Detectors for
Free Electron Laser X-ray sources

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Giornate di studio su IRIDE
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Outline

- ➢ what are the main scientific challenges in X-ray detectors for FEL sources ?
- ➢ which detector needs for the foreseen experiments @ IRIDE ?
- ➢ what are the state-of-the-art and the on-going developments in the FEL detector community ?

Why R&D of "user" detectors is mandatory for FEL sources?

- Differently from HEP/NUP communities, FEL/synchrotron users are not intended/capable to develop novel detection systems (the experiment is the *sample*, not the *detector*)

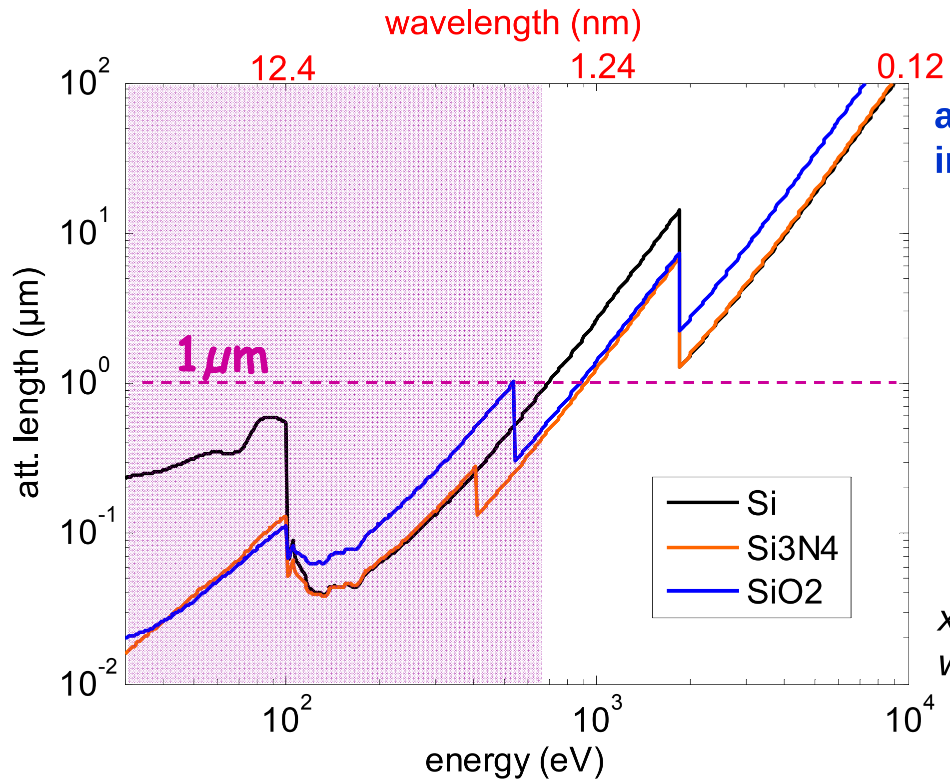
- The unprecedented features of FEL sources ask for novel detectors with specifications in some cases *exceeding the existing technology*

- A successful exploitation of an upcoming FEL facility calls for a targeted detector R&D program

- "Baseline" detectors should therefore be *integral part* of the facility and their development must start in parallel (and in synergy) with machine design.

main scientific challenges in X-ray detectors for FEL sources

#1 - Energy range and Quantum Efficiency (QE)



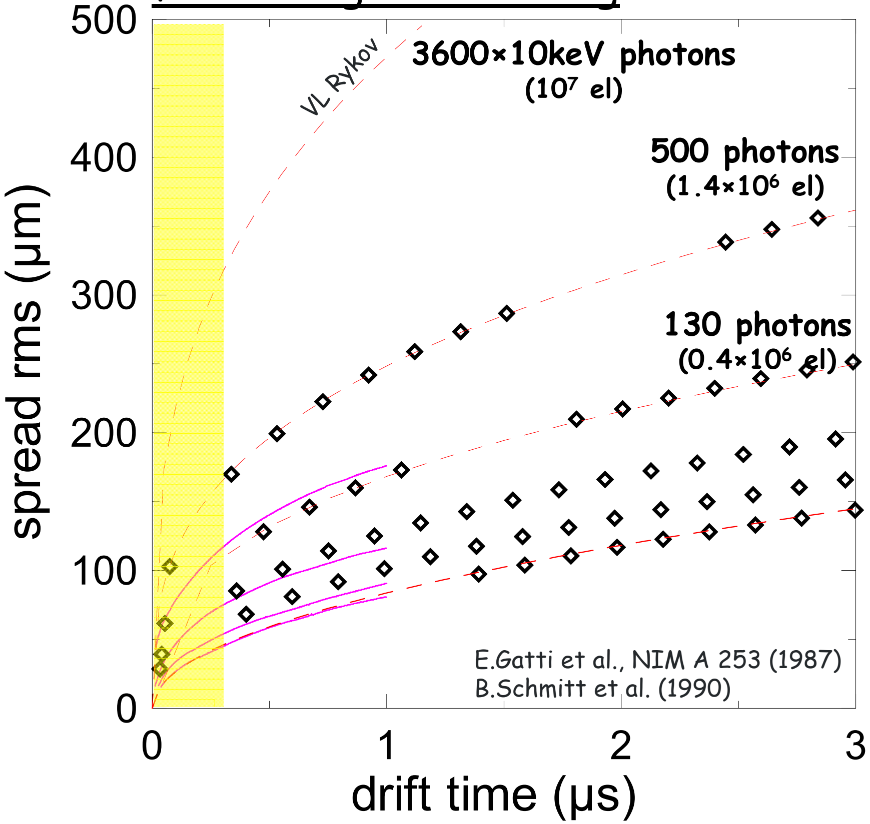
att. length of photons in Si, Si_3N_4, SiO_2

