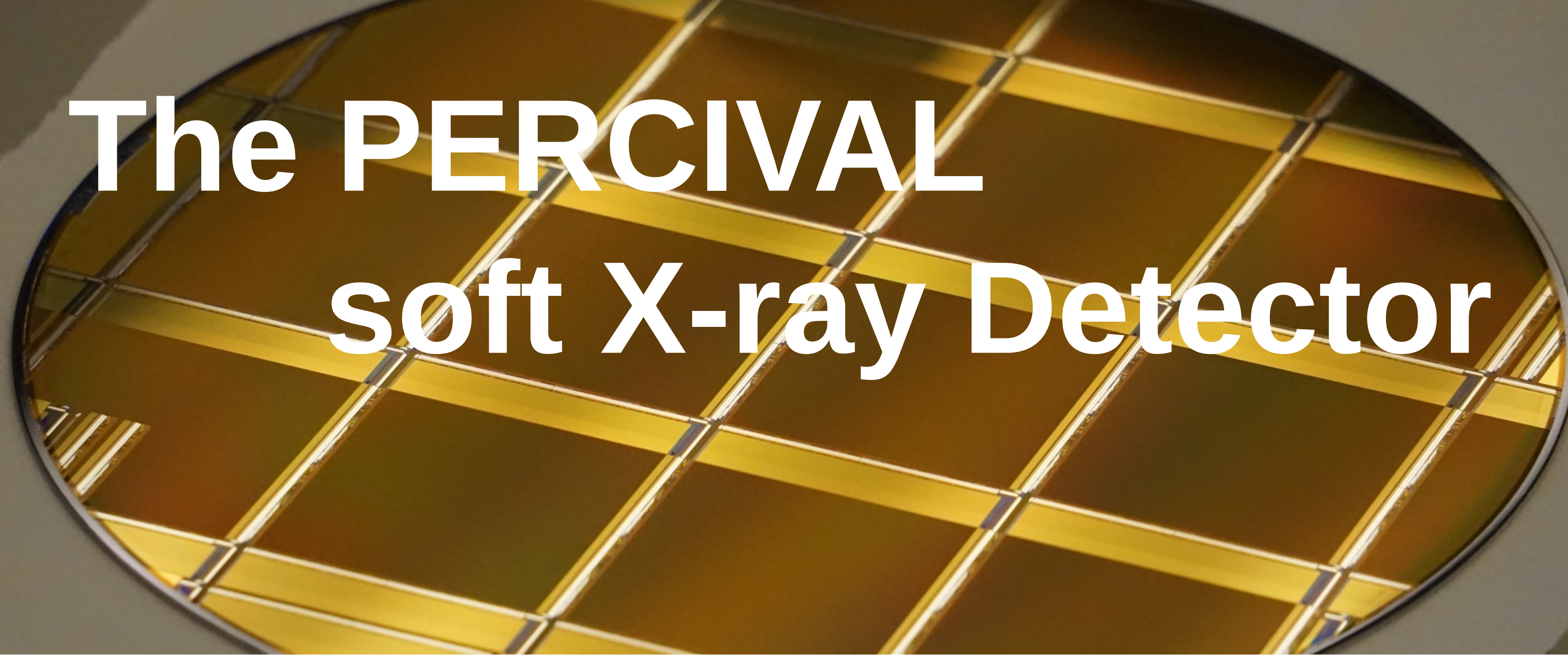
The PERCIVAL soft X-ray Detector



Jonathan Correa
DESY – Photon Science Detectors
IEEE – NSS 2018, Sydney

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CFEL SCIENCE

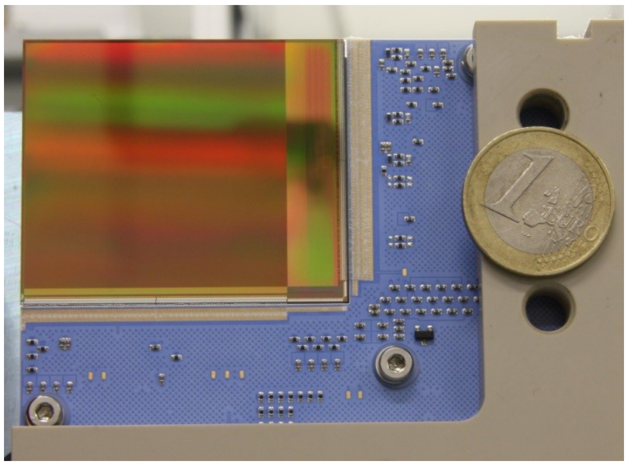
PAL

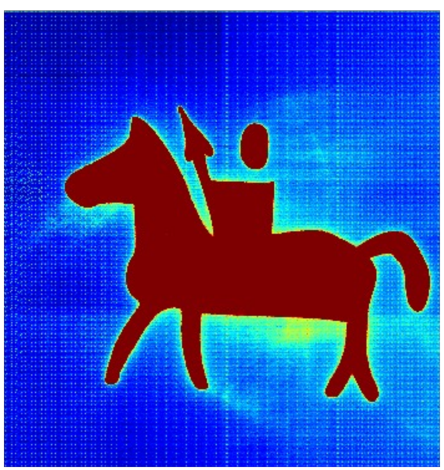
Elettra Sincrotrone Trieste

DESY.

PERCIVAL

in a nutshell





Energy Range	Primary: 250eV – 1keV Extended: 100eV - 3keV
Quantum Efficiency	> 85%, uniform over pixel
Pixel Size	27 um^2
Active Area	1440 x 1484 pixels / 4 x 4 cm^2
Frame Rate	120 / 300 Hz
“Full Well”	> 10^7 e-
Resulting Dynamic Range	10^5 photons (@ 250eV)
Sensor Output	Digital, LVDS
Buttability	2-side (adjacent edges)
Exposure Mode	FEL: all photons in < 300 fs Synchrotron: Quasi-continuous

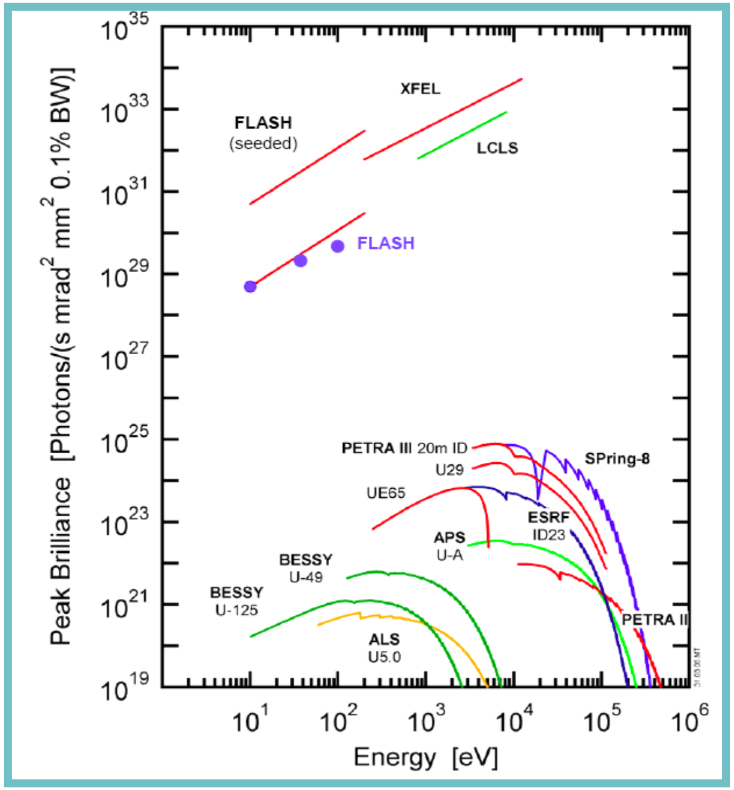
Elettra Sincrotrone Trieste

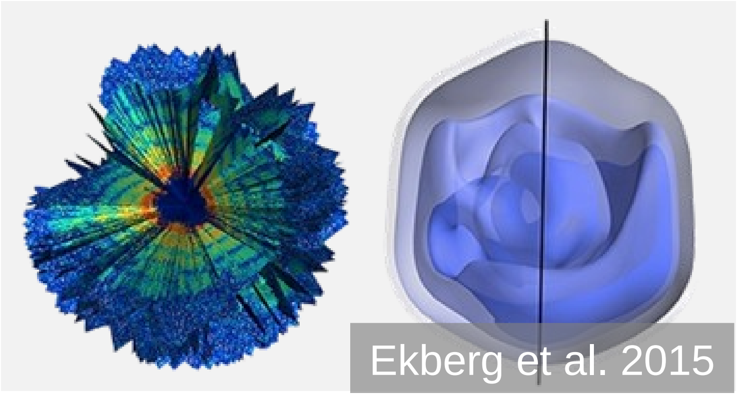
Science Motivation

Watching biomolecules in action … and more

- Making optimal use of the brilliance of today's photon sources requires
  - Single-shot imagers with suitable frame rates
  - Very large dynamic range
    - single-photon discrimination to
    - 10^4 photons/pixel/frame and more
  - Millions of pixels with little/no dead area

- In the soft X-ray regime
  - Scientific interest e.g. biosystems, weakly scattering samples
  - Particular challenge: small signal requires very low noise
  - Particular challenge: sensor surface





P2M Sensor

Designed by partner Rutherford Appleton Lab / STFC

- CMOS imager (180nm technology)

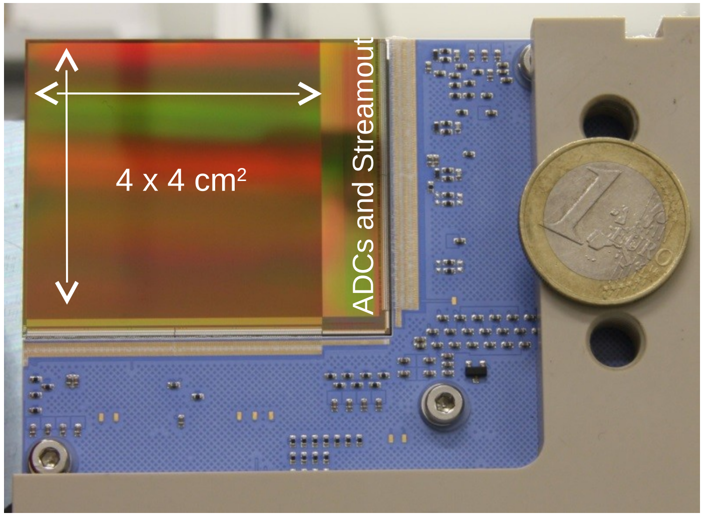
- On-chip digitization (11520 ADCs)

- 3 auto-adjusting gain levels
(per pixel, per frame, overflow)

- 1408 × 1484 pixels, 27µm × 27µm

- 4 × 4 cm² continuous imaging area
(stitched sensor)

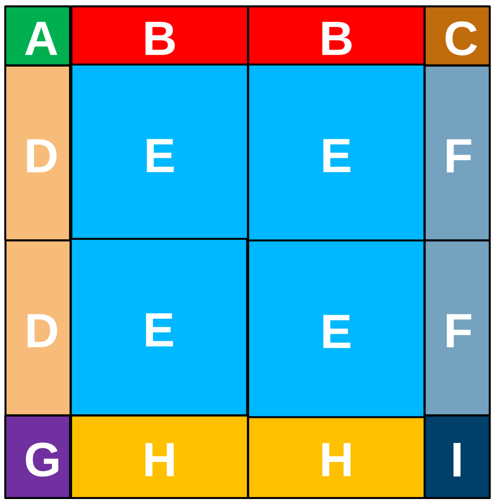
- Data rate at 300Hz frame rate is 20 Gbit/s, streamed out over 45 LVDS lines
(240 MHz, double data rate)



