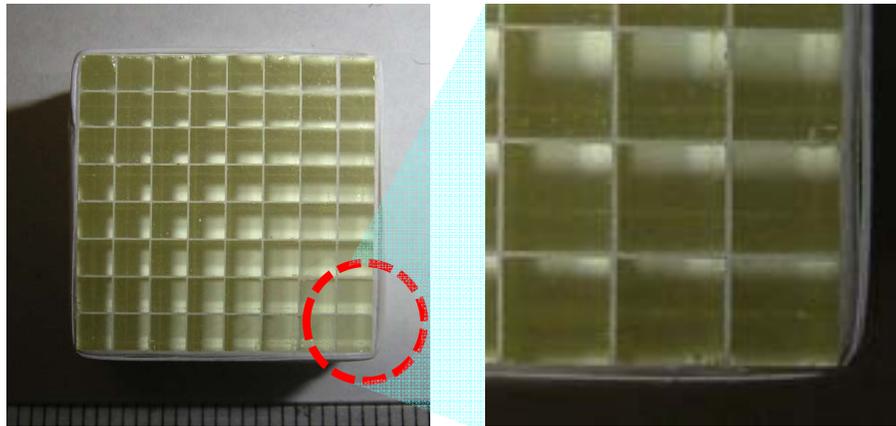
- Image resolution is determined by pixel cross section, not by the length of scintillator.

- Demerit is that, the detector depth is limited to ~ a few cm, which is determined by a scintillator length.



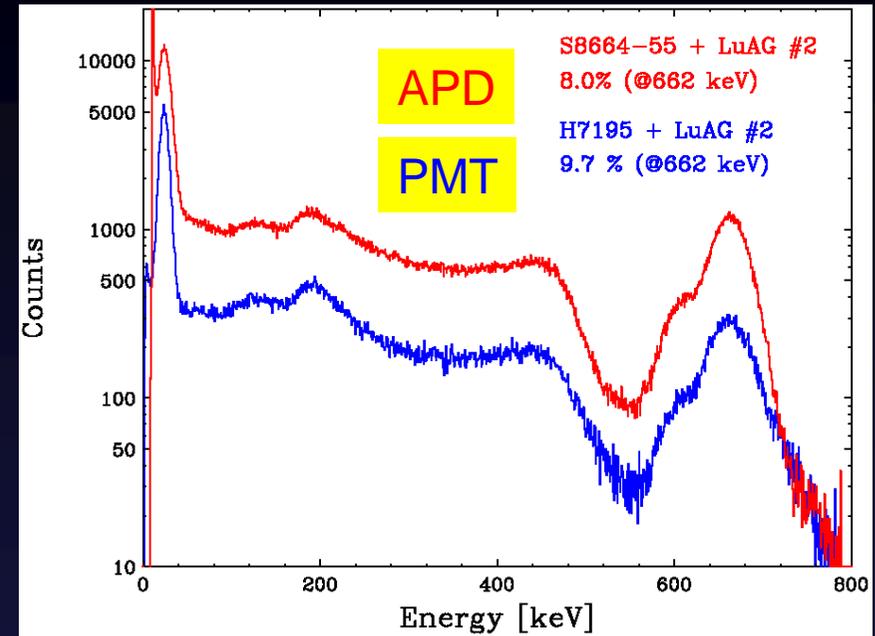
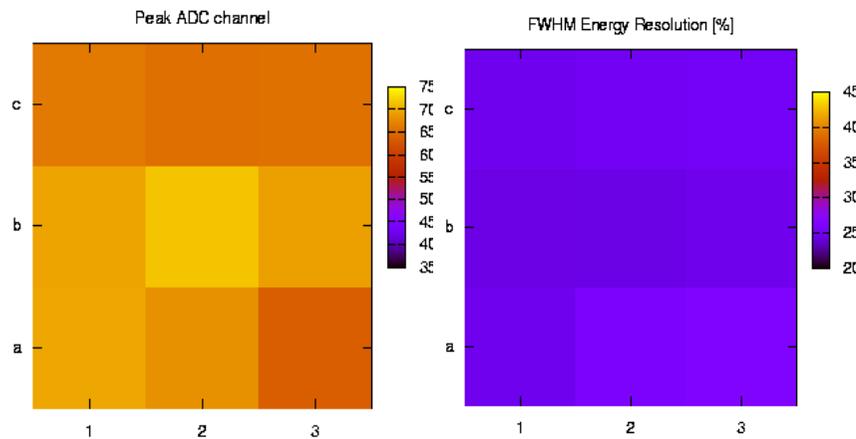
- light sharing, multiple PET arrays?

Pr:LuAG array



(1) Light yield

(2) E-resolution



- Developed in Tohoku U.
- Low cost.
- decay time : 20 ns
- lumi. l : 310 nm

8x8, 16x16 arrays being
fabricated & tested