ARRADIANCE

UNIVERSITY OF TEXAS ARLINGTON

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

panda FAIR

Physics with and Physics of Atomic Layer Deposited Nanofilms

A. Brandt, D. Gorelikov, A. Lehmann,
N. Sullivan*

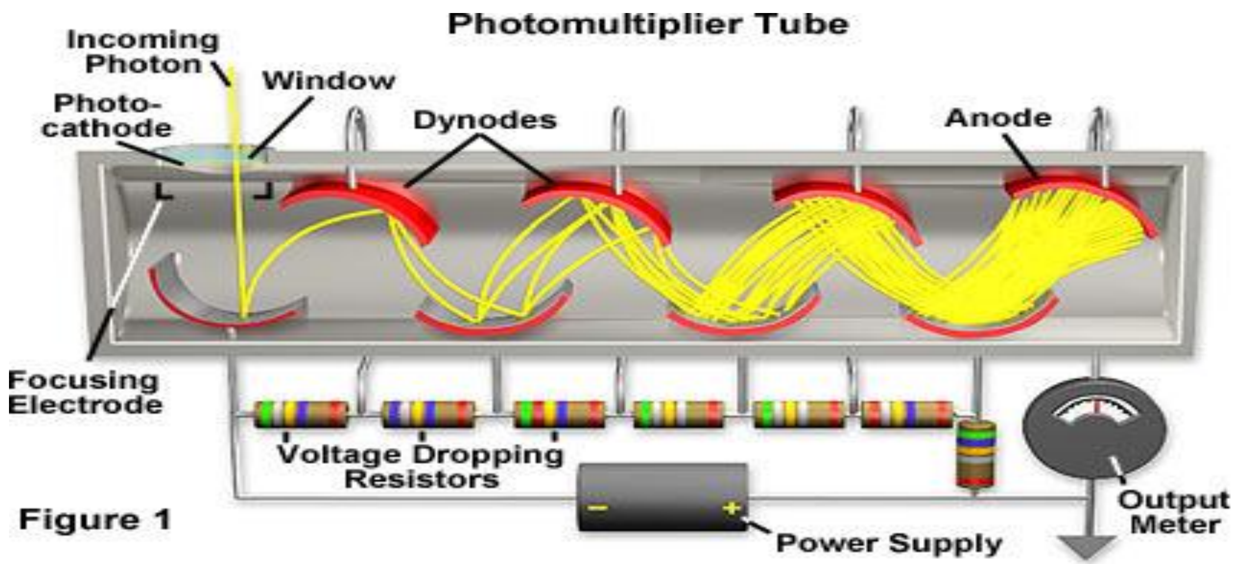
*** Arradiance LLC.**
142 North Road, Suite F-150
Sudbury, MA 01776
(800) 659-2970 Tel and Fax
www.arradiance.com

Outline -

- Background
  - Photomultiplier (PMT) Photo Detectors (c1930)
  - Microchannel Plate Photomultiplier (MCP-PMT)
  - Microchannel Plate (MCP) manufacturing (c1960)
- The MCP-PMT in HEP
- Why does the MCP-PMT fail?
- Failure mitigation strategies
- Atomic Layer Deposited (c1970) nanofilm technology for MCPs
- The role of emissive layer charging
- Analytical results
- MCP-PMT lifetime test results
- What does the ALD nanofilm do?
- Conclusions and future work

PMT principles (1937)

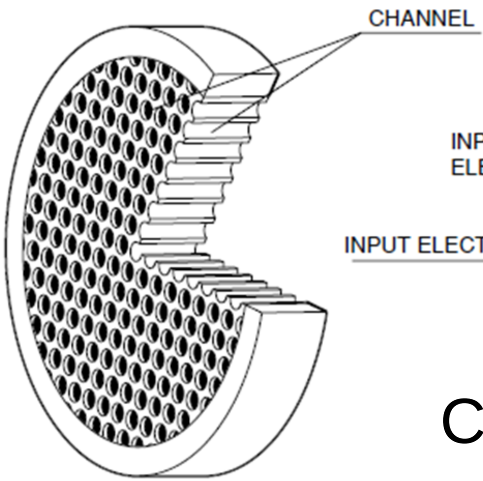
- Capable of single photon detection.
- Quantum Efficiency (QE) of 20-50%
- Low noise amplification of electrons
- Robust, long life
- **BUT:**
  - **Insufficient spatial & temporal resolution (>1ns)**

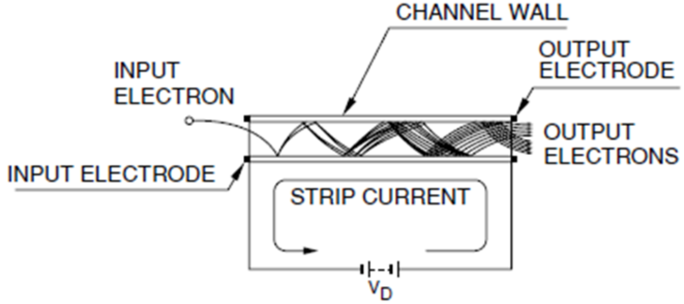


Discrete Dynode

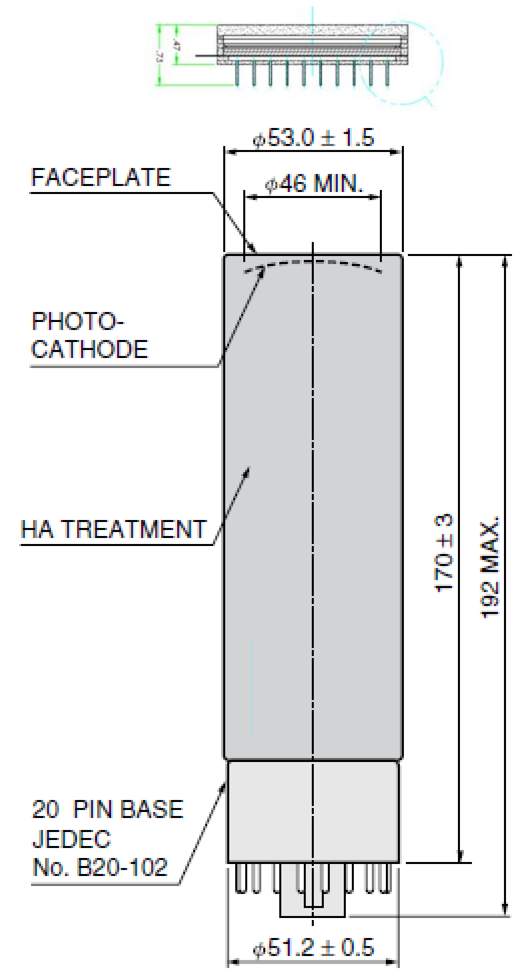
https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf
http://www.olympusmicro.com/primer/digitalimaging/concepts/photomultipliers.html

MCP (1960s) and MCP-PMT (2000)





Continuous Dynode



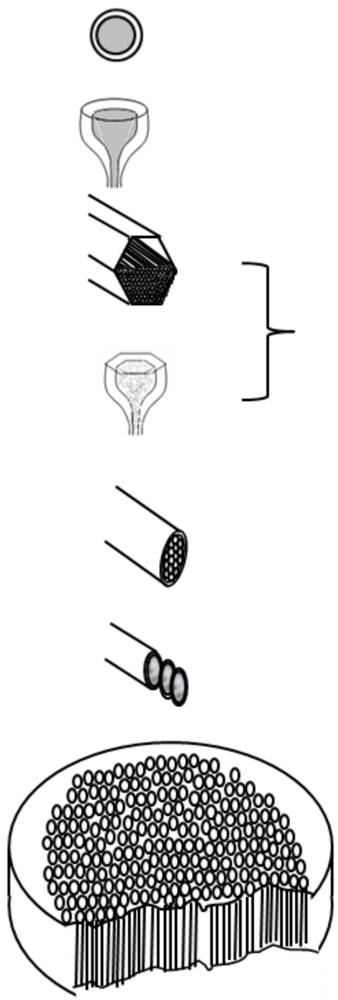
- MCP-PMT vs. PMT
  - Temporal resolution 10-100x BETTER
  - Spatial resolution 10-100x BETTER
- **BUT:**
  - **Poor Lifetime: Photocathode degraded by impact with Positive ions**

https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf
https://www.photonis.com/uploads/literature/library/SquarePMT-Development-SPIE2000.pdf

