Novel Position-Sensitive Particle Tracking Gas Detector

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P. S. Friedman

Integrated Sensors, LLC, Ottawa Hills, Ohio (419-536-3212)
www.isensors.net

Program Subcontractor Collaborators:

D. S. Levin, C. Ferretti, N. Ristow, Michael Ausilio, Ralf Bejko
University of Michigan, Department of Physics, Ann Arbor, MI

Other Collaborating Institutions:

Tel Aviv Univ., Loma Linda Univ. Medical School, Univ. of California at Santa Cruz

Detector Goals

- ***UltraThin*, ultra-low-mass, inexpensive substrates**
  - proposed: **27 µm Glass** (**6.6 mg/cm^2**) substrates
  - new added goal/task: **8 µm Mica** (**2.2 mg/cm^2**) substrates
- **Design to operate in both *vacuum* & *ambient pressure* environment**
- **Hermetically sealed & intrinsically rad-hard material structure**
  - no gas flow system & robust *internal* / *external* construction
- **Performance**
  - Pixel efficiency: ≈ **100%**
  - Time resolution: ≈ **1 ns**
  - Position resolution: ≤ **0.5 mm**
  - Response range: ≈ **1 Hz/cm^2** to > **10^5 Hz/cm^2**
  - Internal gas pressure operational range: ≈ **20 to 800 Torr**
- **Primary Applications – *Beam Monitoring & Beam Tracking***
  - Research: **Nuclear physics** / high energy physics
  - Medical: **Particle beam therapy** (NIH-National Cancer Institute)

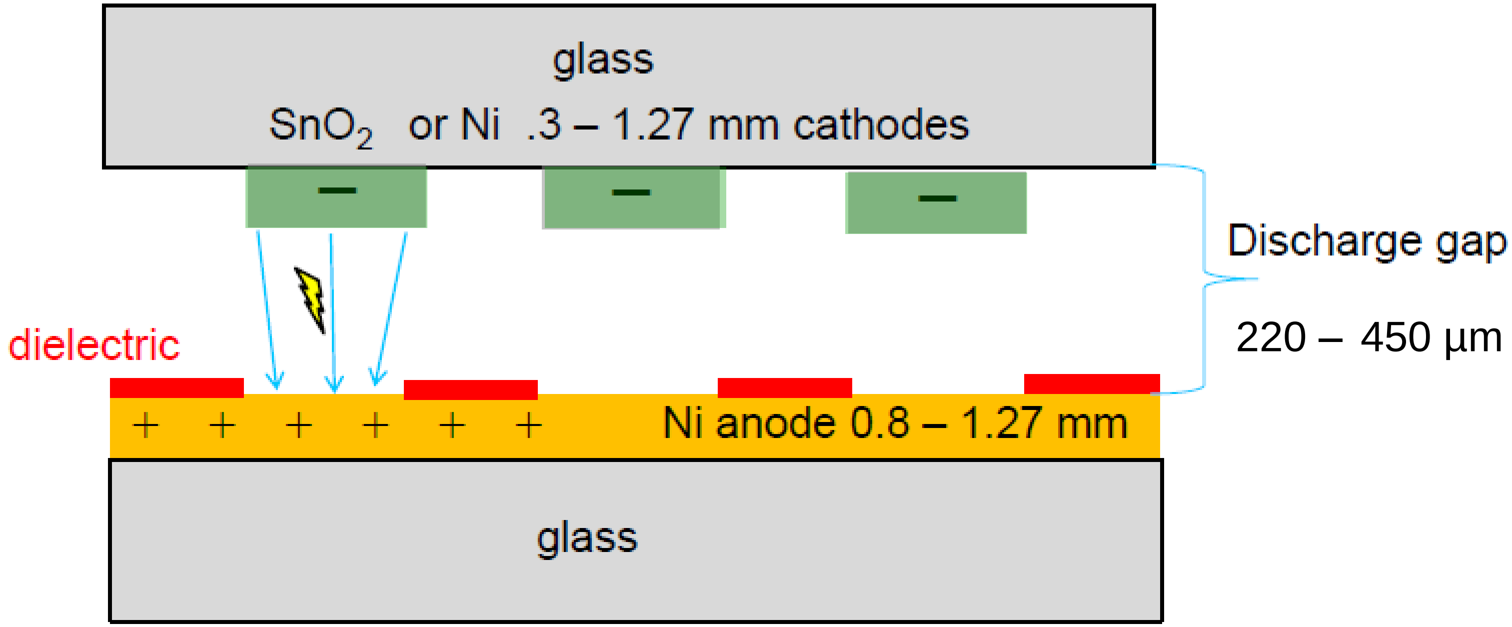
Plasma Panel Sensor (PPS)

“*Open-Cell*” Structure

(DOE-NP & NIH-NCI)

"*Open*-Cell" Commercial Plasma Panel

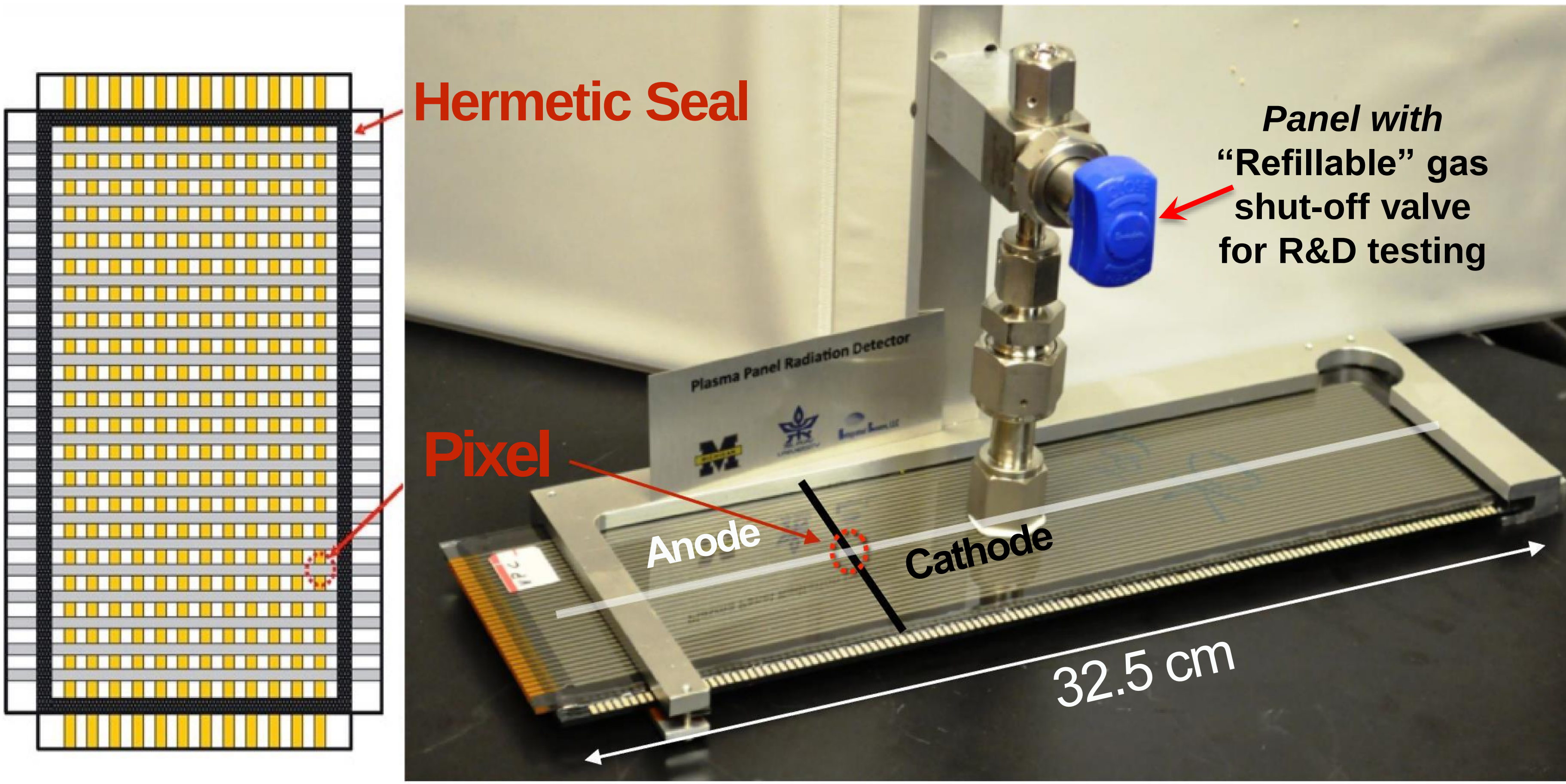
- Columnar Discharge (**CD**) – Pixels at intersections of orthogonal electrode array
- Electrode sizes and pitch vary between different panels



"Open-Cell" PPS Structure

***Modified <u>Commercial</u> PDP:* 2.5 mm Electrode Pitch**

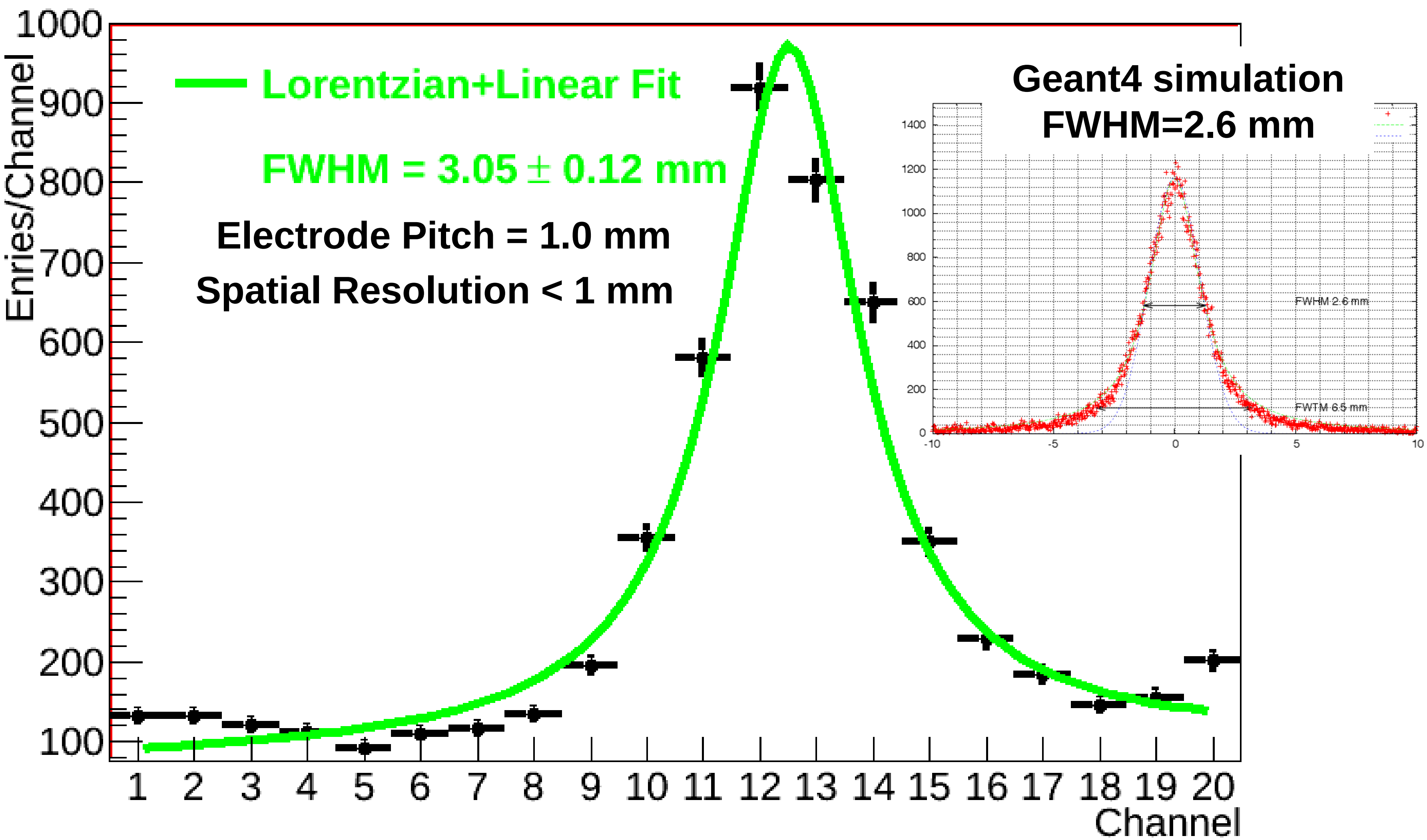
(panels operate for ~1 year after gas-filling)



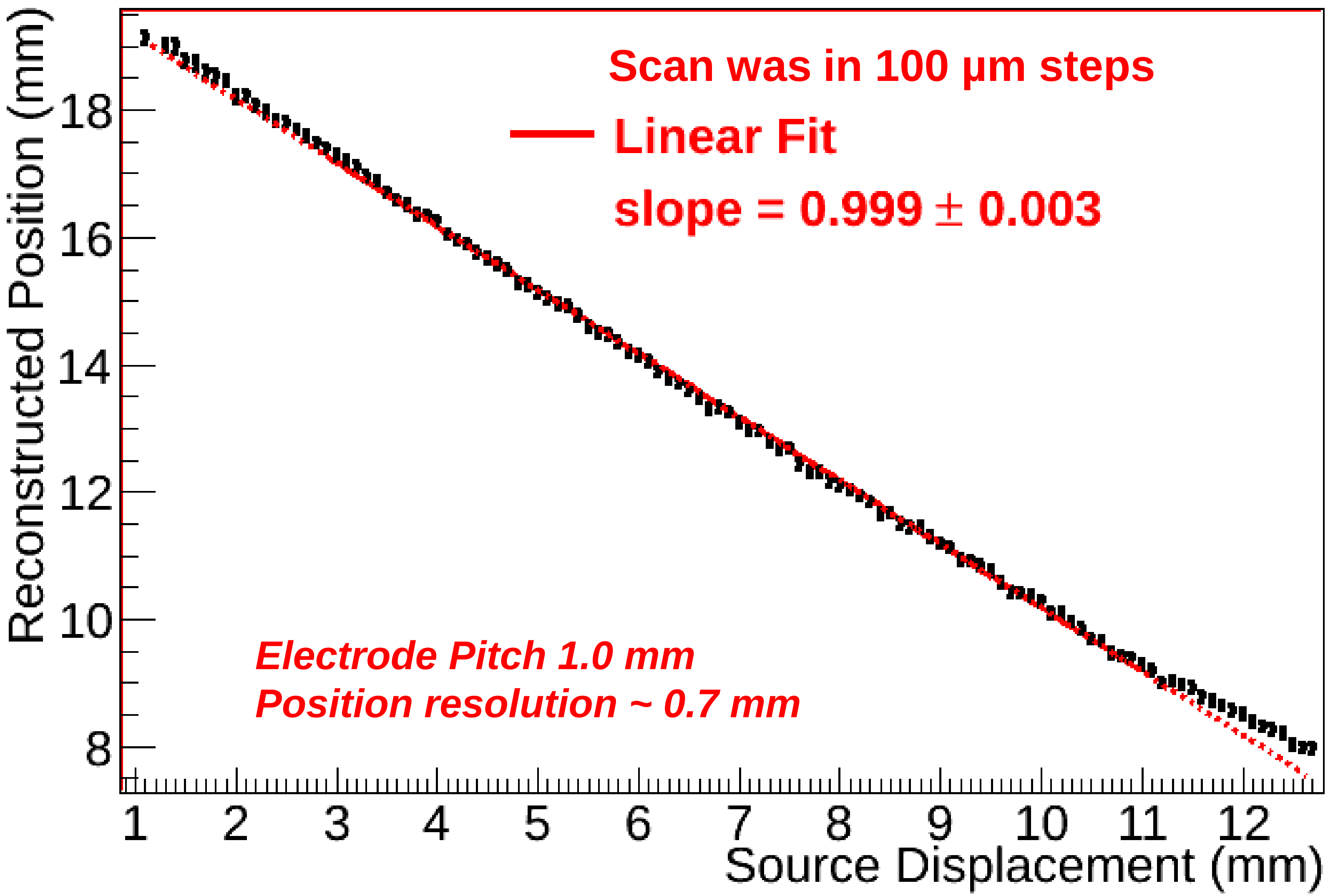
Source Moved in 0.1 mm Increments

(1 mm pitch panel)

