Fabrication and Characterization of Low-cost Microchannel Plate Photodetectors for Fast-timing Applications

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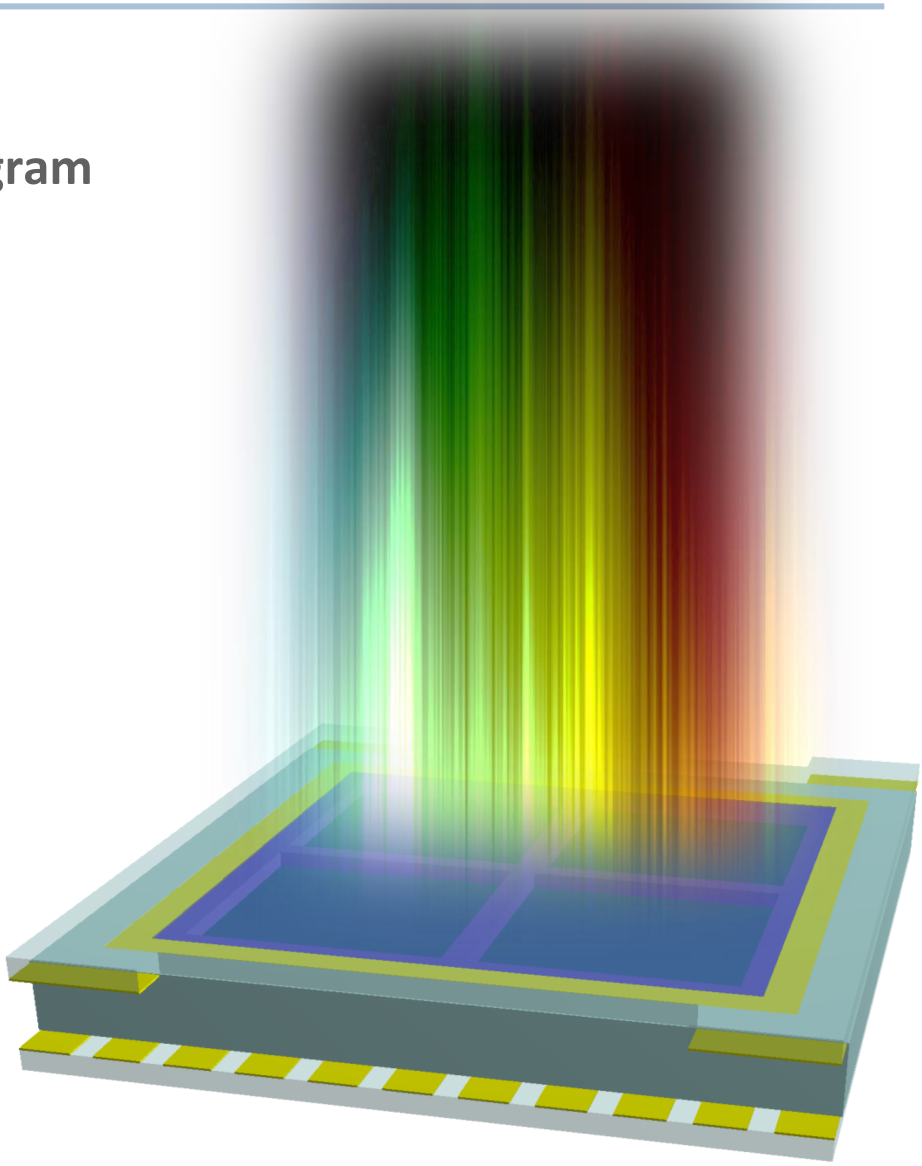
Timing workshop, Kansas city, September 15 - 18, 2016

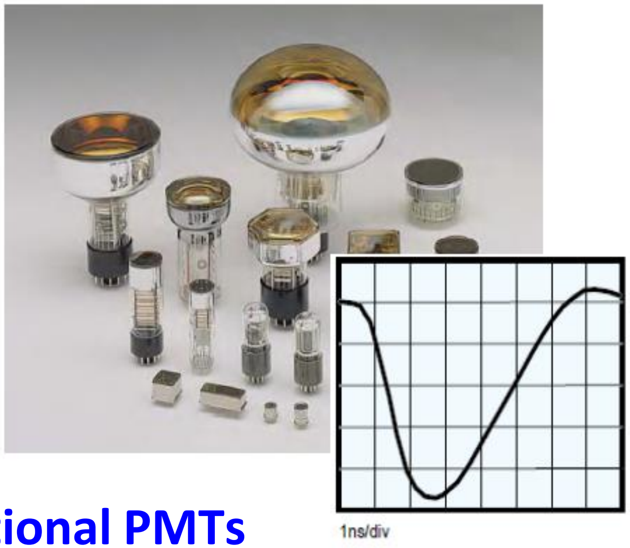
U.S. DEPARTMENT OF ENERGY

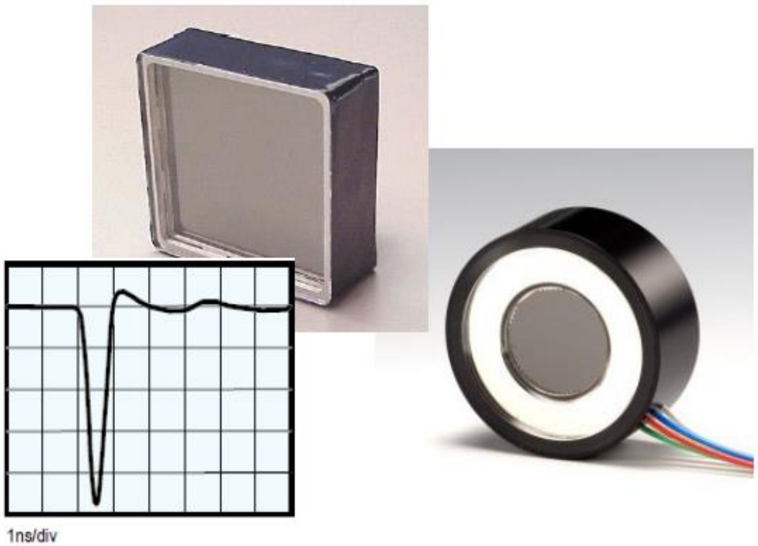
Outline

- **LAPPD project**
- **Argonne MCP photodetector program**
  - Fabrication system
  - Tube processing
- **Testing and characterization**
  - Key performances
  - Optimization
- **Summary**



Motivation: Traditional PMT & MCP-PMT





Traditional PMTs

- Successful technology over decades
- Sensitive to single photons
- Good Quantum efficiency
- Rather fast: several hundred ps time resolution
- But…
  - Limited position resolution
  - Not suitable to high B-field
  - large-area PMTs are still bulky

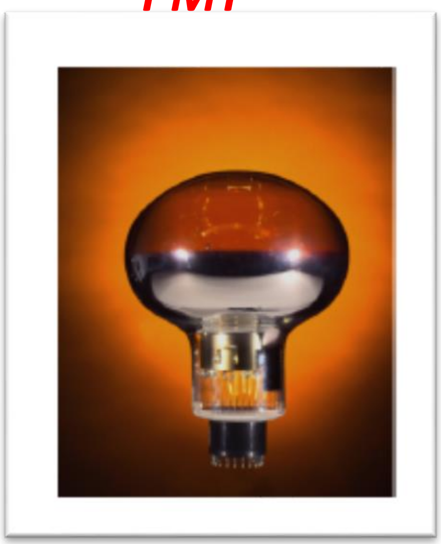
MCP-PMT

- Compact structure
- Tens of picosecond level time resolution
- Micron-level position resolution
- Good B-field performance
- But…
  - Few venders
  - High cost
  - Limited size area

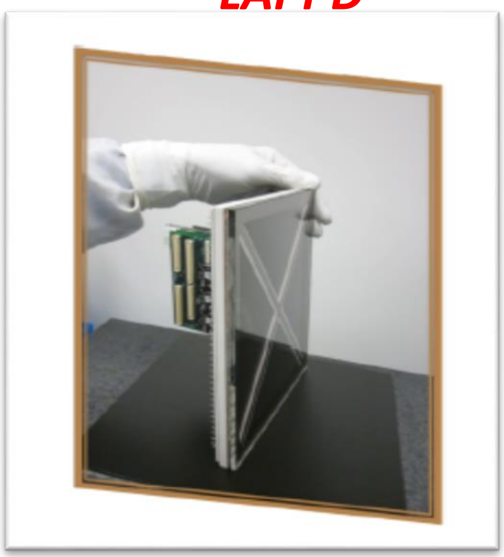
Large Area Picosecond PhotoDetector (LAPPD)

- To address the limitations of commercial MCP-PMTs, the **LAPPD** project reinvents photodetectors using transformational technologies.
- Goals: large-area (20 cm × 20 cm), picosecond-timing, low-cost
- Applications: picosecond timing on large-area
  - ✓ High energy physics: optical TPC, TOF, RICH
  - ✓ Medical imaging: PET scanner, X-ray imaging devices
  - ✓ National security: Detection of neutron and radioactive materials

