



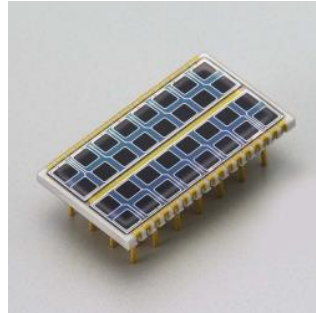
# AN AVALANCHE PHOTO DIODE ARRAY WITH 100% FILL FACTOR

R.H. Richter, A. Bähr, J. Damore, M. Hensel, Ch. Koffmane, J. Ninkovic,  
E. Prinker, G. Schaller, F. Schopper, J. Treis, T. Turkovic

# APD ARRAYS BY COMMERCIAL SUPPLIERS ...



**Hamamatsu APD array S8550-02,**  
4x8 pixels, sensitive area 1.6mm<sup>2</sup>

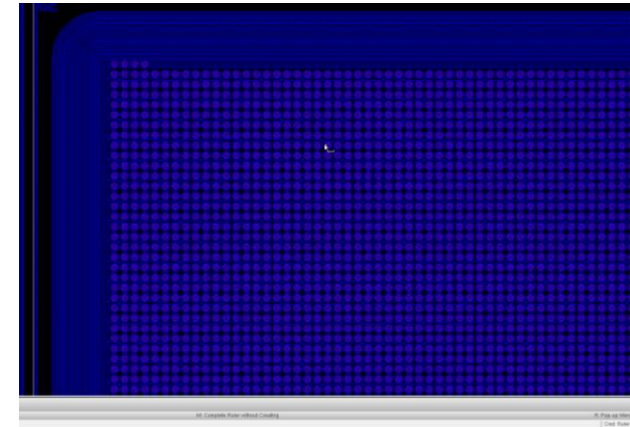
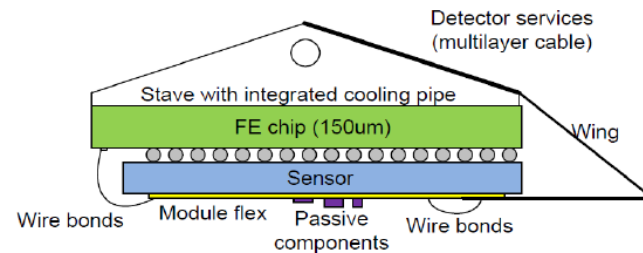


**Laser Components**  
8 or 16 elements (40μm gap only)



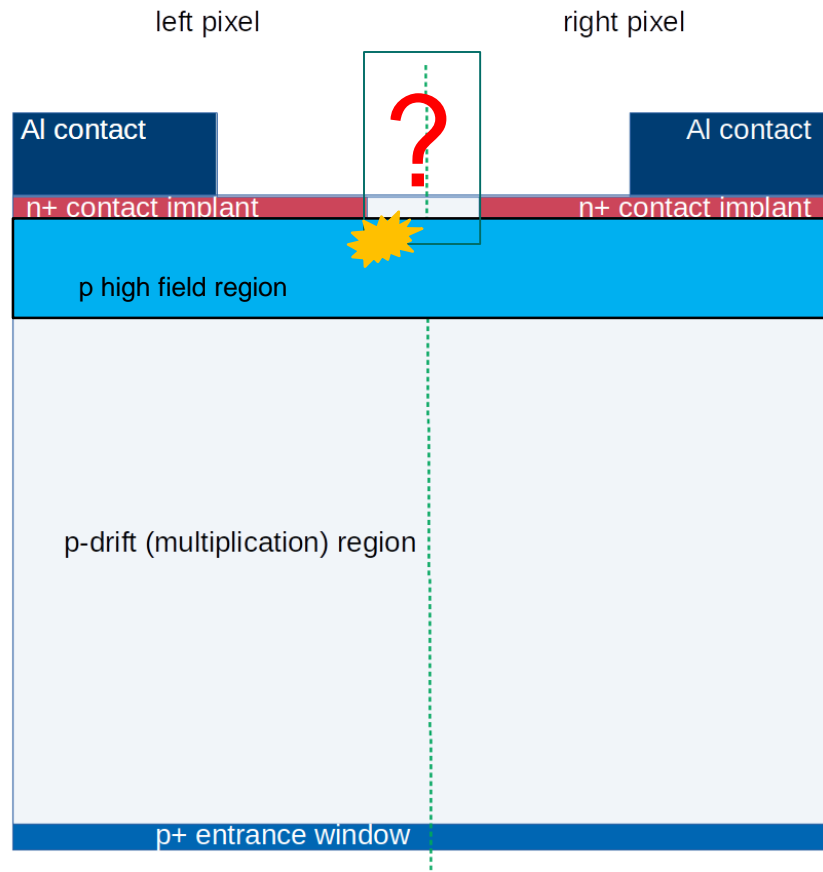
## LHC pin diode array

500k pixel a 50μm  
no dead space in pixel gaps



Main problems with APD arrays: **gain homogeneity, radiation hardness, breakdown suppression at n+ edges**  
attractive field or institutional research see talks by Shudashil, Matteo and Milos

# Interpixel isolation within an APD array



## Requirements

- Isolation (drastic reduction of electron density)
- Edge break down suppression (early breakdown and inhomogeneous response)
- Reduction of E-fields at SiO<sub>2</sub>/Si interfaces (oxide charge up, H-bond cracking)

## Very nice to have

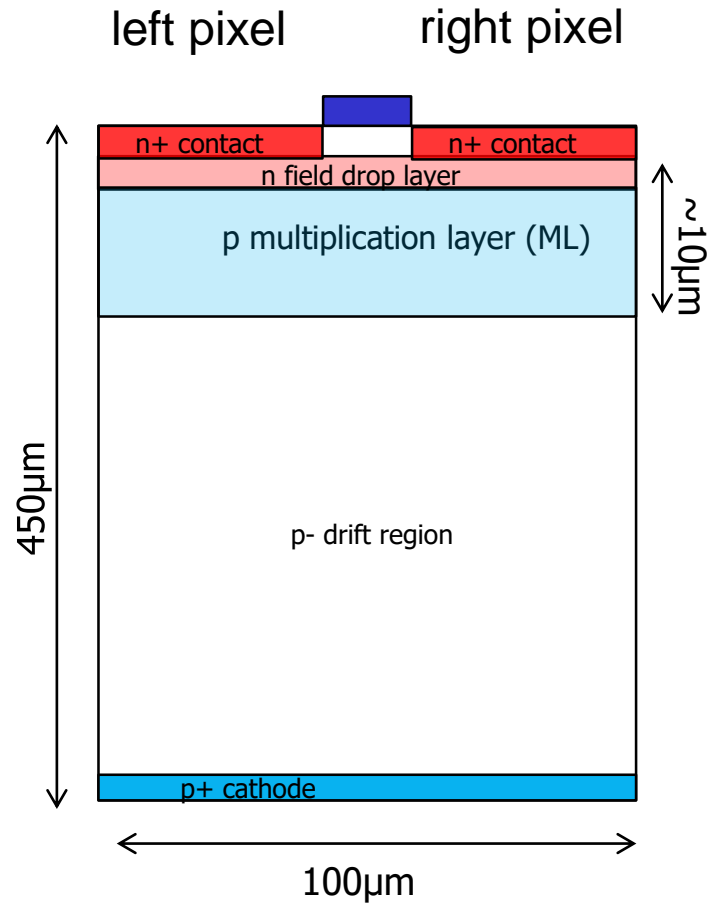
- 100% fill factor (no gain loss -> homogeneous gain)

like classical pin diode arrays

# THE MARTHA CONCEPT



## Monolithic Array of Reach THrough APDs



- reach-through APD flip-chipped to readout electronics
- > 50  $\mu\text{m}$  pitch - depending on technology level (bump bonding)

based on HLL „standard“ technology

- (HLL) thin entrance window + avalanche multiplication
- Aim: fairly homogeneous gain also in the gaps

# WHY DOES IT WORK?



1D Poisson eq.

$$\frac{d^2u}{dx^2} = \frac{dE}{dx} = \frac{1}{\epsilon} (qN(x) + n + p)$$

$$E(x) = \frac{q}{\epsilon} \int_{x_1}^{x_2} N(x) dx$$

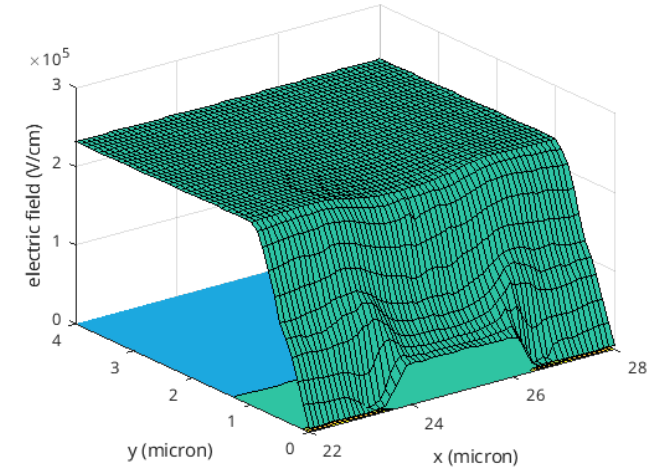
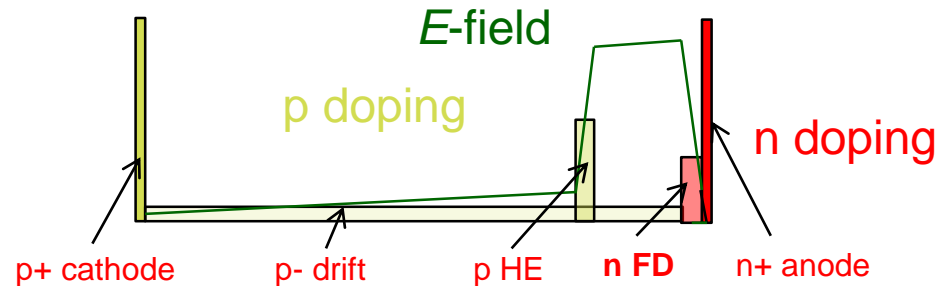
$$D(x) = \int_{x_1}^{x_2} N(x) dx$$

u – potential, n,p electron, hole density  
E – electric field  
N – depleted! doping concentration (cm<sup>-3</sup>)  
ε – permittivity of silicon  
q – electronic charge  
D - (implanted) dose (cm<sup>-2</sup>)

