SDDs

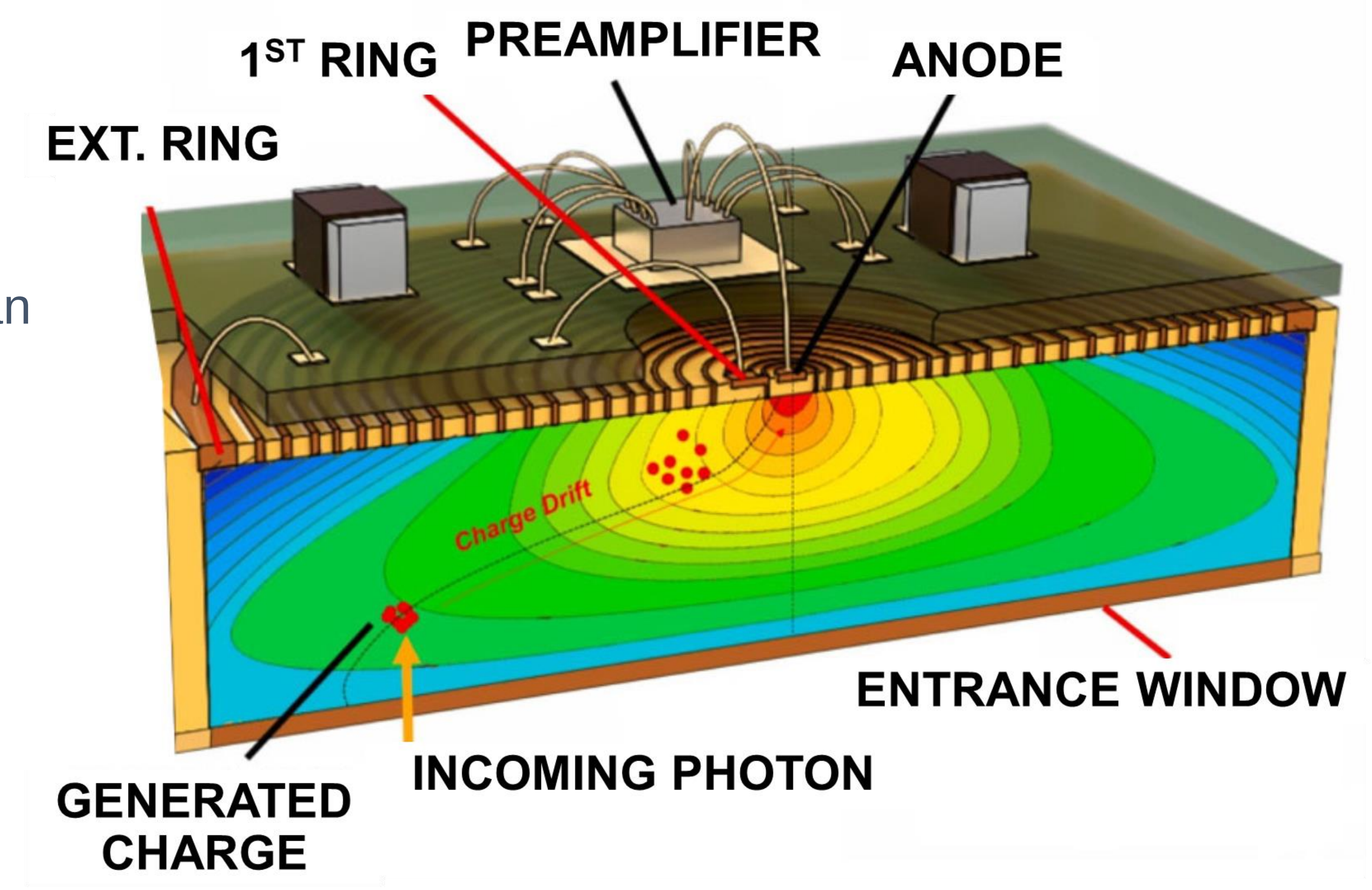
Silicon Drift Detectors (SDDs)
The SDD Technology of Fondazione Bruno Kessler (FBK)

SDD technology

- Best silicon detectors for spectroscopy applications:
  - Small anode capacitance → Possible to approach Fano limit
  - High energy resolution for X-rays in the range of 0.5-15 keV

- FBK has been developing an internal SDD technology since more than 10 years:
  - Low-leakage-current technology (patented):
    → I_{leak} as low as *50 pA/cm^2 @ RT*
  - Thin entrance window
  - Large area linear SDDs and SDD arrays

- Many successful projects in collaboration with:
  - Companies (confidential)
  - Research Agencies (INFN, ASI, ESA, INAF, …)
  - Synchrotrons (ELETTRA, SESAME, …)
  - Universities (PoliMi)



Pictorial representation of the structure of an SDD and of its working principle [3]

Silicon Drift Detectors (SDDs)
The RedSOX Project (INFN)

REDSOX - REsearch Drift for SOft X-rays

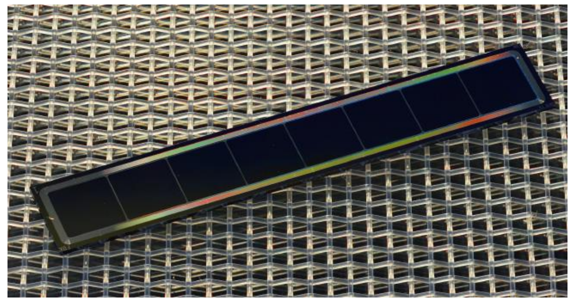
- Participants: INFN (Trieste, Bologna, Roma2, Milano, Firenze, Pavia), FBK, Elettra Synchrotron, IASF-Roma, UniUD, …

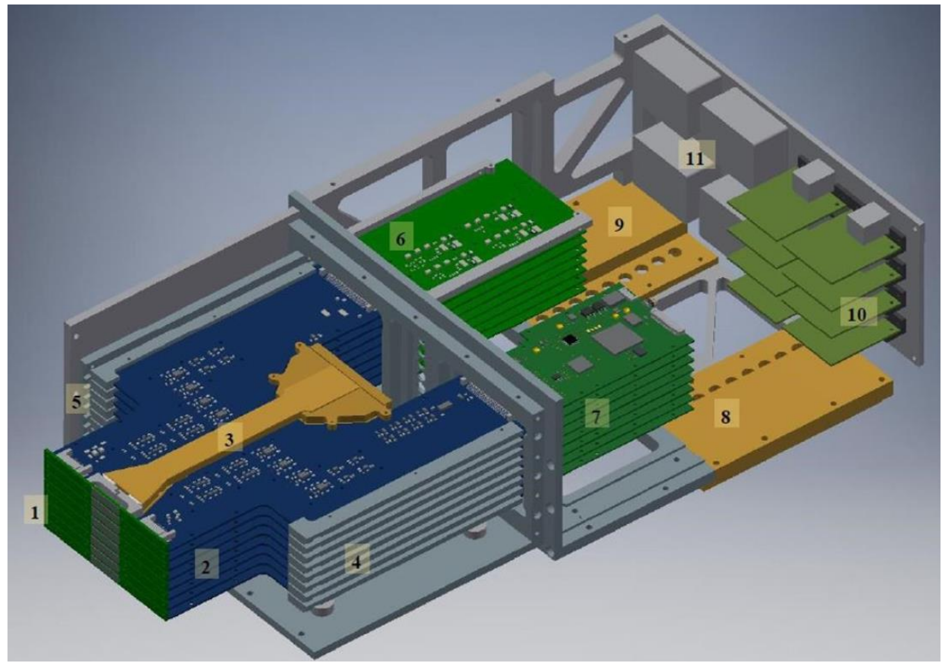
- Aims of the project:
  - development of high energy resolution SDDs for soft X-rays
  - evolution of SDD technology
  - development of SDDs for X-ray astrophysics
  - development of detectors for Advanced Light Sources

- Project follows complete instrument development:
  - SDD sensor (design and production)
  - Readout electronics (ASIC and acquisition systems)
  - Mechanical structure and cooling system

Detector system for XAFS beamline at SESAME synchrotron [1]:

- 8 monolithic SDD arrays (8 pixels, 9 mm^2 each)
- Average I_{leak}: < 100 pA/cm^2 @ 20° C
- Energy resolution (5.9 keV): 180 eV @ RT (150 eV @ 10 ° C)
- Output count rate ≥ 8 Mcps





Picture of the monolithic SDD arrays (left) and mechanical drawings of the complete XAFS detector (right)

Silicon Drift Detectors (SDDs)
The RedSOX Project (INFN)

RESEARCH DRIFT FOR SOFT X-RAYS redSOX

Detector system for low-energy XRF at TwinMic beamline at ELETTRA synchrotron [2]:

- 4 trapezoidal monolithic SDD arrays (8 pixels)
- Total uncollimated area: 1232 mm^2
- Average I_{leak}: < 100 pA/cm^2 @ 20° C

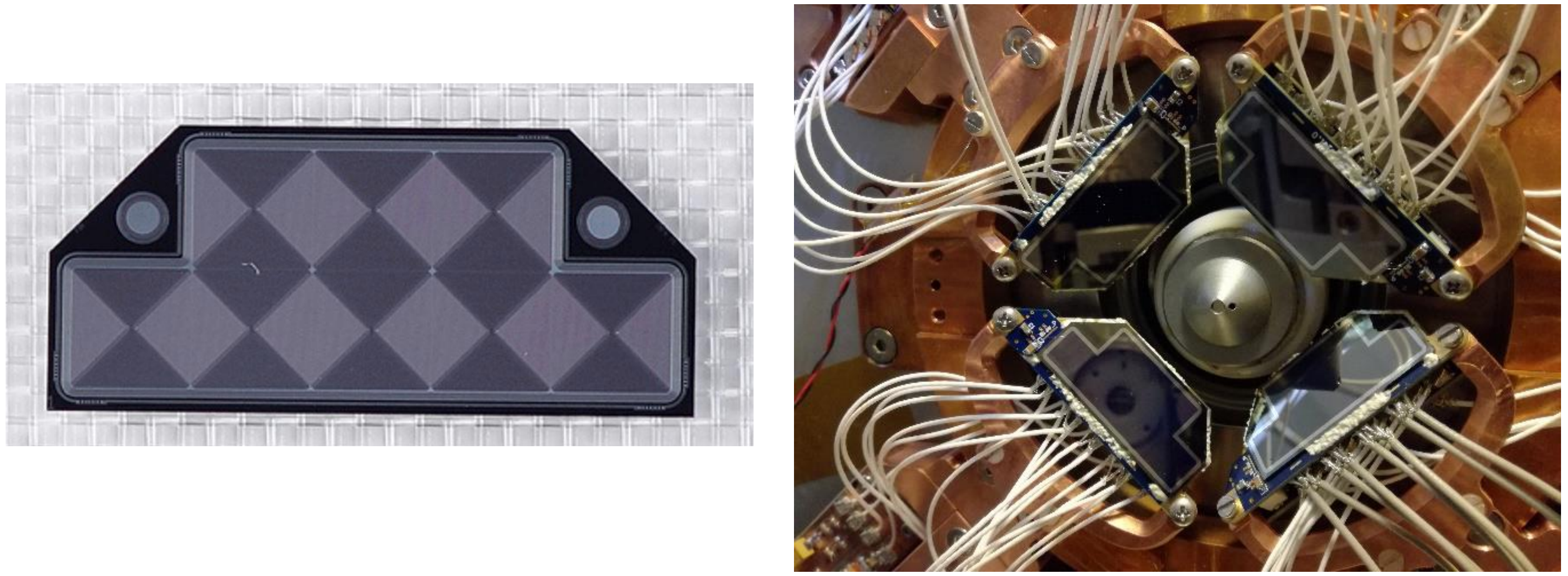
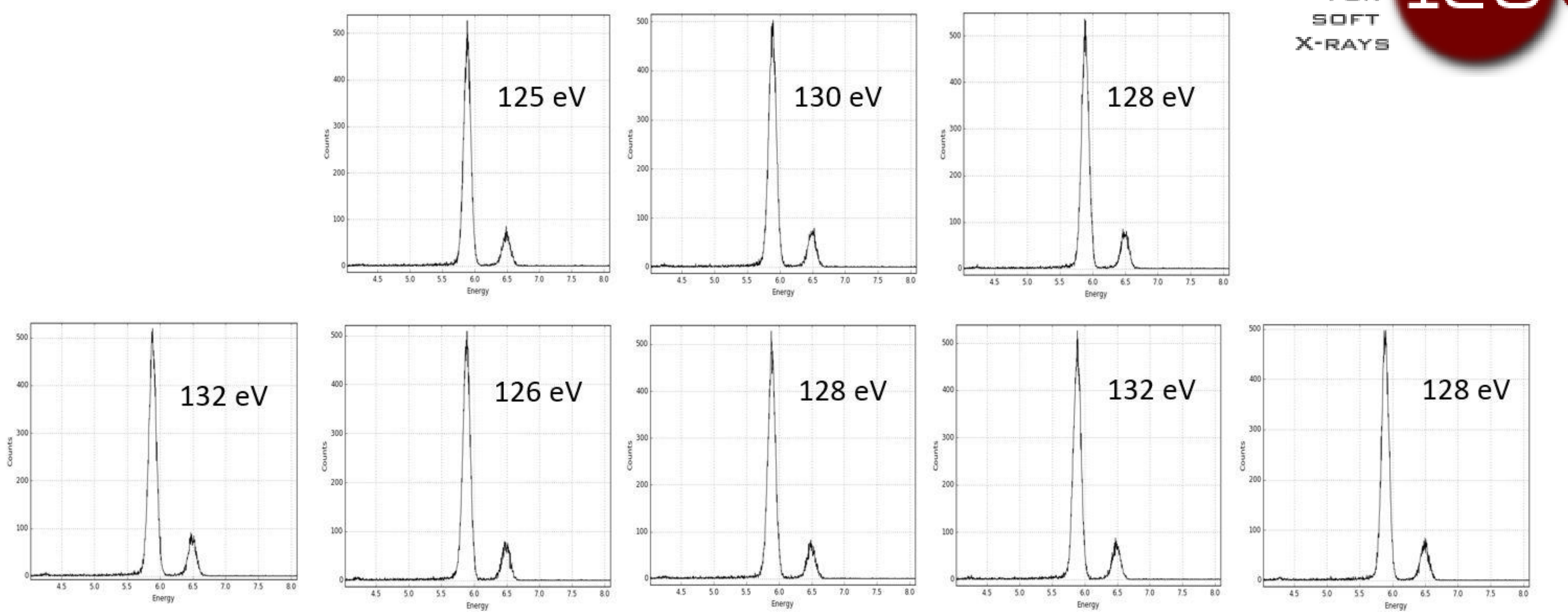
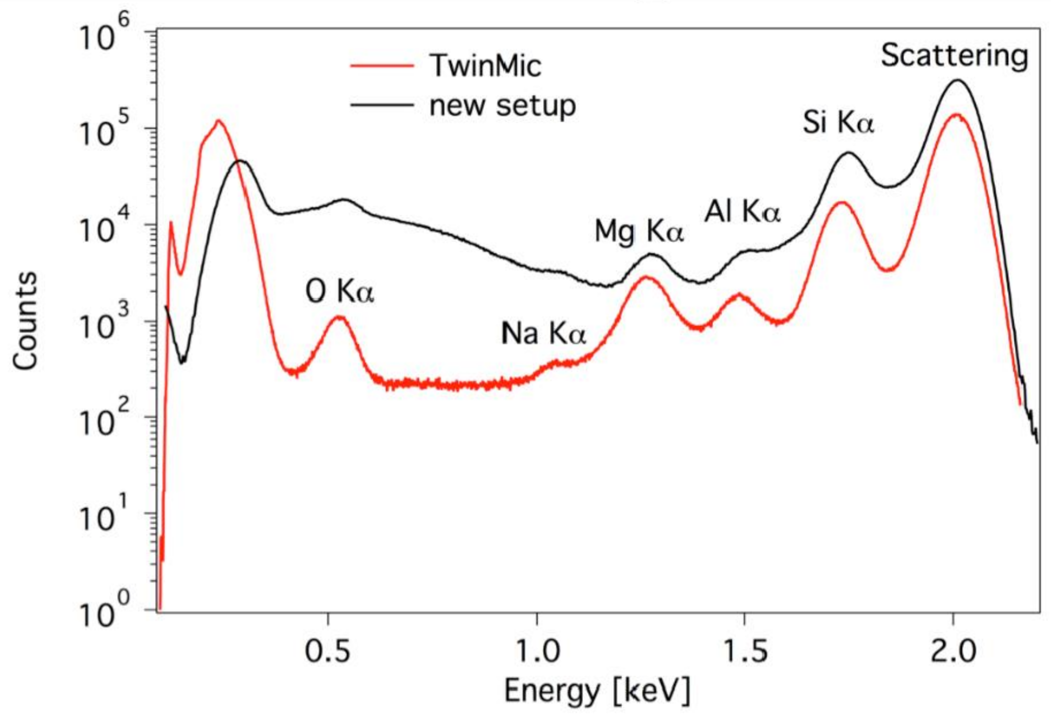


Photo of a trapezoidal monolithic SDD array (left) and of the final detector system assembled on the beamline



Energy resolution (FWHM) at 5.9 keV of an average trapezoidal SDD taken at -20° C with a peaking time of 4 µs



Sum spectra of the current collimated TwinMic system (TwinMic) and of a non-collimated trapezoid (new setup)

