Soft X-ray detectors for synchrotrons and FELs

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Rainer Richter, Alexander Bähr, Christian Koffmane, Eduard Prinker, Jelena Ninkovic - Max Planck Semiconductor Laboratory

MT Annual Meeting - GSI, Darmstadt, 3-5 Nov

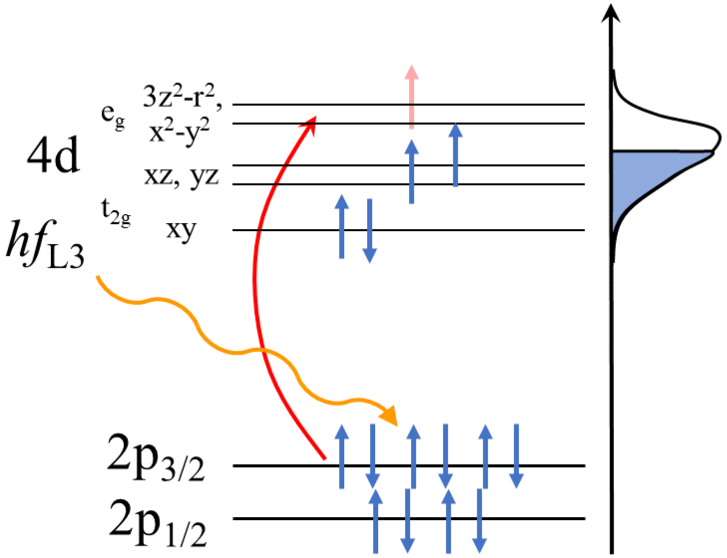
Introduction

- Soft X-ray science
- PERCIVAL – CMOS imager
- LGADs for soft X-ray detection

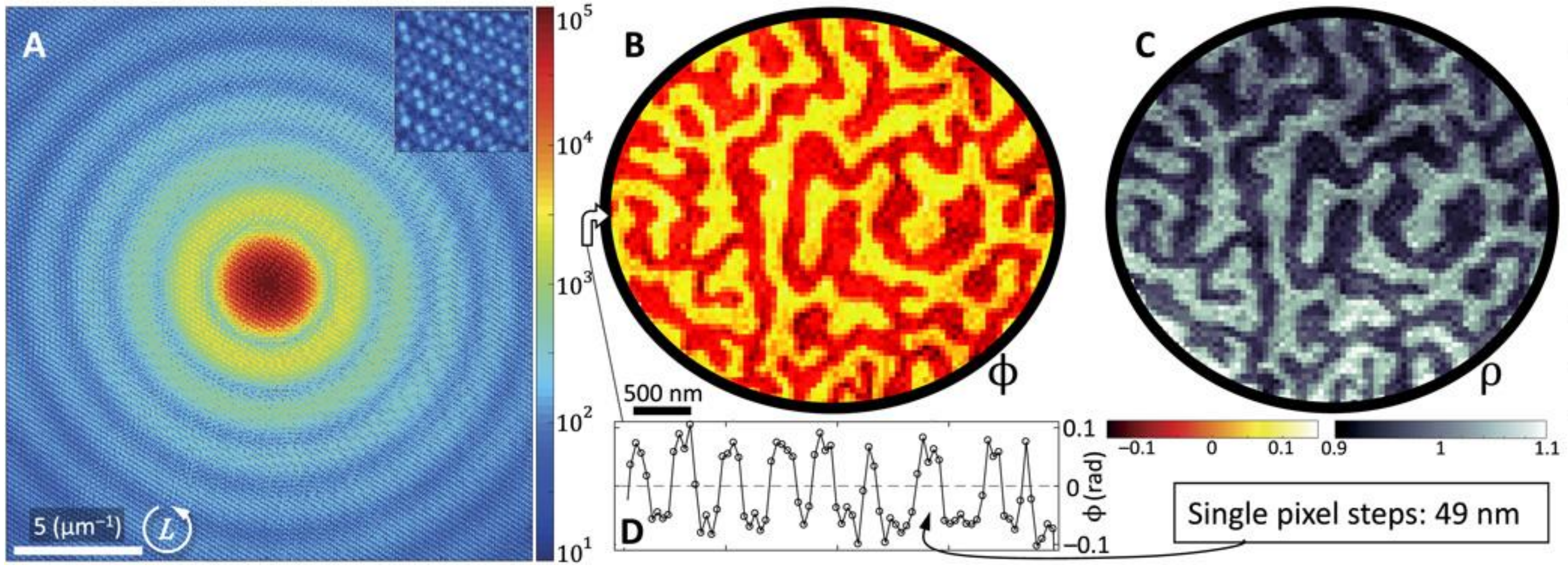
Soft X-rays (50-2000 eV)

Advantages

- Shorter wavelength than visible light (~nm)
- Can tune energy for sensitivity to specific elements and energy levels (e.g. carbon at 284 eV)
- Polarized – sensitive to magnetism



Soft X-ray diffraction from Co/Pd multilayer



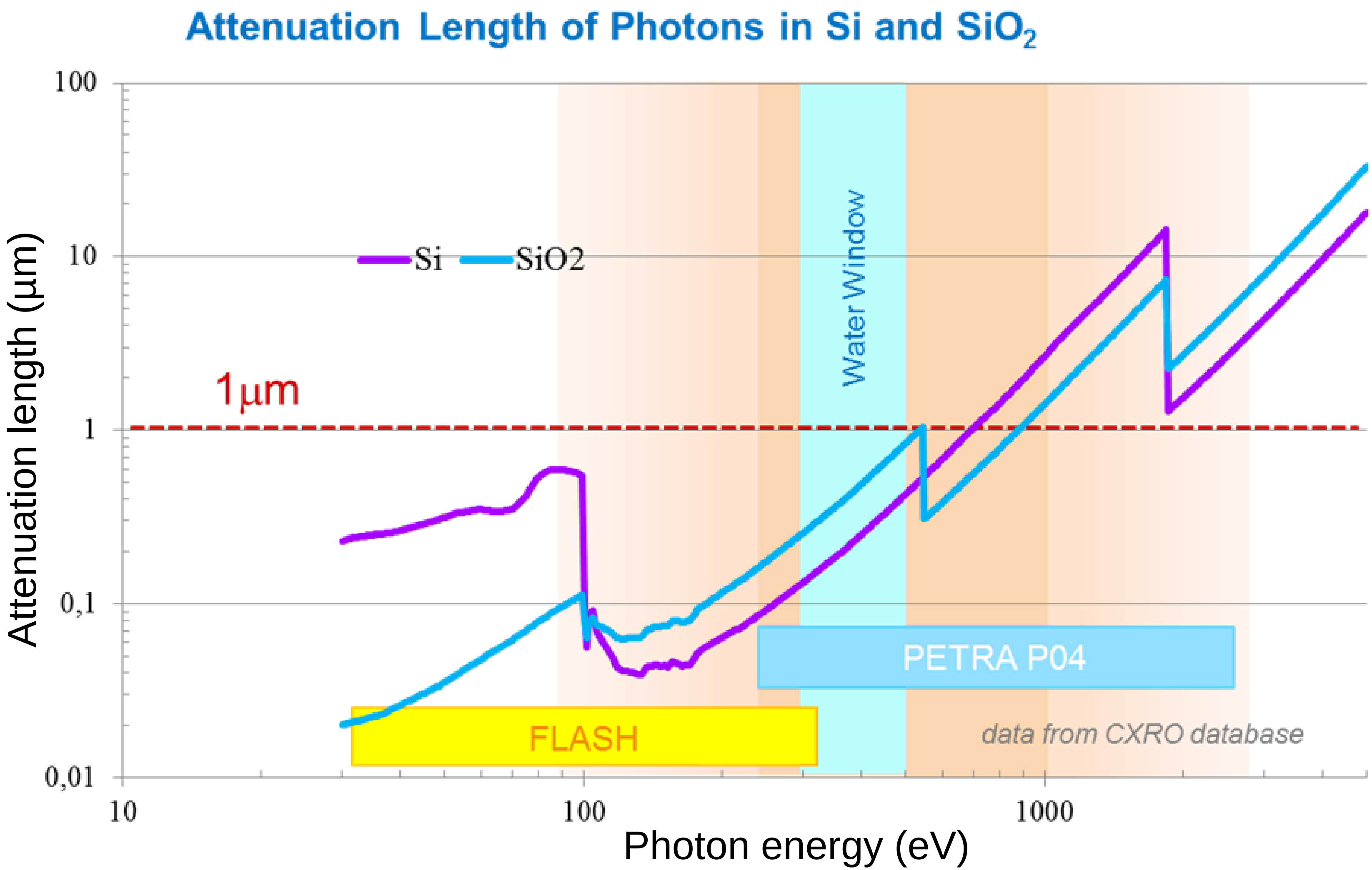
Magnetic domains in multilayer

DOI:10.1126/sciadv.aao4641

Soft X-rays (50-2000 eV)

Challenges

- Lower signal per photon – e.g. 70 e- at 250 eV
- Short absorption length requires minimal insensitive layer and vacuum operation



Percival soft X-ray CMOS imager

- Key features:
  - Sensitive to single soft X-ray photons
  - Signal range 5 x 10^4 photons/pix/image
  - 300 Hz frame rate
  - 1408 x 1408 pixels
  - 27μm × 27μm pixel size

