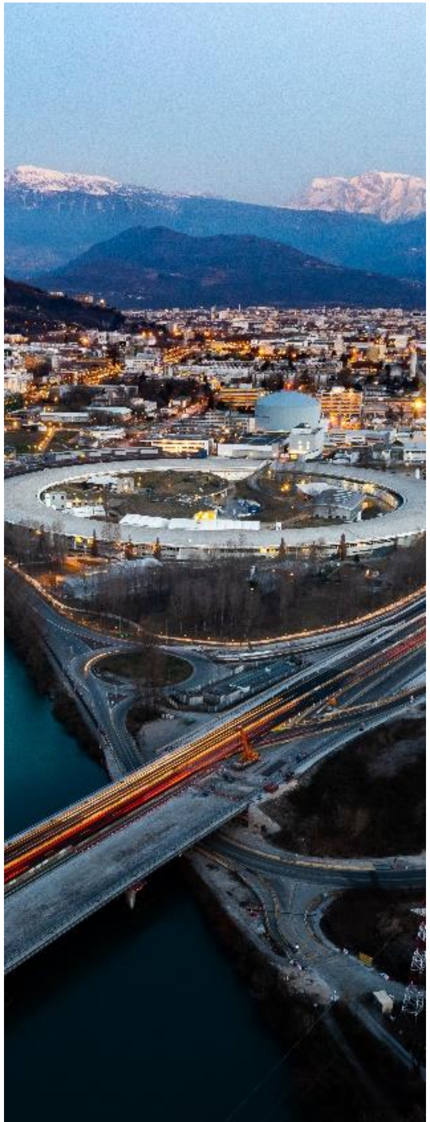

Progress with CdTe and high-flux CdZnTe XIDER detector prototypes

24th International Workshop on Radiation Imaging Detectors

25-29 June 2023

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OUTLINE

- **Introduction**
  - *2D X-ray detectors for scattering/diffraction applications at ESRF EBS*
- **The XIDER project**
  - *Project overview and status*
- **CdTe and high-flux CZT XIDER assemblies**
  - *Direct photocurrent detection: time resolution capablities*
  - *Signal-induced leakage current: comparative measurements*
- **Summary**

ESRF EBS

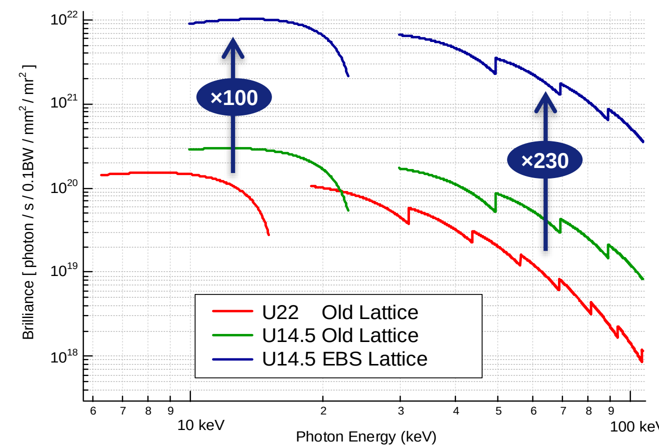
The ESRF upgraded storage ring: Extreme Brilliant Source (EBS)

- **New ring lattice: in user mode operation since 2020**

- **More photons in the sample: up more than 10^{15} X-rays/sec**
  - ***Higher brilliance*** *photon source: lower electron emittance (×30) , reduced gap undulators*
  - *Less divergent / more focused beams:* ***more efficient optics***
  - ***Increased beam*** *coherence → excellent for coherent scattering methods (ptychography, CDI, XPCS)*
  - *Many experimental techniques can move toward* ***higher X-ray energies***

- **New science opportunities require improved instrumentation**
  - *X-ray detectors*
    - ✓ ***Extended dynamic range***
    - ✓ ***Shorter time domains: intrinsic time resolution and frame rate***
    - ✓ ***Detection of high energy photons***

Example of brilliance gain
[photons/s/0.1BW/mm²/mr²]



SCATTERING/DIFFRACTION DETECTORS FOR HIGH PHOTON FLUXES

- **We need detectors able to operate with higher photon fluxes and at high photon energies**
  - Current photon counting detectors are flux limited due to pulse pile-up: *few Mcps/pixel with acceptable losses*
  - Moving from photon counting to charge integration readout with high-Z sensors (e.g. CdTe) would be the natural choice
    - *But the "conventional" charge integration readout scheme cannot be applied with continuous beams*
    - *Charge trapping in deep-level defects of the compound semiconductor*
      - *high value of the dark/leakage current*
      - *with "unpredictable" variations → **signal-induced leakage current** (also called afterglow, aftersignal, …)*

- **At ESRF we have started using/evaluating charge integrating systems**
  - Similar pixel pitch ~75 µm
  - Very high photon flux (if very short integration intervals)
  - Can be used at storage rings with continuous beams, but …
    - *only at relatively low X-ray energies (silicon sensors)*
    - *must operate at their maximum frame rate to "slice" the integration time in the shortest possible sub intervals*
      - *complex and very demanding DAQ and computing infrastructure, regardless of the application requirements*

PAUL SCHERRER INSTITUT PSI — ***Jungfrau*** *(Hybrid pixel detector)*

RIKEN — ***CITIUS*** *(Monolithic silicon CMOS imaging sensor)*

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ESRF APPROACH FOR HIGH-ENERGY 2D DETECTORS

- **No obvious approach for high photon energies → investigate new readout concepts**