PMT



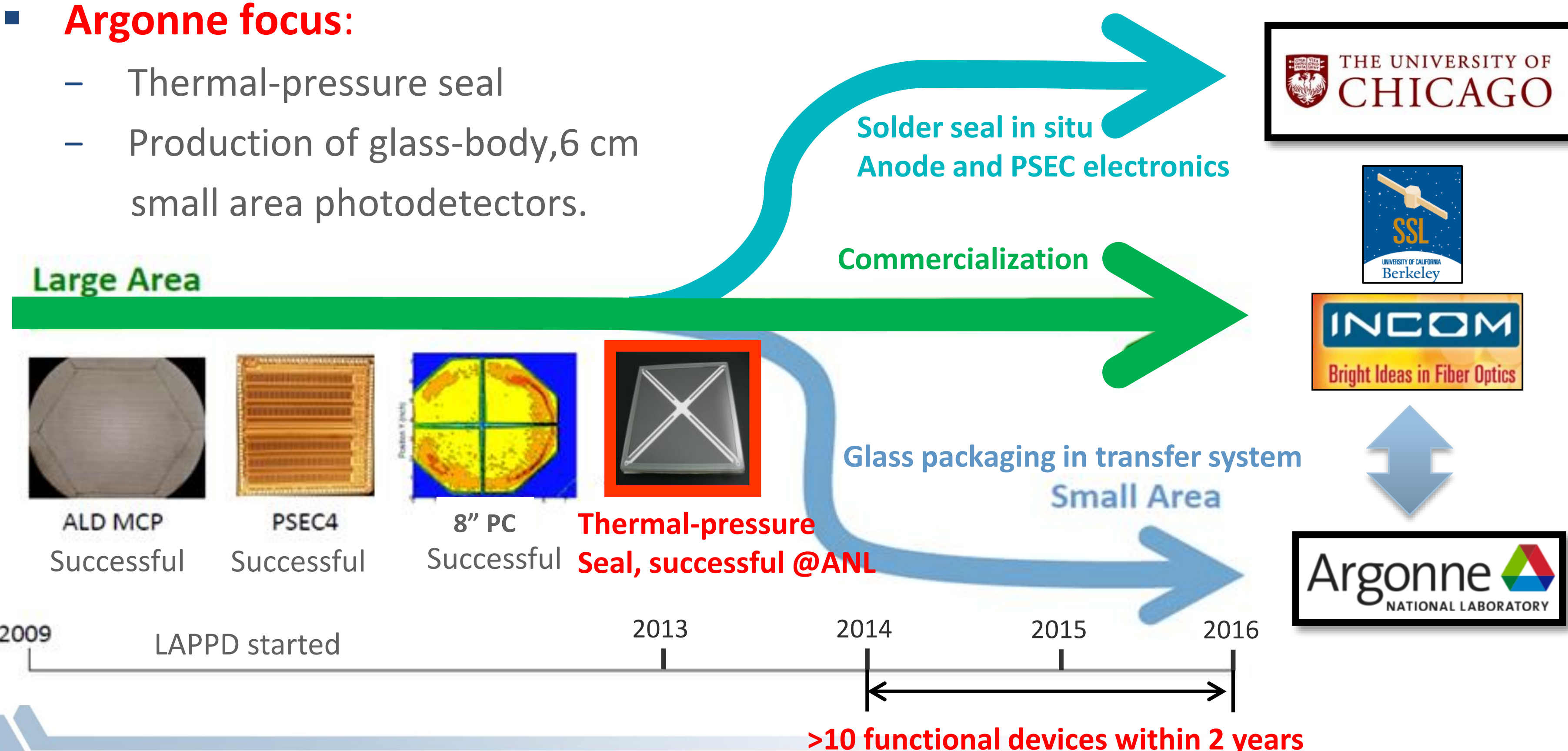
LAPPD



Large Area Picosecond PhotoDetector (LAPPD)

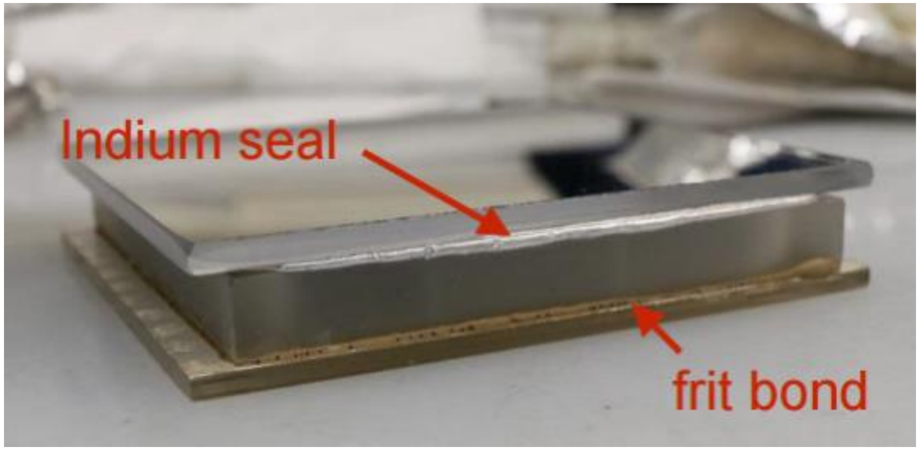
- **LAPPD Status:**
  - Success with MCPs, waveform sampling ASIC, large-area photocathodes
  - Success with the early R&D using a demountable detector *
  - Incom, Inc. is commercializing the LAPPD detectors.
- **Argonne focus**:
  - Thermal-pressure seal
  - Production of glass-body,6 cm small area photodetectors.

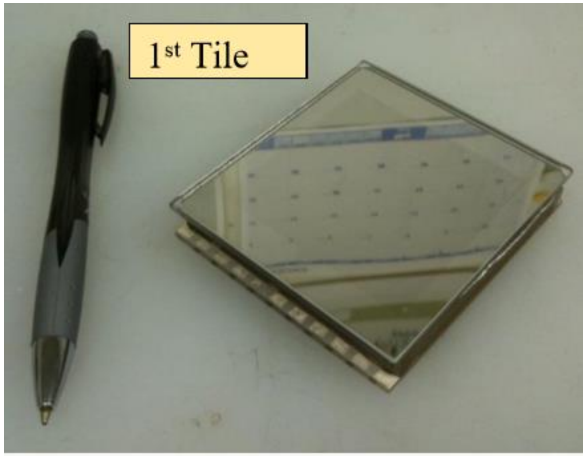
** B. Adams, et al., Nucl. Instru. Meth. A, 795 (2015), 1 - 11*



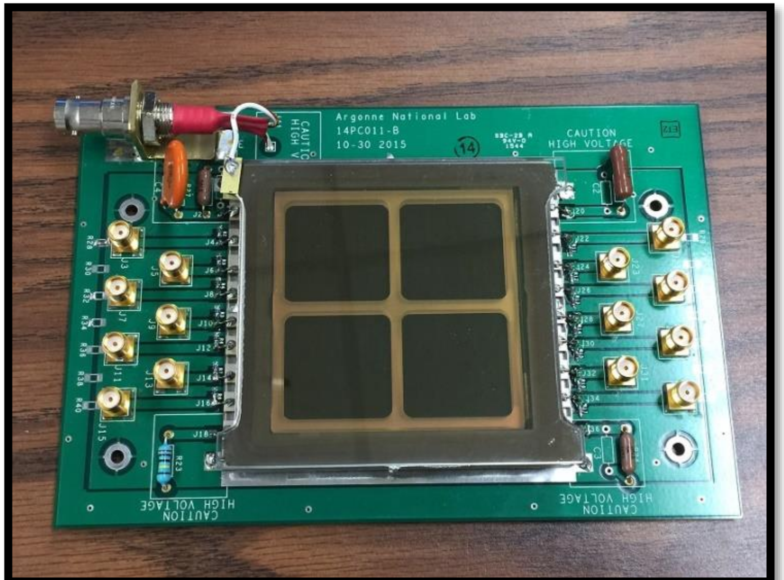
Goals of Argonne MCP photodetector program

- Demonstrate the feasibility of the production of glass body MCP photodetectors
- Produce the first functional devices and provide them to the community for evaluation and incorporation into experiments
- Support the industry for commercialization of large-area devices, ALD, glass package, thermal pressure seal, testing…
- Provide a flexible platform for further R&D efforts (high B-field application, cryogenic application , VUV response, thermal neutron detection…)





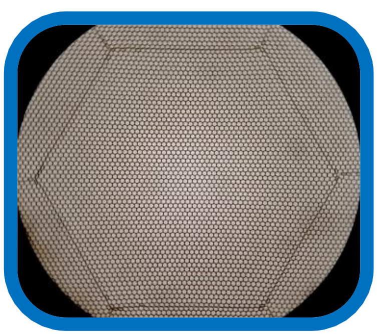
Argonne MCP photodetector program



- **New techniques**
  - **New glass substrates** provided by INCOM. Inc.
  - **ALD functionalization** developed by ANL-ES (**licensed to INCOM**.)
  - **All-glass hermetic packaging with thermal-pressure seal** (leads to lower cost)

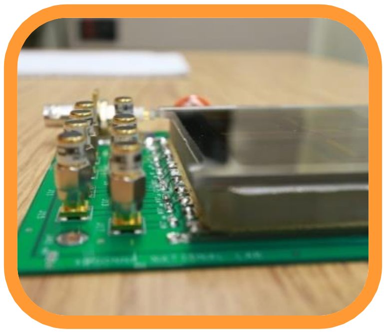
6 cm × 6 cm, all-glass body

ALD-MCP

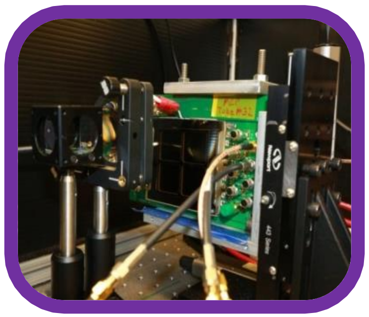


Photocathode

Packaging

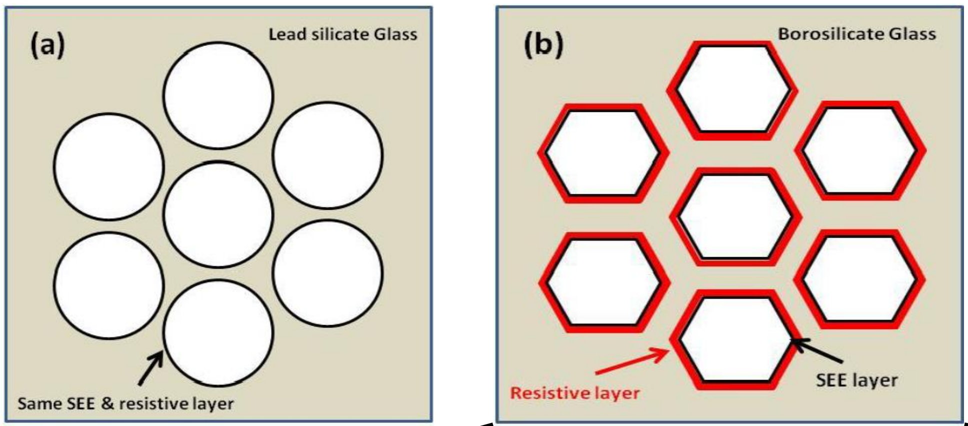


Testing

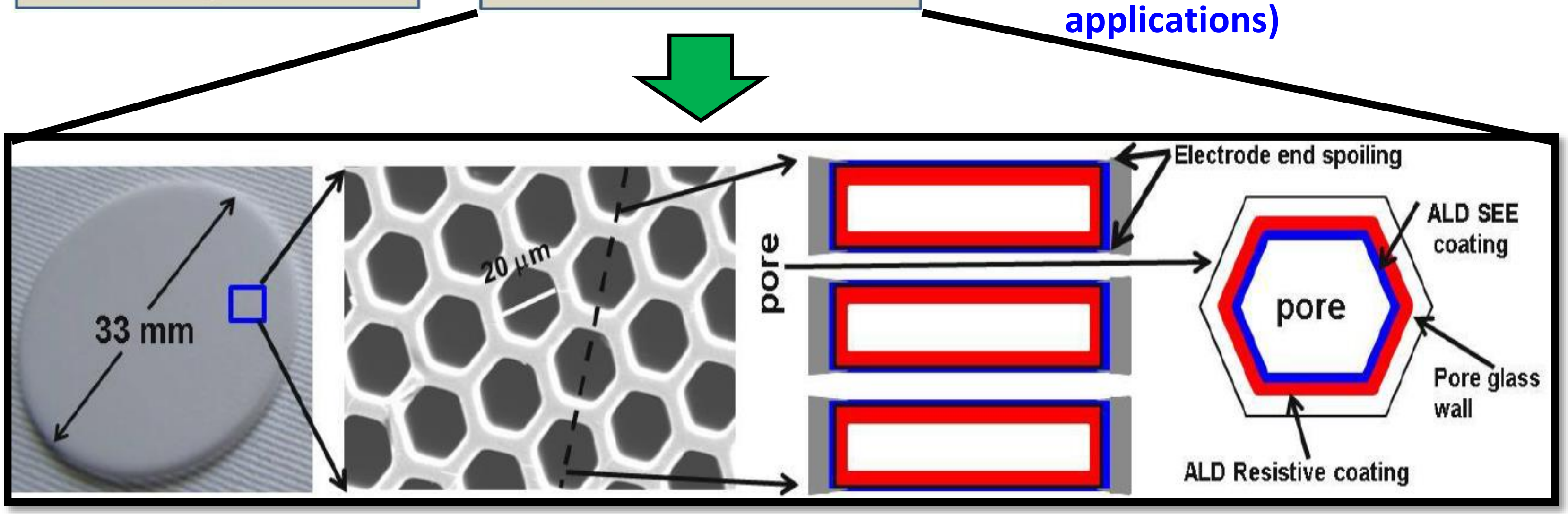


Micro-channel plate by Atomic Layer Deposition

Conventional route | **ALD route**



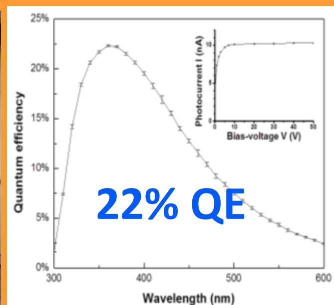
- **Conventional MCP:**
  - Pb-glass provides **pores**
  - Pb-glass provides **resistive layer**
  - Pb-Oxide **emissive layer**
- **ALD-MCP:**
  - New glass substrate from Incom.
  - **Resistive/emissive layers by ALD**
  - **Price reduced. Freedom to tune capabilities (high-rate, cryogenic applications)**