→

Equivalence of electric field and depleted dose !

$$\epsilon E_{max} = q \sum D_p = q \sum D_n \text{ (depleted doses)}$$



$$D_{FD} \approx \frac{2}{3} D_{HE}$$

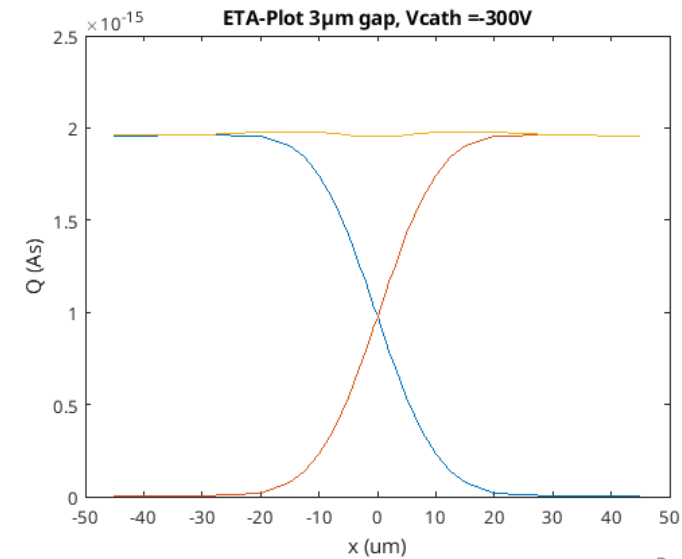
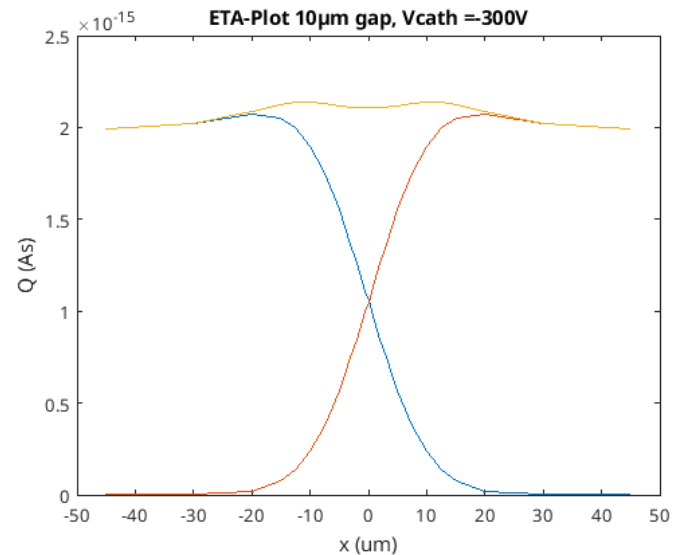
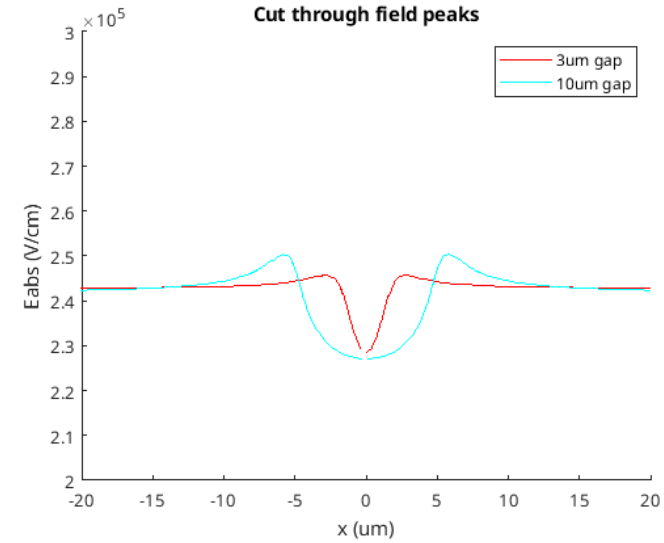
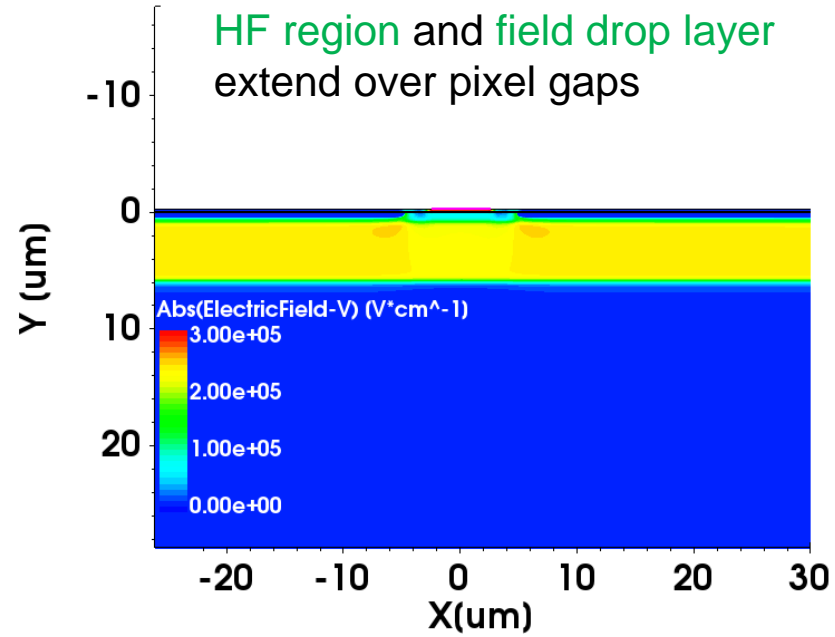
-> 2/3 field drop  
FD gets depleted by HF  
(no pixel shortage)

Overdepletion: space charge region region constant (plate capacitor) -> superposition of const. E-field

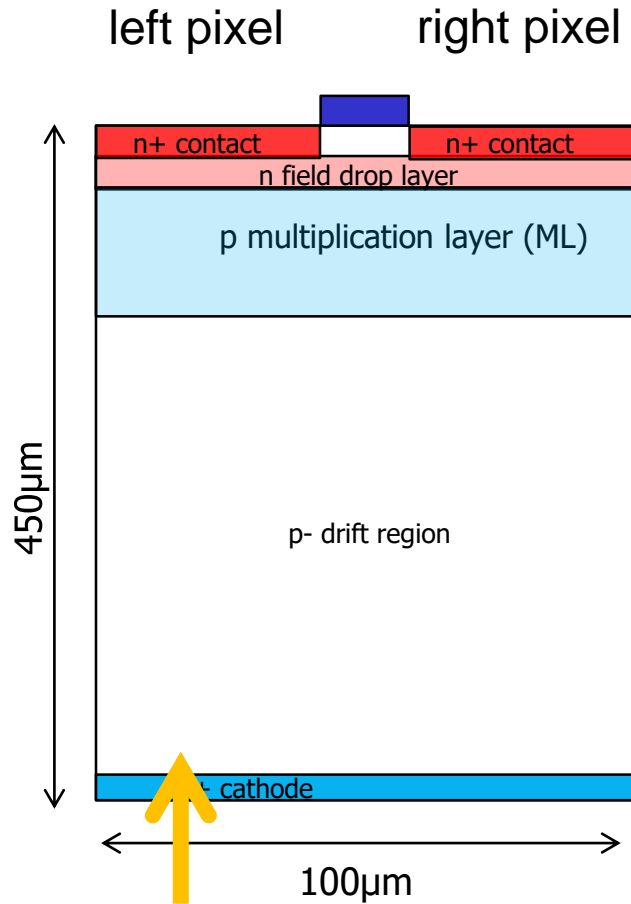
# 2D SIMULATION - ELECTRIC FIELD



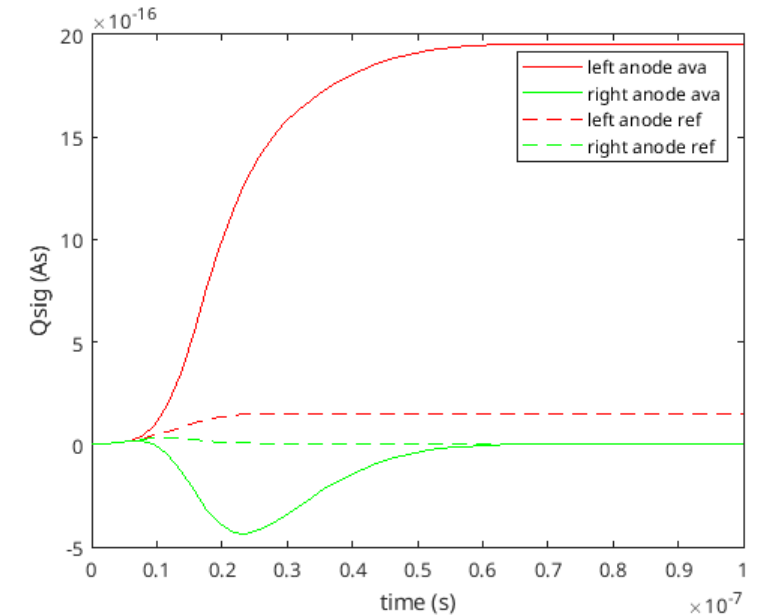
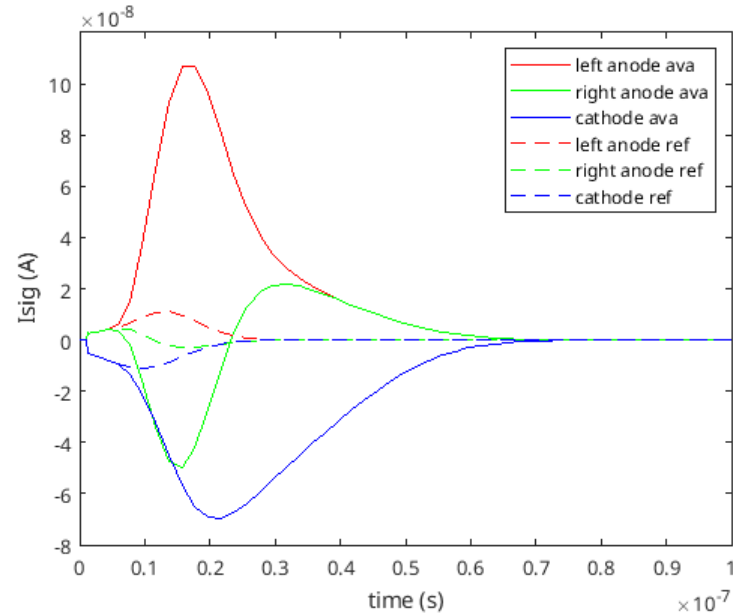
$V_{MOS}=3V$