Collimated β–Source Measurement (^{106}Ru)

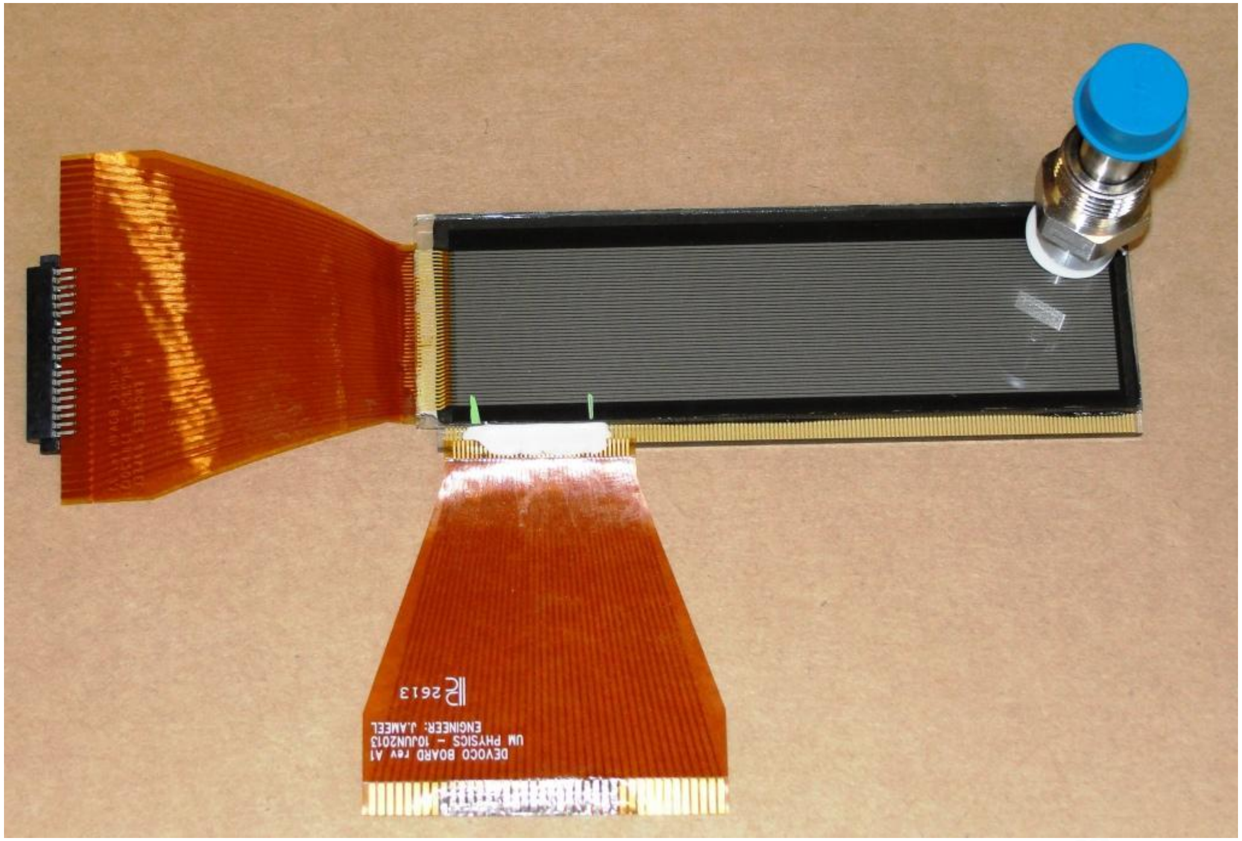


Collimated β–Source Position Scan (^{106}Ru)



"Small Pitch" Open-Cell PPS Structure

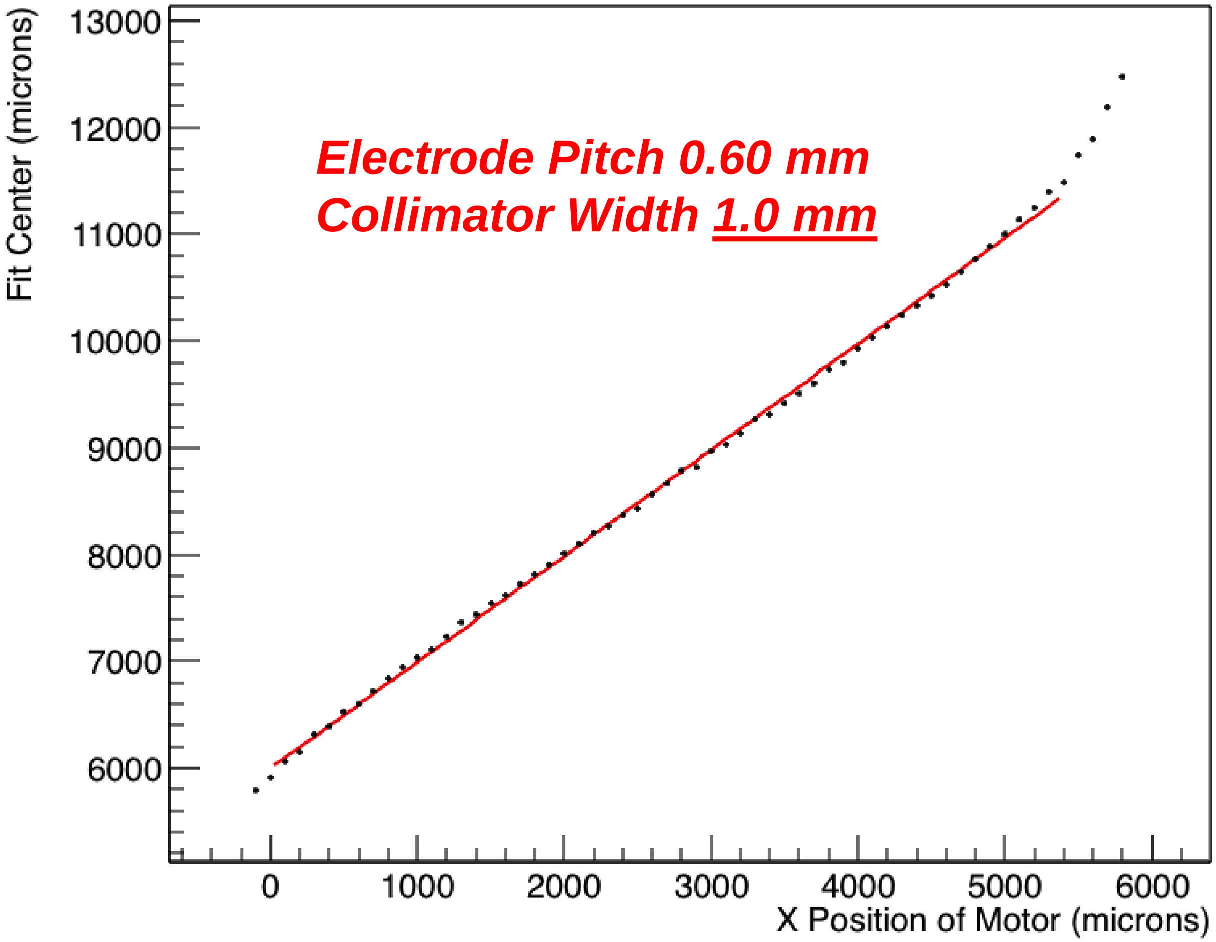
0.60 mm Electrode Pitch



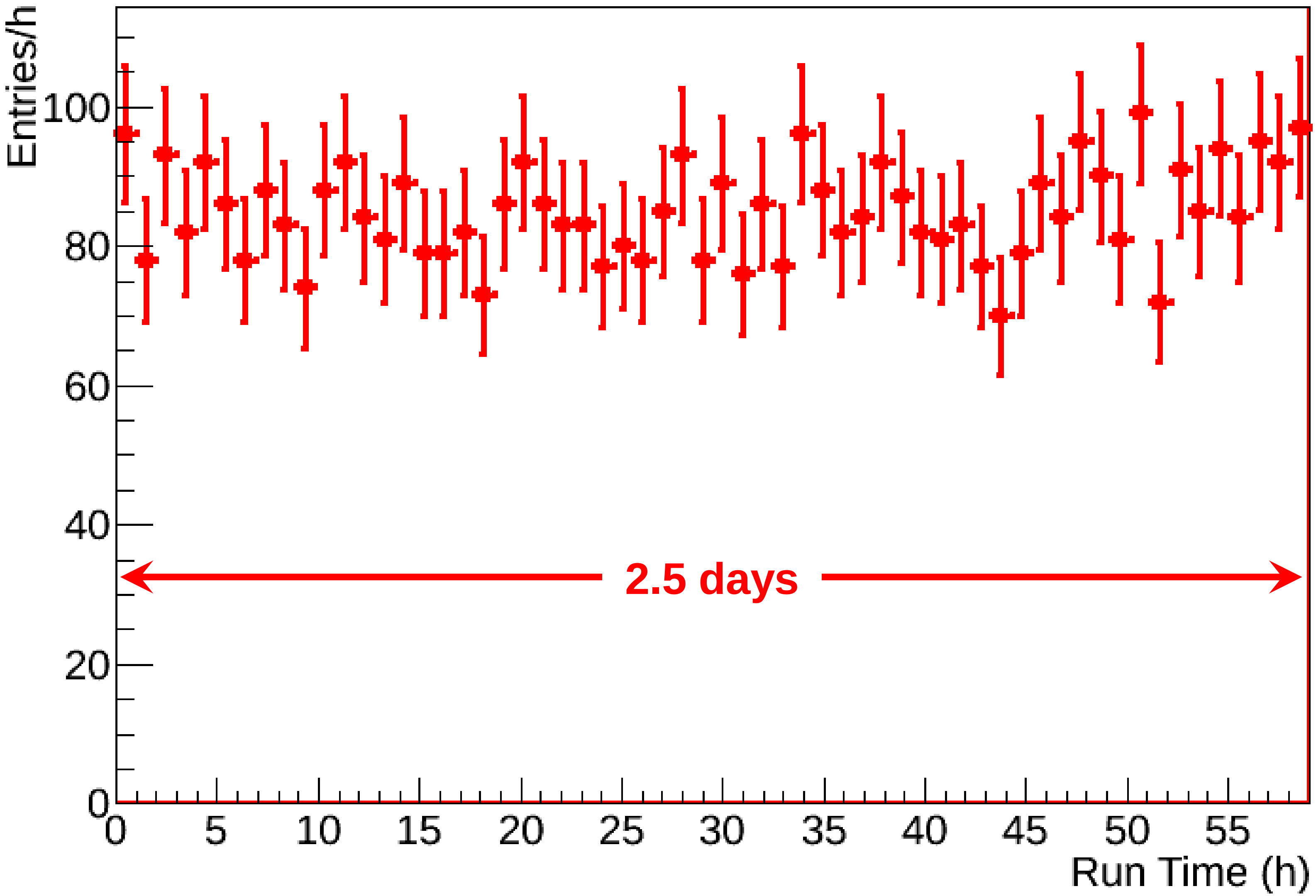
Modified commercial PDP with 1.7 mm thick glass substrates as PPS test panel, 3.9" diagonal, 40 x 160 electrode matrix

Collimated β–Source Position Scan (^{90}Sr)

*Scan of the **0.60 mm electrode pitch** panel in **100 µm steps**. Each point is the Gaussian mean of the hit distribution. The slope is consistent with unity.*



Stability – Response to Cosmic Muons



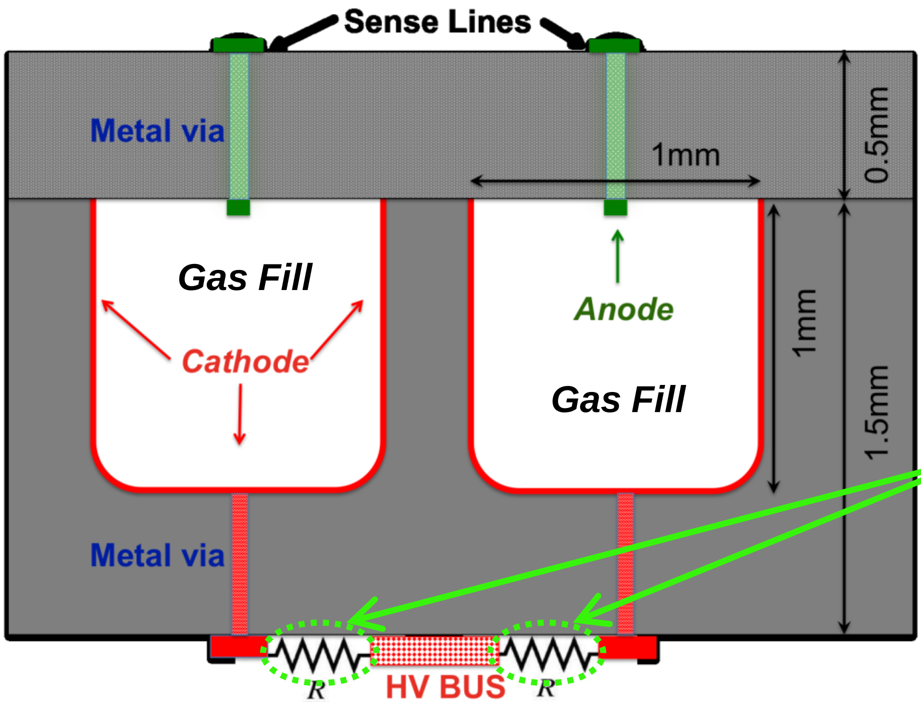
“Closed-Cell” PPS

(Microcavity Structure)

(DOE-NP, DOE-HEP, NSF & BSF*)

