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

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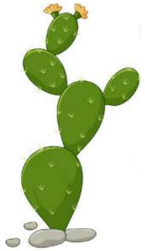
2025 Joint Workshop of FKPPN and TYL/FJPPN
14th - 16th May 2025, Nantes

Context and initial motivation

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

CACTµS (**C**mos **Ac**tive **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)



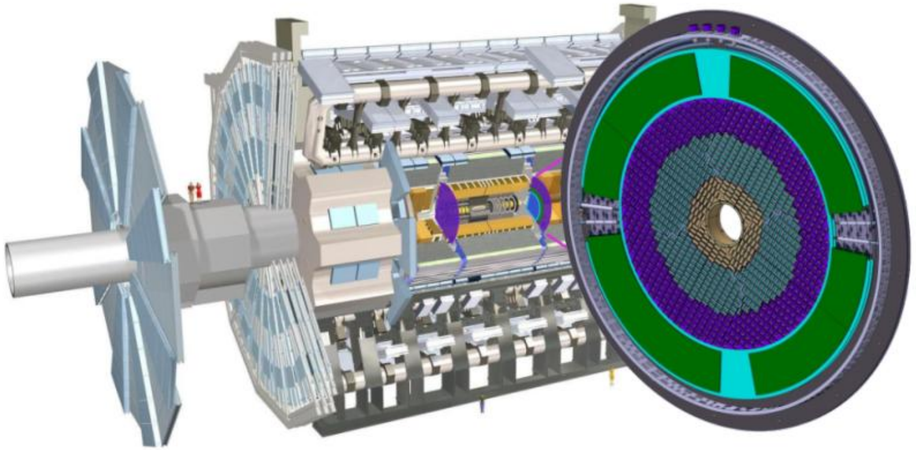
Time resolution ingredients

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

- 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

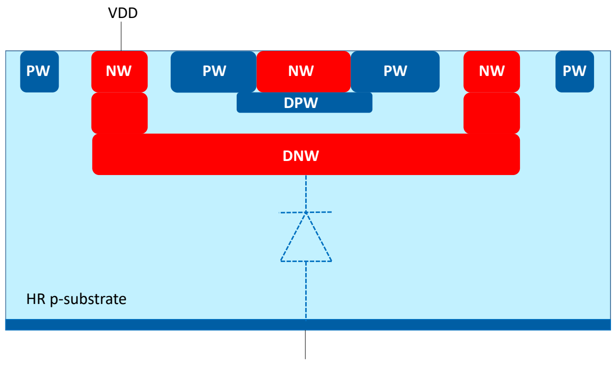
Context and initial motivation

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

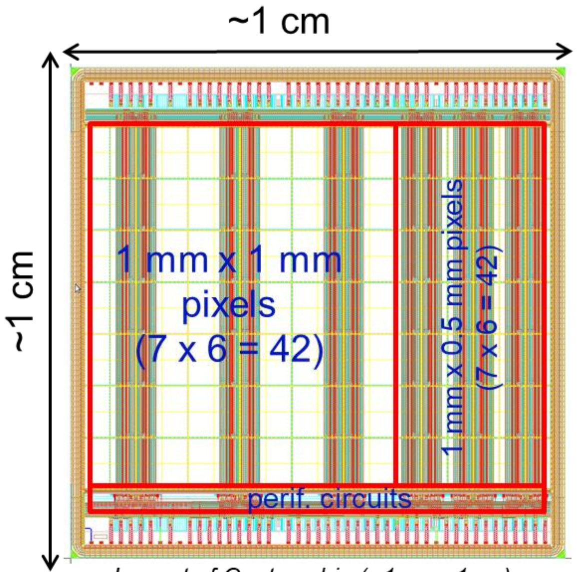
IRFU development

[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) → lower material budget and cheaper than hybrid solutions
- **High-resistivity, fully depleted substrate, fast-rise time, HV tolerance**
- Active array of deep n-well/p-substrate diodes, front-ends (FEs) initially inside the charge collected diode, 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
- Baseline pixel dimensions are 1.0 × 1.0 mm and 0.5 × 1.0 mm
- 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)



