TEMPUS, an event-driven X-ray detector

DESY FS-DS

Photon Science Detector Group

J. Correa, A. Simancas, A. Ferruglio,
D. Pennicard, S. Fridman, S. Lange, H. Graafsma

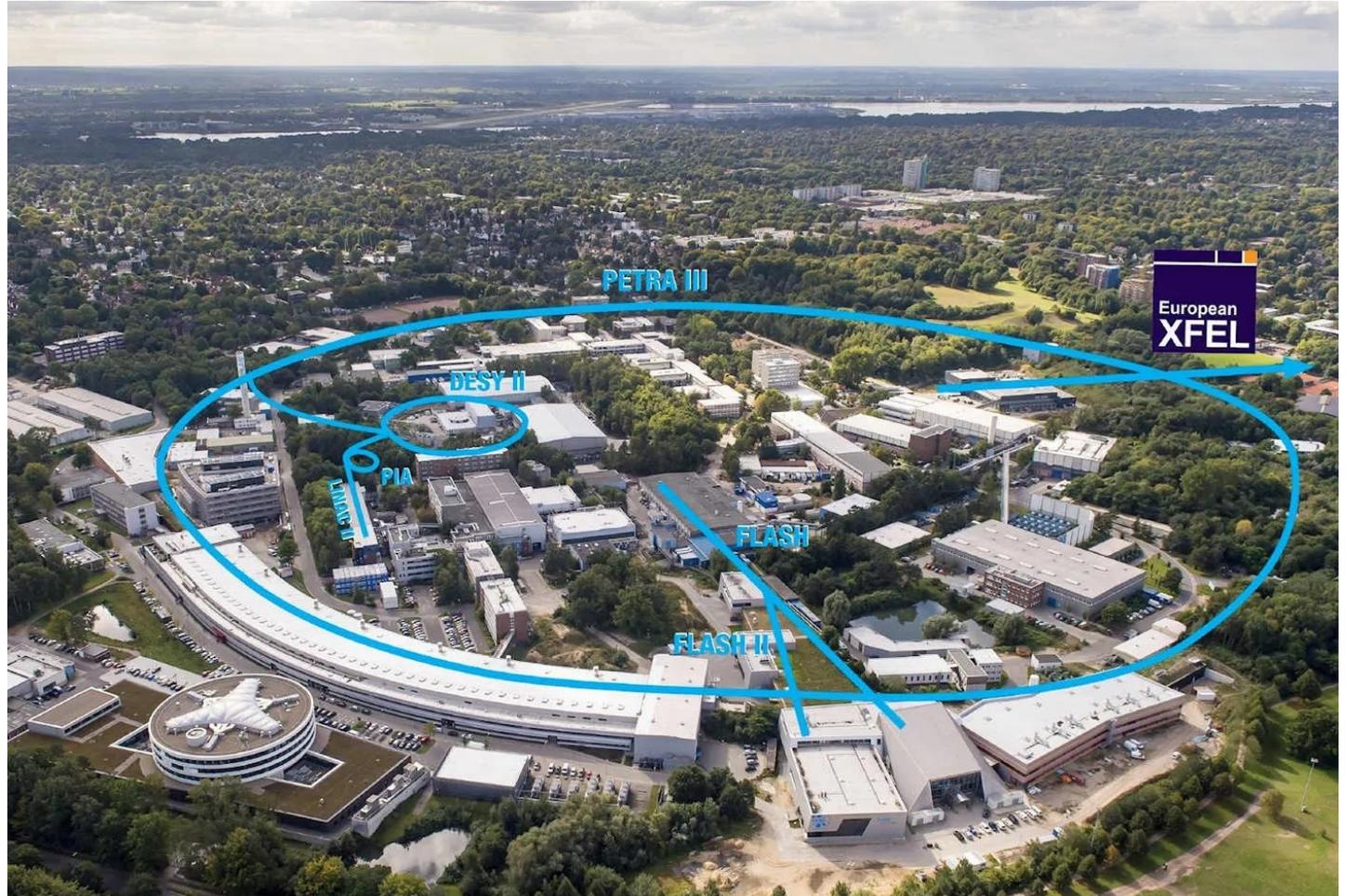# The TEMPUS X-ray detector

Outline

- Frame-based vs. data-driven

- The TEMPUS X-ray detector

- Energy Calibration

- Science driven experiments:

  - **NRS**

  - **XPCS**

  - **AMO**

- Some lessons learnt

- Summary and Outlook
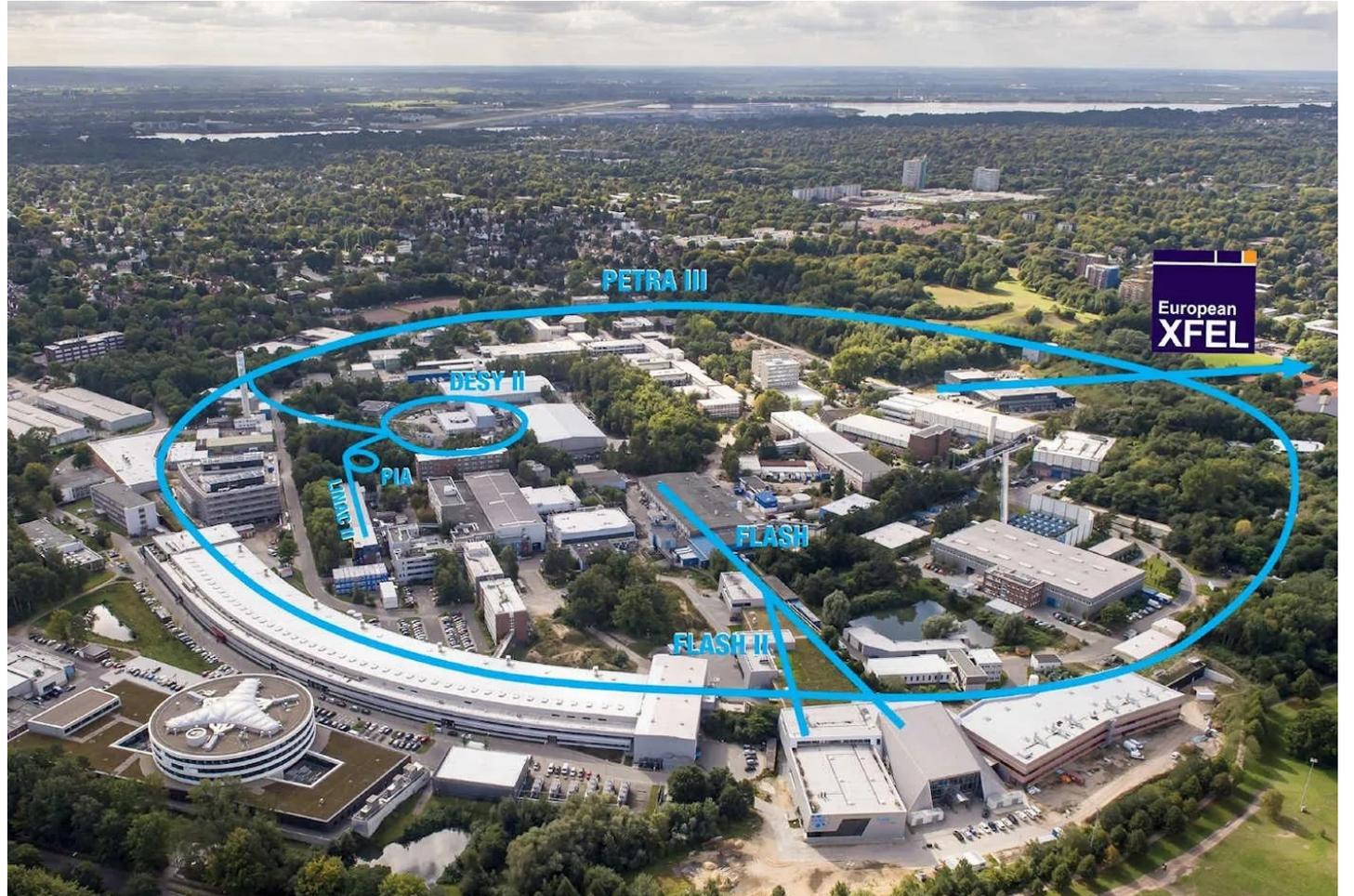
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The TEMPUS X-ray detector