# SIMULATED SIGNAL EVOLUTION



solid - with avalanche  
dashed - without avalanche (pin diode)



generate test charge  
 $Q_{\text{test}} = 1.3 \times 10^{-16} \text{ C}$

full signal formed faster in pin diode  
(generated holes have to drift to backside)  
'anti cross talk'

->  $M = 14.8$

# Why don't we use just avalanche detectors? Signal to Noise of an APD



$$\frac{S^2}{N^2} = \frac{I^2 * M^2}{B((2q(I + Idv) * M^2 * F + 2qIds) + \frac{4kBT}{R_L})}$$

└┘
└┘  
 APD noise                  ro noise

APD user's guide  
(Hamamatsu)

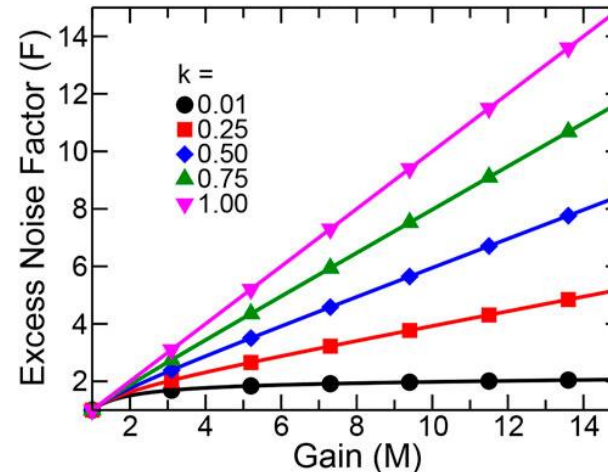
- I – non amplified photocurrent
- M – amplification
- $I_{dv}$  – dark current of silicon volume (amplified)
- $I_{ds}$  – surface generated dark current (not amplified)
- F – excess noise factor
- B – bandwidth
- $R_L$  – load resistance
- q – electron charge
- $k_B$  – Boltzmann constant
- T - temperature

Stochastic nature of the multiplication process:

Excess noise factor

$$F = M * k + (2 - \frac{1}{M}) (1 - k)$$

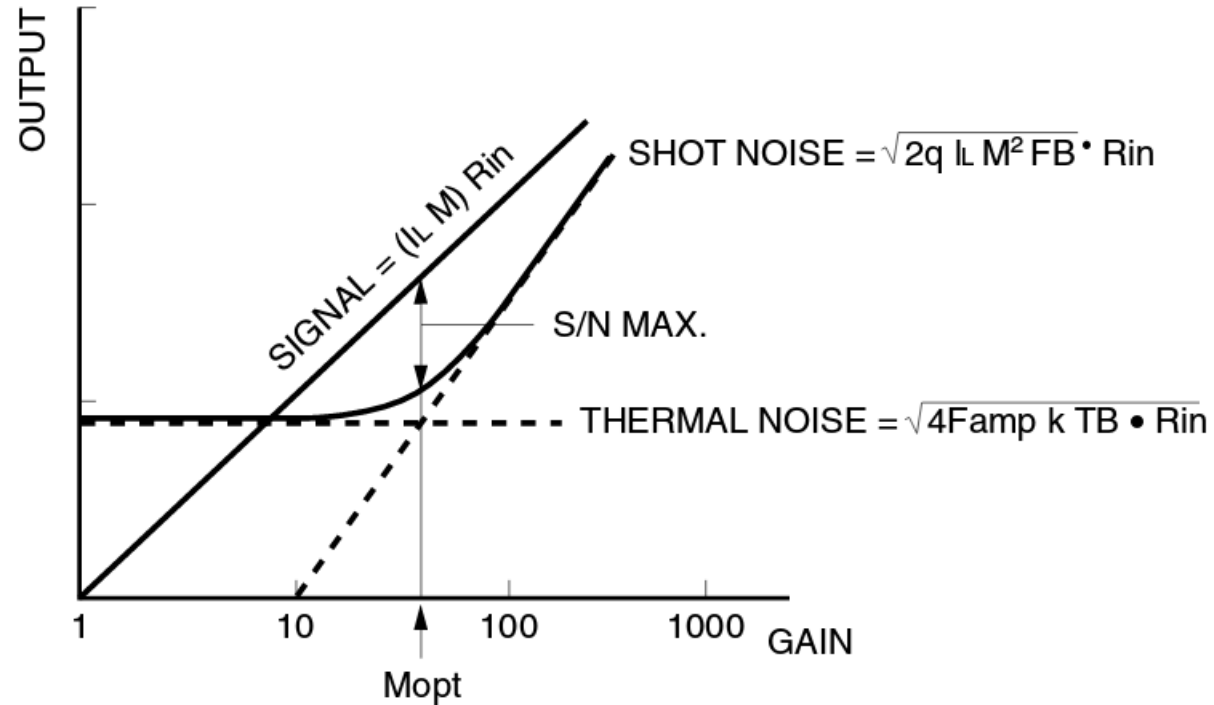
$$k = \frac{\alpha_h}{\alpha_e} \quad \text{ionization length ratio}$$



A. Pilotto et. al. (2022)

# OPTIMAL GAIN FOR MAX. S/N

Every sensor – RO amplifier package has its optimum M



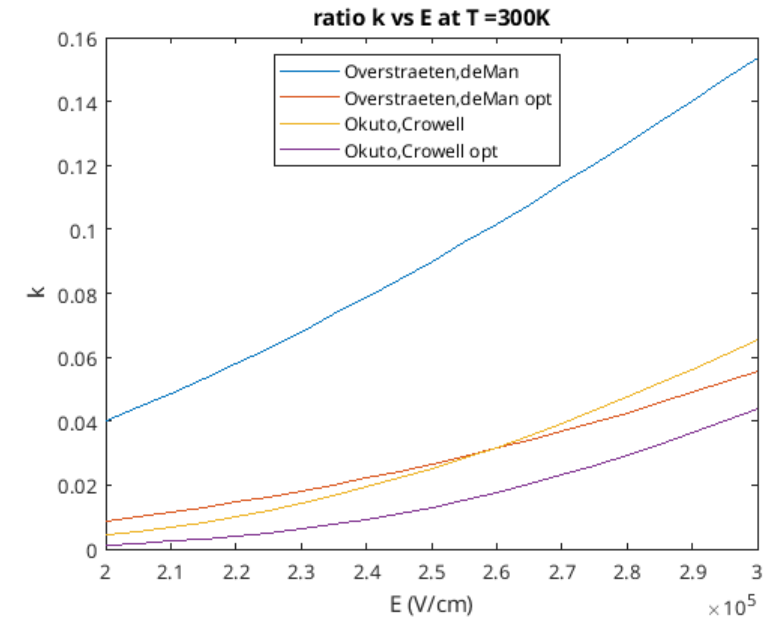
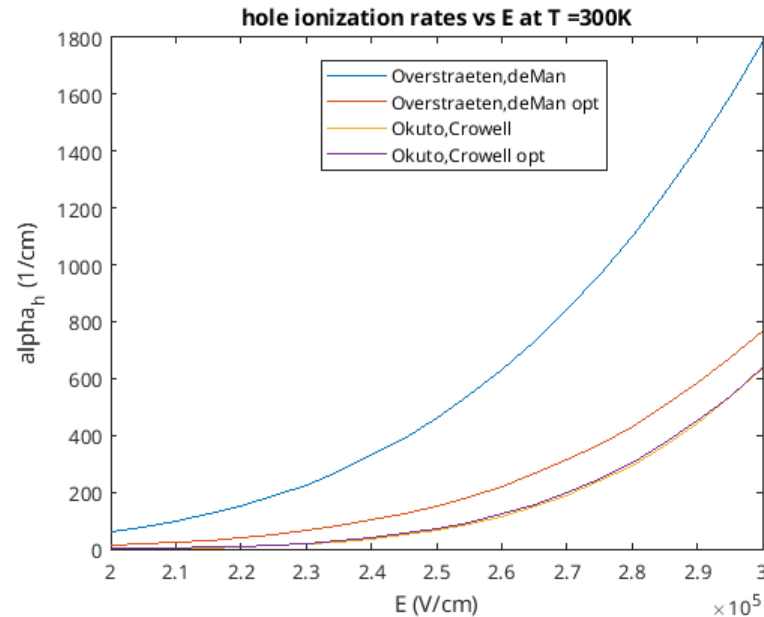
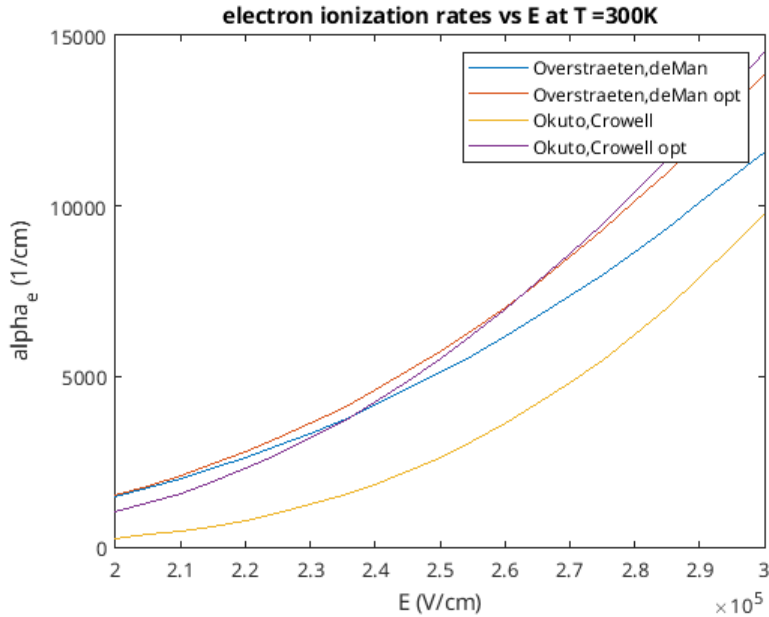
$F_{amp}$ : Noise figure of next-stage amplifier  
 $R_{in}$ : Input resistance of next-stage amplifier  
 $k$ : Boltzmann's constant  
 $T$ : Absolute temperature