MCP Manufacture: Composition determines manufacturing AND structure AND function

Material	Wt % 8161
PbO	50.5
SiO_2	38
K_2O	5.44
Rb_2O	3.7
BaO	2.05
Na_2O	0.34
Cs_2O	0.29
Al_2O_3	0.24
Bi_2O_3	0.04
Fe_2O_3	0.02
B_2O_3	0
MgO	0
CaO	0
As_2O_3	0
Sb_2O_3	0

Substrate Fabrication



1" Etch-able Core Lead Glass Rod

Draw Tower

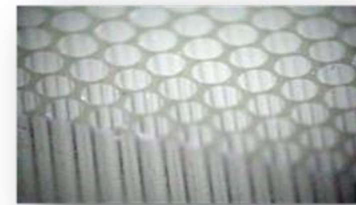
Stacked Draw Tower Repeated

Boule 5-100mm Dia

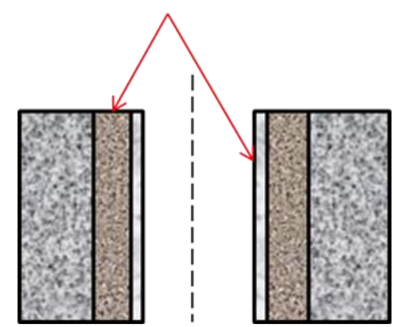
Diced 0.2-0.3 mm thick

Etched Producing >5M 2-10 um pores

Substrate Functionalize



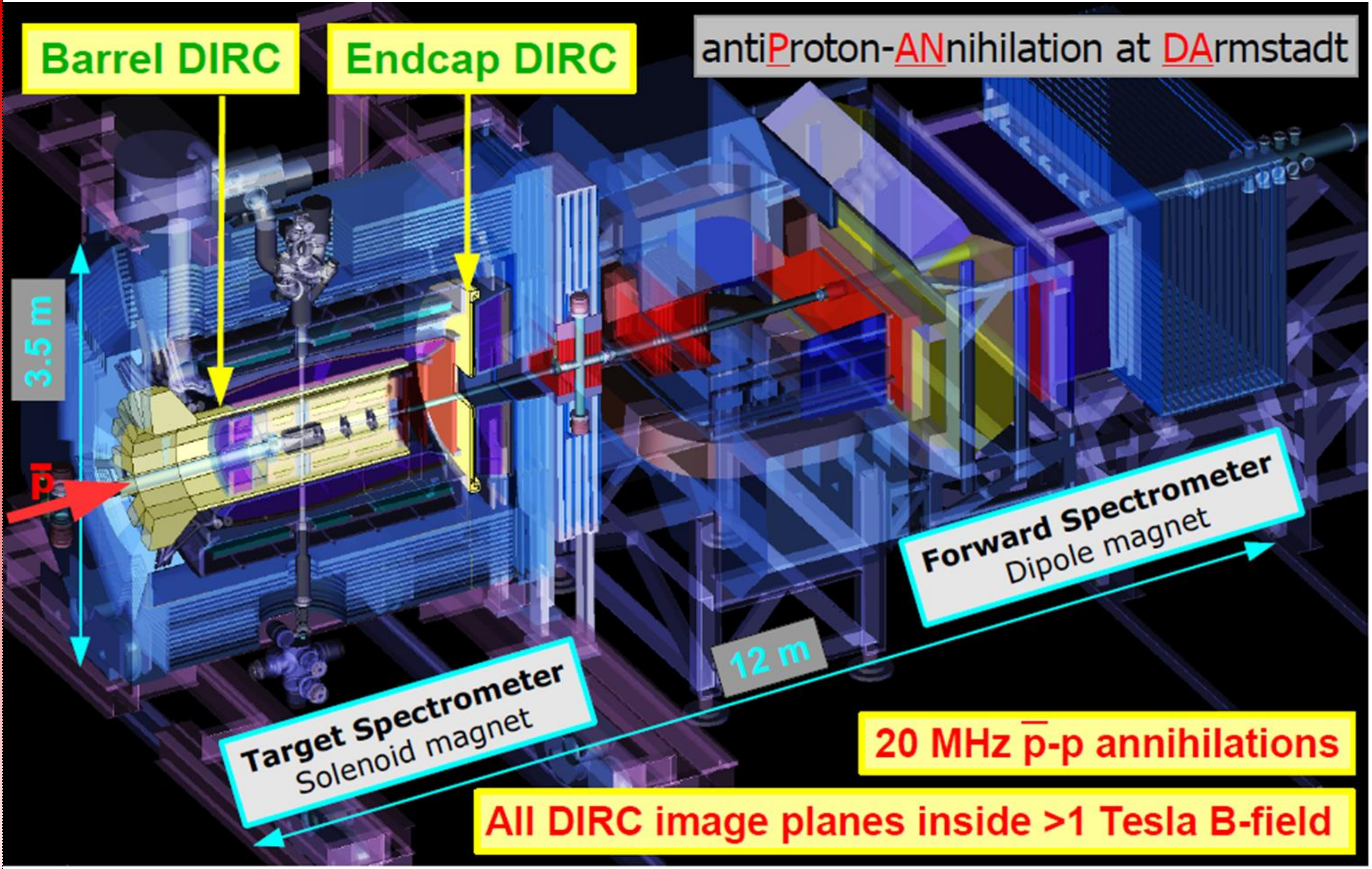
H_2 Firing
conduction & emission layer produced simultaneously



Applications in Particle Physics

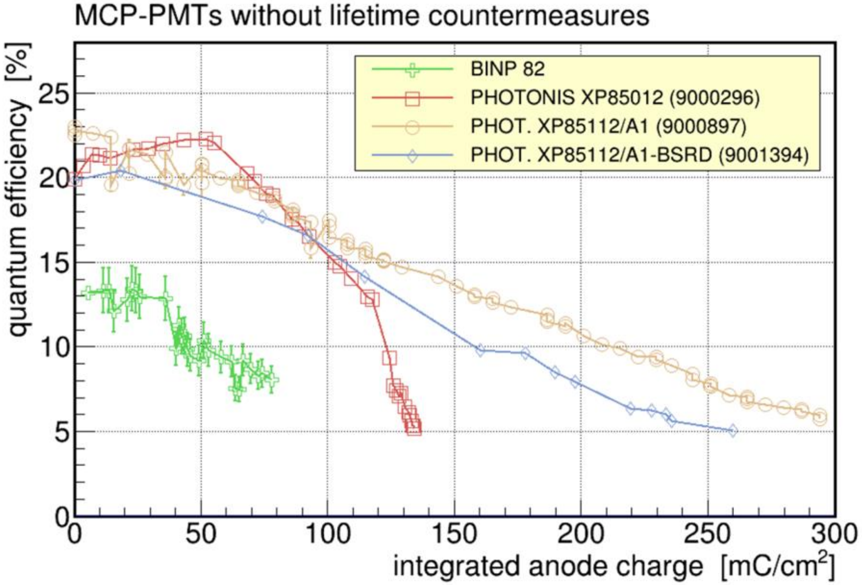
- Latest generation particle physics experiments require
  - Efficient single photon detection in high magnetic fields (>1 Tesla)
  - Capability of dealing with very high photon rates (MHz/cm^2)
  - Picosecond time resolution and ~mm position resolution
  - Compact form factor
- MCP-PMT ideal sensor for use in particle identification
  - Cherenkov detectors (RICH, DIRC)
  - Time-of-Flight detectors (TOF)
- Examples of physics goals addressed
  - Understanding dynamics of heavy quarks (b-physics in Belle & LHCb)
  - Search for new states of matter (hydrid & glueball resonances in PANDA)
  - Spin structure of the nucleon (addressed with planned electron-ion-collider)

$\overline{\text{P}}$ANDA Detector at FAIR



MCP-PMTs for PANDA DIRCs: Lifetime is the issue

- **MCP-PMTs for PANDA DIRCs**
  - MCP-PMTs are the only suitable sensors for PANDA
  - Compact and available as multi-anode devices
  - Single photon detection in B-fields of 1 – 2 Tesla
  - Time resolution <50 ps
  - Low dark count rates
- Barrel DIRC Lifetime
  - Photon rate: ~200 kHz/cm^2
  - **10yr anode: 5 C/cm^2**
  - Pixel size: ~ 6 x 6 mm^2
- Endcap DIRC Lifetime
  - Photon rate: ~1 MHz/cm^2
  - **10yr anode: >5 C/cm^2**
  - **Pixel size: ~ 0.5 x 16 mm^2**



Lifetime status 2011 – < 200mC/cm^2
Barrel DIRC: 3-6 months
Endcap DIRC: < 3 months

Why do MCP-PMTs fail?