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Hamburg Region Light Sources
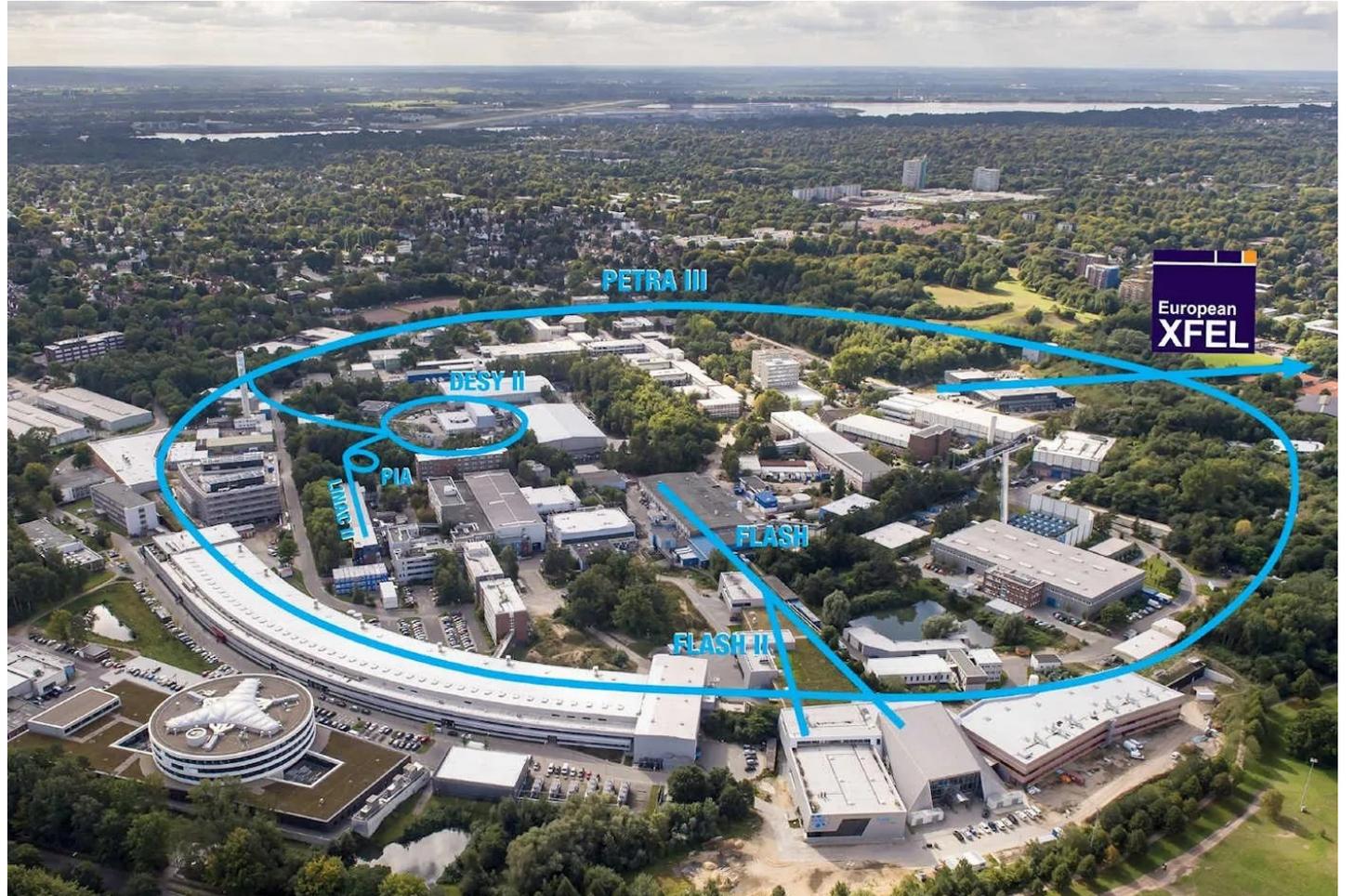
Our Mission

- **PETRA III**
  - 3rd generation SR

- **FLASH I & FLASH II**
  - Soft X-ray FELs

- **Eu.XFEL**
  - High repetition high energy FEL

- **PETRA IV**
  - 4th generation SR
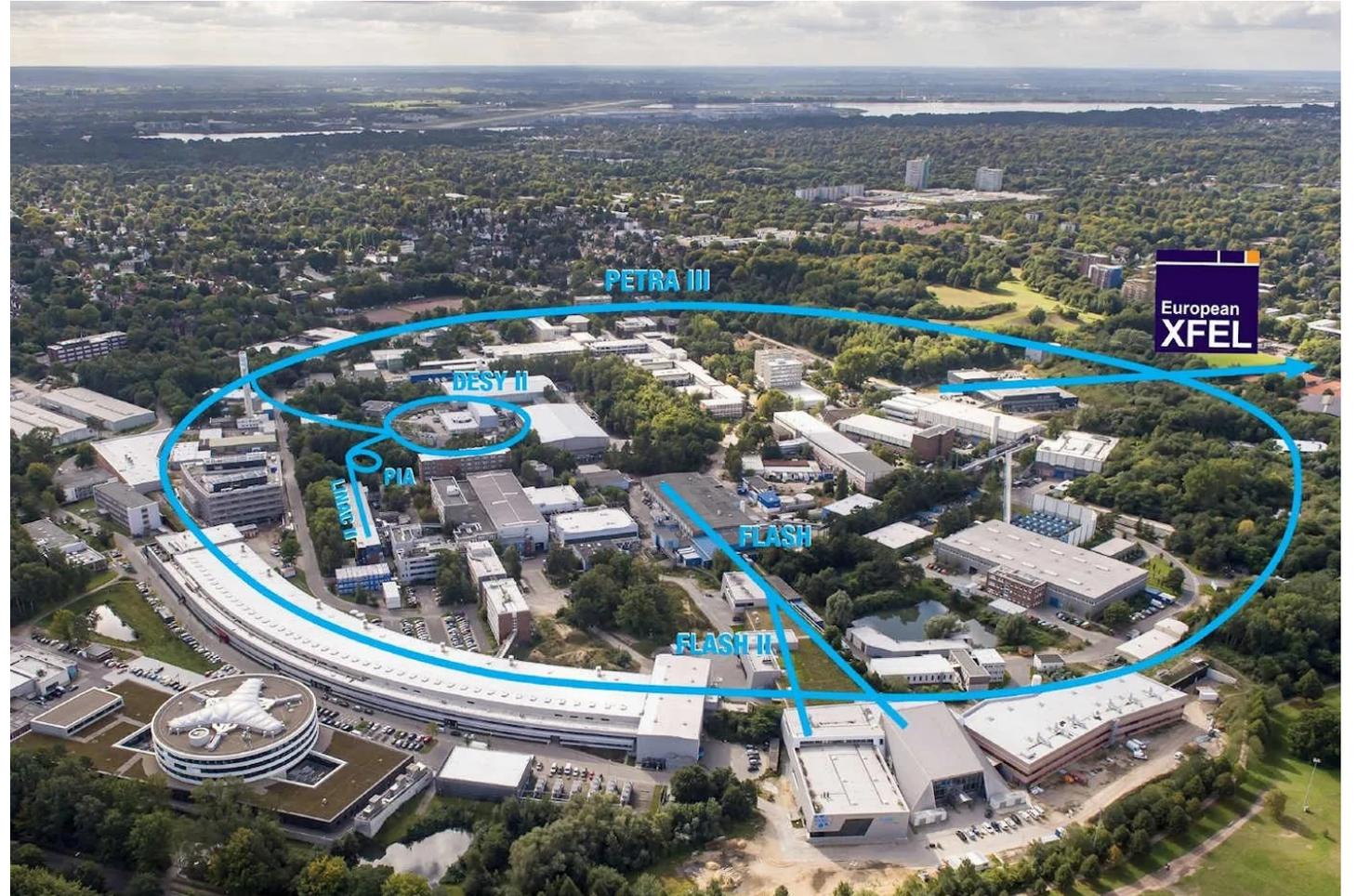
Hamburg Region Light Sources

Our Mission

- PETRA III
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  - **AGIPD**
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  - **CORDIA & TEMPUS**

Hamburg Region Light Sources

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  - **CORDIA & TEMPUS**
- R&D
  - **Sensors, packaging, etc.**

DESY.

Hamburg Region Light Sources

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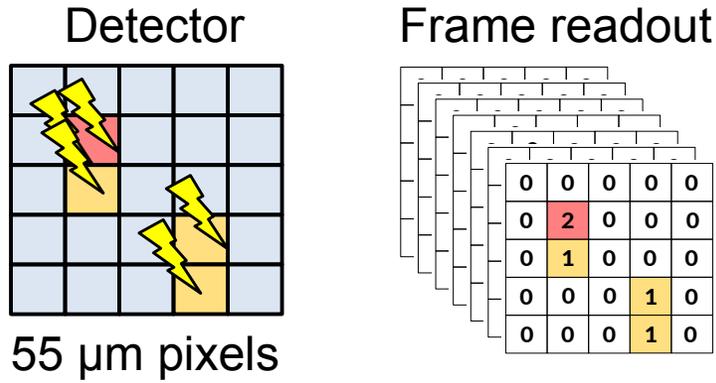- R&D
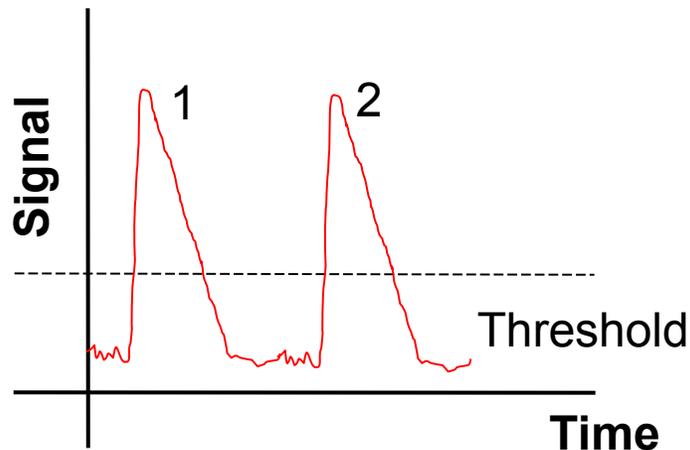 - **Sensors, packaging, etc.**

