MEG II 実験液体キセノン検出器用 VUV-MPPCの放射線損傷に関する研究

(Study on radiation damage of VUV-MPPC for liquid xenon scintillation detector in MEG II experiment)

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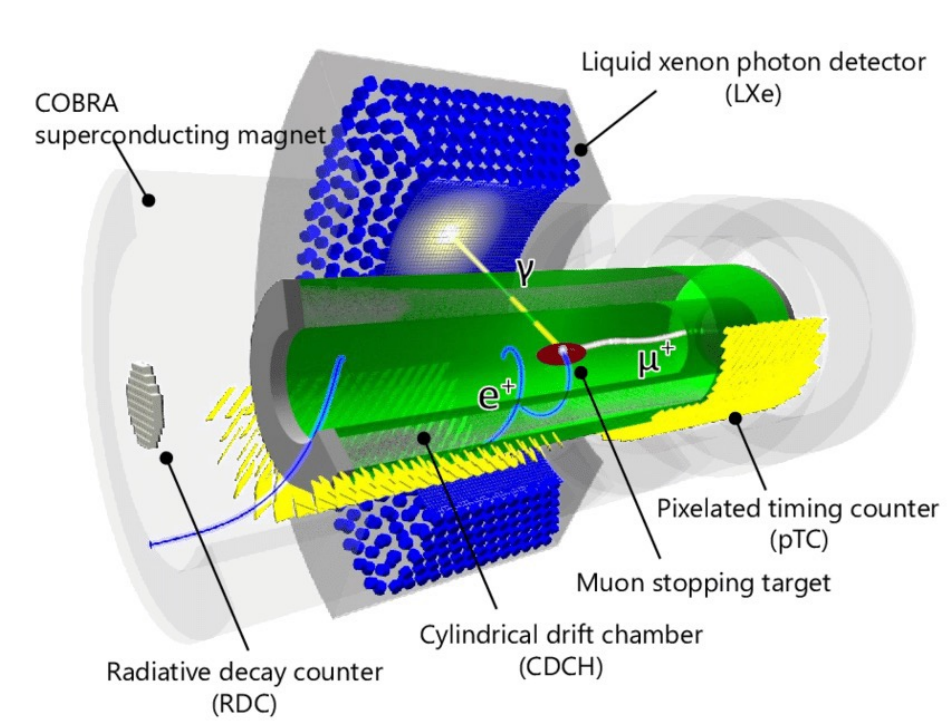
On behalf of MEG II collaboration,
The University of Tokyo

Core-to-Core Program

ICEPP The University of Tokyo

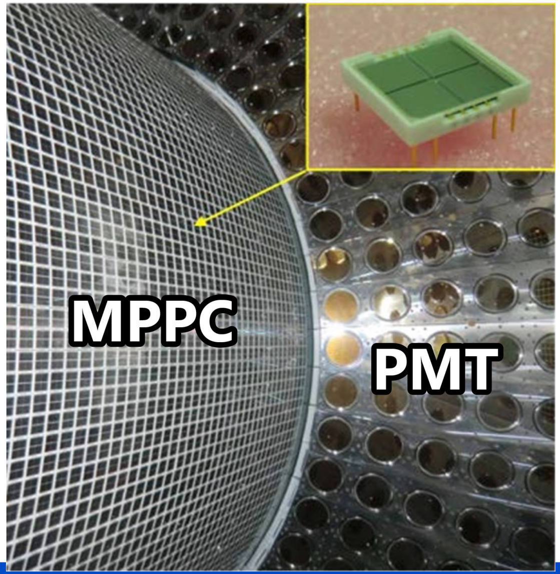
MEG II Mu - E - Gamma collaboration

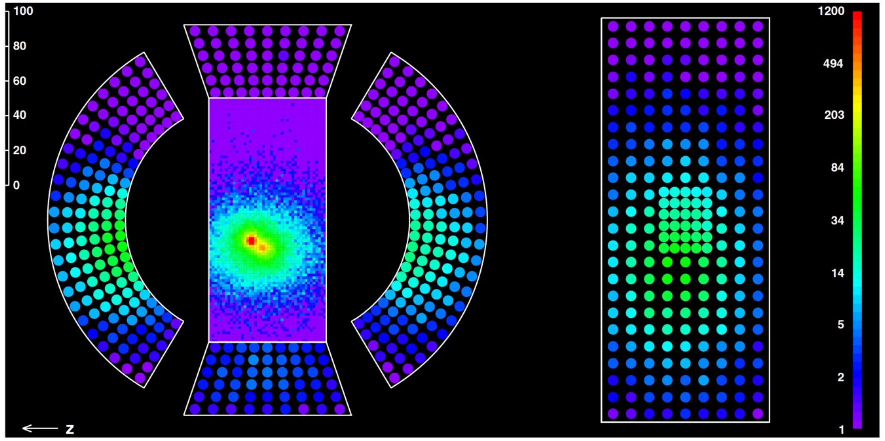
Introduction



- MEG II experiment
  - Searching for $\mu \to e\gamma$ as evidence of new physics with most intense muon beam
  - Liquid xenon photon detector
    - Detect position, energy, time of gamma-ray
  - Using VUV-MPPCs

Vacuum UltraViolet (VUV) light sensitive MPPC

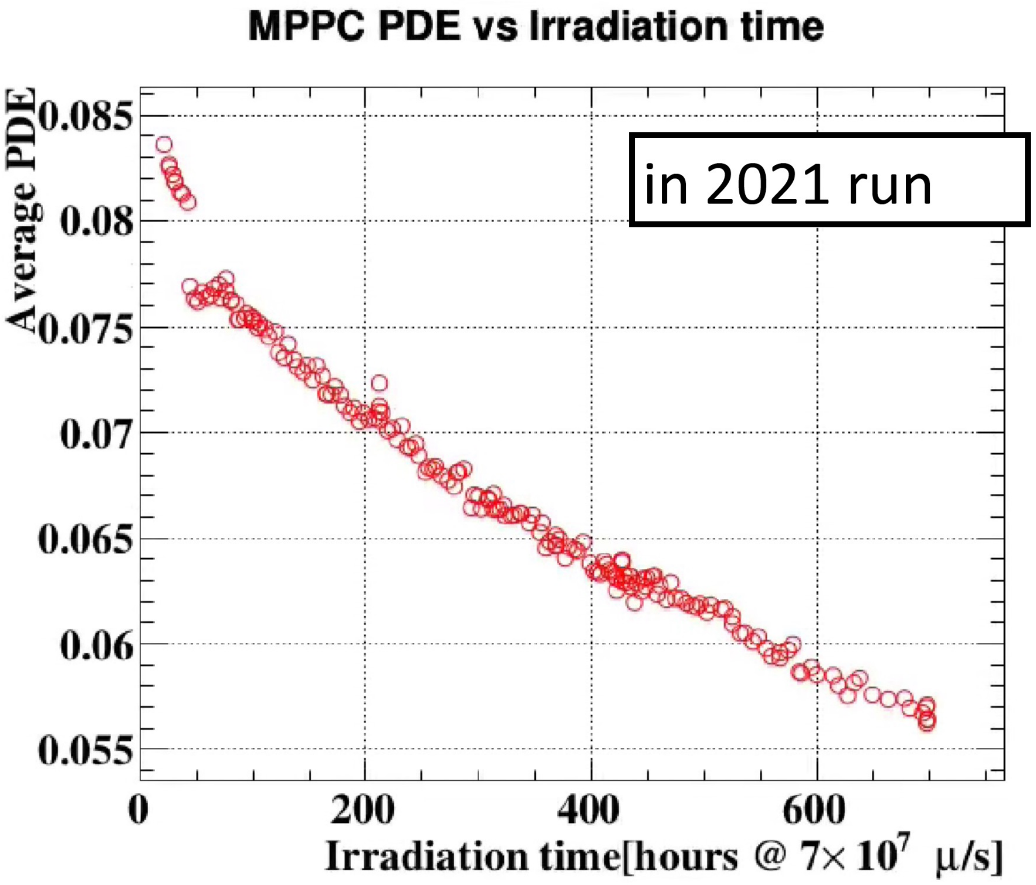




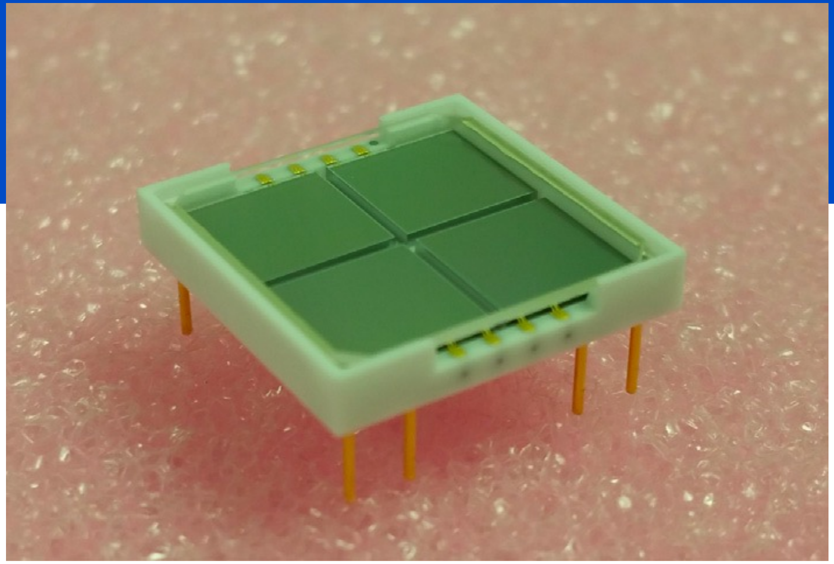
Background of this study

- Photon detection efficiency (PDE) for VUV rapidly decreases during physics run.
  - Found that PDE can recover by annealing (70 ℃, 30h)
    ->not crucial for experiment
  - But we still want to understand cause
- Most likely to be caused by radiation from muon target (radiation damage)
  - Radiation from target: VUV light, gamma-ray

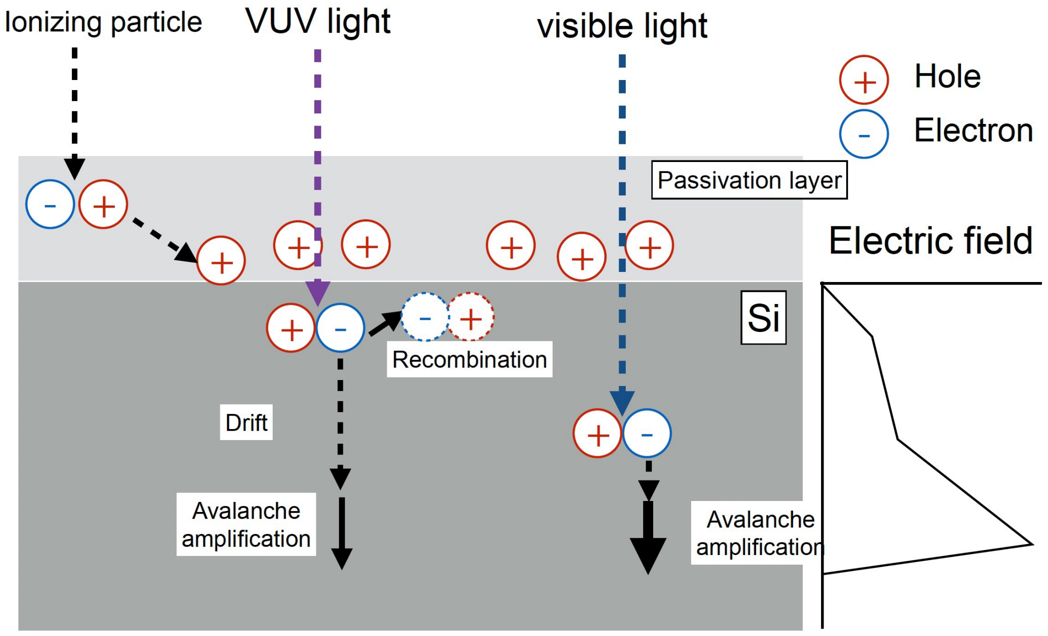
$$N_{photon} = 2 - 2.5\times10^{11}\ \text{photon/mm}^2$$



