Detector R&D for synchrotron facilites

F.J. Iguaz – Journée « La photodetection avec les semiconducteurs »

LPSC, Grenoble, 03-04/06/2024 – *Ref: EXP-DET24-P023-A*

Foreword & acknowledges

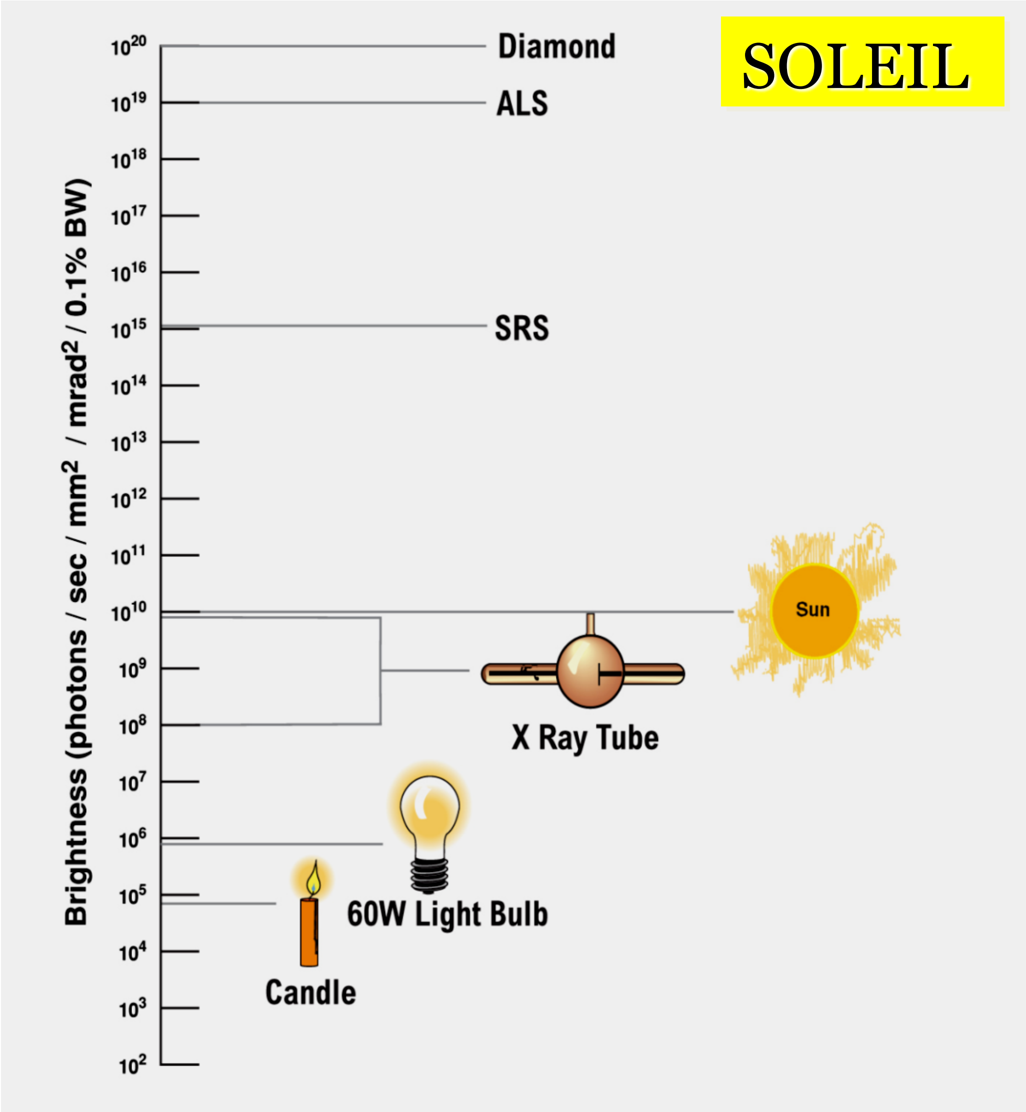
- All material in this presentation come from different sources. >90% are not mine. Please, check references to get more details.
- I thank Ana Torrento for this invitation to give a review talk
- I thank all my SOLEIL detector group colleagues for their work shown here:
  - Marie Andrae, Arkadiusz Dawiec, Kewin Desjardins, Claude Menneglier, Nishu Goyal, Jean Roche
  - Christian Bacchi, Diana Bachiller-Perea, Benjamin Boitrelle, Michel Bordessoule, Brahim Kanouté, Luis Manzanillas, E.A. Mansour, Fabienne Orsini, Elio Sacchetti, Y. Sergent (former)

Outline

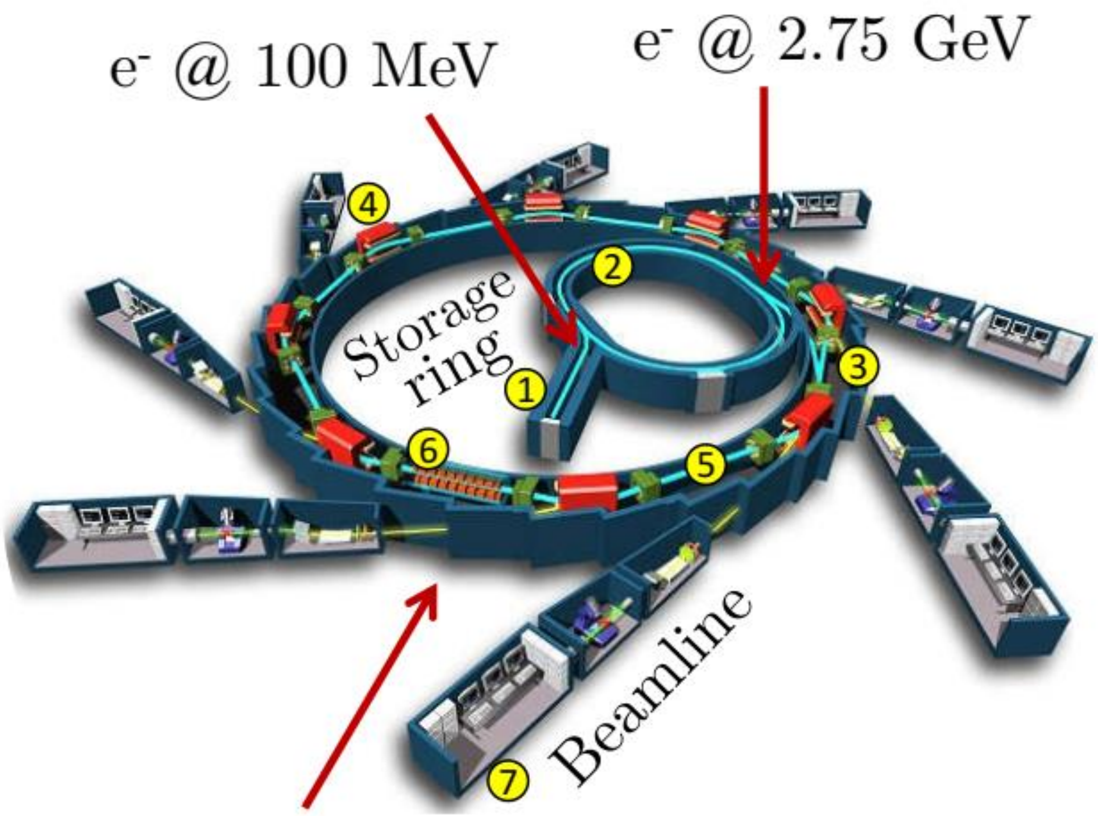
- Synchrotron radiation, production and facilities
- Experimental techniques, energy range and application
- Overview of semiconductor detectors & new developments:
  - Spectroscopy: Silicon Drift Detectors & multi-element germanium
  - Diffraction: pixelized hybrid detectors, CMOS camera
- Conclusions

Synchrotron radiation features:

- Very bright
- Pulsatility (50 ps every 3 ns)
- Polarized
- Adjustable wavelength (broad spectrum)
- Stable (in position and intensity)
- Thin size: 15µm height and 150 µm width (brush of light)
- Low divergence (microfocusing)

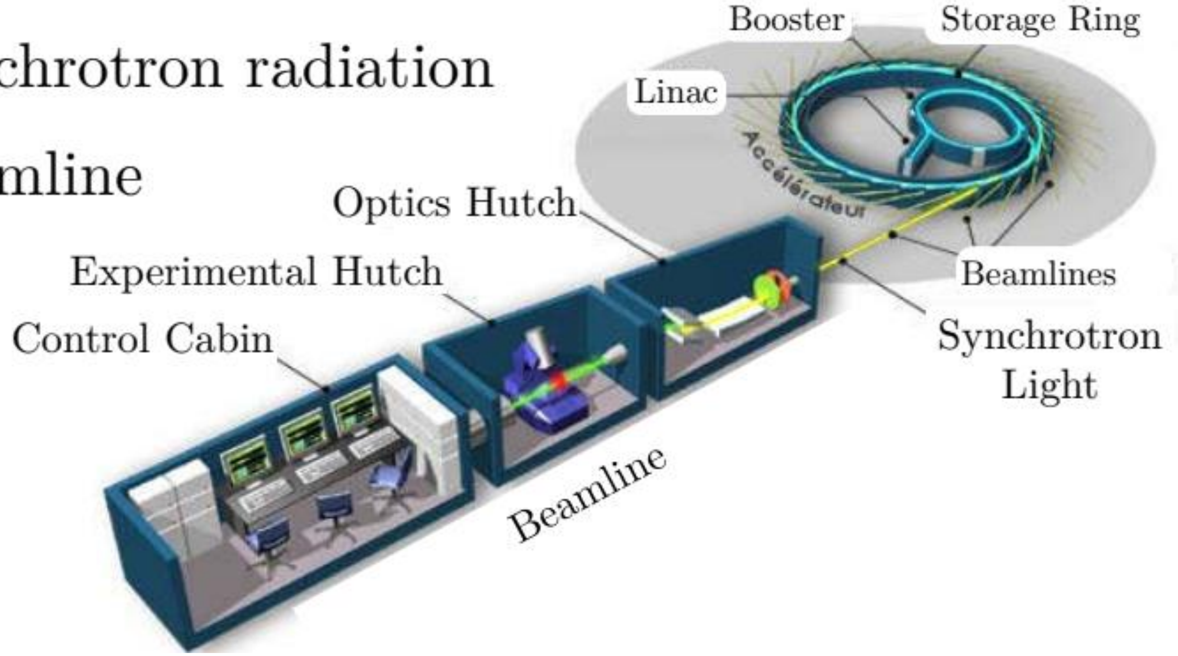


Synchrotron light production



1. Electron gun + Linac (16 m)
2. Booster (circular accelerator)
3. Injection in the storage ring
4. Magnetic devices
5. RF cavities
6. Synchrotron radiation
7. Beamline