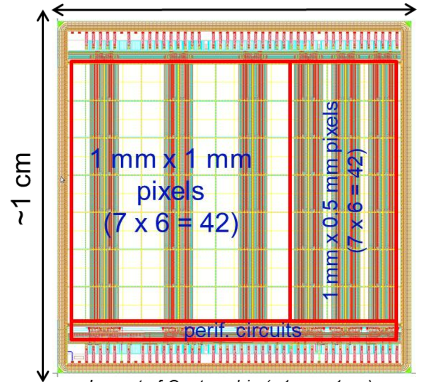
Layout of Cactus chip (~1cm x 1cm)

CACTUS development timeline

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

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

CACTUS demonstrator

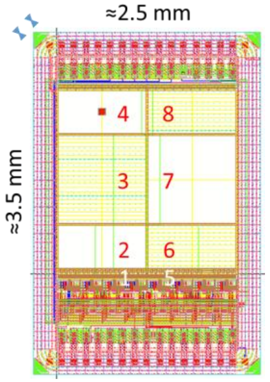


Layout of Cactus chip (~1cm x 1cm)

- 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

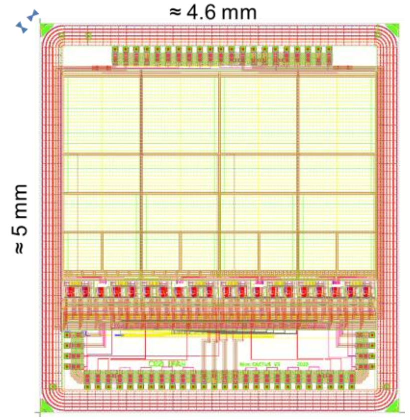
MiniCACTUS v1

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

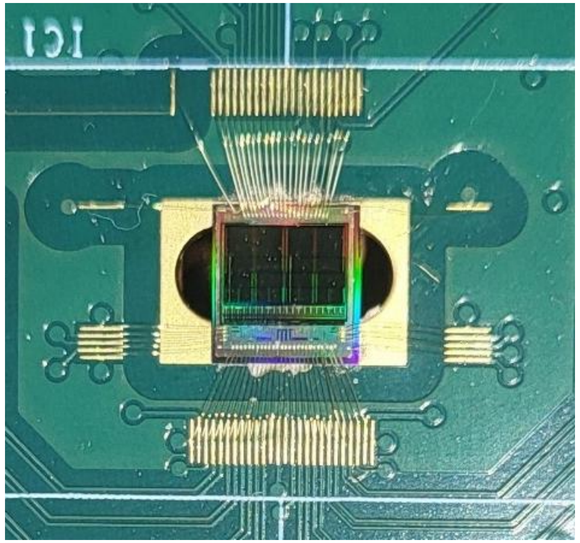
Focus on MiniCACTUS v2

[P. Schwemling, PIXEL 2024]

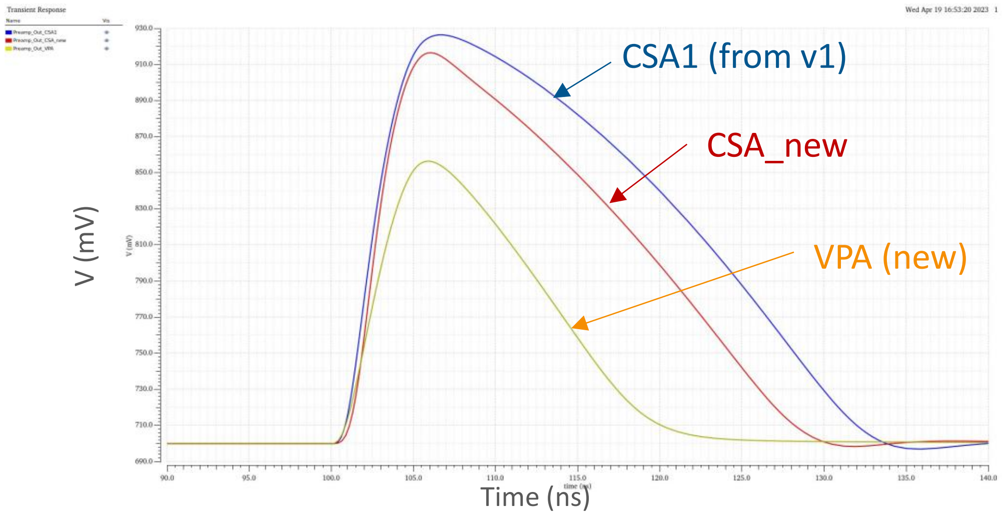
- ~ 2 times larger than MiniCACTUS v1
- Diodes sizes: 0.5 mm x 1 mm (baseline), 1 mm x 1 mm and 0.5 mm x 0.5 mm
- Small test diode: 50 µm x 150 µm and two 50 µm x 50 µm
- 3 different preamplifiers implemented (for better jitter and reduced ToT)
- New multistage discriminator with **programmable hysteresis**
- Improved layout for better mixed-signal coupling rejection
- **CEA-IRFU** & **IFAE-Barcelona** collaboration
- Submitted in May 2023, chips came back from post-processing end of May 2024