Radiation damage of MPPCs



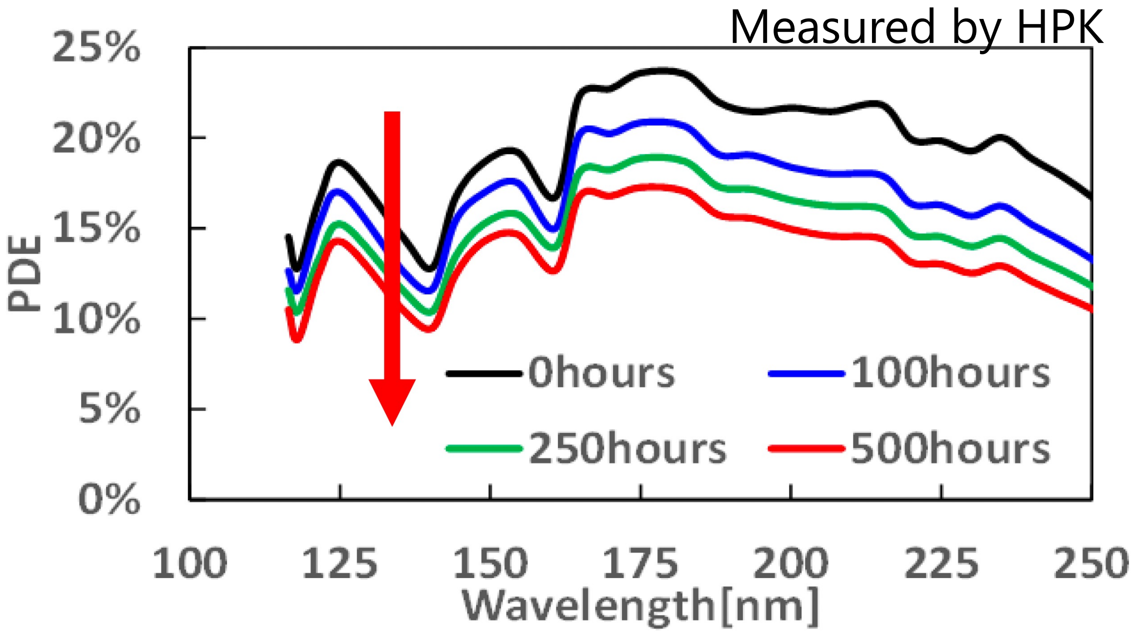
- Previous studies in laboratory
  - VUV light irradiated to MPPCs at room temperature, low temperature (~165 K), in liquid xenon.
  - Gamma-ray irradiated to MPPCs at room temperature, low temperature (~165 K).
- PDE degradation not reproduced in laboratory.
  (PDE degradation actually observed by VUV irradiation, but 10^4 slower.)



Motivation of this study

- It's known that VUV sensitivity worsened by absorbing moisture.
- Hypothesis to test in this study
  - MPPC of LXe detecter in MEG II may be humidified during long period of storage and installation.
  - Moisture inside MPPCs accelerate radiation damage.
- Measure PDE for humidified MPPC after VUV irradiation

Condition: temp=60 ℃ , humidity=90％

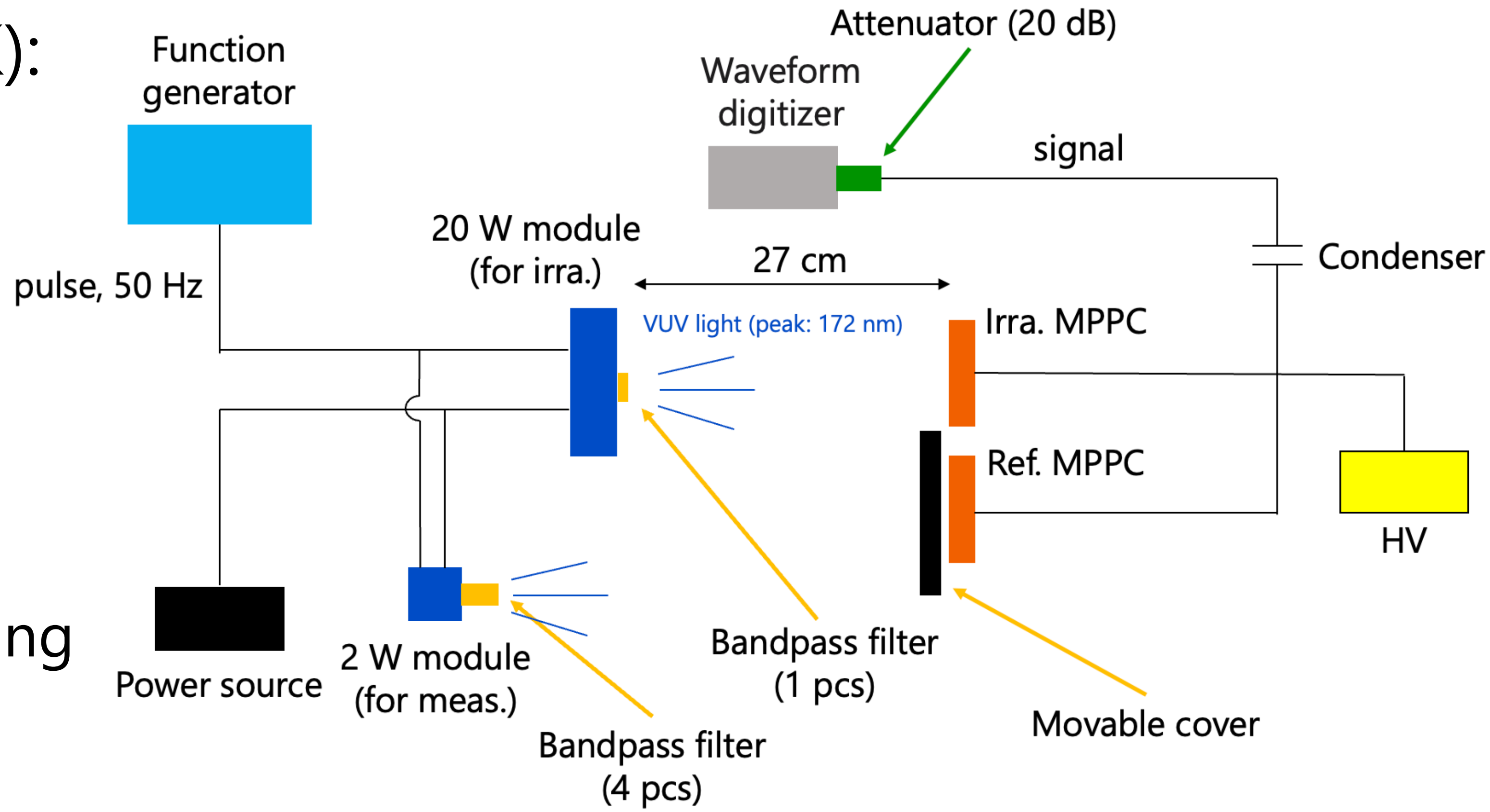


R. Yamada, et al., "Development of MPPC with high sensitivity in NUV or VUV," 2022 IEEE NSS/MIC/RTSD

Setup

- Samples (provided by Hamamatsu Photonics KK):
  - 0h humidified MPPC
  - 125h humidified MPPC
  - 250h humidified MPPC
  - Condition: temp=60 ℃, humidity=90%

  *All sample annealed before humidification under following condition: 150 ℃ x 16 hours

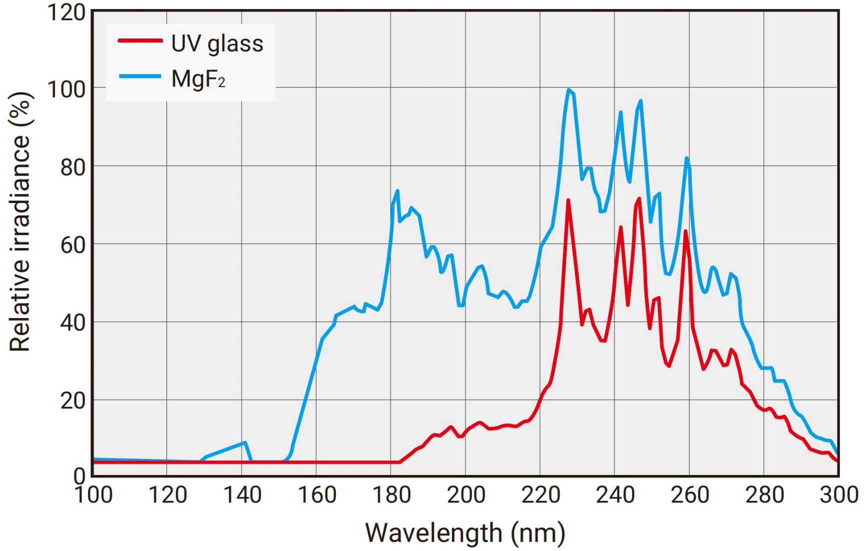


Xenon flash lamp

Hamamatsu Photonics KK

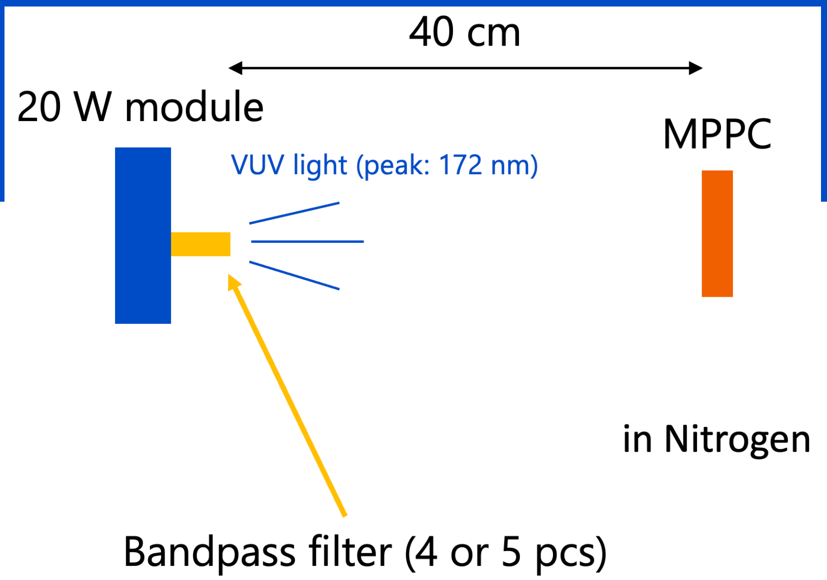
- 20 W module
  - Used for irradiation
- 2 W module
  - Used for measurement
- Pulse operation

- 20 W xenon flash lamp

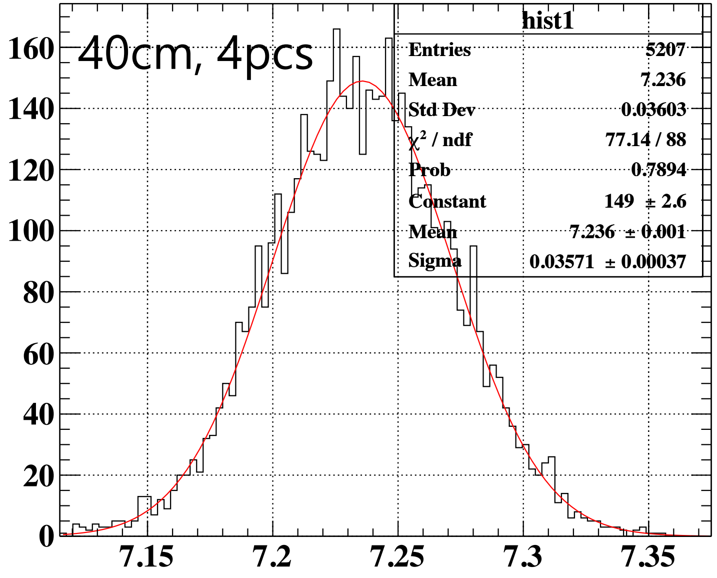


Bandpass filter

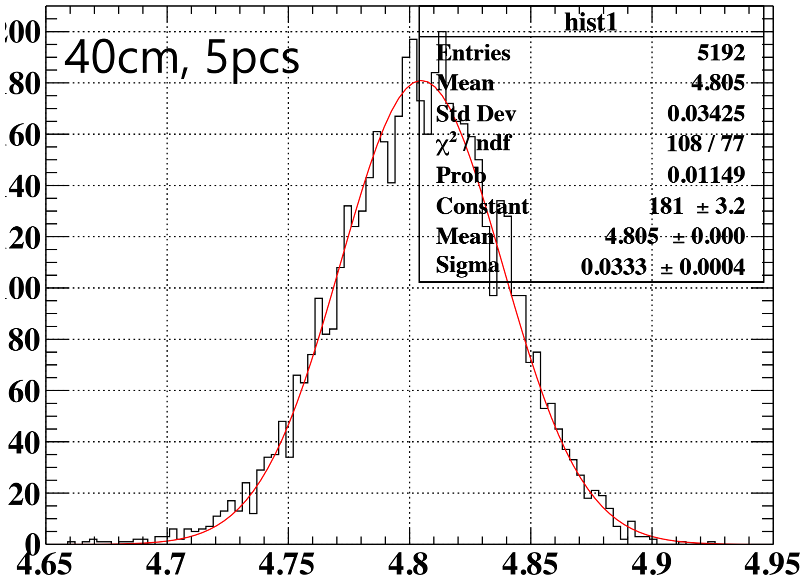
- Measured transmission effect: 66%
- Transmission effect from manufacturer: ~10%
  - This discrepancy not understood yet.