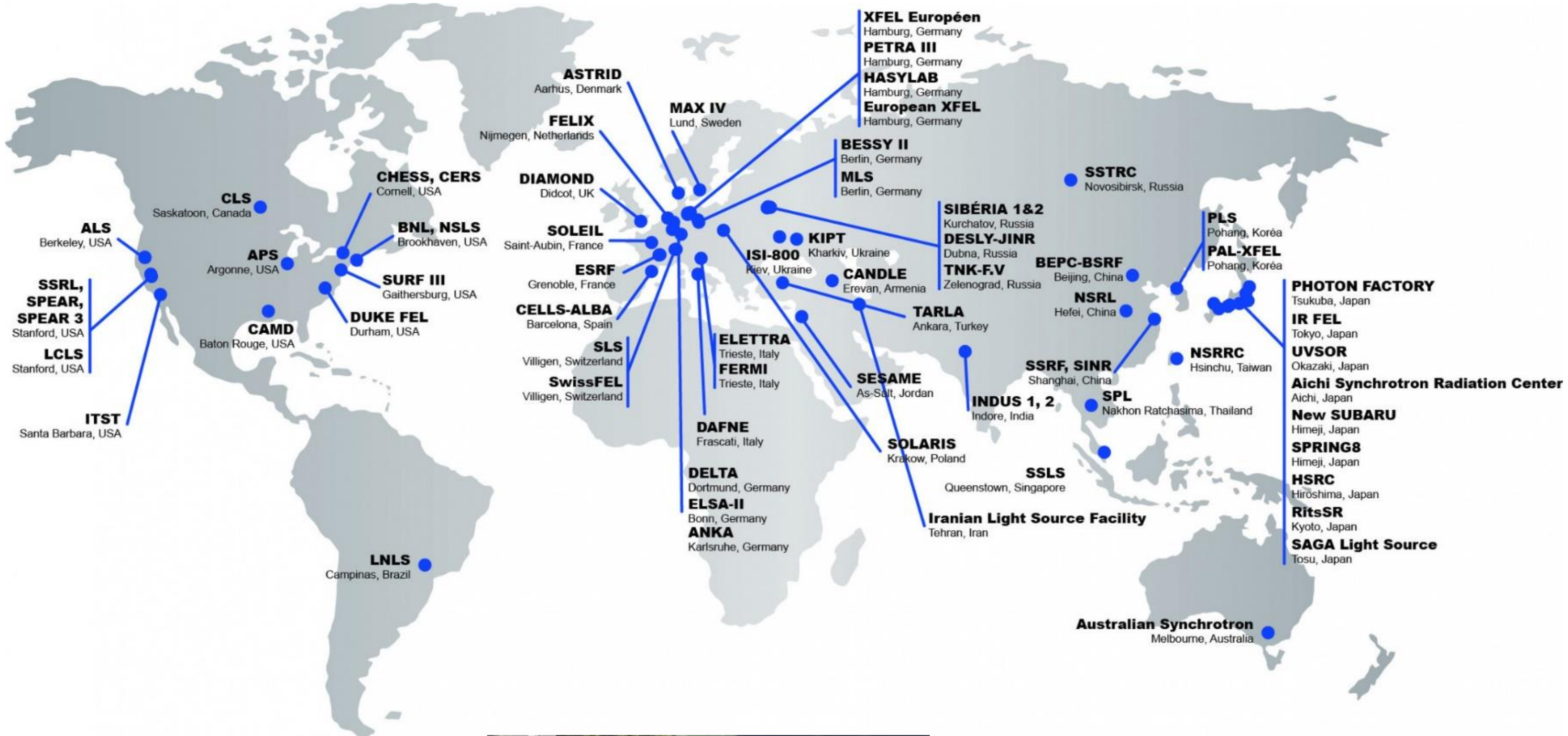
Circumference = 354 m
Diameter = 113 m



Synchrotron facilites in the world

Barcelona, Spain

Grenoble, France

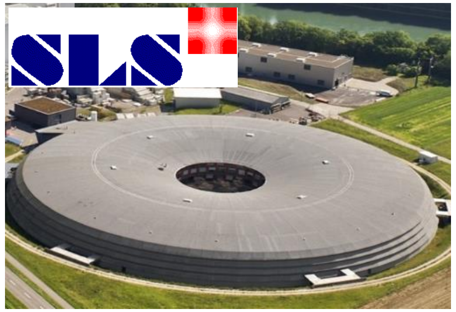


USA

Japan

Triestre, Italy

Ditcot, UK



Villigen, Switzerland

Jordan

Melbourne, Australia

The main part of synchrotron facilites are in Japan, United States & Europe

Synchrotron techniques, energy range & applications

Spectroscopy

XAS, XANES, EXAFS, XRF, PES, …

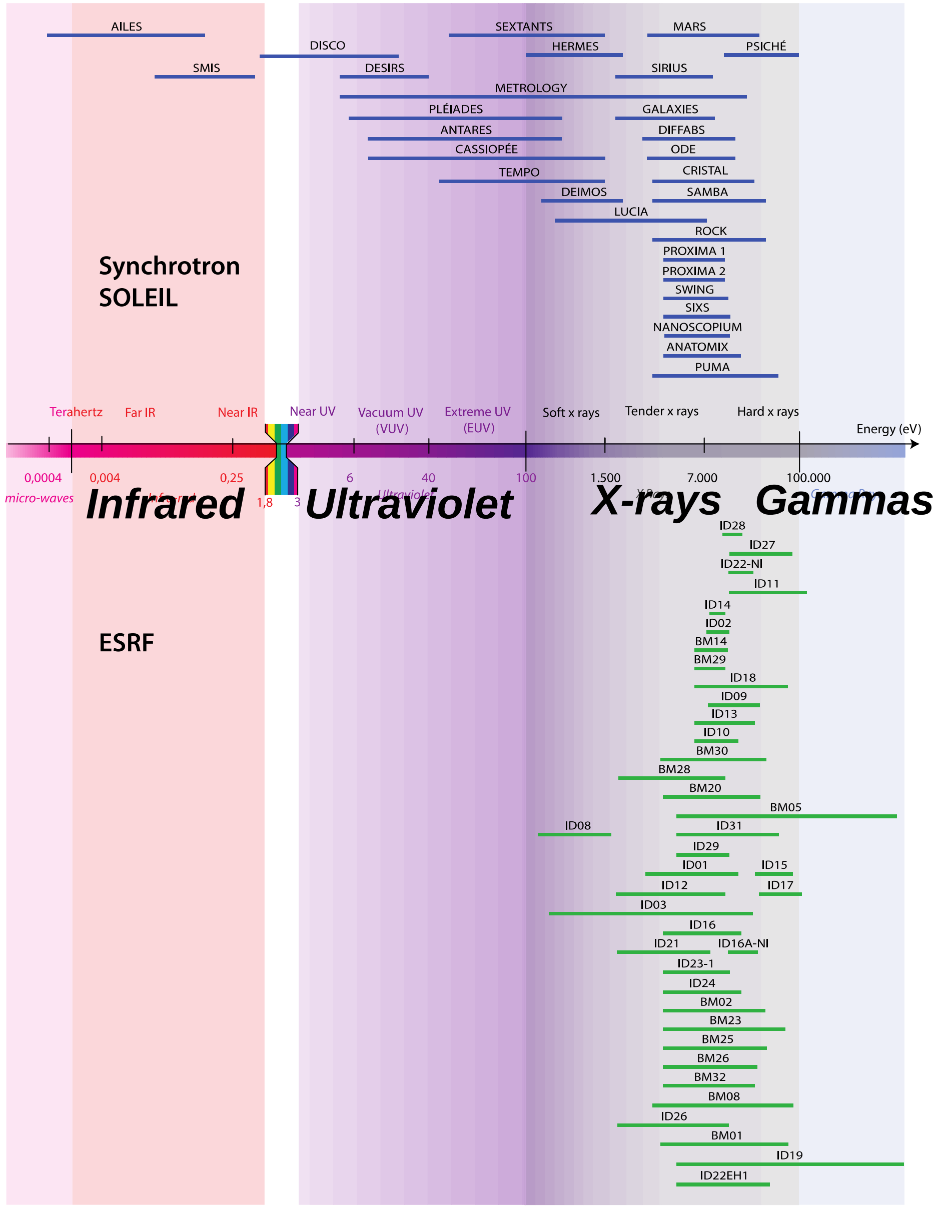
Scattering

XRD, Laue, SAXS, WAXS, GISAXS, XRR, IXS/RIXS, XRMS, …

Imaging/scanning

CDI, STXM, XCT, PCI, CXI, …

And time resolved experiments, exploiting pulsed beam (~3 ns)



Applications


Biology


Medical


Pharmaceutical


Cosmetics


Chemistry


Paleontology and Archeology

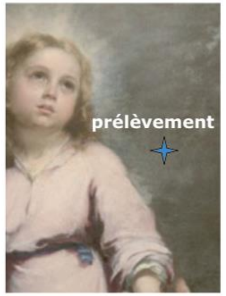

Energy and Environment


Materials

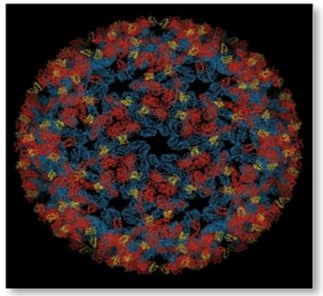

Food


Astrophysics


Geophysics and geology



Smalt of paintings

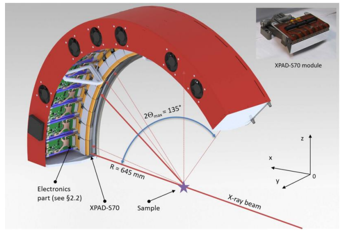


Structure of virus Chikungunya

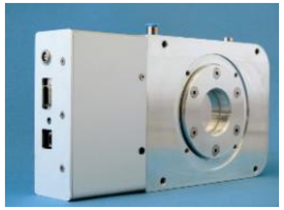
Overview of beamline detectors

CMOS or hybrid pixel detectors
(X-ray diffraction, phytography, …)

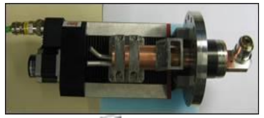




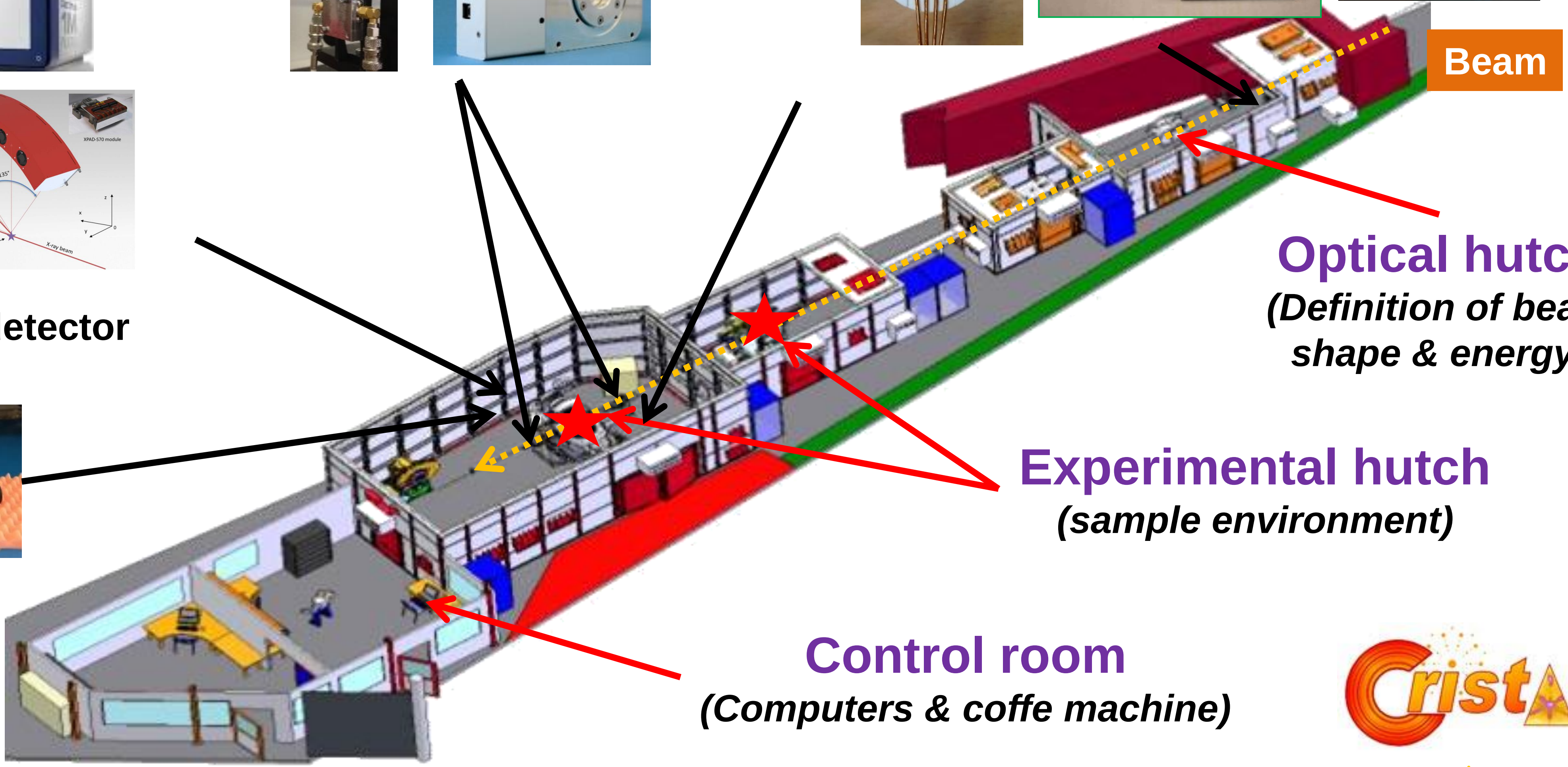
Diode or ionization chamber
(Beam intensity before & after)