x-ray database
www.cxro.lbl.gov

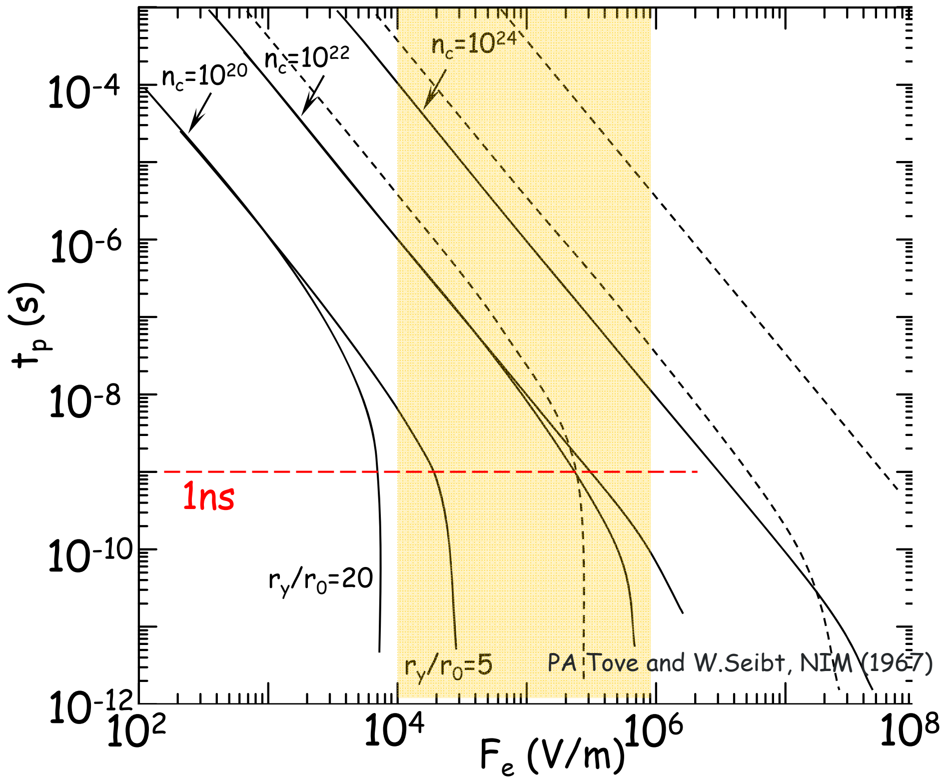
- **wide energy range** (10eV-10keV), cannot be covered by a single detector or by a single technology
- **soft X-rays** (<1keV): performance is limited by entrance window (e.g. 50 nm of SiO2: loss of 25% of 250 eV photons) and electronic noise
- **hard X-rays** (3-15 keV): good QE for 450µm-thick silicon up to 10keV, self-shielding not efficient E>10keV (radiation hardness), dynamic range/PSF issues more severe

#2 - Charge levels >10^4 photons / pixel / bunch ? Coulomb repulsion and plasma effects

experimental measurements of
free charge broadening



10^4×10keV photons = 3×10^7 e-h pairs
5 pC charge cloud → ~10^{22} el/m³ !

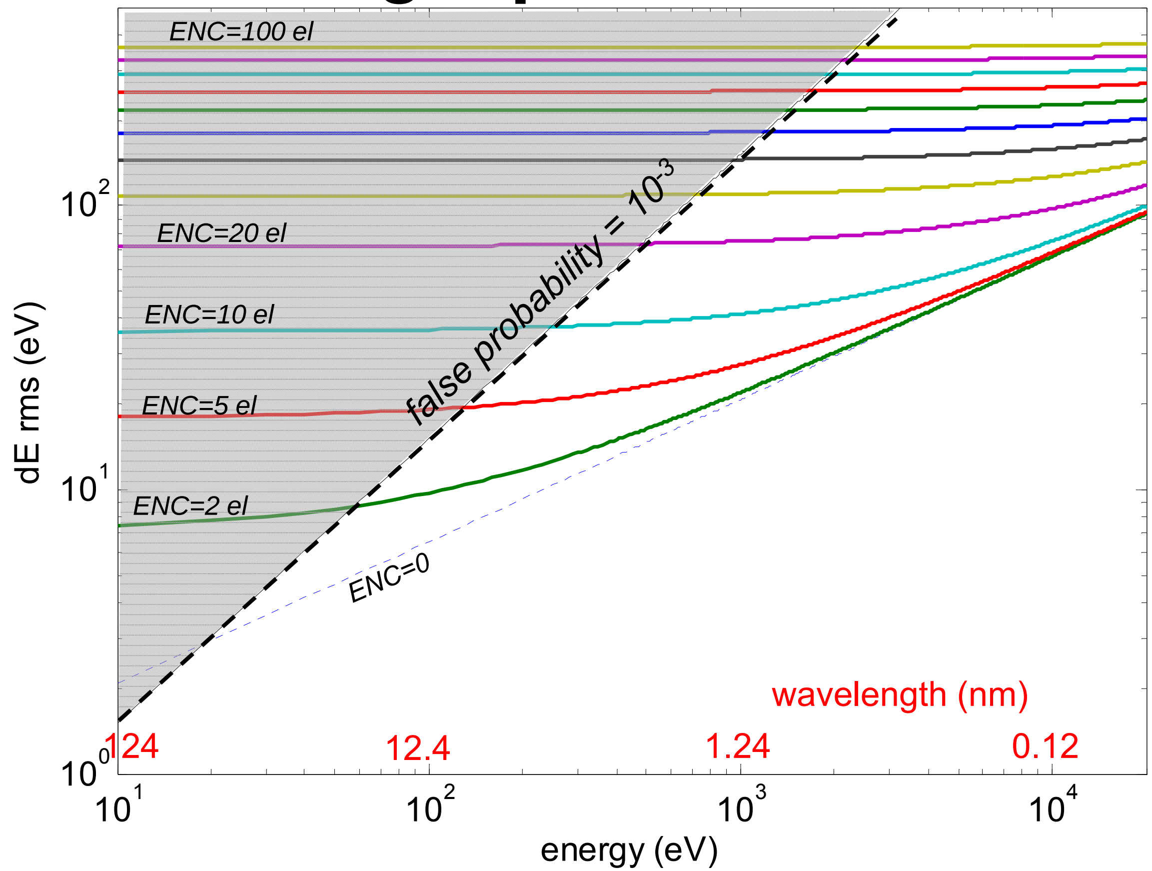


→ Plasma effects: screening of depletion field impacts on collection time, amplitude resp.