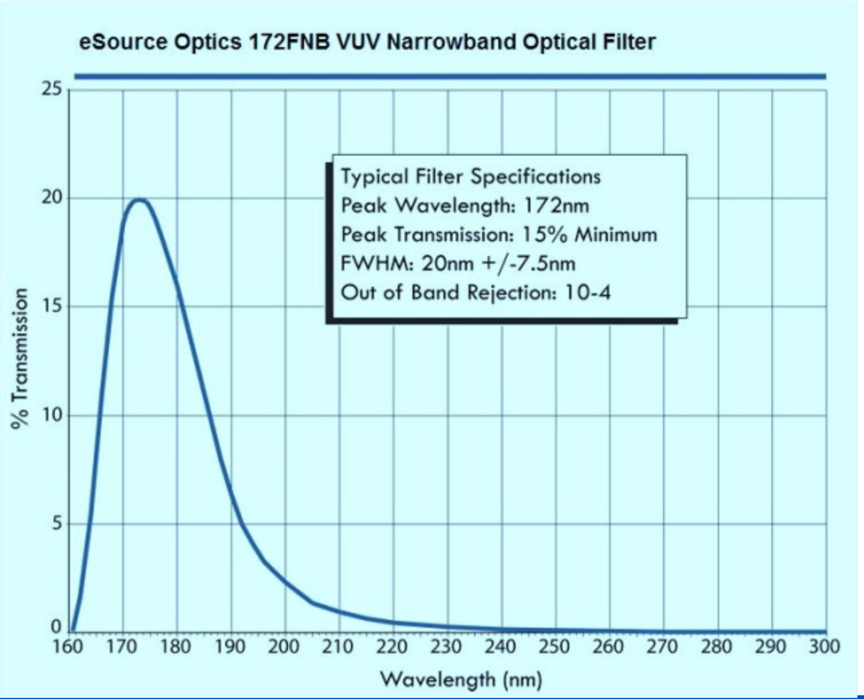


charge hist (run7731)



charge hist (run7729)

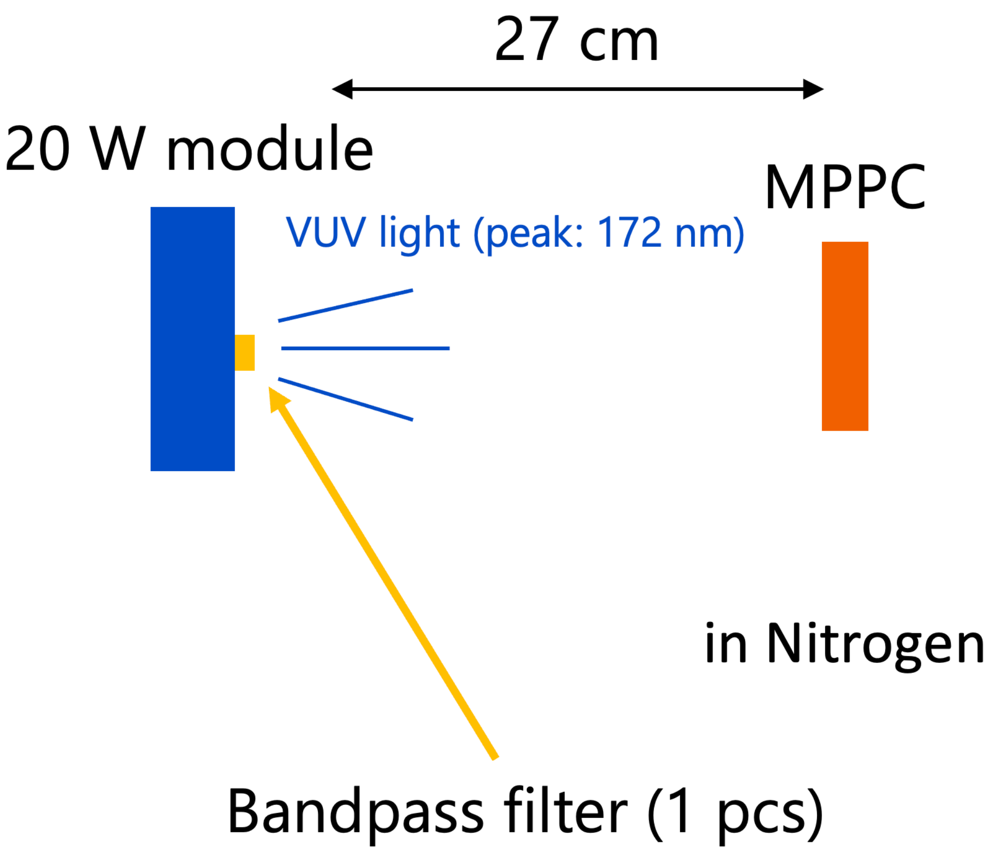




Estimation of radiation dose

Assumed initial PDE	~ 20 %
Area of 1 chip in MPPC	$36\ \mathrm{mm}^2$
Trigger frequency	50 pulse/sec
Irradiation time	5 hour
Number of seeds / Number of pixels fired	2.1

Radiation dose considering pixel saturation	$\mathbf{3.0 \times 10^{11}\ photon/mm^2}$
Radiation dose in LXe detector in 2021	$2.5 \times 10^{11}\ \mathrm{photon/mm^2}$

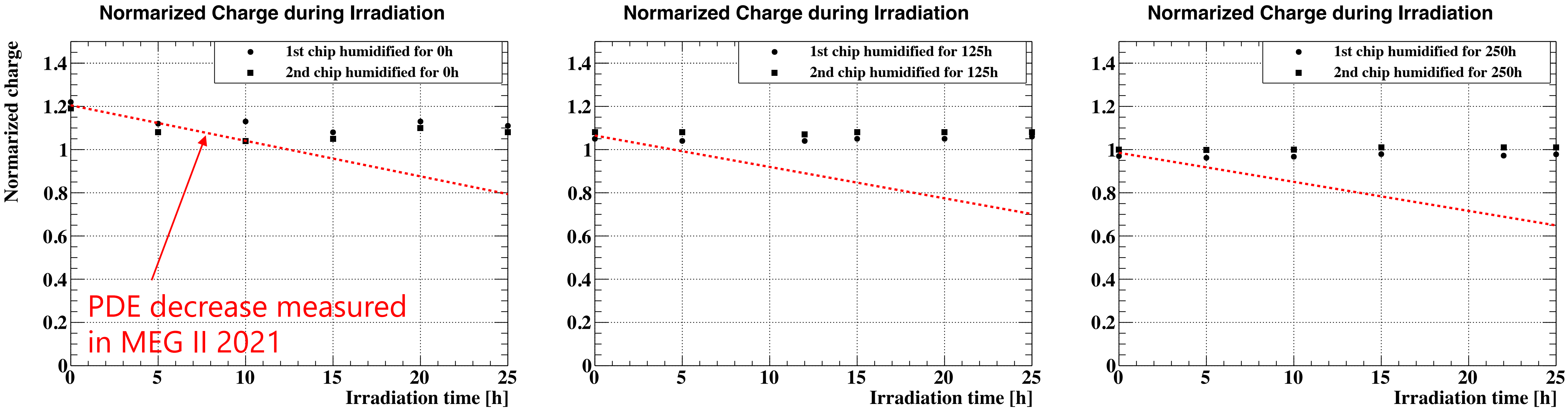


Results

$$\text{Normarized charge} = \frac{\text{charge of chip}}{\text{charge of ref. chip}}$$

$N_{pho} \sim 2.98\times10^{11}$ photon/mm^2

Temp. is stable: 24 ± 1 °C



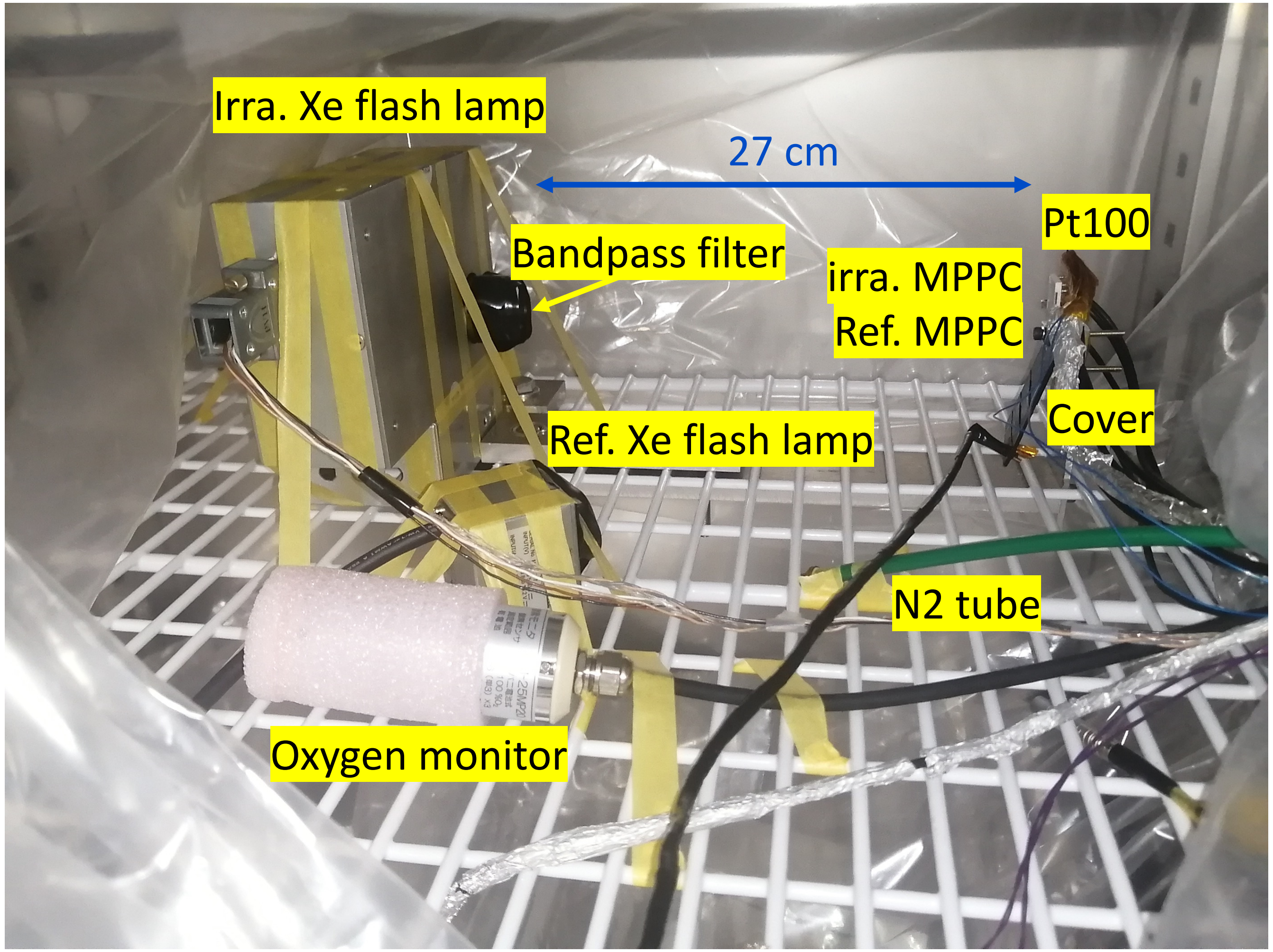
- PDE decrease by VUV irradiation not observed for humidified MPPC.
    - PDE decrease by moisture itself is confirmed as measured by HPK.