XBPM, camera, imager
(Beam position, intensity & shape)



Energy Dispersive detector
(Fluorescence)



Optical hutch
(Definition of beam shape & energy)

Experimental hutch
(sample environment)

Control room
(Computers & coffe machine)

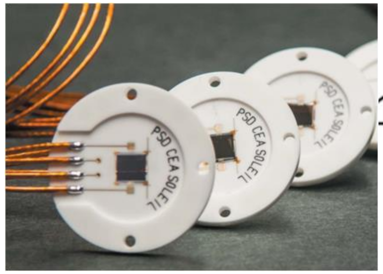
Detector parts & specifications

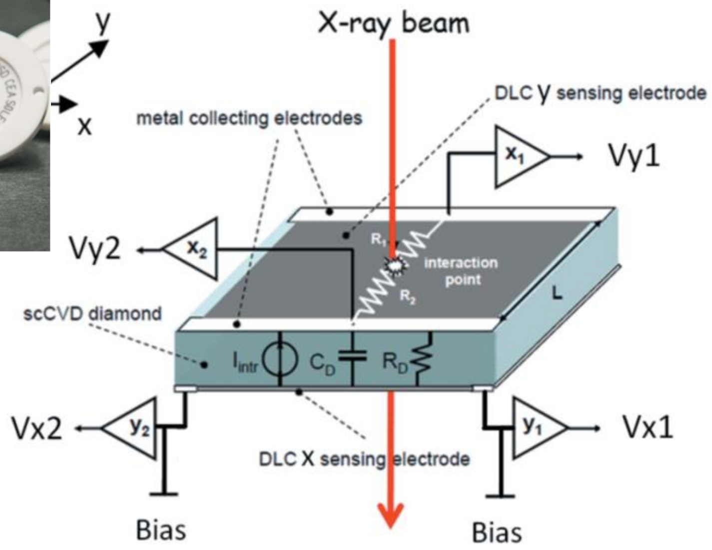
Detector part	Examples	Specifications
Sensor	Si, CdTe, CZT, Ge (100-2000 mm thick)	1. High Quantum Efficiency (QE) 2. Thin Entrance Window (TEW) 3. Uniform response
Bonding	Wire bonding, bump bonding, pogo pin	1. Low capacitance 2. Uniform link
ASIC	XPAD, UFXC, Timepix3, CUBE	1. Small pixel size 2. Low noise level 3. 2-3 gain settings (dynamic range)
Front-end board	FR4, Ceramics	1. Fast heat dissipation 2. UHV vacuum compatibility? 3. No dead area btw FEC boards
Back-end board	FPGA (Firmware)	1. High power consumption 2. Different modes (GATE, threshold) 3. Charge sharing rejection
Server	DELL/HP, optical link, Odin framework	1. Fast data transfer (10 Gb/s) 2. No package loss
Image reconstruction	API library, EPICS, TANGO	1. Beamline integration 2. Image/spectrum in few seconds

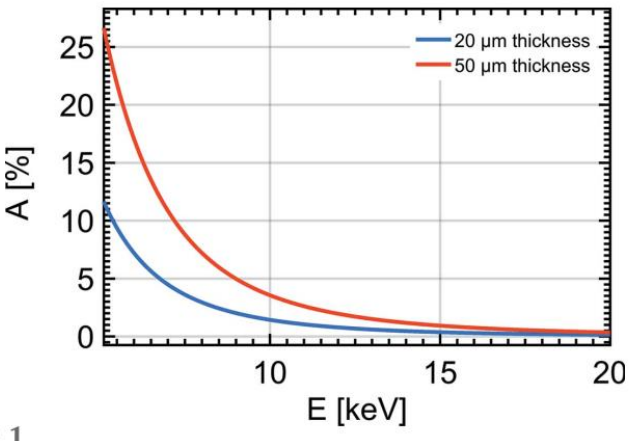
X-ray Beam Position (XBPM) with CVD diamond

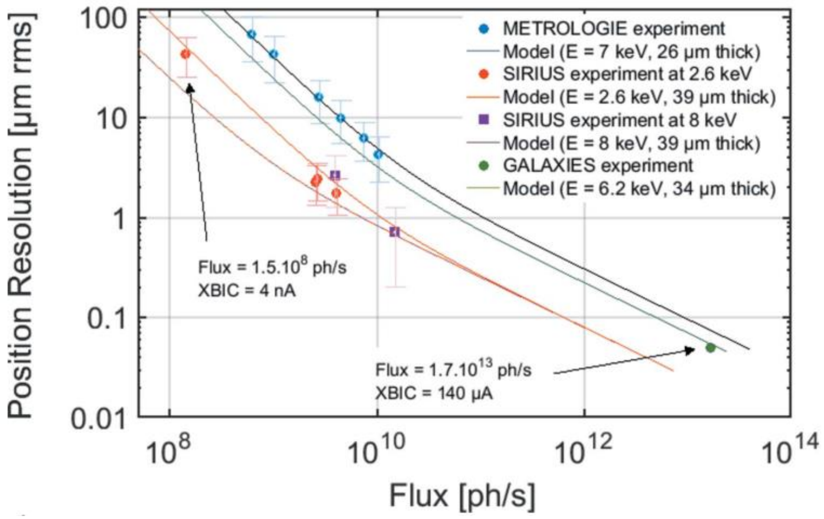
K. Desjardins et al., J. Sync. Rad 25 (2018) 1-8
K. Desjardins et al., J. Sync. Rad 21 (2014) 1217-1223

- Beam diagnostic tool, with low beam flux absorption
- Electronics: LOCUM-4M current-to-voltage amplifier + ADC convertor
- Features:
  - CVD diamond, 4.5 mm x 4.5 mm, 20 µm or 50 µm thickness + DLS coating (100 kΩ, 200 nm)
  - Surface signal variation **< 0.7%** -> Peak-to-peak thickness difference **< 300 nm**
  - Position resolution between **50 – 0.05 µm**, for fluxes between **1.5 x 10^8 and 1.7 x 10^{13} ph/s**







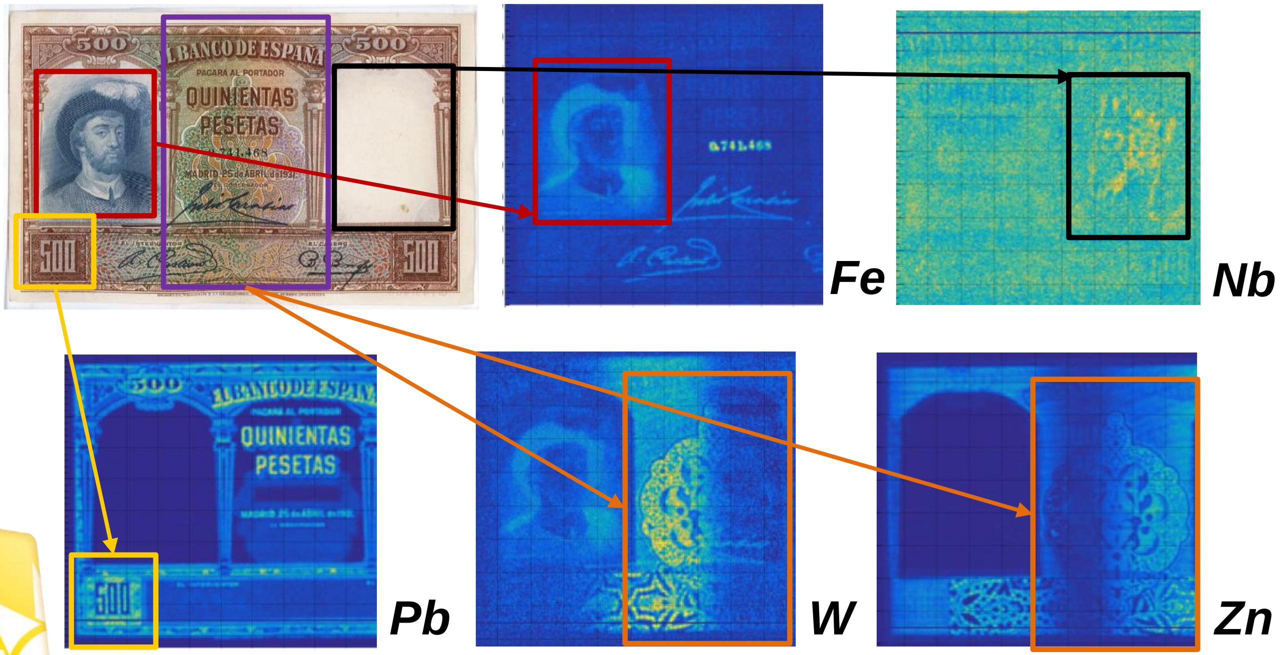


Spectroscopy techniques

Spectroscopy techniques: XRF & XAFS

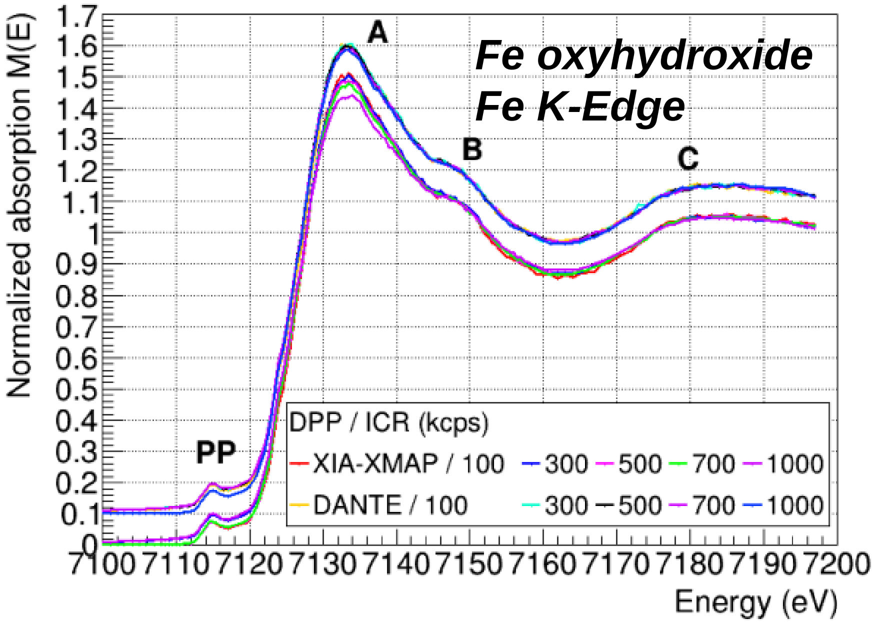
X-ray Fluorescence (XRF)

- Fluorescence signal of a sample is measured after an excitation by incident X-ray photons at a given energy.
- The energy of the fluorescence signal depends on the element (Fe: 6.4 keV, Pb: 10.5 keV).
- Intensity is proportional to the concentration.
- Combined with a micro-beam, an element map can be collected by scanning the sample position.



