Low-Gain Avalanche Detectors (LGAD)

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Introduction and Motivation

Reasons for the wide-spread use of Silicon Detectors in HEP, Astrophysics, Medicine:
+ Proportional response
+ Good efficiency, Signal-to-Noise S/N
+ Segmentation technologically easy [strips, pixels]
but
-- Radiation Damage [worsening of S/N]
-- Time resolution limited [saturation of drift velocity]
Improve Silicon Detector's performance by increasing the S/N with internal gain

Low-Gain Avalanche Detectors [LGADs]

LGADs exploit the avalanche phenomenon of a reverse-biased p-n junction.

Internal gain (~10) is optimized for high bias (fast collection, reduced trapping), low noise, high rate

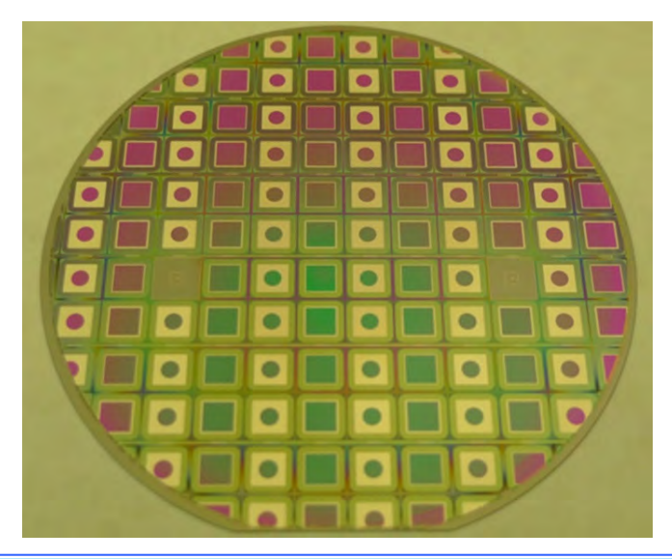
Potential applications:

Thin sensors for tracking,
Ultra-Fast Silicon Detectors UFSD
Fast sensors for Time-of-Flight TOF
Radiation-resistant sensors,
Soft X-rays (good conversion %, improve S/N)

Fabrication of LGADs at CNM

Run #	Geometries	
6474	Pads	1,4,7
6827	Pads, Strips, Pixels	2,4,5,6,7
7062	Pads	1,3,4,7,8

1. Edge of n+ and periphery variations
2. Wafers with different p-layer doping profiles
3. Shallow and deep n-diffusion profiles
4. High resistivity FZ 300 μm p-type substrate
5. Epi 100 Ω-cm p-type wafers,10-75 μm thick
6. Segmented detectors (strips, pixels)
7. Wafers contain reference PiN diodes
8. Backside metal grid allows red laser TCT

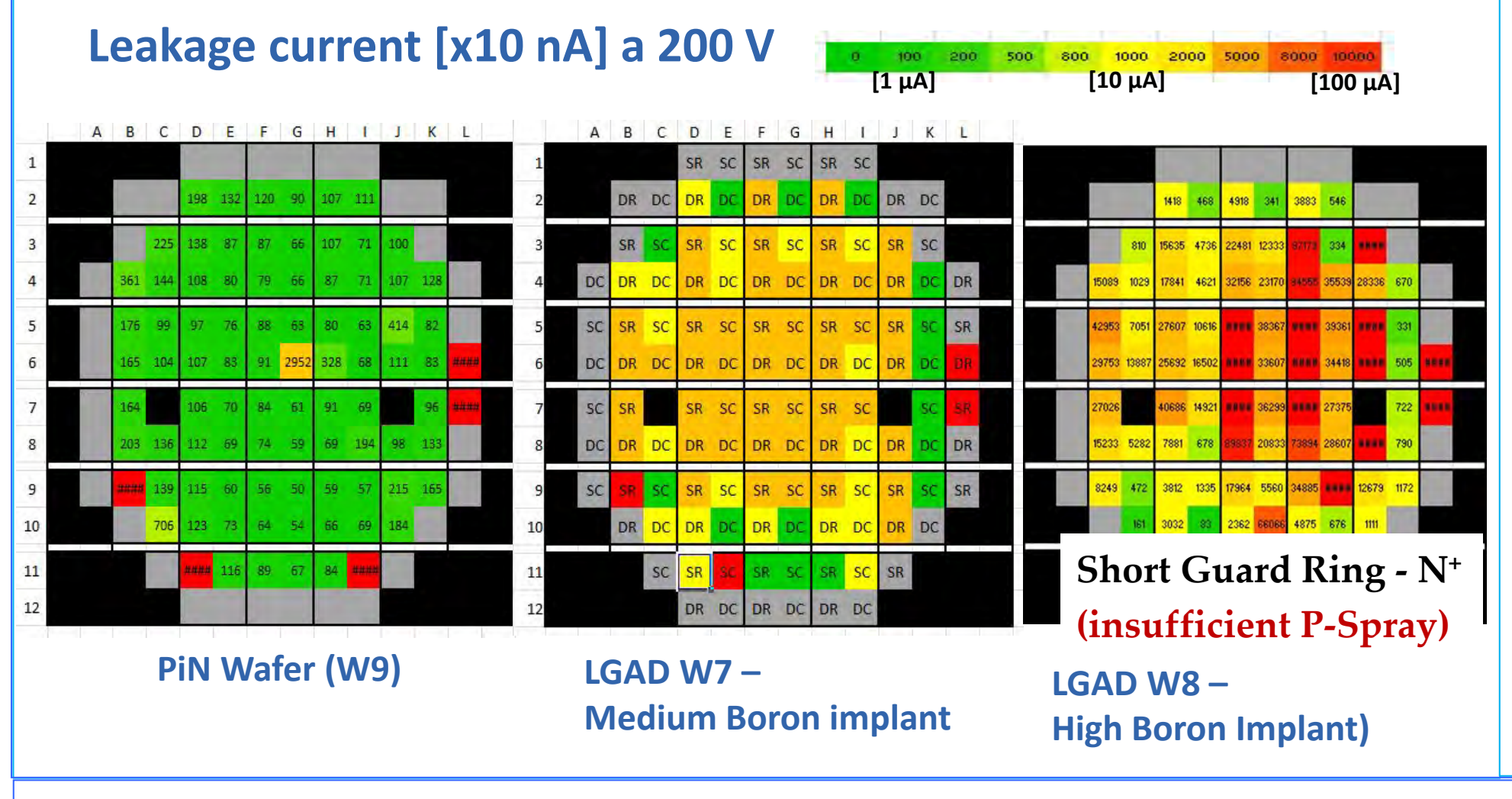


Electrical Characterization

Current – Voltage (I-V): **Run 6474**

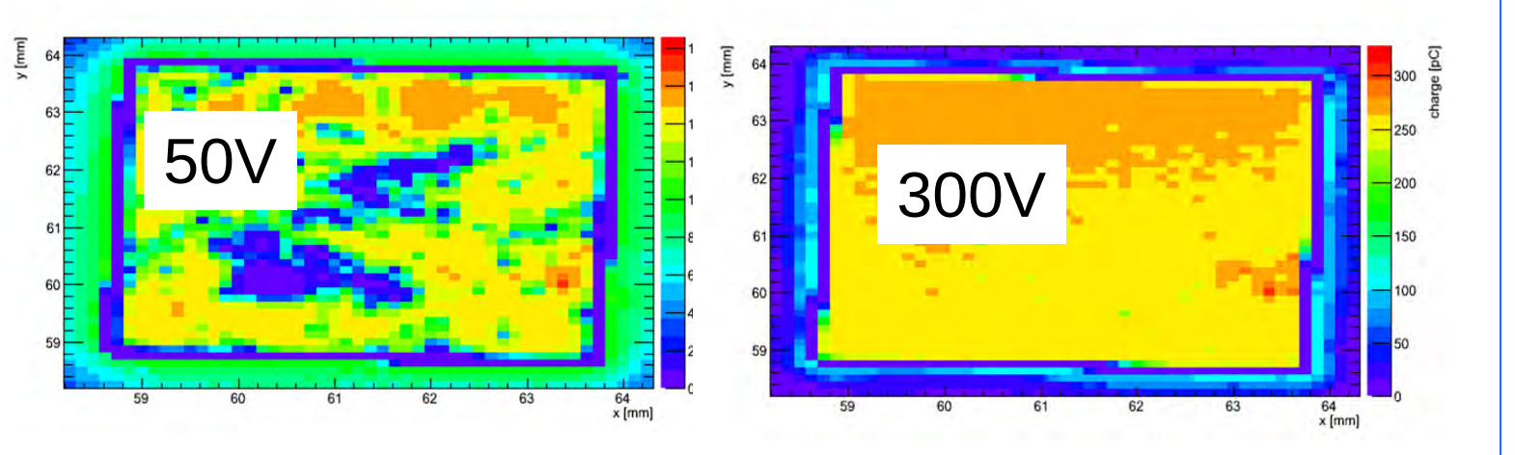
Breakdown Voltages > 1100V

Yield of devices with high current increases with increasing implant dose in the p+ multiplication layer.