Sammaries & Prospects

- Summary
  - Rapid decrease of VUV PDE for VUV-MPPC of MEG II LXe detector
  - Studied effect of absorption of moisture inside VUV-MPPC for VUV irradiation.
  - PDE decrease not reproduced.
- Next step
  - Test effect of moisture inside VUV-MPPC at low temperature or in LXe.

Backup

Setup (photo)

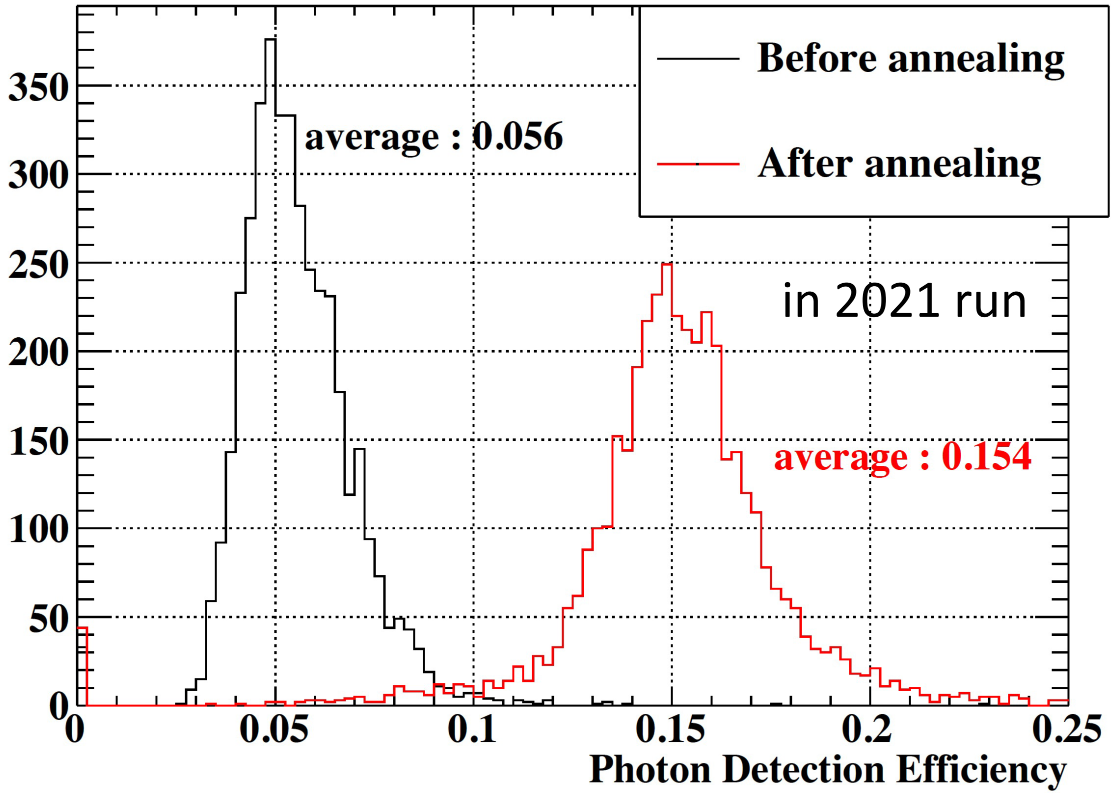


Irra. Xe flash lamp
27 cm
Pt100
Bandpass filter
irra. MPPC
Ref. MPPC
Cover
Ref. Xe flash lamp
N2 tube
Oxygen monitor

Annealing

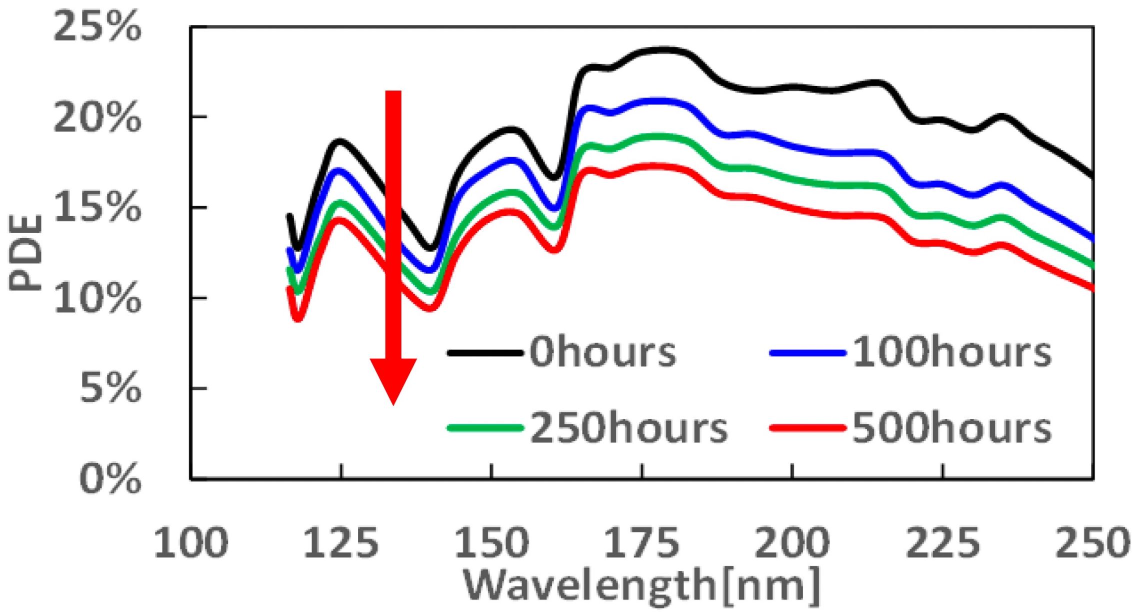
- Remove accumulated hole in surface by heating MPPCs
- PDE can be returned to original value by annealing.
- Sample
  - Baking condition: 150 ℃ x 16 hours

Annealing at 70 °C for 30 hours per MPPC



Calculation for VUV PDE degradation by moisture inside VUV-MPPC

175 nm PDE for MPPC humidified for 0h	18 %
175 nm PDE for MPPC humidified for 250h	23 %
Charge for MPPC humidified for 0h	1.2 a.u.
Charge for MPPC humidified for 250h	0.95 a.u.
Estimated charge for MPPC humidified for 250h	0.94 a.u.



R. Yamada, et al., "Development of MPPC with high sensitivity in NUV or VUV," 2022 IEEE NSS/MIC/RTSD

Effect of bandpass filter

- Bandpass effect: $4.805/7.236 = 0.6640$
- When x=4, charge=$6.877\times(0.6640)^{-4}$=35.38 -> radiation rate=1.70738×10^{6} $\mathrm{photon/mm^2/sec}$
- Irradiation for 25 hours -> radiation dose = 1.53664×10^{11} $\mathrm{photon/mm^2}$
- Consider saturation of MPPC pixels -> radiation dose = 2.97668×10^{11} $\mathrm{photon/mm^2}$
- Radiation dose in LXe detector in 2021 = 2.5×10^{11} $\mathrm{photon/mm^2}$

Radiation rate of VUV light

- Gain of PSI-amp : 30 db (used for measurement of 1pe charge)
- Attenuator: 20 db (used for measurement of VUV light charge)
- 1p.e. charge of VUV-MPPC (S10943-4372, Serial Number:BA00794) = 0.0455057
- Charge of VUV light (20W module, L12745-03-3) = 35.38 ← distance between Xe lamp and MPPC: **27 cm**

$$\frac{35.38\times10^{30/20}\times10^{20/20}}{0.0455057}\frac{\mathrm{p.e.}}{\mathrm{chip}\cdot\mathrm{pulse}} = 2.45862\times10^{5}\frac{\mathrm{p.e.}}{\mathrm{chip}\cdot\mathrm{pulse}}$$

- Estimated PDE of VUV-MPPC (S10943-4372) ≈ 20 %

  -> $2.335\times10^{5}\times\frac{\mathrm{p.e.}}{\mathrm{chip\cdot pulse}}\times\frac{1}{0.2\ \mathrm{p.e./photon}} = 1.22931\times10^{6}\ \frac{\mathrm{photon}}{\mathrm{chip\cdot pulse}}$

- Radiation rate

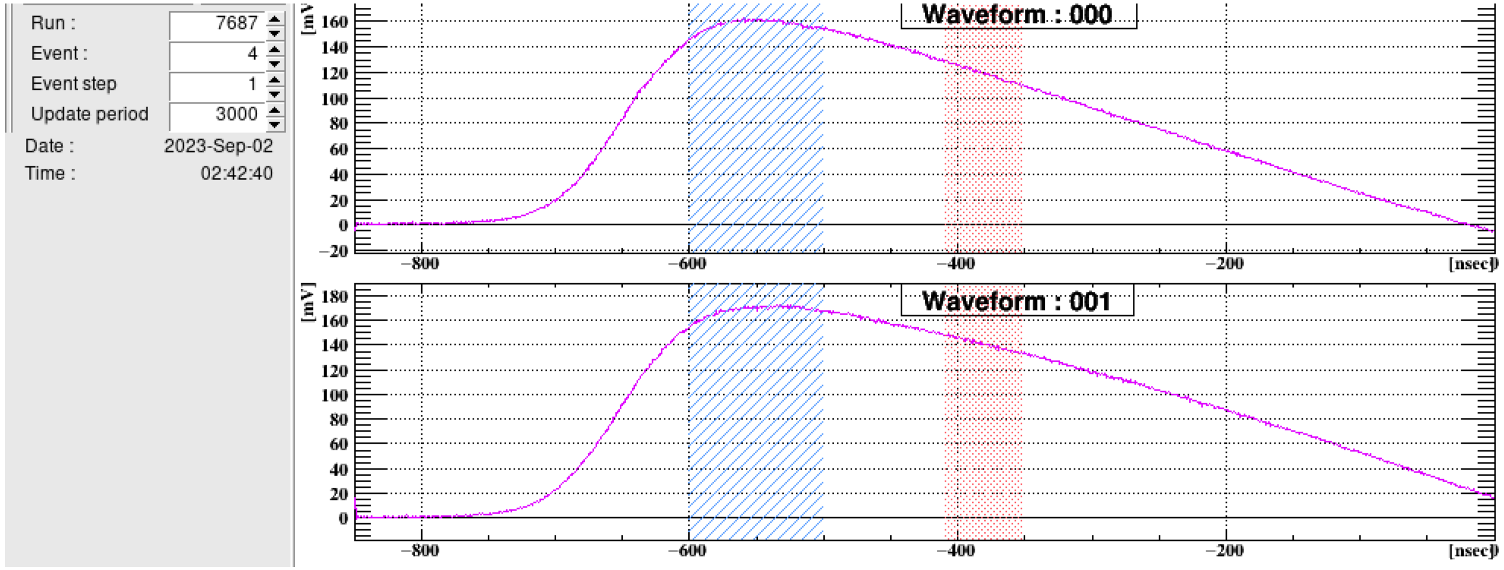
$$N_{pho,VUV} = 1.167\times10^{6}\ \frac{\mathrm{photon}}{\mathrm{chip}\cdot\mathrm{pulse}}\times\frac{1}{36\ \mathrm{mm}^2/\mathrm{chip}}\times50\frac{\mathrm{pulse}}{\mathrm{sec}} = 1.70738\times10^{6}\ \frac{\mathrm{photon}}{\mathrm{mm}^2\cdot\mathrm{sec}}$$