The Timepix4 readout chip

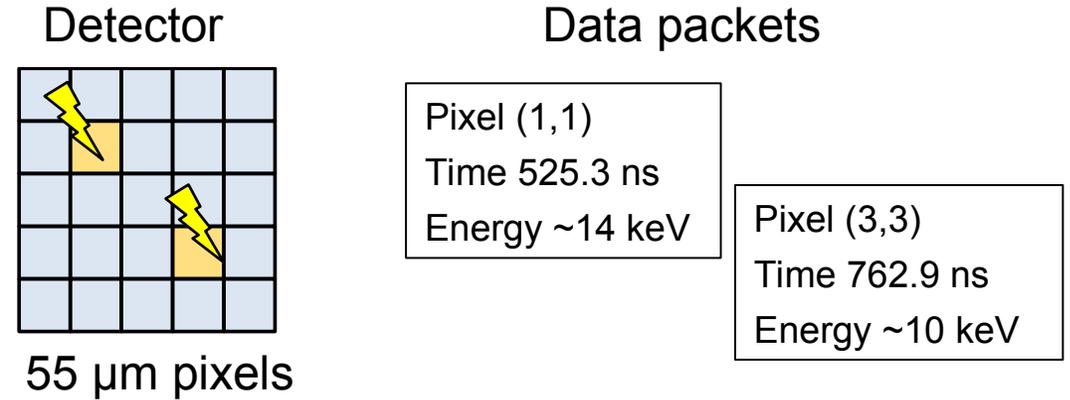## Operation modes

The Timepix4 readout chip

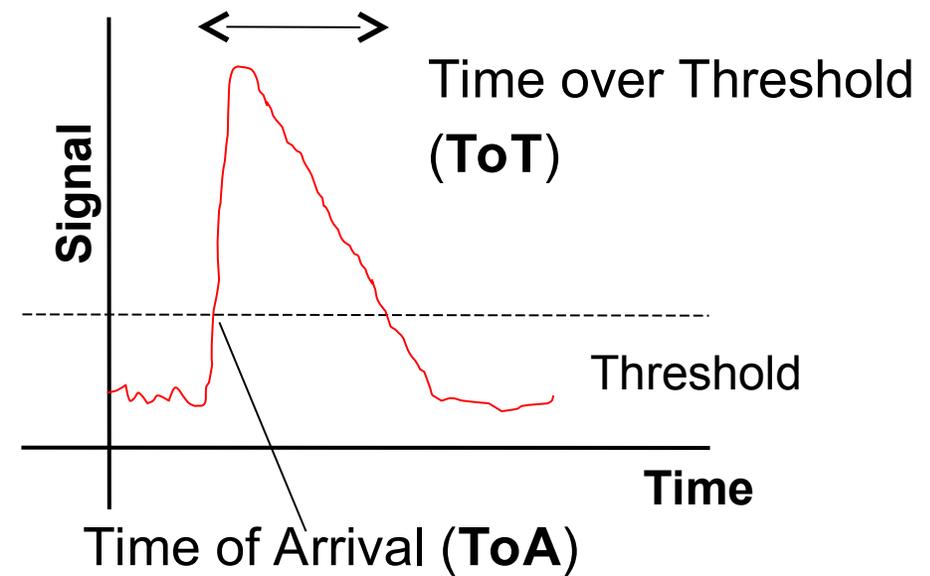**Operation modes**

1) Photon counting and frame readout

Detector

Frame readout

55 μm pixels

0	0	0	0	0
0	2	0	0	0
0	1	0	0	0
0	0	0	1	0
0	0	0	1	0

- 40 kHz frame rate CRW (8 bits)
- ~ 1.5×10^6 counts/pixel/s

Signal

1   2

Threshold

Time

2) Time-stamping and event-driven readout

Detector

Data packets

55 μm pixels

Pixel (1,1)
Time 525.3 ns
Energy ~14 keV

Pixel (3,3)
Time 762.9 ns
Energy ~10 keV

- X-rays ~ ns time resolution
- ~ 1×10^9 counts/chip/s

Signal

Time over Threshold (**ToT**)

Threshold

Time of Arrival (**ToA**)

Time

DESY.

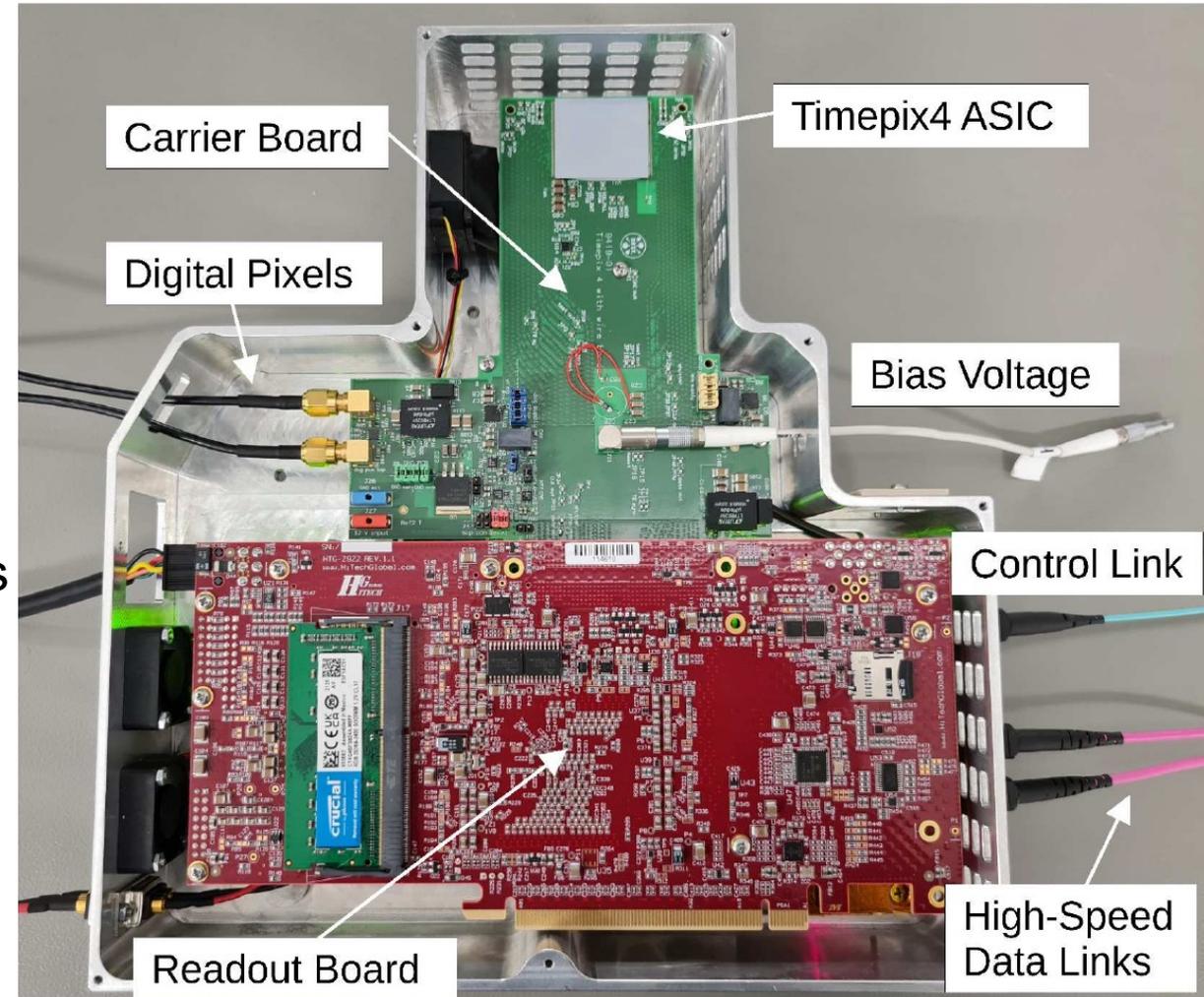# The TEMPUS X-ray detector

System description – planned specs

> Single-chip Timepix4 board connected to off-the-shelf Xilinx board

  - Zynq Ultrascale+ with FPGA fabric and 4-core CPU

> Parallel readout of 16 high-speed links from chip, each up to 5 (or 10) Gbit/s

  - Specialised transceivers on Zynq

> Daughterboard offering 2 x 100 GBE links over "Firefly" optical cable

  - Challenge of dealing with ~ **80 (or 160) Gbits/s**

The TEMPUS X-ray detector

System description – current status

> First version of the single-chip system

  – Underwent tests in several beam-lines

  – Main detector in various user experiments

> Some of the goals of the prototype:

  ▪ Check the usability of the high-speed serialisers

  ▪ Explore the event-driven mode

> Work in progress:

  – Number and stability of actived serialisers

  – Time resolution

  – Energy calibration
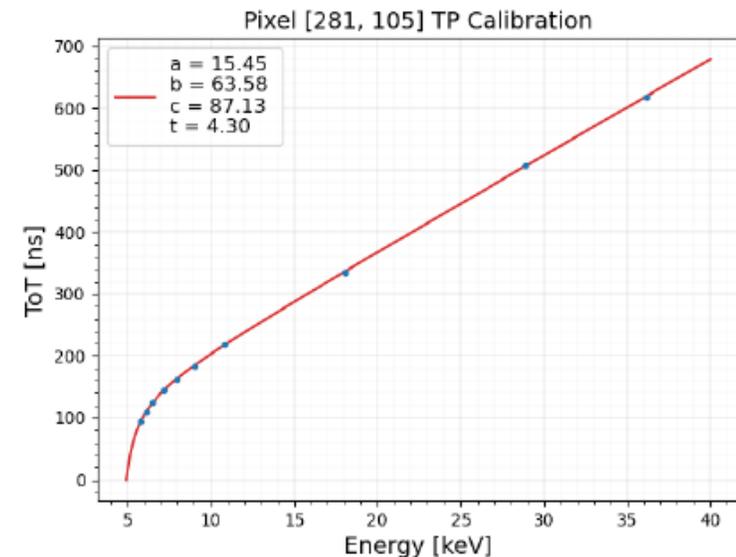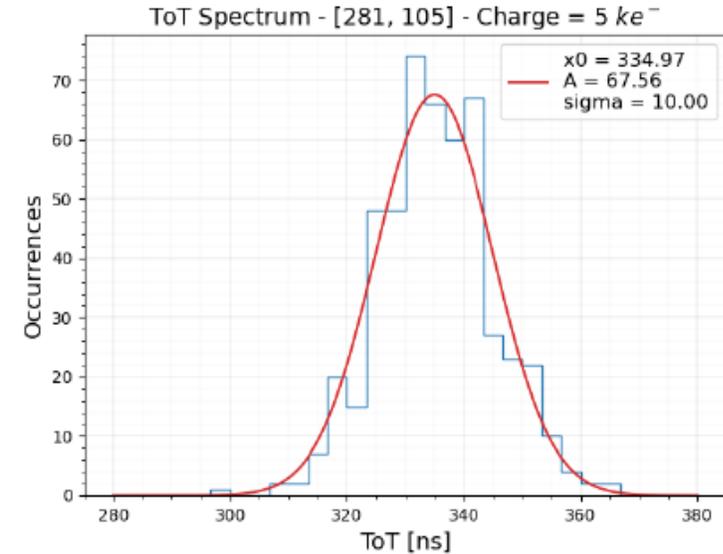
  – ...

J. Correa et al. (2024). **J. Synchrotron Rad. 31**. https://doi.org/10.1107/S1600577524005319

Energy calibration

Done by A. Ferruglio during his stay at DESY

> Test-Pulse calibration validation:

– Issue found while setting up the chip

– Causes are still unknown

> A smaller (7x7 pixels) area was used instead

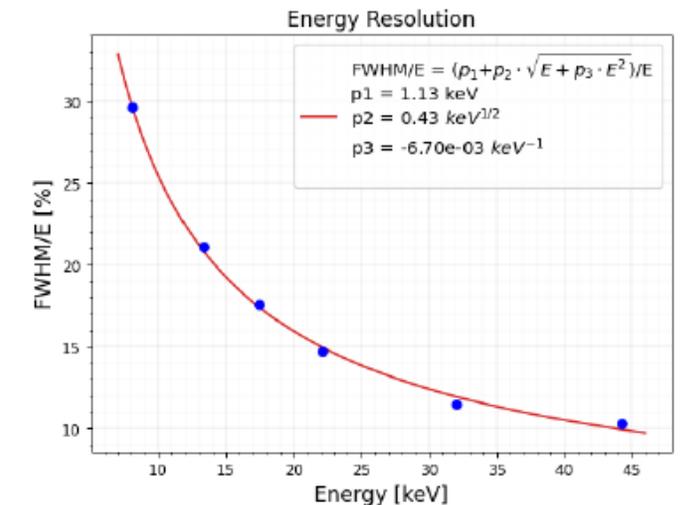> 500 tests pulses of several energies were used
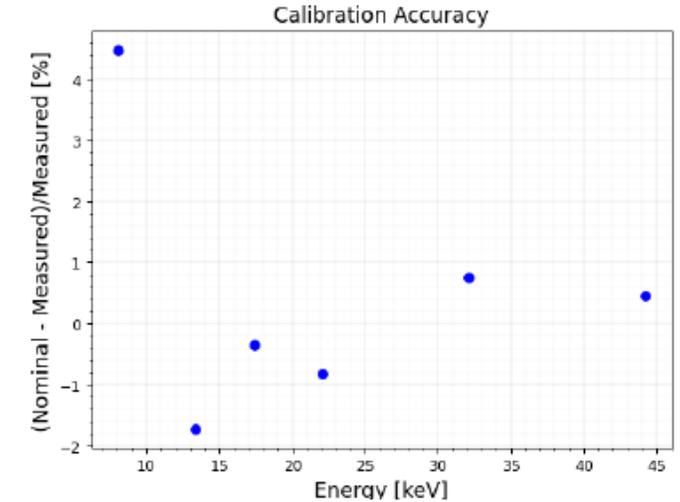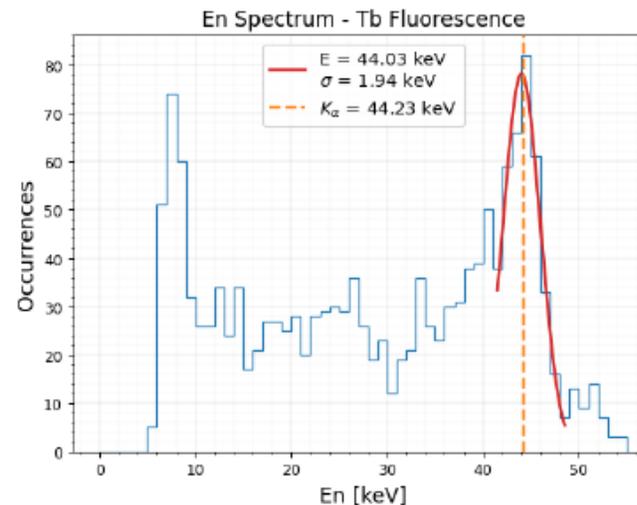
> Results are as expected

$$\mathrm{ToT} = a \cdot E + b - \frac{c}{E - t}$$

ToT Spectrum - [281, 105] - Charge = 5 ke^-

x0 = 334.97
A = 67.56
sigma = 10.00

Pixel [281, 105] TP Calibration

a = 15.45
b = 63.58
c = 87.13
t = 4.30

Energy calibration

Done by A. Ferruglio during his stay at DESY

> Spectra for various elements

> Energy resolution and calibration accuracy found to be as as expected

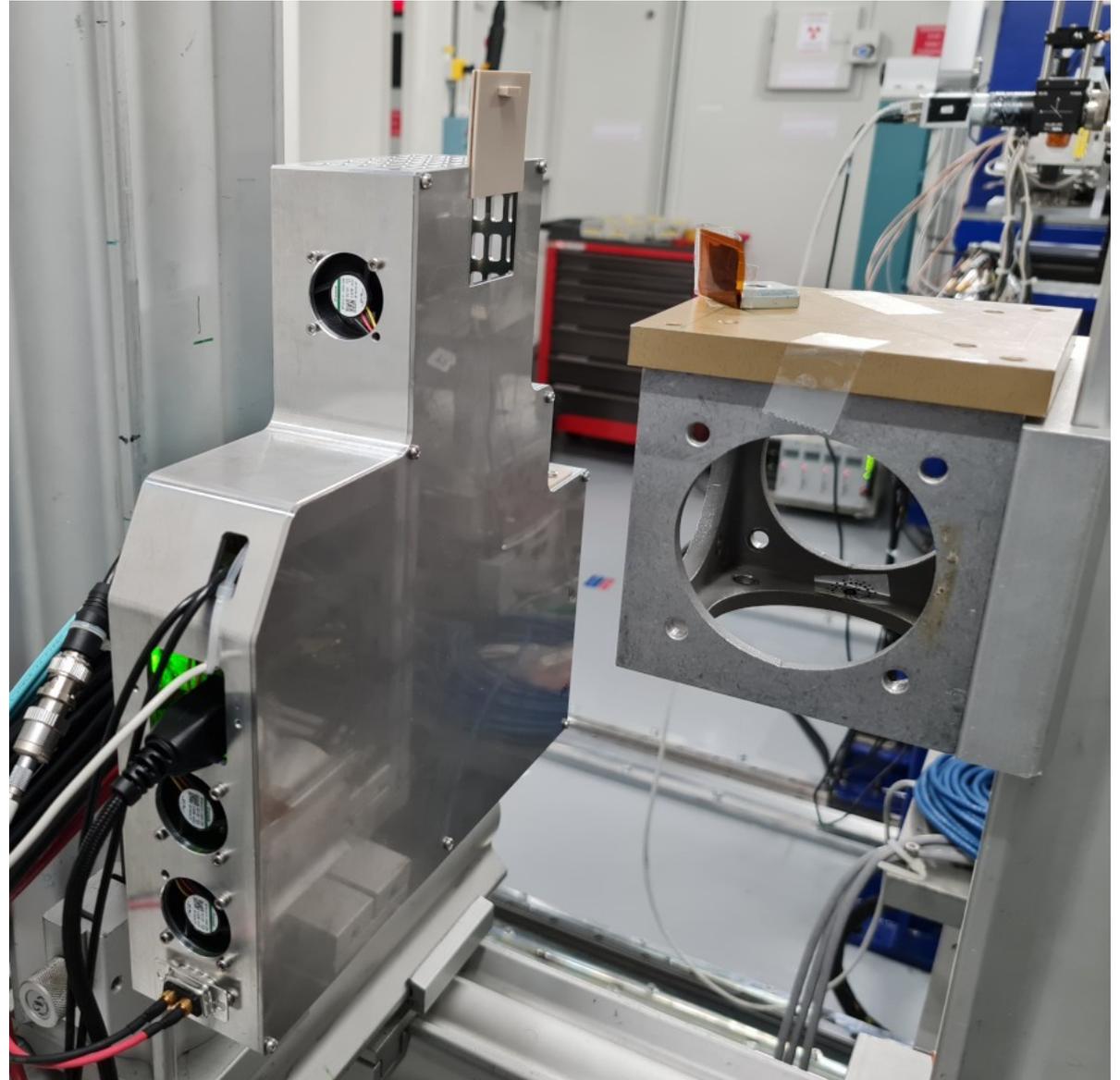> Next step is to solve the issue and perform full matrix calibration