# IONIZATION RATES $\alpha(E)$ (MATERIAL CONSTANT)

Number of generated electron-hole pairs per drift length initiated by an electron or hole along a const. electric field

Silicon best material for prop. APDs

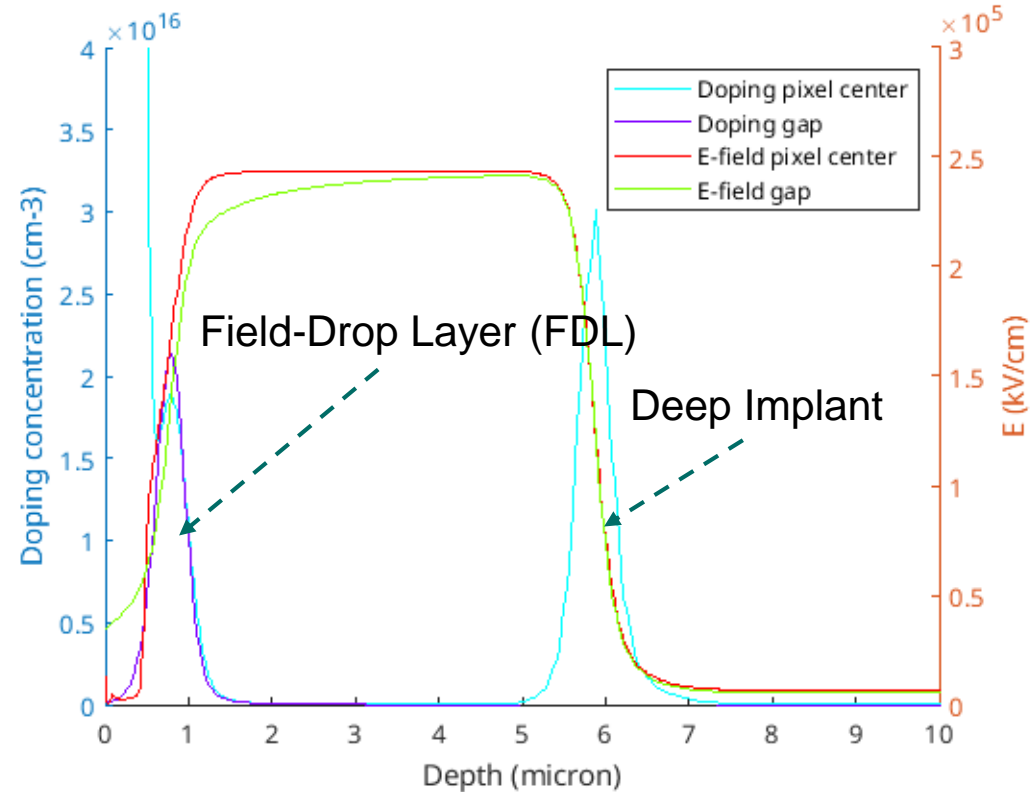
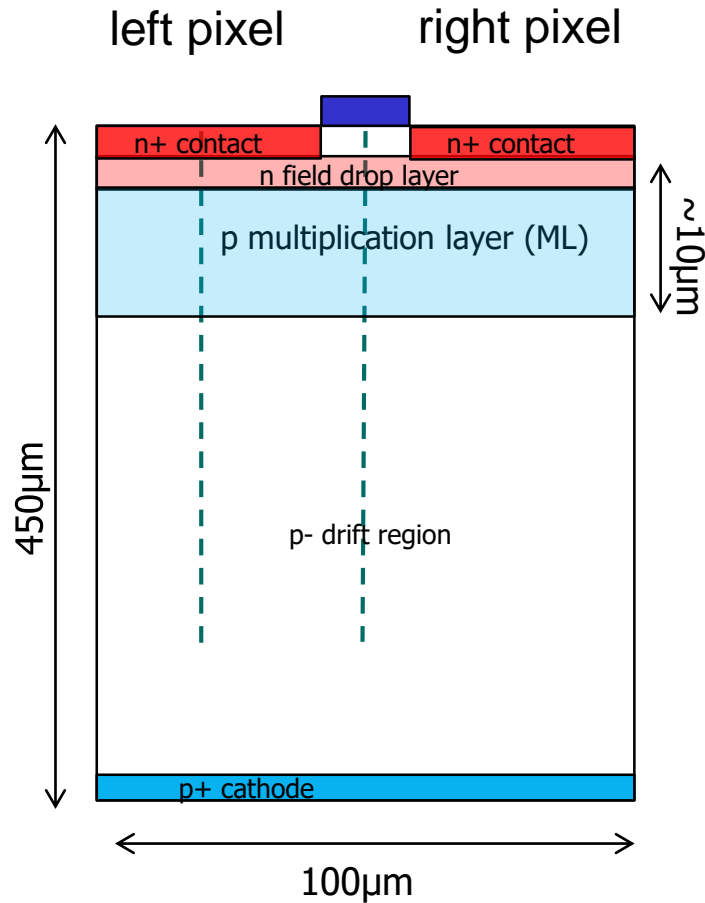
$$k = \frac{\alpha_h}{\alpha_e} < 1$$



Standard parameter proposed by TCAD  
*opt.* optimized parameters for LGADs by Rivera and Moll (2022)

The lower E, the lower k, the lower the noise  
**but the lower gain!**

# 2D SIMULATION - ELECTRIC FIELD



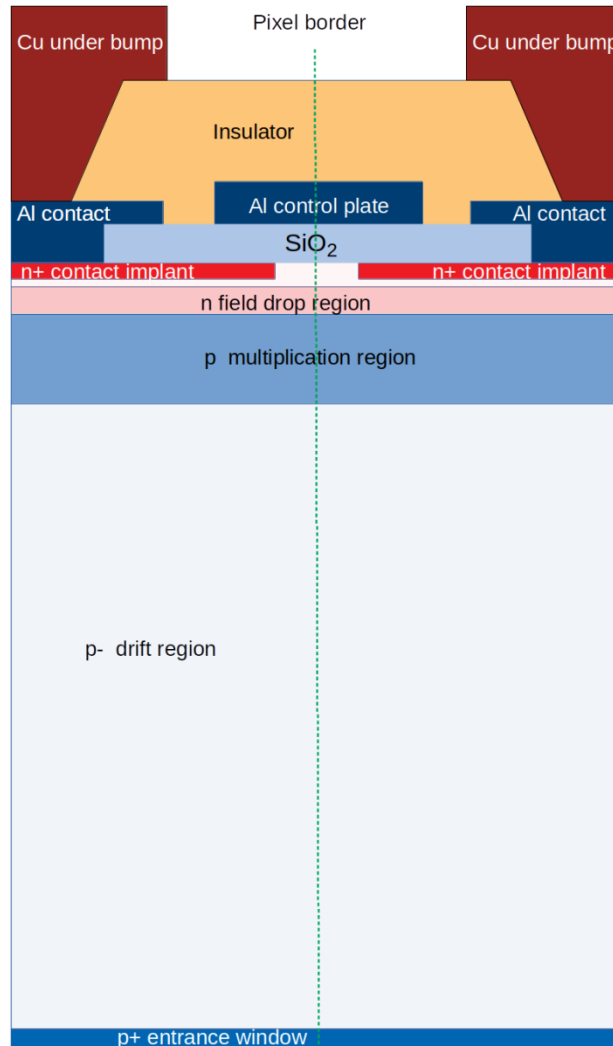
## FDL:

- shift Max E-Field
- prevents edge breakdown

## deep Implant

- extended ML
- -> lower electric field
- -> low k-factor
- -> low excess noise

# FINAL DEVICE - SOFT XRAY DETECTOR



Goals:

Gain ~20

Collection efficiencies: > 99%

Minimum pixel pitch: given by bump bond technology and ro electronics space consumption (LHC - 50 $\mu$ m)

Position resolution:  $\ll \frac{pitch}{\sqrt{12}}$  analog read out

Full signal formation: ~ 50ns (450 $\mu$ m thick sensor)

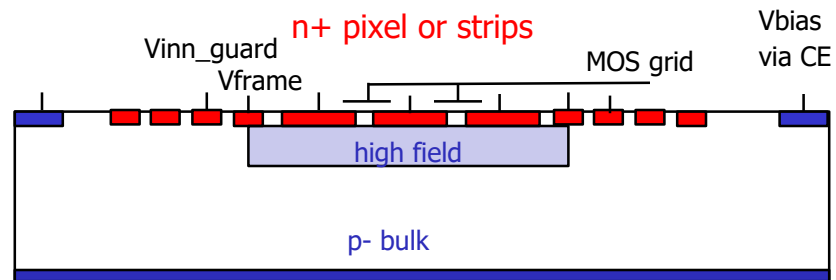
Radiation hardness: top side and RO ASICs are protected by self shielding up to 3keV x-rays