- Necessitated irradiation time: 1.69472 day

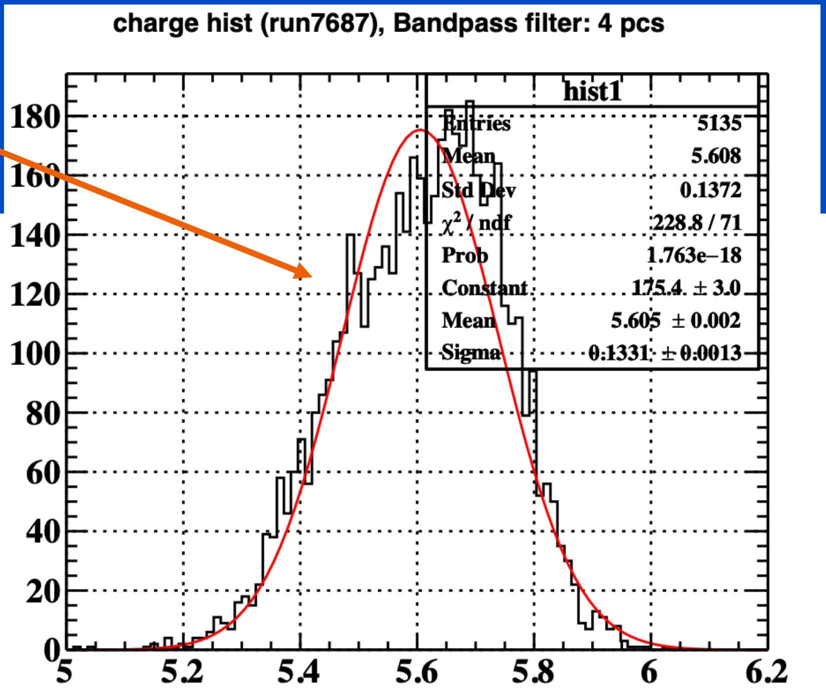
  (c.f. Radiation dose of LXe detector in 2021: about $2.5\times10^{11}\ \frac{\mathrm{photon}}{\mathrm{mm}^2}$)

- Consider saturation of MPPC pixels -> Necessitated irradiation time becomes0.8749 day

Saturation of MPPC

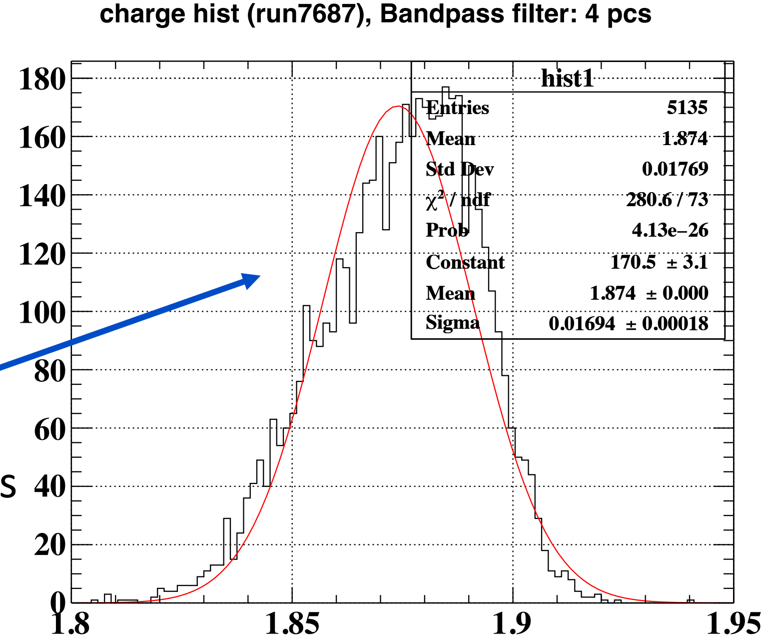


charge of total range



Charge around peak for 100 ns = 1.874

charge around peak for 100 ns



Saturation of MPPC

$$\frac{1.874 \cdot 10^{\frac{30}{20}} \cdot 10^{\frac{20}{20}}}{0.05284} = 11215 \ \frac{\text{p.e.}}{\text{chip} \cdot \text{pulse}} < 14400 \text{ pixel/chip}$$

$$N_{fired} = N_{total} \cdot \left(1 - \exp\left(-\frac{N_{seed}}{N_{total}}\right)\right)$$

$$\Longrightarrow N_{seed} = -N_{total} \ln\left(1 - \frac{N_{fired}}{N_{total}}\right)$$

N_{fired}: Number of pixels fired

N_{total}: Total number of pixels

N_{seed}: Number of seeds

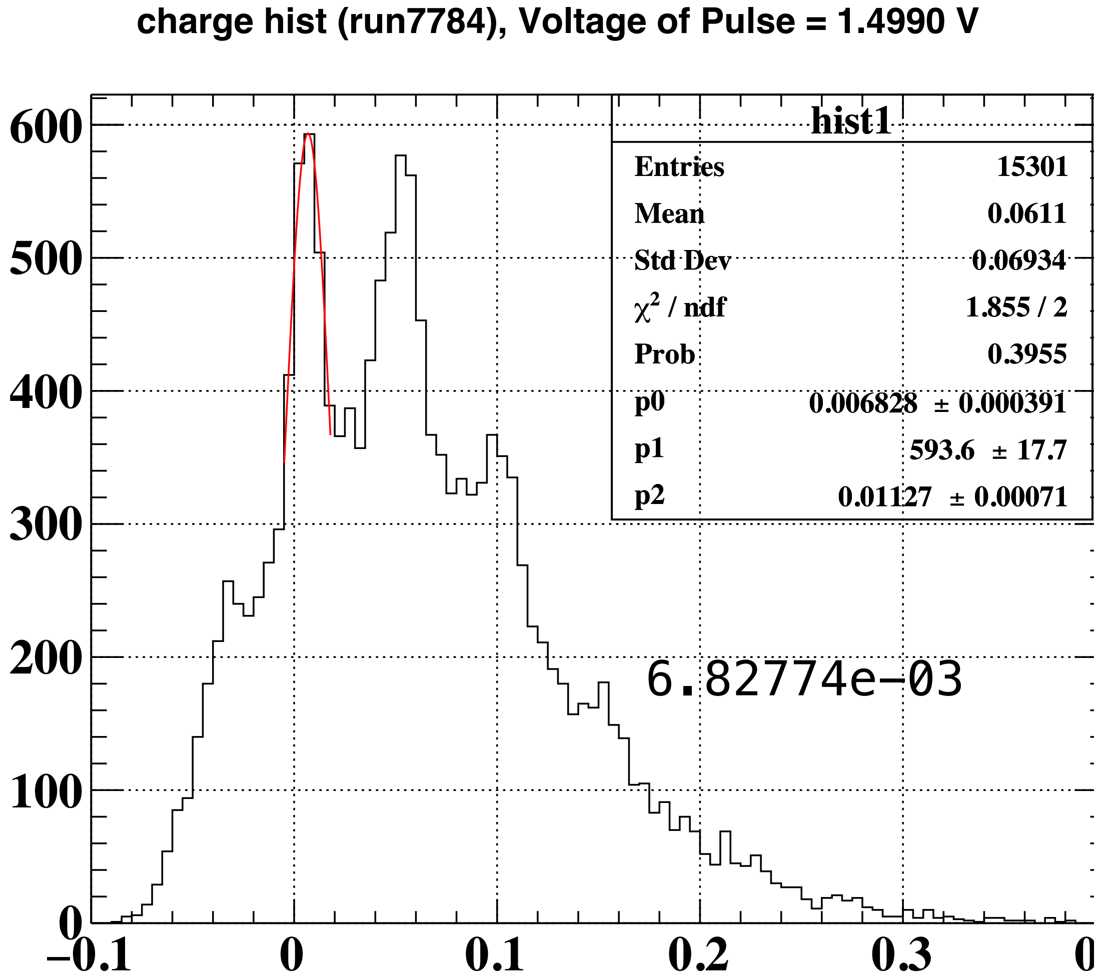
- Substituting $N_{total} = 13685$, $N_{fired} = 11215$,

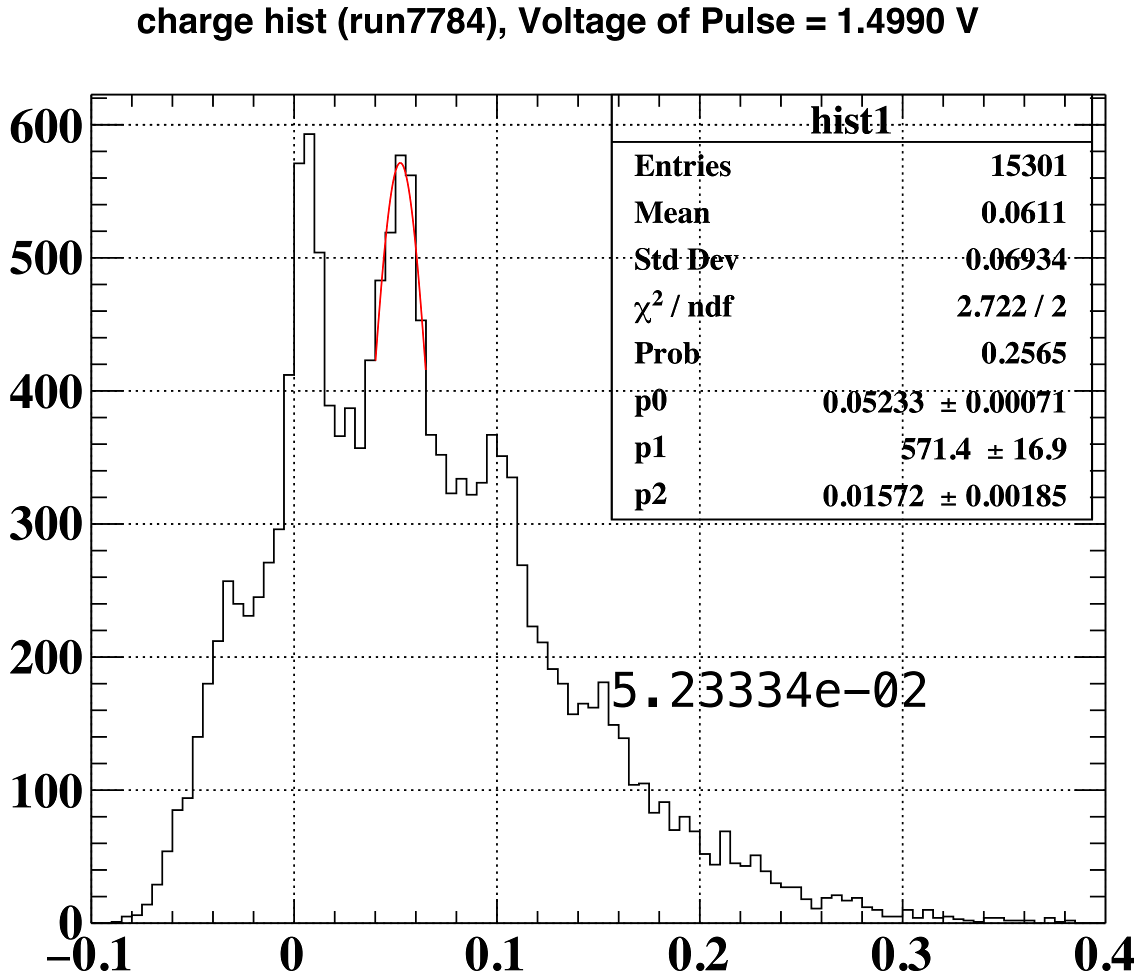
$$N_{seed} = 23430$$

Saturation of MPPC

- Considering saturation of MPPC pixels
  - Necessitated irradiation time:1.69472 $\mathrm{day} \times \frac{11215}{23430} = 0.8112\ \mathrm{day}$