DESY

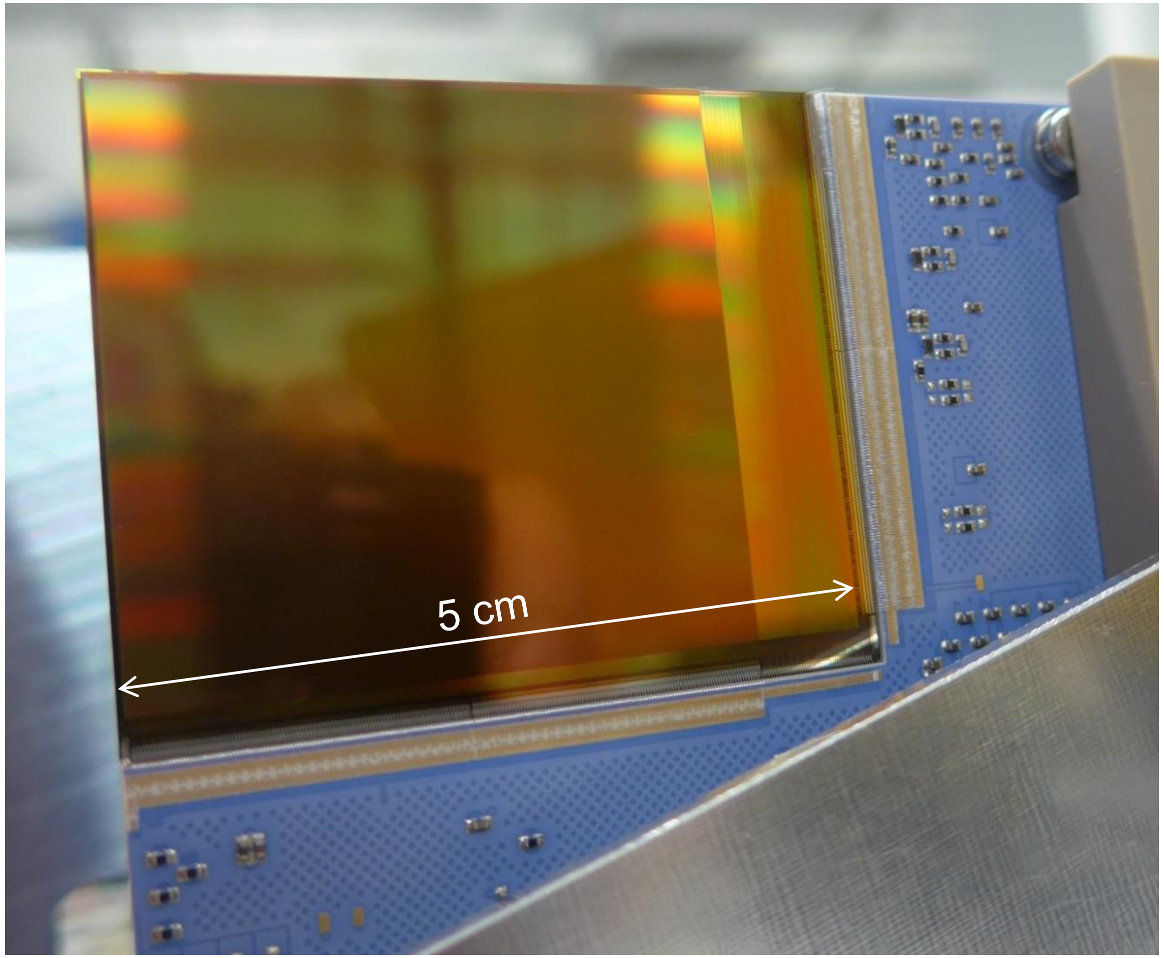
Rutherford Appleton Lab / STFC

Elettra Sinchrotrone Trieste

Diamond Light Source

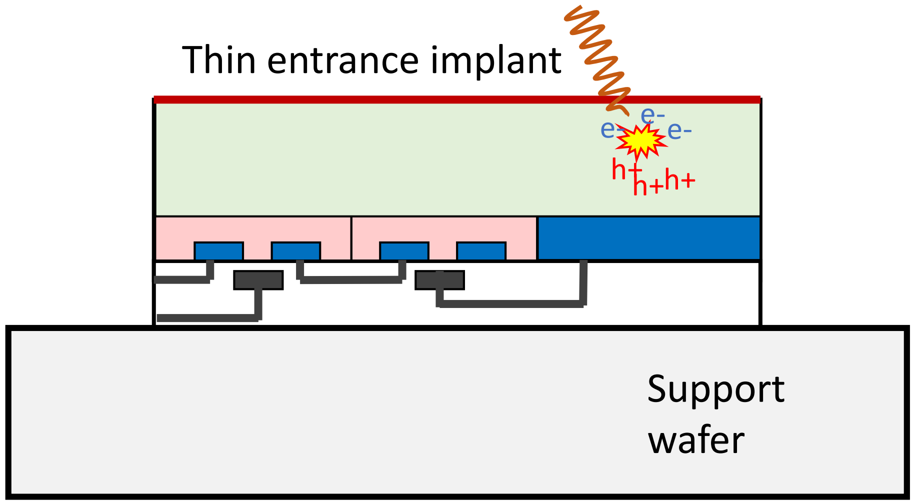
Pohang Accelerator Laboratory

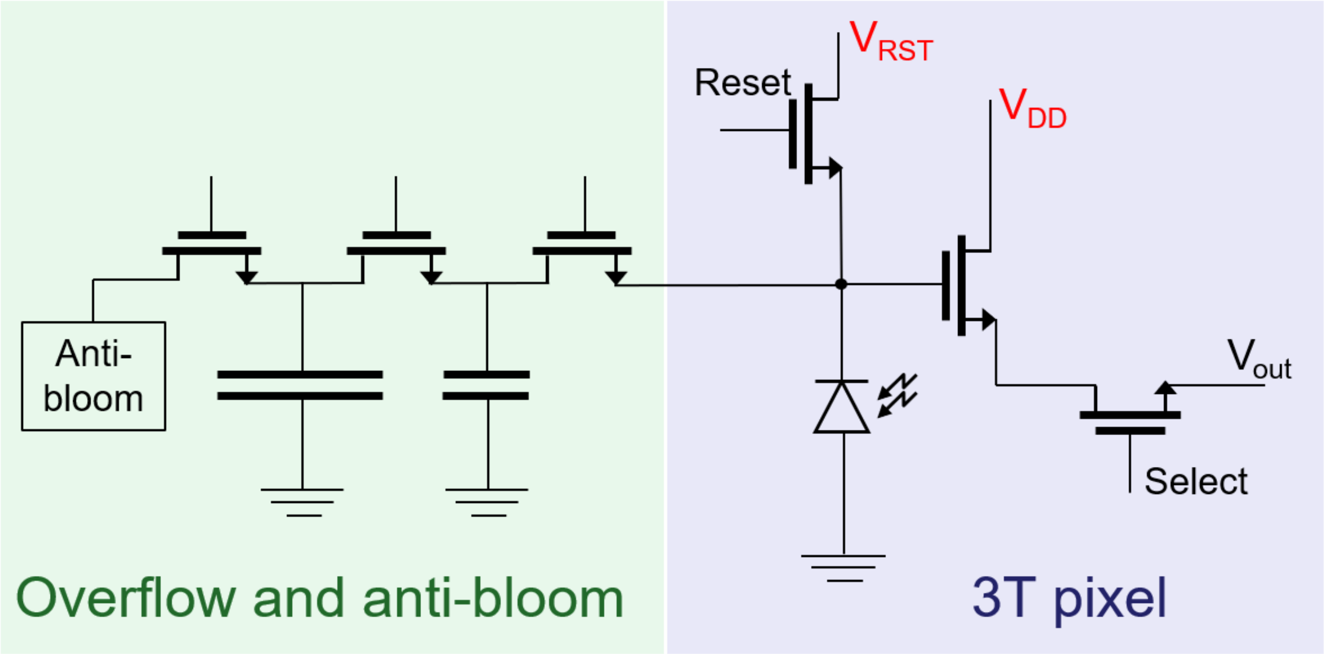
Soleil Synchrotron

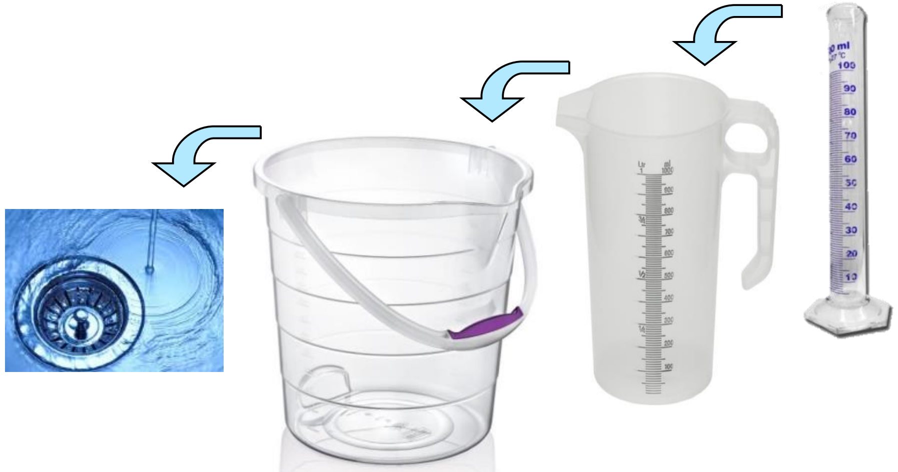


Percival 2M sensor

- Designed by RAL (180 nm CMOS)
- 3 gain levels – overflow mechanism
  - ~15e- noise to 3.5 Me-
- On-chip ADCs
- 20 Gbit/s data at 300 Hz
- Back-side illuminated sensor