X-ray Absorption Spectroscopy (XAS)

- The absorption coefficient of an element is measured as a function of the energy scan around the ionization threshold.
- The XAS spectrum provides information on:
  - **A,B:** Electronic structure of the excited atom (oxidation state & environment)
  - **C:** Interatomic distance between the excited atom & its neighbours
  - **PP:** Oxidation state of the excited atom



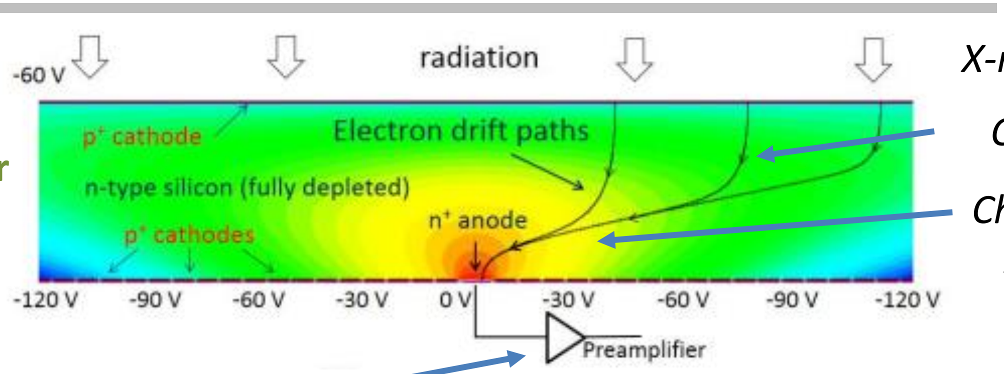
Energy dispersive (EDX) detectors

- Counting detectors resolved in energy.
- Linear counting rate between 10^3 and 10^6 cps
- Types: **Silicon Drift Detectors (SDD)**, multi-element germanium (HPGe), CdTe
- # elements: 1-36. Active surface: 10 to 100 mm^2, collimated to remove border effects

P. Rehak et al., NIMA 624 (2010) 260-264
D.M. Schlosser et al., NIMA 624 (2010) 270-276

Input window (Be, SPD)

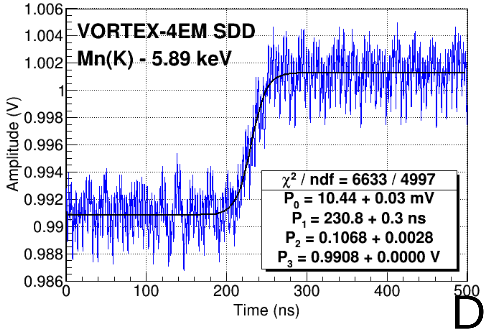
Silicon sensor (450 µm)



X-rays

Charge creation

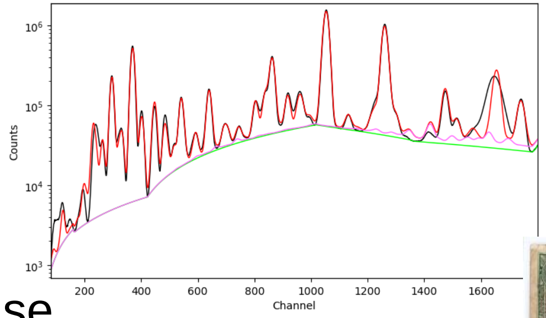
Charge collection & signal induction



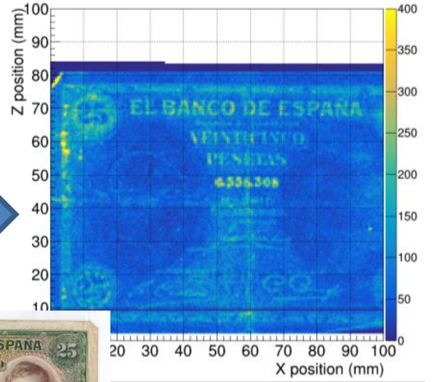
Signal induced by an X-ray

Digital Pulse Processor

(XIA-XMAP, FalconX, Xspress3, DANTE)

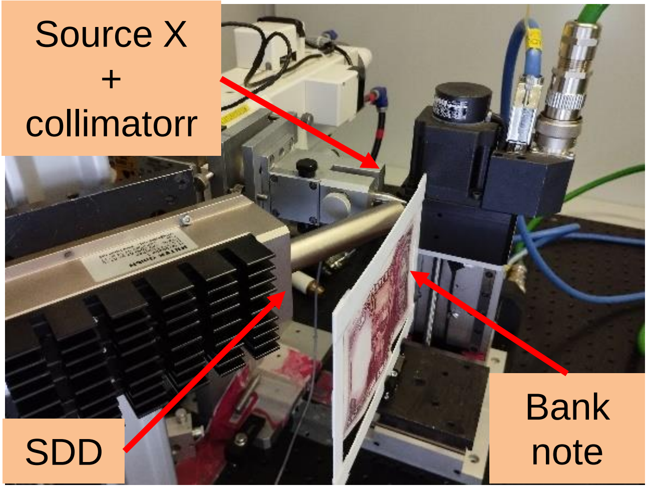


Energy spectrum



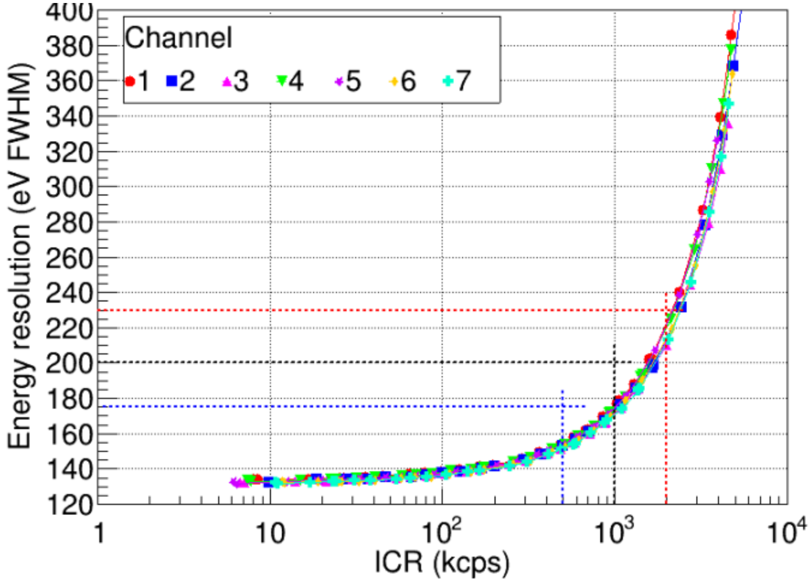
Cartography

(Iron distribution)

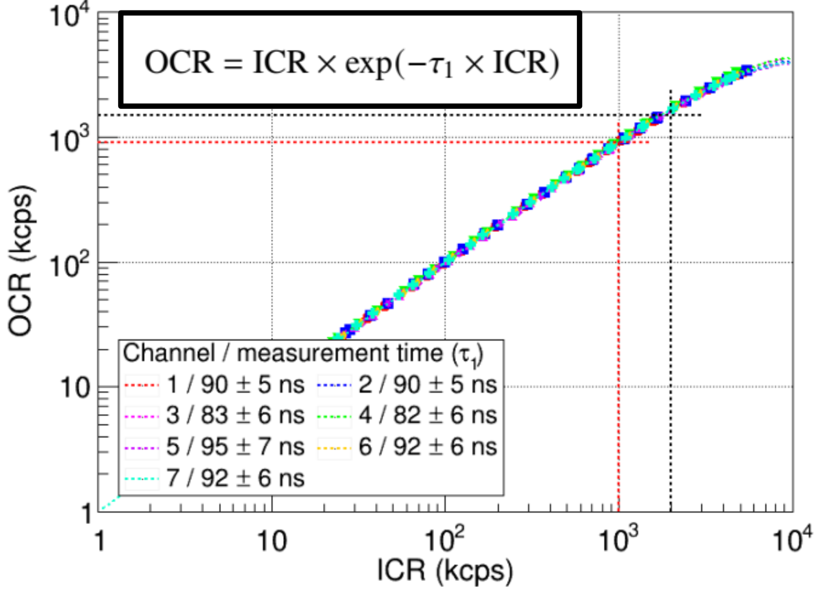


Characterization of EDX detectors

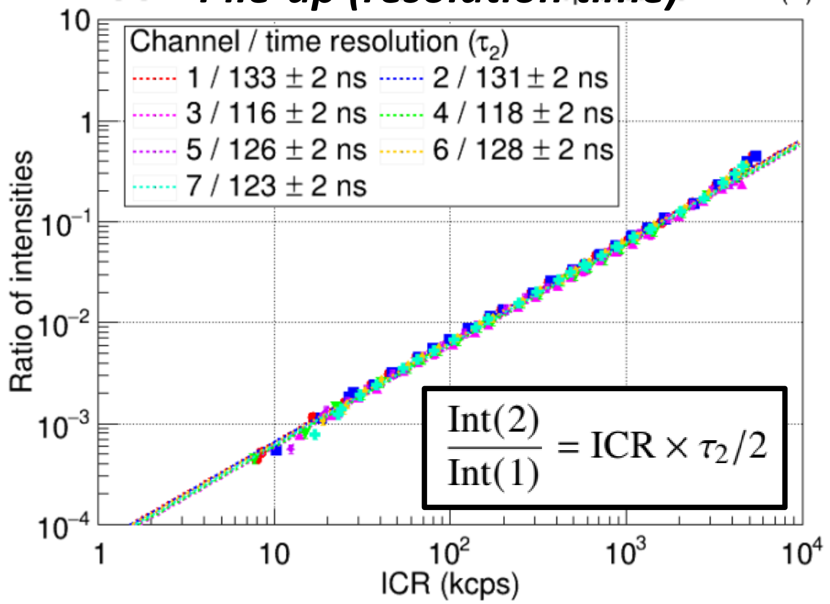
Energy resolution at 5.9 keV



Linear dynamic range (dead time)

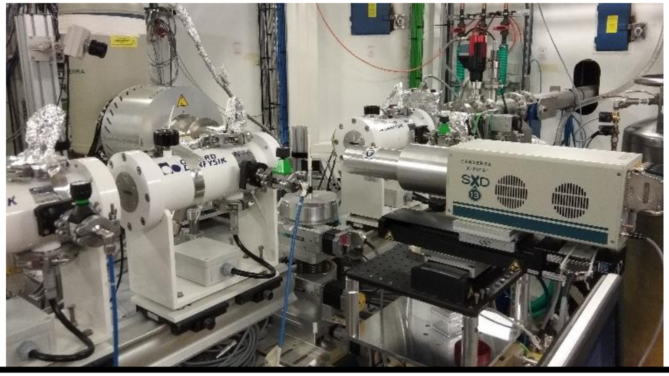


Pile-up (resolution time)



Features for most recent SDD with DPP:

- Signal-to-background (S/B) ratio > 10^3 at 10 kcps
- Energy resolution of 130 eV FWHM at 10 kcps
- Energy resolution < 200 eV FWHM at ICR of 1 Mcps
- Linear dynamic range up to 1 Mcps -> Dead time < 100 ns
- Intensity pile-up peak < 10% up to 1 Mcps -> Resolution ~ 125 ns

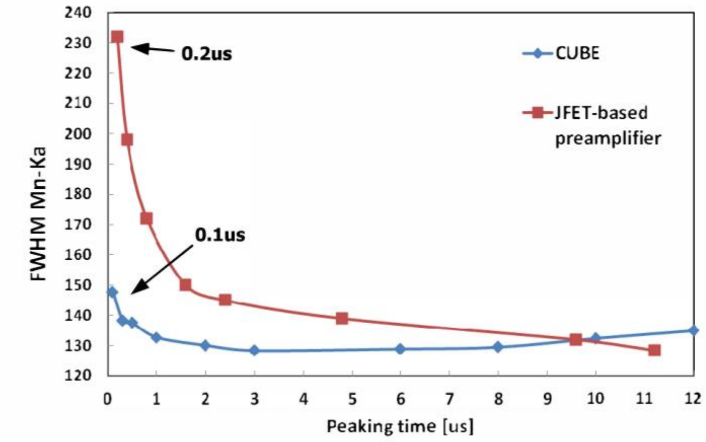


CANBERRA 13EM SDD detector with Xspress3X DPP at SAMBA beamline

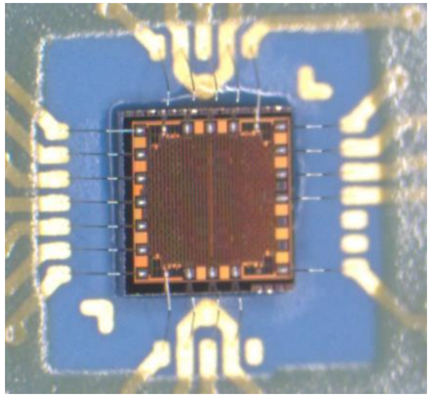
Recent developments for EDX detectors

Detector:

- CUBE ASIC (**integrated preamplifier**)
- 4 channel CUBE ASIC (for SDD & HPGe)
- **Multi-element monolithic** SDD (ARDESIA)
- Polymer windows (AP2.3) for soft X-rays
- **Zero Beryllium** window (90% transmission)
- Cryo-pulsed refrigerator for Ge detectors



CUBE performance
10.1109/NSSMIC.2011.6154396



TETRA ASIC for LEAPS-INNOV project

Digital Pulse Processors (DPP):

- XIA-FalconX & Xspress3M: Pulse analysis in firmware to extend the linear dynamic range
- DANTE: Intermediate performance & cheaper DPP for multi-element detectors
- Xspress4: Charge sharing event rejection in Ge

XIA-FalconX

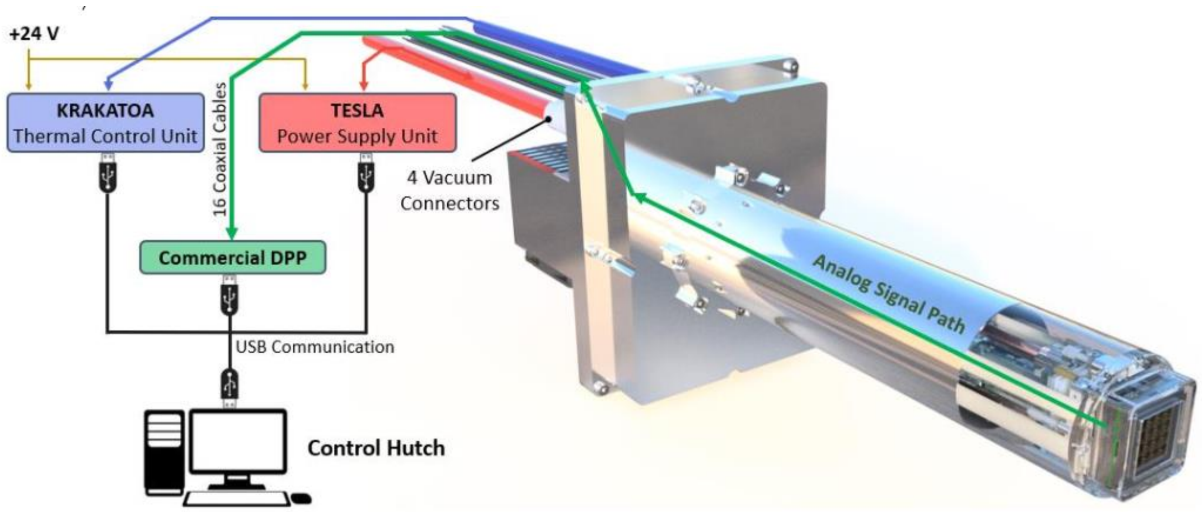
DANTE

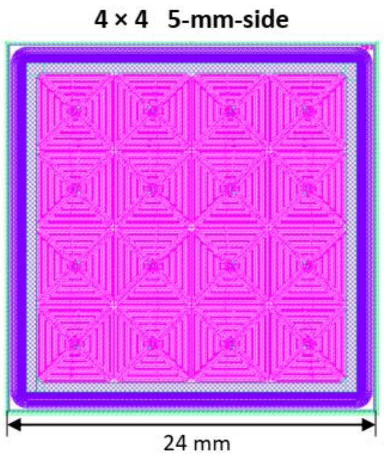
Xspress3X

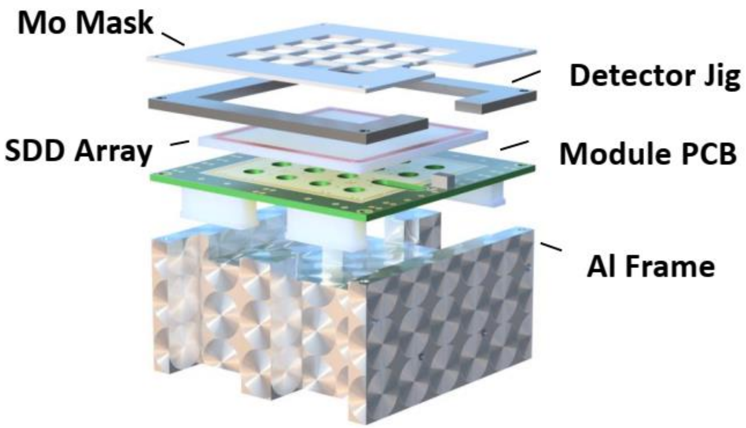
ARDESIA: Multi-element monolithic SDD for high-rate XRF

G. Utica et al., JINST 16 (2021) P07057
I. Hafizh et al., JINST 14 (2019) P06027

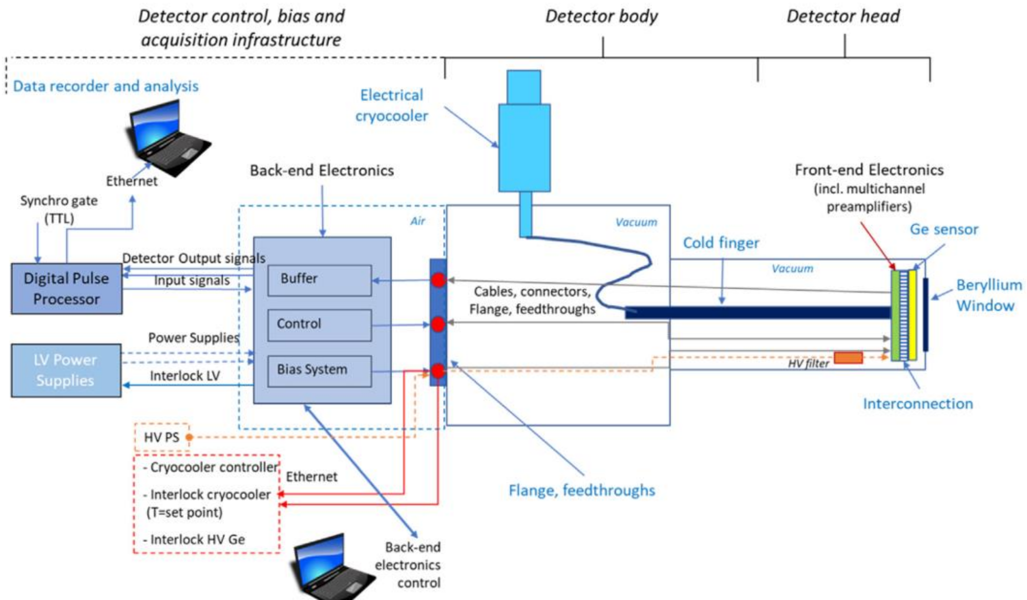
- Spectrometer developed by Politechnico Milano (Carlo Fiorini).
- Three spectrometers being integrated in DESY (ID16A, BM8), ESRF (P06) and LFN (DAFNE-LIGHT).
- Main features:
  - Sensors produced by FBX: **16 pixels**, **5 mm pixel size**, thickness of 450 µm, 800 µm or 1000 µm
  - 500 µm thick Mo/Zr mask (or Zirconium) to prevent charge sharing. Total collimated area = 324 mm^2
  - Four custom-designed 4-channel CUBE preamplifiers.
  - Two external units for bias and cooling control. Dedicated GUI to monitor & control spectrometer.
  - 16 output signals connected to an external DPP (DANTE, FalconX, Xspress3X/M).

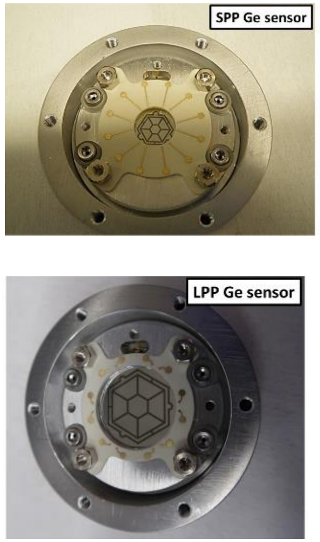




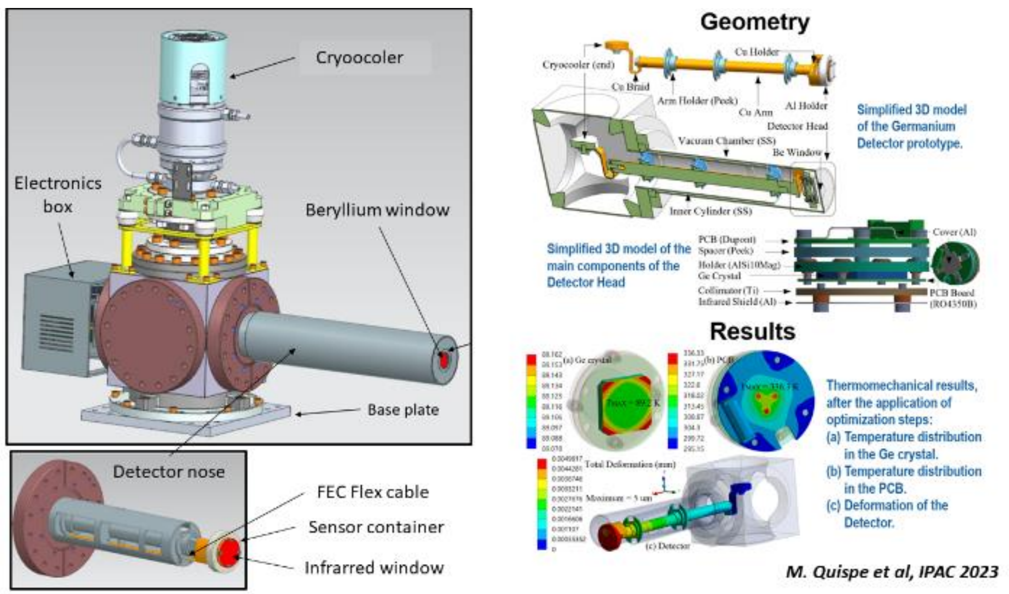


XAFS-DET: Multi-element monolithic HPGe for high-rate XRF





F. Orsini et al., Nucl. Instr. Meth A 1045 (2023) 167600



Two new multi-element monolithic HPGe detectors for synchrotron applications, keeping a good energy resolution at high count rates (passing from 20 to 250 kcps/mm^2) in a broad X-ray energy range (5-100 keV)

Main features:

1. New germanium crystals. Pixels sizes: 5 mm^2 (small) and 20 mm^2 (big).
2. A new full electronic chain (TETRA ASIC, FEC, BEC) has been designed and built.
3. The mechanical design has been optimized using thermal simulations.
4. Xspress4 digital pulse processor will be used to remove charge sharing events.

