High-Performance Plasma Panel Based Micropattern Detectors

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PPS Collaboration

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- **Oak Ridge National Laboratory, Physics Division**
  Robert Varner (PI) , James Beene
- **University of Michigan, Department of Physics**
  Daniel Levin (PI), Robert Ball, J. W. Chapman, Claudio Ferretti, Curtis Weaverdyck, Riley Wetzel, Bing Zhou
- **Tel Aviv University (Israel), School of Physics & Astronomy**
  Erez Etzion (PI), Yan Benhammou, Meny Ben Moshe, Yiftah Silver
- **General Electric Company, Reuter-Stokes Division**
  Kevin McKinny (PI), Thomas Anderson
- **Ion Beam Applications S.A. (Belgium)**
  Hassan Bentefour (PI)

Outline

- **Motivation – *The Concept***
- **Plasma display panel (PDP) operational principles**
- **Plasma panel sensor (PPS) description**
- **Simulations**
- **Lab results**
- **Next generation designs**
- **Summary**

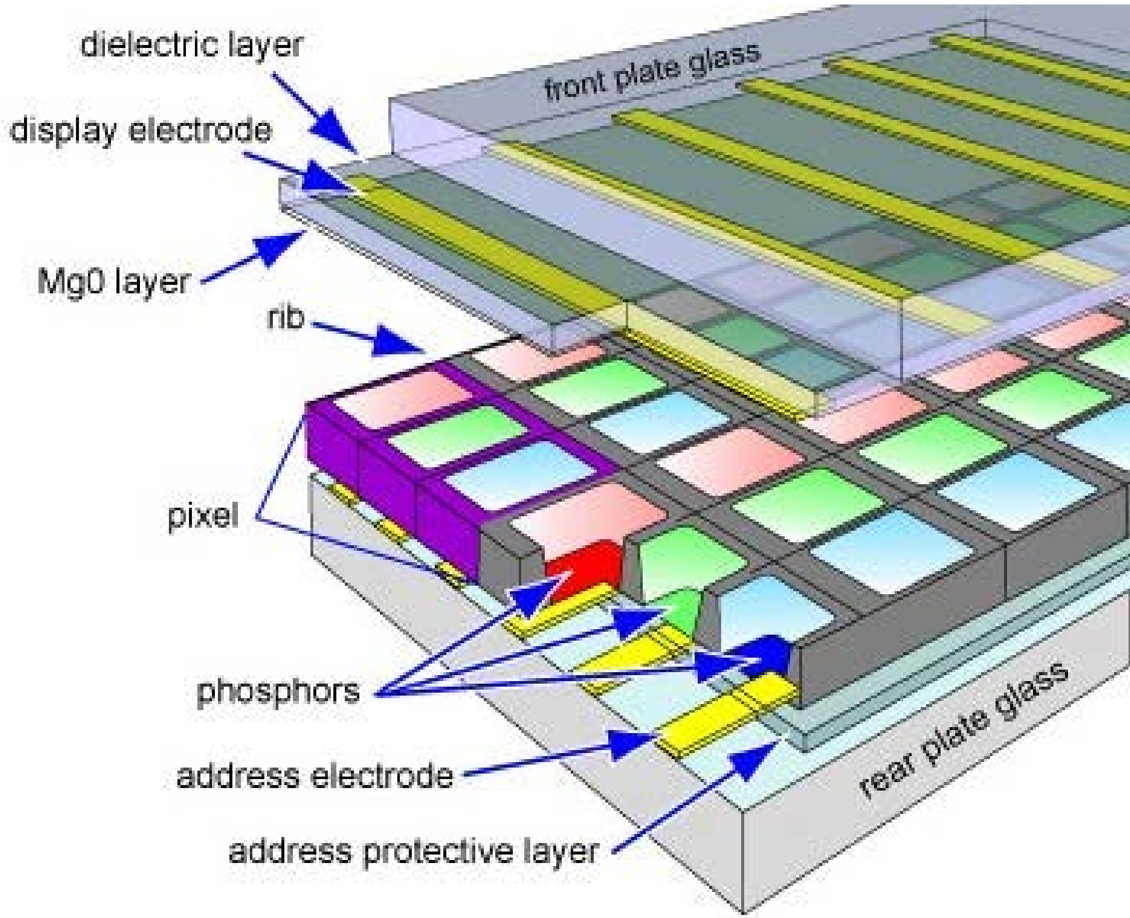
Motivations

- **The Concept:** ***Plasma display panels as particle detectors*** **($0.03/cm^2)**
  - over 40 years of plasma display panel (PDP) manufacturing & cost reductions
- **Hermetically sealed**
  - no gas flow
  - no expensive and cumbersome gas system
- **Scalable dimensions, long life, low mass & compact profile**
  - cm to meter size with thin substrate capability, robust materials/construction
- **Potential to achieve contemporary performance benchmarks**
  - timing resolution ➔ approximately 1 ns
  - granularity (cell pitch) ➔ 50-200 µm, spatial resolution ➔ tens of µm
  - rad hardness, B-field insensitivity, high rates, 2D readout
- **Applications**
  - nuclear & HEP, medical/particle beam imaging, homeland security, industry

TV Plasma Panel Structure

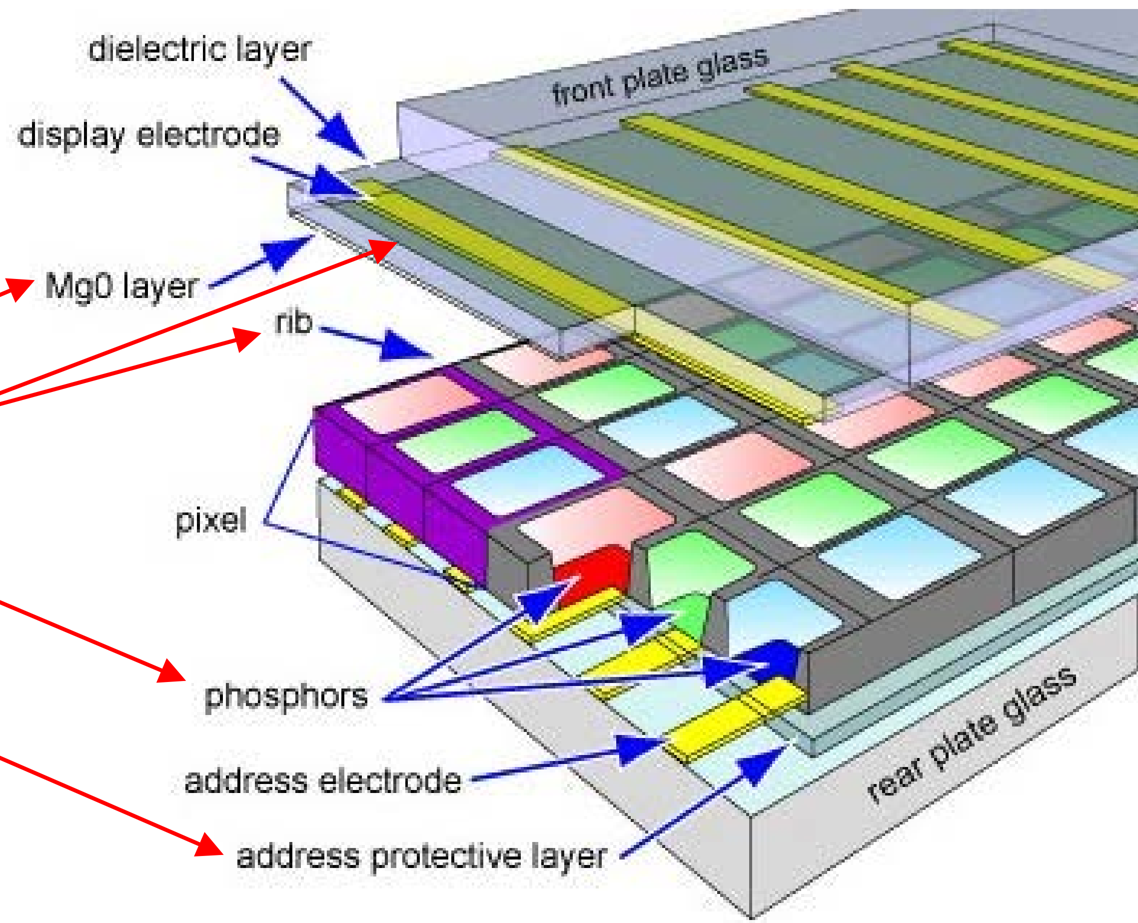
A Display panel is a complicated structure with

- MgO layer
- dielectrics/rib
- phosphors
- protective layer



TV Plasma Panel Structure

- *For **detector**, a simplified version with readout & quench resistor*
  - **No** MgO layer
  - **No** dielectric/rib
  - **No** phosphors
  - **No** protective layer



The Plasma Panel Sensor (PPS)

Each pixel operates like an independent *micro-Geiger counter* and is activated either by ***direct*** ionization in the gas, or ***indirect*** ionization in a conversion layer. The latter results in subsequent emission of charged particles into the gas that initiates a localized gas discharge at a pixel site which is detected by the readout electronics. PPS devices based primarily on direct ionization have been the focus of our research efforts to date.

PPS Radiation Detection

- For ***charged particles*** → ***direct*** ionization in the gas (e.g. alphas, betas, protons, heavy nuclei, minimum ionizing particles or MIPs such as muons, etc.).

- For ***neutral particles*** → ***indirect*** ionization via a conversion layer (e.g. neutron capture in a conversion material such as ^{3}He, ^{10}B or ^{157}Gd that emits charged particles into the gas).

- For ***photons*** (e.g. X-rays / gammas, UV) → ***direct*** ionization in the gas, or ***indirect*** ionization via a conversion layer (e.g. electron emission via Compton scattering or photocathode).

PPS Radiation Sources of Interest

Sources demonstrated to date:

- **Cosmic-Ray Muons** (~ 4 GeV at sea-level)
- **Muon Beam**: 180 GeV range (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 (for ***proton beam cancer therapy & proton-CT***)
- **Neutrons**: Thermal neutrons (for ***neutron scattering & homeland security***)
- **Gamma-Rays**: ^{60}Co (~1.2 MeV), ^{57}Co (122 keV), ^{99m}Tc (143 keV), ^{137}Cs (662 keV)
- **UV-Photons**: "Black UV-lamp" with emission at 366 nm

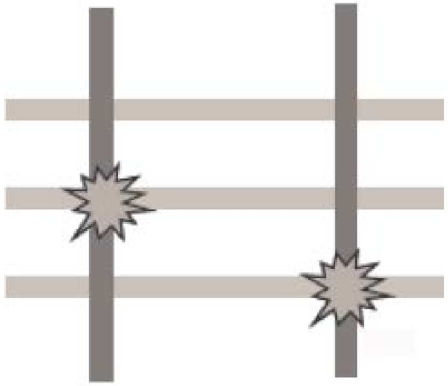
Sources planned for demonstration in 2014 - 2015

- **Radioactive Ion Beams**: 1 - 100 MeV/u (for ***nuclear physics in 2014***)
- **X-Ray Beams**: 6 - 8 MeV (for ***X-ray beam cancer therapy)***
- **Electron Beams**: 6 - 20 MeV (for ***electron beam cancer therapy***)

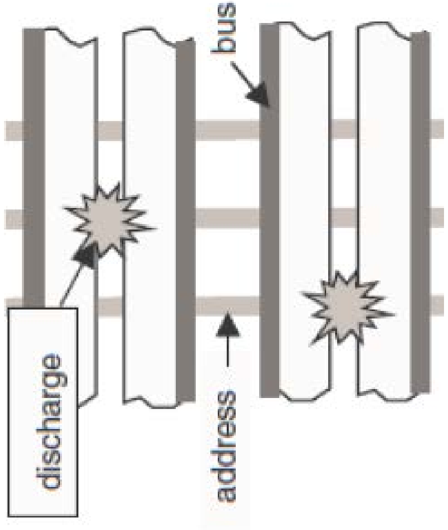
Commercial Panel Designs

- Two basic configurations for the electrodes: **CD** and **SD**
- Discharge dimensions ≈ 100 μm
- Gas pressure ≈ 400-600 Torr (usually Ne, Xe, Ar, Kr, He)
- Applied voltage typically hundreds of volts

Columnar Discharge (CD)

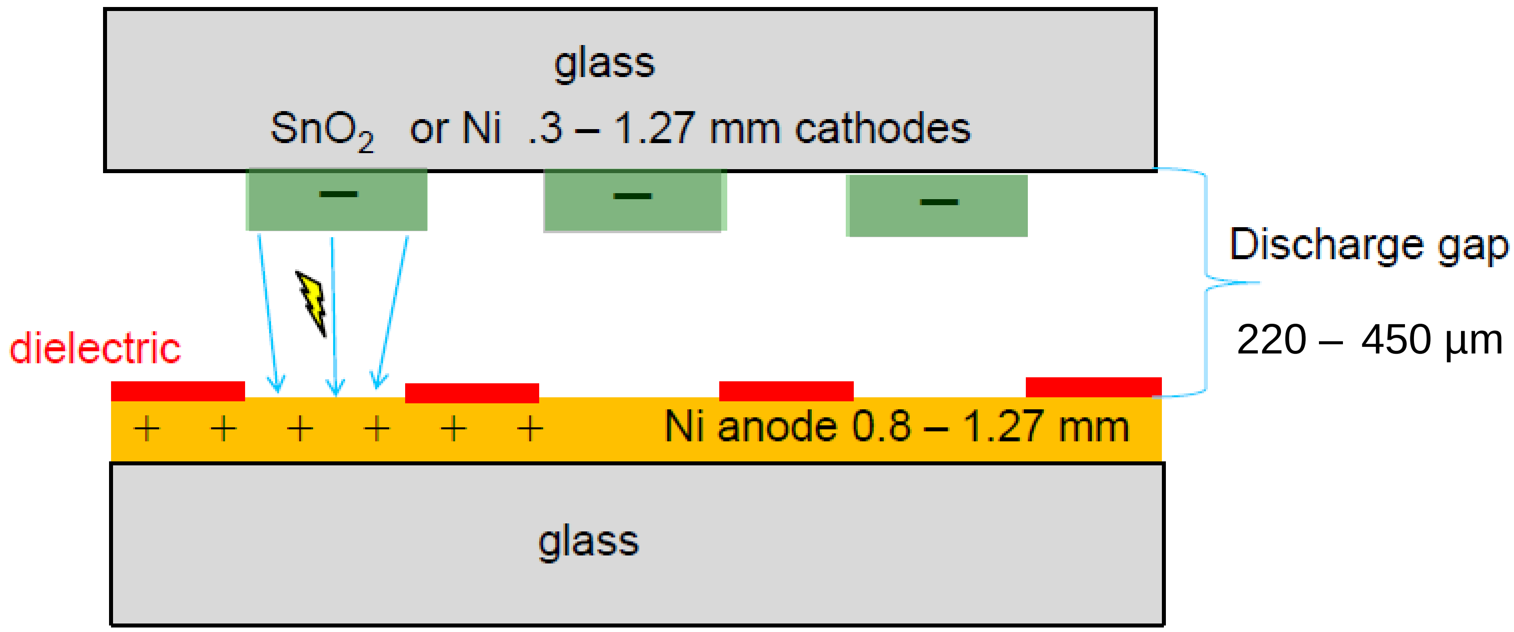


Surface Discharge (SD)



