FJPPN D_RD_37: started in FY2025

Evaluation of Temporal Resolution in Monolithic Pixel Sensors using Time-Structured X-rays at Synchrotron Facility

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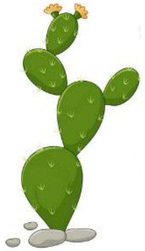
18th - 21th May 2026

Context and initial motivation

‘TIMING’ detector with HV-CMOS / Depleted Monolithic Active Pixel Sensors

CACTµS (**C**mos **Act**ive **T**iming **µS**ensor) is a **monolithic sensor chip** optimized for the timing measurement of charged particles for future large-scale timing detectors (upgrades of timing detectors at HL-LHC, and/or future high-energy physics detector projects)



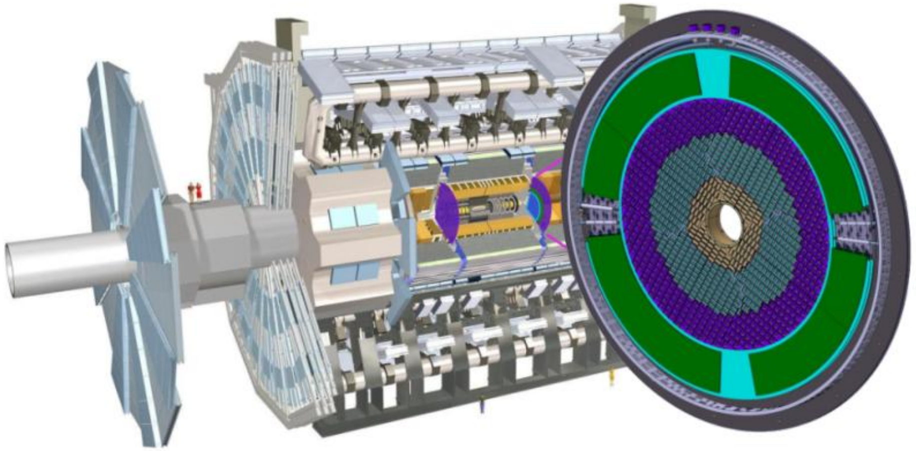
Time resolution ingredients

$$\sigma^2_{Total} = \sigma^2_{Ionization} + \sigma^2_{Elect} + \sigma^2_{Clock}$$

- Amplitude variation (Time Walk correction)
- Non-homogeneous energy deposition (minimized by design)

- Small noise
- Large dV/dt (sensor with internal gain)
- Depend on collected signal

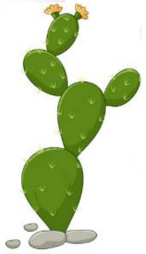
- Jitter from clock distribution



HGTD within ATLAS detector
Hybrid DC-LGAD: sensor choice for ATLAS forward timing layers

Context and initial motivation

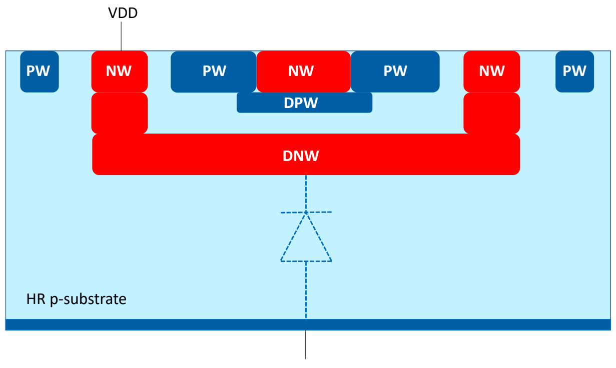
‘TIMING’ detector with HV-CMOS / Depleted Monolithic Active Pixel Sensors



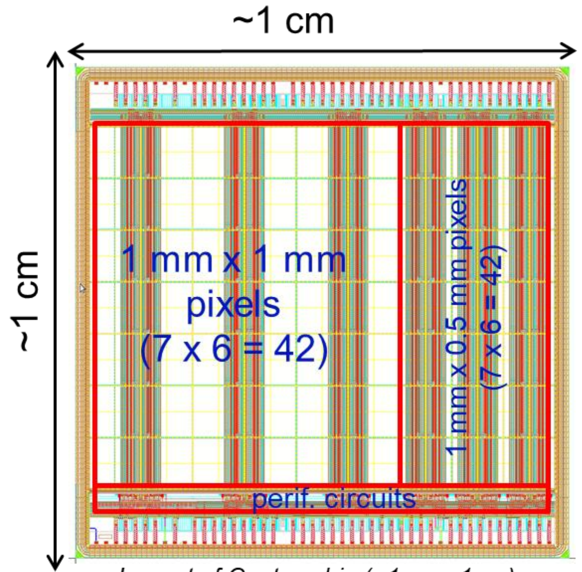
IRFU development

[Y. Degerli, Meeting ATLAS HGTD, 2017]

- ❑ Designed in a standard **LFoundry 150nm HV-CMOS** process without a dedicated amplification layer (LF-CPIX chip architecture-like, a CMOS option for ATLAS Inner Tracker upgrade) → <u>lower material budget and cheaper than hybrid solutions</u>
- ❑ **High-resistivity, fully depleted substrate, fast-rise time, HV tolerance**
- ❑ Active array of deep n-well/p-substrate diodes, front-ends (FEs) <u>initially inside the charge collected diode</u>, a slow control interface, and bias circuitry programmable through internal DACs
- ❑ Optimized guard-rings surrounding the whole chip, more than -350 V can be applied on the high-resistivity substrate, allowing fast charge collection
- ❑ Time over Threshold correction is offline
- ❑ Low power consumption < 500 mW/cm2, compatible with cooling infrastructure available at LHC experiments, and making integration of this concept viable in future high-energy physics experiments



Cross section of a typical pixel implemented in LF 150 nm HV-CMOS process (not to scale)



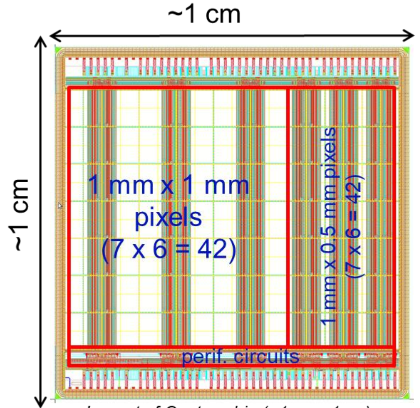
Layout of Cactus chip (~1cm x 1cm)

CACTUS development timeline

[Y. Degerli et al, IEEE TNS vol 70, no11, 2023]

2017-2020 **2020-2023** **2023-2025- …**

CACTUS demonstrator



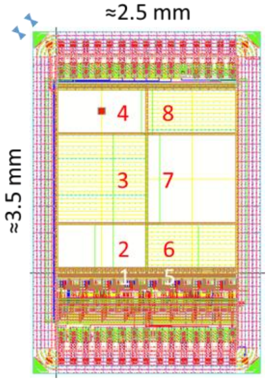
Layout of Cactus chip (~1cm x 1cm)

- Good yield
- High breakdown voltage < -300 V
- Homogeneous charge collection, deep depletion depth
- Chip very sensitive to incoming and outcoming dig. signals
- Injection signal seen even when OFF
- S/N issue

MiniCACTUS v1

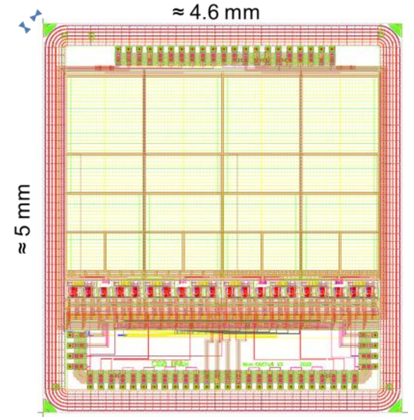
Designed to address the *low S/N issue* observed on previous CACTUS

Front End integrated at the column level



- Previous positive points achieved
- Time resolution with MIPs < 70 ps @ HV_bias < -250 V
- Ringing on Digital Output due to coupling from the digital buffers impacting the Time Walk correction