→ Charge broadening: degradation of spatial (PSF) and time resolution

→ difficult to simulate, direct characterization methods important to qualify true sensor response

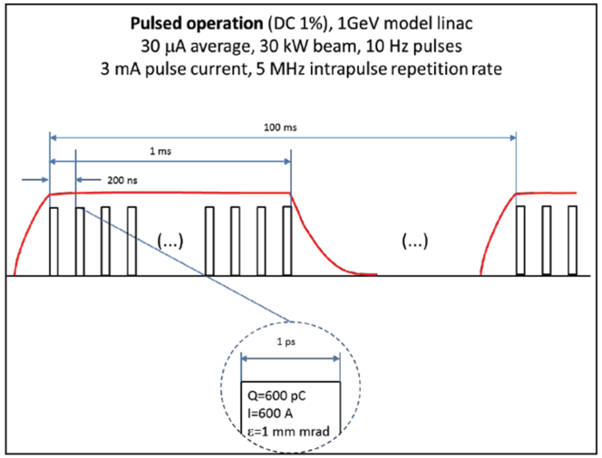
#3 - The issue of high dynamic-range and single-photon resolution

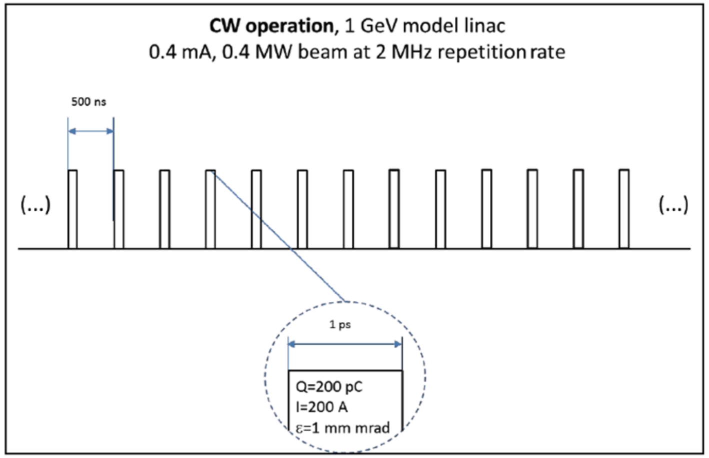


- with 100fs X-ray pulses: forget photon counting → ***only integrating detectors***
- 10^4 photons/pixel (high intensity regions) together with ***single-photon resolution*** (0/1 photon/pixel to be discriminated)
- single photon resolution of ***soft X-rays*** with low false-positives requires *very low electronic noise* (e.g. E=100eV generates 27 e-h pairs in Si → requires ENC<2 el rms)
- ***tradeoff*** between long filtering times for *better noise performance* and *readout speed*

#4 - Time structure of the X-ray pulses

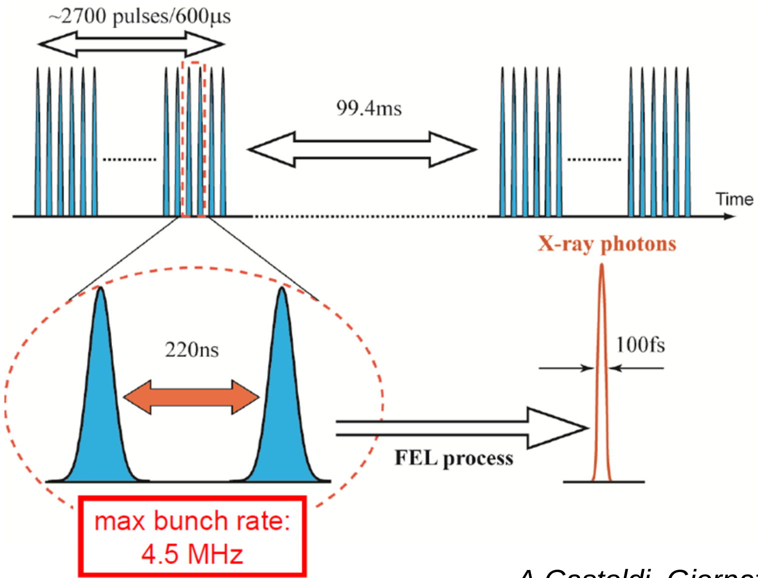
Every X-ray pulse can be regarded as a new imaging experiment → the detector must be able to readout, digitize and store the data before the arrival of the next pulse !





Pulsed vs CW operation ? @ IRIDE

Pulsed operation @ XFEL.Eu



- LCLS/Spring-8/FERMI@Elettra (CW operation, non SC): evenly spaced pulses from 120 Hz to 10 Hz (a *non-critical operating condition*)
- XFEL.Eu at Hamburg (pulsed operation): bunch trains of ~3,000 pulses with a *challenging time separation of 220ns*. Long silent gap (99.4 ms) exploitable for off-chip data transfer. In total ~30,000 pulses per second.
- IRIDE: CW operation at 2 MHz rate will provide nearly 2 orders of magnitude more luminosity than XFEL.Eu but *only 500ns* for frame readout *without any time gap → critical, lower rep frequency recommended*

Which detectors are needed for the foreseen experiments?

In general every experiment may require a specific detection system but we can identify two major scientific cases:

- **energy-sensitive detectors** with Fano-limited energy resolution for spectroscopic experiments, possible position-sensitivity for angular-dispersive experiments (0-D and 1-D detectors):
  - silicon drift detectors
  - high-Z detectors
  - cryogenic detectors
  - etc.

- **area detectors for imaging experiments**, diffraction (2-D detectors):
  - Charge-coupled devices
  - Hybrid Pixel Detectors
  - Monolithic Active Pixel Sensors
  - etc.