Silicon Drift Detectors (SDDs)
The ARDESIA Project (INFN – PoliMi)

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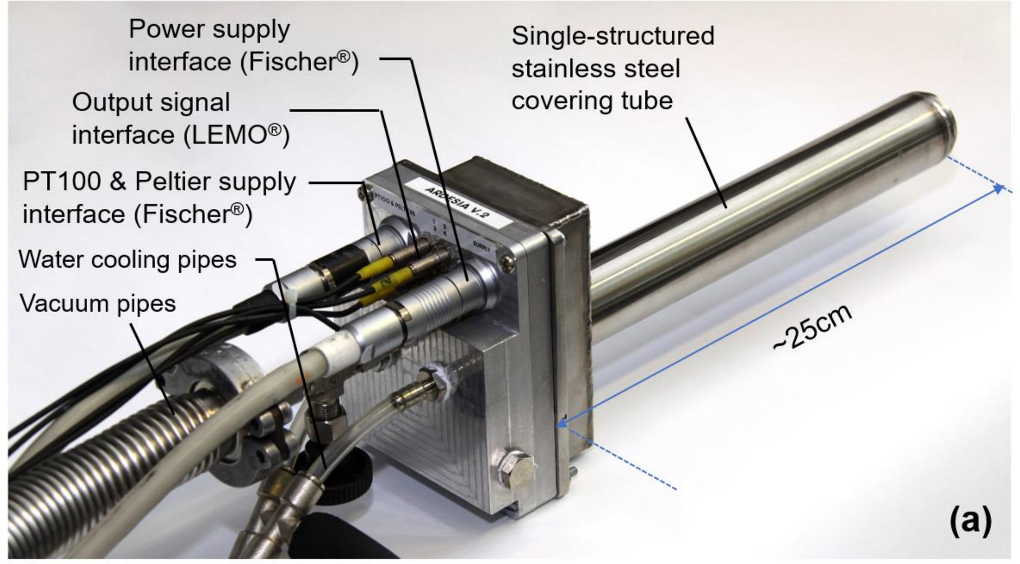
ARDESIA – ARray of DEtectors for Synchrotron radIation Applications [3,4,5,6]

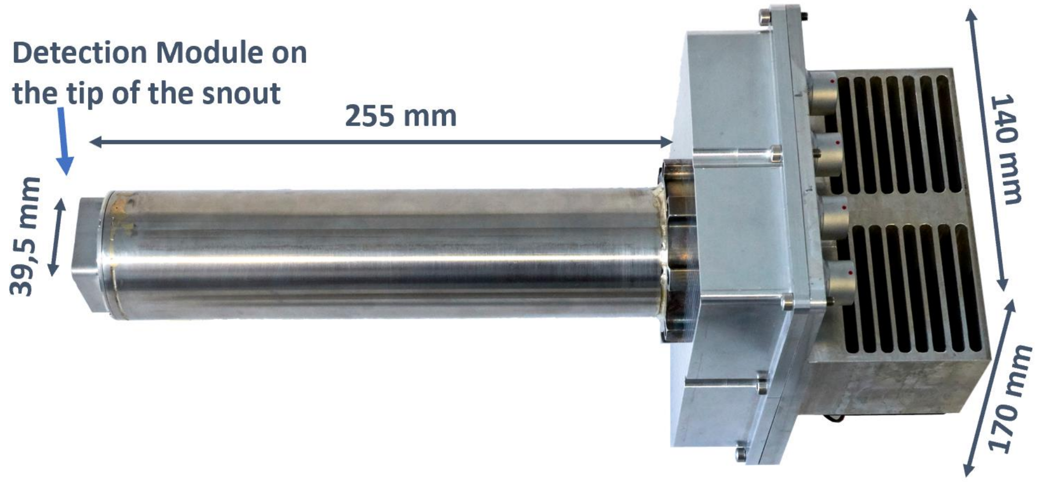
- Develop new spectrometer for high-brilliance synchrotron light sources:
    - Applications: XNP, XAFS, XRF, XAS, …
    - High count rate capability (> 1 MCps per channel)
    - High energy resolution (< 150 eV for T_{peak} < 200 ns)
    - High sensitivity for high-energy X-rays (up to 30 keV)

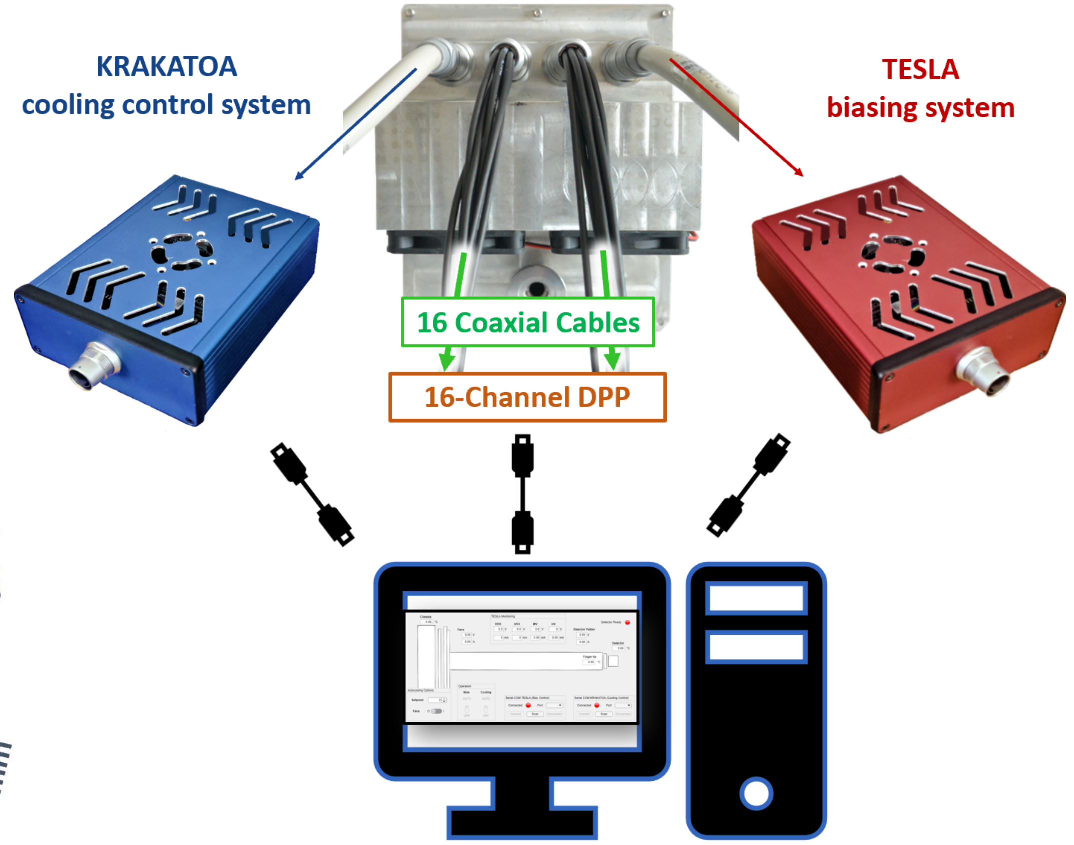
- Approach:
    - Develop compact and portable module
    - Develop multi-channel SDD arrays (4 and 16 elements, 5 mm pitch)
    - Develop thick SDD sensors (1 mm)
    - Develop small pitch SDD arrays (2 mm)



First version of ARDESIA module (4 element SDD array) with integrated power, cooling and vacuum system

Second version of ARDESIA module (16 element SDD array) and schematic configuration of the control and readout system





Silicon Drift Detectors (SDDs)
The ARDESIA Project (INFN – PoliMi)

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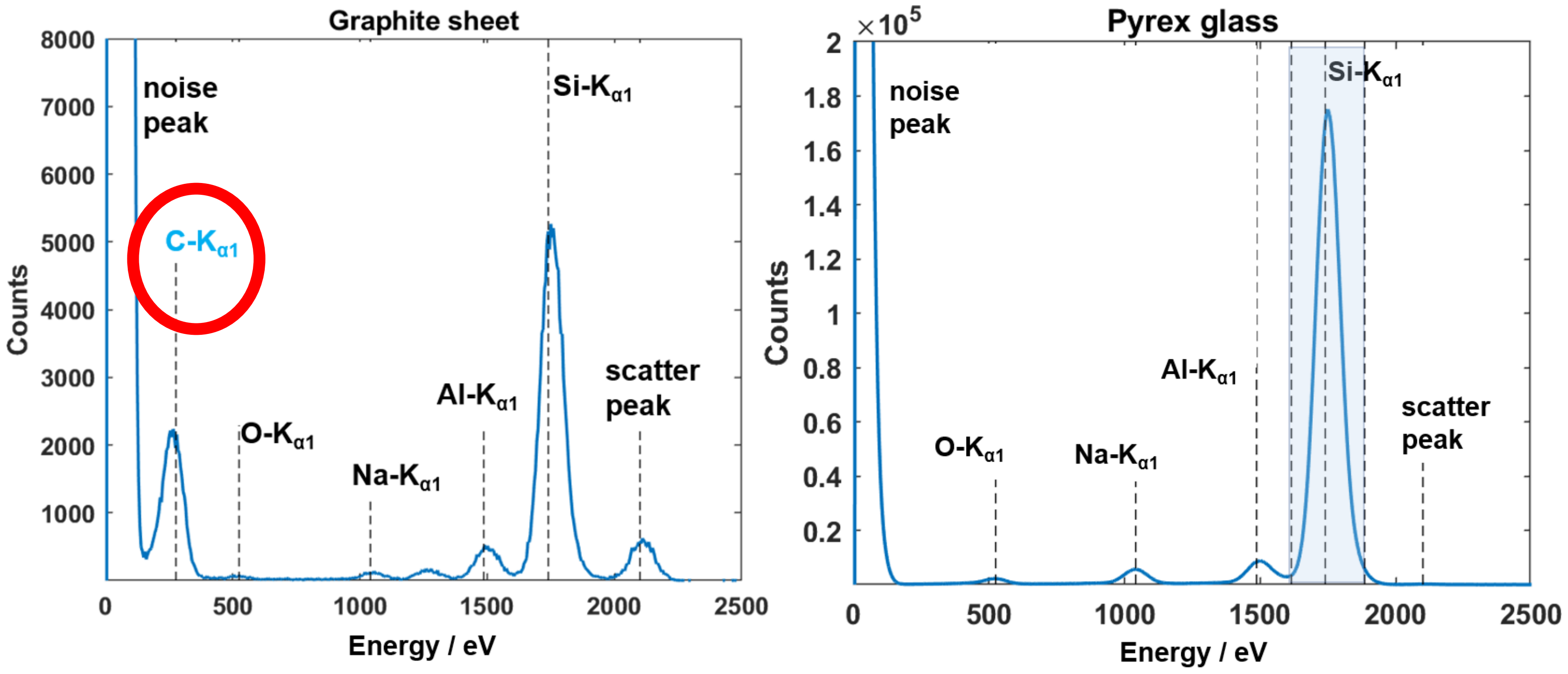
Low-energy X-ray detection [3]

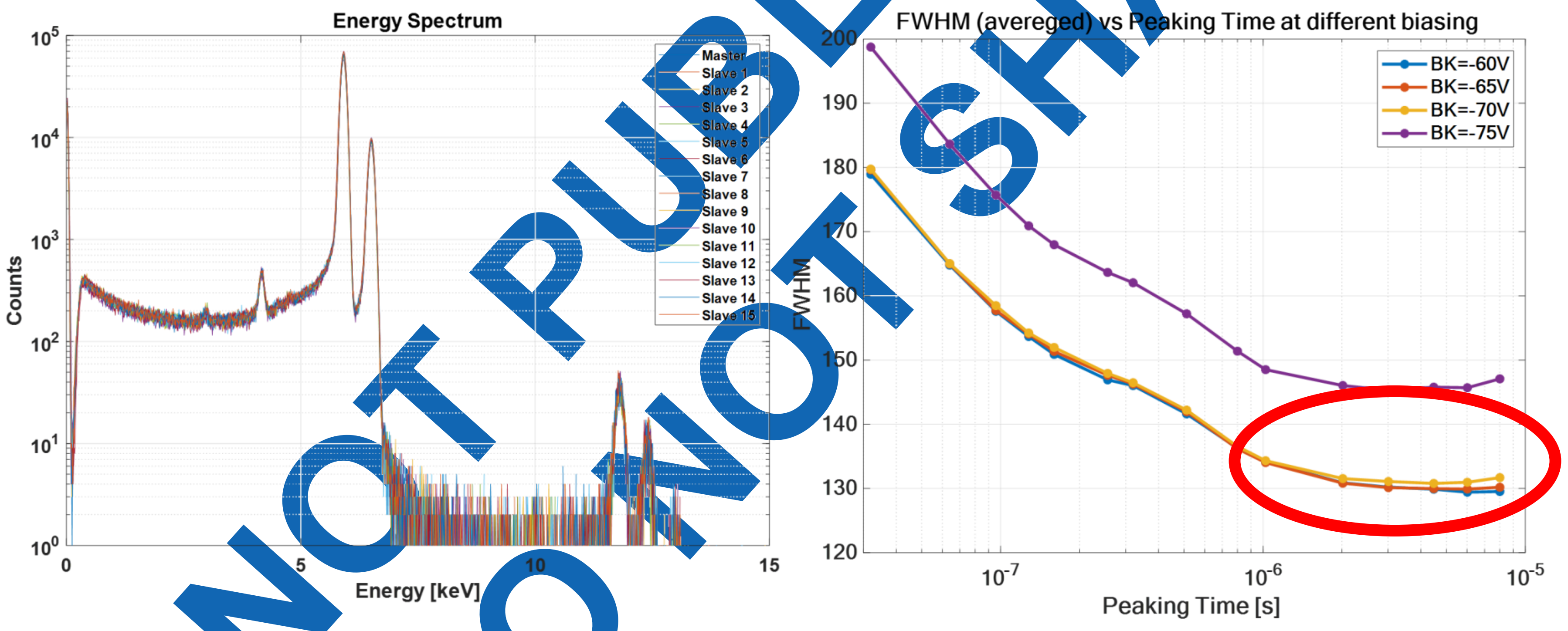
- XRF measurement at LNF DAΦNE Light DXR1 soft X-ray beamline (0.9 – 3.0 keV):
    - 2x2 SDD array (450 µm thick)
    - Room temperature, T_{peak} = 2 µs



XRF measurement results on graphite sheet (left) and Pyrex glass (right), with excitation energy = 2100 eV

Small-pitch SDD array (16 channels - 2 mm) [6]

- Lab characterization using ^{55}Fe source:
    - PTB ≈ 250
    - Detector cooled at T ≈ -20°C
    - I_{leak} (-20°C) = 100 – 270 fA
    - I_{leak} (26°C) = 20 pA

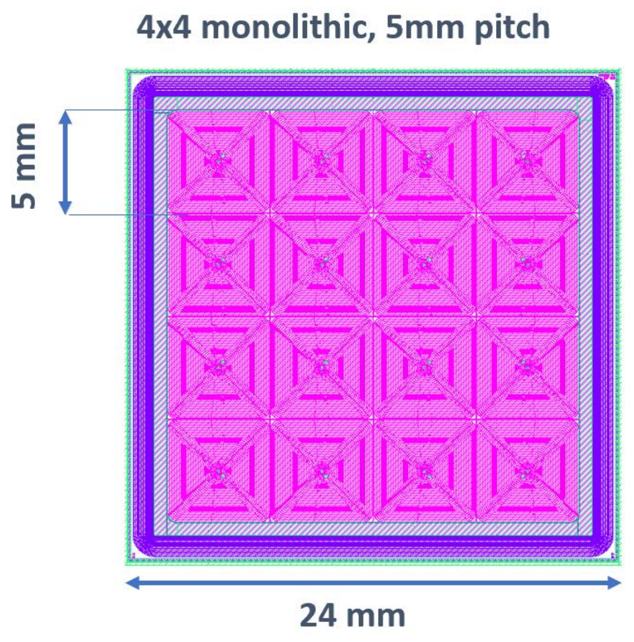


^{55}Fe energy spectra (left) and energy resolution for different polarization conditions (right) for the 2-mm-pitch SDD array