***United States – Israel* Binational Science Foundation**

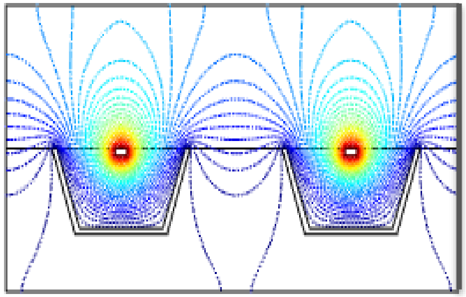
"Closed Cell" Microcavity Concept



1.0 x 1.0 x 2.0 mm
Metallized
Rectangular Cavities

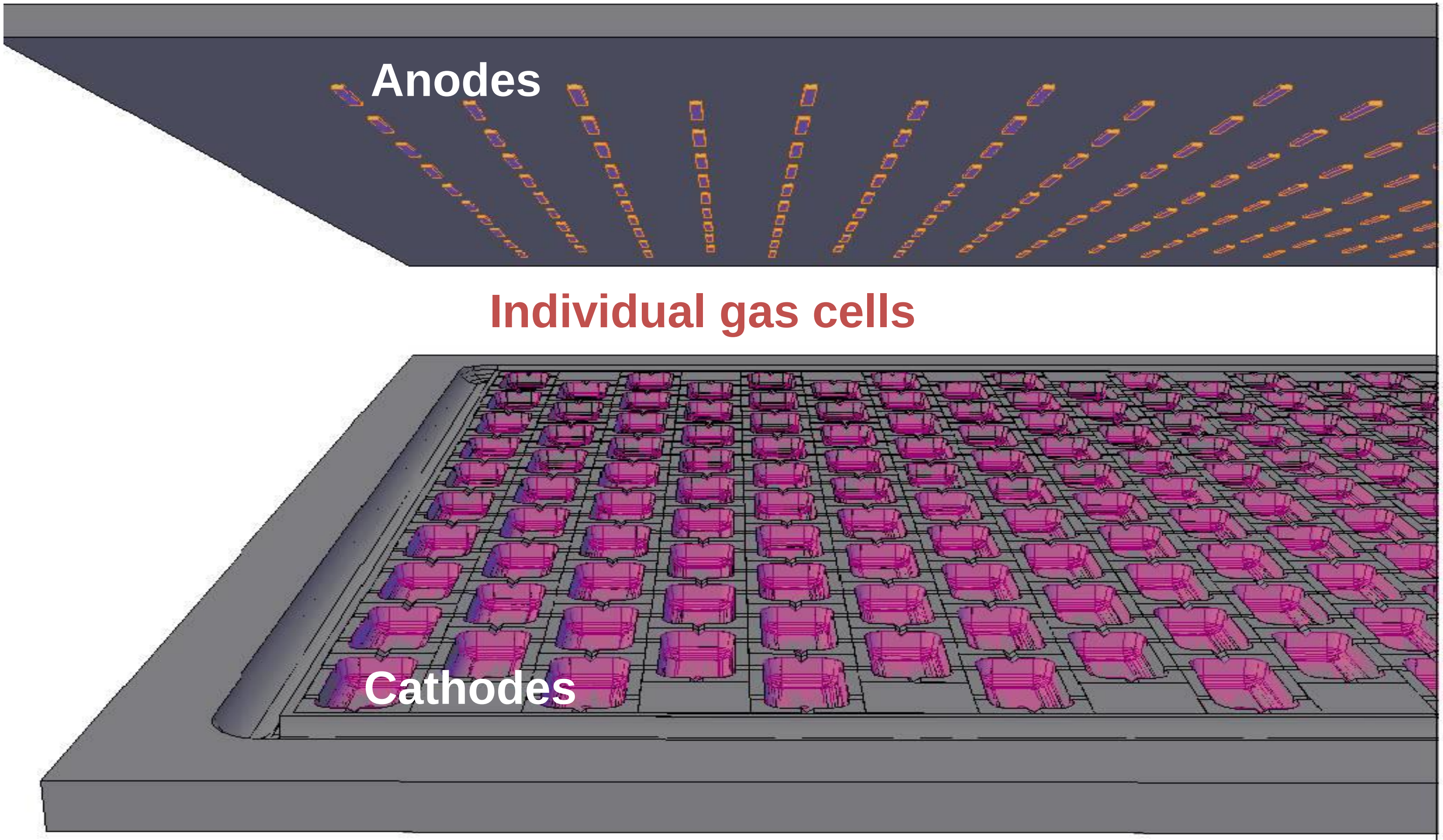
Closed gas cell individually quenched by an external resistor

Electrostatic simulations in COMSOL



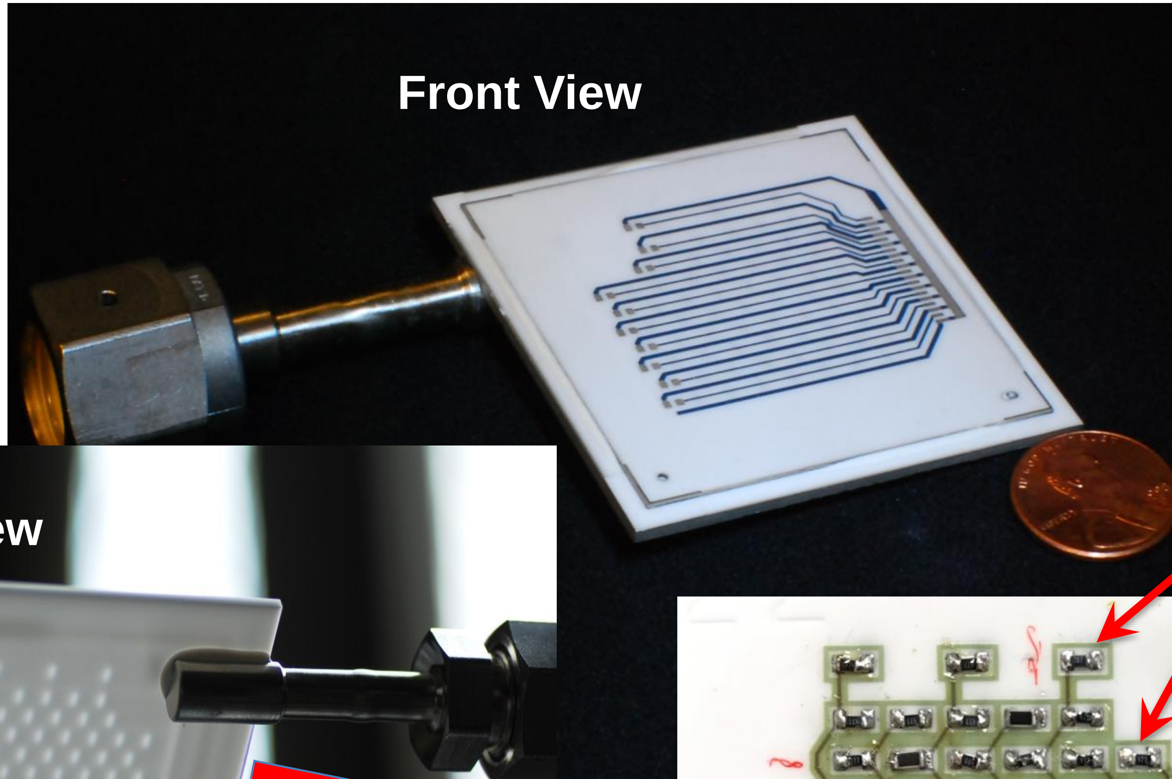
Electric field a few MV/m
→ gas breakdown

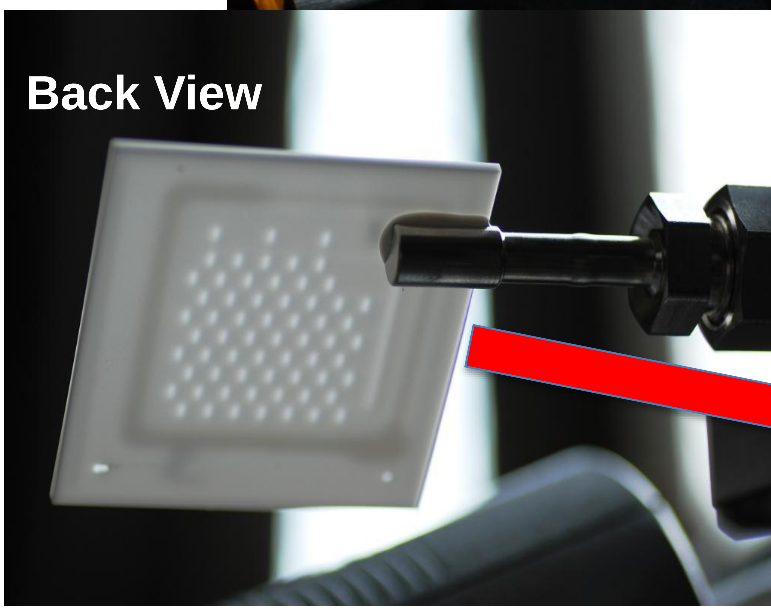
"*Closed*-Cell" Microcavity Concept



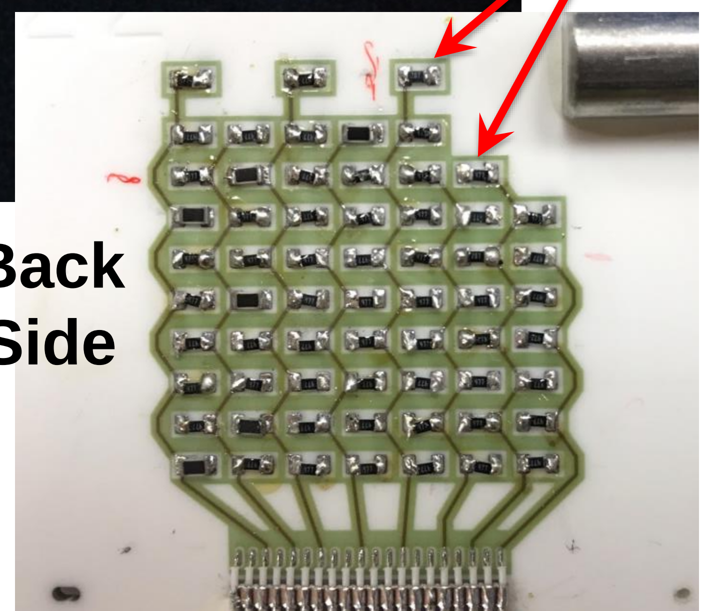
Perspective view of a pixel array with gas channels. Metallized cathode cavities on bottom plate with *vias* to HV bus. Anodes on top plate.

1st Gen. Microcavity-PPS Panel





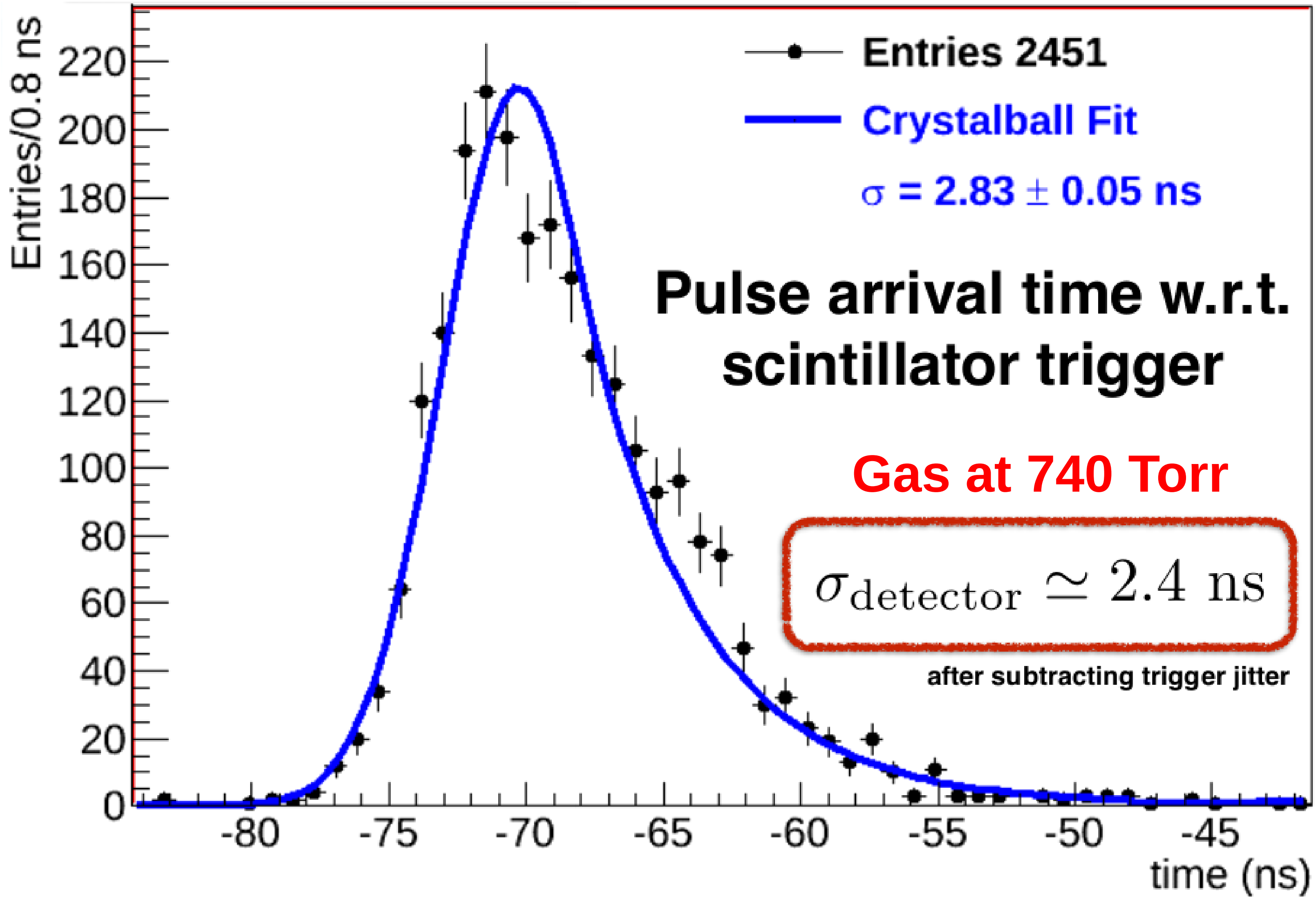
Back Side



Surface mount quench resistors on each cell

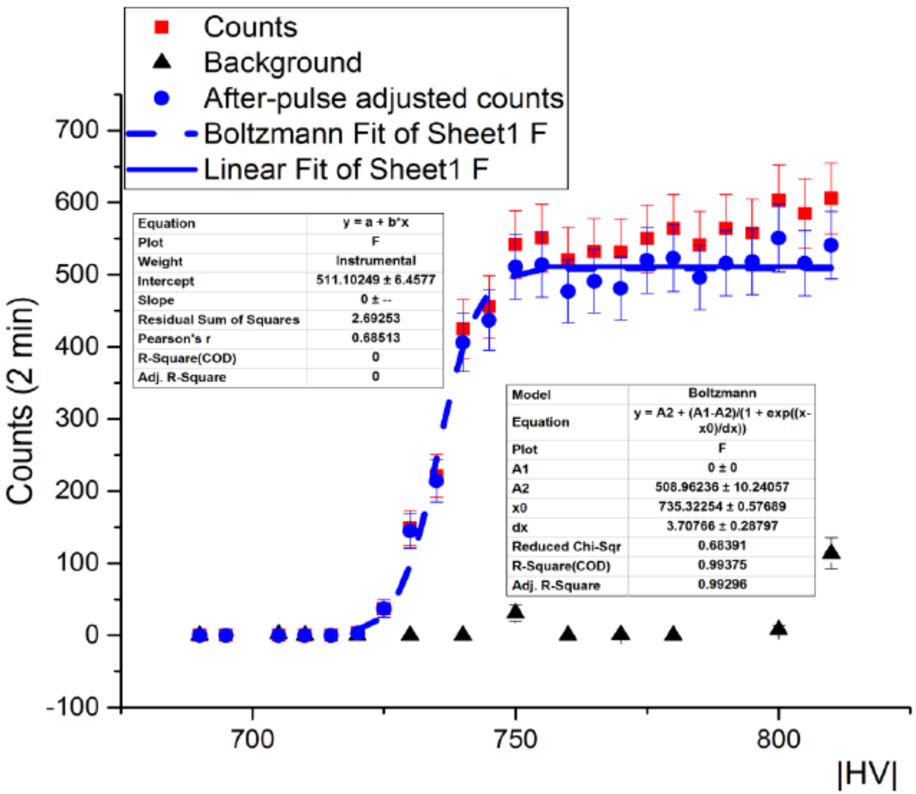
Fill-Factor of 18% in 1st Generation Microcavity Design (*ceramic cover*)