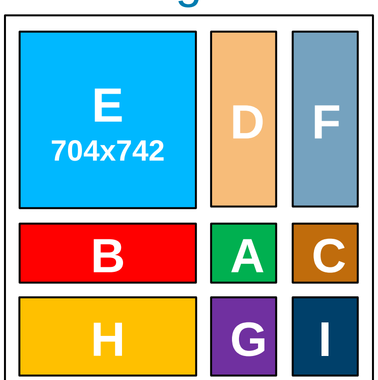
P2M Sensor

Designed by partner Rutherford Appleton Lab / STFC

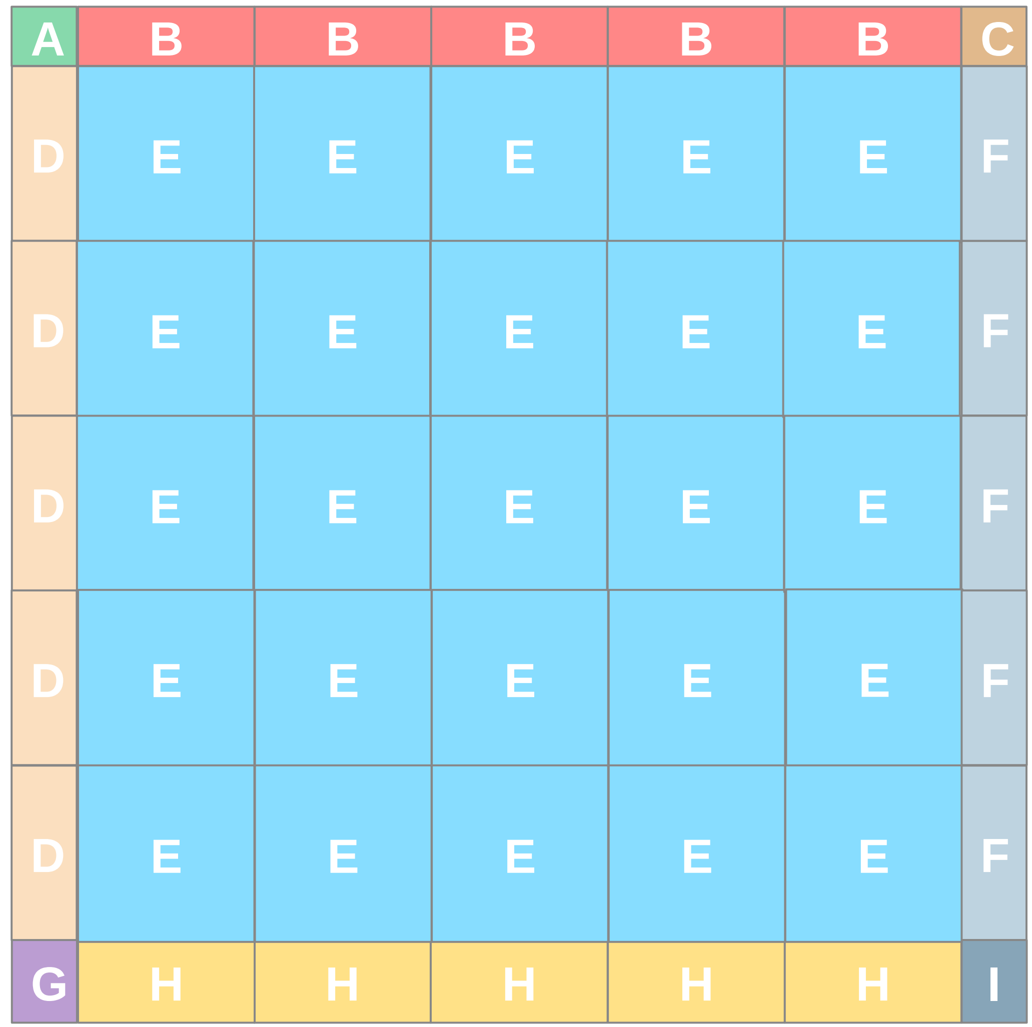
1408 x 1484 pixel P2M



stitching blocks



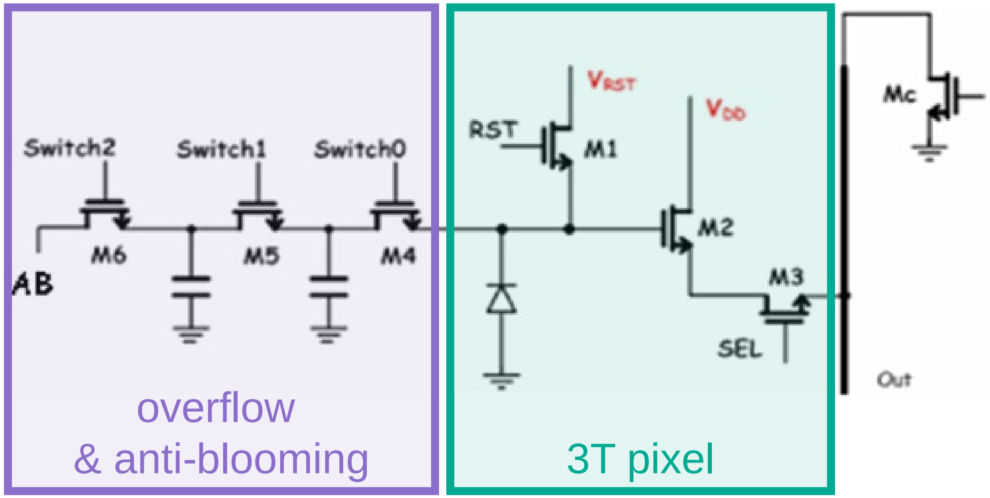
3520 x 3710 pixel variant, P13M ~ 10x10cm^2

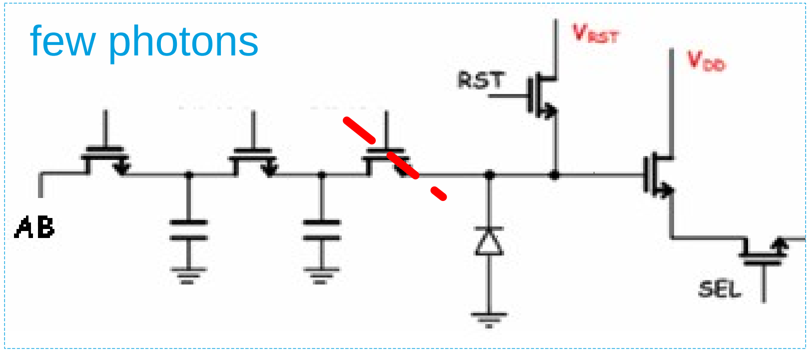


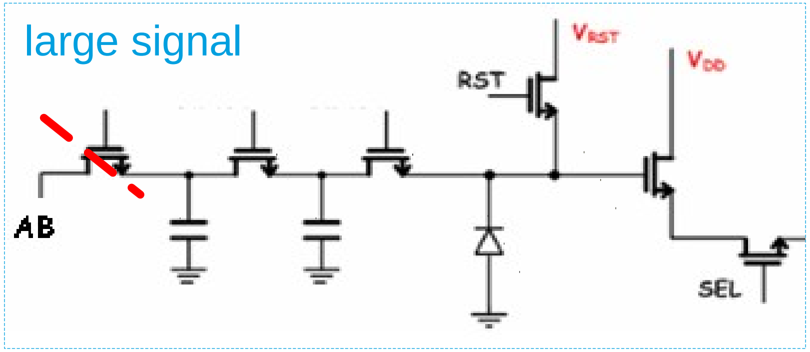
P2M Sensor

Designed by partner Rutherford Appleton Lab / STFC

- 3 auto-adjusting gain levels(per pixel, per frame, overflow)
- Readout sequentially tests all three overflow configurations for each pixel against threshold
- Only best candidate digitized & sent to DAQ