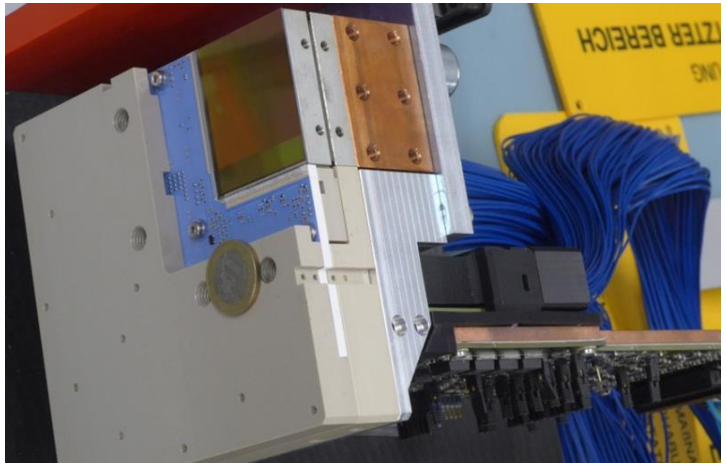


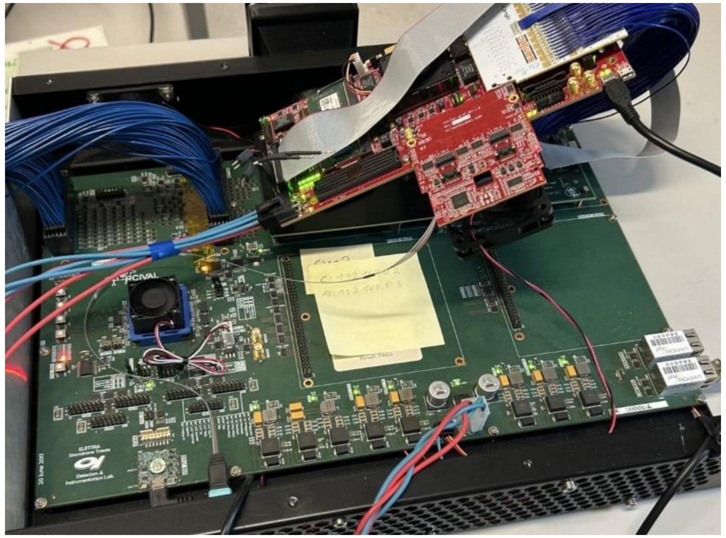


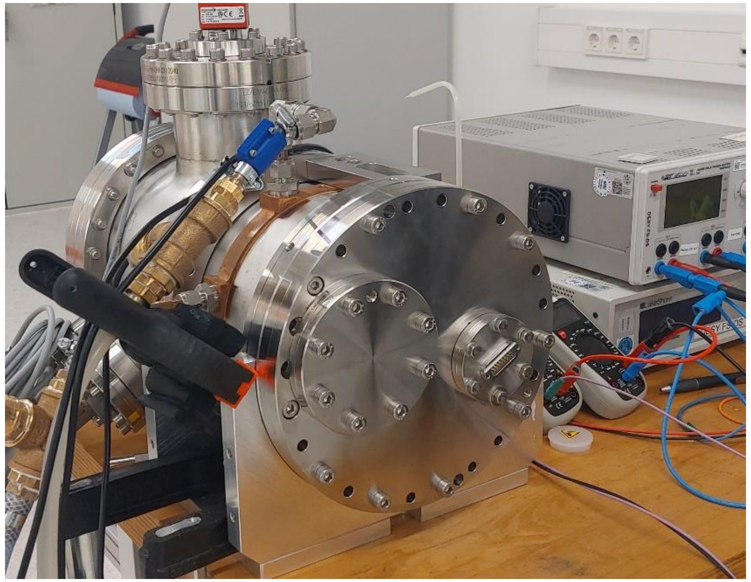


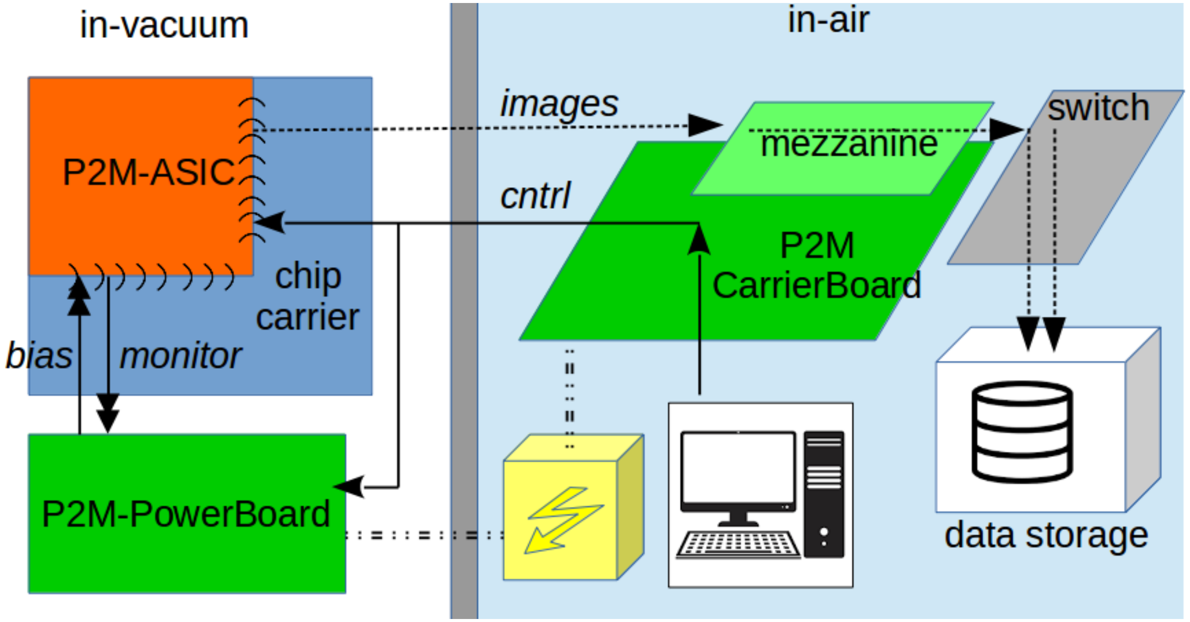
Percival system

- 2-side buttable design
- Sensor in vacuum (cooled)
- 2nd generation version developed
  - More compact chamber with Peltier
  - Modernized DAQ for full readout speed



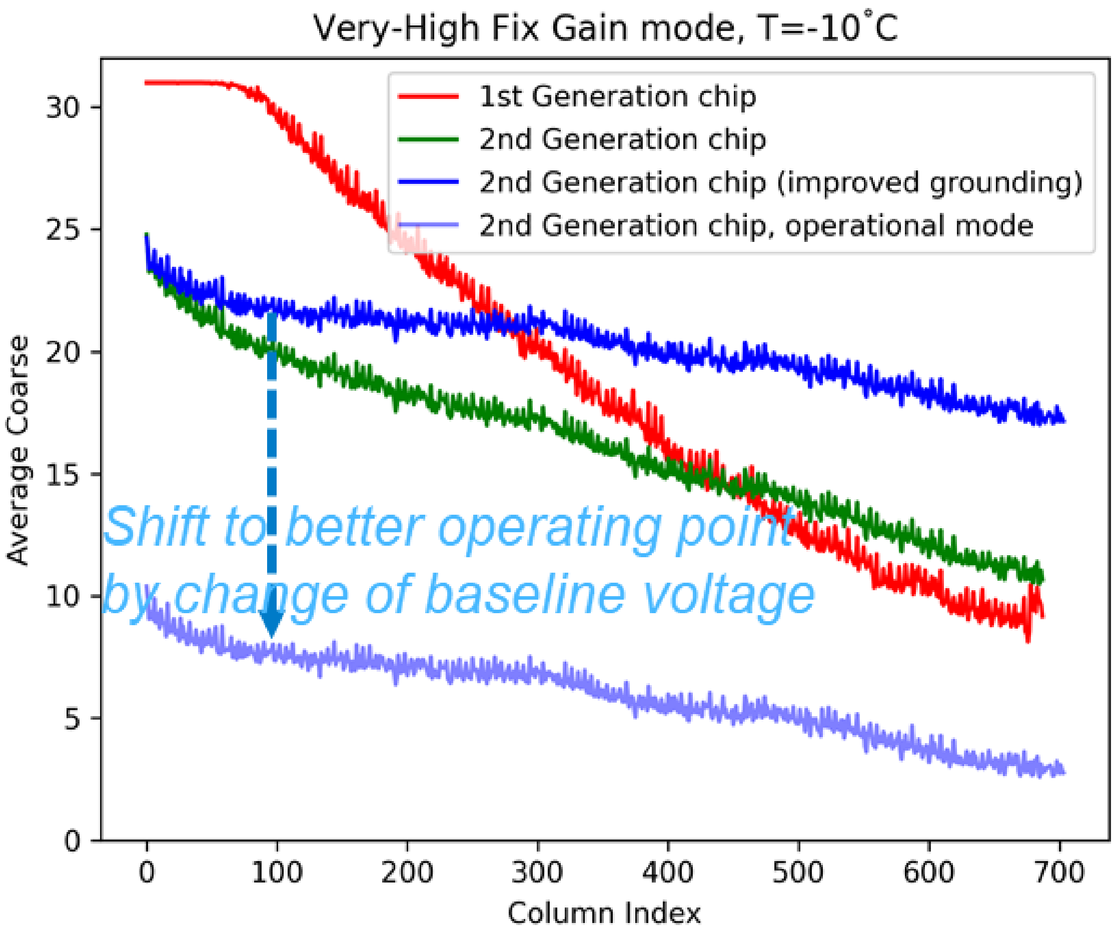






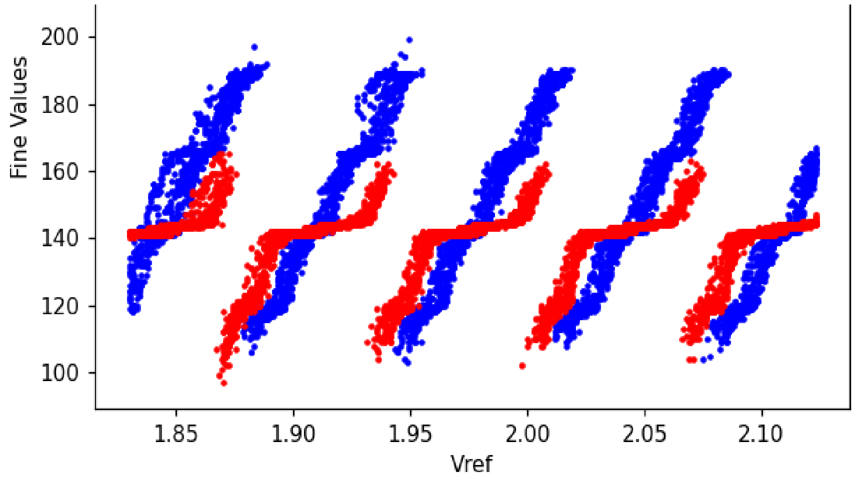
Percival 2nd generation sensor improvements

Baseline voltage lower and more uniform

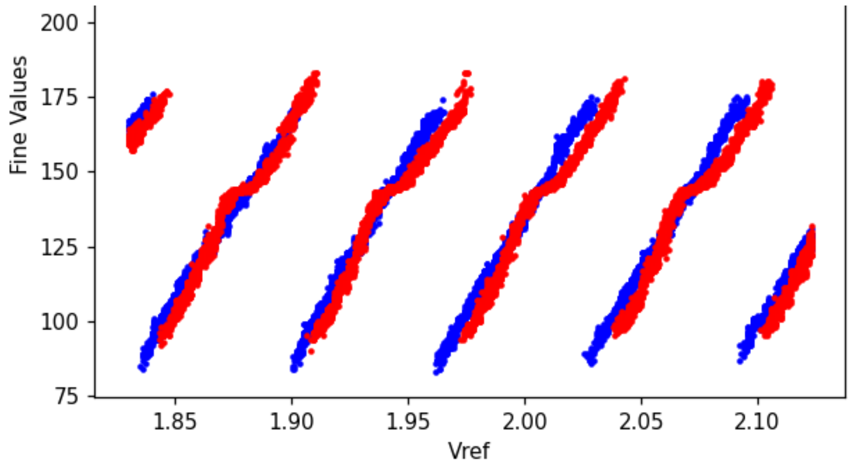


ADC linearity improved (less crosstalk with pixels)

