LIQUID XENON TPC R&D IN KEK

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IPNS, KEK

25/Nov/2010 BINP-KEK Joint Workshop on Liquid TPC

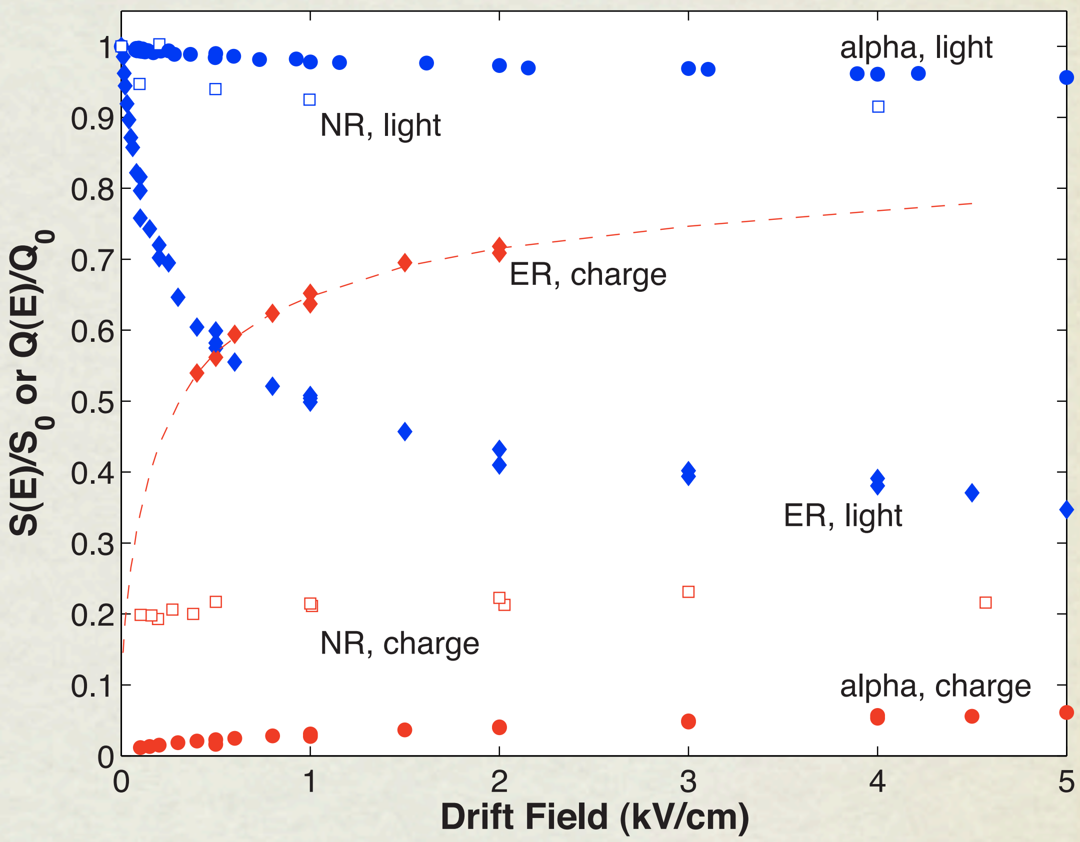
OUTLINE

- Introduction
- Liquid Xenon TPC development at KEK
  - Application to PET
    - Prototype R&D
- Summary

INTRODUCTION

LXETPC PROJECT

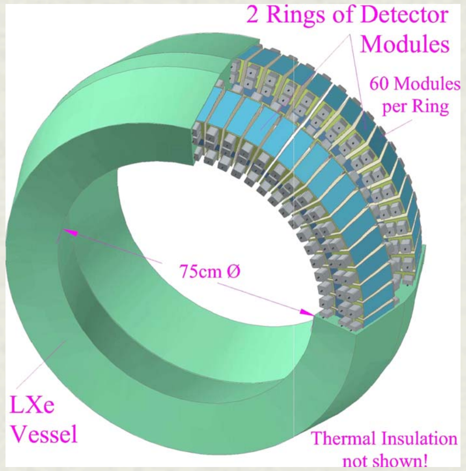
- Detection of KeV-MeV “gammas” with 3D position reconstruction, and high resolution energy measurement
    - Since April 2007 as one of KEKDTP projects
- Possible applications:
    - Gamma-ray astronomy
    - Dark matter search
    - Neutrinoless double beta decay search
    - Single Photon Emission Computed Tomography (SPECT)
    - **Positron Emission Tomography (PET)**

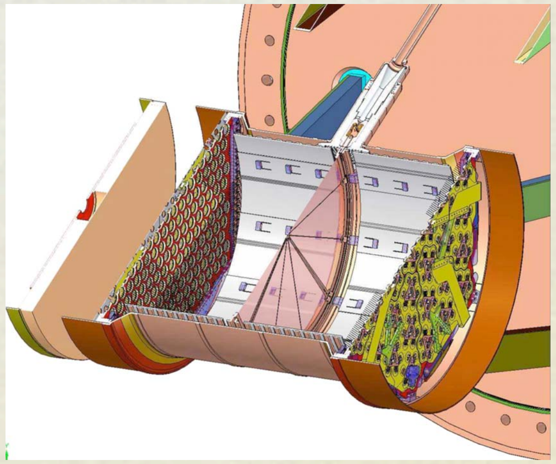


Aprile et al. 2006

APPLICATION AND ENERGY RANGE

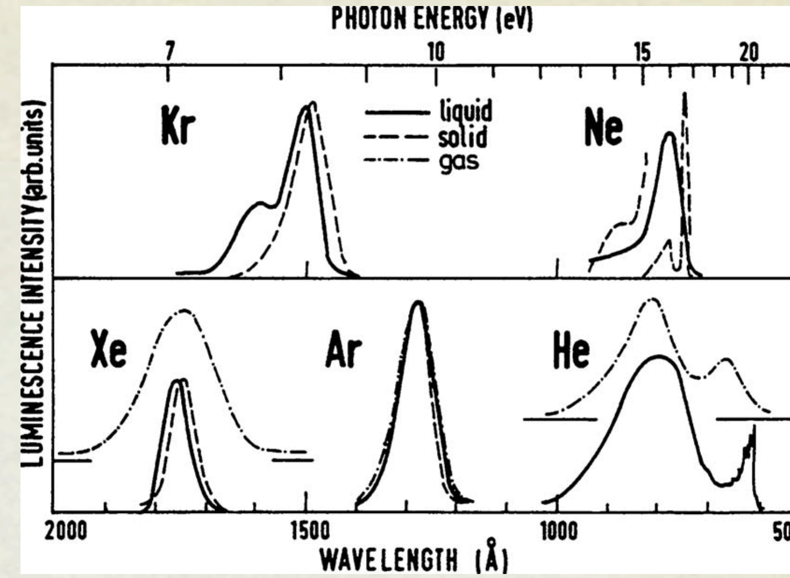
- 10KeV - 10 MeV: Gamma-ray astronomy
- 10KeV: Dark matter search
- 100KeV: Solar neutrino
- 1KeV - 300KeV: SPECT
- **511KeV: PET**
- 2.48MeV: neutrinoless double beta decay



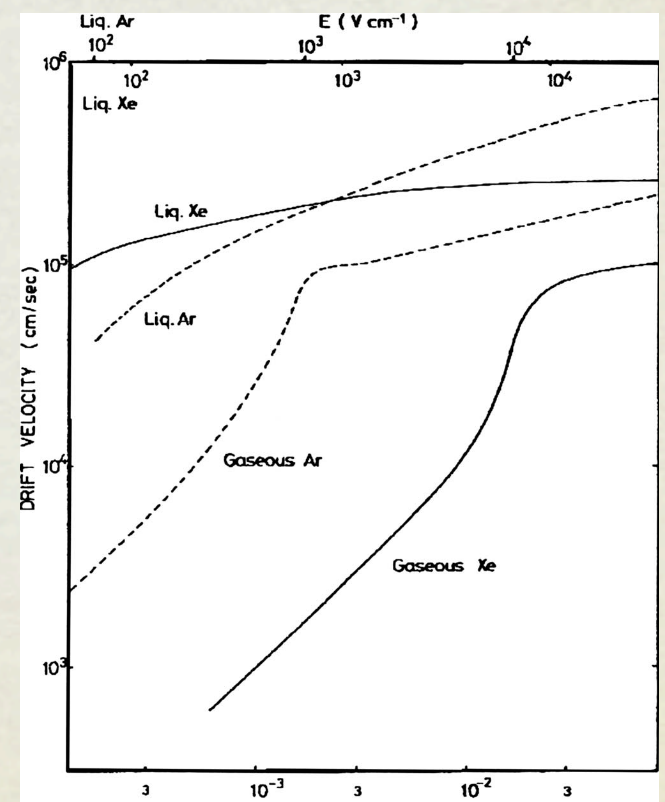


LIQUID XENON AS DETECTOR MEDIUM

- 3 g/cm^3, 165.05 K (1 atm)
- R.L.=2.77cm, R_M = 5.6cm
- Scintillation
  - 170-180 nm wave length
  - W_{ph} = 17.9 eV for α and 21.6 eV for β
- Ionization
  - W = 15.6 eV
  - Drift velocity saturates around 2x10^5 cm/sec



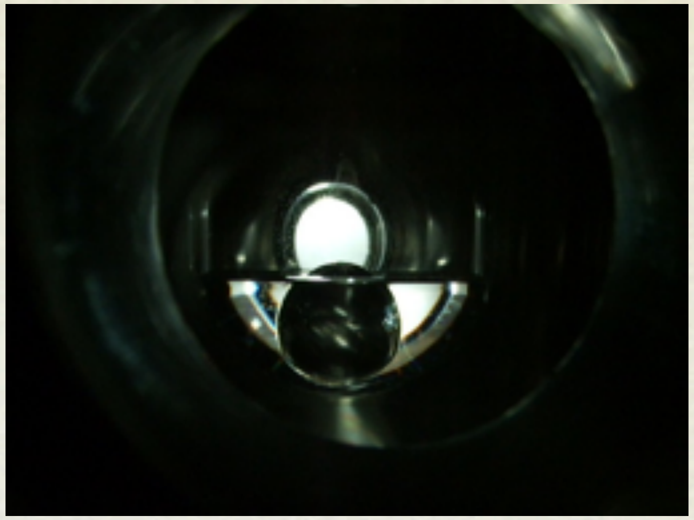
Jortner et al., 1965, Schwenter et al. 1985



Pack et al., 1962, Miller et al. 1968, Yoshino et al. 1976

NIR SCINTILLATION OBSERVATION TEST

- Proposed by Prof. Nakamura of YNU
  - Planning a test in Dec. 2010
  - Photo device selection



種類	素材	型番	メーカー	受光面[mm]	受光面積[mm^2]	感度波長[nm]	ゲイン[M]	受光感度[A/W]
APD	InGaAs	G8931-04	浜松ホトニクス	Φ0.04	1.26E-03	950~1700	10	0.9@1550nm
APD	InGaAs	G8931-20	浜松ホトニクス	Φ0.2	3.14E-02	950~1700	10	0.9@1550nm
APD	InGaAs	KPDEA005-56F	京セミ	Φ0.055	2.37E-03	-	10	0.95@1310nm
APD	InGaAs	KPDEA007-56F	京セミ	Φ0.075	4.42E-03	-	10	0.90@1310nm
APD	InGaAs	59688-L	エドモンド	Φ0.08	5.02E-03	1000~1650	25	1@1550nm
APD	InGaAs	59689-L	エドモンド	Φ0.2	3.14E-02	1000~1650	25	1@1550nm
APD	InGaAs	NR6800EZ	ルネサス	Φ0.08	5.02E-03	950~1650	50	0.94@1310nm

種類	素材	型番	メーカー	受光面[mm]	受光面積[mm^2]	感度波長[nm]	ゲイン[M]	受光感度[A/W]
APD	Si	S8890-02	浜松ホトニクス	Φ0.2	3.14E-02	400~1100	100	70@940nm
APD	Si	S6045-01	浜松ホトニクス	Φ0.2	3.14E-02	400~1000	100	50@800nm

WHAT IS IMPORTANT IN A PET SYSTEM?

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- Quality of Image !

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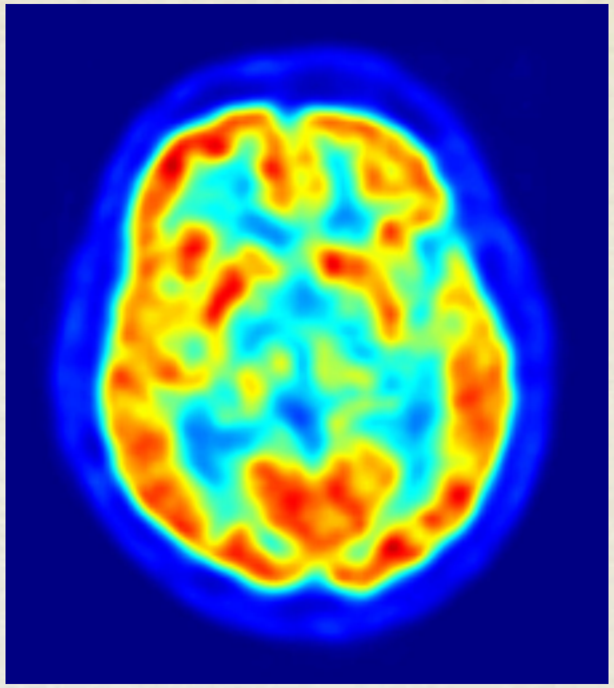
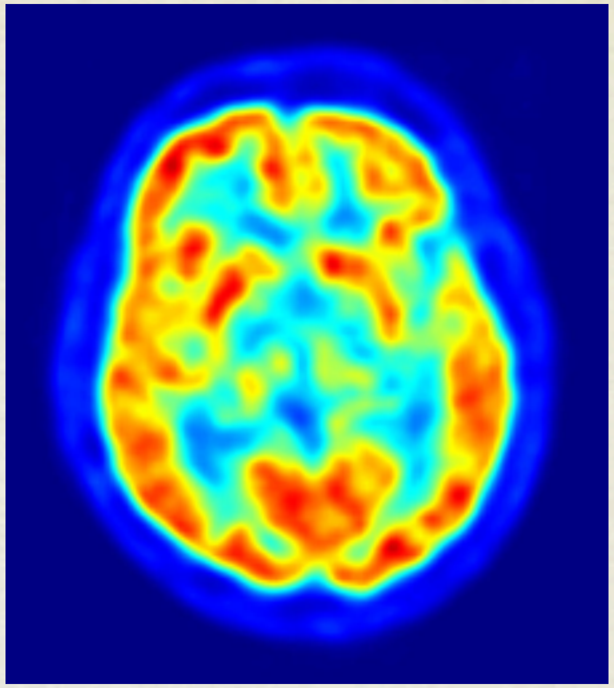


WHAT IS IMPORTANT IN A PET SYSTEM?

- Quality of Image !
- What limits the image quality?
  - Positron travels certain distance
  - 511 KeV gamma rays are not co-linear



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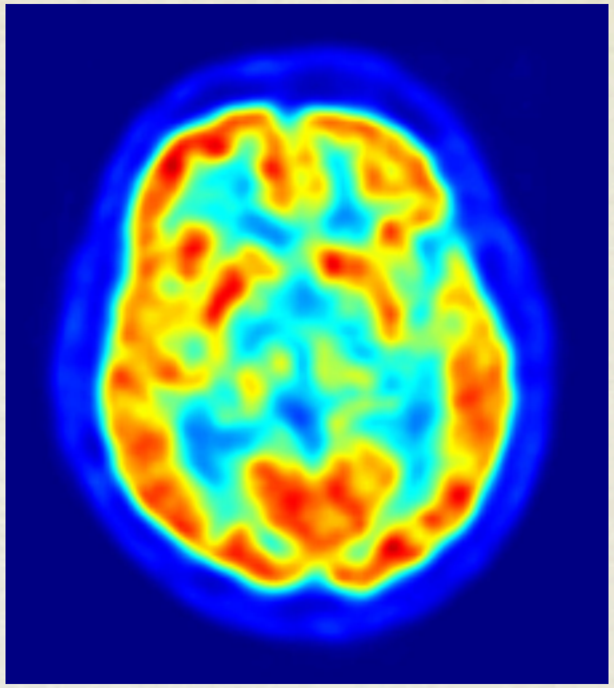

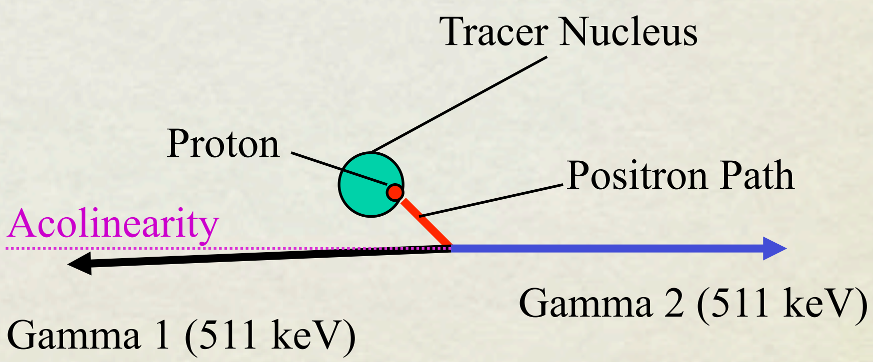

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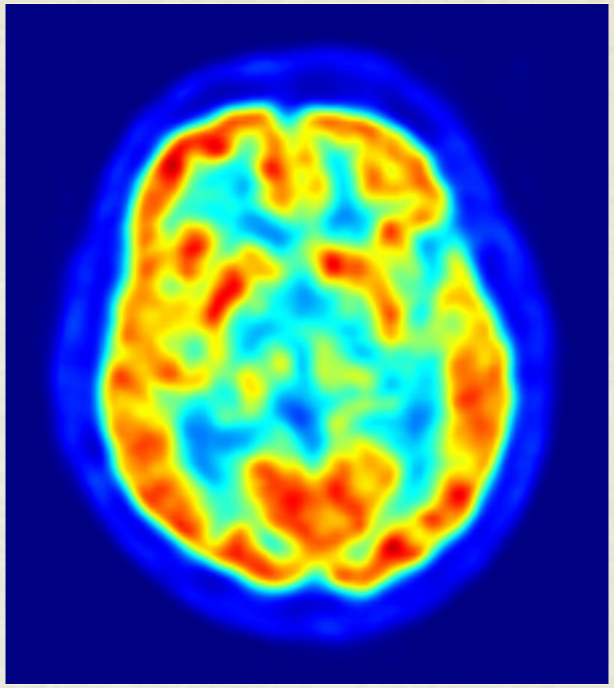
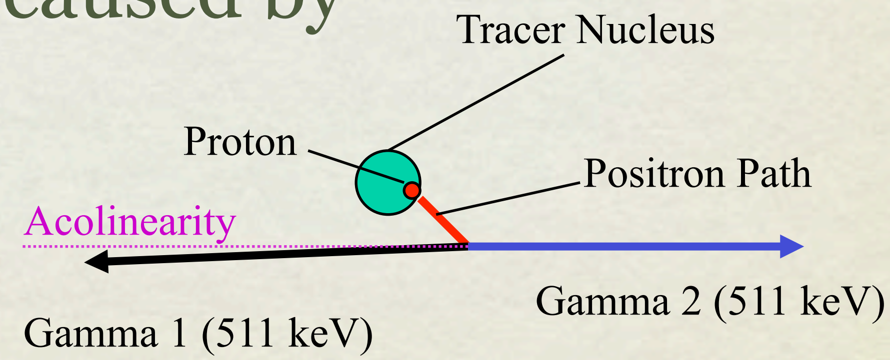