- Positive ions desorb during operation[1]
  - Alkali from bulk migrates to the pore surface[1,2]
  - Residual gases (H, H_2O, CO, CO_2) from MCP fabrication process
- **MCP** permanent gain degradation due to desorption of alkalis
- **Photocathode** - Cs:O layer sensitive to damage
  - QE drops below useful value (~50% of original)

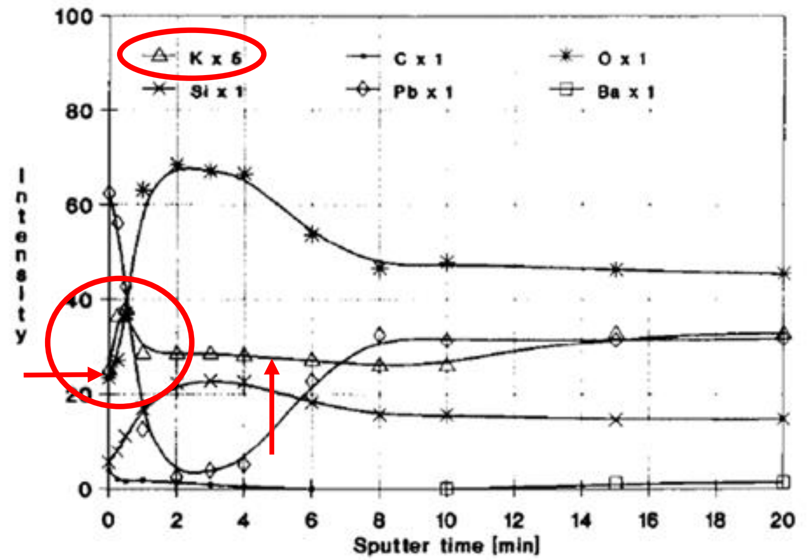


Fig. 2. AES sputter depth profiles of the important elements in the active surface of the channel before ageing of the MCP. The measured peak-to-peak intensity is normalized to the corresponding pure elemental target value which is set at 100.

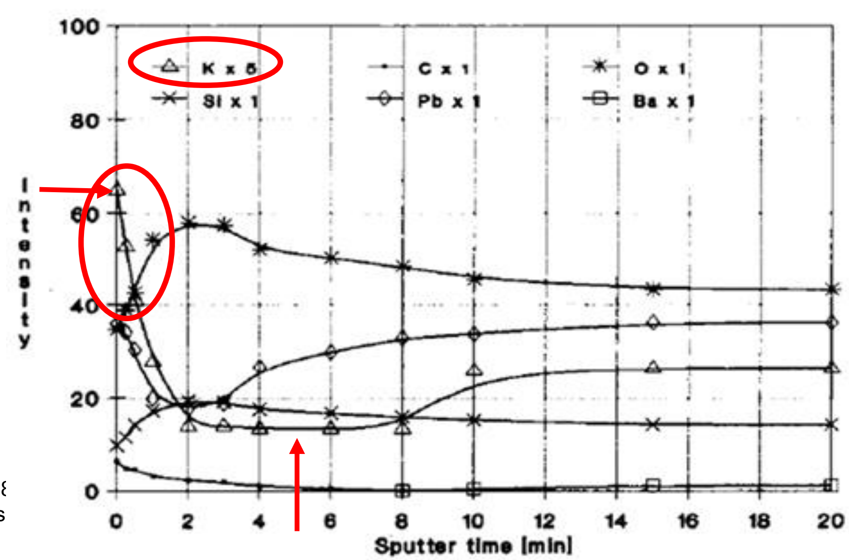


Fig. 3. As fig. 2, but now after ageing of the MCP.

1. A.M. THEN & C.G. PANTANO, "FORMATION AND BEHAVIOR OF SURFACE LAYERS ON ELECTRON EMISSION GLASSES," Journal of Non-Crystalline Solids 120 (1990) 178-18
2. B. PraEek and M. Kern, AES studies of active intrachannel surface in microchannel plates Applied Surface Science 70/71(1993) 169-171

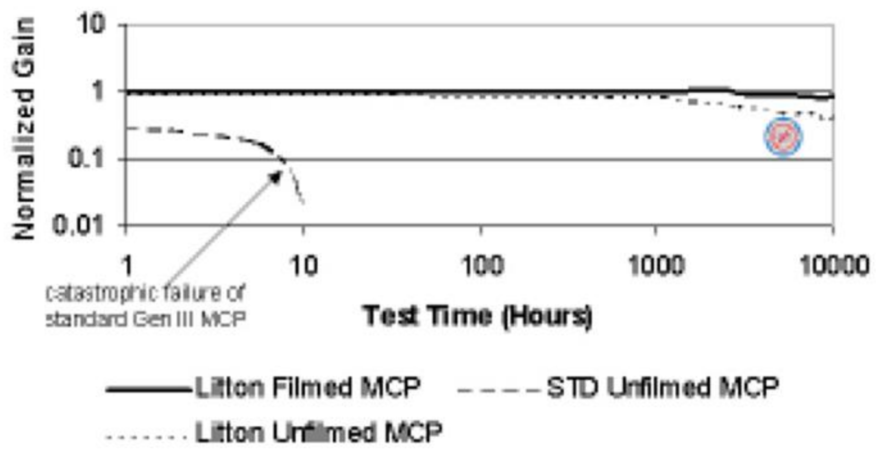
What has been done?

- Bake 350ºC for > 8hrs
- Electron scrub of MCP
  - < 1C/cm² stabilize gain
- Gen III Nightvision
  - Al_2O_3 ion barrier
  - "Long Life" Glass
  - Electronic gating
  - Bulk conductive glass
- High Energy Physics
  - Al_2O_3 ion barrier
  - Package re-design
  - PC robustness
  - Grid field filter
- Can ALD help? Yes!
  - HAR – 60:1
  - High surface areas (m^2)

	Wt %	
Material	8161	L3 NG
PbO	50.5	26.6
SiO_2	38	37
K_2O	5.44	0
Rb_2O	3.7	0.85
BaO	2.05	19.7
Na_2O	0.34	0
Cs_2O	0.29	4.12
Al_2O_3	0.24	1.35
Bi_2O_3	0.04	2.48
Fe_2O_3	0.02	0
B_2O_3	0	2.8
MgO	0	0.85
CaO	0	2.25
As_2O_3	0	0.65
Sb_2O_3	0	0.28

US Pat 6271511

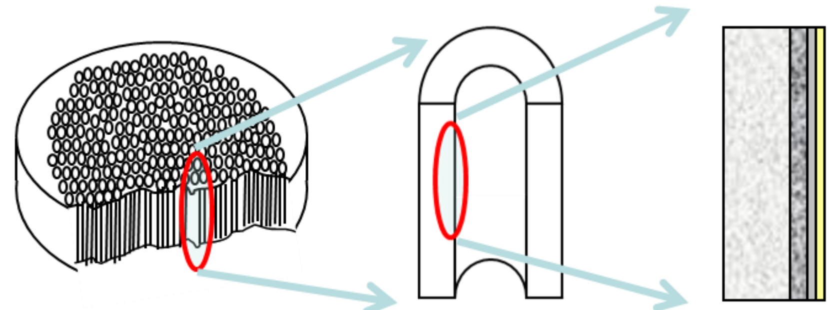
Reliability Test Data (Gain)