TEMPUS detector science driven experiments

TEMPUS detector science driven experiments

Nuclear Resonance Scattering

> Exploits the Mössbauer effect

  – After absorption there is a recoil-free emission due to bound to lattice

  – Relatively long decay time tens of ns

> It works in a small number of isotopes:

  – ^{57}Fe ~ 14.4 keV

> It is used to study hyperfine structures under electric and magnetic fields

> Currently using APD:

  – Very high time resolution ~ 200 ps

  – Lacking hit rate and statistics

TEMPUS detector science driven experiments

Nuclear Resonance Scattering

> Mix of scattered and fluorescence of various elements

  – **Off resonance**

> The structure of the different filling modes can be easily distinguished:

  – **40 bunches at PETRA III**

  – 7/8 + 1 at ESRF

> Time resolution still limited by the system:

  – Thinner sensor & higher sensor bias

  – Other sensor materials

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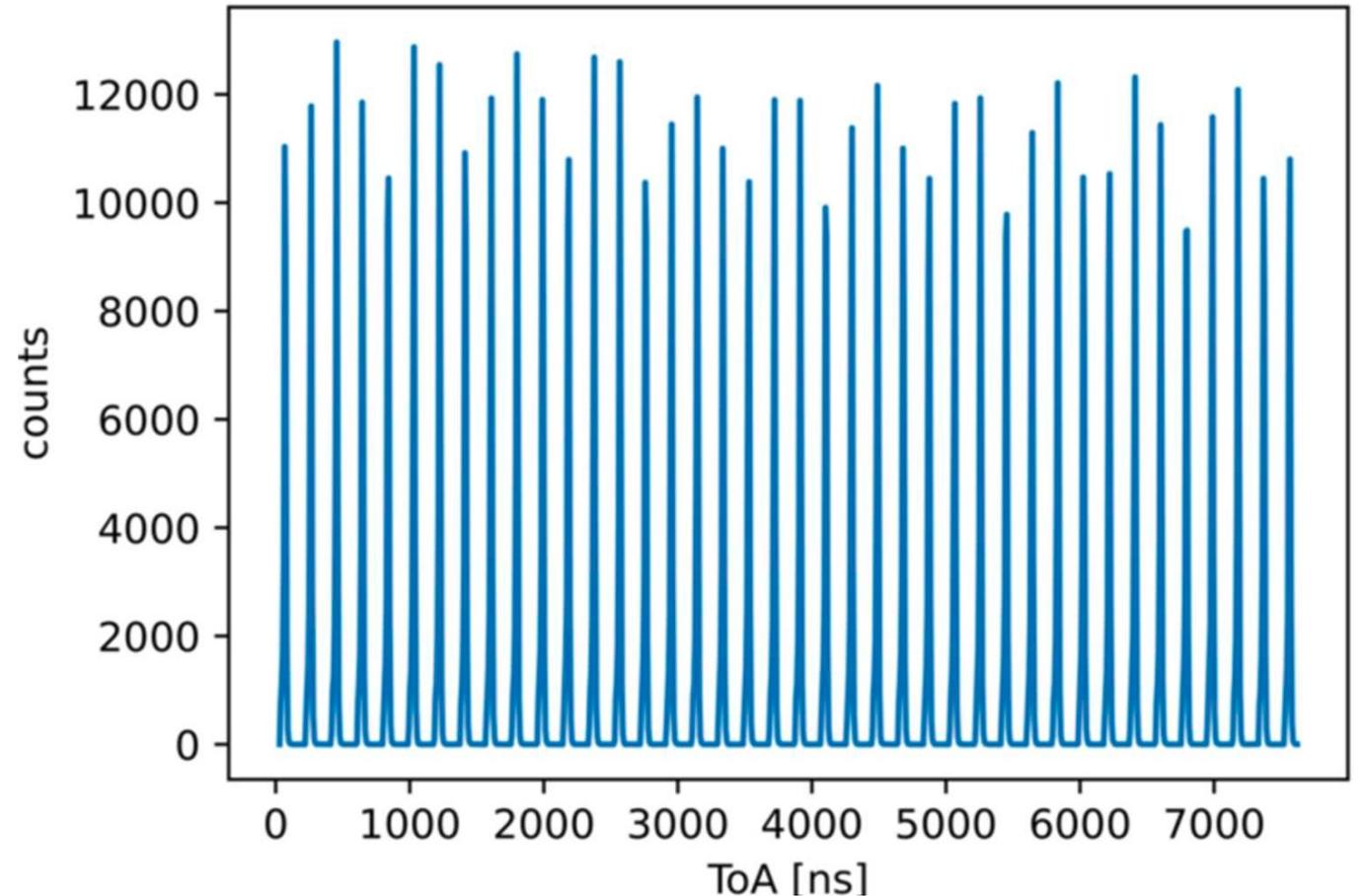 – Thinner sensor & higher sensor bias