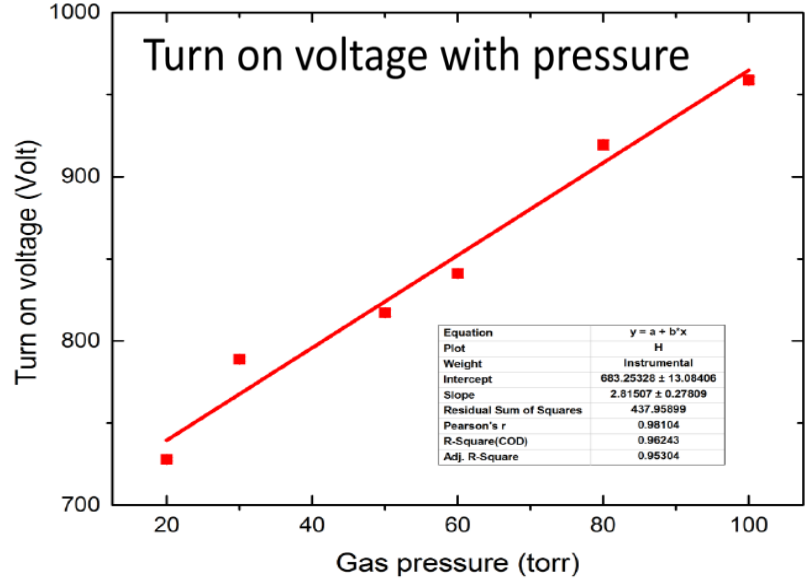
Pixel Time Resolution - Jitter



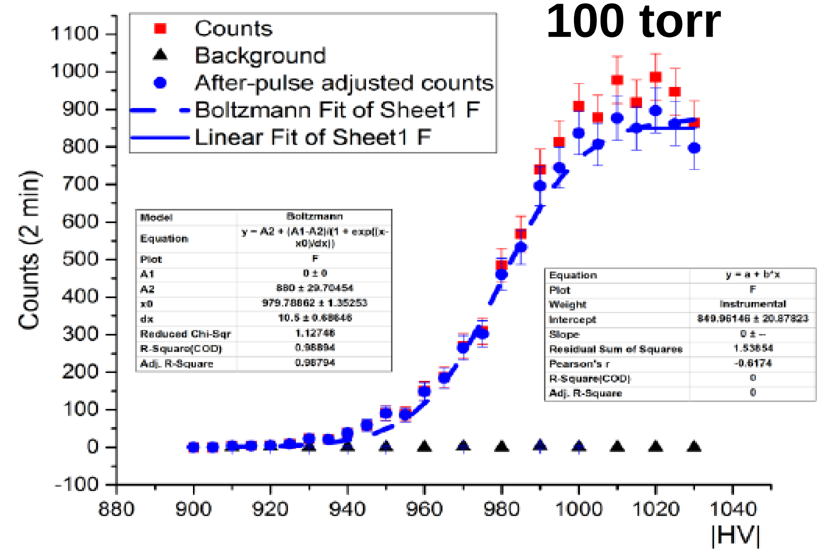
Pixel Response vs. Gas Pressure

20 torr



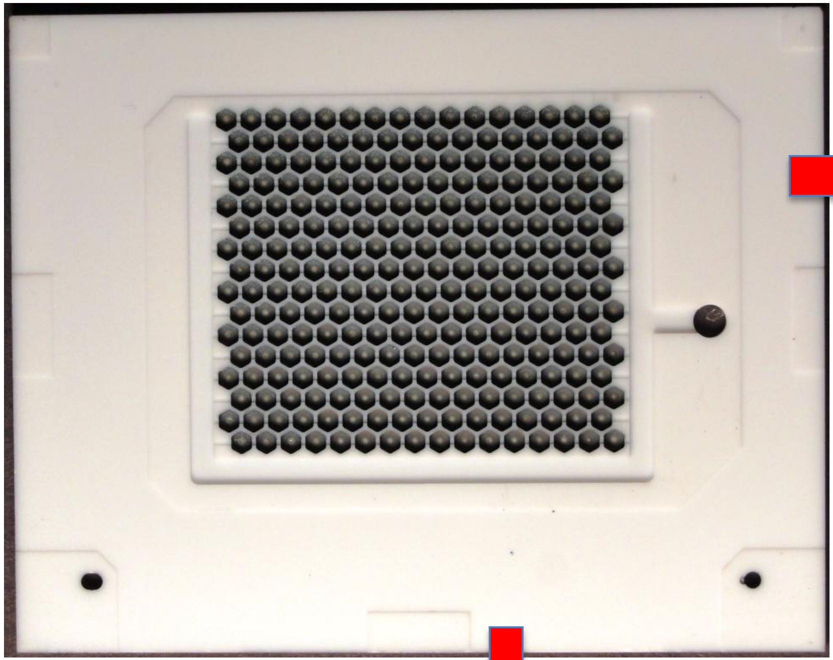


100 torr

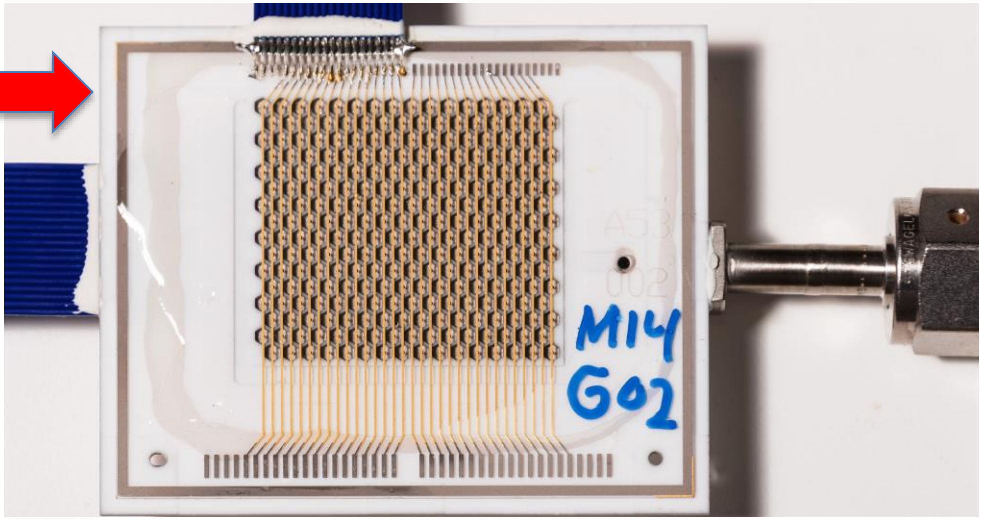


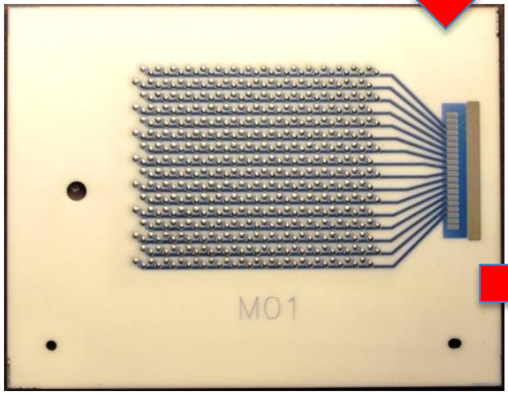
Hexcavity-PPS (2nd Gen. Microcavity)

2.0 mm Hexagon Pixels, 70% Fill-Factor, 256 pixel panel (16 x 16 matrix)



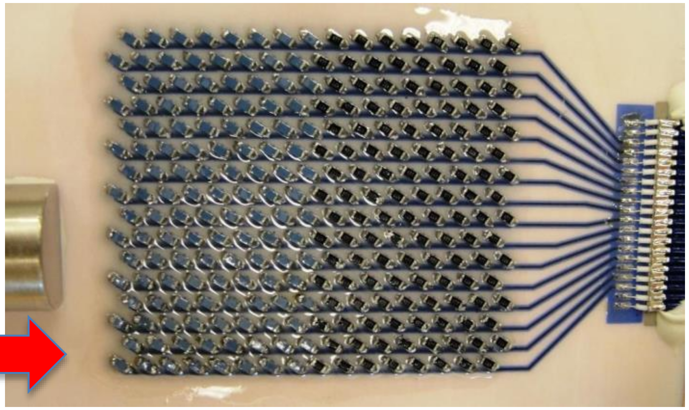
Glass Cover Plate





Ceramic Back Plate
Front with hexagon cavities and conductive vias (dot) to Back side Quench resistors

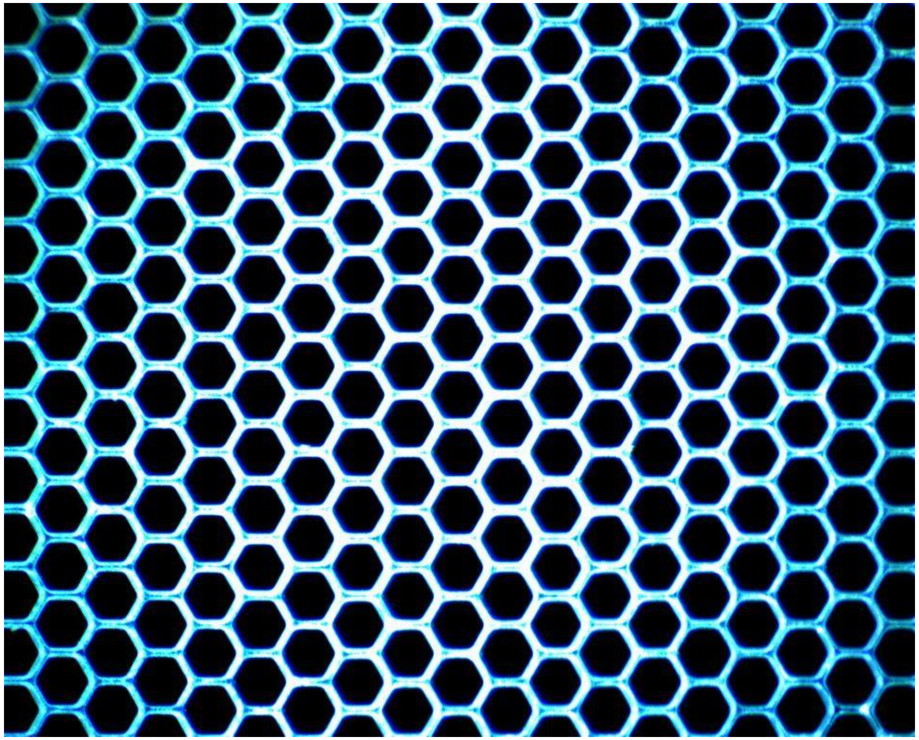
Cavities fully populated: 256 surface mount quench resistors

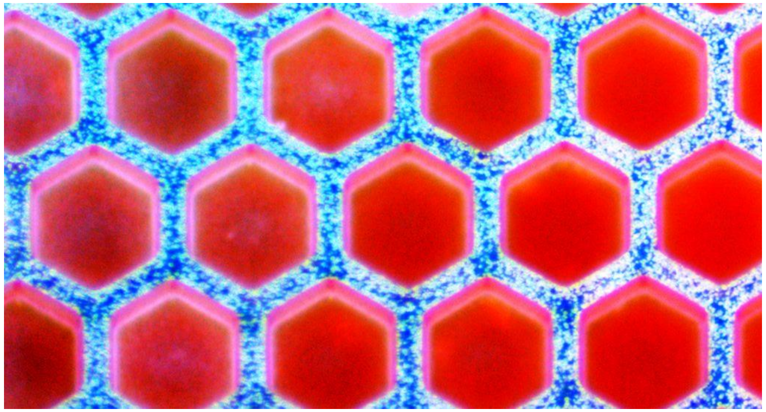


“High-Res” Fab Capability

<u>Fabricated Structure</u>: 0.27 mm Hexagon Pixels, 73% Fill-Factor

14,400 pixel structure (120 x 120 matrix)



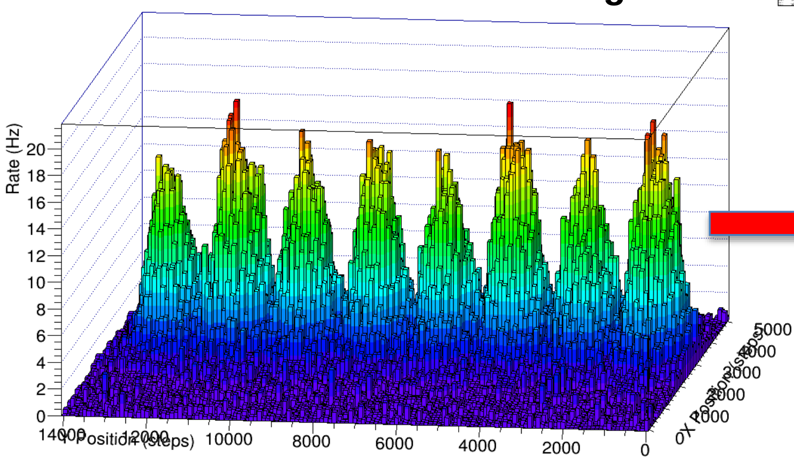


(Left) – Photo of small segment of high-resolution fabricated ceramic SPACER plate with <u>0.05 mm width-wall</u> structure between adjacent hexagon HOLES. Hexagon hole pitch of 0.32 mm (i.e. 120-row x 120-column matrix, with 14,400 pixels). Note the excellent hole & wall uniformity with “zero” defects for 14,400 holes!

(Right) – Photo of small segment of high-resolution fabricated ceramic HEXCAVITY plate with same 0.05 mm width-wall structure and same cavity pitch of 0.32 mm (i.e. 120-row x 120-column matrix). Note off-angle lighting shows reflection of cavity hexagon walls on cavity bottom.

