Development of Deep-UV Sensitive MPPC for LXe Scintillation Detector

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K. Sato[2], R. Yamada[2]

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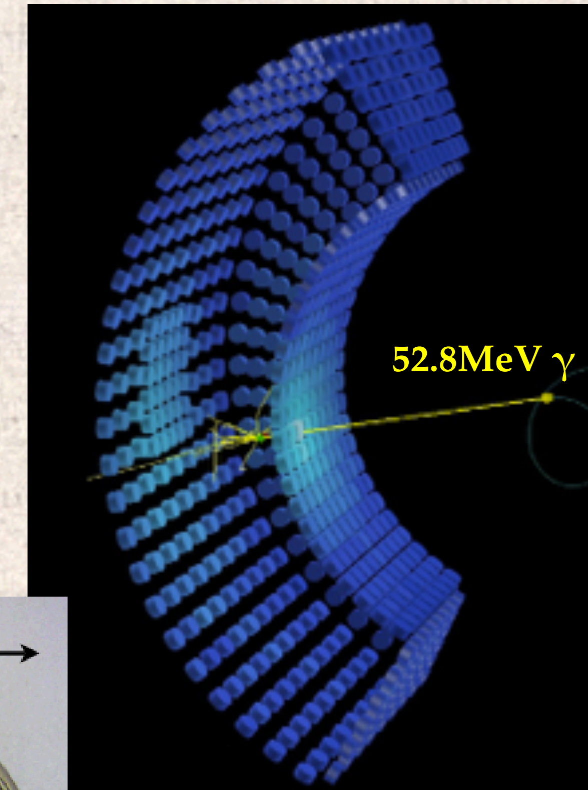
Contents

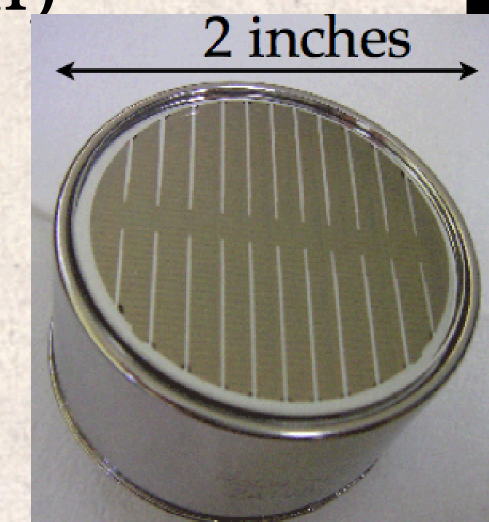
Introduction

- Increasing use and interest in **liquid rare gas** such as **LXe** and **LAr** as a detector medium in many fields
- Technical difficulties
  - Operation at low temperature (**LXe:165K, LAr: 87K**).
  - Detection of **scintillation light in deep-UV range (LXe:~175nm**, **LAr:~128nm)**
- **Development of high performance photosensor sensitive to deep-UV light is a crucial demand.**

MEG LXe Detector

- **World’s largest LXe (900ℓ) scintillation detector** to look for 52.8MeV-γ from μ→eγ
- Scintillation light (λ=175±5nm) collected by 846 **UV-PMTs** immersed in LXe
  - Hamamatsu R9869 (2-inch)
  - Operational in LXe (*T*=165K, *P*<0.3MPa)
- Excellent performance but with limited resolution due to non-uniform PMT coverage

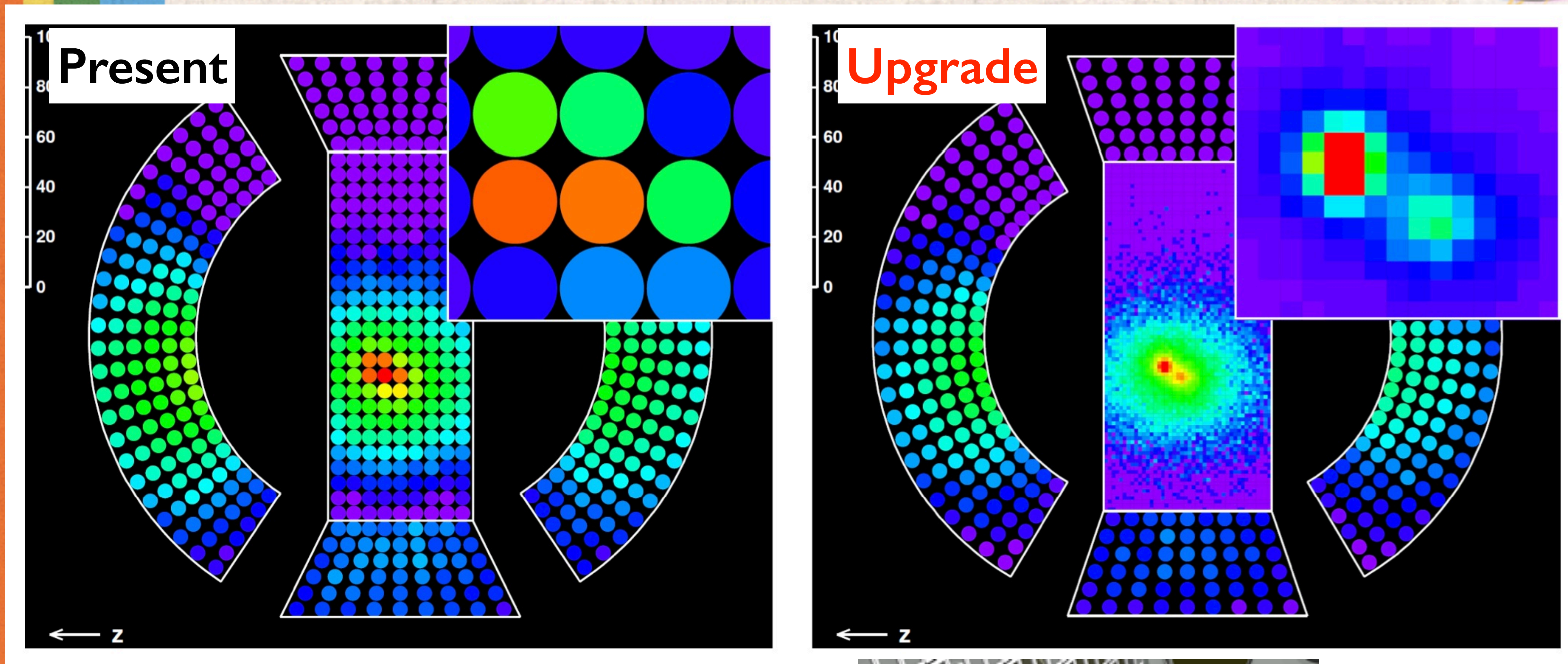




UV-sensitive PMT

MEG LXe Detector Upgrade

- **Highly granular scintillation readout** in LXe detector for MEG upgrade (MEG II)
  - Replace **216 × PMTs(2-inch)** on γ-entrance face with **~4000 × MPPCs (12×12mm^2)**
- Energy and position resolutions will be greatly improved (by a factor of two).
- γ-detection efficiency will also be improved by 10% because MPPC is much thinner than PMT.



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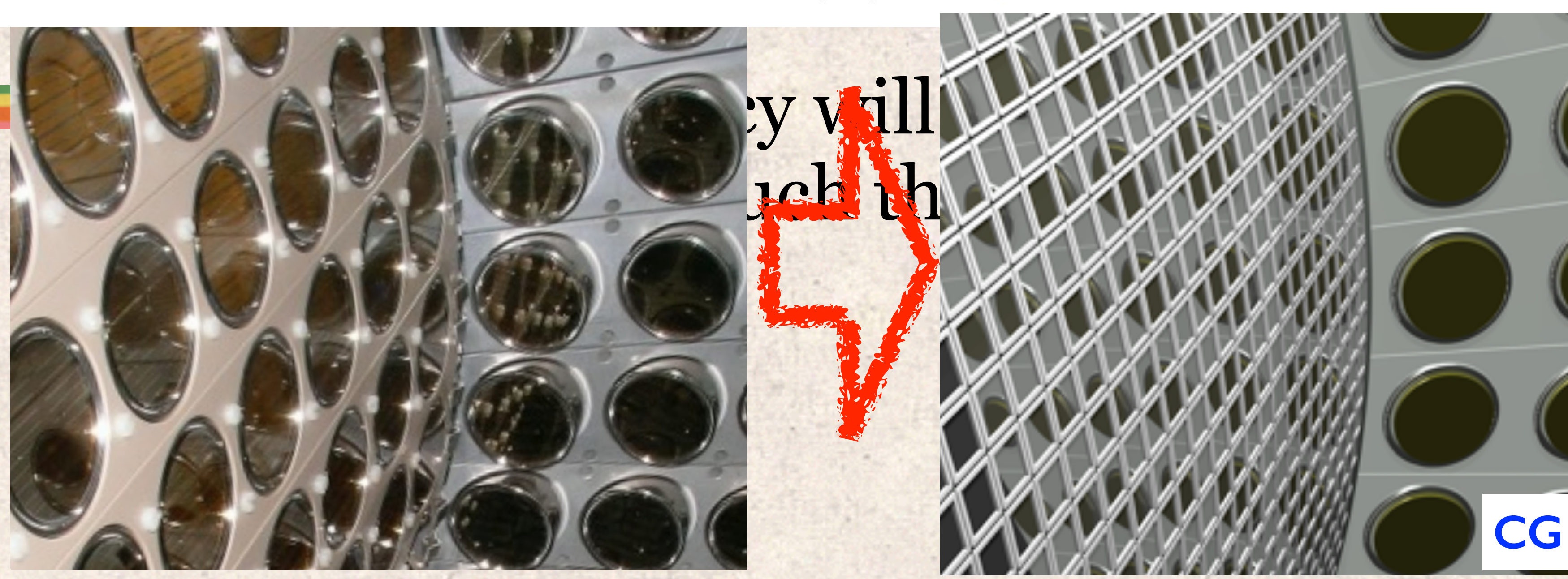

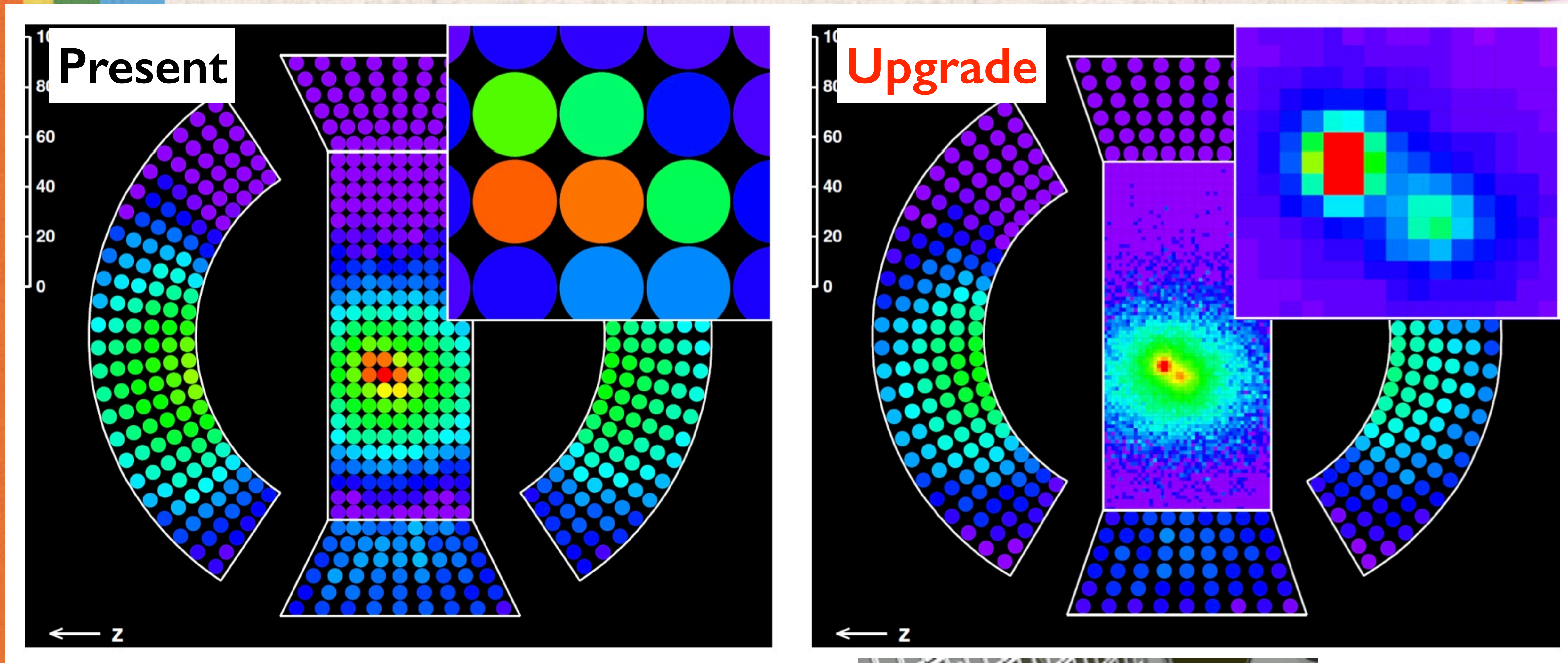

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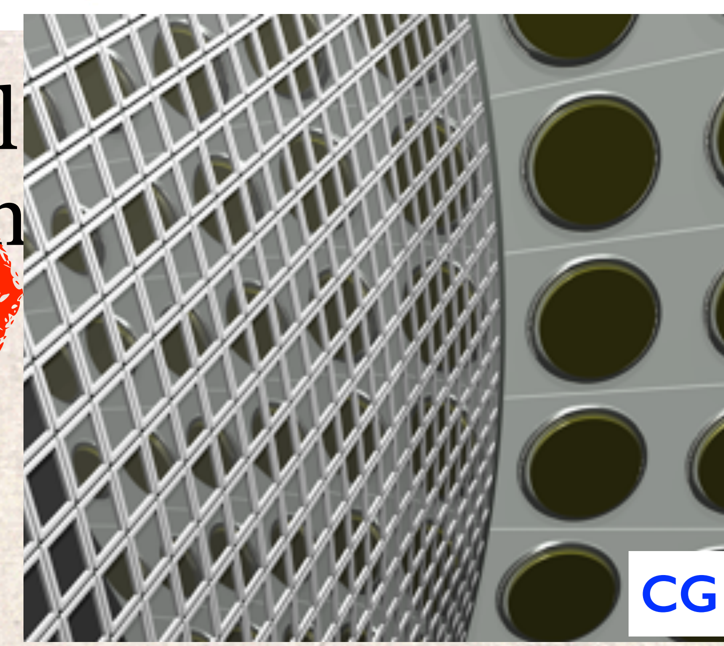
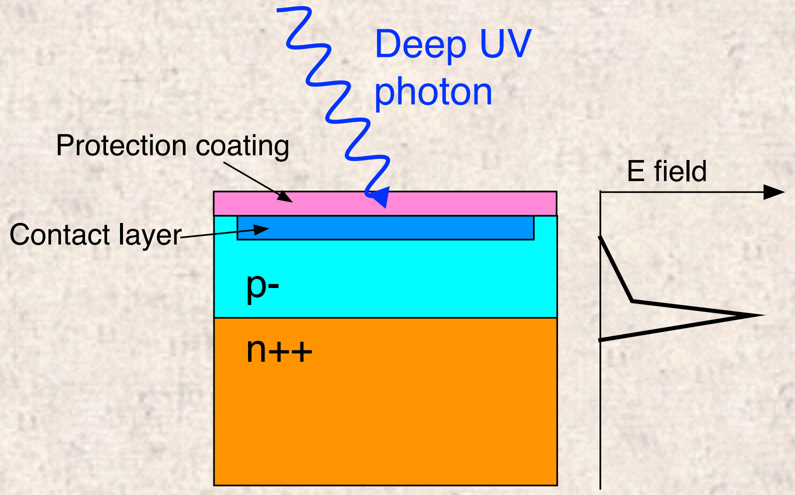


Imaging power will significantly improve!