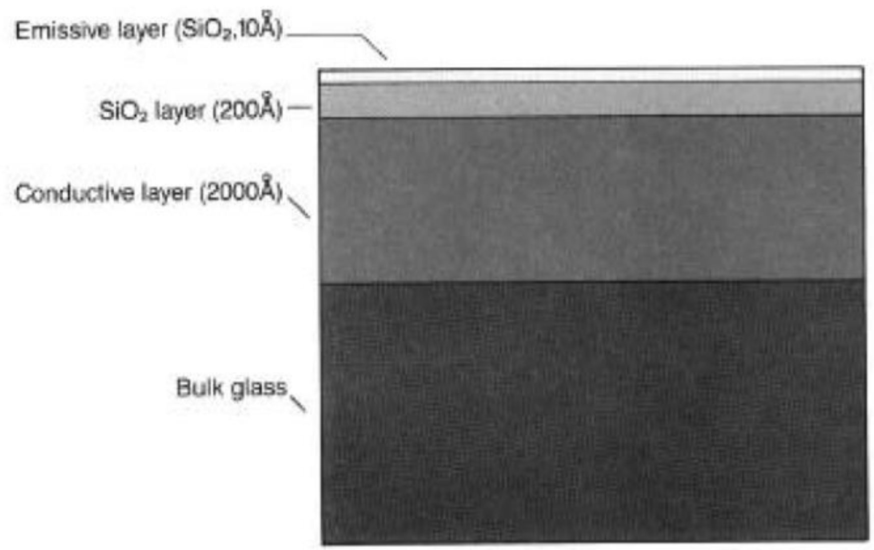


J. P. Estrera etal, "Long Lifetime Generation IV Image Intensifiers with Unfilmed Microchannel Plate," Proceedings of SPIE Vol. 4128 (2000)

Experimental: MCP ALD nanofilm technology on 4 substrates (different compositions and vendors)

- Al_2O_3 Emissive on fired glass MCP substrates (Samples A-D)
  - TMA, H_2O, 150C, 38Å
  - Gain performance correlates with fired MCP performance
- Charging behavior - insulator
  - Charging - permanent gain reduction in vacuum – recovers only with forced dissipation (e.g. exposure to atmosphere)
  - Charging observed as a function of film thickness
  - Charging observed as a function of glass composition

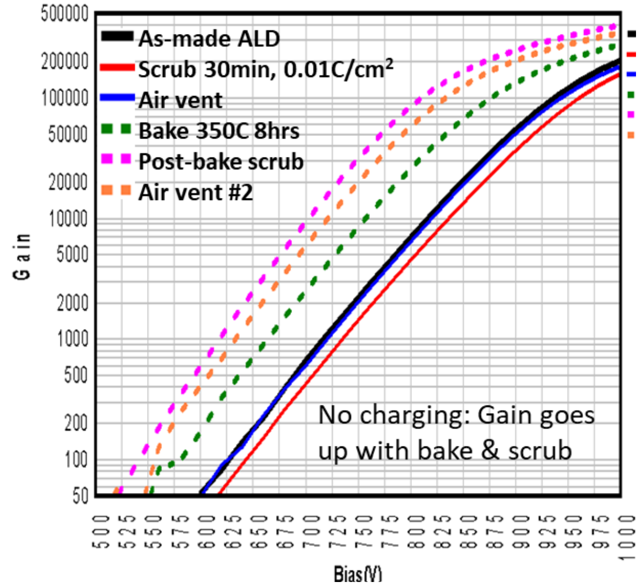




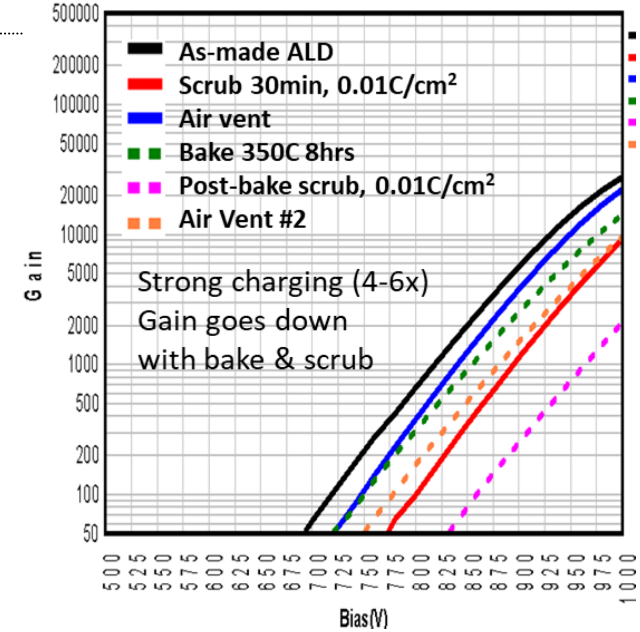
Channeltron electron multiplier handbook (Burle)

