CNM Developments on LGAD and iLGAD Detectors for Linear Colliders

S. Hidalgo, M. Baselga, M. Carulla, V. Fadeyev, P. Fernández, M. Fernández, D. Flores, Z. Galloway, C. Gallrapp, Z. Liang, A. Merlos, M. Moll, F.R. Palomo, G. Pellegrini, D. Quirion, H. Sadrozinski, M. Stricker, I.Vila

Centro Nacional de Microelectrónica, IMB-CNM-CSIC, Barcelona, Spain
Santa Cruz Institute of Particle Physics SCIPP, Santa Cruz, CA, USA
Instituto de Física de Cantabria IFCA-CSIC-UC, Santander, Spain
Universidad de Sevilla, Sevilla, Spain
CERN, Geneva, Switzerland

Outline

1

- **Technological** Developments @ CNM on **LGAD** & **iLGAD** Detectors

2

- **PAD** & **microStrips** LGAD Characterization
  - ✓ **I-V, C-V**
  - ✓ **Gain** Measurements
    - ➢ **Laser**
    - ➢ **Alpha** Particles
  - ✓ **Gamma** Irradiations

3

- **New iLGAD**. Low Gain P on P Detector
  - ✓ **Position-Sensitive** Detectors
  - ✓ **Timing**
    - ➢ Thin Detectors
  - ✓ **Double-Sided** LGAD
    - ➢ **Pad** LGAD @ **Back-side**
    - ➢ **Ohmic** Read Out @ **Front-side**
- microStrip **iLGAD Simulation**
  - ✓ **Optimization**
    - ➢ Technological
    - ➢ Electrical
    - ➢ Thinner Substrates for Timing
- **First** iLGAD **Mask** Set
- **First** iLGAD **Run** @ CNM

LGAD and iLGAD Fabrication Runs Status

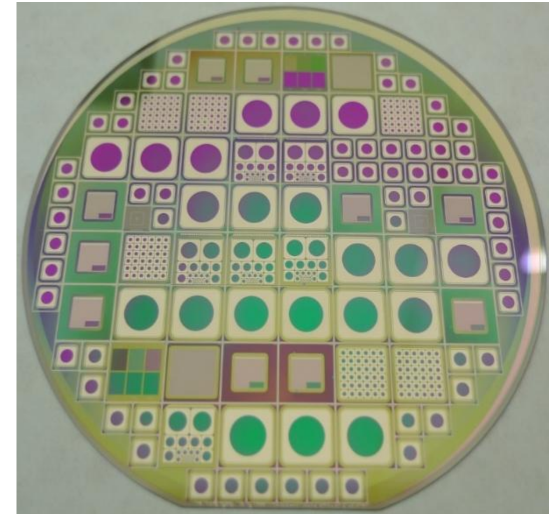
- **2 Runs** with **Boron** Multiplication Layer and **300 µm** Substrate: **Finished**
  - Run 7509
  - Run 7859
- **1 Run** with **Boron** Multiplication Layer and **200 µm** Substrate: **Finished**
  - Run 7782. **Implantation Done at IBS (France)**
- **1 Run** with **Gallium** Multiplication Layer and **300 µm** Substrate: **Finished**
  - Run 7735. **Implantation Done at IBS (France)**

- **1 Run** with **Boron** Multiplication Layer and **300 µm** Substrate: **Finished**
  - Run 8622. **LGAD**. **3 Gallium Wafers**
- **1 Run** with **Boron** Multiplication Layer and **300 µm** Substrate: **On Going**
  - Run 8533. **iLGAD**. **3 Gallium Wafers**. **75 %** Run Steps Done
- **1 Run** with **Boron** Multiplication Layer and **6”-500 µm** Substrate: **On Going**
  - Run 8373. LGAD. It will end during **June**

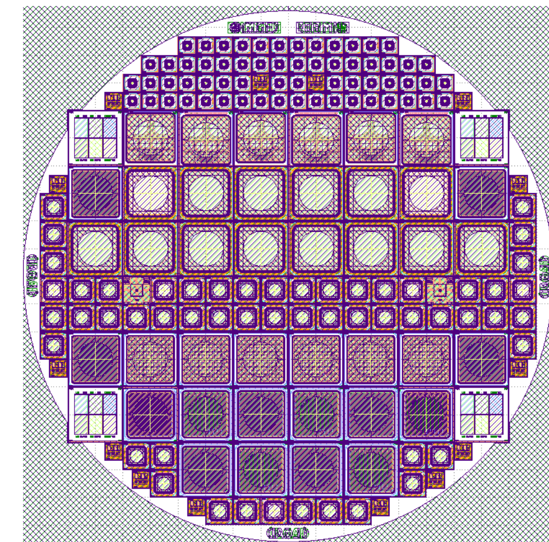
- **New Run** with **Boron** Multiplication Layer and **200 µm** Substrate: **Waiting**
- **New Run** with **Gallium** Multiplication Layer and **300 µm** Substrate: **Waiting**

LGAD and iLGAD Fabrication Runs. At Glance

- **LGAD Run** Basic Information:
  - ✓ **Cnm761** Mask Set
  - ✓ **8** Mask Levels
  - ✓ **70** Technological Steps
  - ✓ **Single** Side Process
  - ✓ Only **Electron** Collection



- **iLGAD Run** Basic Information:
  - ✓ **Cnm809** Mask Set
  - ✓ **12** Mask Levels
  - ✓ **100** Technological Steps
  - ✓ **Double** Side Process
  - ✓ Only **Hole** Collection

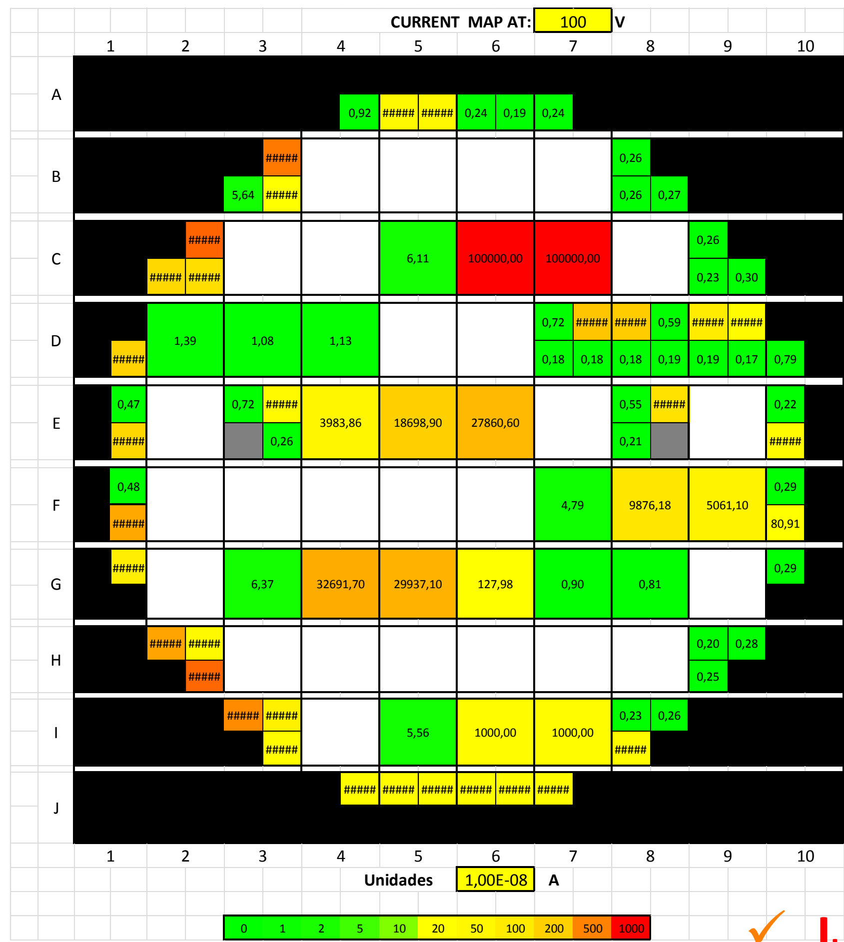


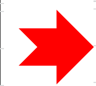
- **Common** Information:
  - ✓ Improve **Surface Isolation** (**P-Stop**. iLGAD @ Multiplication Side)
  - ✓ Different **Terminations**
  - ✓ **Pad** Detectors with Different Sizes
  - ✓ **Strips** and **Pixel** Detectors (iLGAD @ Front Side)
  - ✓ Detectors for **Timing** Applications
  - ✓ **Test Structures** to Measure the Multiplication Layer

LGAD. Boron Multiplication Layer. 300 µm Substrate

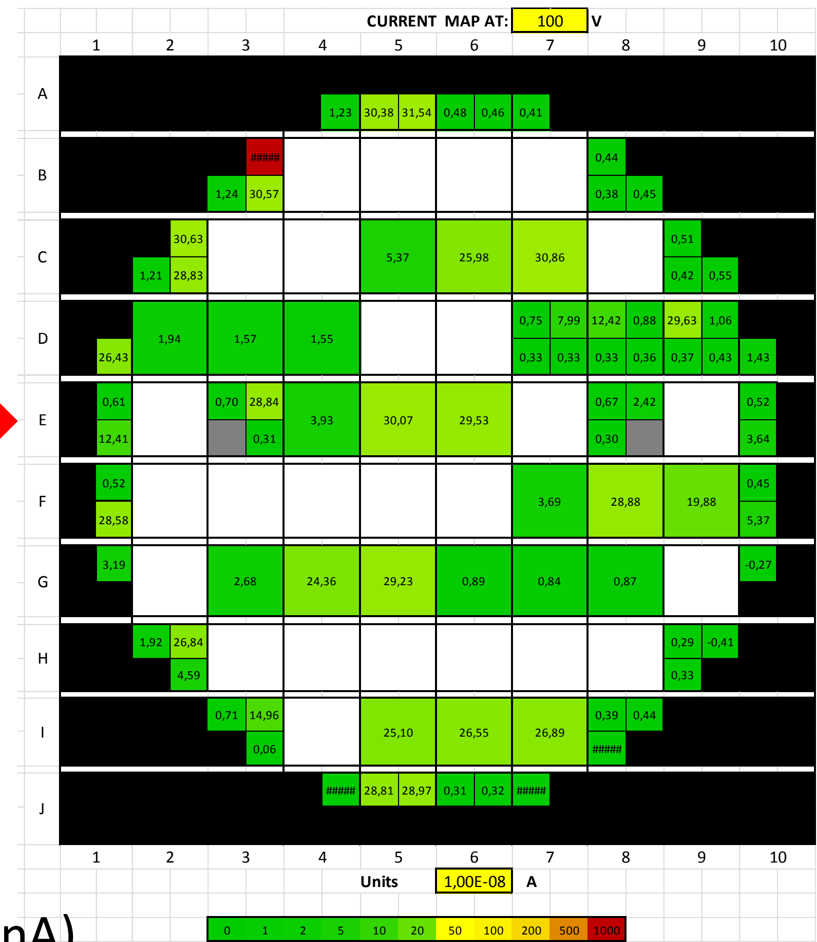
- Yield Improved

✓ Run 7509



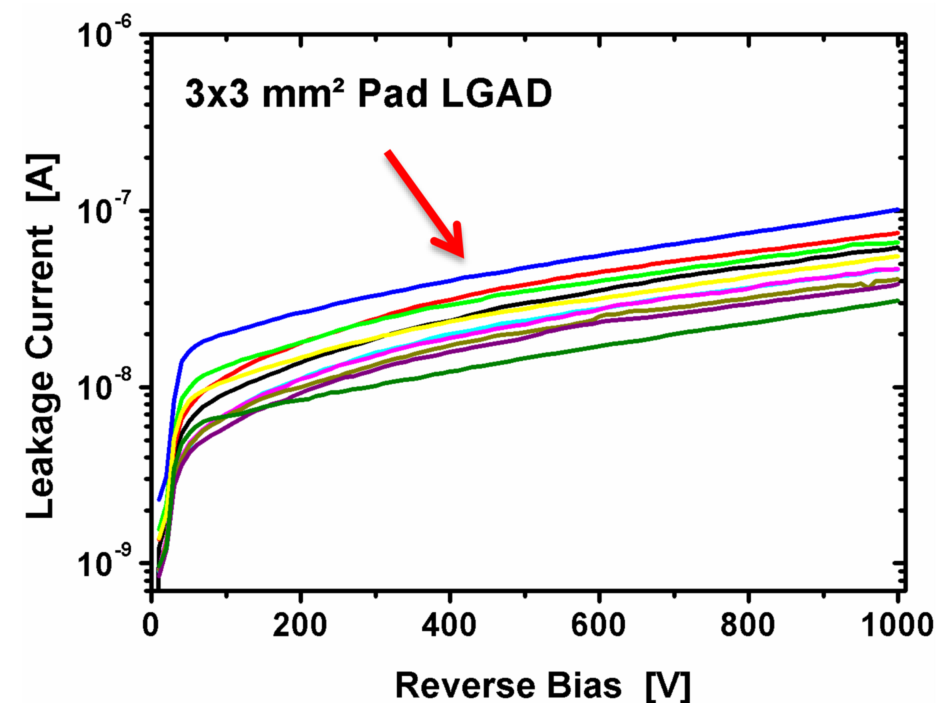


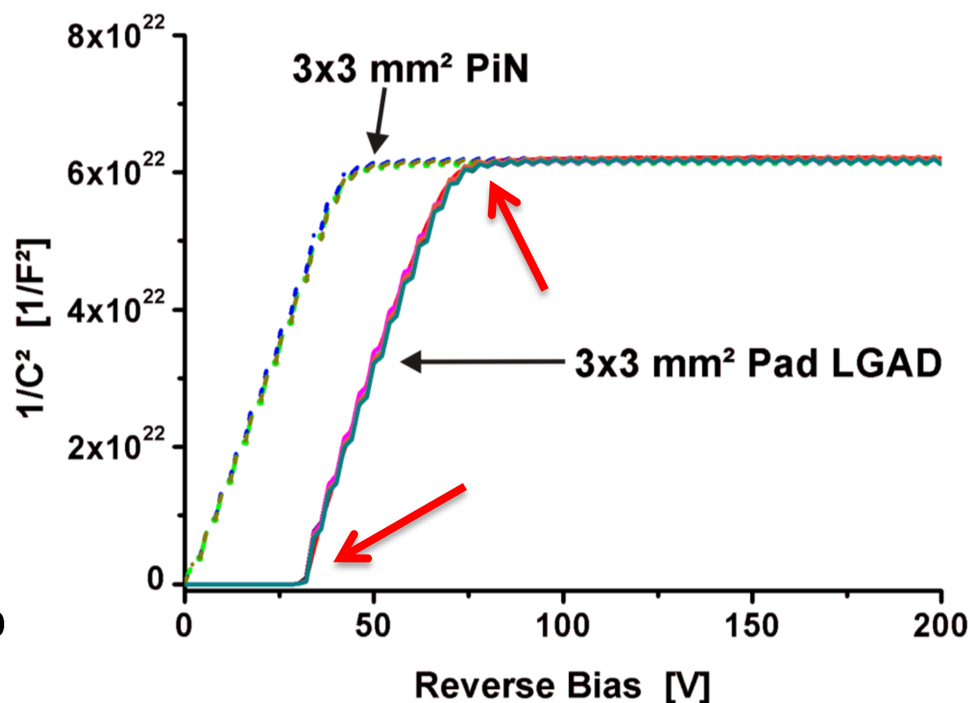
✓ Run 7859



✓ I_{leak} (nA)