Deep-UV Sensitive MPPC

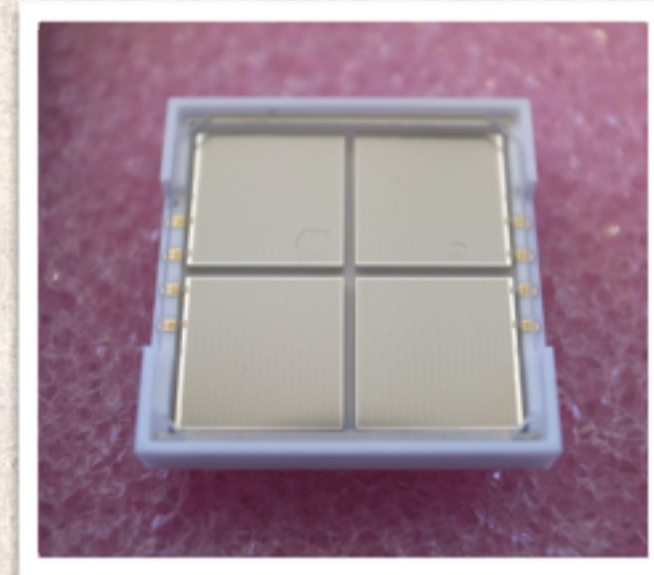
- Requirements
  - Photon detection efficiency (PDE) > 10-15%
  - Large active area ~ 12×12mm^2
  - Good single photoelectron resolution
  - Fast signal (fall time < 50ns)
- **How to improve deep-UV sensitivity**
  - Remove protection coating
  - Optimise optical matching bw/ LXe and sensor (refractive index, AR coating)
  - Thin down contact layer

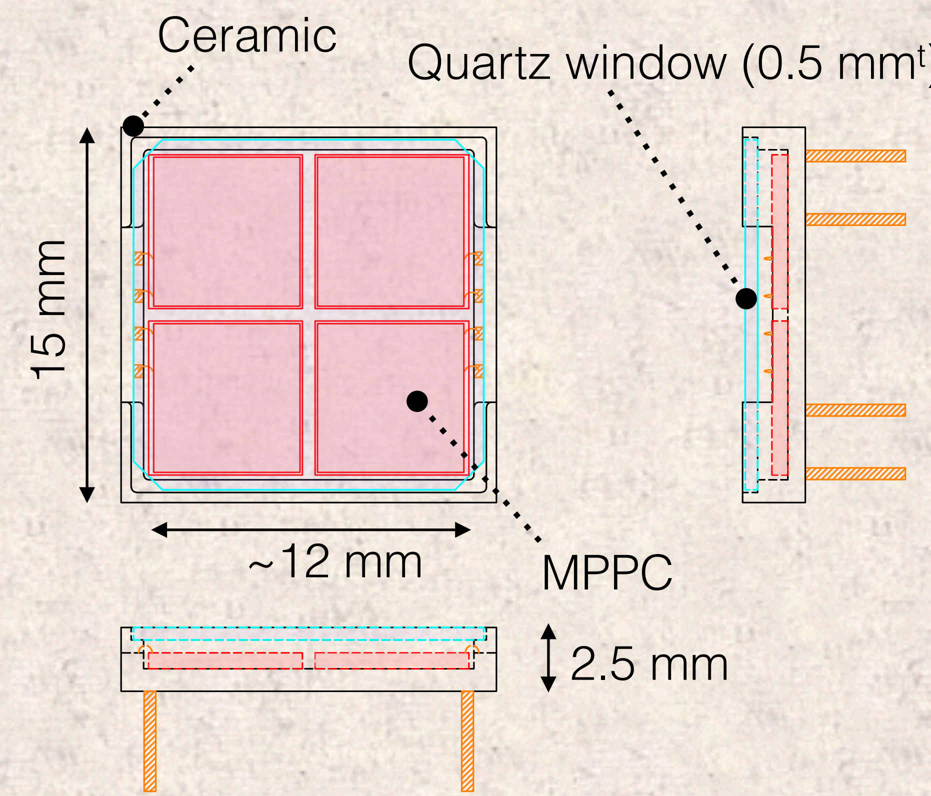


- **Large-area deep-UV sensitive MPPC has been successfully developed** in collaboration with Hamamatsu Photonics.

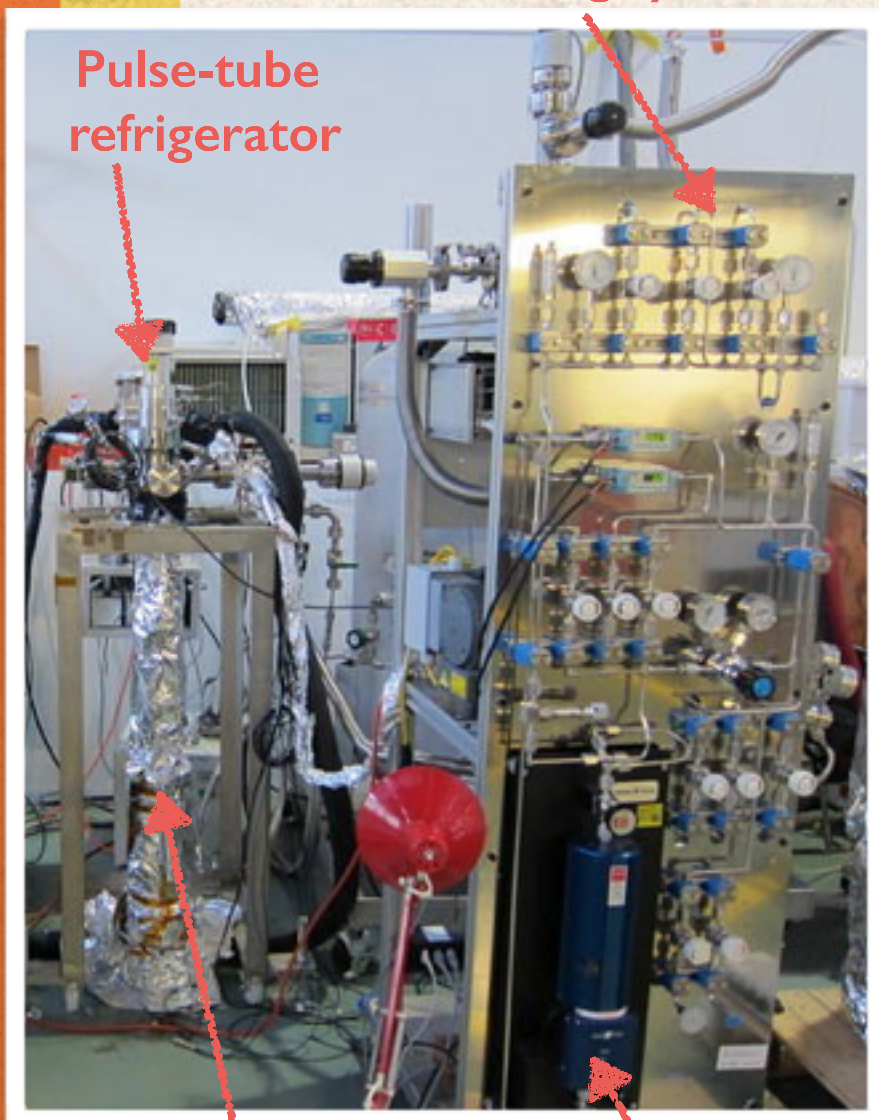
Deep-UV Sensitive MPPC

- **First production model delivered** in March 2014
  - S10943-3186(X)
  - 600 sensors produced for prototype LXe detector
- Active area **~12×12mm²**
  - Discrete array of four independent sensor chips, ~6×6mm² each)
  - **To be operated as a single sensor by connecting 4 chips in series** in external assembly PCB.
- **50μm pixel pitch**
- **Metal quench resistor** (only 20% change at LXe temp)
- **After-pulse suppression**
- VUV-transparent thin quartz window for protection (non-hermetic)



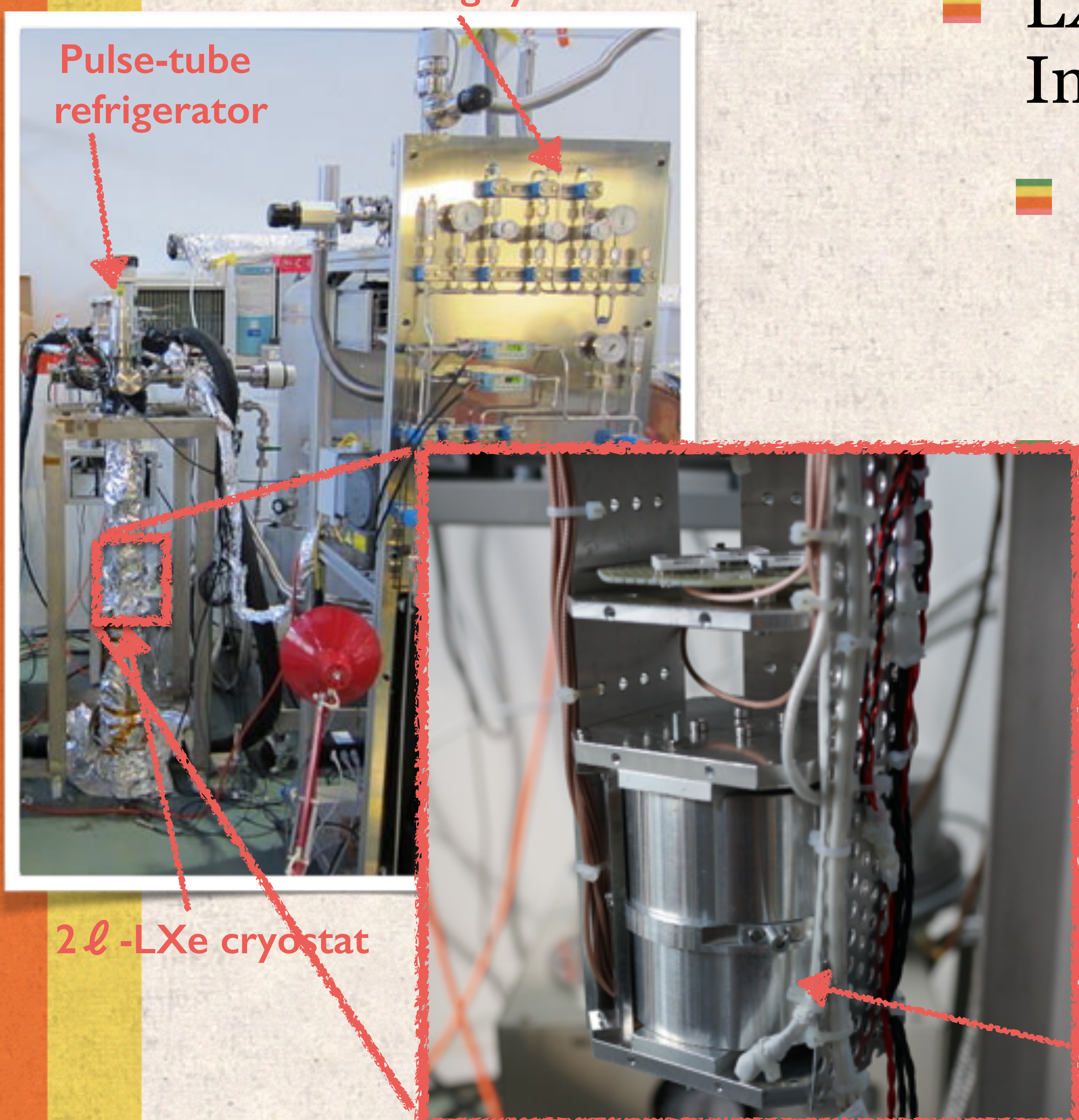


Test Setup



- LXe test facility at Paul Scherrer Institute (PSI) in Switzerland.
  - 2ℓ-LXe liquefied in small cryostat with pulse-tube refrigerator (Iwatani PDC08)
  - Blue LEDs for calibration
  - Am-241 α-source for PDE measurement (=point-like light source)
  - Mounted inside cylinder with “VUV-black” coating to suppress reflection

Test Setup



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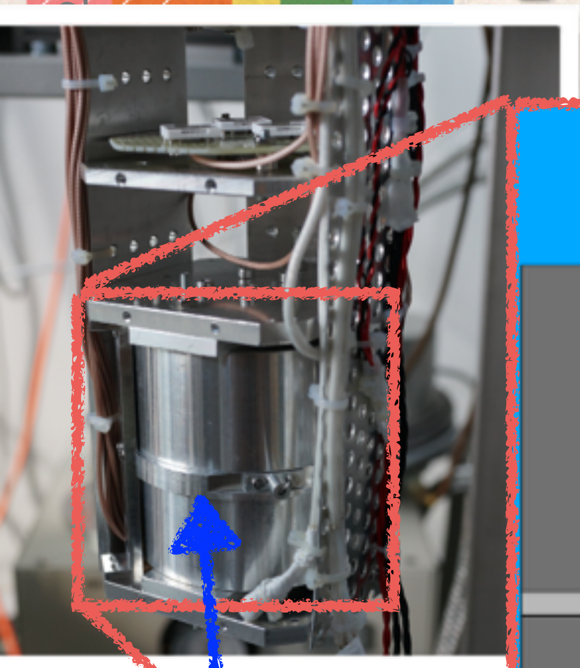
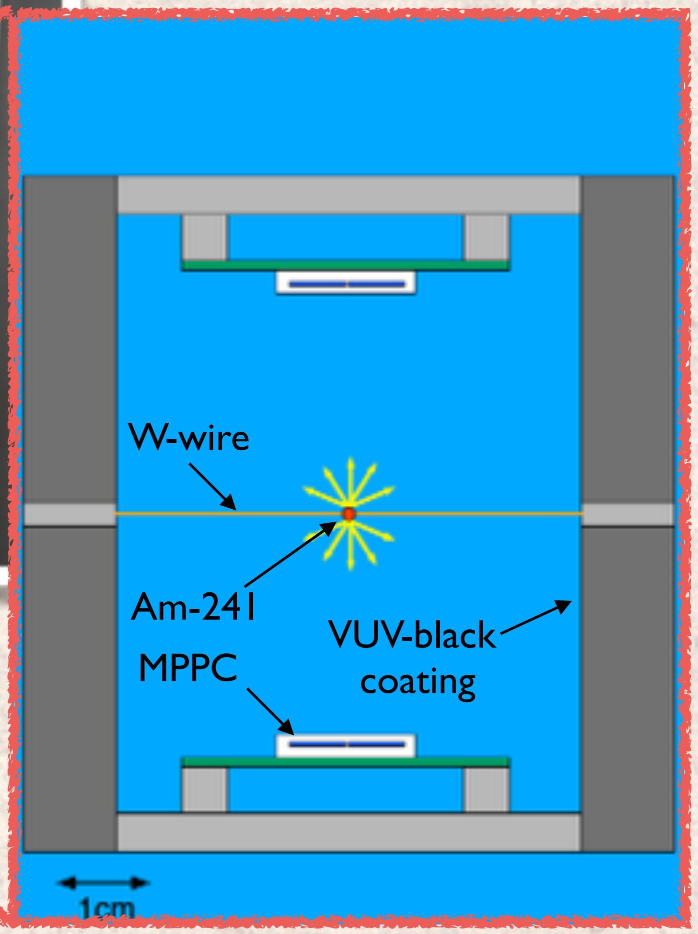
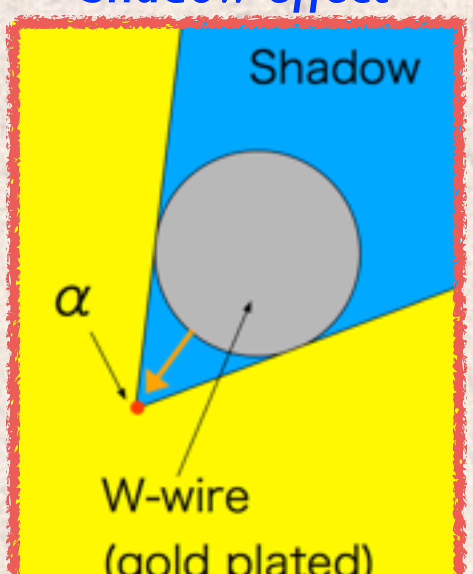
PDE Measurement