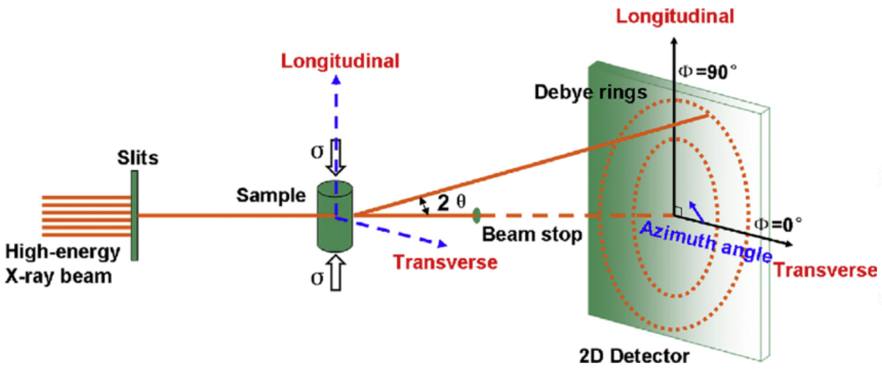
More details at the poster by Nishu GOYAL (SOLEIL)

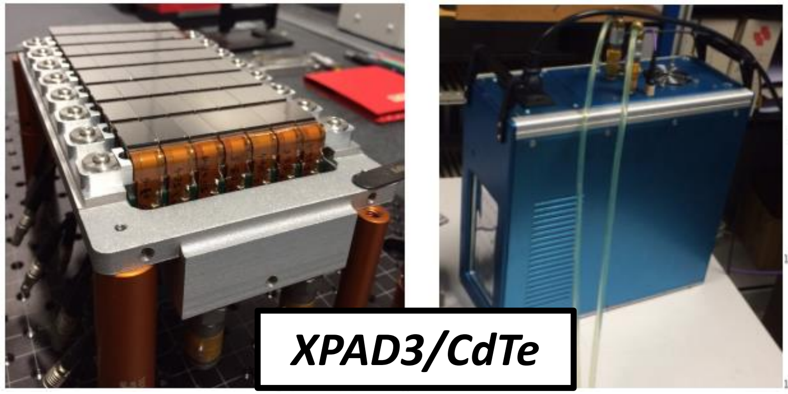
Diffraction techniques

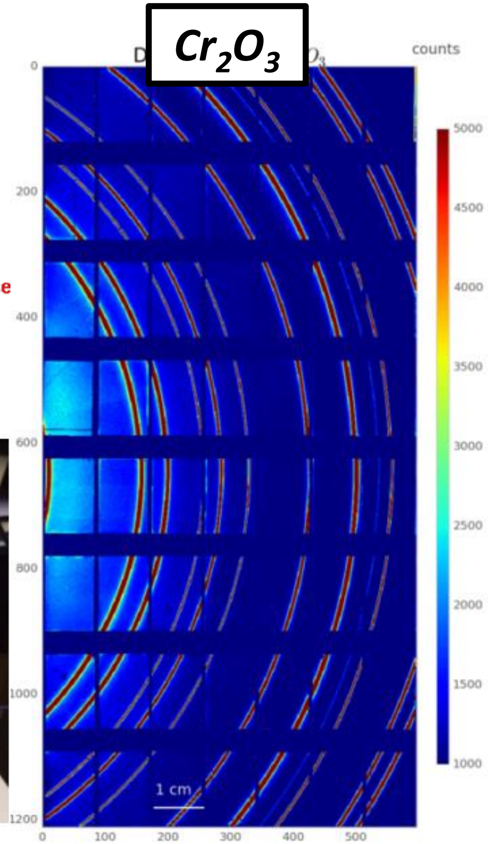
Diffraction techniques

X-ray Powder Diffraction (XRPD)

- Technique for **structure characterization of materials**
- The **sample is rotated** so as it randomly arranged. A significant number of each plane of the crystal structure will be in the proper orientation to diffract the X-rays.



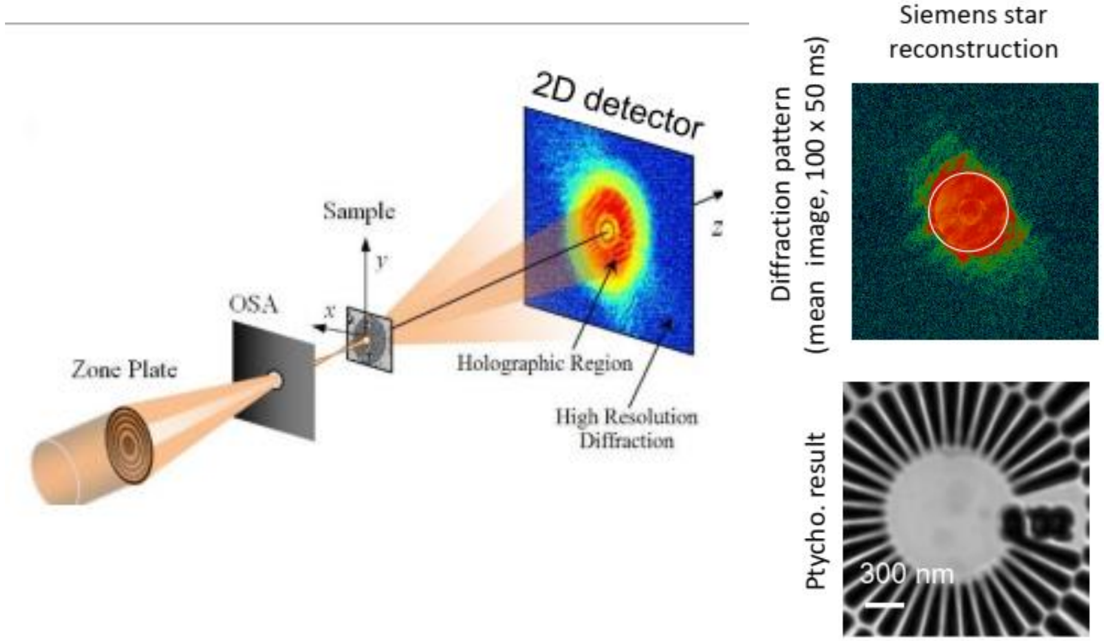




F. Cassol et al., JINST 10 (2015) C11010

Ptychography

- Imaging technique based on the coherent scattering of soft X-rays in transmission mode with variable angle.
- The **sample position is scanned** with respect to the incoming coherent beam (the probe) to create a sequential array of overlapping illuminated areas.
- For each position, the coherent diffraction pattern is recorded by a 2D detector in the far-field region.

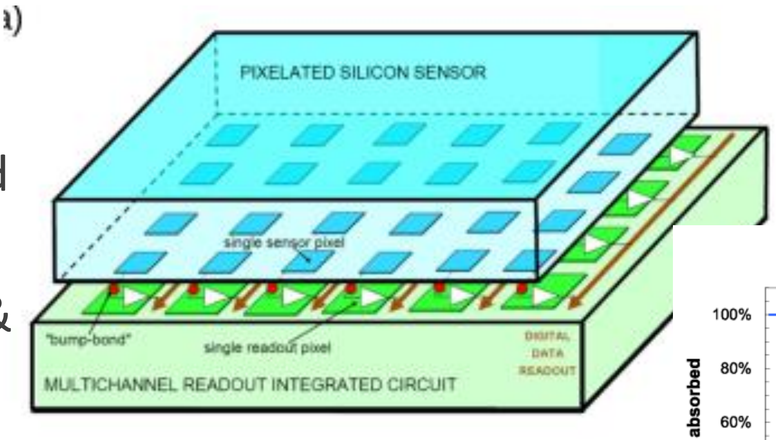


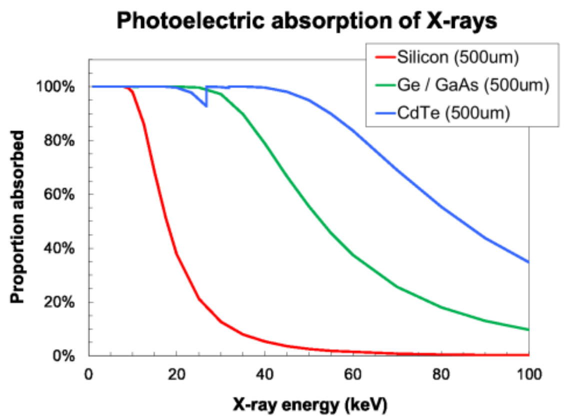
N. Milles et al., Communication Materials 3 (2022) 8

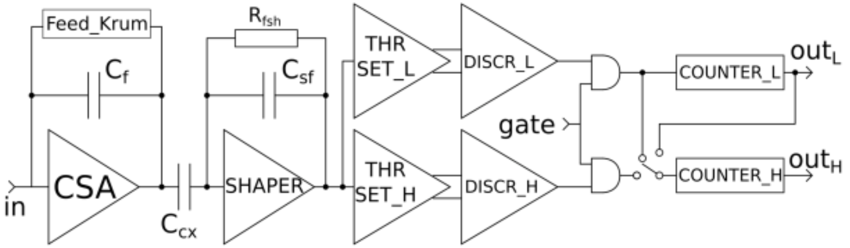
Hybrid pixel detectors

A. Dawiec et al., JINST 12 (2017) C03057

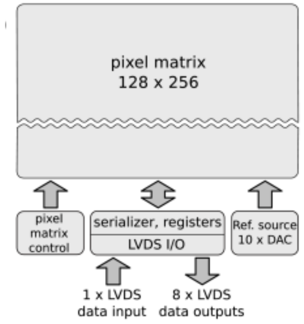
- 2D photon counting detector
- It is composed of a sensor and an ASIC
  - **Sensor**: Material & thickness is chosen accord to X-ray energy range
  - **ASIC**: Pixel size, single readout pixel scheme & block diagram are designed according to performance (counting rate, frame rate,…).
- Detector design:
  - Large surface (several sensor-ASICs)
  - Compact (global design)
  - Temperature stability (cooling system)
  - Fast frame rate & image reconstruction (firmware, back-end & software design)







Single readout pixel scheme of UFXC32 ASIC

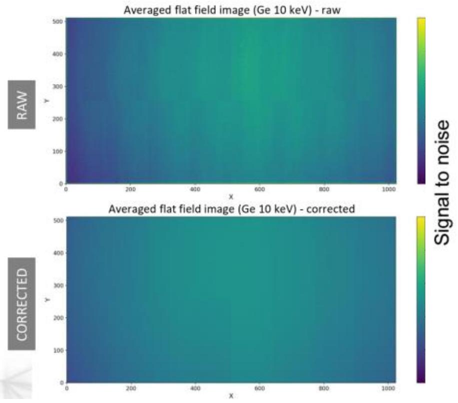


Simplified block diagram

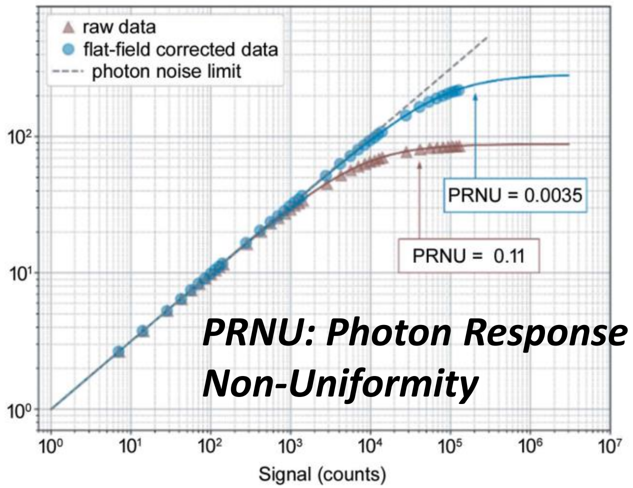
Characterization of hybrid pixel detectors

Y. Nakaye, […], A. Dawiec et al., J. Sync. Rad 28 (2021) 439-447

Flat field correction

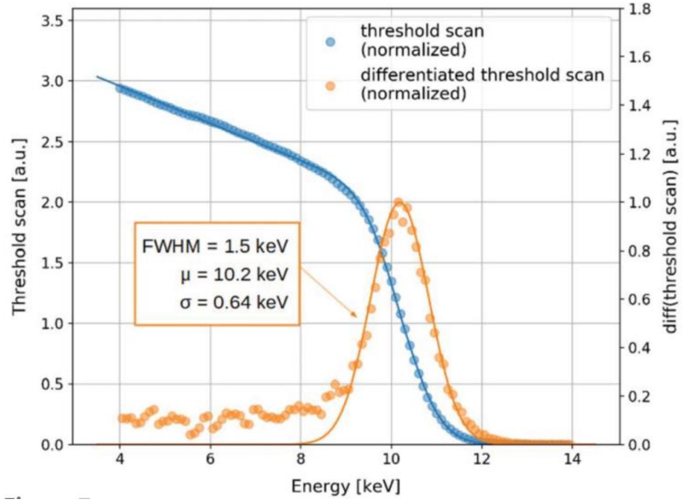


Signal-to-noise ratio
(before & after flat field correction)