➡ Analog/Digital couplings were efficiently corrected

MiniCACTUS v2 wire-bonded on its PCB



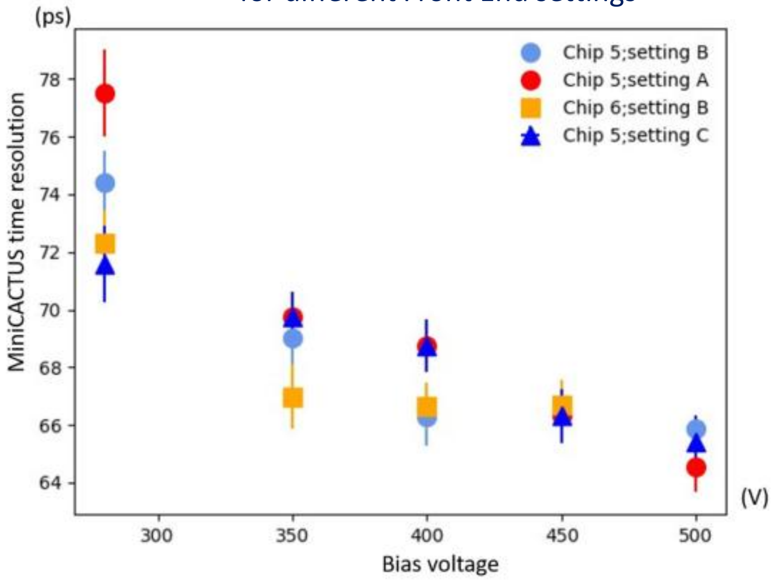
Responses of the 3 preamps to an input pulse of 12 ke- (Tcoll = 5 ns)