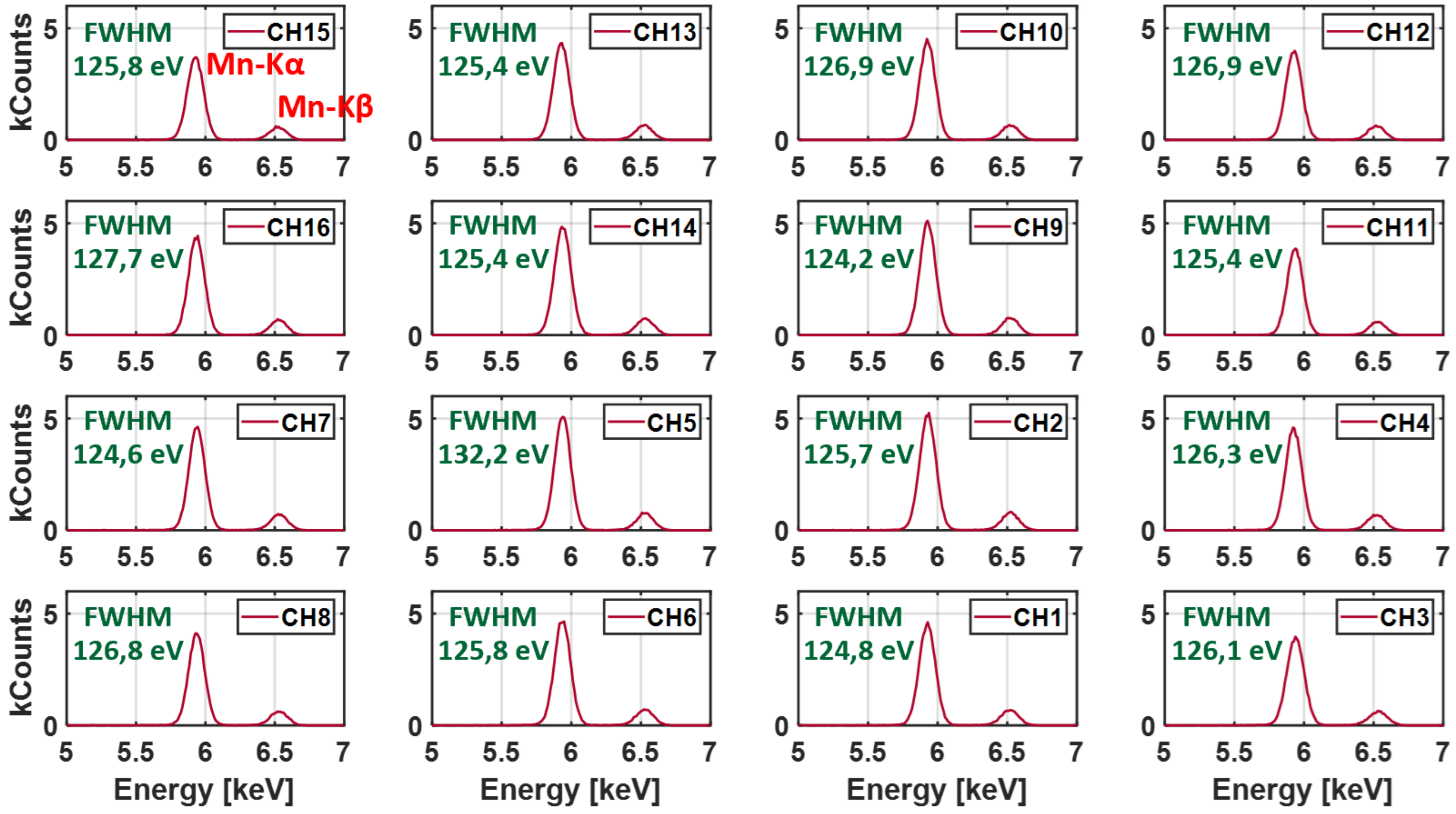
Silicon Drift Detectors (SDDs)
The ARDESIA Project (INFN – PoliMi)

ARDESIA-16 Detection module [5]

- Characterization of the 4x4 SDD array (450 um thick):
    - Energy resolution measured with ^{55}Fe source in laboratory setup
    - T = -30° C
    - Molybdenum collimator to avoid charge sharing (0.5 mm)



ARDESIA-16 Detection module: (left) design of the 4 x 4 array of square SDDs (pixel area 5 mm x 5 mm) (right) assembled detection module



Optimum energy resolution measured with a 55Fe source and a 2 µs peaking time

Silicon Drift Detectors (SDDs)
The ARDESIA Project (INFN – PoliMi)

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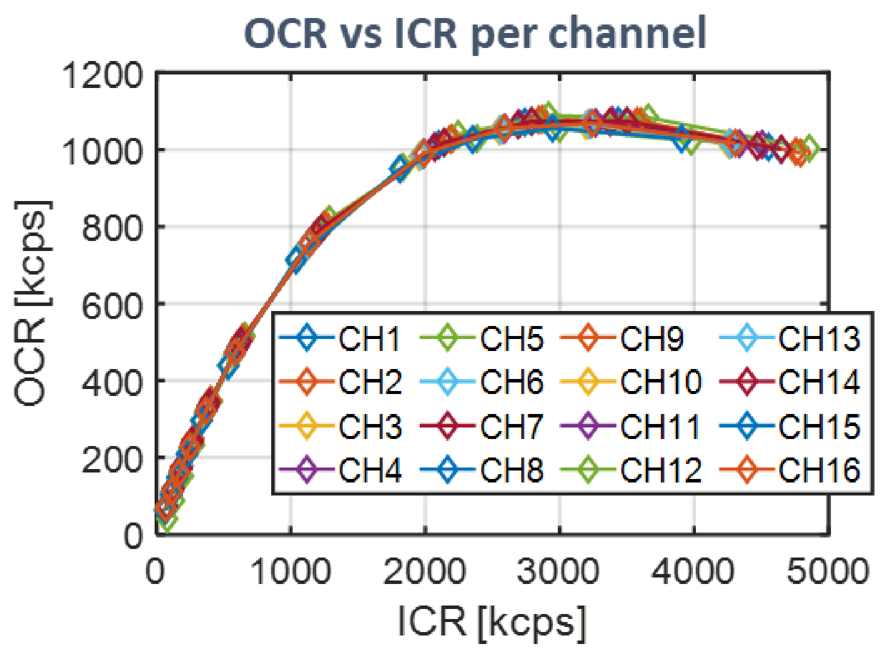
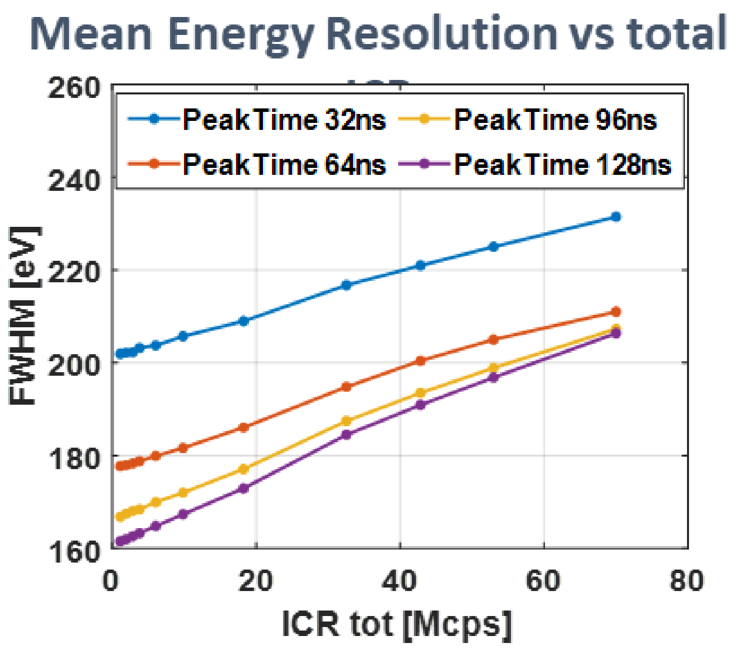
ARDESIA-16 Detection module [6]

- Characterization of the 4x4 SDD array (450 µm thick):
  - Measurements performed with synchrotron light at P06 beamline at PETRA (Hamburg)
  - T = -35° C
  - Molybdenum collimator to avoid charge sharing (0.5 mm)





Measurement carried out irradiating with synchrotron light a Mn sample and using a 16-channel Dante DPP.

Silicon Drift Detectors (SDDs)
The ARDESIA Project (INFN – PoliMi)

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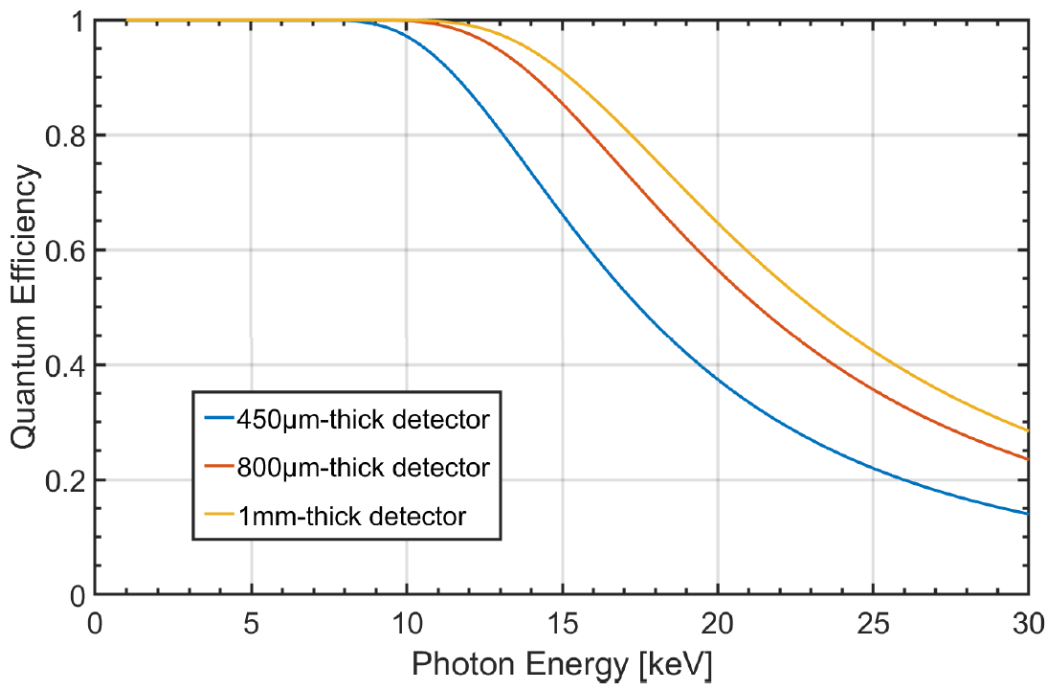
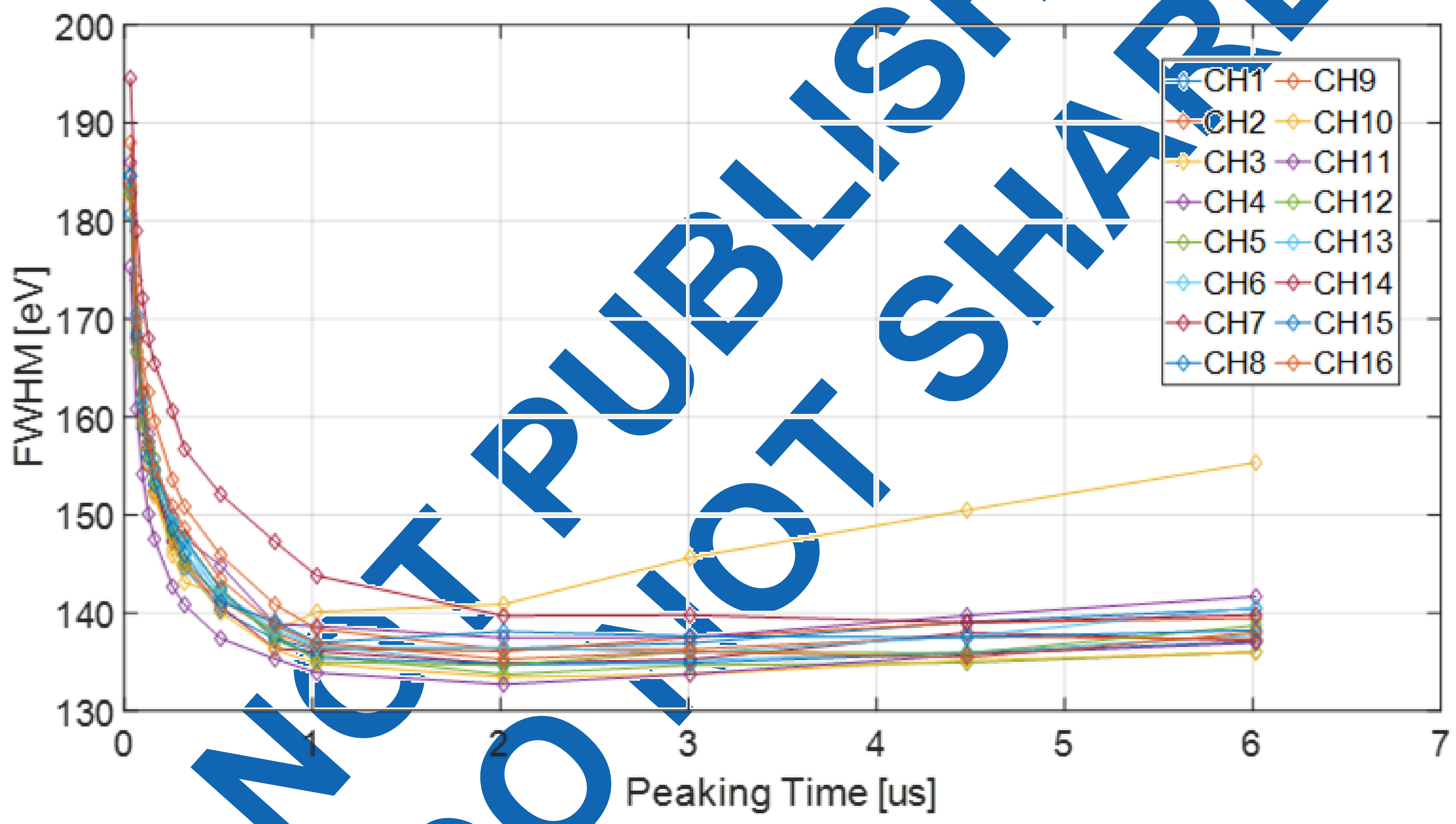
ARDESIA-16 Detection module [6]

- Characterization of the 4x4 SDD array (1000 µm thick):
  - Energy resolution measured with ^{55}Fe source in laboratory setup
  - T = -30° C
  - Molybdenum collimator to avoid charge sharing (0.5 mm)



Calculated quantum efficiency (QE) of a 450 µm, 800 µm and 1000 µm thick SDD

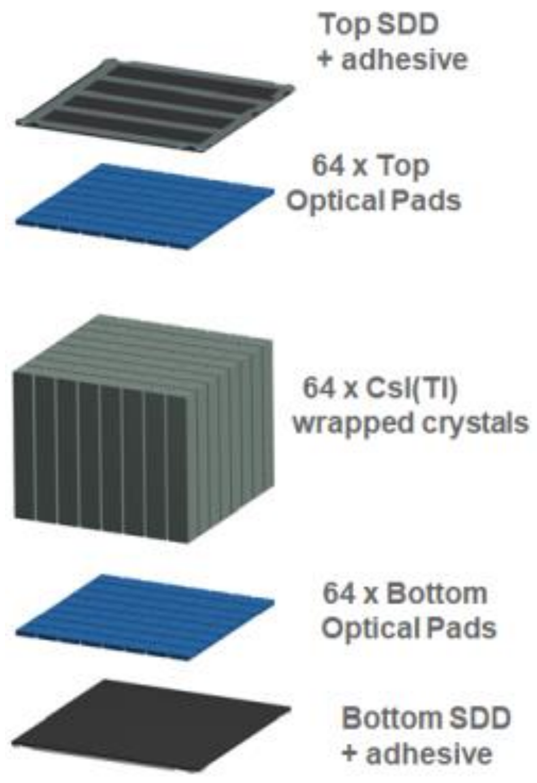


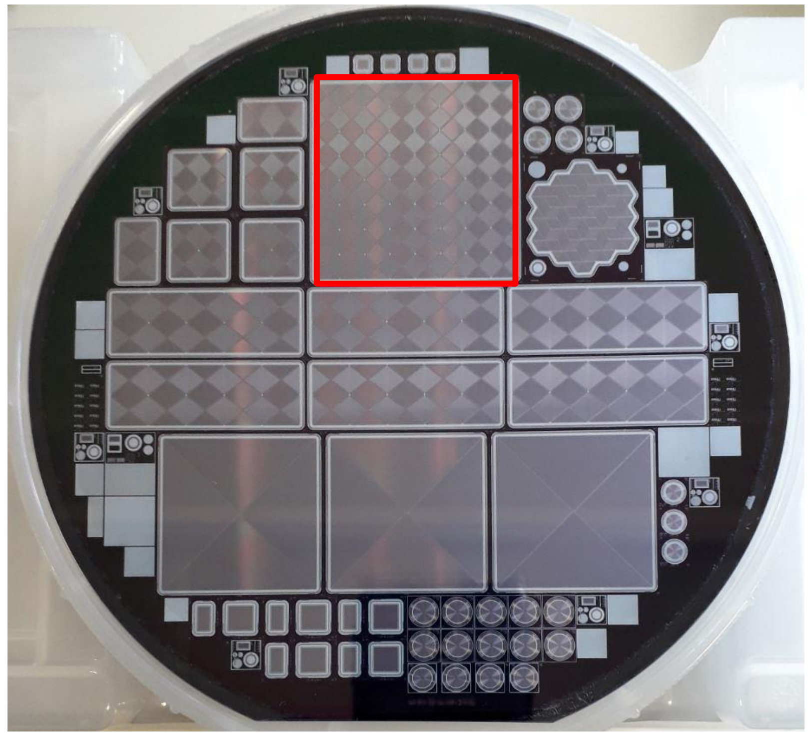
Energy resolution as a function of the peaking time for all the channels of the 4 x 4 array (1000 µm thick)

Silicon Drift Detectors (SDDs)
SDDs for Space Application I – THESEUS / HERMES / eXTP