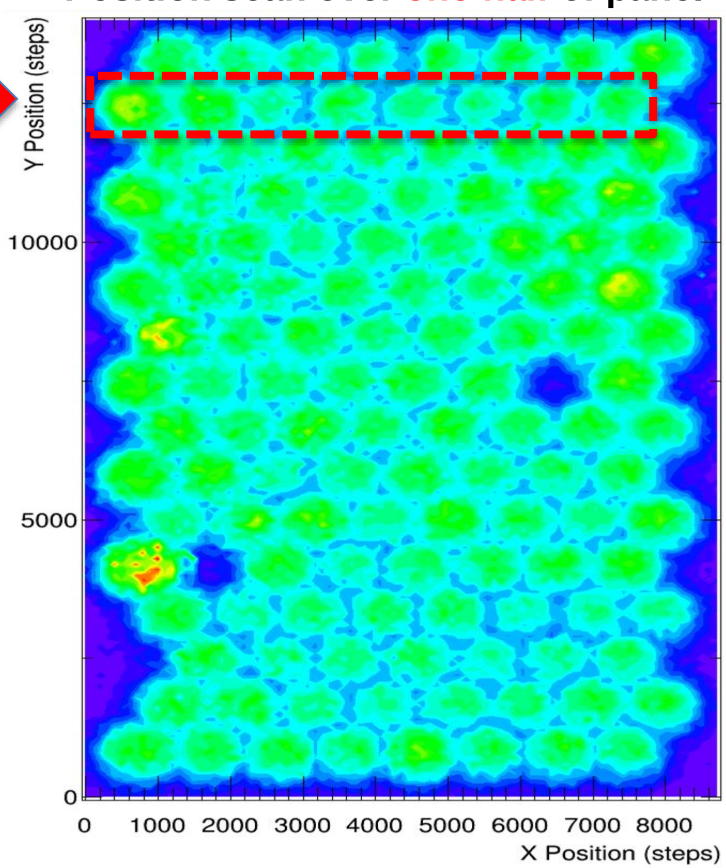
Position Scans

Rate vs. Position Scan over Single Line



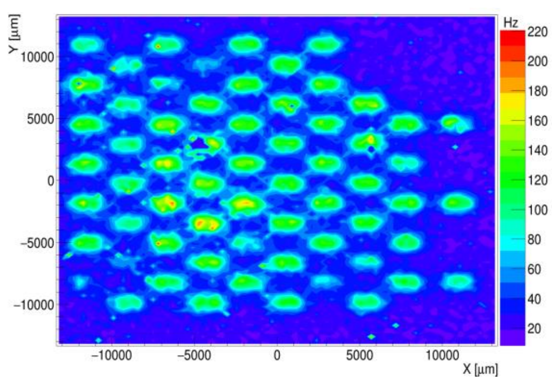
2nd Gen Microcavity – <u>70%</u> Fill Factor

Position scan over *one-half* of panel*



1st Gen Microcavity
<u>18%</u> Fill Factor

Position scan over *total* panel - 63 pixels

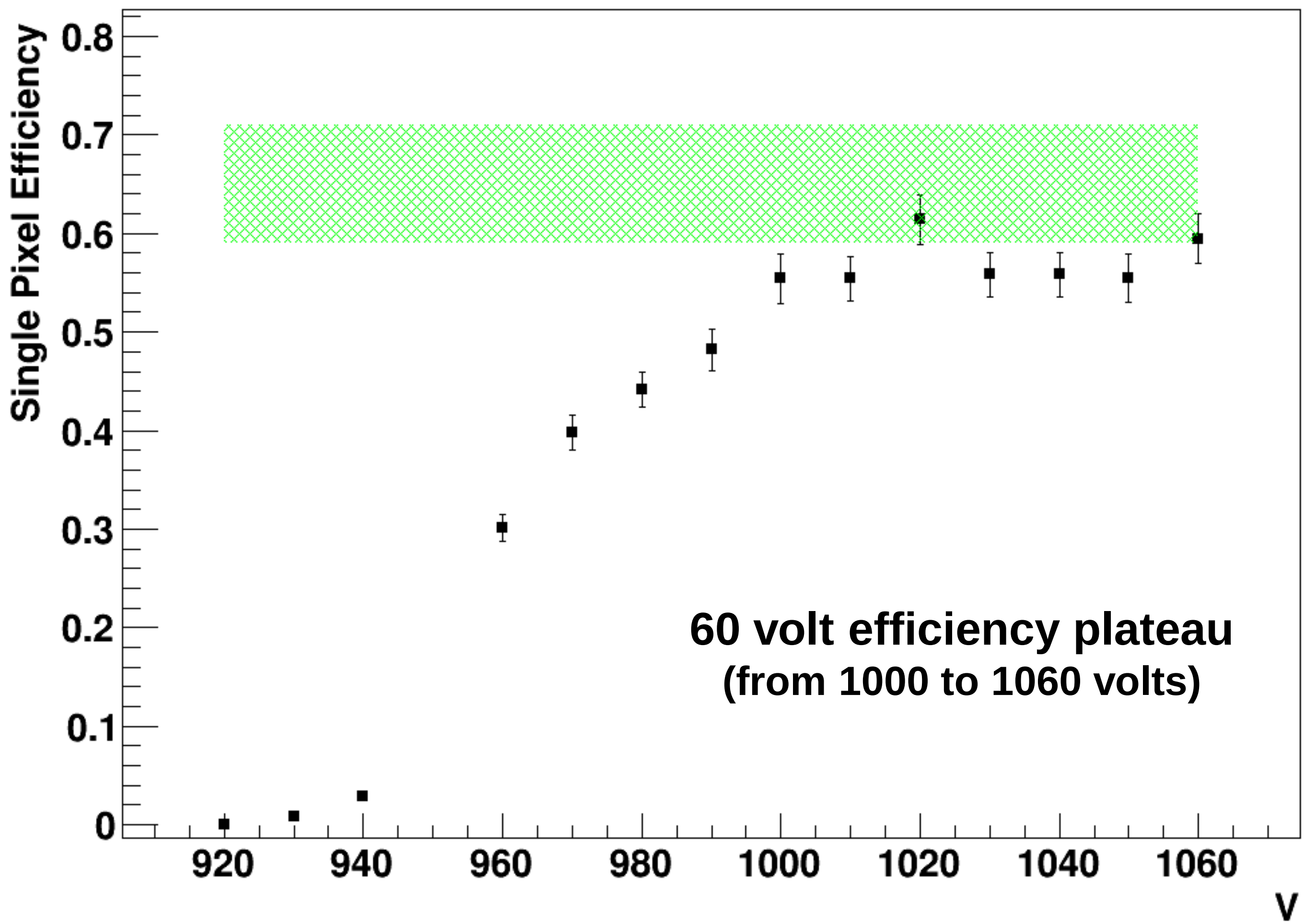


***125 Instrumented pixels (3 disconnected)**

Fill-Factor increased from <u>18% to 70%</u> from 1st to 2nd Gen. Microcavity-PPS design

- **^{90}Sr beta-source with 1.0 mm collimator**
- **Each pixel responds only when irradiated**
- **No discharge spreading**

Hexcavity Efficiency for Cosmic Muons



Measured single pixel efficiency in Discharge Mode with Ne-based gas mixture is close to maximum efficiency estimated by Geant4 simulation.

Hexcavity-PPS Operation: Gas Discharge vs. Avalanche Mode

Discharge Mode – High gain (volt level signals), no amplification, higher panel fabrication cost with one quench resistor per pixel, detection of heavy ions with high efficiency and low to “zero” spontaneous hits. Because of long dead time (~ 1 ms), high rates require small pixels.

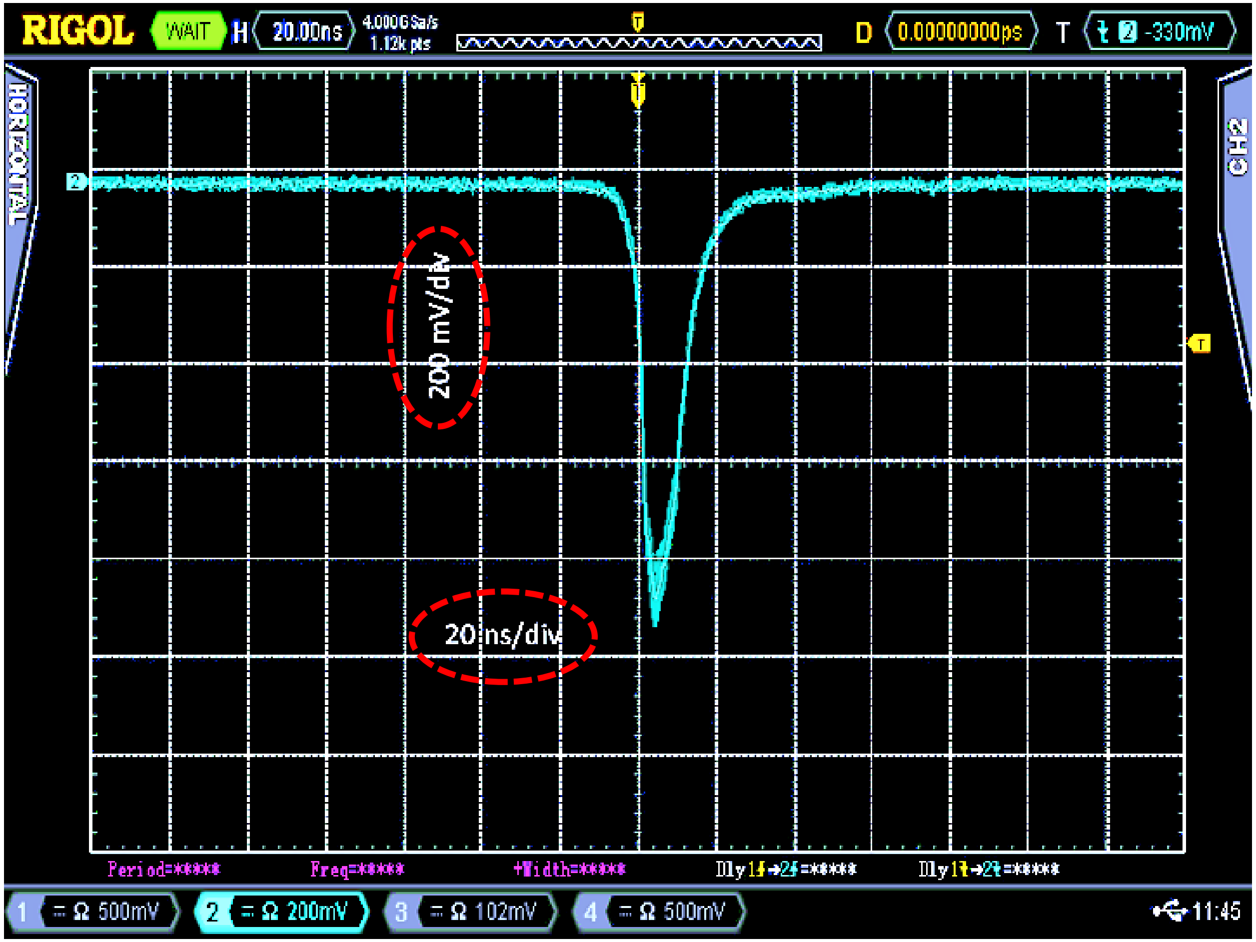
Avalanche Mode – Low gain (mV level signals) with amplification required, superior high rate performance with minimal degradation at high rates. Performance at low pressures has not yet been tested.

Signal Envelope from Hexcavity Pixel in *Discharge Mode* with β-Source (^{90}Sr)

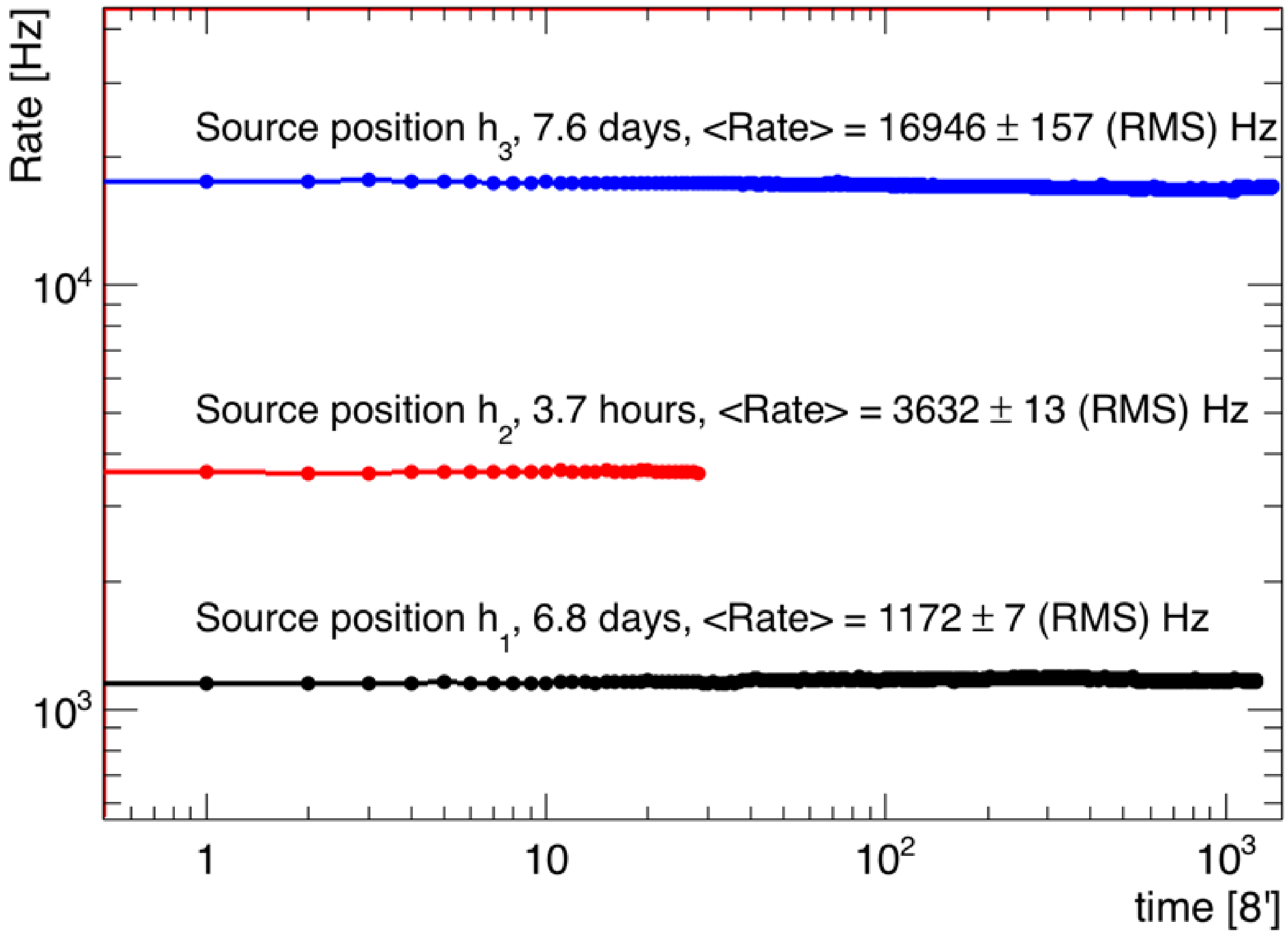
Signal envelope contains ***dozens*** of traces and demonstrates excellent uniformity.

FWHM is ~ 12 ns* and rise time ~ 5 ns* Average signal is about 0.85 Volt.

*Half-size cavities with different gas mixture achieved FWHM of 2-3 ns and rise time ~ 2 ns.



Single Pixel Response to β-Source (^{90}Sr) in Avalanche Mode

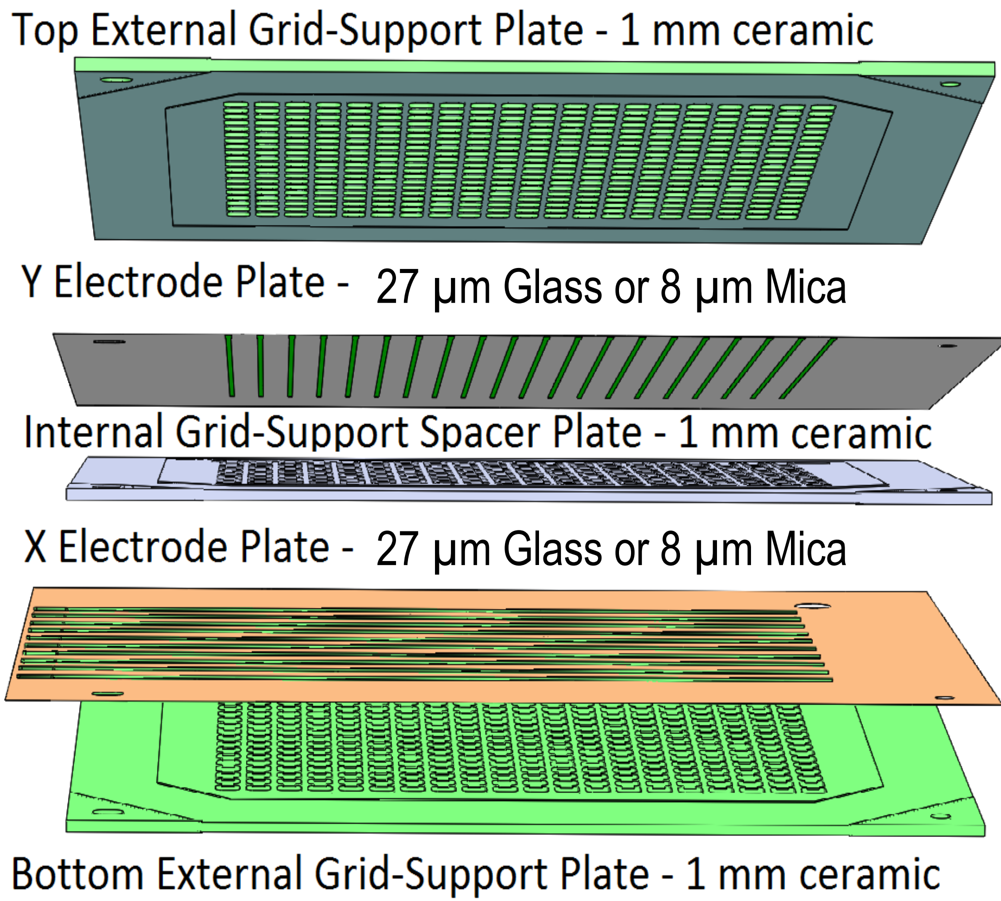


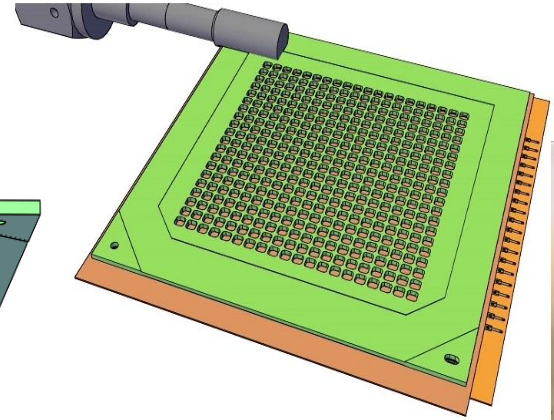
Hit rate for a single hexcavity pixel measured in 8 minute bins is 16.9 kHz, or 346 kHz/cm^2, and stable over 8 days.