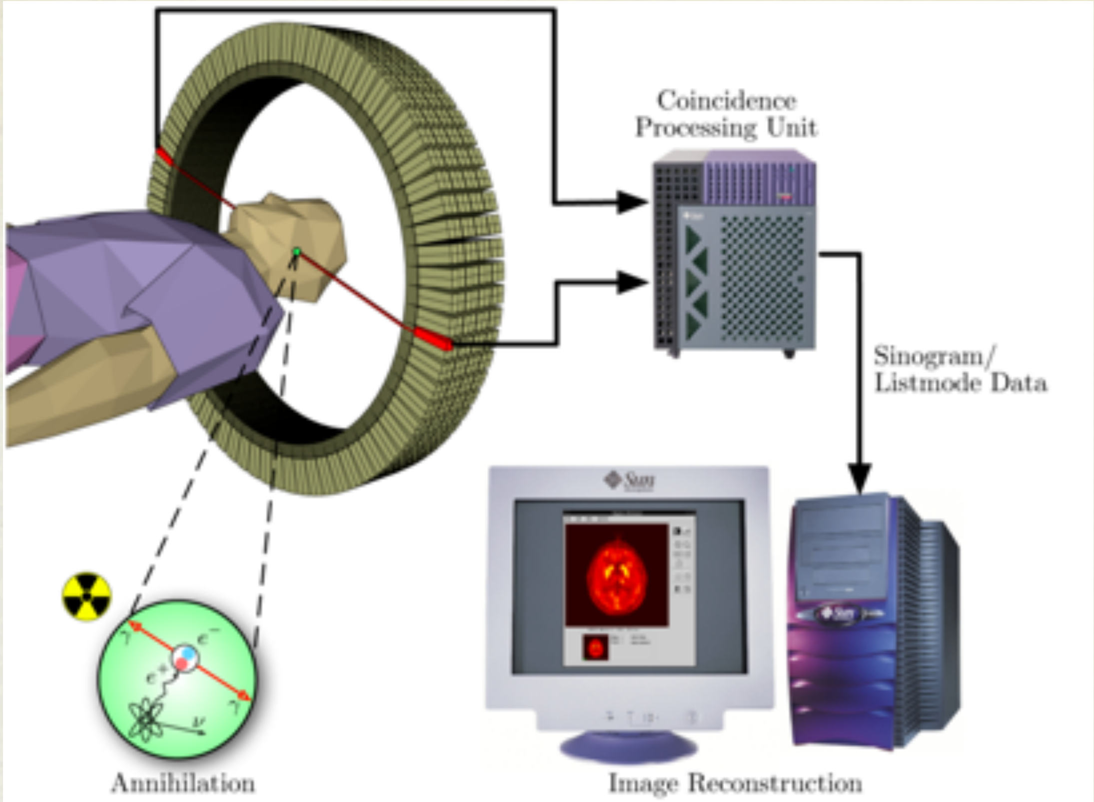
- Quality of Image !
- What limits the image quality?
  - Positron travels certain distance
  - 511 KeV gamma rays are not co-linear
- Necessary to reduce a “gray” background caused by
  - Random coincidence background
  - Gamma-ray scattering



Giboni KEK Seminar

POSITRON ANNIHILATION

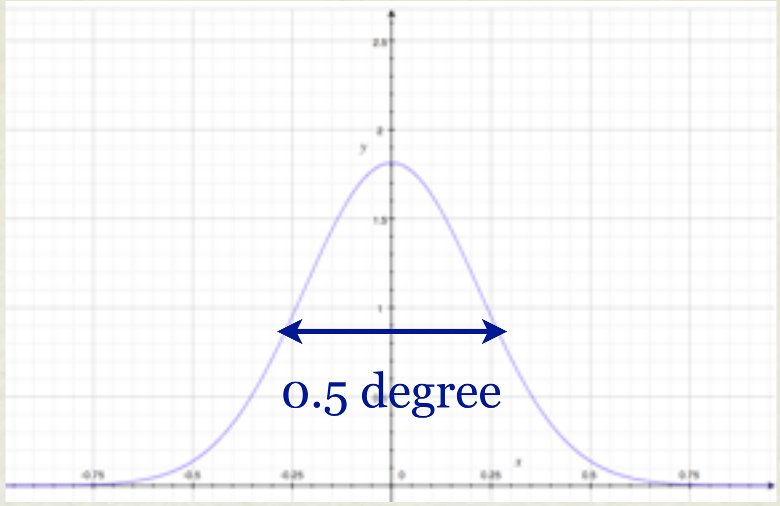
- Positron emission in unstable tracer nucleus
- The positron travels and annihilates with an electron
- The motion of the electron introduces an perpendicular momentum

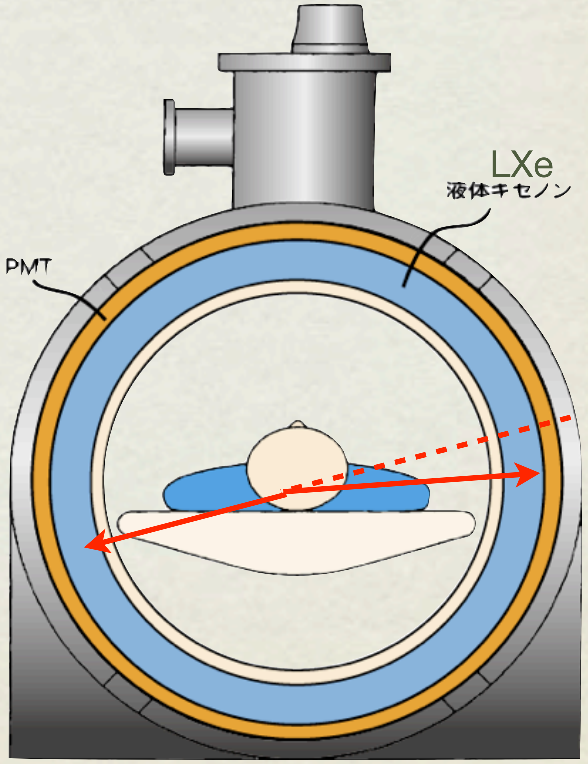


Isotope	Emax[MeV]	Path[mm]
C	0.959	5.0
N	1.197	5.4
O	1.738	8.2
F	0.633	2.4

NON-CO-LINEAR GAMMA RAYS

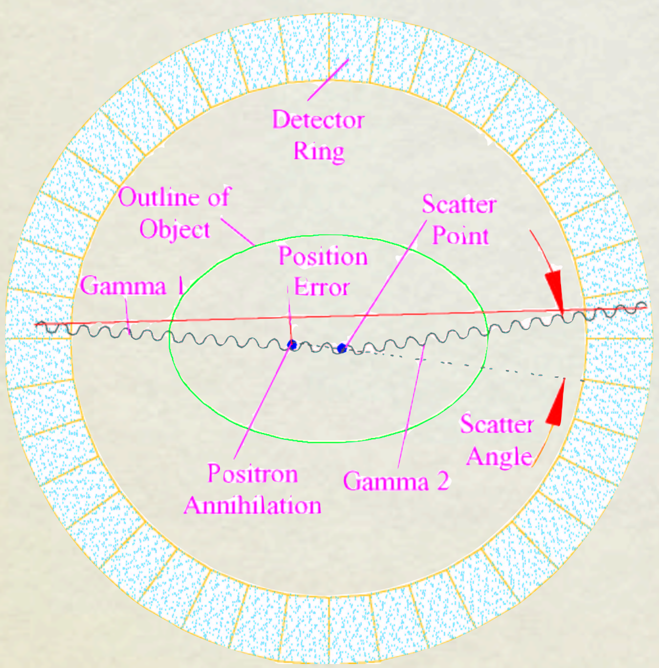
- Suppose acolinearity has a normal distribution FWHM of 0.5 degree
- This, along with positron path in the body, provides uncertainty of 4-5 mm at the detector
- Further improvement of the PET performance can be realized by other improvement than position reconstruction





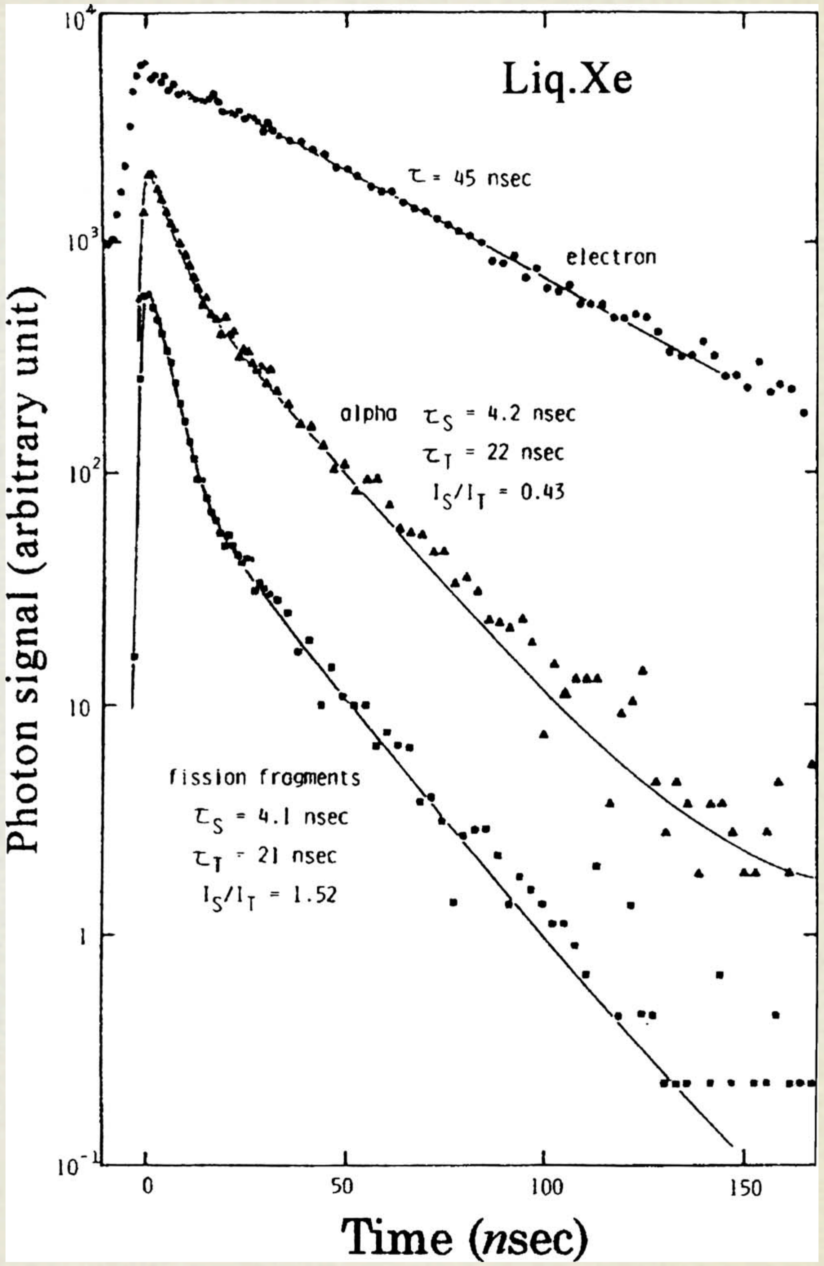
BACKGROUND REJECTION

- Reduce a “gray” background !
- Background sources
  - Accidental pileup
  - Gamma-ray scattering



Energy of Scattered gamma ray

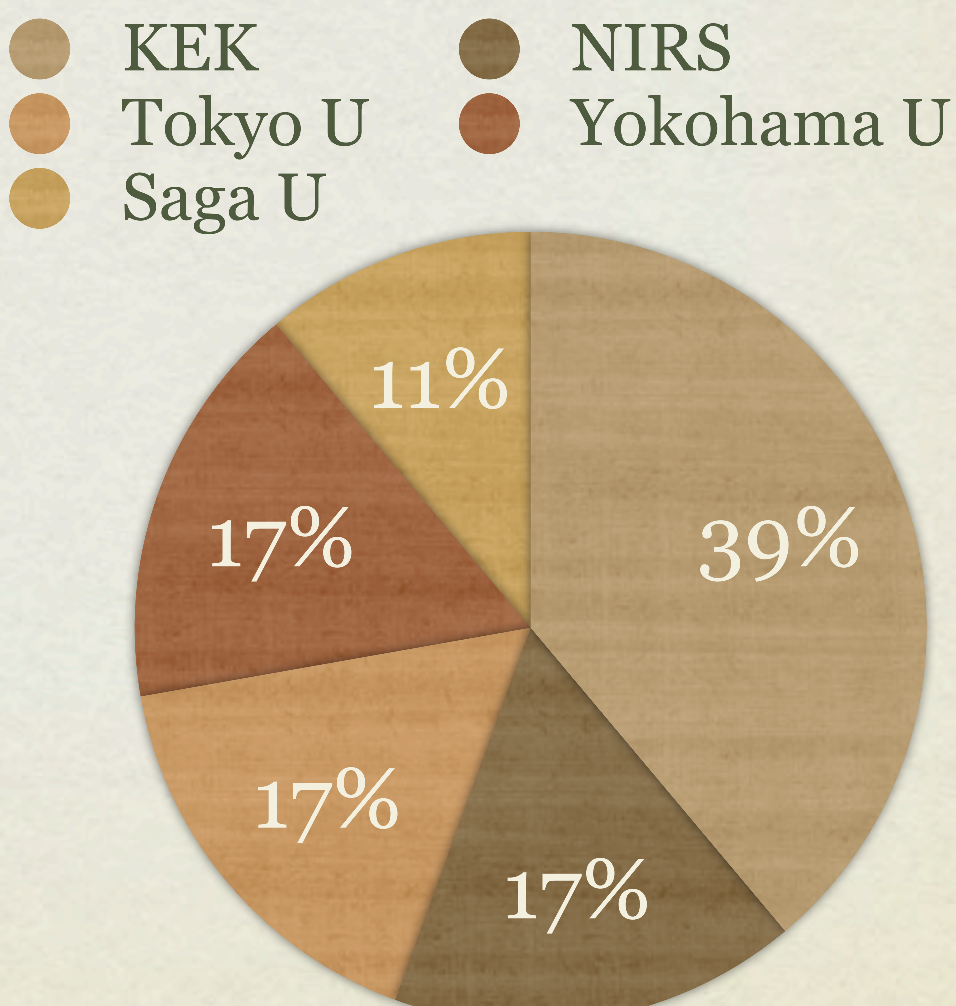
$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_o c^2}(1 - \cos\theta)}$$



LIQUID XENON TPC DEVELOPMENT

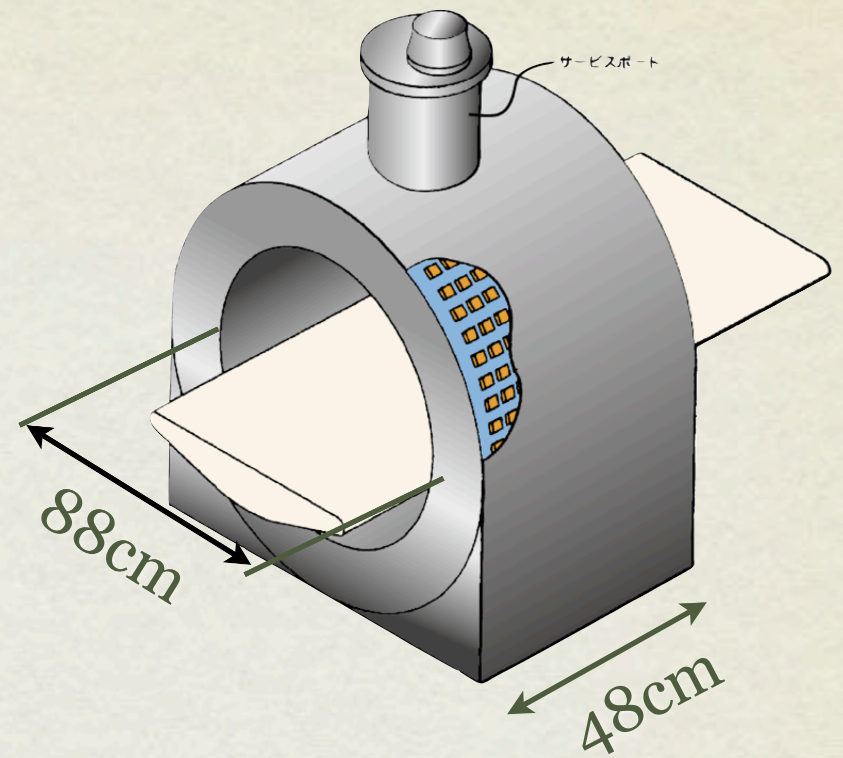
19 MEMBERS FROM 5 INSTITUTES

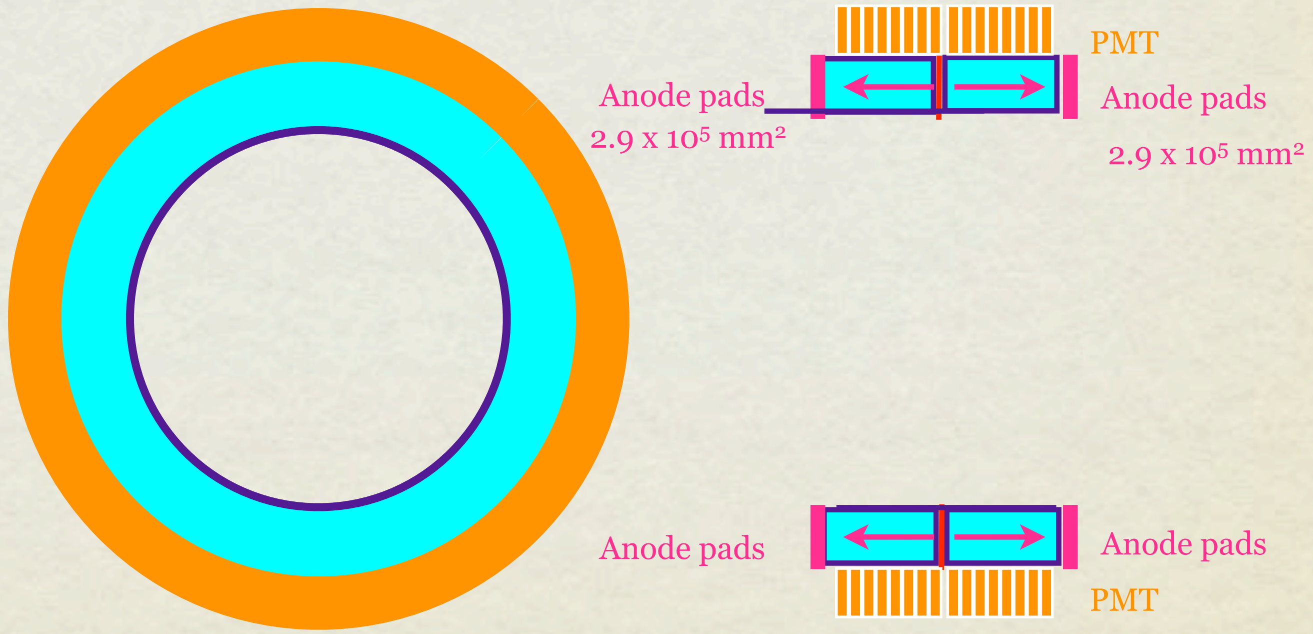
- ***Half of the members are from universities***
- KEK for liquefaction & purification, PMT, TPC, and DAQ
    - T.Tauchi, A.Maki, T.Haruyama, S.Tanaka, S.Mihara, T.Saeki, K.Kasami, S.Suzuki
- National Institute of Radiation Science for PET
    - M. Kumada, T. Tomitani, C. Toramatsu
- Saga Univ. for TPC, Simulation, FE ASIC development
    - A. Sugiyama, *T. Higashi*
- Univ. of Tokyo for TPC, PMT, Simulation
    - T. Mori, *Y. Fujii, T. Chiba*
- Yokohama National Univ. for PMT, xenon property
    - S. Nakamura, *Y. Takagi*, *Y. Endo*