Commercial Plasma Panel

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



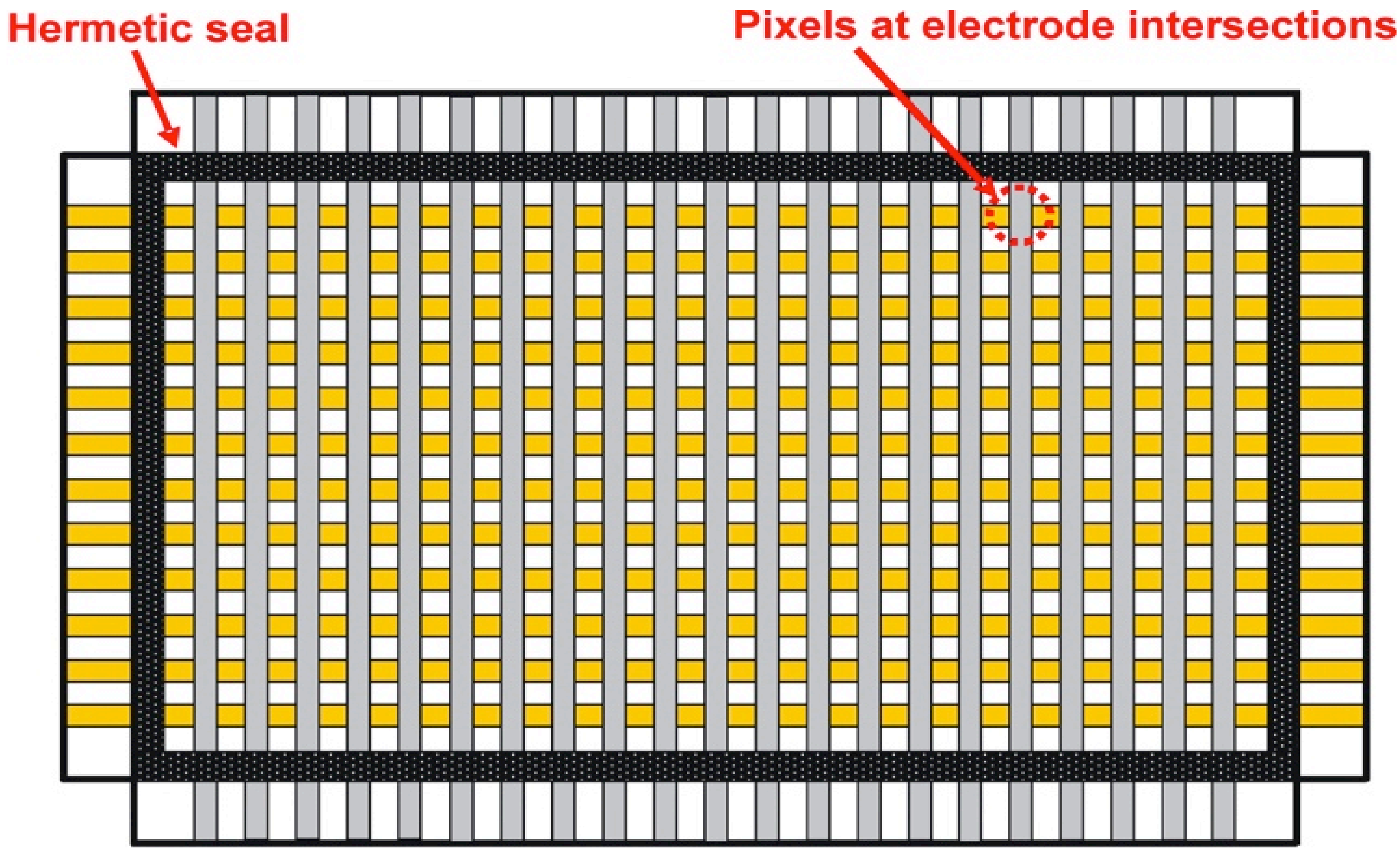
PDP → PPS

1. **Procure OEM *(pinball machine)* panels *without* PDP gas**
2. **Alter OEM electrode material (e.g. replace SnO_2 with Ni)**
3. **Modify seal, add gas port and high vacuum shut-off valve**
4. **Pump down, bake-out**
5. **Fill with custom gas mixture, *seal by "closing" valve***
6. **Configure with HV feed, quench resistors, readout/DAQ**

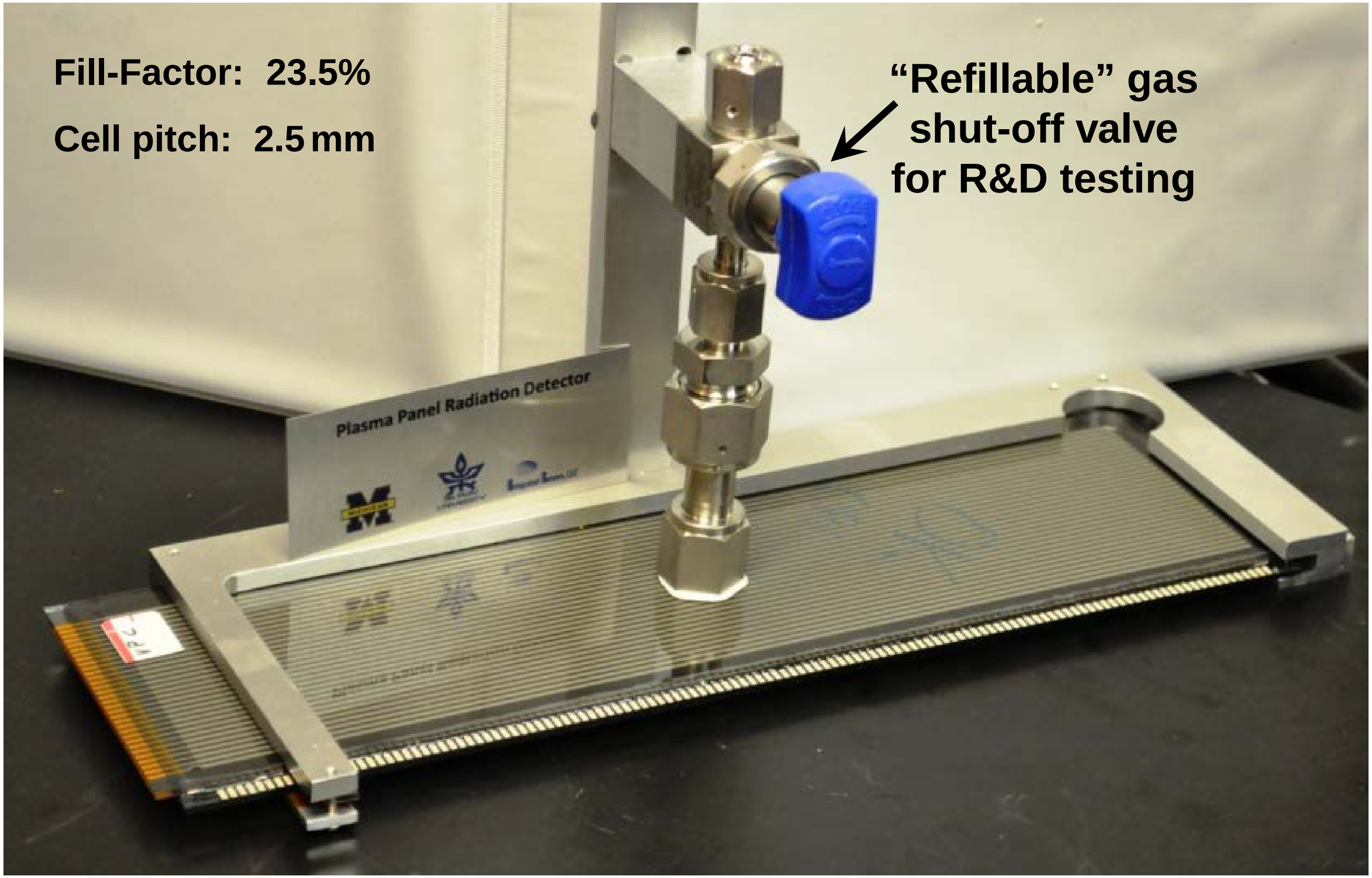
- **Panels operable for months (even 1 year) after gas-filling *without* hermetic seal (i.e. only "closed" shut-off valve)**

PPS with CD-Electrode Structure

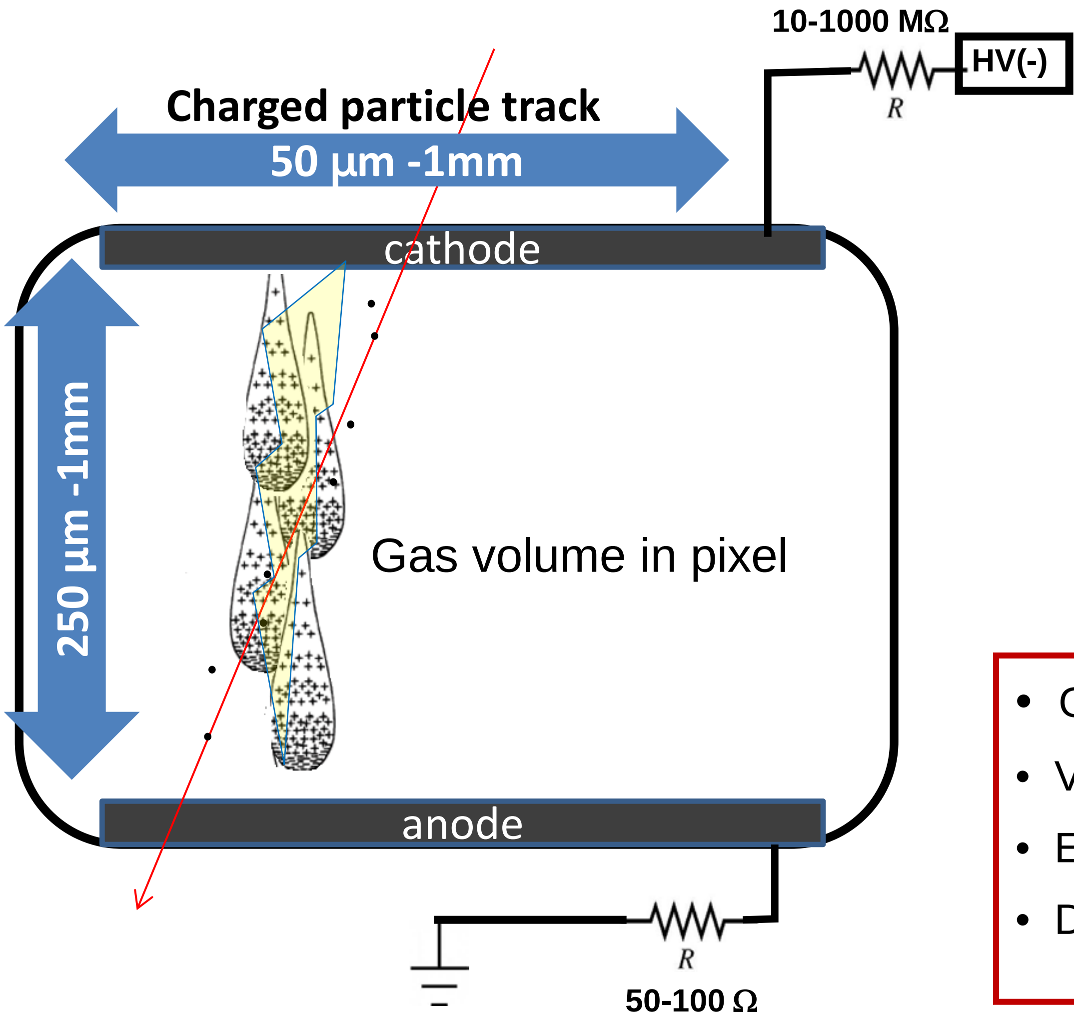
(≈ 20-25% active cell/pixel fill-factor)



1^{st} Generation Prototype PPS
Modified Commercial Panel



Principles of Operation



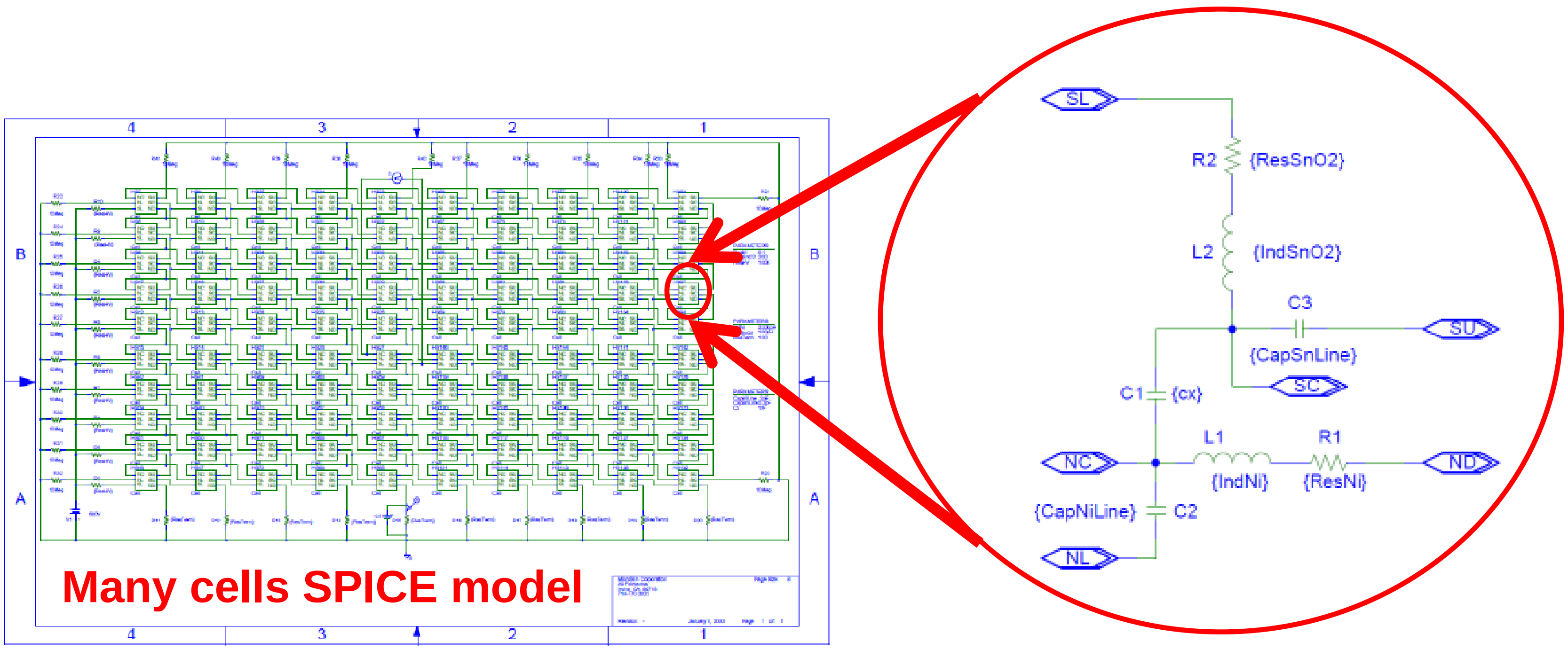
- Accelerated electrons begin ***avalanche***
- Large electric field leads to ***streamers***
- Streamers lead to ***breakdown*** - roughly follows Paschen's law.