- **Two different R&D directions followed from ESRF:**
  - Pushing photon rate capabilities of counting detectors → **SPHIRD** (small pixels)
  - Incremental digital integration → **XIDER** (highest dynamic range and time resolution)

D. Magalhães talk
Tuesday @ 11h20

- **The XIDER project:**
  - R&D collaboration: ESRF and University of Heidelberg
  - Reference application: **time resolved high energy diffraction** (material science)
  - **Charge integration hybrid pixel detector** with high-Z sensors
  - Able to work with **high energies** (30-100keV) and **high photon fluxes**
  - Operation with **continuous** and **pulsed** beams

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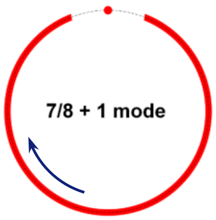
XIDER TARGET SPECIFICATIONS

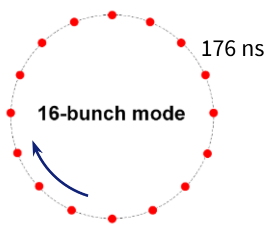
Some target features/specifications :

- Sensor material: pixelated **CdTe** and **high-flux CZT**
- Configurable pixel pitch: **100 µm** (physical) and **200 µm** (2×2 binning)
- Dynamic range: from **single photon** sensitivity up to **10^9 X-ray/s/pixel**
- Readout ASIC:
  - Microelectronics technology node: **CMOS 65 nm**
  - Nearly 100% duty cycle, **deadtime free** readout
  - Burst mode up to **5.68 MHz** (ESRF 16-bunch repetition frequency)
  - In pixel **memory** (> 100 frames)
- Implementation and validation of the concept of **incremental digital integration**

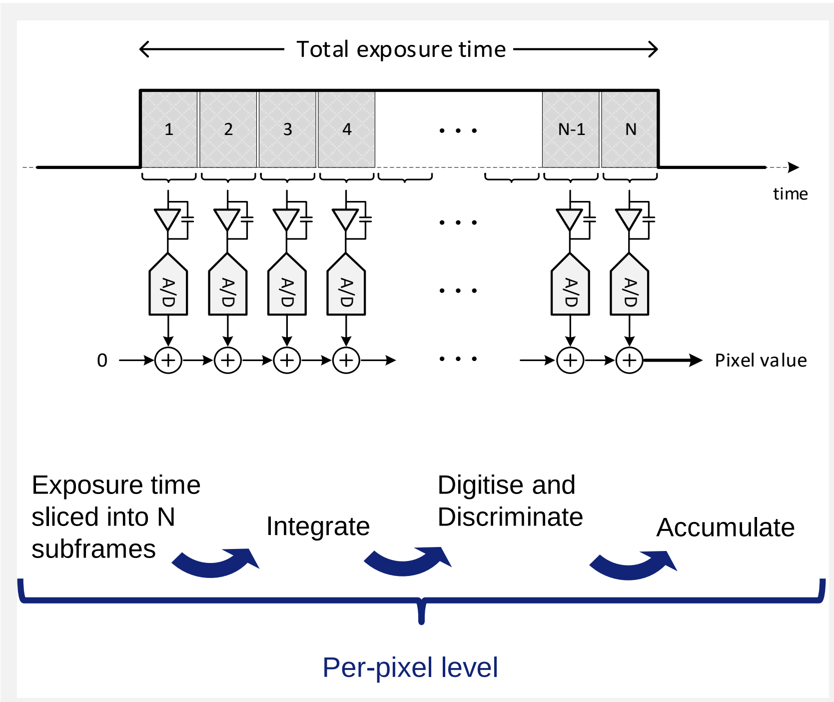
Ccontinuous beam
(highest flux)



Pulsed beam
(time resolved)



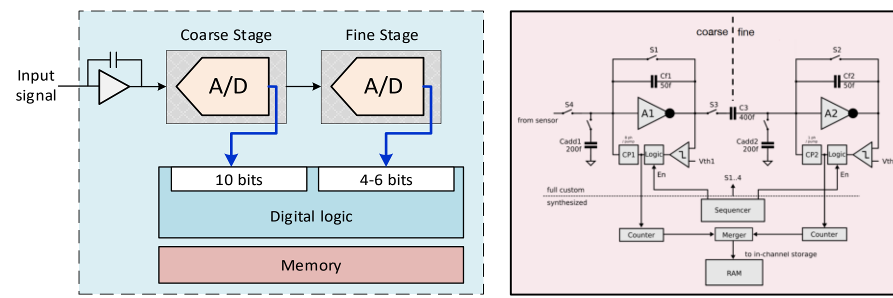
INCREMENTAL DIGITAL INTEGRATION CONCEPT



Incremental digital integration:

- Fine slicing (**subframes**) of the total integration interval (micro and sub-microsecond range)
- Noise and leakage contributions **partially suppressed** by signal thresholding/quantization
- **In-pixel ADC** → fully digital readout
- Possibility of **accumulation** of subframes and in-pixel **data storage**

XIDER pixel



Incremental digital integration discussed in: *J. Inst.* **15** C01040
https://doi.org/10.1088/1748-0221/15/01/C01040

Readout implementation discussed in: *J. Inst.* **16** P03023
https://doi.org/10.1088/1748-0221/16/03/P03023

The XIDyn collaboration

- Other labs have shown interest in some of the concepts proposed in XIDER
- **UKRI-STFC** and **Diamond Light Source** are working on **DynamiX,** a new generation of high-dynamic range 2D diffraction detectors for Diamond-II
- We have initiated a collaboration aiming at:
  - **Sharing experience** and know-how
  - Investigating the feasibility of a **single ASIC design** matching the application requirements of both Diamond-II and ESRF-EBS: This requires extending the initial target specifications of XIDER
  - Working on a **common platform** for the full detector systems: sensors, module construction, DAQ, firmware/software, …
- **European XFEL** has recently joined as an observer