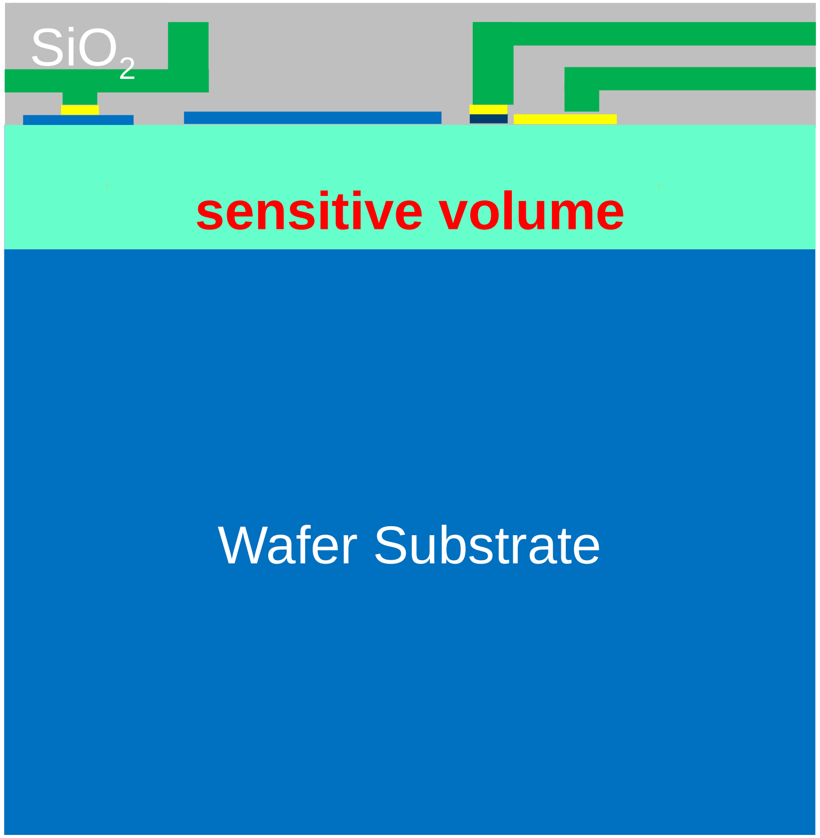






Backside Illumination

How to enable soft X-rays to interact in the sensitive volume



~ 10 µm SiO_2 & metals

~ 10 µm epi Si

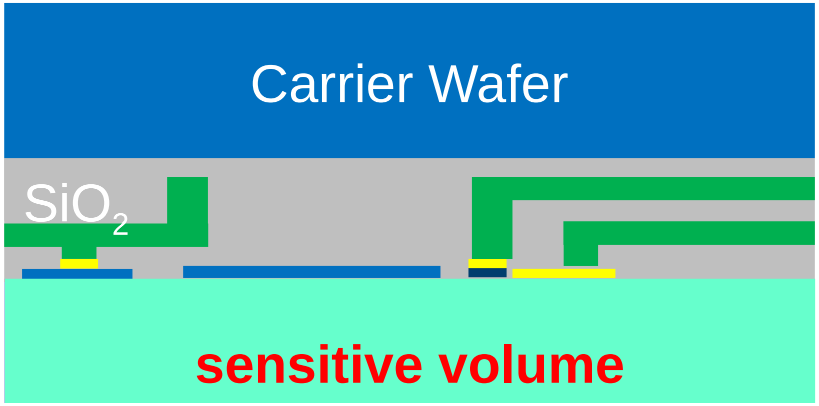
~ 700 µm low-resistivity Si

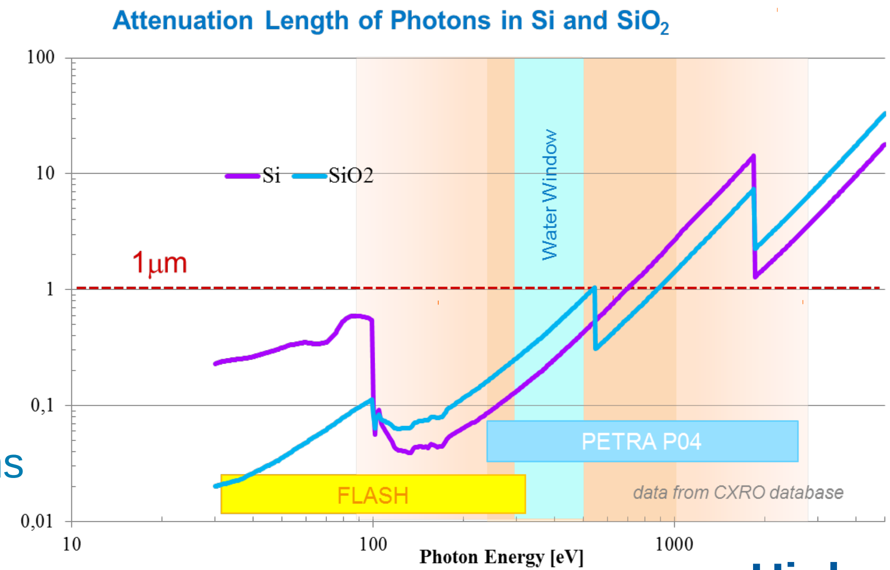
Entrance Window Post-processing

How to enable soft X-rays to interact in the sensitive volume

High sensitivity to low-energy radiation requires:

- Absence of passive material and traps
- Optimized field geometry at sensor surface



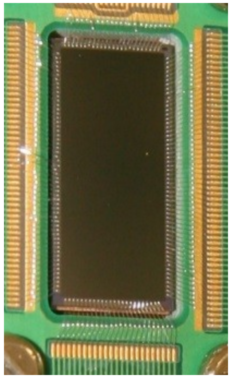


e.g. 50 nm of SiO_2:
loss of 25% of 250 eV photons

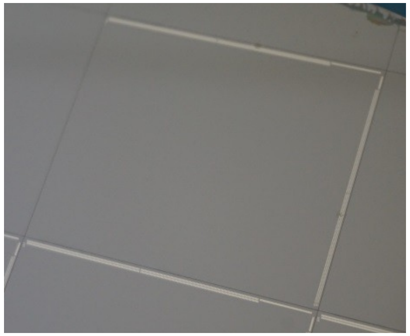
High-quality backside processing is crucial!

Post-Processing for PERCIVAL

- Prototype Sensor post-processed by NASA's JPL "delta-doping"



  - Pioneered ultra-thin entrance windows (few nm)
  - Bureaucratic difficulties mainly make access difficult & time-consuming
  - TS sensors processed by JPL give nice soft X-ray performance
  - Unfortunately e.g. not possible to BSI-process 2nd generation test devices in reasonable time

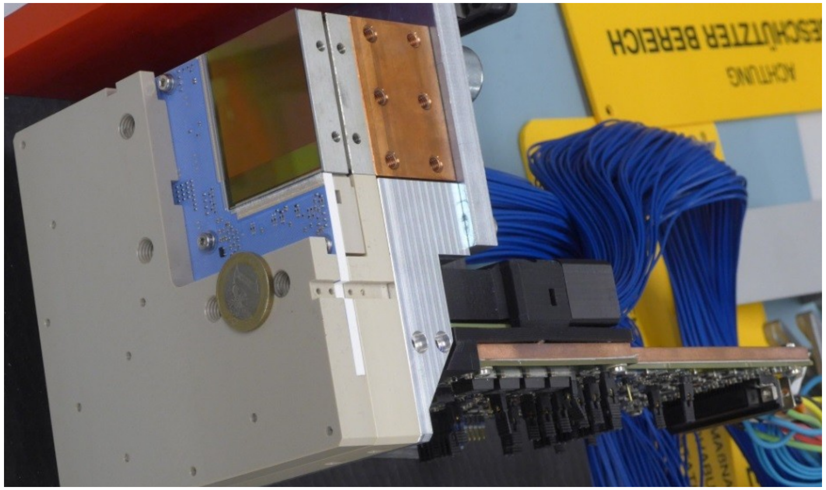


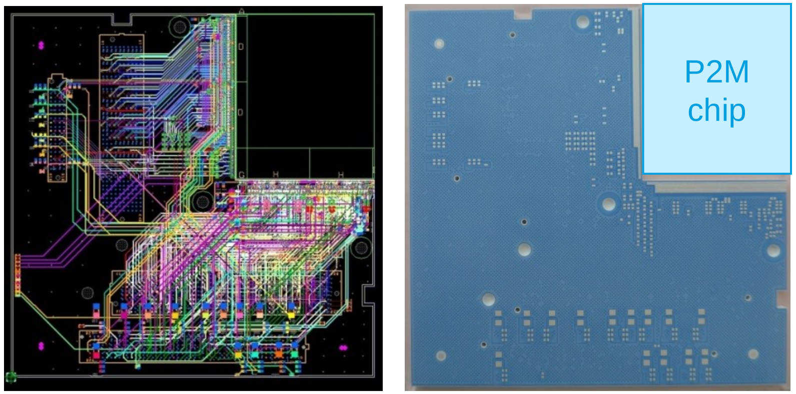
- P2M sensor post-processing
  - JPL remains a key partner and will process wafers
  - Exploring alternate routes to "good" post-processing (for some applications 10s of nm are acceptable)
  - EMFT currently a partner in tests (bonding, thinning, pad exposure)
  - Some routes to thicker dopant layers (10s to 100s of nm) exist, not tried yet
  - Easier-to-access MBE-based post-processing capable of processing both wafers and single (prototype) sensors direly needed

P2M System

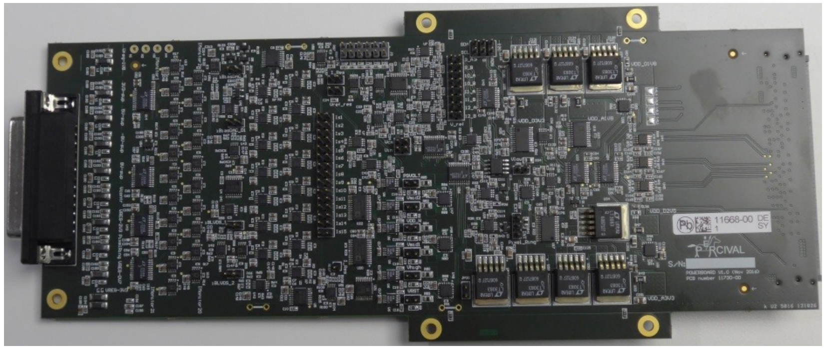
Currently undergoing benchtop tests in front-illuminated configuration

- In-vacuum detector head
  - sensor
  - Includes sensor biasing board
  - Several hundred LVDS control & data lines, are (re)distributed here
  - Sensor will be cooled to ~ -30°C
  - 2-side buttable
  - movable





LTCC routing & actual board

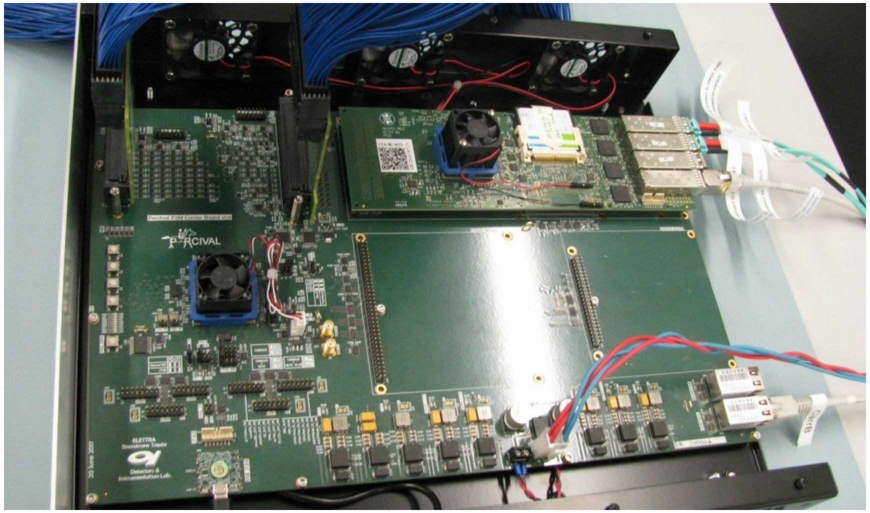


PowerBoard for sensor supply & biasing

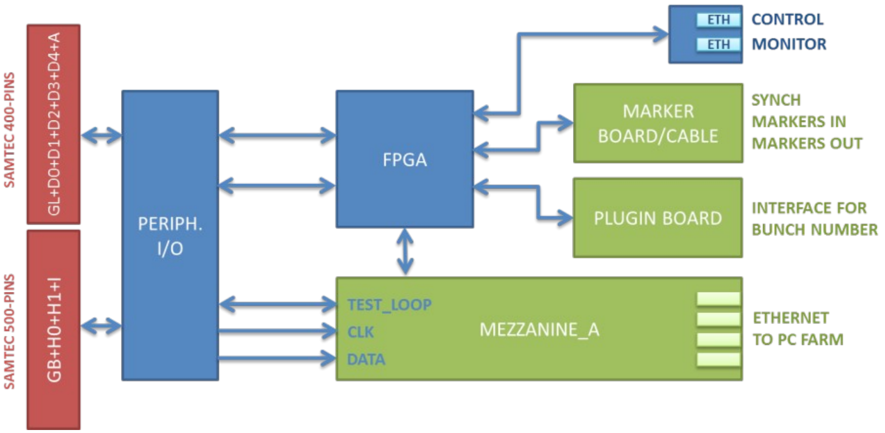
P2M System

Currently undergoing benchtop tests in front-illuminated configuration

- Carrier board hosts
  - FPGA running finite state machine
  - Mezzanine board (also AGIPD, Lambda) reordering data for easier processing streaming out 20 Gbit/s data
  - Interface to slow control, facility information, trigger