- Gas gap becomes conductive
- Voltage drops on quench resistor
- E-field inside the pixel drops
- Discharge terminates

Equivalent Circuit Simulations

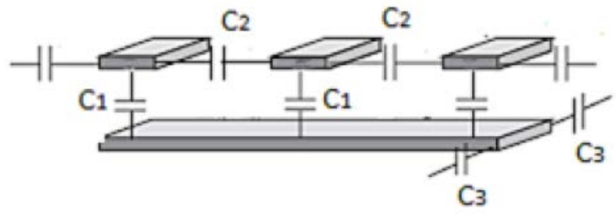
- SPICE simulation incorporates the inductances and capacitances calculated with COMSOL
- Electrical pulse is injected into the cell and the output signal is simulated

Single cell SPICE model

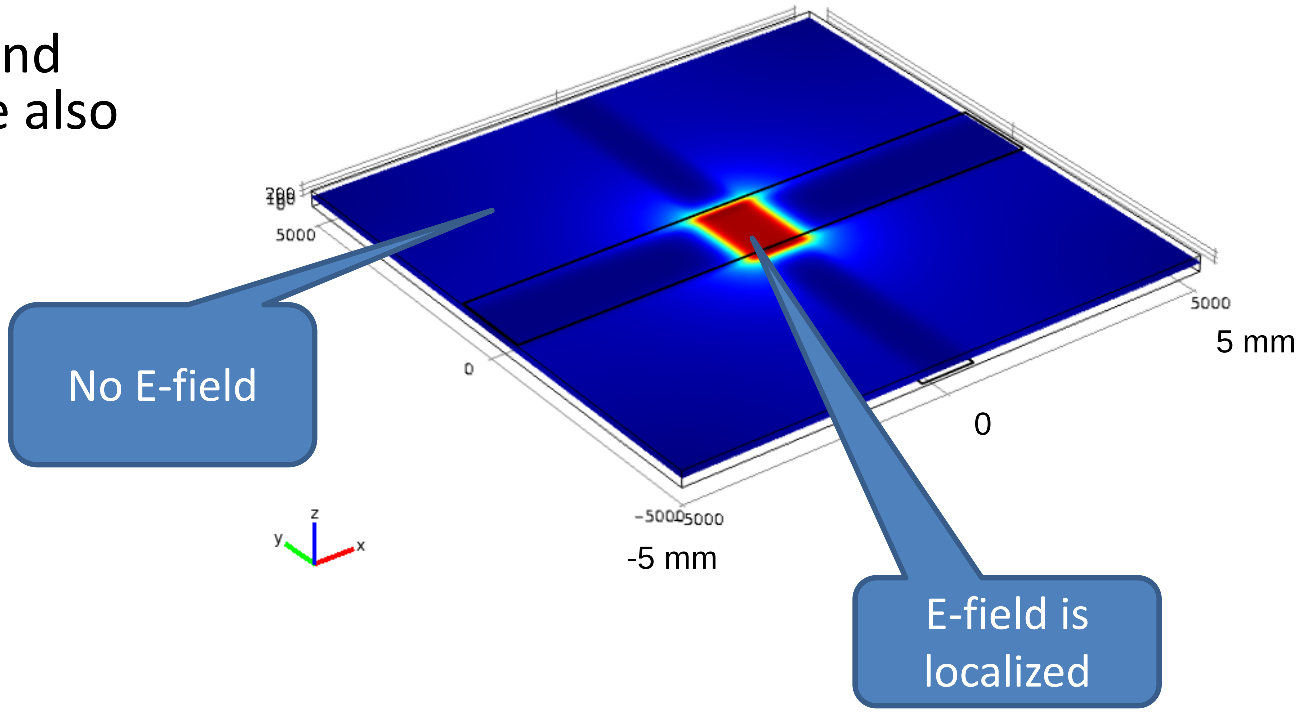


Electromagnetic Field Model

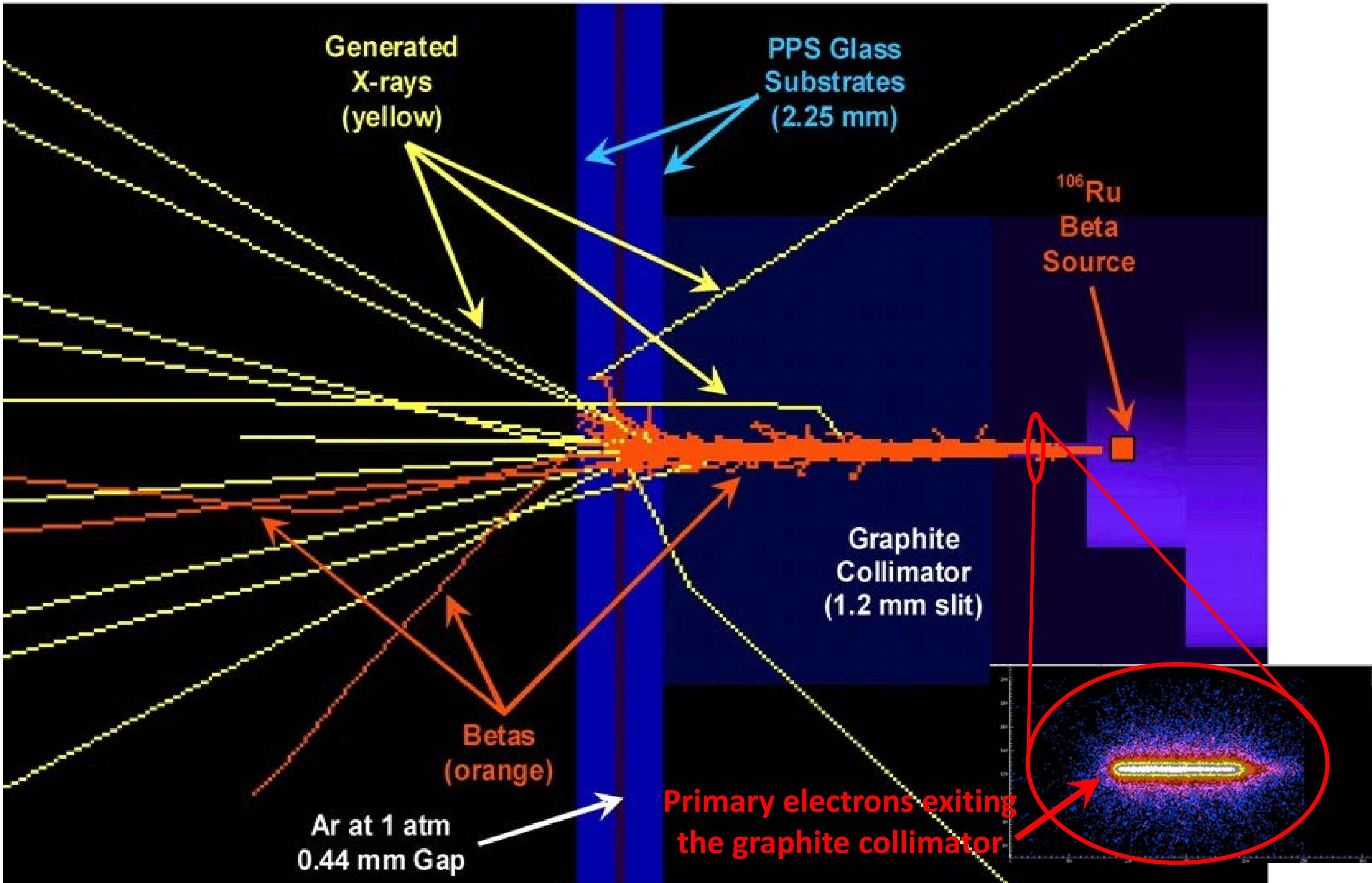
- Each cell is modeled as a capacitor
- COMSOL model for the electric field inside the cell
- Capacitances and inductances are also calculated



E-field in the PDP pixels



Collimated β-Source Simulation



Design & Operating Parameters

(most of which are currently being investigated)

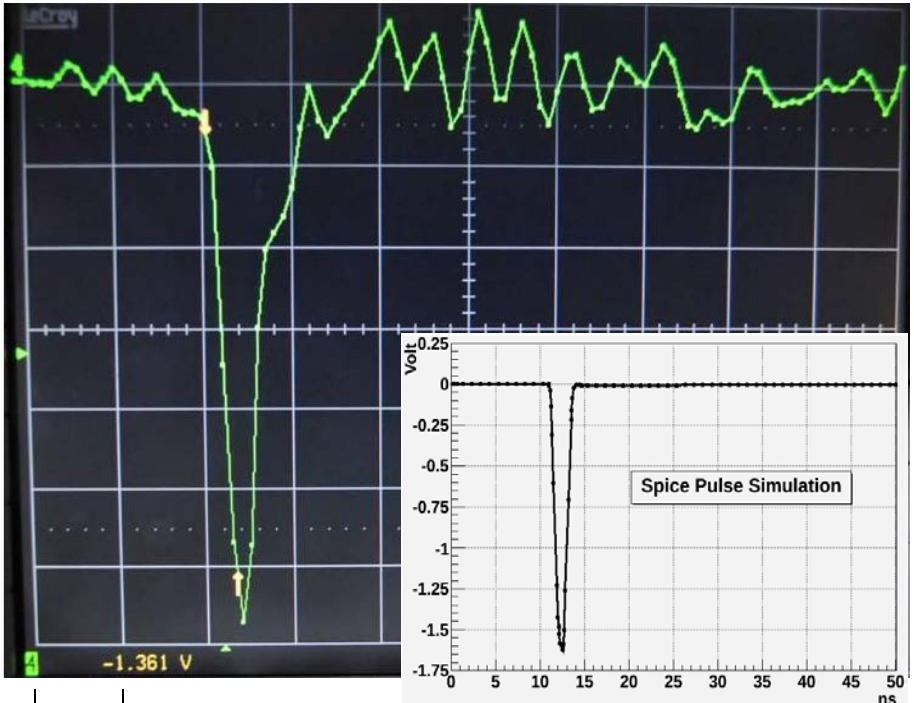
- **Cell Design: fill-factor, gas gap, discharge gap**
  - **- open vs. closed architecture**
  - **- columnar vs. surface discharge**
- **Electrodes: pitch, width, material**
- **Cell capacitance**
- **Operating voltage**
- **Quench resistance**
- **Gas mixture & pressure**
- **Substrate material (e.g. thickness, density)**
- **Dielectric surfaces**

Performance Issues

(most of which are currently being addressed)

- **After pulsing & discharge spreading**
- **Gas hermeticity & decomposition**
- **Response in magnetic field**
- **Electrode degradation**
- **Radiation hardness**
- **High rate response**
- **Spatial uniformity**
- **Spatial response**
- **Time response**
- **Efficiency**
- **Readout**
- **Cost**

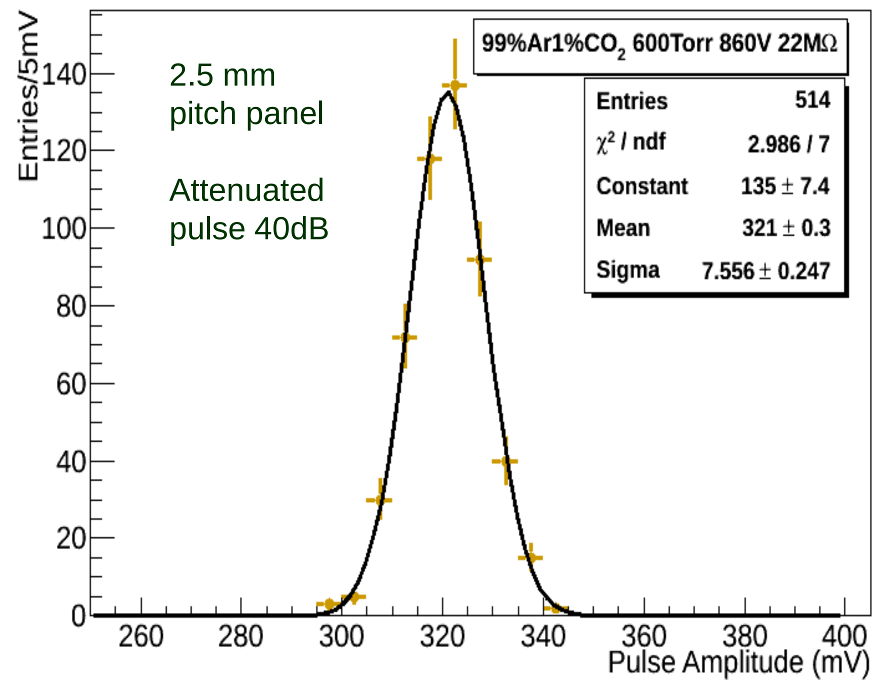
Panel Signals (β-source)



← Pulse from ***Xe filled panel in 2003***, tested ***2010***, 1.0 mm electrode pitch.