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XIDER READOUT ASICs

T1

T2

T3

T4

T5

T6

ASIC design:

The XIDER pixel functionality is **particularly complex**:

- ✓ Fast analog front-end
- ✓ In-pixel analog-to-digital conversion
- ✓ Digital logic, sequencer, multiple modes of operation
- ✓ Built-in memory
- × Power hungry

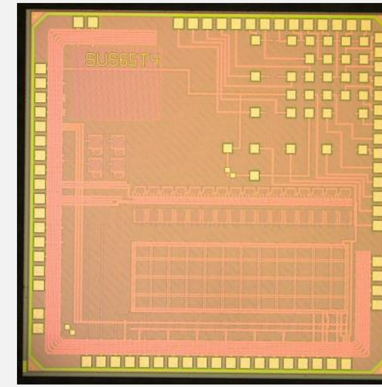
The pixel design has **progressed incrementally**:

- Six chips (T1 to T6) designed so far
- Not all the chips have used for X-ray testing
- Last X-ray measurements with T4: investigation at the pixel level

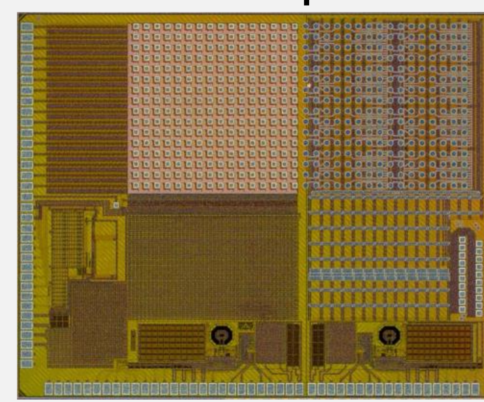
The last version (T6) includes a **16×16 pixel minimatrix:**

- Includes all the required functional blocks
- Includes **14 Gbps high-speed data** serializers from STFC
- Design directly **scalable to larger size** chips

ASIC T4: 4×4 pixels



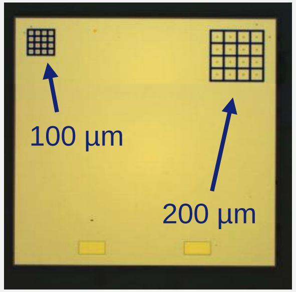
ASIC T6: 16×16 pixels



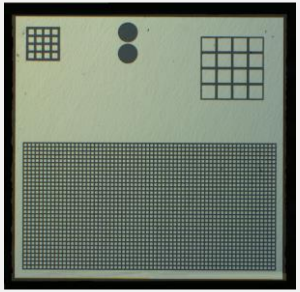
XIDER TEST PROTOTYPES

Prototypes T4:

- 100 µm and 200 µm pixel pitch
- 4×4 pixel structures (in a 4×4 mm² total sensor size)
- 1 mm thick CdTe (ohmic contacts)
- 2 mm thick high-flux CZT



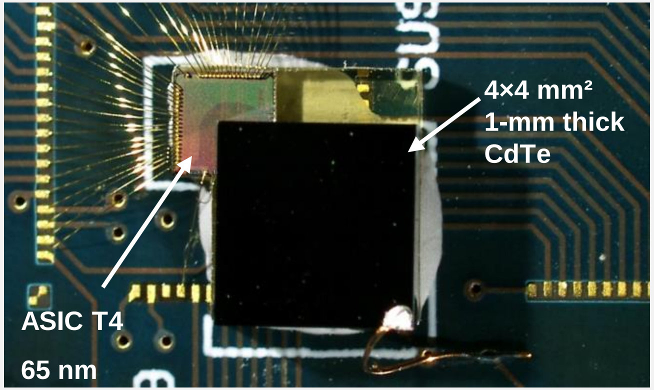
CdTe
(Acrorad)



High-flux CZT
(Redlen / Due2lab)

Characterization:

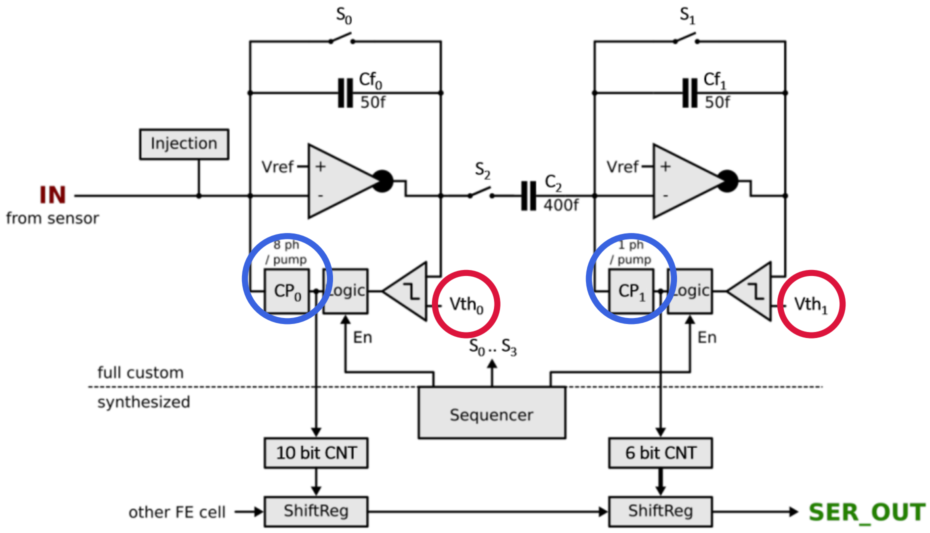
- The initial investigation work was done with CdTe assemblies
  - ➢ CdTe devices perform poorly (as anticipated) : instability and irreproducibility of dark/leakage current behaviour
- High-flux CZT assemblies available only very recently
- Measurements taken both with 30 keV X-rays at BM05/ESRF and with calibrated LED sources at the lab:
  - ➢ LED light (730 nm) reproduces in the laboratory a similar behaviour than observed with 30 keV X-rays at the beamline