LGAD. Run 7859. I(V) and $1/C^2(V)$

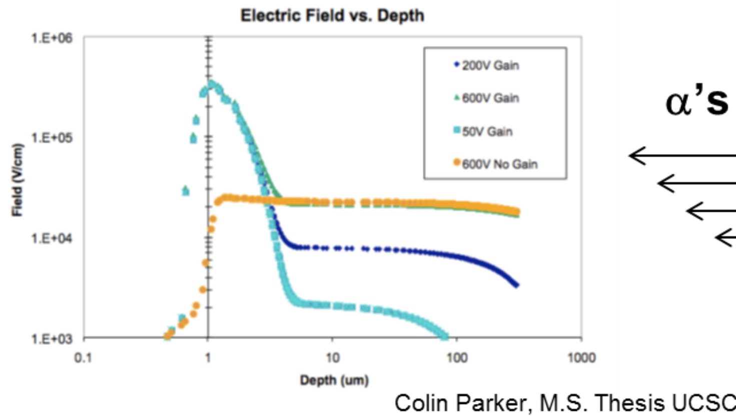




- **Wafer 2**. Multiplication Layer Dose **1.8e13 atm/cm²**
- Low **Leakage Current**. **10-30 nA** @ **500 V**
- Multiplication Layer **Depletion Voltage** ~ **30 V**. **Full Depletion Voltage** ~ **80 V**

LGAD. Run 6474. Gain Calibration with α's from Am(241)

Hartmut F.-W. Sadrozinski, Ultra-Fast Silicon Detectors. CPAD

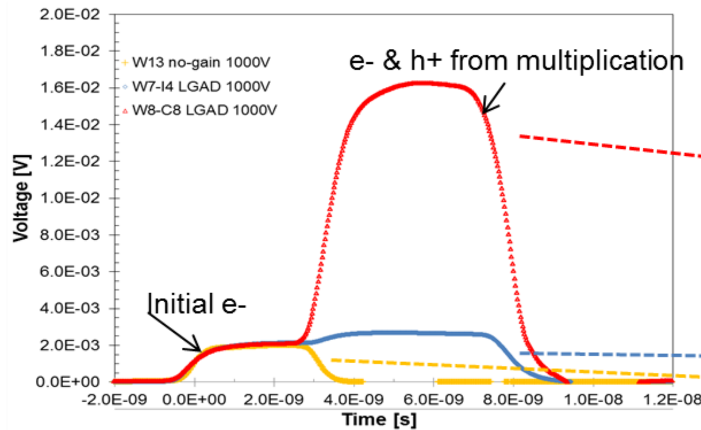


Colin Parker, M.S. Thesis UCSC

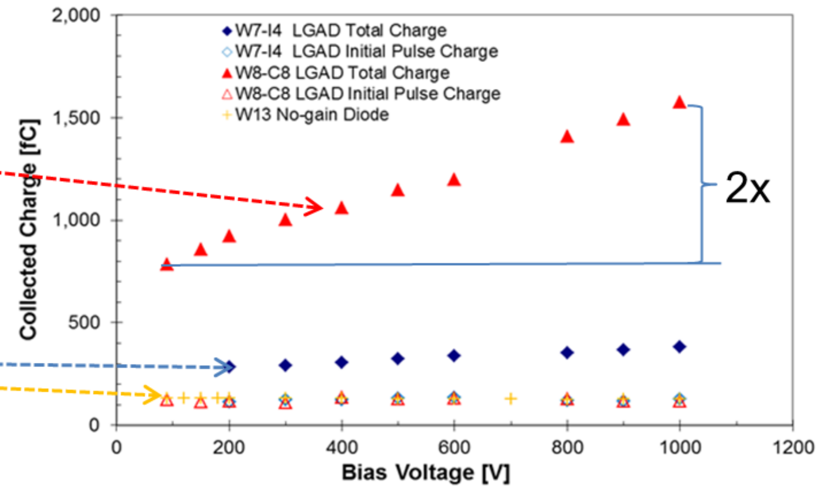
α's

"Electron injection" with α's from Am(241) or with red laser illuminating the back side, range ~ few um's, electron signal drifts and is then amplified in high field, holes drift back.

Pulse shapes for high-gain (red), low-gain (blue) LGAD and no-gain sensor (yellow)



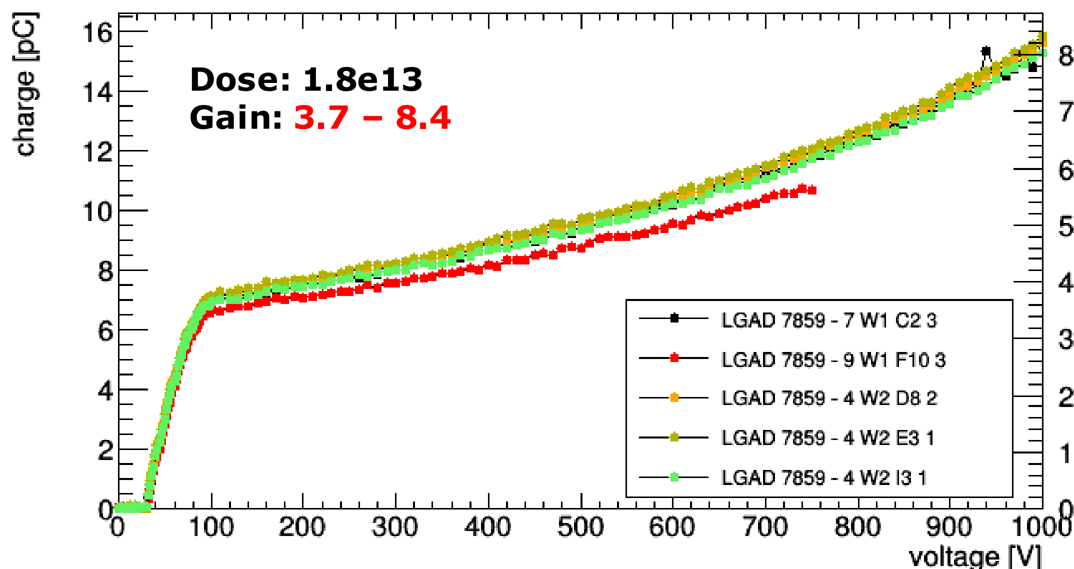
Large bias voltages reach.
Gain of 15, can be tuned within factor 2x with bias voltage.

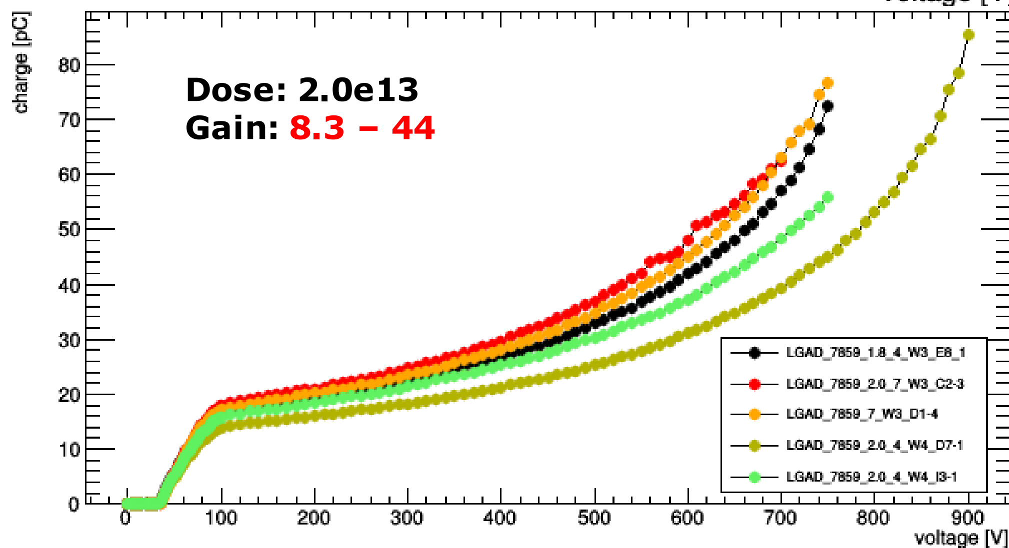


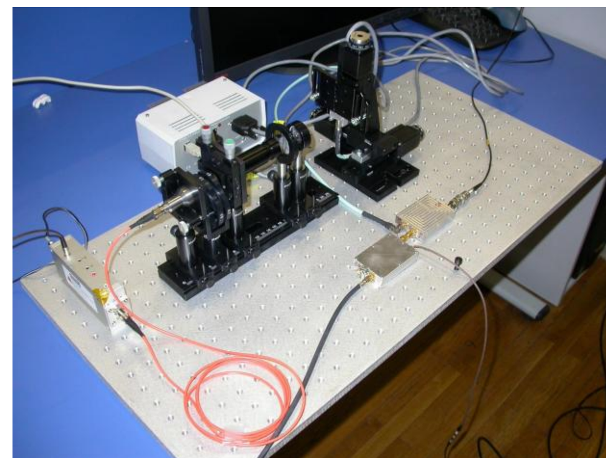
$$Gain = \frac{electrons + holes}{initial \cdot electrons}$$

○ **Wafer 8**. Multiplication Layer Dose **1.8e13 atm/cm²**

LGAD. Run 7859. TCT Measurements. IR. Back



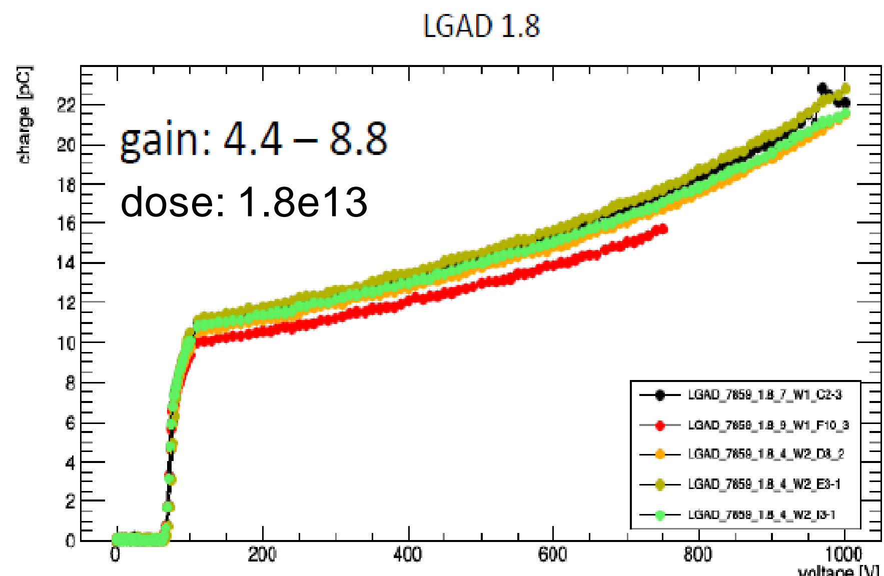


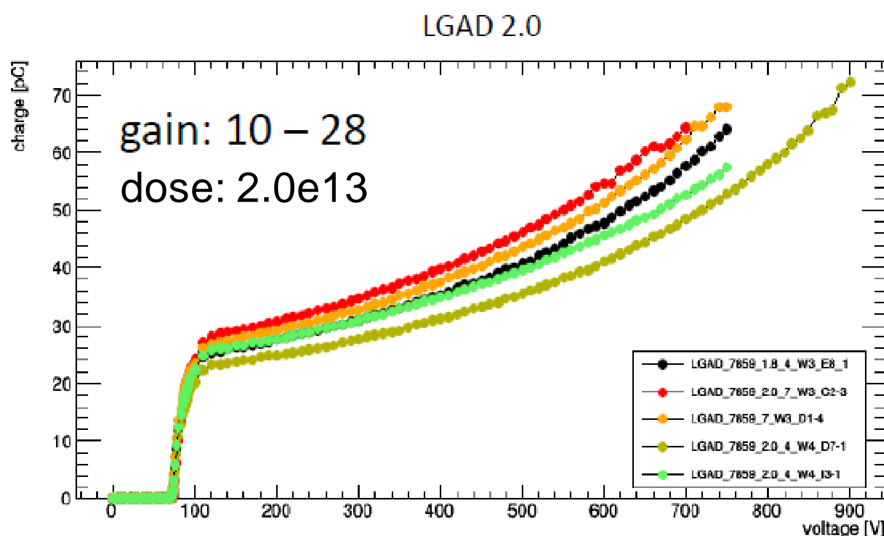


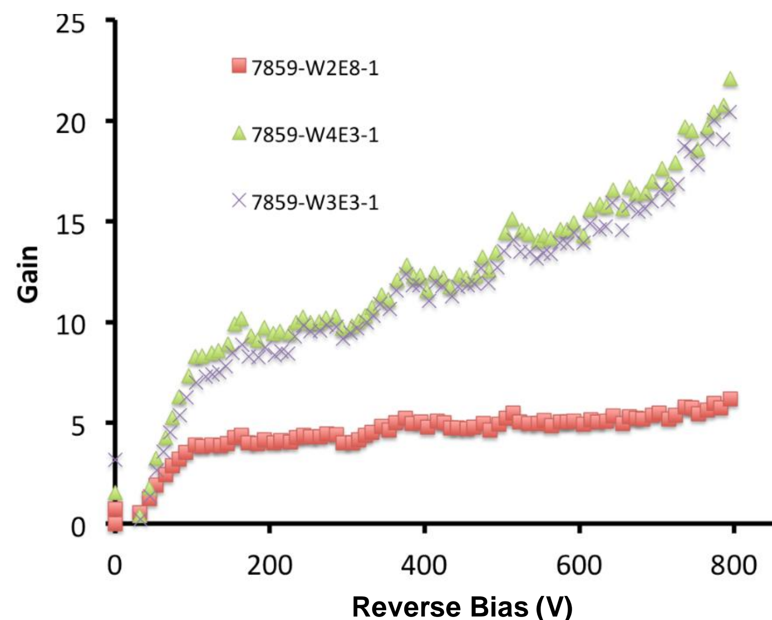
G. Kramberger, 20th RD50 Workshop, Bari, 2012

- Measurements done at **CERN Silicon Lab** by C. Gallrapp, M. Stricker. M. Fernandez and M. Moll.