1st gen sensor

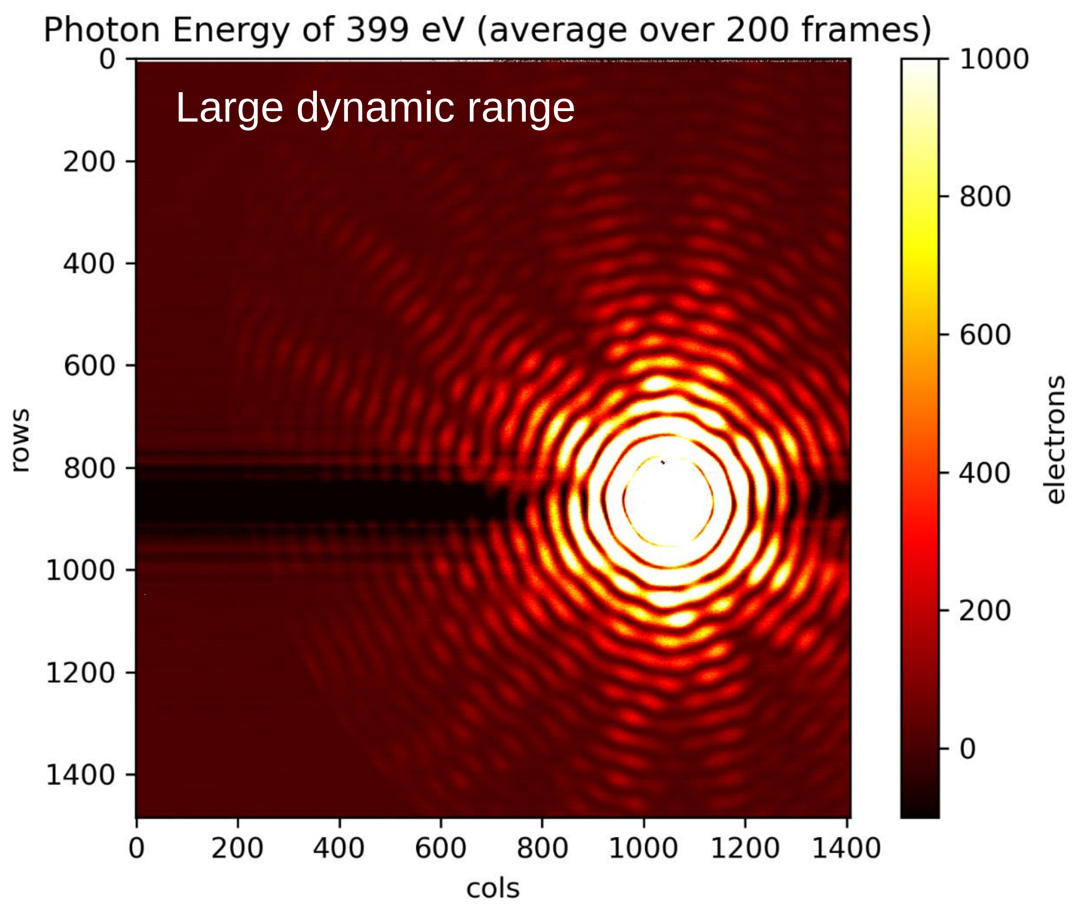


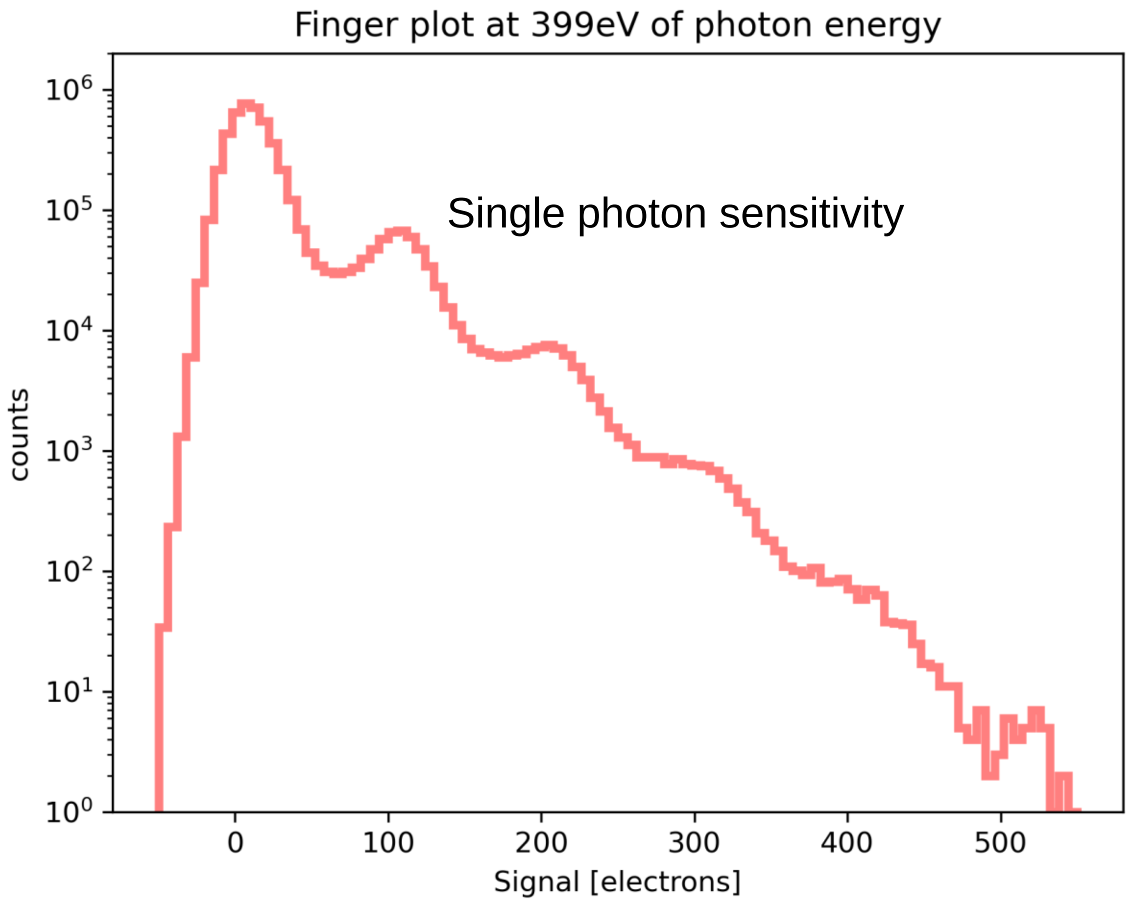
2nd gen sensor



2^{nd} gen backthinned sensor – beam tests

Measurements at PETRA-III P04, October 2025





NB – Backthinning provided by foundry

Low Gain Avalanche Diodes

- LGAD boosts signal by avalanche multiplication
- Allows tender X-ray ASICs to operate with soft X-rays
- E.g. AGIPD operation with 1 MHz bursts at FLASH
  - x 25 gain factor; **300 eV** photons produce signal like **7.5 keV**

Collaborating with institutes producing AGIPD / Timepix LGADs

MAX PLANCK HALBLEITERLABOR

MARTHA – Monolithic Array of Reach-THrough Avalanche photodiodes

SINTEF

Inverse LGADs for shallow absorbed photons

J. Segal et al., NIMA 2025
https://doi.org/10.1016/j.nima.2024.169467

MARTHA concept

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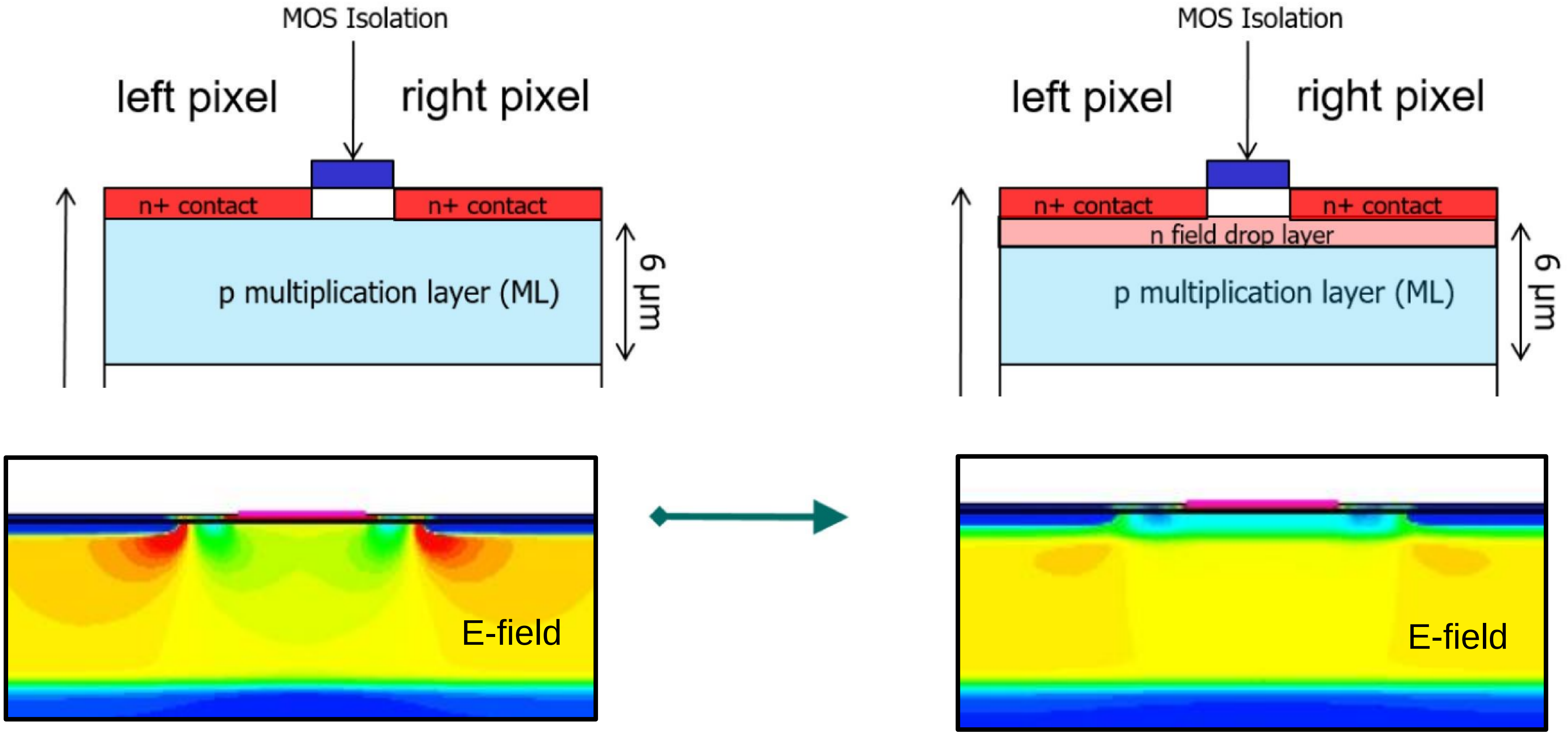
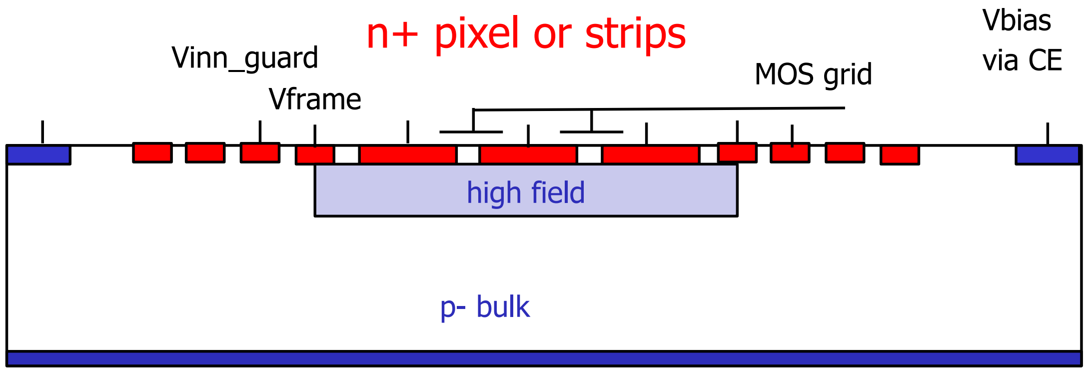