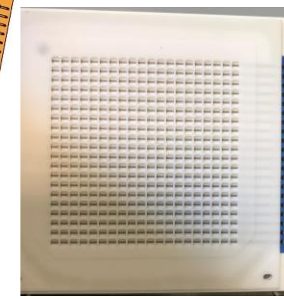
UltraThin Grid-Support PPS

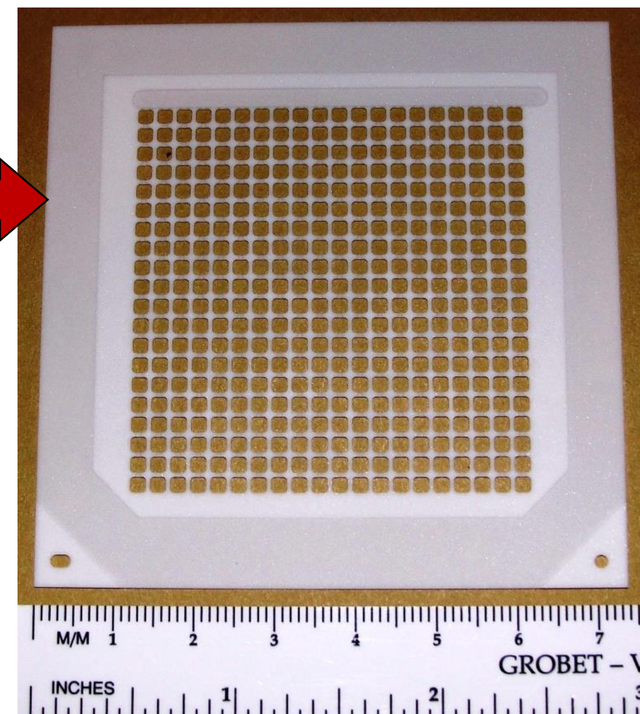
(Hybrid "*Closed Cell*" Structure)

UltraThin Grid-PPS (27 µm Glass and 8 µm Mica)







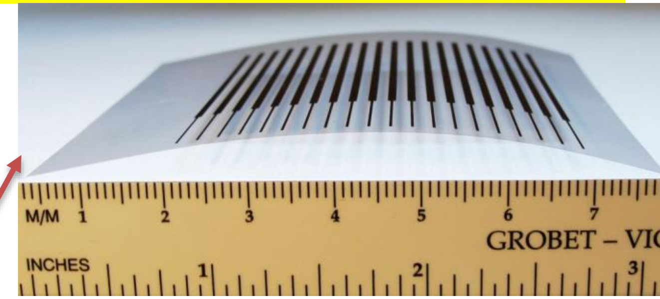


Electrodes on *UltraThin* Mica & Glass

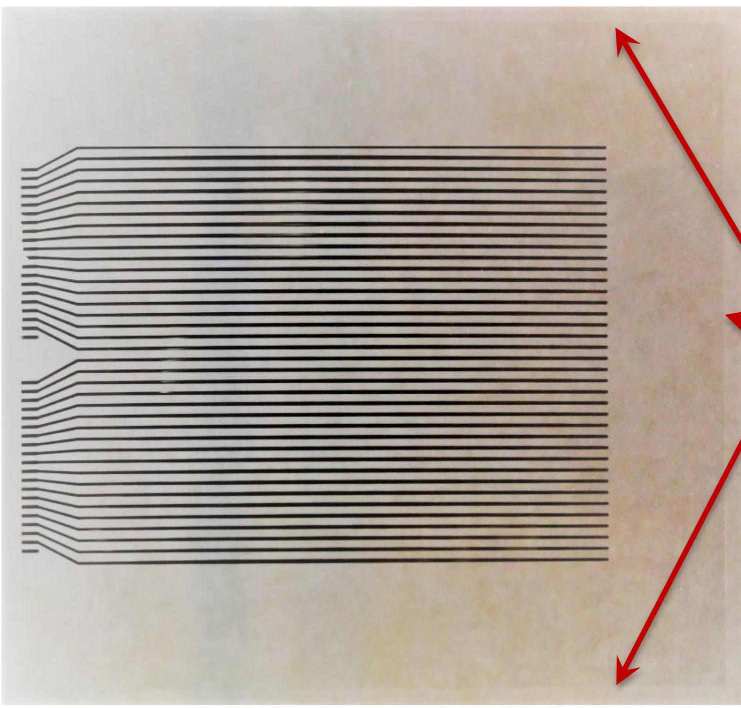
Substrate Size: 3.00” x 3.15”

Areal Density / Mass Thickness:

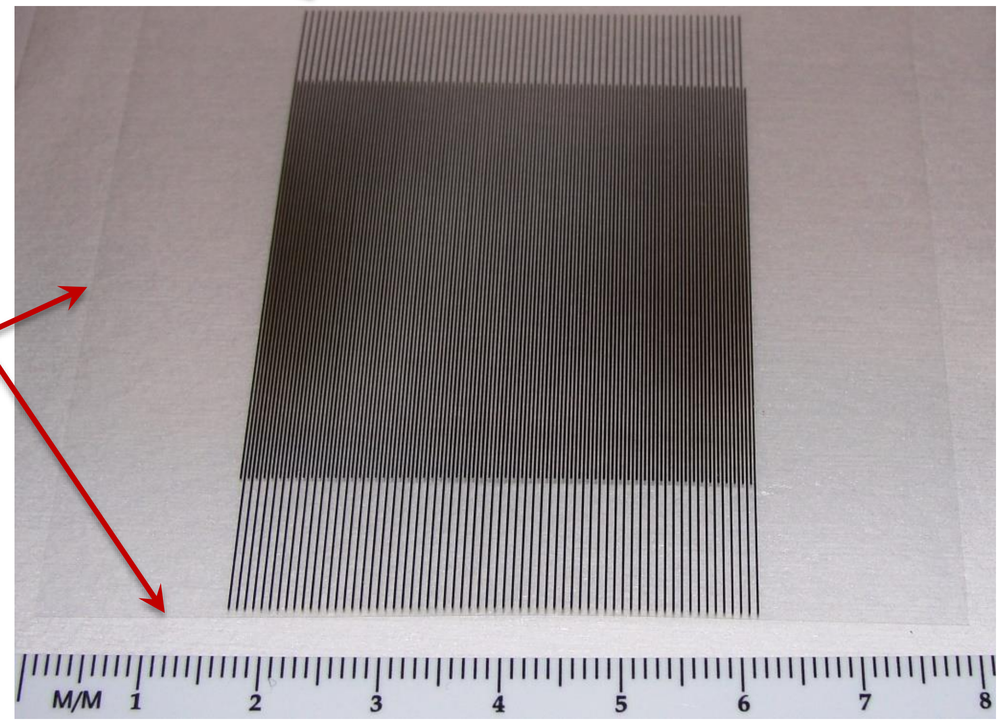
2.2 mg/cm^2 (Mica) vs. 6.6 mg/cm^2 (Glass)



8 µm Mica

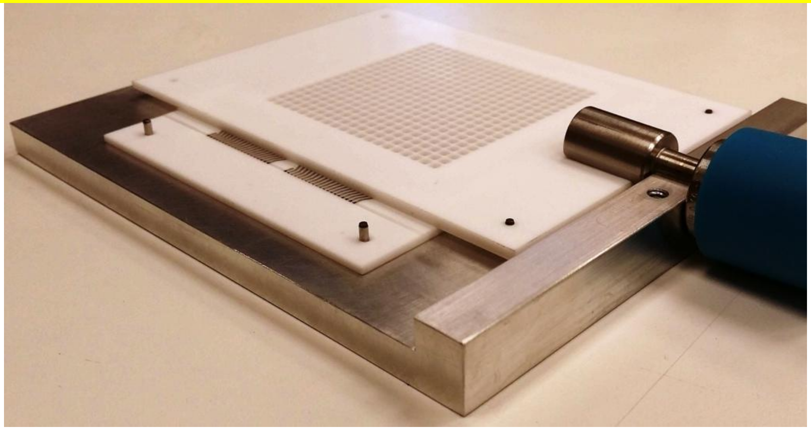


27 µm Glass

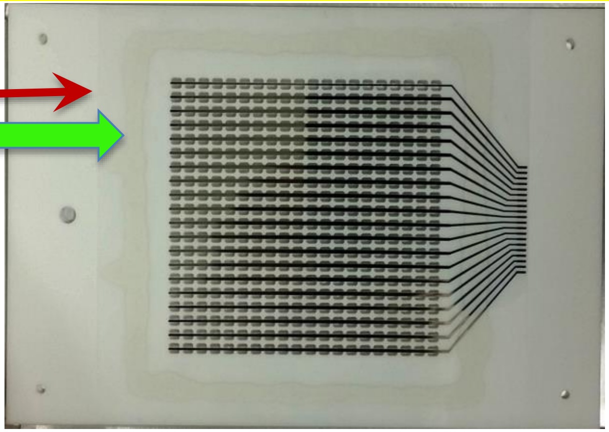


Left: Electrode pitch of ***1.00 mm***. **Right:** Electrode pitch in active area (center) of ***0.35 mm***. Narrow electrode width & spacing created Lissajou type interference pattern, which is an optical artifact of image magnification and viewing angle. The actual electrode pattern is very uniform as seen at top & bottom.

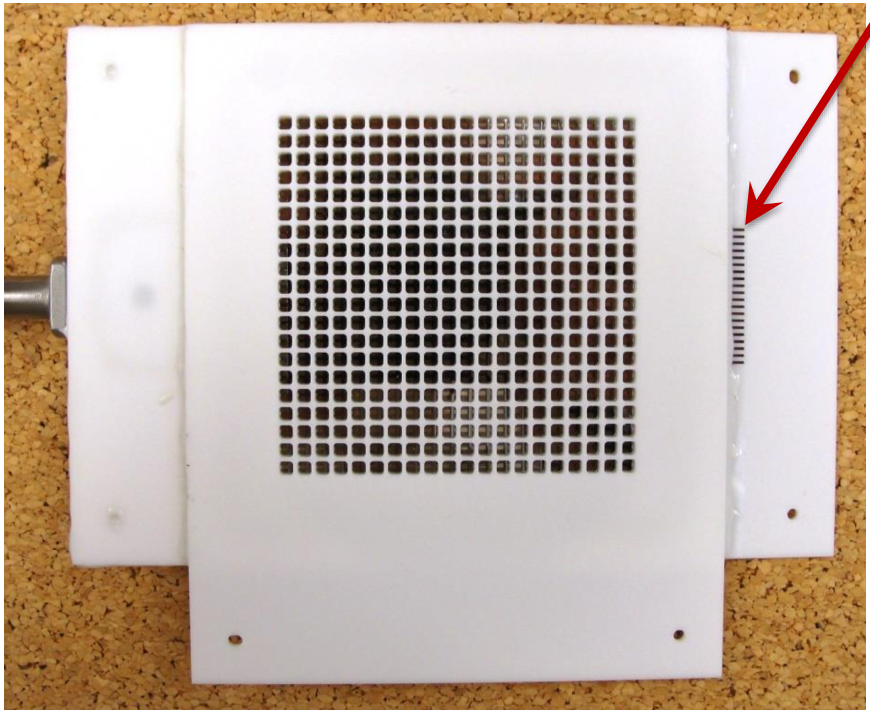
UltraThin Grid-PPS Panel (64% Fill-Factor)



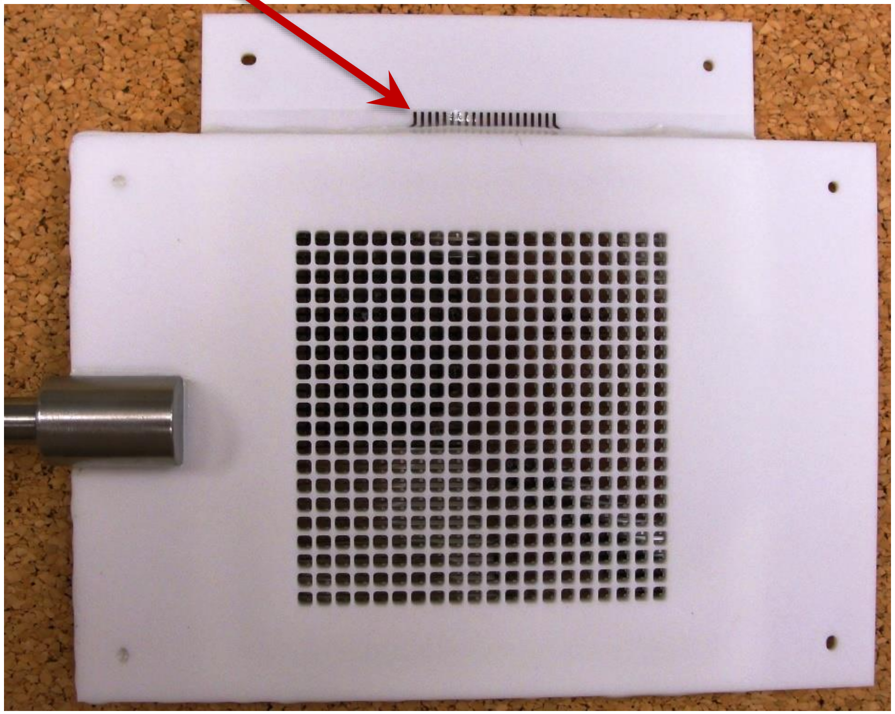
Assembled Front plate (glass seal)