LGAD. Run 7859. TCT Measurements. Red. Back

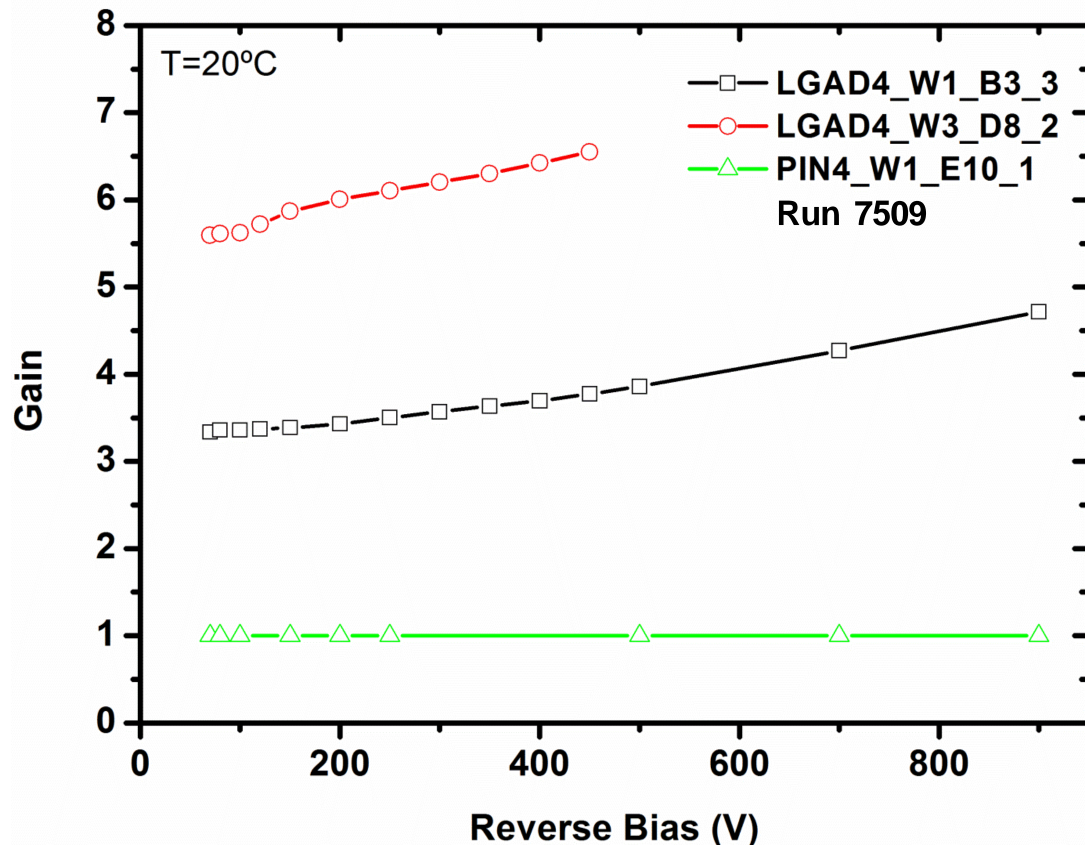


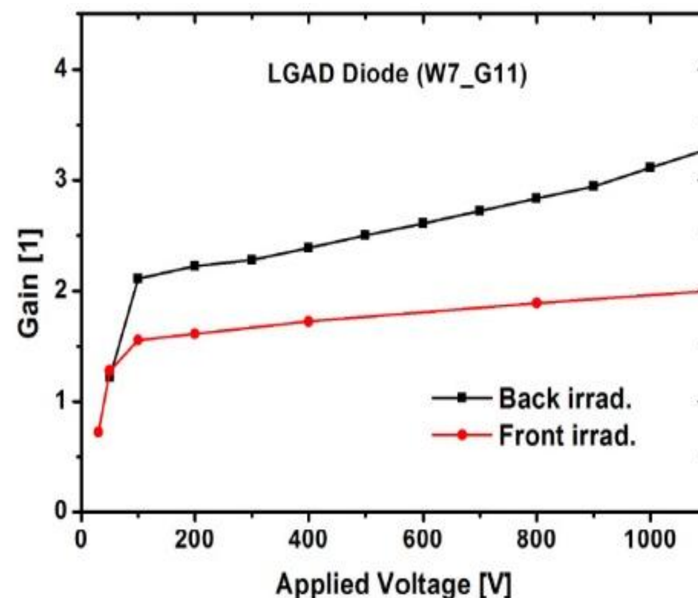




- Measurements done at **CERN Silicon Lab** by C. Gallrapp, M. Stricker. M. Fernandez and M. Moll., and at **INFN Torino** by N. Cartiglia

LGAD. Run 7509. Charge Collection. Alpha. Back Illumination





- **Wafer 1**. Multiplication Layer Dose **1.8e13 atm/cm²**
- **Wafer 3**. Multiplication Layer Dose **2.0e13 atm/cm²**

Gamma Irradiated LGAD. Run 7859. Charge Collection. Alpha

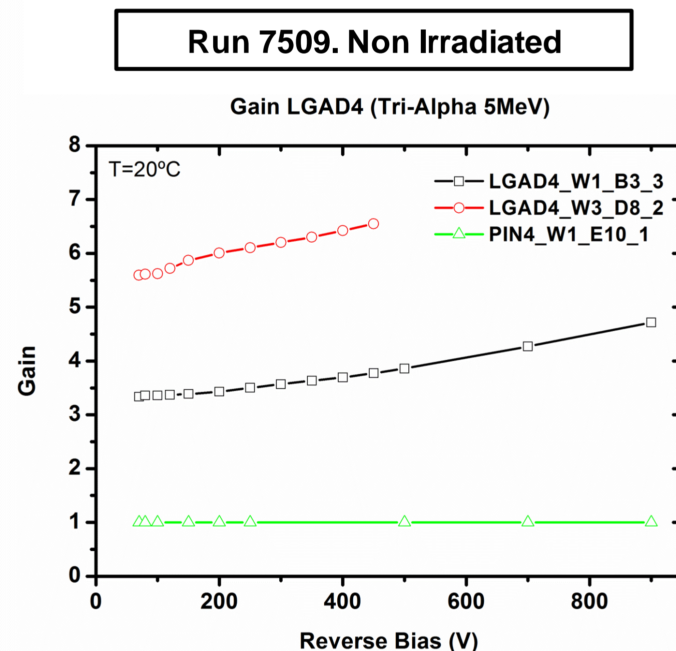
Gain Irradiated LGAD4 (Tri-alpha 5MeV) Run 7859

T= 20ºC

LGAD4_W2_C2_3_100Mrad
LGAD4_W2_A4_4_30Mrad
LGAD5_W2_E8_2_NoIrr
LGAD4_W4_B3_3_100Mrad
LGAD4_W4_A4_4_30Mrad
LGAD4_W3_D8_2_NoIrrad
PIN4_W1_D8_4_NoIrr

Gain

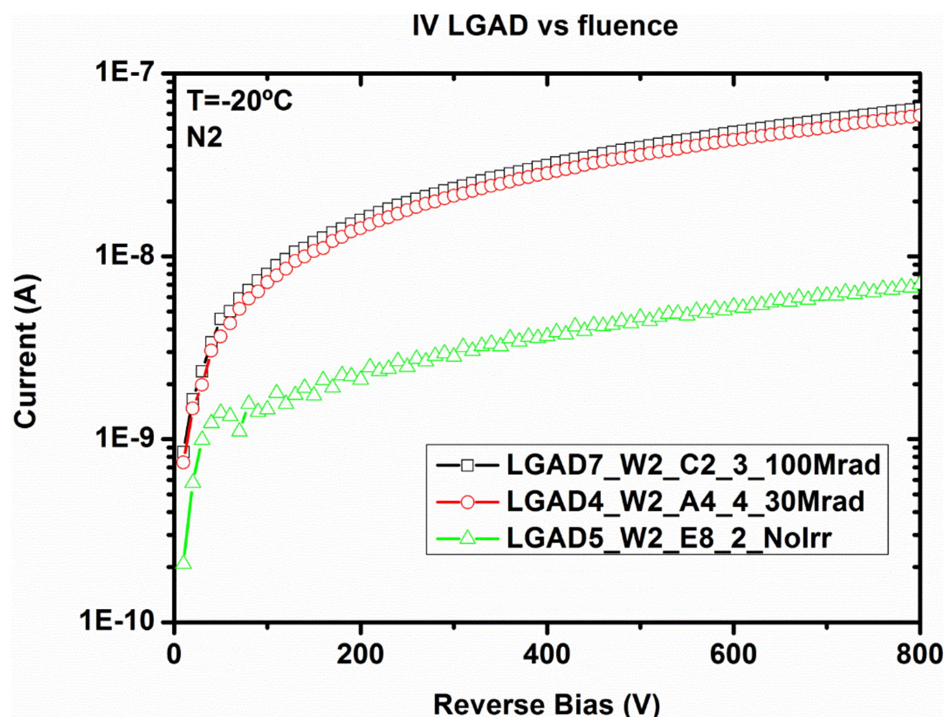
Reverse Bias (V)

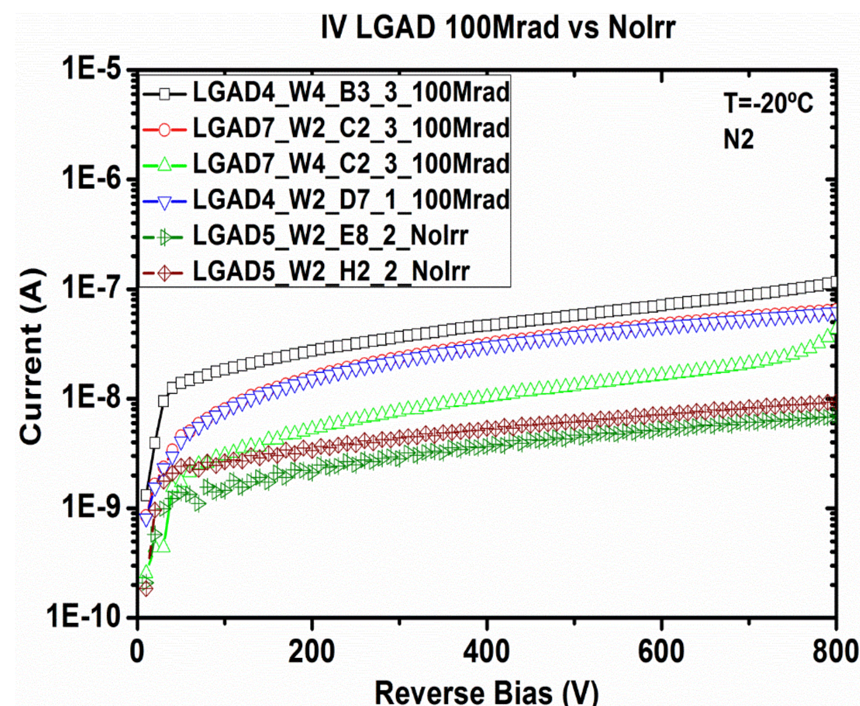


- **Wafers 1, 2**. Multiplication Layer Dose **1.8e13 atm/cm²**
- **Wafers 3, 4**. Multiplication Layer Dose **2.0e13 atm/cm²**
- **Gamma** Irradiation with ^{60}Co

Los Alamos NATIONAL LABORATORY
SCIPP

Gamma Irradiated LGAD. Run 7859. I(V)



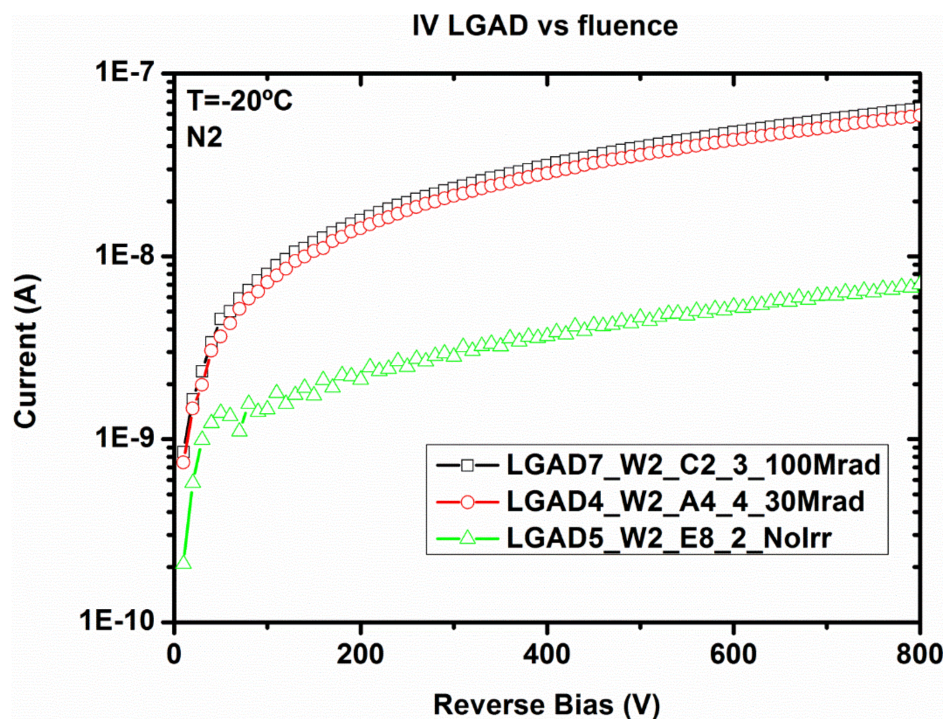


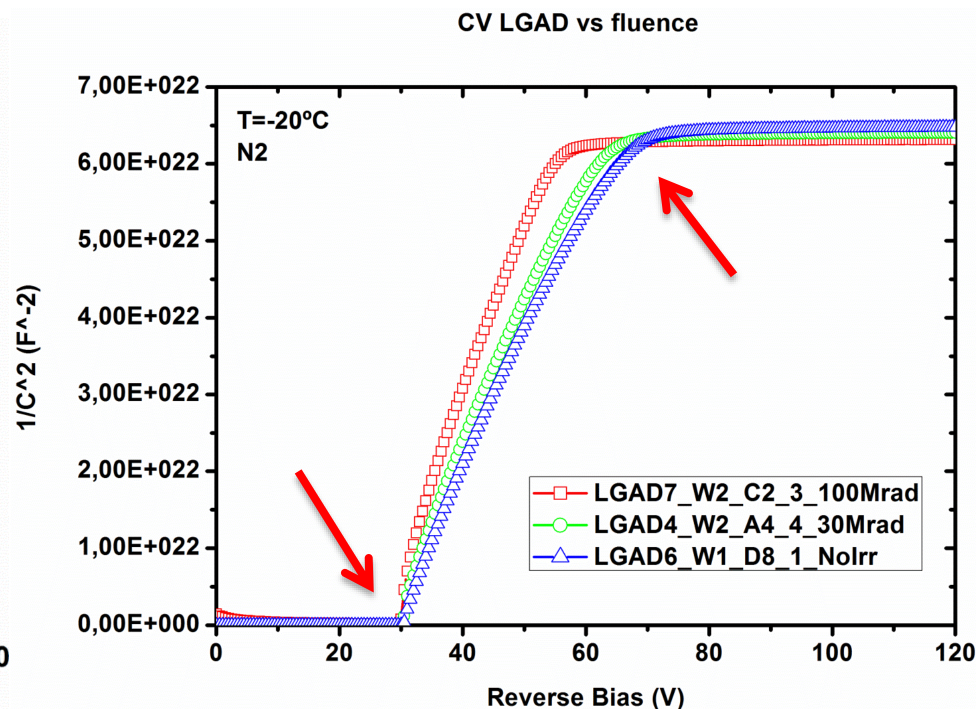
- **Wafer 2**. Multiplication Layer Dose **1.8e13 atm/cm^2**
- **Wafer 4**. Multiplication Layer Dose **2.0e13 atm/cm^2**
- **Gamma** Irradiation with ^{60}**Co**
- Leakage Current **Moderate Increase**. From **10 nA** to **100 nA** @ **800 V**

Los Alamos NATIONAL LABORATORY

SCIPP

Gamma Irradiated LGAD. Run 7859. I(V) and $1/C^2(V)$



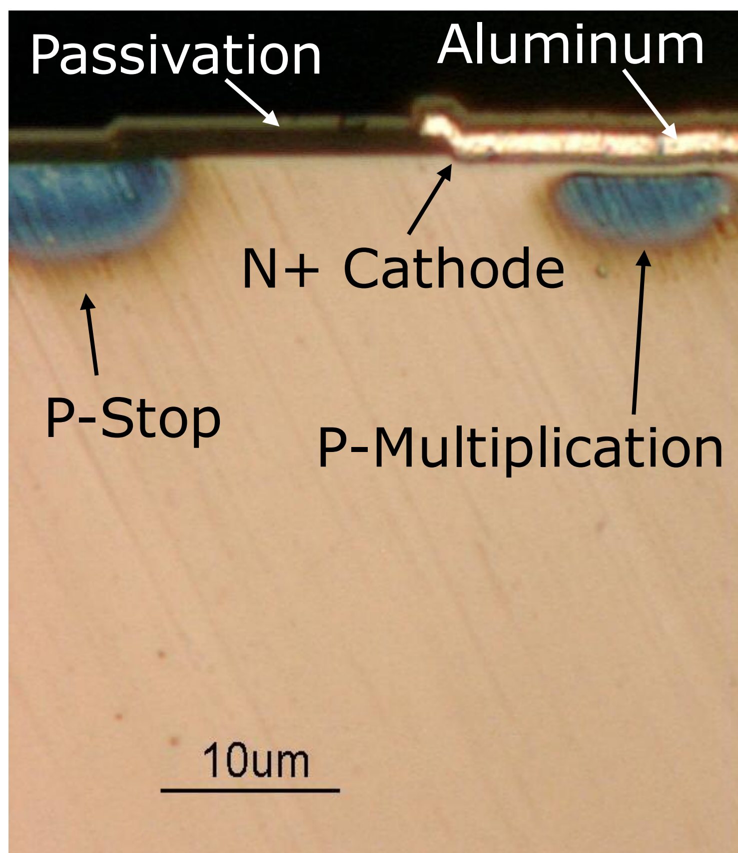


- **Gamma** Irradiation with ^{60}**Co**
- Leakage Current **Moderate Increase**. From **10 nA** to **100 nA** @ **800 V**
- Multiplication Layer Depletion Voltage **~ 30 V** for **All Fluences**
- **Full Depletion** Voltage **Decreases** if **Fluence Increases**