R. Richter et al. 2024, NIMA, https://doi.org/10.1016/j.nima.2024.169761

MARTHA sensor production and test

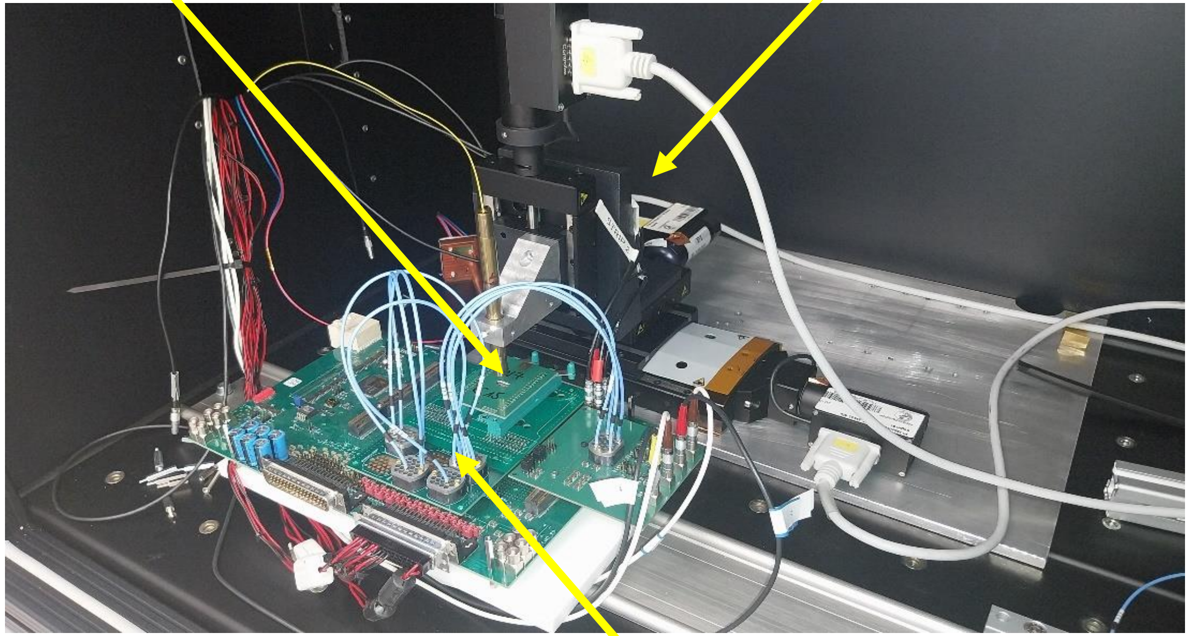
- Various strip and small pixel array devices produced
- No Al on back surface – tests with laser



backside p+ entrance window
non structured, no Al

DUT

x-y-z stage + laser



flexible connections to different ROE

MARTHA test results

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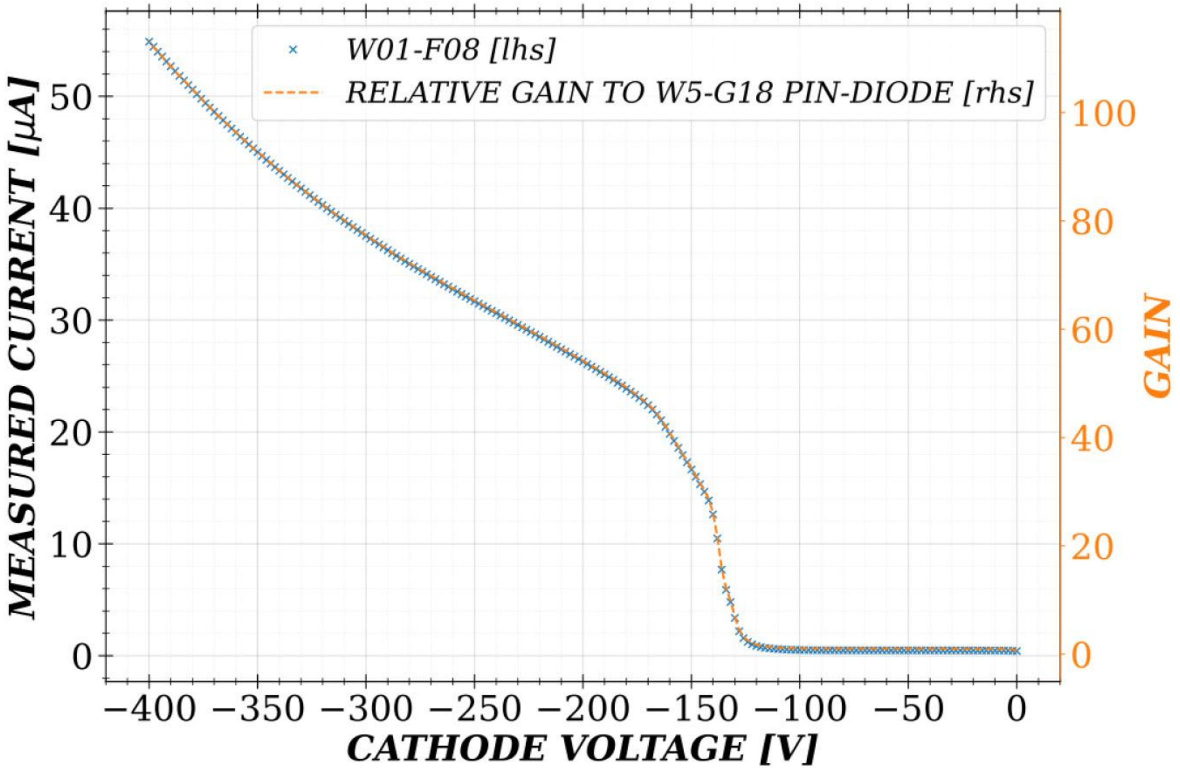
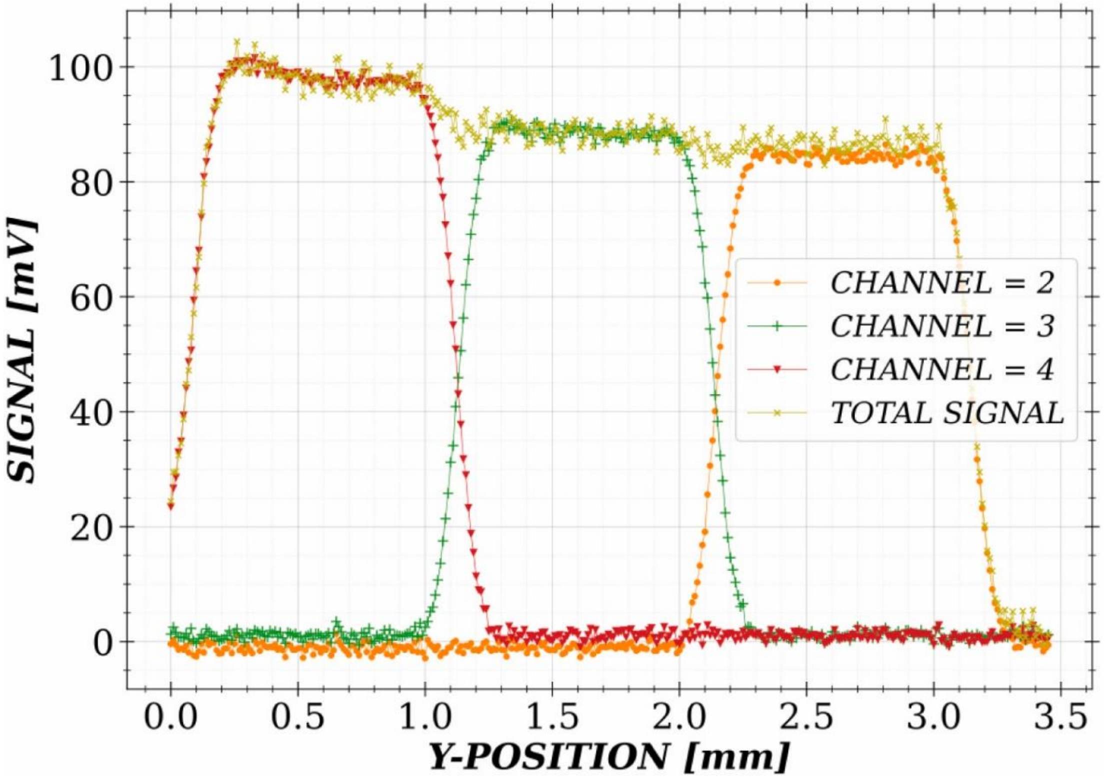
- Gain factor at 300V: 26 (low gain wafer), 80 (high gain wafer)

Photocurrent under illumination



Laser scan across strips



A. Bähr et al. 2025, NIMA, https://doi.org/10.1016/j.nima.2025.171039

Summary

- Soft X-rays allow nm-scale resolution and sensitivity to elements, band structure and magnetism
- Challenges: Low signal and short absorption length
- New Percival system demonstrates good functionality in PETRA beam test at 250 eV
  - Quantum efficiency curve still to be quantified
- LGADs are a promising technology for extending the energy range of hybrid pixels
  - First MARTHA devices tested by HLL

Thank you for listening

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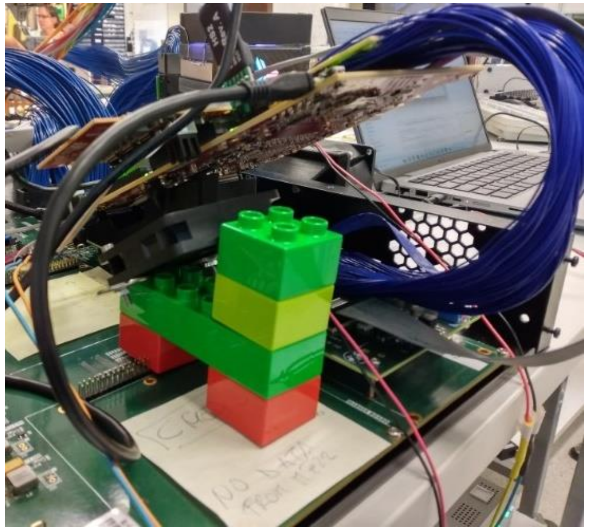
Mabel Ruiz-Lopes
Seung-gi Gang