MiniCACTUS v2



~ 2 times larger than MiniCACTUS v1

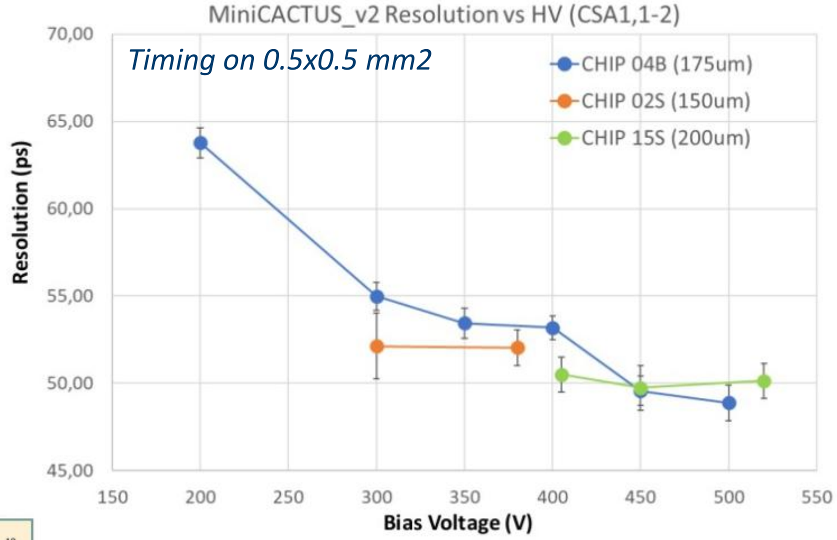
- Improved layout for better mixed-signal coupling rejection
- Discriminator stage improvements

[P. Schwemling, PIXEL 2024]

Achieved performances with MIPs

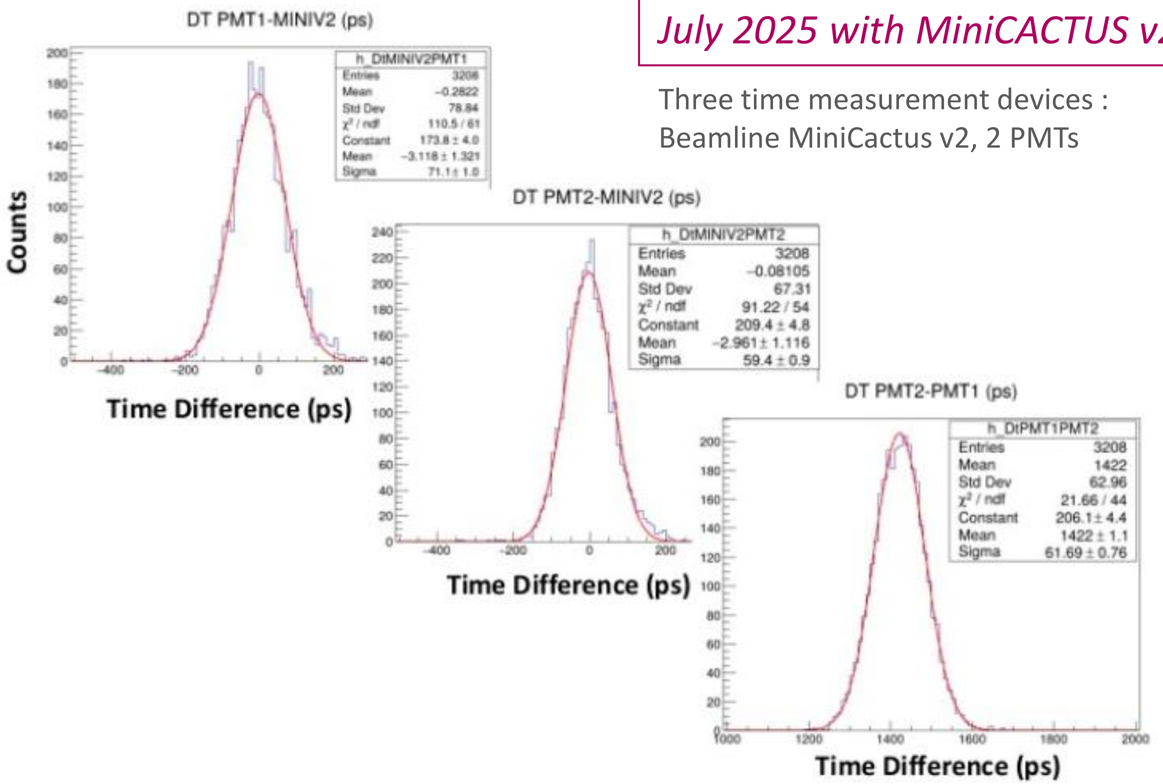
[G. Pinol, 4th DRD3 Week, Nov. 2025]

Time resolution of MiniCACTUS v2 as a function of HV_bias
for different chip thicknesses



Testbeam performed at CERN SPS in July 2025 with MiniCACTUS v2

Three time measurement devices :
Beamline MiniCactus v2, 2 PMTs



The time resolution of several sensors with different thicknesses has been measured in several testbeam campaigns using high-energy muons (MIPs) at CERN SPS.

MiniCACTUS v2: the best timing resolution measured was **48.9 ps** with the ON-chip FE and discriminator *(July'2025 results)*

Timing performances in the case of photon detection? → Sensor chip characterization with high-flux photon beam

SPring-8: 3rd generation synchrotron facility

SPring-8 current parameters:

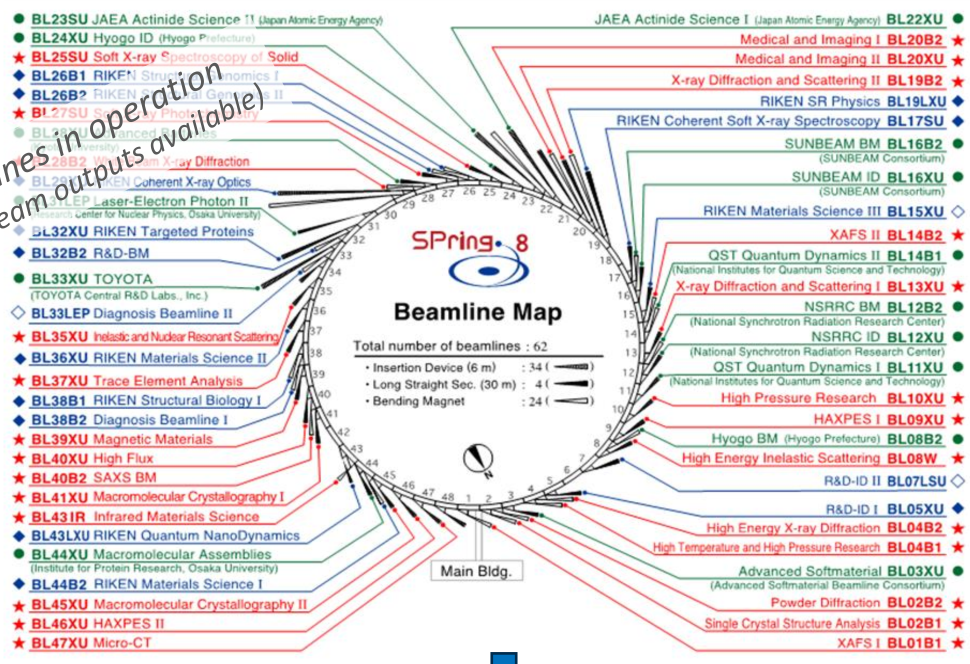
8 GeV beam energy	*100 mA stored current*	*1432.95 m circumference*
2.4 nm.rad emittance	*508.58 MHz RF frequency*	