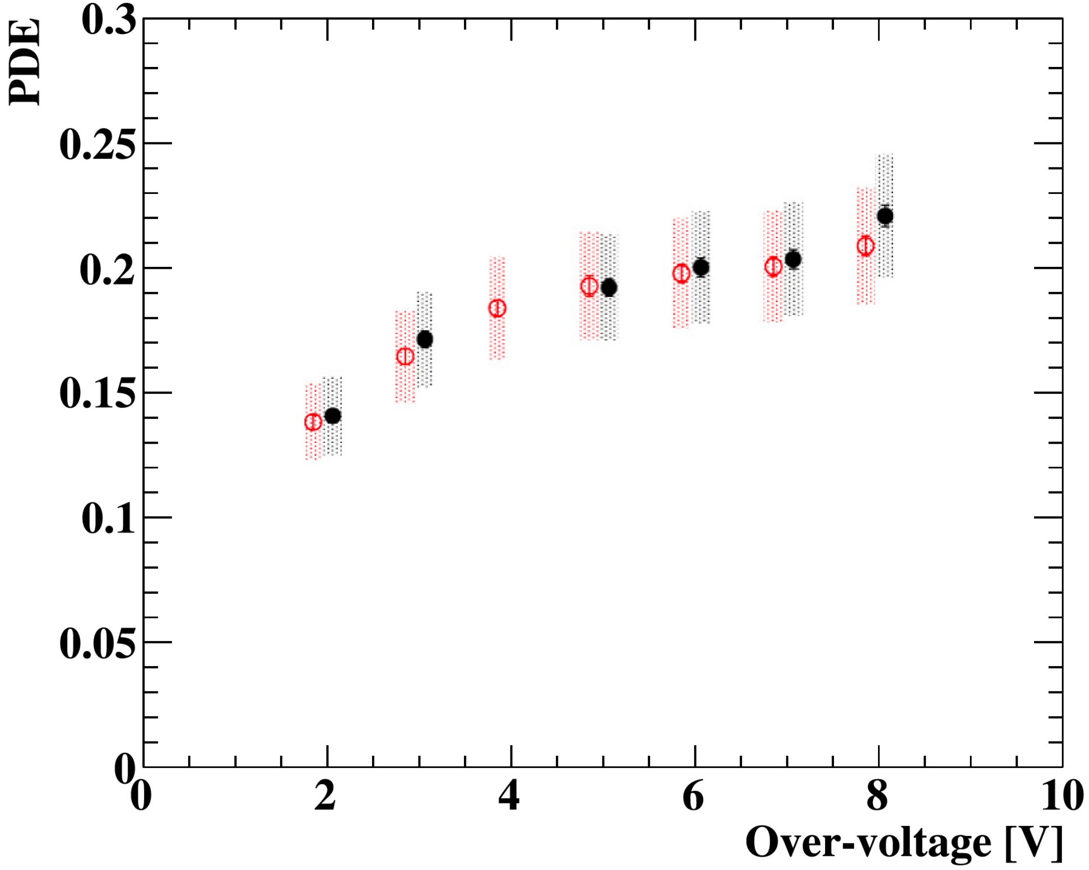
1 p.e. charge

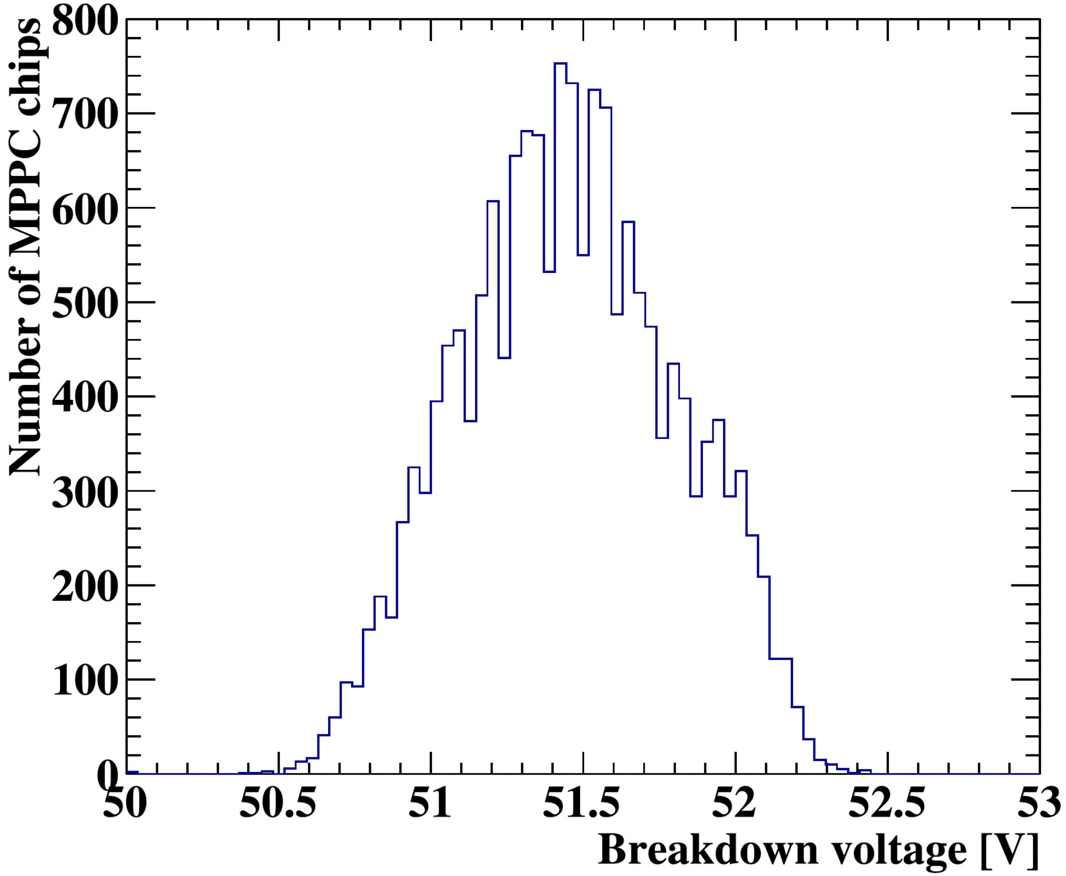




$$5.23334\times10^{-2} - 6.82774\times10^{-3} = 0.0455057$$

Relationship between over-voltage and PDE





$V_{bias} \approx 56.5 \rightarrow PDE \approx 20\ \%$

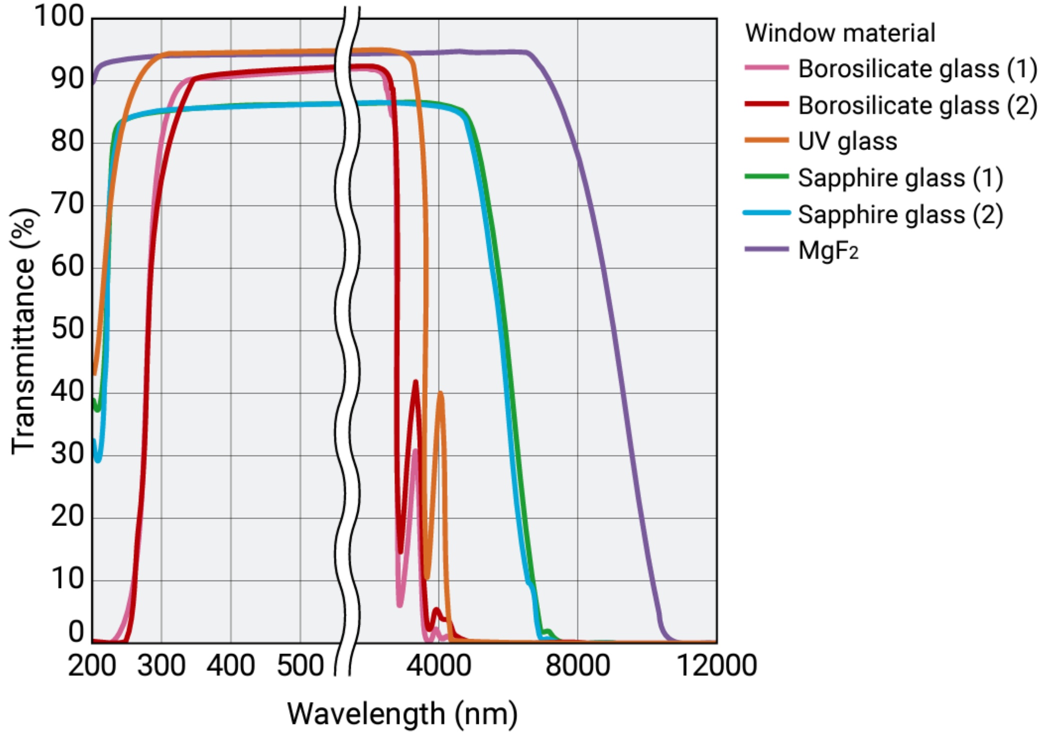
Light output window

- The spectral emission range of xenon flash lamps differs according to the window material

■ **Table 1: Spectral transmission range of window materials**

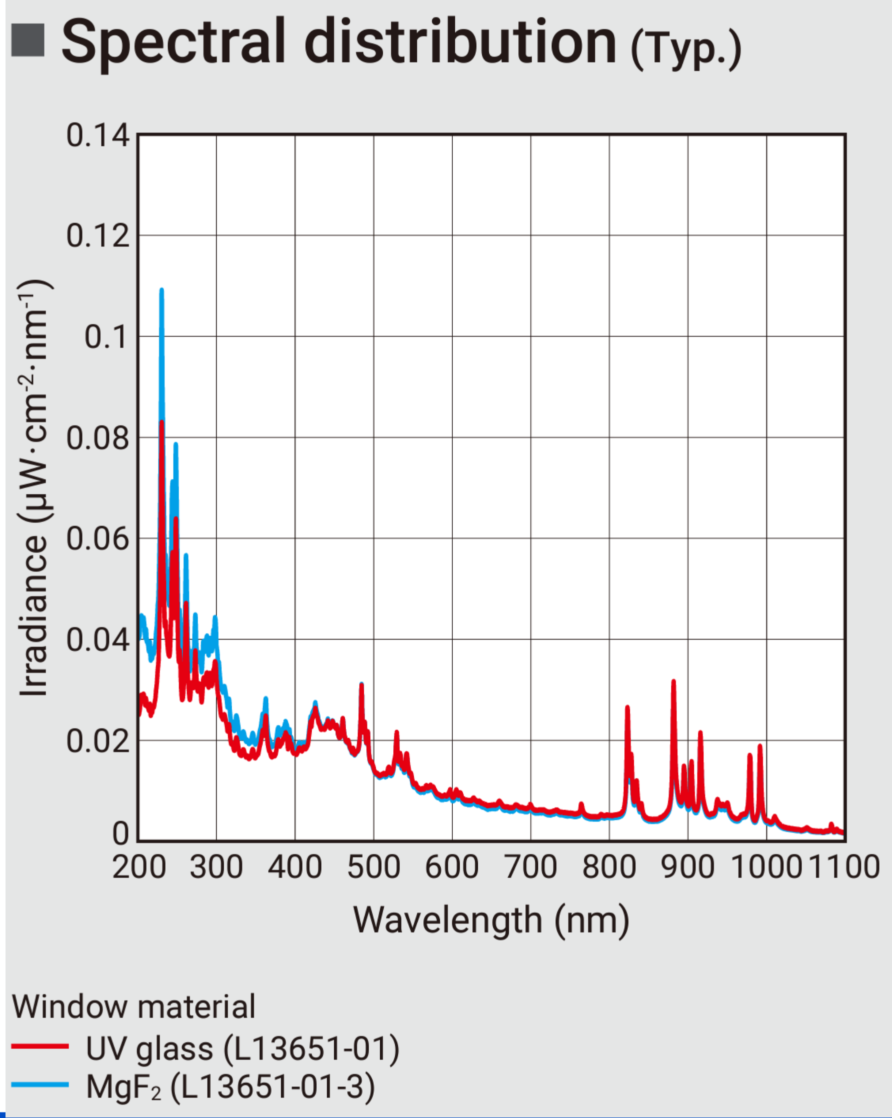
Window material	Spectral transmission range (nm)
UV glass	185 to 2500
Borosilicate glass	240 to 2500
Sapphire glass	190 to 5000
MgF_2	160 to 7500

■ **Figure 3: Transmittance of window materials (Typ.)**



https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/Xe-F_TLS1023E.pdf

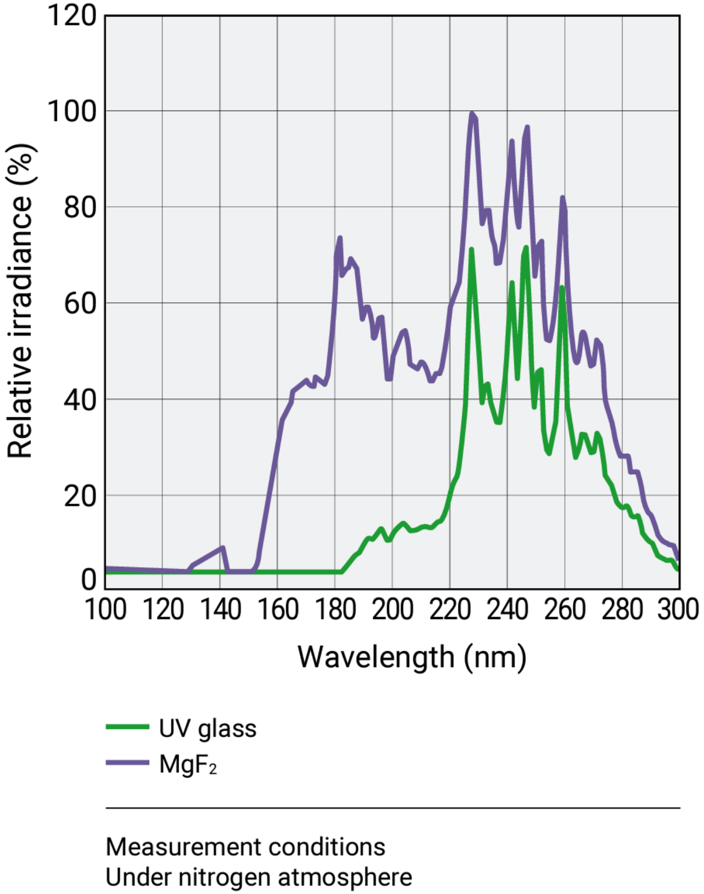
2W module (L13651-03-3 , MgF2 window)