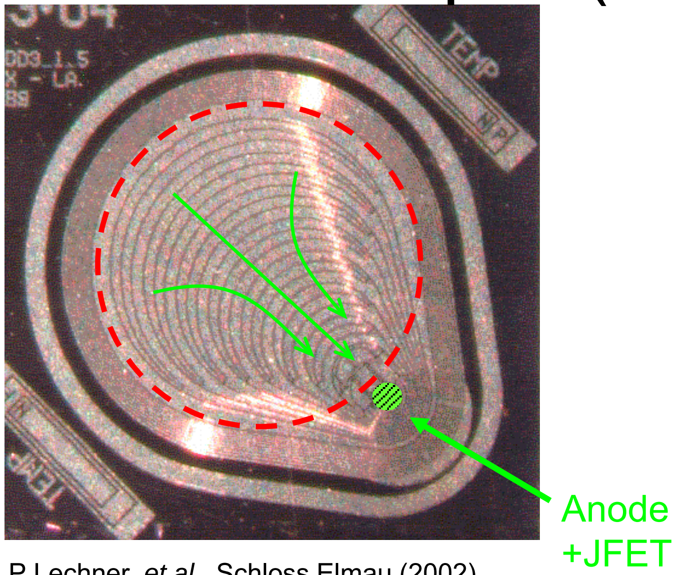
state-of-the art and ongoing detector developments for FEL experiments

(only relevant examples, not a full review)

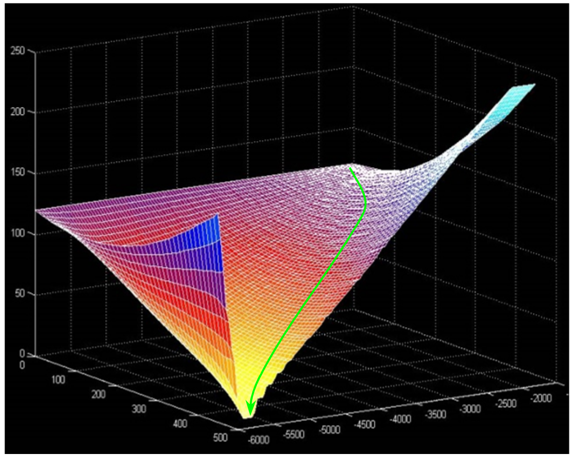
Energy-dispersive detectors
SDD Droplet (SD^3)

→ SDD: leading technology for high res. spectroscopy

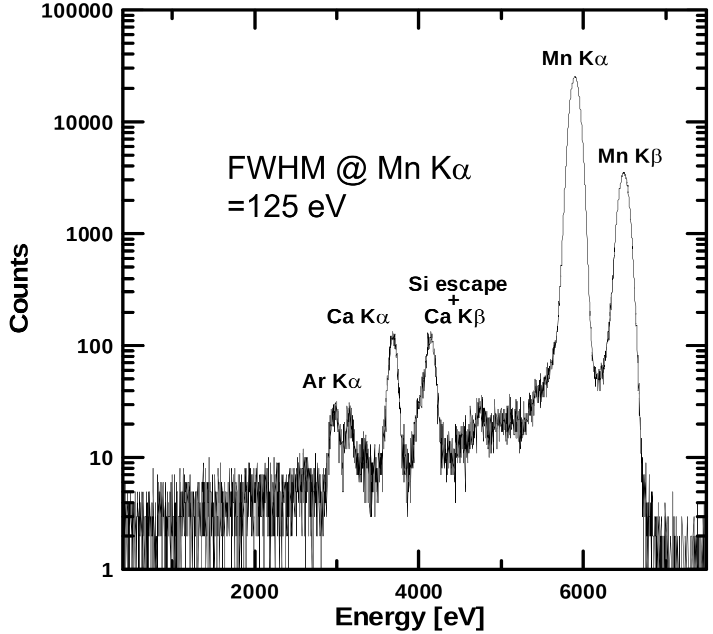
→ SDD-Droplet: anode moved to periphery of active area and drift field shaped accordingly



P.Lechner, *et al.*, Schloss Elmau (2002)



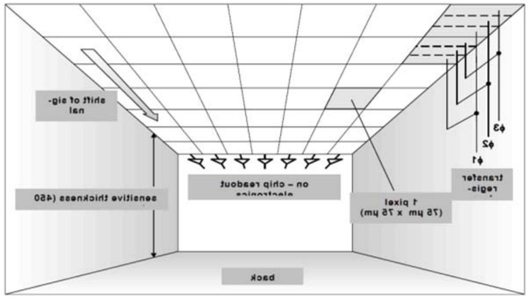
- Anode capacitance: ~100 fF
- Energy resolution: ΔE_{FWHM} = 125 eV (equivalent to ENC=4 el. r.m.s.) @ 200kcps
- Count rate capability: up to 10^6 cps
- Peak/Background ≈ 10.000 : 1
- Quantum efficiency: > 90% @ 0.3-10 keV Rad. hardness: > 10^{14} Mo_K photons
- Operating temperature: T ≈ - 10° C



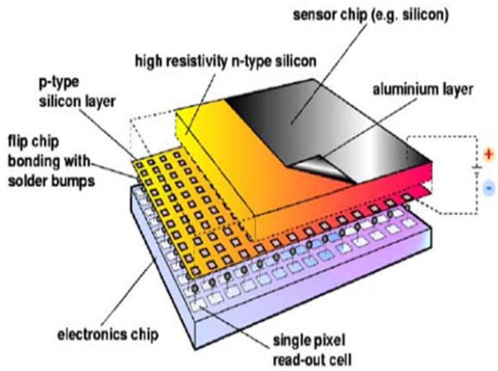
At high rates dedicated developments in the readout electronics and processing also required

Technology options for 2D X-ray detectors

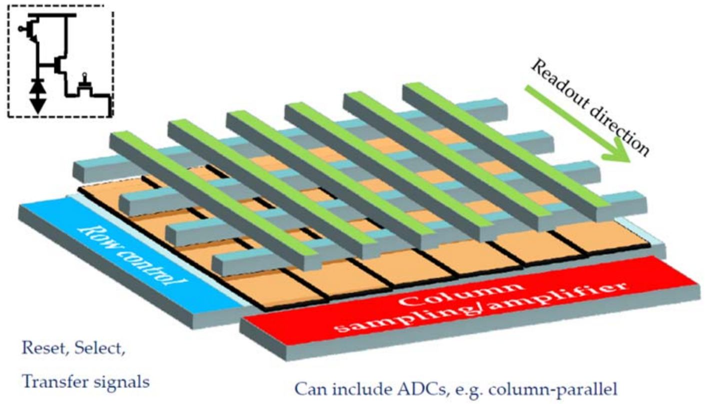
- ❑ **Fully-depleted pn-Charge-Coupled Devices (pnCCDs)**
  - o very low noise (~2 el rms)
  - o high QE in the range E=0.1-10keV
  - o full frame rates limited to 200 Hz
  - o full well capacity ~ 10^6 el. (but horizontal blooming)



- ❑ **Hybrid pixel detectors (HPDs)**
  - o detector and front-end ASIC optimized separately
  - o bump-bond size limits pixel size and capacitance
  - o low energy X-rays critical if no on-chip transistor is available
  - o issue of bump-bonding process