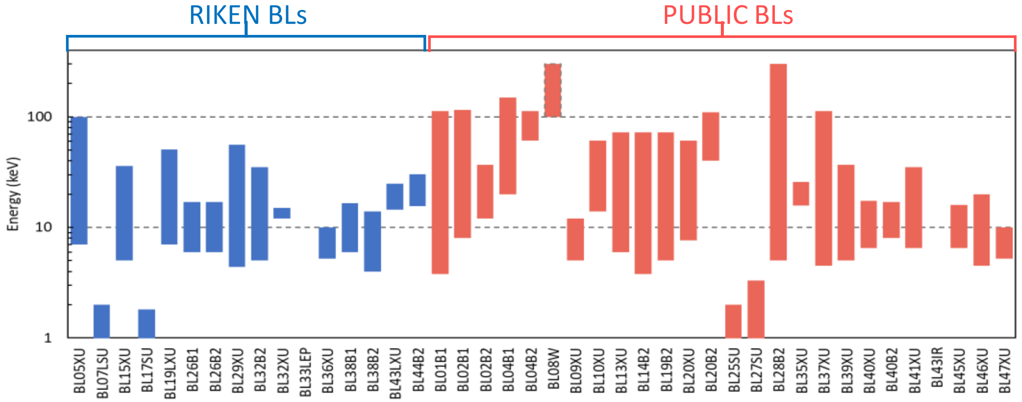
Upgrade program towards SPring-8-II has started

[H. Tanaka et al., JSR (2024), 31]

RIKEN Beamline (16) / Public Beamline (26) / Contract Beamline (15)

57 beamlines in operation
(+ 5 other beam outputs available)



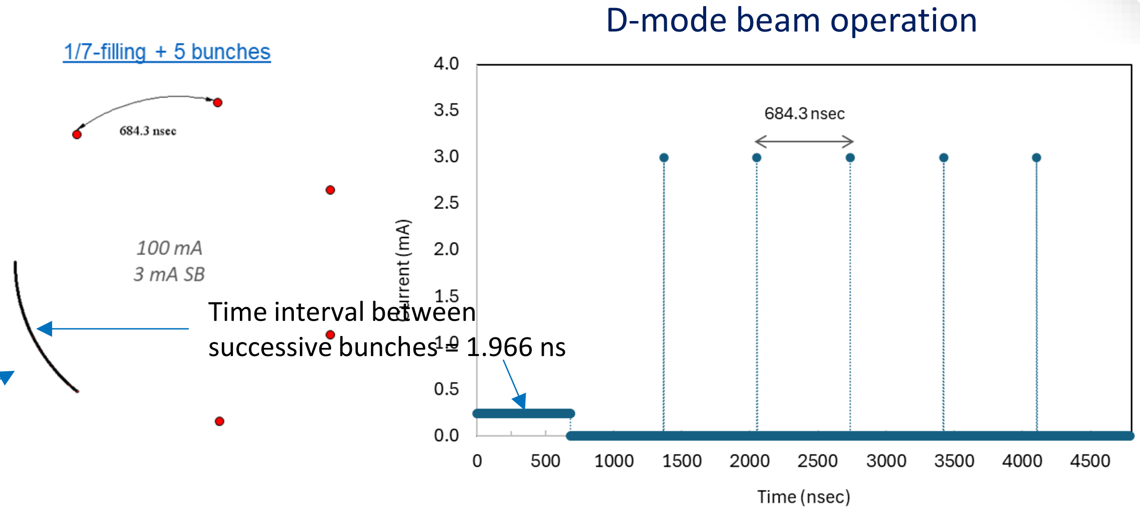


Using the time-structured X-rays

Many applications need using the time-structured X-rays of the synchrotron facility

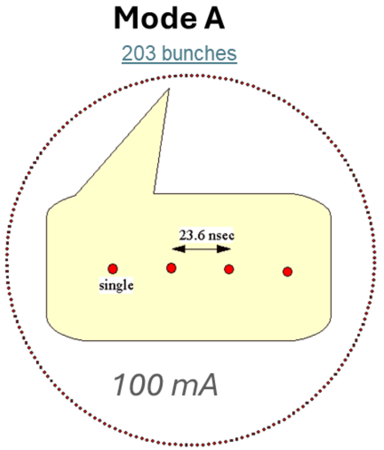
Hard X-rays range: ESRF, APS, SPring-8, (EU-XFEL, SLAC)

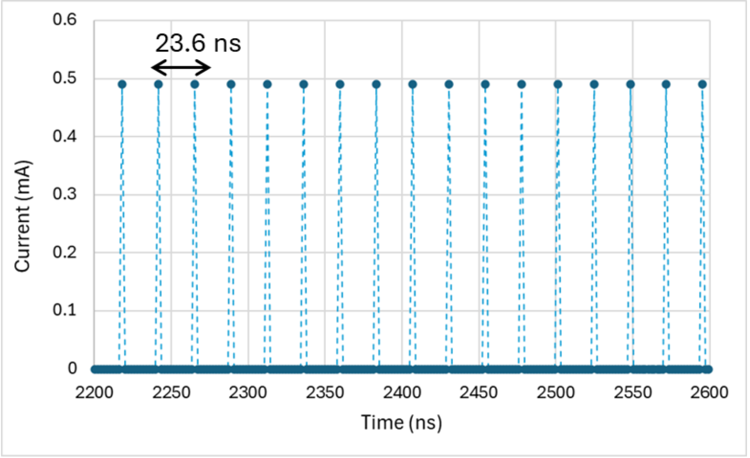
8 bunch modes of operation are available at SPring-8


D-mode beam operation

Several applications at SPring-8

- ☐ Single-crystal diffraction
- ☐ **Nuclear Resonant Scattering**
- ☐ Time-resolved X-ray diffraction on surface and interface structures
- ☐ Time-resolved diffraction on powder
- ☐ Fast time-resolved X-ray diffraction and scattering experiments on nanoparticles
- ☐ Structural biology – X-ray diffraction



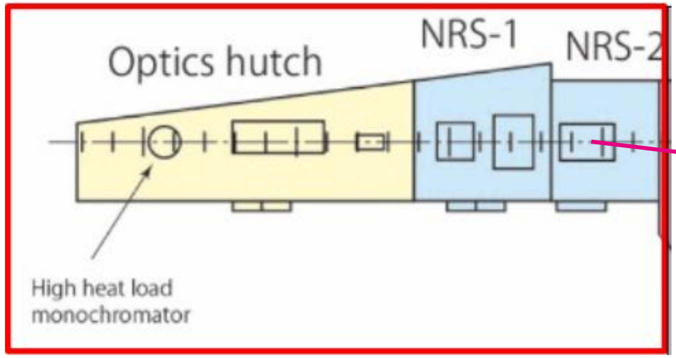

A-mode beam operation

Nuclear Resonance Scattering

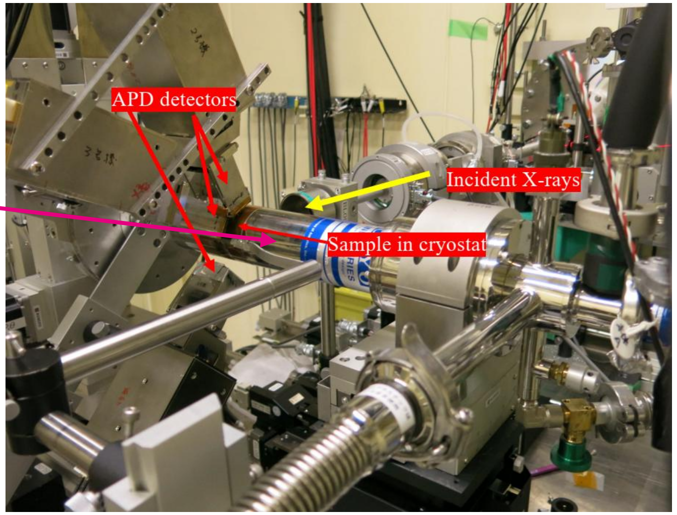
Quasi-elastic scattering using Time-Domain Interferometry provides unique information on atomic and molecular-scale dynamics: many research topics from fundamental to materials and life sciences

[Y. Yoda, 6th Inter. Nuclear Resonance Workshop, 2024]

NRS beamline at SPring-8: BL35XU

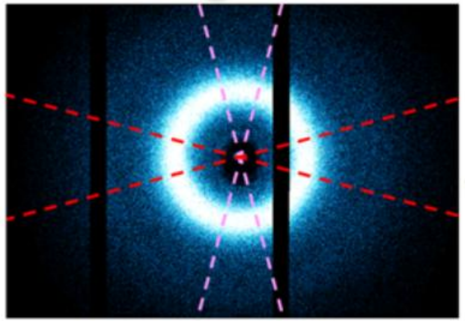


Setup for Quasi-Elastic Scattering

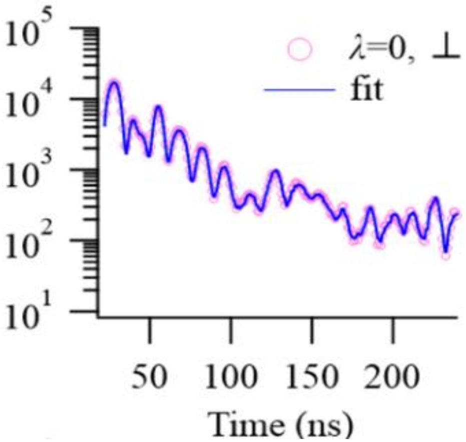


[R. Mashita et al., ACS Macro Lett., 13, 2024]

2D X-ray scattered image of a polymer sample



Typical resulting time spectra which contains dynamic information



This type of experiment is currently performed with a one-dimensional APD-type detector with a limited time resolution to 1 ns

Motivation / Synchrotron user’s request:
Strong need for gating time resolution of sub-ns
In bonus: a 2D ‘large’ pixel matrix could provide information at several scattering angles at the same time !