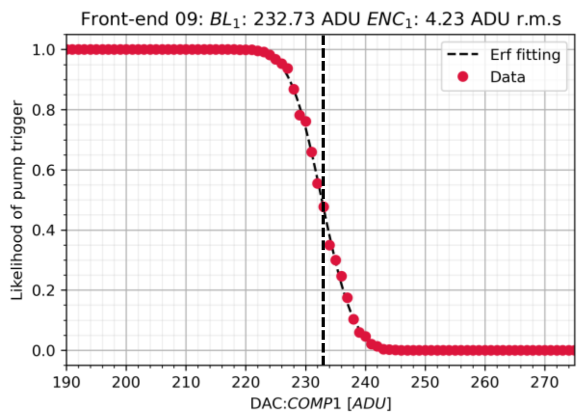
CALIBRATION PROCEDURE

Parameters to be calibrated:

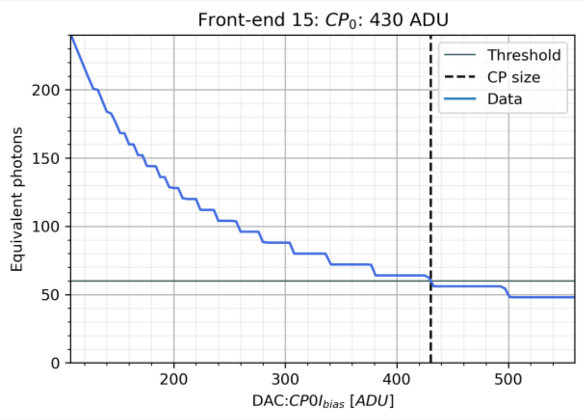
- Thresholds and charge pumps (×2)
- All trimmable with 10-bit DACs
- Using internal charge injection