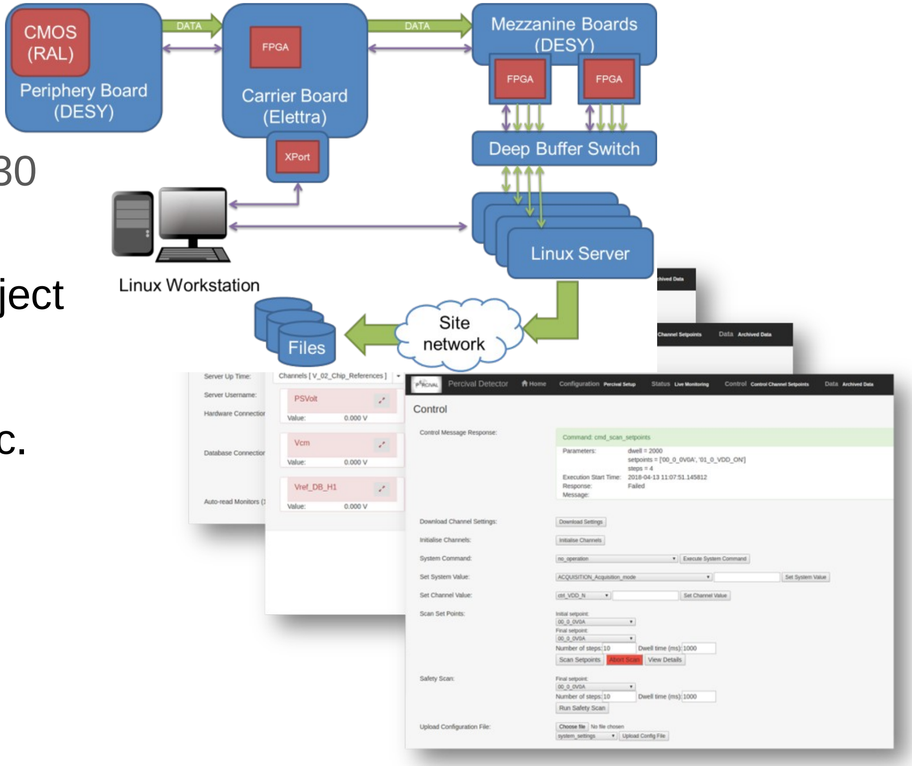
Mezzanine for data streamout
shared by AGIPD, LAMBDA, and Percival



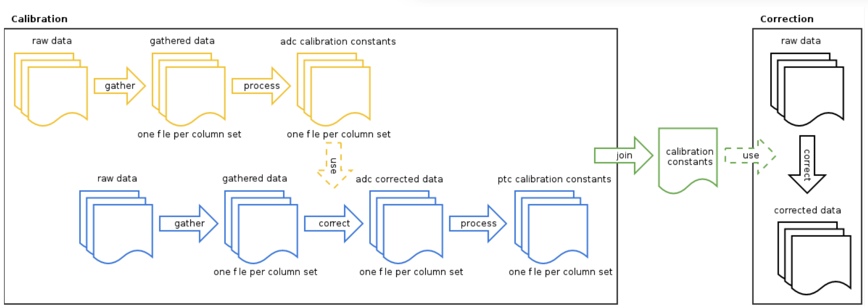
P2M System

Currently undergoing benchtop tests in front-illuminated configuration

- Control & DAQ
  - 20 Gbit/s from one sensor
    (reading full images: 300 Hz, 2M pixels, 30 bit/pixel incl. CDS)
  - Virtual hdf5 developed in part for this project
  - Python interface & Odin GUI interface
  - API for link to Tango, DOOCs, EPICS, etc.



- Software Framework for Characterization
  - Data validation
  - Calibration constants
  - Sensor characterization

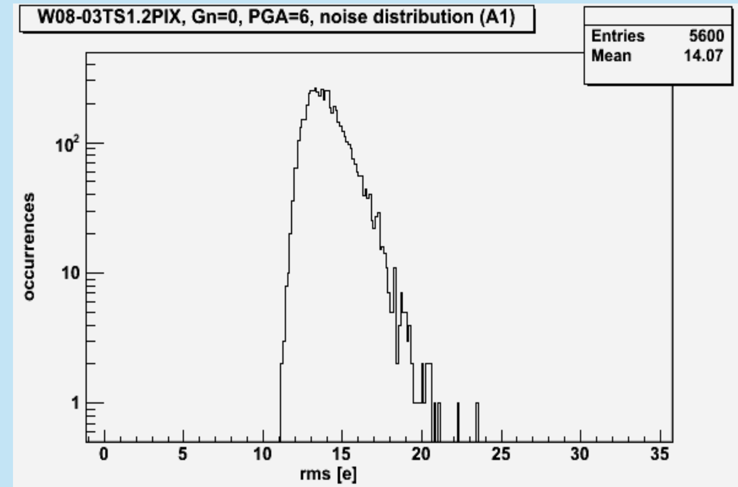


- Testing

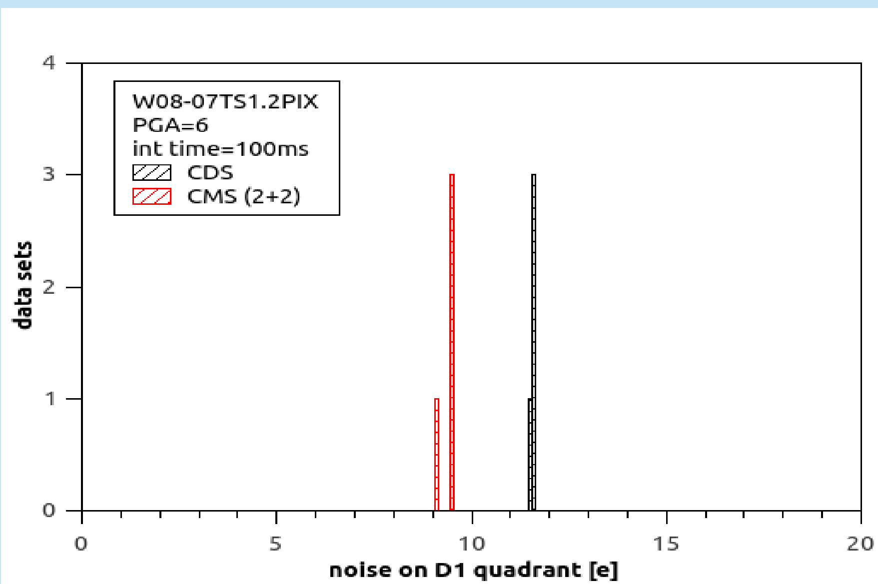
Prototype Performance - Noise

Noise

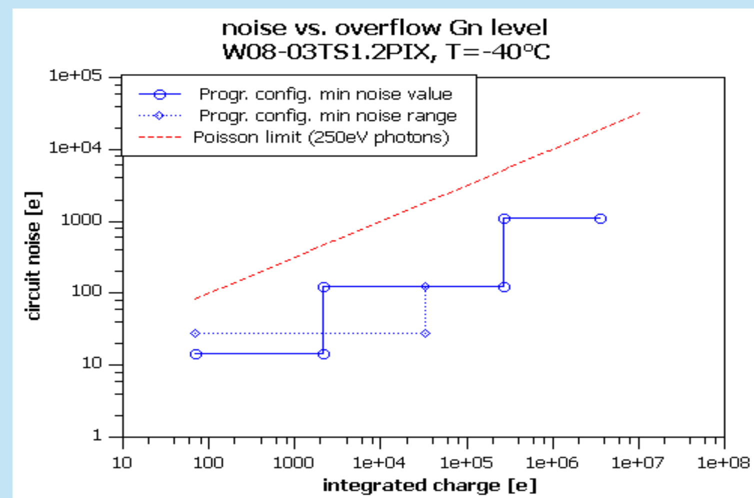
- reasonably low parameter dispersion between different samples (and wafers)
- Noise below Poisson limit
- preliminary tests indicate ~10 e^- rms reachable by multiple sampling



Dispersion of pixel noise values (TS1.2)



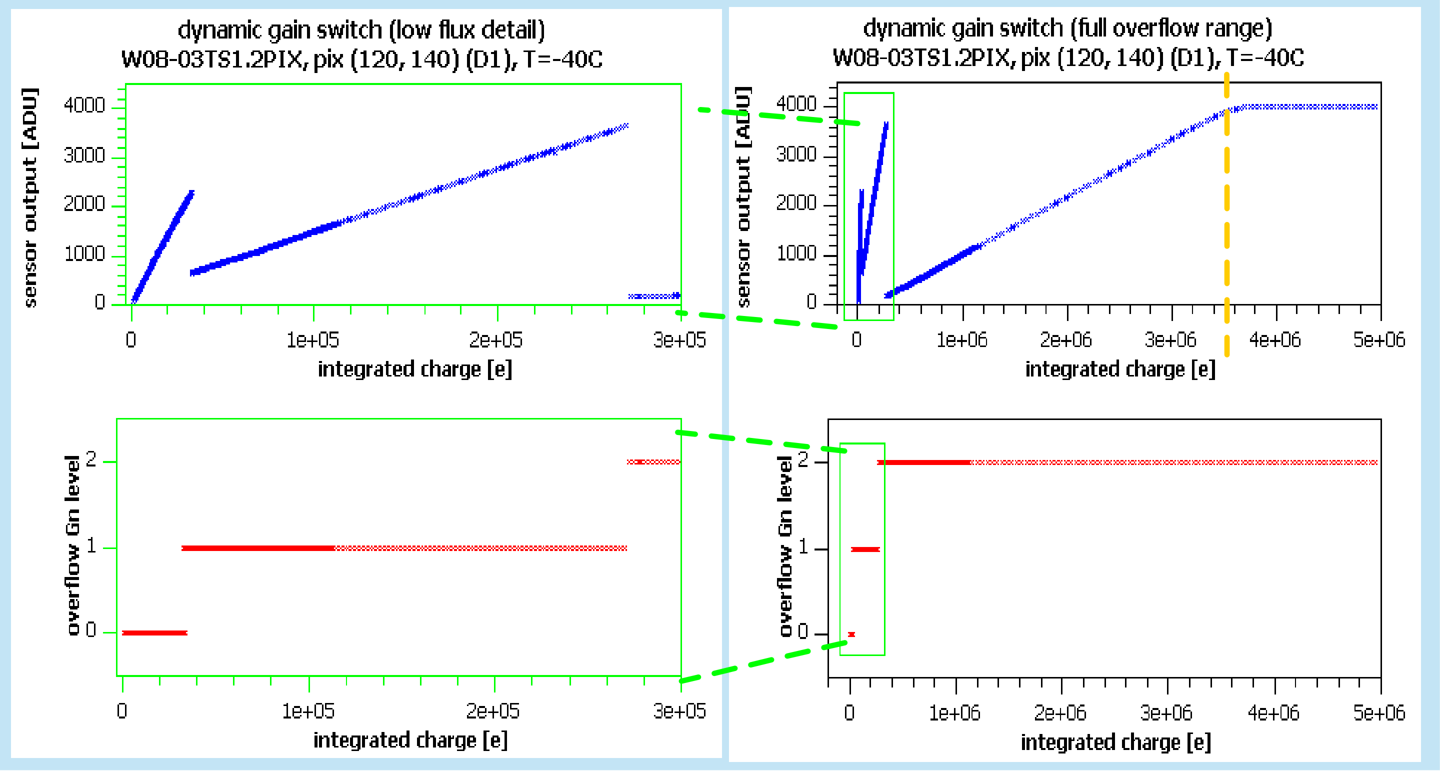
Multiple Sample Trial: Proof of principle.



