Integration and first operation of the GOTTHARD-II detector at the European XFEL

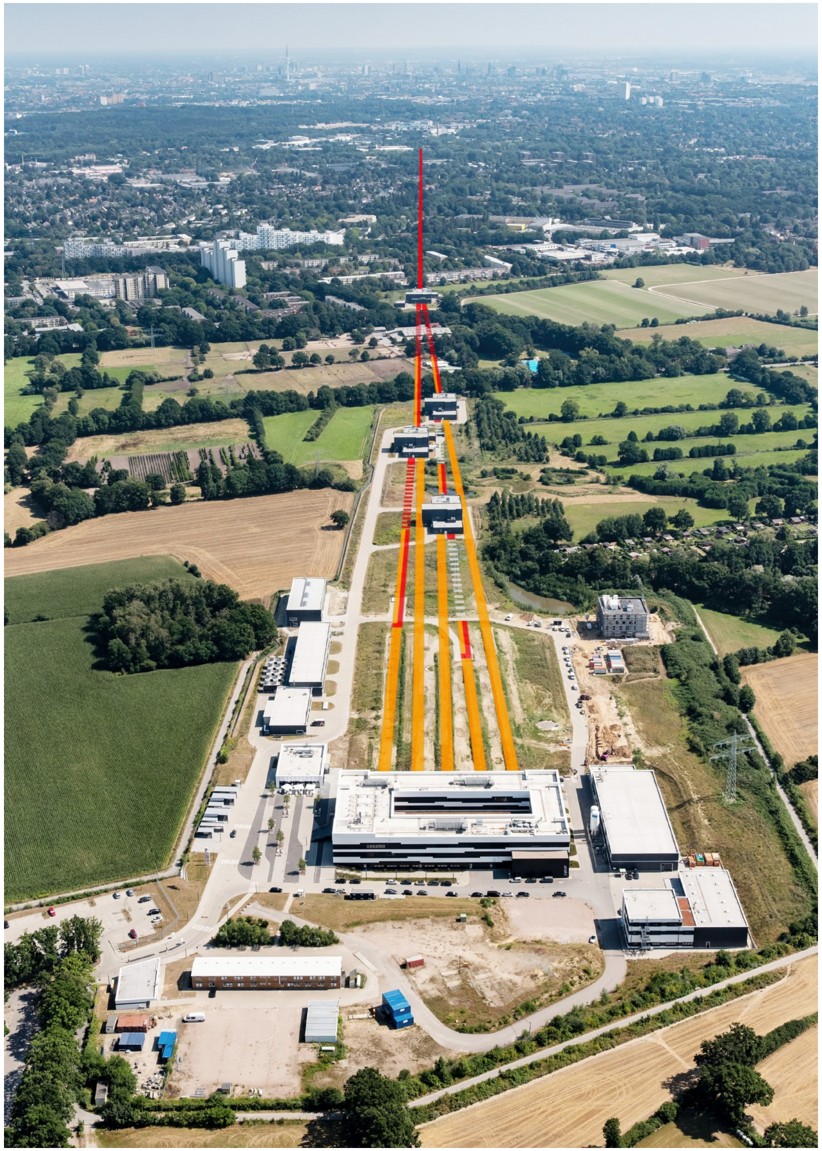
Marco Ramilli[1], K. Ahmed[1], D. Hammer[1], C. Lopez-Cuenca[2], B. Fernandes[1], D. Mezza[2], A. Mozzanica[2], A. Parenti[1], P. Schmidt[1], B. Schmitt[2], M. Turcato[1], J. Zhang[2]

[1] European X-ray Free-Electron Laser Facility GmbH, Holzkoppel 4, 22869 Schenefeld, Germany
[2] Paul Scherrer Institut, Forschungsstrasse 111, 5232 Villigen, Switzerland