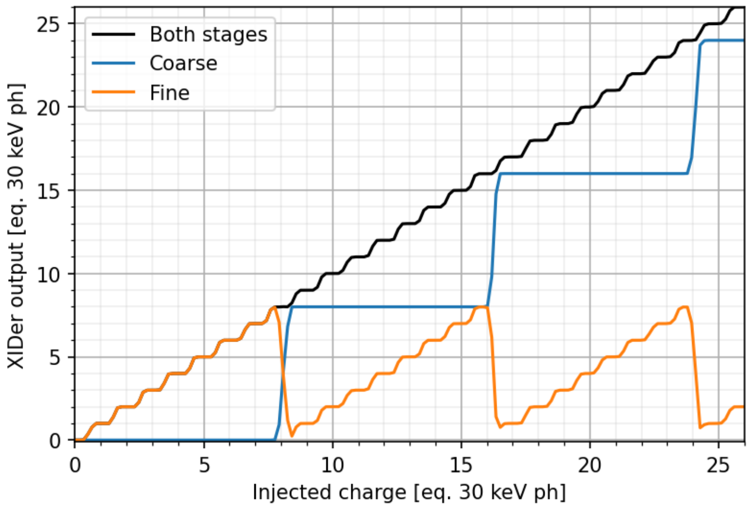
Threshold calibration

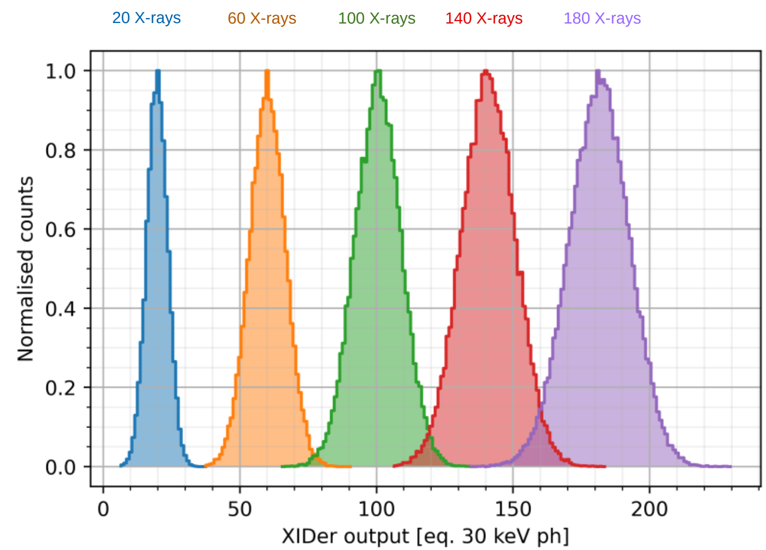


Charge packet calibration



CALIBRATION ASSESSMENT





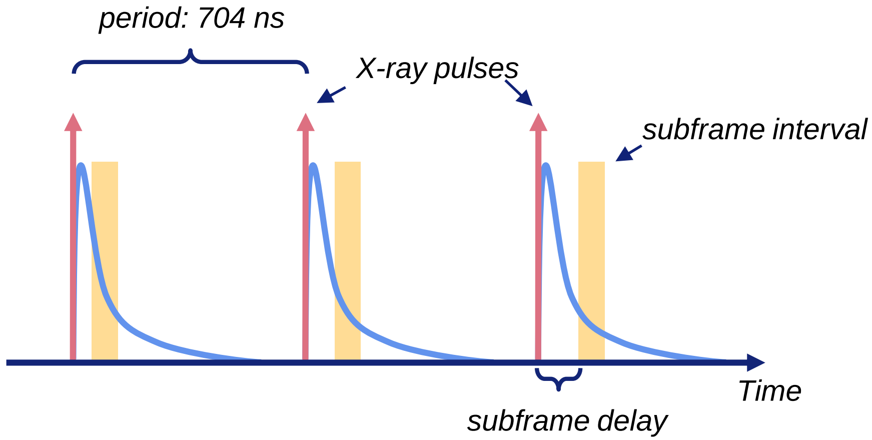
Internal charge injector:

- Injection circuit: 10-bit DAC
- Mid-tread ADC response
- Electronic noise: 350 e^- rms

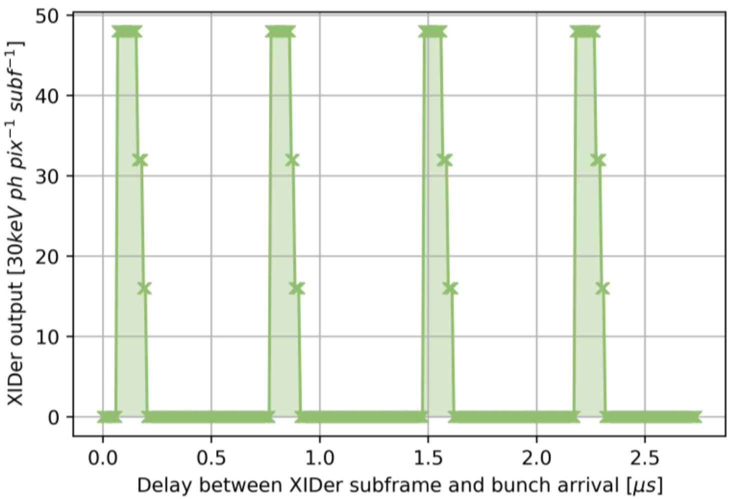
External electronic injection:

- External waveform generator
- Emulates Poisson statistics with Gaussian noise

DETECTION OF DIRECT PHOTOCURRENT: TIME-RESOLUTION



- XIDER active subframe of ~100 ns
- 4-bunch filling mode: 100 ps X-ray pulses every 704 ns
- Photon induced signal



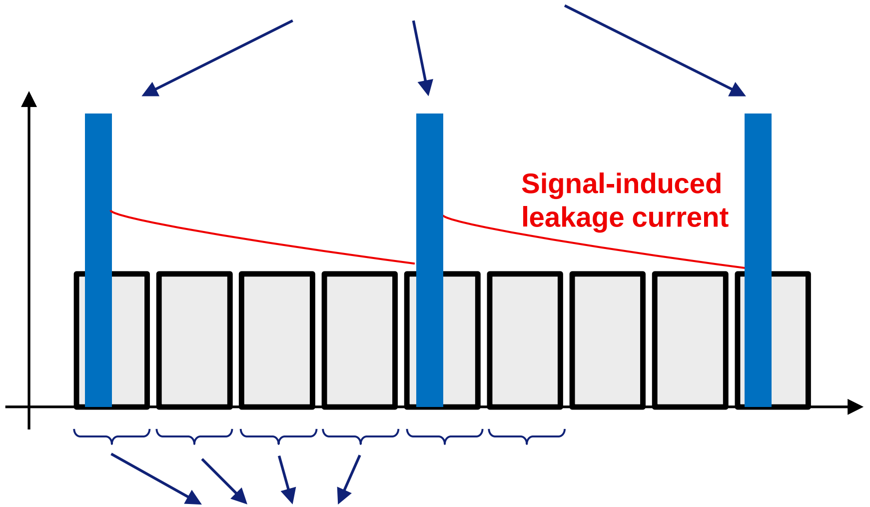
- Example of 4-bunch full orbit scan using a CdTe XIDER assembly
- Similar results with high flux CZT

Notes:

- Energy: 30 keV in 4-bunch filling mode
- XIDER subframes synchronous to the X-ray pulses
- Delay between X-ray pulses and the subframe start is changed

- Results are consistent with the collection of “direct photocurrent” in few 10s of nanoseconds

STUDYING THE SIGNAL-INDUCED LEAKAGE CURRENT



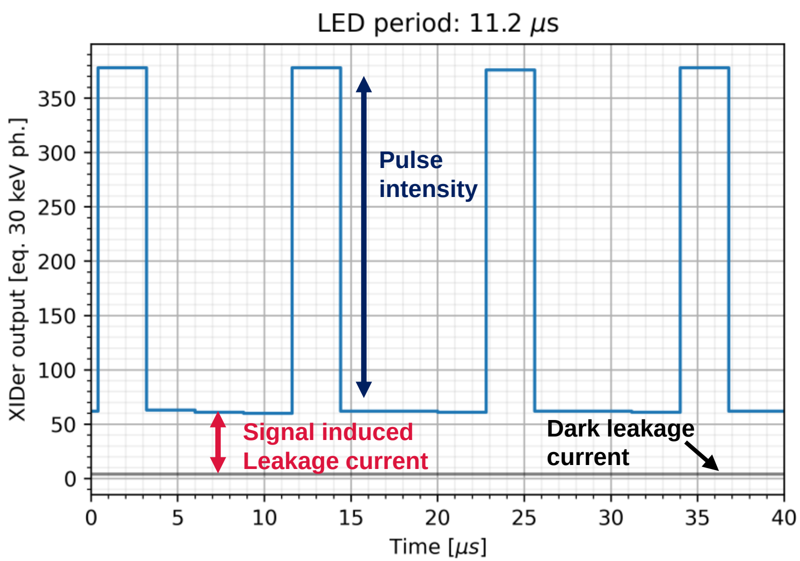
We use discontinuous (pulsed) illumination to separate the direct photocurrent (signal) from the signal-induced leakage current