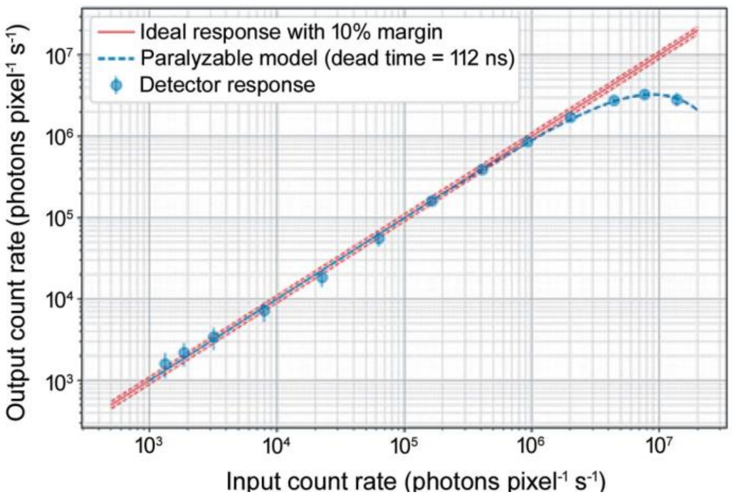


PRNU: Photon Response Non-Uniformity

Energy threshold (S-curve)



Count rate linearity



Calibration & characterization process:

a) Flat field correction & detector homogeneity
b) Bad pixel identification (dead, undercounting, good, noisy)
c) Signal-to-noise ratio measurement
d) Energy resolution (S-curve)
e) Modulation Transfer Function
f) Counting rate linearity

XSPA-500k detector (RIGAKU company)

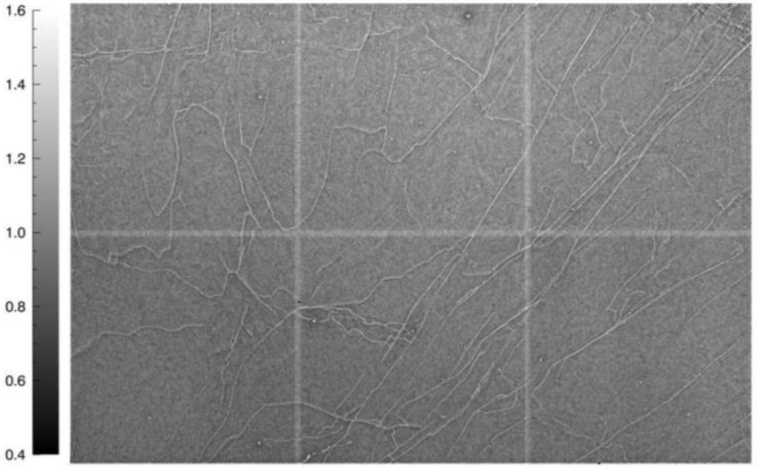
- Detection area: **77.8 × 38.9 mm²** / Sensor: **Si 320 µm**
- Image size: **1024 × 512 pixels** / Pixel size: 76 × 76 µm²
- Readout ASICs: **16 UFXC** (no inter-chips gaps)
- Framerate: **8.6 kfps @ 16 bits**, 56 kfps @ 2 bits

Recent developments for hybrid pixel detectors

Sensor materials:

- CdTe/CdZnTe/GaAs:Cr (for hard X-rays)
  - *Large sensor area, uniform, radiation hardness*
- LGAD (for soft X-rays, 250 eV - 2 keV)
  - High QE, low entrance window

Flat field X-ray response LAMBDA (CdTe 1mm)

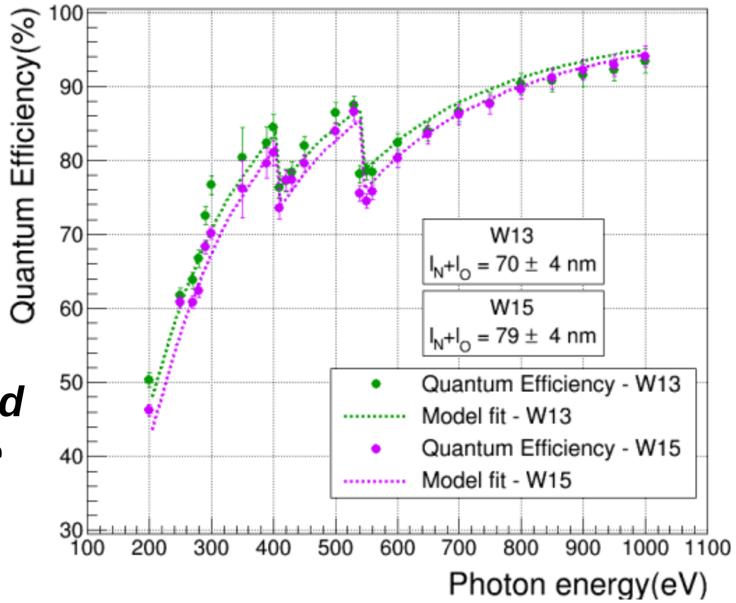


C. Ponchut et al., Rad. Meas. 140 (2021) 106459

ASIC development:

- Lower noise -> Lower threshold
- Lower threshold dispersion -> Better flat field
- Increase count rate -> Work at higher flux

iLGAD + optimized entrance window



A. Ligouri et al., JINST 18 (2023) P12006

Building readout systems:

- Cooling system -> Stable calibration & operation
- Data-flow optimization -> Increase of fps

Medipix & Timepix-based detectors

	MAXIPIX	LAMBDA	MERLIN	EXCALIBUR
Developper	ESRF	DESY (Spectrum)	Diamond (QD)	Diamond
Chip	Medipix2	Medipix3RX	Medipix3	Medipix3RX
Pixel size	**55 µm**	**55 µm**	**55 µm**	**55 µm**
Sensor	Si 500 µm CdTe 1 mm	Si 300, 500 µm CdTe 1 mm Ga As 500 µm	Si 500 µm	Si 500 µm
Matrix	256 x 256 (1) 512 x 512 (2x2) 1280 x 256 (5x1)	512 x 512 (2x2) 1536 x 1536 (5x5) 4608 x 2560 (18x10)	256 x 256 (1) 512 x 512 (2x2)	2048x512 (8x2)
Frame rate	1.4 kfps	2.0 kfps	100 fps (1) 25 fps (2x2)	100 fps (cont) 1 kfps (burst)

MAXIPIX

LAMBDA

MERLIN

EXCALIBUR

Eiger2 & Pilatus4 detectors

	Eiger2 XE-16M	Eiger 2 X 1EM	Pilatus4 XE 4M	Pilatus4 X 1M
Developper	Dectris	Dectris	Dectris	Dectris
Pixel size	**75 µm**	**75 µm**	**150 µm**	**150 µm**
Sensor	Si 450 µm	Si 450 µm	Si 450 µm Cd 1 mm	Si 450 µm Cd 1 mm
Area	311 x 327 mm^2	77 x 79 mm^2	311 x 327 mm^2	155 × 162 mm^2
Matrix	4,148 x 4,362	1,028 x 1,062	2,073 × 2,180	1,033 × 1,080
Count rate	10^7 Hz	10^7 Hz	10^7 Hz	10^7 Hz
Frame rate	550 fps	2250 fps	2000 fps	2000 fps

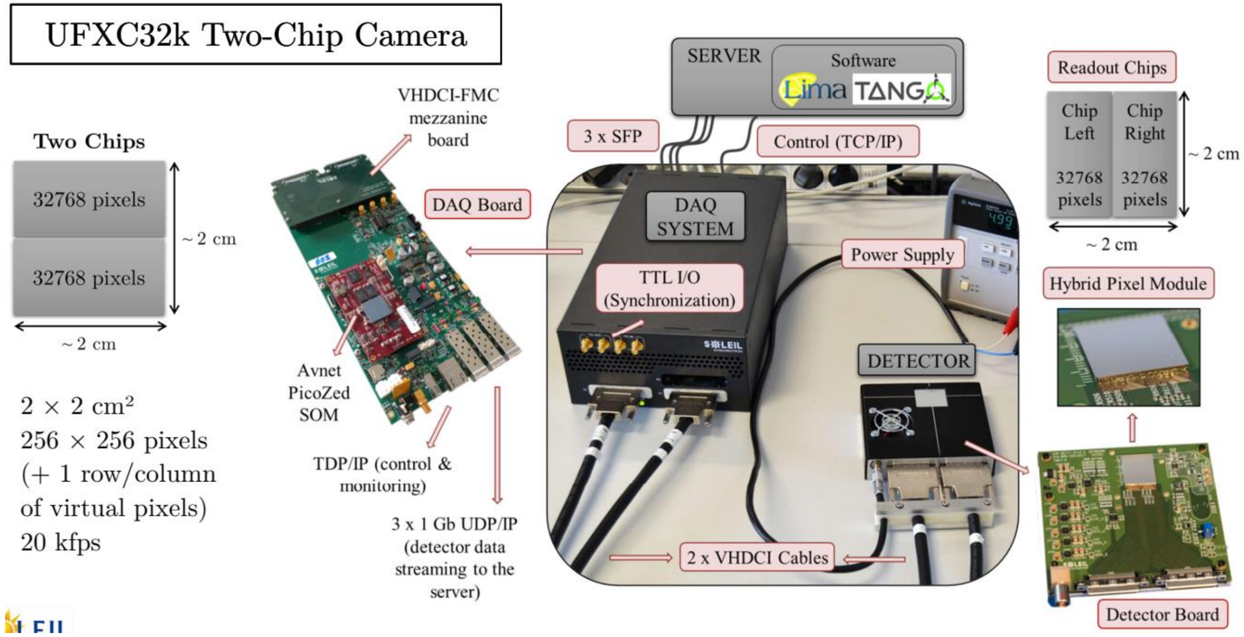
Eiger2

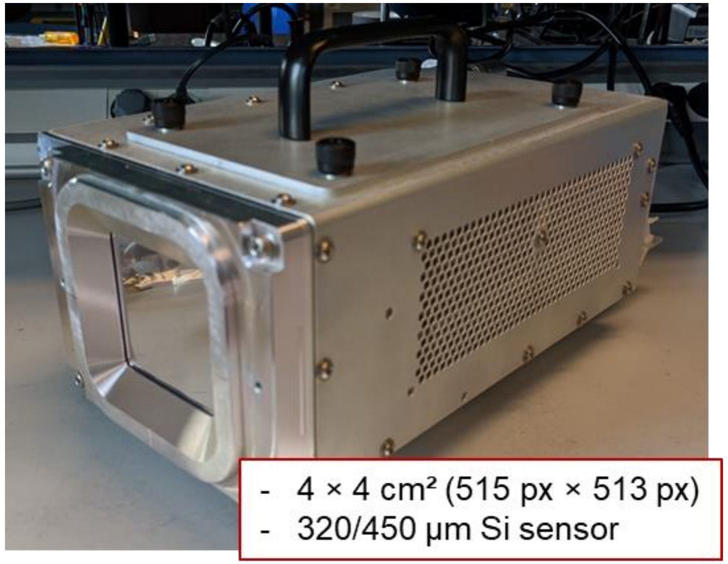
Pilatus

UFXC: Ultra-fast hybrid-pixel camera for hard X-rays

D. Bachiller Perea et al., J. Sync. Rad 27 (2020) 340-350
A. Dawiec et al., IEEE NSS-MIC (2021)

- SOLEIL R&D in collaboration with **AGH** (Poland).
- Pixel size: 75 × 75 µm², 2 threshold & 2 counters
- Linear count rate up to 2×10^6 ph/pixel/sec (max 10^7 ph/pixel/sec)
- Different readout modes: standard, continuous and pump-probe-probe
- Two versions: 2 chips (square, rectangular), 8 chips (software being finalized).
- Fully integrated in several beamlines (CRISTAL, SIRIUS, NANOSCOPIUM, …)