0.25 volts / div

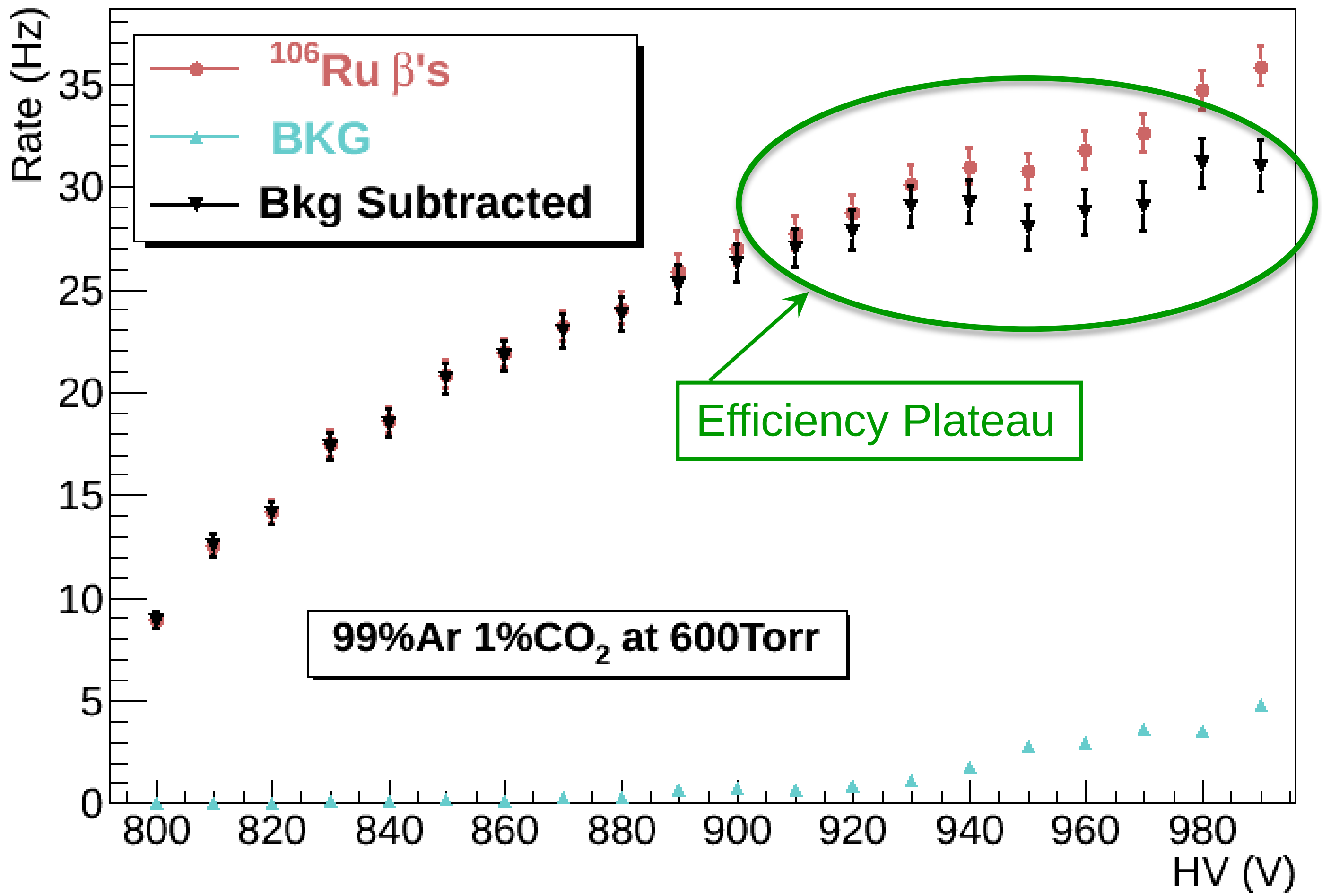
5 ns



Volt level amplitudes
Rise time 1-2 ns
Uniform pulse shape →

Response to β- Source

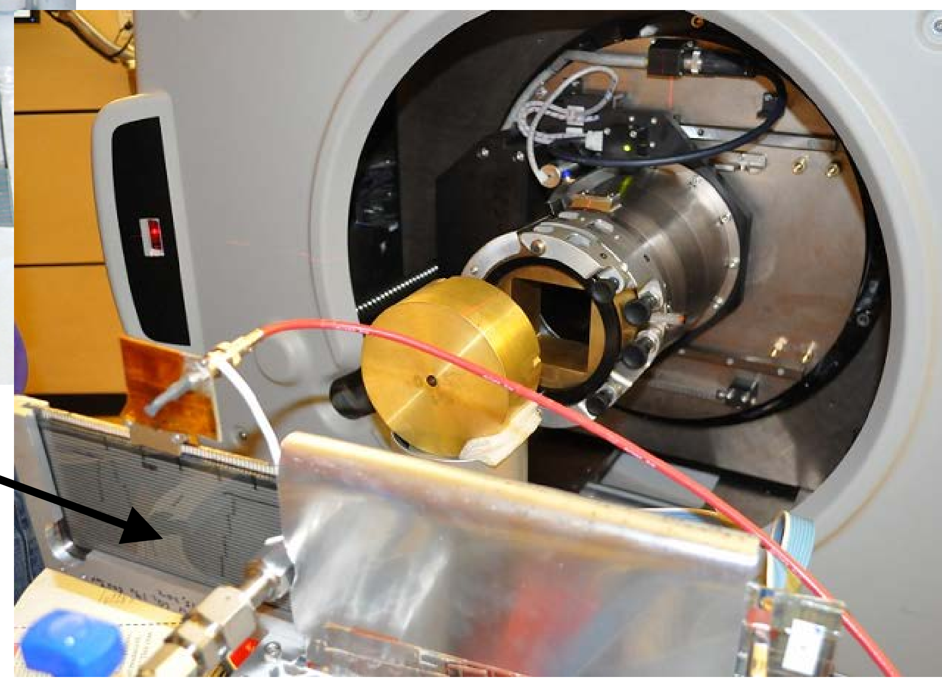
Vs. applied High Voltage



IBA Proton Beam Test

- Cancer treatment facility (ProCure in Warrenville, IL)
- Beam energy 226 MeV, proton rate > 1 GHz

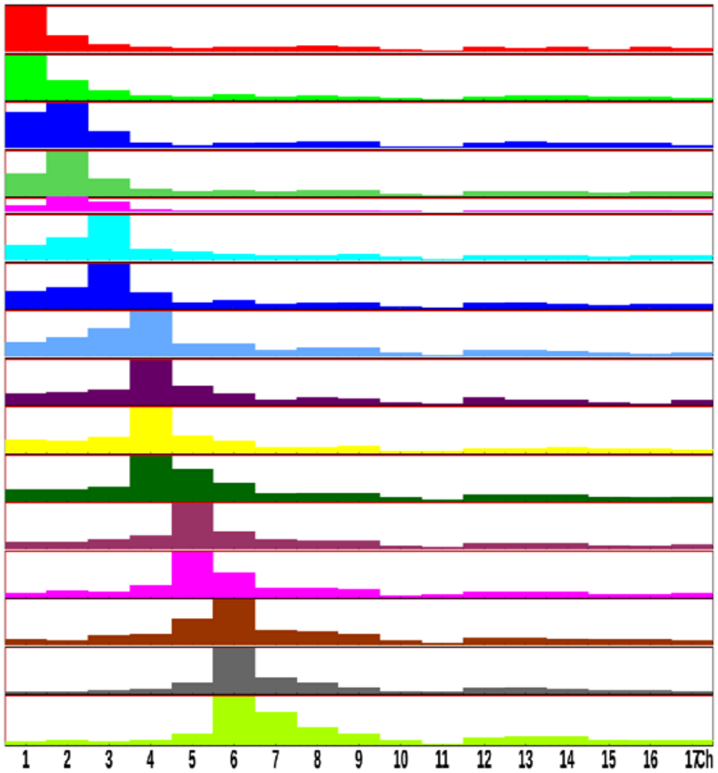
Panel on motorized patient table

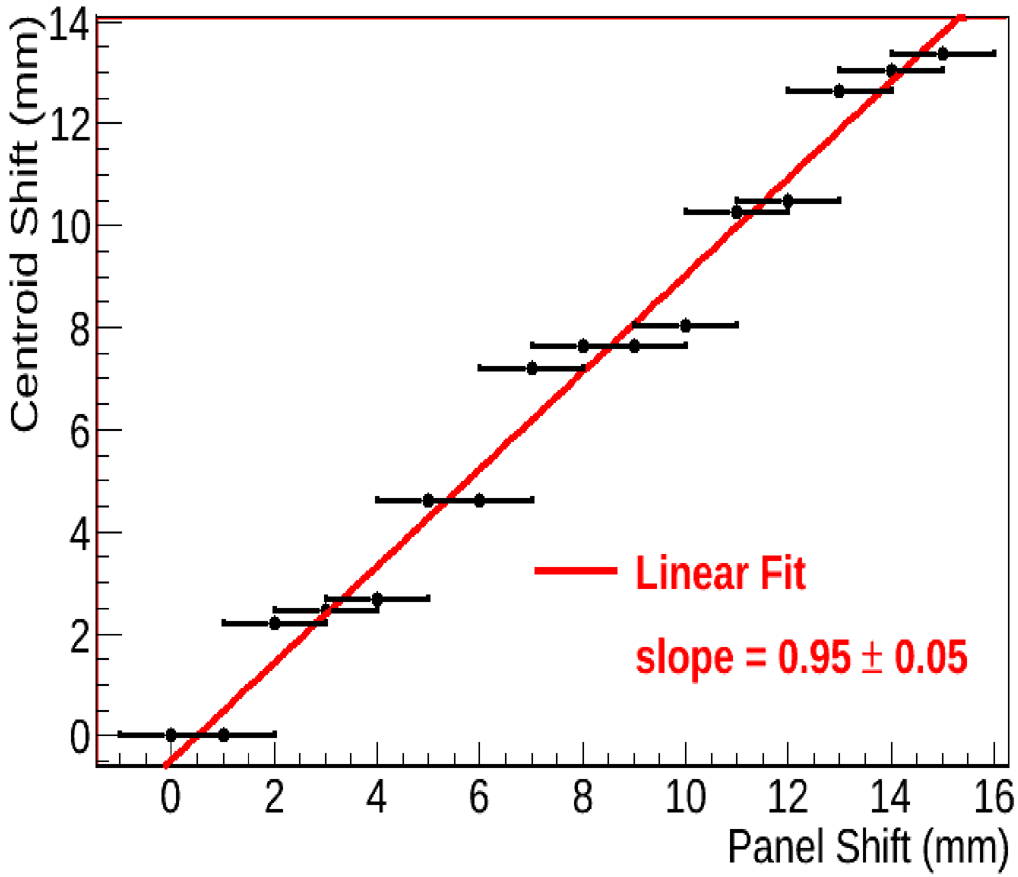


The Panel
1% CO2 in Ar
(600 Torr)

Proton Beam Results - 1 mm Scan

- 1 mm diameter collimator on the beam axis
- Proton rate on panel ~ 2 MHz (centered over ~ 1 pixel)