SDDs for Combined X- and Gamma-ray Detectors

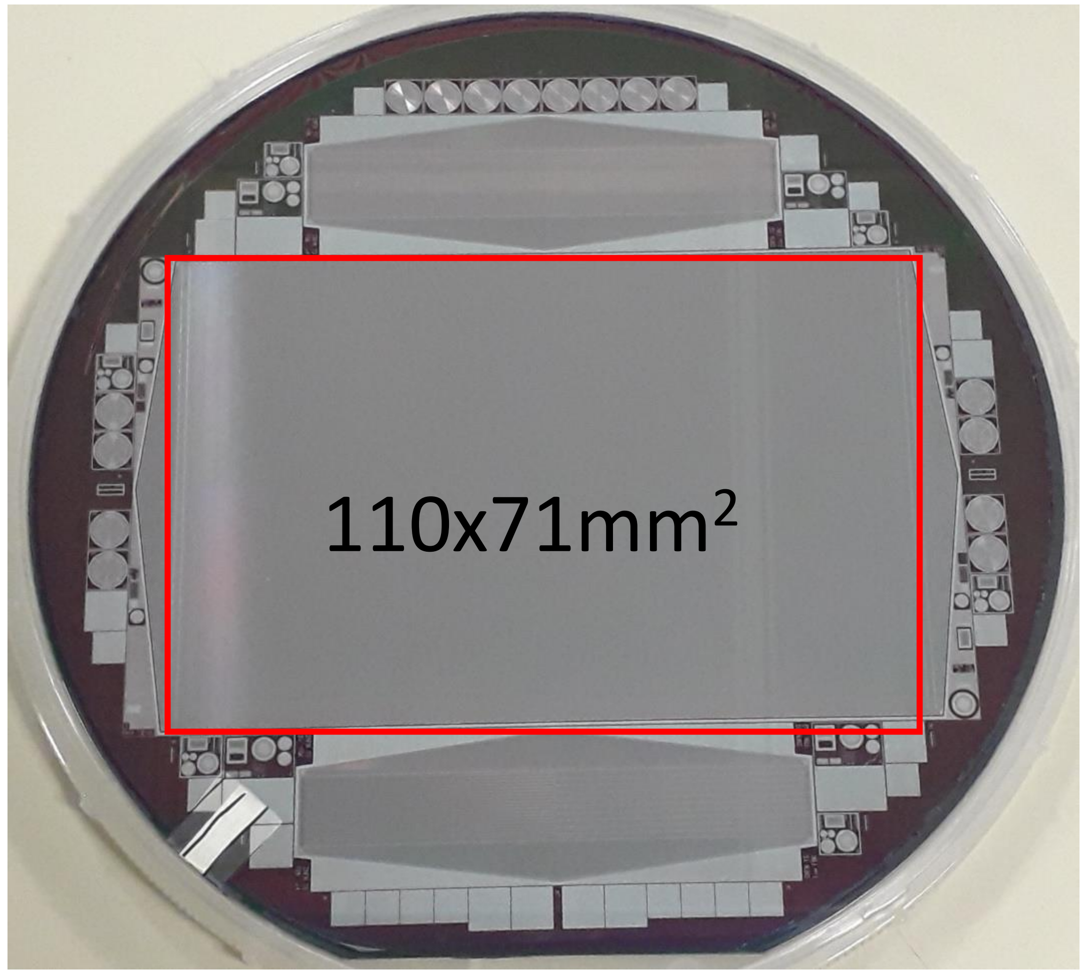
- SDD used as:
    - Photosensor for CsI (Gamma rays up to few MeV)
    - Direct detectors for X-rays (3-20 keV)
- HERMES: constellation of CUBESAT satellites (ASI) [7,8]
- THESEUS: European collaboration to develop an instrument for a M5 ESA mission (phase A) (European project) [9,10]





Large area SDDs for X-ray astronomy

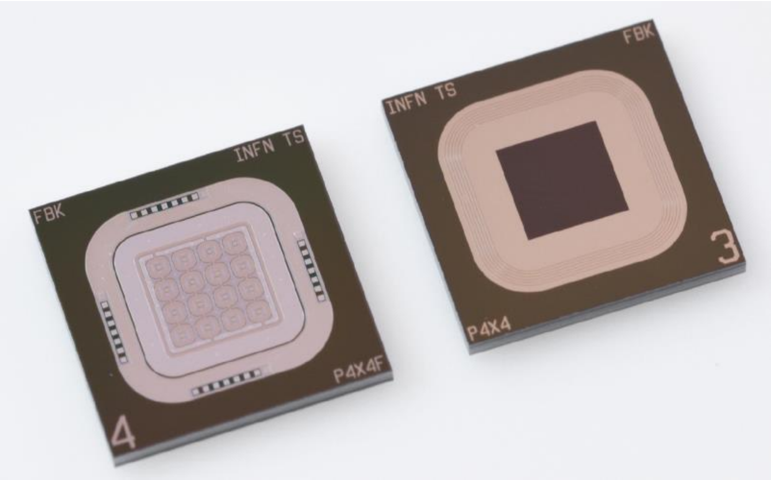
- On development for a Chinese mission (eXTP) [11]:
    - Widest SDD ever produced
    - Simultaneous X-ray spectroscopy and imaging
- Currently optimizing the process to obtain low-leakage devices
- Project financed by ASI

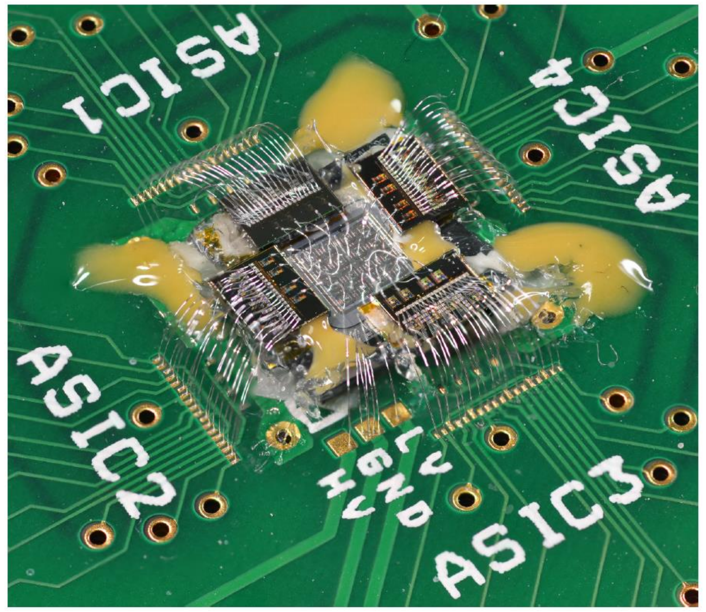


Silicon Drift Detectors (SDDs)
SDDs for Space Application II – PixDD and ADAM

ADAM

- Project financed by ASI
- Final goal: develop an X-ray spectroscopic imager with 300 µm pixels (16 × 16 pixels)
- Hybrid detector (sensor + ASIC) based on SDD technology
- New technology to reduce border regions under development (based on slim-edge technology)





The first PixDD detector prototype (4×4 mini-SDD array, 500 µm pitch) [12,13]

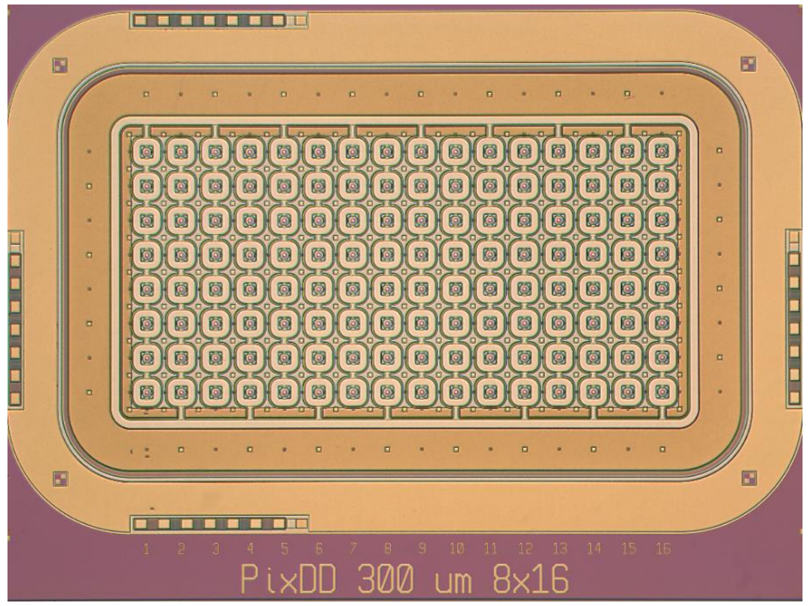
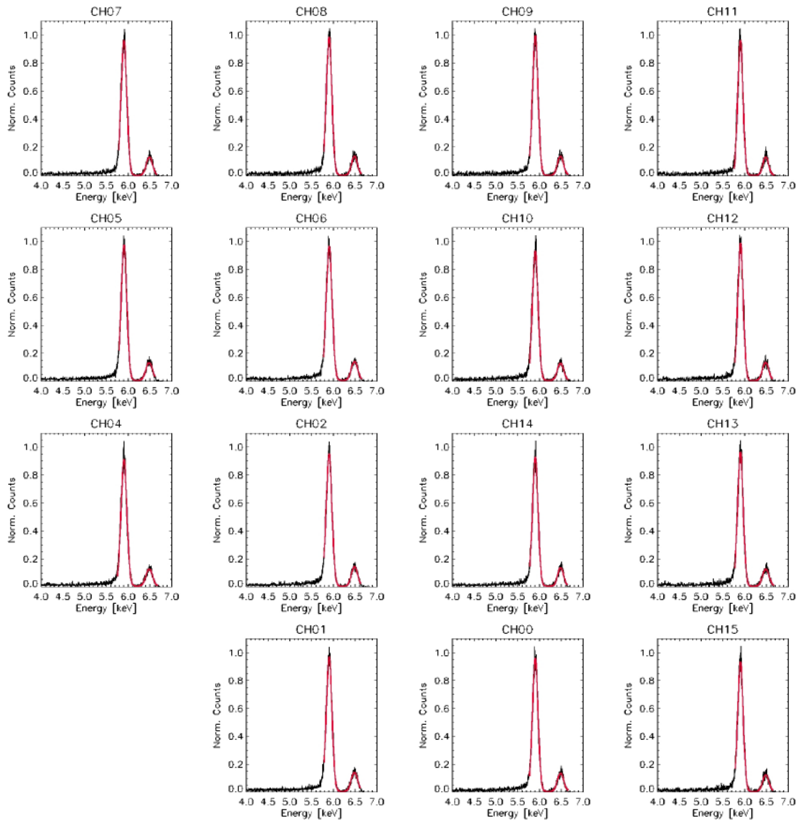


Photo of a PixDD sensor composed of 8×16 mini-SDDs (300 µm pitch)

^{55}Fe energy spectra acquired with 1 µs peaking time

Energy resolution < 150 eV [12,13]



Silicon Drift Detectors (SDDs)
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[1] A. Rachevski et al., "The XAFS fluorescence detector system based on 64 silicon drift detectors for the SESAME synchrotron light source," Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 936, pp. 719–721, Aug. 2019.

[2] J. Bufon et al., "A new large solid angle multi-element silicon drift detector system for low energy X-ray fluorescence spectroscopy," J. Instrum., vol. 13, no. 03, pp. C03032–C03032, Mar. 2018.

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[4] G. Utica et al., "Towards Efficiency and Count-Rate Enhancement of X-ray ARDESIA Spectrometer," in 2019 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2019, pp. 1–4.

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[6] C. Fiorini, G. Utica (Private communications)

[7] F. Fuschino et al., "An innovative architecture for wide band transient monitor on board HERMES nano-satellite constellations," in Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, 2020, vol. 11444, p. 167.

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Silicon Drift Detectors (SDDs)
References

[9] F. Fuschino et al., “The XGIS instrument on-board THESEUS: the detection plane and on-board electronics,” in Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, 2020, vol. 11444, p. 277.

[10] C. Labanti et al., “The X/Gamma-ray Imaging Spectrometer (XGIS) on-board THESEUS: design, main characteristics, and concept of operation,” in Space Telescopes and Instrumentation 2020: Ultraviolet to Gamma Ray, 2020, vol. 11444, p. 303.

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[13] M. Sammartini et al., “Pixel Drift Detector (PixDD) – SIRIO: an X-ray spectroscopic system with high energy resolution at room temperature,” Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol. 953, p. 163114, Feb. 2020.

LGADs

Low Gain Avalanche Diode (LGAD) Detectors
The Problem of 4D Tracking in High-Energy Physics

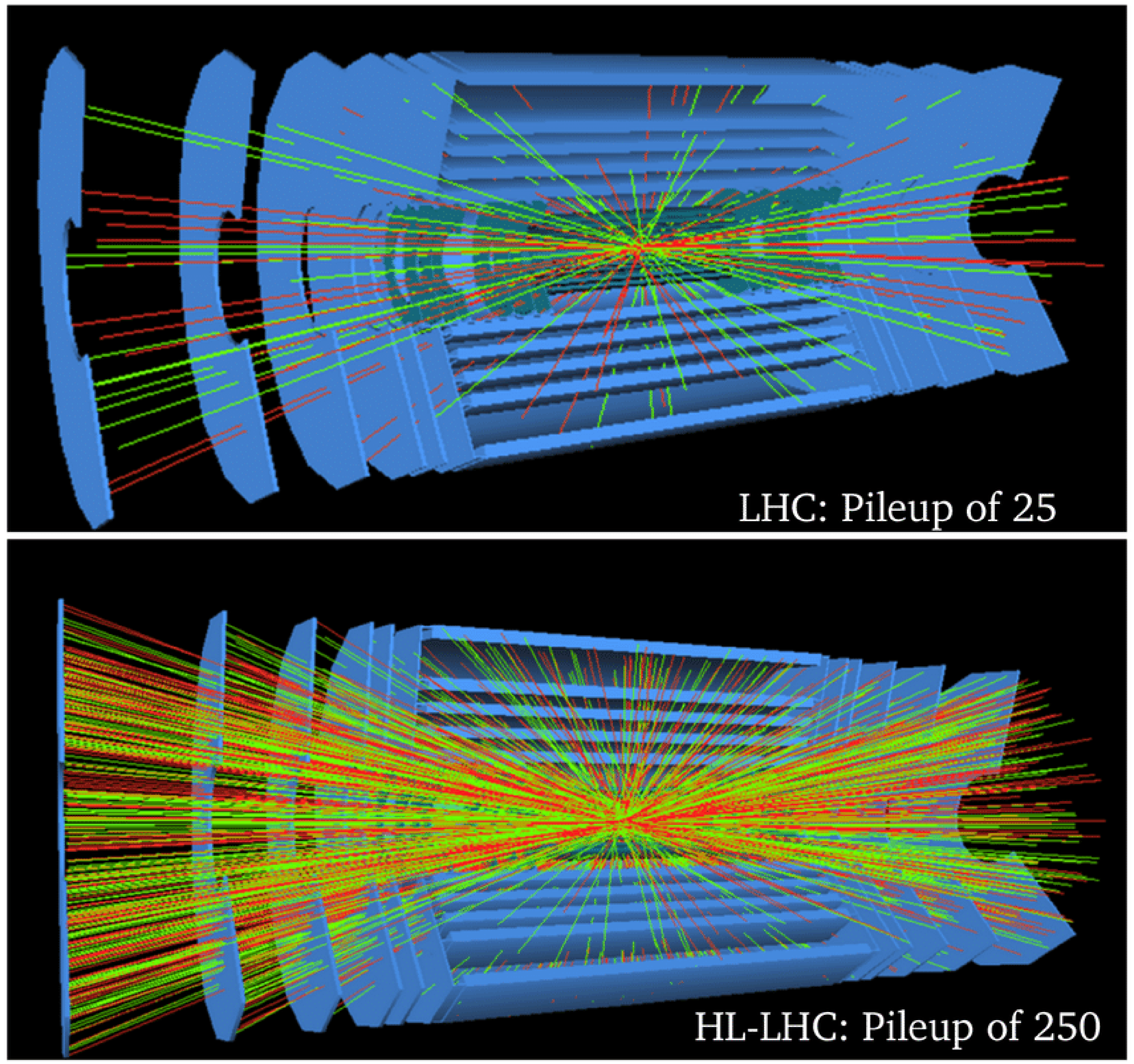


Image from: "Development and evaluation of novel, large area, radiation hard silicon microstrip sensors for the ATLAS ITK experiment at the HL-LHC" Hunter, R.F.H.. (2017)