27 µm Glass substrate, 1.00 mm electrode pitch



View from panel FRONT side



View from panel BACK side

First Results with Grid-PPS in Discharge Mode

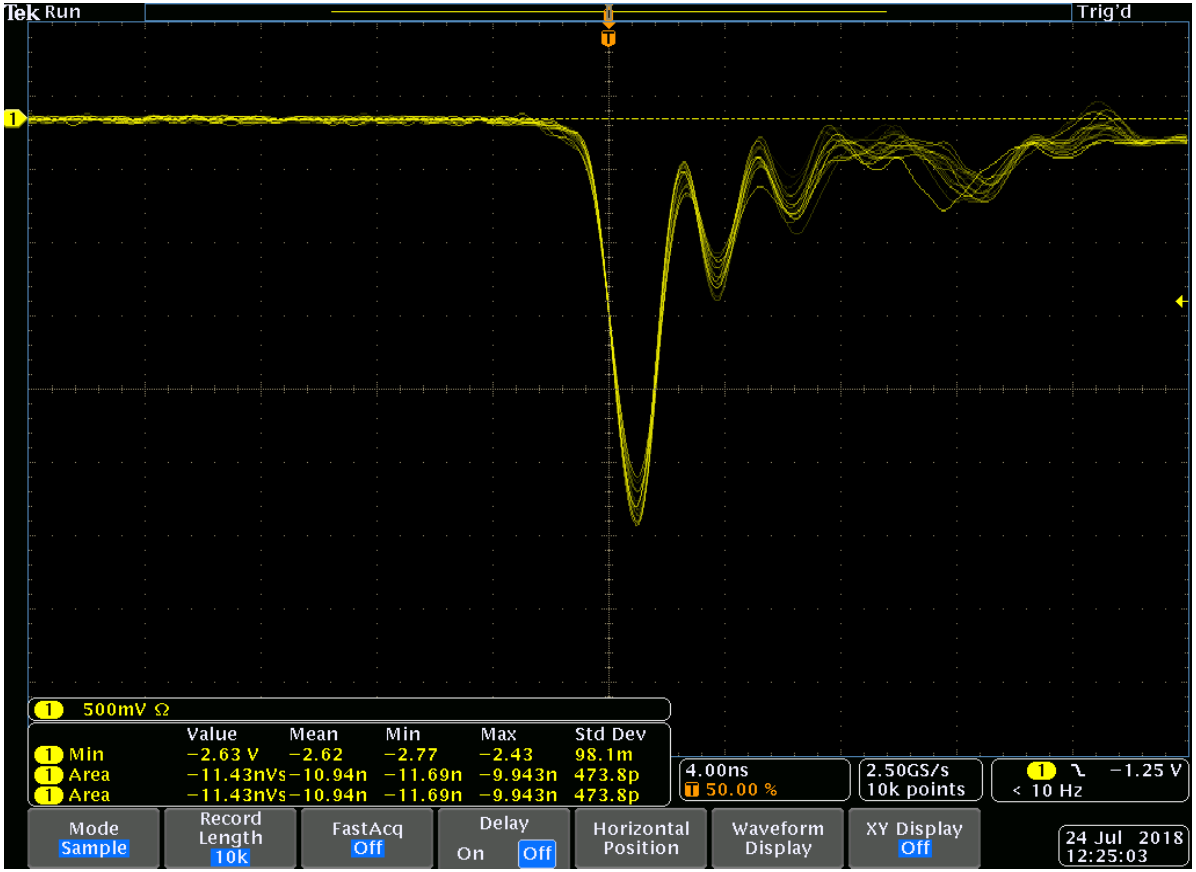
Signal envelope contains ***dozens*** of hits, demonstrating excellent uniformity.

FWHM = 2 ns
Rise Time = 1 ns

Signal amplitude is 3V with 20 dB

16 lines connected with clamping diodes to ground

^{90}Sr (beta source) ~7 cm above panel



Summary

- PPS detectors have *demonstrated: submillimeter* position-resolution, good pixel-to-pixel uniformity, *nanosecond*-scale time resolution, excellent S/N, and close to maximum theoretical efficiency over wide volt ranges for both beta & cosmic muon particle sources. Smaller pixels at < 100 Torr pressure expected to provide ***sub-nanosecond*** timing.

- Each PPS pixel responds as an individual detector. Spatial fill-factors have increased from 18% (1^{st} generation) to 70% (2^{nd} generation), with ***fill-factors ≥ 80%*** for future designs. PPS microcavity panels can operate with a 50 volt efficiency plateau at gas pressures of ***20 Torr***, which bodes well for ***ultrathin*** grid-support PPS panels in a vacuum environment.

- The "***ultrathin***" grid-support PPS operates as expected as a "hybrid" between "open" and "closed" cell PPS structures and with a path towards larger area, low cost structures.

- Ultrathin grid-PPS panels operating in the avalanche mode are expected to have a wide dynamic range from a few ***Hz/cm²*** to ~***10^5 to 10^6 Hz/cm²***, and perhaps higher.

- Two ***ultrathin*** grid-PPS panels have been under development: **27 μm** thick Glass and **8 μm** thick Mica. We have *demonstrated* both substrates capable of holding a vacuum, but the *thicker Glass substrates are more fragile than the thinner Mica*! Our current focus is on Mica substrates with a *modified* grid-spacer structure and *modified* grid-support plates.

Backup

Plasma Panel Sensor (PPS)

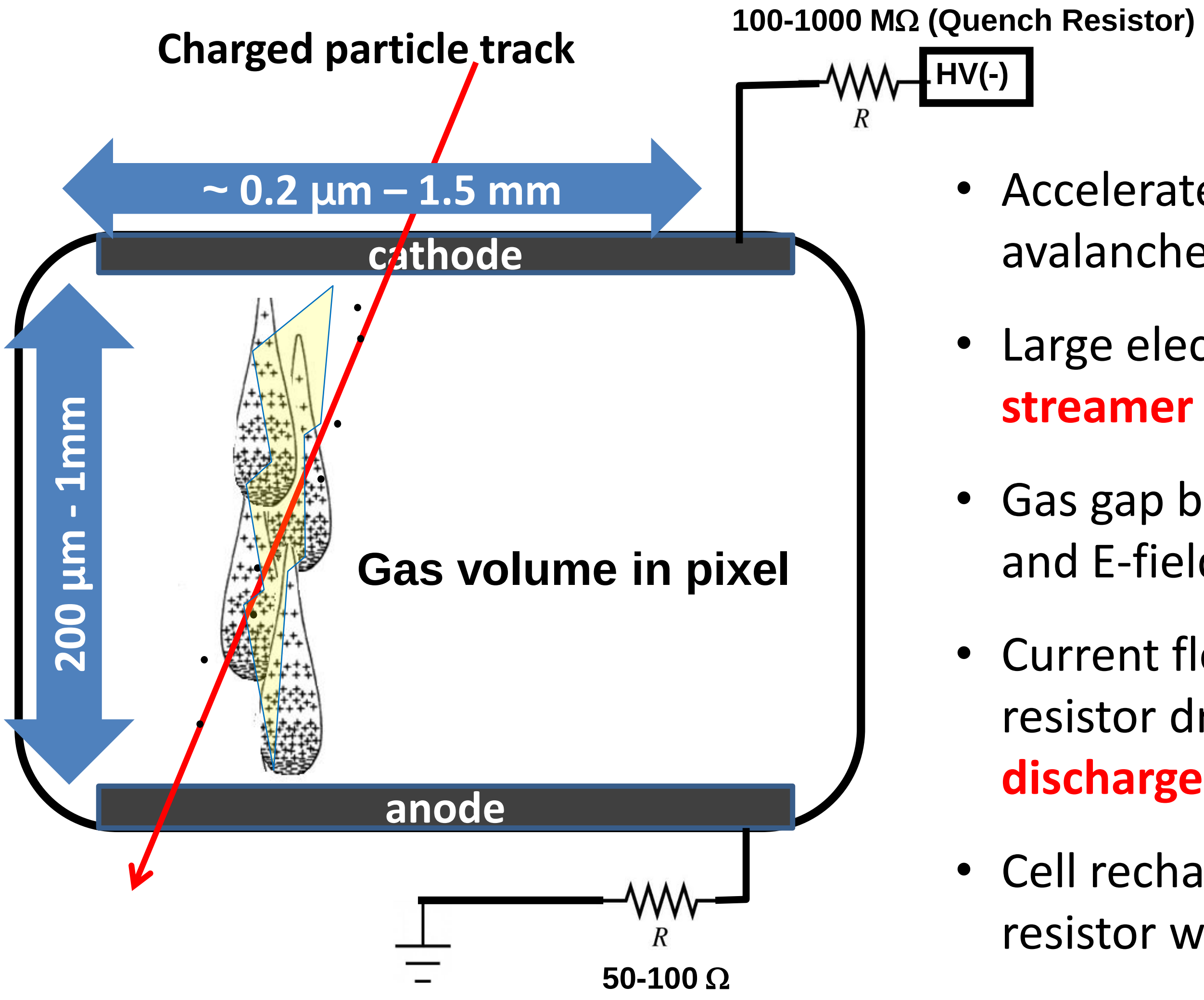
- **The PPS, conceived as a high-performance, low-cost, particle detector, based on *plasma-TV display* panel technology.**

- **Each pixel operates like an independent *micro-Geiger counter,* activated by *direct* ionization in the gas, or *indirect* ionization via a conversion layer.**

- **Both "*open*-cell" and "*closed*-cell" PPS devices based on *direct* ionization are the primary focus of our research efforts.**

- ***Ultrathin*-PPS based on ultrathin *27 µm* Glass and *8 µm* Mica substrates, integrated into a "*grid-support*" structure, which is a *hybrid* between the "*open*" and "*closed*" cell configurations.**

Single Pixel: Principles of Operation



- Accelerated electrons begin avalanche.
- Large electric field leads to **streamer filaments**.
- Gas gap becomes conductive and E-field collapses.
- Current flow across quench resistor drops pixel voltage and **discharge terminates**.
- Cell recharges through quench resistor with RC time constant.

Sources Detected

Cosmic-Ray Muons (≈ 4 GeV at sea-level)

Muon Beam: 180 GeV range (at **H8-CERN** for ***high energy physics)***

Beta Particles (max. energy): ^{137}Cs (1.2 MeV), ^{90}Sr (2.3 MeV), ^{106}Ru (3.5 MeV)

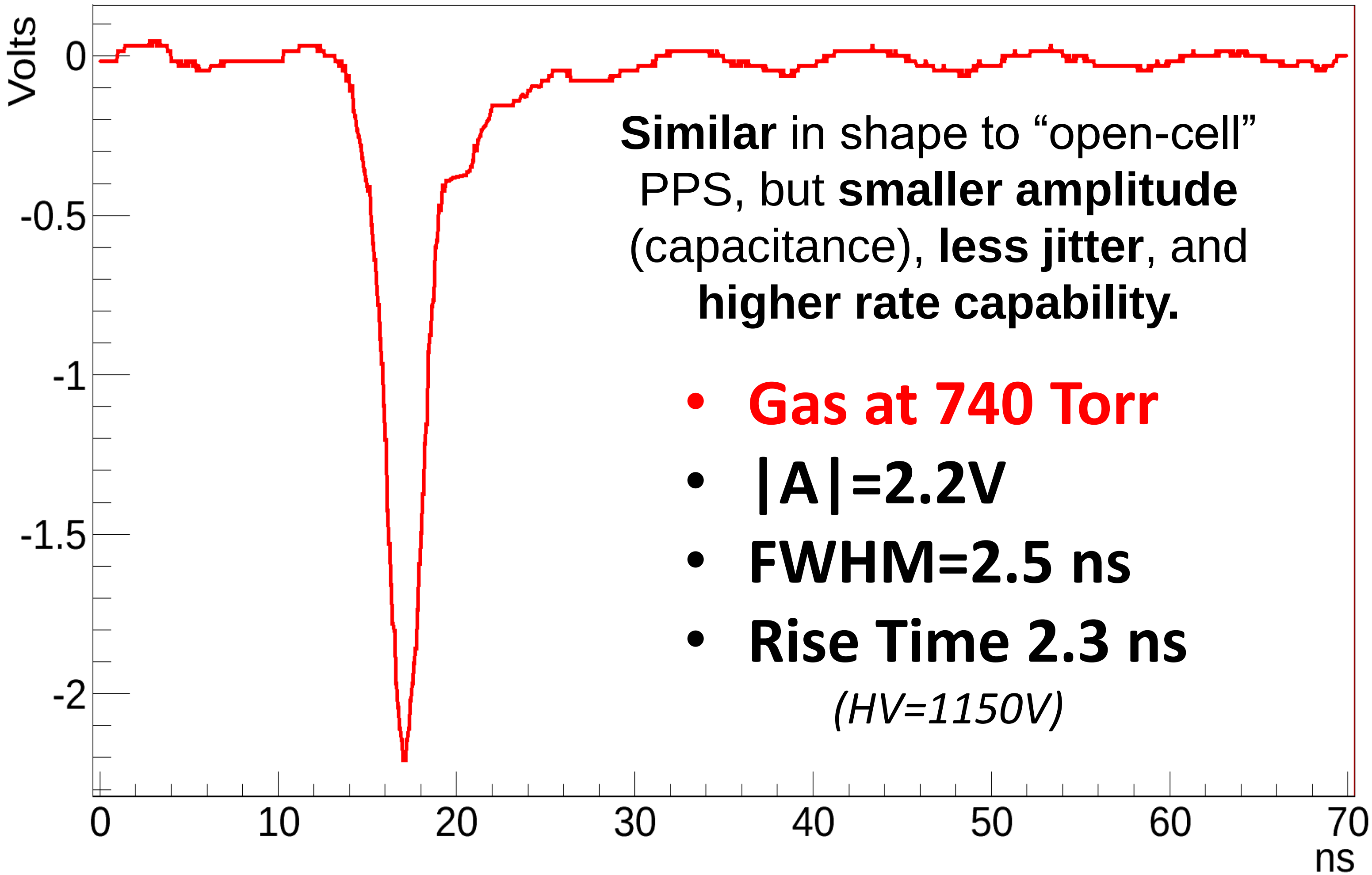
Proton Beam: 226 MeV (***proton beam cancer therapy & proton-CT***)

Neutrons: Thermal neutrons (***neutron scattering***)

Gamma-Rays: ^{60}Co (1.2 MeV), ^{137}Cs (662 keV), [***can be gamma "blind"***]