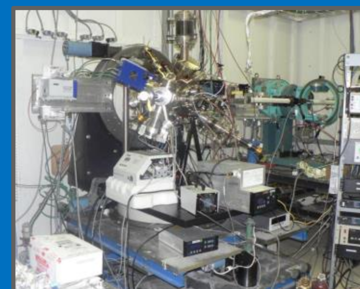
ALD = Atomic Layer Deposition

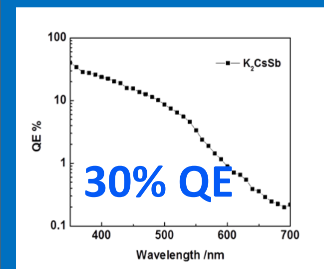
Photocathode development

Commercial Burle facility



X-ray study to enhance QE





Improving QE; study VUV photocathode

Jan. 2011

Jan. 2012

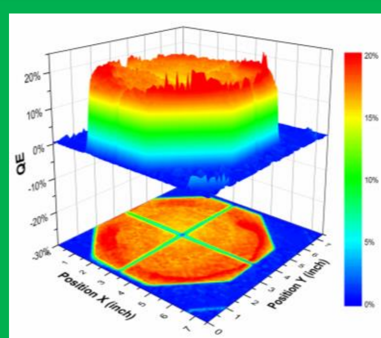
May. 2013

May. 2015

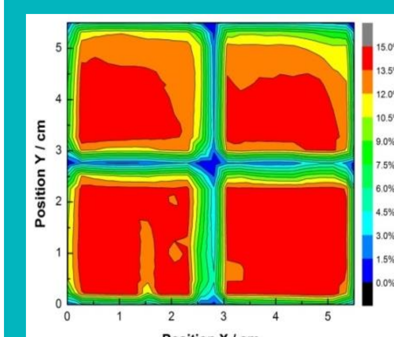
Recent

7" photocathode

20% QE

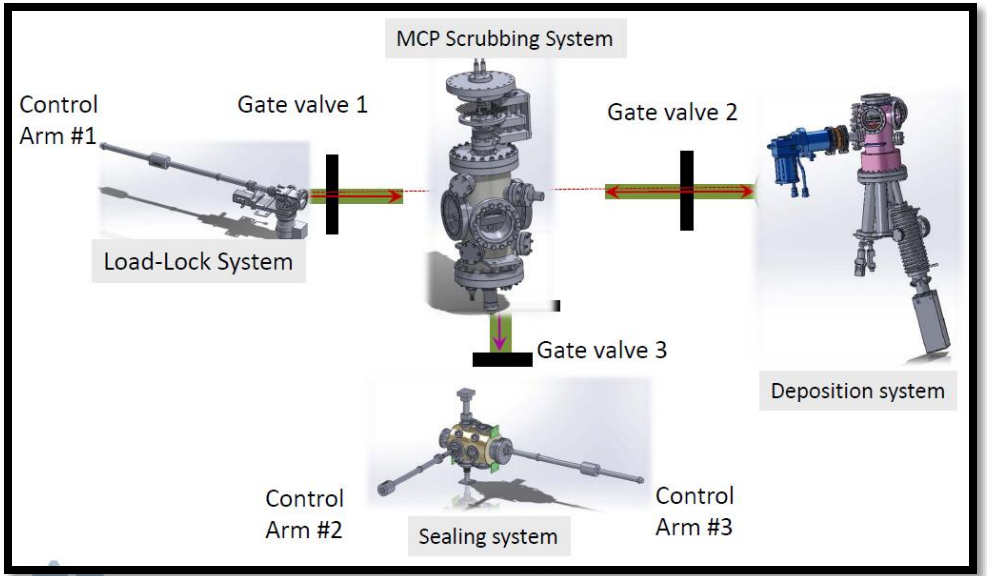


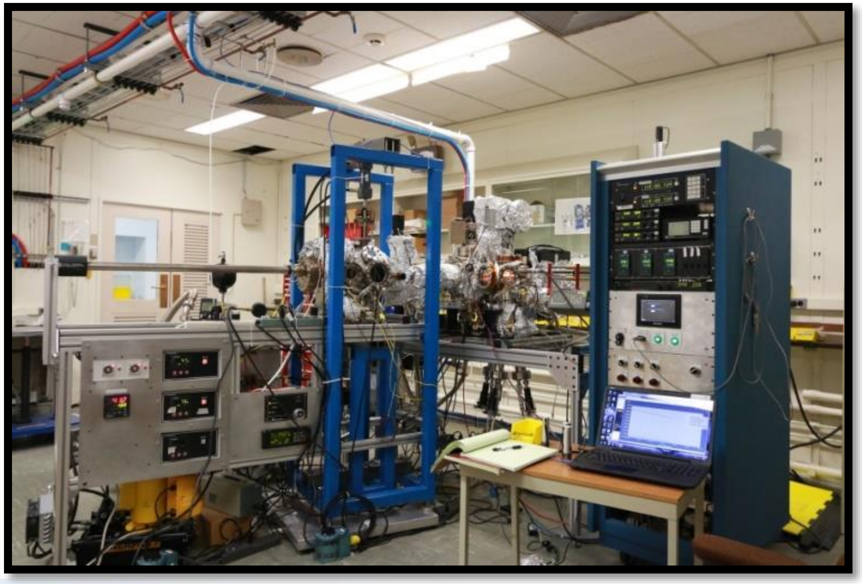
6 cm sealed tube 13% QE, goal is 20%



Small Single Tube Processing System (SmSTPS)

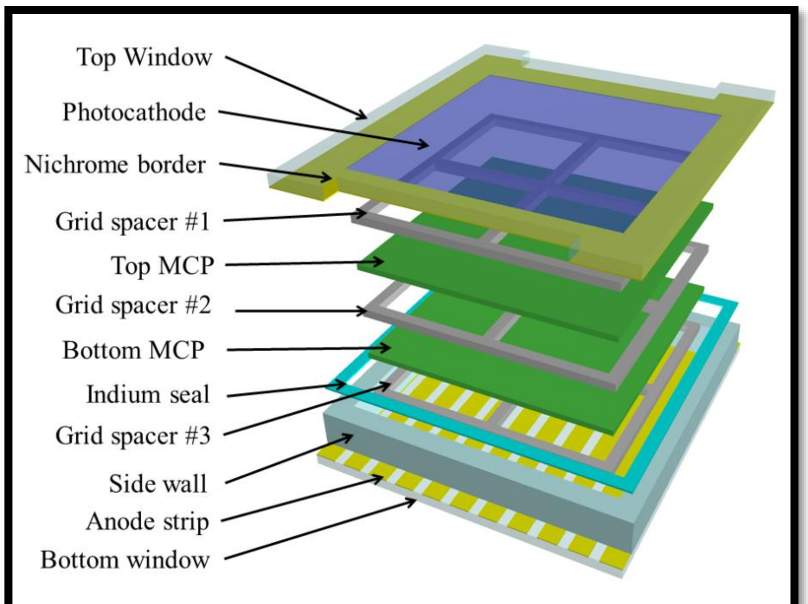
- The goal is to bring everything together and make a sealed device
- Unique features:
  - Vacuum transfer system : external magnetic arm
  - Each process is done in its own chamber: very flexible for R&D
  - **Thermo-pressure indium seal** using hydraulic driven platens : demonstrated for large-area (20 cm × 20 cm tiles);
  - **Effusion cells** for bialkali photocathode deposition: efficient method for mass production
- Serves as a flexible platform for R&D needs to address new requirements

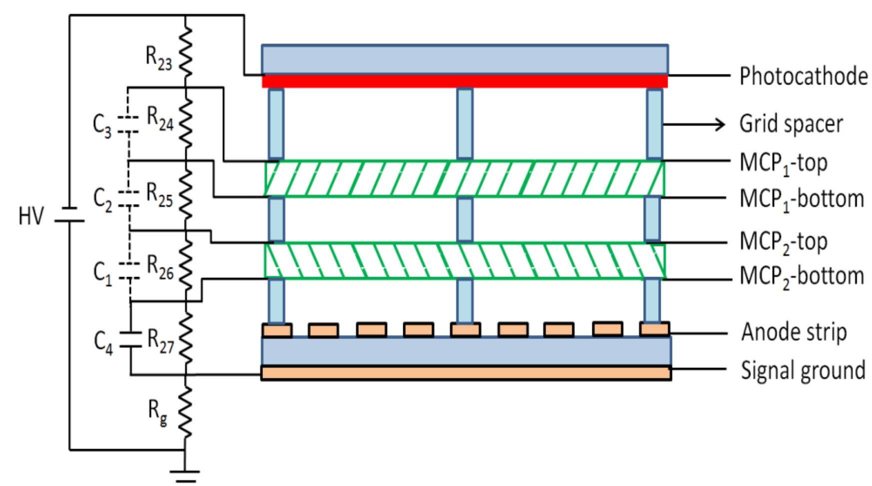




ANL 6 cm × 6 cm photodetector

- A glass bottom plate with stripline anode readout
- A glass side wall that is glass-frit bonded to the bottom plate
- A pair of MCPs (20µm pore) separated by a grid spacer.
- Three glass grid spacers.
- A glass top window with a bialkali (K, Cs) photocathode.
- An indium gasket between the top window and the sidewall.