Experimental: Test sample charging results

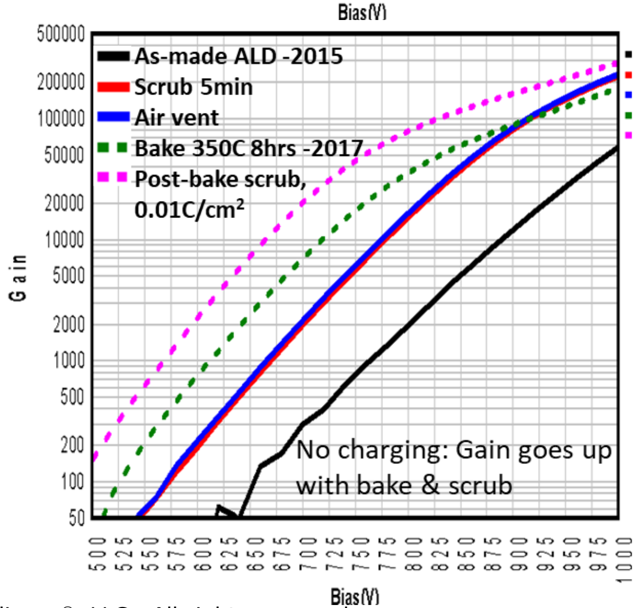
A



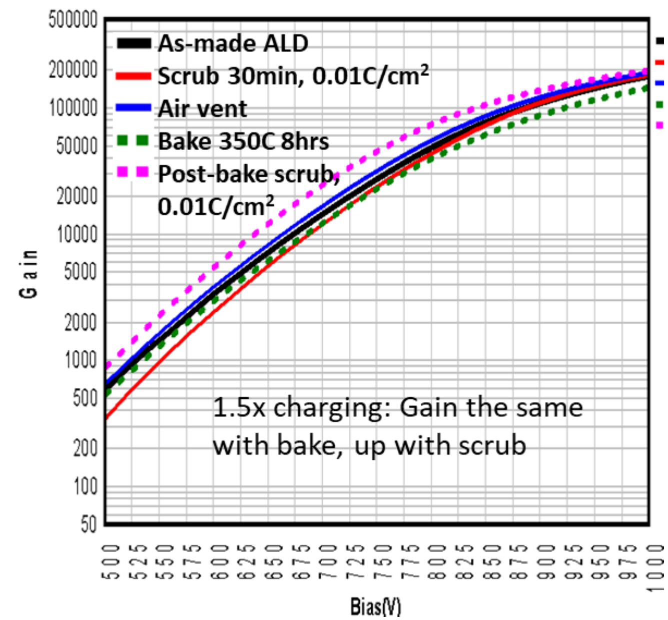
B



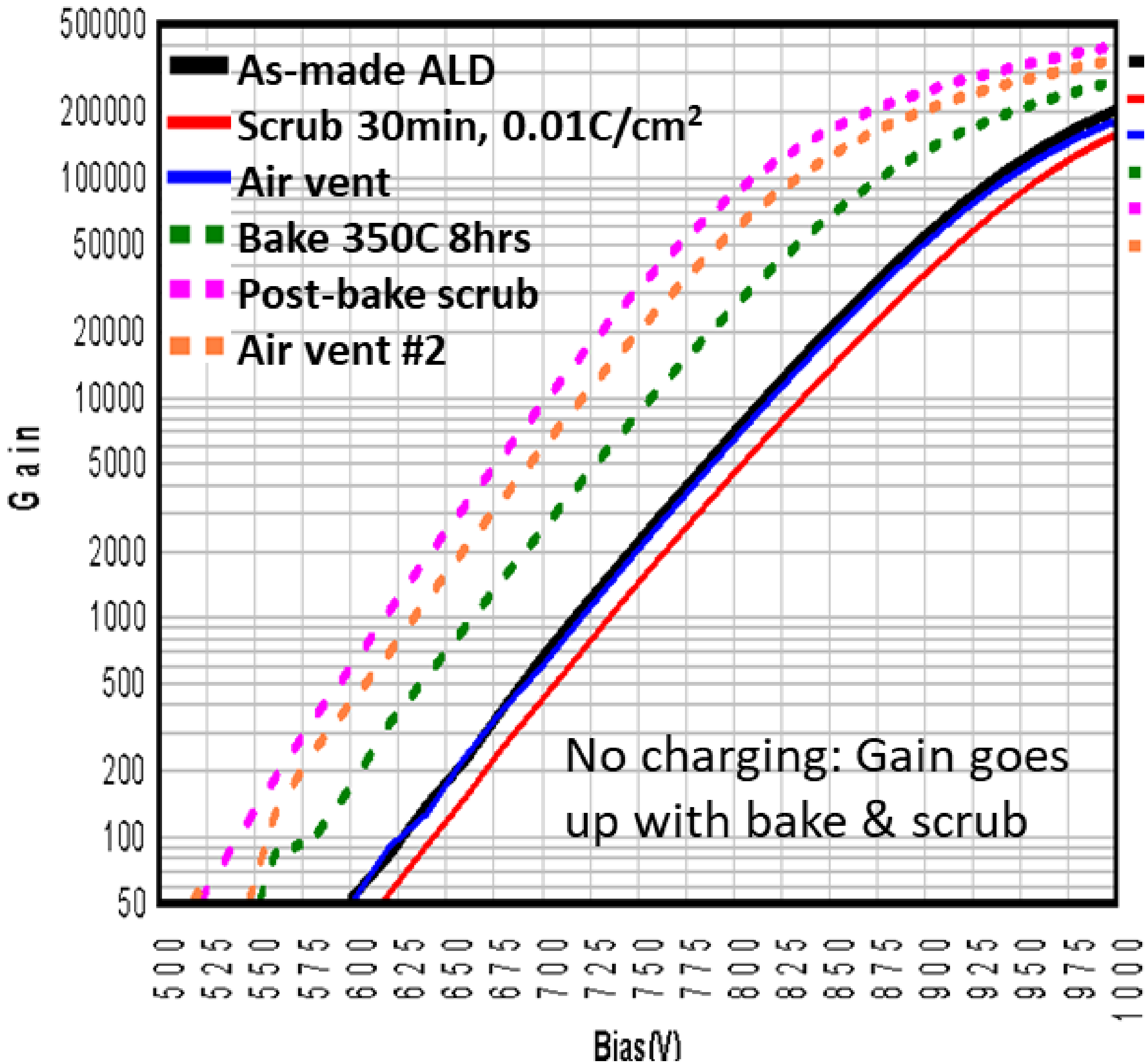
C



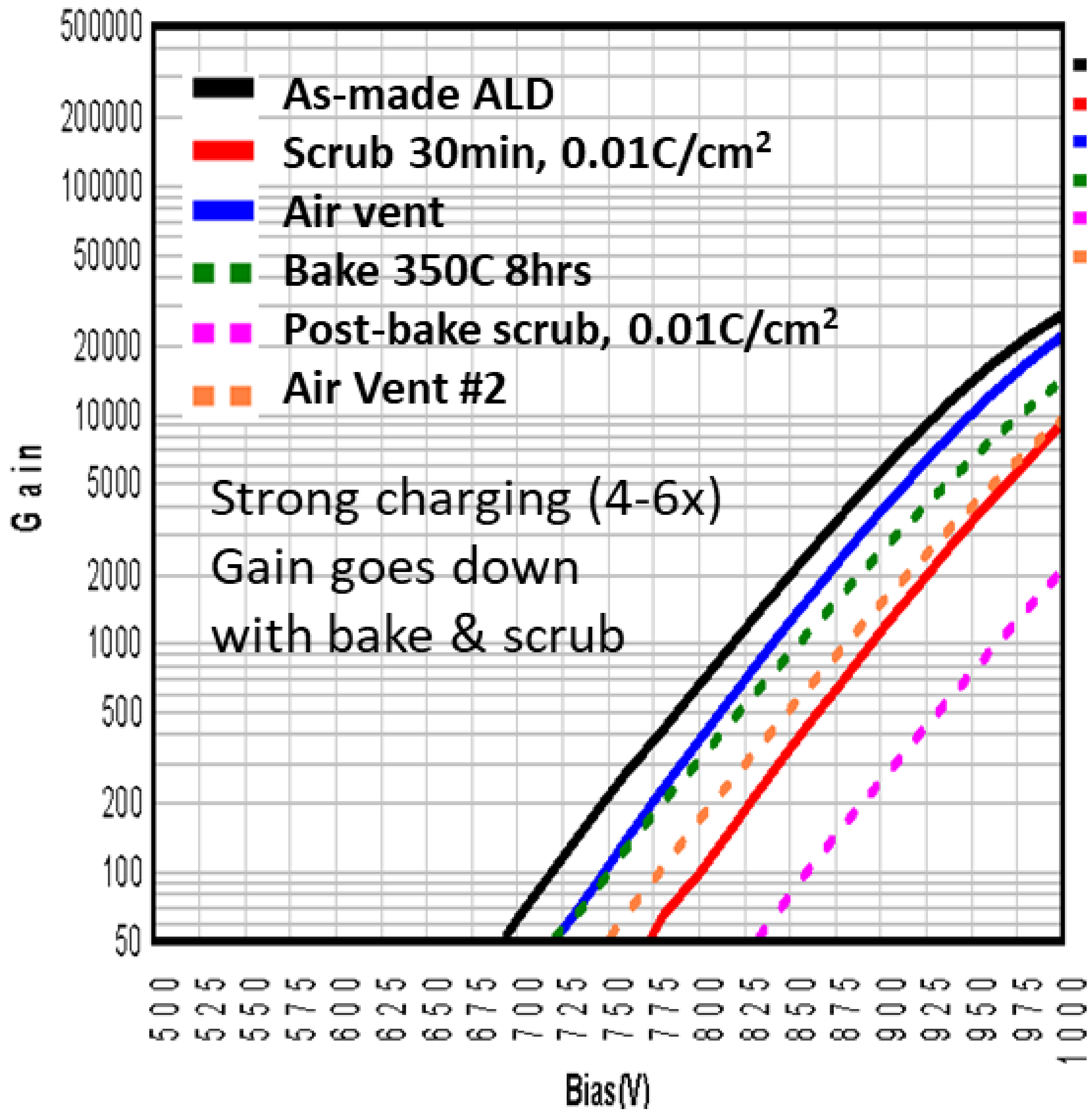