Preparatory work in FR/JP laboratories

From May 2025 to January 2026

- Meetings between PIs and teams
- Preparation of mechanical drawings + auxiliaries equipments

January 2026

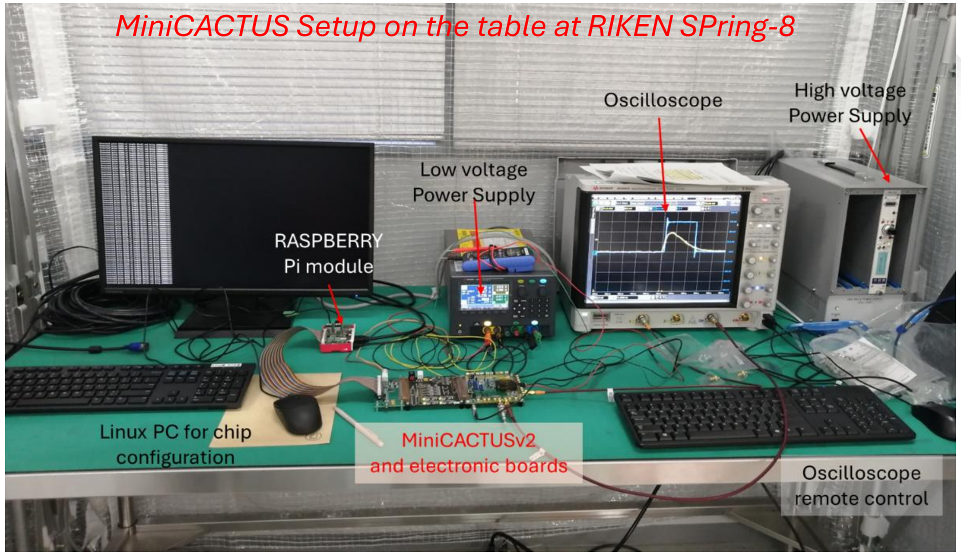
- Training session on MiniCACTUS v2 in CEA/IRFU Laboratory:
  - Getting started with the detector
  - Understand basic settings *(optimal working settings for MIP detection)*
  - Learn to operate the detector

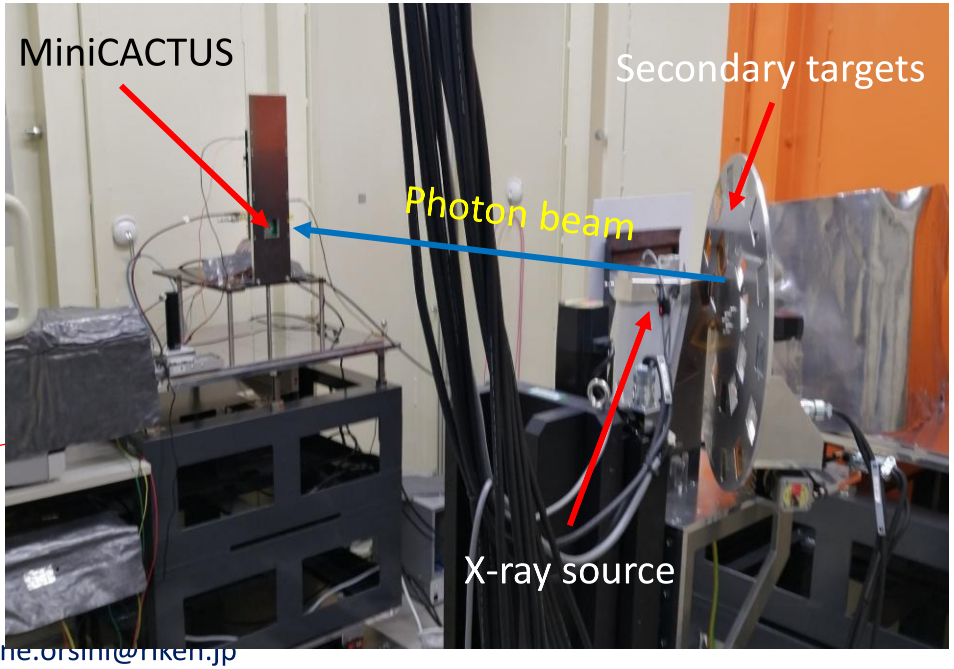
February 2026

- Transfer of MiniCACTUS v2 + its electronic boards to JAPAN at RIKEN SPring-8
- Fabrication of mechanical supports + all the necessary auxiliaries (HV and LV power supplies, oscilloscope, etc)
- Implementation and testing of remote control for the acquisition system