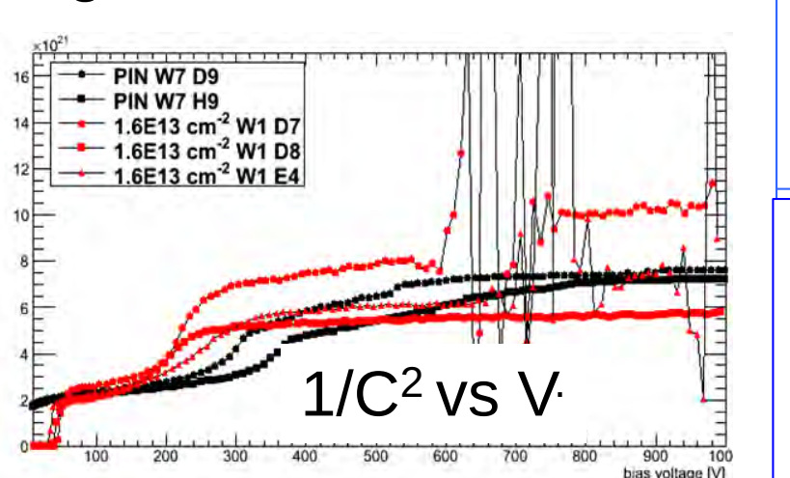
Inhomogeneity & Instability (Run 7062)

On a few sensors, inhomogeneous regions are observed with TCT before full depletion, which disappear after depletion of the multiplication p-layer.



Instability at high bias voltages visible in CV, IV & TCT, but disappears at higher bias.

Under investigation.

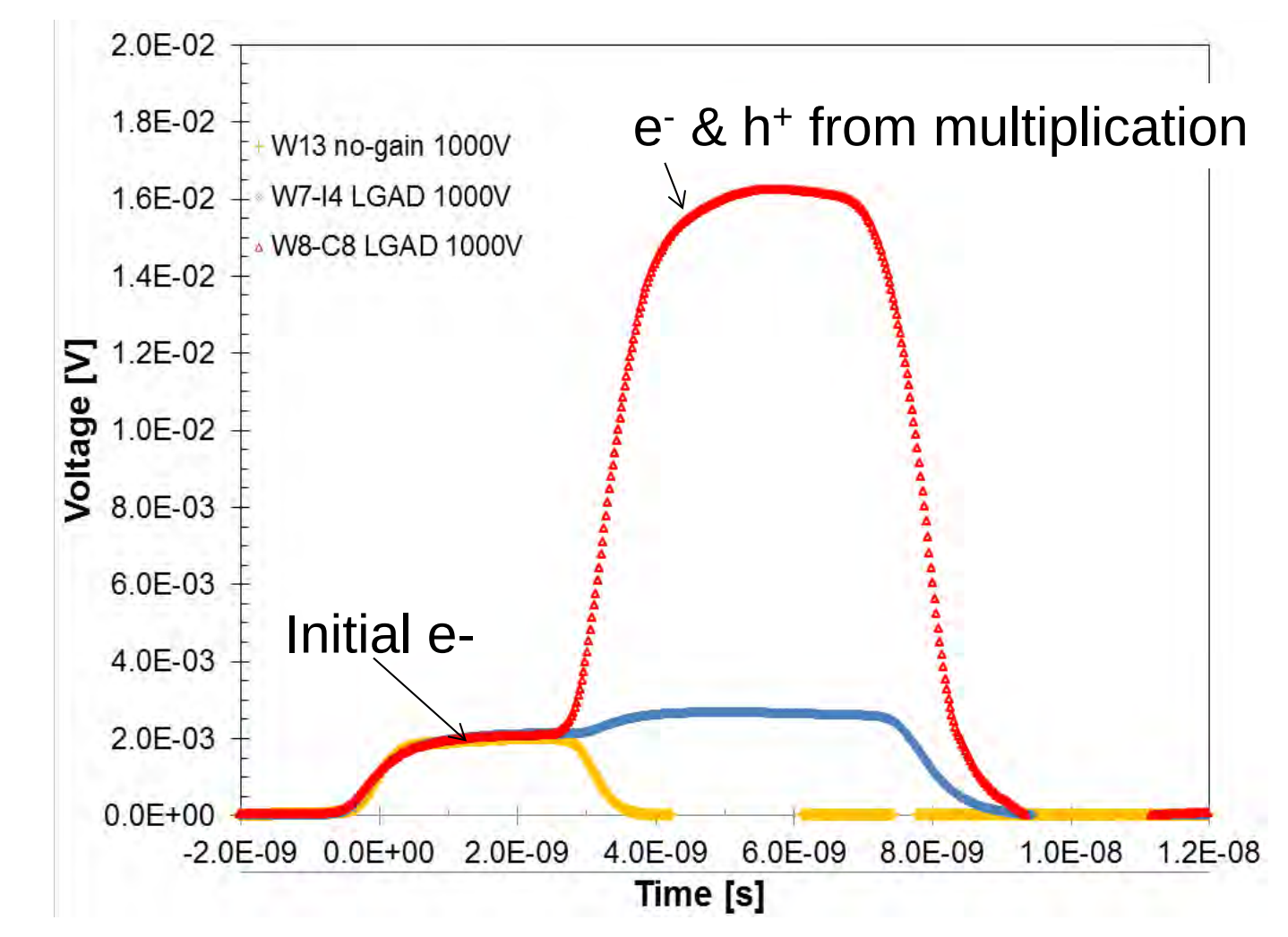


Gain Testing of LGAD's

Several methods showing good agreement

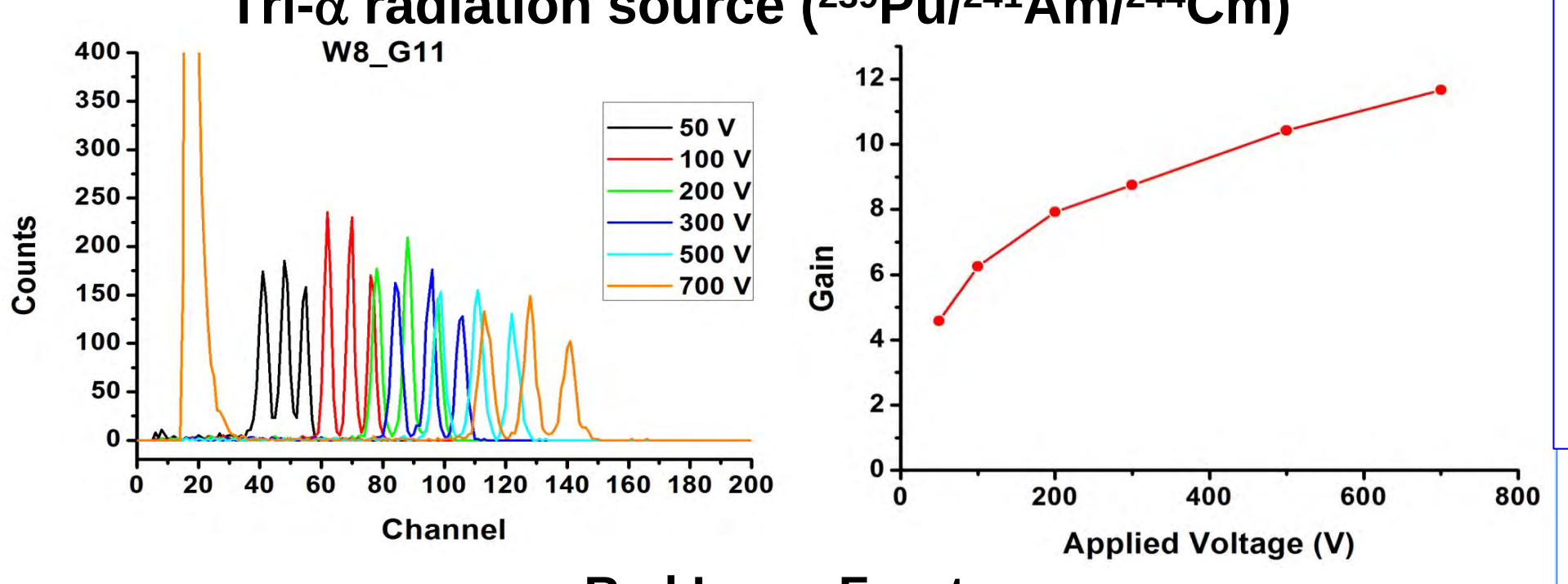
Comparison with non-gain detectors required:
2. Front-side hole injection with α / red laser
3. MIP injection of IR laser