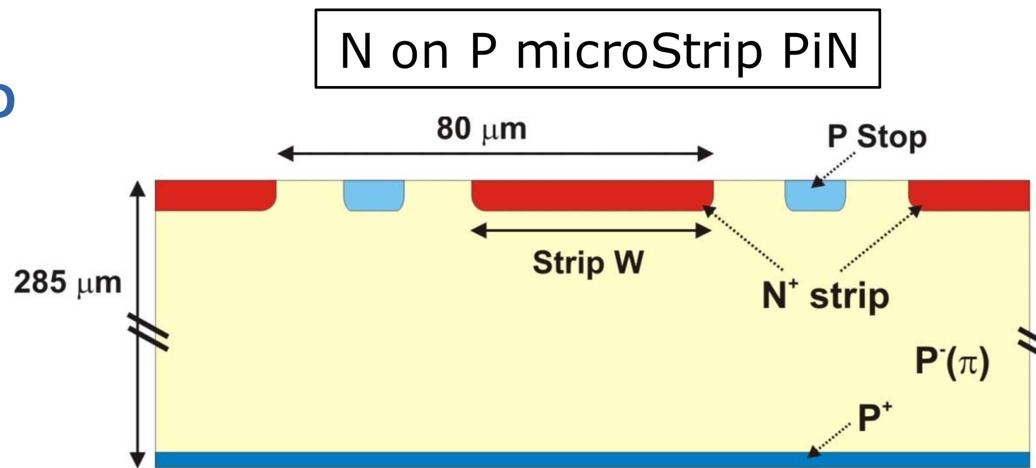
Los Alamos NATIONAL LABORATORY
SCIPP

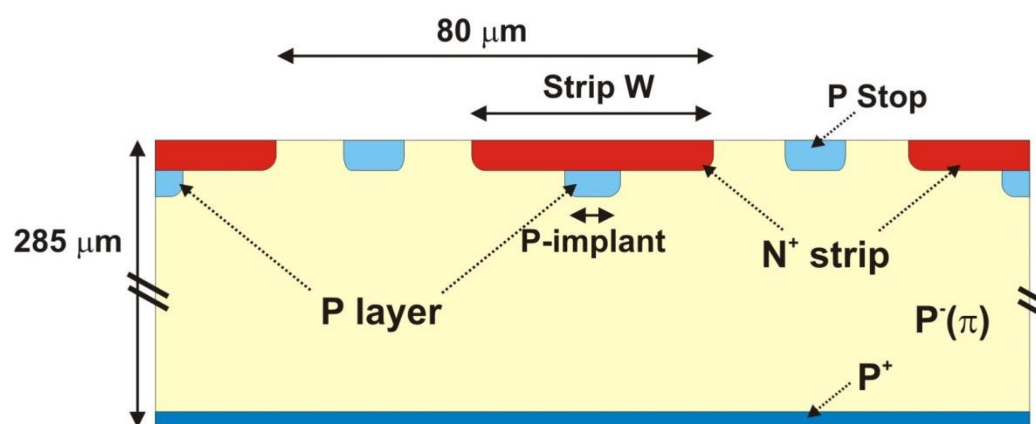
Strip LGAD. Segmented Amplification

- **N on P** microStrips. **PiN** vs **LGAD**



N on P microStrip PiN

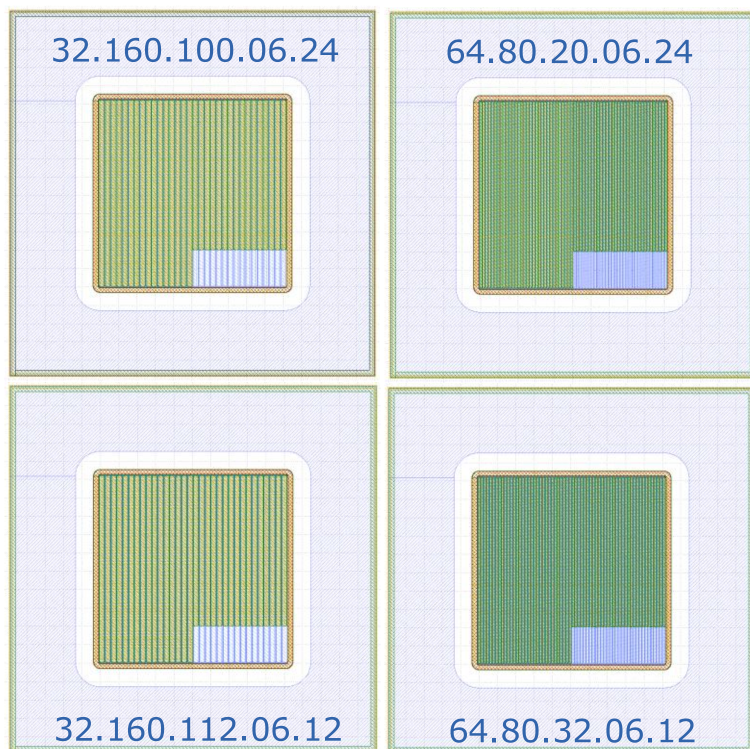




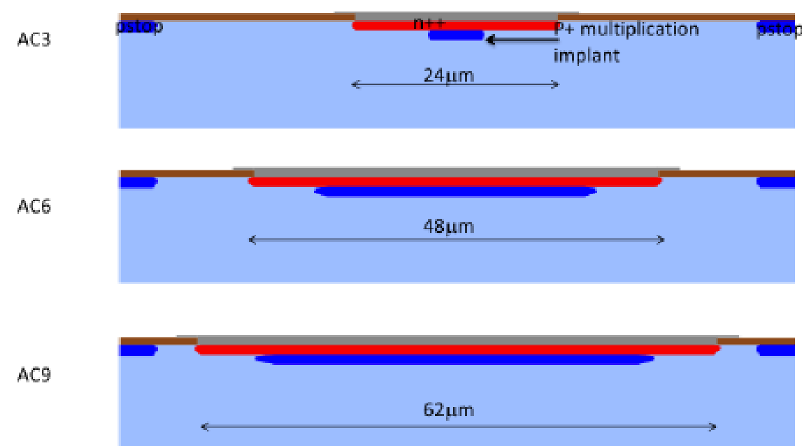
N on P microStrip LGAD

First Approach. Strip LGAD. Segmented Amplification

- Runs **7509** and **7859**, with **Optimized P-well** Engineering
  - ✓ First prototypes characterization **On Going**
- **Several** Layouts with **Different P-well Width** and **N-well Depth**
- **Constant Pixel Size**



Strip outline



- **Key Legend**
  - ✓ **AA-BB-CC-DD-EE**
  - ✓ **AA,** Channels
  - ✓ **BB,** Pixel Size
  - ✓ **CC,** Multiplication Width
  - ✓ **DD,** P-Stop Width
  - ✓ **EE,** P-Stop Position

First Approach. Strip LGAD. SCIPP TCT Set Up

✓ **All** other Channels **Floating**

- Measurements done at **SCIPP** by Zachary Galloway, Giulio Pellegrini and Zhijun Liang

First Approach. Strip LGAD. SCIPP TCT. X Scan vs Voltage

Reverse Bias = 50 V

Strip Center

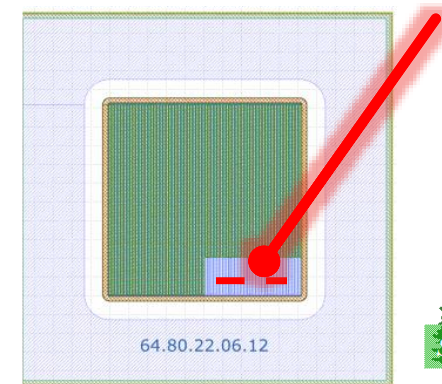
Signal Amplitude [mV/50Ω]

0, 10, 20, 30, 40, 50, 60

50, 100, 150, 200, 250, 300

Position (μm)

- TCT Basic Information:
  - ✓ Run 7859. W4-E2. 50 V
  - ✓ Red Laser from Top
  - ✓ All 3 Channels Connected
  - ✓ DRS4 Circuit Amplifier
  - ✓ Strips Without Metal
  - ✓ No Signal in the Middle of the Strip. No Gain



First Approach. Strip LGAD. SCIPP TCT. X Scan vs Voltage

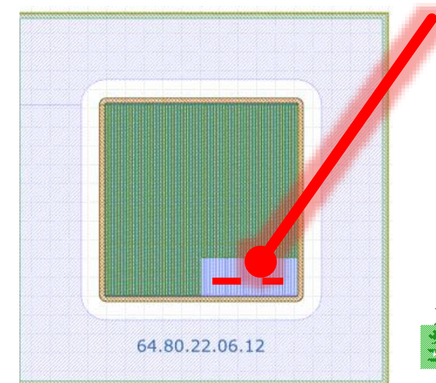
Reverse Bias = 100 V

Strip Center

Signal Amplitude [mV/50Ω]

Position (μm)

- TCT Basic Information:
  - ✓ Run 7859. W4-E2. 100 V
  - ✓ Red Laser from Top
  - ✓ All 3 Channels Connected
  - ✓ DRS4 Circuit Amplifier
  - ✓ Strips Without Metal
  - ✓ Low Signal in the Middle of the Strip. Low Gain



First Approach. Strip LGAD. SCIPP TCT. X Scan vs Voltage

Reverse Bias = 150 V

Strip Center

2x

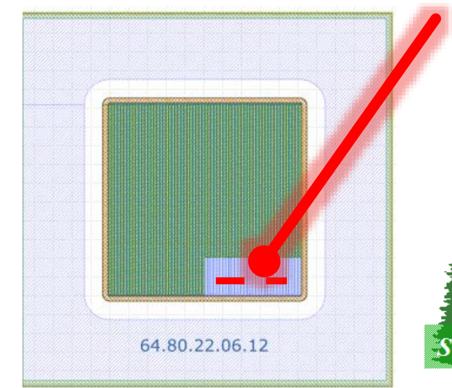
Signal Amplitude [mV/50Ω]

0 10 20 30 40 50 60

50 100 150 200 250 300

Position (μm)

- TCT Basic Information:
  - ✓ Run 7859. W4-E2. 150 V
  - ✓ Red Laser from Top
  - ✓ All 3 Channels Connected
  - ✓ DRS4 Circuit Amplifier
  - ✓ Strips Without Metal
  - ✓ High Signal in the Middle of the Strip. High Gain



First Approach. Strip LGAD. SCIPP TCT. Signal Amp vs Bias

Run 7859

Strip PiN
Strip LGAD

2x

Signal Amplitude [mV]

Reverse Bias [V]

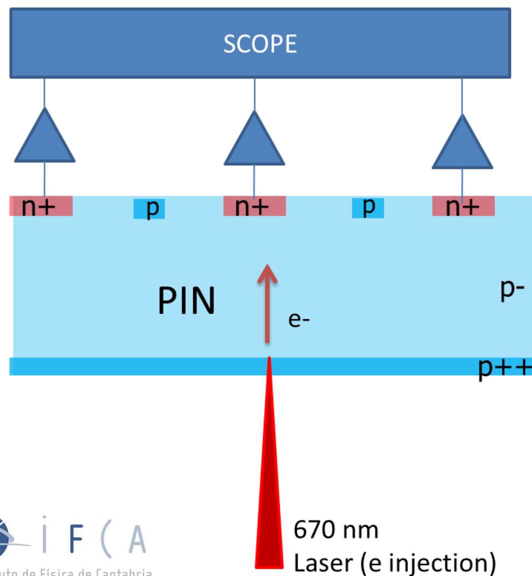
✓ Preliminary Results

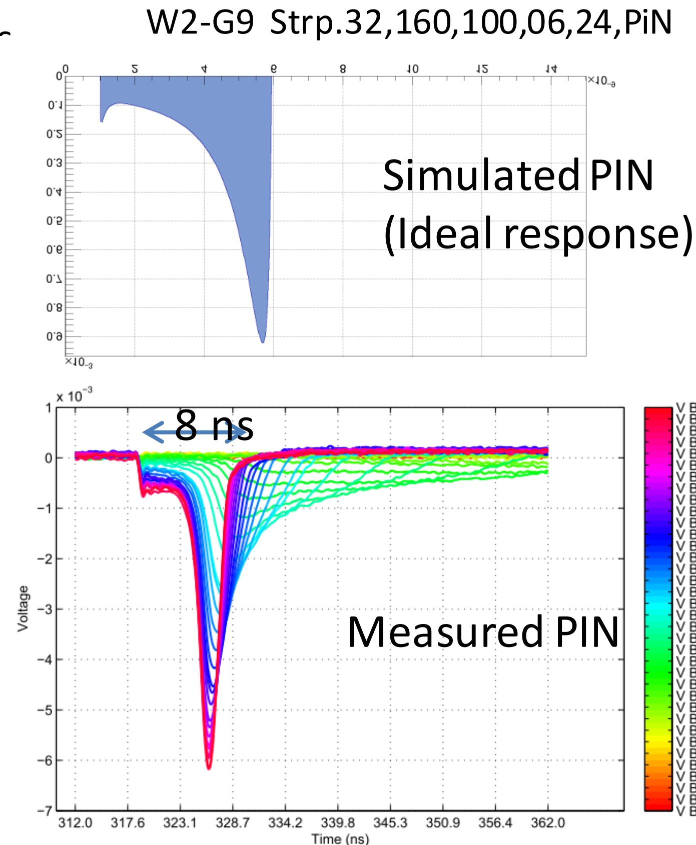
- Measurements done at **SCIPP** by Zachary Galloway, Giulio Pellegrini and Zhijun Liang