Achieved performances with MIPs

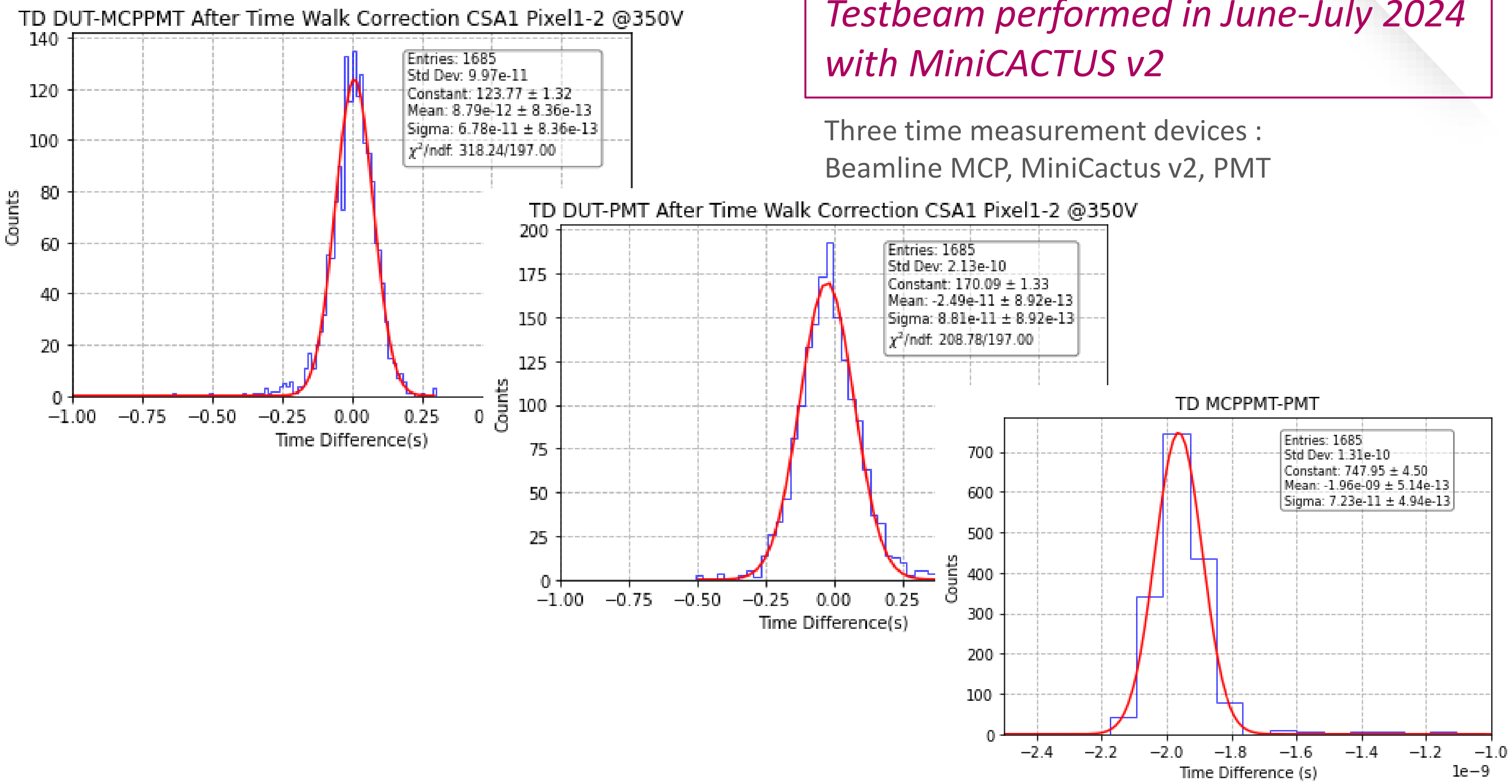
[P. Schwemling, PIXEL 2024]

Time resolution of MiniCACTUS v1 as a function of HV_bias for different Front End settings



Testbeam performed in June-July 2024 with MiniCACTUS v2

Three time measurement devices :
Beamline MCP, MiniCactus v2, PMT



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 **59.9 ps** with the ON-chip FE and discriminator *(July'2024 results)*

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

SPring-8: 3rd generation synchrotron facility

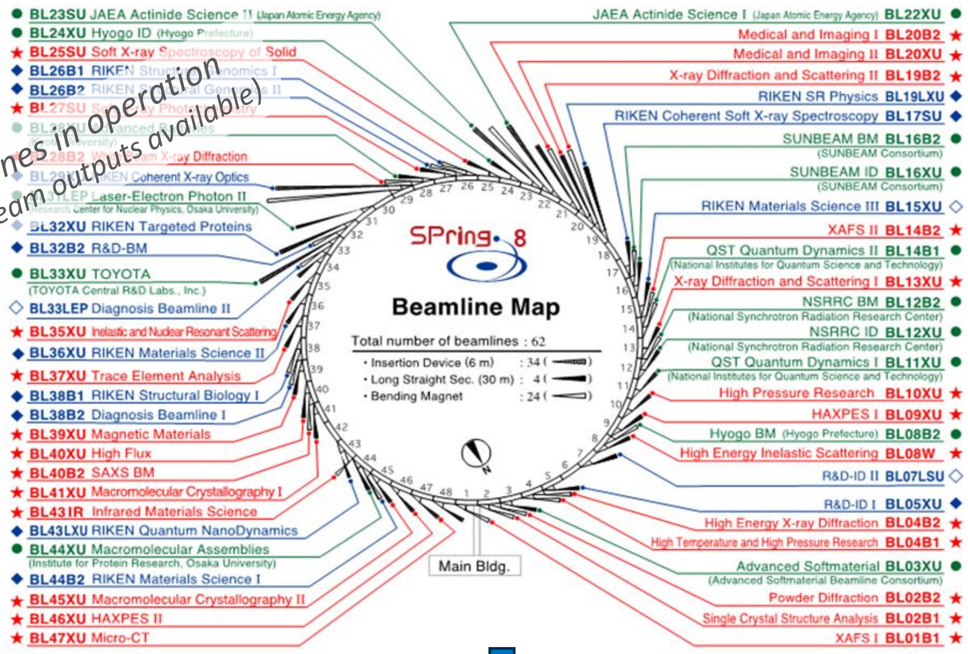
SPring-8 current parameters:

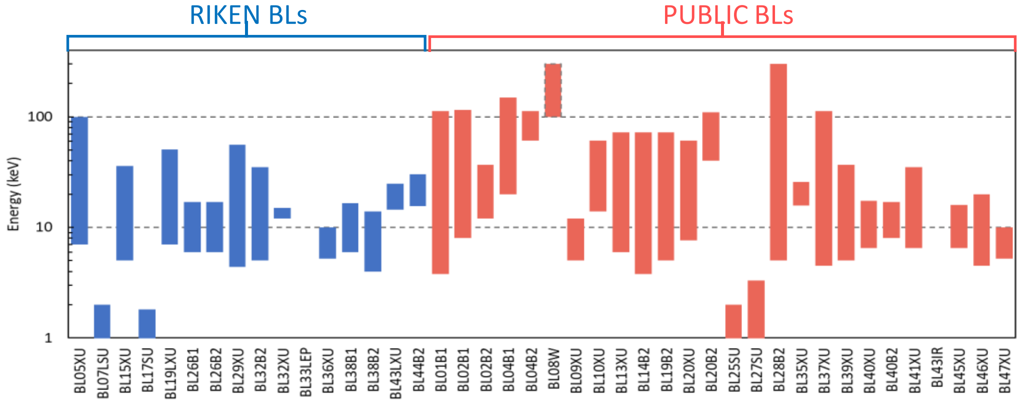
8 GeV beam energy — *100 mA stored current* — *1432.95 m circumference*
2.4 nm.rad emittance — *508.58 MHz RF frequency*

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)