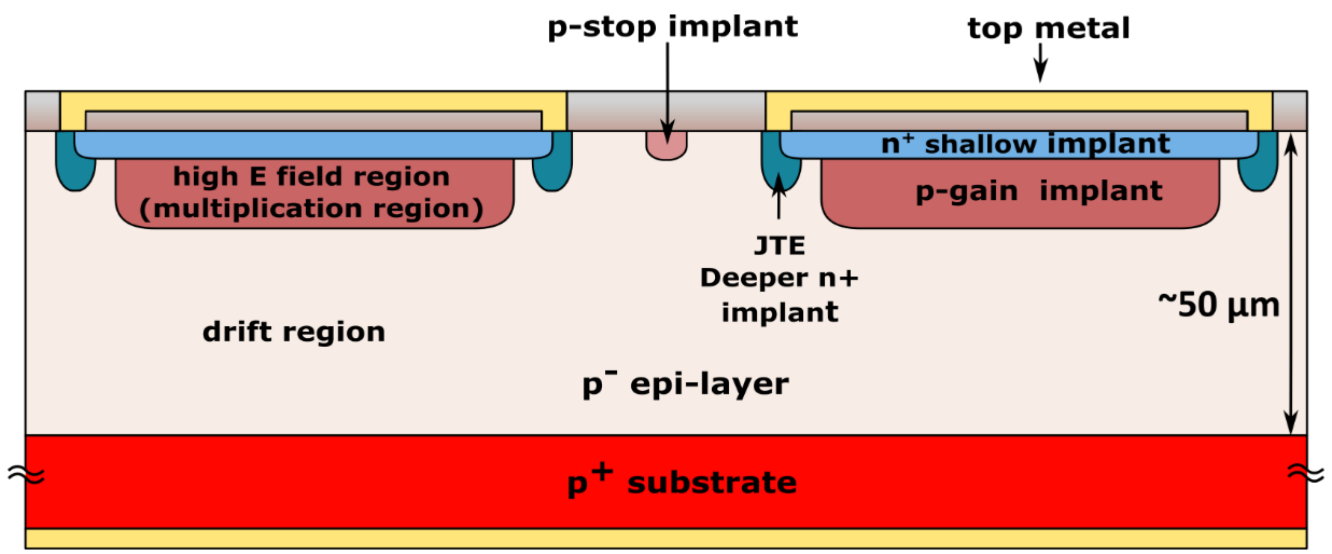
Particle tracking in HEP experiments

- High Luminosity LHC (HL-LHC, operational in 2025) [1,2]:
  - Luminosity: ×5 compared to LHC → 150-200 events per bunch crossing
  - Timing and spatial resolution of standard silicon tracking sensors not sufficient: *10-15% of vertexes composed of 2 events*

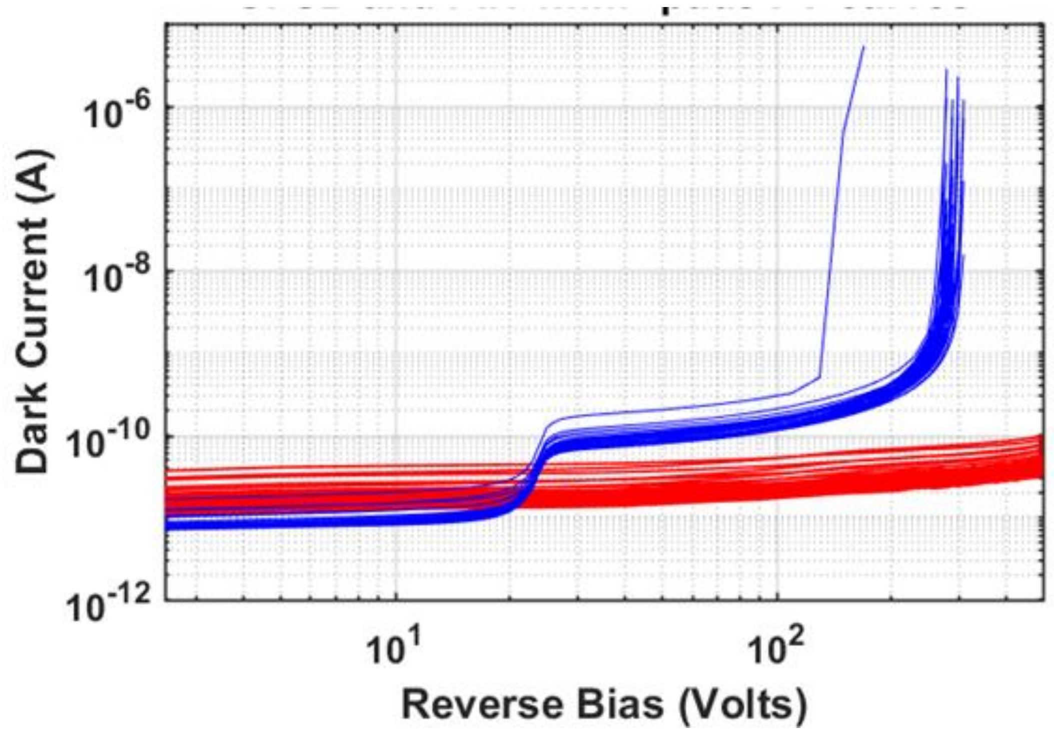
- Requirements for silicon timing detectors in HL-LHC:
  - Timing resolution: *30 ps (rms)*
  - Low spatial granularity: ~1 mm (timing information assigned to the track)
  - High radiation hardness: $> 1 \cdot 10^{15}\ n_{eq} \cdot cm^{-2}$

- Real 4D tracking detectors required for future colliders (CLIC, FCC, etc.) [3]:
  - Timing resolution: ~10 ps (rms)
  - High spatial granularity: ~10 µm
  - High radiation hardness: $> 1 \cdot 10^{16/17}\ n_{eq} \cdot cm^{-2}$

Low Gain Avalanche Diode (LGAD) Detectors
UFSD – New Silicon Detectors for Timing Applications



Schematic cross- section of an LGAD detector



IV curves of standard PiN diodes (red) and LGAD sensors (blue)

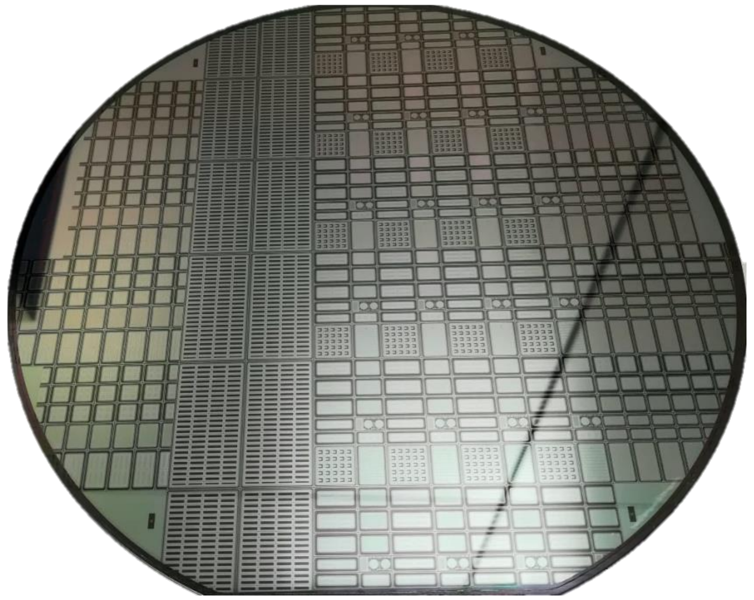
Particle tracking in HEP experiments

- Traditional silicon sensors cannot fulfill requirements:
  - Standard PiN diode sensors (pixels/microstrips): limited timing resolution (~200 ps)
  - APDs: excessive shot noise

→ Low Gain Avalanche Diode (LGAD) detectors proposed for timing applications [4]

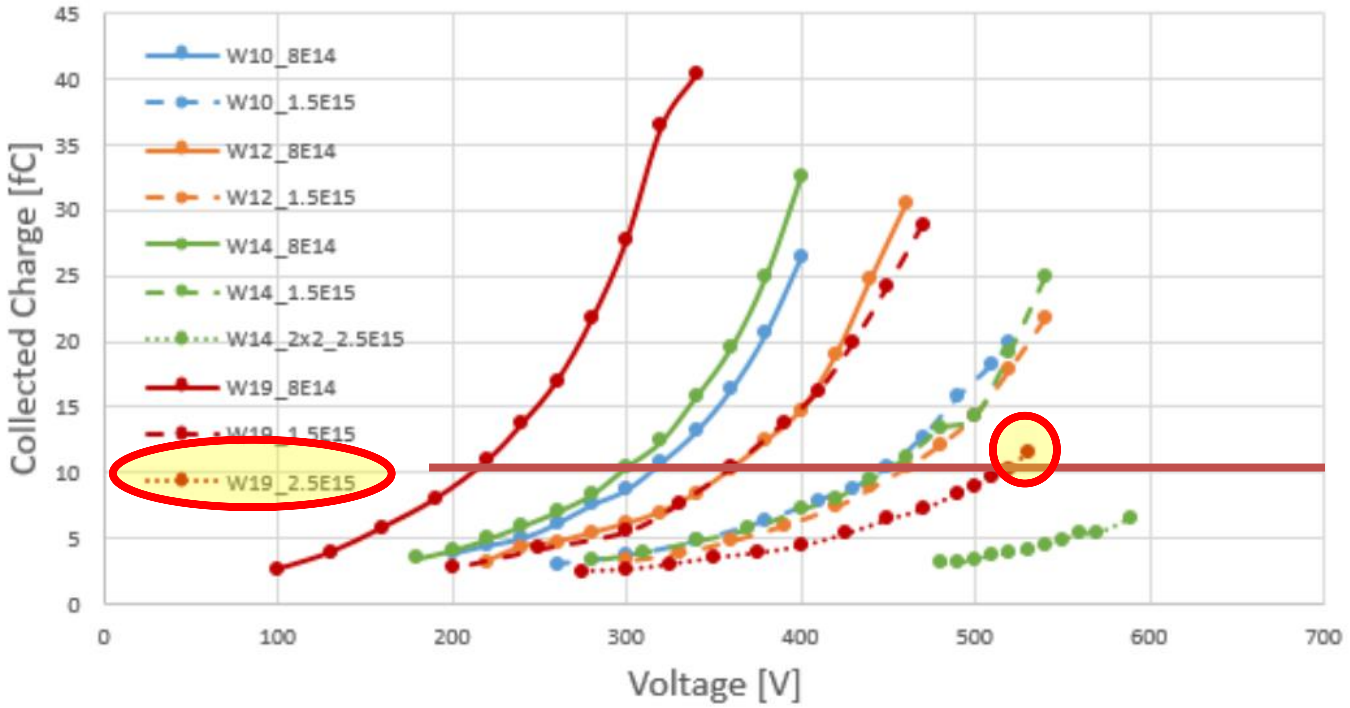
- Ultra Fast Silicon Detectors (UFSDs) are LGAD detectors optimized for timing [2]:
  - Low gain (~10) → Reduce excess noise factor
  - Reduced thickness (50 µm) → Increase slew rate of the signal
  - Uniform weighting field (large pad area) → homogeneous time response
  - Saturated drift velocity (Efield > 30 kV·cm-1) → Reduce jitter
  - Small pad volume → reduce noise after irradiation

Low Gain Avalanche Diode (LGAD) Detectors
UFSDs for ETL @ CMS and HGTD @ ATLAS

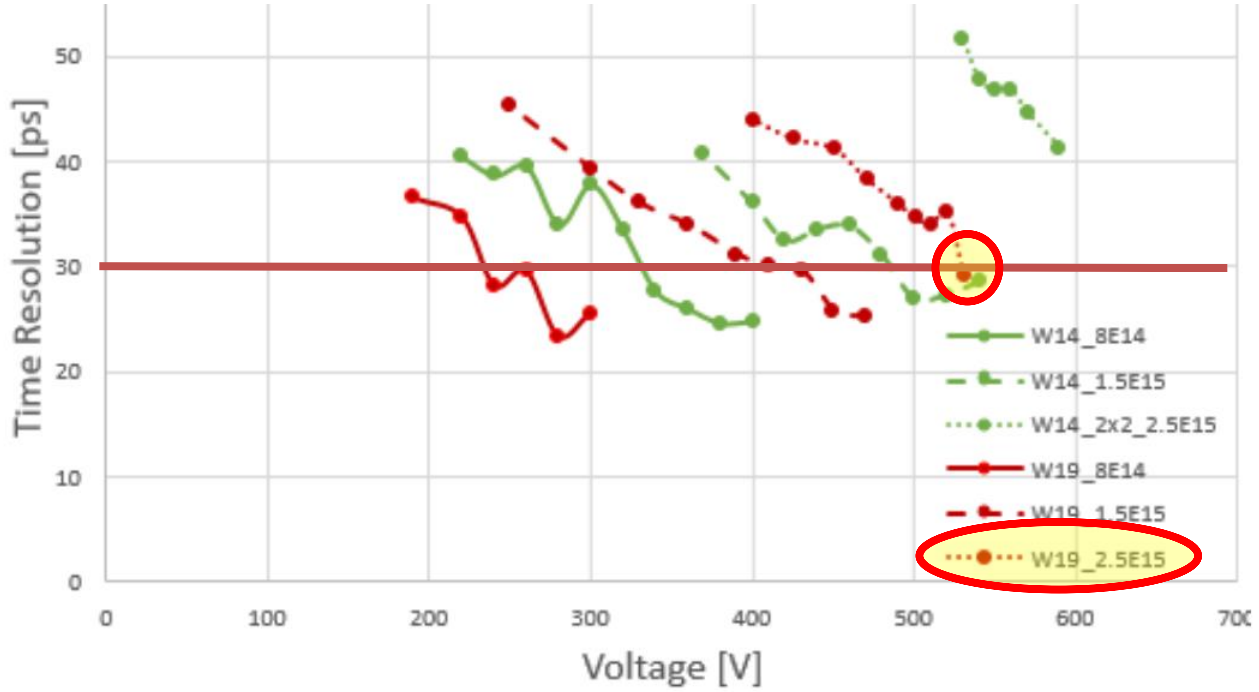


FBK developed new rad-hard technology using carbon co-implantation

- The technology meets the operational requirements up to fluences of *$2.5{\cdot}10^{15}$ $n_{eq}{\cdot}cm^{-2}$*
    - Charge generated for a MIP > 10 fC
    - Timing resolution < 30 ps (rms)
- Sensor could be used for the upgrade of:
    - Endcap Timing Layer in the CMS experiment
    - High Granularity Timing Detector in the ATLAS experiment



Collected charge as a function of the bias voltage for different processes and fluences



Time resolution as a function of the bias voltage for differer processes and fluences

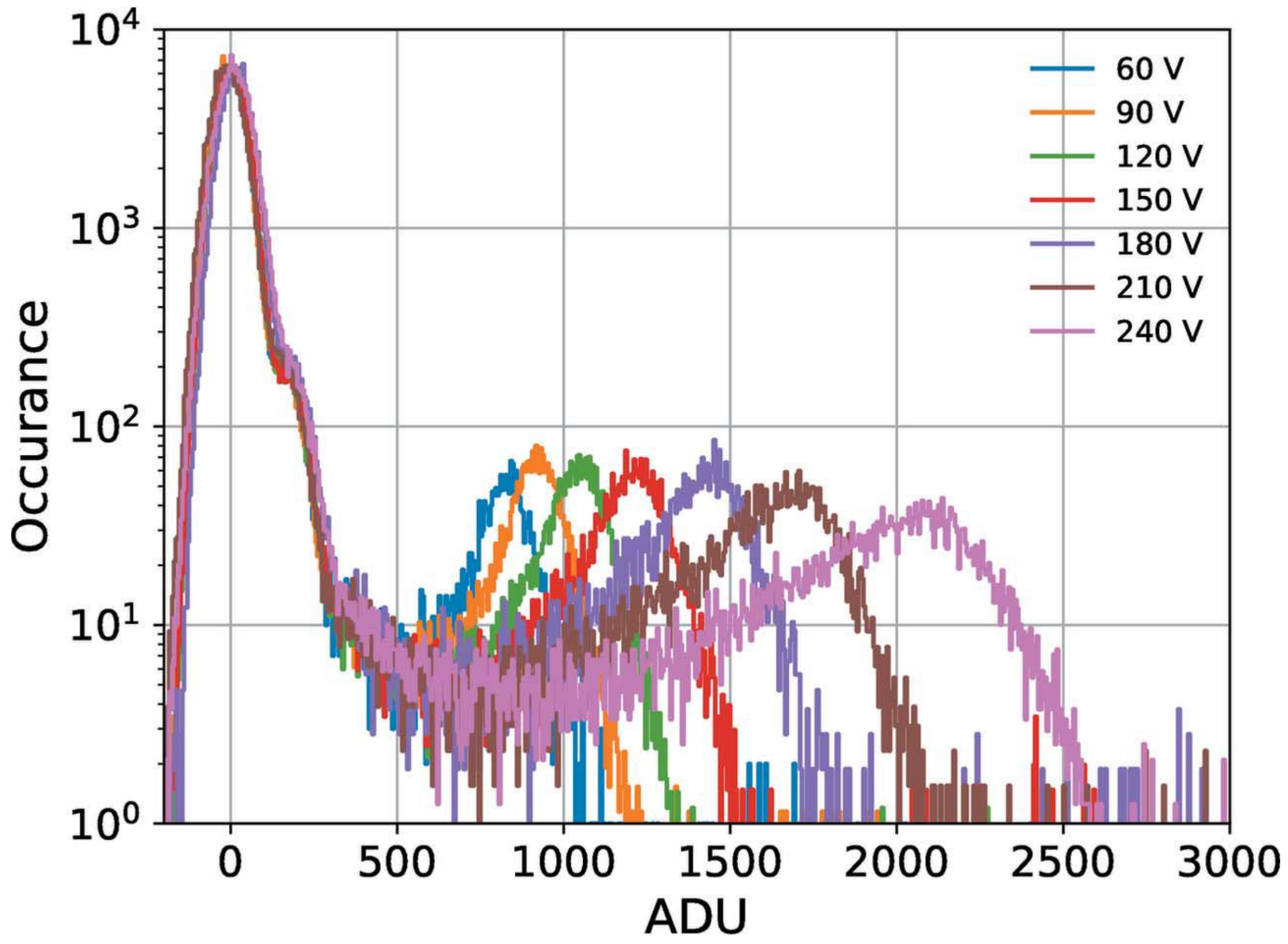
Low Gain Avalanche Diode (LGAD) Detectors
LGADs for (Soft) X-Rays in Synchrotron and FEL Experiments