First Approach. Strip LGAD. IFCA TCT. PiN Strip

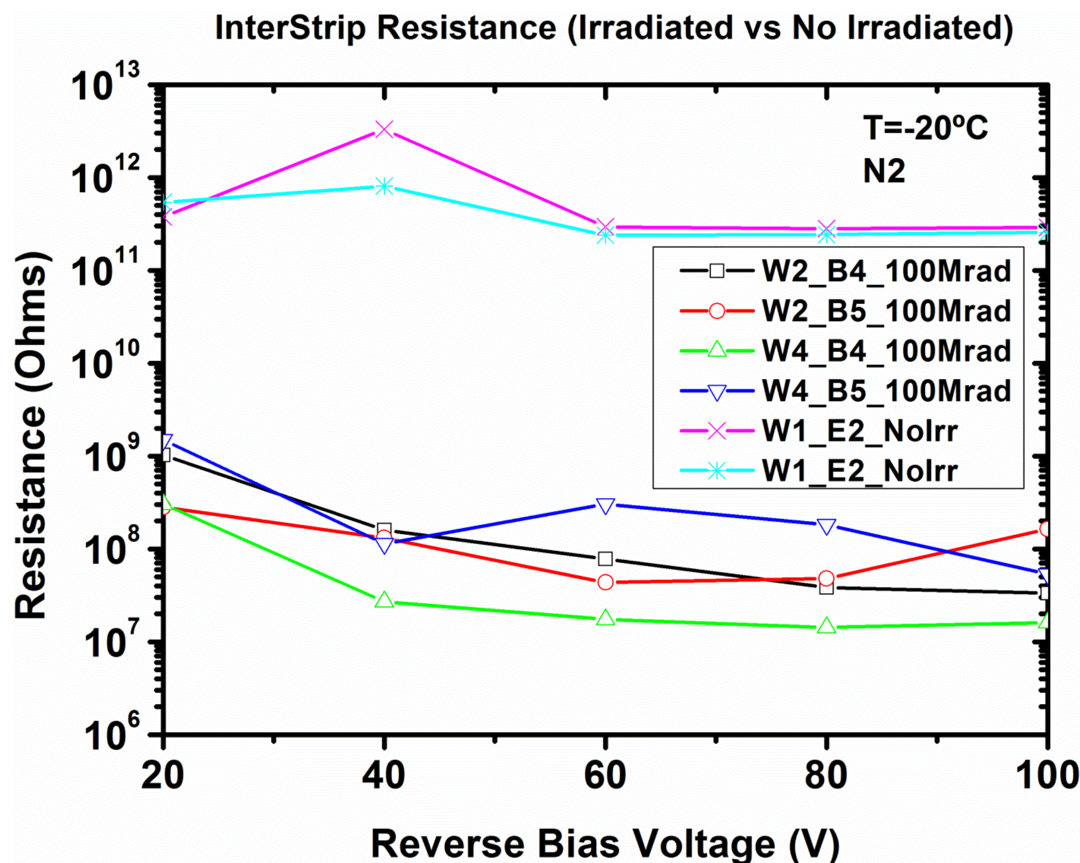
- See Next Presentation by Iván Vila (IFCA)

- Comparing LGAD microStrips vs microStrip PIN
- Red Laser, Bottom Illumination (Electron Injection)





Gamma Irradiated LGAD. Run 7859. Inter-Strip Resistance



- **Gamma** Irradiation with ^{60}**Co**
- Inter-Strip Resistance **Reduction** @ **100 Mrad**, for **Every** Reverse Bias and Sample

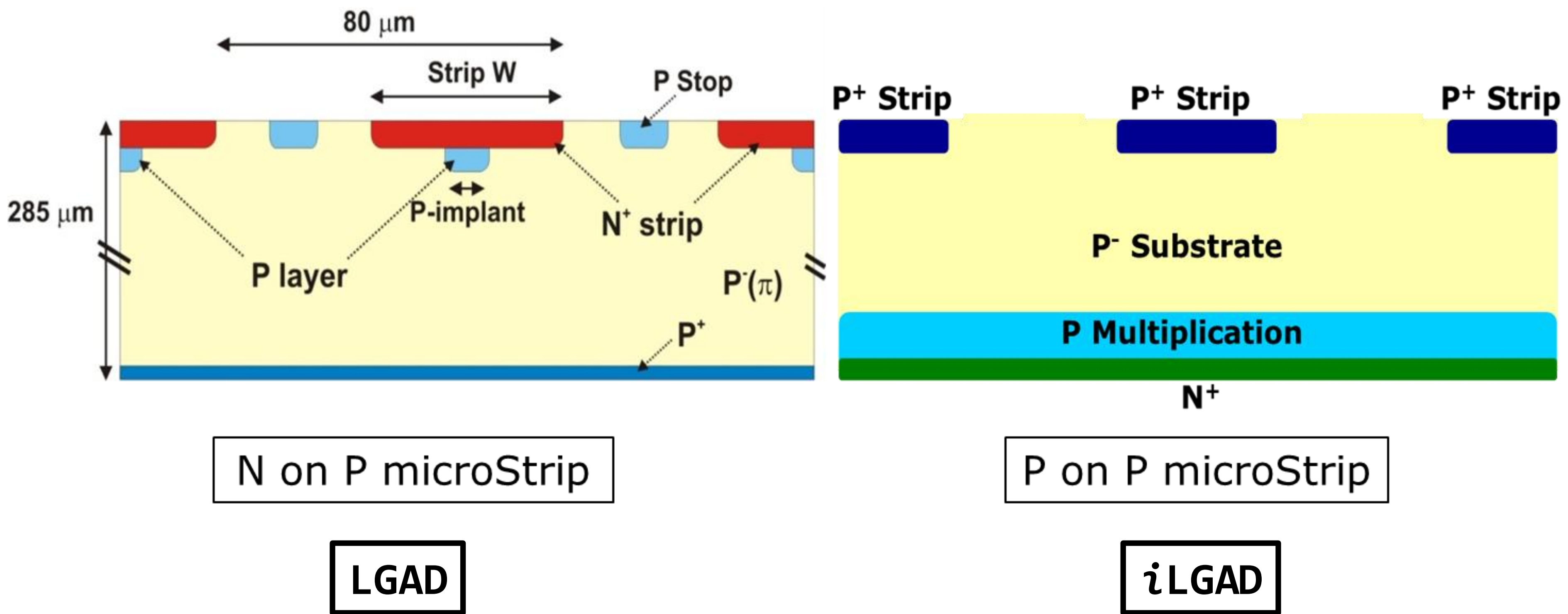
Los Alamos NATIONAL LABORATORY

SCIPP

Second Approach. P on P Strip iLGAD: The "Inverse" LGAD

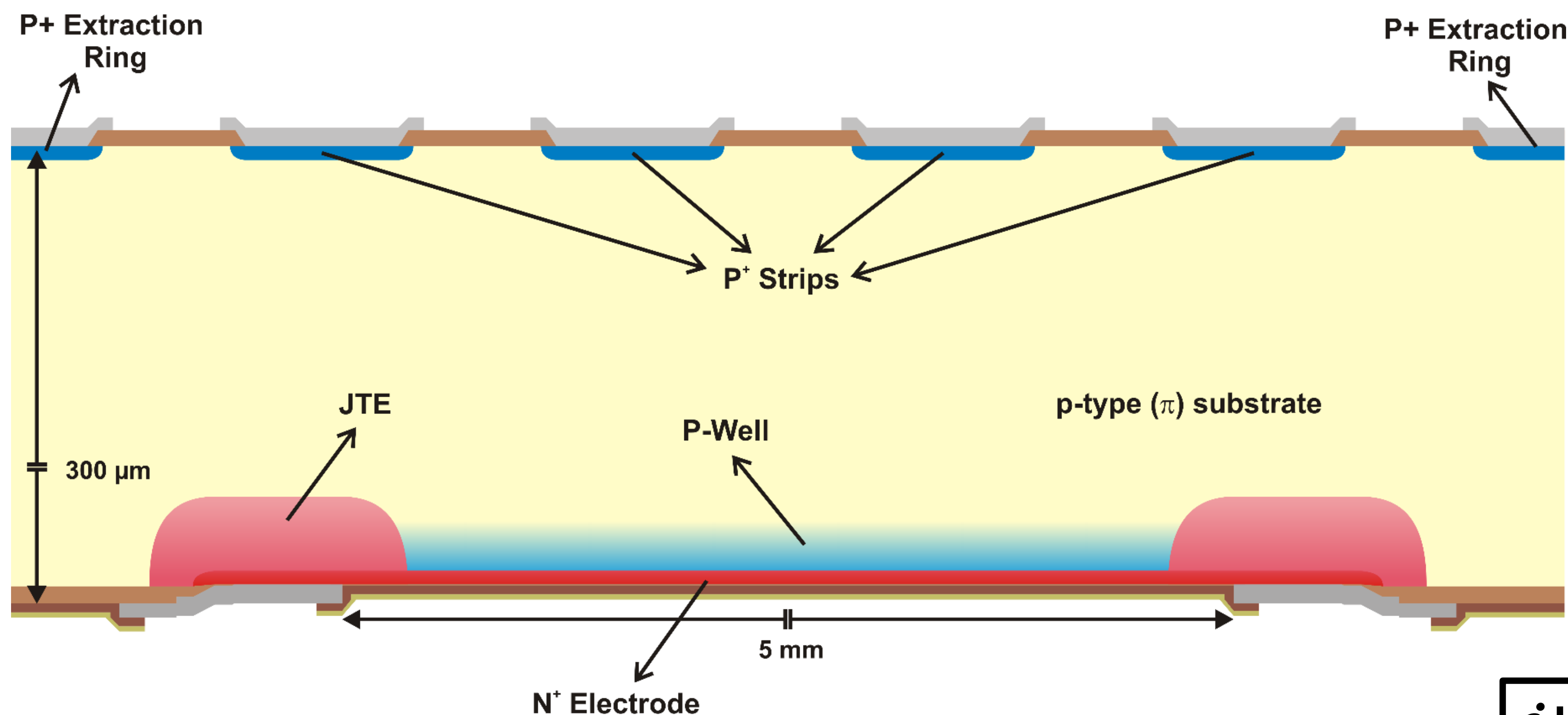
- **Double-sided LGAD** with **pad-like multiplication** structure in the **back-side** and **ohmic read out** strips, or pixels, in the **front-side**

- **N on P** vs **P on P LGAD** microStrips Comparison



P on P Strip iLGAD: The "Inverse" LGAD

- **Double-sided LGAD** with **pad-like multiplication** structure in the **back-side** and **ohmic read out** strips, or pixels, in the **front-side**
- **First Design and Run**. Include Pads, microStrips and pixelated i**LGADs**

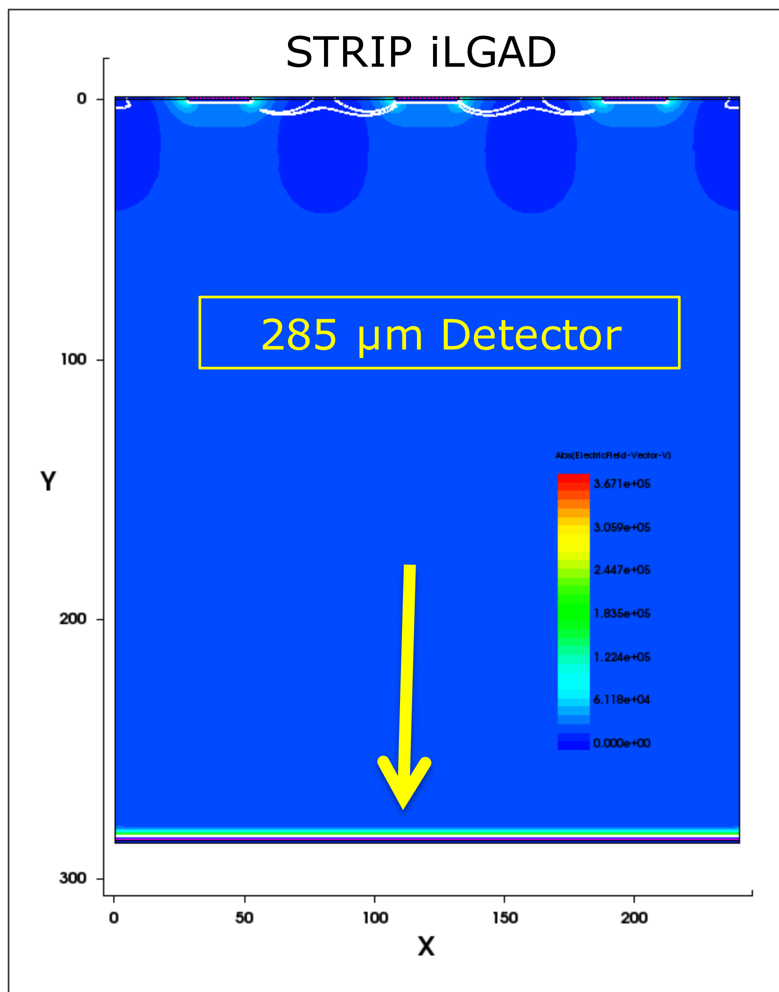


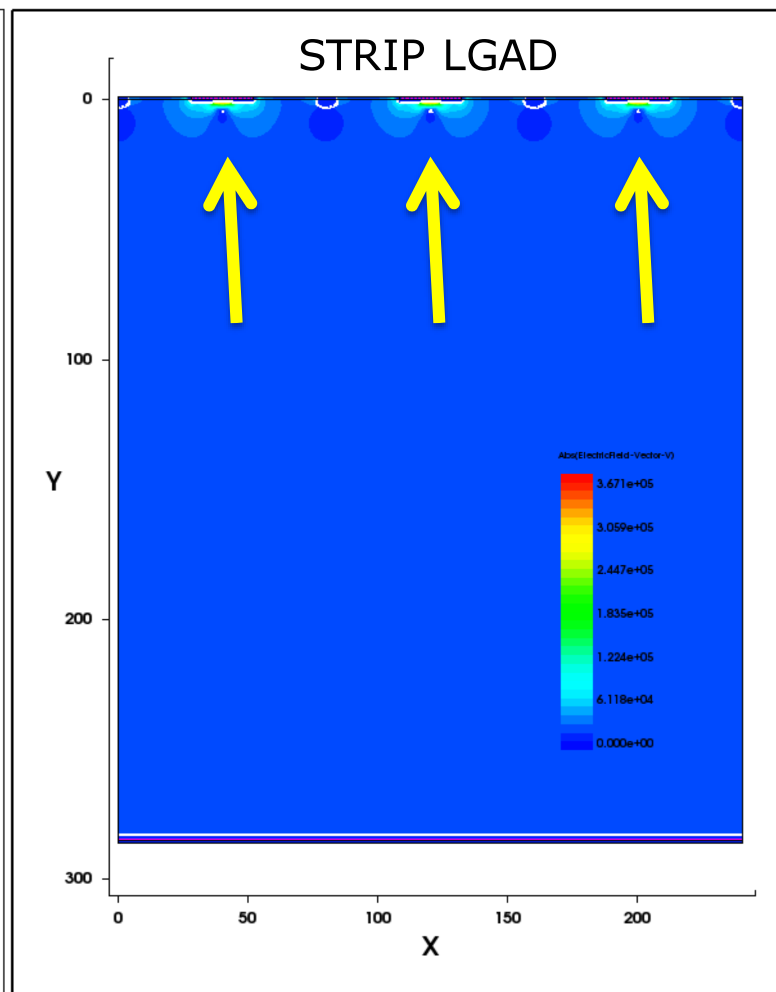
*1987 **United States Patent. Paul P. Webb** et al. RCA Inc. "Avalanche photodiode"*

iLGAD

iLGAD. P on P MicroStrips. 2D Simulation

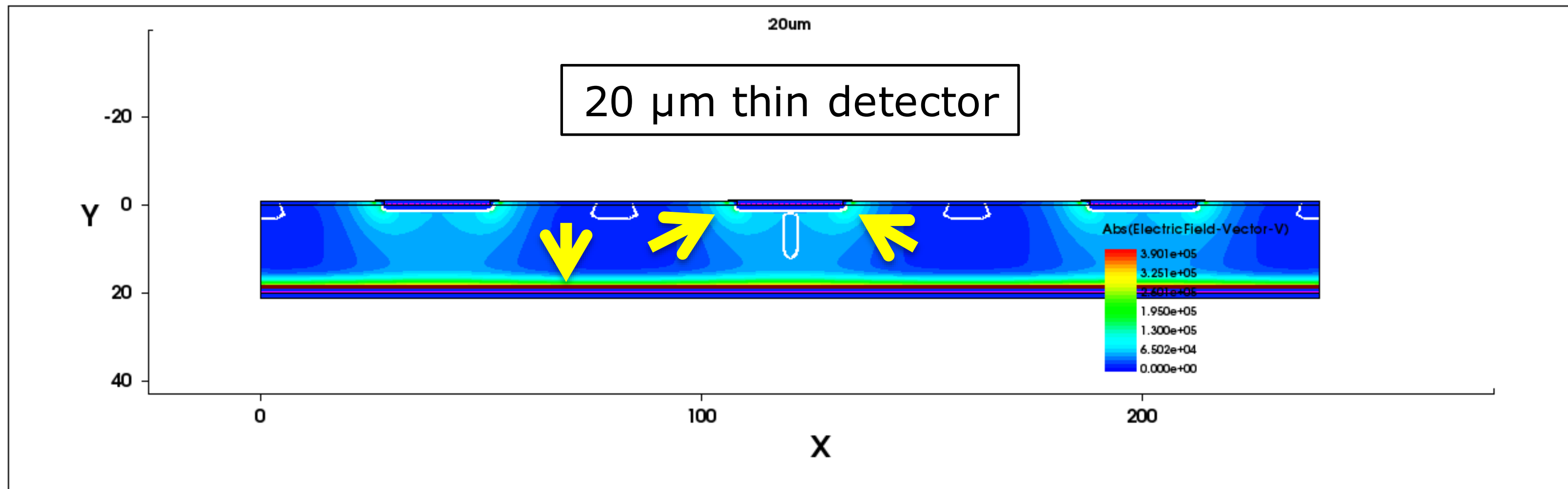
- **Three** microStrips. **Electric Field** Distribution: **Maximum value @ P-N Junctions**