APPLICATION TO PET

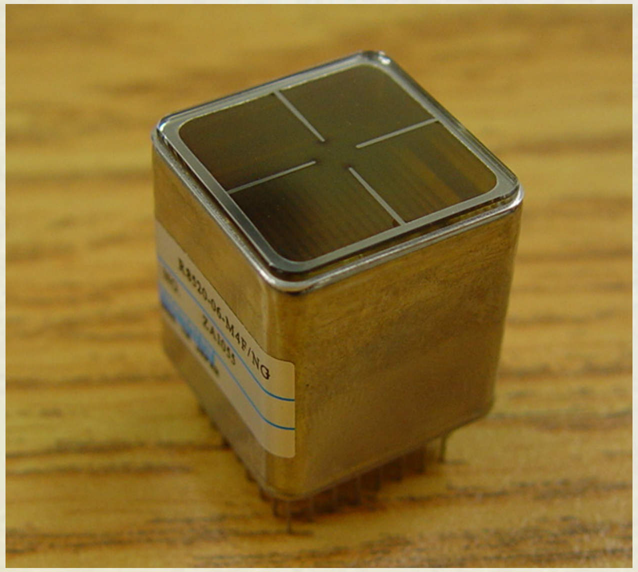
- Hybrid detector composed of
  - scintillation light readout by PMT
    - trigger, initial information for position reconst., pile-up rejection
  - ionization signal PAD readout
    - precise measurement of position and energy
- Volume
  - 88cm diam, 48cm FOV, 9cm DOI (93% γ det. eff.), 140 liters LXe



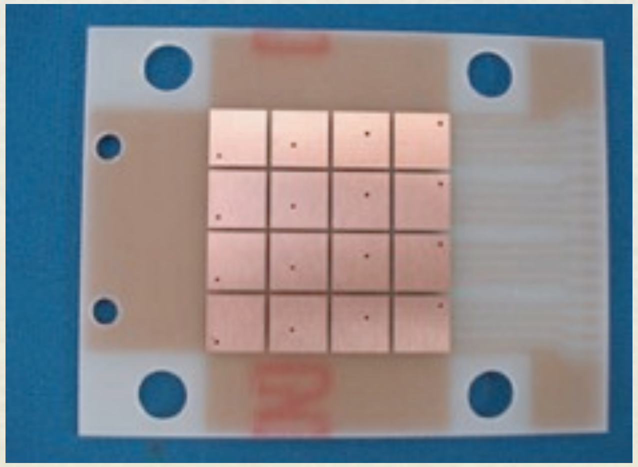
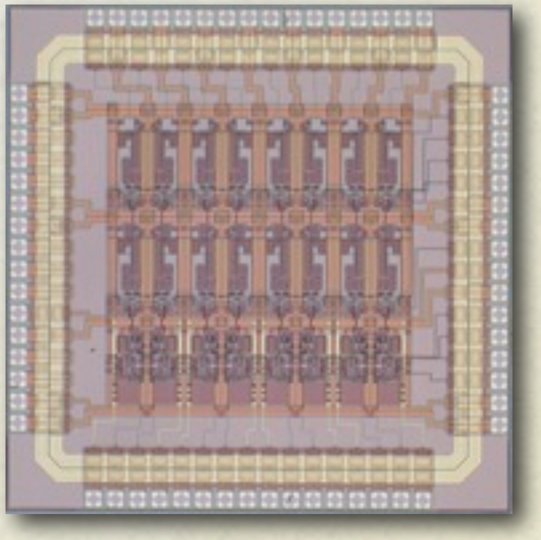


SIGNAL READOUT

- Scintillation light
  - 1 inch PMT developed for LXe use
  - 8 x 112 x 2 = 1792 PMTs
  - 10 nsec coincidence time
  - time stamp for TPC




- Ionization signal
  - anode pad readout
  - 48 kV/24cm
  - drift time 104 μsec (+/- 24cm)
  - front end ASIC and pipe-line readout

R&D HISTORY

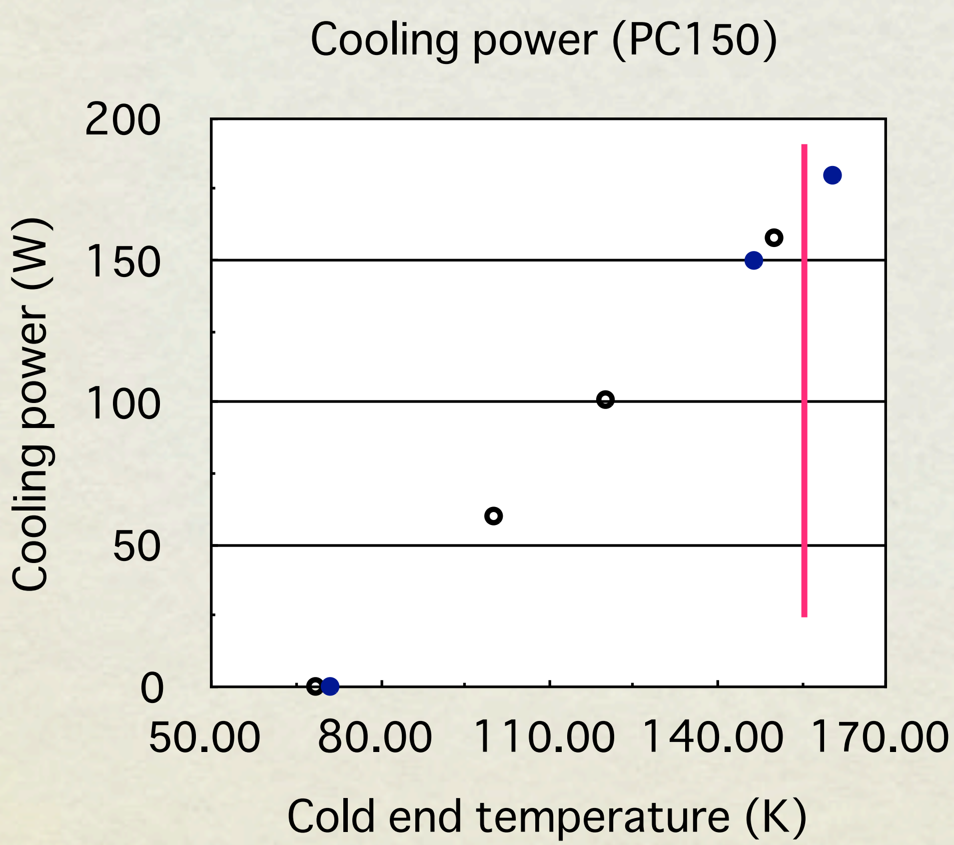
- Cryogenics
  - liquid xenon handling
- Photomultipliers
- Ionization signal readout
- Electronics

CRYOGENICS

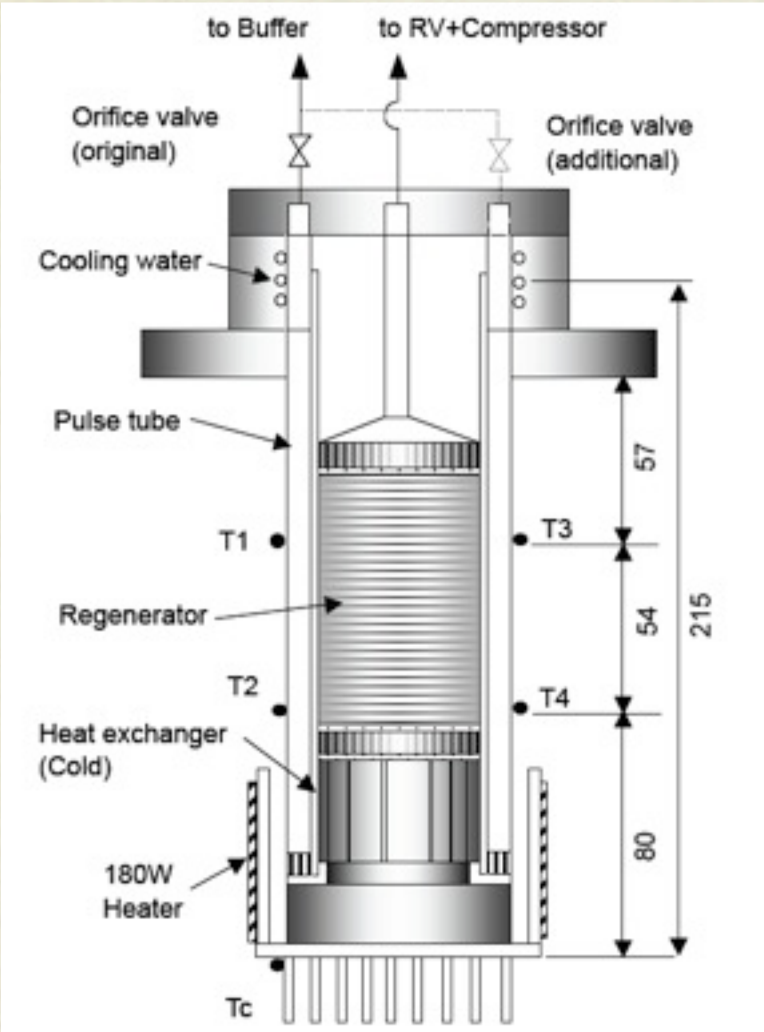
- Most of basic techniques have been developed for the MEG liquid xenon detector
  - Evacuation
  - Liquid filling and recovery
  - Cooling
    - Currently we are using small PTR produced by Iwatani Ltd.
    - 24 W cooling power at LXe temperature
  - Purification

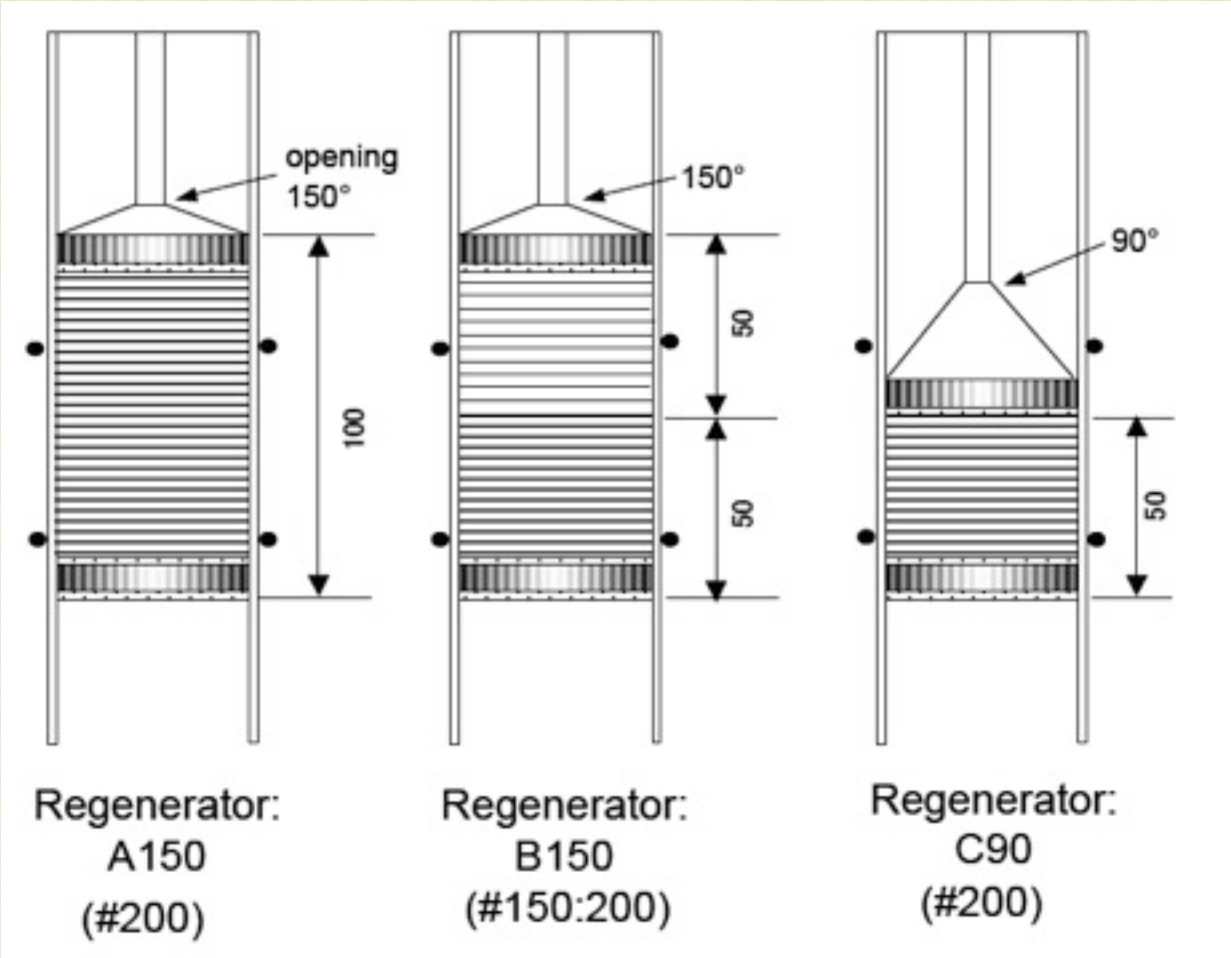
COOLING
SUFFICIENT FOR PET APPLICATION

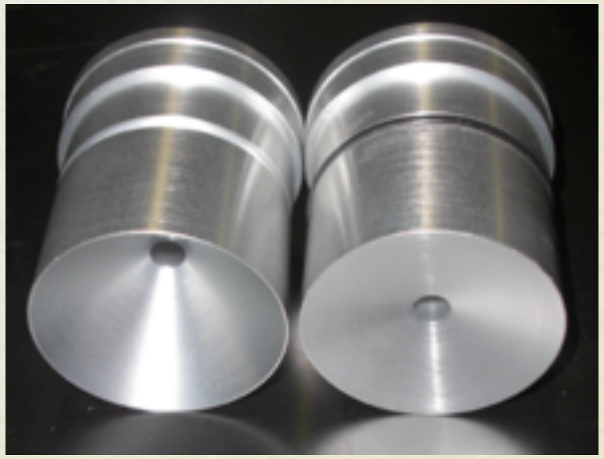
- MEG 1st spin-off
- Technology transferred to a manufacturer, Iwatani Co. Ltd
- Performance
  - > 189 W @165K
  - 6.7 kW compressor
  - 4 Hz operation
- Further R&D to improve the cooling power



REGENERATOR FURTHER R&D BY TH







Regenerator configuration:

- *A150: #200 mesh (700 sheets) (phosphor bronze)*
- *B150: #150 mesh (350) + #200 mesh (350)*
- *C 90: #200 mesh (350)*

PHOTOMULTIPLIER R&D

- Developed for MEG in collaboration with HPK
- Photocathode
  - Bialkali :K-Cs-Sb, Rb-Cs-Sb
    - Rb-Cs-Sb has less steep increase of sheet resistance at low temperature
    - K-Cs-Sb has better sensitivity than Rb-Cs-Sb
  - Multialkali :+Na
    - Sheet resistance of Multialkali dose not change so much.
    - Difficult to make the photocathod, noisy
- Dynode Structure
  - Compact
  - Possible to be used in magnetic field up to 100G
    - Metal channel ← Uniformity is not excellent

Ichige et al. NIM A327(1993)144

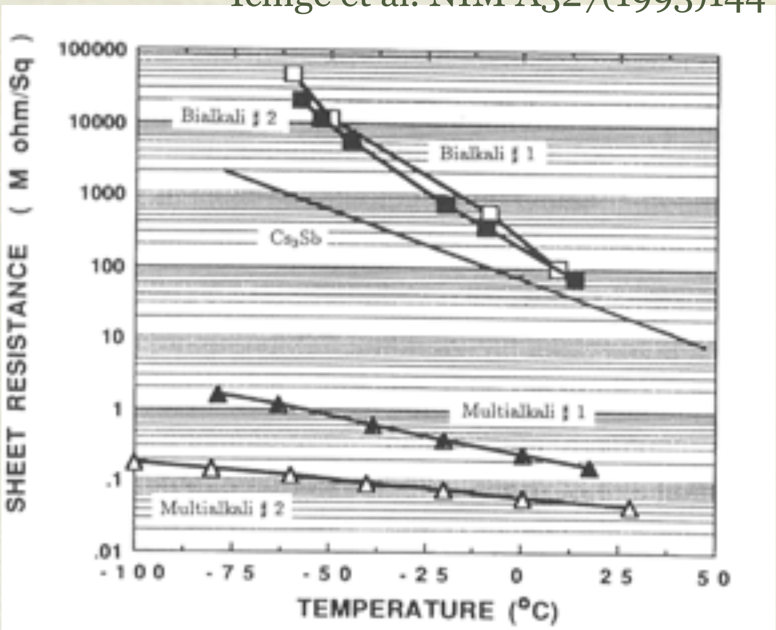
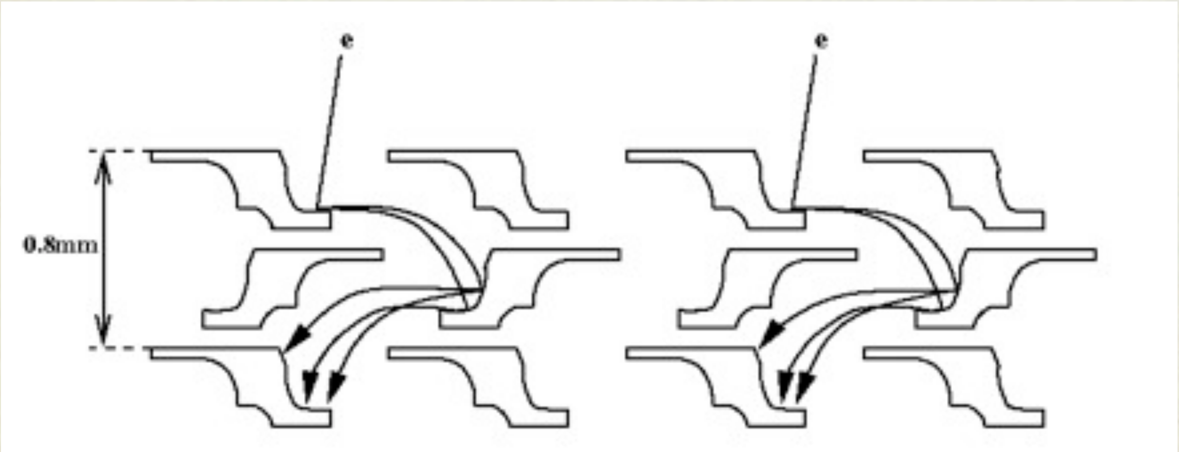
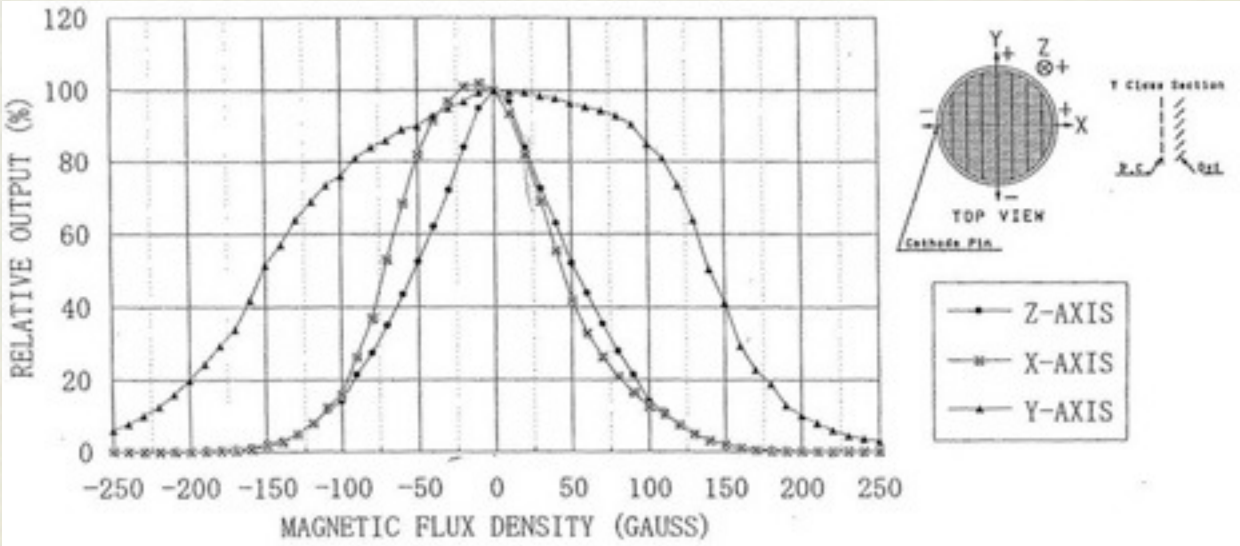


Fig. 8. The sheet resistance of different photocathodes as function of temperature.