LGADs are being considered for soft X-ray detection in synchrotrons and FELs

- Ongoing project between FBK and PSI to develop LGAD sensors optimized for for soft X-ray detection (250 eV – 2 keV)

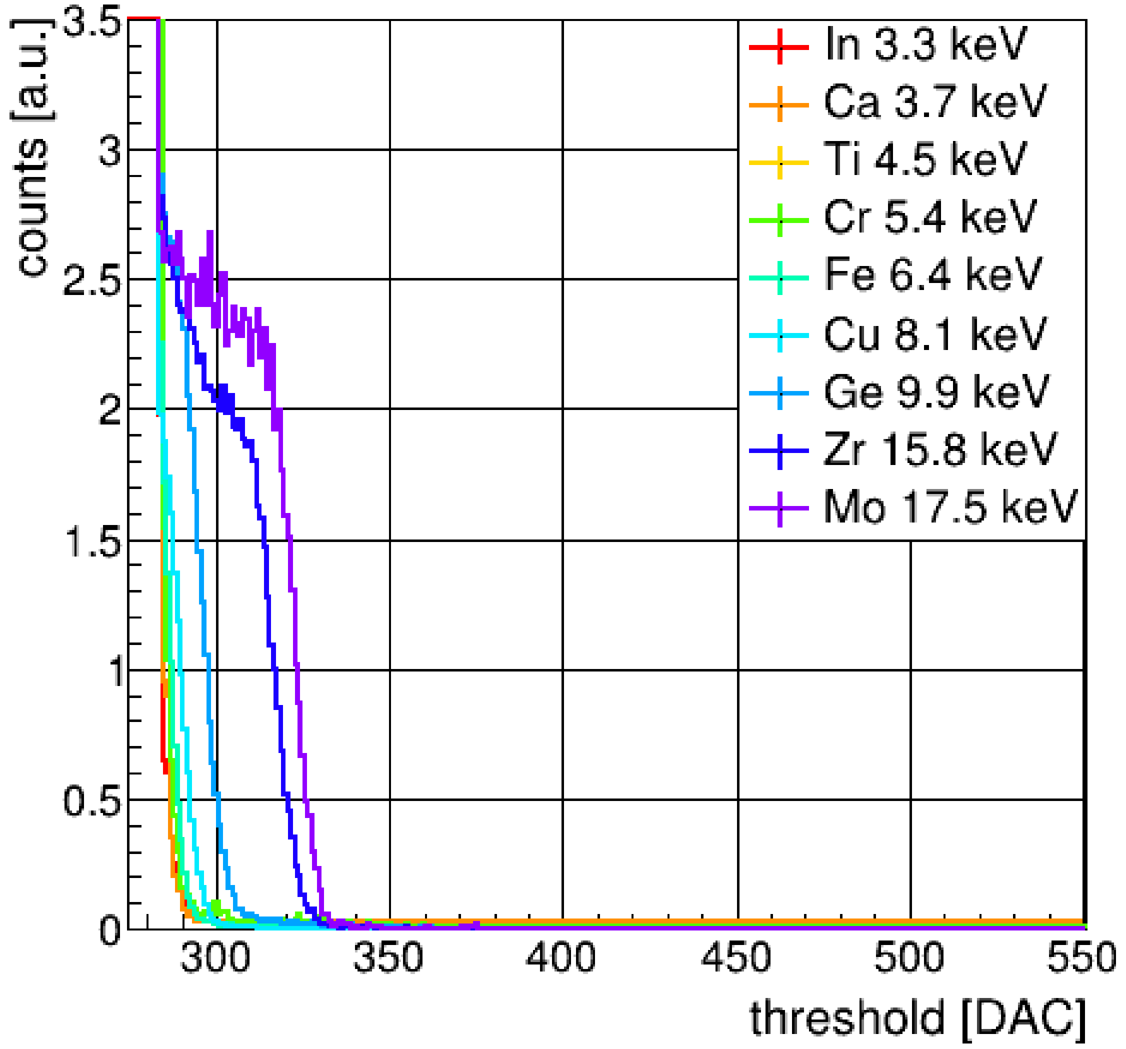
- Advantages of charge multiplication of LGADs:
  - → Lower detection limit of single photon counting detectors
  - → Improve SNR of charge-integrating detectors

- Further developments required to fully exploit LGAD technology for X-ray detection:
  - Fully depleted sensors with thin entrance window
  - New LGAD technologies with reduced dead borders (see next slides)

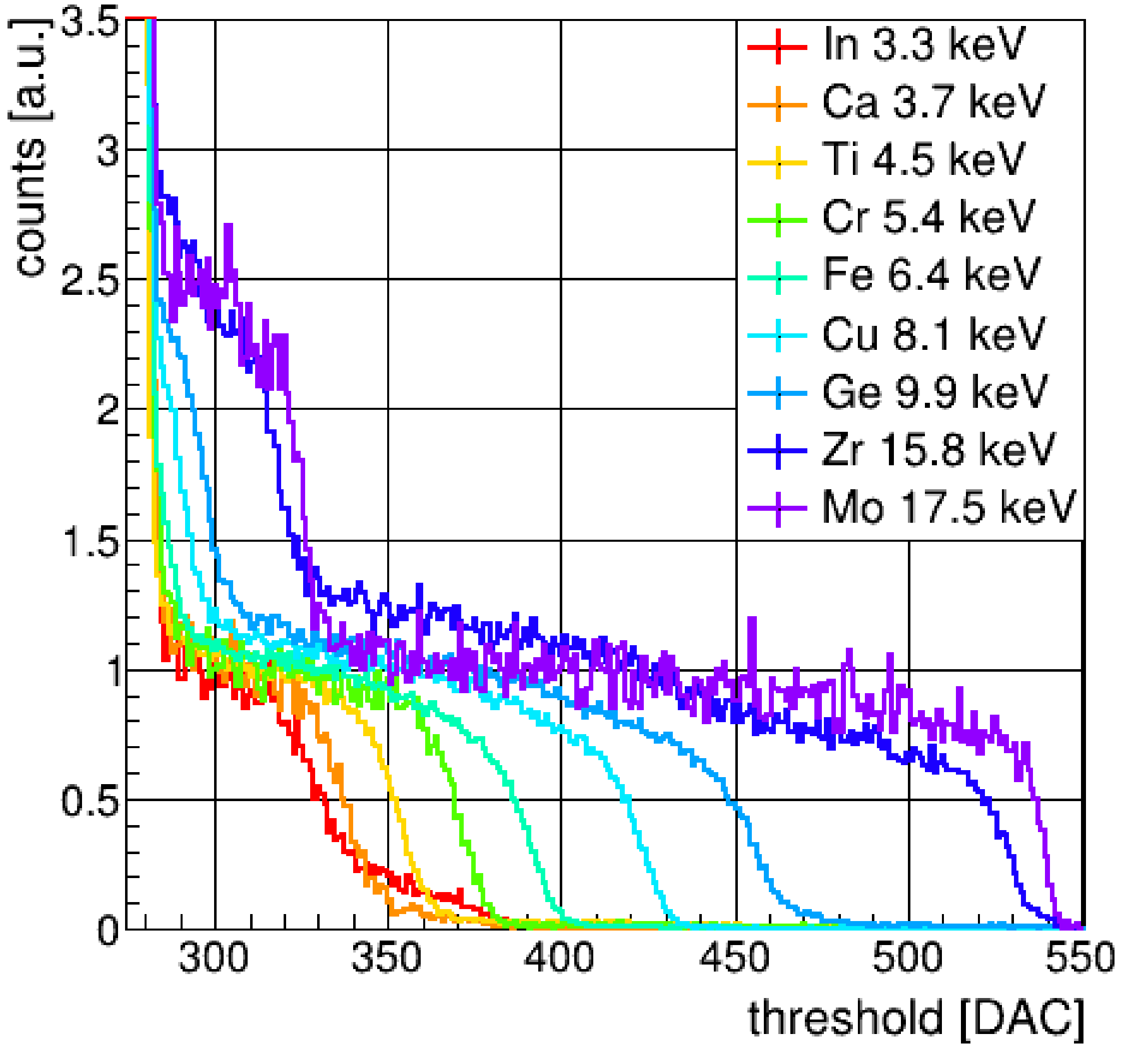


Pulse height distributions acquired at different bias voltages in response to 8.05 keV copper fluorescence radiation using an LGAD sensors and the ASIC Gotthard-1.7 [5]

Low Gain Avalanche Diode (LGAD) Detectors
LGADs for (Soft) X-Rays in Synchrotron and FEL Experiments

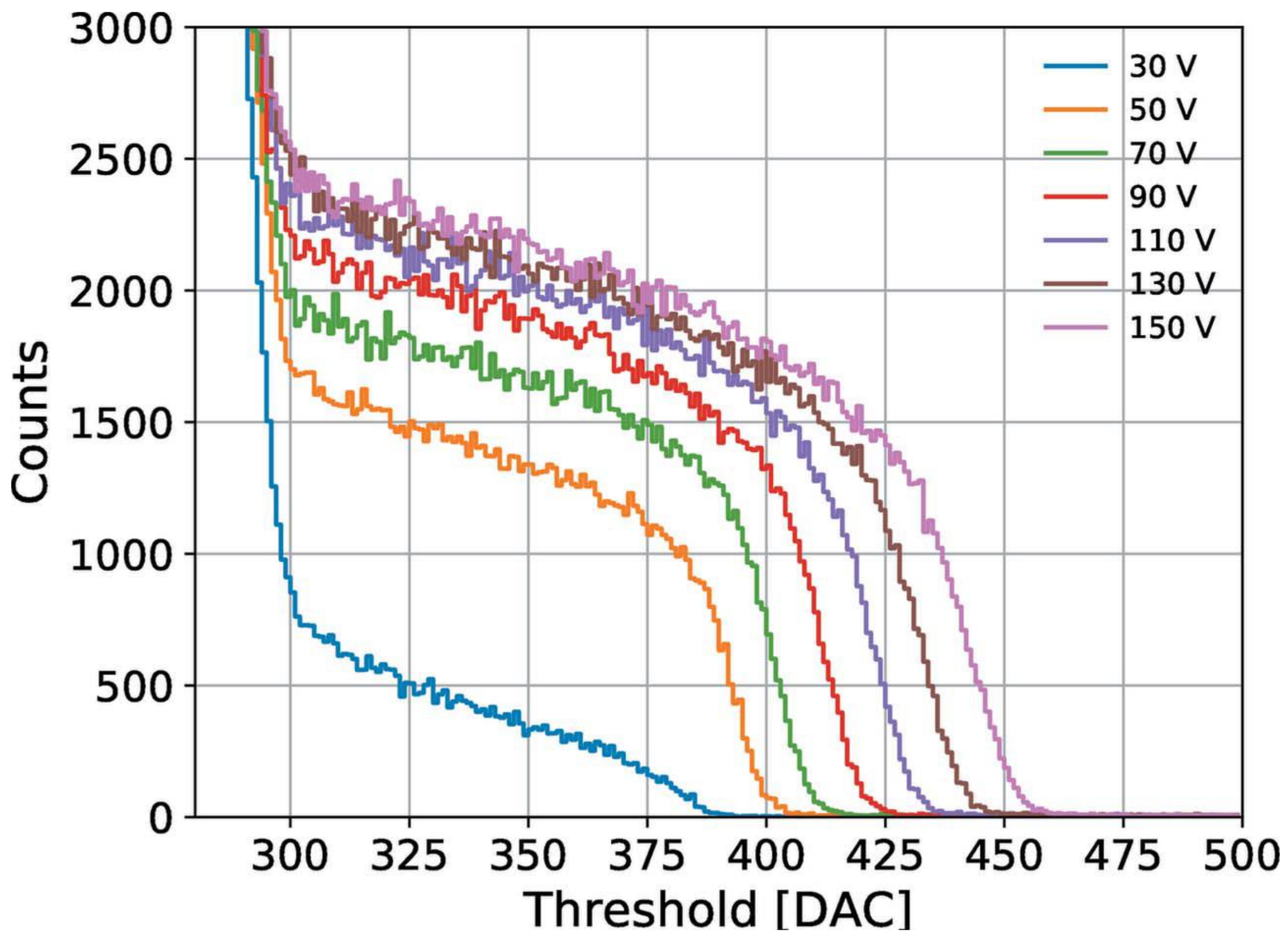


S-curves showing the energy response of a PiN microstrip sensors (at 150 V) acquired using the ASIC Mythen-II [6]

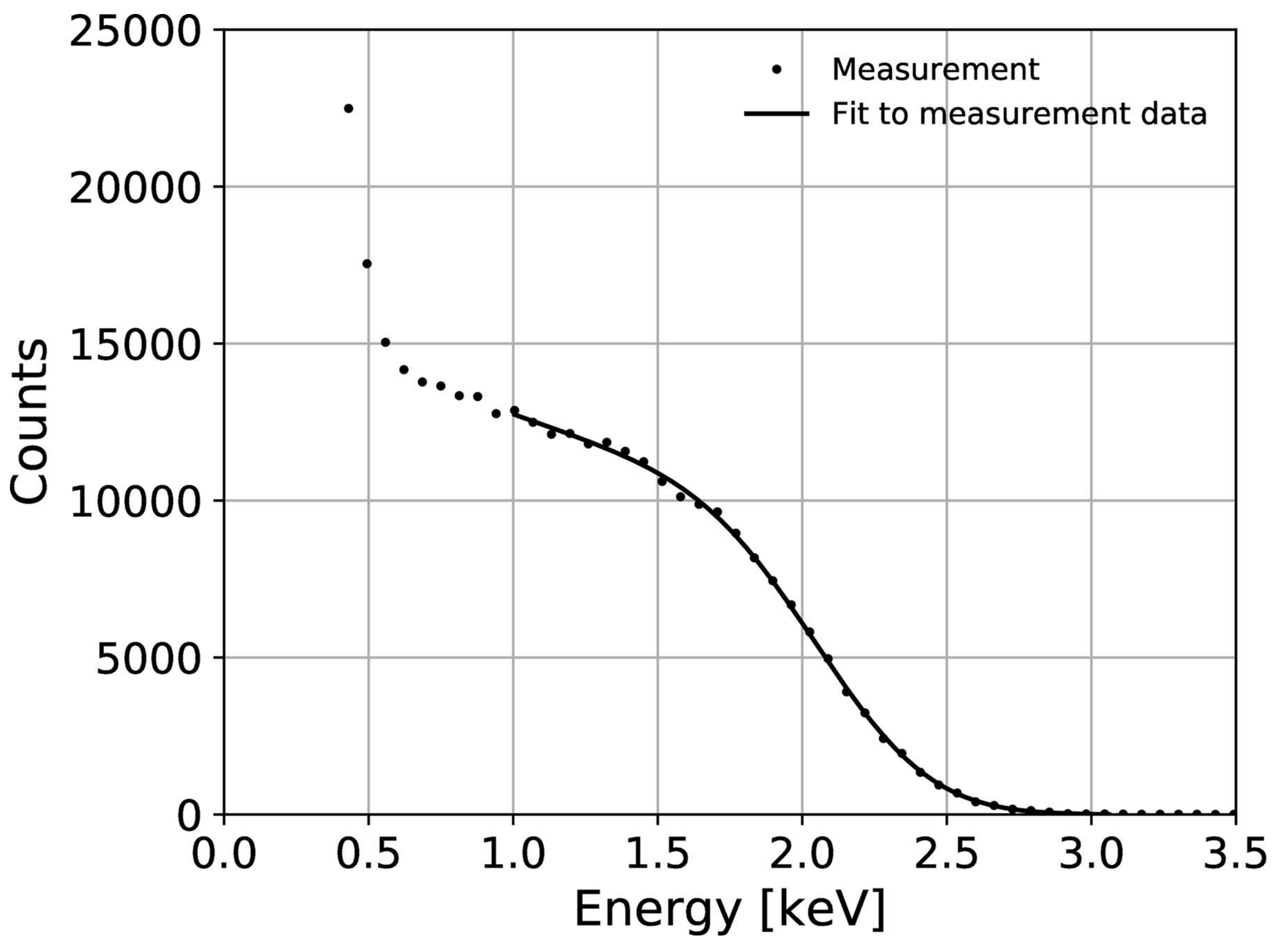


S-curves showing the energy response of an LGAD microstrip sensors (at 150 V) acquired using the ASIC Mythen-II [6]

Low Gain Avalanche Diode (LGAD) Detectors
LGADs for (Soft) X-Rays in Synchrotron and FEL Experiments



S-curves acquired at different bias voltages in response to 8.05 keV copper fluorescence radiation using an LGAD sensors and the ASIC Mythen-II [5]