March 2026

- First tests in the laboratory at RIKEN SPring-8 with X-ray source

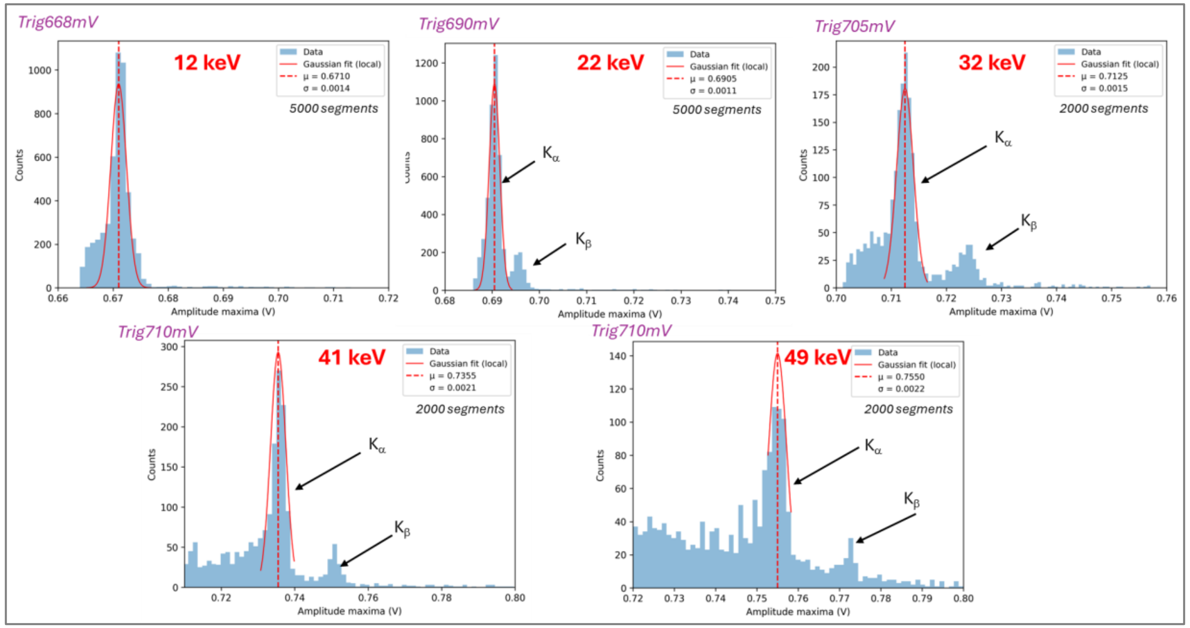

MiniCACTUS Setup on the table at RIKEN SPring-8

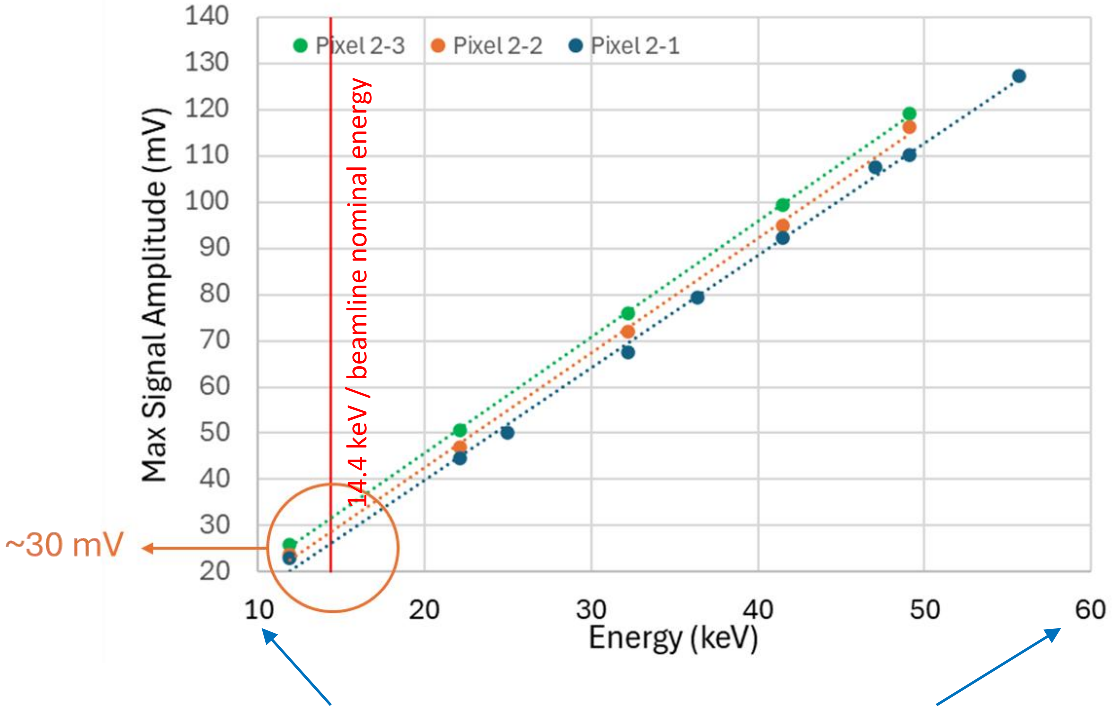


First tests in the laboratory at SPring-8

March-April 2026

- Energy calibration with X-rays from 12 keV up to 49 keV → Technical report #2
  - The three pixels tested have a linear energy response.
  - The small pixel 2-1 distinguishes Kα and Kβ lines very well. Not enough time to check the performance with other pixels.
  - Verify the detection at 14.4 keV: energy from the BL35XU beamline, where the experiment will take place (end of April 2026)





It may be possible to distinguish photons with energies < 10 keV, as well as 60 keV photons; starting in June / July 2026.

First experiment on BL35XU

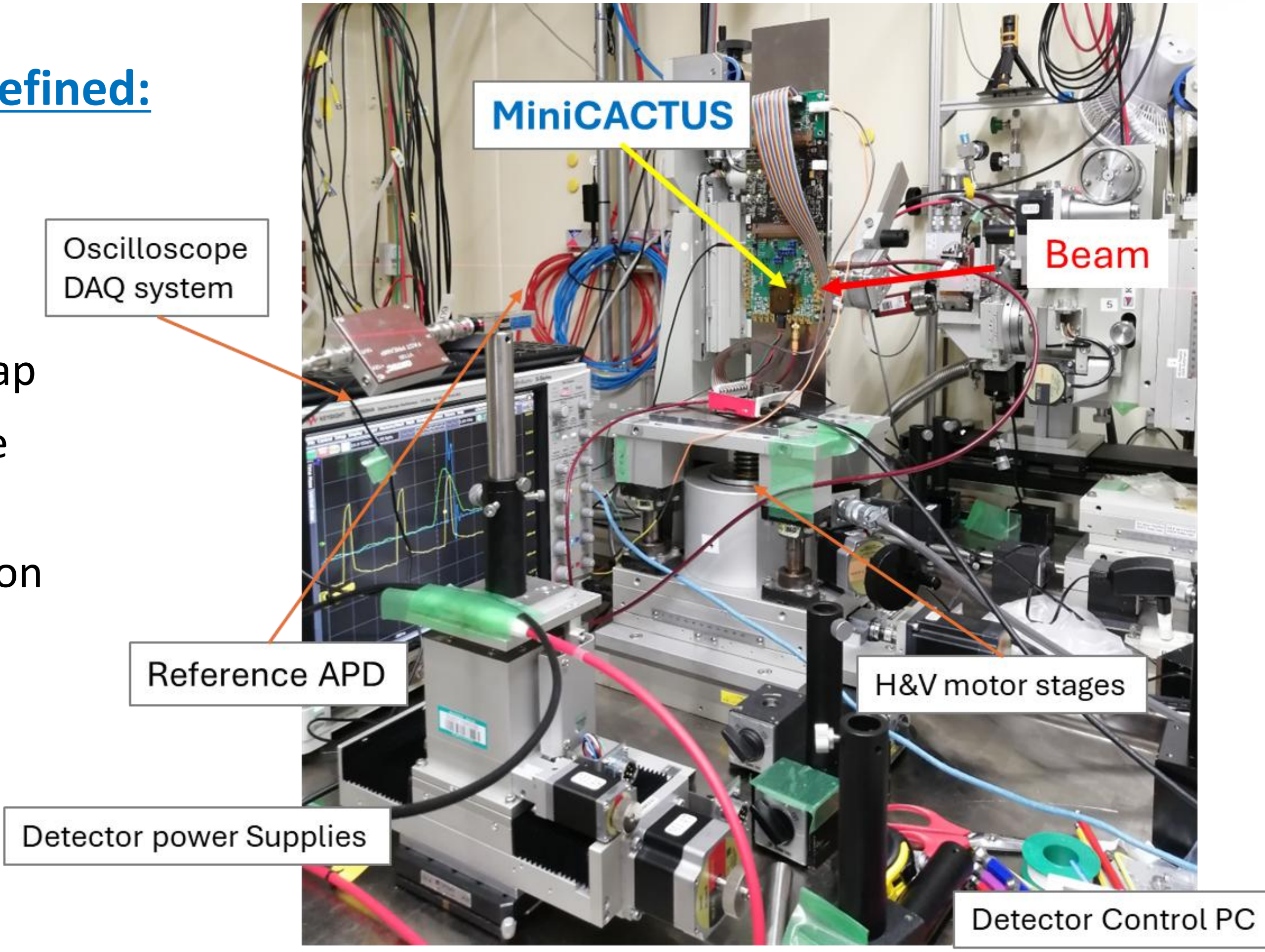
20-22 April 2026

Nuclear Resonant Scattering beamline

Energy = 14.4 keV

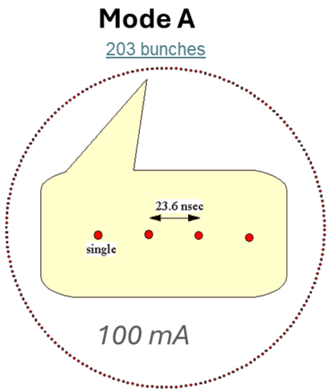
For this first experiment, several main objectives were defined:

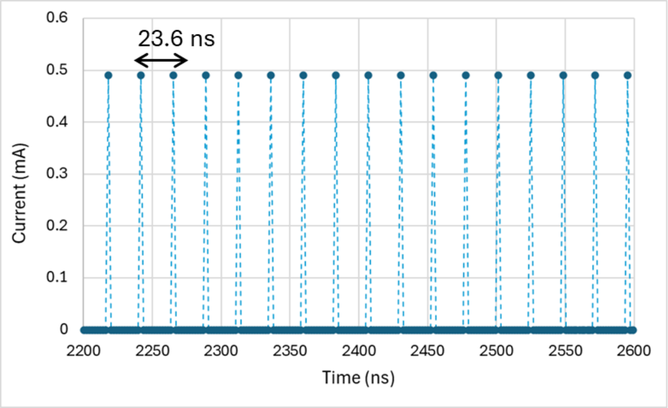
- Detection efficiency at 14.4 keV
- Count rate capability up to a million photons per second (pile-up?)
- Quality of the bunch separation in A mode with 23.6 ns gap
- Detection of the 'weak' nuclear resonance signal from the 57Fe isotope
- Timing resolution at 14.4 keV and what limits the resolution
- Comparison with the standard APD of the beamline
- Any impact from pixel size



First experiment on BL35XU

Temporal structure of the beam during the experiment



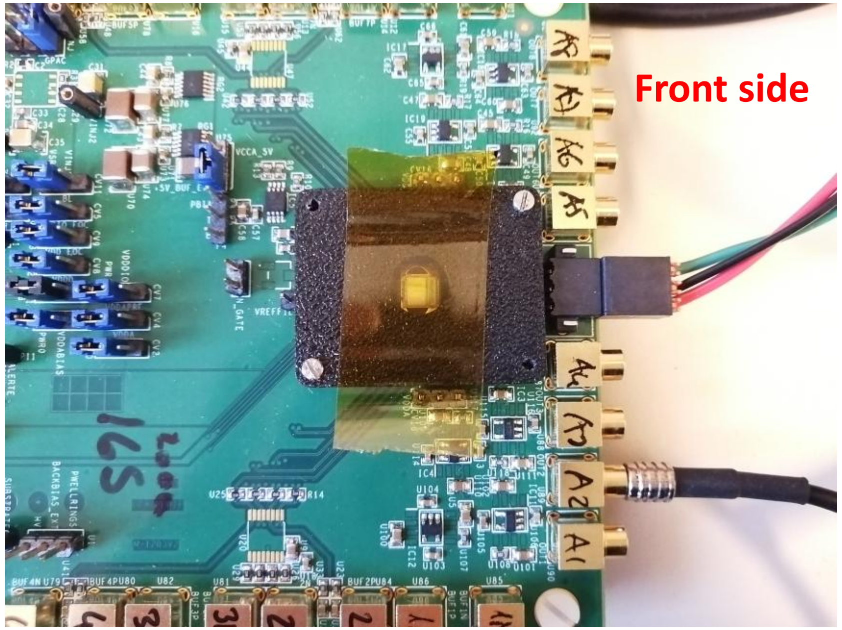


Input Trigger = clock of the accelerator → 42.4 MHz in A mode

Challenging operating mode for the detector with only **23.6 ns** gap between each beam pulse !

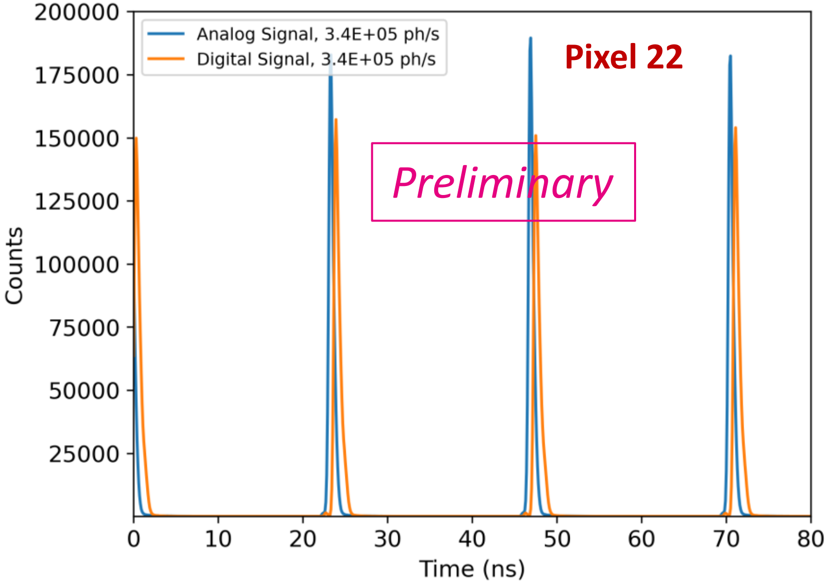
Ideally, a ‘good’ detector should see each beam pulse with a good separation (no overlap)

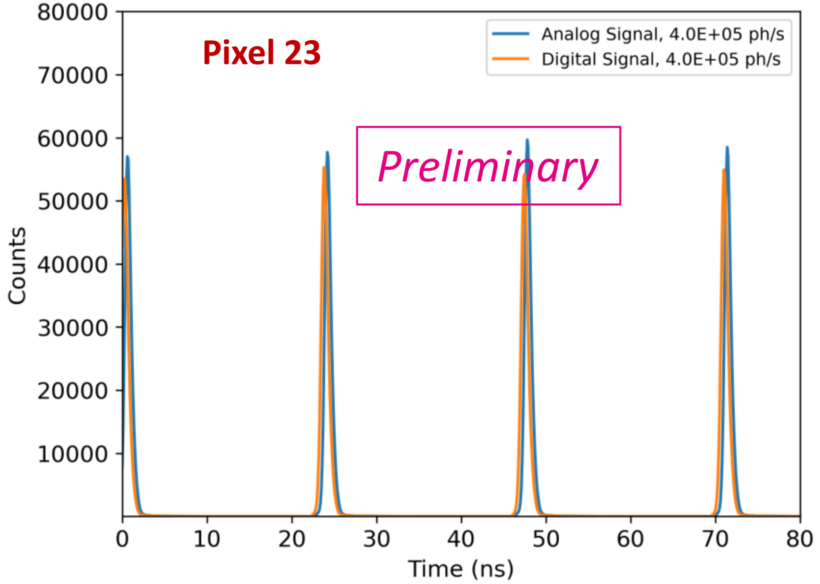
MiniCACTUS prototype was tested with the back side and the front side illuminated



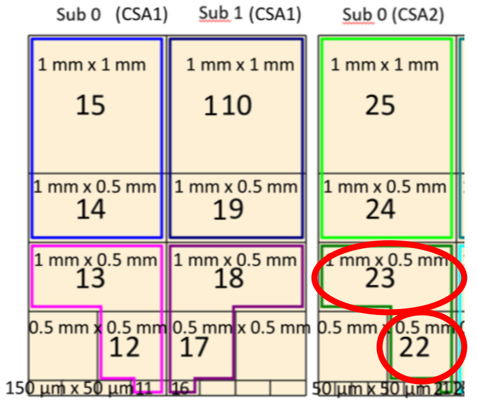
No cooling
T ambient
HV = -200 V

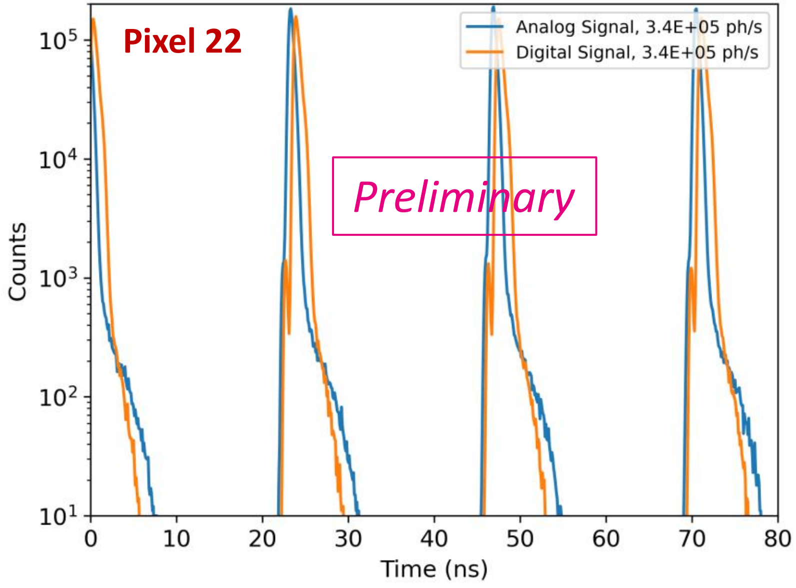
14-keV photon detection and bunch separation capability