Self-Calibrating:
1. Back-side electron injection α / red laser

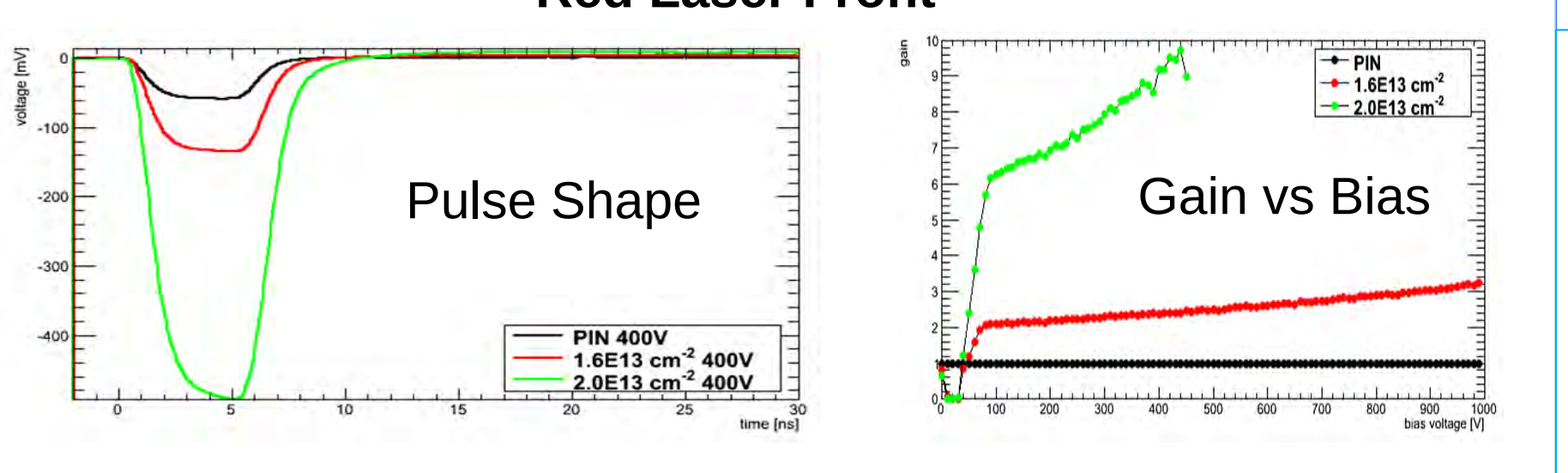


Gain = total pulse area / initial pulse area

Tri-α radiation source (^{239}Pu/^{241}Am/^{244}Cm)



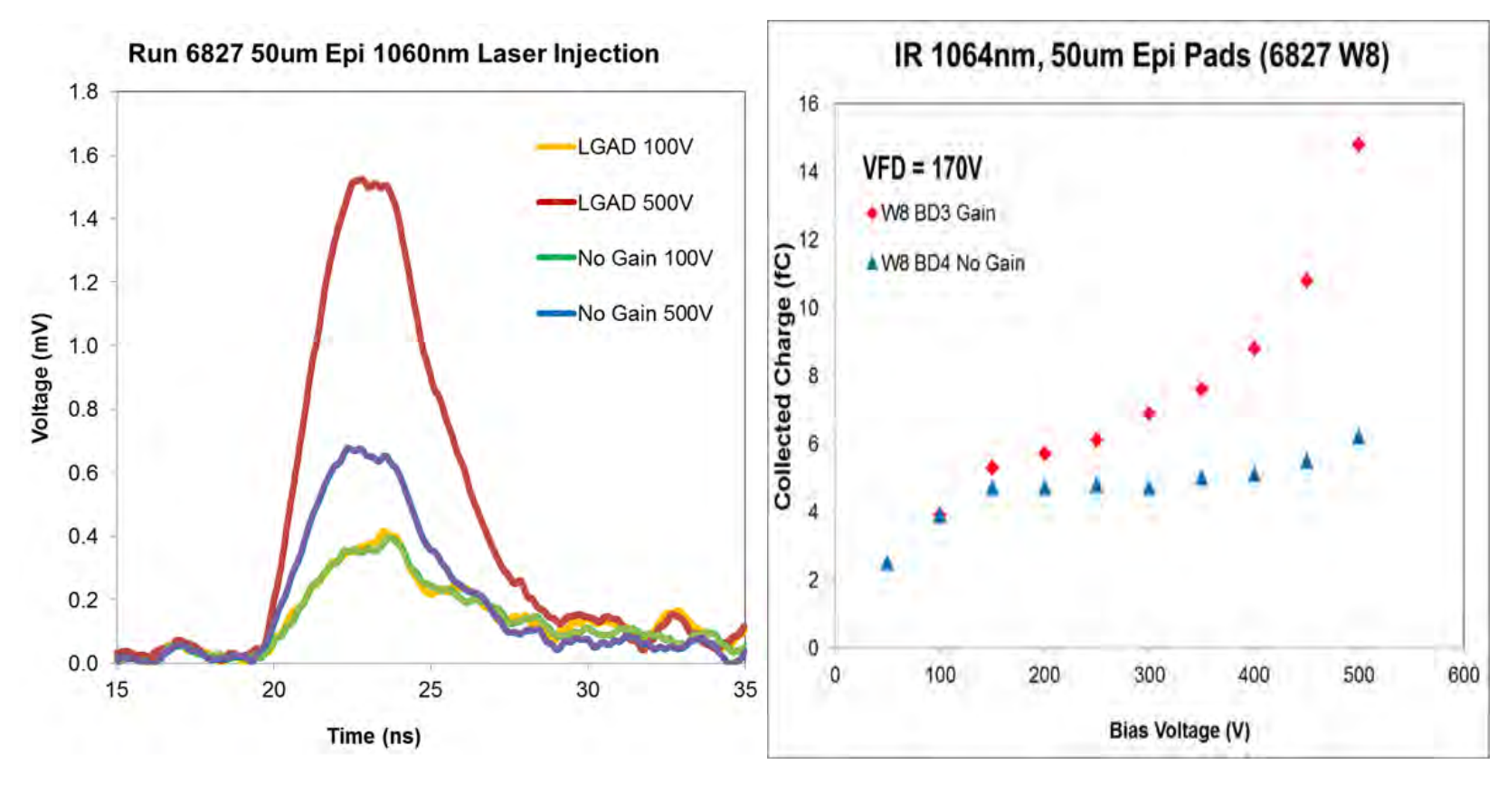
Red Laser Front



Gain in thin LGAD

Gain in 50 μm 100 Ω-cm epi LGAD (6827)

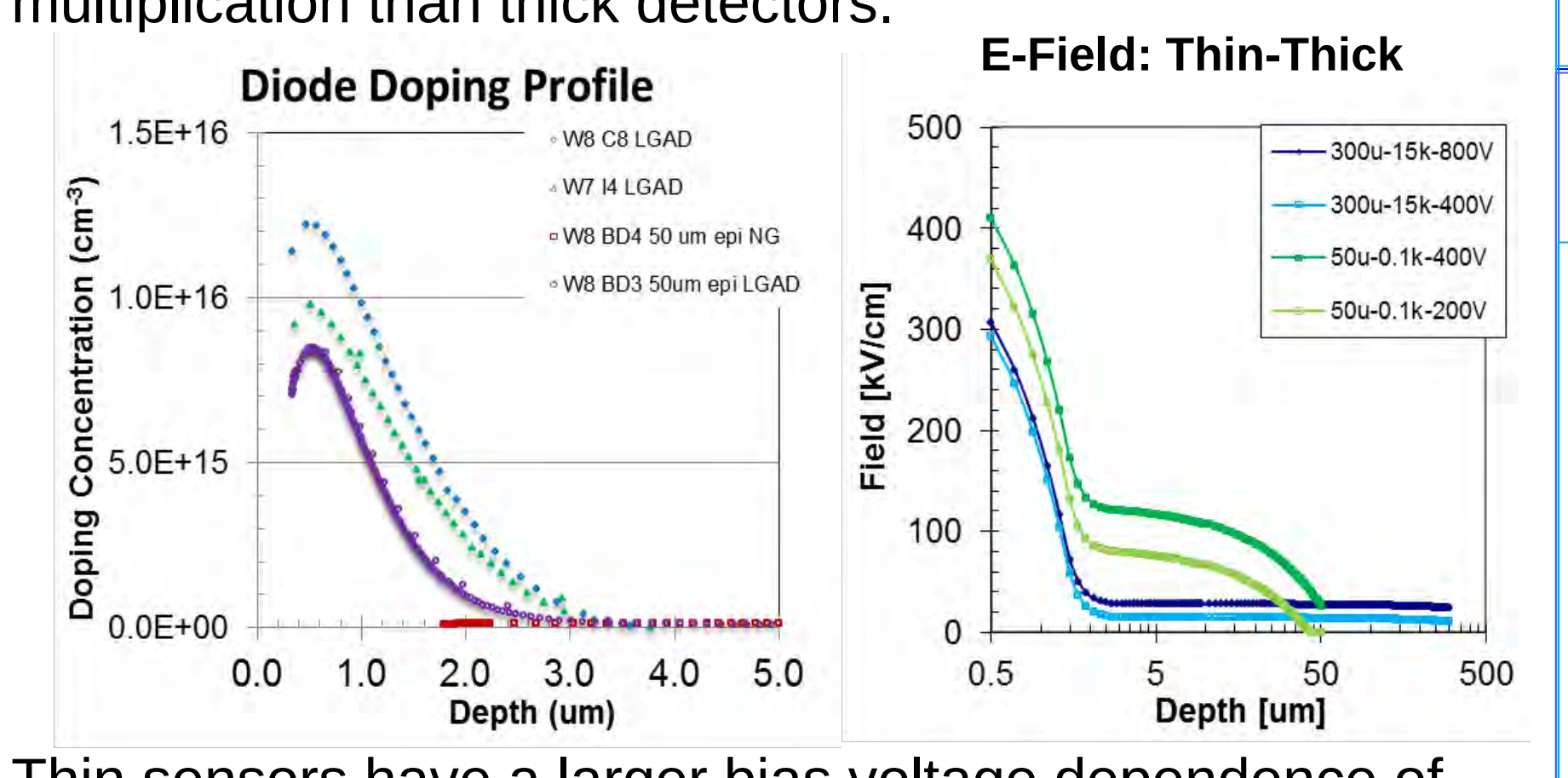
IR laser injection from front shows characteristic LGAD voltage dependence of signal, while no-gain diode is constant above full-depletion voltage VFD



No gain was observed on 300μm 10 kΩ-cm FZ LGAD with same p-layer doping (see above) due to the low doping level.