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)	Used in the final detector
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

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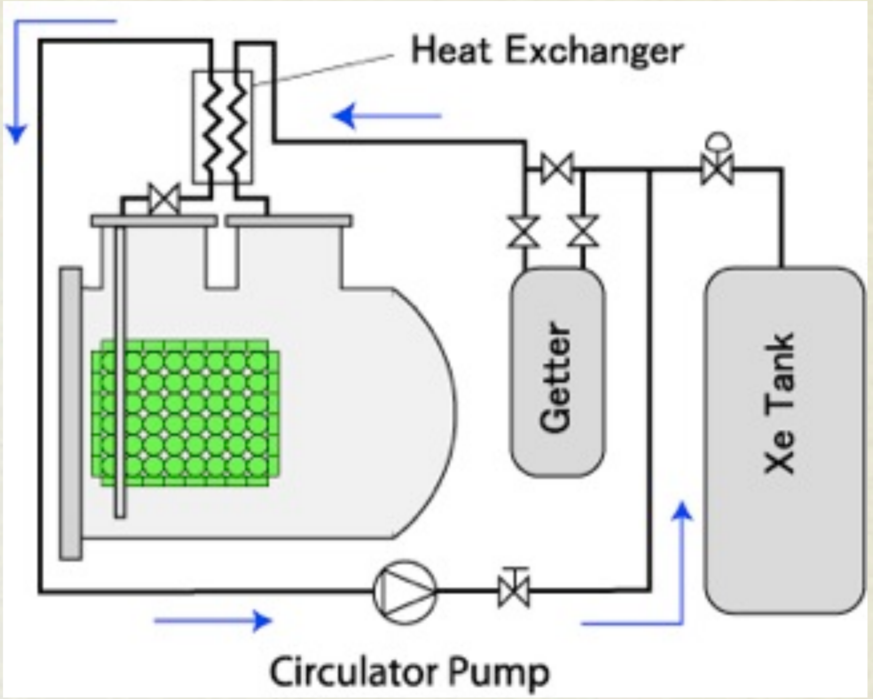
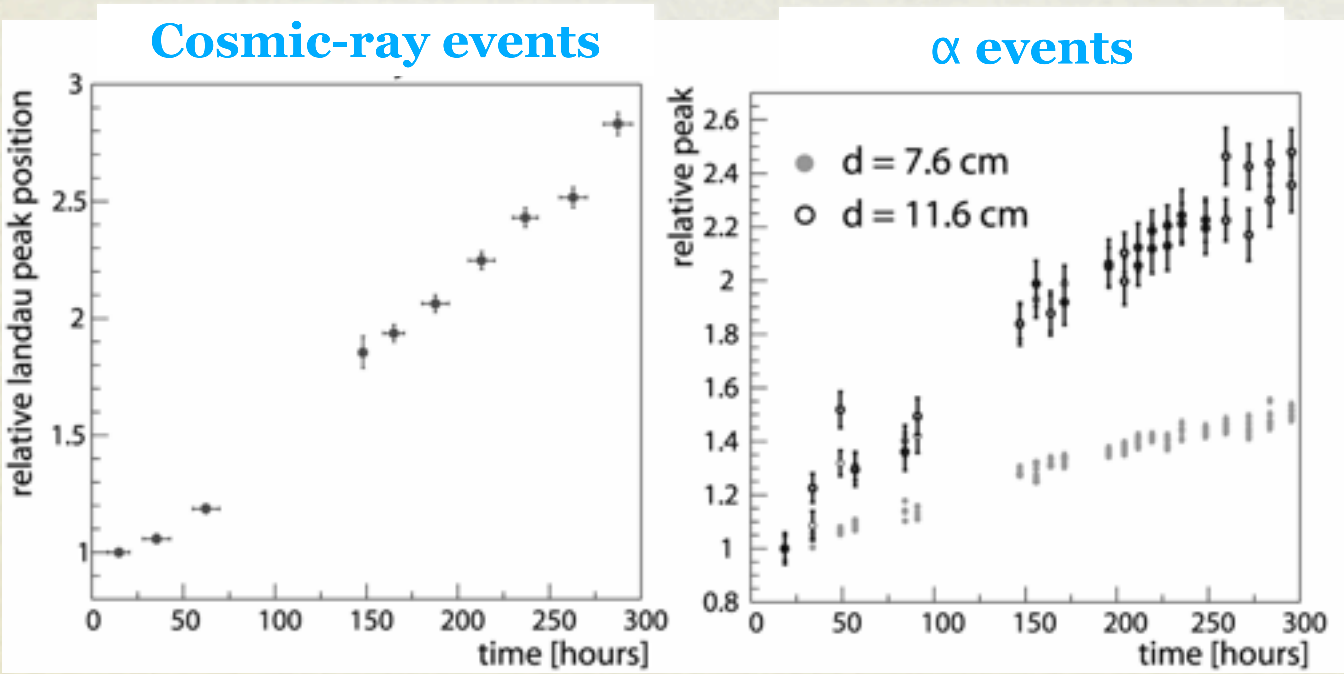
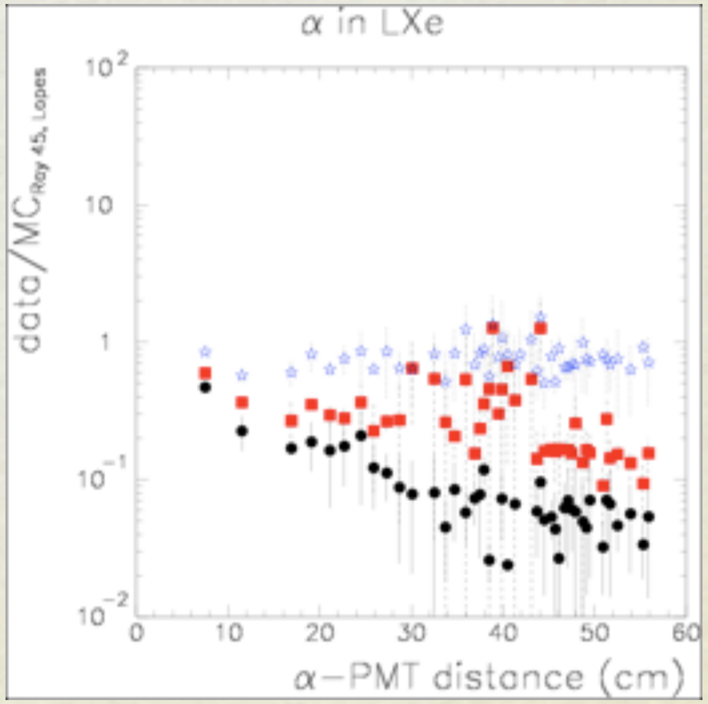
GASEOUS PHASE PURIFICATION

- Developed for the MEG LXe detector
  - Xenon extracted from the chamber is purified by passing through the getter.
  - Purified xenon is returned to the chamber and liquefied again.
  - Circulation speed 5-6cc/minute
- Same technology is applicable for LXeTPC

MEG prototype R&D



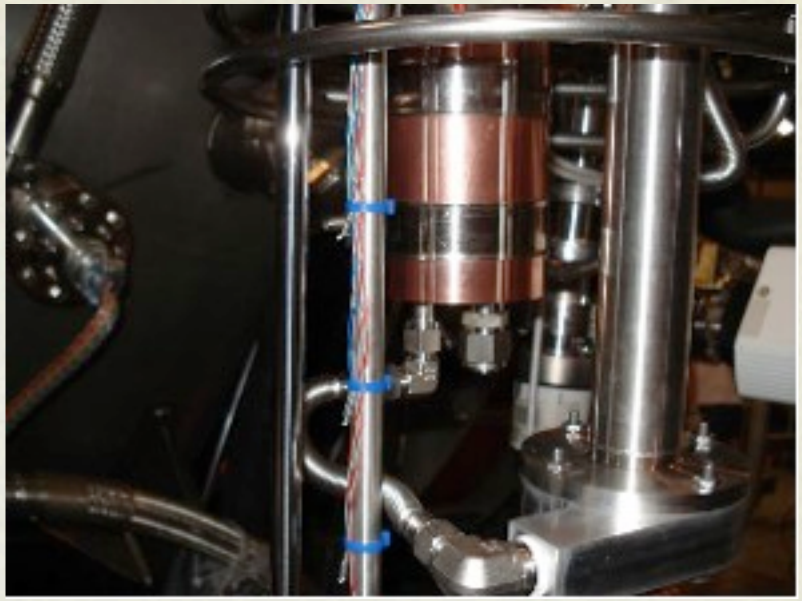


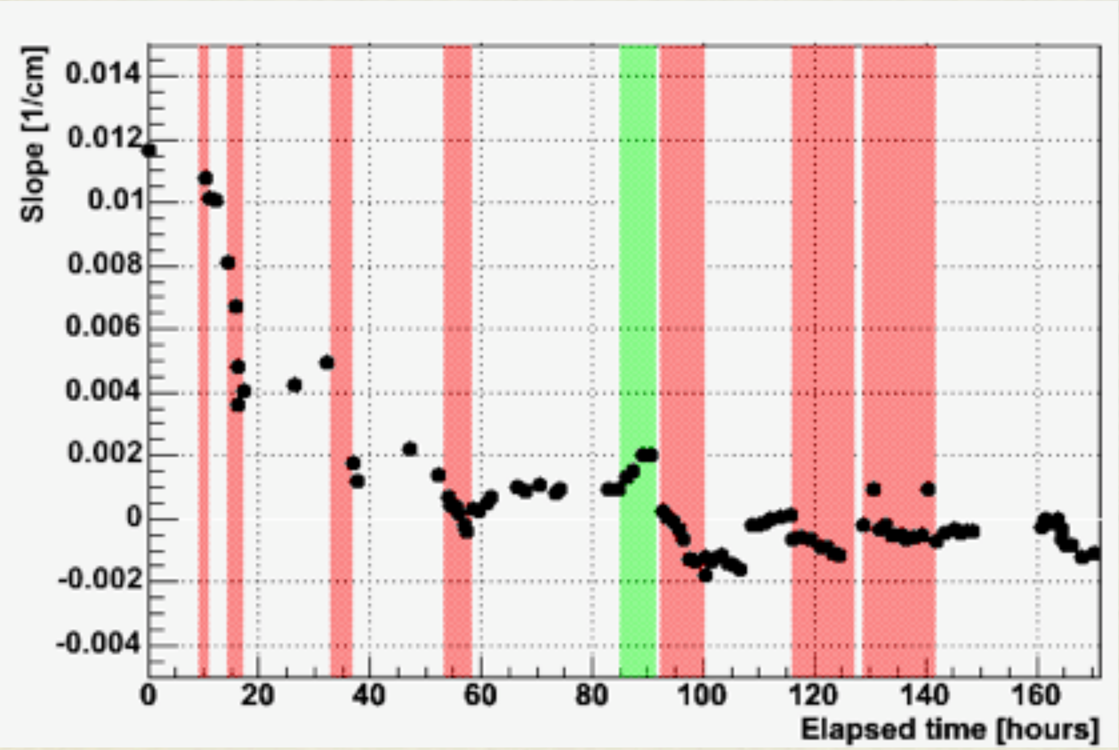


LIQUID-PHASE PURIFICATION

- For faster purification, MEG liquid-phase purification technology is applicable
  - centrifugal pump/piston-type pump
  - 70-200 liters/h liquid circulation
- Impurity is removed by a purifier cartridge

MEG centrifugal pump



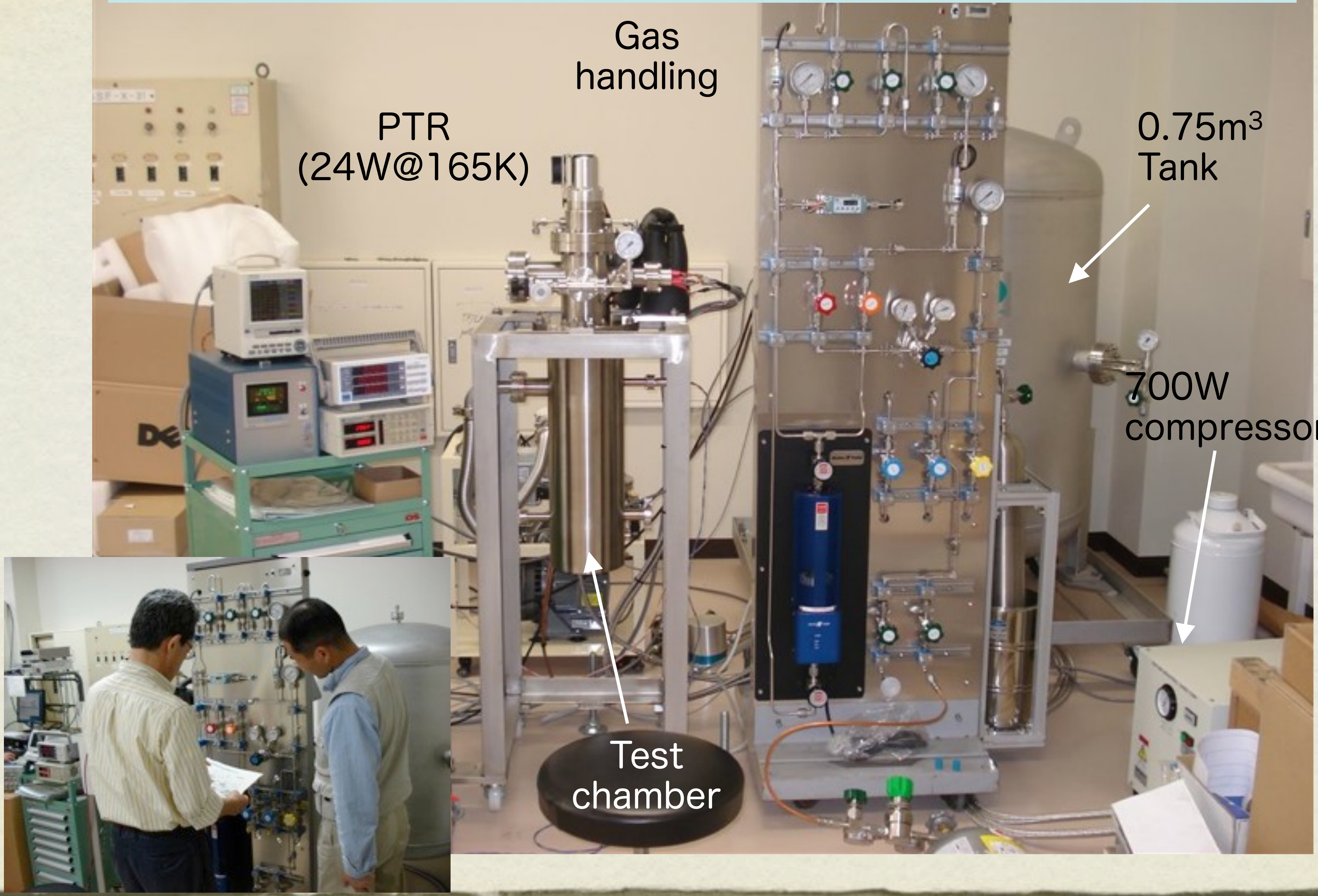


MEG Data for Water Removal

<u>In ~10 hours, λabs ~ 5m</u>

LXETPC TEST FACILITY

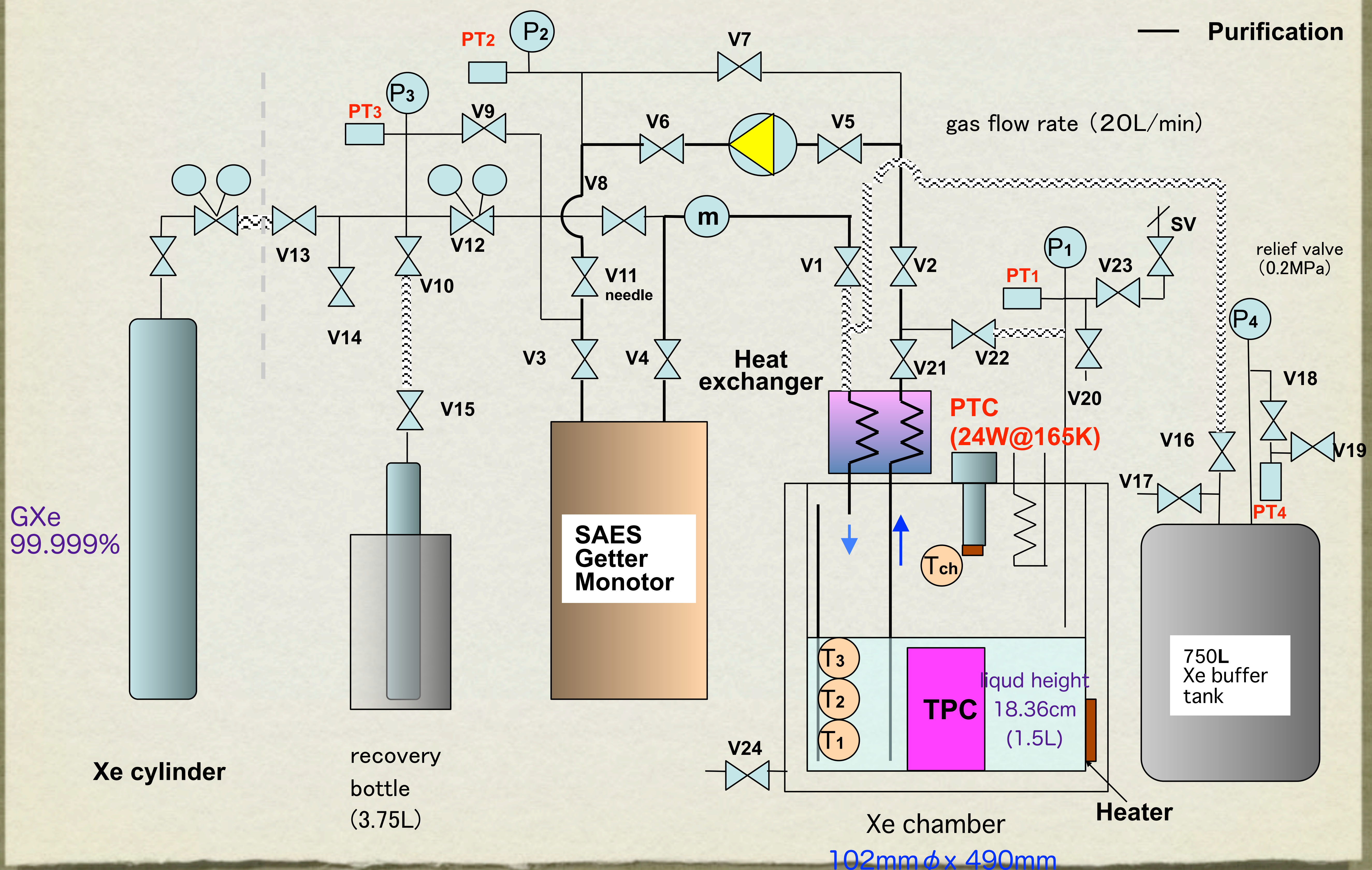
LXe Cryogenic system at KEK , operational since May 2008



LXeTPC : Liquefaction / purification

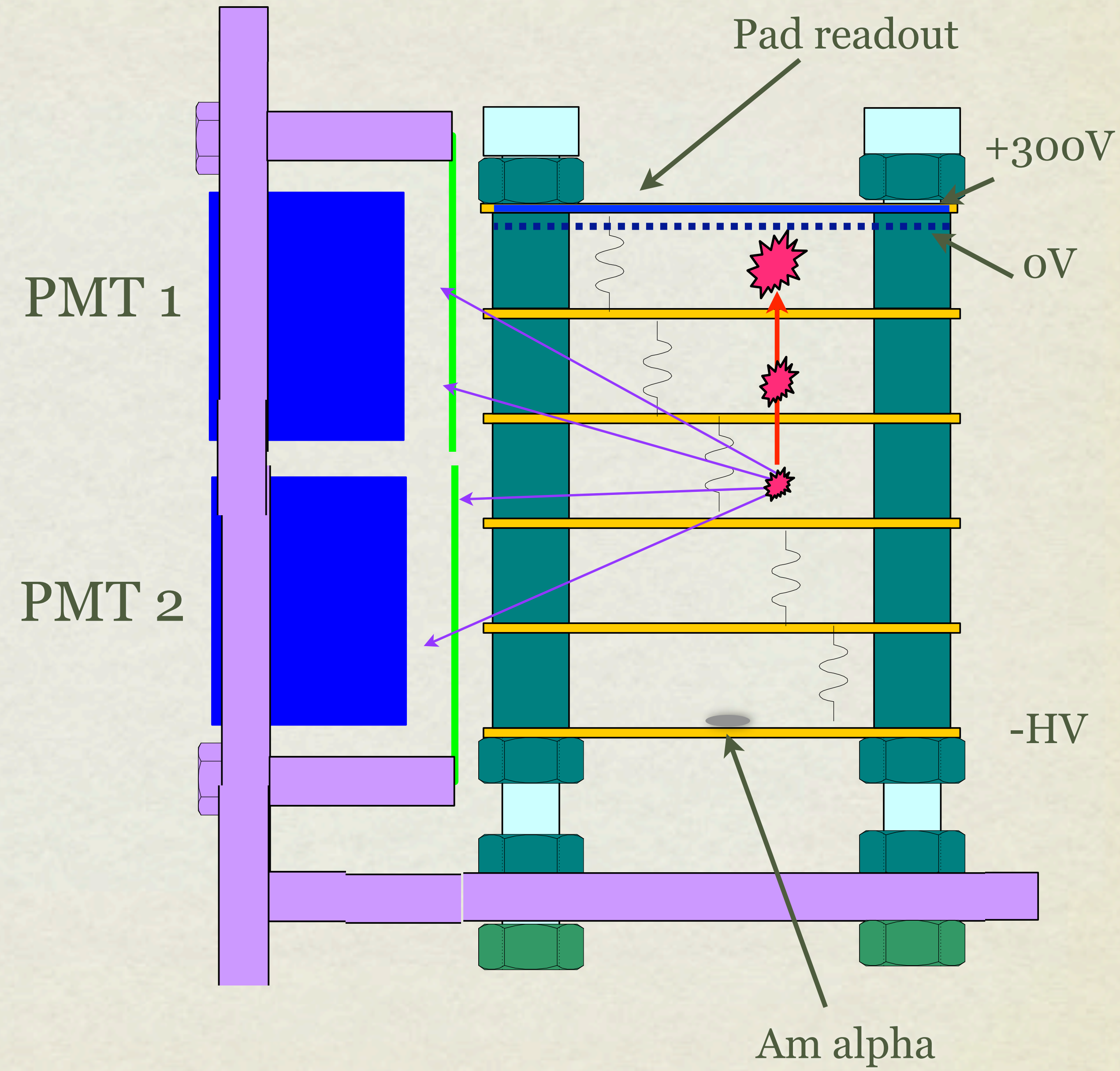
June 2008

Circulation by an oil-free diaphram pump (Enomoto co.)