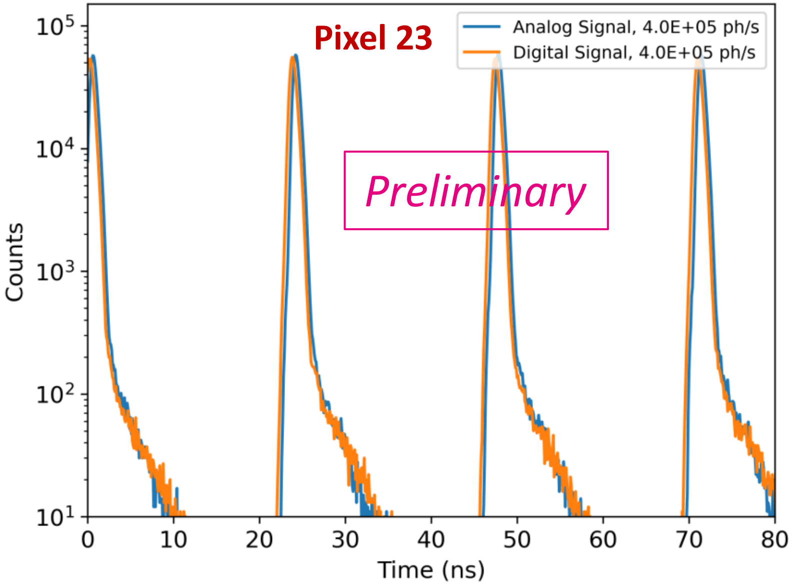




Back Side





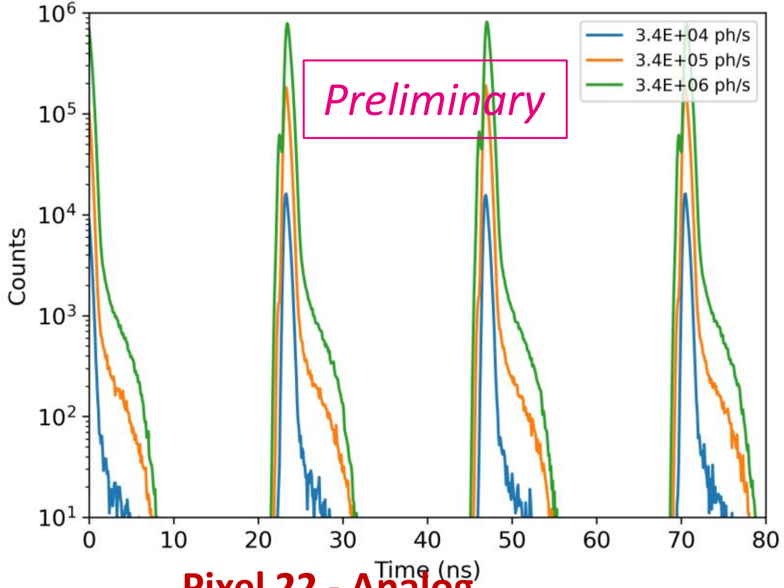


Several pixels can detect each bunch separately (no overlap)

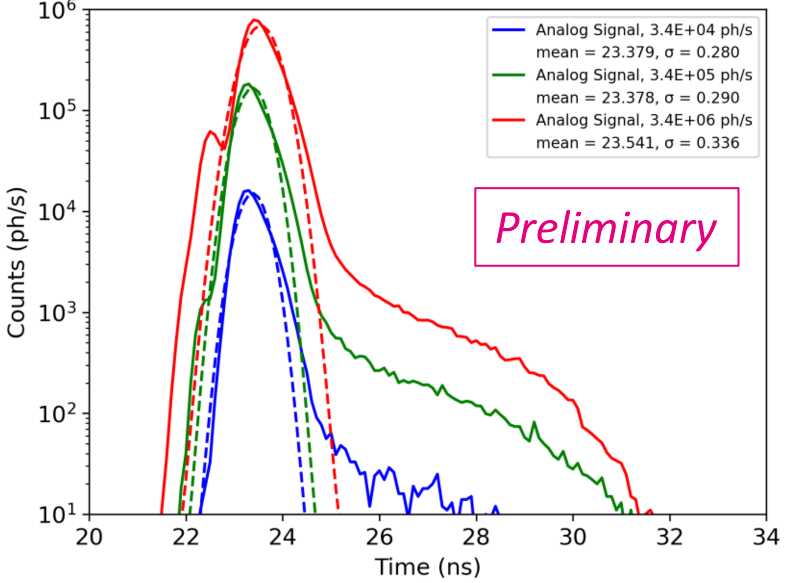
Evolution of photon distribution vs photon fluxes