# PROTOTYPE PRODUCTION – FINAL LAYOUT



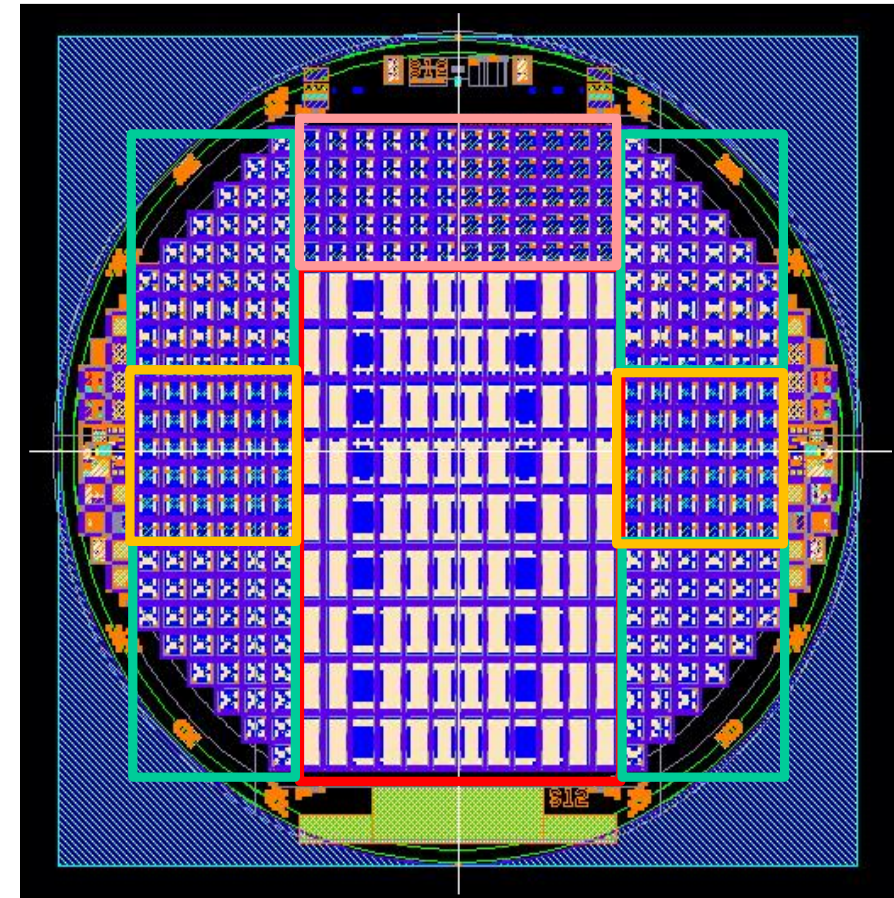
## Aims

- proof of principle
- efficiency, gain, cross talk, noise
- find reliable narrow guard ring structure (in view of buttable arrays)



backside p+ entrance window  
non structured, no Al

Pixel Strips Diodes MGR Diodes



# MULTI PURPOSE MEASUREMENT SETUP

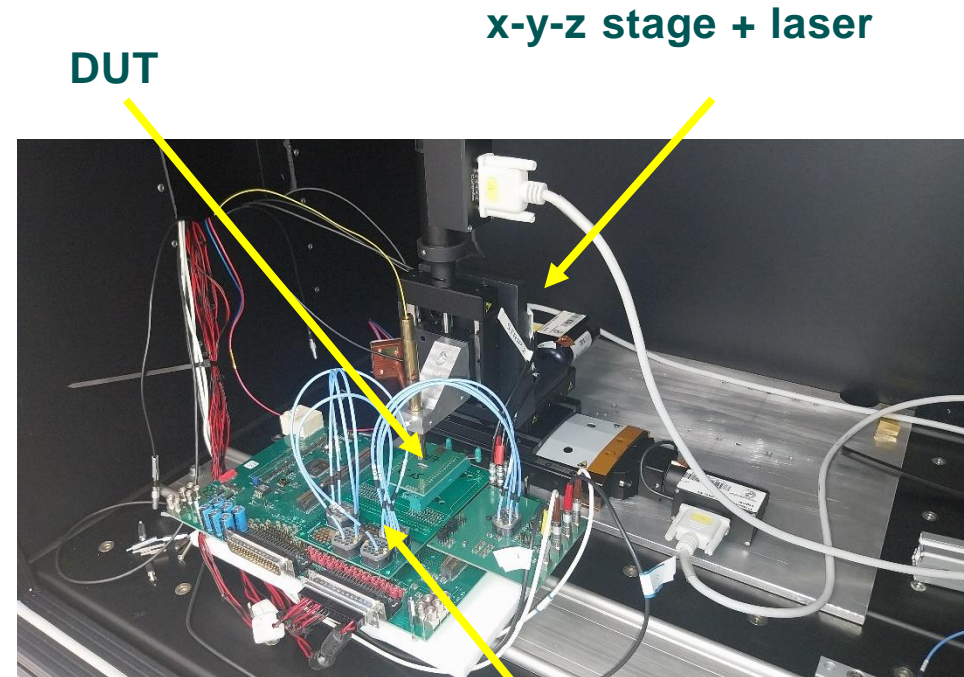


## static measurements

- Keithley Parameter Analyser 4200A

## dynamic measurements

- 4 channel transimpedance amplifier PCB
- Lecroy Oszilloscope

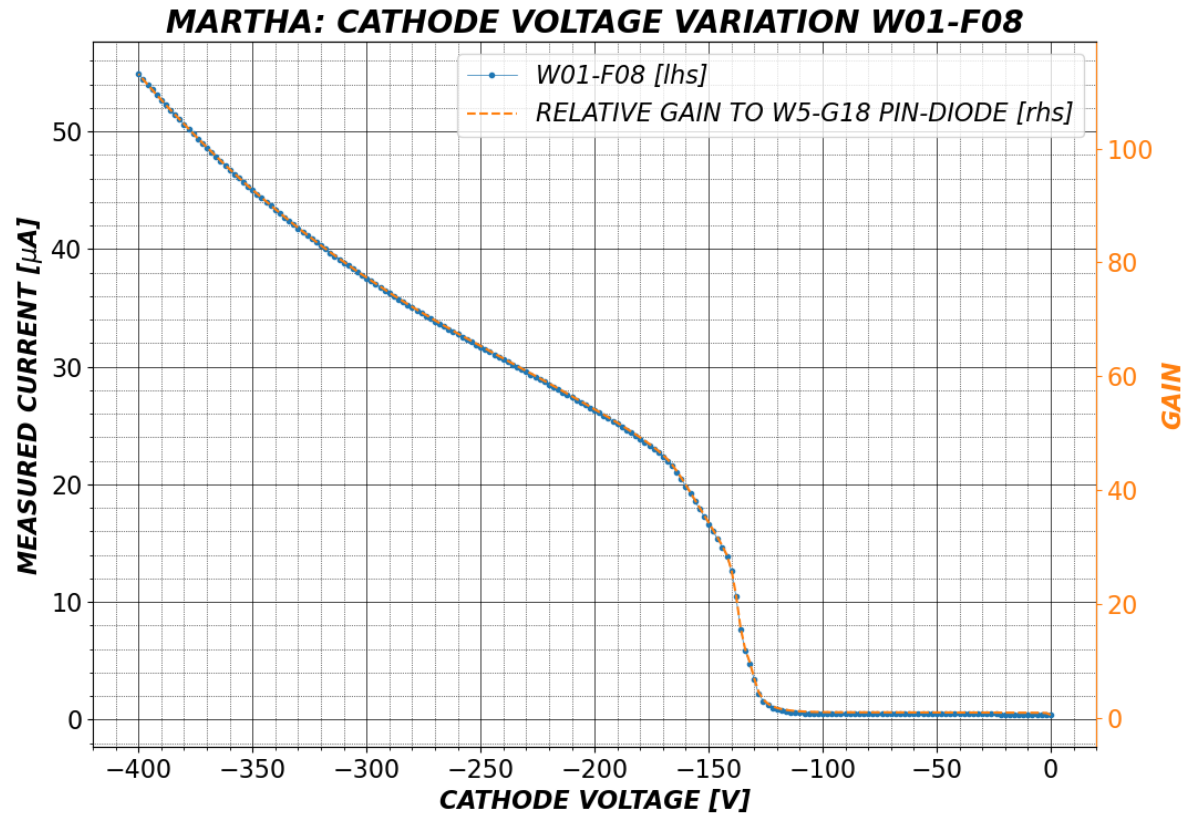


DUT

x-y-z stage + laser

flexible connections to different ROE

# GAIN OF FIRST PROTOTYPE(S)



## gain measurement

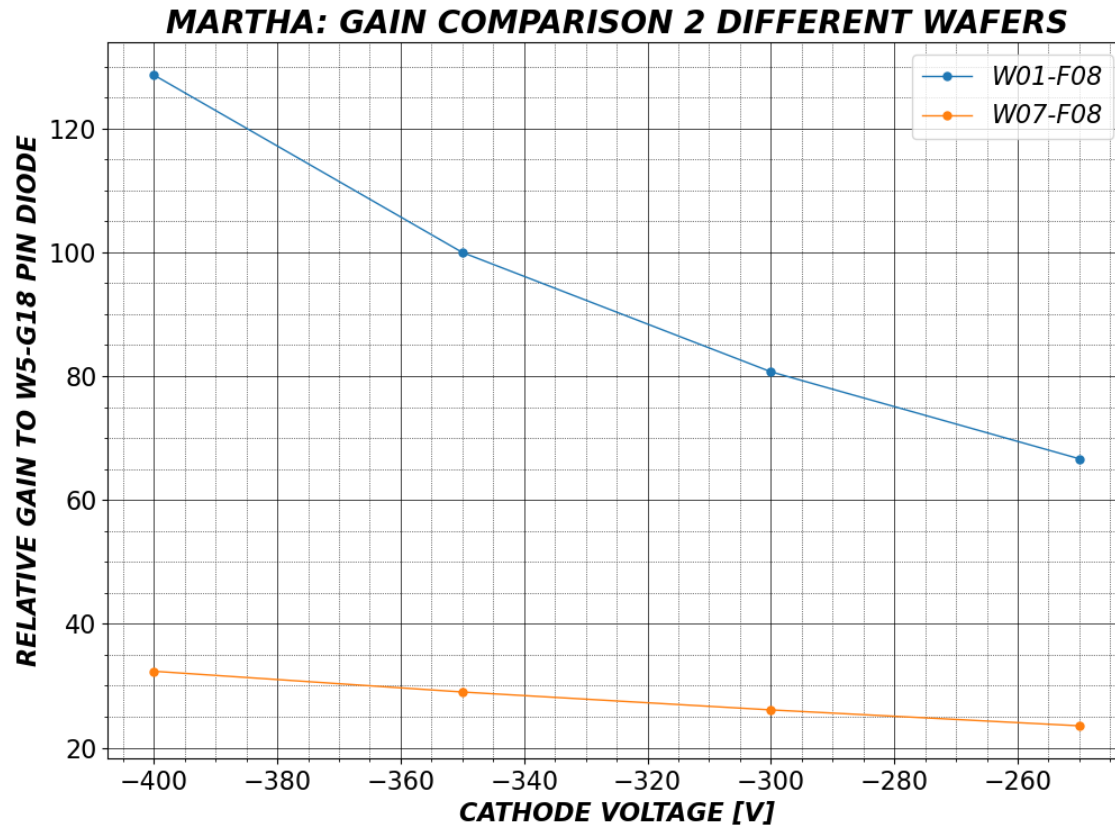
- diodes illuminated by red laser
- measure photocurrent of APD and PIN diode
- Gain as ratio of photocurrents
- backside voltage sweep