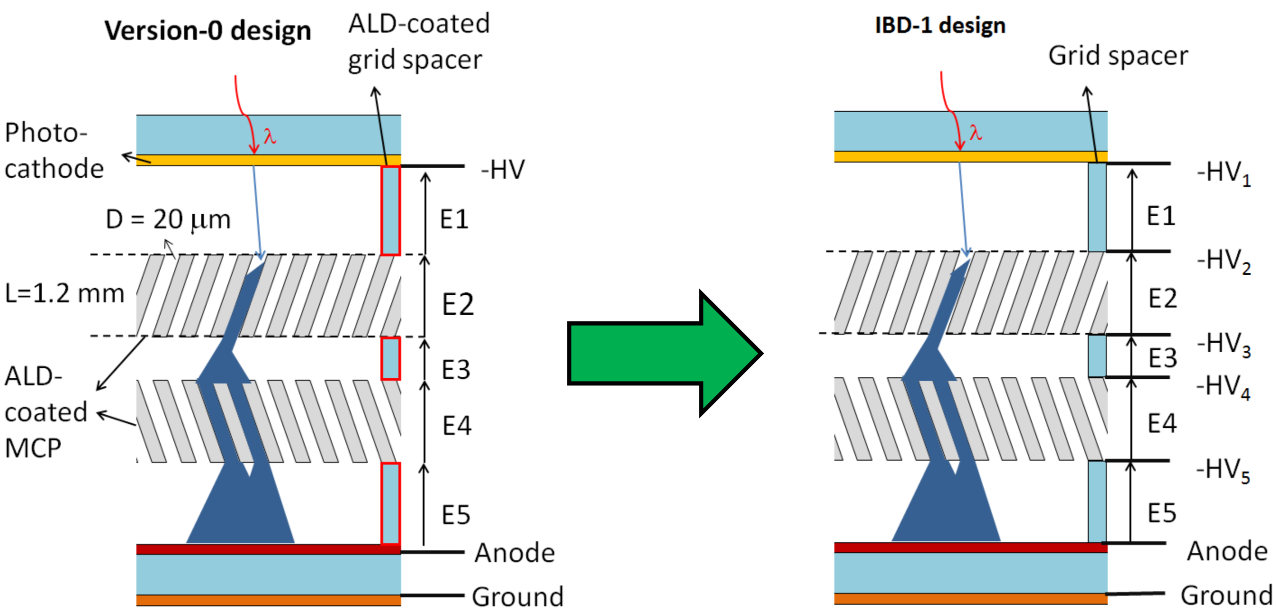




J. Wang, et al., Nucl. Instru. Meth. A, 804 (2015), 84 - 93

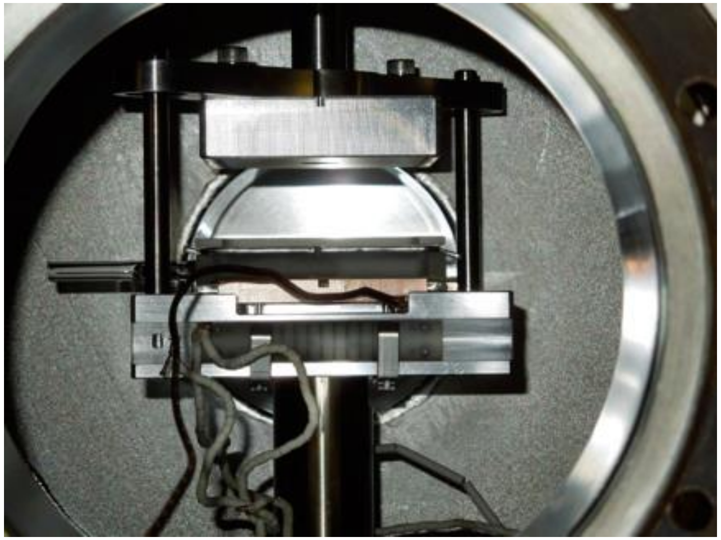
Design improvement

- **Internal resistor biased design (original LAPPD design): grid spacers are resistively coated**
  - No direct way to measure QE in sealed tube
  - Need fine matching between component resistances
  - Can't optimize each internal component
- **Independently biased design (IBD-1): grid spacers are insulators**
  - **Performances significantly improved after HV optimization : 65 ps -> 35 ps**
  - **This new biasing design in glass-body has filed a patent**

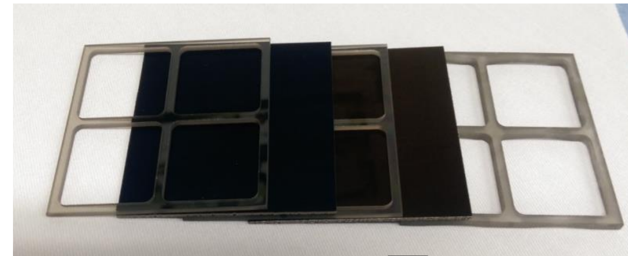


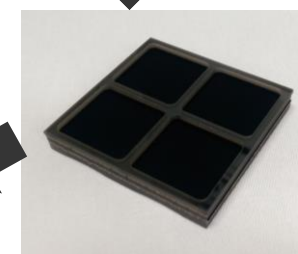
Tube processing

hydraulic driven platens



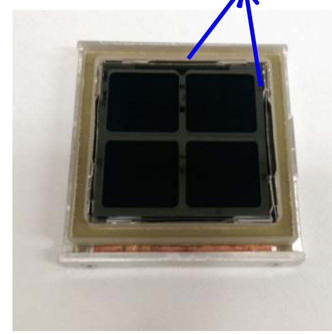
MCP & Resistive Grid Spacer Stack



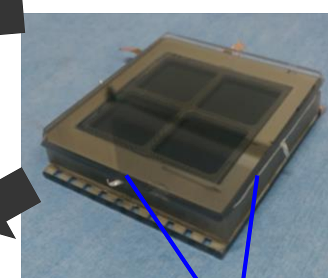


Getter strips

Tile base



Sealed tube



Indium gasket

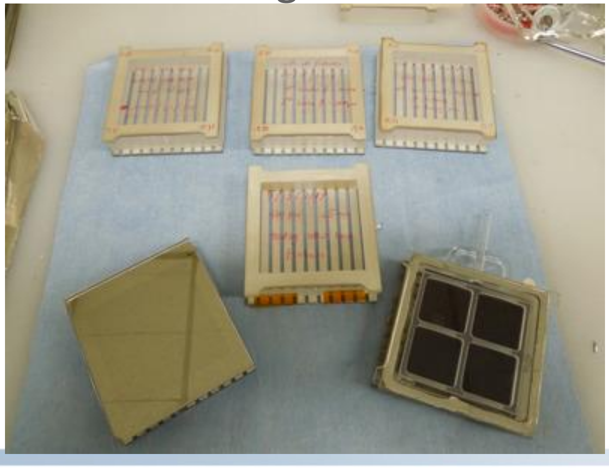
Completed tube

- **Tube processing is challenging**
  - Baking & scrubbing
  - Getter activation
  - Photocathode deposition
  - Thermo-pressure indium seal
- Solved problems and achieved a reliable seal
- Current status: 10^{-10} Torr, one tube / 2 weeks
- Production rate can be improved

Status of the tube production

- **The 1st production run began in 07/2014 and concluded in 12/2014**
  - Addressed many issues (baking and scrubbing, sealing, outgassing control…)
  - Produced 6 working devices, **3 long-lived (>1 year).**
  - Discovered limitations of the first design: no HV access to the internal components
- **The 2nd production run began in 06/2015 and concluded in 12/2015**
  - Improved design: allows **HV optimization for each component**
  - Produced 10 detectors with a **100%** sealing yield and 90% production yield.
- **The 3rd production run has just started:** more working detectors
- **Now on track of providing photodetectors to the community.**

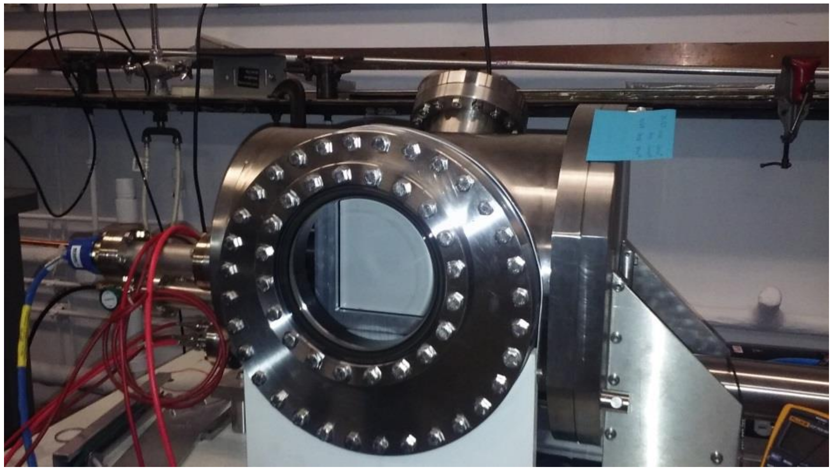
Sealing trials



Working detectors

Test facilities

Phosphor screen chamber for MCP test



Photodetector laser test stand

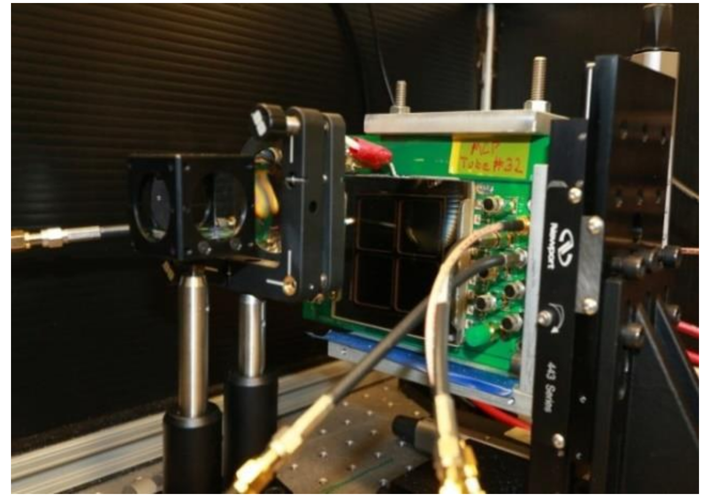
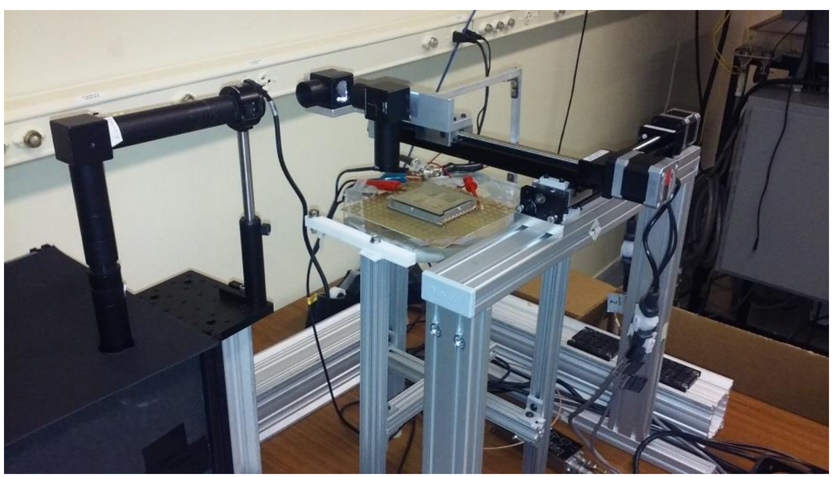