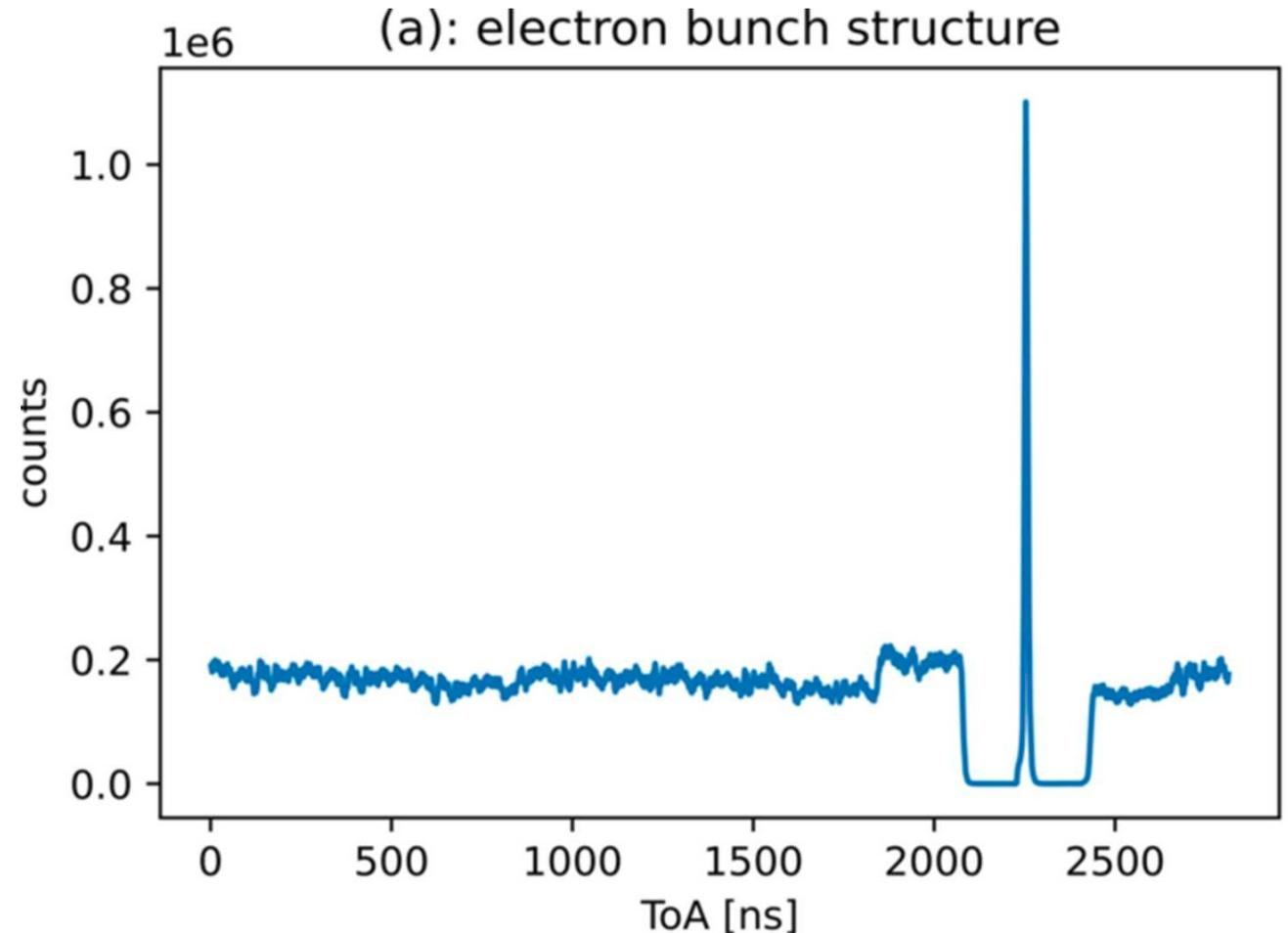 – Other sensor materials

(a): electron bunch structure

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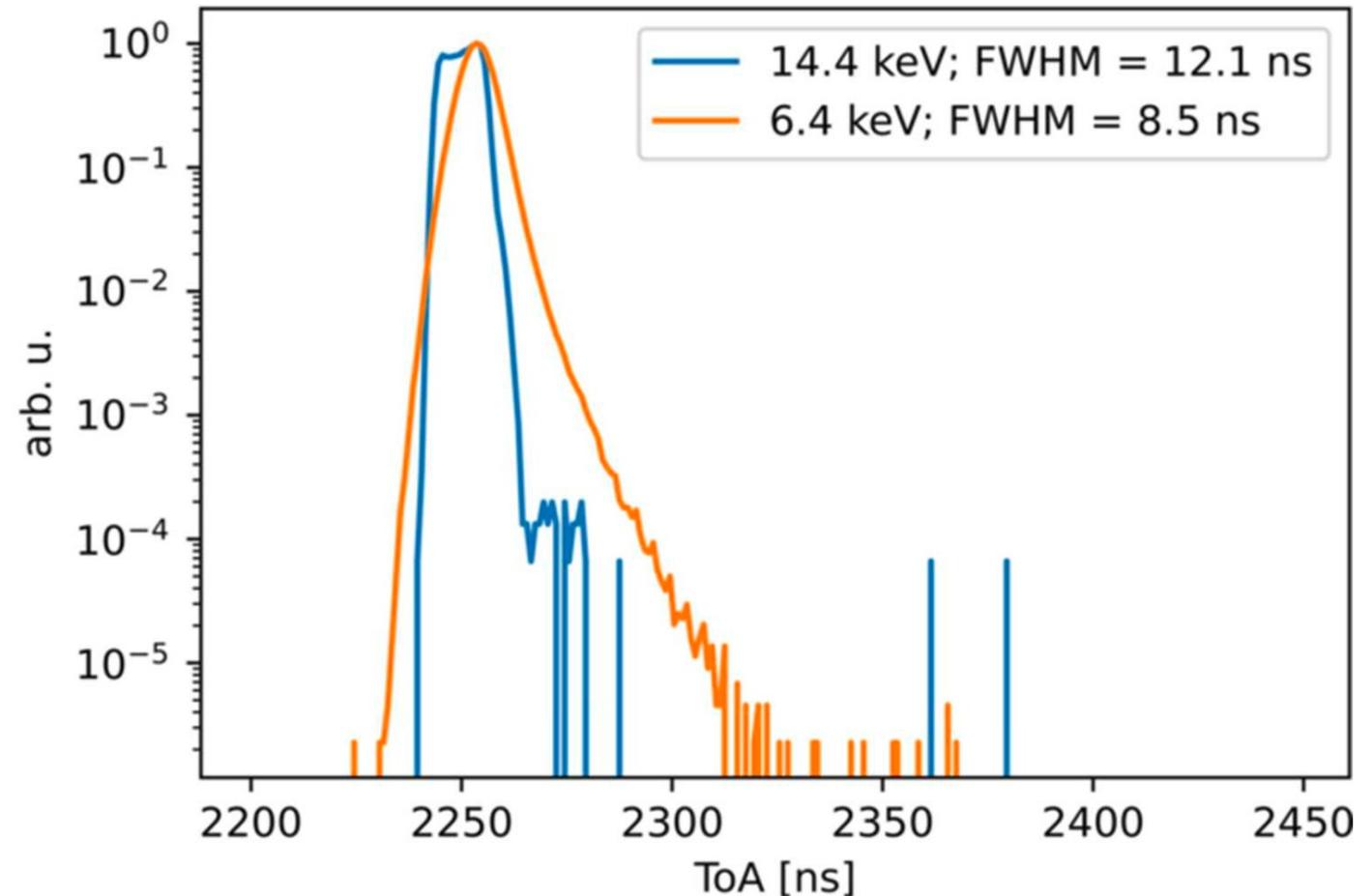 – Thinner sensor & higher sensor bias
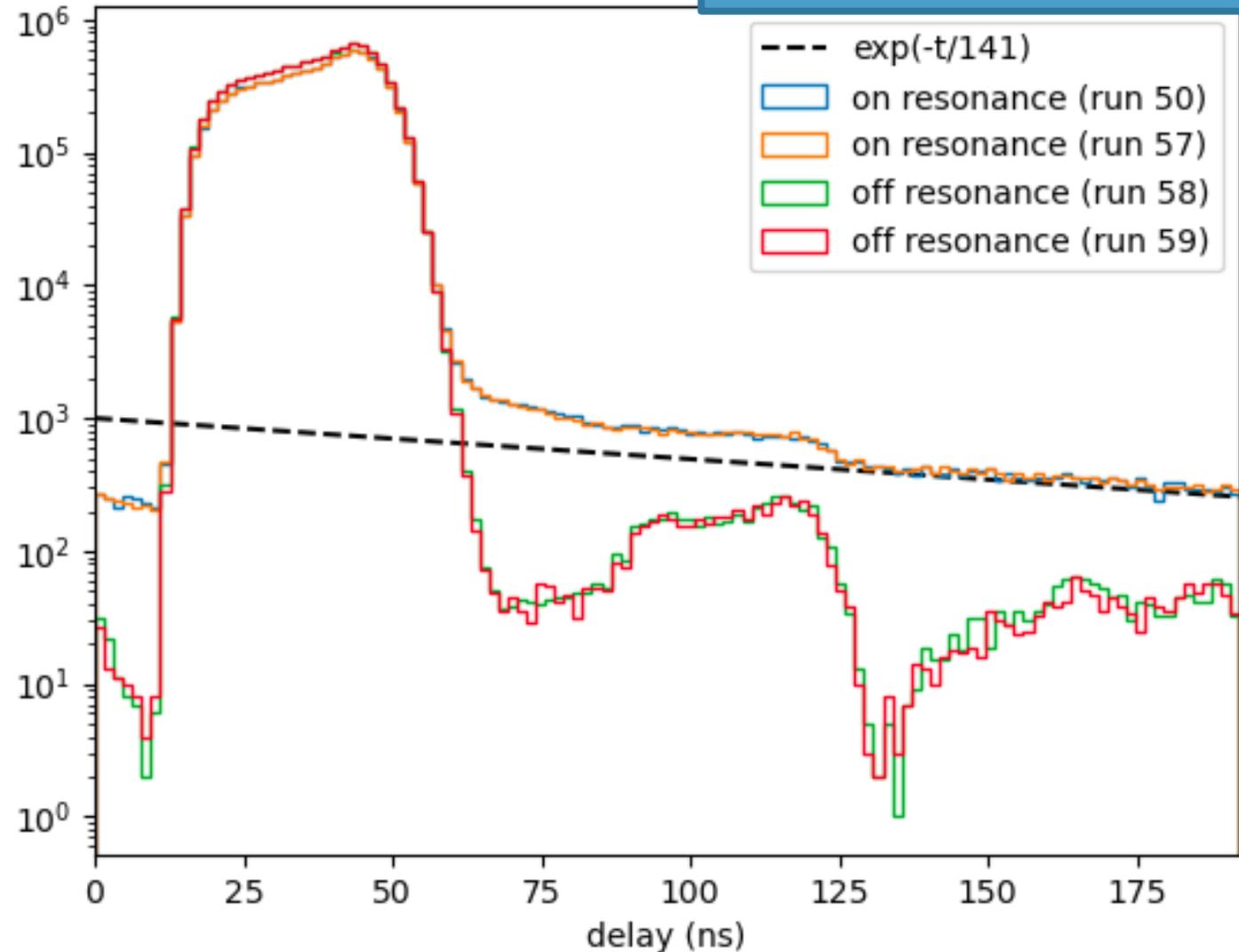
  – Other sensor materials

(b): ToA distributions

Legend:
- 14.4 keV; FWHM = 12.1 ns
- 6.4 keV; FWHM = 8.5 ns

x-axis: ToA [ns]
y-axis: arb. u.

TEMPUS detector system first users experiments

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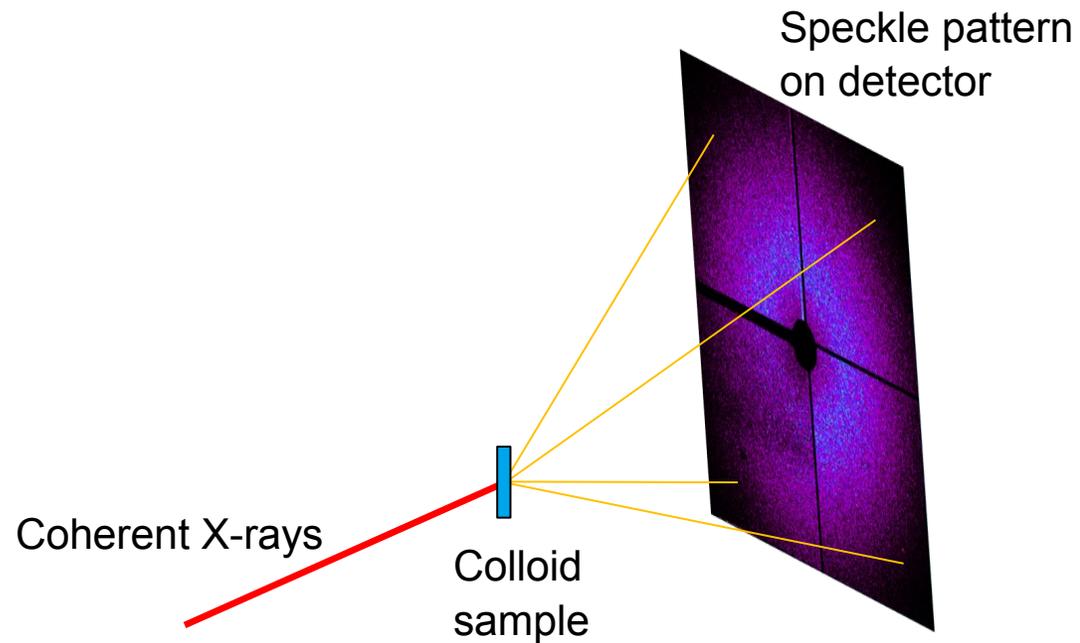
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TEMPUS detector by users experiments