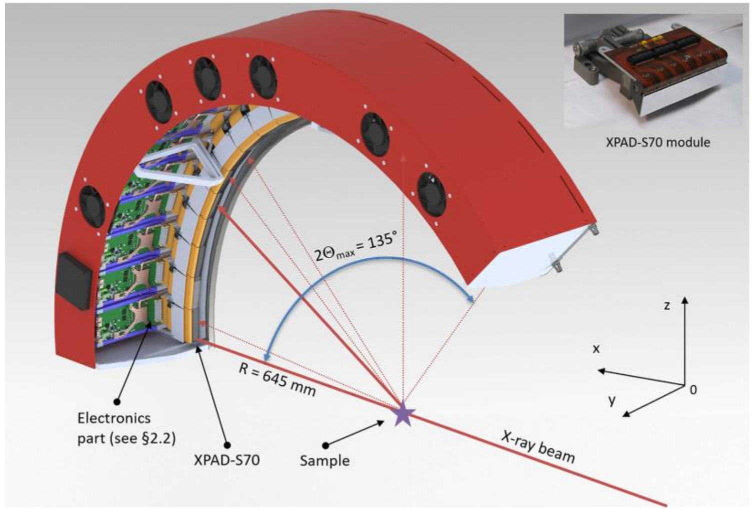


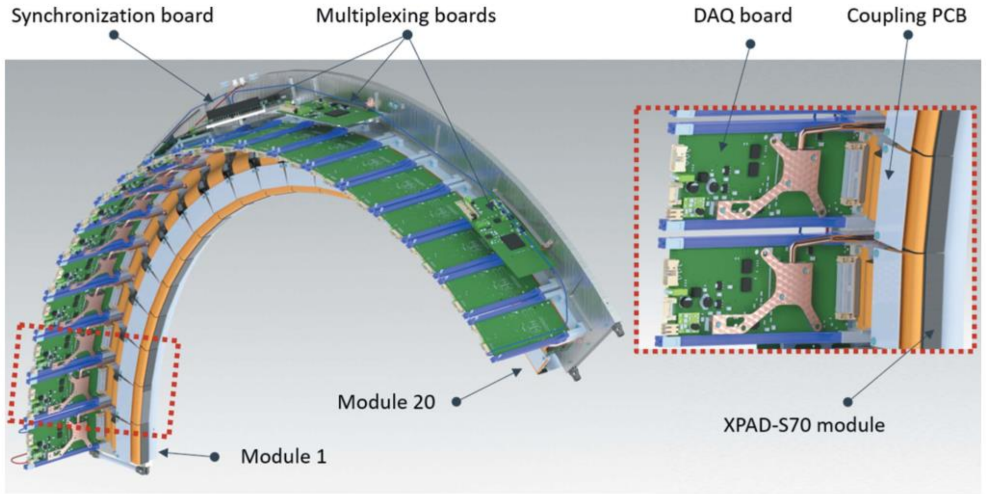
- 4 × 4 cm² (515 px × 513 px)
- 320/450 µm Si sensor

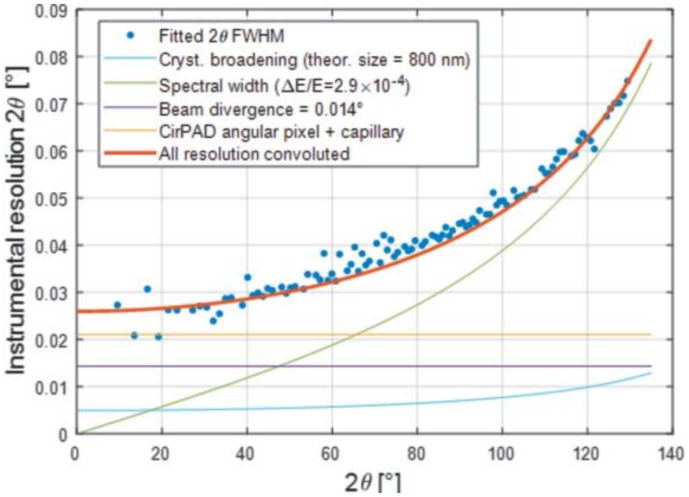
CirPAD: a circular 1.4 M hybrid-pixel detector for diffraction

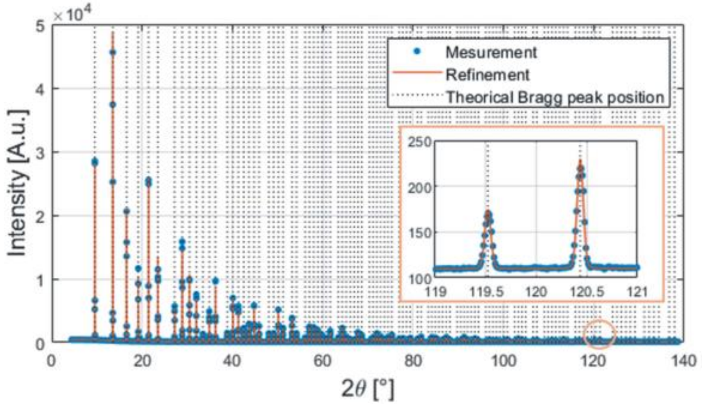
K. Desjardins et al., J. Sync. Rad 29 (2022) 180-193

- Diffractometer composed of 20 modules XPAD-S70 (67200 pixels/module) developed for DIFFABS beamline at SOLEIL
  - XPAD-S70: hybrid pixel detector (500 µm Silicon, 130 µm x 130 µm pixel size)
- Main features:
  - X-ray energy range = **7 – 35 keV**
  - Angular acceptance = **6.67° x 1.38°** (1 module) / Resolution = ~**0.02°**
  - Frame rate = **250 Hz** (continuous), **700 Hz** (980 frames)
  - Count rate limit = **0.84** (SLOW mode) - **2.5 x 10^6 ph/sec/pixel** (FAST mode)
  - Defective pixels = **0.02%** (SLOW) - **0.09%** (FAST) / Few hot pixels (0.0001%)





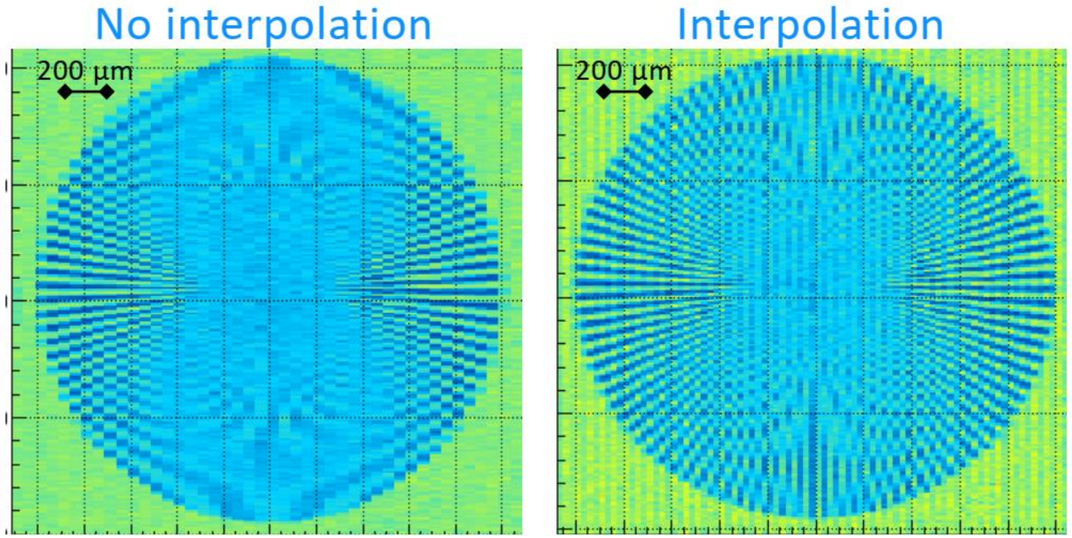




Mythen (I, II & III): Micro-strip detector for powder diffraction

A. Bergamaschi al., JSR 17 (2010), 653-668

- Diffractometer covering 120 degrees (4 mdeg resolution) composed of 24x2 modules Mythen-III developed for PSI synchrotron
- Features of Mythen-III module:
  - 1280 strips module, 50 µm pitch, 8 mm length
  - Noise level: **350-900 eV (FWHM)** / Threshold dispersion: **~20 eV**
  - Count rate capability: **3.5 – 7.75 MHz** / Frame rate = **400 fps**
  - Three counters with independent gate: **increase of count rate & sub-strip spatial resolution**



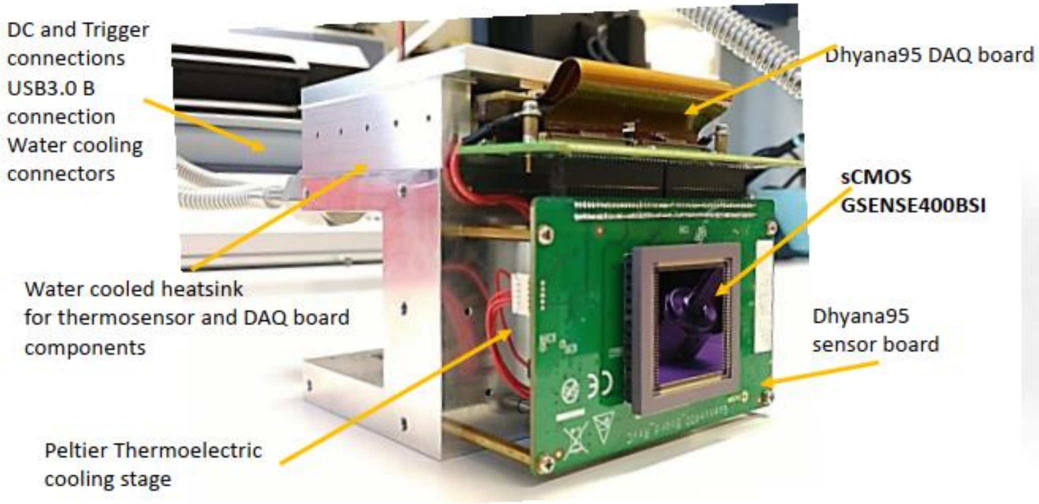
A. Bergamaschi, M. Andrä, et al., JINST 17 (2022) C11012

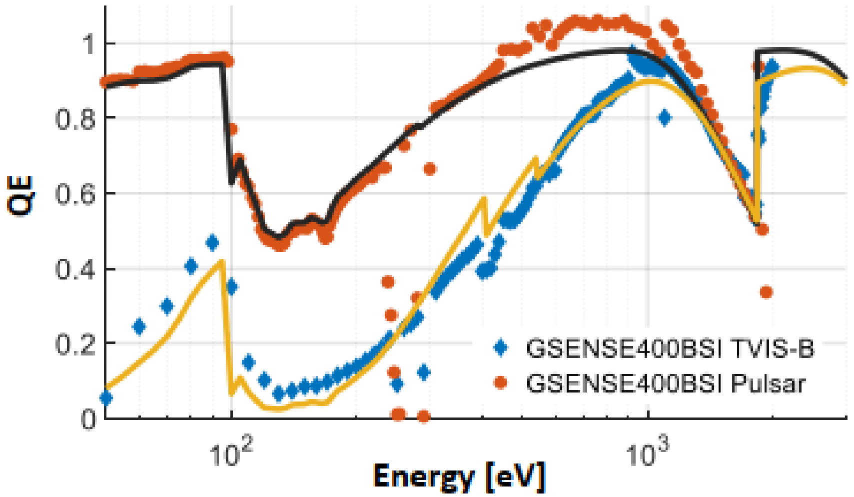
Dhyana CMOS camera for soft X-rays

K. Desjardins et al., J. Sync. Rad 27 (2020) 1577-1589

- SOLEIL internal development. Commercialized by AXIS photonics
- First version based on TUCSEN Dhyana95 camera (4 Mpx, GSENSE400BSI)
- Features: 2x2 cm^2 sensor size, low noise, large dynamic range, high QE
- Fully integrated in HERMES, SIRIUS & SEXTANTS (~10^{-6} mbar, software)
- **Current activites: 6 x 6 cm^2 sensor + spectroscopy (clustering by software)**

Camera specification	
Resolution	2048 x 2048
Pixel size	11 µm x 11 µm
Sensitive area	22.5 mm x 22.5 mm
Shutter type	Rolling shutter
Dark noise	1.7 e- (HRD)
Full well charge	85 ke- (Low Gain mode) 30 ke- (HDR mode) 2 ke- (High Gain mode)
Frame rate	24 fps (Full frame)
Dark current	> 3 e-/s/pix @ -20°C





More details at the presentation by Kewin DESJARDINS (SOLEIL)

Conclusions & outlook

- Big development of detector based on semiconductor for Synchrotron facilities
  - Sensor -> Uniform response & radiation hardness
  - ASIC -> Small pixels and large dynamic range
  - Firmware -> Reduction of charge sharing for spectroscopy
  - Readout system -> Large area covering, high frame rate
- Detector development is made by synchrotron facilities, research laboratories and private companies
- Synchrotron are pushing detector limits for facilities upgrades