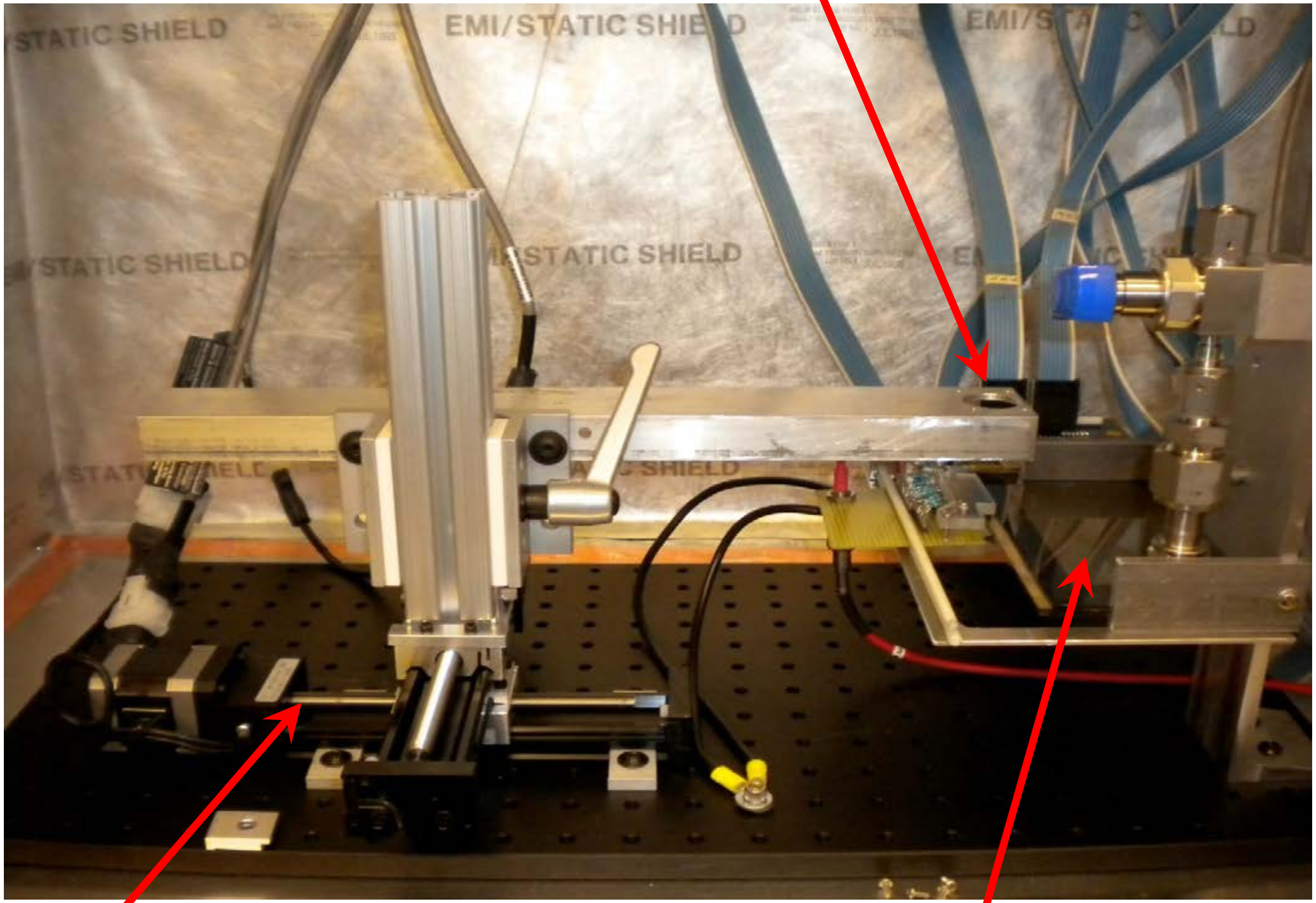




Collimated Source Position Scan

^{106}Ru collimated source

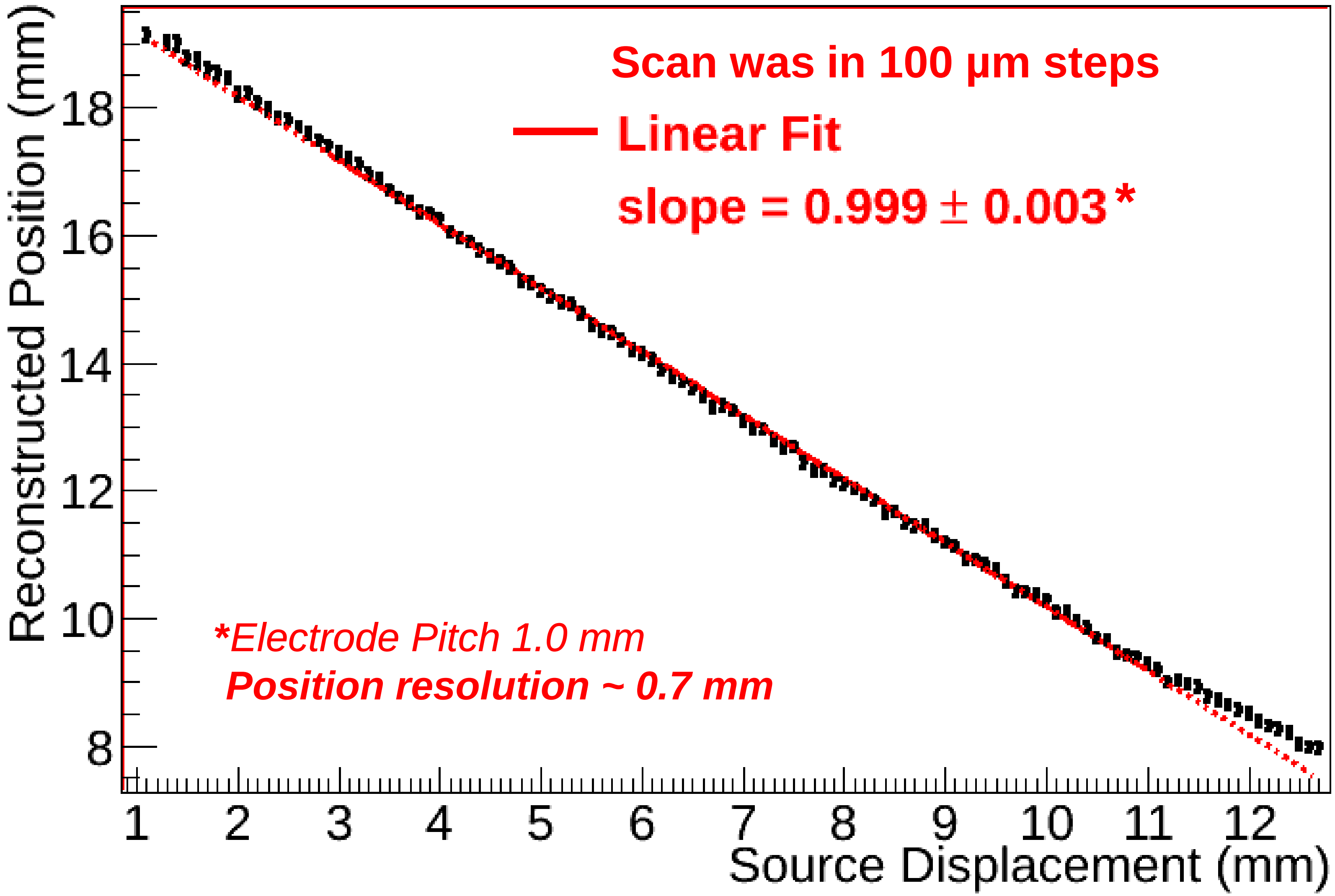
- Light-tight , RF shielded box
- 1 mm pitch panel
- 20 readout lines
- 1.25 mm wide graphite collimator



Motorized X-Y table

Test Panel

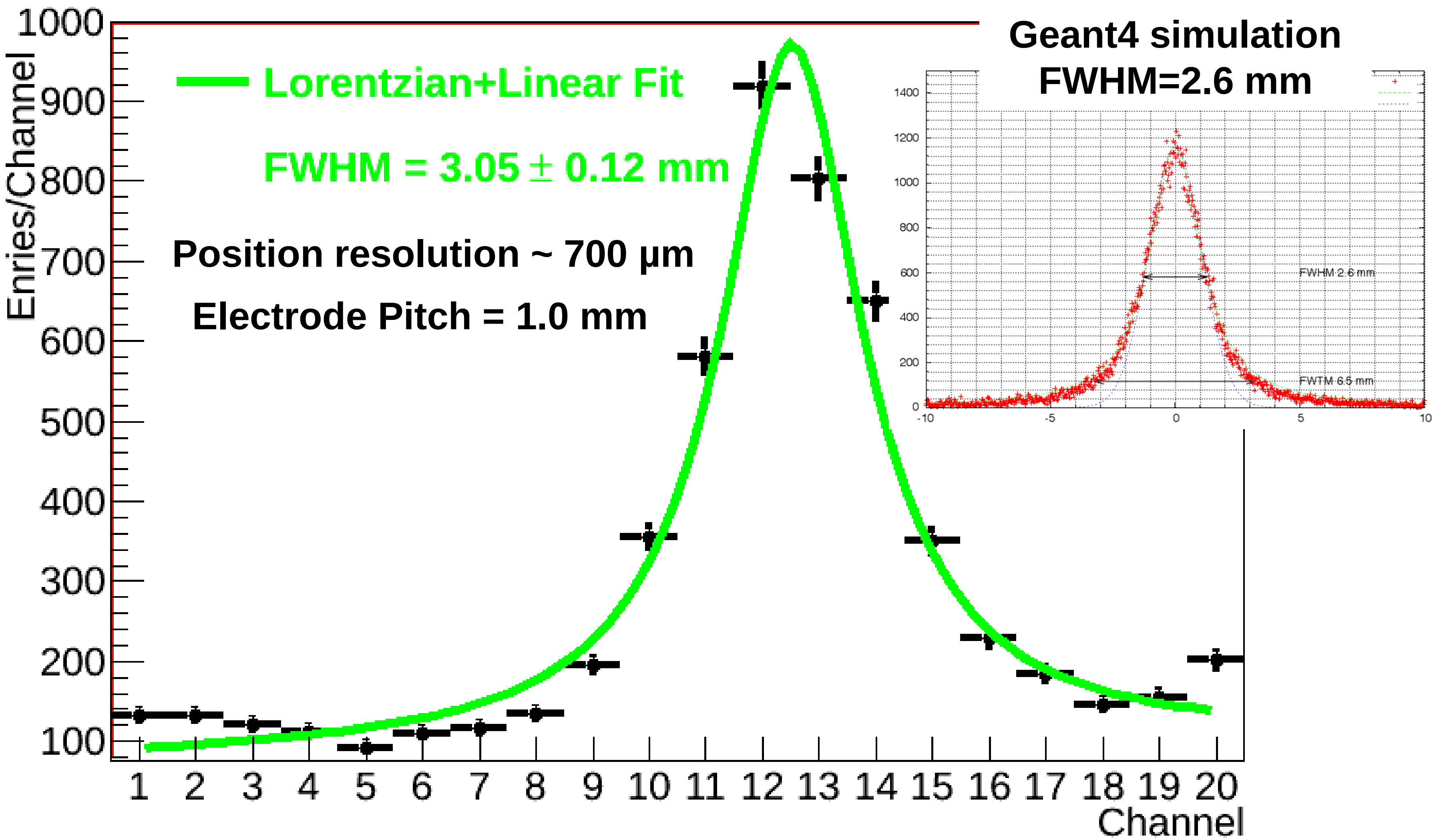
Collimated β – Source Position Scan (^{106}Ru)



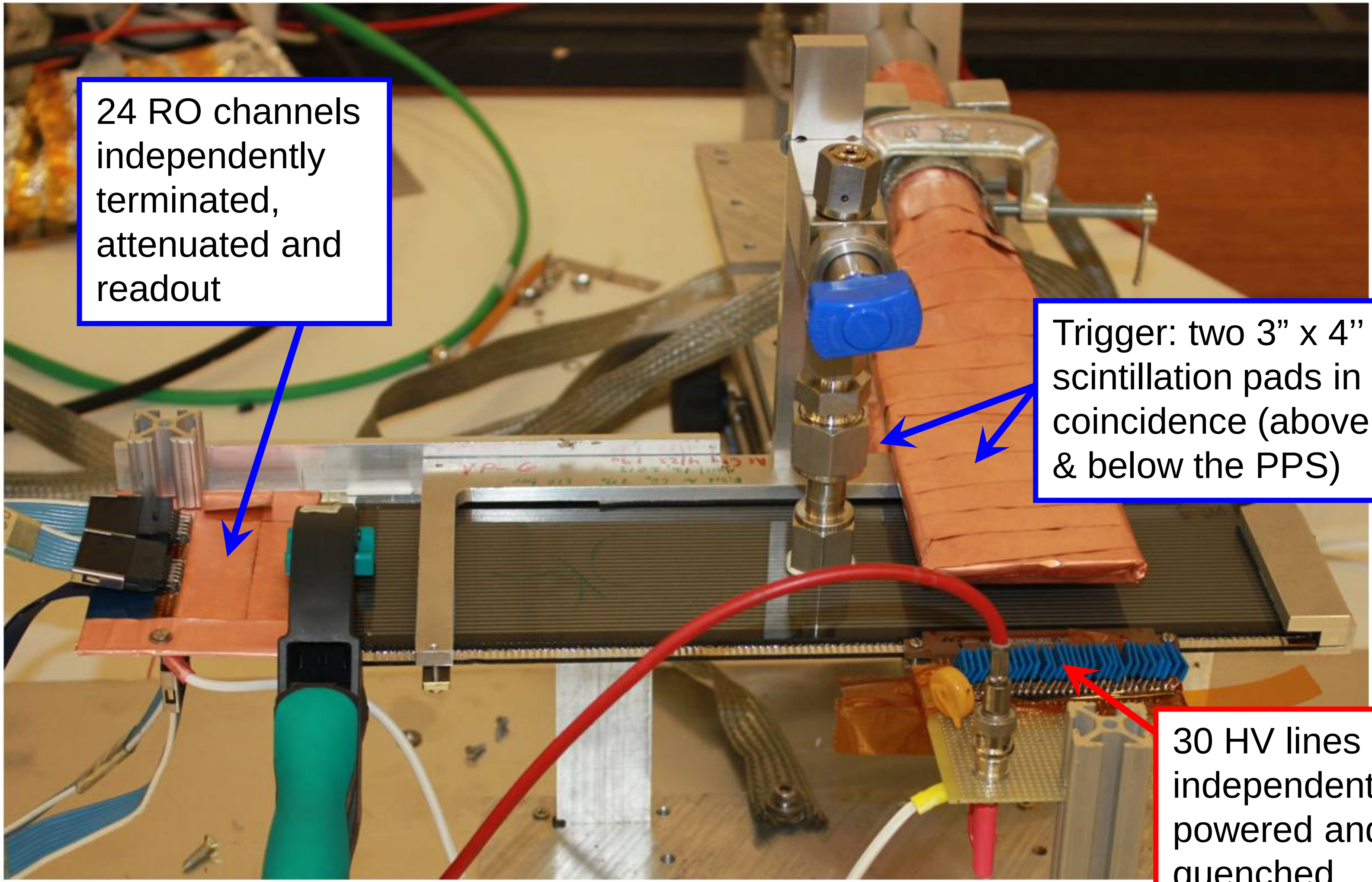
Source Moved in 0.1 mm Increments

(1 mm pitch panel)

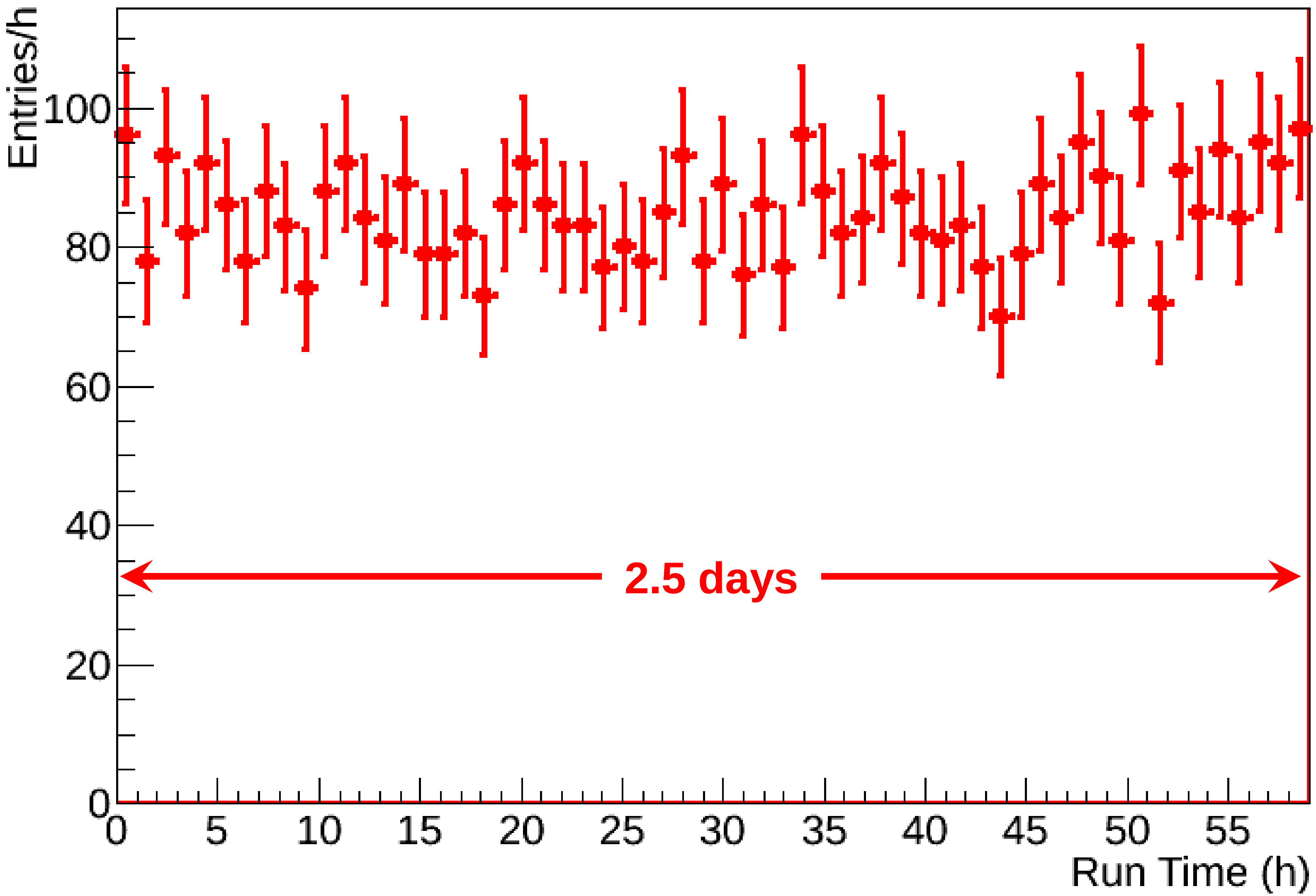
Collimated β – Source Measurement (^{106}Ru)