Shadow effect



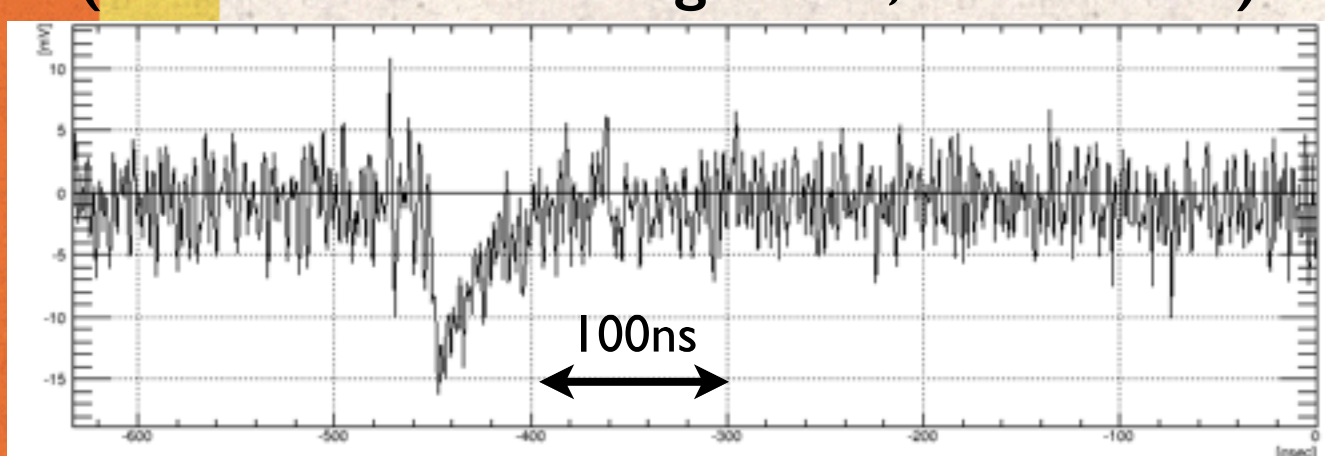
- **Am-241 spot α-source on tungsten wire** (φ100μm, gold-plated) *A. Baldini et al., NIMA 565(2006)589*
  - Shadow effect (range of α in LXe ~40μm < wire diameter)
  - Reflectivity on gold surface ~20%
- **PDE = (measured # of photoelectrons)/(expected # of photons)**
- Vetoed events with shadow effect using signal from sensor on the other side
- PDE is measured individually for 4 segment chips on MPPC.

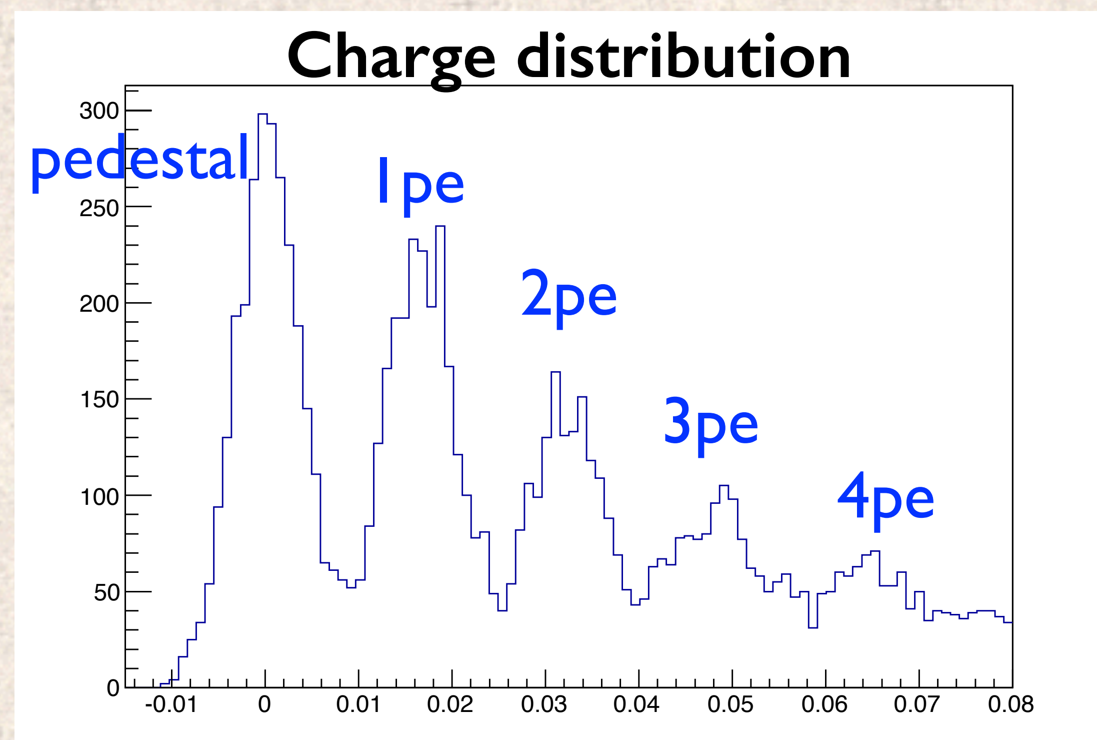
W. Ootani et al., “Development of Deep-UV Sensitive MPPC for LXe Scintillation Detector”, NDIP2014, Tours France

Performance

- **Single photoelectron peak clearly resolved** with large-area sensor (**12×12mm²**) .
- This is made possible by
  - Excellent cell-to-cell gain uniformity
  - **Extremely low dark count rate** (**~1Hz/mm²**) at LXe temp. (×~10⁵ lower than at room temp.)

Single photoelectron signal
(series-connected segments, 12×12mm²)

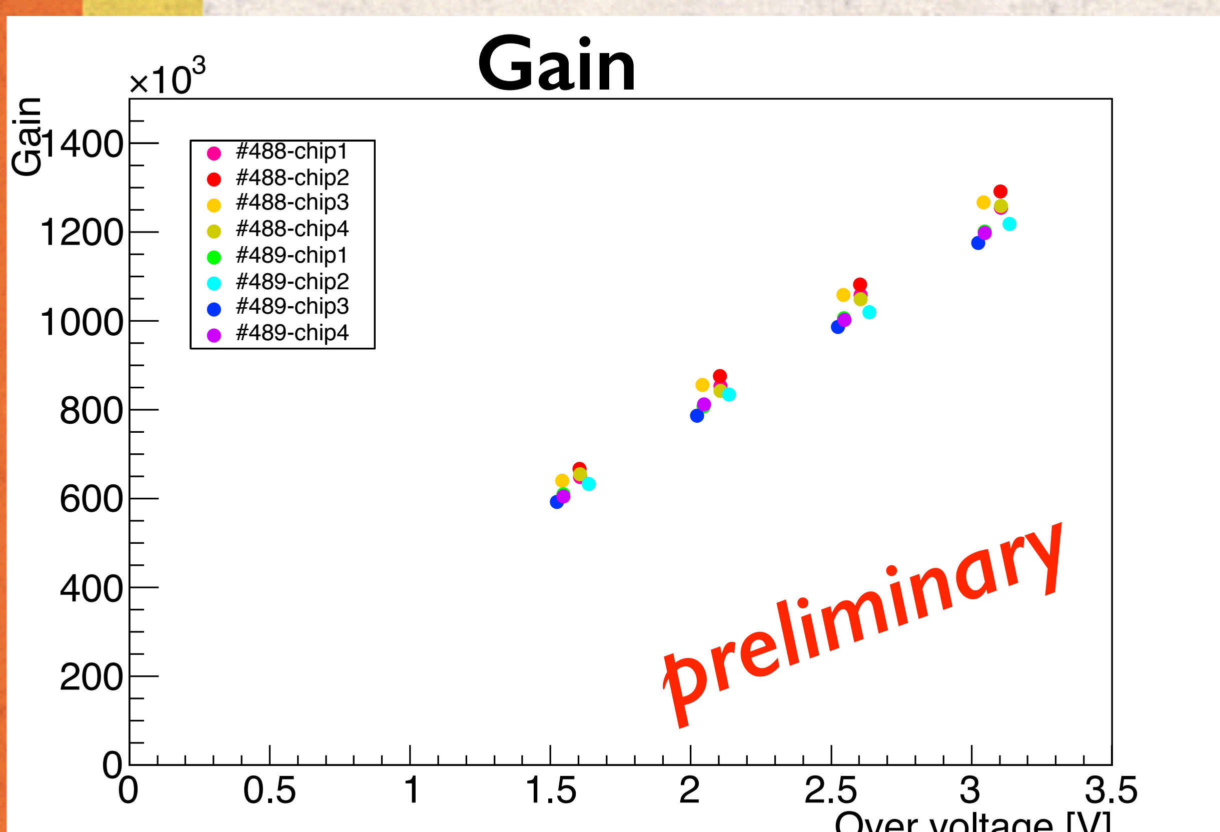


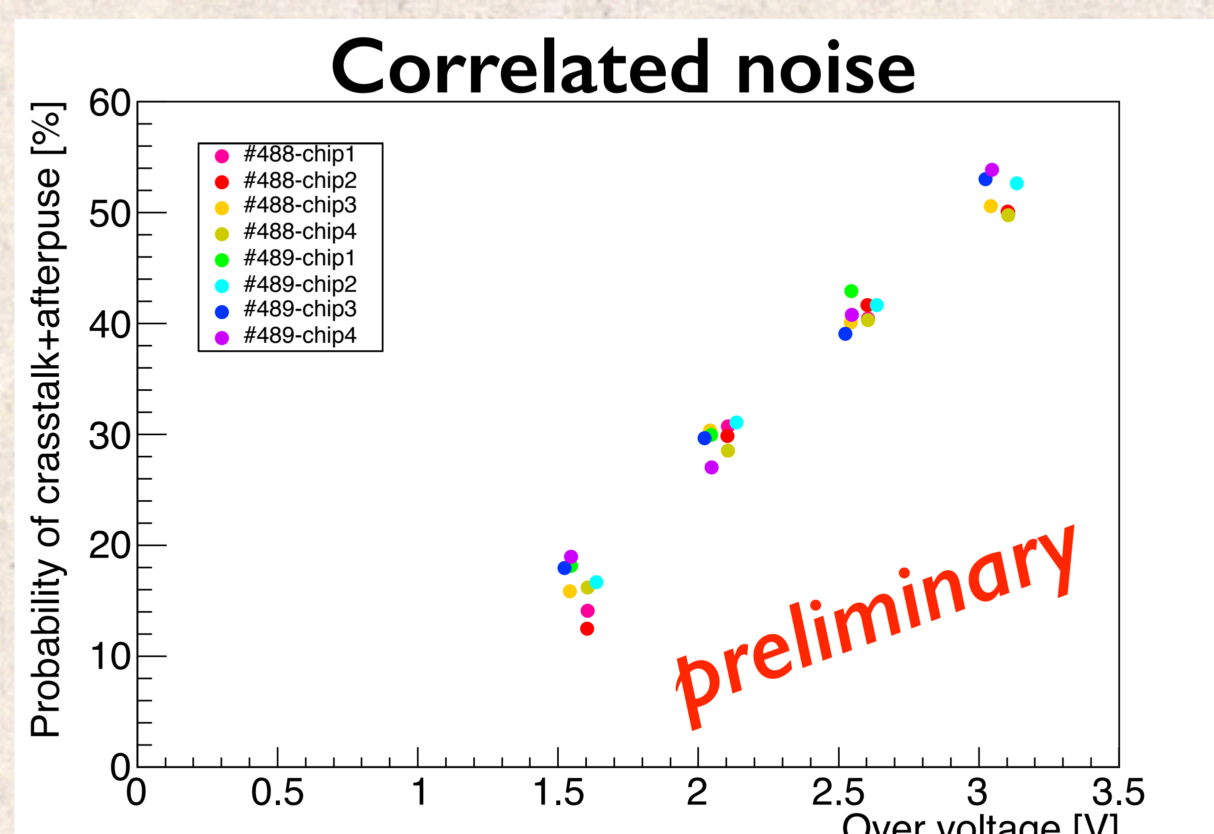


Performance

- Basic properties measured for individual chip
  - **Gain >5×10⁵** (for single segment chip)
  - **Dark count rate ~1 Hz/mm²**
  - Correlated noise probability
    - **After-pulsing: <10%**
    - **Optical crosstalk ~35%**