E-Field in thin sensors

Evaluation of the electric field shows that thin sensors have a much stronger E-field, and thus larger charge multiplication than thick detectors.



Thin sensors have a larger bias voltage dependence of the field, permitting the multiplication to be tuned largely by the bias voltage instead of mainly by the doping profile as in thick sensors.

Mitigation of Radiation Damage

Details: G. Kramberger et al, Radiation Hardness of LGAD, Talk N55-3

Large hadron fluences damage LGADs two ways:

- Damage in the bulk (well-measured increase of leakage current and depletion voltage)
- Damage to the multiplication p-layer (removal of the Boron in the p- multiplication layer, decreasing the field and loss of gain)

Damage to the multiplication layer can be expressed by the fluence **$\phi_{1/2}$** at which the gain drops by **50%.**

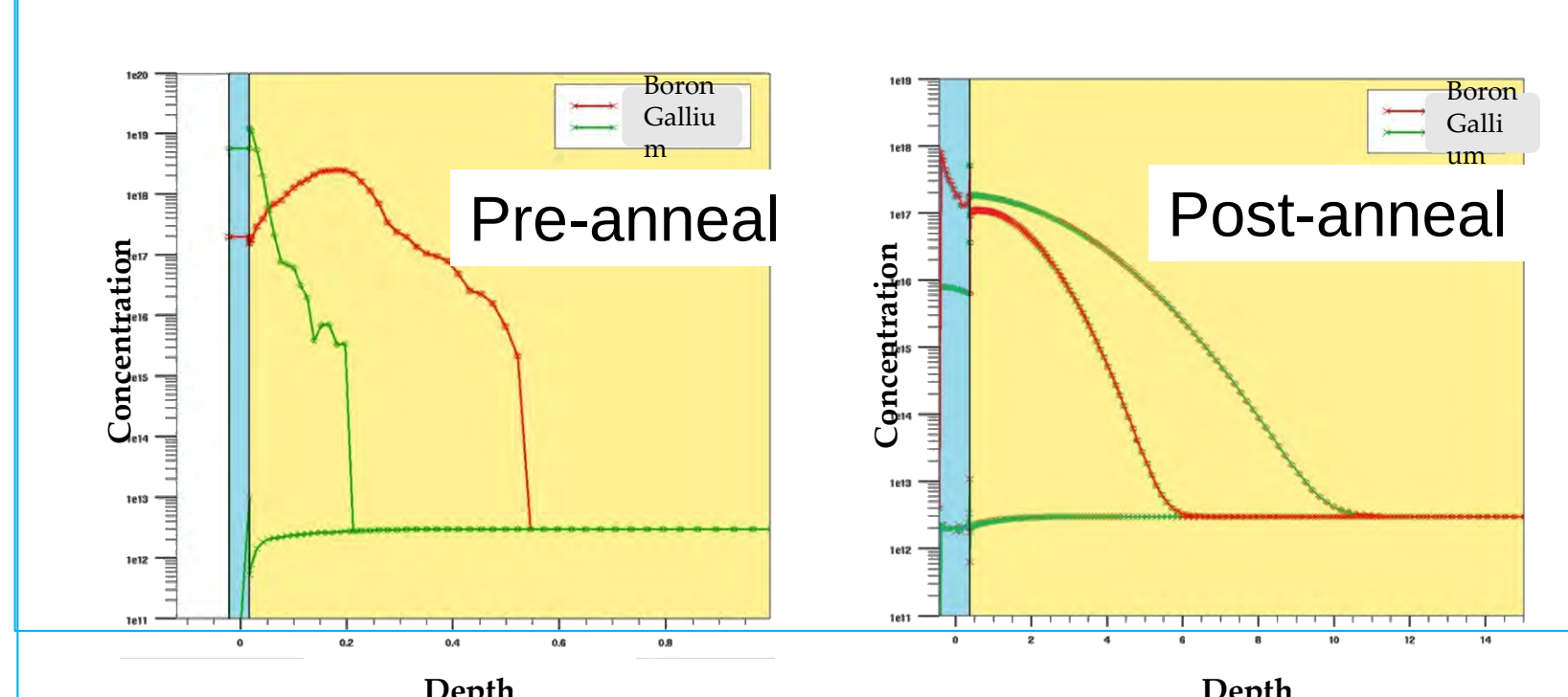
Irradiations with 800 MeV protons (Los Alamos) and reactor neutrons (Ljubljana) resulted in

$$\phi_{1/2} > 1\cdot 10^{14}\ n_{eq}\text{cm}^{-2}$$

(possibly with faster degradation with protons).

The observed radiation sensitivity may require a new technology development of the p-multiplication layer. The approach is to replace the **Boron** by **Gallium**, which would incur less displacement damage.

Compared to B, the heavier Ga has lower penetration depth, but higher diffusion coefficient.



Conclusions

LGADs show uniform gain for pads across wafers with same p-dose
High breakdown voltage (even for thin sensors)
Mitigation of radiation damage planned (B ➔ Ga)
Thin sensors: fast timing, prospect of p-in-p for segmented LGAD

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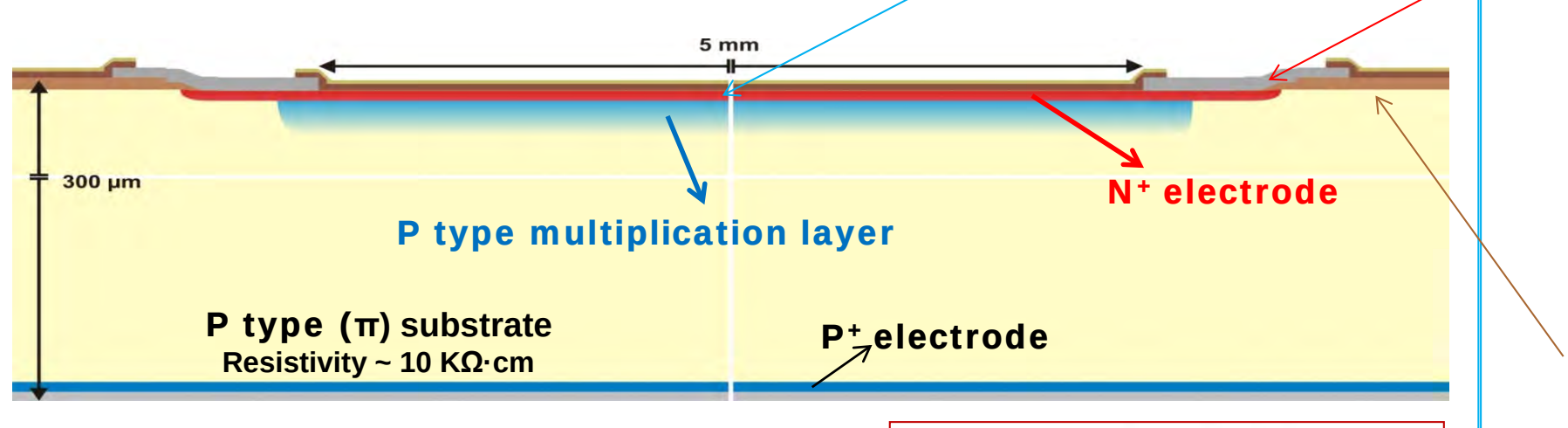
LGAD Design

LGAD Structure:

- Highly resistive *p*-type substrate
- ***n*+ and p+ diffusions** for the electrodes
- ***p* diffusion** under the cathode

➔ enhanced electric field ➔ multiplication



Electric field profile is critical since the charge multiplication depends **exponentially** on it.

$$N(x) = N_o\, e^{(\alpha x)}$$

$$\alpha_{e,h}(E) = \alpha^{\infty}_{e,h}\, e^{-\left(\frac{E_o}{E}\right)}$$

Three critical regions of the LGAD design:

Central area (gain region, multiplication layer)
Uniform electric field, sufficiently high to activate mechanism of impact ionization (multiplication)