BACKUP SLIDES

System improvements – new readout

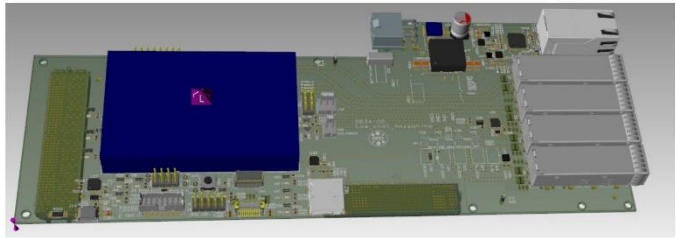
- Pre-2024 DAQ firmware not fast and flexible enough, limited sensor readout speed (83 Hz) & modes
- 2nd generation – based on modern Xilinx Zynq eval board
  - Overcomes data speed limit (250MHz instead of 125MHz)
  - Provides flexibility (data line delays, output sequencing & addresses, …)
  - Enables ROI (and thus >1k frames/s)
  - No longer working with ‘frozen code’

Old Mezzanine shared with 1st-gen. AGIPD and LAMBDA systems



2nd-generation DAQ development based on Xilinx Zynq Ultrascale eval board

- *Next steps*
  - *Record reference pixel data*
  - *Record bunch IDs (FLASH)*
  - *Compact custom board*

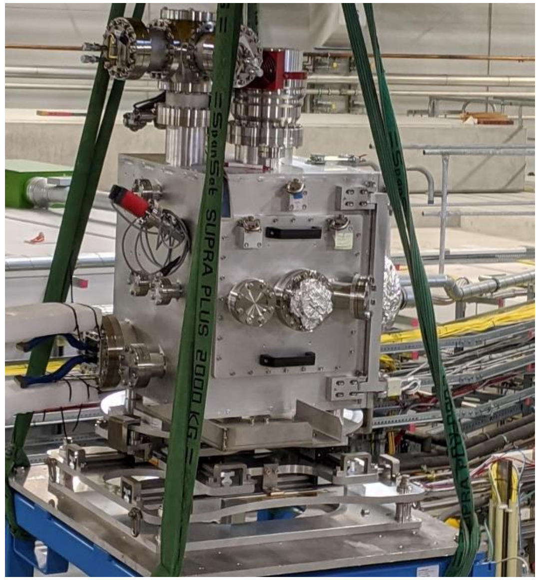


Custom DAQ board with Trenz FPGA module

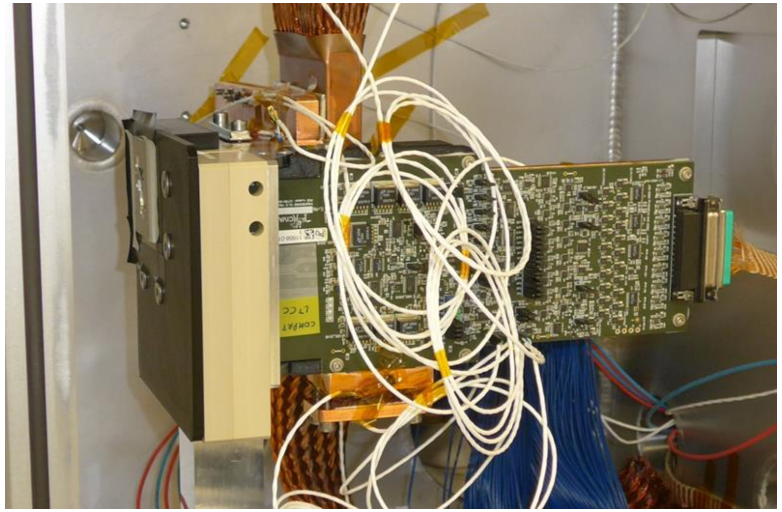
System improvements – compact system

Initial chamber devised for easy access and verification flexibility

- Cumbersome
- Long cooling & warmup times with Cryotiger-based setup

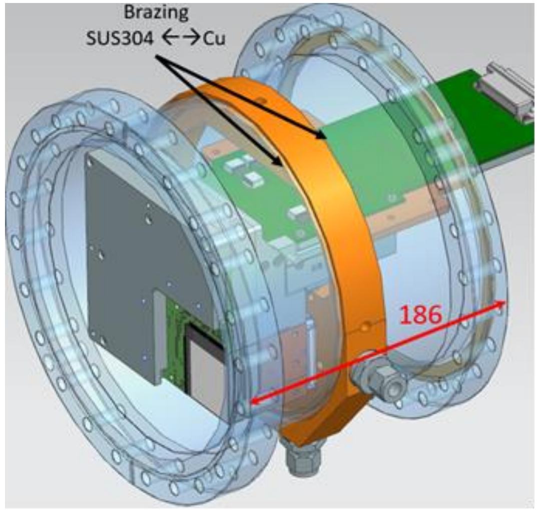


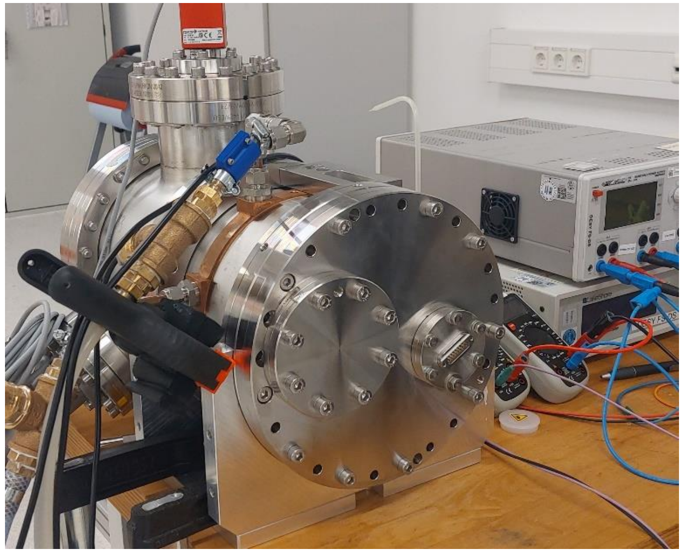
almost 1t on the crane … and spacious interior

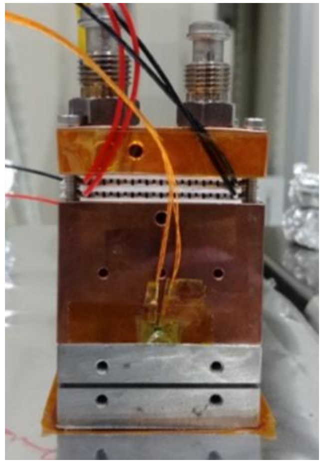


Compact chamber with Peltier cooling next step at DESY – utilizing Peltier element commissioned by & tested already at PAL

- Much more compact (also: less access …)
- Lightweight setup



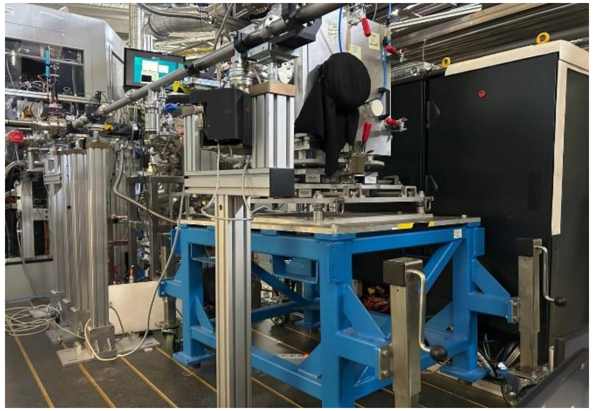




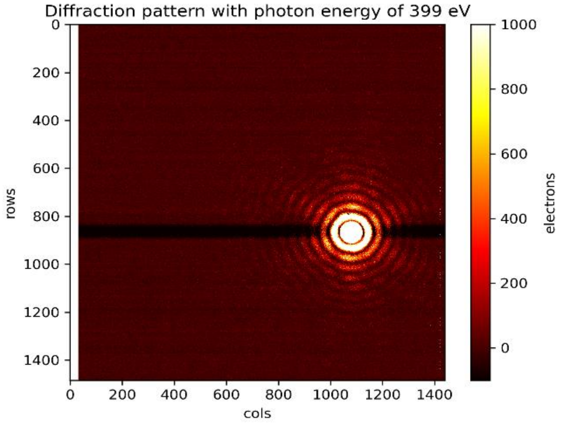
Peltier prototype @ PAL

Percival at P04 – beam test results

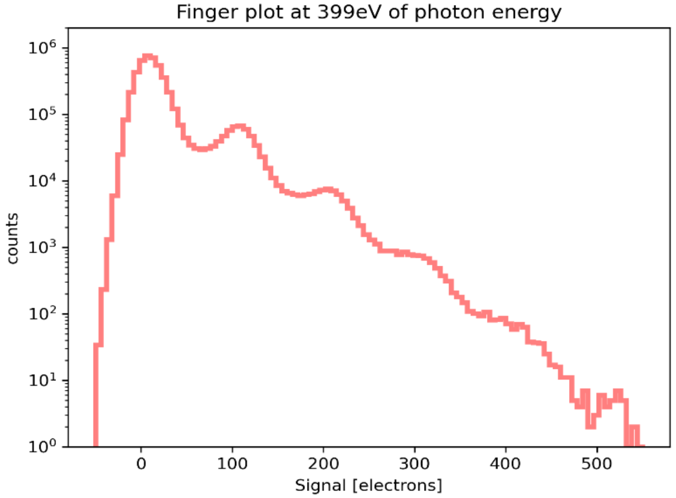
PERCIVAL at P04 beam-line



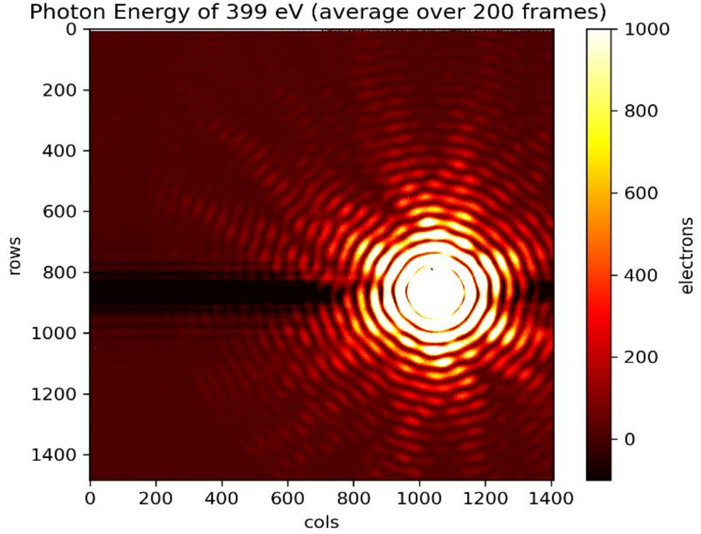
Exposure time : 3.8 ms (263 Hz) (Single frame image)