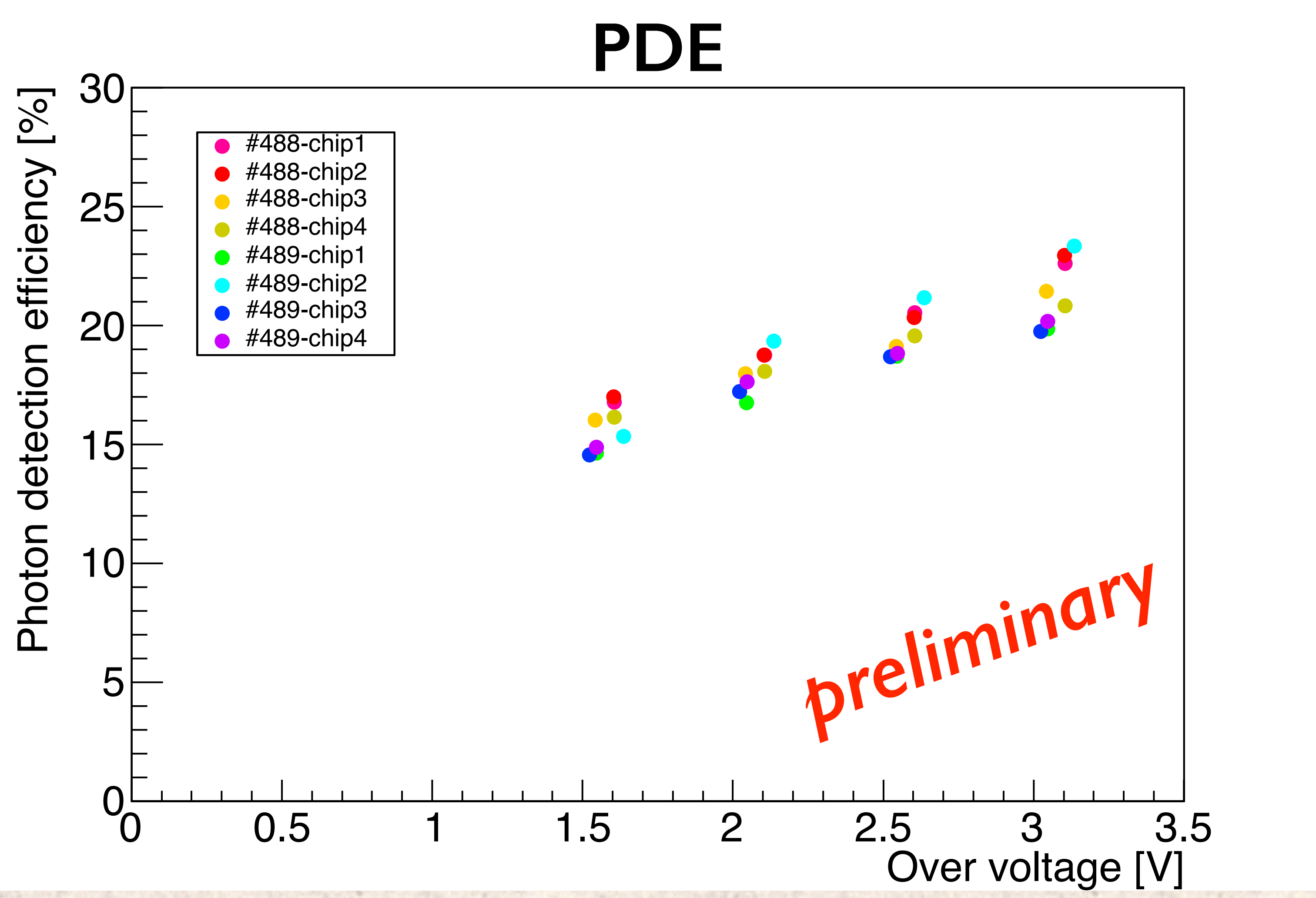
← all numbers are for ΔV=2.5V





Performance

- Excellent **PDE (>15%)** is achieved.
    - Largest uncertainties (~10%) in estimation of expected # of photons impinging MPPC (geometrical acceptance, effect of reflection on surrounding materials)

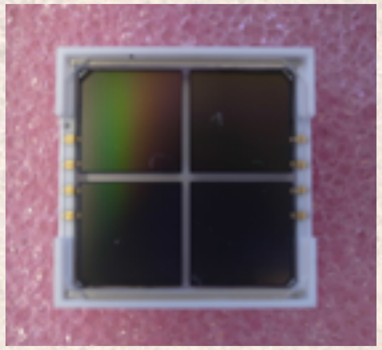


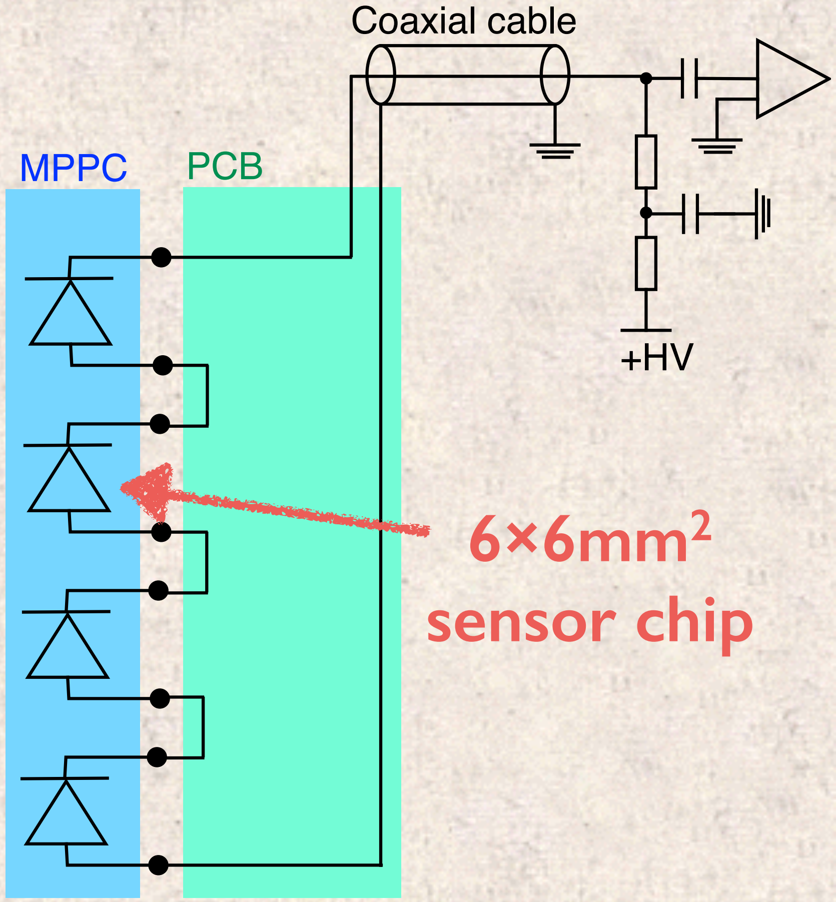
Sensor Capacitance Issue

- Issues caused by large sensor capacitance (~5nF) for large sensor area (12×12mm²)
  - **Long signal tail (~150ns)**
  - **Higher noise**
- **All segments are connected in series** to reduce overall capacitance
  - Drawback: reduced gain
  - Series connection of multiple SiPMs has been proven to be useful already in other detectors.

A. Stoykov et al., NIMA 695(2012)202
W. Ootani et al., DOI 10.1016/j.nima.2013.07.043

Sensor segmentation (×4, 6×6mm² each)

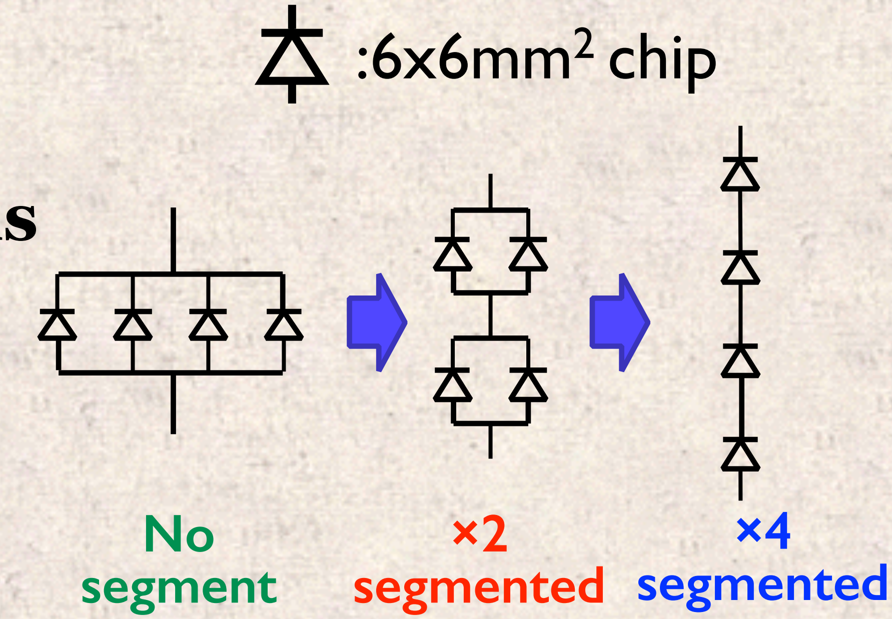




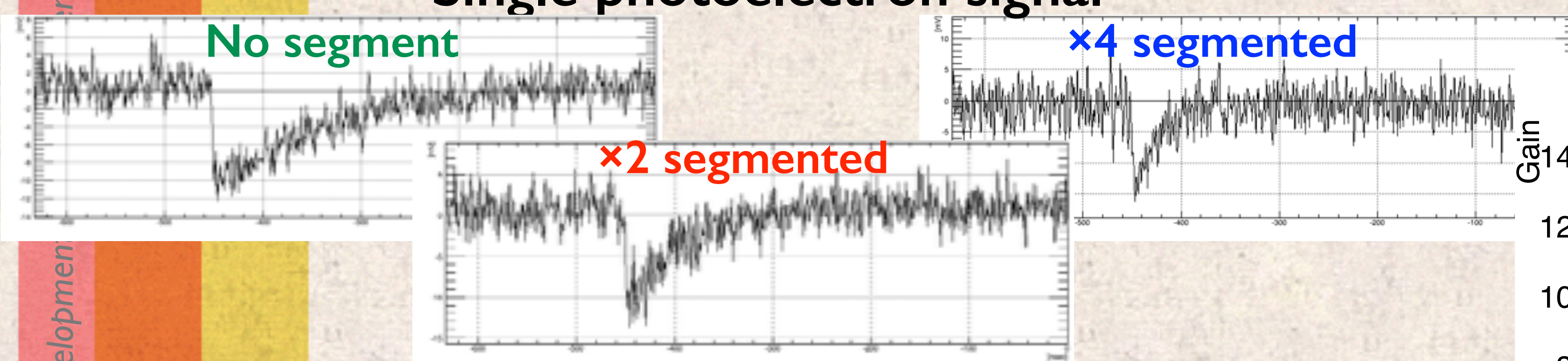
Sensor Capacitance Issue

- Performance compared bw/ different segmentations.
- **Signal fall time reduced down to 25-50ns with series connection**
- Still reasonably high gain (>2×10^5)

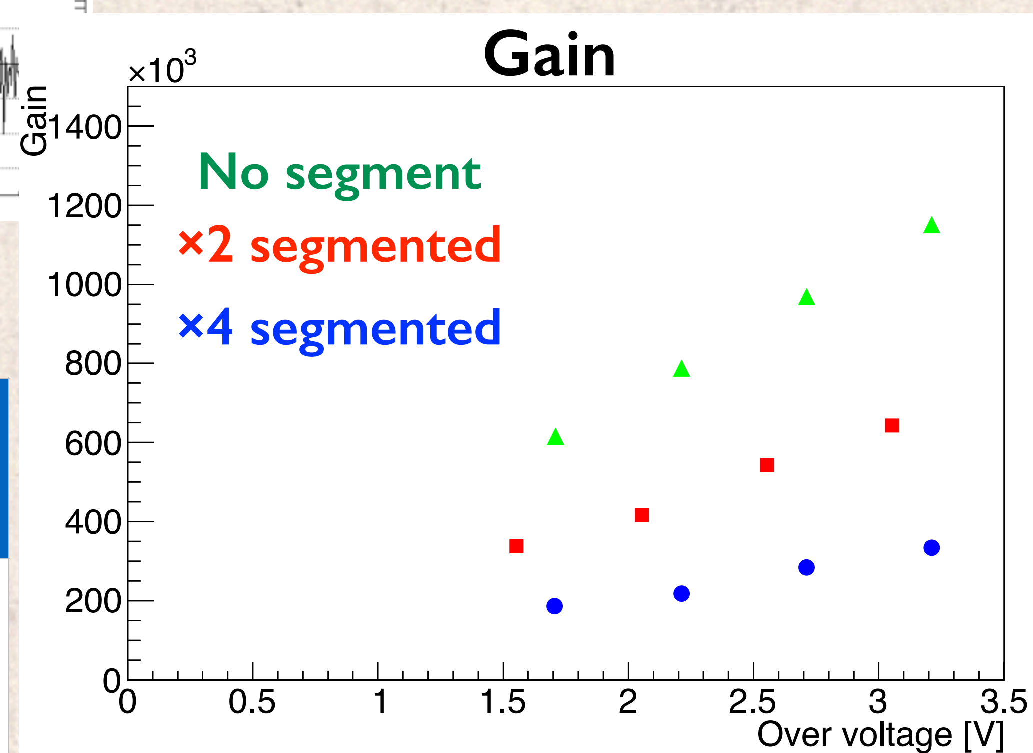
→ **We decided to have 4 segments.**



Single photoelectron signal



	Non-segmented	×2 segmented	×4 segmented
Fall time	135ns	⇨ 49ns	25ns



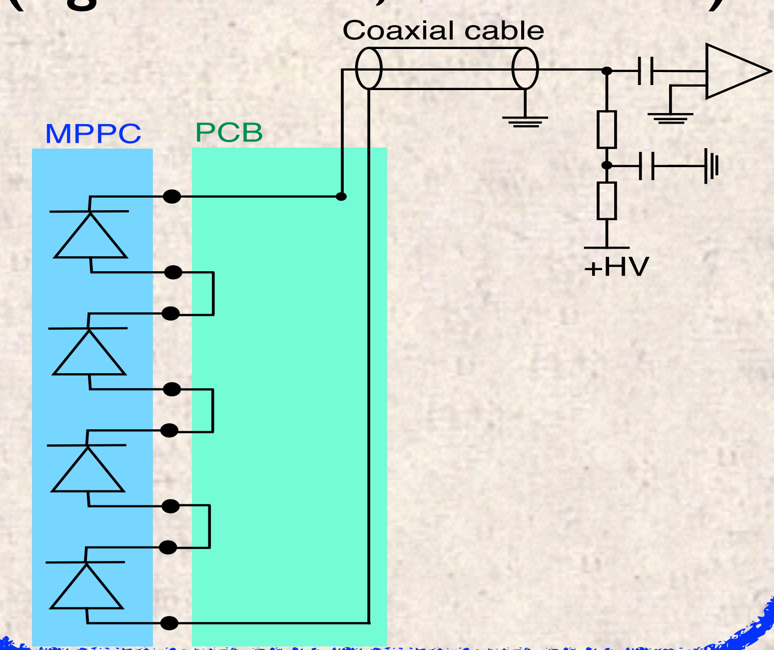
Sensor Capacitance Issue

Two options for series connection

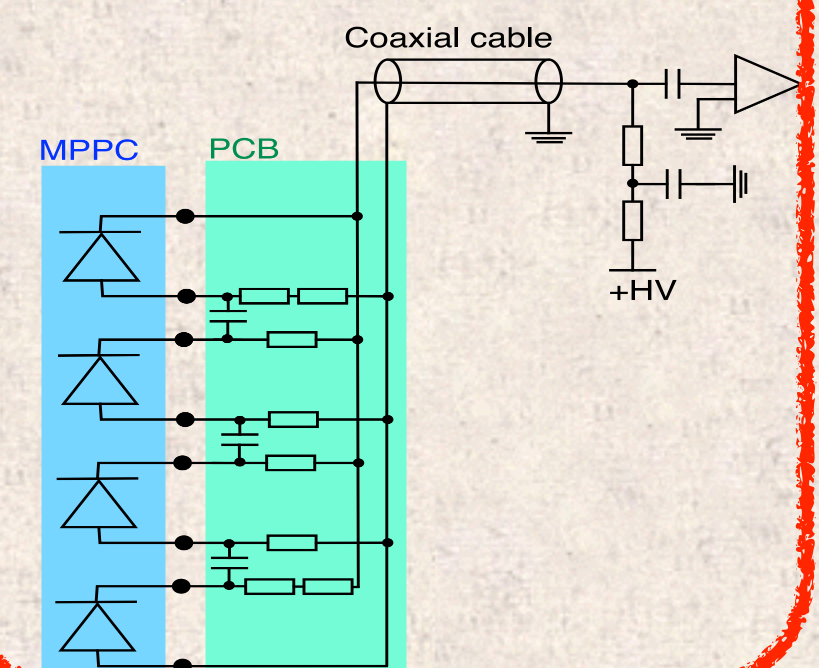
	"Simple"	"Hybrid"
Bias	4×55 V ☹☹	55V (common) ☺
V_{BD} uniformity	Automatic V_{BD} equalisation ☺	Required ☹
Potential diff. bw/ adjacent segments	>55V ☹☹	0V ☺
External circuit	No ☺	Required ☹
High rate performance	Good ☺	Not excellent, but OK ☹

→ Both work at LXe temp.!
"Hybrid" is more advantageous in our case.
(Issues can be solved relatively easily.)