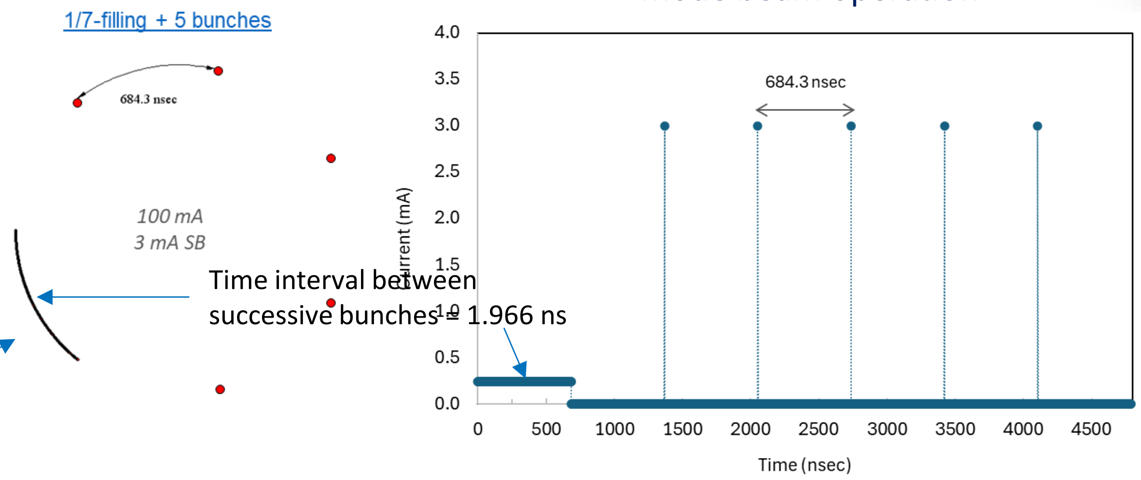
Using the time-structured X-rays

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

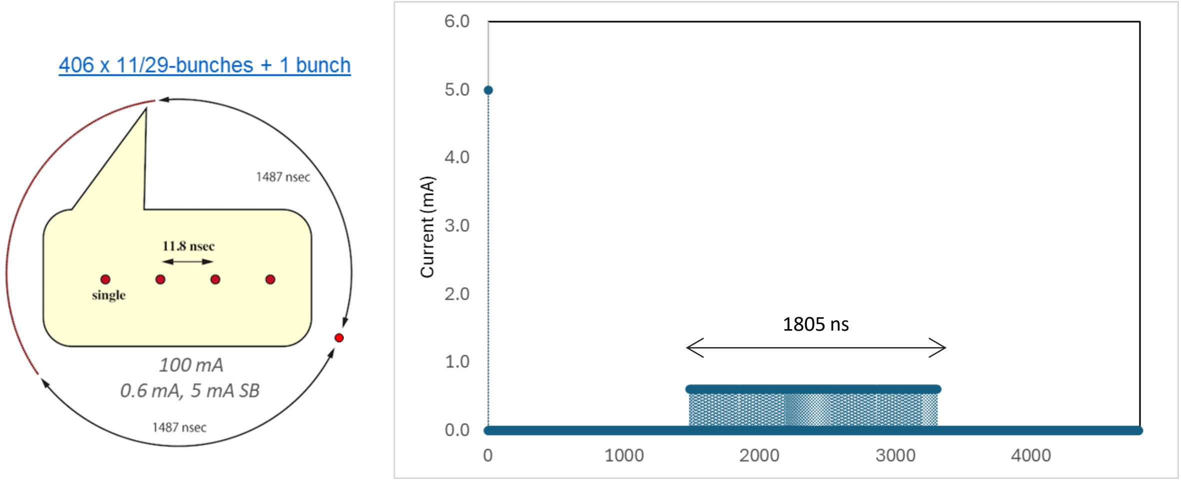
Hard X-rays range: ESRF, APS, SPring-8, (EU-XFEL, SLAC)

8 bunch modes of operation are available at SPring-8

D-mode beam operation



H-mode beam operation



Several applications at SPring-8

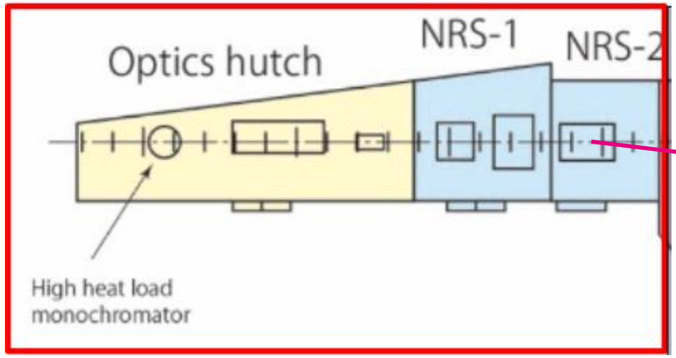
- ❑ Single-crystal diffraction
- ❑ **Nuclear Resonant Scattering**
- ❑ Time-resolved X-ray diffraction on surface and interface structures
- ❑ Time-resolved diffraction on powder
- ❑ Fast time-resolved X-ray diffraction and scattering experiments on nanoparticles
- ❑ Structural biology – X-ray diffraction

Nuclear Resonance Scattering

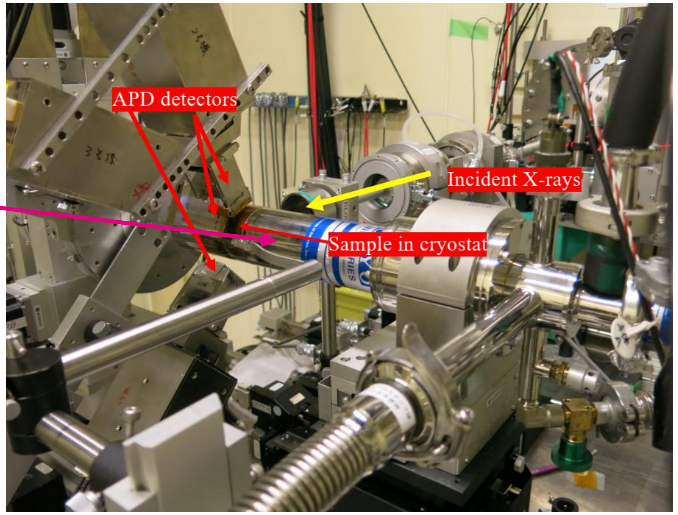
Quasi-elastic scattering using Time-Domain Interferometry provides unique information on atomic and molecular-scale dynamics: many research topics from fundamental to materials and life sciences