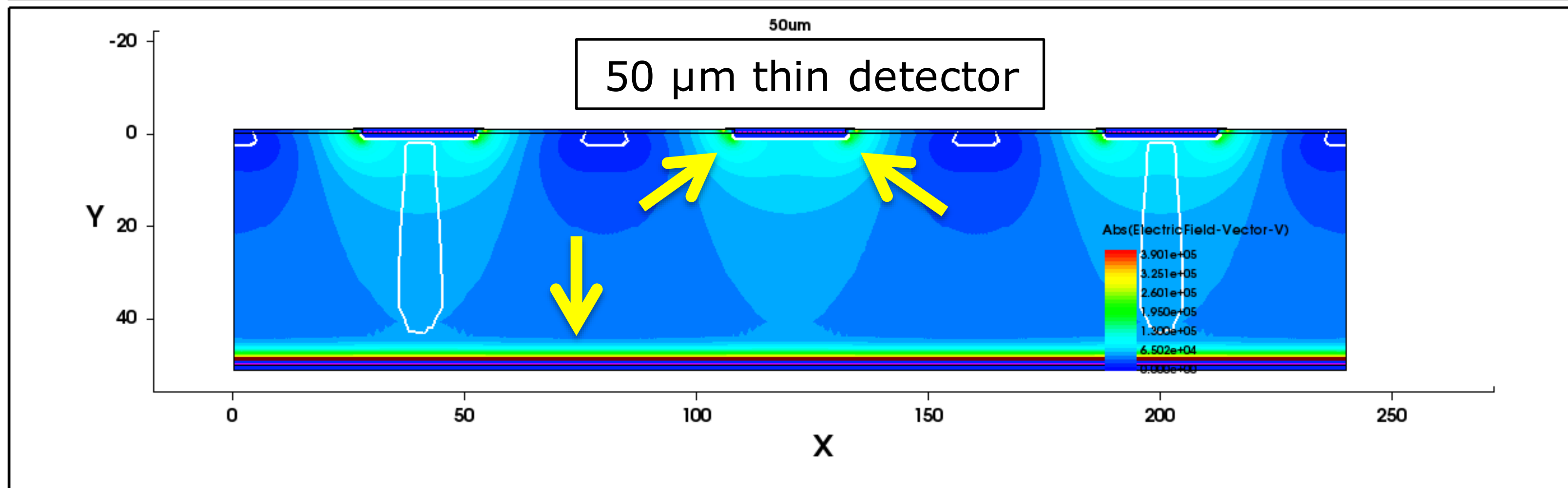




iLGAD. P on P MicroStrips. 2D Simulation

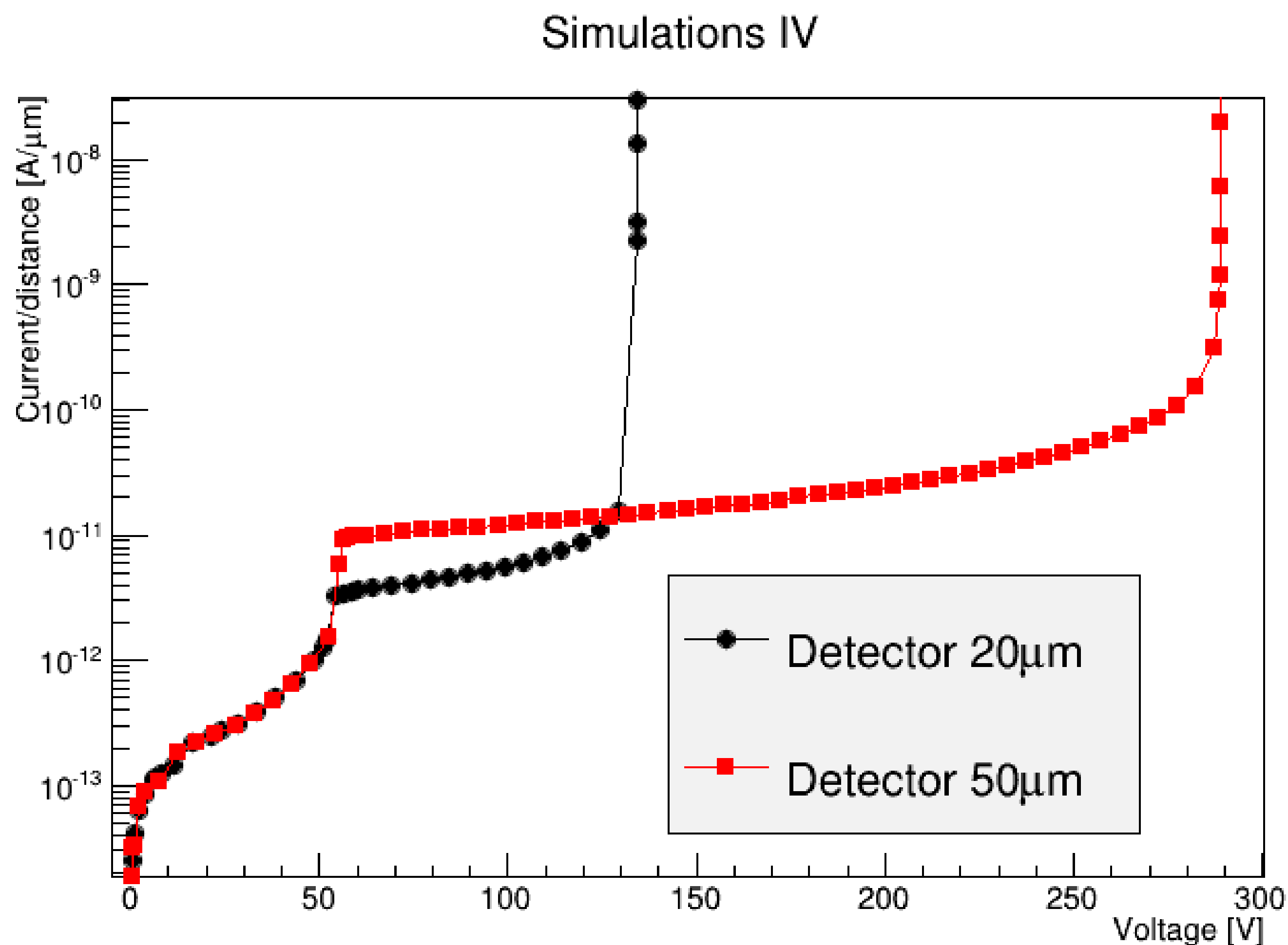
- MicroStrips Simulation. **Electric Field** 2D Distribution **@ V_{BR}**





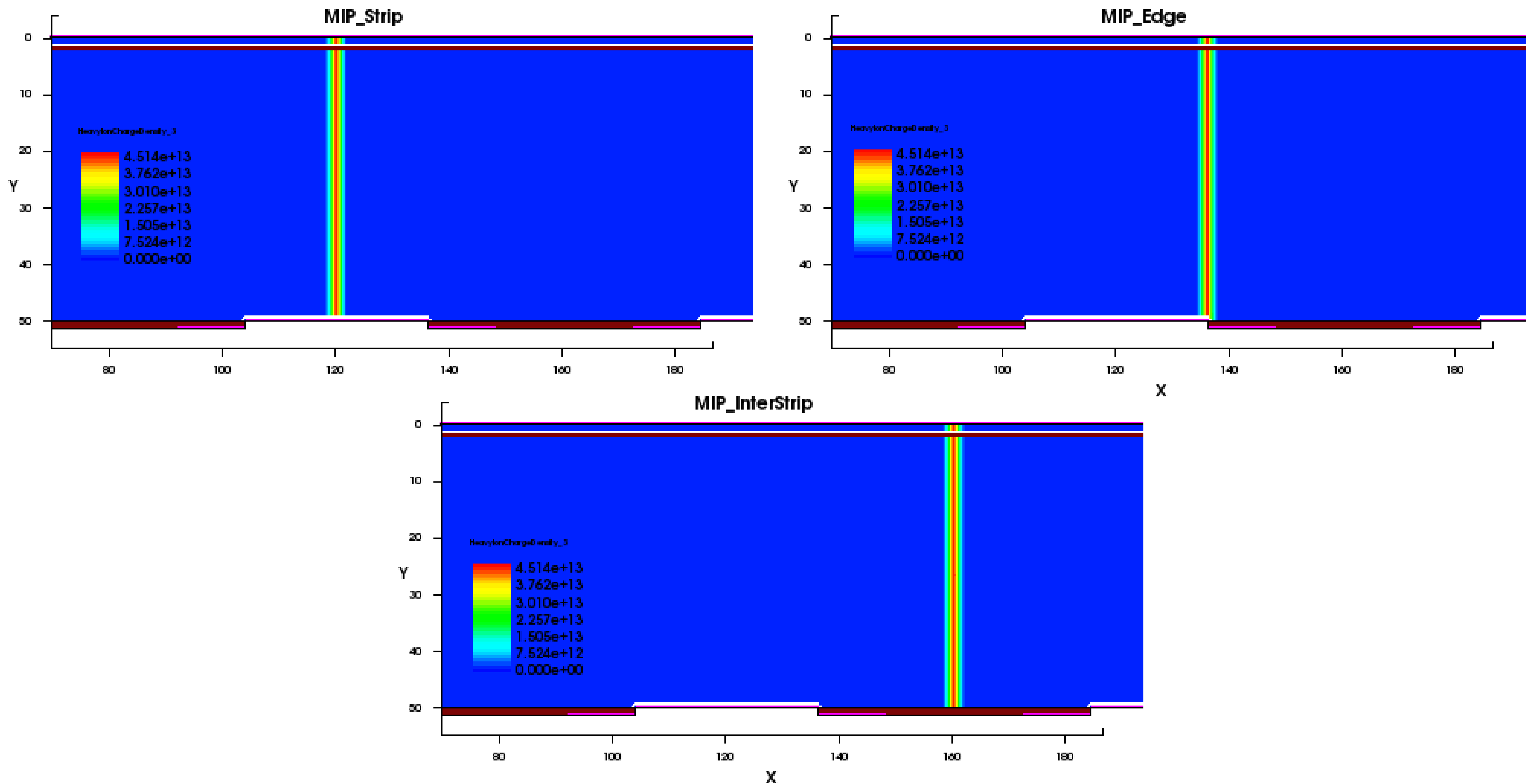
iLGAD. P on P MicroStrips. 2D Simulation