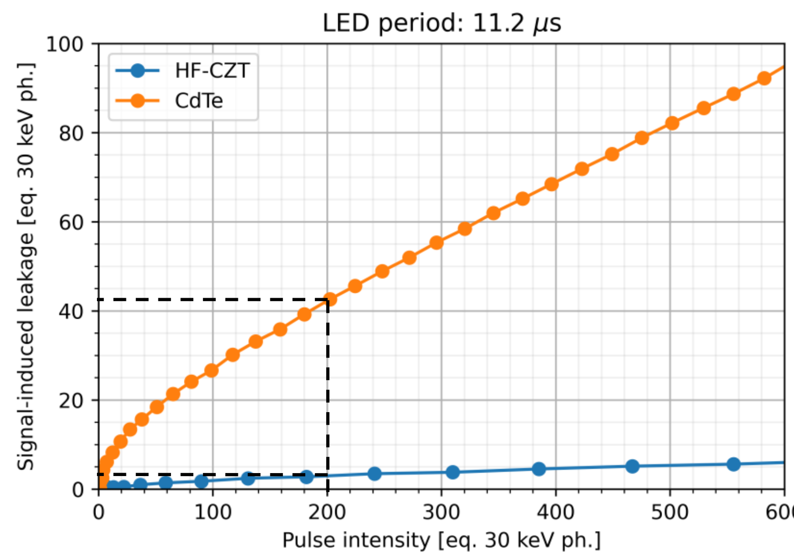
Measurement Setup:

- CdTe and CZT sensors:
  - cathode electrodes: <20 nm thick platinum
- Light pulses:
  - Used to emulate 'low-energy' X-rays
  - Duration: 1 µs, repetition 4 subframes (11.2 µs)
  - Tuneable intensity
  - Characterised with a silicon photodiode
- LED source:
  - λ_{LED}: 730 nm (far red)
  - $E_{gap,\ Cd(Zn)Te}$: 1.5 eV (830 nm)

SIGNAL-INDUCED LEAKAGE CURRENT: STEADY-STATE MEASUREMENTS

Objective: to characterize the relation between pulse intensity (direct photocurrent) and leakage current induced by the pulsed illumination in **steady state** conditions





Notes:

- Measurements in steady state conditions
  - CdTe: 2 mins of stabilization after illumination start
  - CZT: 15 seconds
- Dark leakage current (in absence of illumination) subtracted

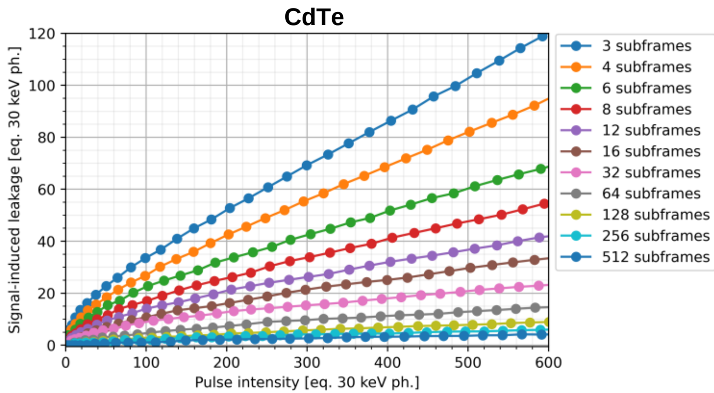
Comparison of CZT and CdTe sensors:

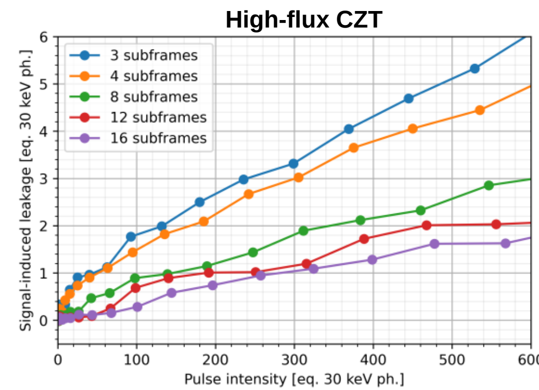
- Leakage-to-pulse ratio as figure of merit:
  - CdTe: ~20% per subframe, ~80% integrated
  - CZT: ~1% per subframe, ~4% integrated