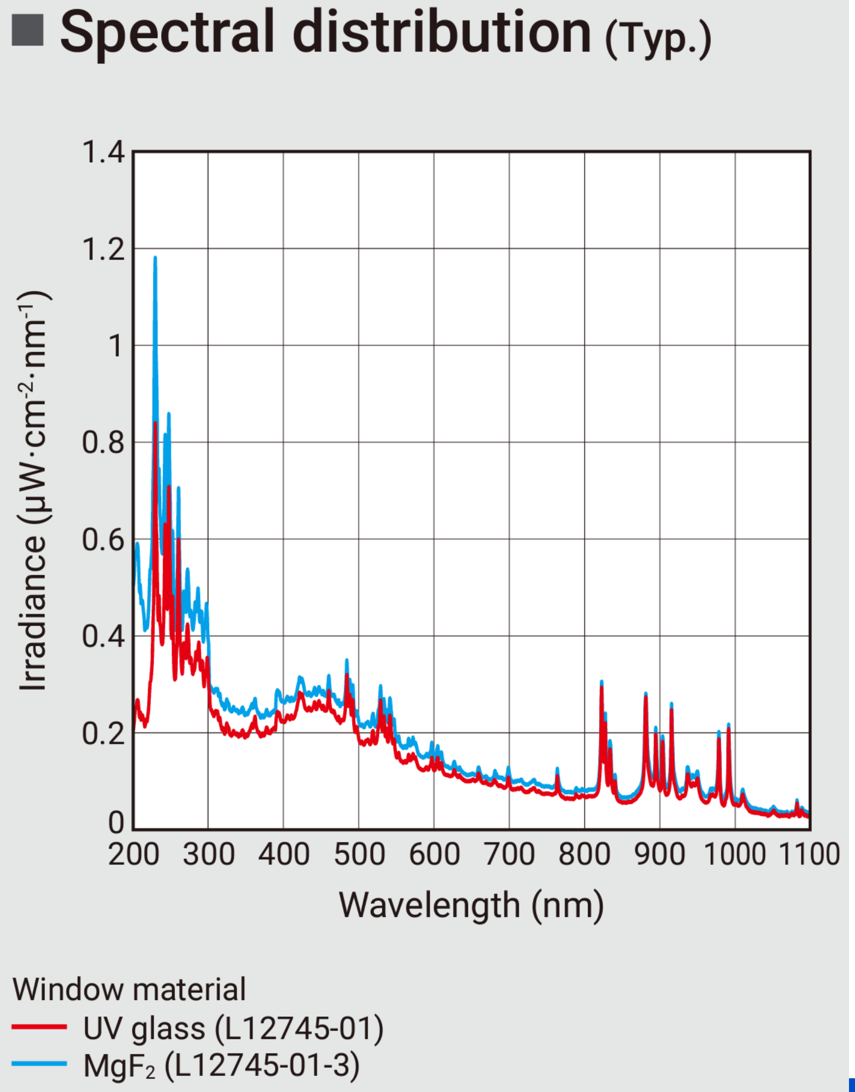


20W module (L12745-03-3, MgF2 window)

■ Figure 16: Spectral distribution (Typ.)

・UV region
of 20 W xenon flash lamp





Bandpass Filter (25172FNB)

Vacuum UV Optical Bandpass Filters

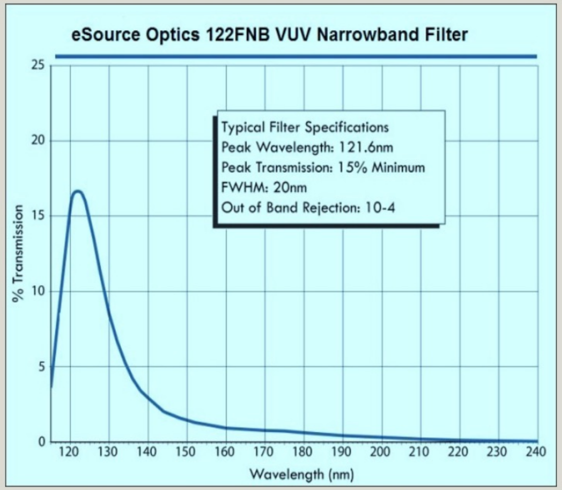
eSource Optics **Vacuum Ultraviolet (VUV) Optical Bandpass Filters** are available at specific peak Vacuum UV (VUV) wavelengths as short as the 122nm Lyman Alpha line up to 214nm, within the UV-C Short-Wave Ultraviolet spectrum.

Narrow Bandwidth VUV Optical Bandpass Filter designs are available designated as "**FNB**" having a **~20nm FWHM**. Extra Narrow Bandwidth 121.6nm Lyman Alpha VUV Optical Bandpass Filter designs are available designated as "**FXB**" having either a **~10nm** or **~15nm FWHM**. Popular Vacuum Ultraviolet (VUV) Analytical and Laser Lines are available including 122nm Lyman Alpha line, 155nm Carbon IV (C IV) line, 158nm Fluorine (F) Laser line, 172nm Xenon (Xe) Laser line, 184.9nm Mercury (Hg) Lamp line, 193nm Argon Fluoride (ArF) Laser line & 214nm Zinc (Zn) line. Other Vacuum Ultraviolet (VUV) wavelengths are available upon request. All VUV Optical Bandpass Filters are available in standard 12.7mm, 25.4mm, and 50.8mm Diameters. Very Narrow Bandwidth VUV Optical Bandpass Filter designs are available at select 214nm and longer VUV to UV wavelengths designated as "**FVN**" having a **~10nm - 15nm FWHM** in both a 25.0mm & 50.0mm Diameter size. "**FVN**" type Optical Filters are available at other wavelengths from 214nm to 313nm upon request.

Broad Bandwidth VUV Optical Bandpass Filter designs are also available designated as **"FBB" having a ~35-50nm FWHM**.

VUV NARROWBAND FILTER SPECIFICATIONS

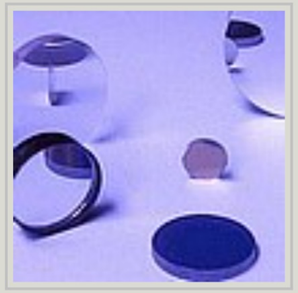
Substrate Material : VUV Grade MgF2 & VUV Grade CaF2 crystals, Crystal Quartz & UV Grade Fused Silica
Diameter (Ø) Tolerance: ± 0.80mm (FNB Filters); + 0.0/-0.25mm (FVN Filters)
Thickness: ~ 2.0 - 3.0mm (FNB Filters)
1.5 +/- 0.25mm (FVN Filters)
Surface Quality:~20-10 to 40-20 scratch-dig (FNB Filters);≤80-50 scratch-dig (FVN Filters)
Parallelism: ~ 5 arc minutes
Clear Aperture: central 80%
Edge Chamfer: ~0.5mm x 45 degrees
Filter Blocking: Approx ~10^{-3} range to 10^{-4} range ~350nm to Vis through NIR typical
Construction: Unmounted and Open-Faced; >170nm FNB's can be covered (contact us)



Typical 122nm Filter VUV % Transmission P/N 122FNB

Bandpass Filter (25172FNB)

25172FNB

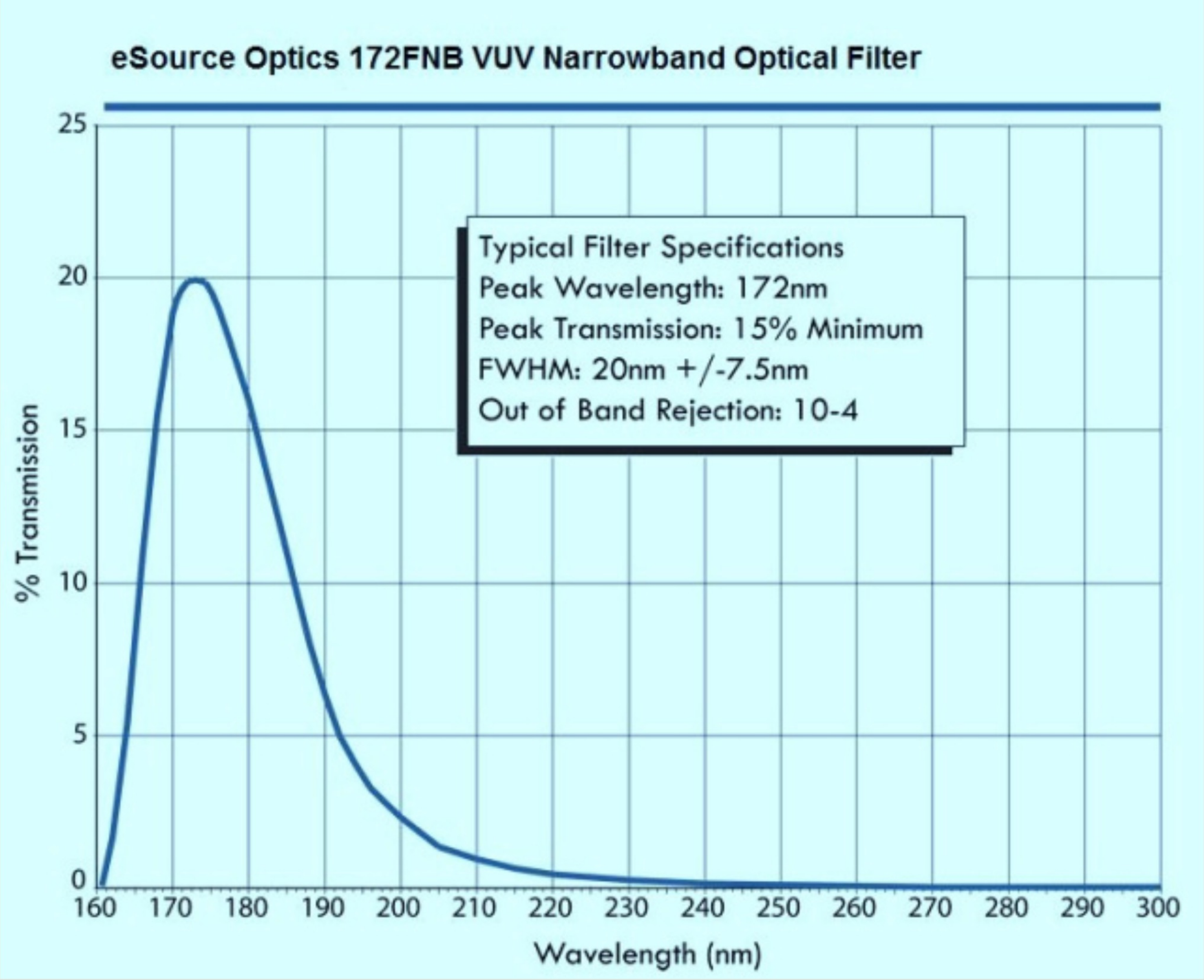


Price:	**$995.00**
Availability:	Contact eSource Optics
Prod. Code:	VUV Optical Bandpass Filters