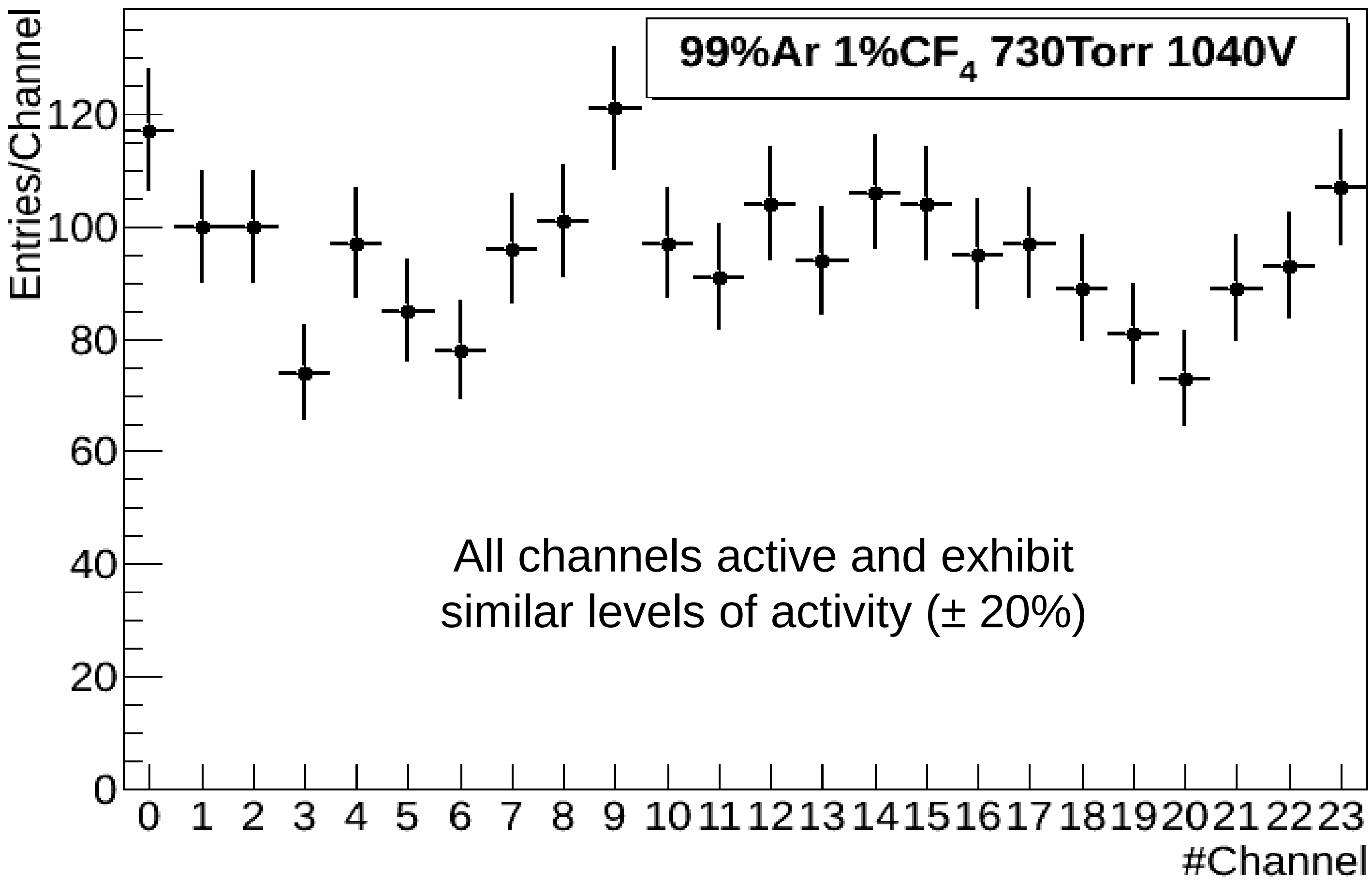
CR Muon Measurement Setup



Stability - Response to CR Muons

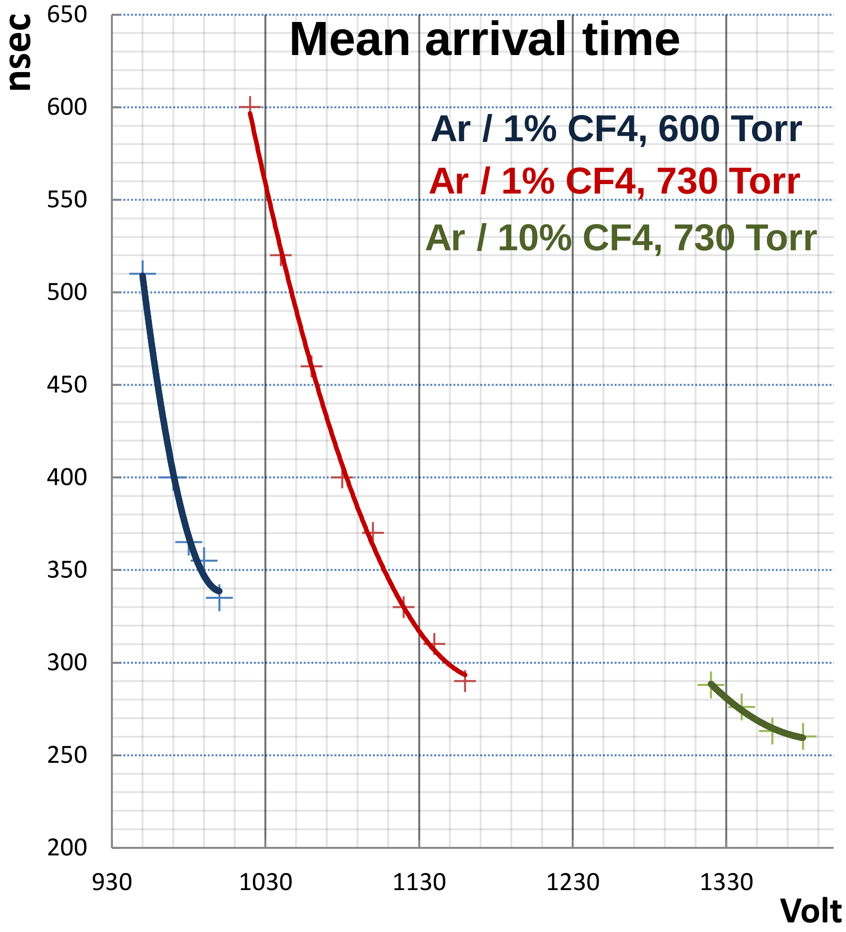


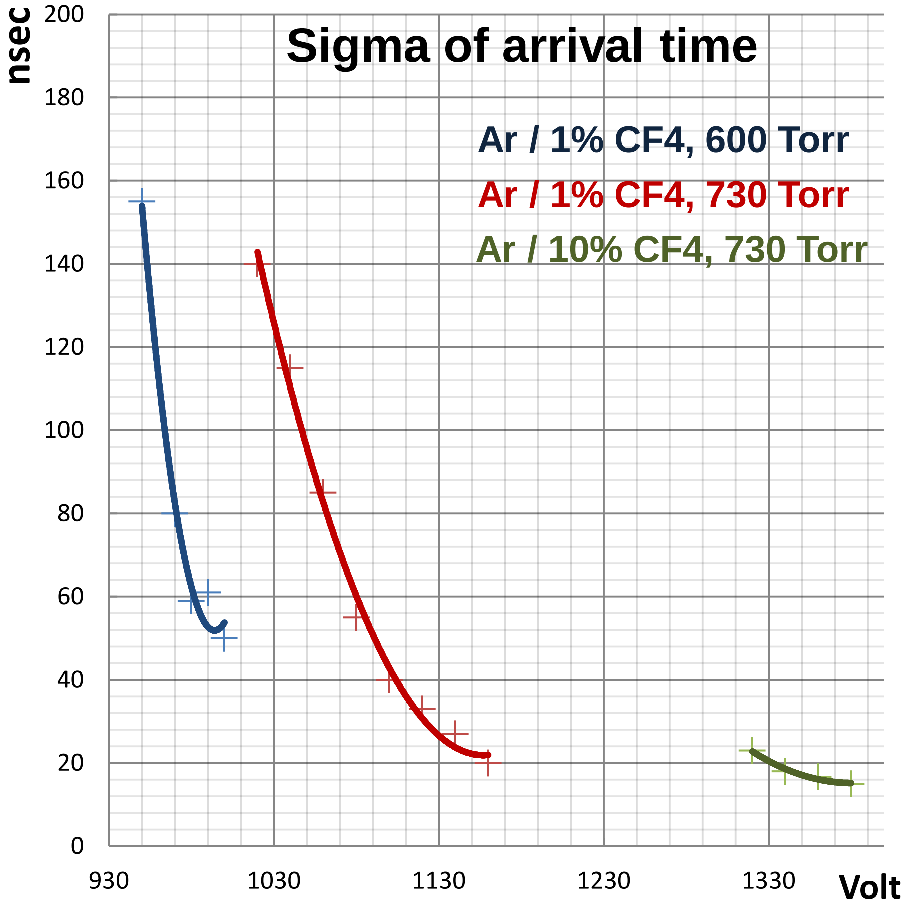
Uniformity - Response to CR Muons



Timing for Different Gases

(raw signals – not trigger subtracted)