steep current increase at -140V

- depletion of MR

- further increase of gain with backside voltage

# WAFERS WITH HIGH AND MEDIUM GAIN



comparison of gain of two APDs from different wafers

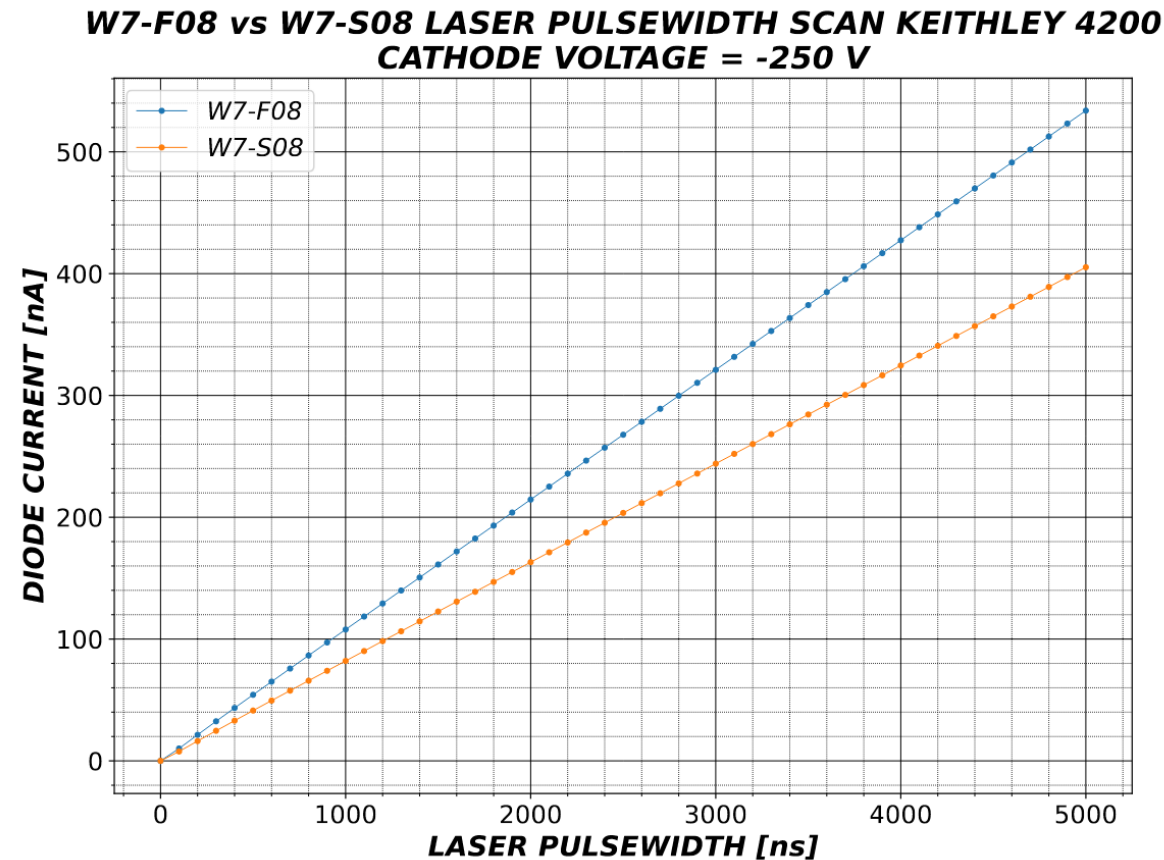
dose difference of  $10^{11}/\text{cm}^2$

gain of 26 and 78 (@-300V)

full depletion @ -250V

- depletion of MR + Bulk

# LINEARITY (OF TWO DEVICES)



40 ns Laser Puls ~ 10000 e<sup>-</sup>

laser focussed to ~ 10 μm

maximal Signal ~ 10<sup>6</sup> e<sup>-</sup>

diode response linear

But the long pulse width do not reflect the requirements of the applications

Measurements with short pulse laser are in preparation

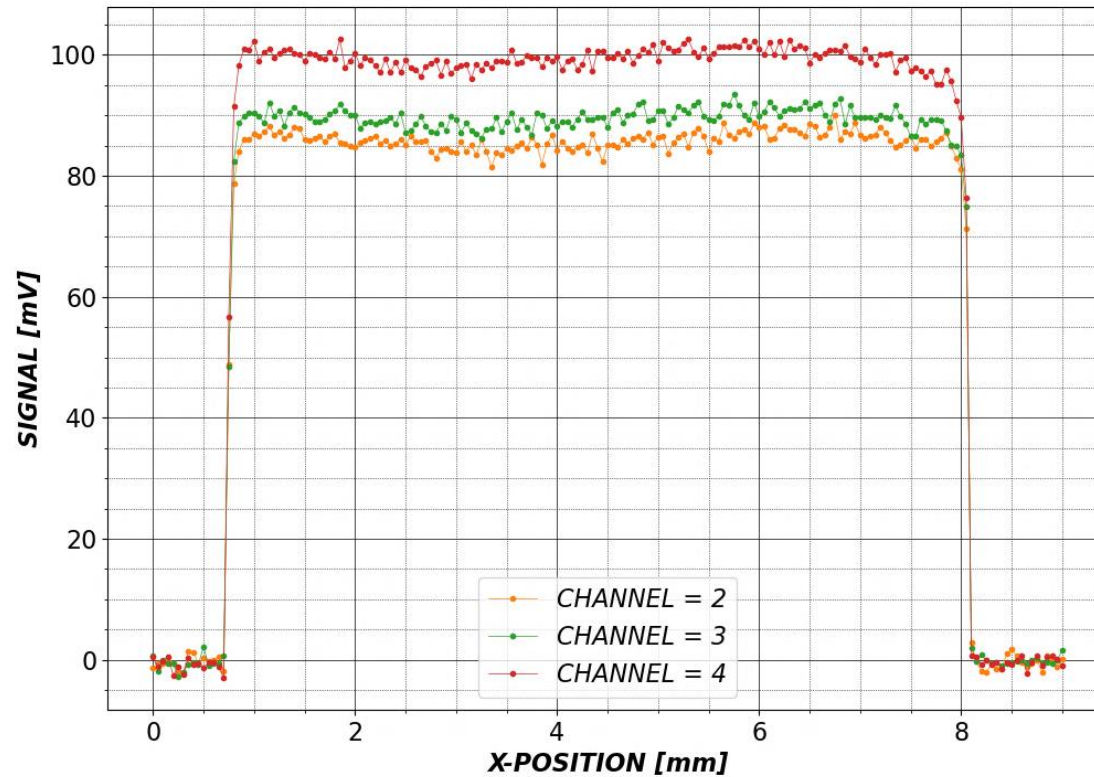
two diodes at 6.5 cm distance

gain variation ~ 25%

# GAIN HOMOGENEITY



**W7-N15 MAXIMUM AMPLITUDE OF DIFFERENT CHANNELS**



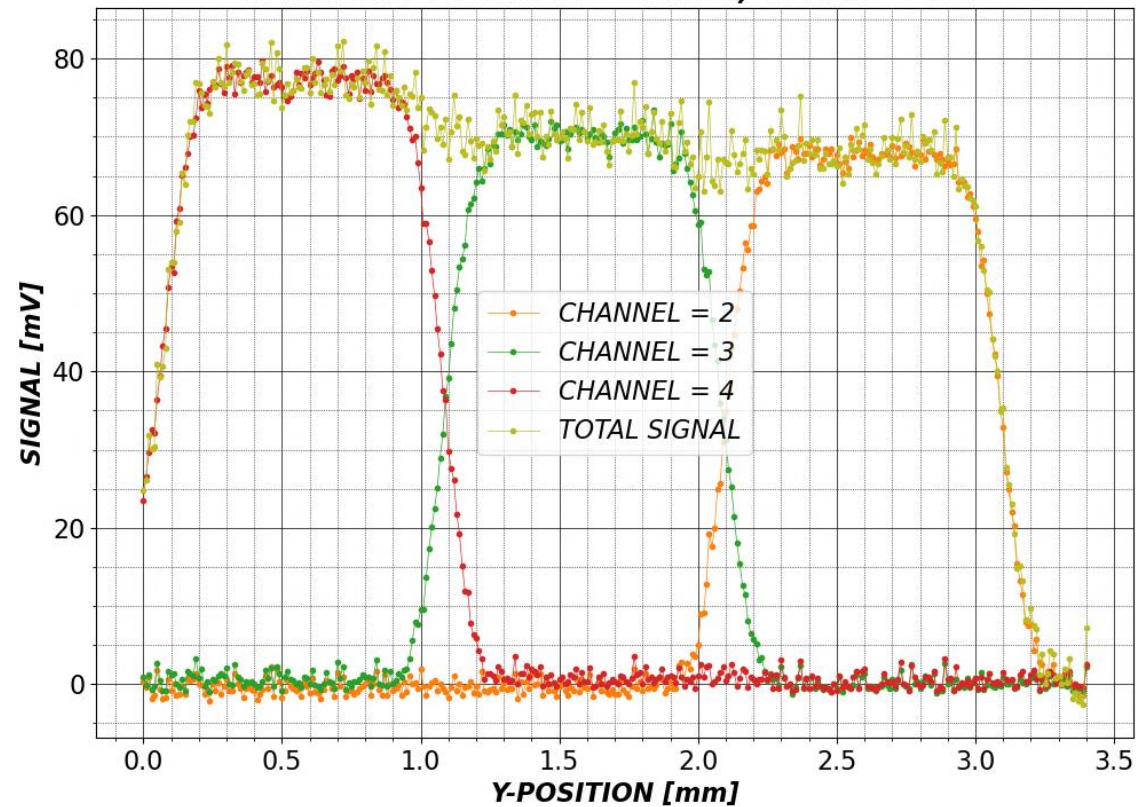
**laserscan over the length of the strip.**