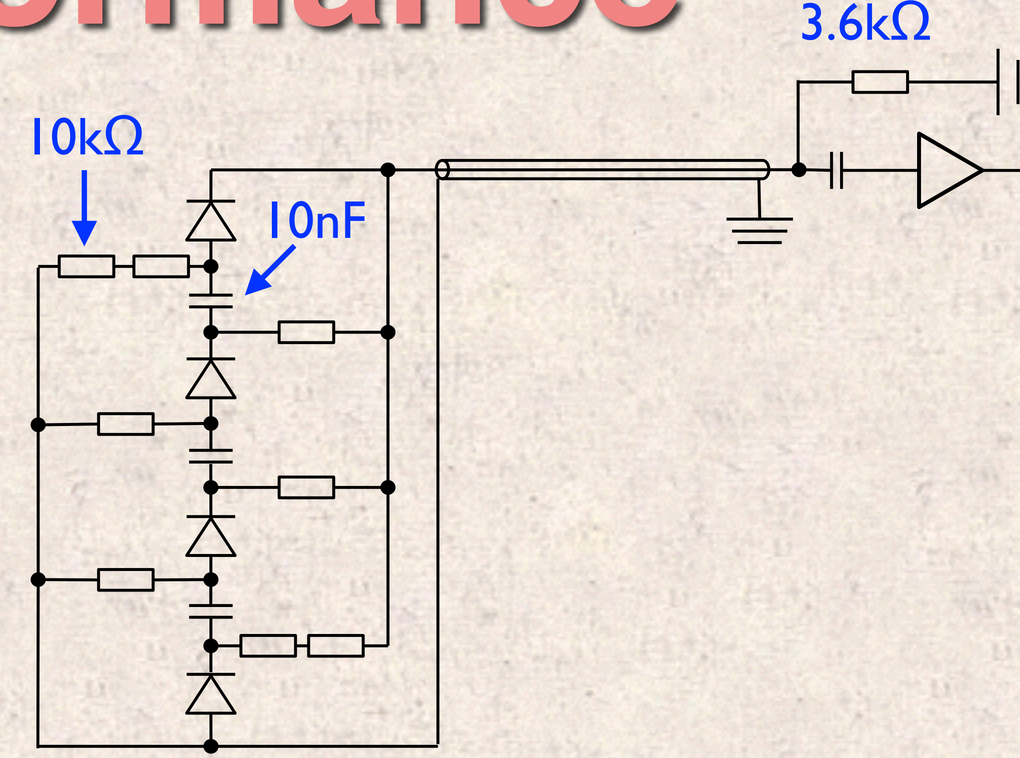
"Simple"
(signal: series, bias: series)



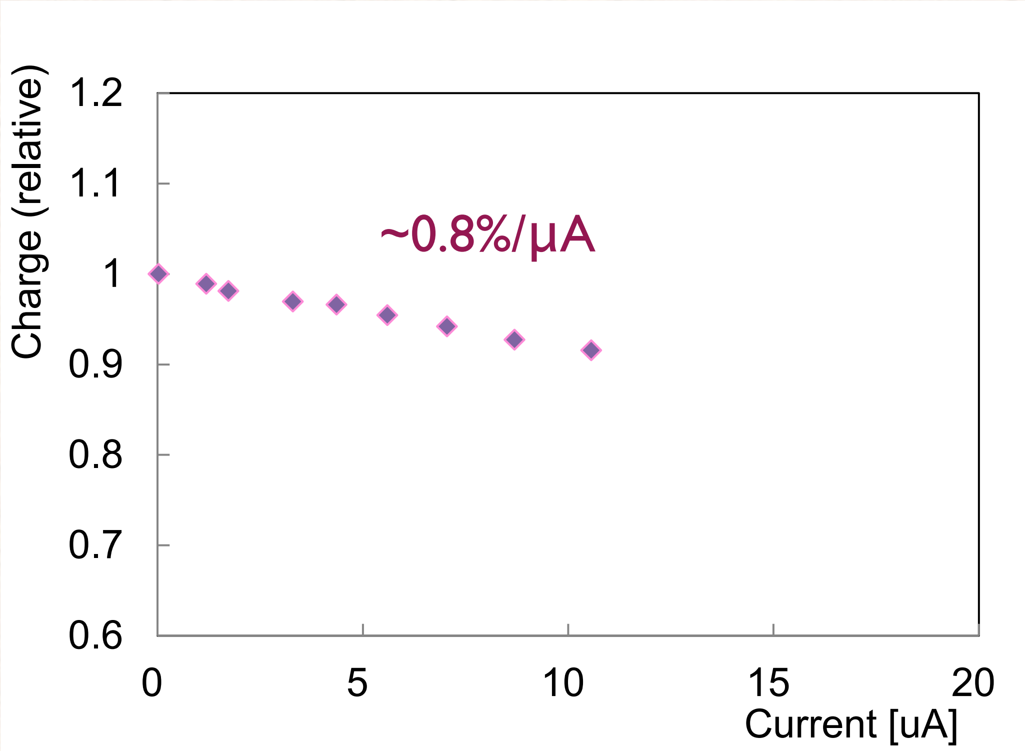
"Hybrid"
(signal: series, bias: parallel)



High Rate Performance

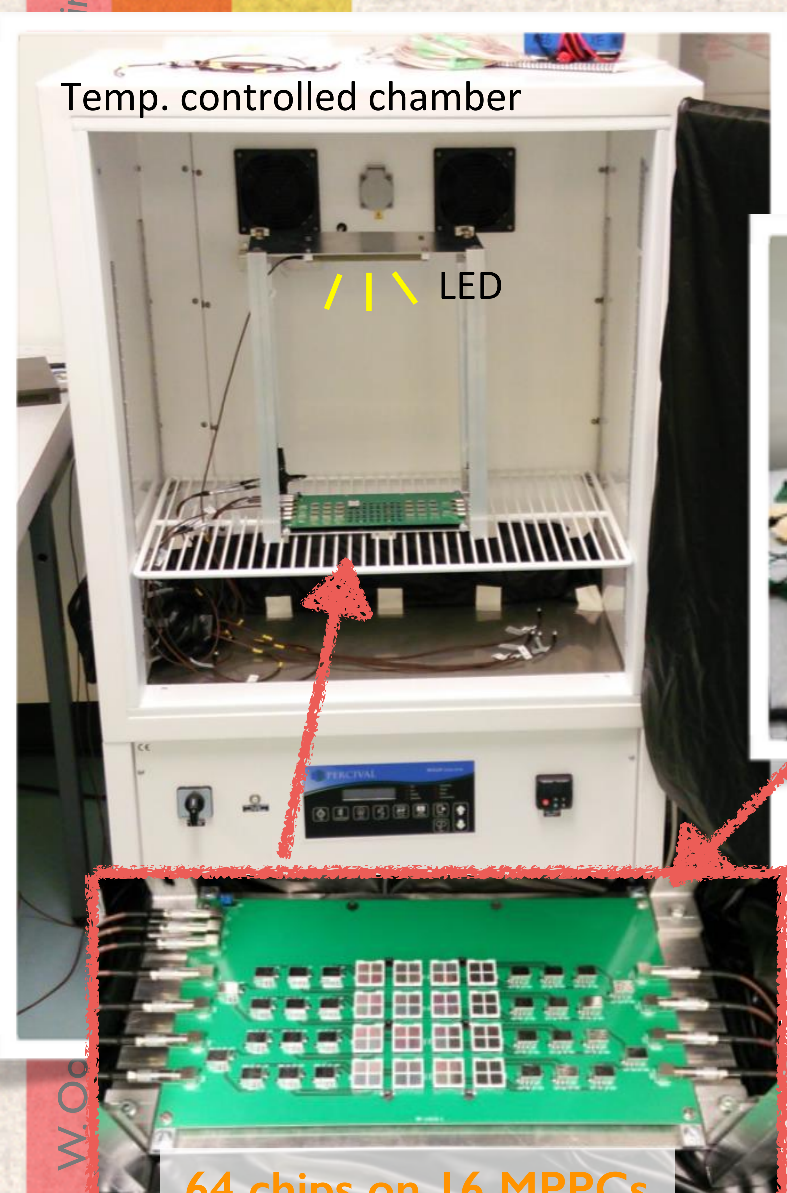


- **Gain degradation at high rate environment** observed especially for "hybrid" segment connection.
  - Caused by voltage drop in resistor(s) in series connection and bias line
  - **~0.8%/μA @R=10kΩ, C=10nF**
    - N.B. leakage current w/o incident photons is negligibly small at LXe temp.
- **Possible solutions**
  - **Optimising resistor and capacitor**
    - Smaller resistance → voltage drop↓, but signal leakage to bias line
    - Signal leakage to bias line can be reduced with smaller capacitance.
  - **Simple series connection**



Mass Test at Room Temp.

- Mass test of 600 × MPPCs at room temp is under way before being installed in prototype LXe detector
- Basic properties (gain, V_{BD}, DCR, SPE resolution, ...) will be checked.



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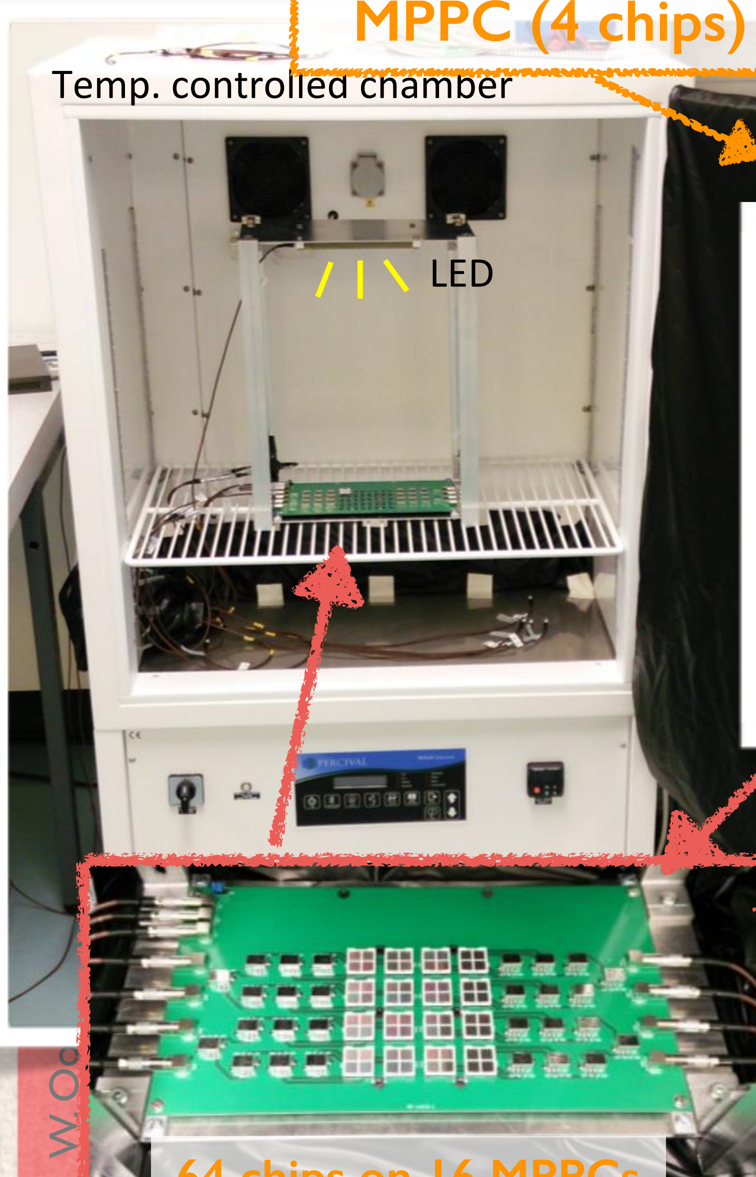
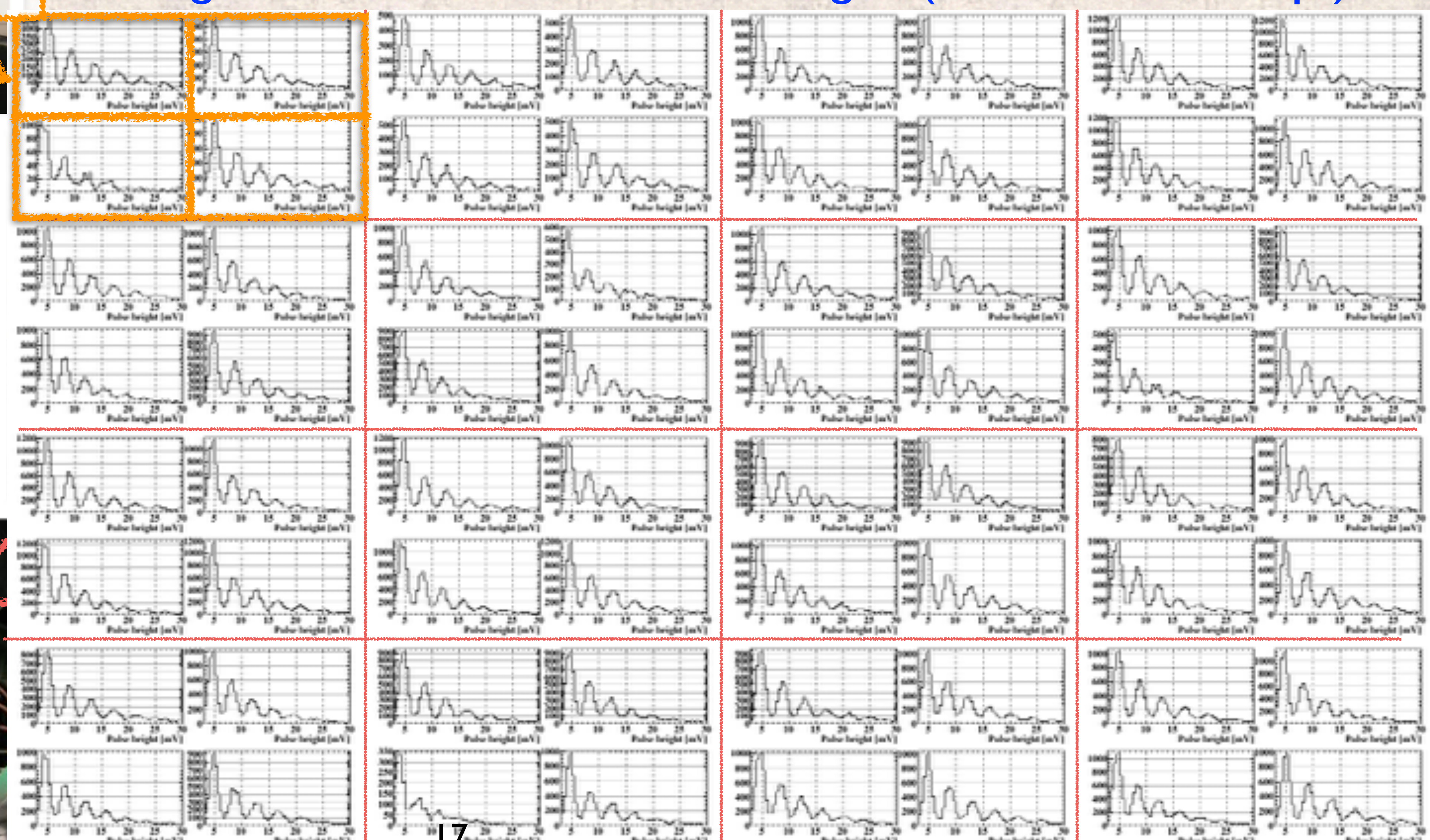
MPPC (4 chips)