UV-Photons: "Black UV-lamp" with emission at 366 nm

Typical Microcavity-PPS Signal Pulse

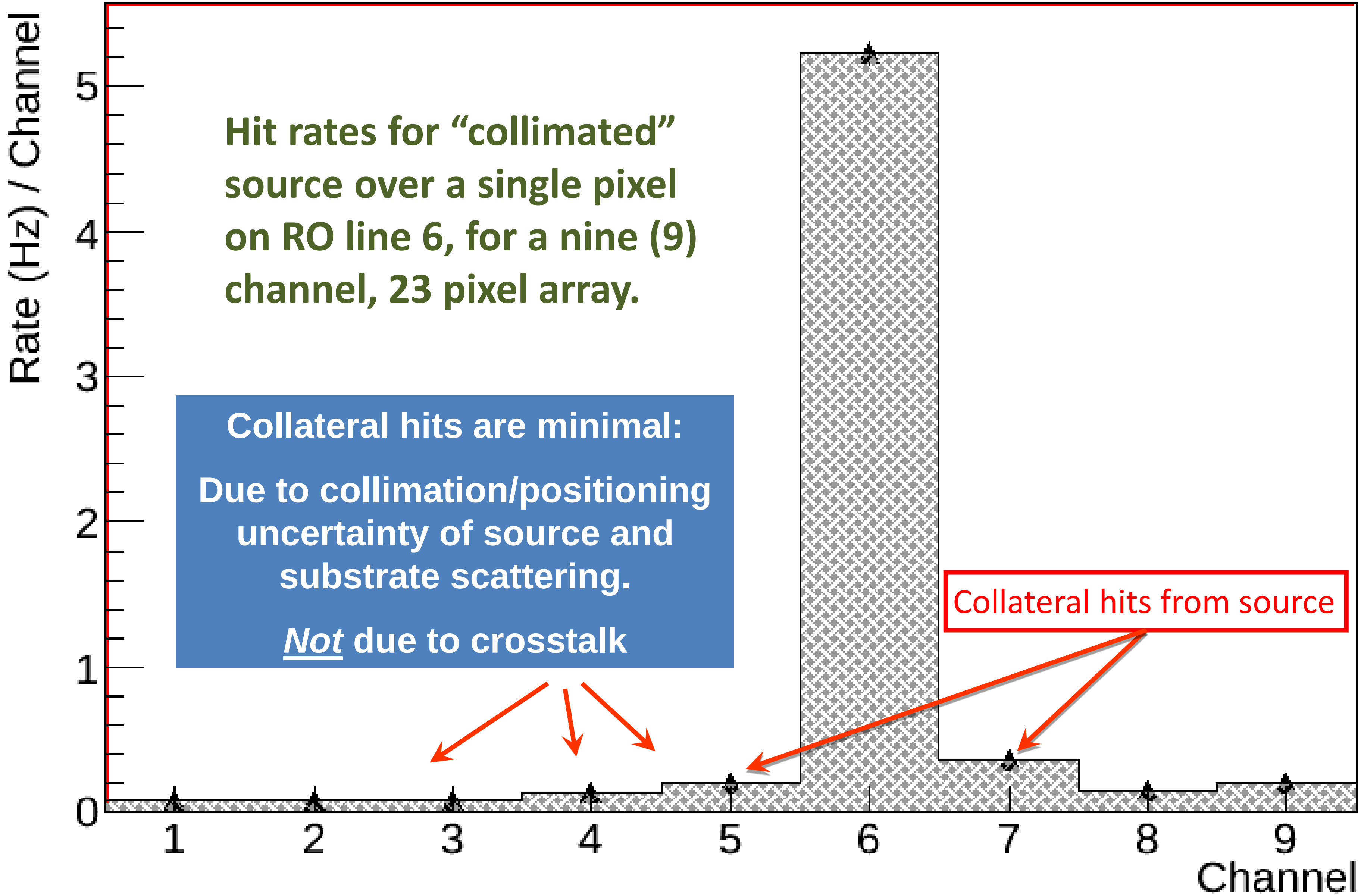


Similar in shape to “open-cell” PPS, but **smaller amplitude** (capacitance), **less jitter**, and **higher rate capability.**

- **Gas at 740 Torr**
- **|A|=2.2V**
- **FWHM=2.5 ns**
- **Rise Time 2.3 ns**

(HV=1150V)

Pixel Isolation



Beam Energy Loss* in *UltraThin* Glass vs. Mica

Energy Loss in 25 µm *thick Glass* cover PPS for selected Ion Beams
(gas is 1.0 mm of Ar at 100 Torr. *NO* nuclei get through the glass at 1 MeV/A)

Energy (MeV)/A	Ion Energy (MeV)	Energy *loss in Glass* (MeV)	Energy *loss in Gas* MeV (# ion pairs)
3.0 (Ni-64)	192	190	0.13 (4,700)
3.0 (Sn-124)	372	348	0.57 (21,000)
3.0 (U-238)	**714**	**570**	1.52 (58,000)

Energy Loss in 8 µm *thick Mica* cover PPS for selected Ion Beams
(gas is 1.0 mm of Ar at 100 Torr. *ALL* nuclei get through the Mica at 1 MeV/A)

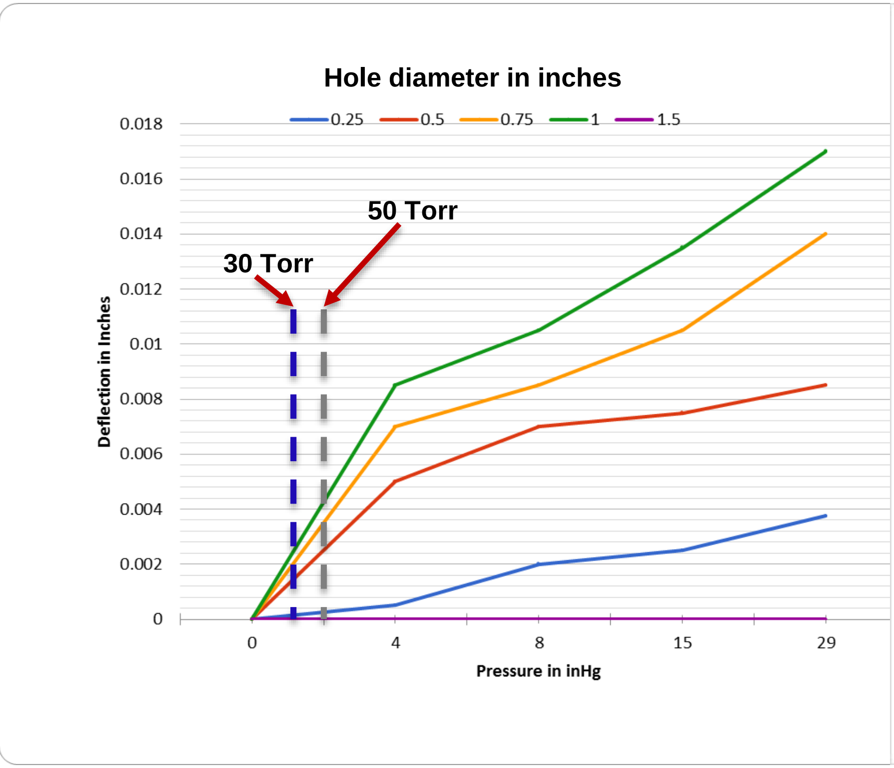
Energy (MeV)/A	Ion Energy (MeV)	Energy *loss in Mica* (MeV)	Energy *loss in Gas* MeV (# ion pairs)
1.0 (H-1)	1	0.5	0.006 (210)
1.0 (He-4)	4	2	0.02 (810)
1.0 (C-12)	12	12	0.04 (1,400)
1.0 (Ni-64)	64	62	0.14 (5,400)
1.0 (Sn-124)	124	107	0.53 (20,000)
1.0 (U-238)	**238**	**143**	1.20 (47,000)

******Energy Loss calculated using Geant4. A value of 26 eV was used for the effective Ar ionization energy and came from the tabulation in "Average Energy Required to Produce an Ion Pair", ICRU Report #31.*

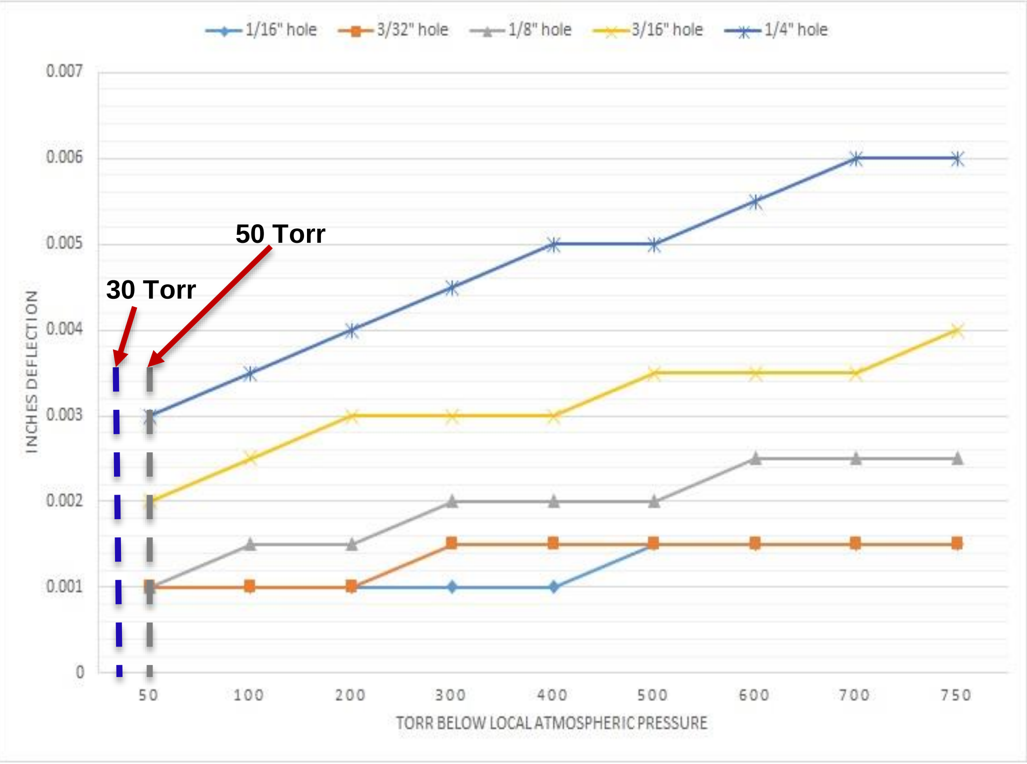
Deflection of *UltraThin* Substrates

Deflection as a Function of Hole Diameter & Net External Pressure

Deflection of 27 µm Glass over holes of incremental size in inches.



Deflection of 6.9 µm Mica over holes of incremental size in inches.



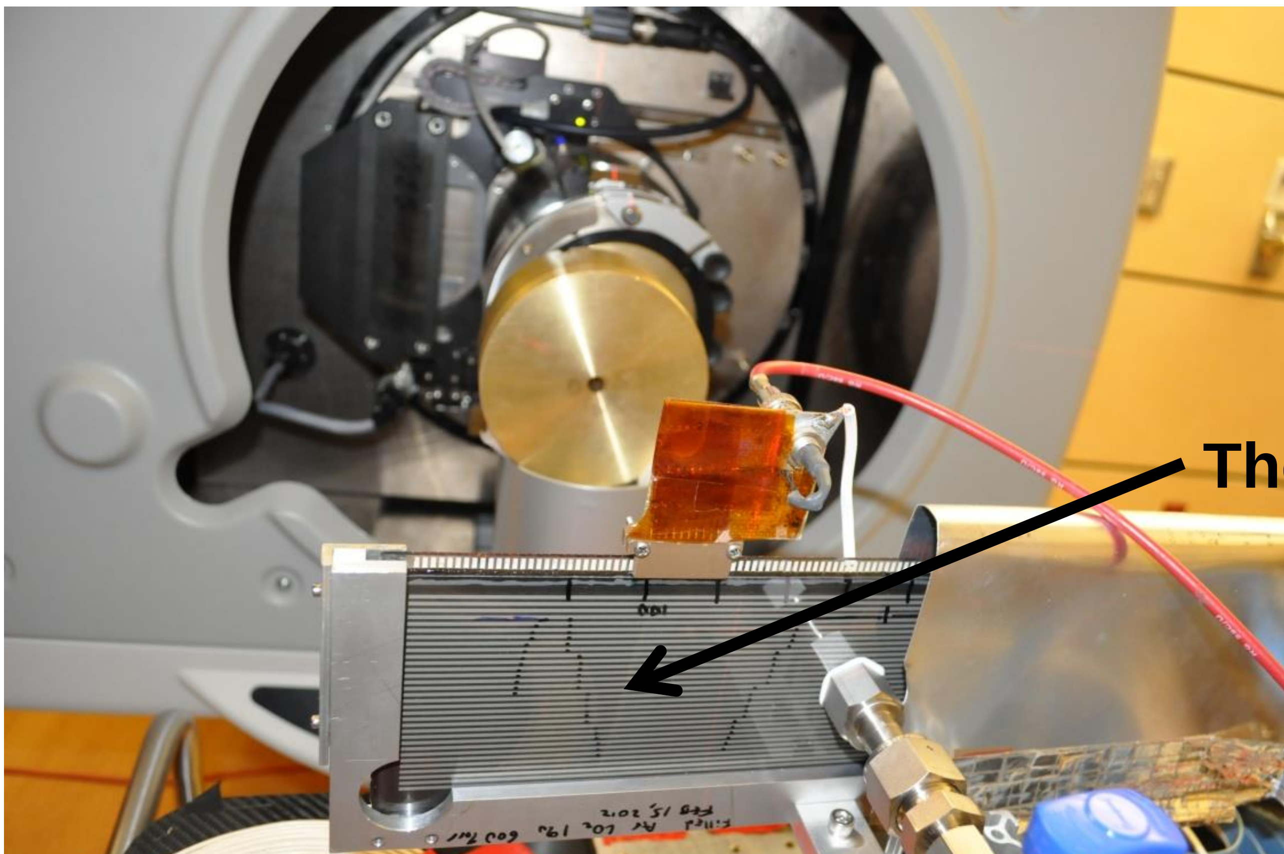
For a 2 mm width grid-spacer opening at 50 Torr of net pressure, there will be essentially no deflection of 27 µm thick Glass substrates, while for thinner 6.9 µm Mica substrates there will be ~ 25 µm of deflection. For a 1 mm gas-gap this represents a 2.5% change in gas-gap which is insignificant. For the slightly thicker 8 µm Mica, this deformation will be less, and at 30 Torr there is essentially no deflection. For 6 mm hole diameters, with 1 atm of pressure, neither the Glass nor Mica will break.

Proton Beam Test
(Northwestern Medicine Chicago Proton Center)

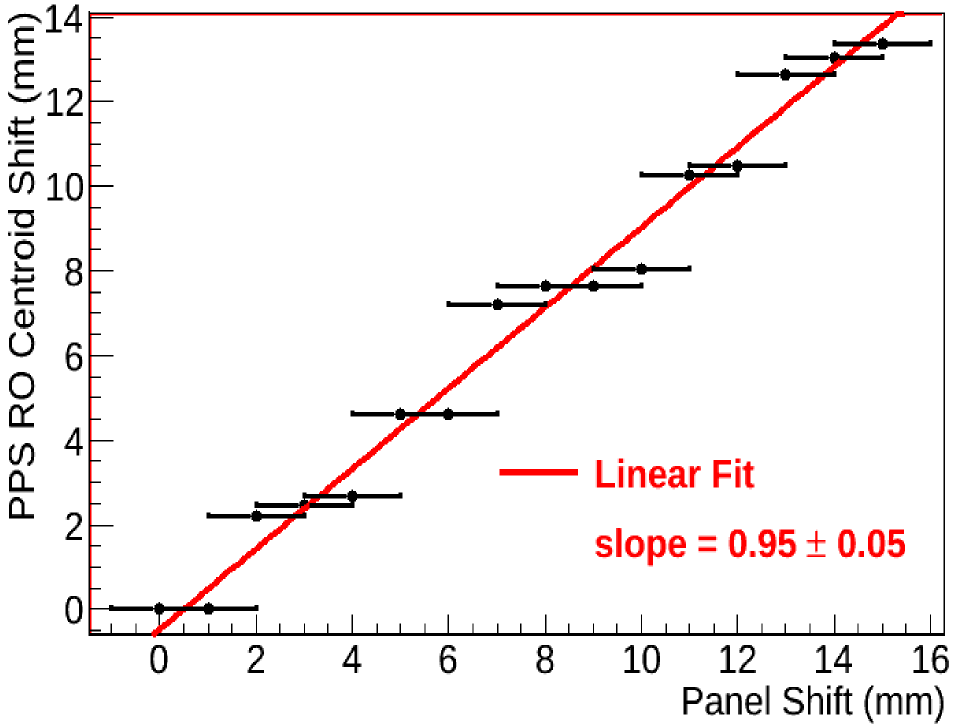
- Medical Accelerator: beam energy 226 MeV, Gaussian distributed with 0.5 cm width
- Proton rate was larger than 1 GHz on the entire spread of the beam

Position Scan Setup

- Position scans (panel filled with 1% CO_2 in Ar at 600 Torr)
  - ***1 mm steps*** using brass collimator with **1 mm hole** directly in beam center
- Rate of protons thru 1 mm hole in center of beam was **measured at 2 MHz**



1 mm Position Scan Results



Reconstructed centroid of hit map vs. panel relative displacement with respect to panel's initial position.