Photo cathode test stand

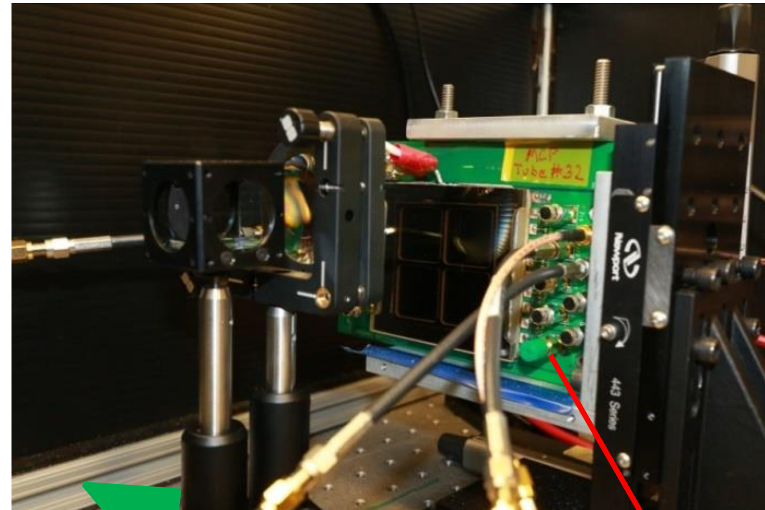


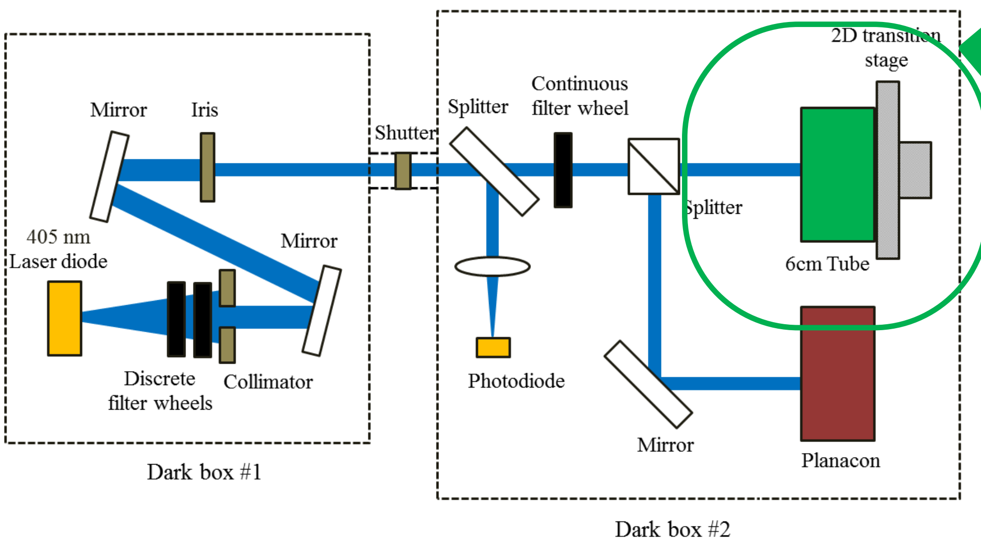
Cryogenic test setup

Blue laser test facility

- Hamamatsu PLP-10 pulsed blue laser
- Wavelength: **405 nm**
- Pulse duration: FWHM = 70 ps (**σ = 30ps**)
- Frequency: 2 Hz – 10 MHz
- Beam size: ~1 mm
- Start signal: laser synchronization pulse
- Translation stage: um precision
- Readout: Programmable Oscilloscope