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

NRS beamline at SPring-8: BL35XU

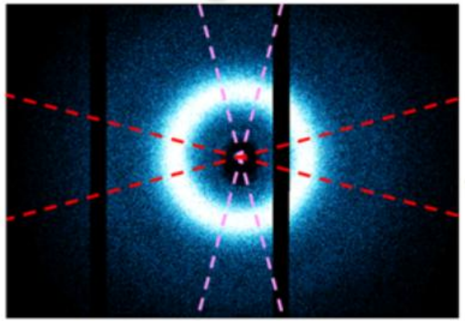


Setup for Quasi-Elastic Scattering

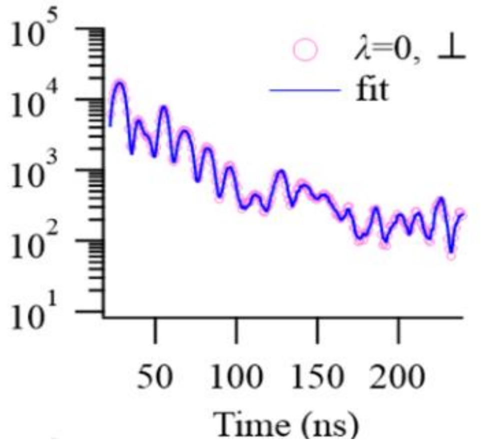


[R. Mashita et al., ACS Macro Lett., 13, 2024]

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

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 !

Test program and expected outputs 1/2

@ Beamline BL35XU

1 / 14-keV photon beam – Without a sample

[Test repeated for 2 sensor thicknesses]

5×10^{13} ph/s within a beam size (FHWM) of 0.5 mm (V) $\times$ 1.2 mm (H)

Define trigger conditions to see the 'isolated' bunch(es)

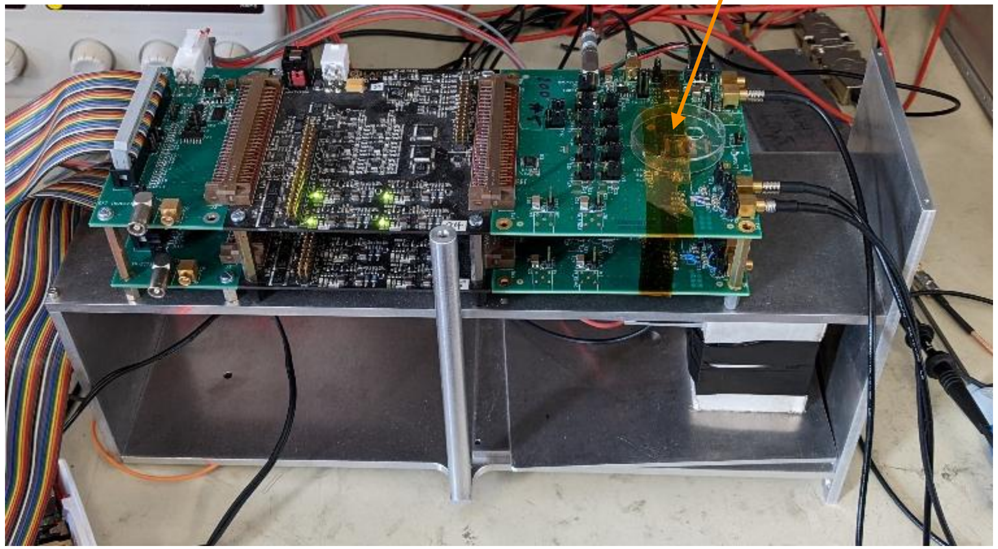
- Study the pulse shape, dependence on photon fluxes (pile-up)
- Detection efficiency
- Timing resolution as a function of HV_bias, for different pixel sizes and preamplifier types