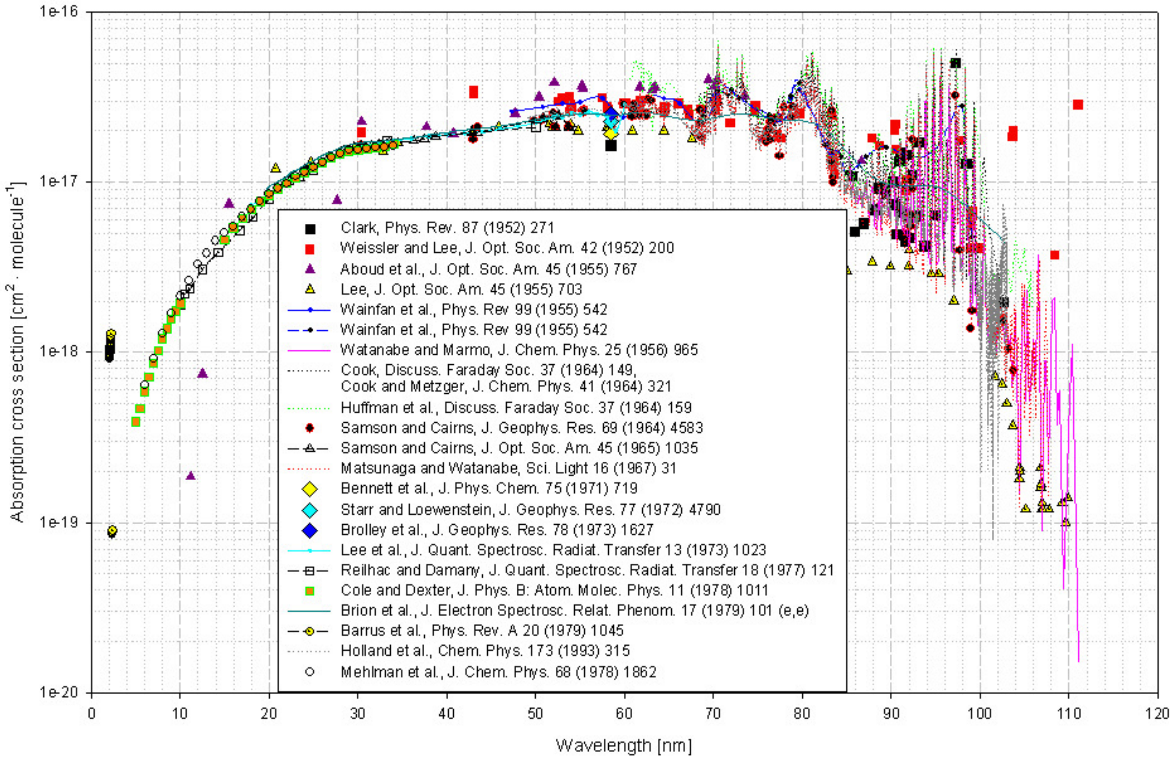
View Images

eSource Optics P/N 25172FNB

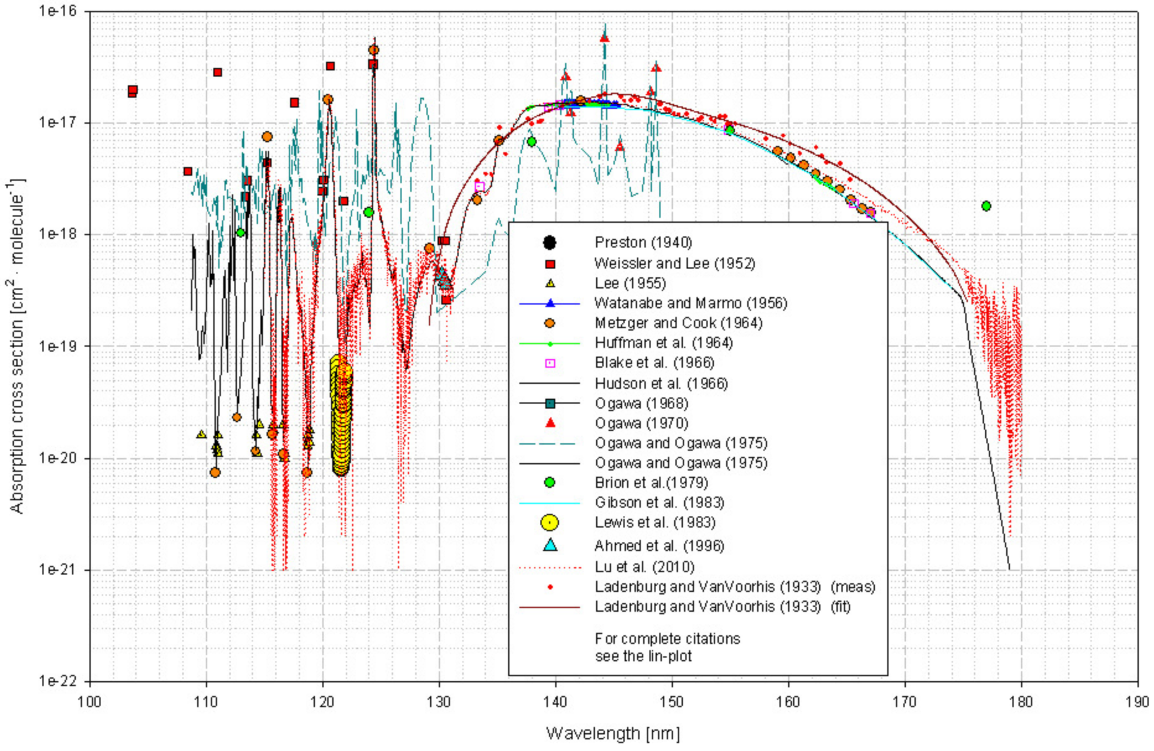
Peak WL: 172 +/- 2.5nm
FWHM: 20 +/- 7.5
Peak Transmission: 15% Minimum
Diameter: 25.4mm ± 0.25mm
Thickness: ~1.5 - 5.0mm
Filter Blocking: Approx ~10^{-3} UV through FIR typical
Construction: Unmounted and Open-Faced



Absorption cross section of oxigen



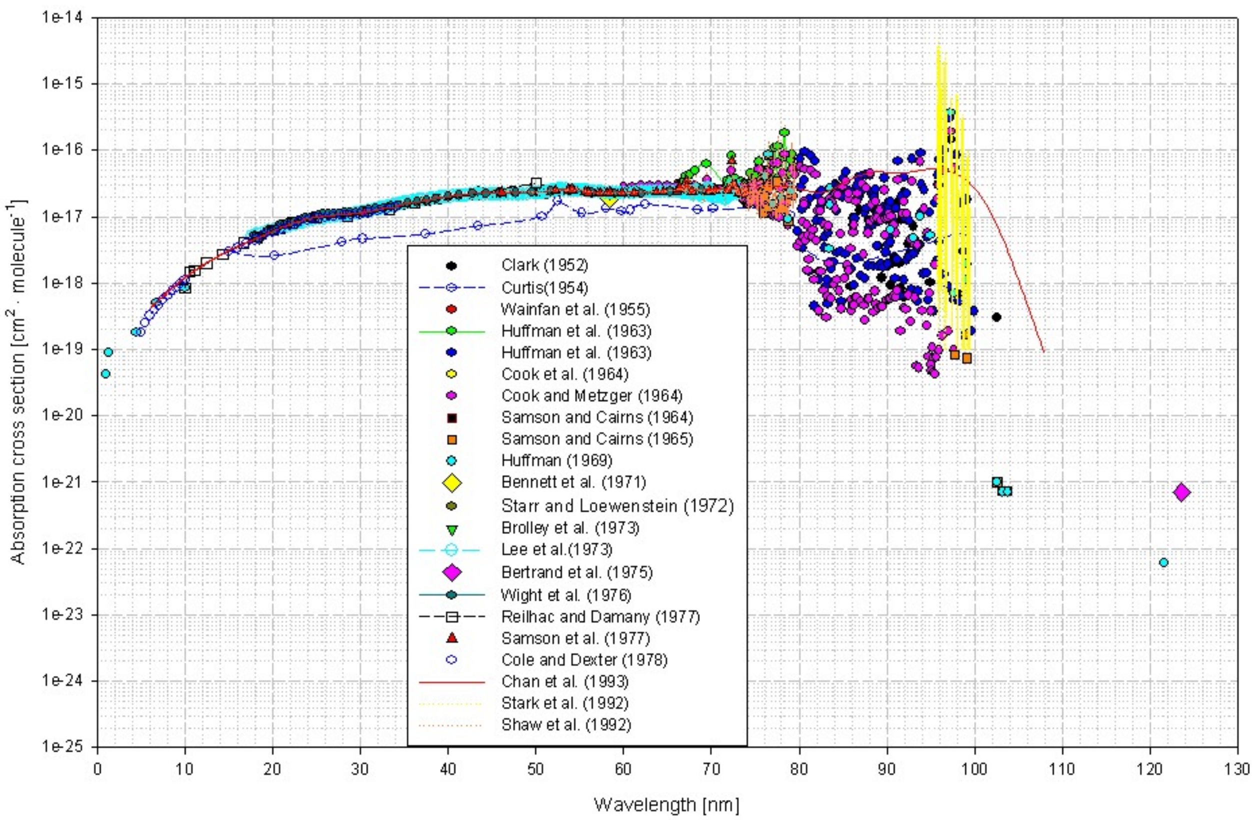
VUV and extreme UV absorption cross sections of oxygen O_2 at room temperature (2-111 nm)



VUV absorption cross sections of oxygen O_2 at room temperature (104-180 nm)

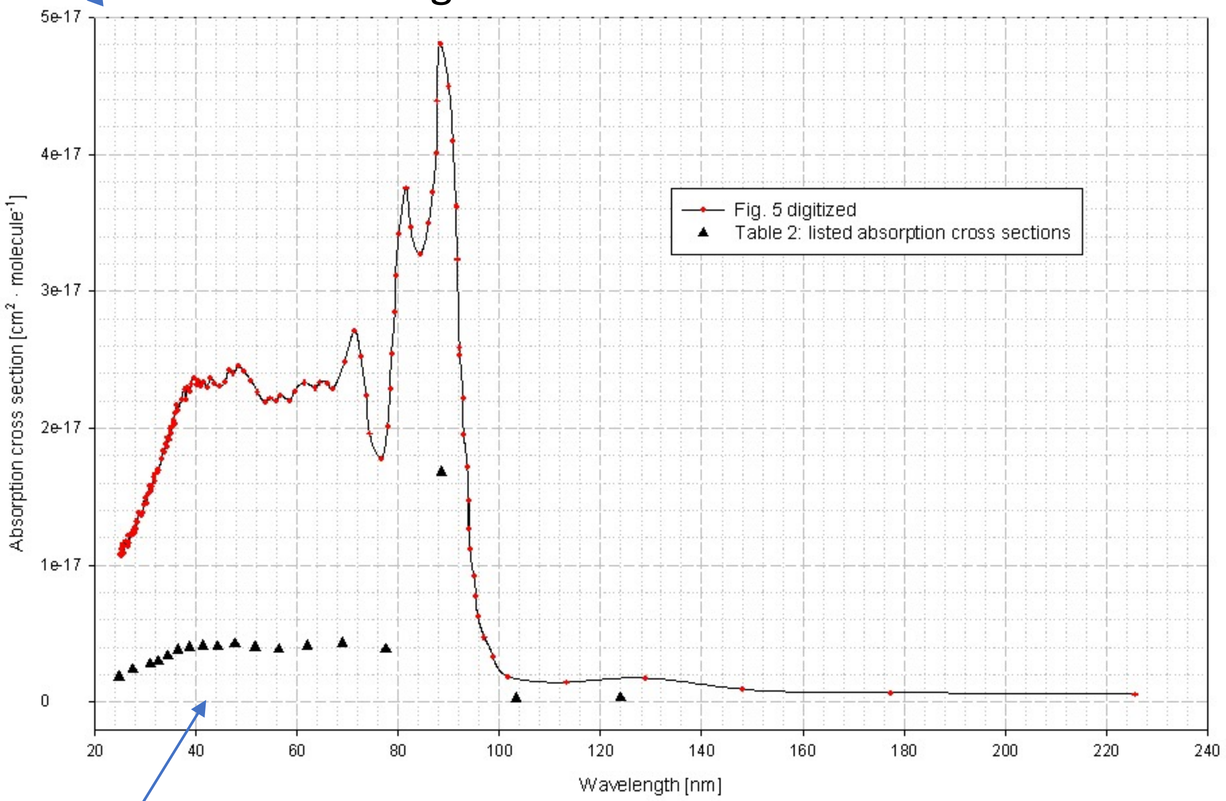
https://uv-vis-spectral-atlas-mainz.org/uvvis/cross_sections/Oxygen/O2.spc

Absorption cross section of nitrogen



VUV absorption cross sections of nitrogen N_2 at room temperature (1-123 nm)

Not logarithm coordinate



Absorption cross sections of nitrogen N_2 at room temperature,
Souza and Srivastava, J. Braz. Chem. Soc. 5 (1994) 59

Why are there gap? (This is not main problem...)

https://uv-vis-spectral-atlas-mainz.org/uvvis/cross_sections/Nitrogen+compounds(N,H,O)/N2.spc