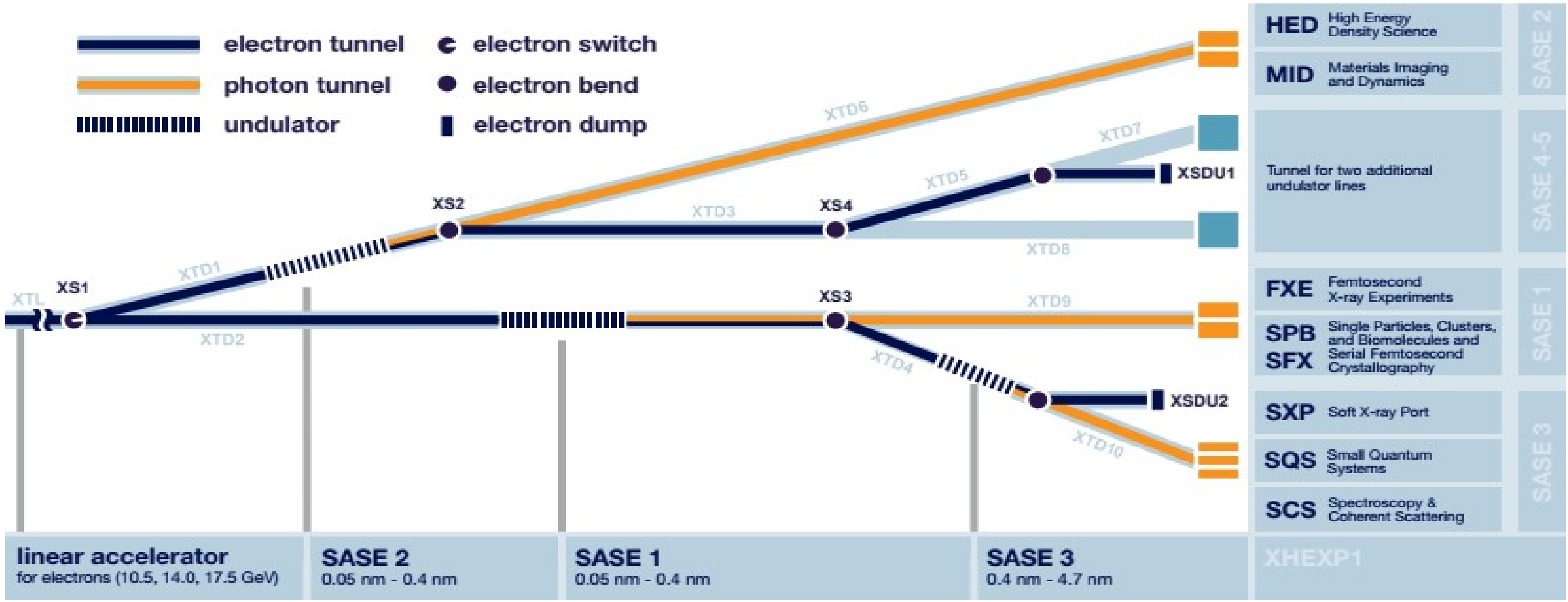
Ultrafast Imaging and Tracking Instrumentation, Methods and Applications – ULITIMA 2023
13- 16 March 2023, Menlo Park, CA

Overview

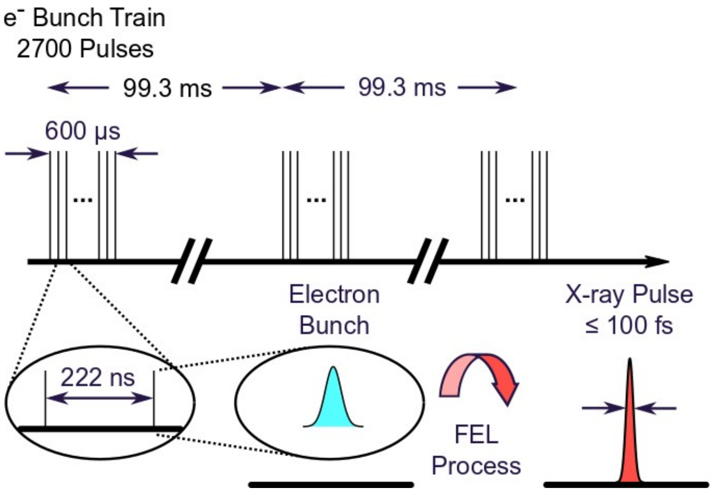
- Introduction
- The GOTTHARD-II detector
  - The ASIC
  - Readout board and mechanics
  - Detector calibration
- Integration in the EuXFEL system
  - Control system
  - Correction pipeline (online and offline)
- First test: von Hamos spectrometer at FXE
- Test with pulse arrival monitor (PAM) at SPB/SFX
- Conclusions and Outlook