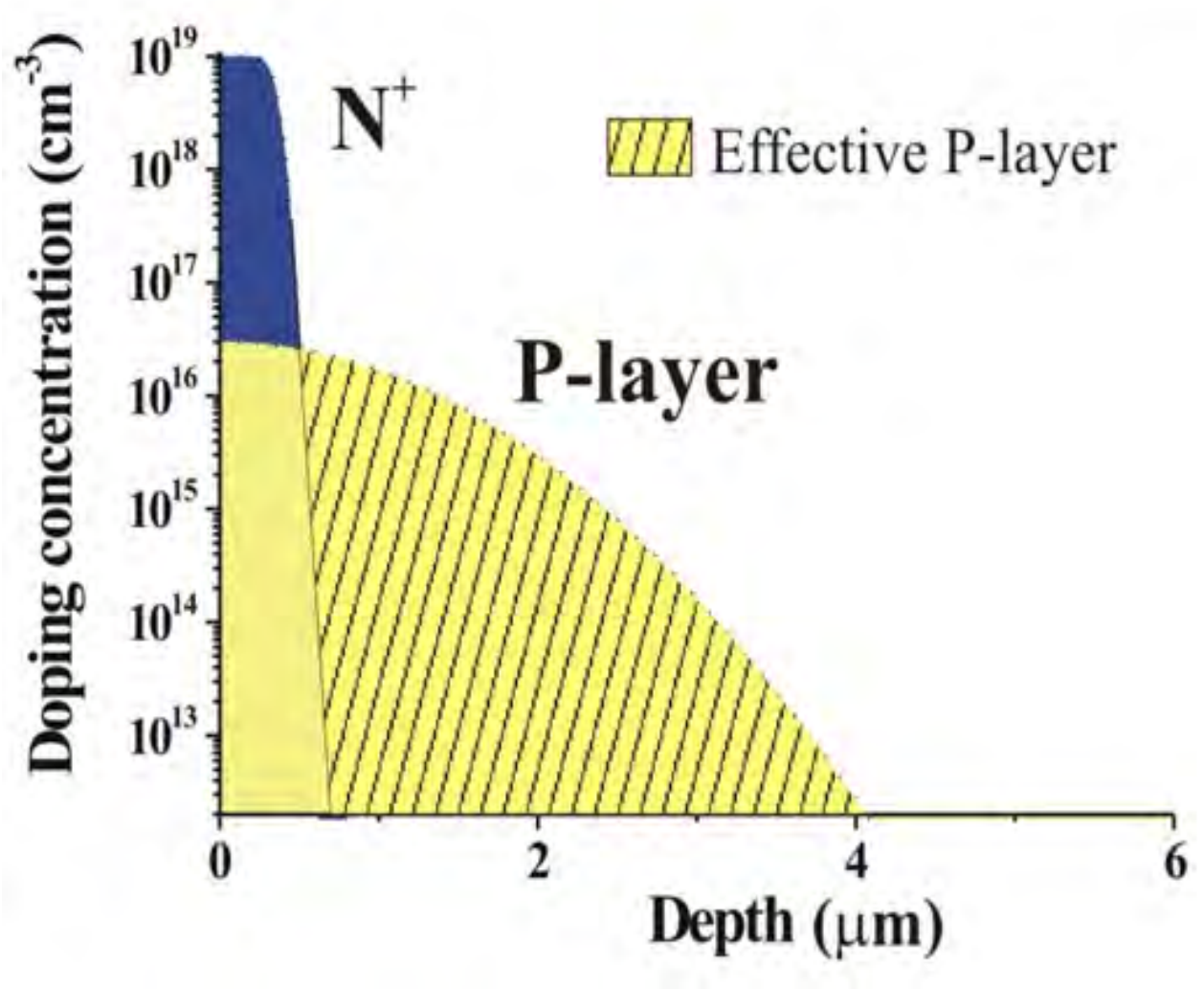
N - Implant Edge Termination
Lightly-doped N-type deep diffusion (JTE)
and addition of a field plate
Allows high electric field in the central region since breakdown voltage V_{BD}(Edge) >> V_{BD} (Central)

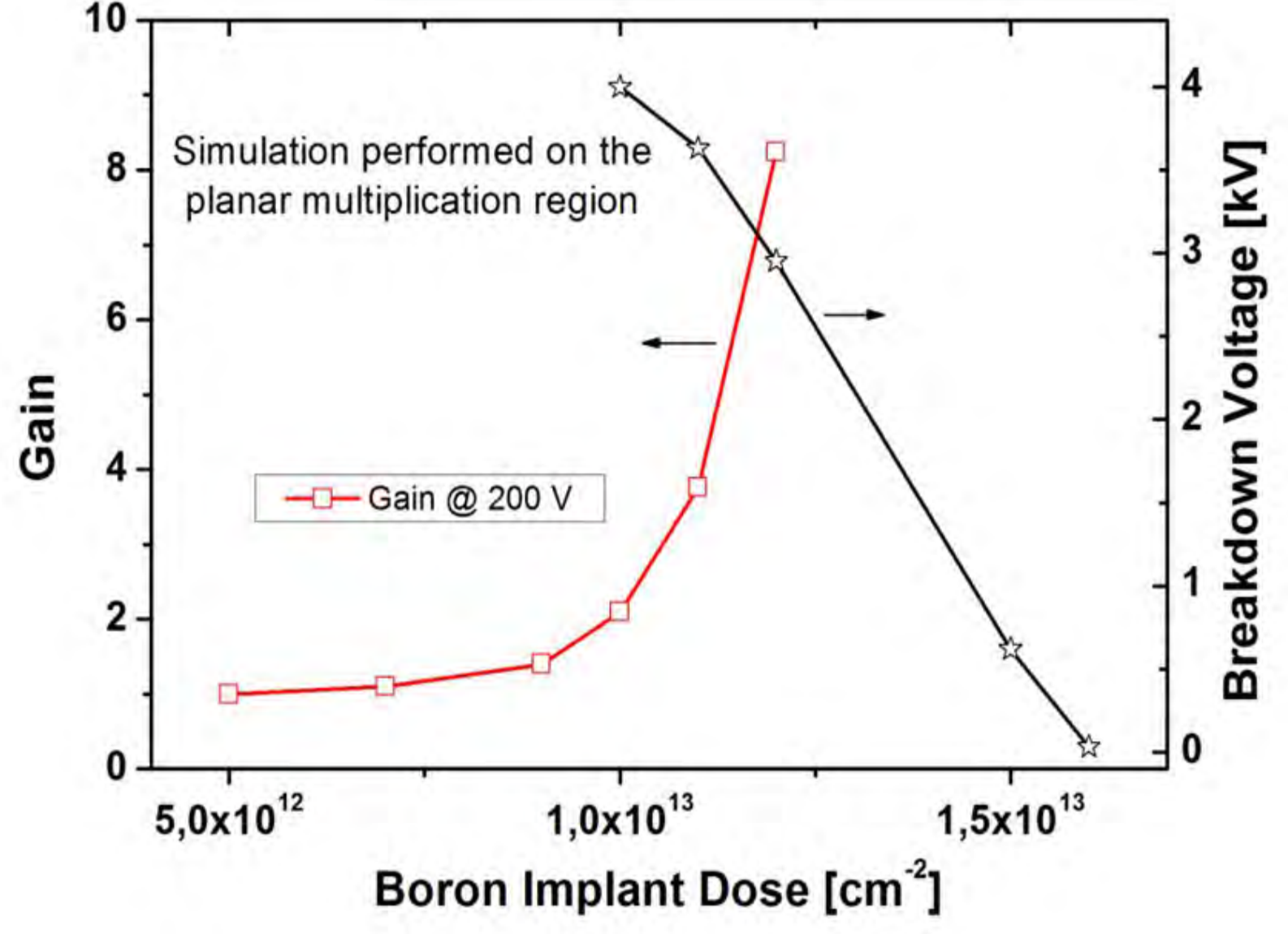
Periphery
P-spray/stop: counteracts inversion and cuts off current path
Biased guard ring around the detection region collects the surface component of the current

Optimization of the Gain Region

Higher Boron implant Dose:
- Higher Gain
- Lower Breakdown

Doping profile of the P-type multiplication layer determines both Gain and Breakdown.





Small variations in the Boron implant dose lead to large changes in Gain and V_{BD} values