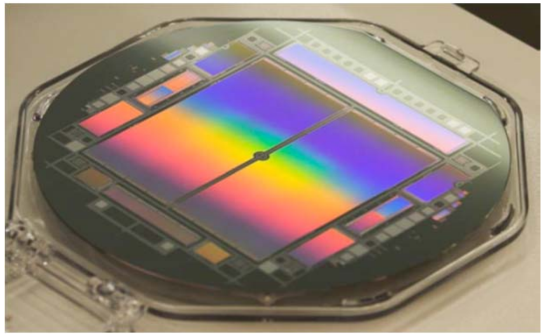
- ❑ **CMOS Monolithic Active Pixel Sensors (MAPS)**
  - o depleted region is the epilayer (max ~20µm), poor QE for E>1keV
  - o charge collection by diffusion
  - o large full well capacity
  - o high dynamic range (20bit?)
  - o high readout speed (up to few kHz frame frequency)

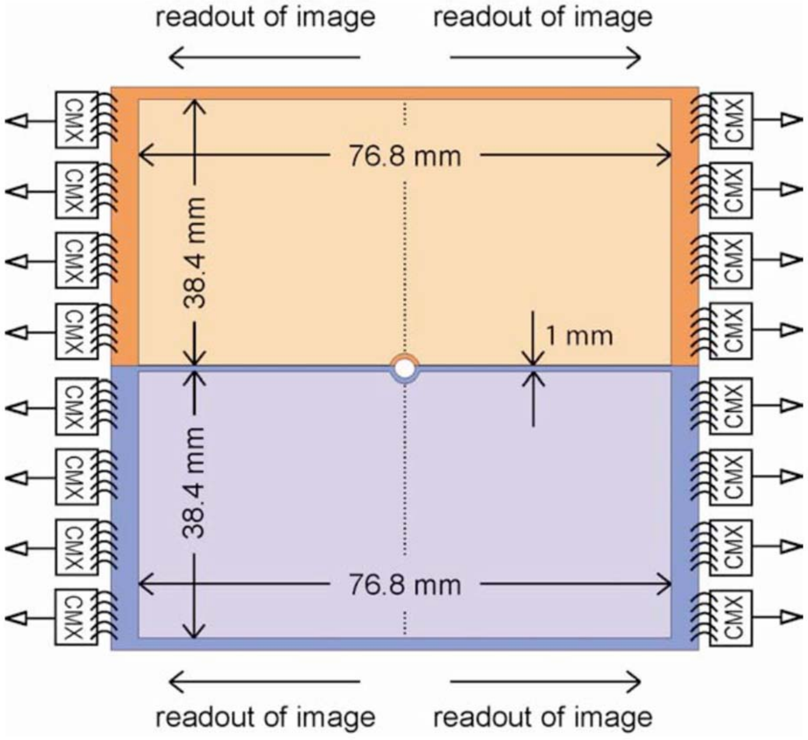


and other choices under continuous development:

- ❑ MOS CCDs
- ❑ «Passive» pixel sensors
- ❑ Position-sensitive Silicon Drift Detectors
- ❑ ……

Fully-depleted pnCCD for the CFEL-ASG Multi-Purpose (CAMP) chamber





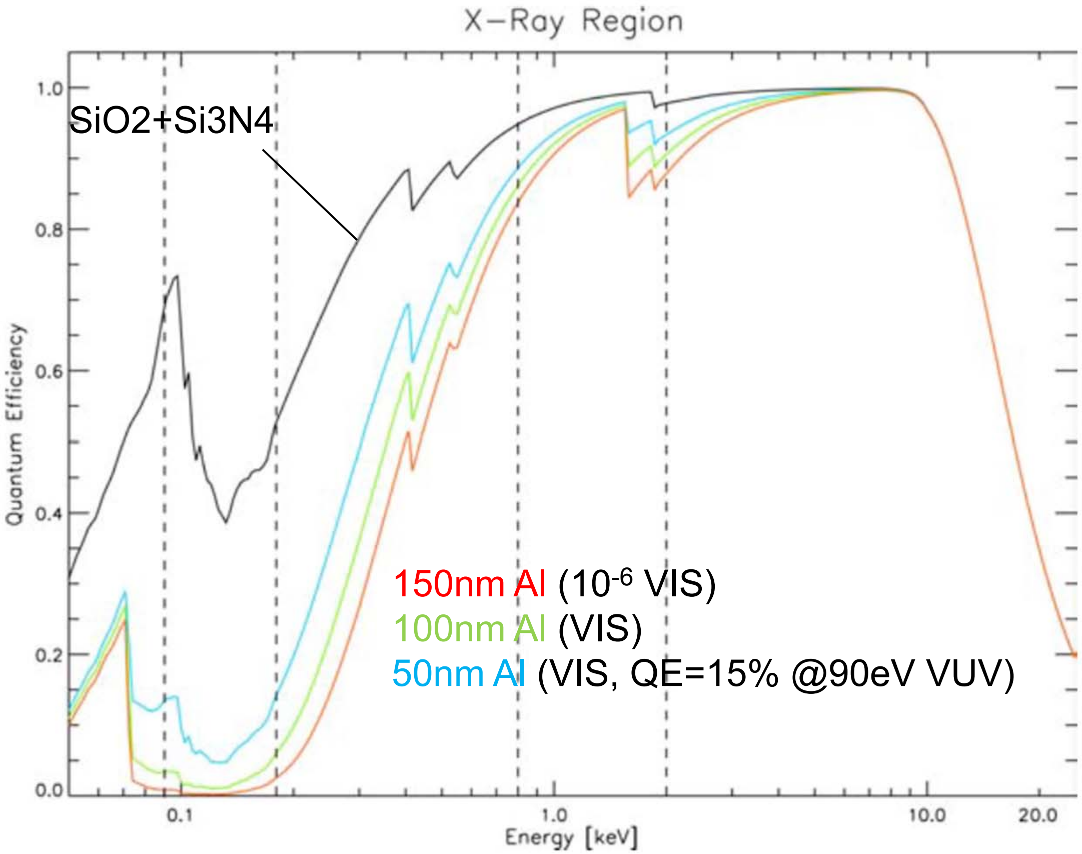
L.Struder, et al., Large-Format, High-Speed, X-ray pnCCDs Combined with Electron and Ion Imaging Spectrometers in a Multipurpose Chamber for Experiments at 4th Generation Light Sources, NIM A 614 (2010) 483-496