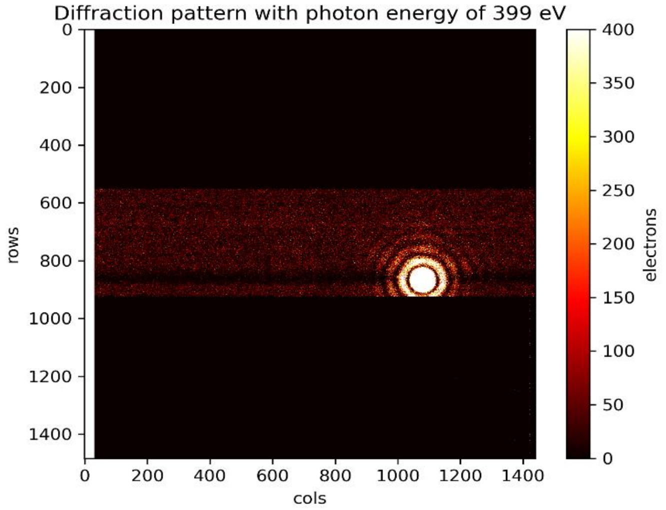
Exposure time : 50 ms (20 Hz)



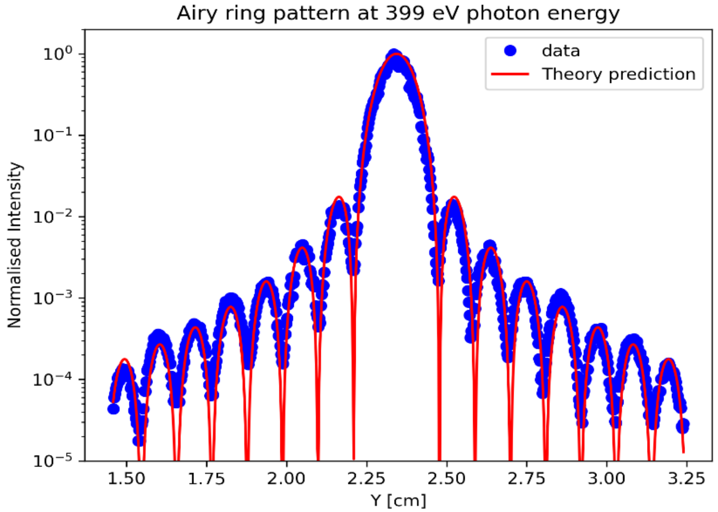
Exposure time : 50 ms (20 Hz) (Average image over 200 frames)



Exposure time : 1.0 ms (1000 Hz)



Exposure time : 50 ms (20 Hz)



“Dry Numbers” – Achieved vs Aims, today

- **Frame rate today: 270Hz demonstrated, 300+Hz feasible (at increased noise)**
  - Established ‘fast ADC operation’ enables 285Hz
  - Tested data clocked to 250MHz -> ~340Hz feasible
  - Demonstrated 1kHz frame rate in ROI operation
- **Dynamic range**
  - Best respin sensor below 12e- noise
    (non-linear calibration might improve this further)
  - 3Me- with dynamic gain & overflow, 3.6Me- if fixed
    (1st gen sensor, no change expected)
- **Only small variations over chip area**
  respin sensor will enable full use of dynamic gain
- **Soft X-ray QE**
  - 1st gen Sensor: have seen 250eV photons without evidence of higher harmonics at P04, same for 92eV at FLASH
  - 2nd generation: Oct 2025 test results under analysis

- **Design: 300 Hz, proportionally faster for partial readout**
- **Design dynamic range**:
  - single photons at 250eV / <15e-,
  - 50k Photons at 250eV (3.5Me- for 100% CCE)
- **Soft X-ray QE**:
  1st generation: using NASA JPL’s delta-doping BSI process for ultrathin entrance windows (~ 5nm) and soft X-ray QE > 85%
  2nd generation: foundry-supplied BSI process

MPG HLL

New Building

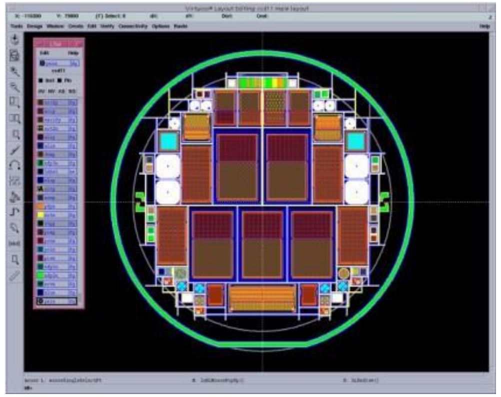
- IPP Campus Garching
- recently moved

- 1500 m² cleanroom area
- 600 m² ISO3 & ISO4 area
- 6/8 inch silicon process

Central facility of the Max Planck Society
40 scientists, engineers and technicians
+ guest scientists, and students