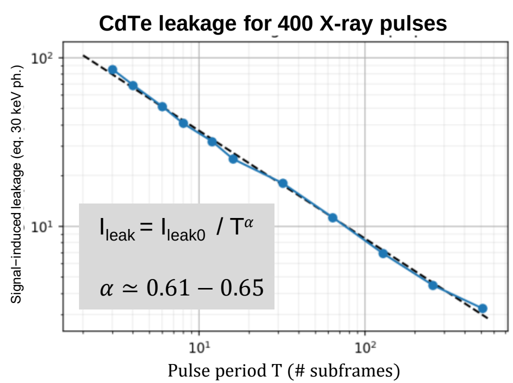
SIGNAL-INDUCED LEAKAGE CURRENT: STEADY-STATE MEASUREMENTS

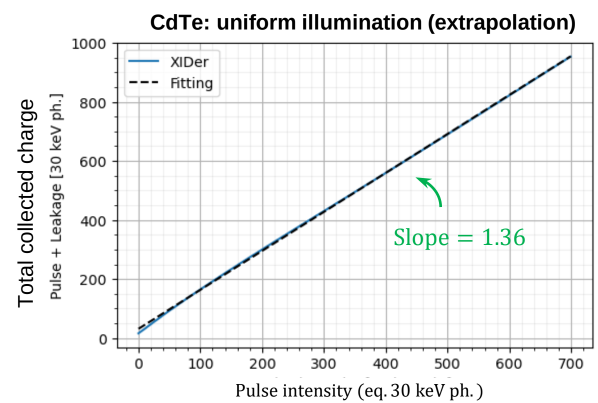
Notes:

- The curves and the leakage-to-pulse ratio depends on the LED periodicity (integrated dose)
- The usual observation is confirmed: high flux CZT performs considerably better than CdTe









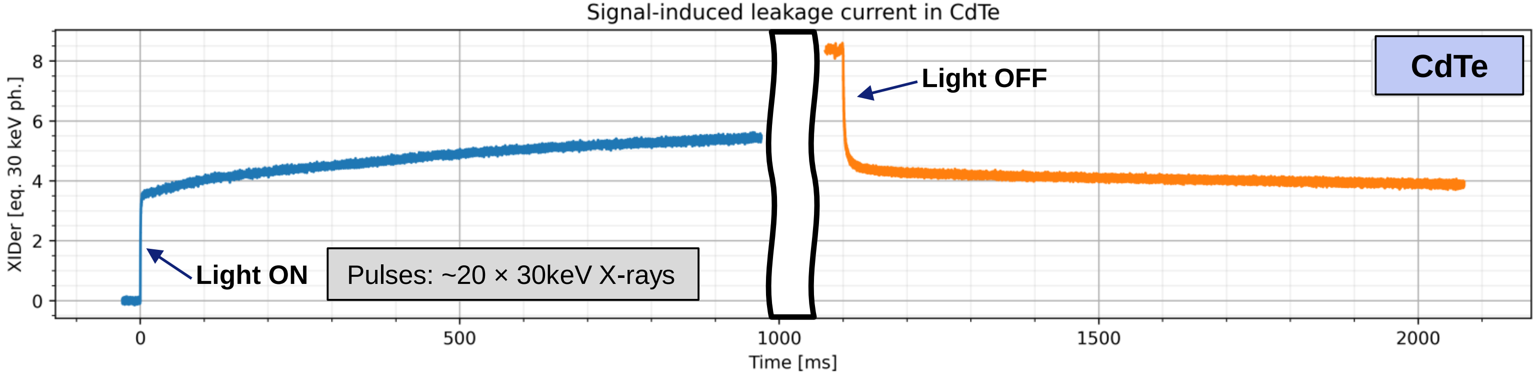
Preliminary results!

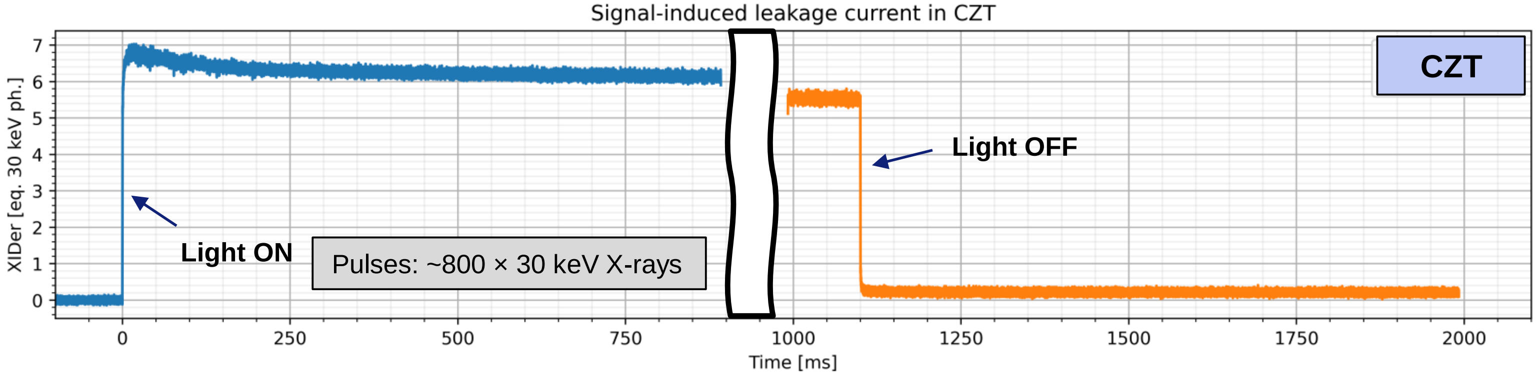
36% excess current !!