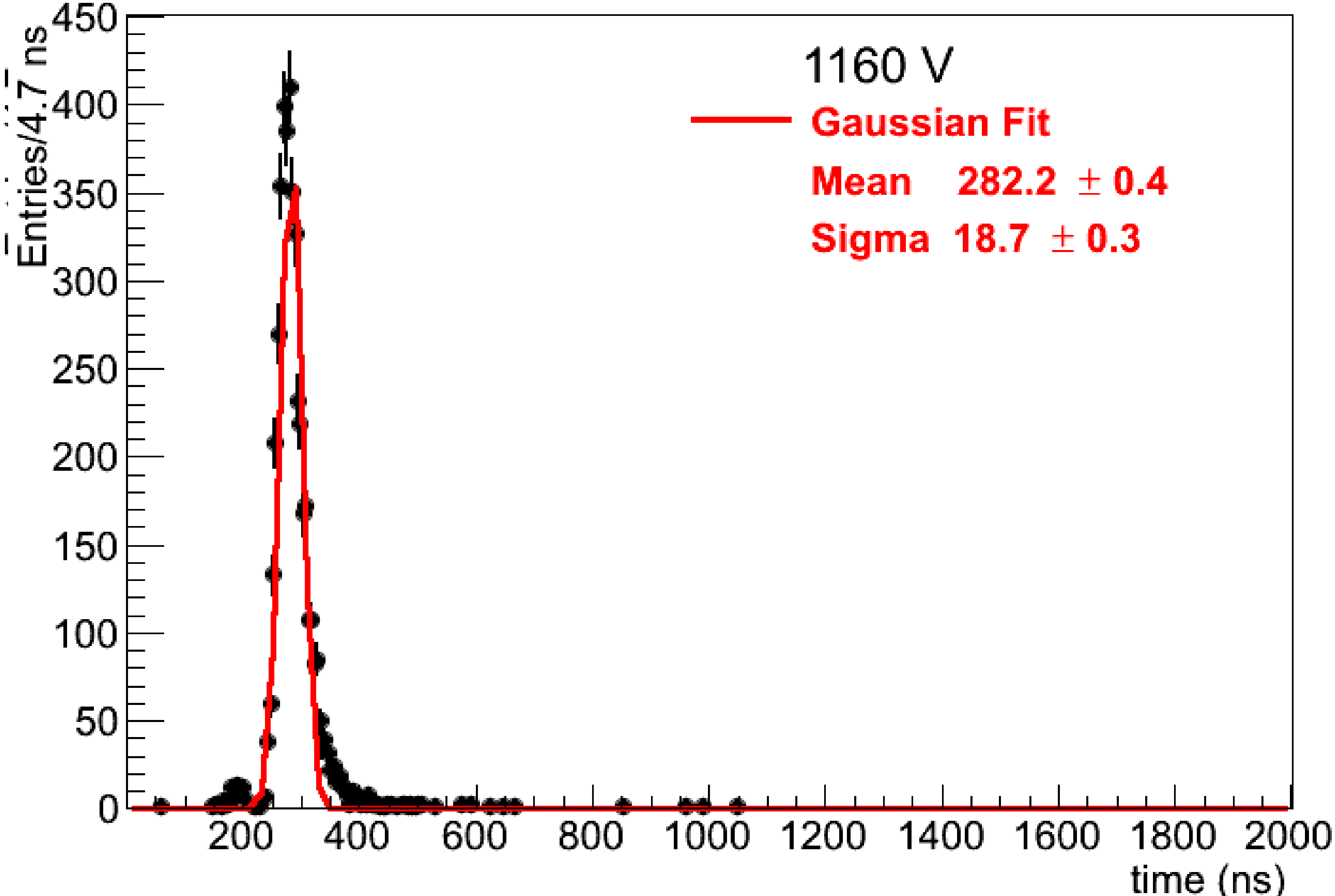




Gas mixtures & pressures working at ***higher voltage*** ➡ ***faster timing***

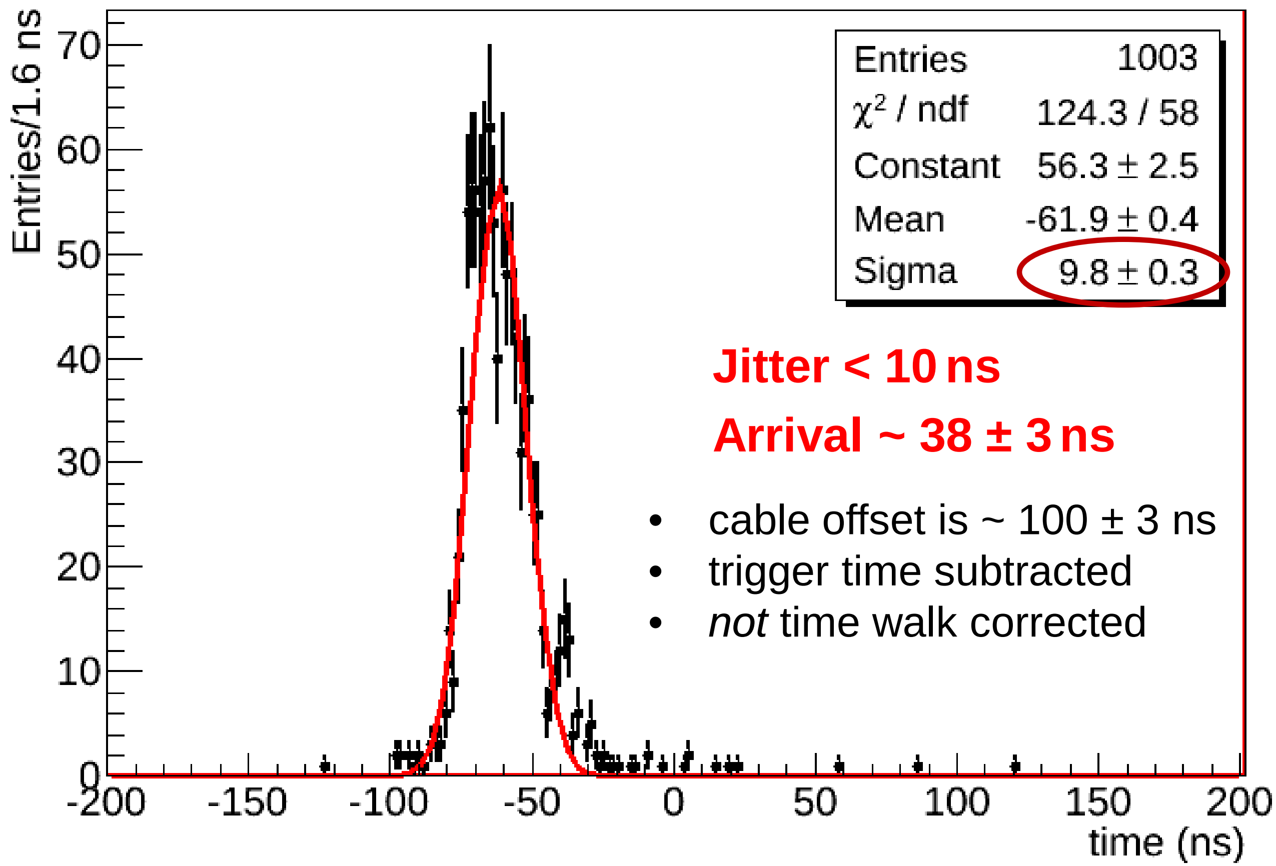
CR Muon Arrival Time vs. HV

Ar / 1% CF_4 at 730 Torr *(raw signals – not trigger subtracted)*



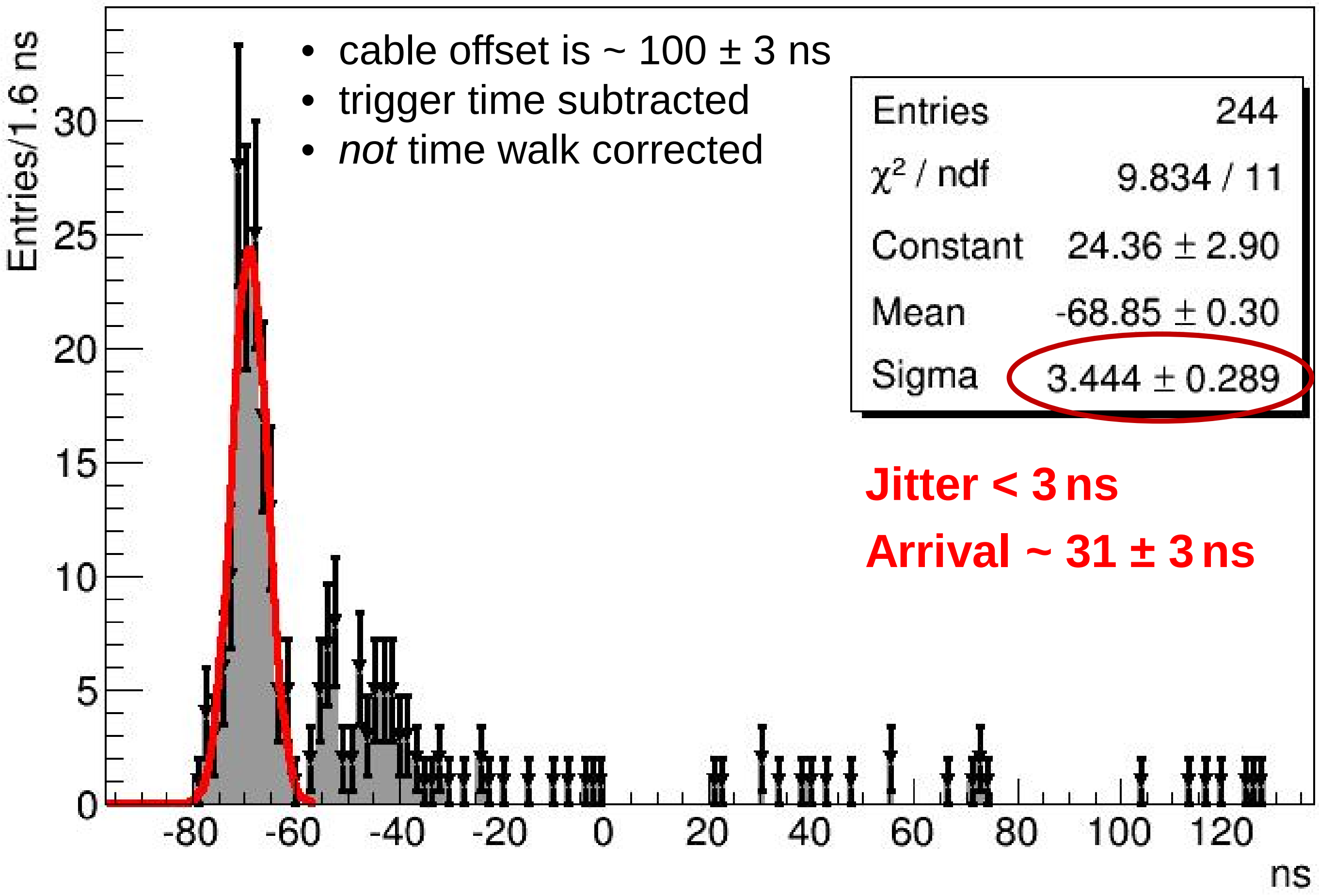
Time Spectrum of CR Muons

Using 65% ^4He / 35% CF_4 at 730 Torr



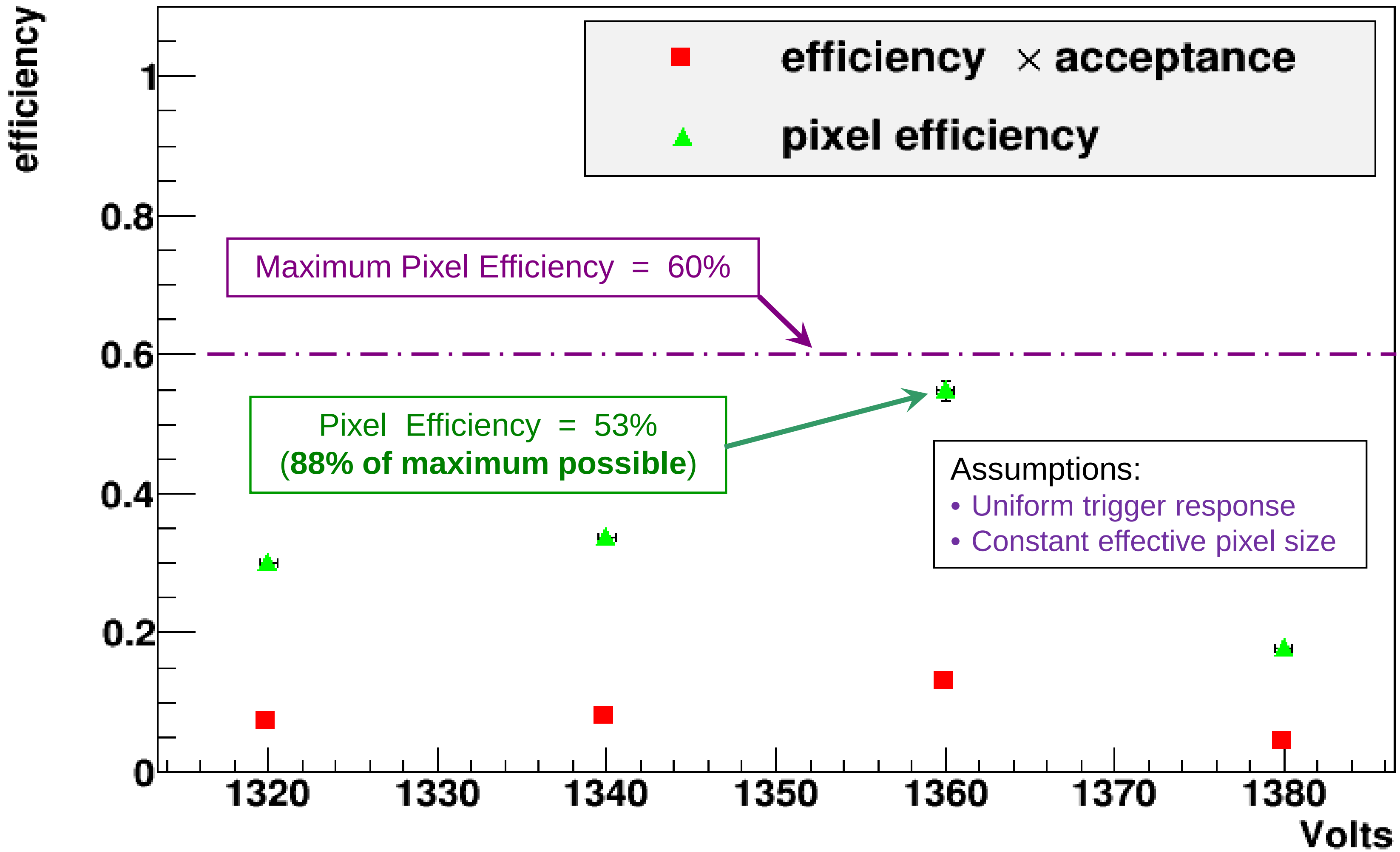
Time Spectrum of CR Muons

Using 80% ^{3}He / 20% CF_4 at 730 Torr



PPS Efficiency for CR Muons

(10% CF_4 in Ar, at 740 Torr, 0.38 mm gas gap, 2.5 mm electrode pitch)



Thermal Neutron Detection

(in collaboration with GE, Reuter-Stokes)

Objectives: Develop alternative to **^{3}He** as high efficiency neutron detector with high γ rejection

This Test: Explore PPS as a general detector structure for converting neutrons using thin gap **^{3}He** gas mixture

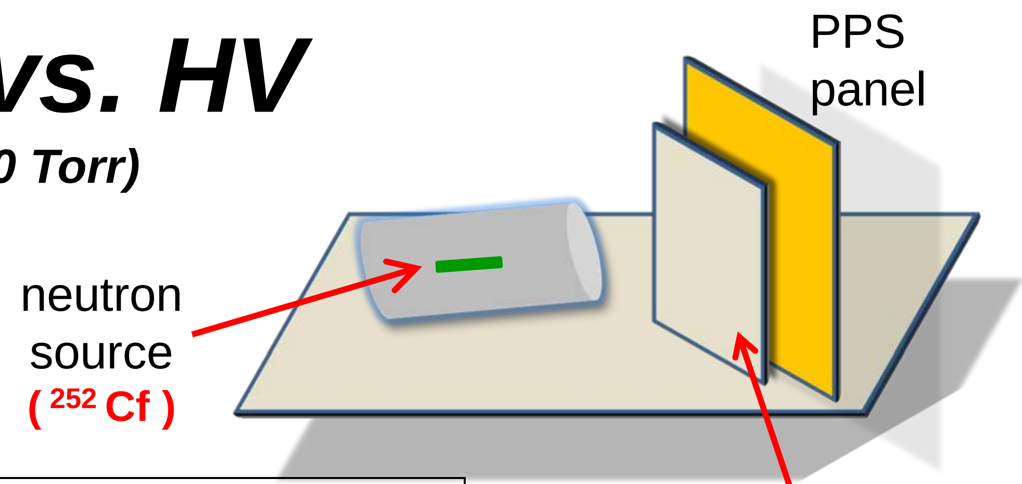
Gas Fill: 80% **^{3}He** + 20% CF_4 at 730 Torr

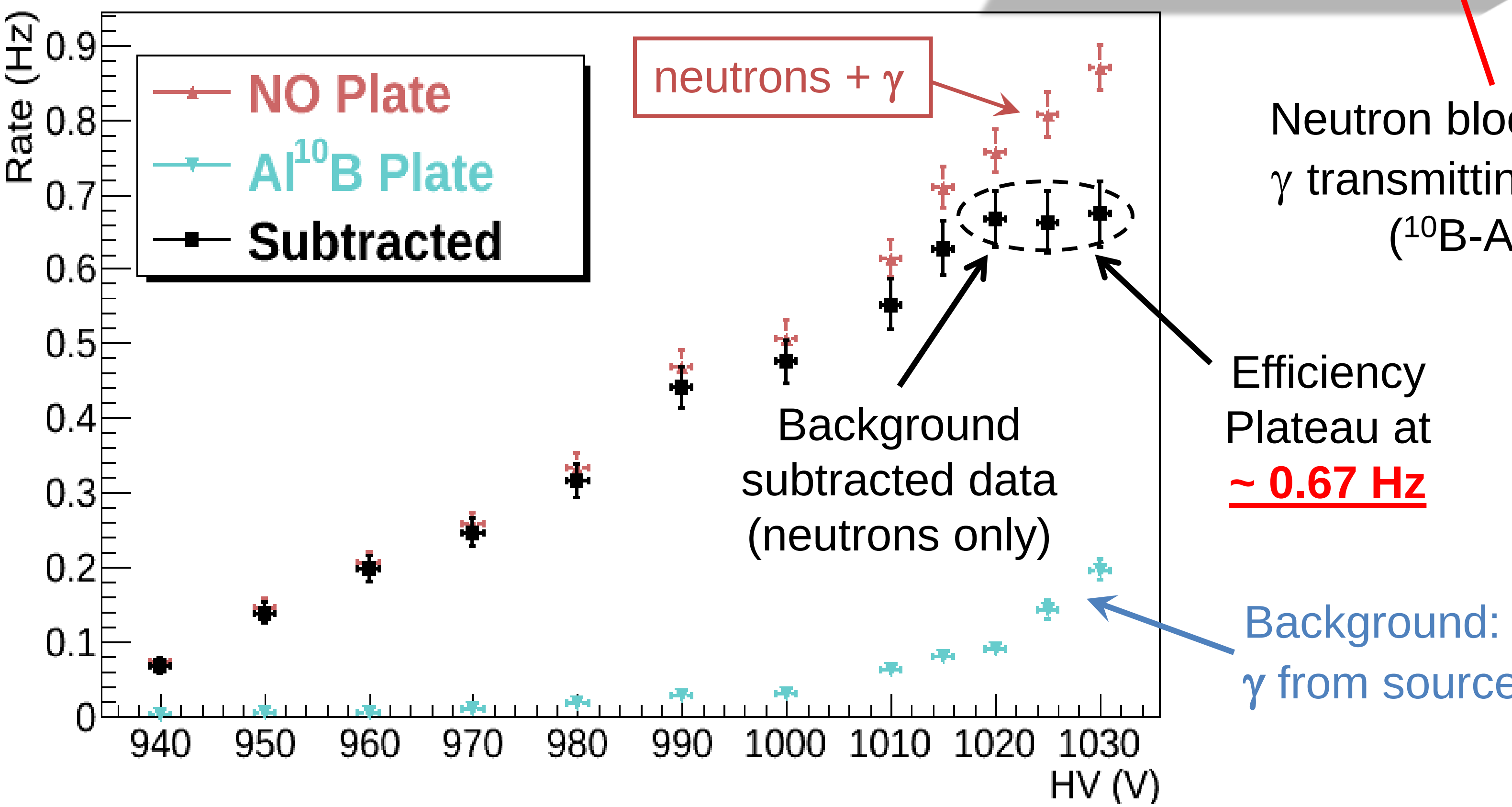
Panel: 2.5 mm pitch large panel used for CR muons
Instrumented pixels = 600, Area: 6 in^2