sensor

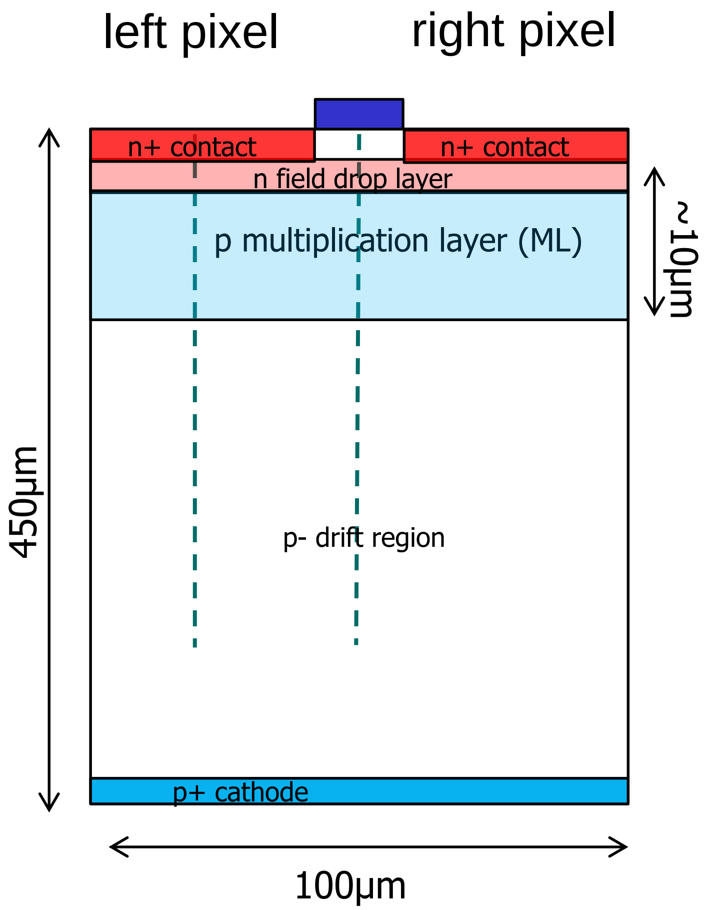
- simulation
- design
- fabrication

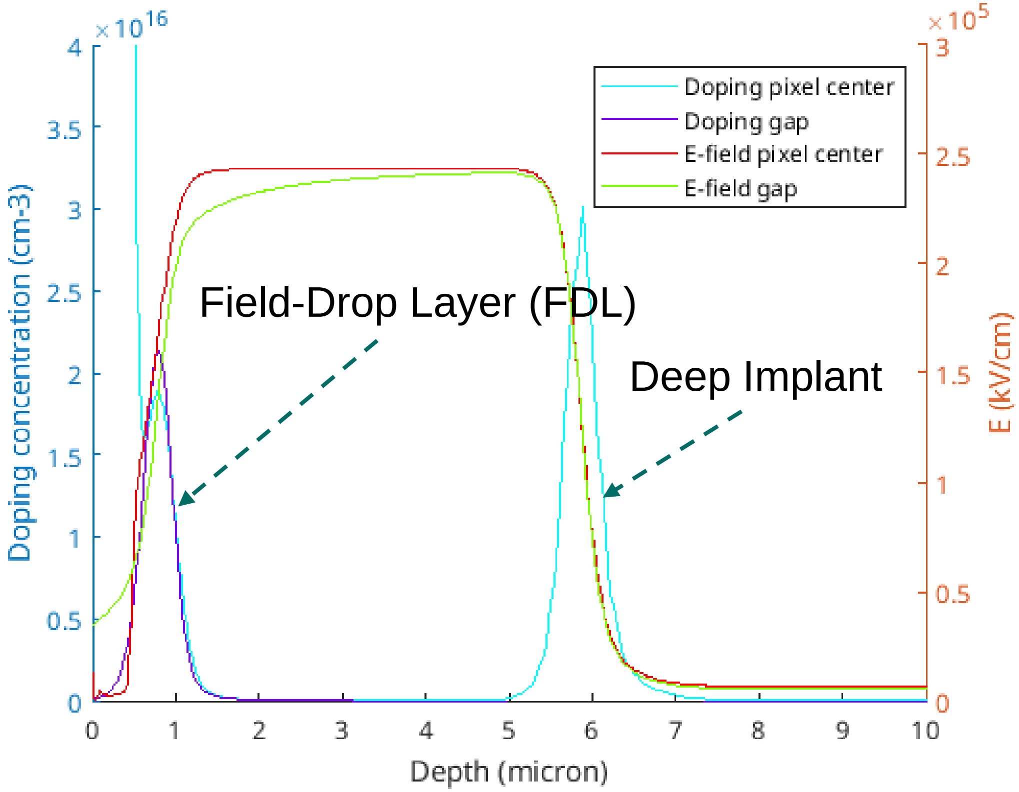


camera

- design
- assembly
- test

2D SIMULATION - ELECTRIC FIELD





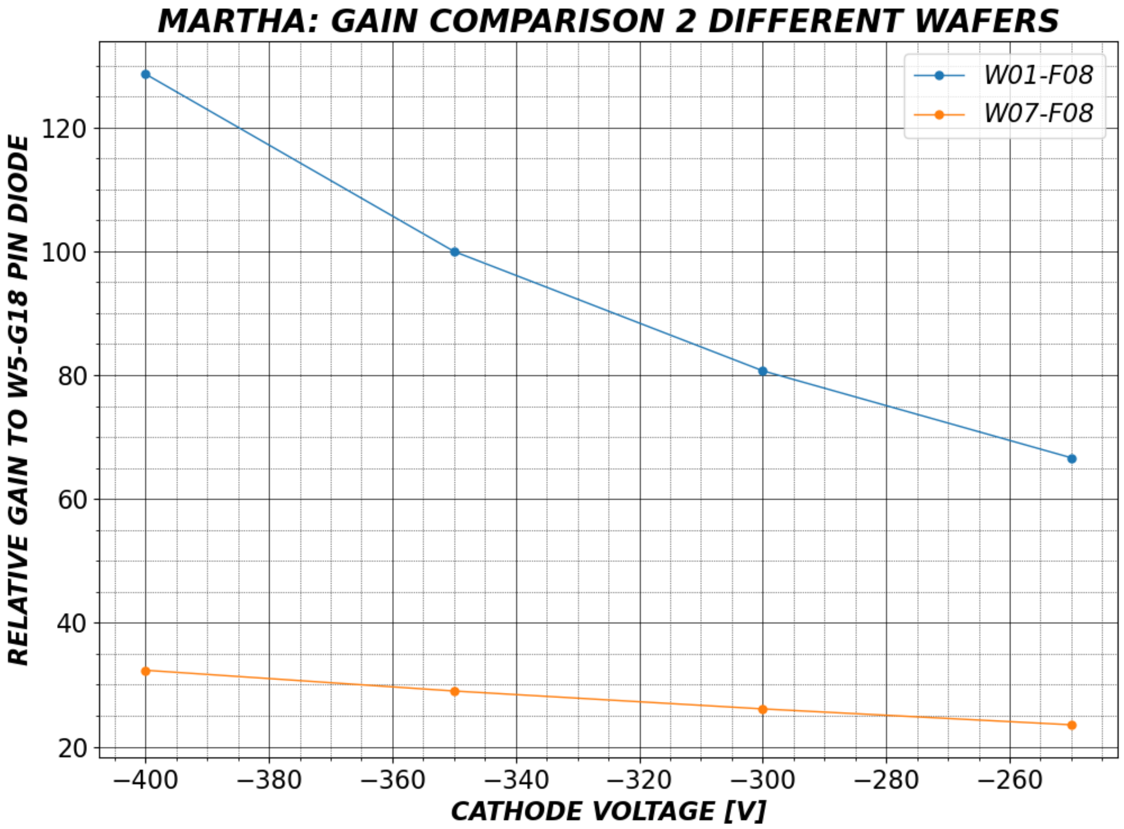
FDL:

- **shift Max E-Field**
- **prevent breakdown**

deep Implant

- **extended ML**
- **lower field**
- **low k-factor**
- **low excess noise**

PRODUCED GAIN RANGE



comparision of gain of two APDs from different wafers

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

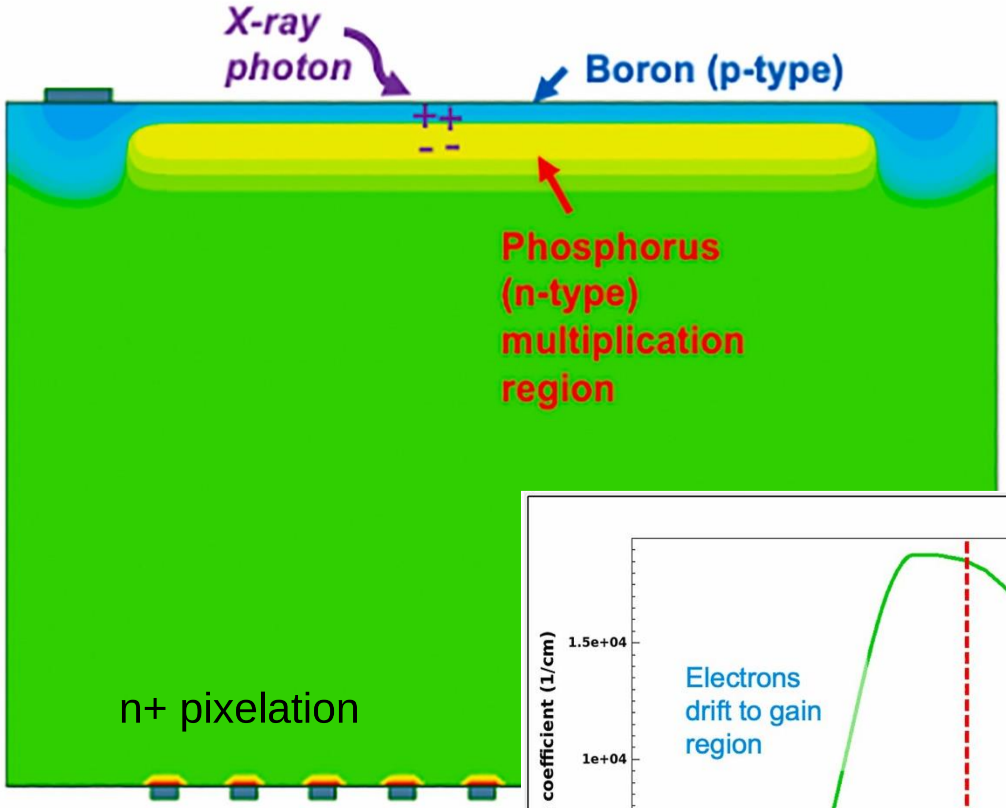
gain of 26 and 78 (@-300V)

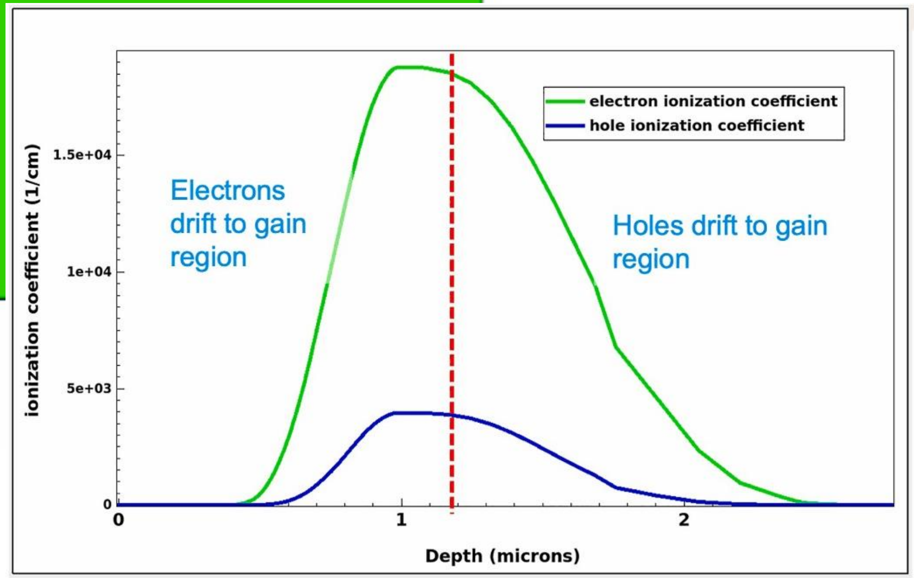
full depletion @ -250V

- **depletion of MR + Bulk**

Sintef iLGAD developments

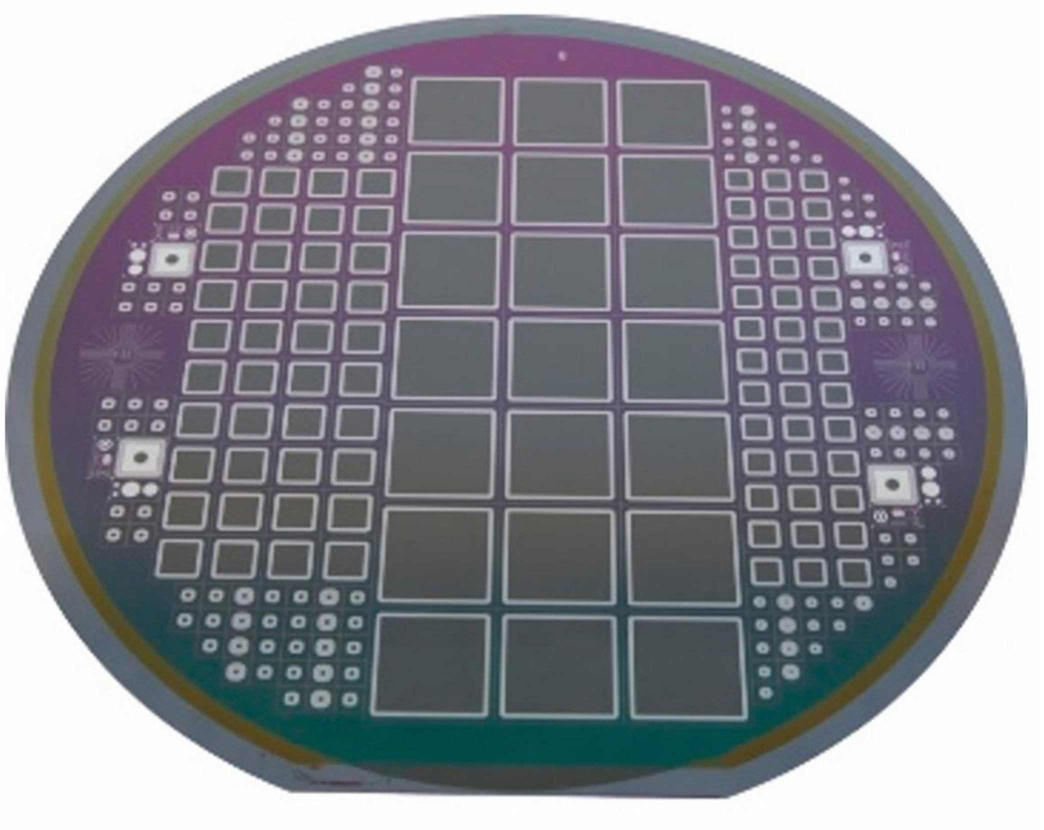
- Inverse LGAD design with n-type multiplication layer and pixelation
- Relies on soft X-ray photons being absorbed at sub-µm depth
- Thin entrance window design
- AGIPD-compatible test structures currently being bonded





J. Segal et al., NIMA 2025
https://doi.org/10.1016/j.nima.2024.169467

Sintef iLGAD test results



illumination	Measured Gain	Gain-generating carriers
no light	1.4	mostly holes
microscope light	3.0	unknown
470 nm	6.9	electrons
530 nm	4.8	more electrons
660 nm	3.3	more holes
940 nm	1.4	holes