Gain Sensitivity to Boron Doping: β MIP's

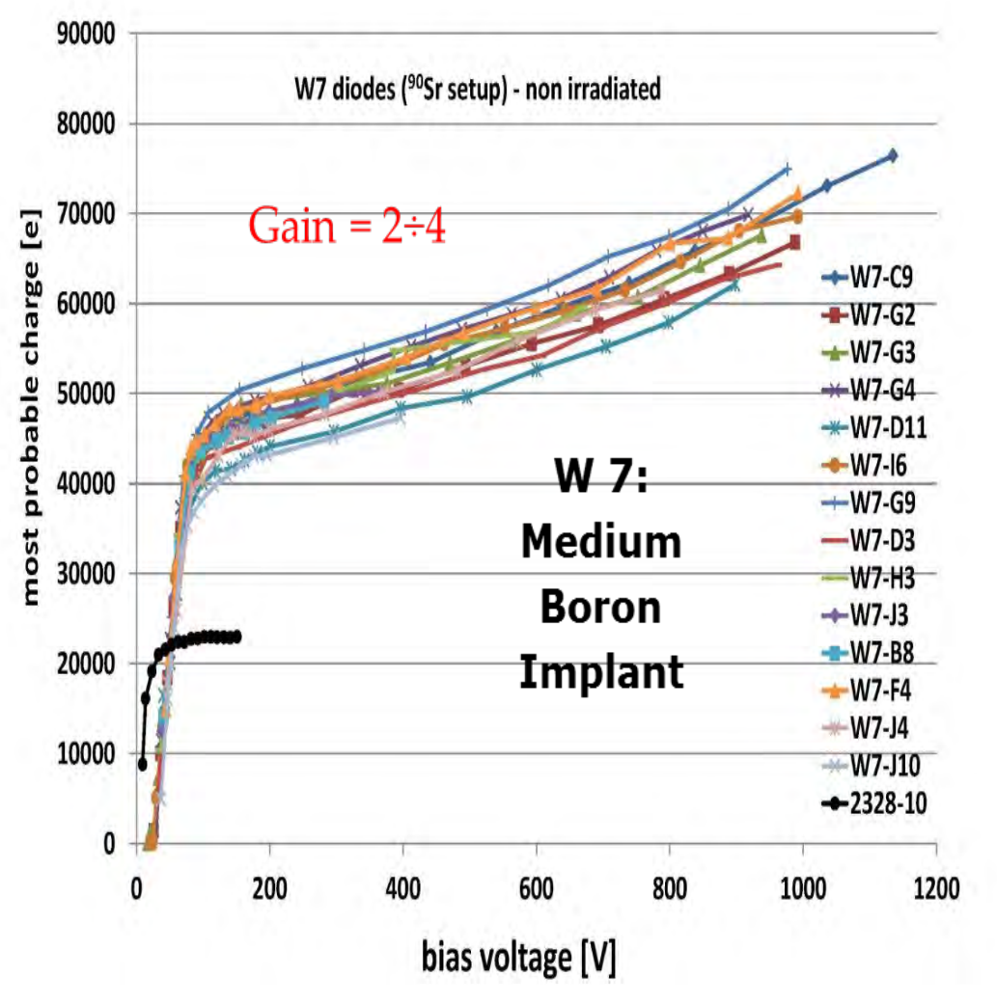
Boron implant dose is varied from wafer to wafer (Run 6474).

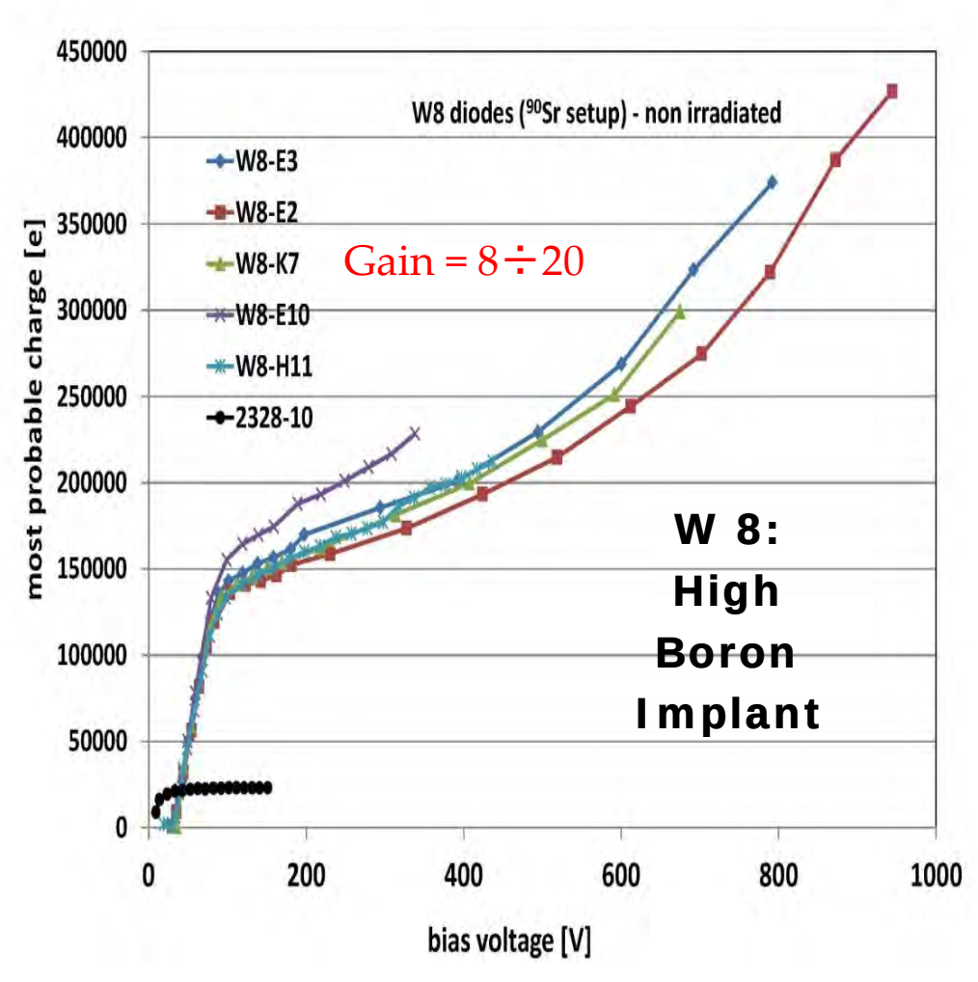
Comparison with no-gain pad gives reliable measurement of the gain.

Boron doping is from process simulations.

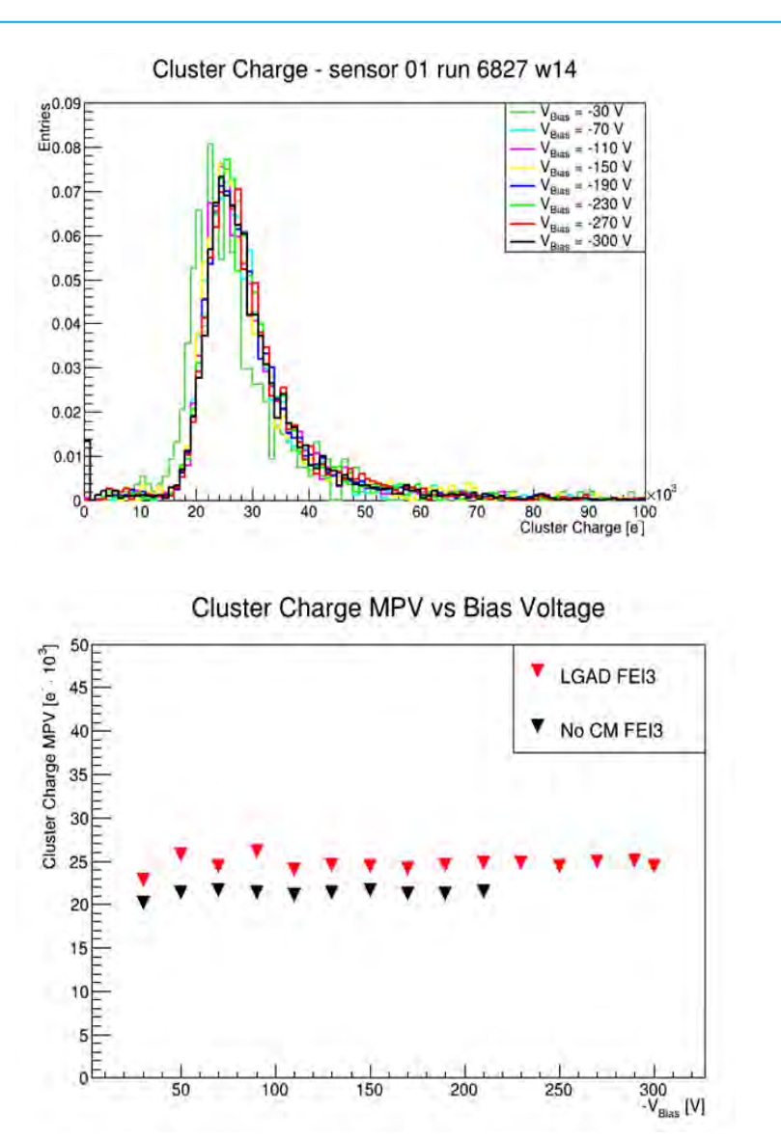
W7 ➔ 1.6 × 10^{13}cm^{-2} gain = 3
W8 ➔ 2.0 × 10^{13} cm^{-2} gain = 15

Good gain uniformity across the wafer.