Method: Irradiate panel with thermal neutrons from various sources
high activity (10 mrem/hr) gammas
conduct count rates experiment with & w/o neutron mask plates

Neutron Rate vs. HV

(20% CF_4 in 80% ^3He, 730 Torr)



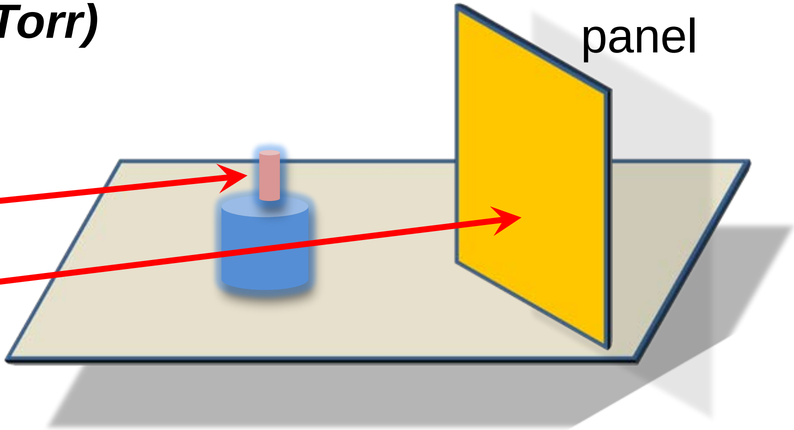


γ Rate vs. HV

(20% CF4 in 80% 3He, 730 Torr)

Calibrated intense γ-source (^{137}Cs)

3×10^5 γ/sec at instrumented region



3×10^5 γ/sec at instrumented region

HV (volts)	γ rate (Hz)	γ efficiency
970	0.09	***3.0×10^{-7}***
1000	1.2	***3.7×10^{-6}***
1030	7.9	***2.5×10^{-5}***

Good γ rejection even before any optimizations offered by:

1) Thinner substrates
2) Lower gas pressure
3) Thinner metallization
4) Pb free dielectric around pixels

Neutron Efficiency Results

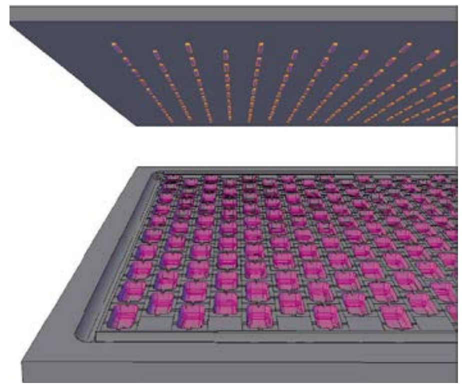
- Geant4 simulation (GE) of the neutron capture rate based on source activity: **0.70 ± 0.14 Hz**

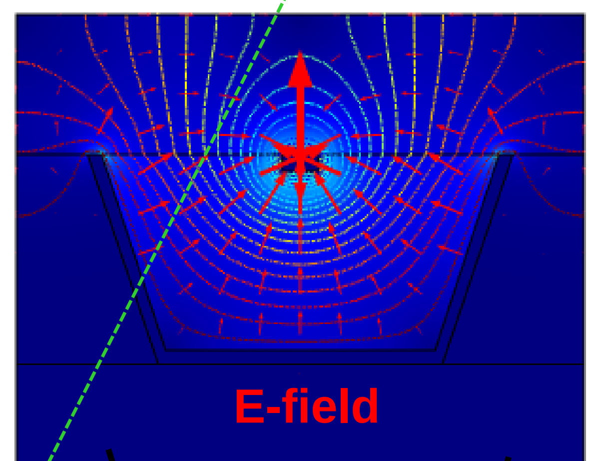
- PPS measured rate: **0.67 ± 0.02 Hz**

Approximately 100% of captured neutrons were detected

Microcavity Concept

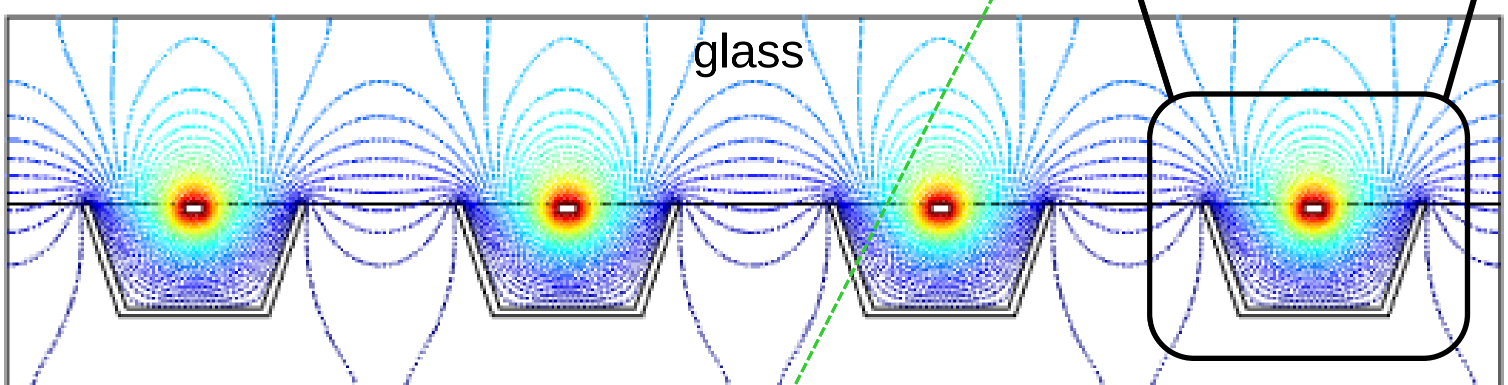
radial discharge gaps
cavity depth → longer path lengths
individually quenched cells
isolation from neighbors



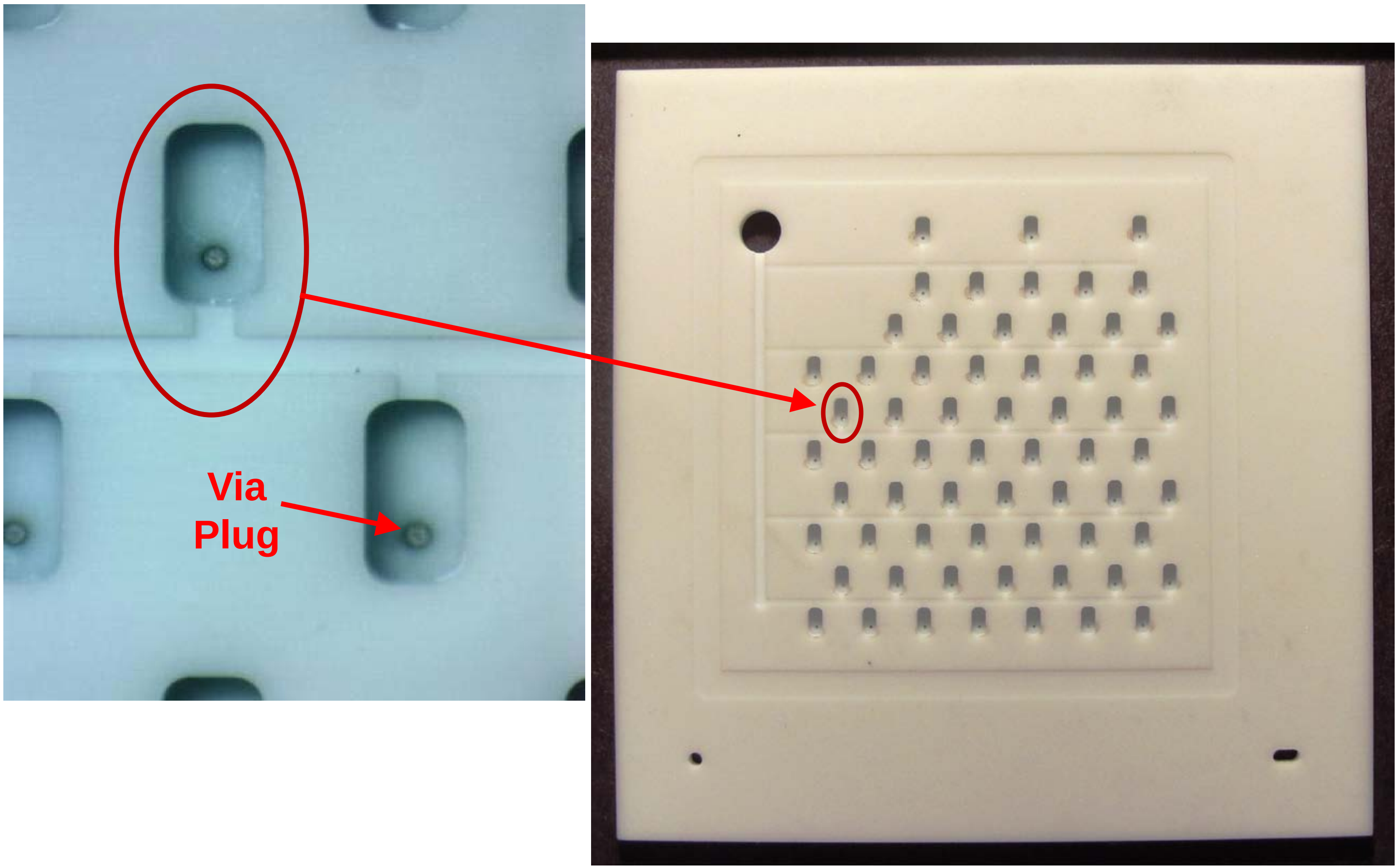


COMSOL simulation:

Equipotential lines

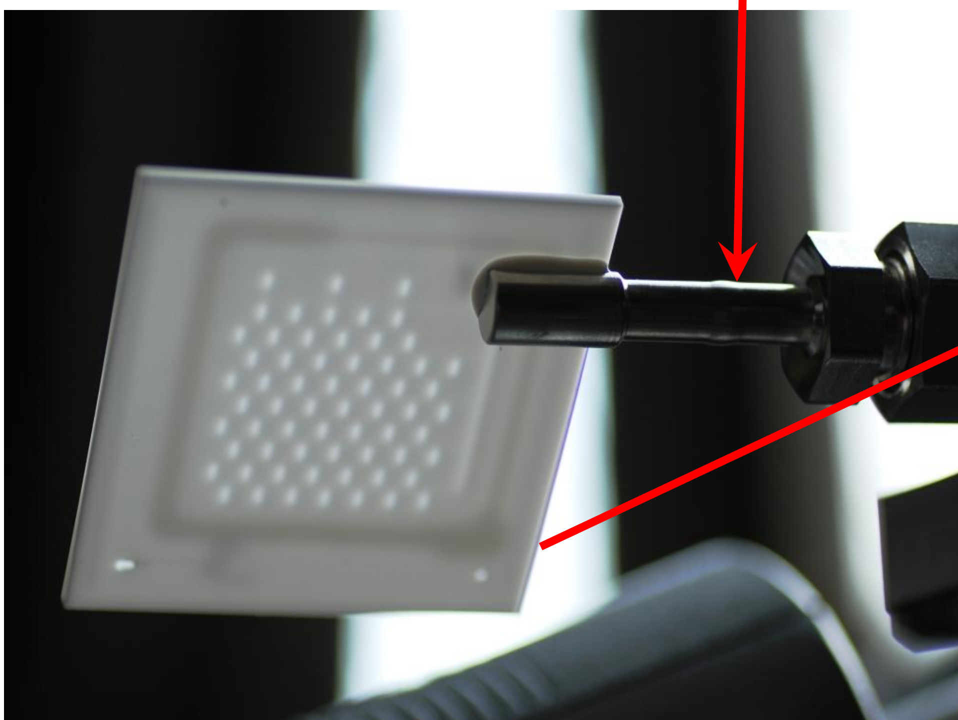


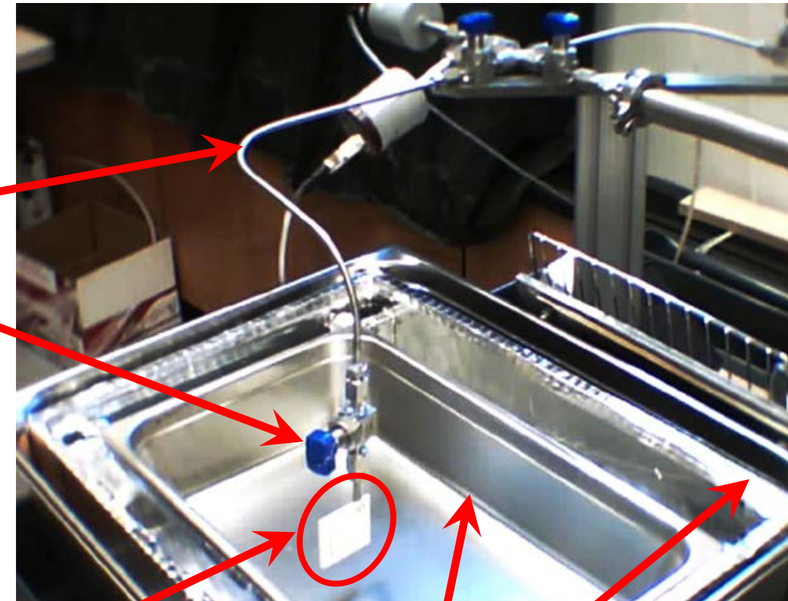
Microcavity Prototype (Back Plate)



Sealed Microcavity-PPS

Microcavity-PPS attached to vacuum-line / gas-fill system





Bottom Half of "*Open*" Bakeout Oven

Ongoing Efforts (2013 - 2014)

- Microcavity-PPS program
  - Final fabrication & initial testing
  - Thin & ultrathin cover plates
- 2D readout
- Demonstrate high cell / pixel efficiency
- Pursue higher resolution panels, faster timing
- Stacked panels for 3D tracking

Summary of 1st Generation Prototypes

PPS sensitive to:

- **Highly ionizing particles: betas, protons, neutrons (with good gamma rejection)**
- **Minimum ionizing particles: muons**

Large amplitude (volts) & fast pulses (1 ns rise time)

Timing resolution < 10 ns & *dropping* (e.g. 3 ns)

Spatial resolution < electrode pitch (1 mm) & *dropping*

Operate for months, even 1 year (sealed only by valve)

Operate in high rate environments