Noise well below Poisson shot noise at all times

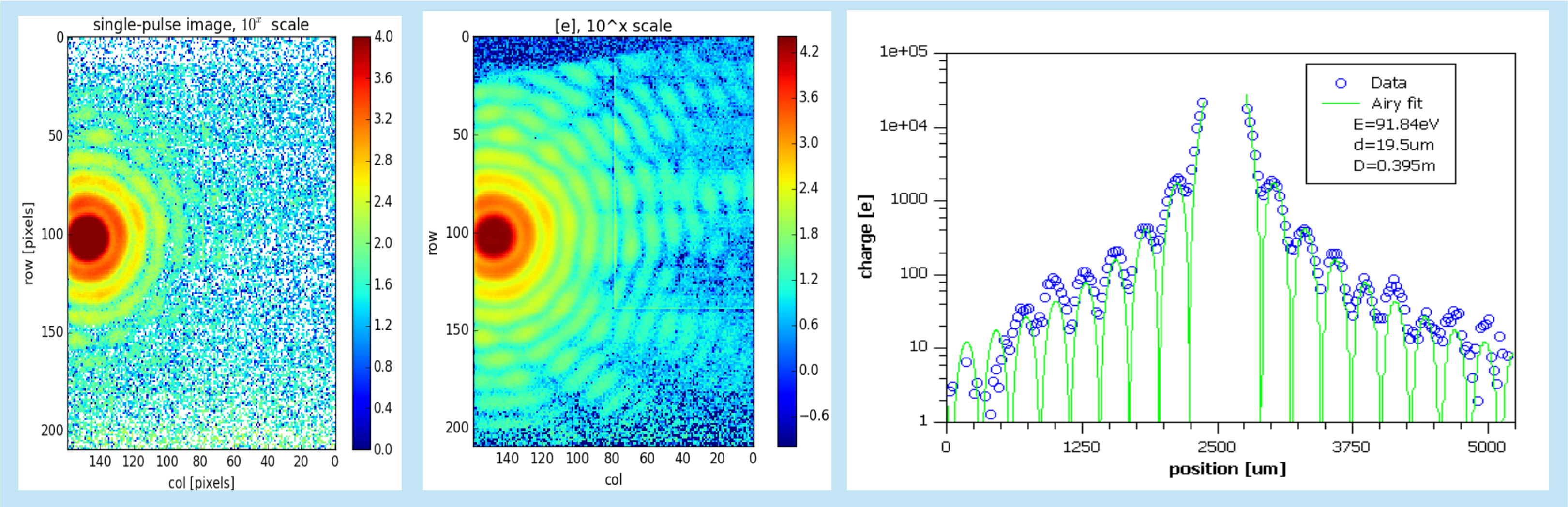
Prototype Performance
Gains

- Automatic gain adjustment works
- 3 gains accessible via overflow switch architecture
- Dynamic range to 3.5 Me$^-$ i.e. 50k photons at 250eV

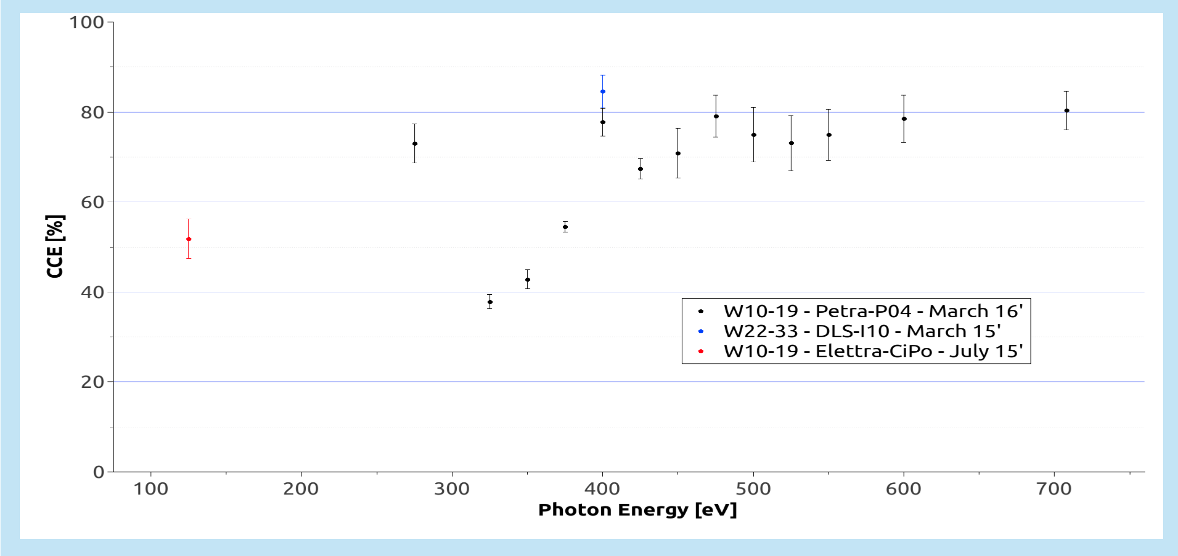


Prototype Performance

Backside-illuminated (BSI)

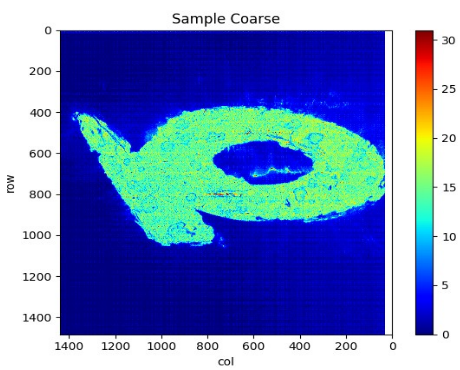


- Imaging at 92 eV, single-shot at FLASH
- Airy rings matching output
- CCE (lower limit to QE) measured at ~70% above 400 eV

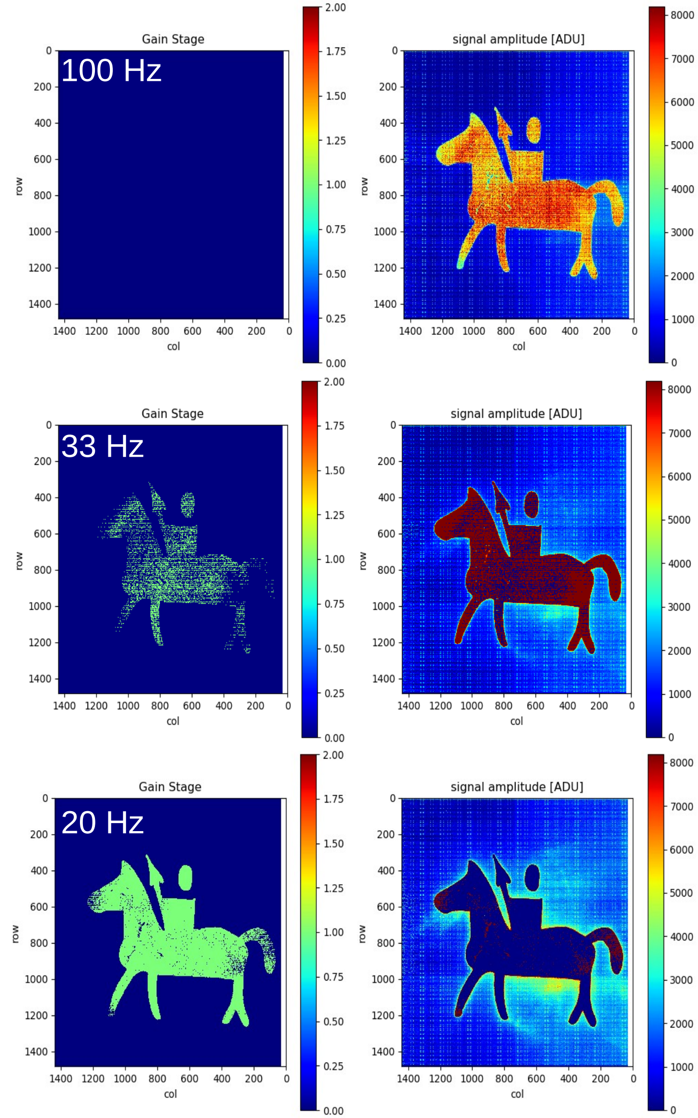


P2M Operation

- First light
- Visible light, room temperature
- 100Hz frame rate (streamout speed of full acquisition system still ramping up)
- Automatic gain switching works
- Deployment. Two more system working and providing, last one at Elettra: 150Hz



- Gain
- ADUs



Project Status & Outlook

P2M FSI undergoing benchtop testing

- P2M system operates, saw first light
- P2M sensor demonstrates auto gain switching in response to illumination
- Detailed characterization (including bias tweaking etc.) ongoing
- Chip functionality at 300Hz frame rate demonstrated, full readout & system ramping up to this

- P2M backthinned sensor in hand, awaiting wirebonding
- Expect first X-ray tests in Xmas 2018
- First delta-doped P2M BSI ~ March 2018

Thanks to Percival Collaborators:

P2M FSI undergoing benchtop testing

DESY:
Cornelia Wunderer
Alessandro Marras
Steve Aplin
Peter Goettlicher
Frantisek Krivan
Manuela Kuhn
Sabine Lange
Magdalena Niemann
Frank Okrent
Igor Shevyakov
Sergej Smoljanin
Manfred Zimmer
Heinz Graafsma

RAL:
Iain Sedgwick
Ben Marsh
Nicola Guerrini

Elettra:
Giuseppe Cautero
Dario Giuressi
Giovanni Pinaroli
Luigi Stebel
Ralf Menk

Diamond:
Alan Greer
Tim Nicholls
Ulrik Pedersen
Nicola Tartoni

PAL:
HyoJung Hyun
KyungSook Kim
Seungyu Rah

Soleil & DESY:
Benjamin Boitrelle

JPL:
April D. Jewell
Todd J. Jones
Michael E. Hoenk
Shouleh Nikzad

EMFT:
Andreas Drost
Christof Landesberger
Armin Klumpp

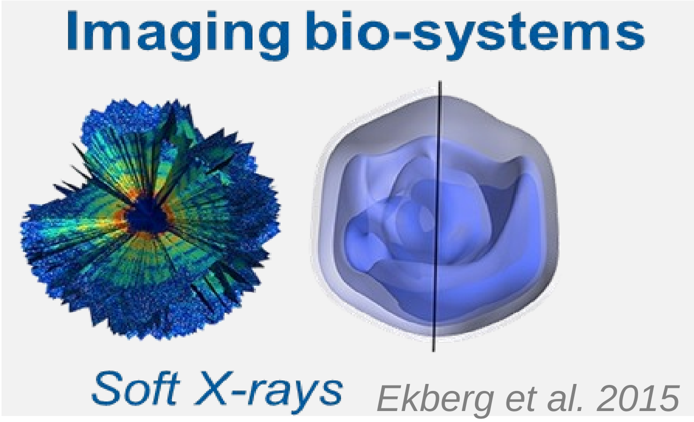
and beamline staff at Petra P04, Elettra TwinMic & CiPo, DLS I10, and Flash BL2 for their support