**no significant change of signal over 7 mm**

# GAP BEHAVIOUR OF FIRST PROTOTYPE STRIP DETECTOR 100MU PITCH, 3MU GAP



**W7-N15 ETA PLOT OF DIFFERENT CHANNELS**  
**CATHODE VOLTAGE = -300 V, VMOS = -3 V**



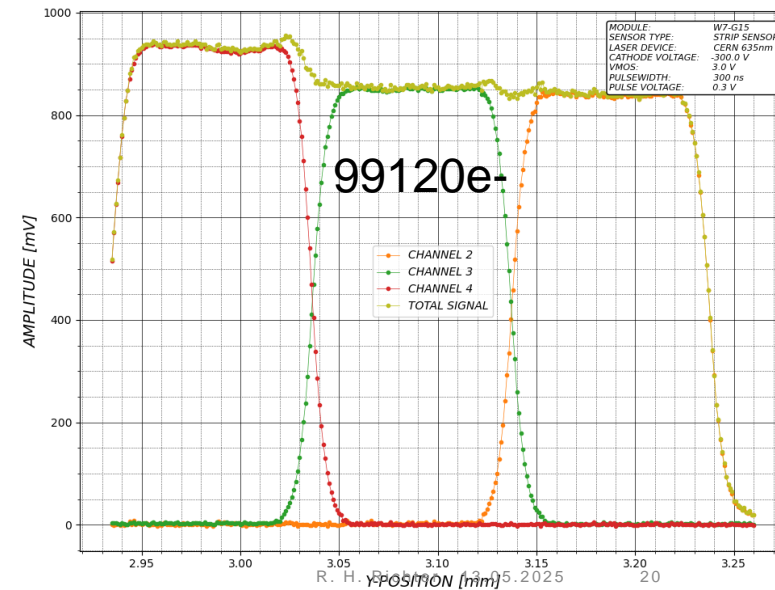
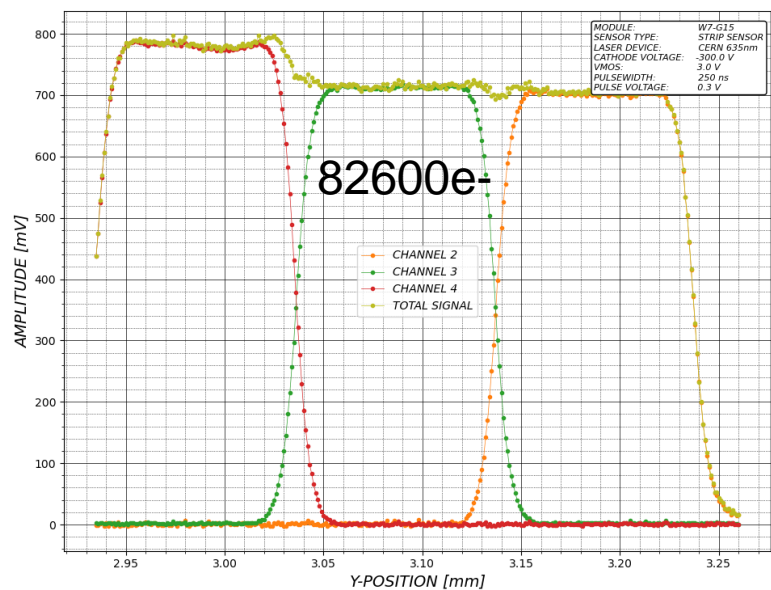
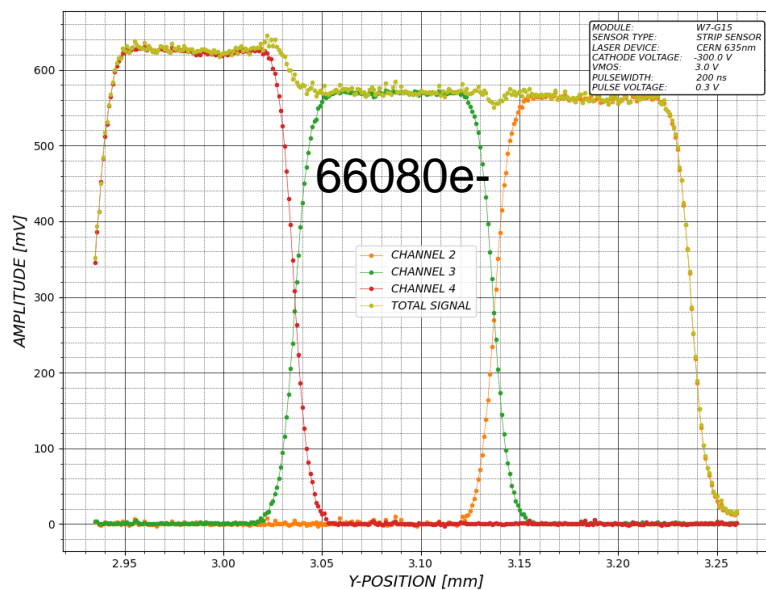
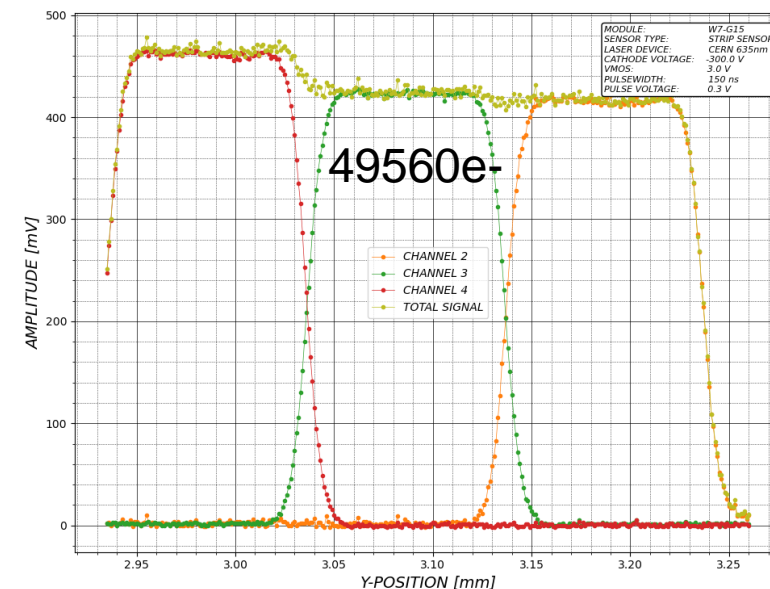
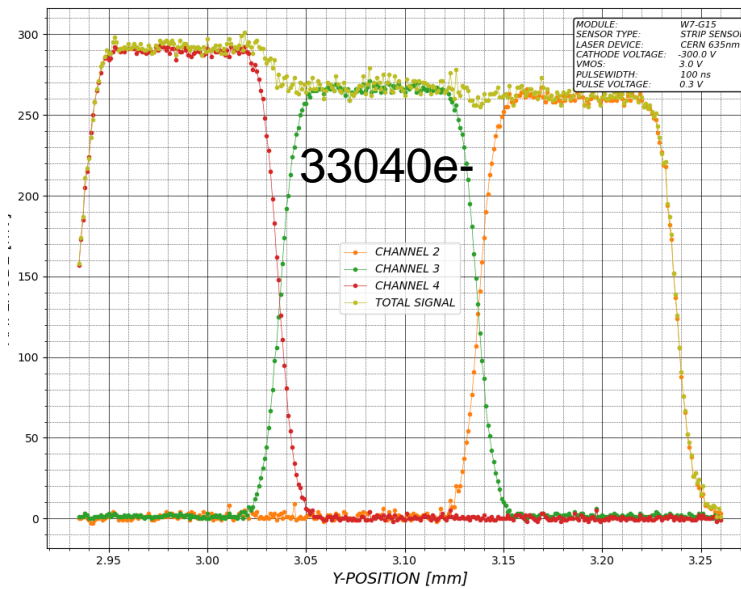
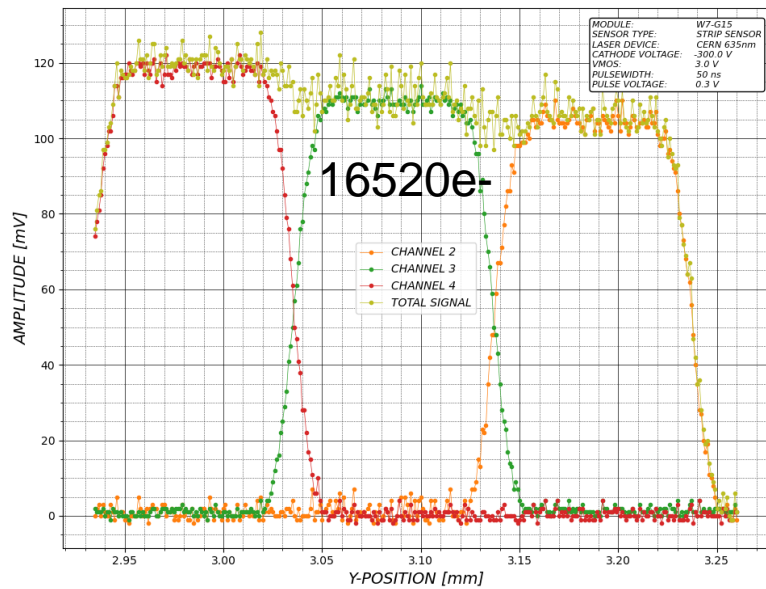
**40 ns Laser Puls ~ 10000 e<sup>-</sup>**

**laser focussed to ~10 μm**

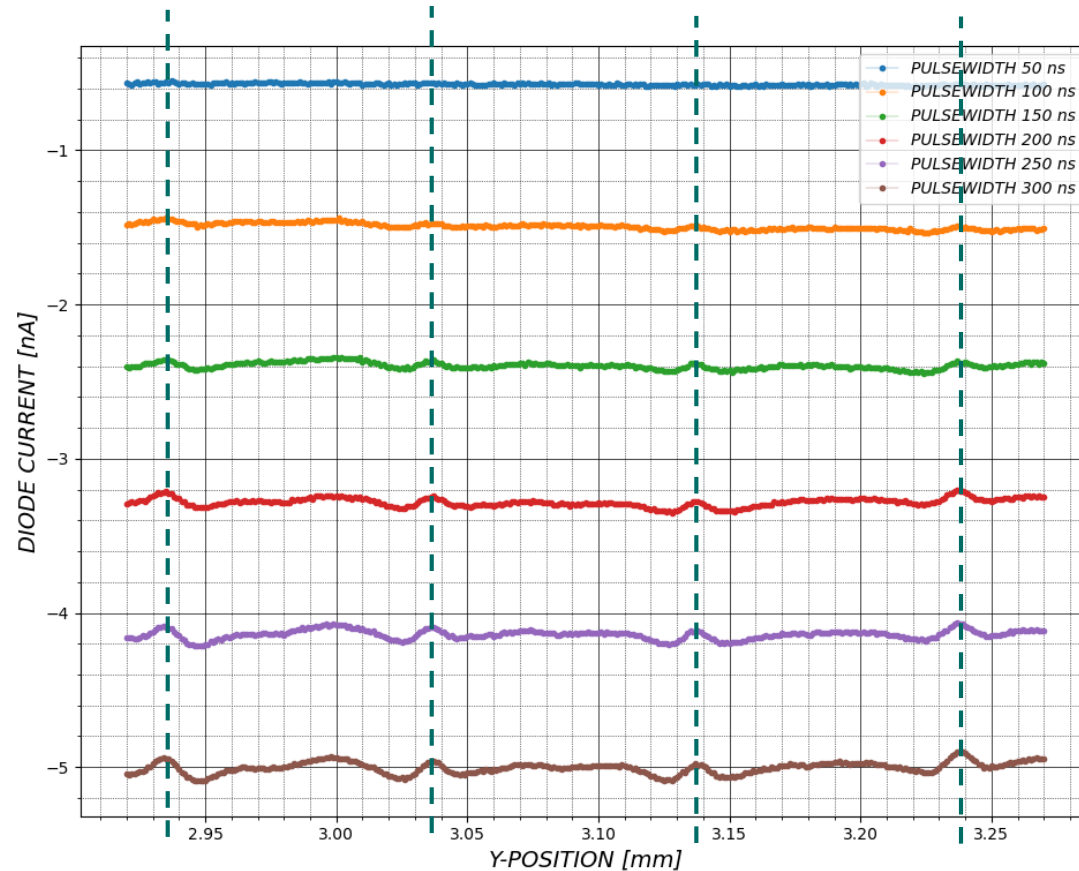
**different signal height due to  
variation of the ROE**