- MicroStrips **I(V)**. **Breakdown** performances **limited** by **Thickness**

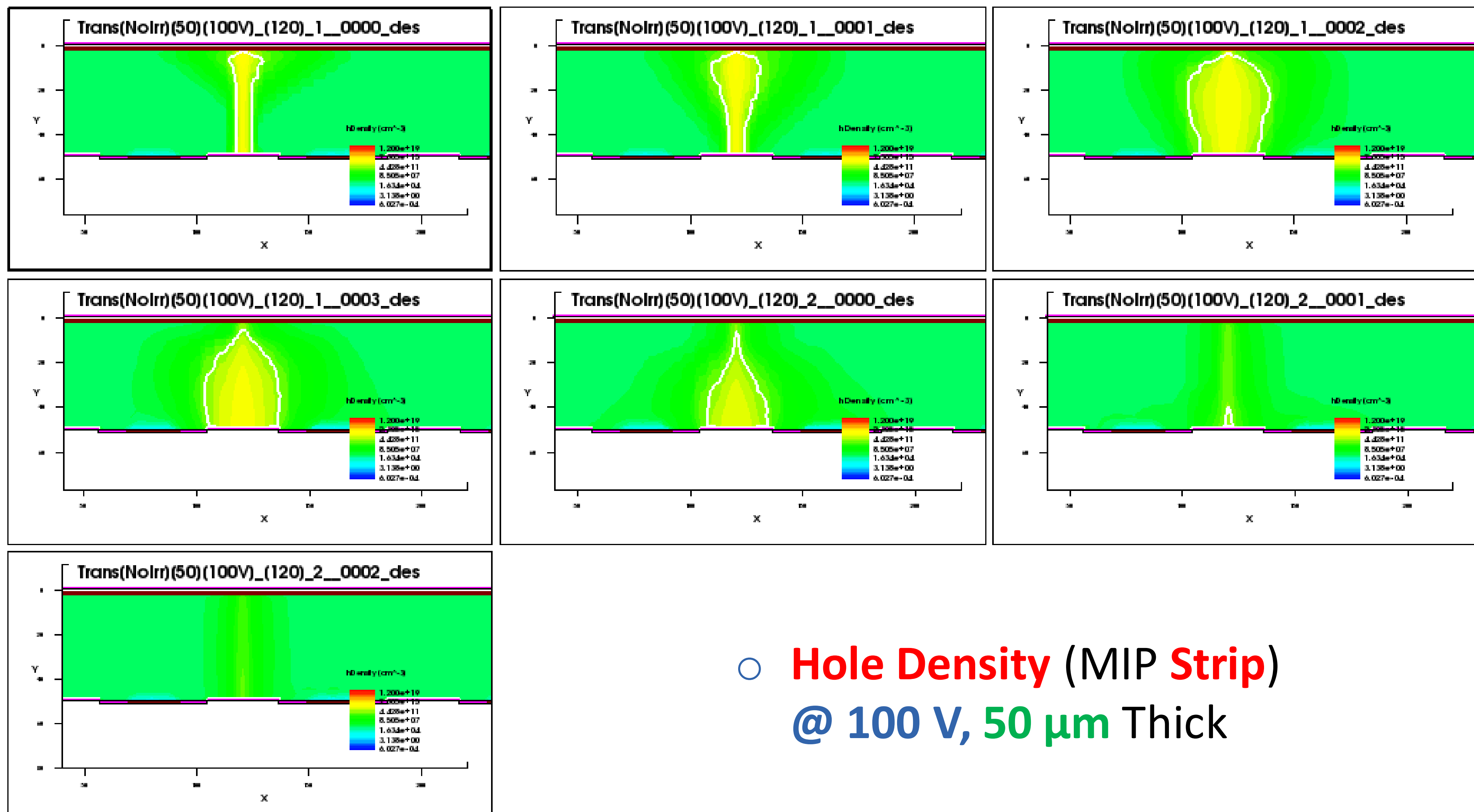


iLGAD. P on P MicroStrips. 2D Simulation. MIP

- **Charge Collection** (MIP) **@ 100 V, 50 µm** Thick

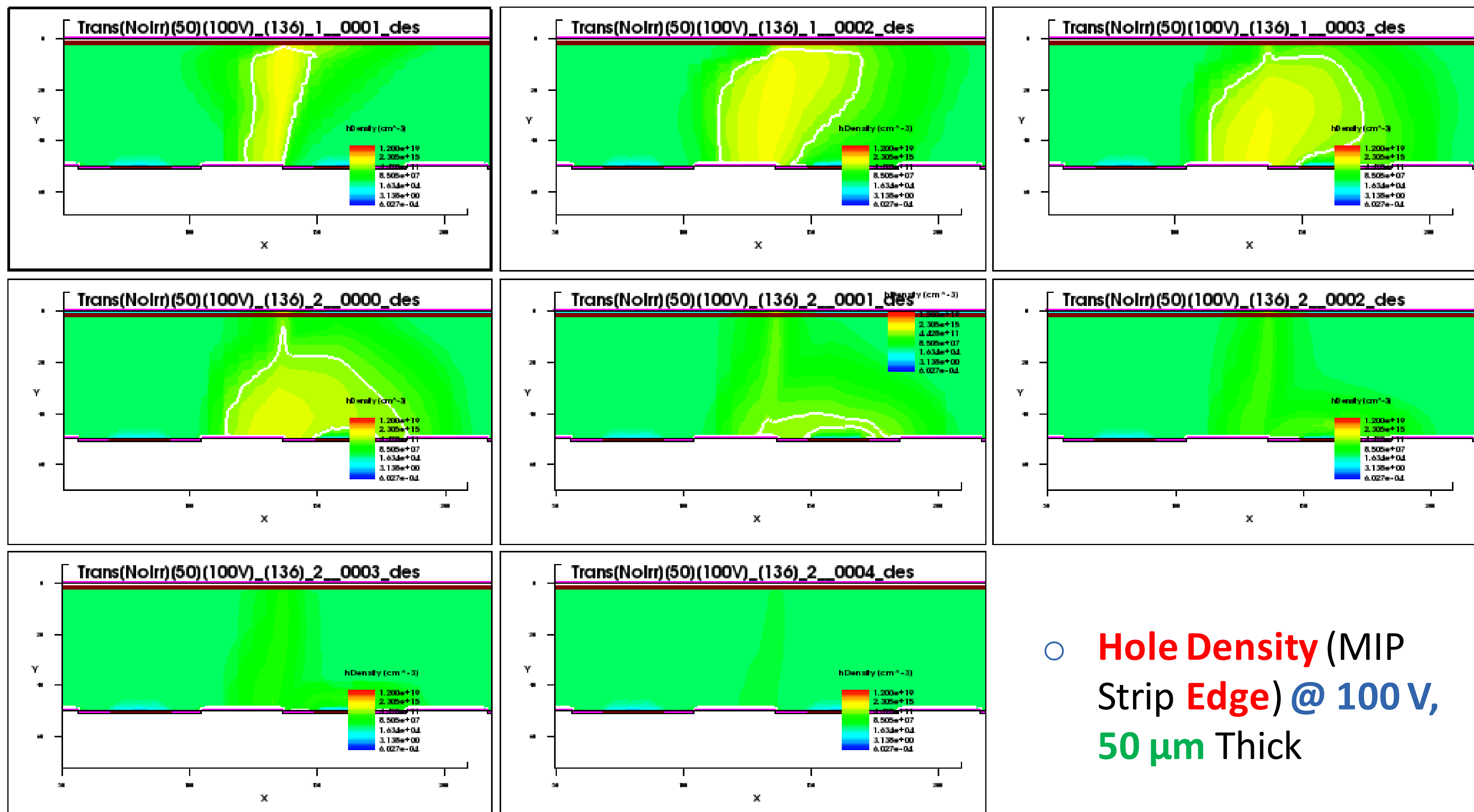


iLGAD. P on P MicroStrips. 2D Simulation. MIP. Strip Center



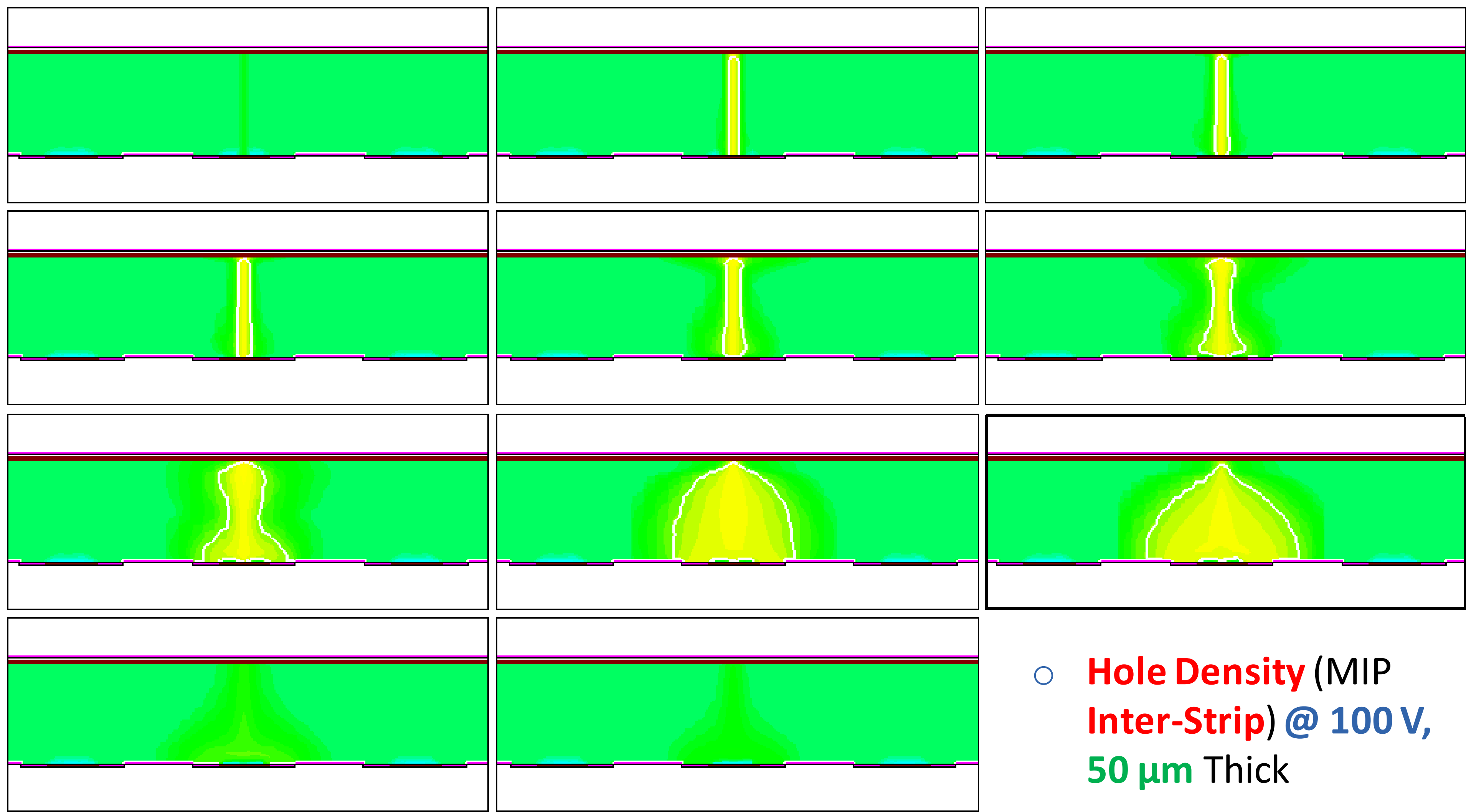
- **Hole Density** (MIP **Strip**)
  @ 100 V, 50 µm Thick

iLGAD. P on P MicroStrips. 2D Simulation. MIP. Strip Edge



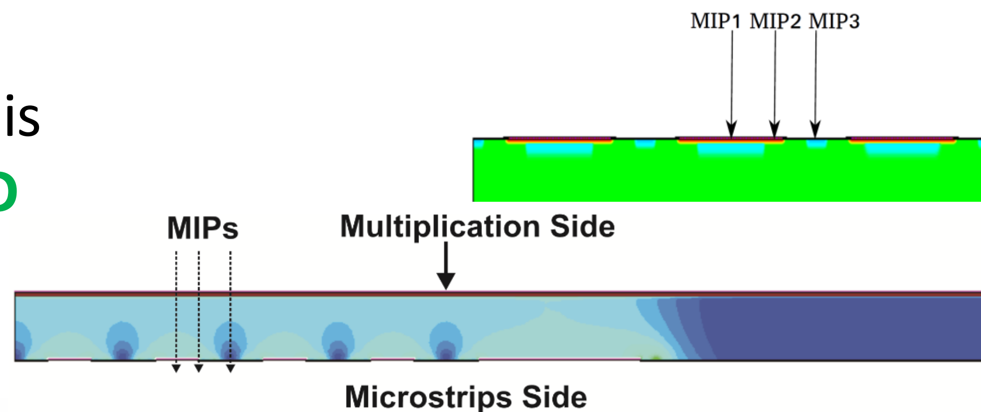
- **Hole Density** (MIP Strip **Edge**) **@ 100 V, 50 µm** Thick

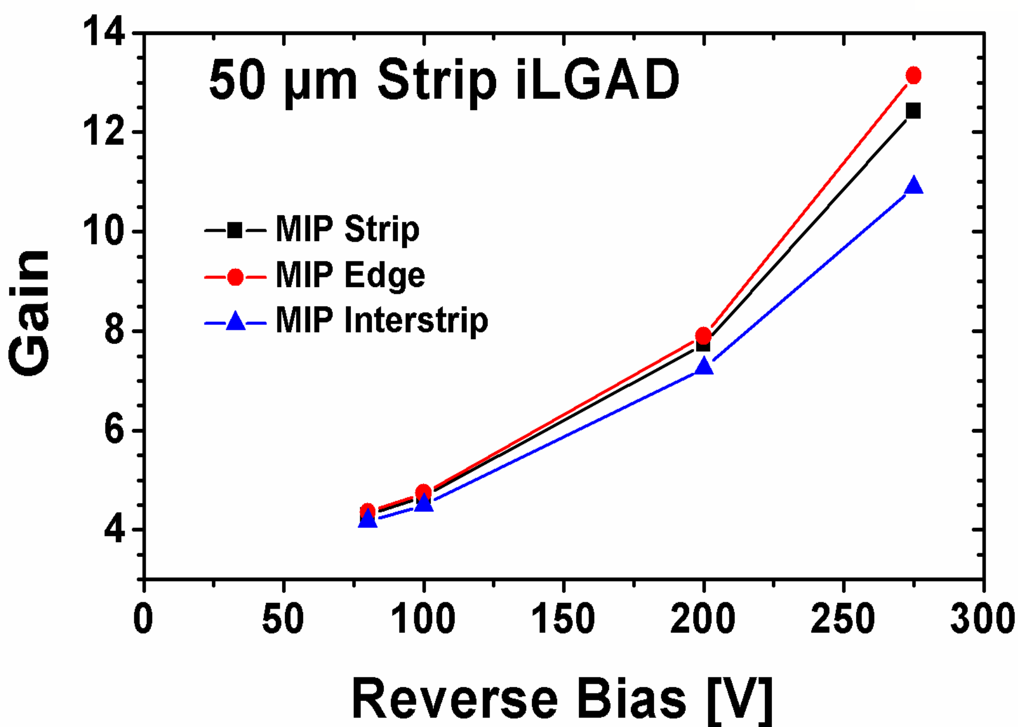
iLGAD. P on P MicroStrips. 2D Simulation. MIP. Inter-Strip