Backup Slides

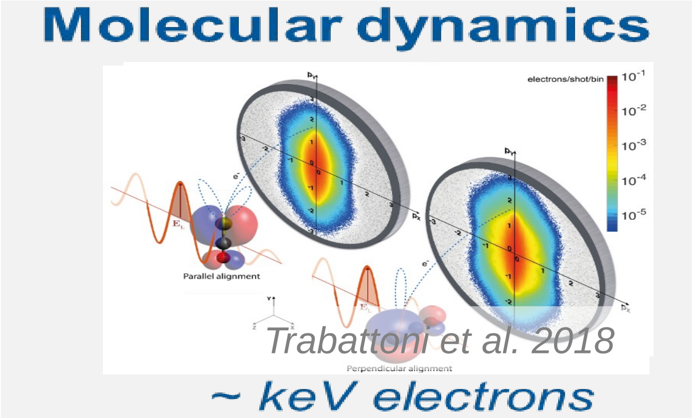
Post-Processing is necessary

Science challenges – two examples

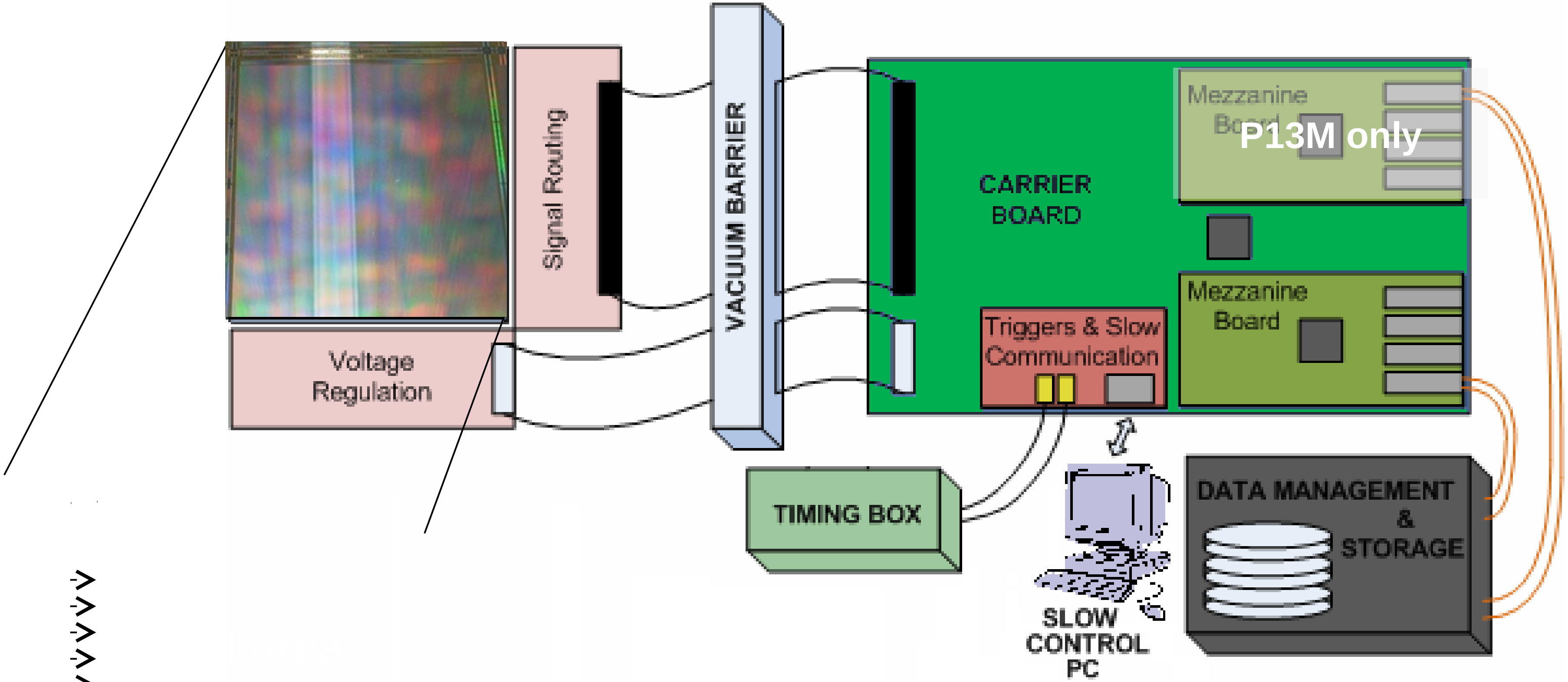
- Water window offers unique view of biological systems:
  Between Carbon and Oxygen edges, water is transparent but carbon absorbs
- 282 eV to 533 eV photons



- Laser-Induced Electron Diffraction:
  re-scattered electrons can give simultaneous access to sub-100pm-spatial and sub-fs temporal resolution
- Sweet spot for these measurements is around 500 eV electron energy
  (plus few keV acceleration from optics)



The full PERCIVAL system



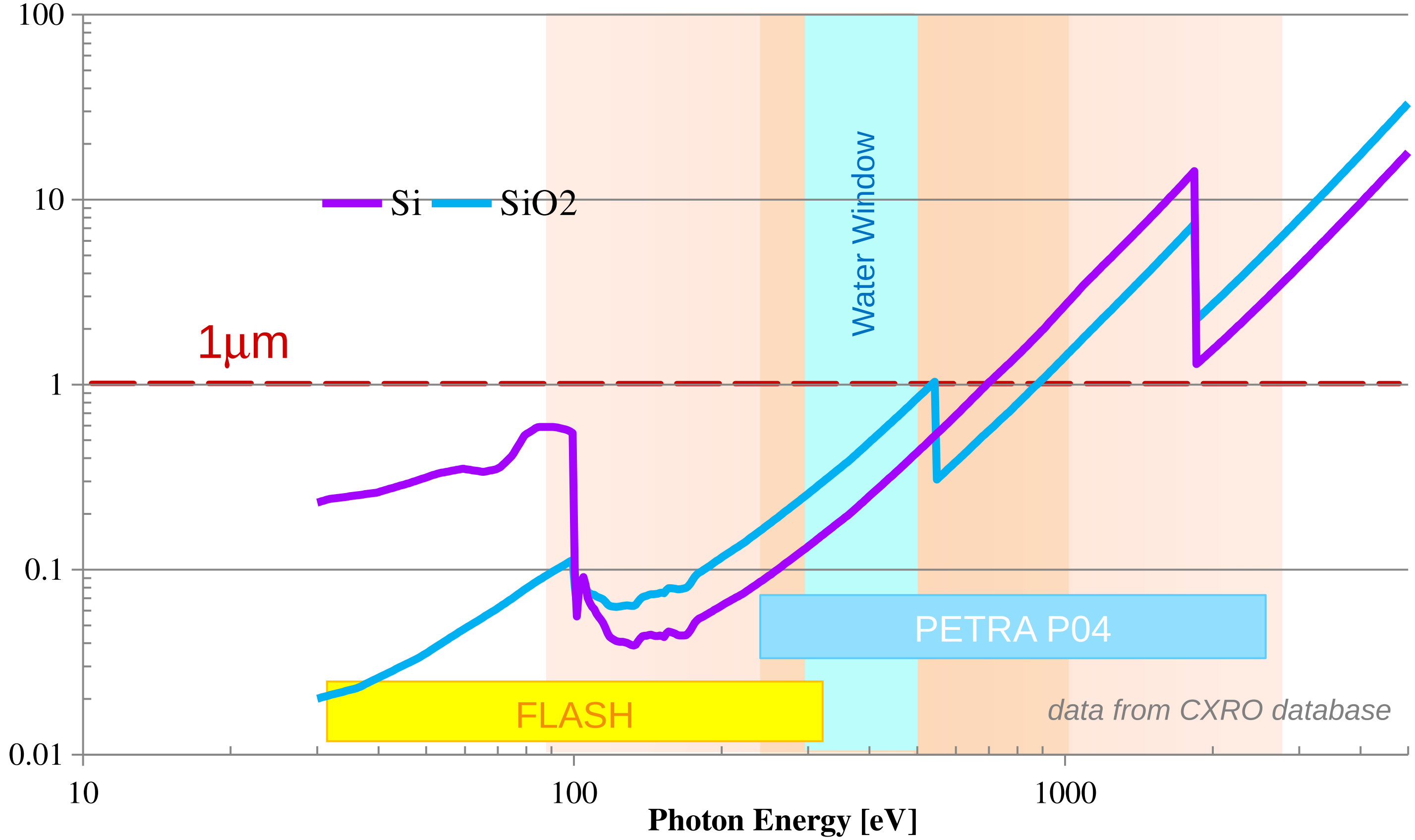
P2M

- 2 Mpixels
- ~4×4cm² area
- 2-side buttable
- 27µm pixel pitch
- available ~2017

Soft X-ray Challenges – reaching the sensor

PERCIVAL

Attenuation Length of Photons in Si and SiO_2

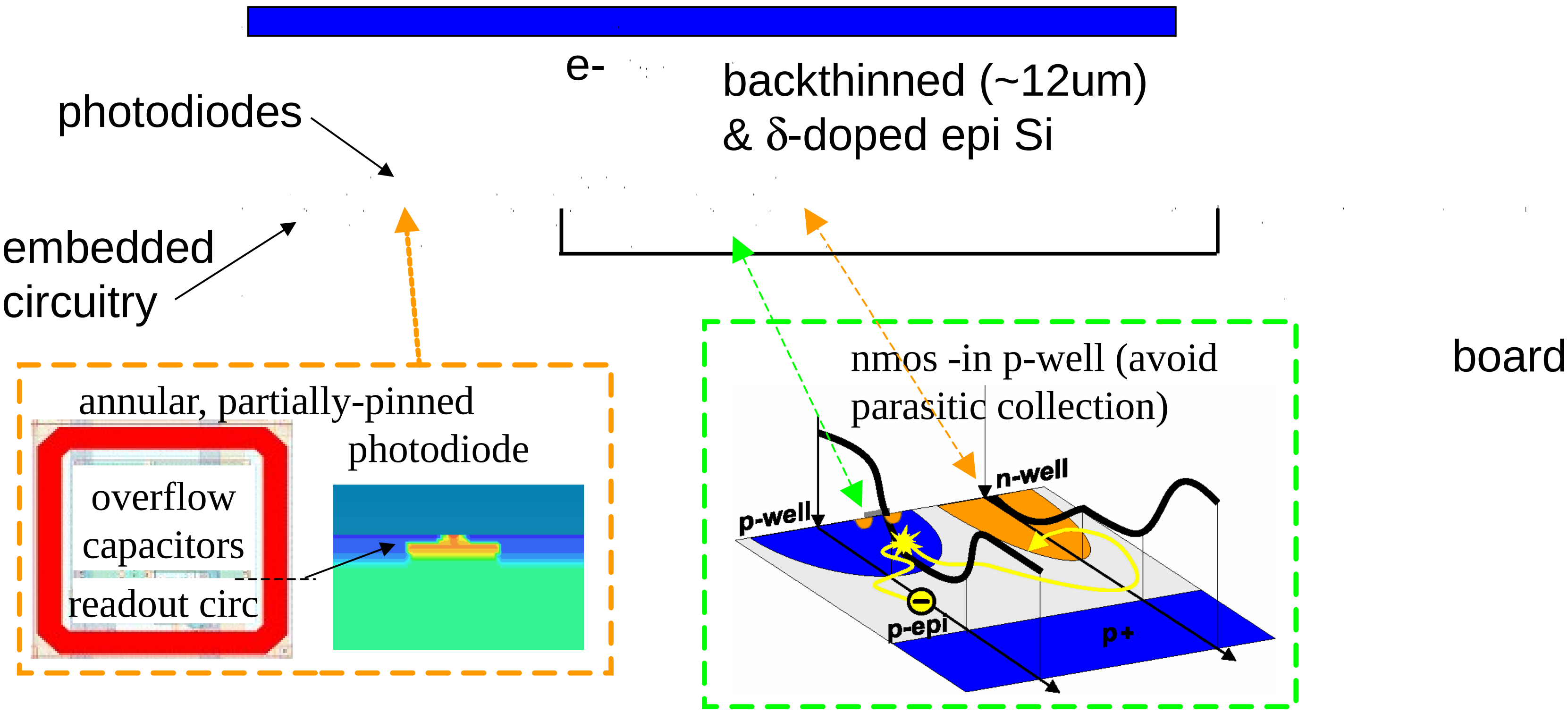


At (very) soft X-ray energies, QE is limited by passive window thickness!