**gain in gap-region (mostly)  
constant**

# VARYING PULSE WIDTH (50NS ... 300NS)



# PHOTO CURRENTS MEASUREED AT BACKSIDE



Input Signal (Gain ~22)

16520e- (59.5keV xray)

33040e-

49560e-

66080e-

82600e-

99120e- ~4% fluctuation



## MARTHA – a new approach for an APD pixel array

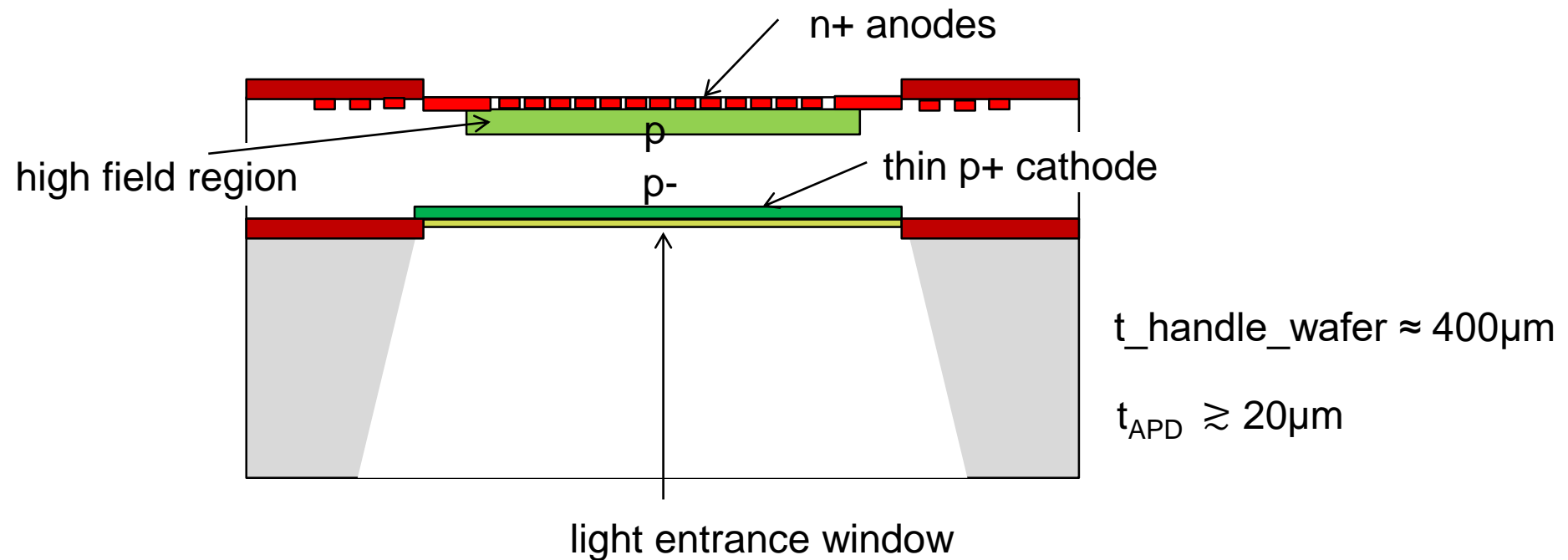
- operated in RT proportional mode
- no inter pixel dead space – 100% fill factor
- optimized for soft x-ray detection
- low excess noise (low k) due to HE high field implantation
- first prototyping – small APD arrays and strips, encouraging results 😊
- suitable for large pixel arrays ?
- **Lot to do:**
- losses in interpixel gaps, pixel leakage, gain homogeneity, noise measurements, M vs T
- improvement of read out electronics
- **Next prototyping:**
- containing Cu under bumps to include small sensors for existing RO chips
- **Adaption of the concept for fast timing sensors together with Uni HH (Erika Garutti, PHD Constanze Wais)**



# BACKUP SLIDES



- **MARTHA sensors can also be produced on thinned wafers**
  - improved timing capabilities



# PIXEL CAPACITY



## expected pixel capacity

- 50um Pixel 3um gap: ca. 35fF
- 50um Pixel 10um gap: ca. 20fF

# EXCESS NOISE FACTORS VS IONIZATION RATES

$$F = M * k + (2 - \frac{1}{M}) (1 - k) \quad M = f(E(x)), \quad k = g(E(x))$$

MARTHA prototyping: measured M, E = const.

W07	Vbias, Gain		
F @ 300K	<b>-300V, 26</b>	<b>-350V, 29</b>	<b>-400V, 33</b>
Overstraeten de Man	3.9	4.3	4.6
Overstraeten de Man opt	2.5	2.6	2.7
Okuto Cromwell	2.45	2.5	2.6
Okuto Cromwell opt	2.2	2.25	2.3

W01	Vbias and Gain		
F @ 300K	<b>-300V, 81</b>	<b>-350V, 100</b>	<b>-400V, 128</b>
Overstraeten de Man	9.7	11.7	14.7
Overstraeten de Man opt	4.4	5	5.9
Okuto Cromwell	4.3	5	5.9
Okuto Cromwell opt	3.3	3.6	4.2

# HLL THIN ENTRANCE WINDOW

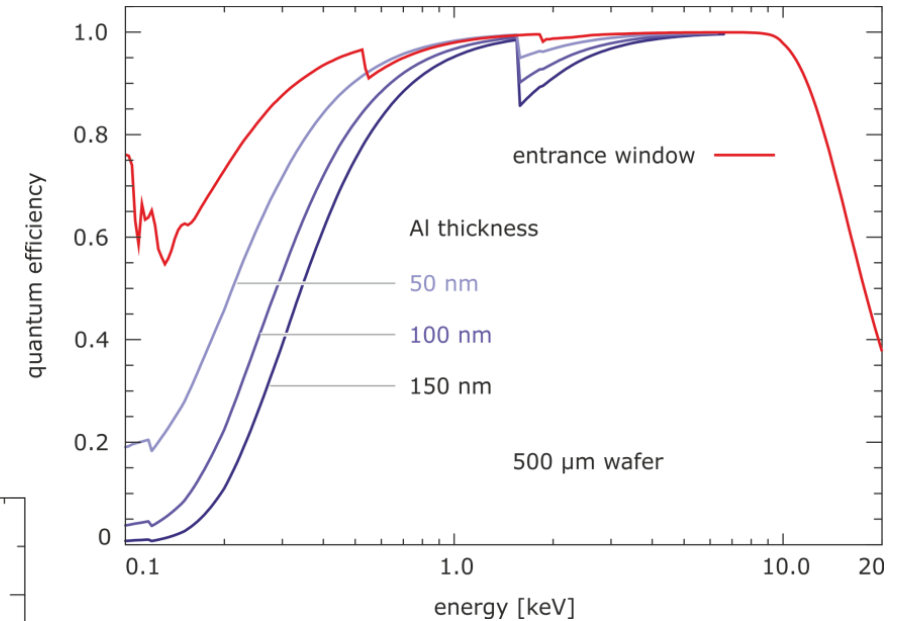
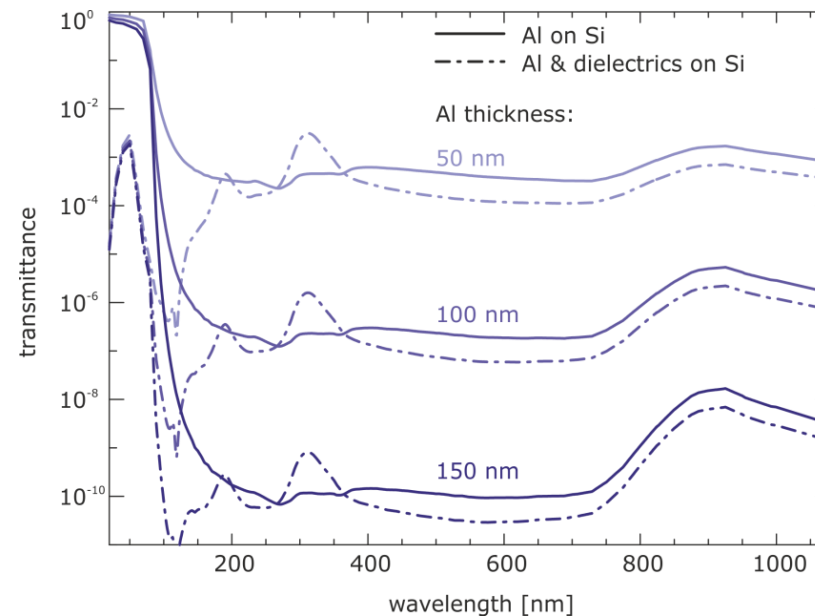


## fully depleted

sensitive over the complete bulk  
thickness 50 .. 450 .. 1000  $\mu\text{m}$   
thin, non-structured entrance window  
QE > 90% for 0.3 keV < E < 15 keV  
radhard @ soft X-rays (self shielding)

## backside irradiation

100 % fill factor  
optional light (& UV) filter



# VMOS=-5V