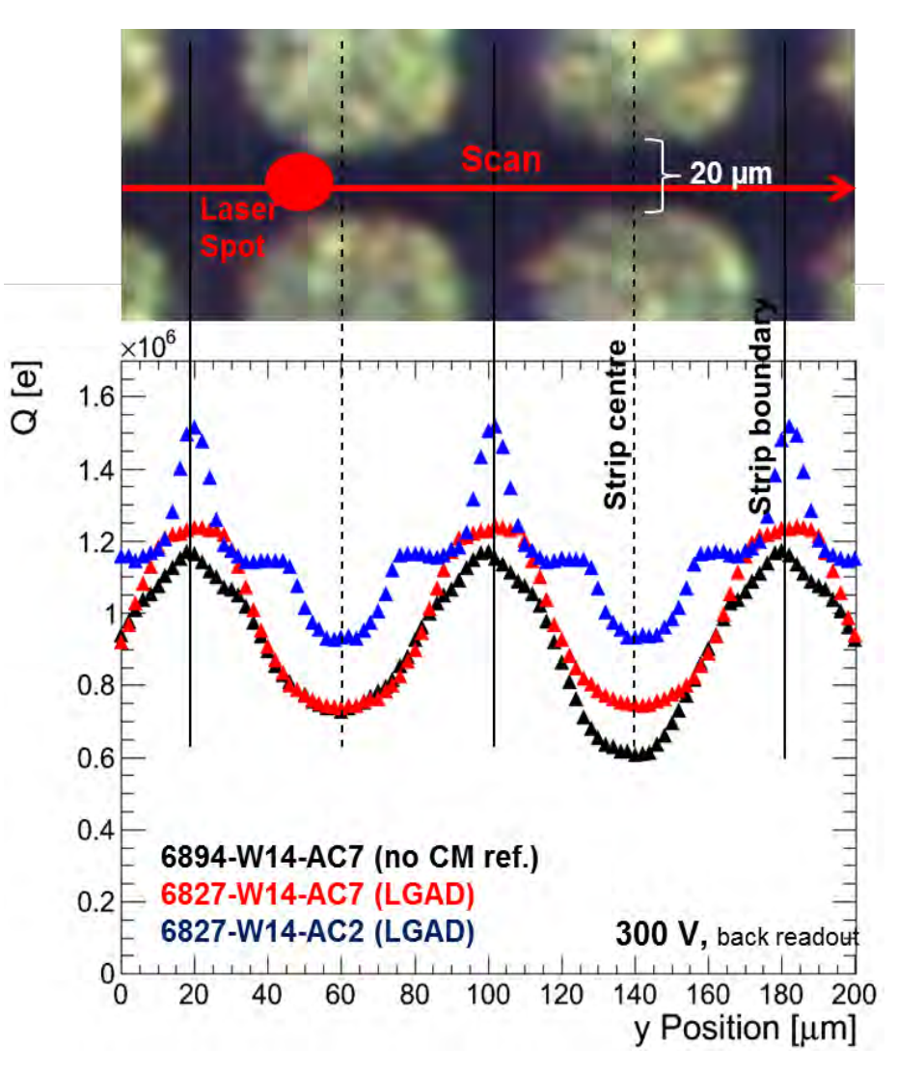


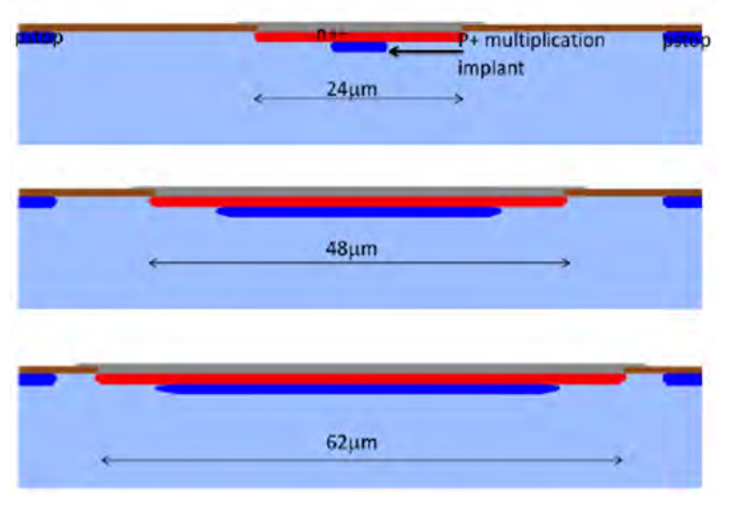
Segmented LGADs



300 μm FZ (6827)
low p-dose
Pixels:
First measurement of LGAD pixels (FE-I3 and FE-I4).
Collected charge with ^{90}Sr for LGAD and no-gain reference same up to 300V within calibration uncertainty
➔ No multiplication observed

Strips



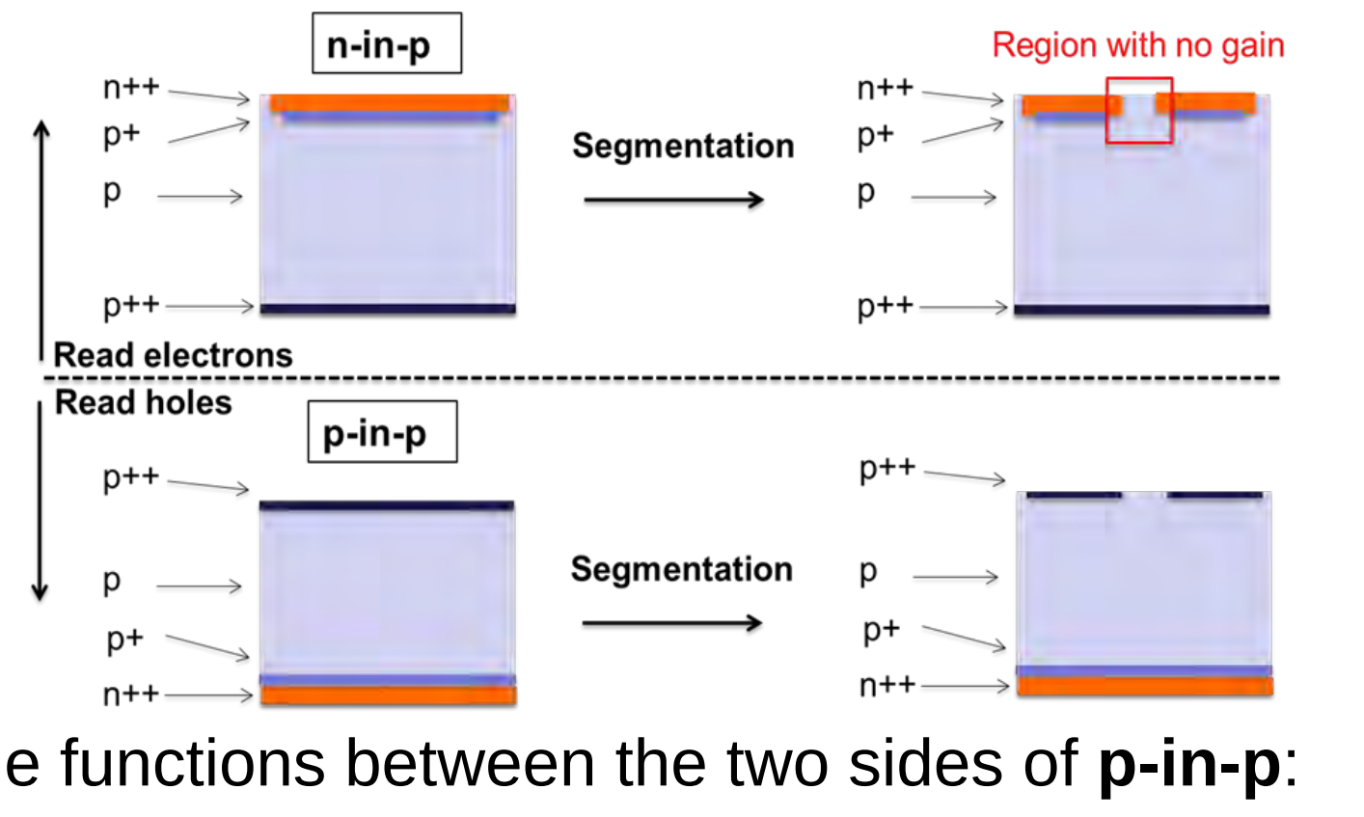


Scan with focussed IR laser across strips with different p⁺ and n⁺ widths.
Same charge measured (within laser intensity variations) for LGAD strips and no-gain reference up to 600 V.
➔No multiplication observed in center of p⁺ layer, or at implant edges.

Segmented LGAD R&D

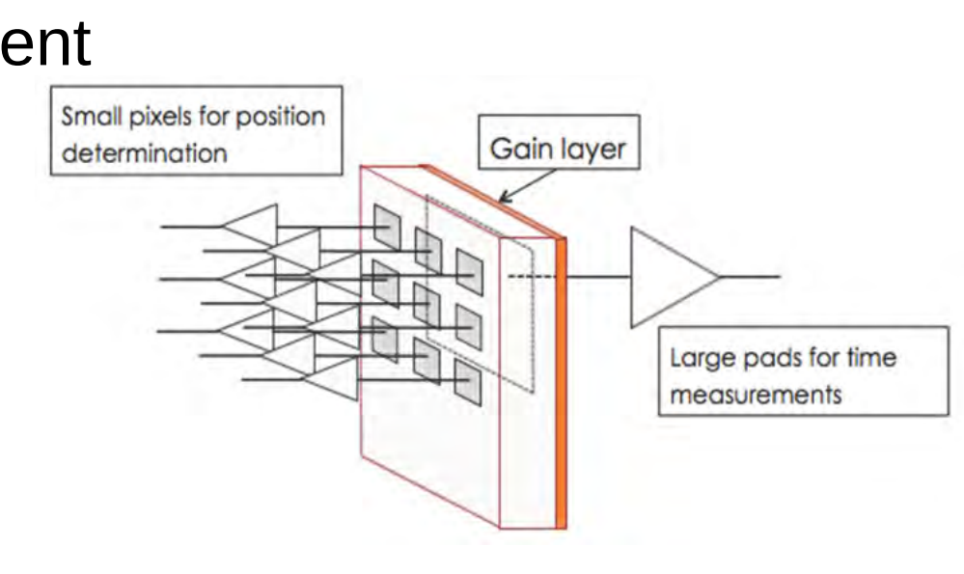
Gain on LGAD **pad** detectors is well developed. Implementation of **uniform gain** on the **segmented** side of LGAD pixel or strip detectors appears difficult.