Define trigger conditions to see the 'bunch train'

- Bunch separation capability → is an important asset for synchrotron users

[Position scan with 'pencil beam' on a chosen pixel → uniformity of pixel response by scanning the pixel surface]

Full setup of MiniCACTUS v2



2 / 43-keV photon beam – Without a sample

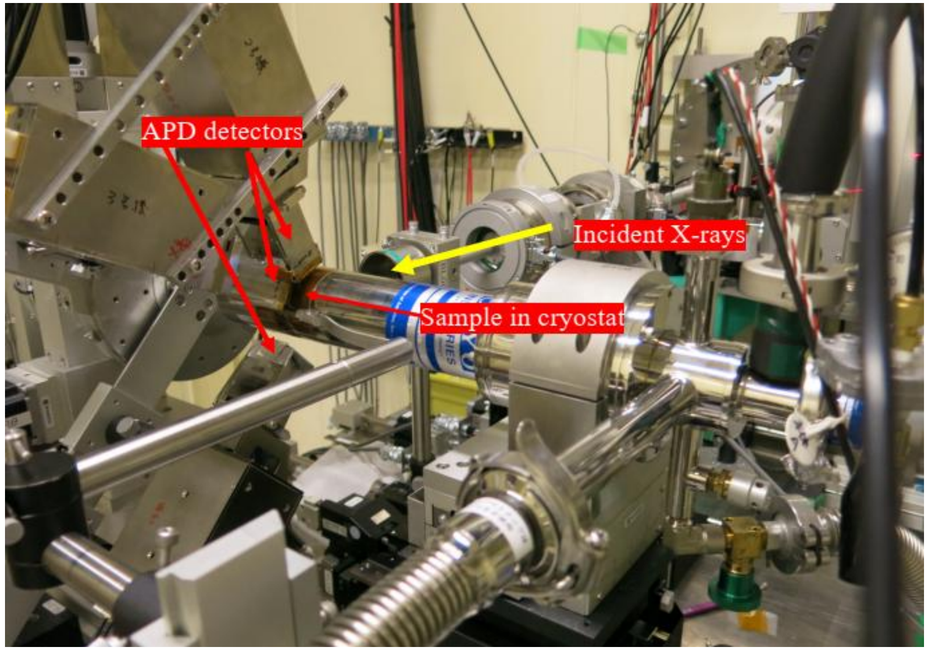
~ 1×10^{10} ph/s within a beam size (FHWM) of 0.5 mm (V) $\times$ 1.2 mm (H)

Previous tests repeated at higher energy

Test program and expected outputs 2/2

@ Beamline BL35XU

Time-Domain Interferometry performed on BL35XU



3 / Quasi-elastic scattering at 14 keV – With 'reference' sample

5 $\times 10^{10}$ ph/s within a beam size (FHWM) of 0.5 mm (V) $\times$ 1.2 mm (H)

Highlight the timing resolution and fast readout capabilities
→ build the time spectrum from the sample relaxation

MiniCACTUS will be positioned at a fixed scattering angle
Tests repeated on different pixel sizes
HV_bias fixed

A timing resolution of ≤ 500 ps is expected for photons of this energy

➡ Enhancement of the understanding of charge collection dynamics and help optimize detector performance
Interest from the synchrotron community, where sub-nanosecond time resolution detection is essential

Summary / expected outputs

- ❑ Promising results have already been obtained with MiniCACTUS v2 in the case of MIPs
- ❑ Characterization of performances with ‘time-structured’ high photon flux will help optimizing the FE efficiency (S/N)
- ❑ Several lessons to learn from such detector for the synchrotron community → time-resolved applications are limited today by the detection system, in particular for the Nuclear Resonant Scattering experiments

- ❑ The next version of MiniCACTUS implements an intrinsic gain layer and other improvements are considered at short-term: improvement of time resolution with better S/N, reduction of the pixel pitch, reduction of the FE power consumption
  Note: tests of test-structures with integrated gain layer have started at CEA/IRFU