PROTOTYPE DETECTOR

- Study of basic properties of electron drift in LXe and gain experiences
- Establish our skill to realize 1-5cm drift of electrons induced by 511keV
- Electronics development in a realistic condition

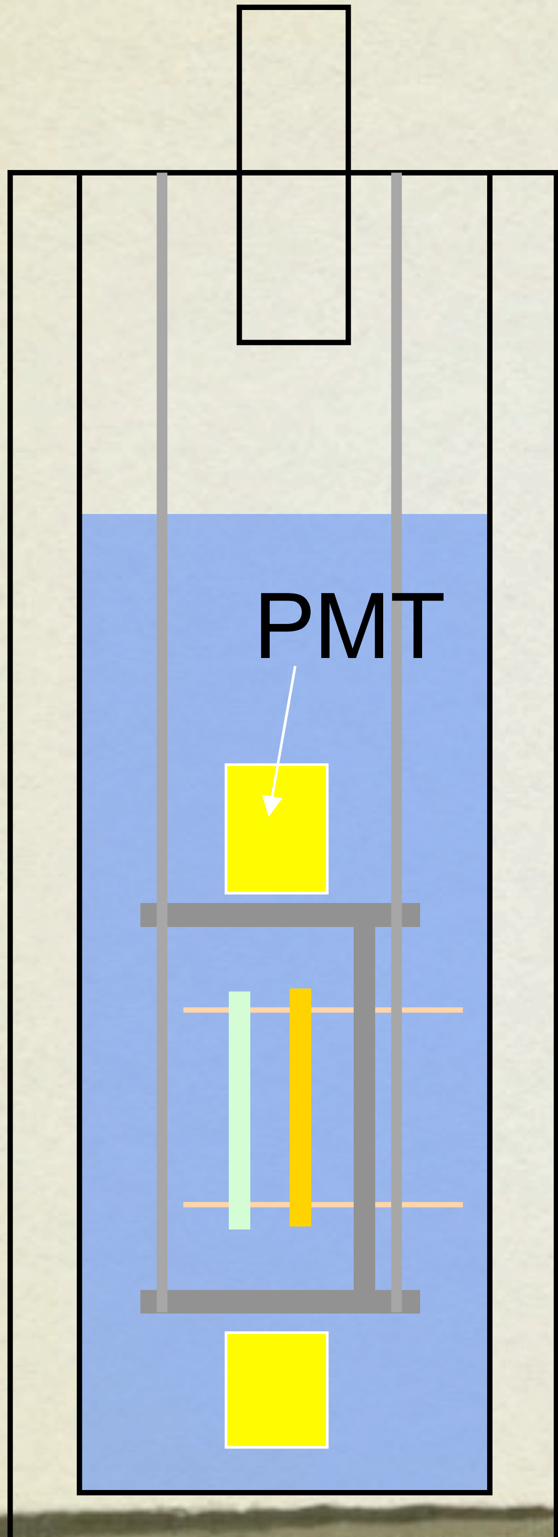


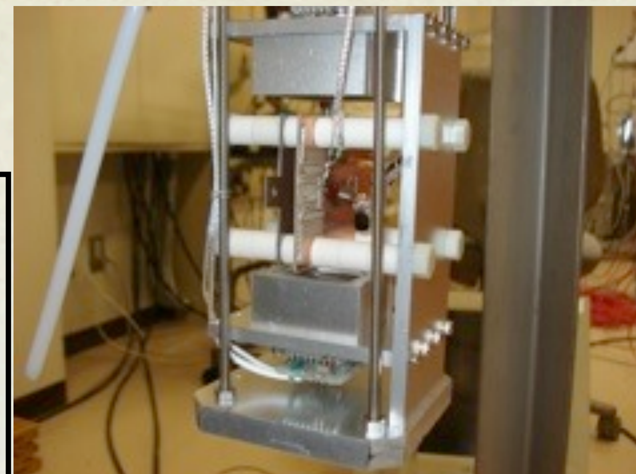
PROTOTYPE DETECTOR STUDIES

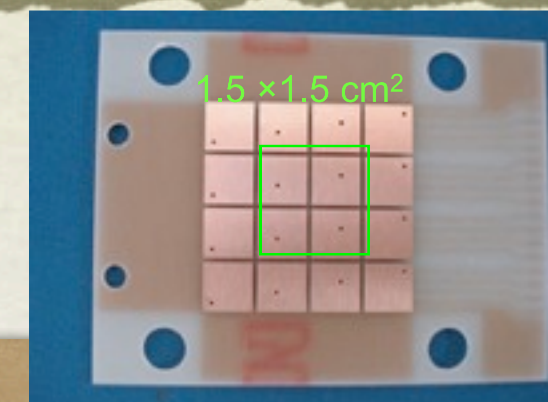
- 1st test using a simpler setup
  - 1cm drift length
  - 4 ch pad readout
- 2nd test (in progress)
  - 5cm drift length
  - 16 ch pad readout