Table 1: *Experimental requirements for the 2-D detectors and current pnCCD properties*

Parameter	2-D imager requirements for FLASH, LCLS, SCSS and XFEL requested by the user community	pnCCD properties
single photon resolution	yes	Yes
energy range	0.05 to 24 keV	0.05 to 25 keV
signal rate/pixel/bunch	10^3 (10^5)	10^3 at 2 keV
charge handling capacity	—	approx. 5 x 10^5 electrons per pixel
quantum efficiency	> 0.8	> 0.8 from 0.3 to 12 keV
number of pixels, format	512 × 512 (min.)	1024 × 1024 and 2048 × 2048
pixel size	< 100 × 100 μm^2	75 × 75 μm^2
frame rate repetition rate	5 Hz to 120 Hz (except XFEL´s 5 MHz operation)	continuous up to 200 Hz
externally triggerable	—	yes
integrated center hole	Ø 3 mm	Ø 2.4 mm
European XFEL burst mode	5 MHz (3 000) bunches	not applicable
readout noise	< 150 electrons	20 e$^-$ (low gain), 2 e$^-$ (high gain)

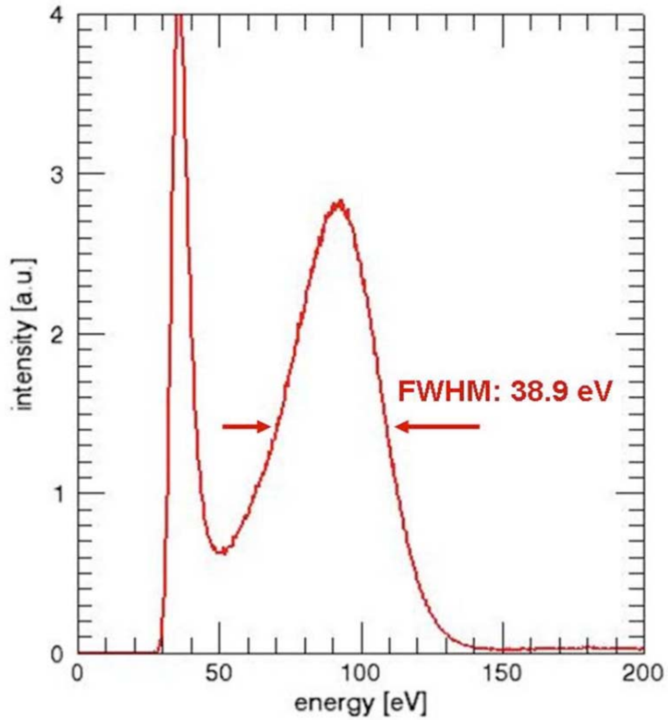
- joint effort of Max-Planck, DESY, Un. Hamburg
- Aim: meet requirements of novel VUV and Xray FEL sources
- the world's largest pn-CCD chips (60 cm2)
- present 1k x 1k pixels (75 x 75 μm2) → future 2k x2k
- frame readout rate of up to 200 Hz → compatible with LCLS (up to 120 Hz) and SCSS (up to 60 Hz)
- High QE fully-depleted high resistivity silicon
- read-out noise of 2.5 electrons (rms) at -50°C

Fully-depleted pnCCD - performance



QE of the pnCCDs as a function of energy for a 450 μm thick pnCCD detector for different tailoring of the X.ray entrance window.

Energy resolution measured at FLASH with 90 eV (11.4 nm) photons. Every photon generates approximately 25 electron-hole pairs. They have been detected with a read noise of 2.5 electrons (rms)

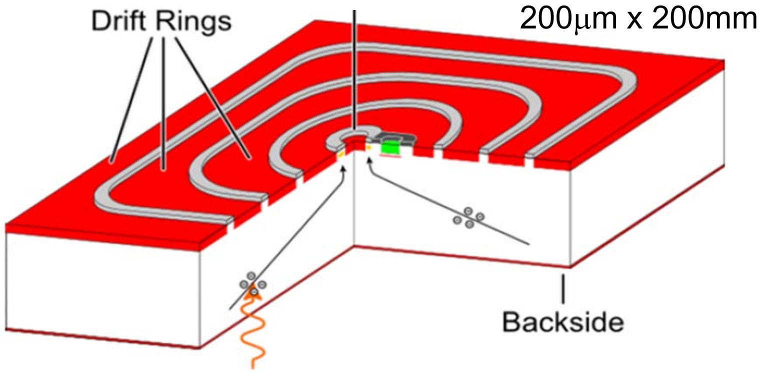


R.Hartman, et al., Large format pnCCDs as imaging detectors for X-ray Free-Electron Lasers, 2008 IEEE NSS Conf. Records, pp.2590-2595

Active Pixel Sensor with Depleted PMOS readout and signal compression for XFEL.Eu