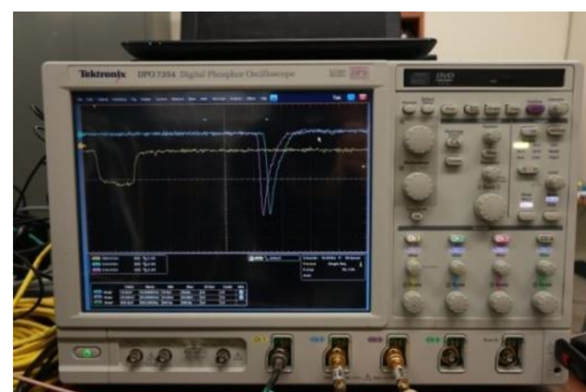
Dark box #2





40 Gs/s scope

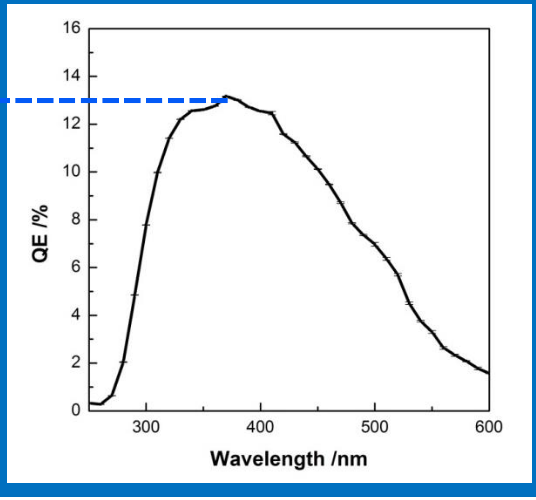
Readout board



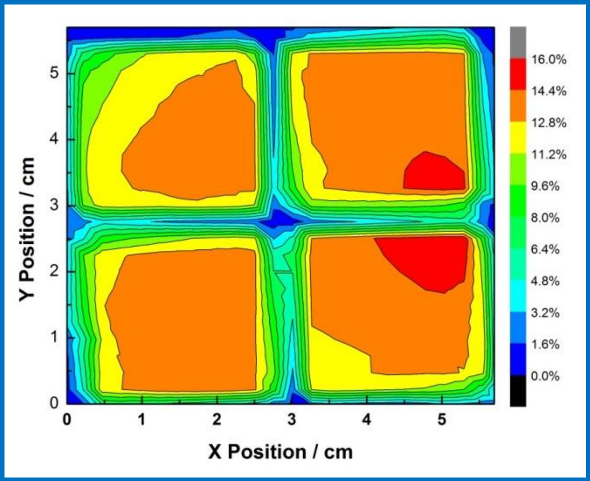
Key performances

QE = 13.2%
@ 370 nm

QE Spectra response



QE 2D map

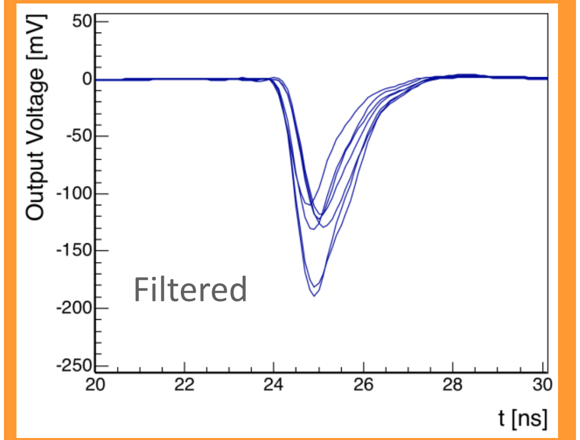


QE = 13 %

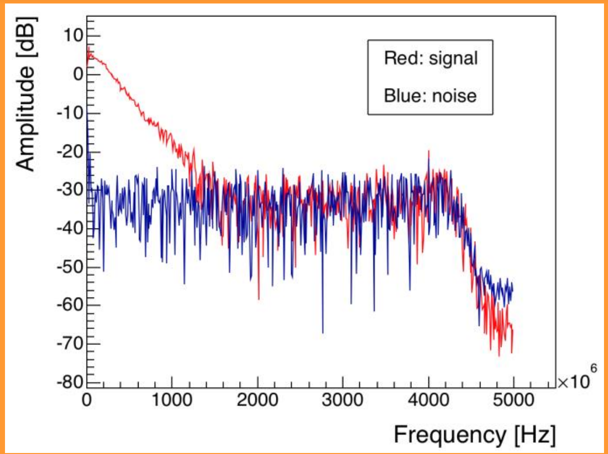
15.5%
maximum

0.5 ns
rise time

Filtered signals



Frequency components



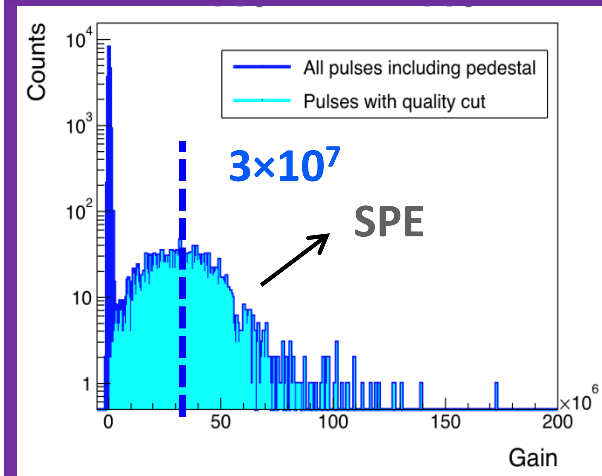
Signal bandwidth
up to1.3 GHz

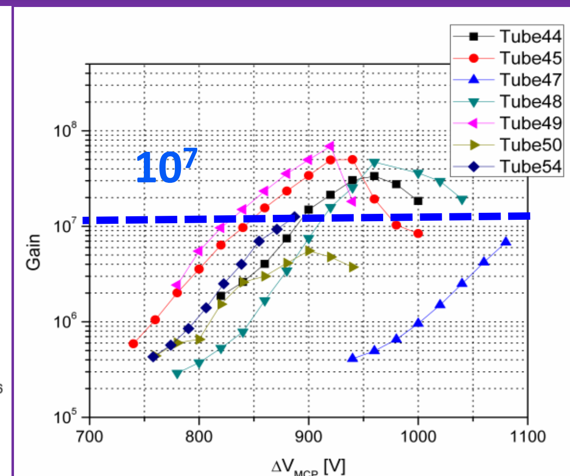
Key performances

Gain distribution

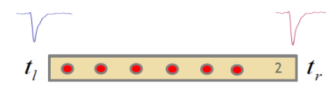
Gain VS HV

Gain > 10^7





Gain VS HV_{MCP}

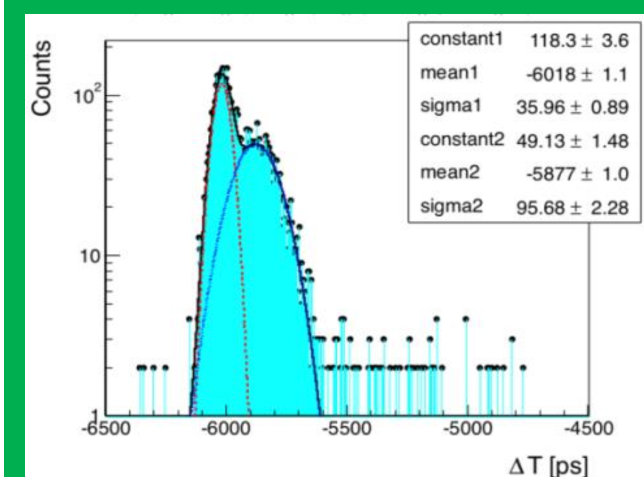


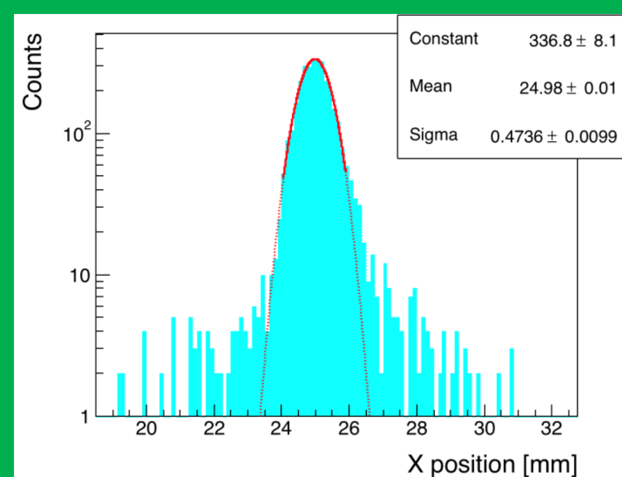
Timing distributions

Position resolution

σ_{IRF} ~ 35 ps for SPE, including Laser jitter

σ_{TTS} ~ 20 ps





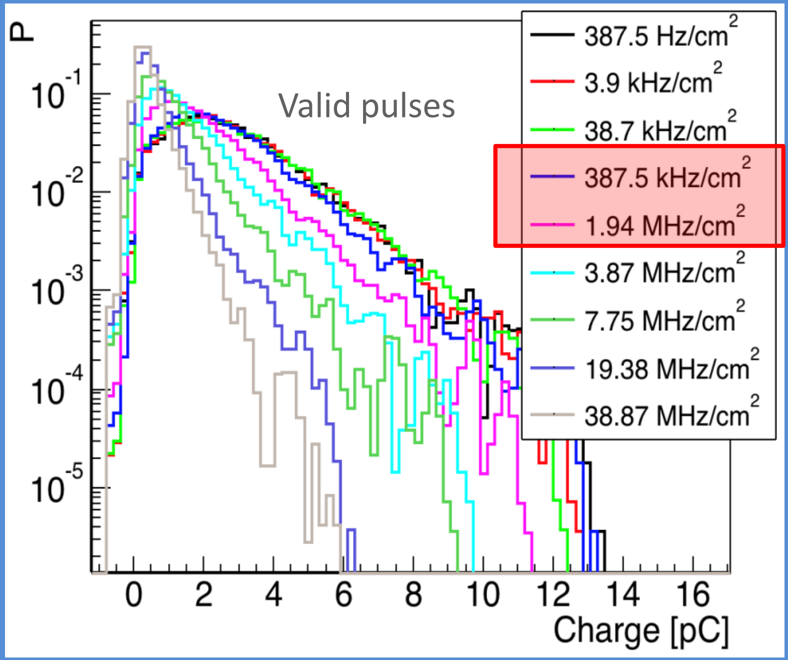
σ < 1 mm for SPE

Key performances

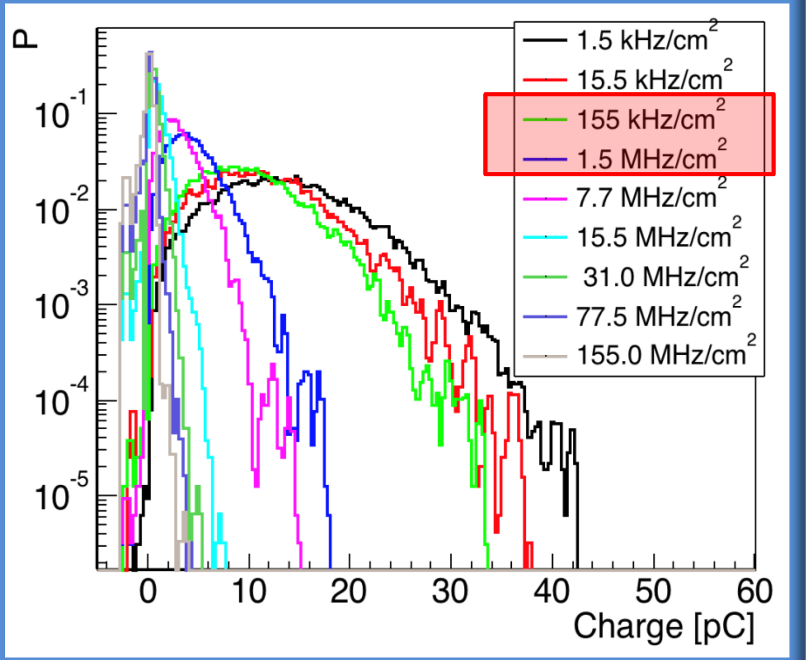
- **Rate capability** was recently measured with a pulsed laser
- Beam size is diffused: $\sigma_x = \sigma_y = 2.0$ mm, A* ~ 0.5 cm^2
- **HV = 2800 V, without pre-amplifier**

Preliminary

Charge distribution at 1.1 <N*$_{pe}$>



Charge distribution at 4.2 <N*$_{pe}$>



The spectrum shifts to left with the increase of the beam flux

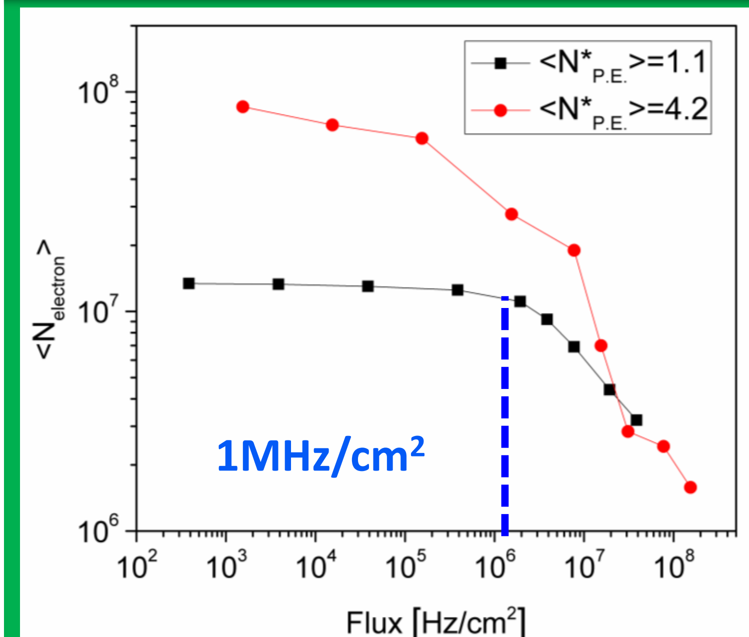
See a fast drop between 155 KHz/cm^2 and 1.5 MHz/cm^2

Key performances

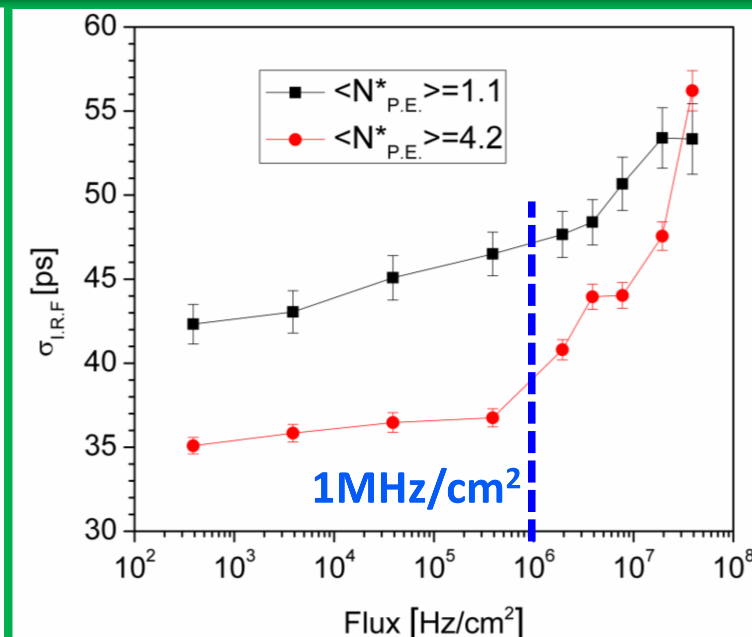
- **Rate capability** was recently measured with a pulsed laser
- Beam size is diffused: $\sigma_x = \sigma_y = 2.0$ mm, $A^* \sim 0.5$ cm^2
- **HV = 2800 V, without pre-amplifier**

Preliminary

Number of electrons VS flux



Time resolution VS flux

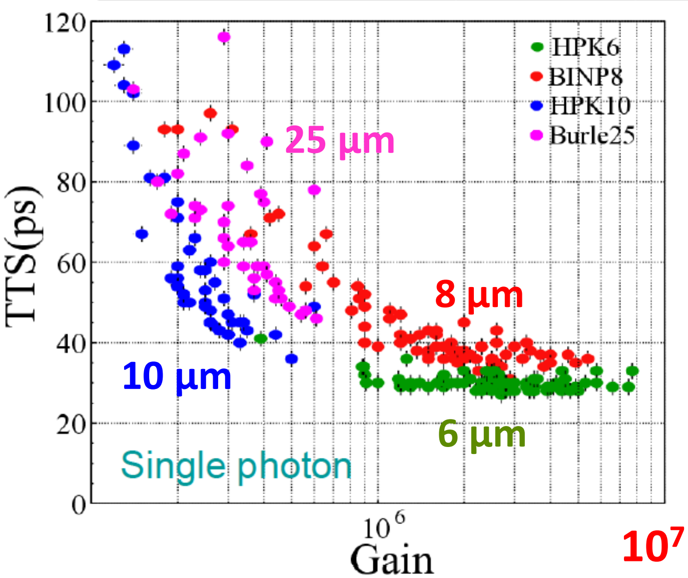


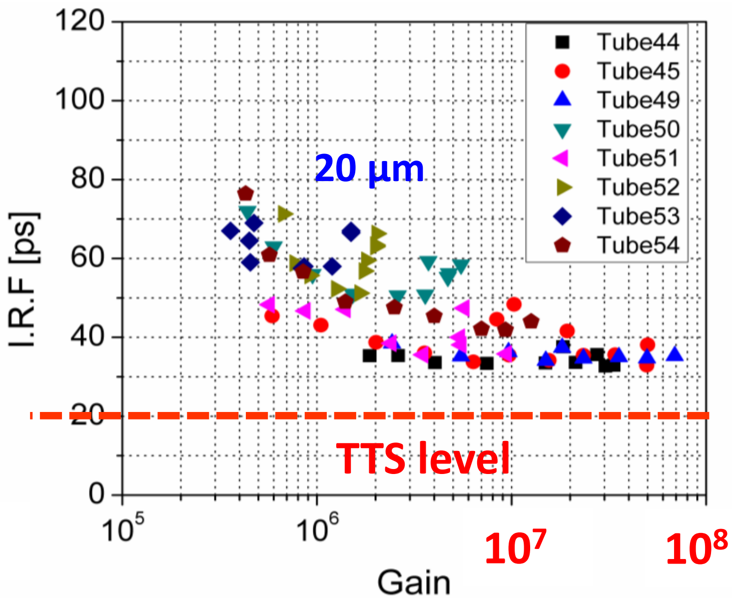
Comparison to commercial products

MCP-PMT	HPK6 R3809U-50-11X	BINP8 N4428	HPK10 R3809U-50-25X	Burle25 85011-501	ANL 6cm tube
PMT size(mm)	45	30.5	52	71x71	85×76
Effective size(mm)	11	18	25	50x50	60×60
Channel diameter(μm)	**6**	**8**	**10**	**25**	**20**
Length-diameter ratio	40	40	43	40	60
Max. H.V. (V)	3600	3200	3600	2500	2900
photo-cathode	multi-alkali	multi-alkali	multi-alkali	bi-alkali	Bi-alkali
Q.E.(%) (λ=408nm)	26	18	26	24	13