Introduction: European XFEL



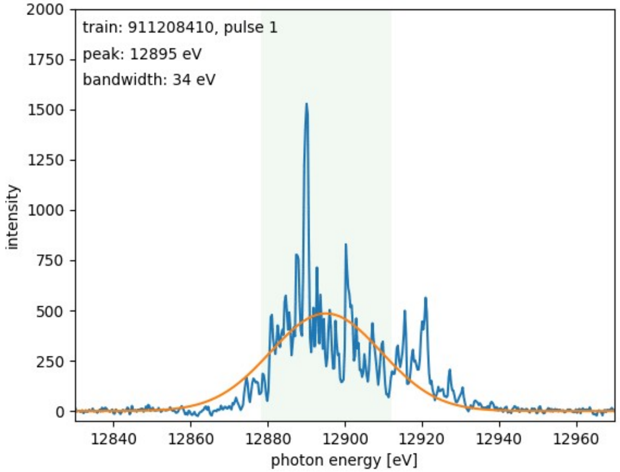
- Three main undulator systems (SASE 1, 2, 3)
  - Supply six scientific instruments
  - SPB/SFX, FXE, MID, HED (‘hard X-ray’)
  - SCS, SQS, SXP (‘soft X-ray’)
- 10 Hz train rate
- Bunch train internal structure
  - **2700 pulses** for 600 μs
  - **4.5 MHz pulse rate** (~222 ns spaced)
  - Lasing pulses < 100 fs width



GOTTHARD-II future installations: beam diagnostic

- HIREX spectrometers
  - Located near SASE1 and SASE 2 undulators
- Provide single shot pulse resolved diagnostic
  - Fundamental for beam qualification
- Currently using GOTTHARD-I 25 µm
  - Frame rate does not allow pulse-by-pulse measurements
  - Undersampled by a factor eight
- GOTTHARD-II 25 µm installation this summer
  - Small pitch needed for better energy resolution

Pulse resolved movie of single-shot spectrum in a train



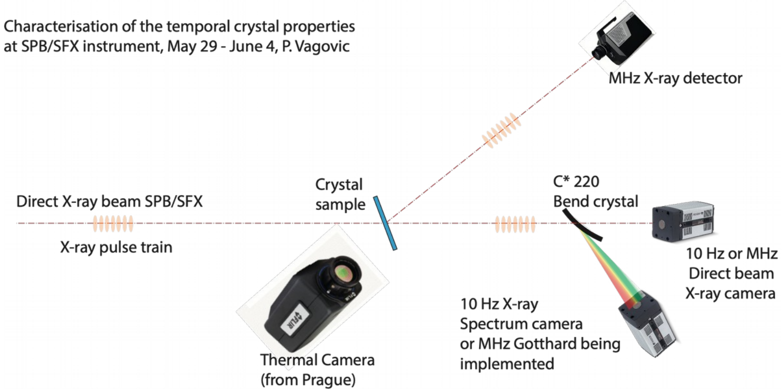
Crystal: C (440)
Detector: Gotthard setup with 0.5 MHz (pick up every 8th pulse/train)
Ep=12900 eV, Ee=16.5 GeV, 0.25nC
Machine with 400 pulses@4.5 MHz

N. Kujala, et al., Review of Scientific Instruments 91(10), 2020

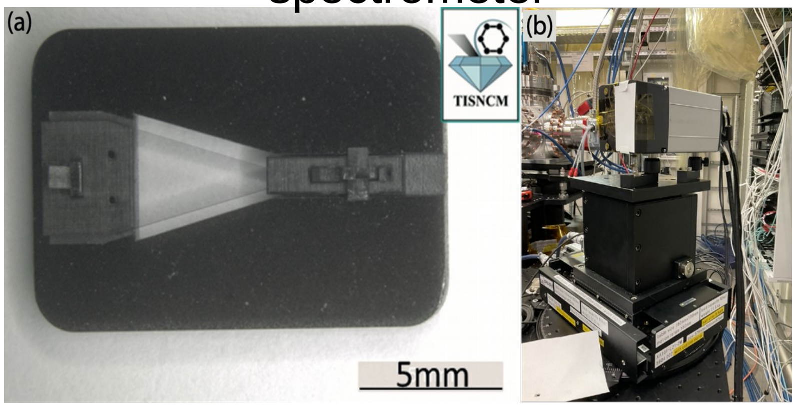
GOTTHARD-II future installations: MHz-TOMOSCOPY project