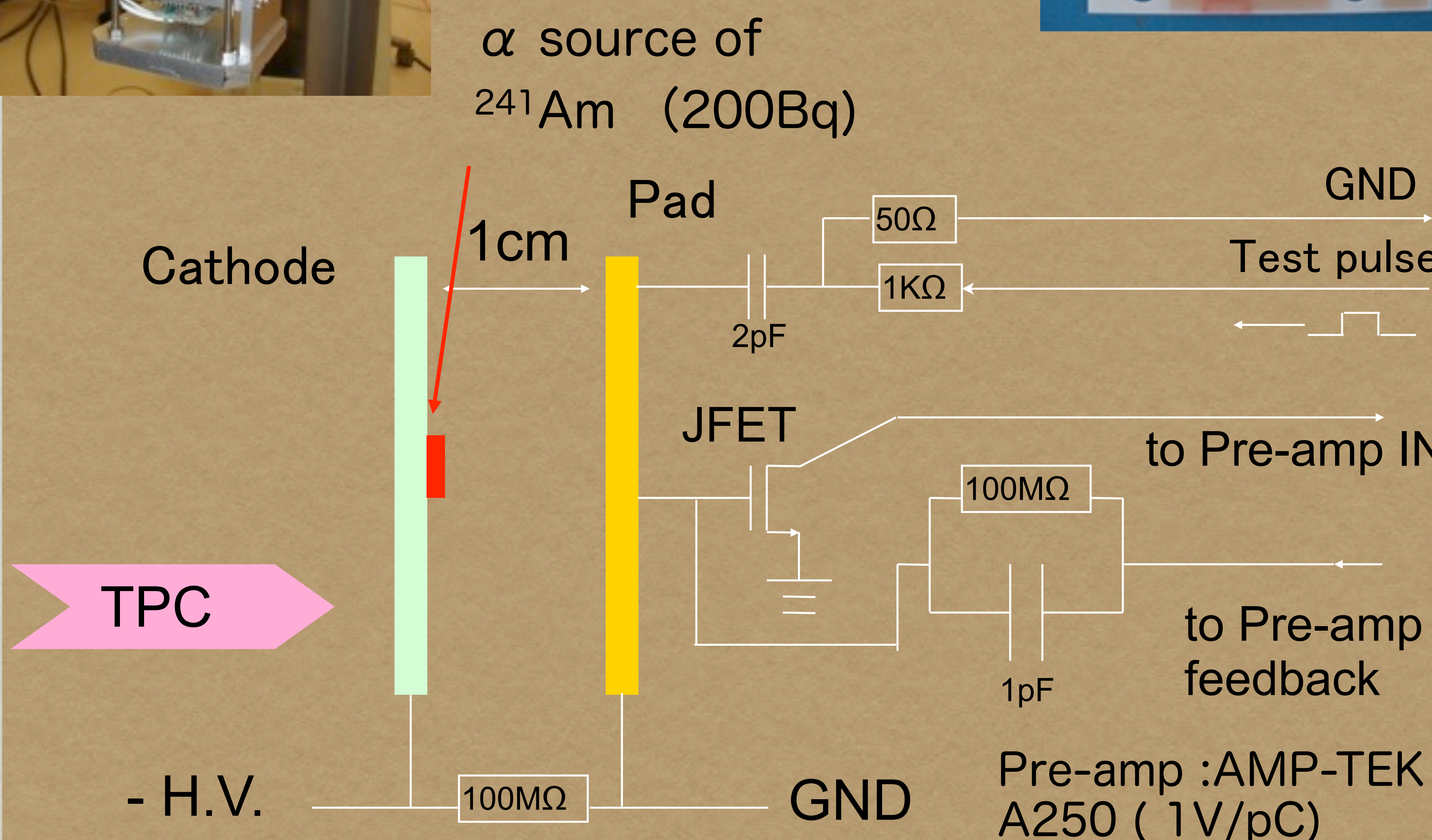
setup for 2nd test

1st TEST
1cm DRIFT LENGTH

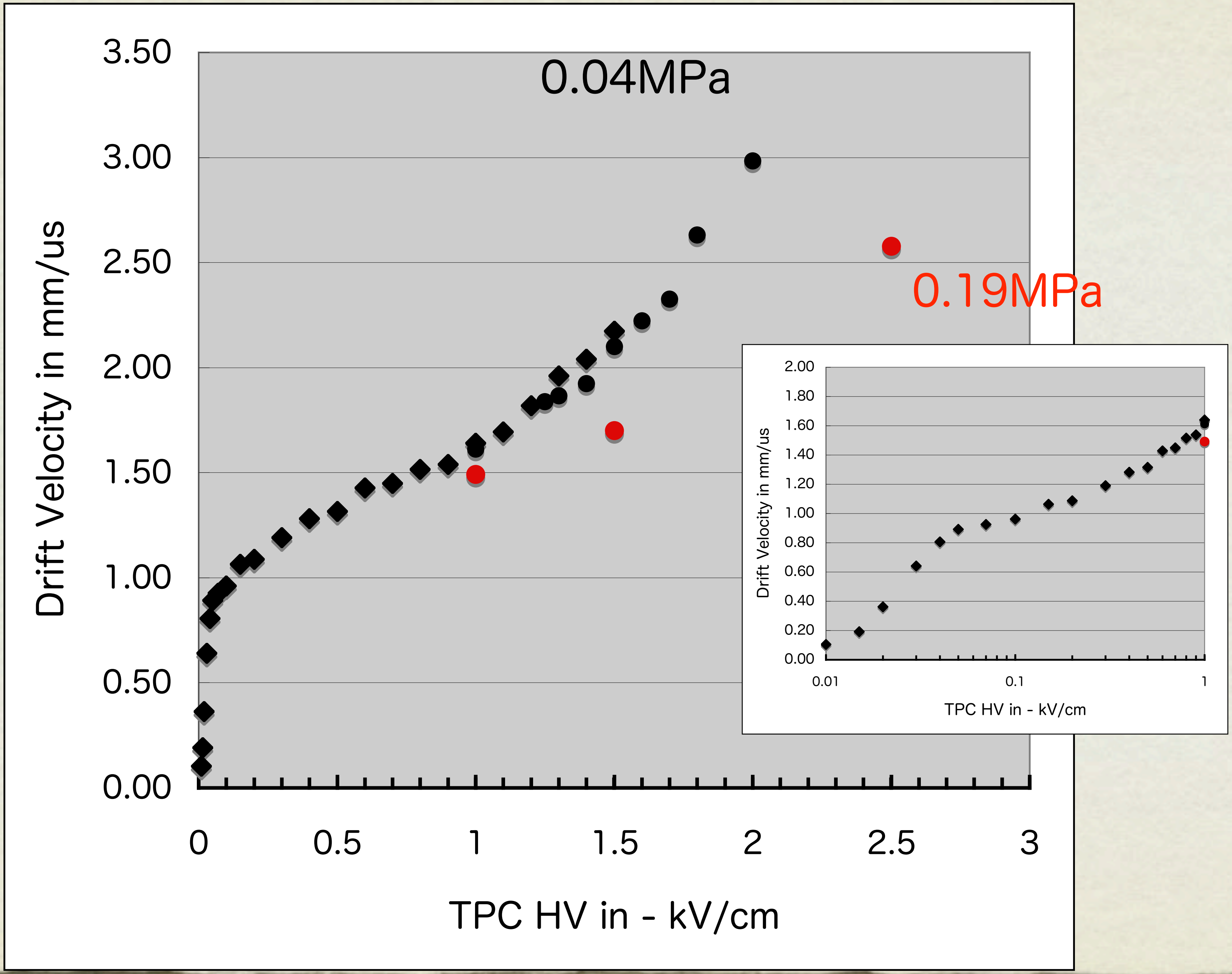




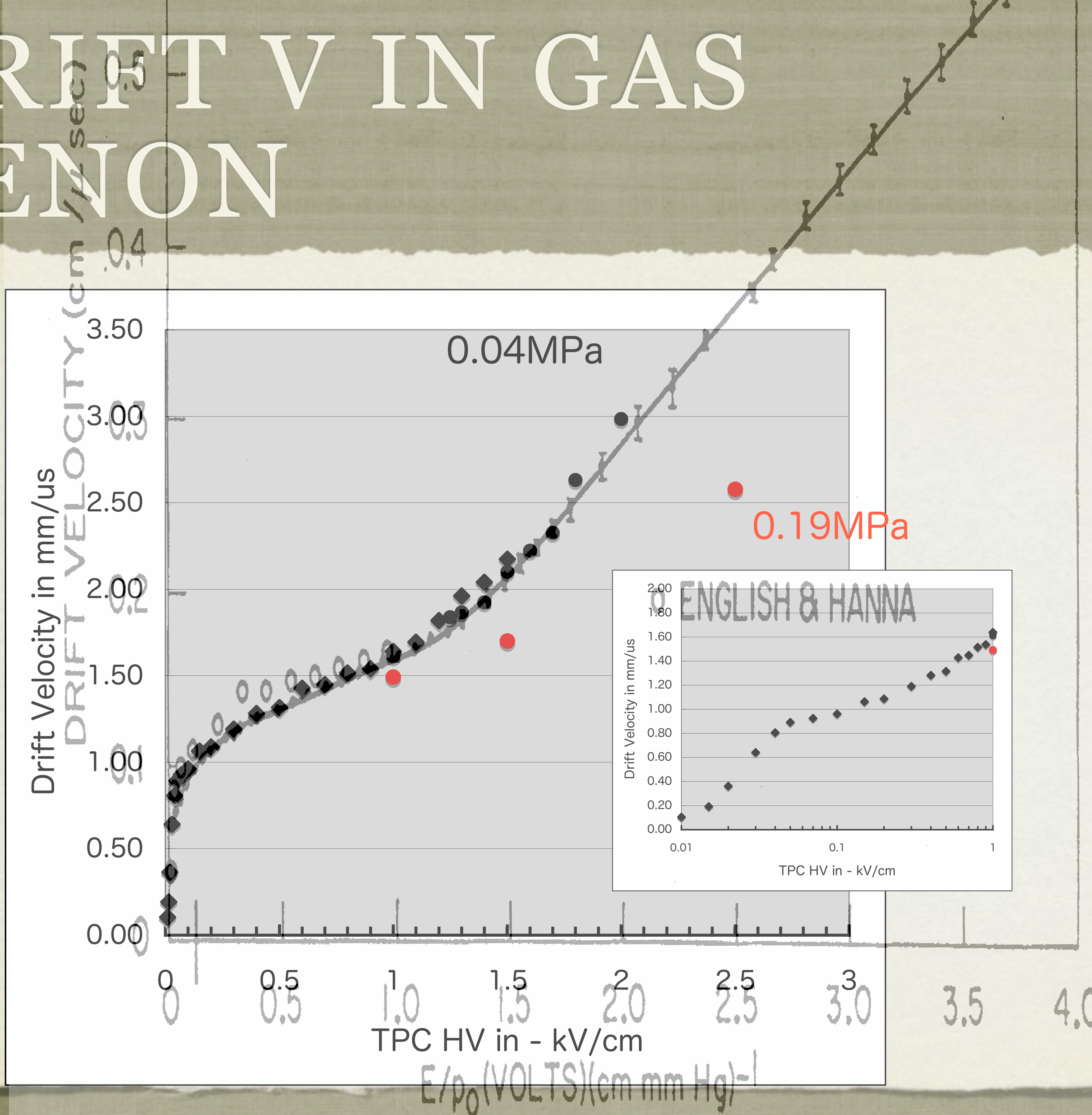




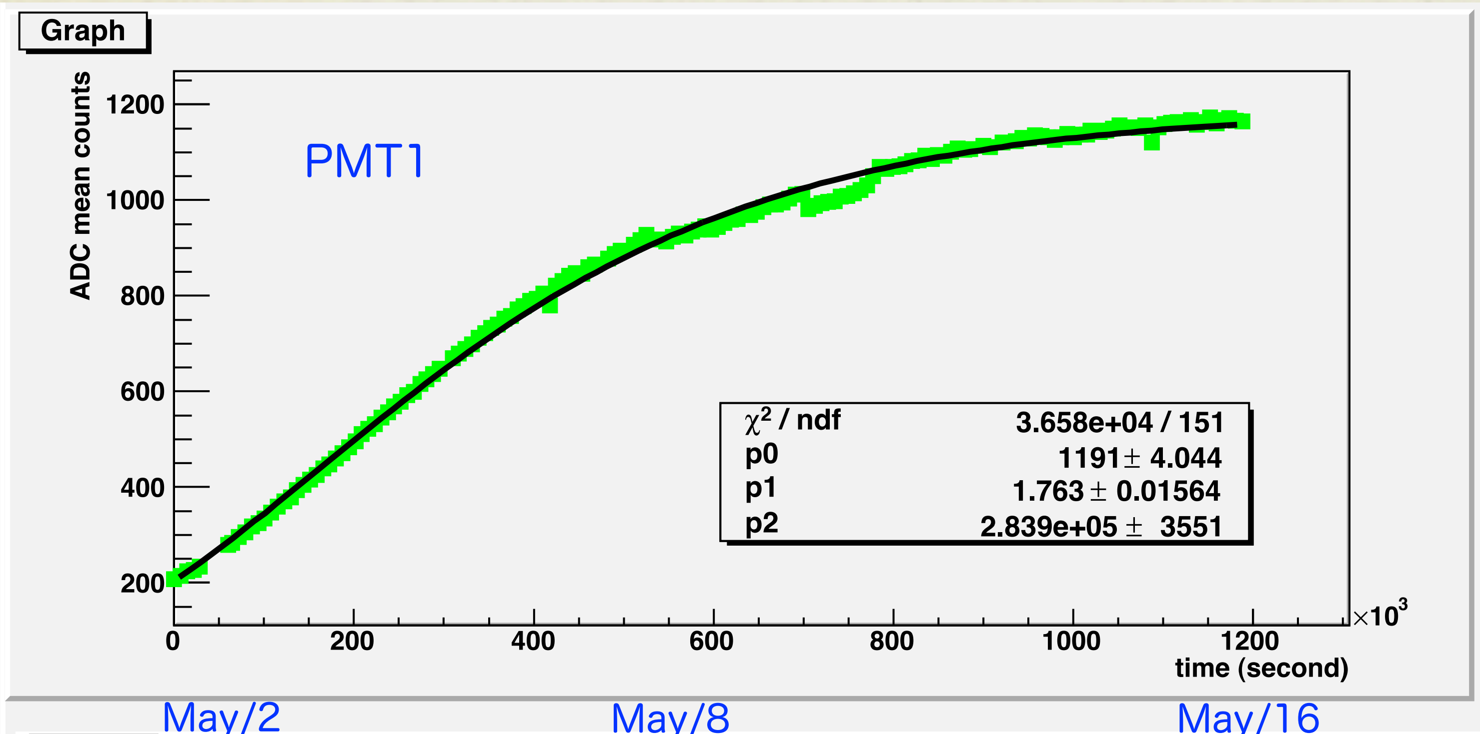
DRIFT V IN GAS XENON

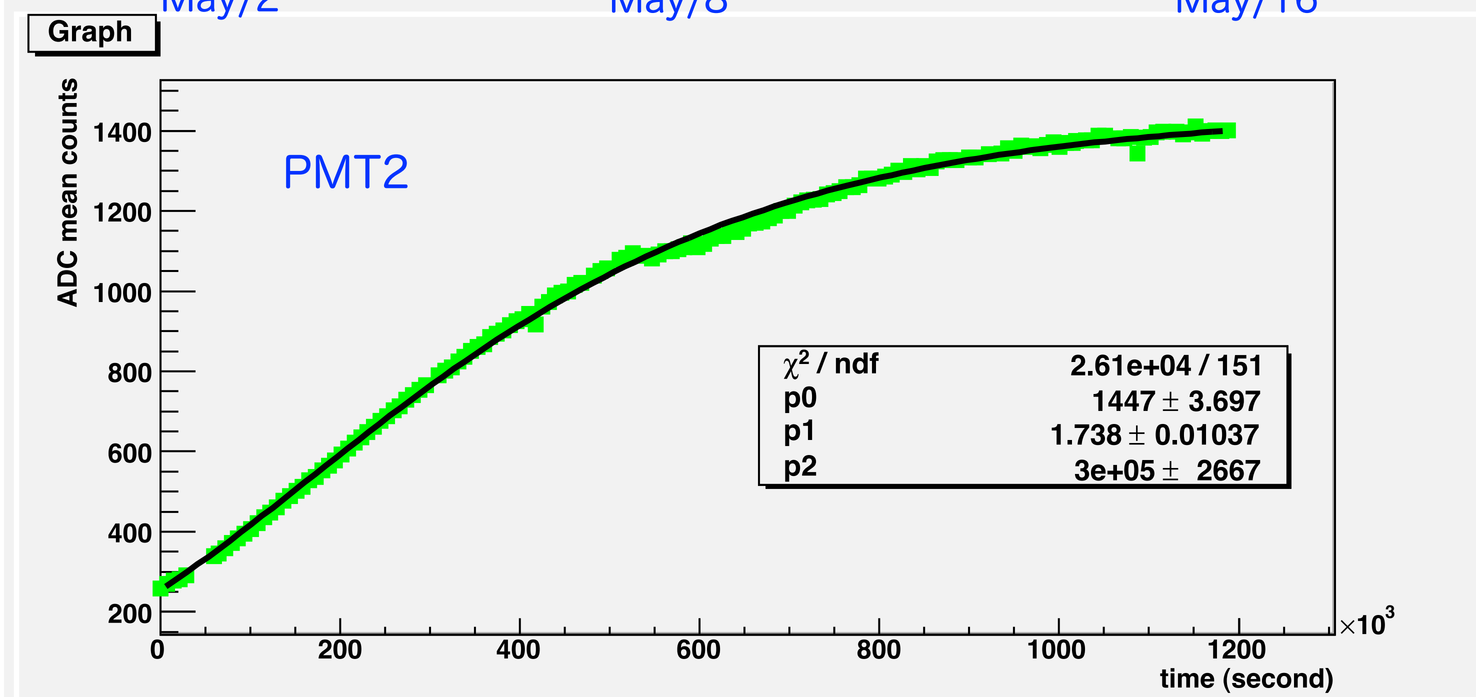


DRIFT V IN GAS XENON



LIQUID PURIFICATION MONITORING





fitted by $p(d,t) = p_0\, e^{-d/\lambda}$

$\lambda=\lambda_0\, e^{t/\tau}$, where

λ_0 = initial attenuation length and

τ= time constant of purification

$p_1 = d/\lambda_0 = 1.75$

$p_2 = \tau = 2.9\mathrm{x}10^5$sec

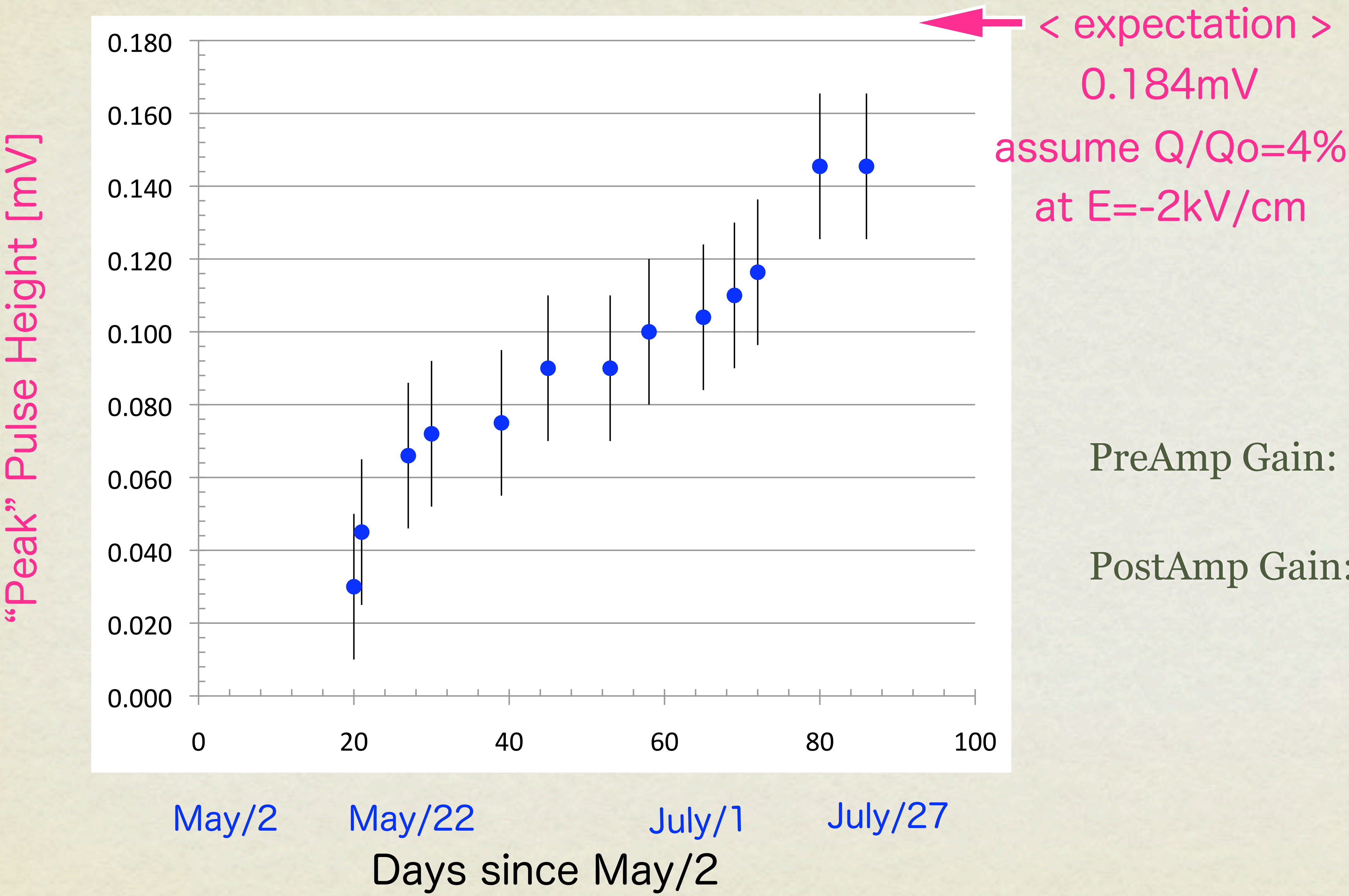
τ= 3.4 days

d = 5 cm

λ_0 = 2.9 cm

λ =160cm in 14days

ALPHA SIGNALS



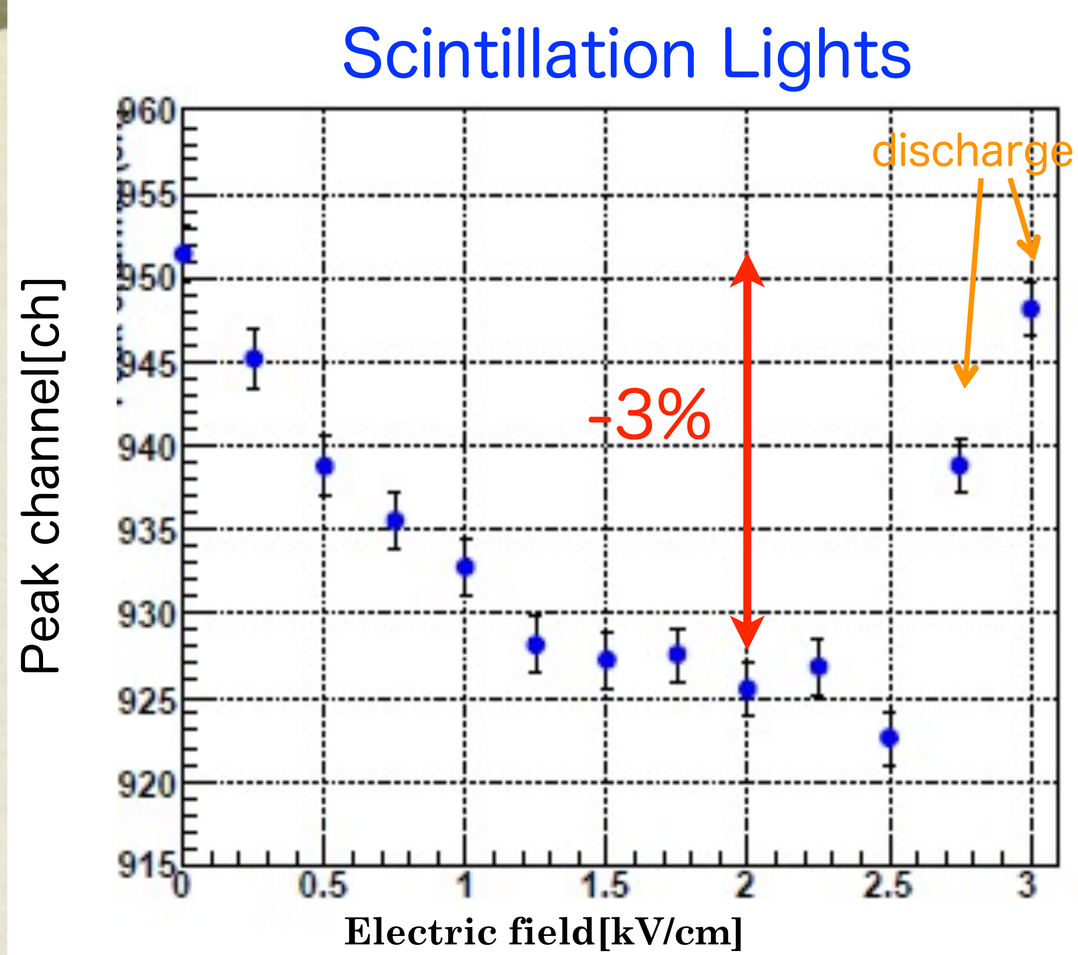
PreAmp Gain: 10^{15} mV/C

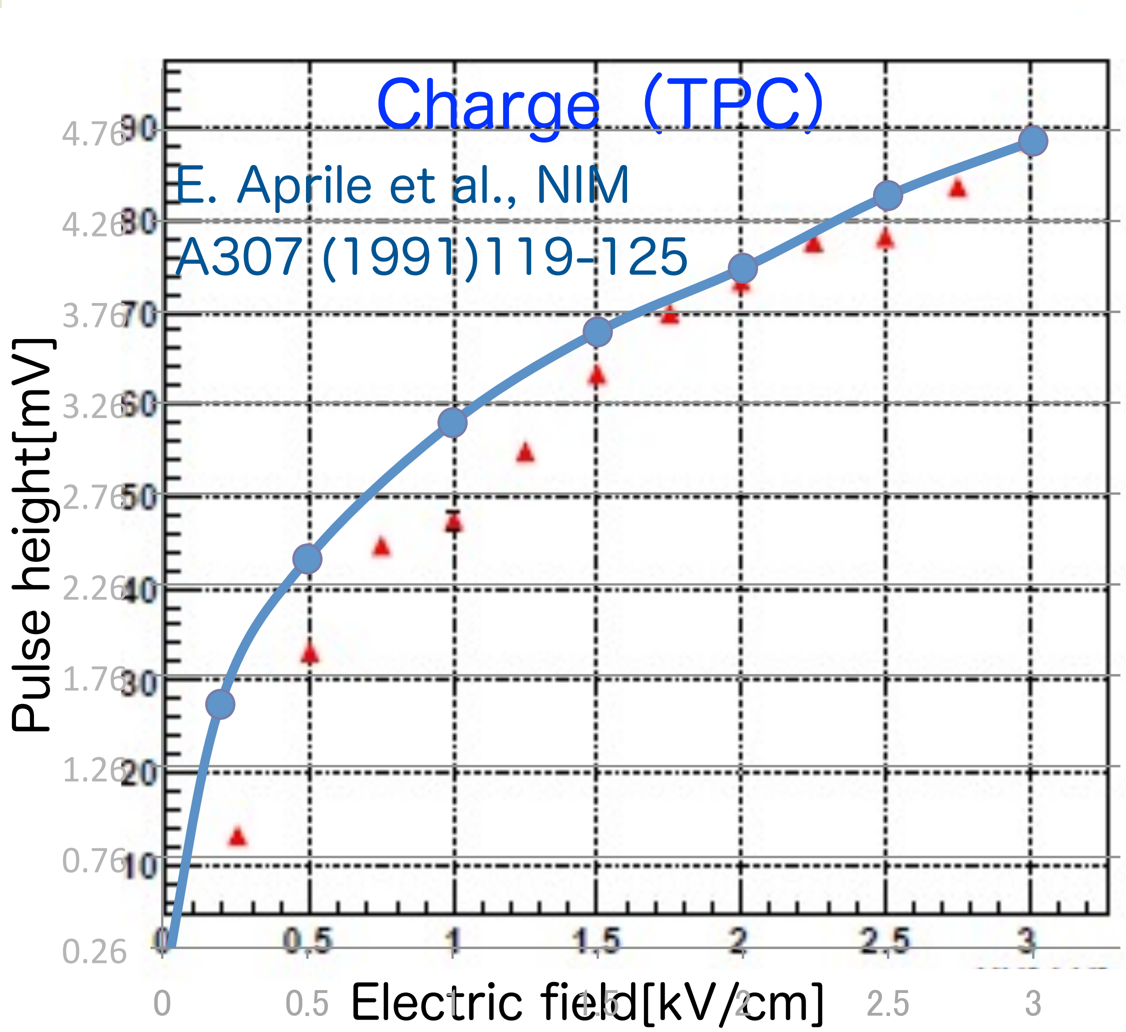
PostAmp Gain: 80

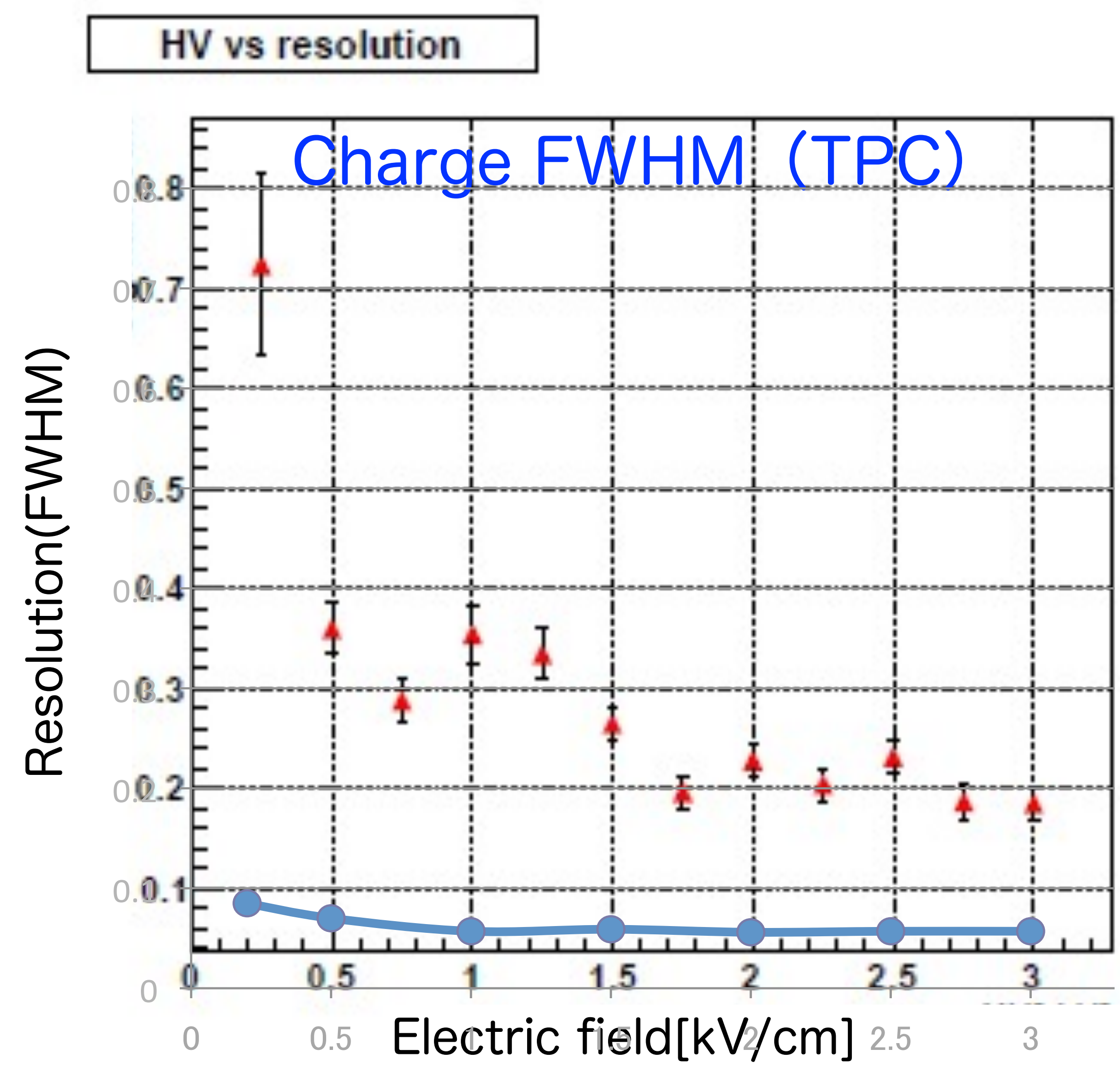
Electric field dependence (α)

including attenuation due to impurity and drift time (E-field)