D



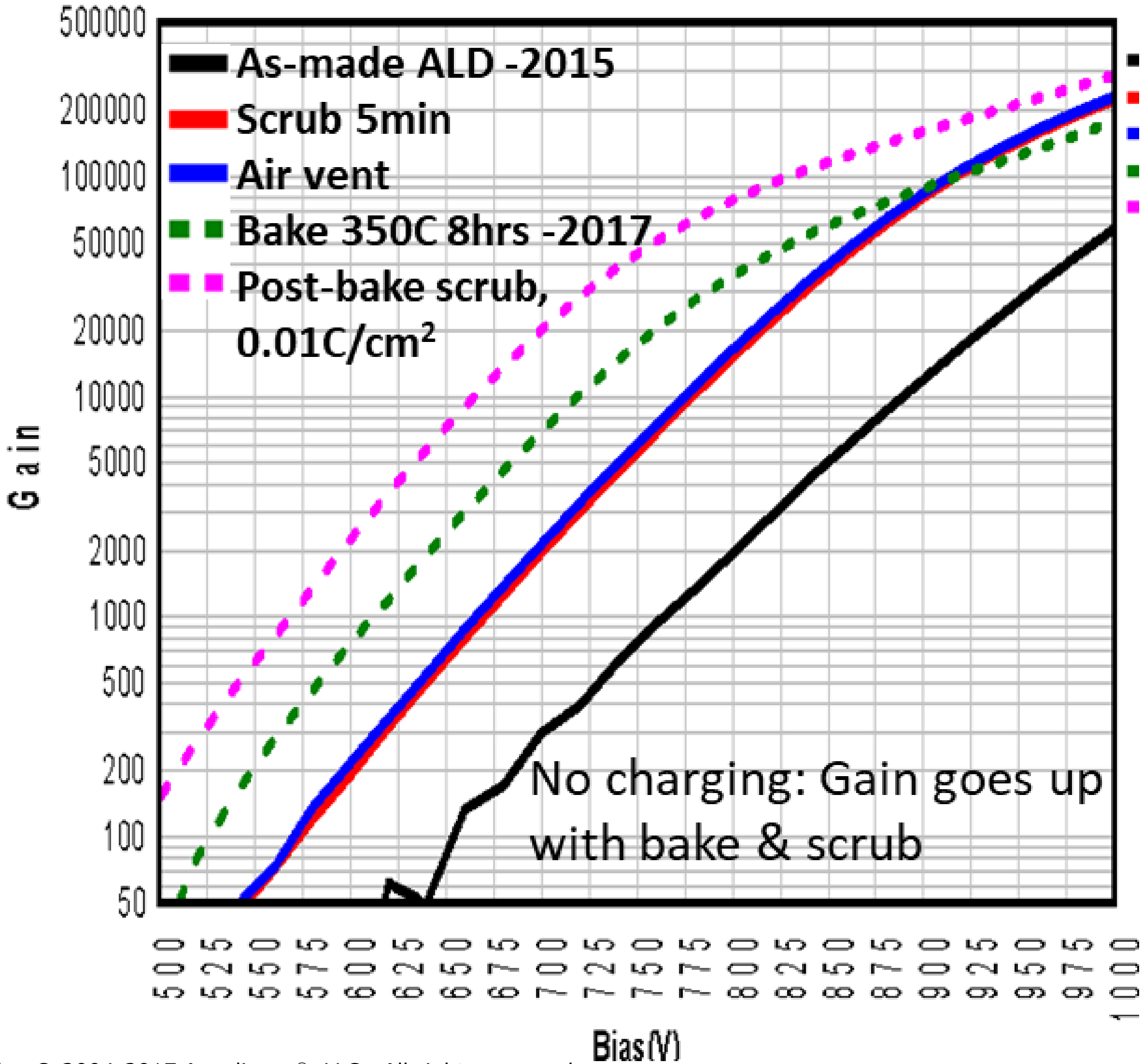
Experimental: Test Sample Charging Results – Sample A



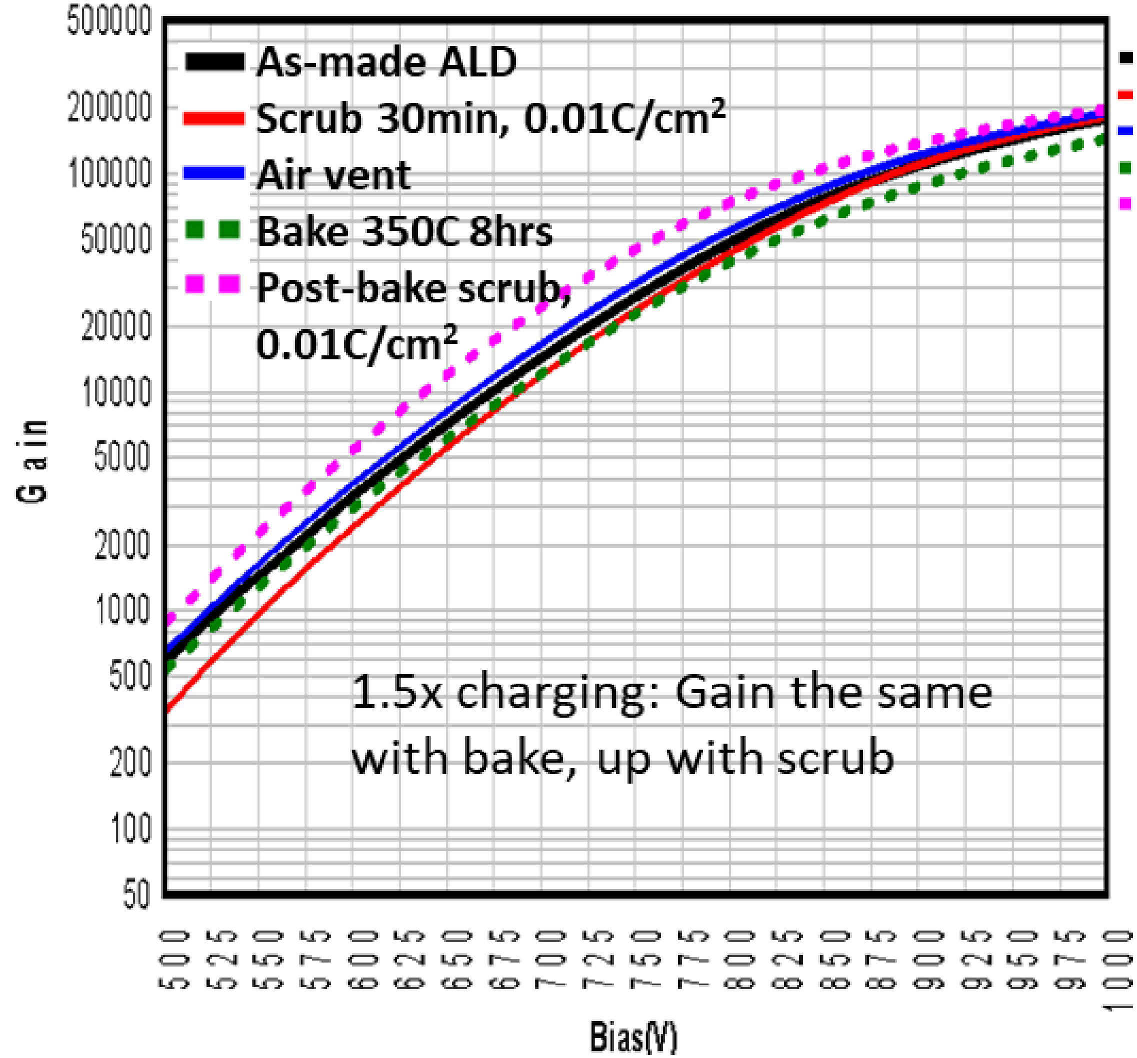
Experimental: Test Sample Charging Results – Sample B