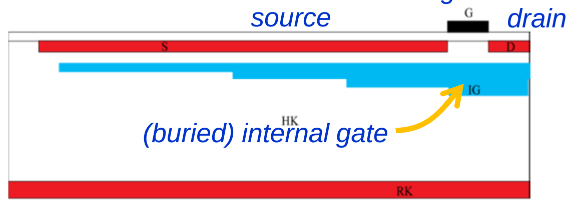
DePMOS with signal compression

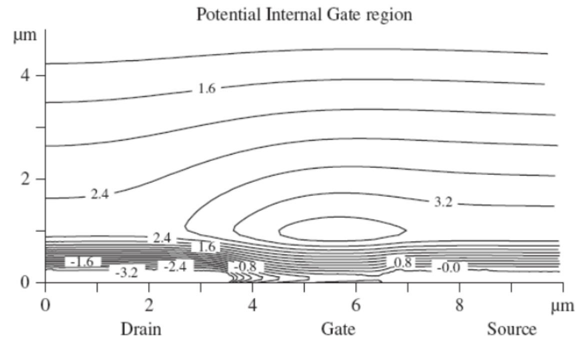
200µm x 200mm

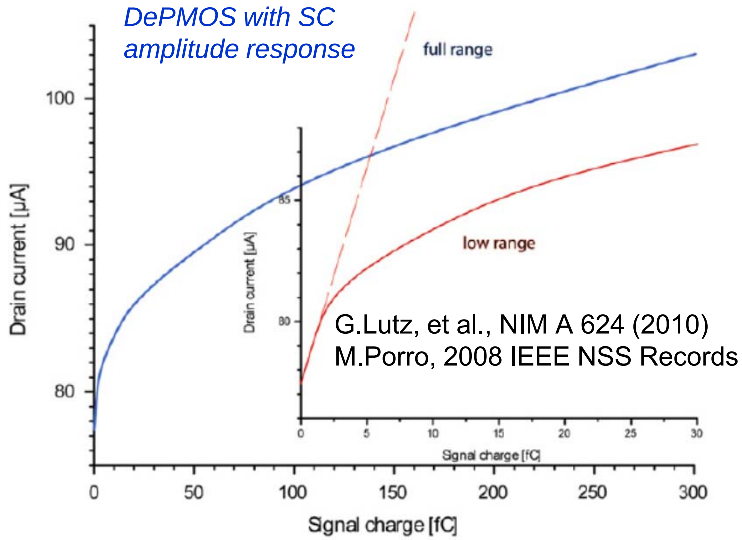


Cut through a macropixel cell

DePMOS with signal compression







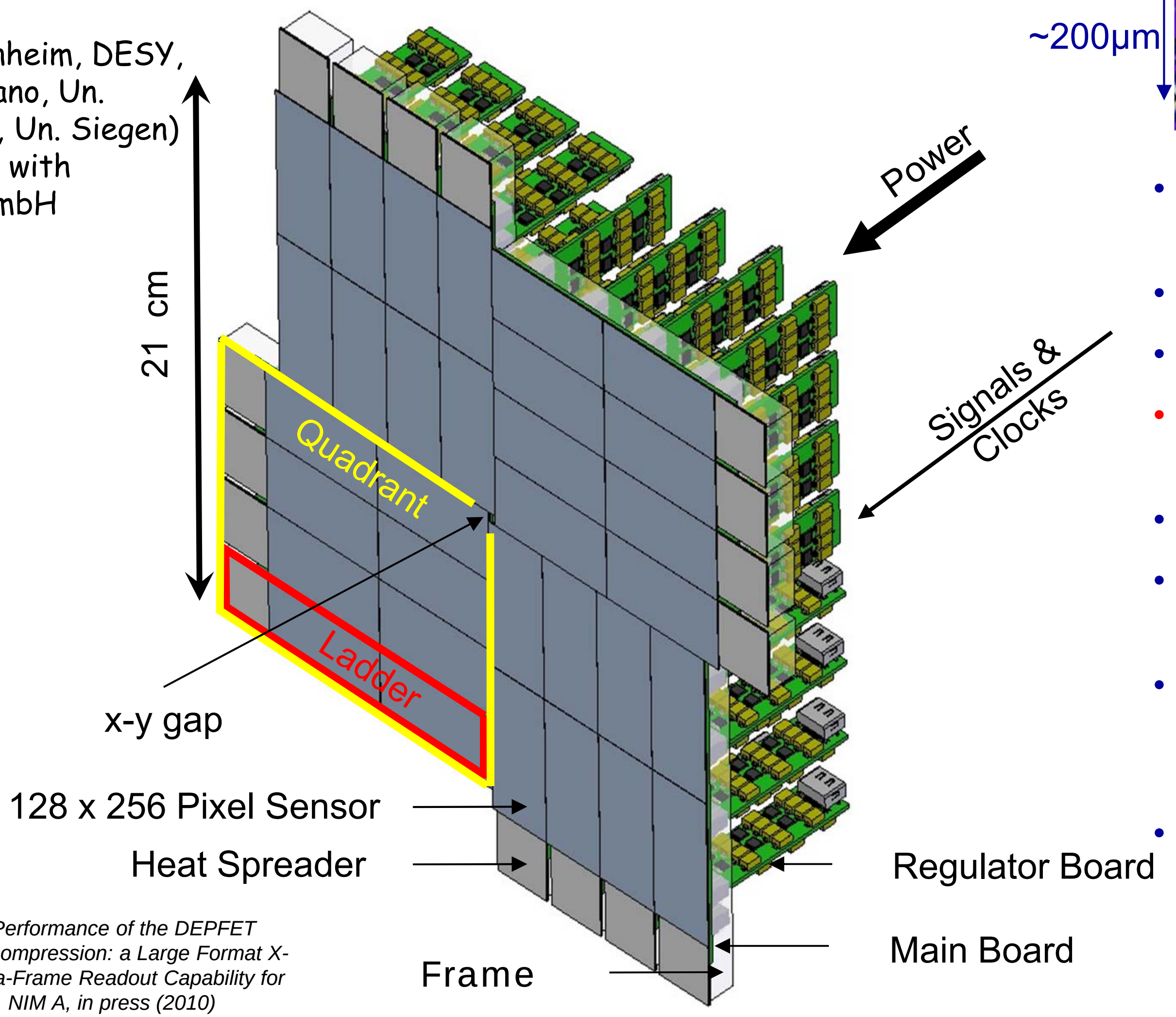
G.Lutz, et al., NIM A 624 (2010)
M.Porro, 2008 IEEE NSS Records

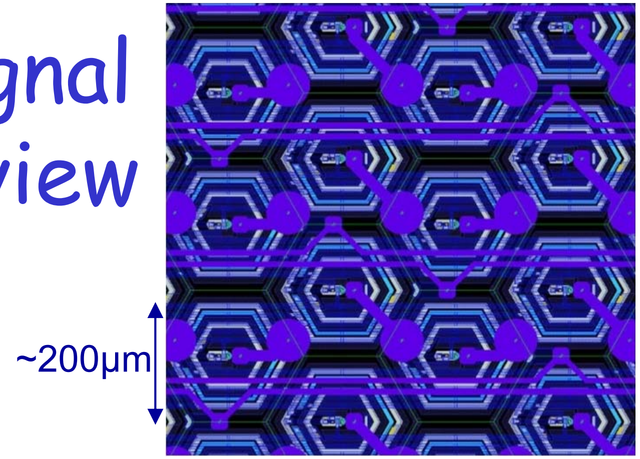
- one of the 3 currently on-going Hybrid Pixel Detector developments @XFEL.Eu (DSSC, AGIPD, LPD)
- optimized for the low energy (down to 0.5 -1keV)
- **In-pixel drift structure** to allow fast and complete collection at buried gate
- **DePMOS readout**
  - collecting anode=internal gate
  - high energy resolution (single photon counting @ 0.5 keV and 1keV)
  - fast readout up to 4.5 MHz rate
- analog **signal compression** mechanism in the DePMOS for high dynamic range operation