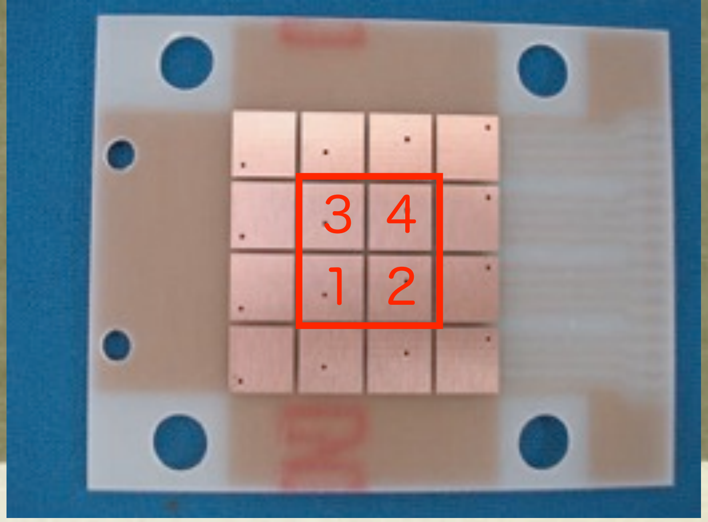
Electric field	2kV / 1kV
Scintillation lights	-3% / -2%
Charge	73mV / 46mV =1.6
	1.27
Charge res. FWHM	0.22 / 0.35 = 0.6
	0.056/0.057= ~1





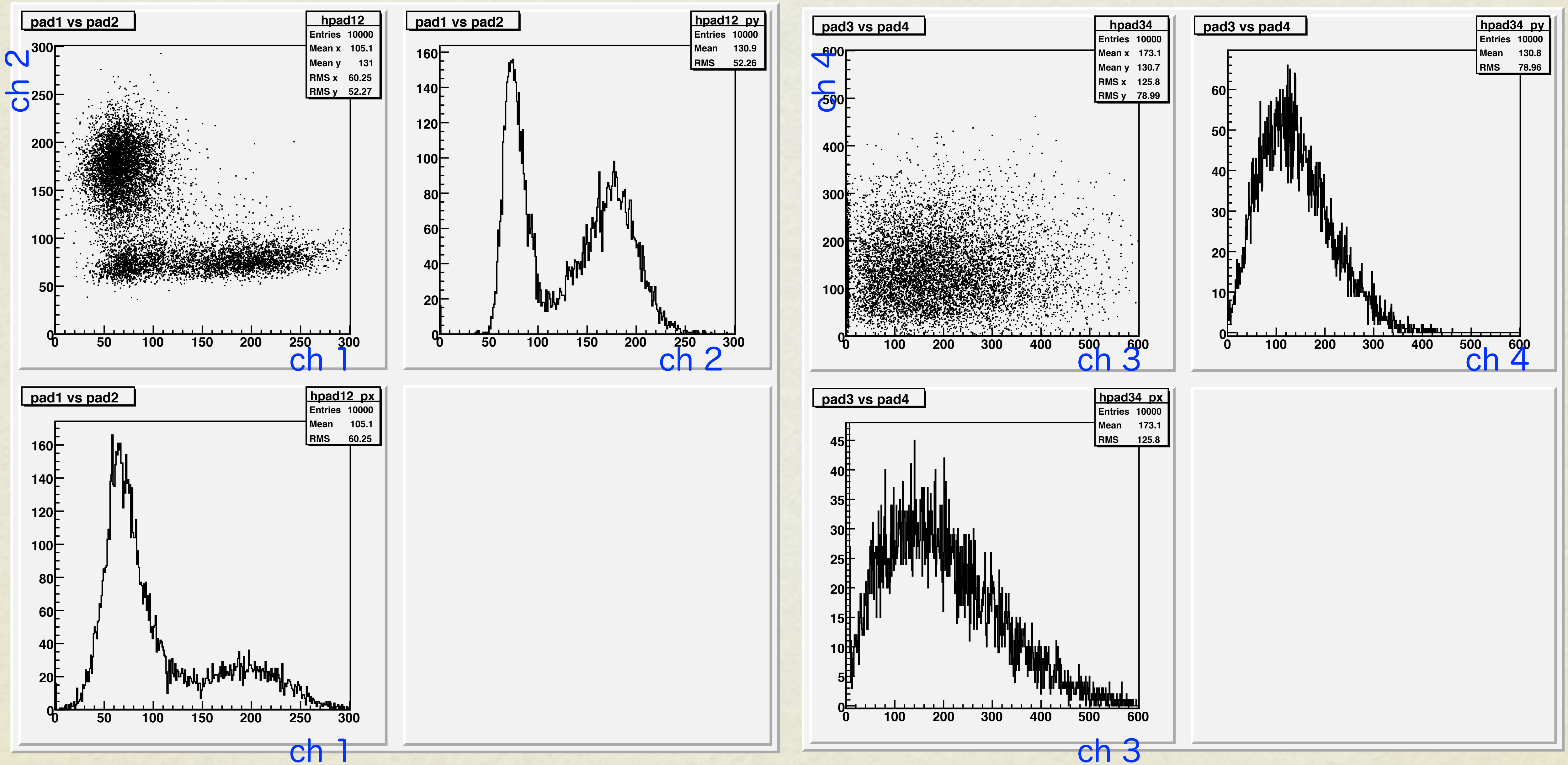


ALPHA EVENTS



1.1fC measured at the α peak

(about 91ppb O_2 eqiv., λ_{att}=15.3mm)



2ND TEST
5CM DRIFT LENGTH

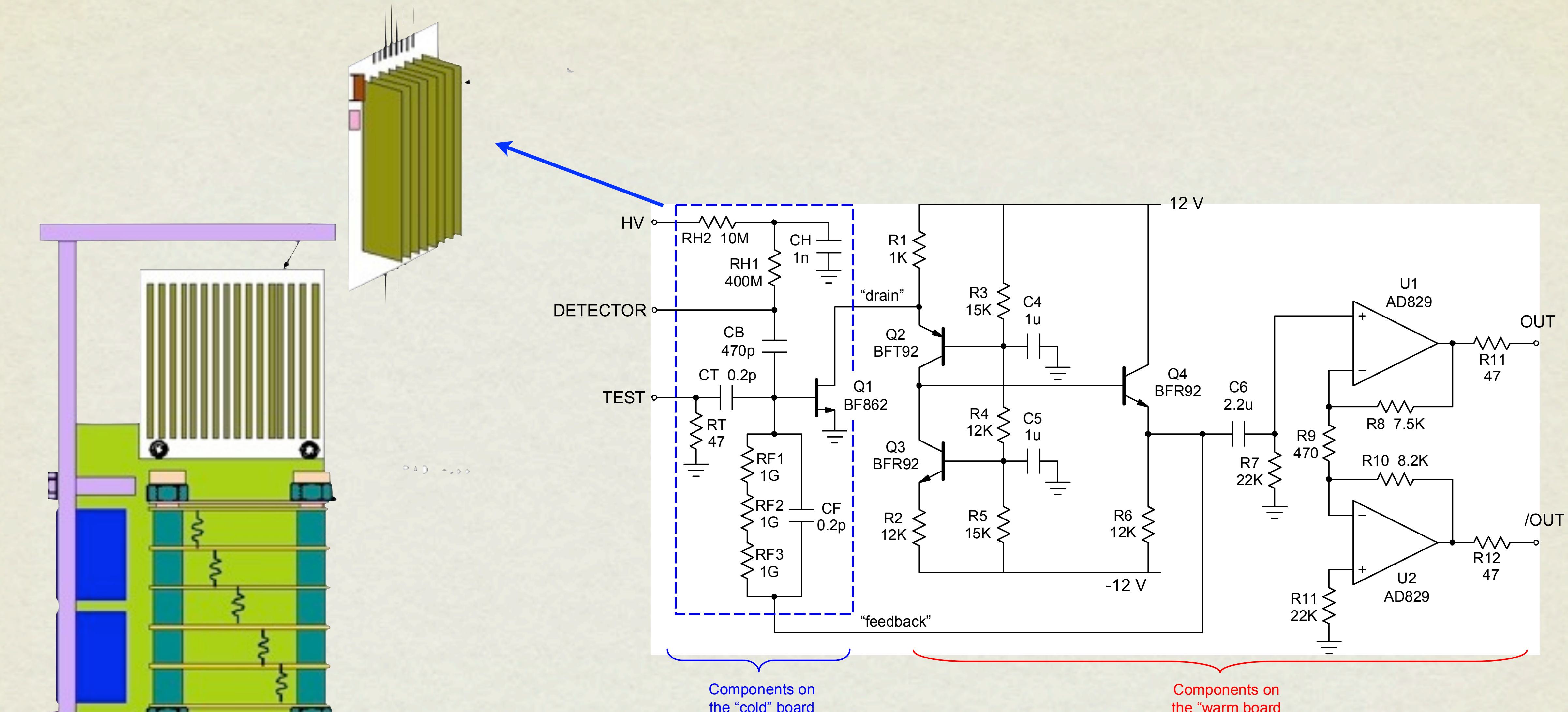


Fig. 3. Simplified schematic diagram of the charge sensitive preamplifier.

"A Cold Low Noise Preamplifier for Use in Liquid Xenon", A. Pullia et al.

2ND TEST
5CM DRIFT LENGTH

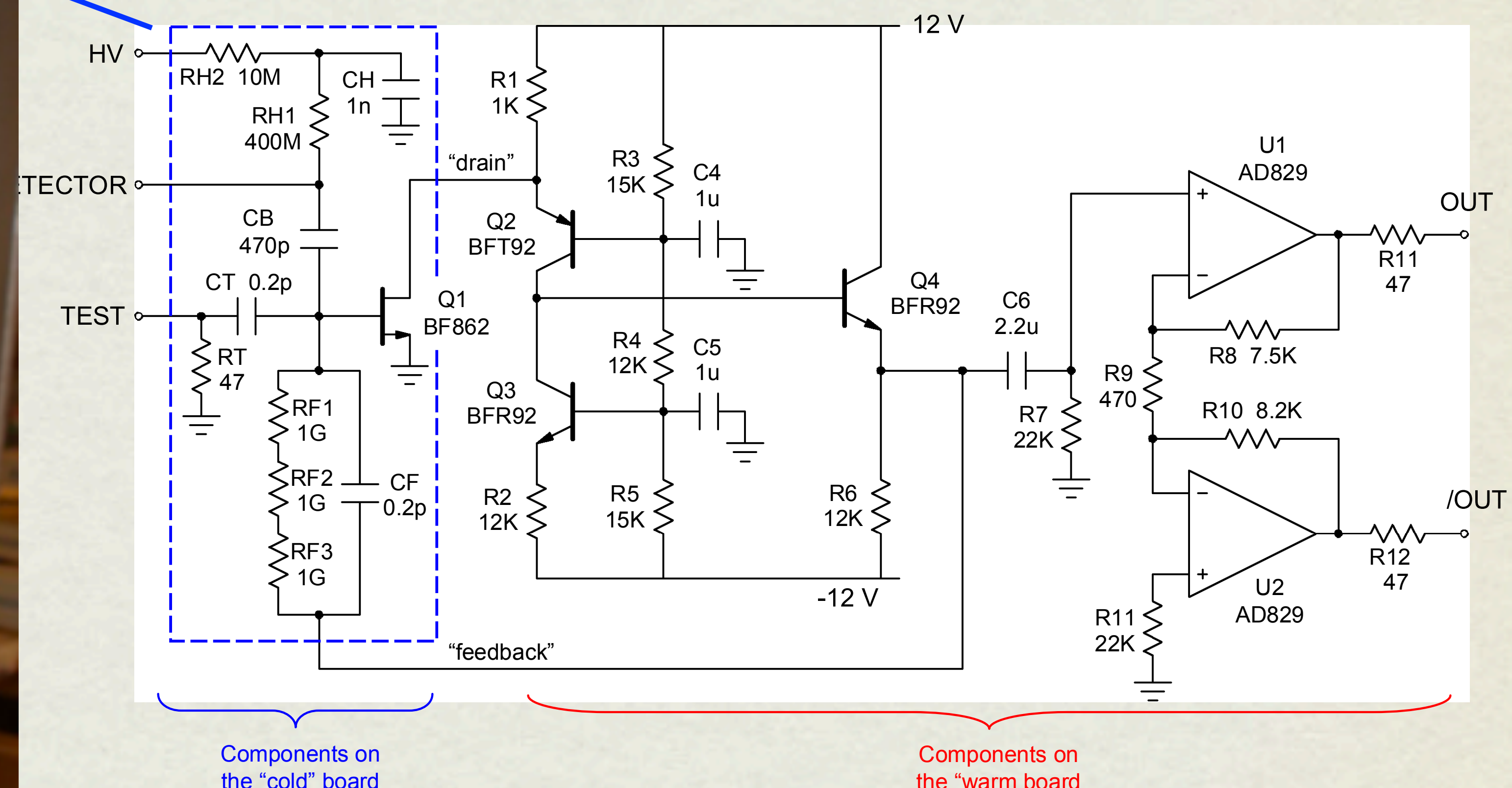
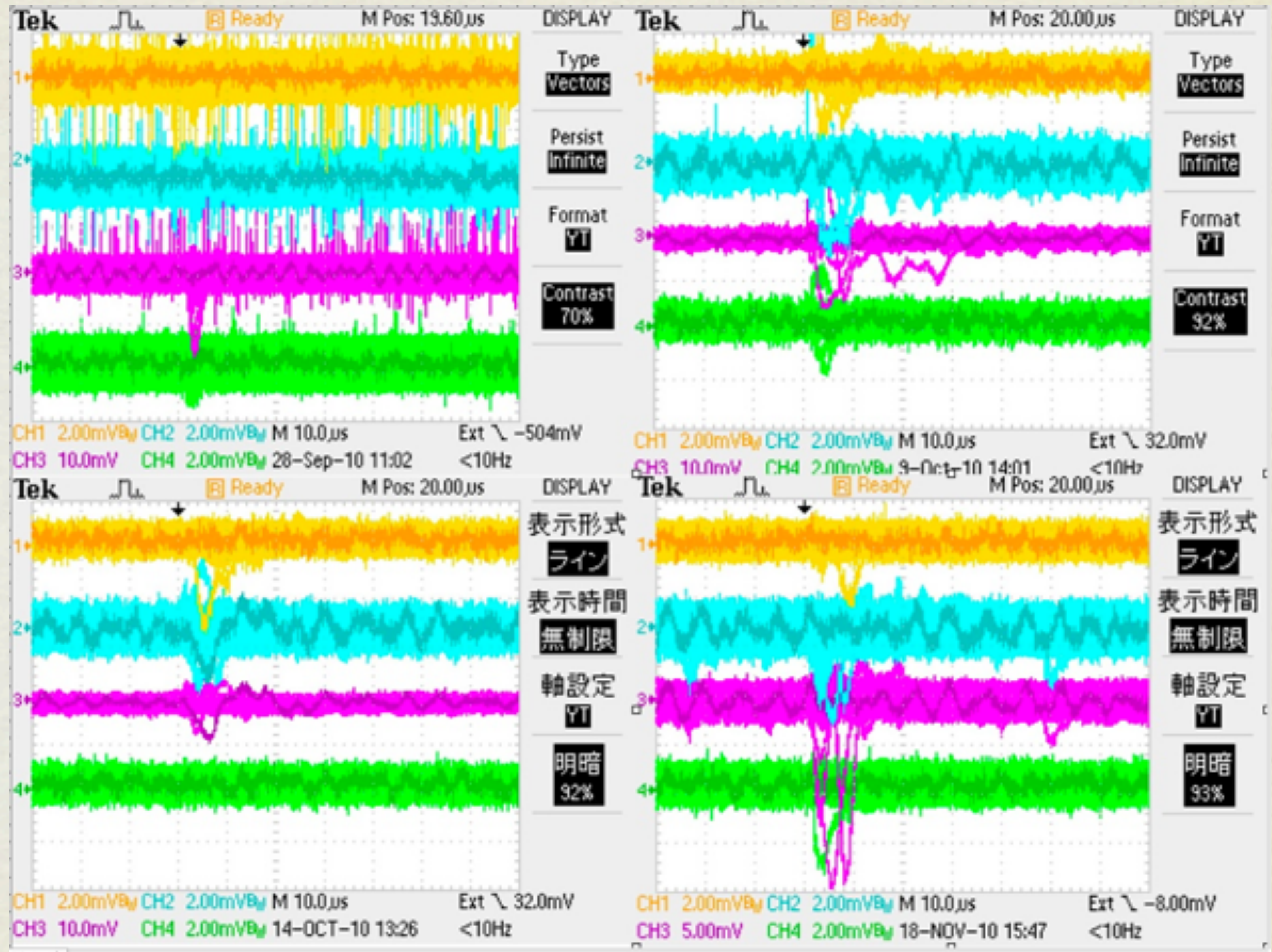


Fig. 3. Simplified schematic diagram of the charge sensitive preamplifier.

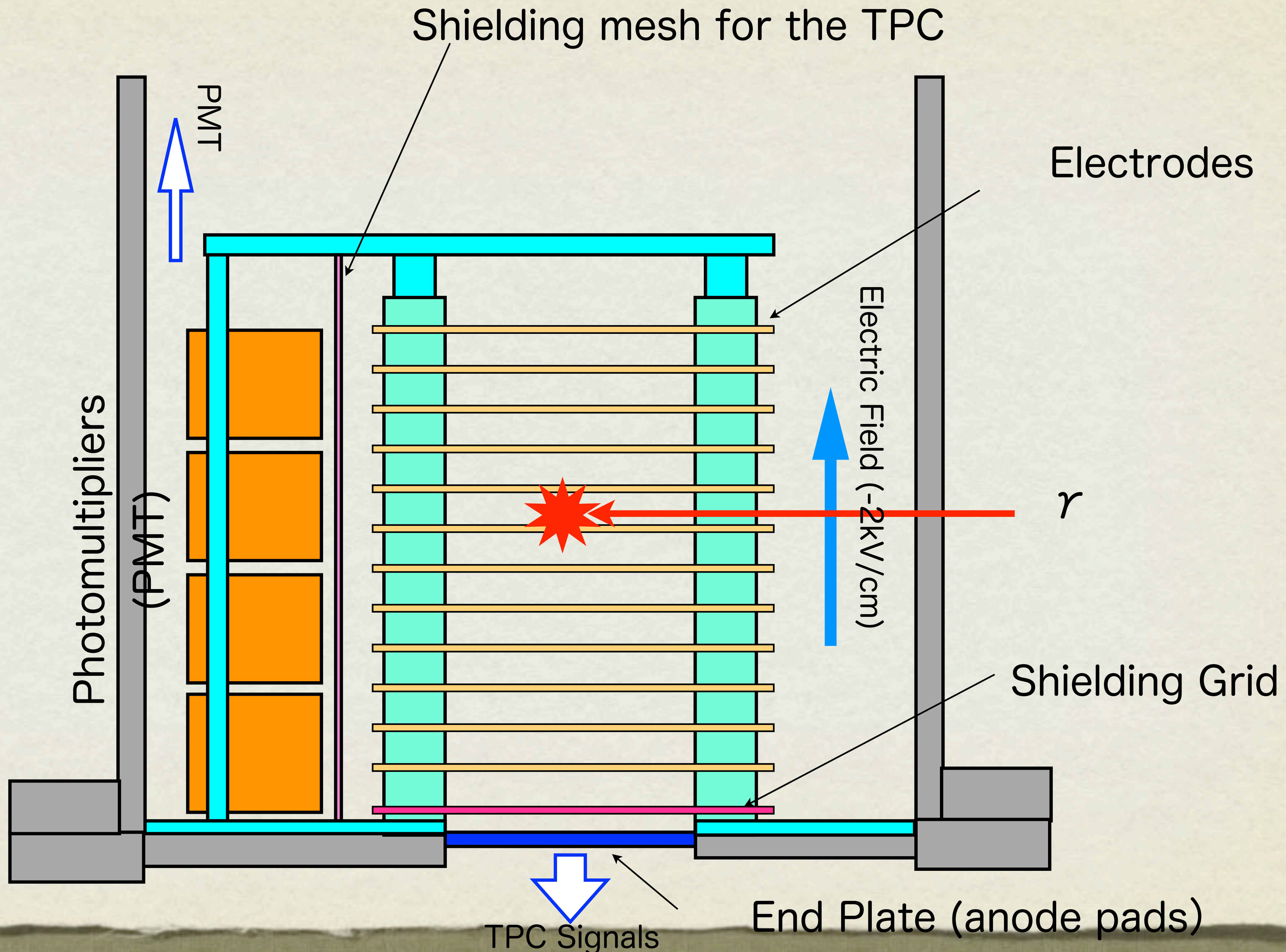
"A Cold Low Noise Preamplifier for Use in Liquid Xenon", A. Pullia et al.