64 chips on 16 MPPCs tested at once

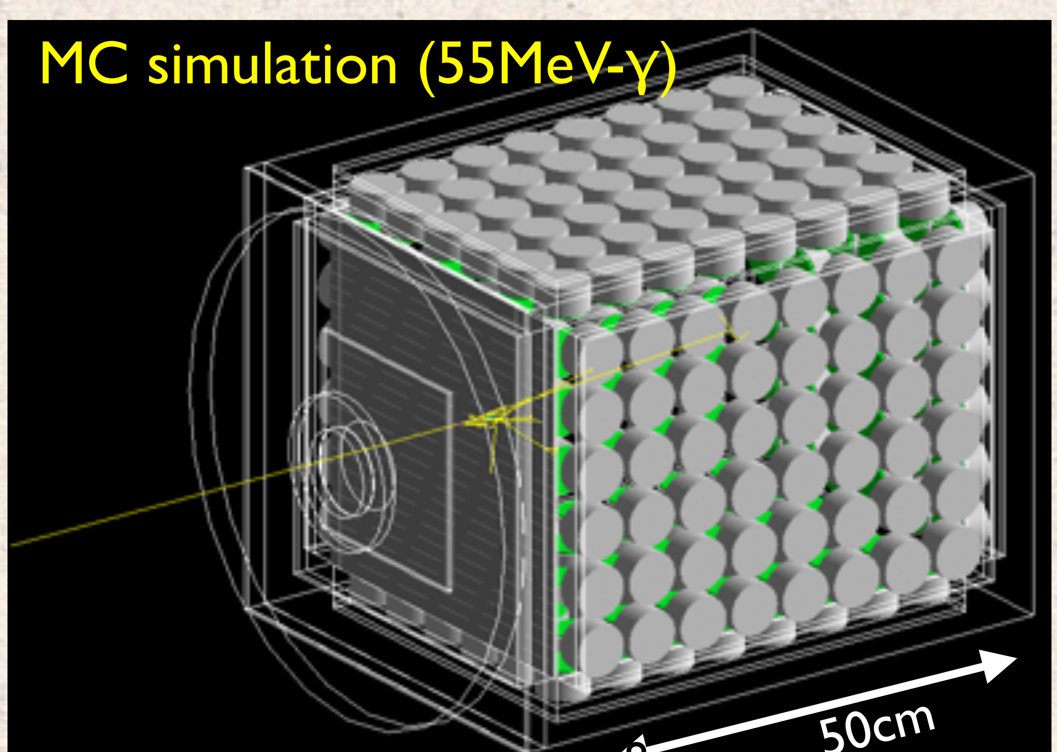
Signal distributions for weak LED signal (16 MPPCs = 64 chips)



W.Ootani et al., "Development of Deep-UV Sensitive MPPC for LXe Scintillation Detector", NDIP2014, Tours France

Prototype Detector

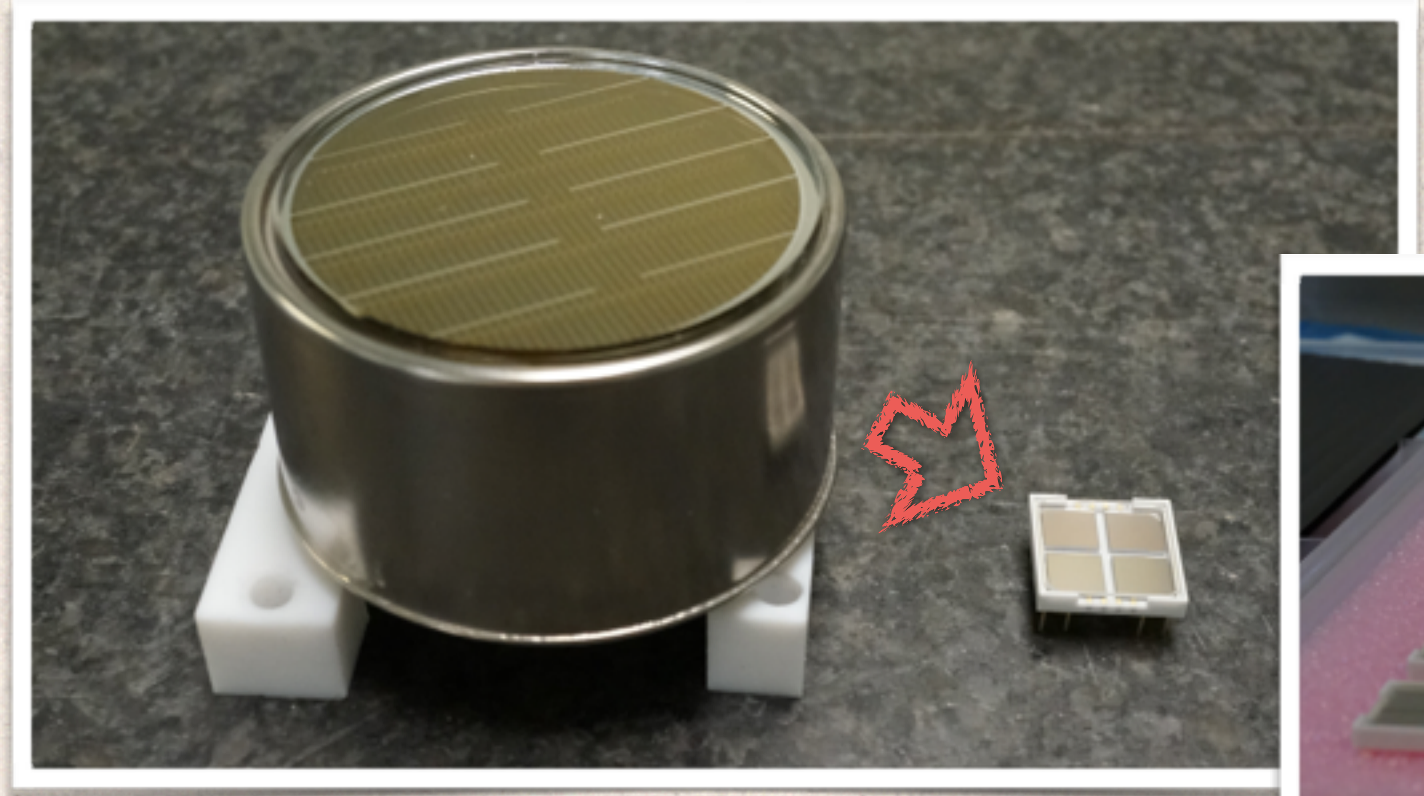
- **Prototype LXe detector** (100ℓ-LXe, **576×MPPCs**, ~200×PMTs) will be constructed.
  - Mass test for 600 × MPPCs in LXe
    - Mass test will start late summer.
  - Demonstration of performance of the proposed LXe detector with high granular scintillation readout with MPPCs
    - Test beam experiment planned in next year.

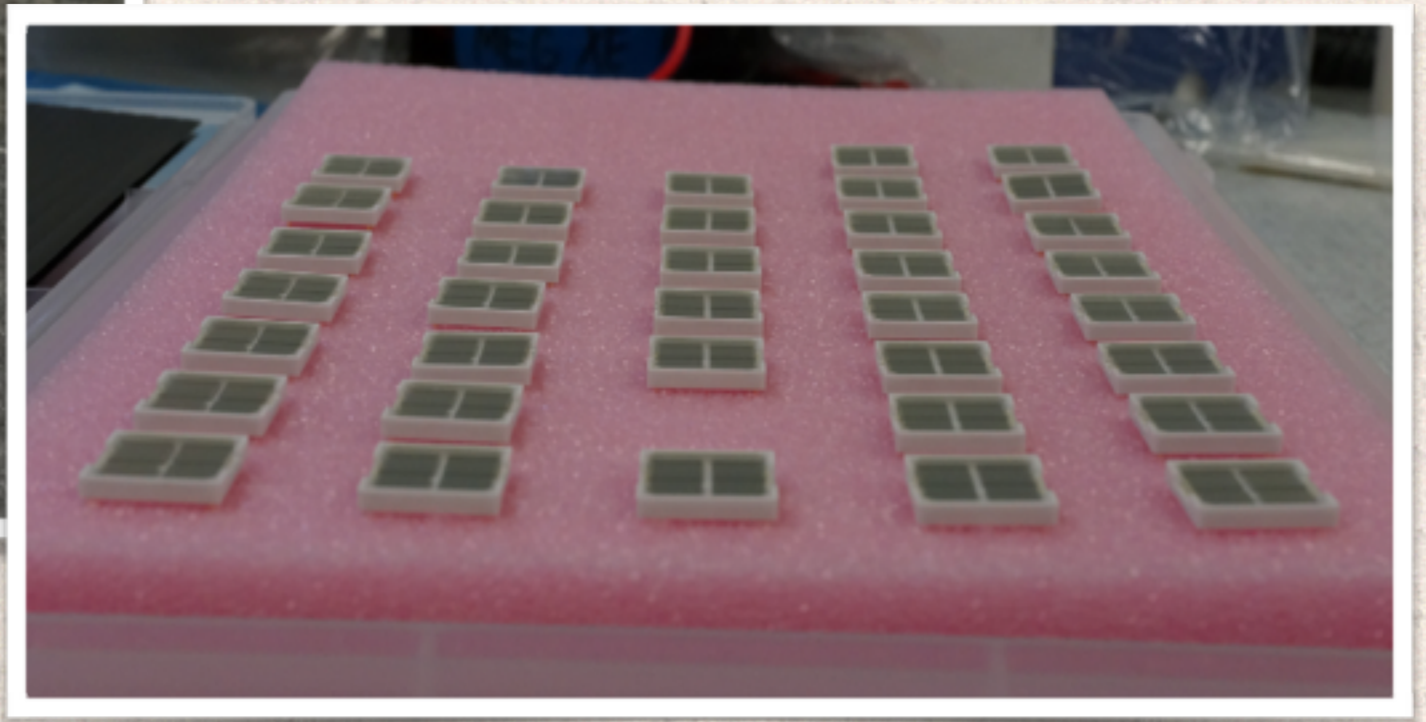


Summary and Prospects

- **Large-area deep-UV sensitive MPPC has been successfully developed for LXe scintillation detector.**
  - First production model shows an excellent performance.
- **Large sensor capacitance issue has been solved by a novel method with series-connected segments.**
- Mass test is in progress at room temp. and later in LXe.
- Prototype LXe detector will be built to demonstrate the performance of the new LXe detector with high granular readout by MPPCs.
- **Suppression of optical cross-talk is expected in the final production model** (~4000 pcs) for the full-scale detector.
  - Prototype sensor will be tested late summer.
- This technology is expected to work also for LAr, although further optimisation of surface coating would be required.

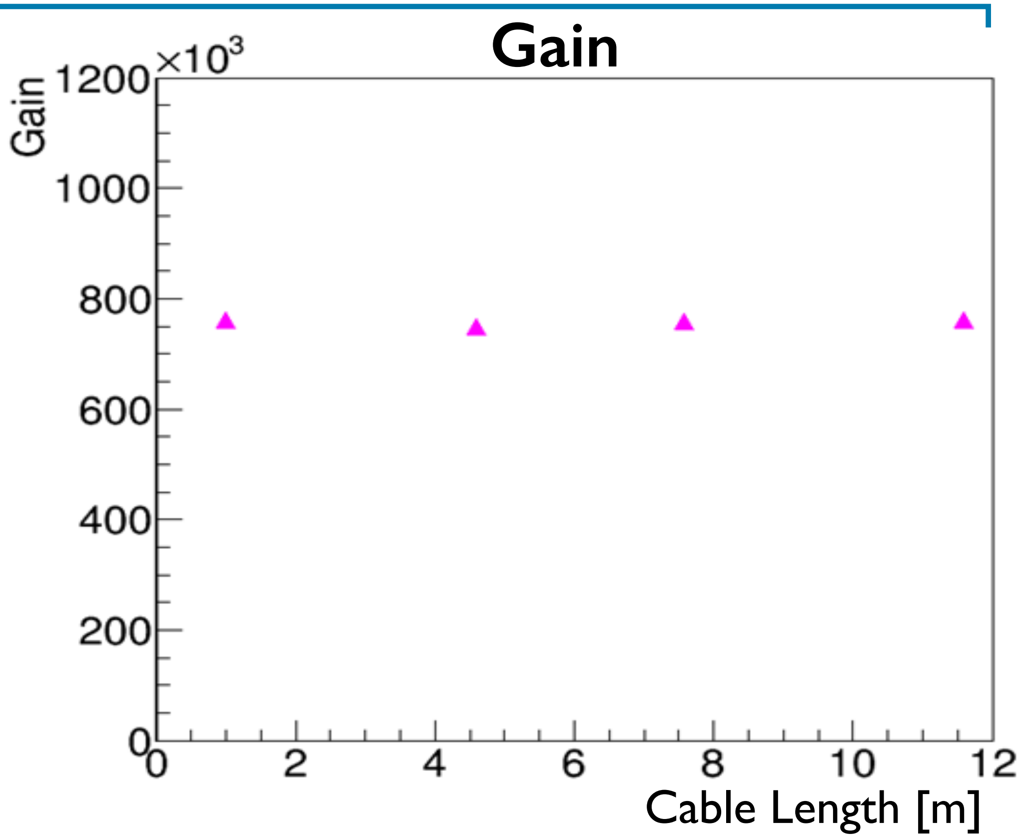
Thank you for your attention!