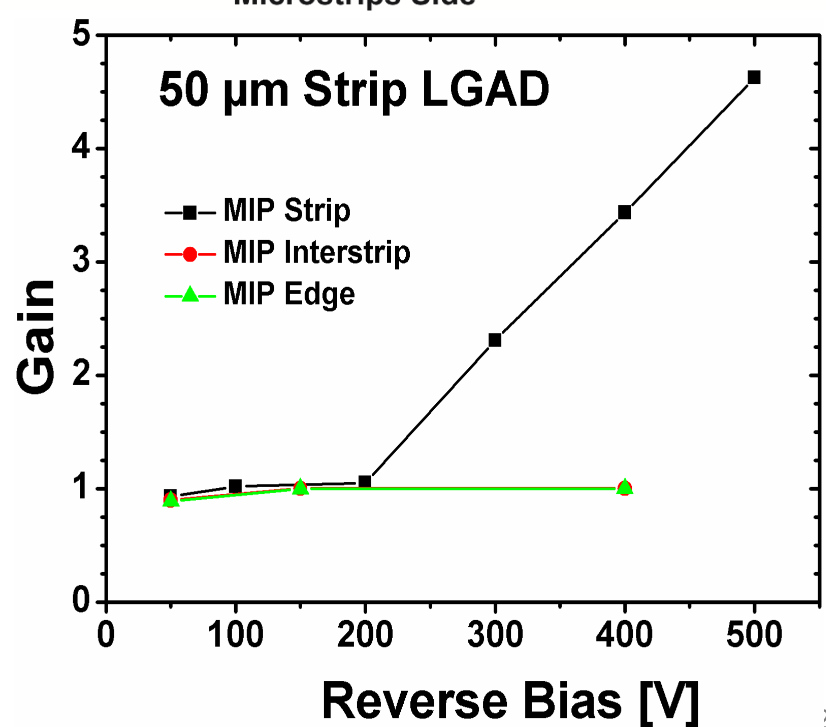


Strip LGAD vs iLGAD. MIP Simulation. Gain Evolution

- µStrip iLGAD **Charge Collection** is **More Efficient** than µStrip LGAD

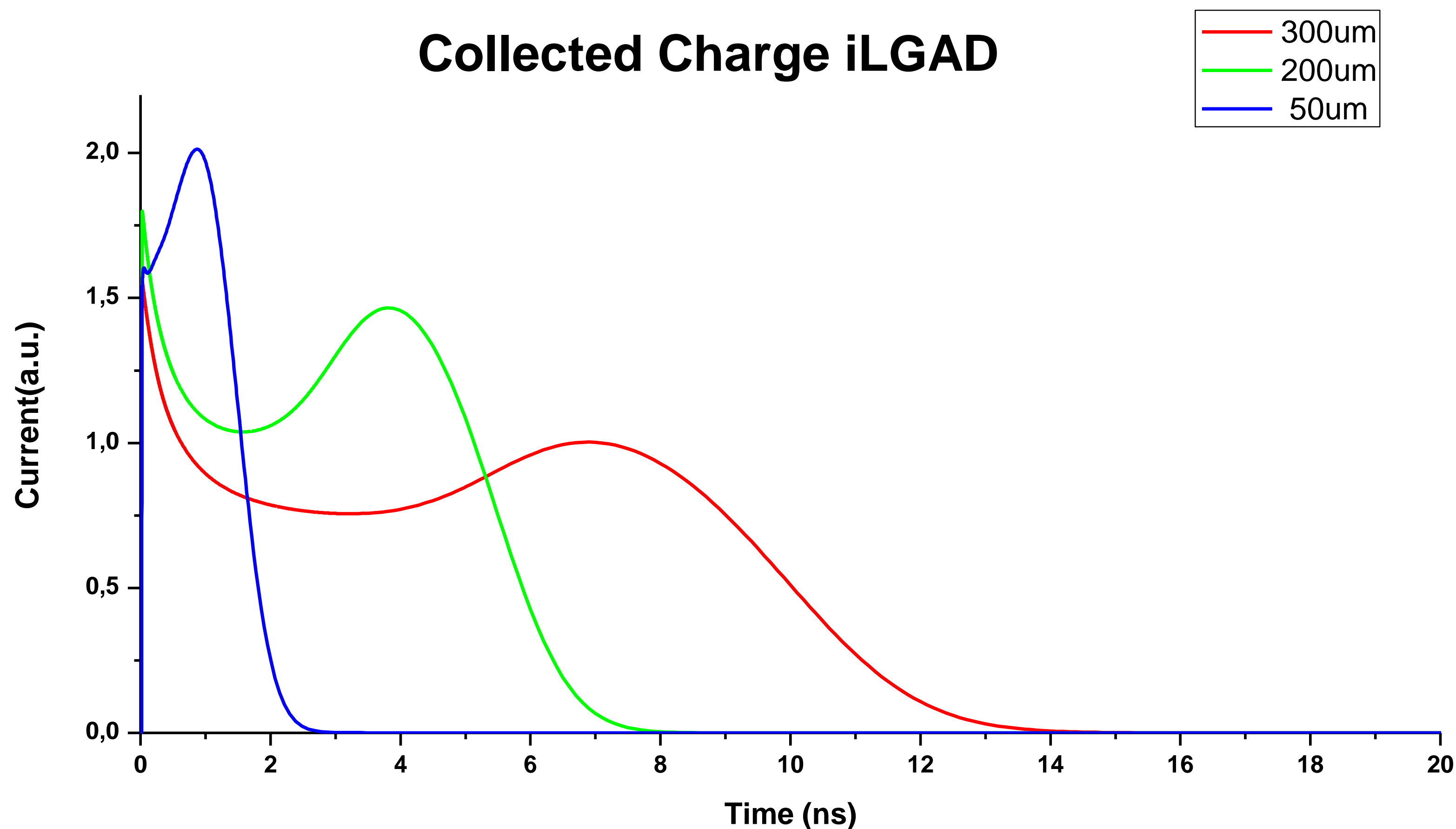






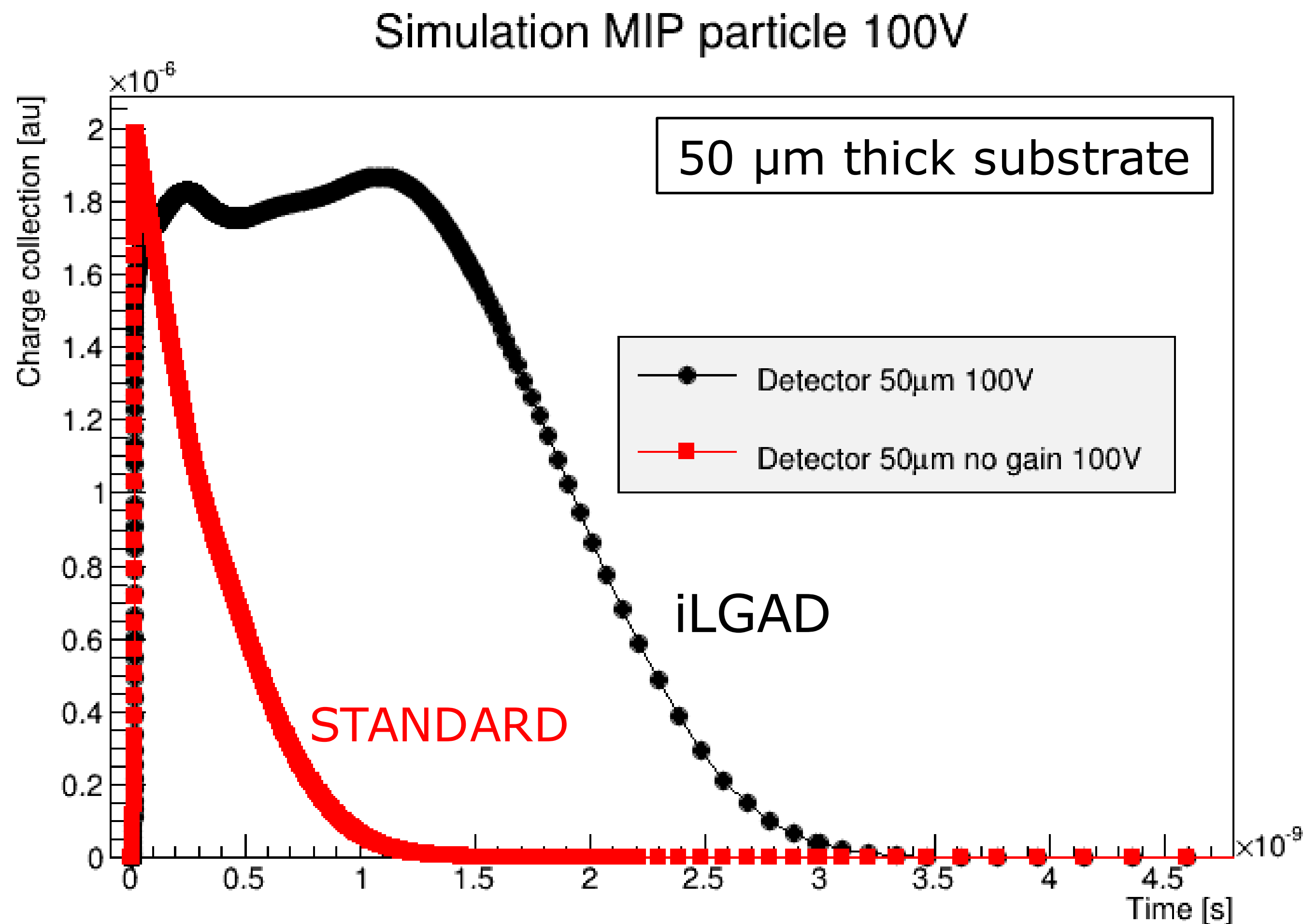
iLGAD. P on P MicroStrips. 2D Simulation. Timing

- **MIP** through the middle of the sensors (central strip) **@ 500 V** and **300 V (50 µm)**



iLGAD. P on P MicroStrips. 2D Simulation. Timing

- **MIP** through the middle of the sensors (central strip) **@ 100 V**



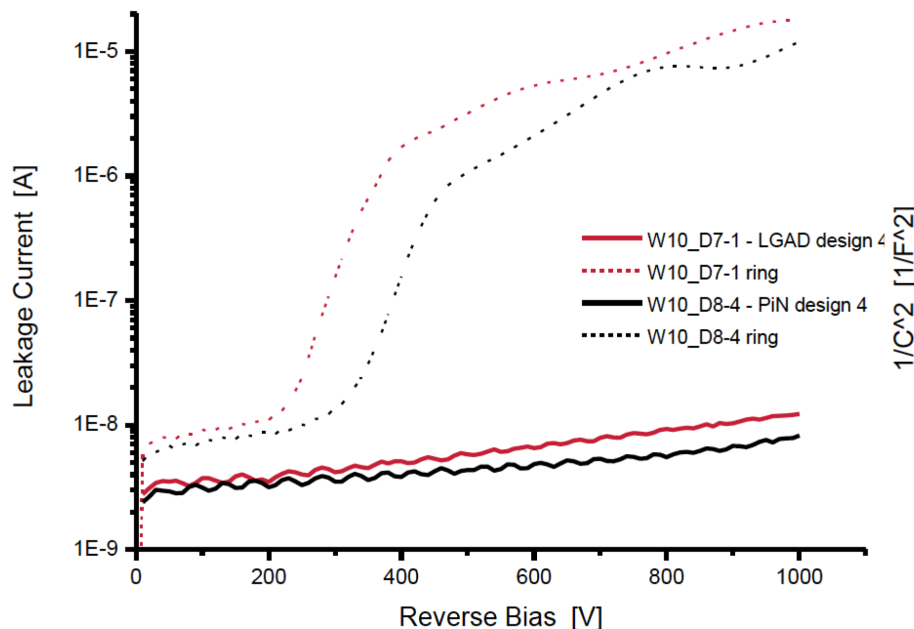
Conclusions

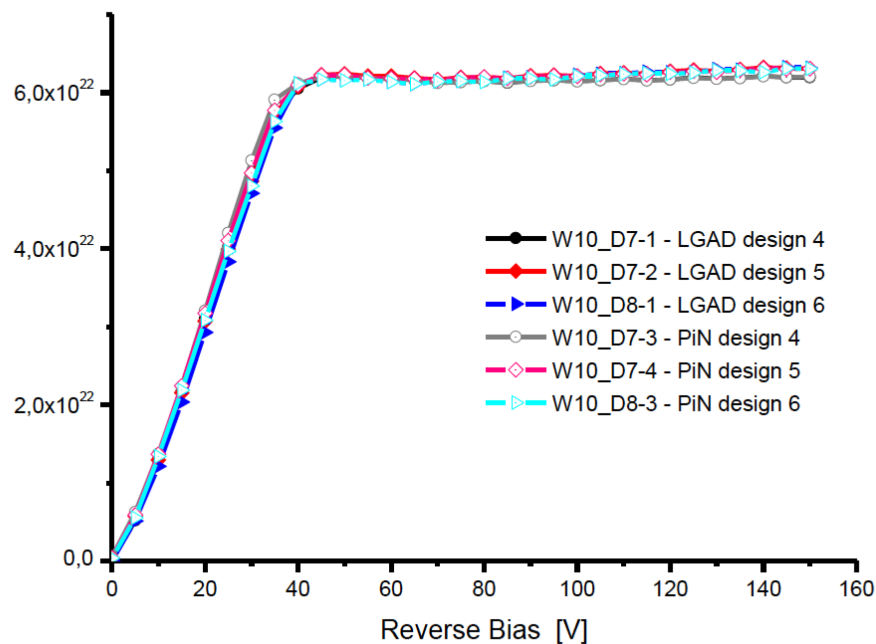
- Technological Developments @ CNM on LGAD & iLGAD Detectors
- PAD LGAD Shows
  - ✓ Gain: 3.7 – 8.4, Dose: 1.8e13
  - ✓ Gain: 8.3 – 44, Dose: 2.0e13
  - ✓ Good Homogeneity
- microStrips LGAD Shows
  - ✓ Low Gain: 2.0 @ 200 V
  - ✓ Charge Collection. Center of Multiplication Area
- New iLGAD. Low Gain P on P Detector
  - ✓ Position-Sensitive Detectors
    - ➢ Thin Detectors
    - ➢ Fine Pitch
  - ✓ Timing
    - ➢ Thin Detectors
- Double-Sided LGAD
  - ✓ Pad LGAD @ Back-side
  - ✓ Ohmic Read Out @ Front-side
- microStrip iLGAD Simulation
  - ✓ Optimization
    - ➢ Technological
    - ➢ Electrical
    - ➢ Thinner Substrates for Timing
  - ✓ Detectors Shown Good Performances
  - ✓ µStrip iLGAD charge collection is better than µStrip LGAD
- First Mask Set
  - ✓ microStrips
  - ✓ Pixels
- First iLGAD Prototypes
  - ✓ 12 Mask
  - ✓ 100 Steps
  - ✓ 5-6 Months
- First iLGAD Run Already Started @ CNM

Thank you for your attention !!!!

LGAD. Gallium Multiplication Layer. 300 µm Substrate

- I-V, C-V on Wafer (Implantation @ IBS)

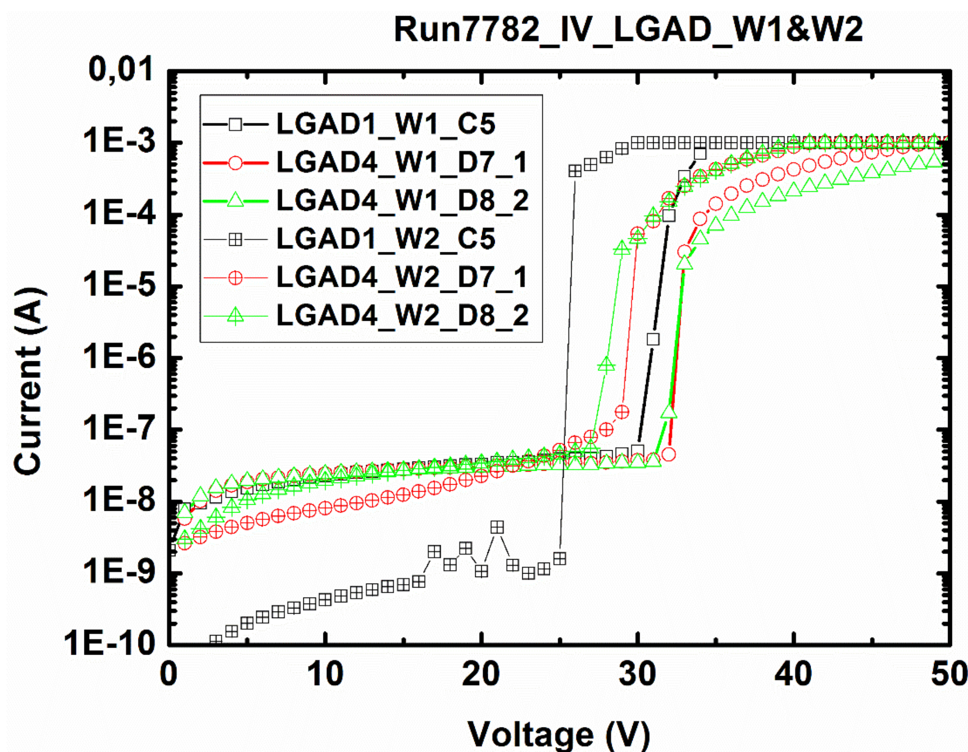


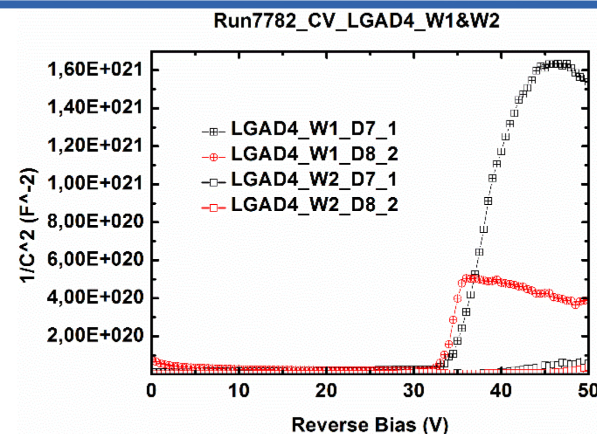


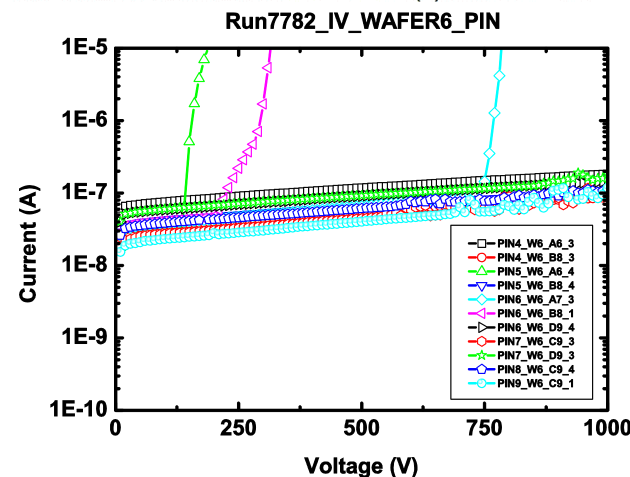
- LGAD Devices with Gallium Multiplication Layer have Similar I-V and C-V Characteristics than PiN Detectors. We do not Observe the Multiplication Layer Depletion

LGAD. Boron Multiplication Layer. 200 μm Substrate

- **I-V, C-V** on Wafer **(Implantation @ IBS)**







- **LGAD** devices with **200 μm substrate** have **Low Breakdown Voltage** Characteristics than **300 μm substrate** Equivalent LGAD Detectors
- **Doping** Level of the **Boron** Multiplication Layer is **Higher** than Expected by Simulations
- **Neutron Irradiation** at **JSI Ljubljana** to **Reduce Boron** Peak Concentration