DATA EXAMPLE

- Cosmic-ray data during purification on the central 4 pads
    - 0-1300 hours
- No alpha data seen ???



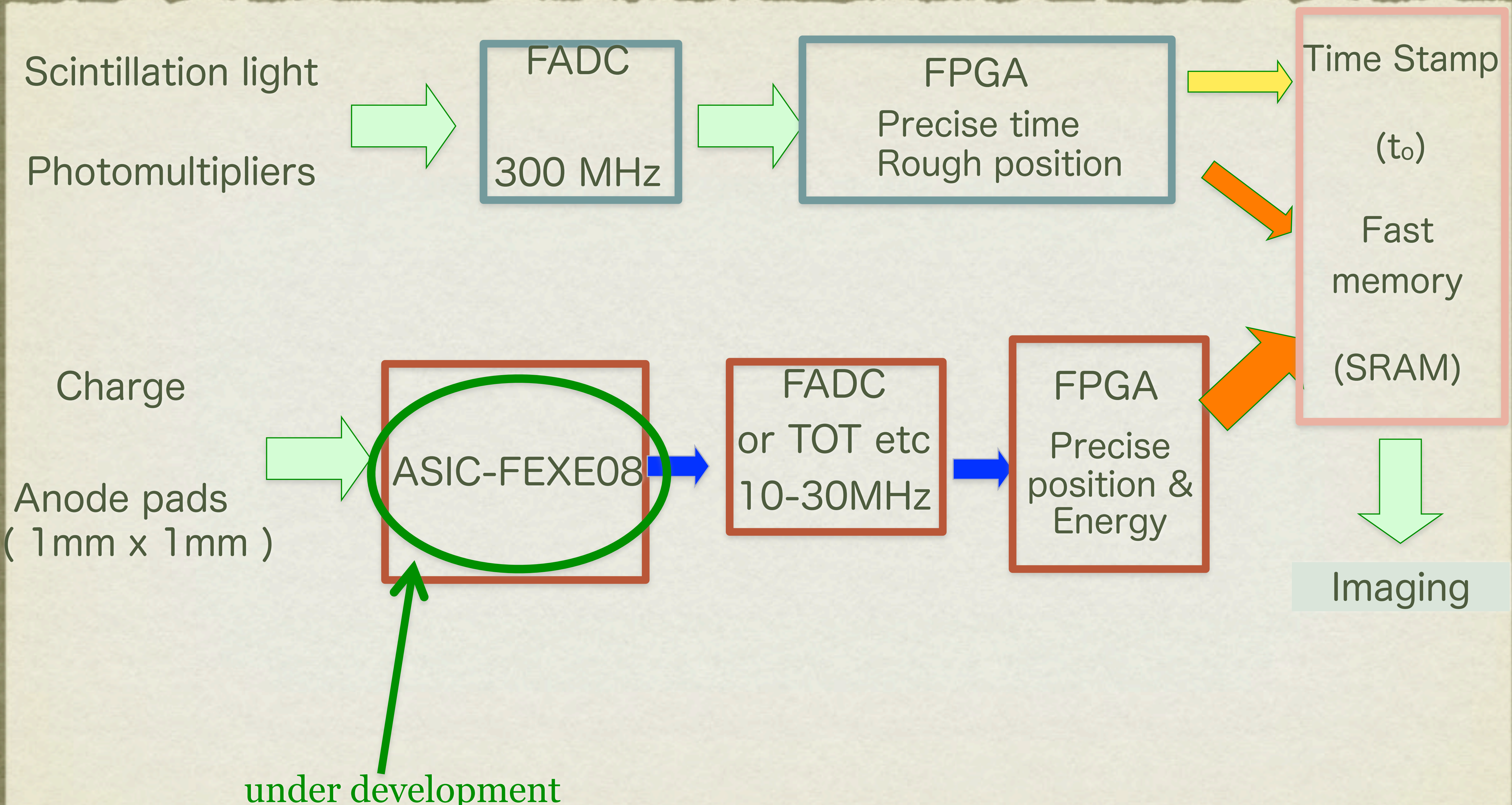
NEXT PROTOTYPE



ELECTRONICS

ELECTRONICS SYSTEM

Pipeline readout (digital processing)



supported by ASIC education & fabrication program, KEK

WHY ASIC?

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- Implementation of high density front-end electronics

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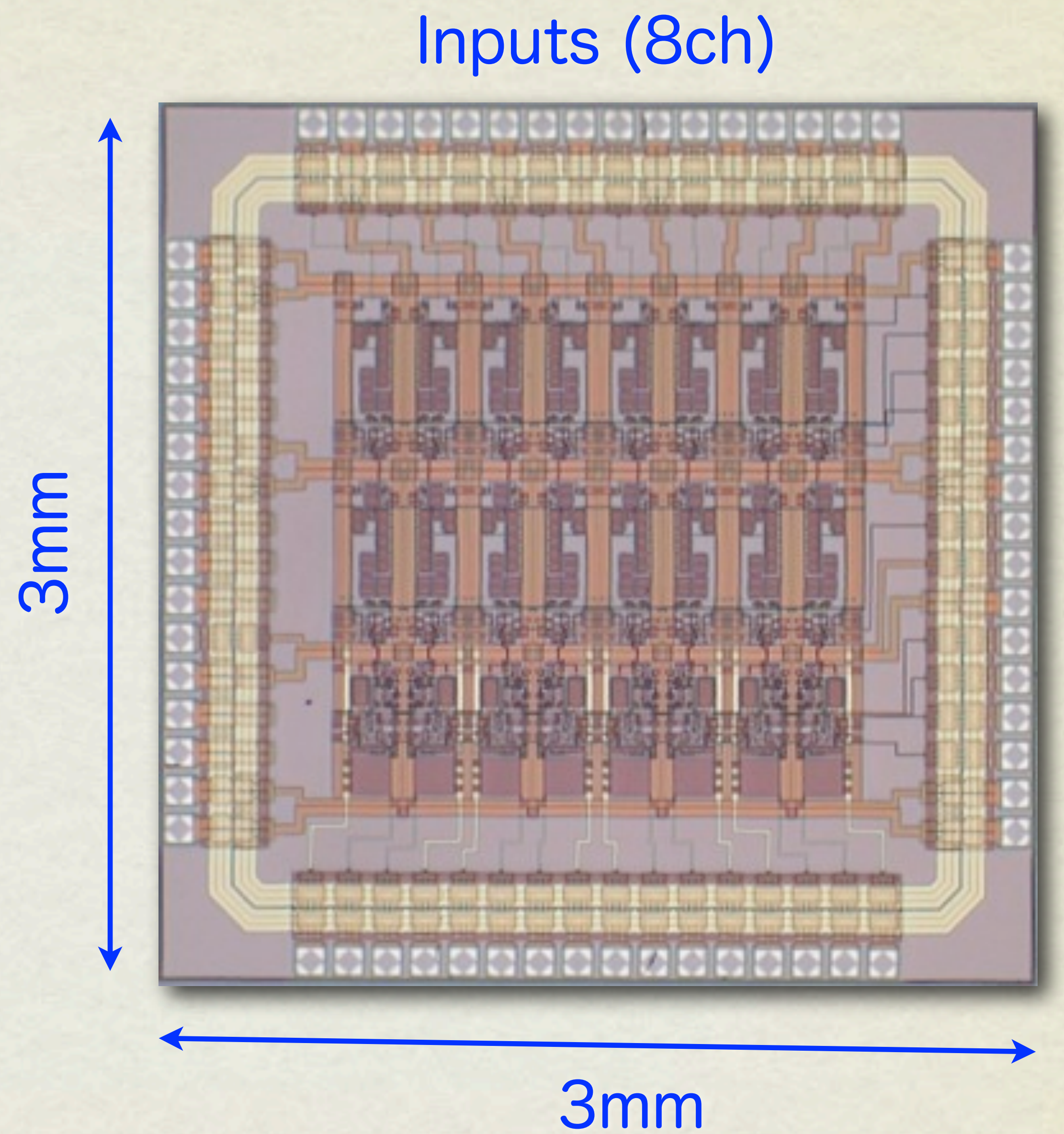
- Implementation of high density front-end electronics
- Charge transfer distance from the PAD to the electronics should be shortened to minimize ENC
- Digital electronics implementation can help to reduce impurity contamination caused by cable in (or near) the liquid

FRONT-END ASIC R&D

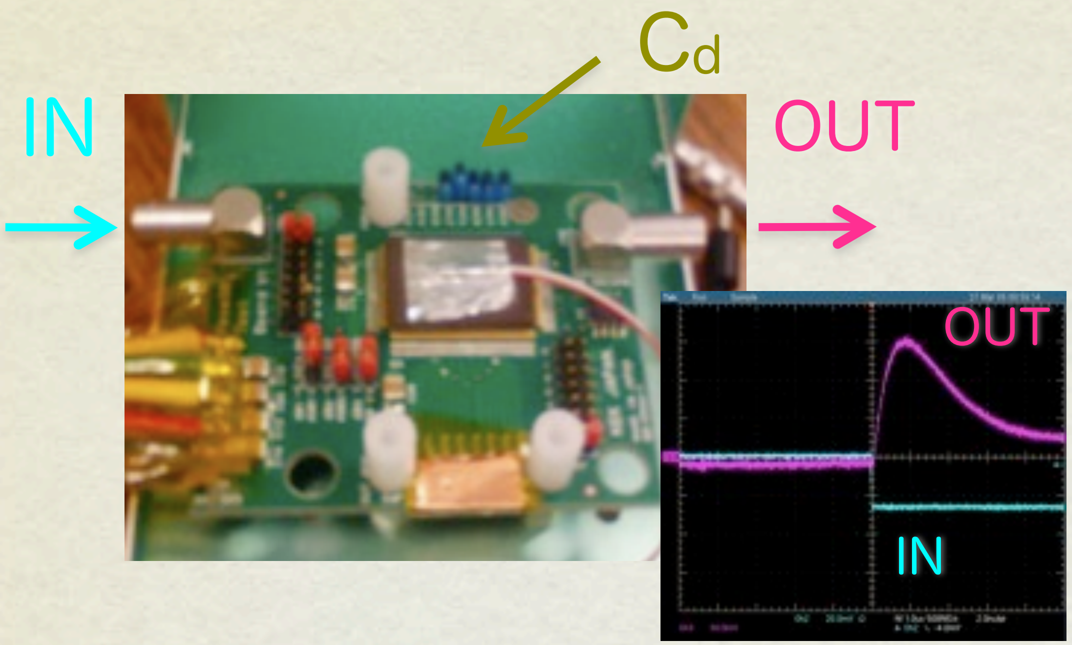
Pre-amp. to PZC to shaper - output all analog channels

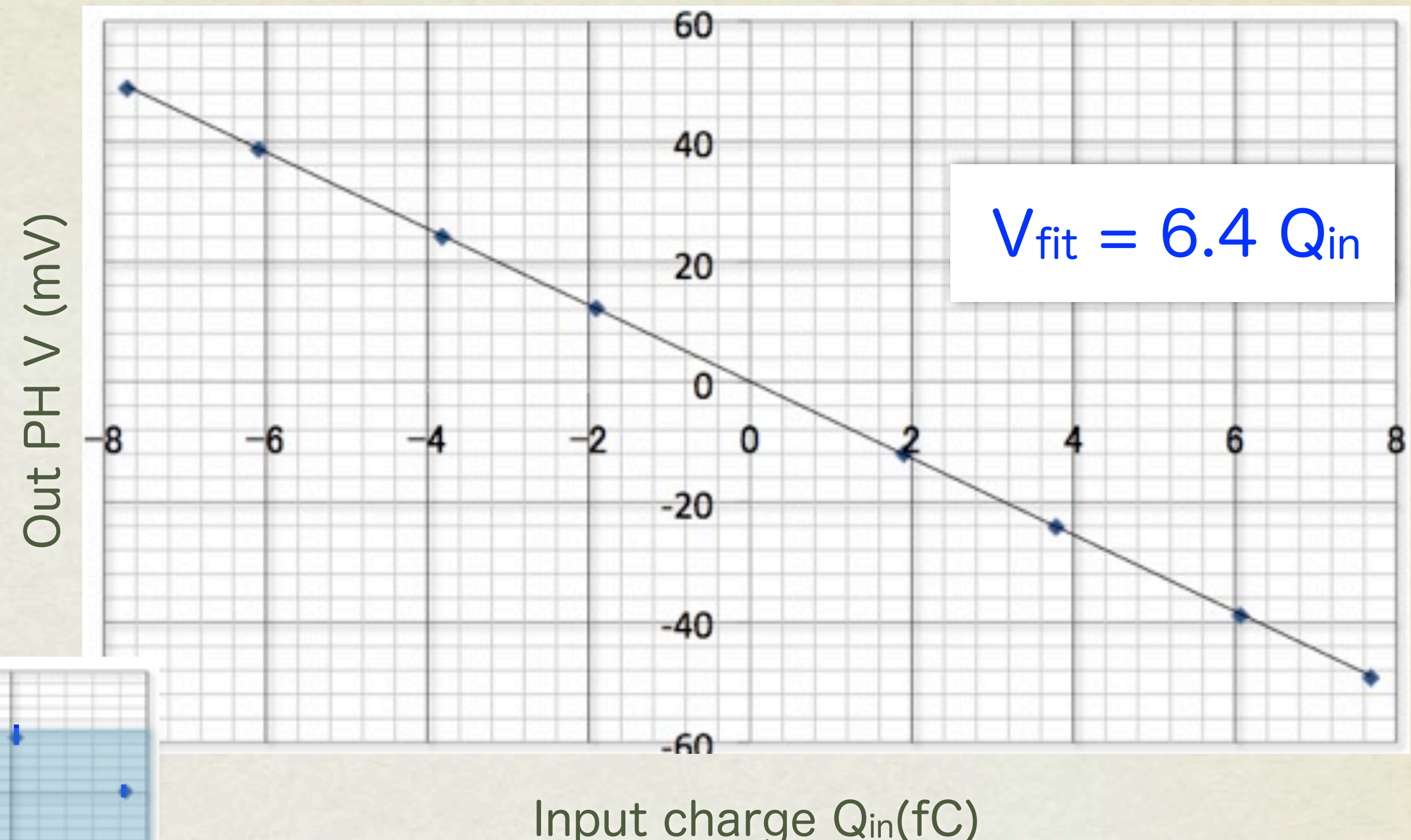
PARAMETER	SPECIFICATION	Achieved
chip size	3mm x 3mm	
channel number	8	
power supplies	±2.5V	
dissipation power	<10mW/ch	
gain	8.2V/pC	6.0±0.5V/pC
Input charge	±25fC	-60~100fC
peaking time	0.5, 1us, variable (>1us)	
prod. process	0.5um CMOS	
ENC	2,000e (C_d=1pF)	400e (C_d=1pF)

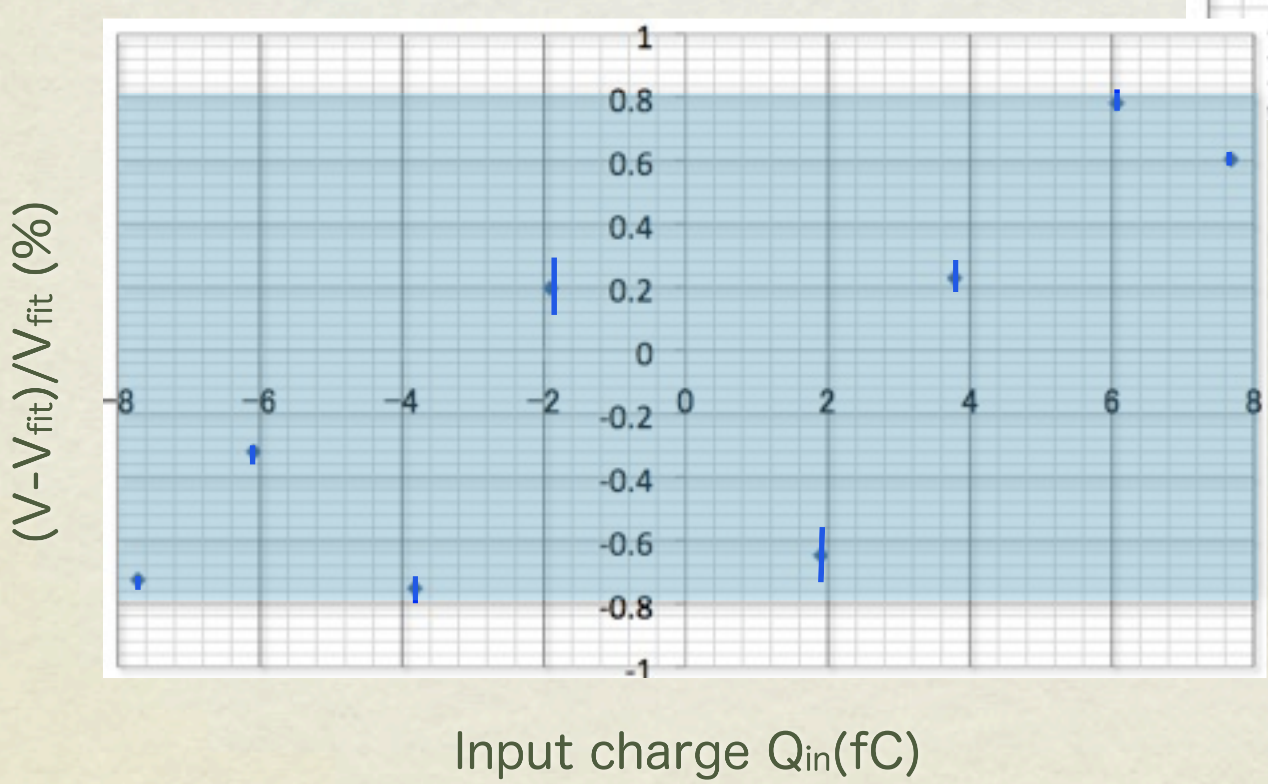


T. Higashi, JPS fall meeting, Kohnann univ., 9 Oct. 2009

TEST RESULTS : LINEARITY







Since σ of V (out) is about 1mV ;

σ=1mV/(6.4mV*Qin) σ= 0.16/Qin[fC]

Linearity less than 0.8%.

SUMMARY

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- Thanks for kind support of KEKDTP
- LXeTPC PET development is in progress at KEK
- Developed technologies for the MEG LXe detector are applicable w/o major difficulty
- Prototype study is in progress
  - Our goal is to realize 24cm electron drift induced by 511 keV gamma rays and to measure gamma-ray energy with good precision
  - Readout electronics development is indispensable for realization of the LXe PET system