$$\sigma^2_{I.R.F} \sim \sigma^2_{.T_{MCP}} + \sigma^2_{.T_{laser}}$$

By Nagoya University

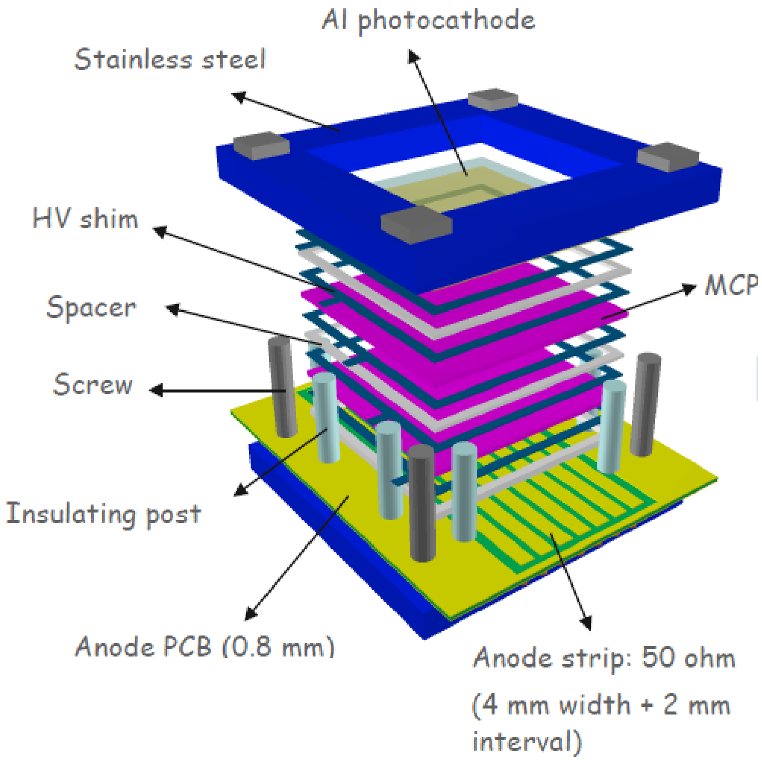




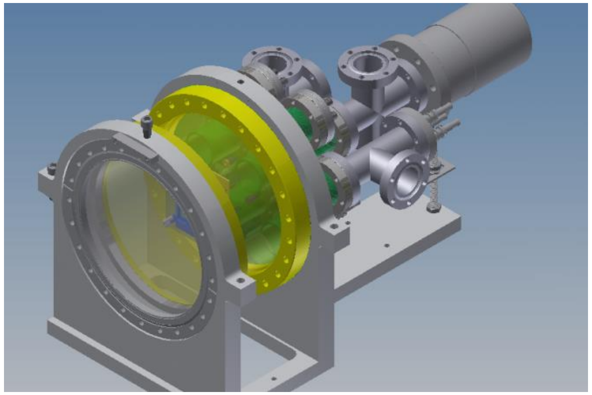
Argonne

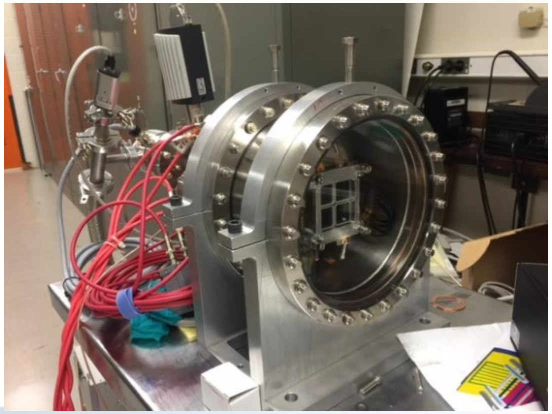
- **Pore size is an important parameter to obtain ultimate time resolution**
- **Estimated by subtracting the laser jitter, the Transit Time Spread (TTS) is close to 20 ps (need to be confirmed by a faster laser)**

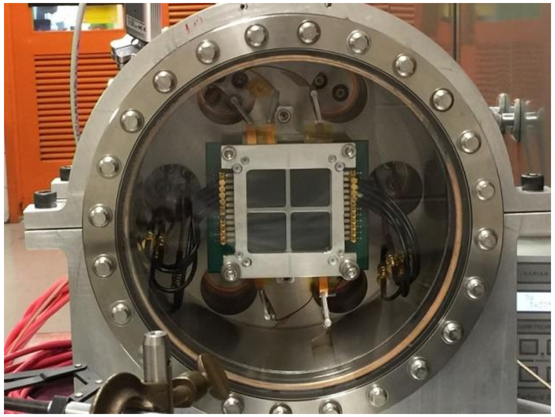
Detector optimization



- **Test chamber**
  - The internal MCP/spacer stack can be assembled in arbitrary configuration
  - Allow to optimize the detector design without building a lot of sealed tubes
  - To do: improvement on timing and B-field performance
  - Allow to study other ideas: neutron detection, x-ray detection…

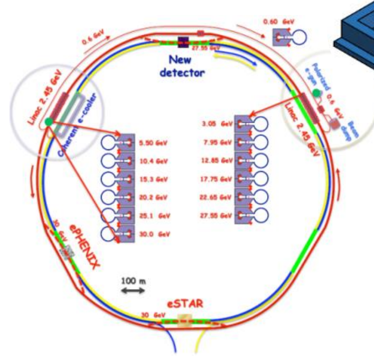


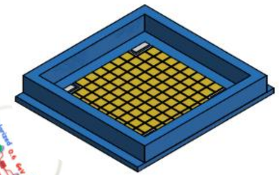




Future development path

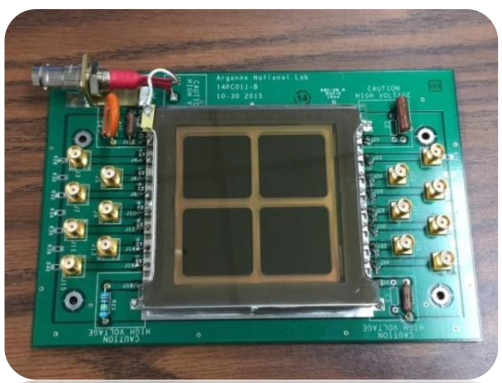
- High QE over 20%
- Geometry optimization
- Pad readout design
- …





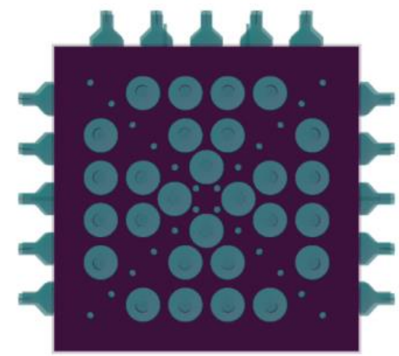
Others: SoLID, BELLE II…

EIC



Today

Feedback from users helps to improve the design



ANNIE

annie

TARDIS

EIC: **E**lectron **I**on **C**ollider
ANNIE: The **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment
TARDIS: **T**iming and **A**dvanced **R**econstruction **D**one **I**n **S**cintillator

Summary

- The Argonne MCP photodetector program has been successful, benefiting from advances in different disciplines.
  - **Completed >13 working Photodetectors; achieved 100% sealing yield**
  - **Gain > 10^7;**
  - **Time resolution including the laser jitter: $\sigma_{I.R.F}$ ~ 35 ps;**
  - **Position resolution along the anode strip: < 1 mm**
  - **Rate capability > 1 MHz/cm^2 for single photoelectrons**

- The Small Tube Processing System is an **ideal R&D platform** for addressing new requirements and studying new ideas (VUV photocathode, cryogenic application, thermal neutron detection…).

- On track of providing photodetectors to the community for evaluation and testing: ANNIE, TARDIS, Proto-DUNE, EIC, BELLE II…

- You are very welcome to discuss with us about your requirements and great ideas.

Acknowledgments

A.Mane, K. Byrum, M. Demarteau, R. Dharmapalan, J. Gregar, E. May, R. Wagner, D. Walters, J. Elam, J. Xie, L. Xia, H. Zhao, Argonne National Laboratory, Lemont, IL, US

M. Chiu, Brookhaven National Laboratory, Upton, NY, US

H. Frisch, A. Elagin, University of Chicago, Chicago, IL, US

M. Minot, Incom Inc., Charlton, MA, US

M. Malek, The University of Sheffield, Sheffield, UK

A. Ronzhin , Fermilab, Batavia, IL, US

M. Sanchez, M. Wetstein, Iowa State University, Ames, IA, US

R. Svoboda, UC Davis, Davis, CA, US

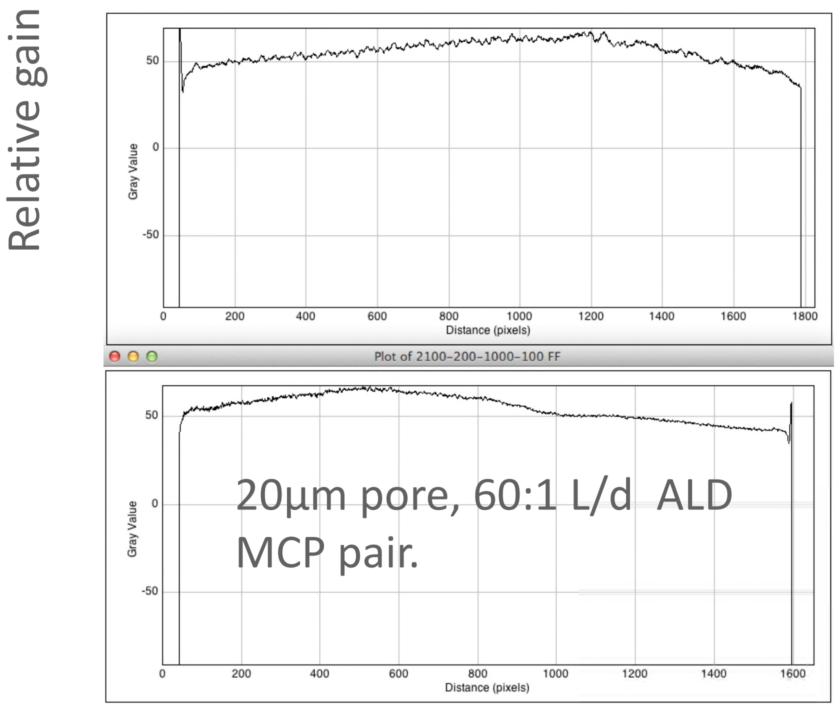
C. Zorn, Jefferson Lab, Newport News, VA, US

Thanks for listening!