Options for electron multiplying structures

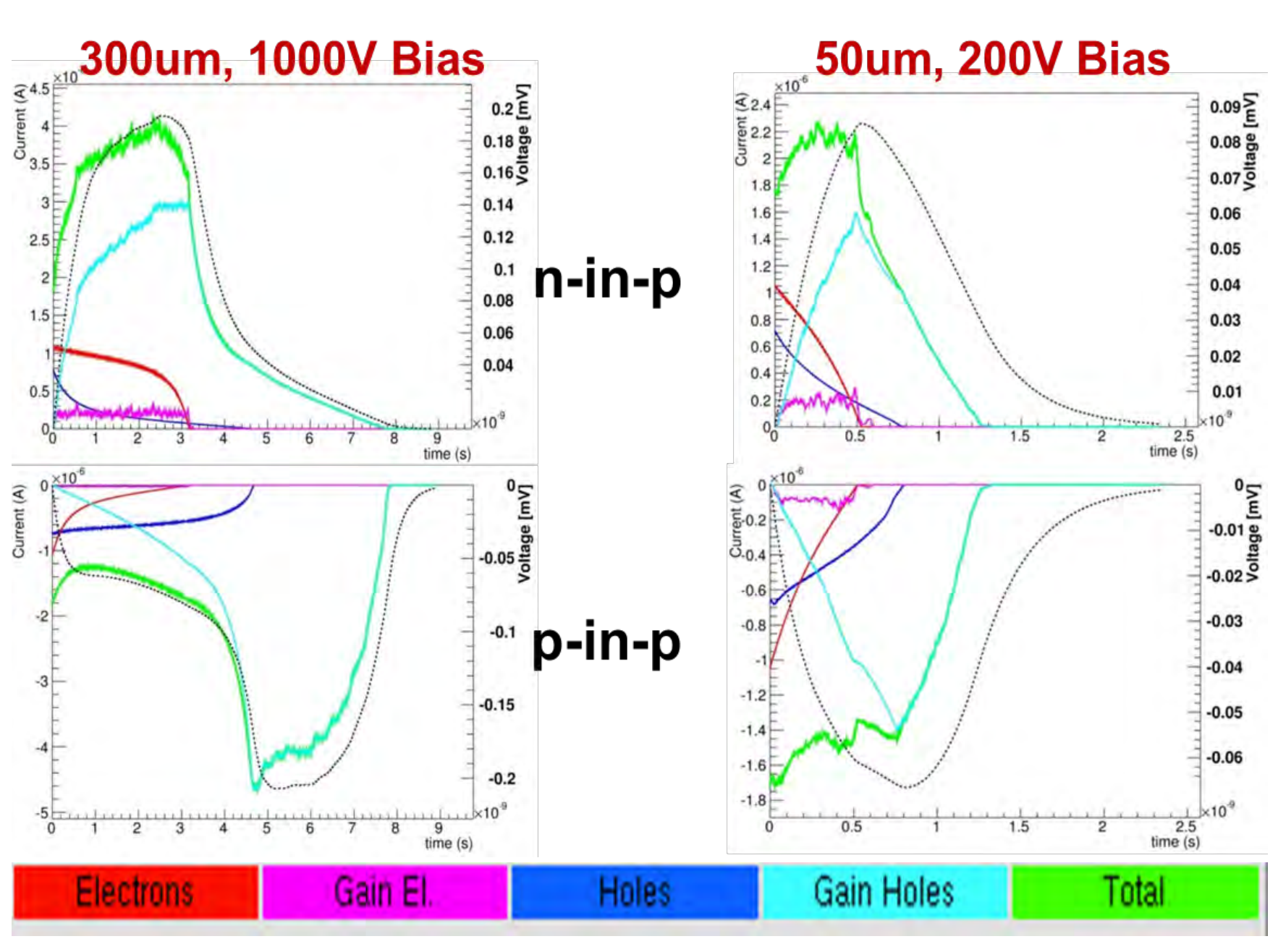


Divide functions between the two sides of **p-in-p**:

- Position measurement in the small pixel (p)
- Time measurement on the gain side (n) with segmentation of macro – pixels ~1mm², C ~1pF



Pulse shapes for MIP's in FZ LGAD
N. Cartiglia et al, Weightfield Simulation: Poster N11-8



Thick p-type LGAD relies on late hole collection: p-on-p not viable.

Thin p-in-p LGAD has a very fast slew rate comparable to n-on-p

Time Resolution

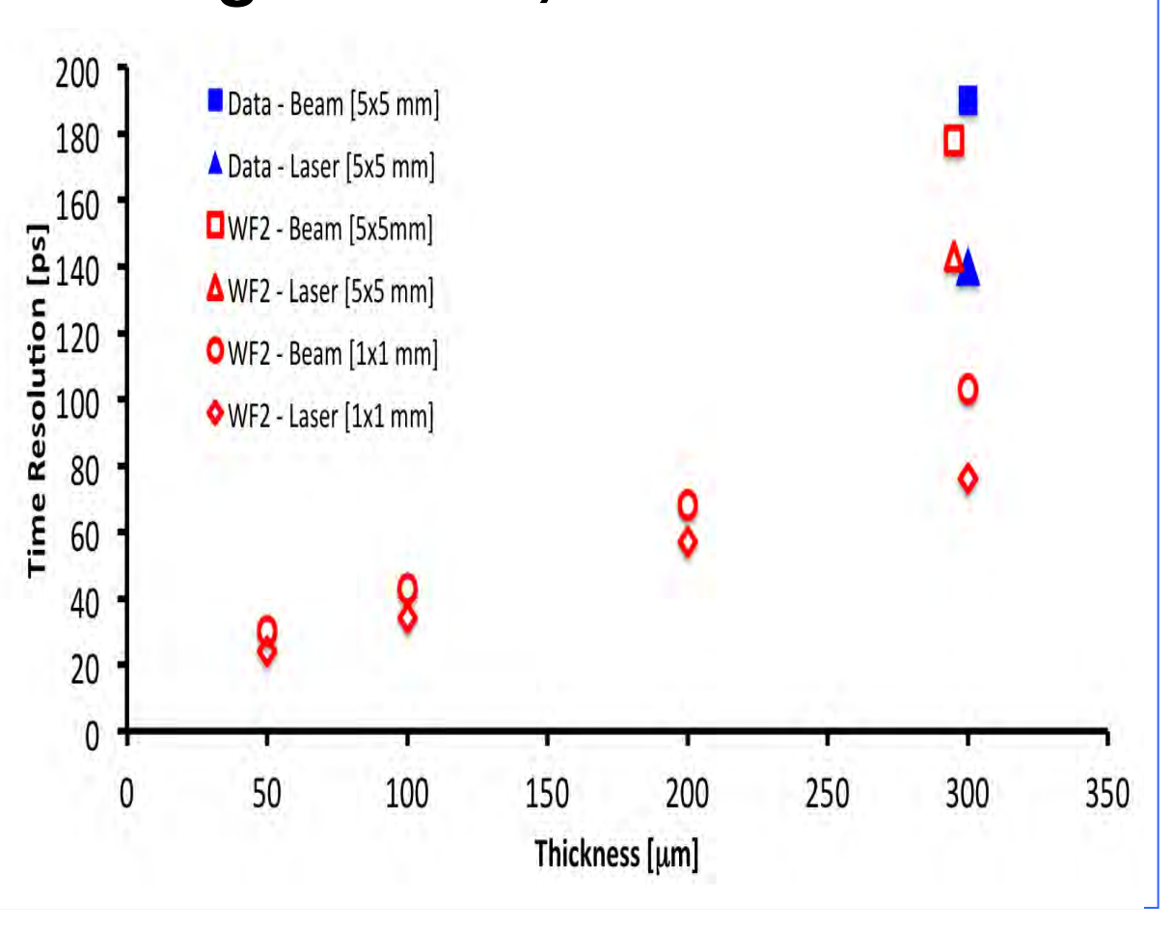
Measurements: N. Cartiglia et al., Talk N41-5; WF Simulation: N. Cartiglia et al., Poster N11-8

The time resolution has contributions from **jitter, time walk and TDC resolution**:

$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{t_{rise}V_{th}}{S}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$$

The rise time t_{rise} depends on the collection time (i.e. the detector thickness). Thin LGADs have a large advantage.

In a beam test (BT), a time resolution of **σ_t = 180 ps** for the 300 μm LGAD is measured, which in turn is matched by a Weightfield (WF) simulation. WF simulations of reduced thickness indicate indeed much improved time resolution, e.g. σ_t = **30 ps** for 50 μm thick LGADs.



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