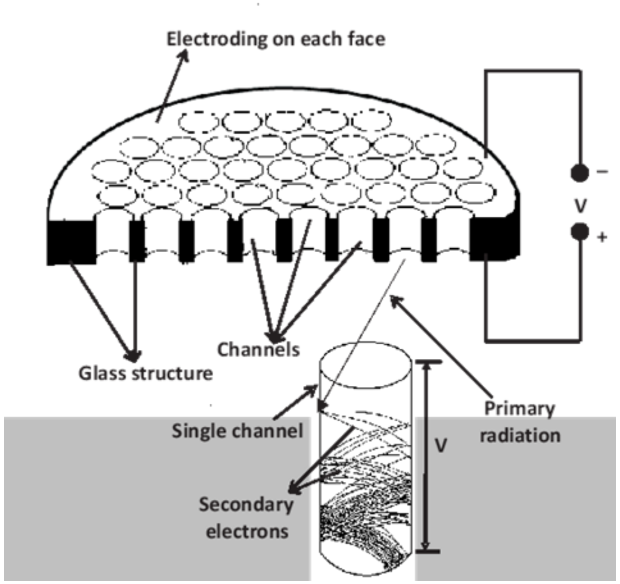
Experimental: Test Sample Charging Results – Sample C



Experimental: Test Sample Charging Results – Sample D



Experimental: FESAM Analytical methodology



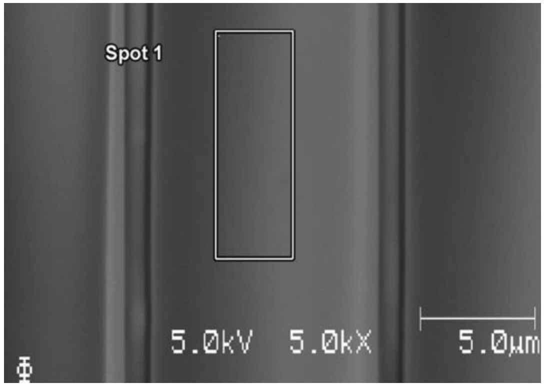
Elemental composition of MCP glass[a].

Z	Element	Weight percent
82	Pb	47.8
8	O	25.8
14	Si	18.2
19	K	4.2
37	Rb	1.8
56	Ba	1.3
33	As	0.4
55	Cs	0.2
11	Na	0.1

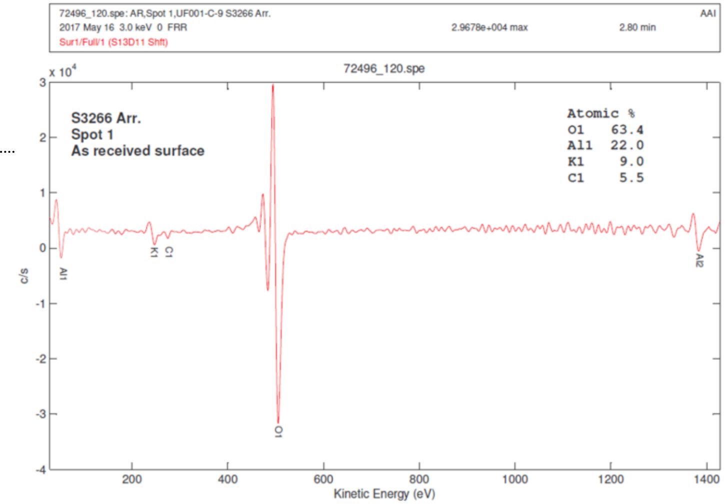
[a] Density – 4.0 g./cm^3.

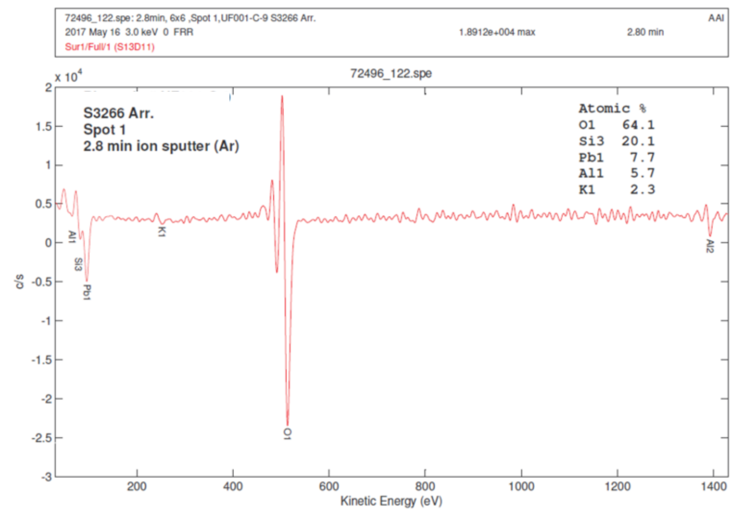
- Available literature analyses performed on processed, flat, Pb-glass test coupons
- This study on ALD nanofilmed and tested MCP device pore.
- MCP critical dimensions
  - Pore diameter (d) = 10μm
  - Pore pitch = 12μm
  - Pore Aspect Ratio = 60:1
  - NiCr Electrode 2d into pore
- PHI 670 Auger Nanoprobe
  - Multipak and CASAXPS software
  - Conditions - 3kV, 10nA tilt ~30°
- Ar+ ion gun sputter at 4kV and a raster area of 6x6mm.

Experimental: FESAM Results



- Data from Sample **A**
  - Survey area within MCP pore indicated by rectangular box
  - Profile Data 12s (~24 Å/min)
  - Information depth few nanometers at 3kV