e.g. 50 nm of SiO_2: loss of 25% of 250 eV photons

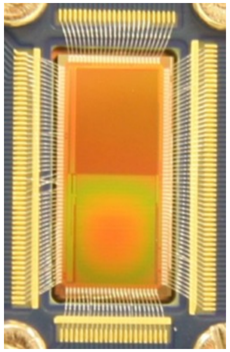
DESY

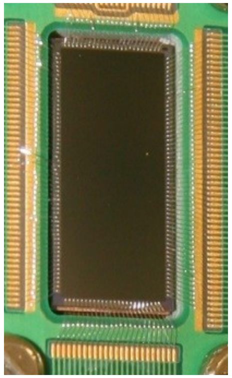
Monolithic Active Pixel Sensor

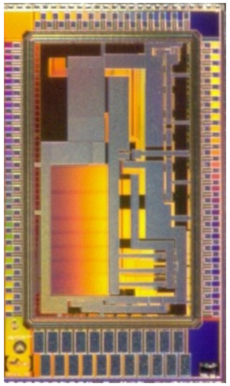


Monolithic: Collecting diodes & readout circuitry share the same substrate
commercial standard 0.18um CMOS techn, over high-resistance thick epi
Coupled to handling wafer, back-thinned, back-illuminated: 100% fill factor
Back surface delta-doped, post-processed: almost no entrance window

Prototype Sensors & Beamline Tests



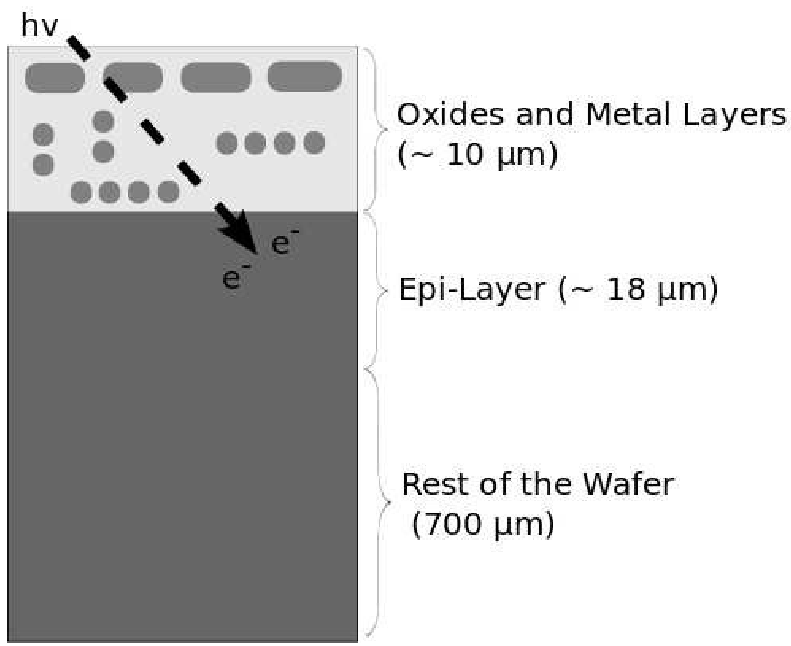


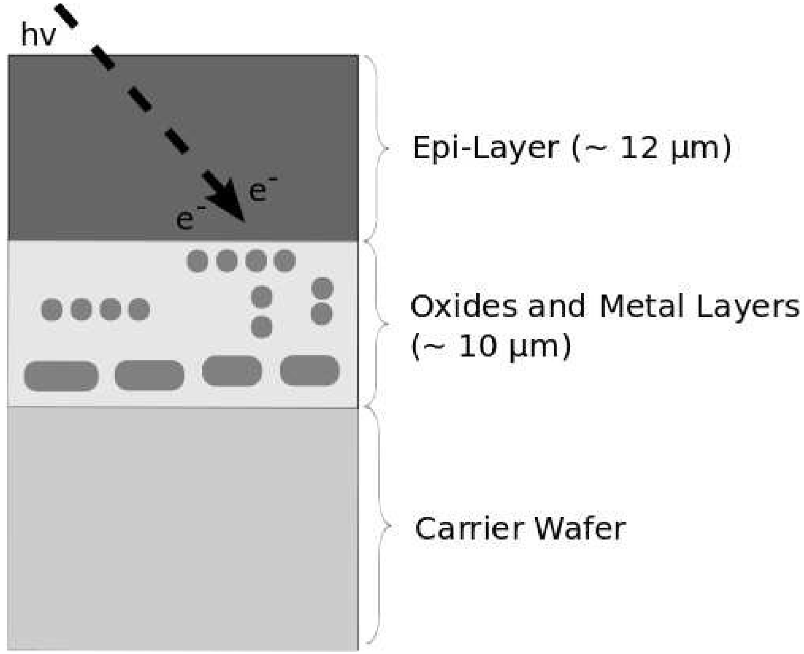


- TS1 & TS2 (pixels & ADCs)
  - FSI fall 2012
  - BSI 1st round Feb 2014
  - BSI 2nd round Mar 2015
- TS3 (fast digital readout)
  - Fall 2012
- TS1.1 (capacitors, noise)
  - Jul 2014
- TS 1.2
  (added amplification for better noise, other crucial improvements over TS1)
  - Apr 2015

- TS1 FSI *(all parasitic)*
  - PETRA III P04,
    May, Aug, Nov, Dec 2013,
    Jan 2014
- 1st round BSI TS1
  - Elettra TwinMic, Mar 2014
- 2nd round BSI TS1
  - Diamond I10, Mar 2015
  - Elettra CiPo, May 2015
  - FLASH BL 2, Dec 2015
  - PETRA III P04, Mar 2016
  - PETRA III P04, Apr 2016
  - PTB@BESSY, May 2016

Back-side Illumination

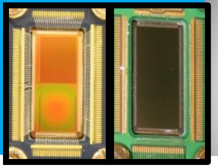


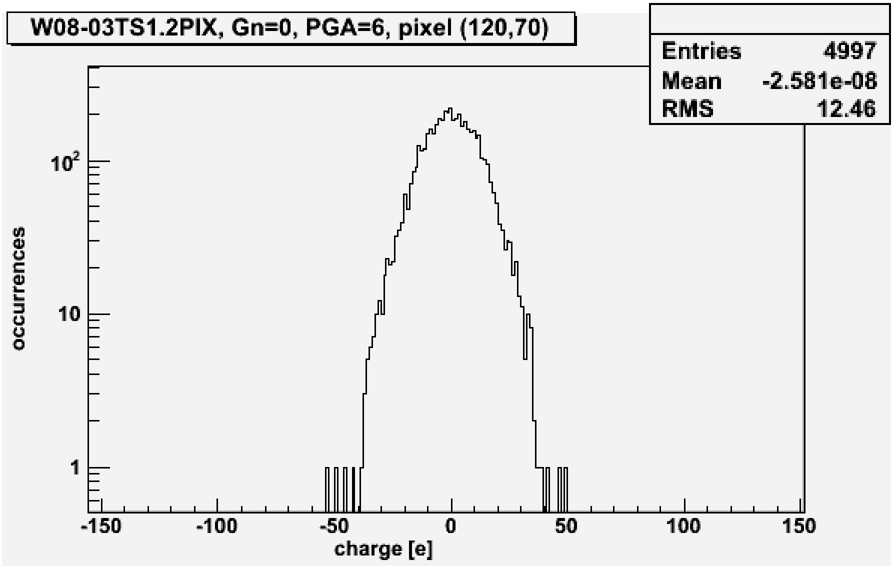


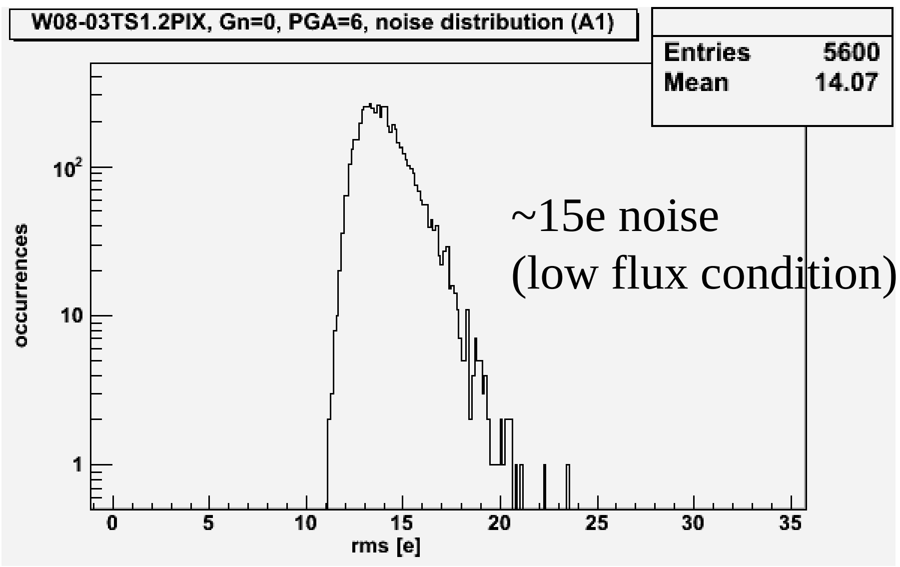
- Front-side illuminated (FSI) sensor
- Photons have to traverse oxides and metals
- Limited and non-uniform sensitivity to soft X-rays

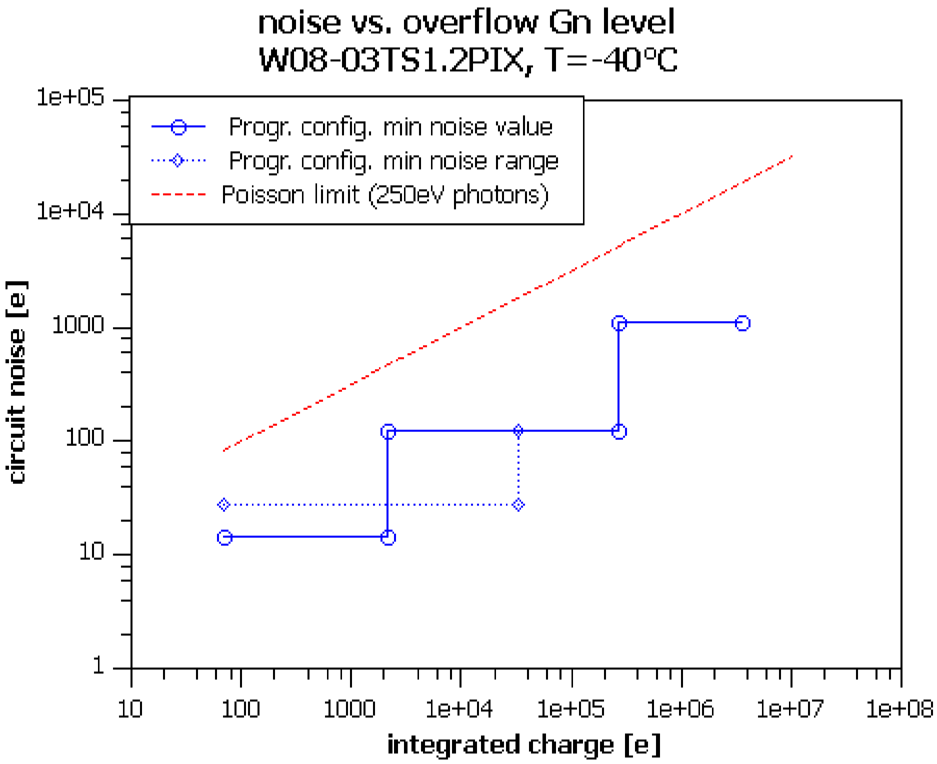
- Back-side illuminated (BSI) sensor bonded to carrier wafer
- High and uniform soft X-ray sensitivity possible
- Percival prototypes are BSI-processed at JPL (delta-doping)