X-ray Photo Correlation Spectroscopy – sub μs correlation functions

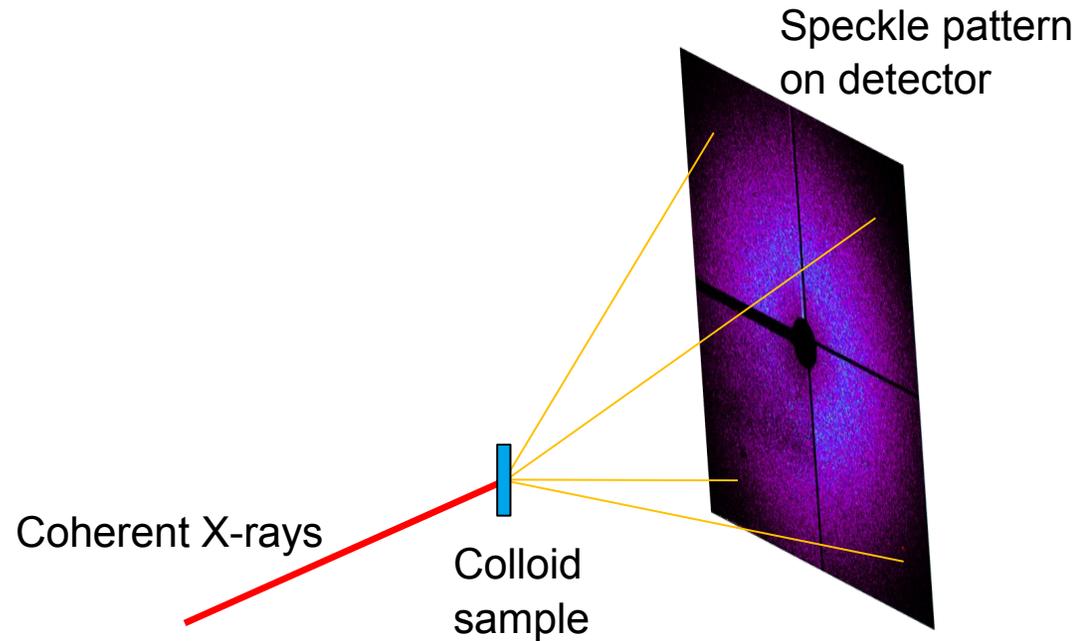- Campaigns at **ESRF - ID10** and **Eu.XFEL - MID**

Speckle pattern
on detector

Coherent X-rays

Colloid
sample

TEMPUS detector by users experiments

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Speckle pattern on detector

Coherent X-rays

Colloid sample

MOVIE: 2D Brownian Motion of 100 particles

MOVIE: Portion of the scattering pattern

$$g_2(q,\tau) = \frac{\langle I(q,t)I(q,t+\tau)\rangle}{\langle I(q,t)\rangle^2}$$

TEMPUS detector by users experiments

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Y. Chushkin et al. (2025). **J. Synchrotron Rad. accepted**

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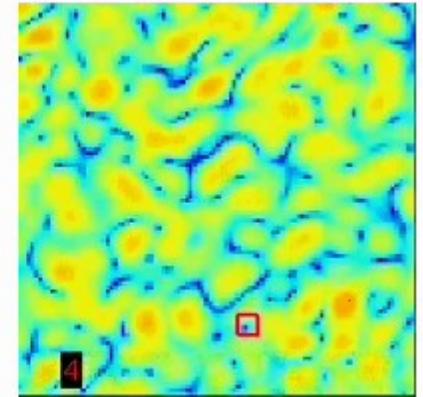

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TEMPUS detector by users experiments

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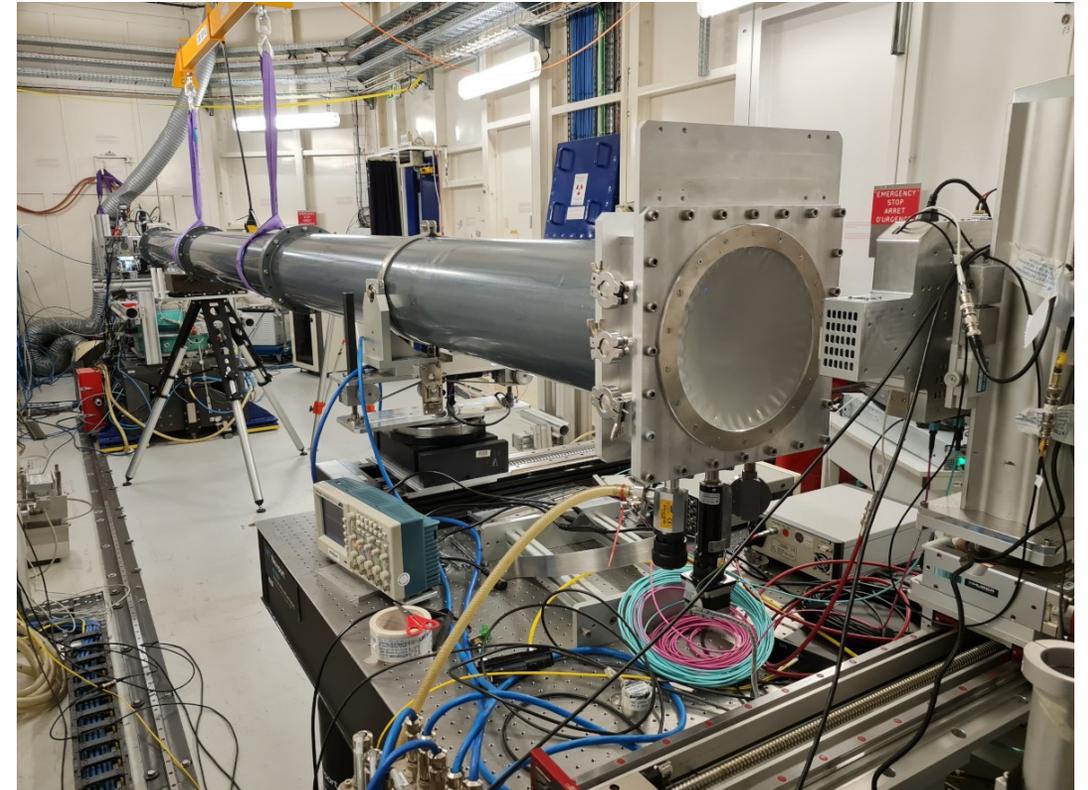
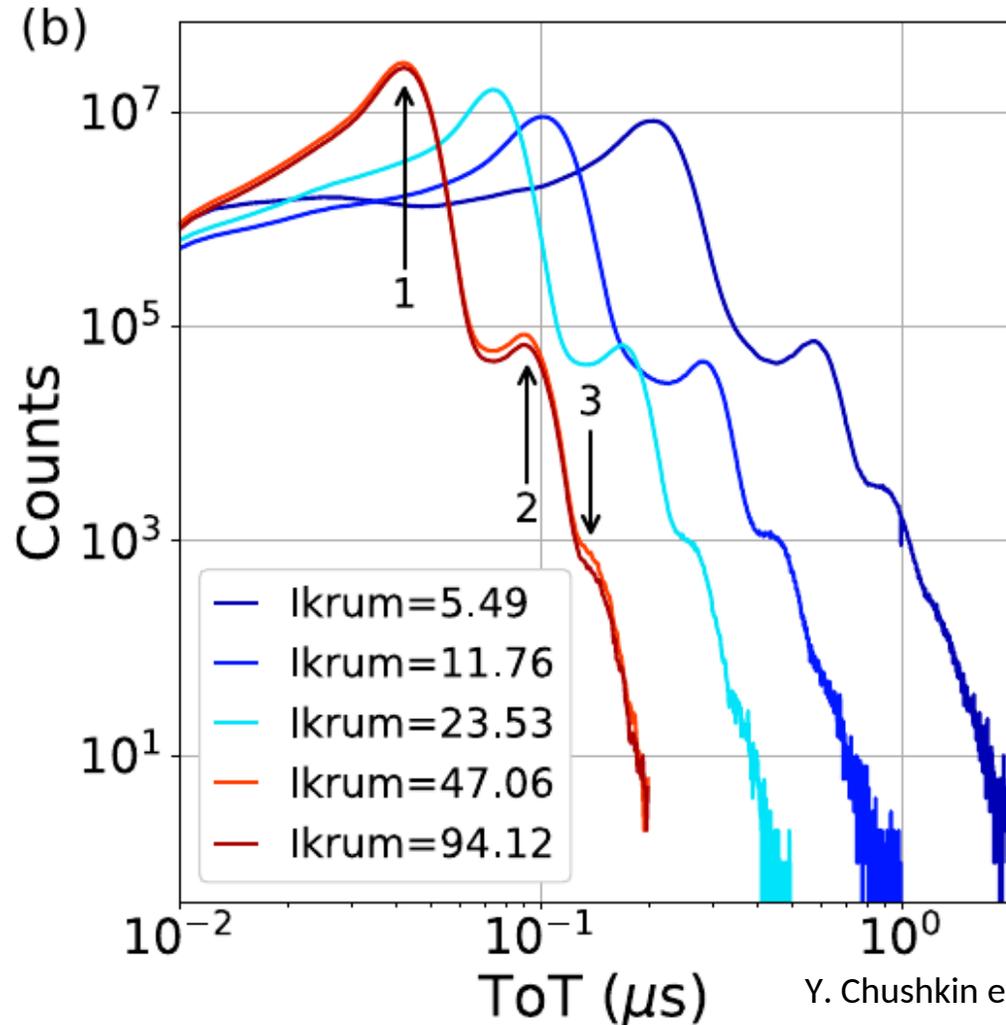- Campaigns at **ESRF - ID10** and **Eu.XFEL - MID**