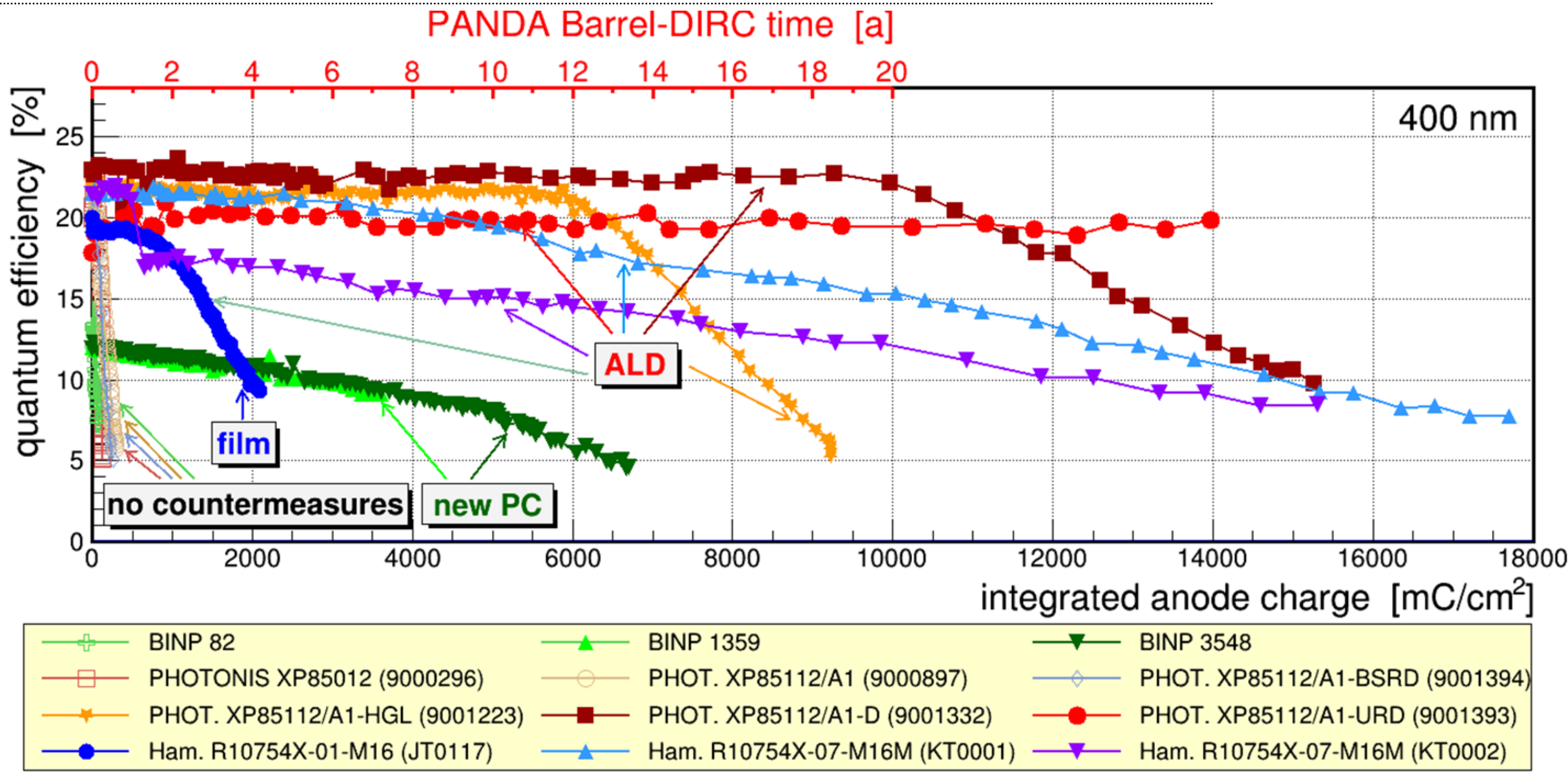




Summary Table: % Potassium vs Charging

SN	A	B	C	D
Gain multiplier	10	0.2	5	1.5
Potassium %	4.5	0	4.1	0*

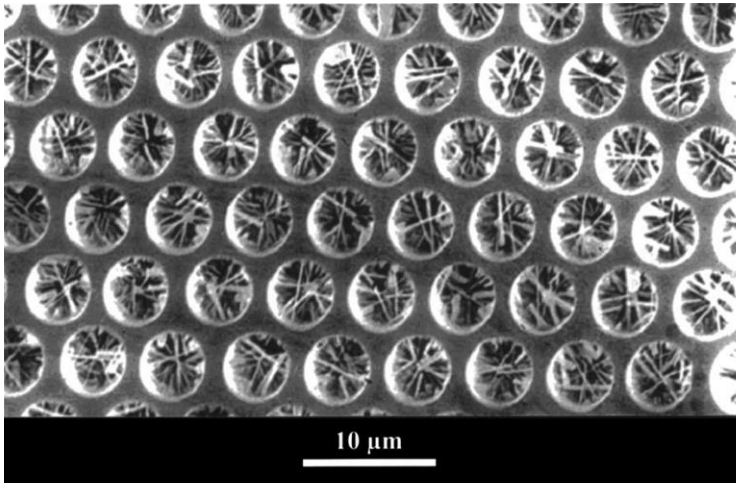
Experimental: Lifetime of MCP-PMTs (06/2017)



- No countermeasures: unusable after <200 mC/cm2
- Modest lifetime improvements with film and new PC
- "Quantum leap" in lifetime (x70) with ALD:
  - **best performing device at 14 C/cm^2** – No QE Loss!

Discussion: 38Å of Al_2O_3 = No photocathode degradation! SPECIAL K

- MCP-PMT test results
  - Sample **D** formulation >10C/cm^2
  - Sample **C** up to 20C/cm^2 in other testing[1]
- Literature findings:
  - Monolayer of K on pore surface[2]
  - ALD of KCl in MCP devices[4]
  - ALD of potassium aluminate[3]
- Characterization & Test results
  - Substrate (**B**) cannot be optimized by Al_2O_3 layer properties alone
  - Al_2O_3 Conductivity improved with presence of K
  - Final gain is correlated to initial fired substrate gain

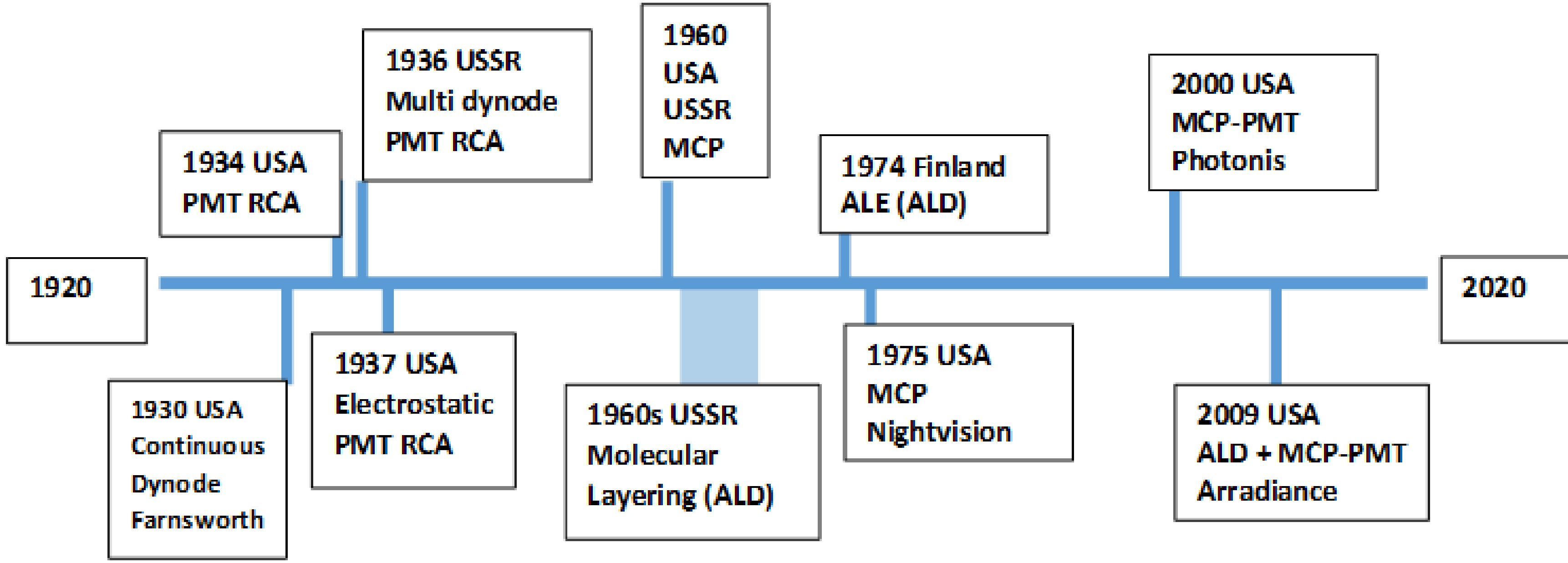


1 https://indico.cern.ch/event/393078/contributions/2195231/attachments/1332045/2002282/RICH2016_matsuoka.pdf
2Then, A.M., Pantano, C.G., “Formation and behavior of surface layers on electron emission glasses”, J. of Non-Cryst. Solids Vol. 120(1-3), 178-187(1990)
3 E. Østreng et al, “Atomic layer deposition of sodium and potassium oxides: evaluation of precursors and deposition of thin films,” Dalton Trans., 2014, 43
4 Zhang et al, “**Potassium chloride nanowire formation inside a microchannel glass array.”**. Appl. Phys. Lett. 86, 263110 2005

Summary and Future Work

- Summary
  - FESAM results, in pore, demonstrate viability of method and correlate well with literature from flat test samples
  - Presence of Alkali, specifically K, in Al_2O_3 film correlates with best operational MCP-PMT performance
  - TMA + H_2O reacts with K
    - To lock down K & produce conducting "aluminate"
  - Resistive & Emissive ALD layers best lifetime 14 C/cm^2 (24yrs Barrel DIRC)
    - remove other residual species (H, H_2O, CO, CO_2) due to the eliminating of the firing step and the thicker encapsulation
- Next Steps – Still many Questions…
  - Perform analytical testing "aluminate" composition
    - SEM evidence of additional "reactions" on surface
    - Role of KOH in sustaining the reaction
  - Study aluminate formation through deposition temperature
  - Investigate methods to optimize "long Life" glasses

Acknowledgements – Thank You for Your Attention!



- Jeff DeFazio
  - Photonis Inc.
- Andrey Elagin
  - University of Chicago HEP
- Darlene Reid
  - Analytical Answers