SIGNAL-INDUCED LEAKAGE CURRENT: TRANSIENT RESPONSE

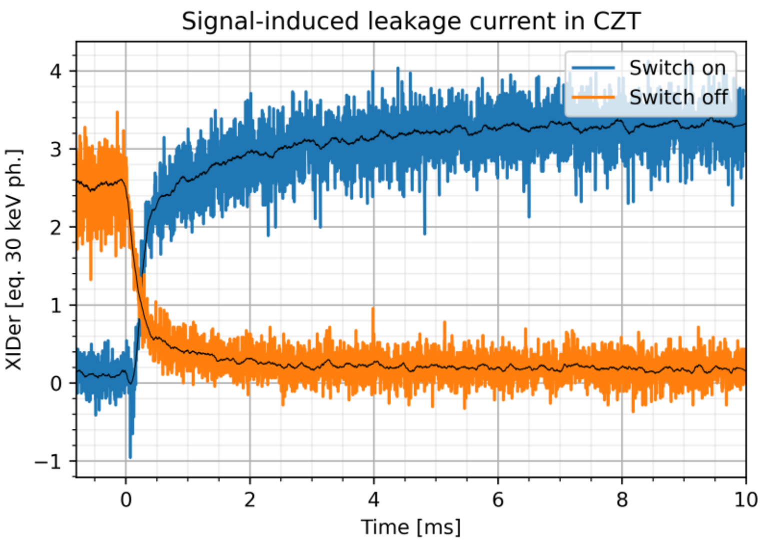
Objective: to characterize the evolution of the leakage current induced by the pulsed illumination in transient conditions by switching ON and OFF the periodic pulsed illumination

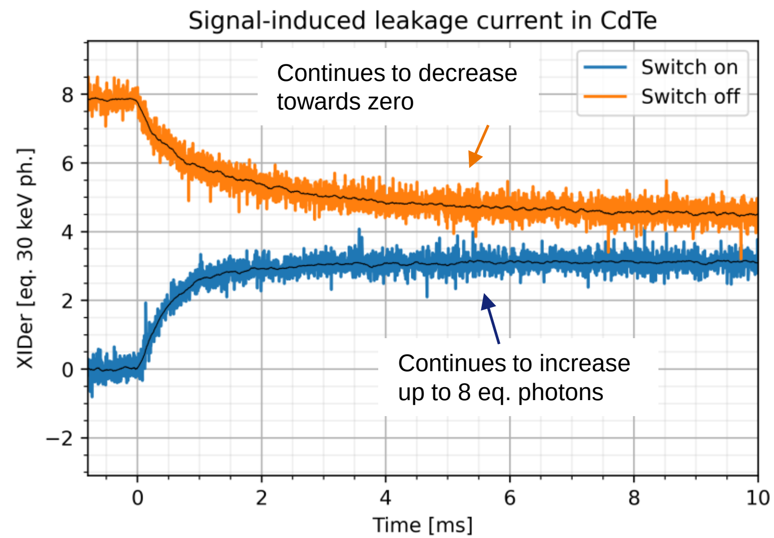
ON/OFF interval: 5 minutes





Comparison of CZT and CdTe sensors
(Data are dark current corrected)





CZT: **s**teady state is reached (90%) in less than 5ms

CdTe: it takes seconds/minutes to approach steady state

SUMMARY

- **Building charge integrating hybrid pixel detectors with high-Z sensors is challenging**
  - The major issue is the variation of leakage/dark current induced by X-ray irradiation

- **But a crucial matter for high-energy high-brilliance synchrotrons such as ESRF-EBS**
  - The XIDER project is our approach to address this problem
  - Potentially of interest for other applications and/or facilities (e.g. the XIDyn collaboration)

- **XIDER is also a tool to explore the response of CdTe and high-flux CZTs In micro and sub-microsecond time scales**
  - Direct photocurrent is collected in few tens of nanoseconds
  - But the irradiation induced leakage/dark current variations are substantial at high X-ray fluxes
  - Our initial measurements confirm that high-flux CZT performs much better than CdTe:
    - ✓ *In terms of leakage amplitude variations: about 40 times smaller*
    - ✓ *In terms of time response: milliseconds vs seconds/minutes*

- **We are starting the evaluation of pixelated CZT with XIDER. We plan to complete/continue the study:**
  - Linearity of the photocurrent component, response under different illumination patterns/conditions
  - Response at higher X-ray energies (up to 100keV)
  - Temperature dependence
  - …

THANK YOU FOR YOUR ATTENTION

https://indico.esrf.fr/event/18/

- HiZPAD webinars were established during the pandemic by scientists from several light sources
- A forum dedicated to the discussion of high-Z sensors and associated technology
- In-person meeting at DESY - Sept. 20-21st
- Hybrid meeting (no registration fees)
- Plenty of time for open discussions
- Young researchers are encouraged to present and discuss their results

Scan me!

HiZPAD workshop - HAMBURG

Sep 20 – 21, 2023
CFEL, DESY CAMPUS, HAMBURG
Europe/Paris timezone

Enter your search term

- Overview
- Timetable
- Registration
- Participant List

Contact

marie.ruat@esrf.fr
+33476882111

As the use of High-Z detectors becomes more prevalent to meet the challenging needs of the photon science community (higher photon energy, fluxes, frame rates...), this workshop aims to provide a forum that fosters discussion between scientists in the field.

Although you are highly encouraged to come discuss in person, this meeting can be followed remotely.

The deadline for registration is June 31st. Timetable and joining instructions will be communicated upon registration.

You're welcome to volunteer for a talk!

GENERAL TOPICS:

- (High-Z) Detector Developments
- High-Z sensors: contacts, interconnects and material characterization
- Applications of high-Z detectors in Photonic Science

ADDITIONAL EVENTS:

- **Sept. 20th: Workshop Dinner**
- **Sept. 21st: Scientific Brunch** | an opportunity to showcase your work (poster) over an informal brunch
- **Sept. 21st: Capability Showcase** | As a community we developed a framework of material characterization expertise, which we would map during this showcase! Experts are encouraged to present their developed capabilities, to foster information crossing and future inter-institutes collaborating work.

Participants are only expected to finance their travels and accommodation.