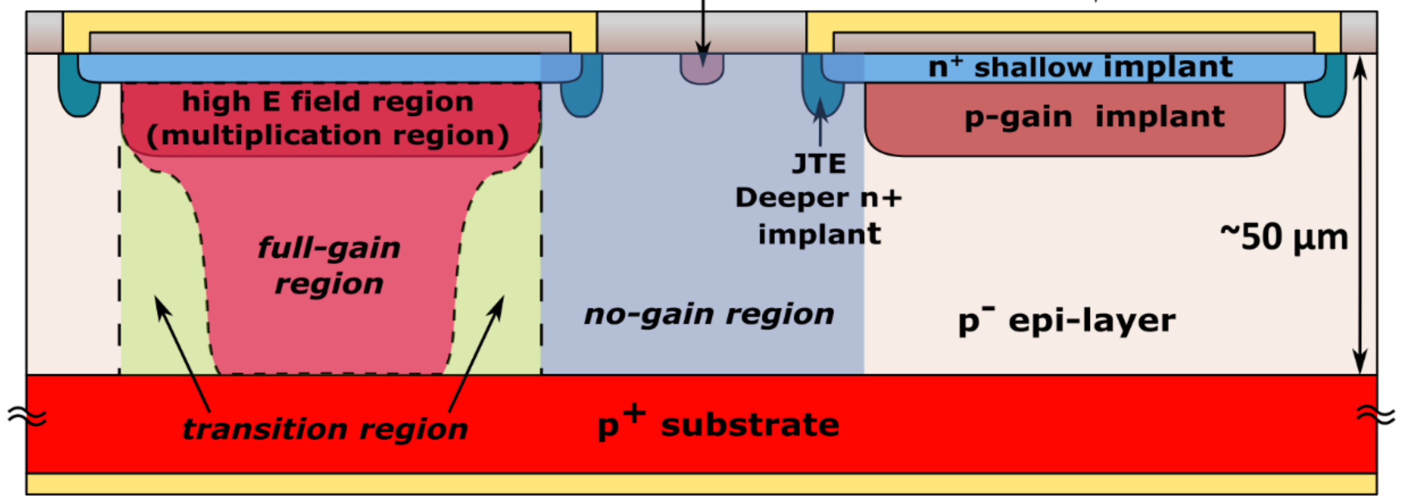
S-curve of a single strip taken in direct beam of 2.1 keV at the PHOENIX beamline of SLS with a bias voltage of 150 V. The energy resolution estimated from the fit for this specific channel is ~0.31 keV [5]

Low Gain Avalanche Diode (LGAD) Detectors
The Segmentation Issue: Fill Factor Loss

LGADs pixels have limited Fill Factor

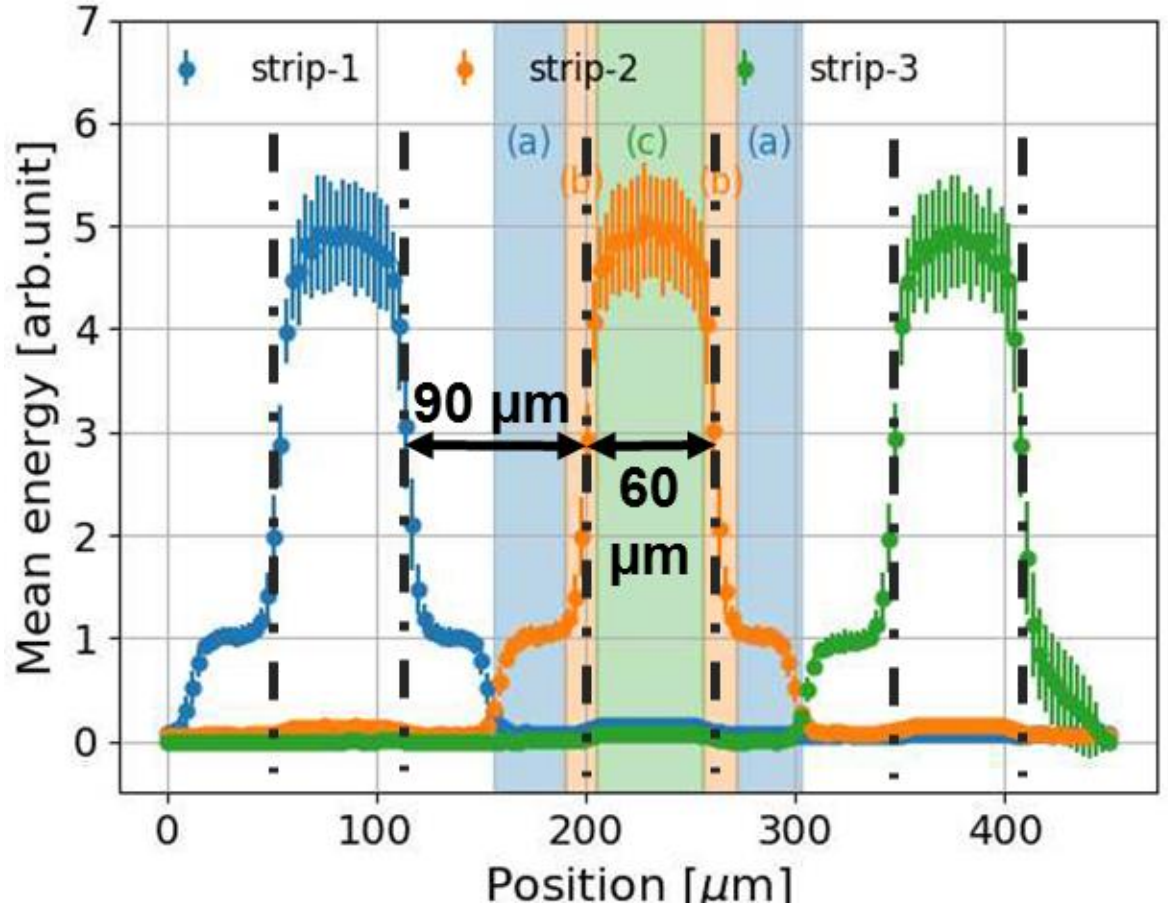
- No-gain region at the pixel border due to isolation and termination structures:
  - Dimensions defined by technological and physical constraint
  - Dead volume for charge multiplication ≥ 30/40 μm

- Low fill factor limits LGAD for:
  - Real 4D tracking in HEP experiments
  - Highly-segmented detectors for x-ray detection



Experimental measurement of LGAD fill-factor using a micro-focused x-ray beam (3 μm, 20 keV) at Swiss Light Source at PSI [5]:

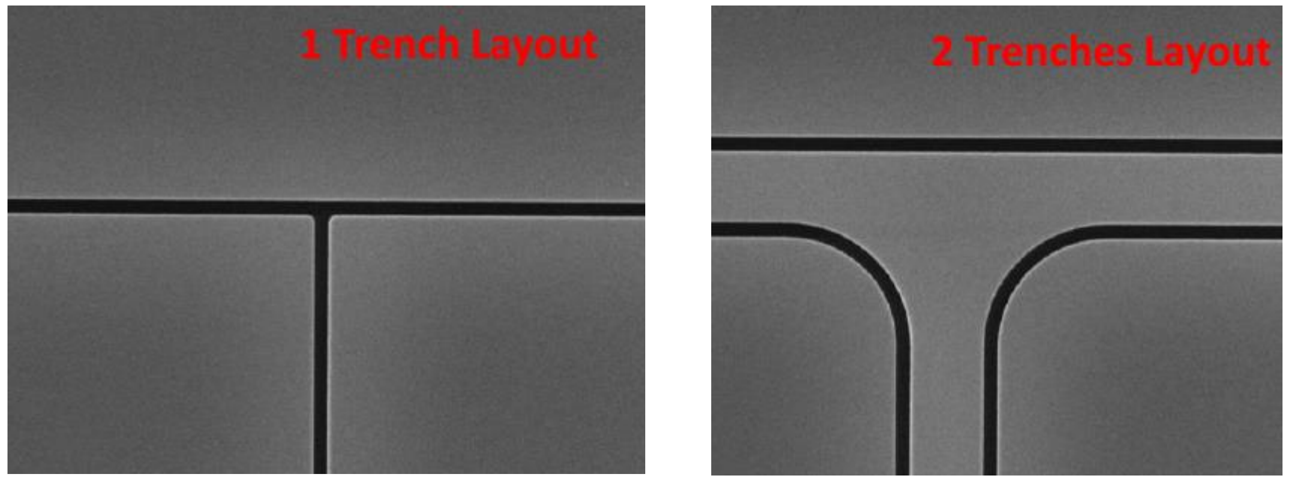
- LGAD micro-strip (146 μm pitch, older UFSD technology)
- Spectrum mean energy as a function of beam position crossing 3 strips
- Nominal FF: 80 μm (55%)
- Measured FF: ~60 μm (40%)

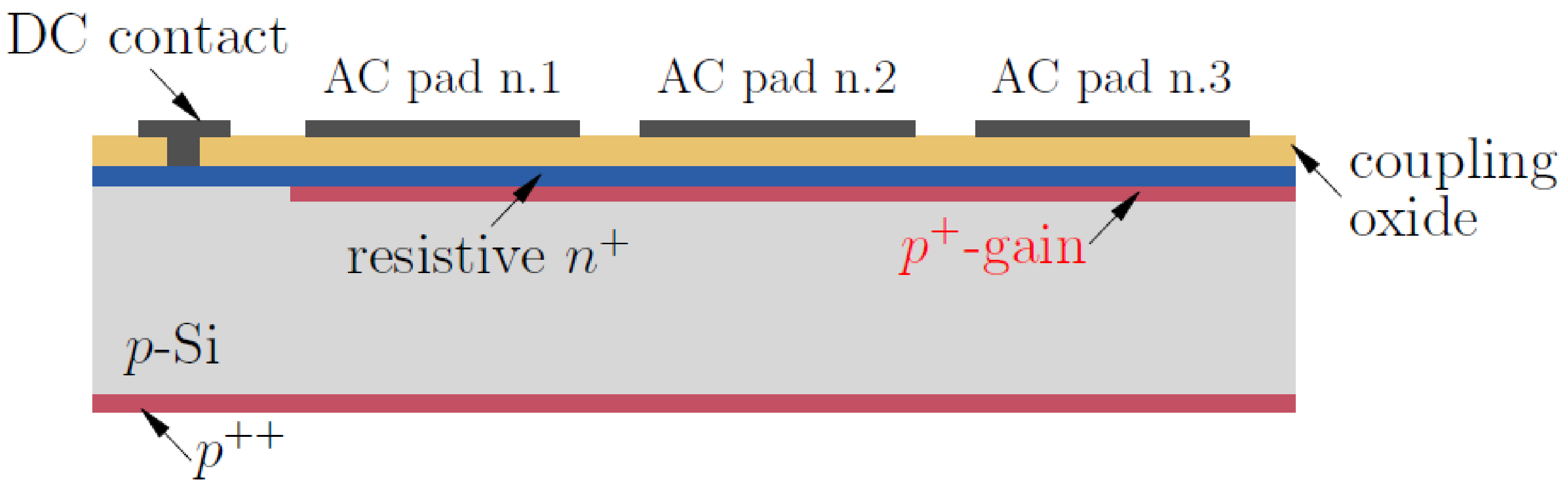


Low Gain Avalanche Diode (LGAD) Detectors
New LGAD Technologies Under Development in FBK

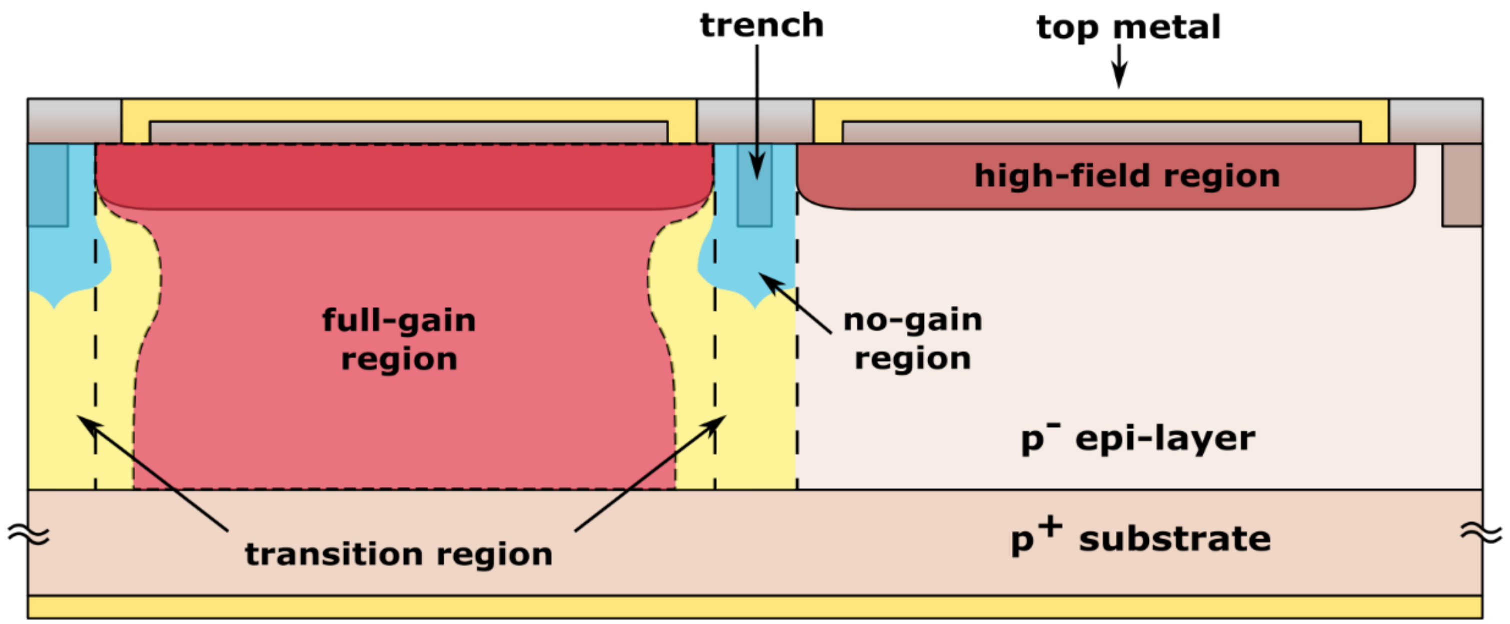
New high-fill-factor technologies under development

- Trench-isolated LGADs [9]
    - Dead border ~5 µm measured on first prototypes
- Resistive silicon detector (RSD, i.e. AC-coupled LGADs) [10,11]
    - Potentially, 100% fill factor
    - Spatial resolution ~10 µm and timing resolution ~30 ps





Schematic cross- section of an RSDs

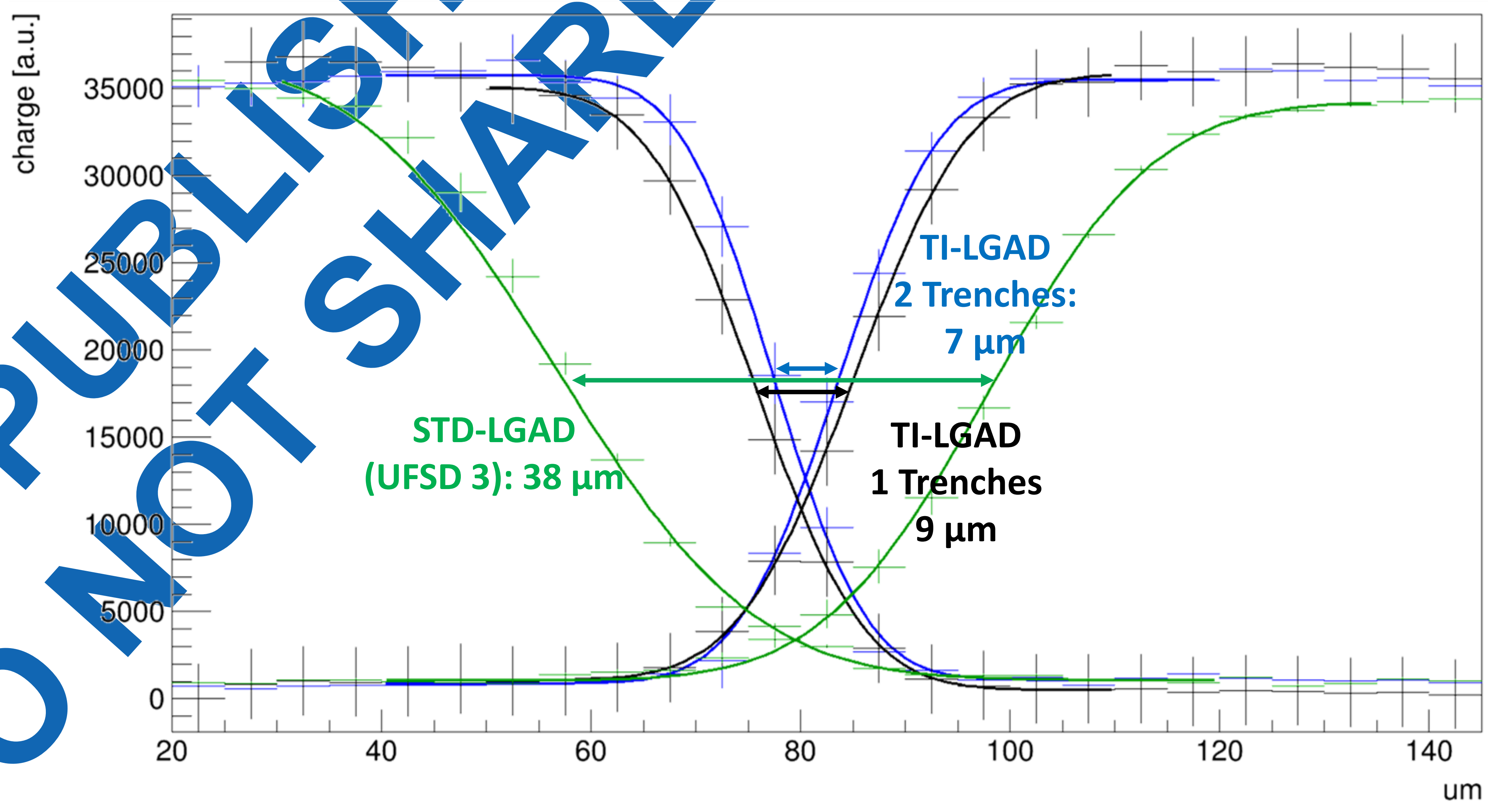


Schematic cross- section of a TI-LGADs

Low Gain Avalanche Diode (LGAD) Detectors
Trench-Isolated LGADs (TI-LGADs) – First Results