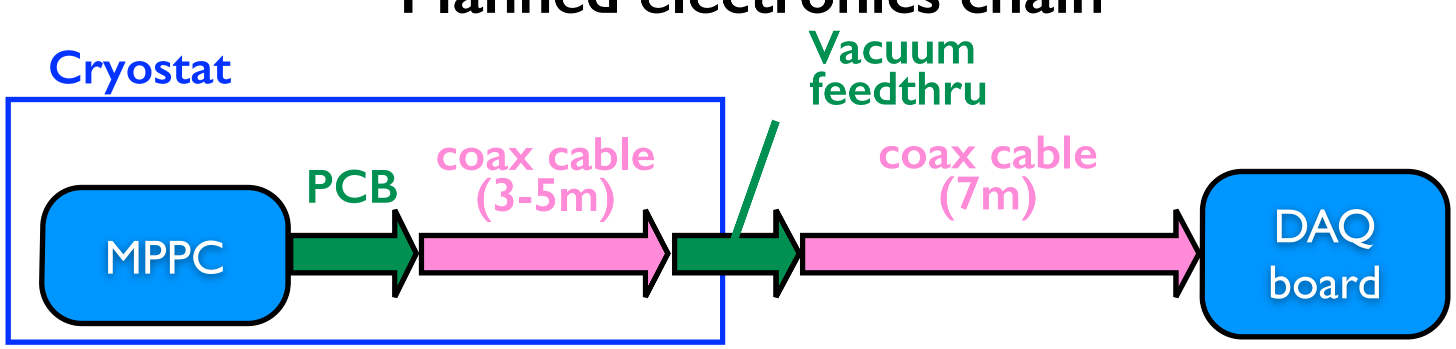


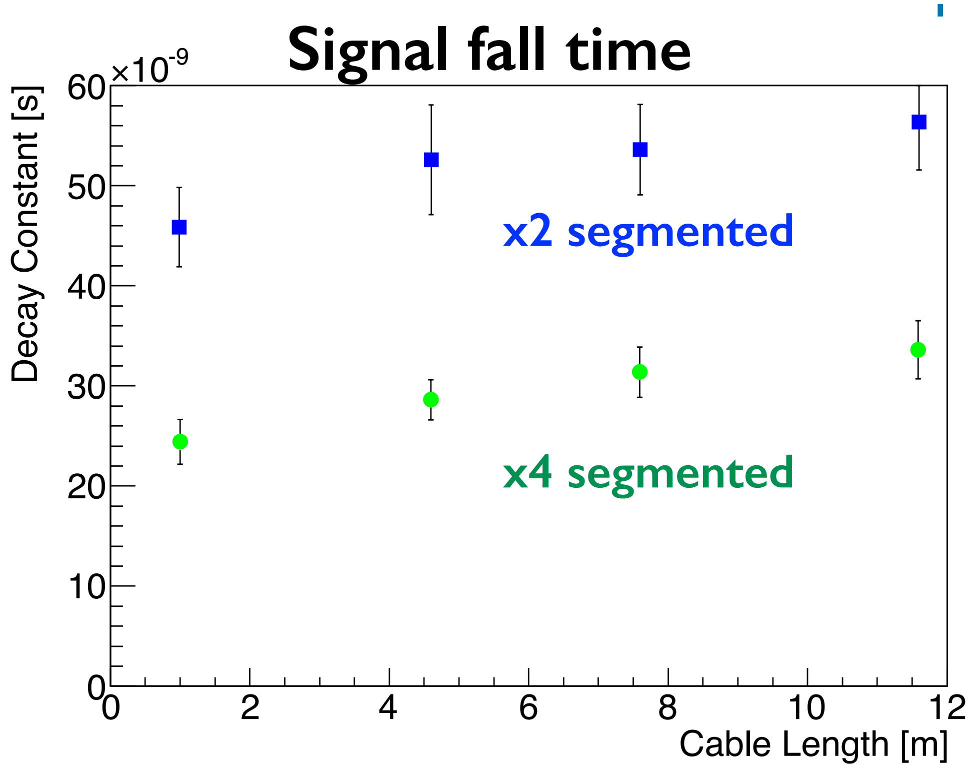
Signal Transmission

- MPPC signals in the final detector are supposed to be **transmitted over long coaxial cable (~12m)** without any amplification.
- Effect of long cable is measured.
  - **No significant deterioration of signal observed.**



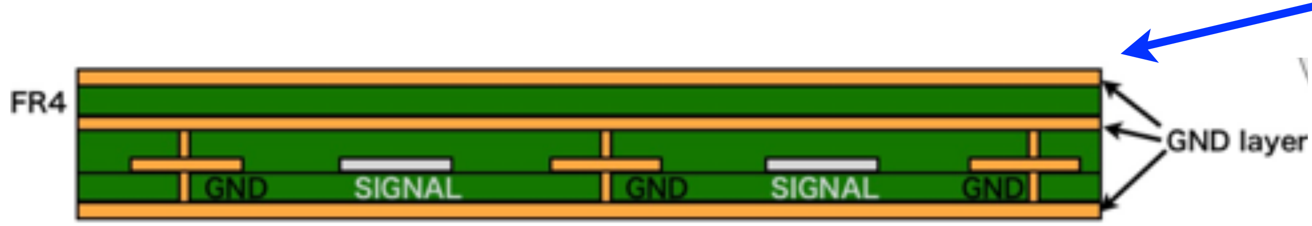
Planned electronics chain

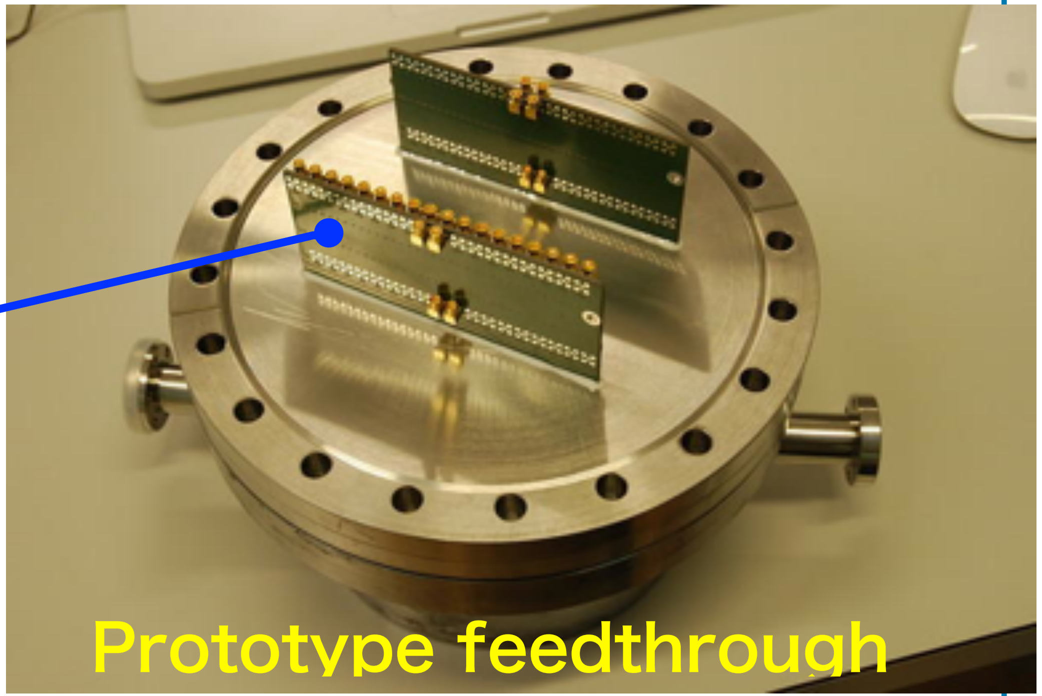




Vacuum Feedthrough

- PCB-based vacuum feedthrough is under development.
  - PCB with coaxial-like signal line structure
    - 50Ω impedance, good shielding, high bandwidth, small crosstalk (<0.3%)
  - High density
    - 72ch in each PCB
    - 6×PCBs on each flange (DN160)
    - 10×flanges in total

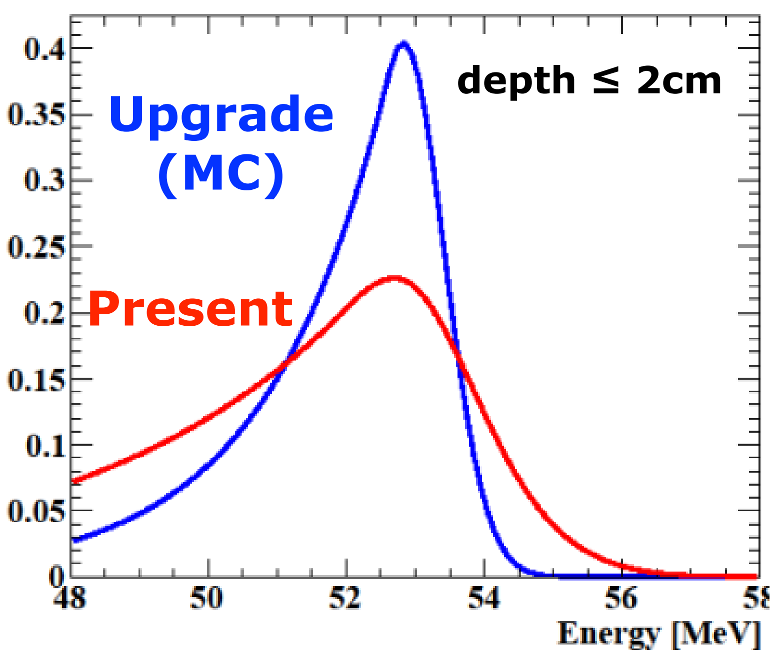


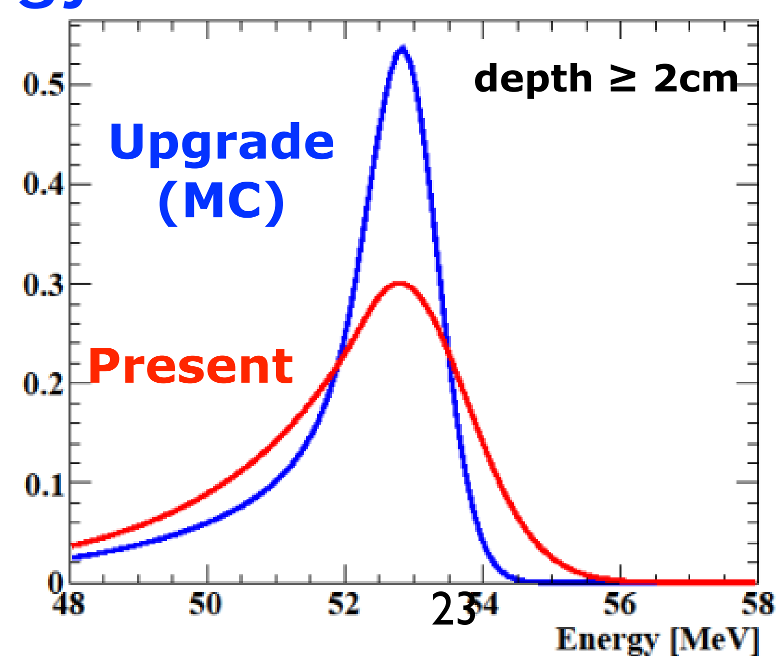


Expected Detector Performance

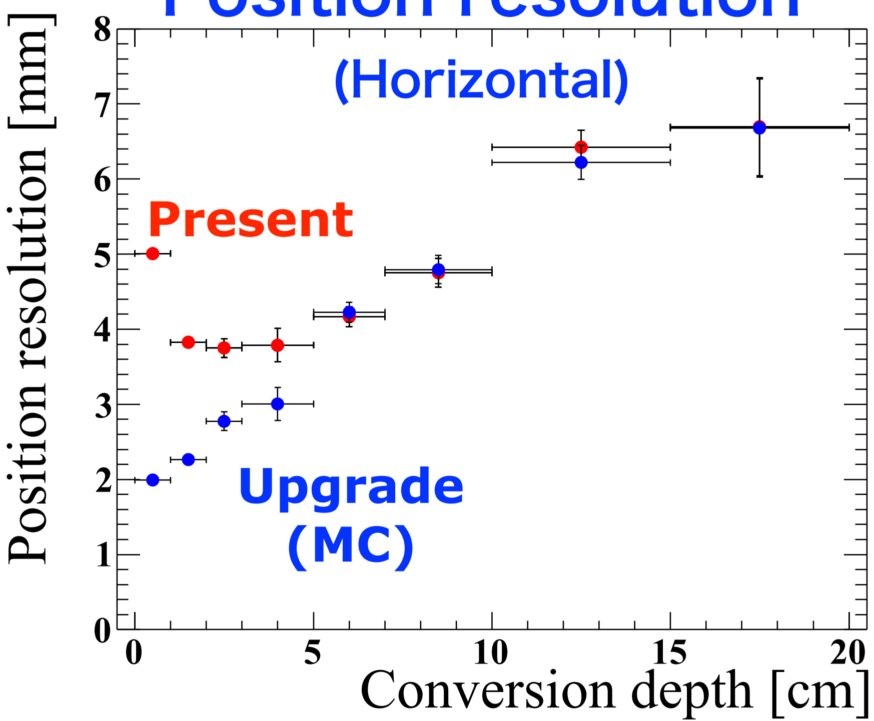
- **Energy resolution**
  - Uniform coverage with MPPCs → events near entrance face
  - Modified PMT layout → deep events
  - Low energy tail reduced because of smaller energy leakage
- **Position resolution**
  - Higher granularity with MPPC
- **Efficiency**
  - 10% improvement (MPPC is much thinner than PMT)

Energy





Position resolution



Expected Detector Performance

	Present	Upgrade
Energy (depth<2cm / depgh	2.4/1.7	1.1/1.0
Position (u/v/w)	5/5/6	2.6/2.2/5
Timing	67	76
Efficiency	63	69