Noise vs Poisson Limit









Post-Processing needs

PERCIVAL

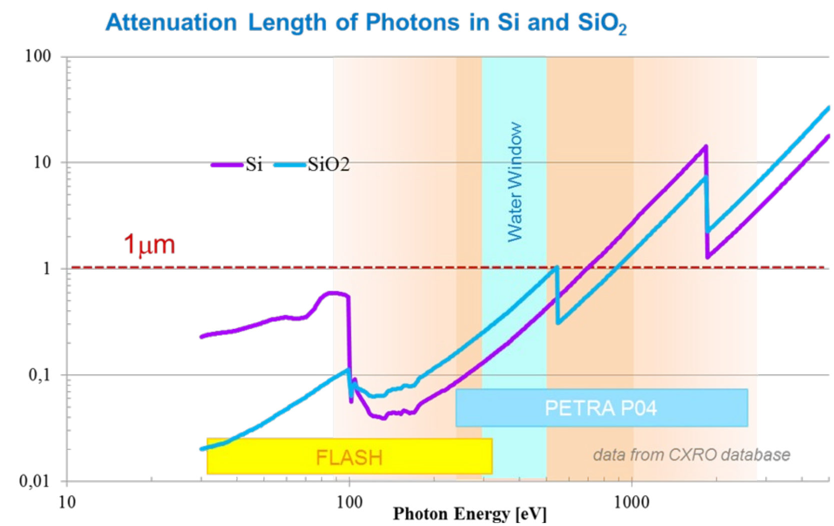
> Attenuation lengths in Si / SiO_2 at or below 100nm for soft X-rays

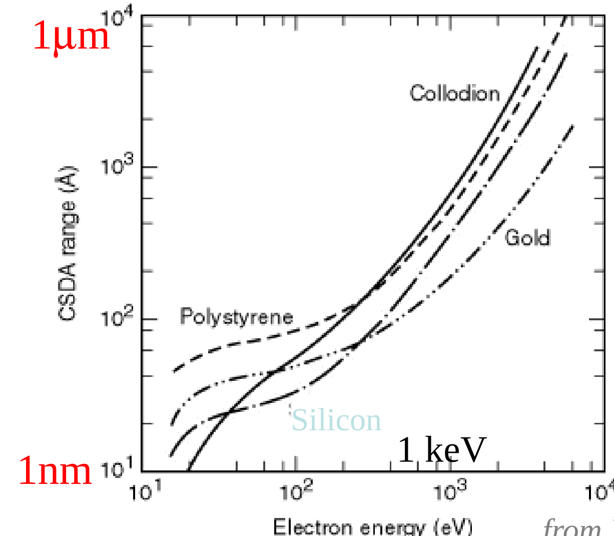
> Attenuation lengths for few-keV electrons in Si are on the order of 10s of nm

> Interaction must happen in active Si, and generated charge cloud must reach the circuitry

> Requires:

- Negligible passive layer
- Negligible traps
- Optimized geometry of electric field at surface of sensor





from X-ray Data Booklet

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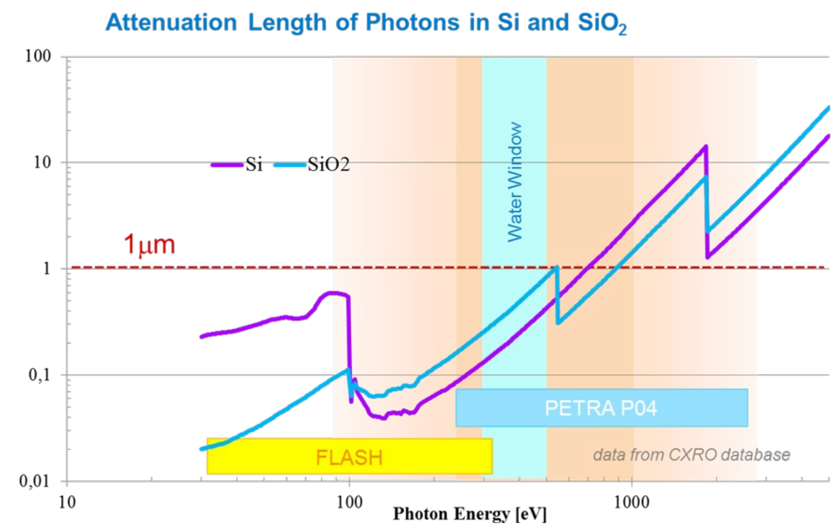
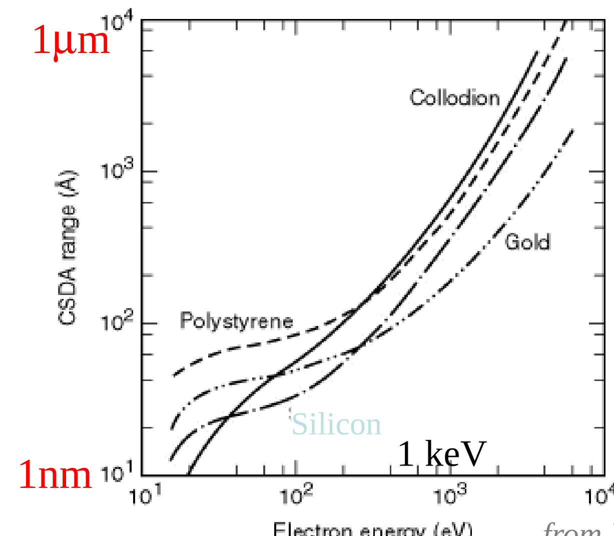
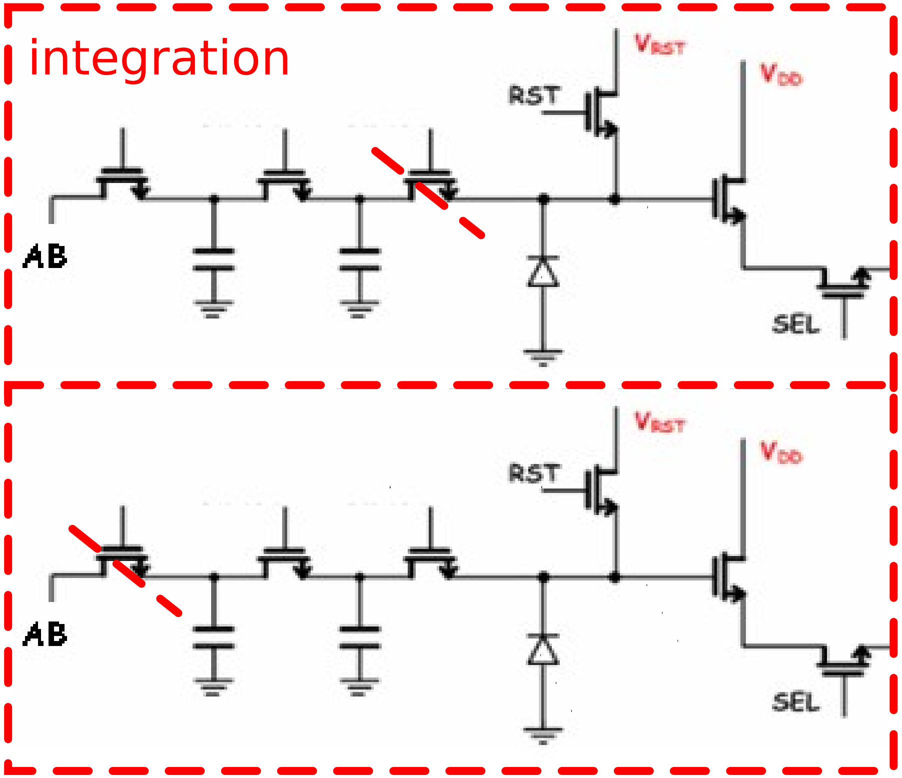
  - Optimized geometry of electric field at surface of sensor

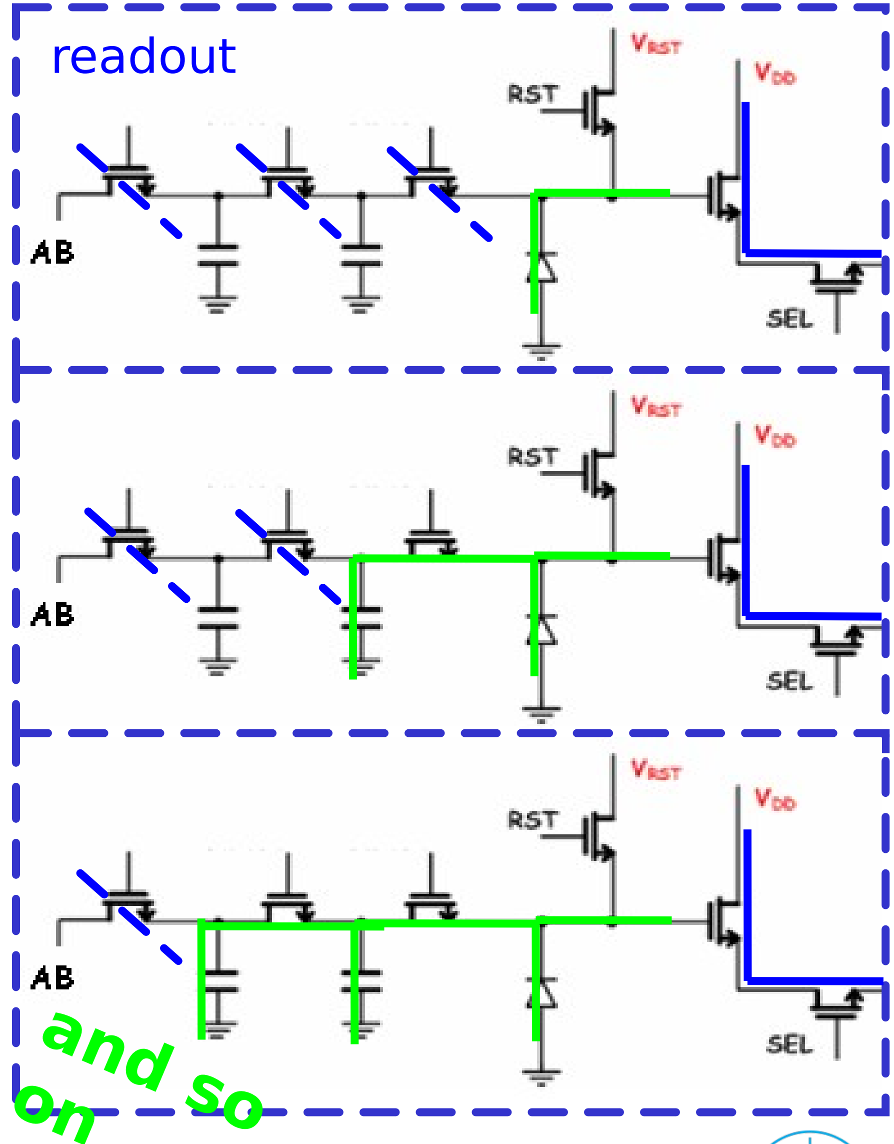




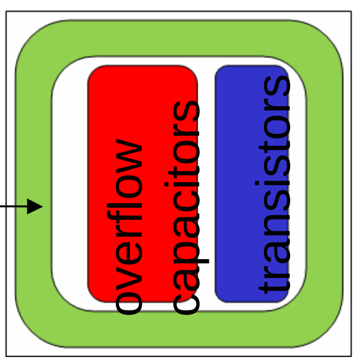
from X-ray Data Booklet

Lateral Overflow





annular-shaped partially-pinned photodiode



automatic selection of appropriate overflow Gn level (only relevant data streamed out)