First TI-LGAD batch produced in 2019

- Dead border of different samples (1 and 2 trenches) characterized illuminating the borders with a collimated laser



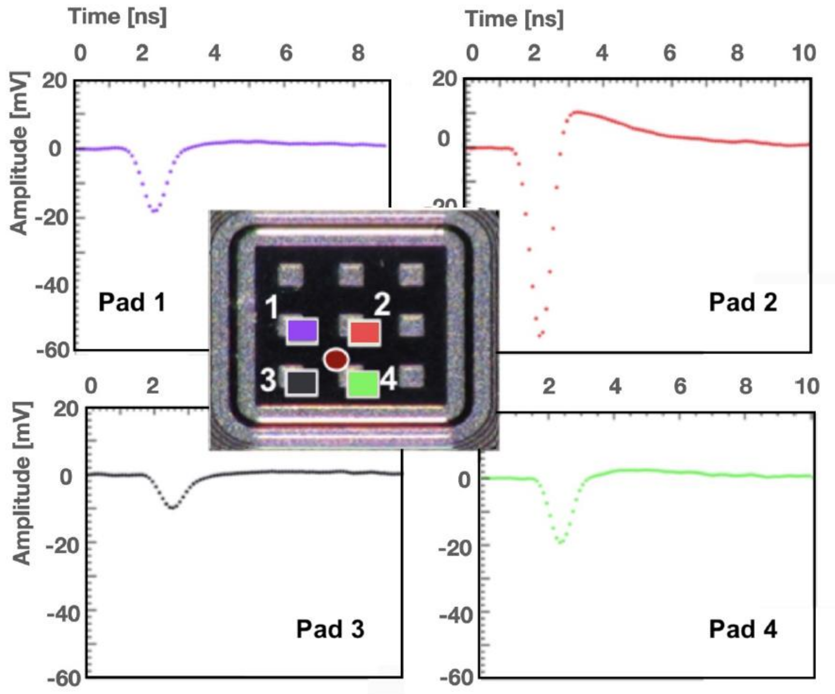
Layout	Effective inter-pad
STD-LGAD	~ 38 µm
1 Trench	9 ± 1 µm
2 Trenches	7 ± 1 µm

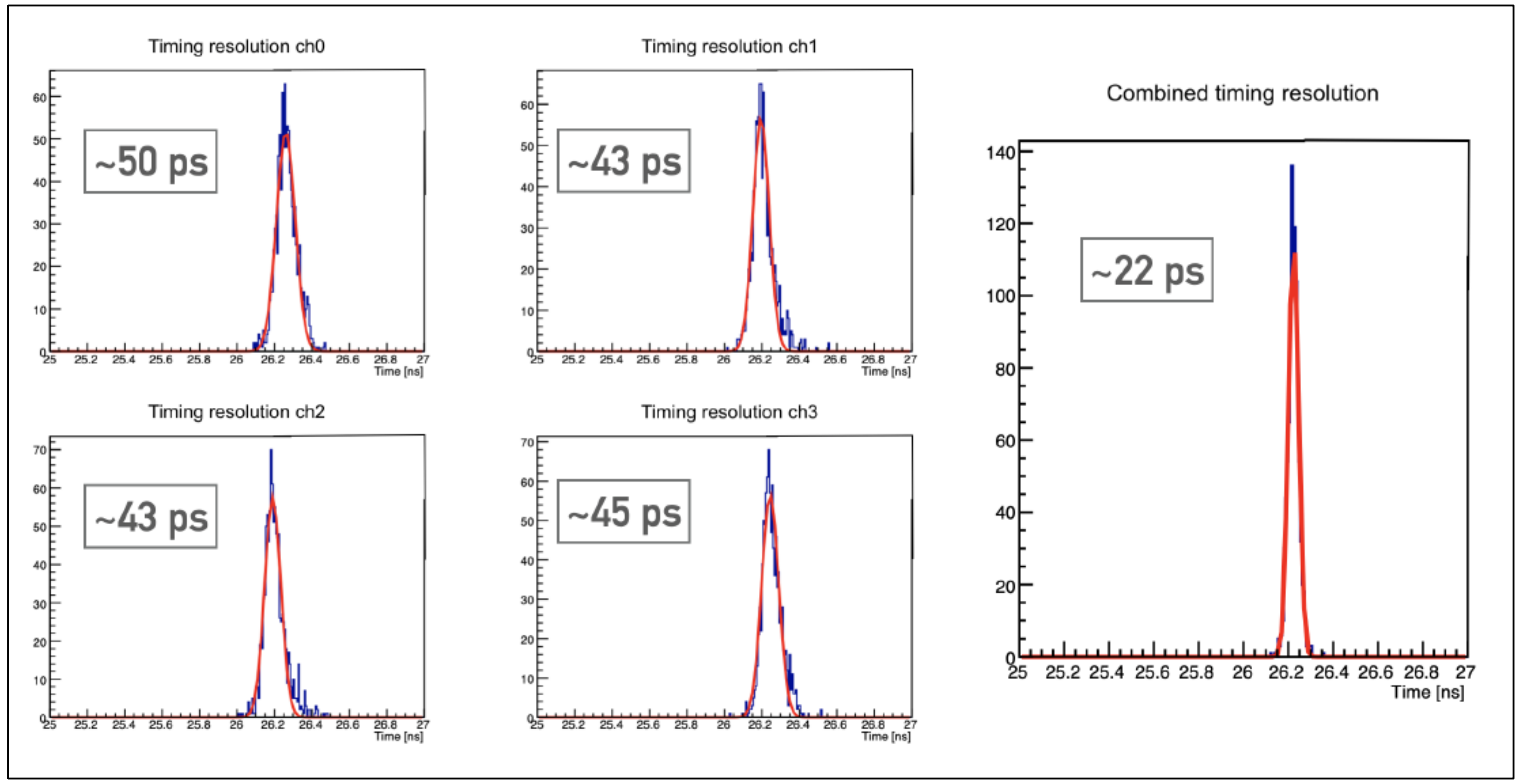
FBK SENSORS AND DEVICES
FONDAZIONE BRUNO KESSLER

Low Gain Avalanche Diode (LGAD) Detectors
Resistive Silicon Detectors (RSDs) – First Results

First RSD batch produced in 2019

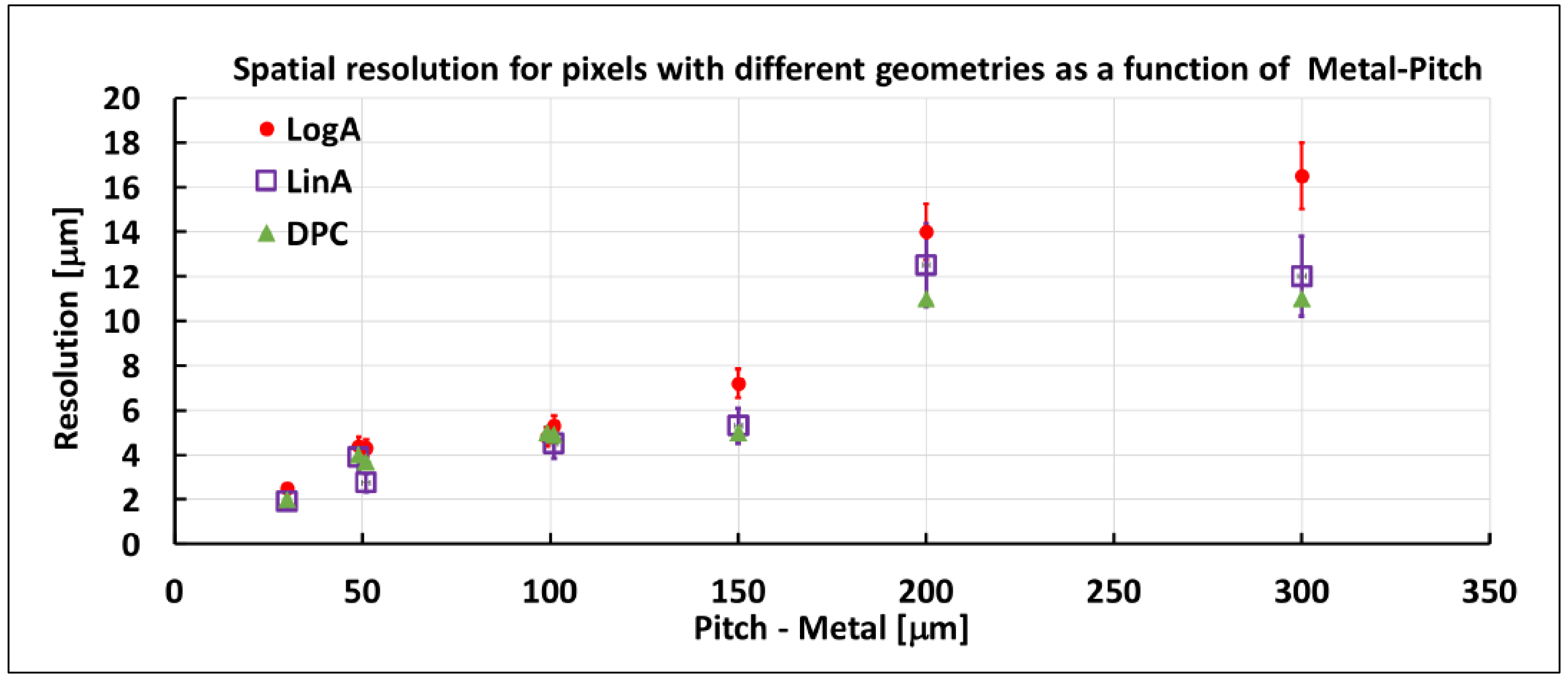
- Excellent positioning capability between pads
- Excellent timing resolution using the information from all neighboring pads





Single-channel (left) and total (right) temporal resolution for a four pad RSD sensor (type 100-200) using laser data. [11]

Spatial resolutions obtained with three different for different RSD geometries as a function of the inter-pad distance



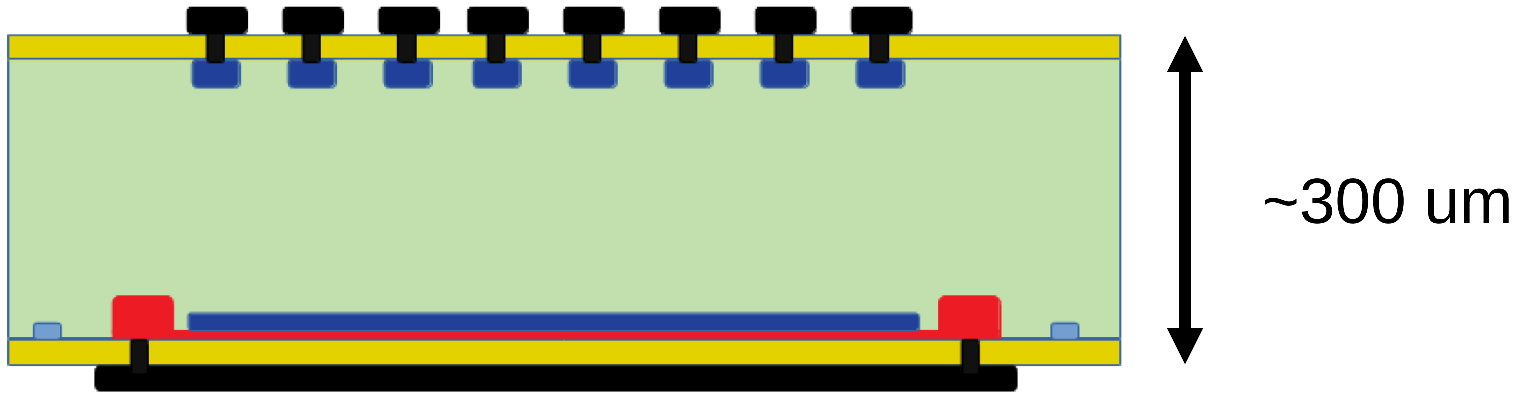
Low Gain Avalanche Diode (LGAD) Detectors
Possible LGAD Sensors Optimized for X-Ray Detection

LGADs for (soft) X-ray detection

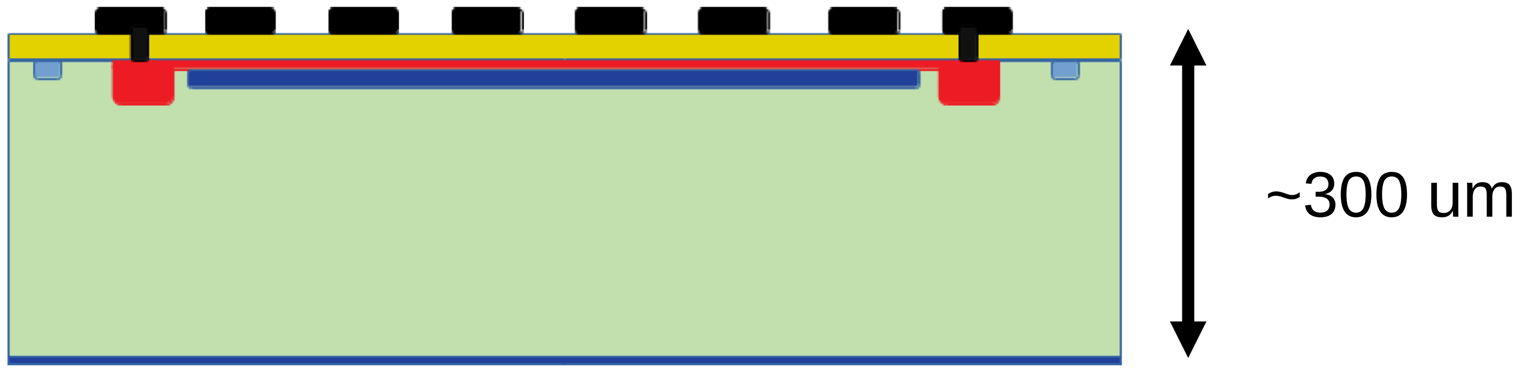
- Requirements:
  - Thin entrance window
  - (Almost) homogenous gain in the whole active area

- Possible LGAD structures :
  1. Inverted LGADs (continuous gain region in the active area, segmented readout on the ohmic side)
     → Currently under development with PSI
  2. RSD sensors on fully depleted substrates with thin entrance window
  3. TI-LGADs on fully depleted substrates with thin entrance window

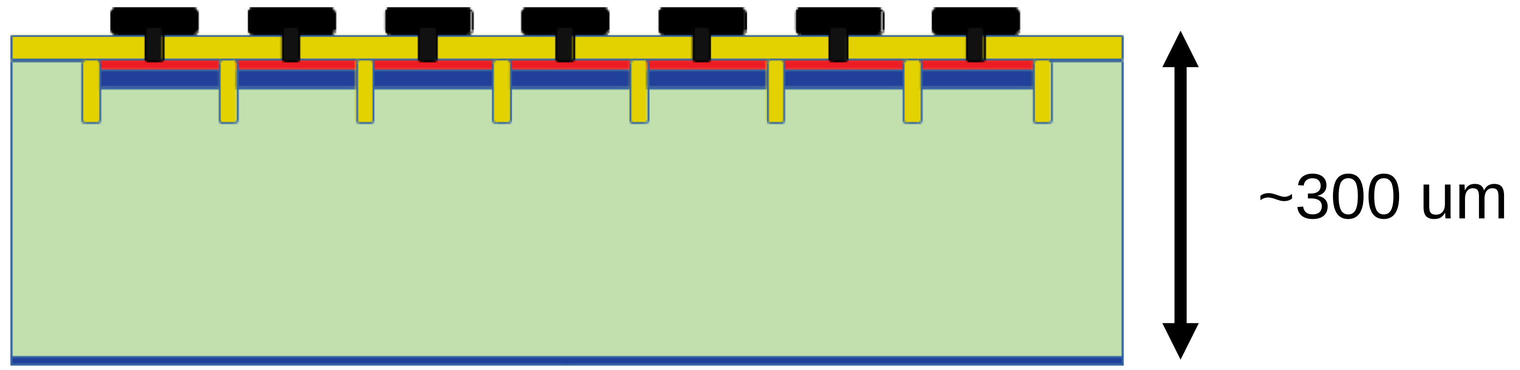
1.



2.



3.



Low Gain Avalanche Diode (LGAD) Detectors
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[8] M. Mandurrino et al., “Demonstration of 200-, 100-, and 50- µm Pitch Resistive AC-Coupled Silicon Detectors (RSD) With 100% Fill-Factor for 4D Particle Tracking,” IEEE Electron Device Lett., vol. 40, no. 11, pp. 1780–1783, Nov. 2019.

Low Gain Avalanche Diode (LGAD) Detectors
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[9] G. Paternoster et al., “Trench-Isolated Low Gain Avalanche Diodes (TI-LGADs),” IEEE Electron Device Lett., vol. 41, no. 6, pp. 884–887, Jun. 2020.

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