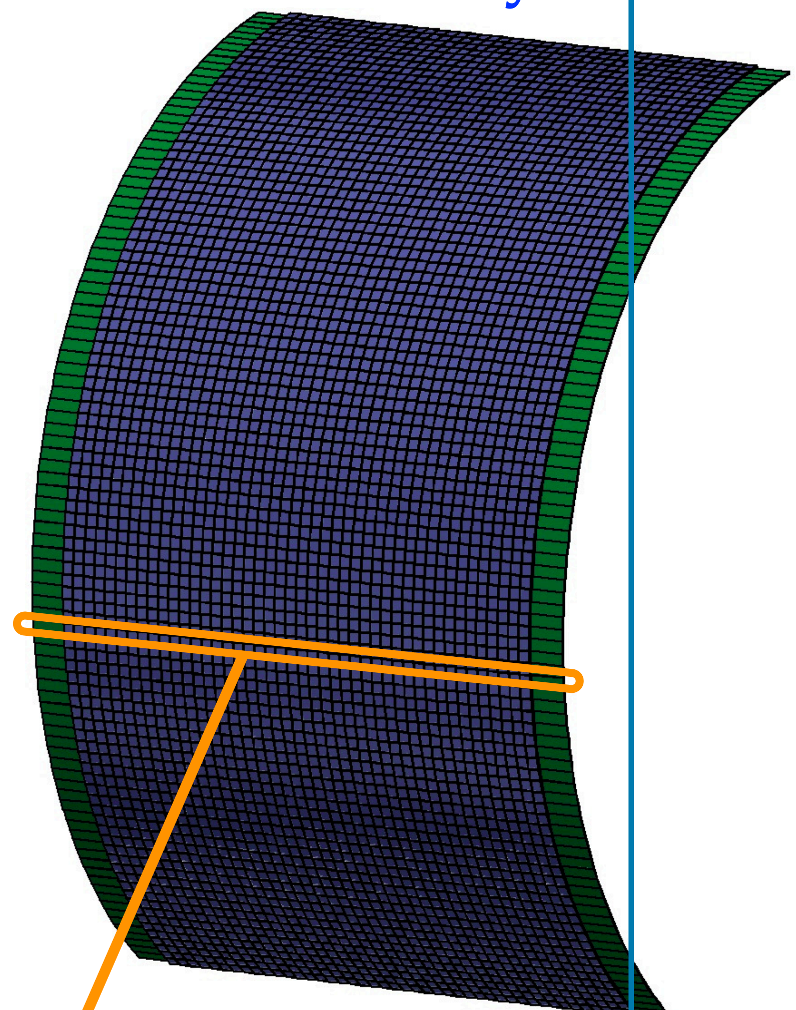
resolutions in sigma

*** 0.7% fluctuation added to MC σ**
**** Preliminary estimate**

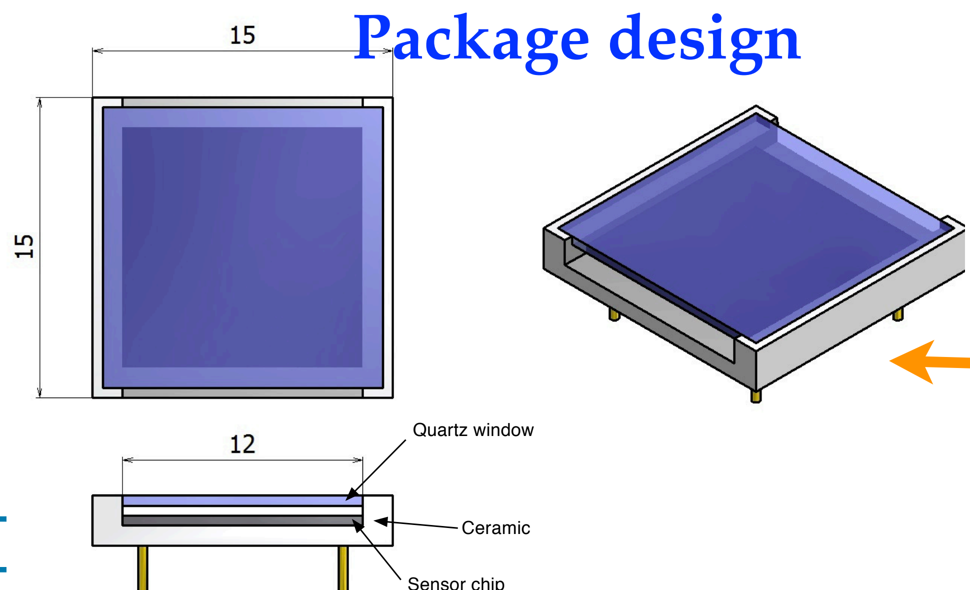
MPPC Package and Assembly

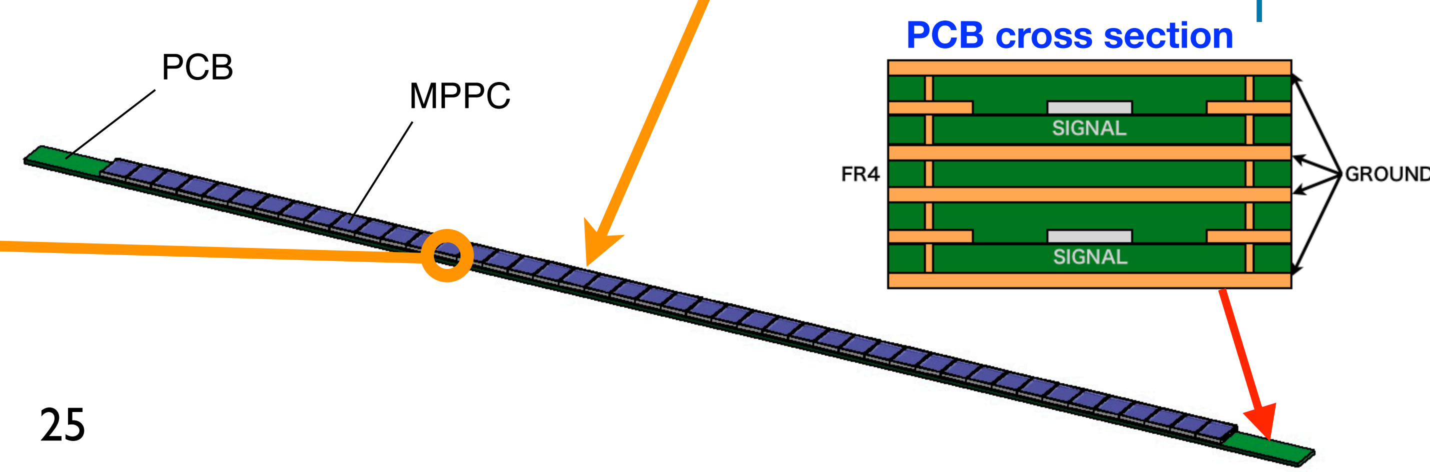
- Package design of MPPC
  - Sensor chip mounted on ceramic base
  - Thin quartz window for protection
- Assembly
  - Sensor is plugged in socket pins on assembly PCB. (44 MPPCs on each PCB strip (~15×800mm^2))
  - 93 PCB strips assembled on inner wall of cryostat
  - PCB has coaxial-like signal line structure

Assembly



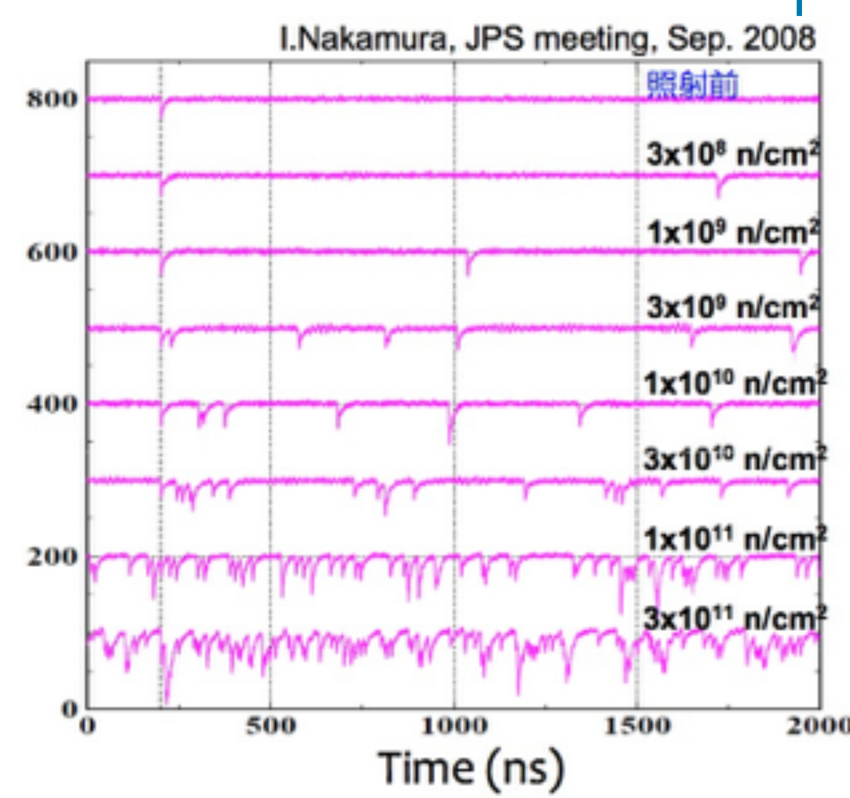
Package design





Radiation Hardness

- Modest radiation hardness is a kind of weak point of SiPM (MPPC).
- Possible effects
  - Increase of dark noise
  - Gain degradation



Expected radiation in MEG upgrade

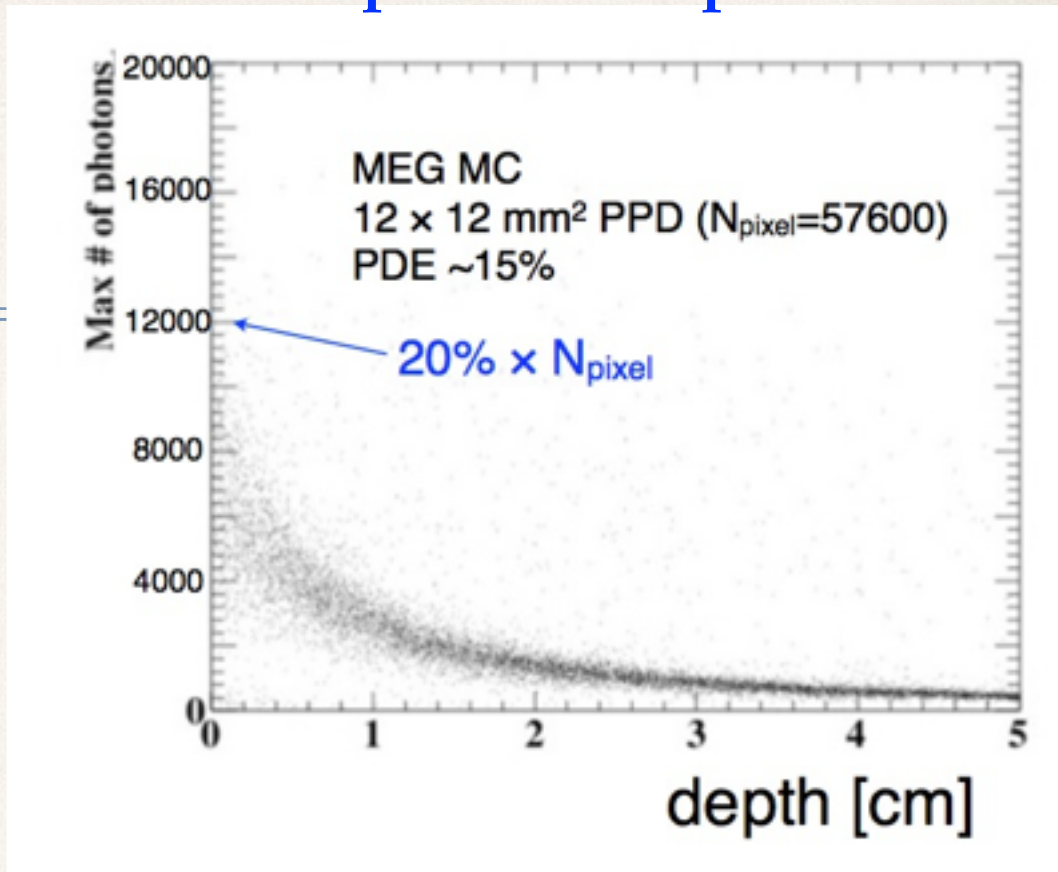
	MEG upgrade (3 years)	Threshold
Neutron	7×10	≳
γ	0.3Gy	200Gy

- **Radiation hardness of MPPC should NOT be an issue in MEG upgrade.**

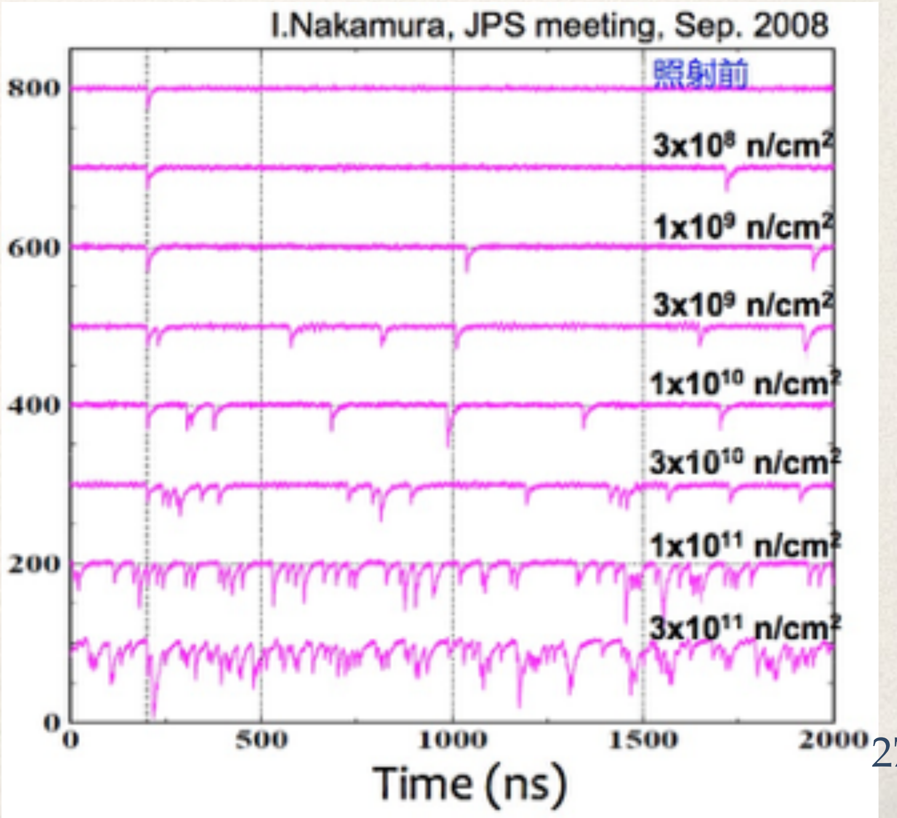
Other Issues

- **Dynamic range**
  - # of p.e. expected in MEG LXe detector
    - 12000p.e on 12×12mm^2 sensor area (20% of N_{pixel})
    - N.B.: time constant of scintillation emission of 45ns is comparable to cell recovery time.
  - → **OK**. Non-linearity can anyway be corrected by a careful calibration.
- **Radiation damage**
  - Irradiation foreseen at upgrade MEG
    - **Neutron: <1.6×10^8 *n*/cm^2** for 5-years operation
    - **γ: 0.6 Gy** for 5-years operation
  - → **OK**.

Expected # of p.e.



Effect of neutron irradiation



Reflection on Si Surface

- Reflectivity of Si is high due to high imaginary refractive index.
- ~60% of incident light is reflected for VUV.
- Reflection can be reduced with anti-reflective coating.
  - Need to be optimized for interface LXe/Si