Y. Chushkin et al. (2025). **J. Synchrotron Rad. accepted**

TEMPUS detector system first users experiments

Atomic and Molecular Physics

TEMPUS detector system first users experiments

Atomic and Molecular Physics

Pump + disruptive probe

Detection scheme

pump pulse

probe pulse

Δt

E

Detector

Atomic and Molecular Physics

Mass spectrum & ion plot of singly ionised water dimer fragments

TEMPUS detector system first users experiments

Soft X-ray 1D Imaging Spectrometer – MCP-Phosphor-Stack + TEMPUS – Fluorescence of highly ionized Ne

Commissioning/Test Campaign at **Eu.XFEL - SQS**

ANALYSIS ONGOING

Agåker *et al.* (2024).
J. Synchrotron Rad. **31**

Some lessons learnt

After the first user experiments

Some lessons learnt

- **Data Deluge**

  - Data reduction is… complicated

  - Infrastructures not ready

  - Keep flexibility… to some extend

- **Early deployment / adoption**

  - Commitment from communities

  - Slow down short term development

  - Net benefits both users and developers

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shape: (11_049_380, 10)

index	top	toa48_ns	toa48_raw	tot_ns	x	y	pileup	dpx_bot	dpx_top
u32	bool	f64	i64	f64	i16	i16	bool	bool	bool
4446931	false	3.0002e9	120008073	51168.75	241	352	true	false	false
4448800	false	3.0000e9	120000395	14.0625	208	509	false	false	false
4448801	false	3.0000e9	120000484	223.4375	39	459	false	false	false
4448802	false	3.0000e9	120000393	131.25	209	509	false	false	false
4448807	false	3.0000e9	120000470	164.0625	72	454	false	false	false
…	…	…	…	…	…	…	…	…	…
10188005	true	3.9999e9	159995303	278.125	57	255	false	false	false
10188006	true	3.9999e9	159995143	137.5	218	254	false	false	false
10188007	true	3.9999e9	159995186	243.75	134	213	false	false	false
10188011	true	3.9999e9	159995211	314.0625	362	160	false	false	false
10188017	true	3.9999e9	159995216	29.6875	5	196	false	false	false

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Summary

TEMPUS, an X-ray event-driven detector

- A **single-chip Timepix4-based prototype** is being developed at DESY

  - Reach the **limits of the chip**

  - Help the community understanding and using **the event-driven** readout

- Energy calibration has just started

  - Issue found programming the test pulses

- Some communities have a strong interest in the development:

  - **NRS** → high time resolution, and high counting rate

  - **XPCS** → small pixel size and short dead times

  - **AMO** → high time resolution, 2D capabilities, and high count rate

Outlook

TEMPUS, an X-ray event-driven detector

- Next steps:

  - **Continue finding applications** that could benefit from this technology

  - **Frame-based mode** → interest for many beam-lines in the upgraded **PETRA IV**

  - **Time calibration** → push the limits of time resolution on silicon

  - Using the **TSV** capability offered by the chip

  - Use of **alternative sensors** such as **high-Z** materials and **LGADs**:

    - **Expand the photon energy range** of current system

    - Overcome the silicon sensor **time resolution** limitations for X-rays

Acknowledgments

Collaborators

DESY

Jonathan Correa
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Fabian Westmeier

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Aleksandr Chumakov
Marco Cammarata
Rudolf Rueffer

FAU

Sebastian Karl
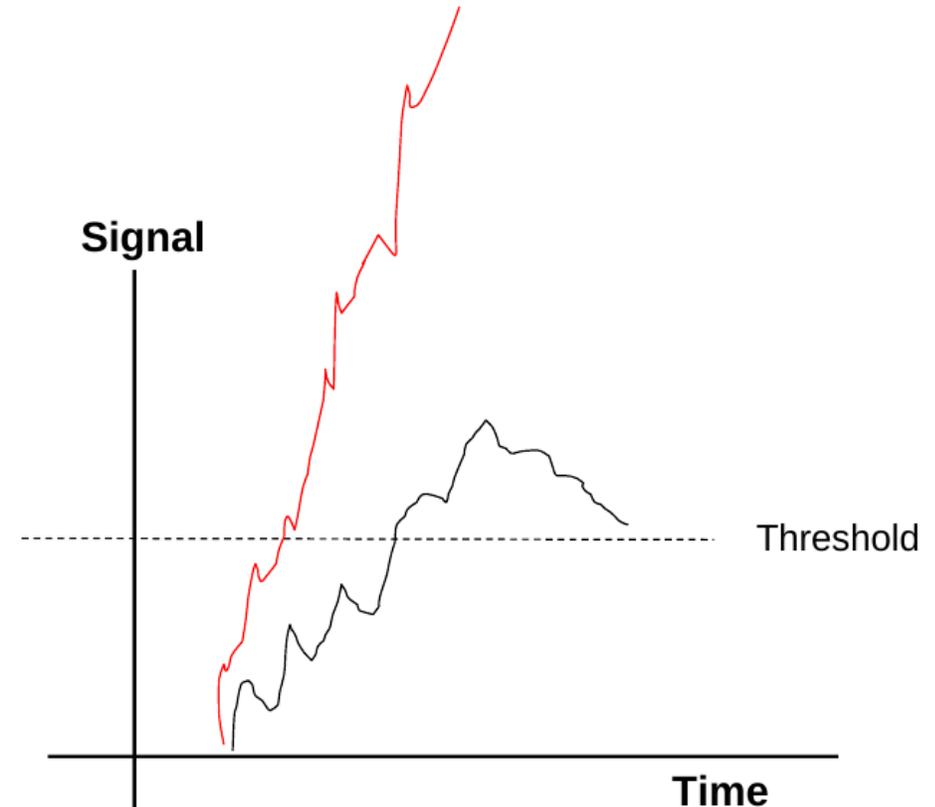Joachin von Zanthier

Alexandr Ignatenko
Ralf Roehlsberger

European XFEL

Bjoern Senfftleben
Michael Meyer
Thomas Baumann
Rebecca Boll
Simon Dold
Yevheniy Ovcharenko
Matthew Robinson
Sergey Usenko

DESY.   **HELMHOLTZ**

Backup Slides

Some comments on time resolution

Timewalk

> Time delay before signal reaches threshold

  ▪ Assuming instant signal, this depends on peaking time of amplifier response

Jonathan Correa | The TEMPUS X-ray detector system | 6th International Nuclear Resonance Workshop

Some comments on the time resolution

Signal speed

> Absorption depth leads to time variation of signal pulse

> Resulting time variation depends on both **absorption profile** and **carrier velocity**

Jonathan Correa | The TEMPUS X-ray detector system | 6th International Nuclear Resonance Workshop

Some comments on the time resolution

First Experiments @ ESRF

- Time-walk correction

  ▸ Helped to improved the time resolution obtained

(a): ToA vs ToT - timewalk

(b): ToA vs ToT - timewalk corrected

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The Timepix4 readout chip

Comparison with Timepix3

			Timepix3 (2013)	Timepix4 (2019/20)	
Technology			IBM 130 nm – 8 metal	TSMC 65 nm – 10 metal	
Pixel size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable (TSV) 512 x 448	**3.5 x**
Sensitive area			1.98 cm²	6.94 cm²	
Readout modes	**Data driven (tracking)**	**Mode**	ToT and TOA		
		Event packet	48-bit	64-bit	
		Max rate	< 43 Mhits/cm²/s	357.6 Mhits/cm²/s	**8 x**
		Pix rate equiv.	1.3 kHz/pix average	10.8 kHz/pix average	
	Frame Based (imaging)	**Mode**	Count: 10 bit + iToT	Count: 8 or 16 bit CRW	
		Frame	Zero suppressed (with pix addr)	Full frame (no pix addr)	
		Max count rate	82 Ghits/cm²/s	~ 800 Ghits/cm²/s	**10 x**
		Max frame rate	N/A (worst case: 0.8ms readout)	80 kHz CRW	
TOT energy resolution			< 2 keV	< 1 keV	**2 x**
Time resolution			1.56 ns	~ 200 ps	**8 x**
Readout bandwidth			≤ 5.12 Gbps (8 x 640 Mbps)	≤163.8 Gbps (16 x 10.2 Gbps)	**32 x**
Target minimum threshold			< 500 e⁻	< 500 e⁻	