Backup

Performance of ALD-MCP

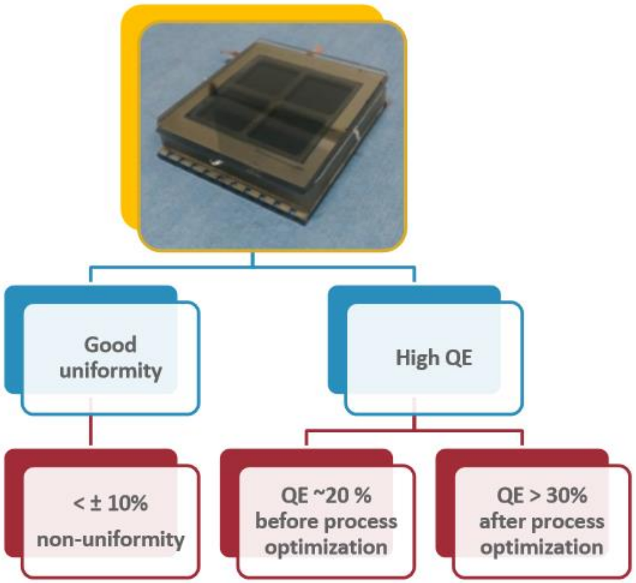
- 20 µm pore, 60:1 L/d ALD MCP pair.
- Uniformity was measured for a 20cm x 20cm MCP pair with MgO Secondary Emission Layer.
- Average gain ~ 7×10^6
- Map shows <10% MCP gain variation



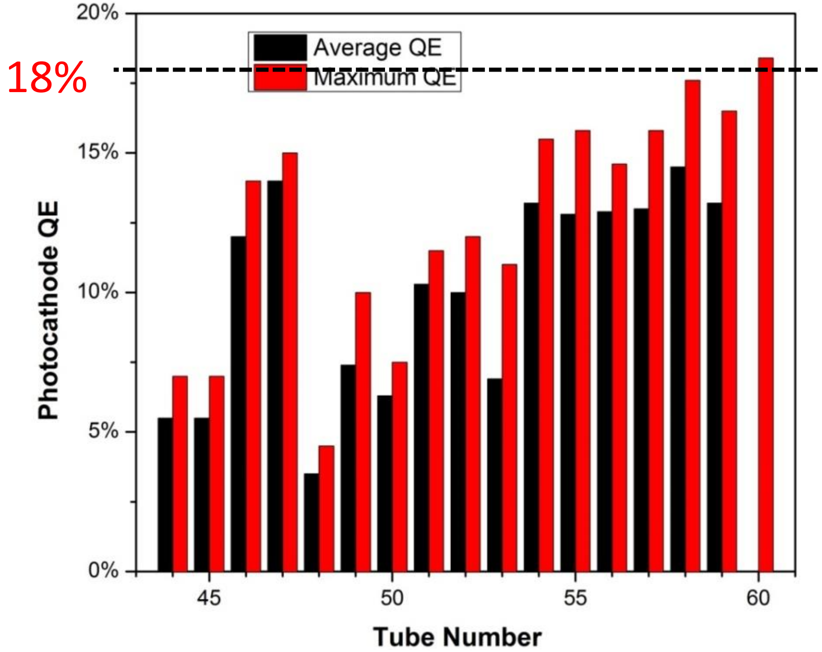
Average gain image "map"

QE improvement

Goals:



goal 20%



- **Understanding the issues:**
  - ✓ Anti-reflection layer is missing; plasma generator under repair)
  - ✓ Halogen lamp heater not uniform; need a rotation stage
  - ✓ MCP outgas and getter material activation may contaminate the chamber
  - ✓ Cooling time is too long
  - ✓ Enhance light collection by means of internal reflective surface coating

Datasheet

- We use the pulsed blue laser (405 nm) facility to test and characterize the 6 cm tubes.

- Standard tests are performed for each tube
  - QE spectrum response
  - QE uniformity scan
  - Overall uniformity scan
  - Gain VS HV
  - Time resolution VS HV
  - Position resolution

- Each tube will be sent out to the users with a detailed datasheet

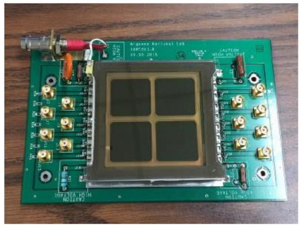
Argonne NATIONAL LABORATORY

High Energy Physics Division

6 cm x 6cm Photodetector Data Sheet
Photodetector Tube No.: # 44
Mfg Date: Jun. 10, 2015

DESCRIPTION

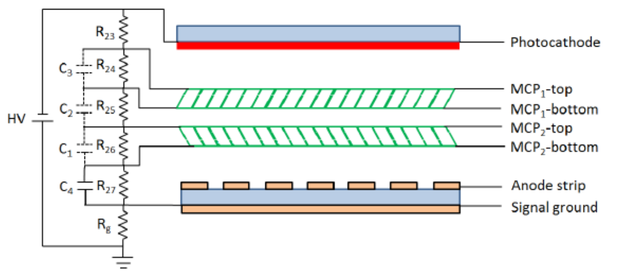
Window Material	Borosilicate glass
Window Mask	NiCr
Photocathode Type	Bialkali
Multiplier Structure	MCP chevron (2), 20 µm pore, 60:1 L:D ratio
Stack Structure	Independently Biased Design (IBD)
Anode Structure	0.47 cm sliver strip line, 0.23 cm interval
Active Area	6 cm x 6 cm
Package open-area-ratio	65 %



CHARACTERISTICS

Parameter		Min.	Typ.	Max.	Unit
Overall High Voltage		-	-2900	3100	V
Voltage Divider Current		-	230	-	µA
Photocathode	Spectral Response	300	-	600	nm
	Quantum Efficiency	-	6%@350nm	7.0%@380nm	-
Gain at -2900 V		-	1×10^7	-	-
Time Response	Rise Time	-	0.62	1.4	ns
	Fall Time	-	1.85	2.2	ns
	I.R.F. (σ)[1] / I.R.F. (FWHM)	-	35 / 90	-	ps
	T.T.S. (σ)[2] / T.T.S. (FWHM)	-	18 / 57	-	ps
Spatial Response	Differential Time resolution (σ)	-	13 (Single-PE)	-	ps
	Position Resolution (σ)	0.7 (Multi-PE)	-	1.3 (Single-PE)	mm

CONNECTION SCHEMATIC



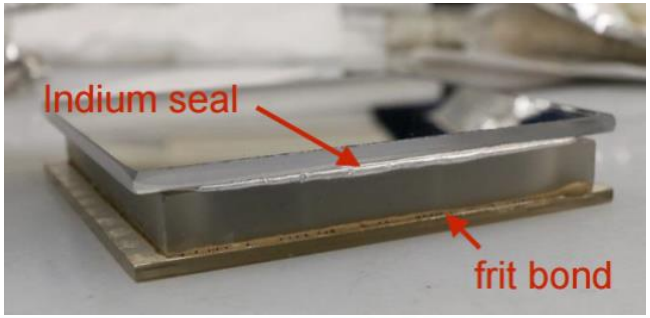
R_{23} = 2 MΩ
R_{24} = 5 MΩ
R_{25} = 1.5 MΩ
R_{26} = 5 MΩ
R_{27} = 2 MΩ
R_9 = 100 Ω
R_{MCP1} = 24 MΩ
R_{MCP2} = 25 MΩ
C_4 = 1 µF
Dash line: not installed yet

Cryogenic detector

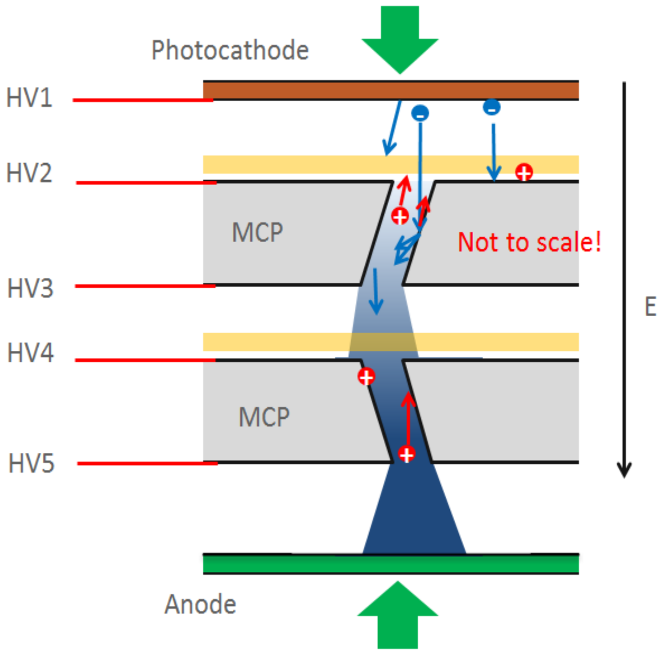
- **Structural integrity**, mainly the indium seal and frit bond, cause some worry
  - Work already done: sealed and devices 'dunked' into liquid nitrogen
  - → MCP photodetector with glass package DO survive in cryogenic environment

- **Detector window:** quartz or MgF_2 with VUV photocathode (CsI) for direct VUV detection

- **Cryogenic MCP**
  - Current MCP resistive coating will lose its conductivity at cryogenic temperature
  - → Working on tuning the ALD recipe to bring down resistivity
  - → Also need to verify the ALD secondary emission layer properties at cryogenic temperature



Detector optimization



Aluminum Ion protection layer significantly suppresses the ion feedback, but lose 50% of electrons.

Done

HV optimization

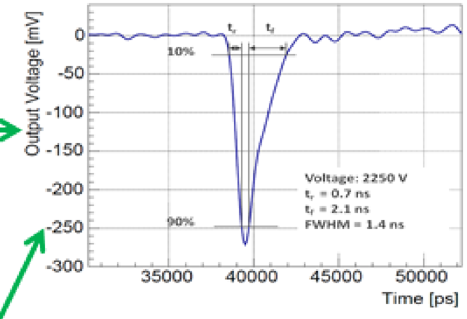
Next step

Geometrical modification

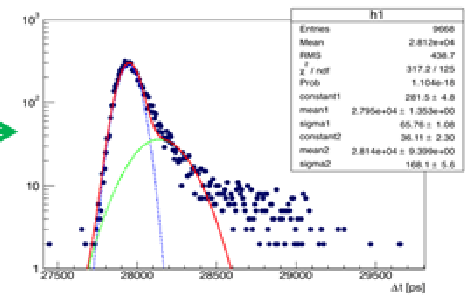
Near future

Ion protection layer

Improve time resolution



Suppress Back scattering



Suppress ion feedback