DSSC (DePMOS Sensor with Signal Compression) - Focal plane overview

scheduled for the middle of 2015

Developed by DSSC Consortium (MPI, Un. Mannheim, DESY, Politecnico Milano, Un. Pavia/Bergamo, Un. Siegen) under contract with DESY/XFEL GmbH





- E=0.5-25keV **(optimized for 0.5-6keV)**
- 1024x1024 pixels
- DR>6000 photons@1keV
- **Single photon resolution @ 1keV @ 5MHz**
- Noise <50 el rms
- ~600 stored frames/macro-bunch
- DePMOS Sensor bump bonded to 8 Readout ASICs (64x64 pixels)
- Dead area: ~15%

M.Porro, "Expected Performance of the DEPFET Sensor with Signal compression: a Large Format X-ray Imager with Mega-Frame Readout Capability for the European XFEL", NIM A, in press (2010)

PERSIVAL
Pixelated Energy Resolving CMOS Imager, Versatile And Large

- joint effort of DESY, RAL and Elettra (DIAMOND in the process of joining)
- Aim: develop X-ray imager for FLASH and FERMI, ELETTRA, DIAMOND and other facilities for CFEL (Center for Free Electron Laser Science) scientists
- Sensor developed at RAL, readout at DESY

Sensor goals

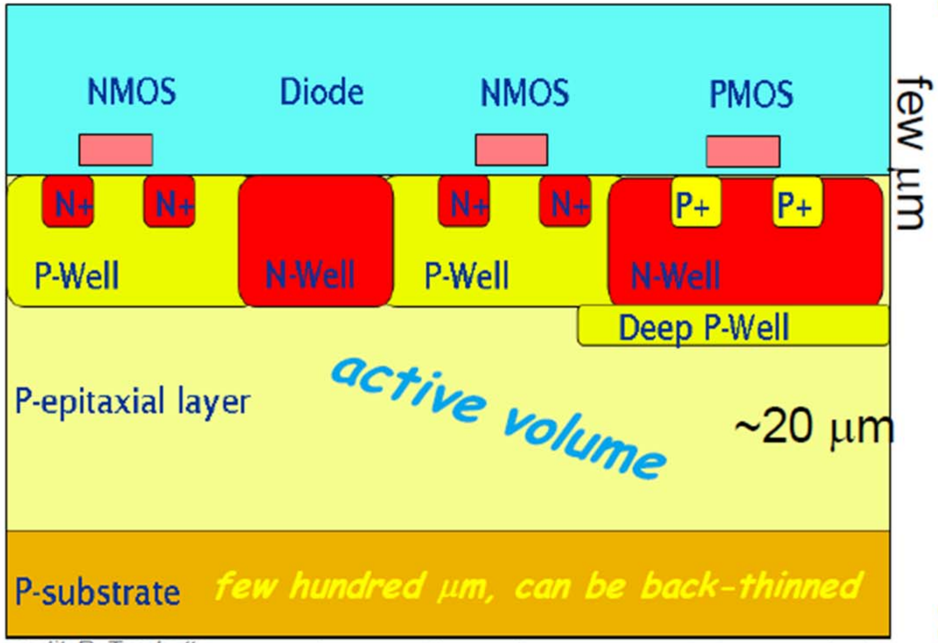
- **Energy range** (<200 eV –) **250 eV – 1 keV** (- few keV)
- **minimum 1k x 1k (more is better!) pixels** ⇨ **4kx4k pixels**
- need **10 – 100 μm pixels,** best <30μm ⇨ **25 μm pixels**
- **single-photon sensitivity** with low probability of false positives
- **(very) high Quantum Efficiency** ⇨ need > 85%, wish > 95%
- **QE uniform over sensor** (bragg peaks might be sub-pixel size!)
- sensors must be **2-side buttable**
  ⇒ can combine to form a 8k x 8k cloverleaf
- faster frame rate is better

Sensor needs specific to FEL usage

- **120 Hz frame rate** and lower
  (to work at base rate of existing/near future FELs)
- **large dynamic range**
  (10^5 photons/pixel/image good, 10^6 photons/pixel/image great)
- **No bleeding** to neighboring pixels, even if dynamic range is exceeded

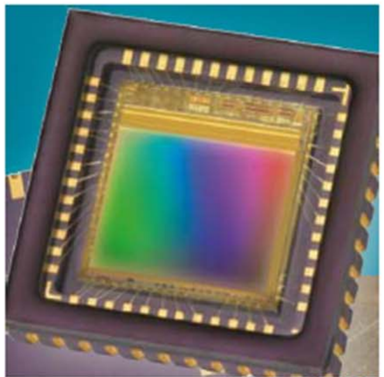
credit C.Wunderer @CFEL, Jan 2013

MAPS



credit: R. Turchetta

schematic – layers not to scale!



one commercial CMOS imager (e2v)

Note small number of connections!

> Front illumination:

- ~100% fill factor only for for harder X-rays or energetic charged particles
- Smaller fill factors (active area adjacent to logic) feasible especially for optical light where lenses can be used to compensate
- Then sensing area and logic area compete for space

> Back illumination:

- Photons incident from back (=bottom)
- Substrate thinned / removed
- Then can achieve ~100% fill factor for X-ray and soft X-ray photons

Project is underway, first back-thinned system foreseen in 2014

Some conclusions, so far

- The evaluation of the advantages/disadvantages of different detector technologies and architectures and discussion of FEL experiments @ IRIDE should continue in the next months
- Detectors for day-one operation should be decided - together with the needed resources and time scale - both on the basis of existing&proven technologies and with novel (and strategic) development programs where a step in sensor performance is mandatory to fulfill the requirements of the experimental cases
- Several other open & challenging issues: radiation hardness, front-end electronics, calibration and digitization/data reduction/data transfer/etc, not analyzed here for brevity, should be part of any instrument development.
- Detectors for X-ray beam diagnostics, not discussed here, a fully different detector family with other challenging issues, to be defined together with the design of the beamline frontend