Back Side

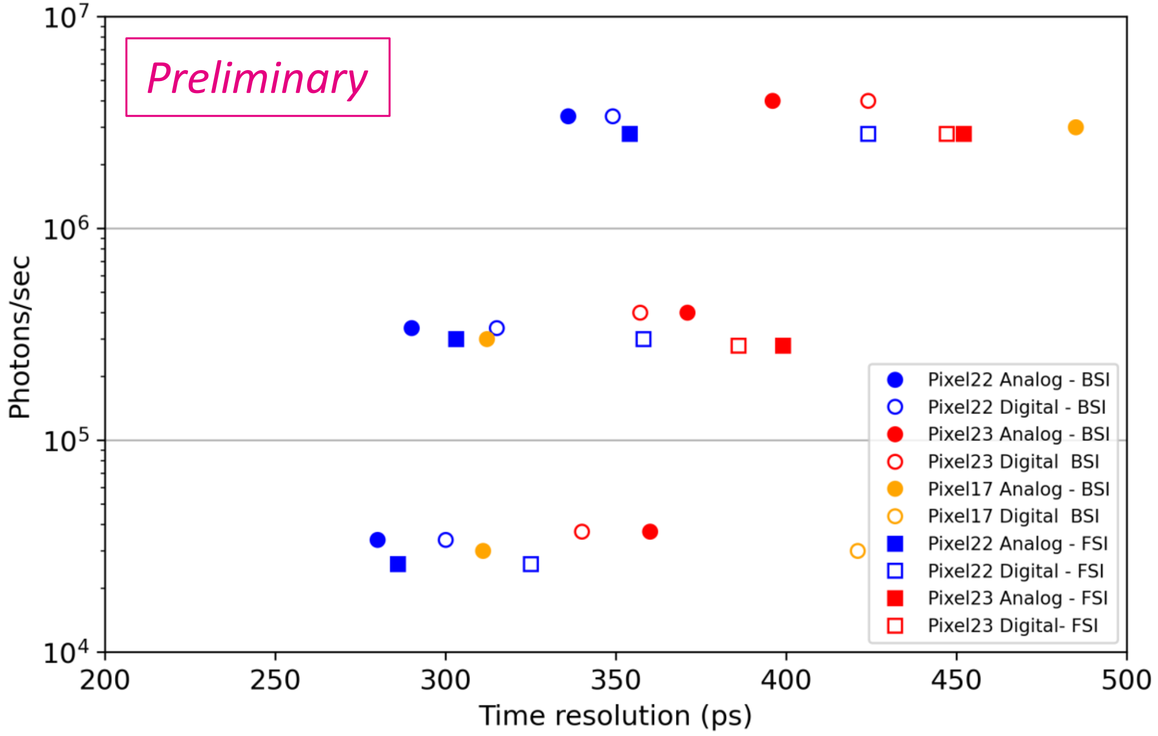
Pixel 22 - Analog



Pixel 22 - Analog

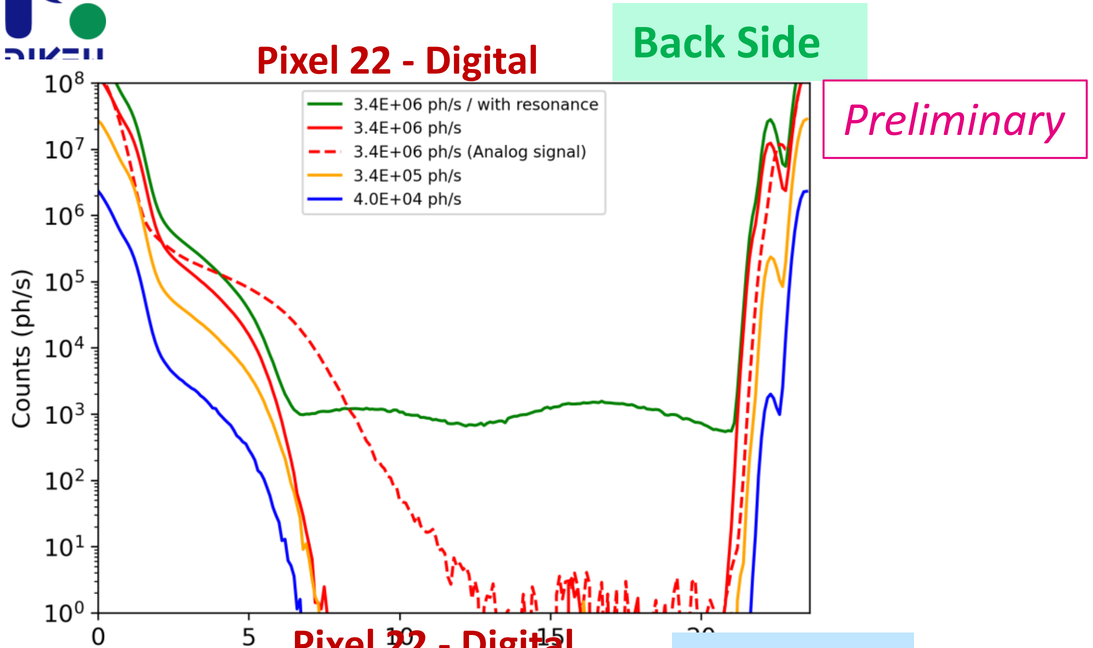


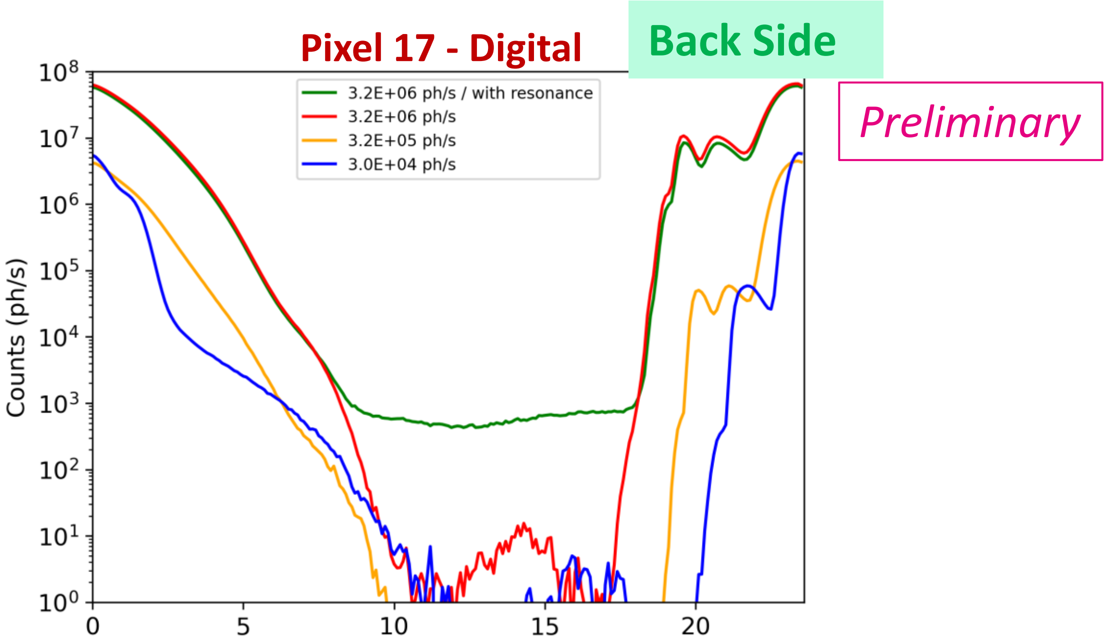
Time resolution vs photon flux

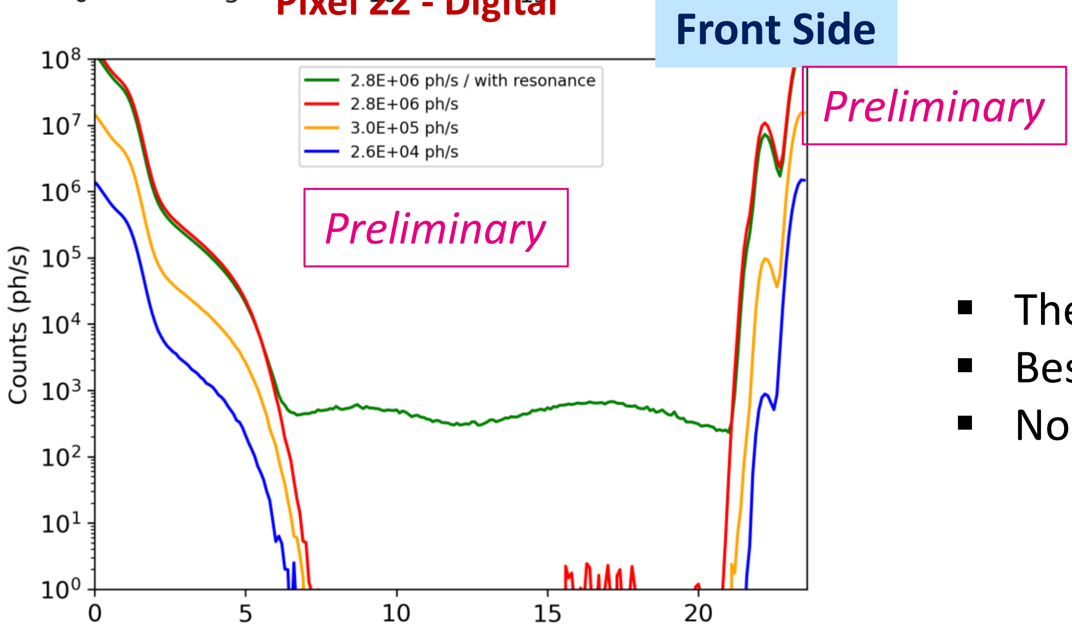


- **4 pixels (22, 23, 24, 17) have a time resolution better than 500 ps at 14.4 keV**
- No big difference BSI and FSI for pixel 22 Analog signal
- Best time resolution is **280 ps at 14.4 keV** obtained for Pixel22

Detection of the Nuclear Resonance of 57Fe







- The Nuclear Resonance of the sample (weak signal) is correctly detected
- Best results are obtained for Pixel 22 *(so far, with pixel settings used)*
- No difference between BSI and FSI

Summary of the first experiment / open questions

❑ Several objectives were achieved and met with some success for a first experiment

Objectives	**Performances demonstrated**
Detection efficiency at 14.4 keV	Very good
Count rate capability	Up to ~ 4×10^6 ph/s/pix
Bunch separation in A mode with 23.6 ns gap	Very good for several pixels *a tail of ~ 0.1-0.2% appear from 10^5 ph/s/pix*
Detection of the 'weak' nuclear resonance signal from the 57Fe isotope	Detected / better results with preamplifier of type #2 with smaller pixels
Timing resolution at 14.4 keV	~300 ps *(280 ps for Pixel 22)* at -200 V as expected

❑ Open questions and next steps

- Time resolution:
  - In most cases, the time resolution was better with the analog signal than with the digital signal (origin of this difference? Can the digital signal be improved with better pixel settings?)
  - What limits the time resolution? Origin of the tail in the event distribution (noise, pile-up, baseline fluctuation?) and how can it be improved (or not) in various conditions?
- Smallest pixels (Pixels 11/16/21): we were unable to detect the signals correctly → need to be investigated
- Interest from the beamline scientists to detect lower energy photons resonance → to be tested in the laboratory

Thank you for your attention