HORIZON-EIC-2021-PATHFINDEROPEN-01-01, Grant agreement: 101046448

Slide courtesy of P. Vagovich



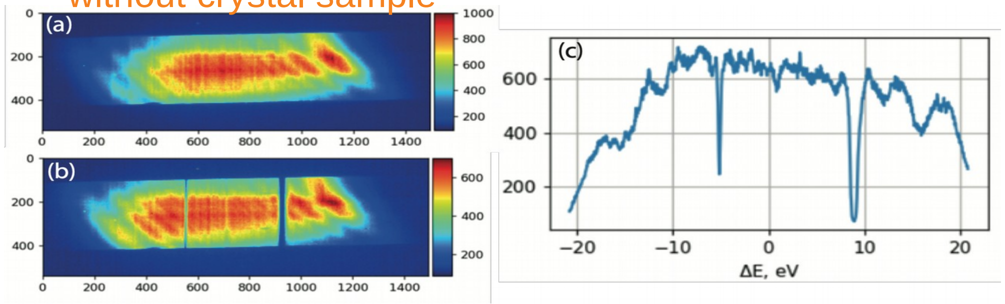
spectrometer



- MHz-Tomoscopy project
  - New Horizon Europe project
- Provide microscopy device at MHz sampling rate
- Current spectrometer only 10 Hz
  - pulse-by-pulse spectral information needed
- First tests with GOTTHARD-II in April 2023

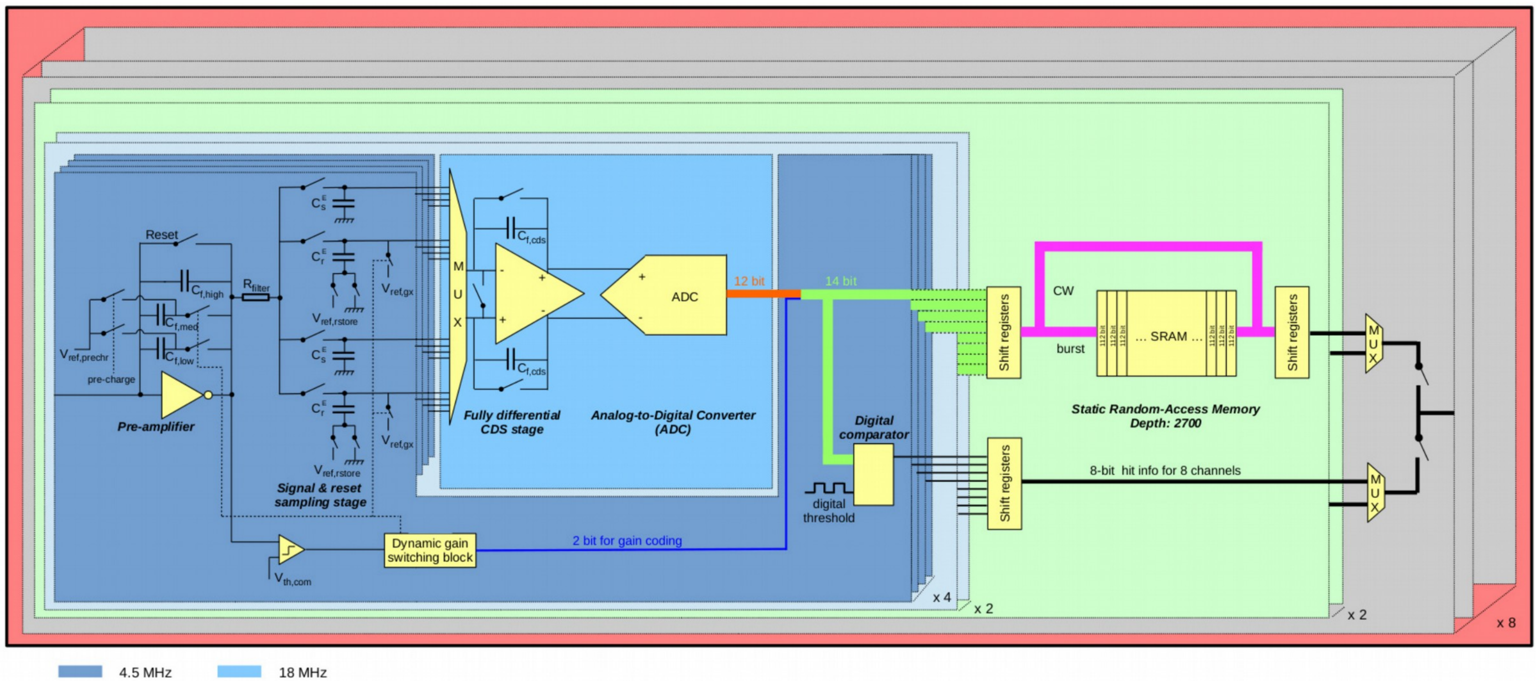
Petrov, I. et al.
Absolute spectral metrology of XFEL pulses using diffraction in crystals,
arXiv, **2023, https://doi.org/10.48550/arxiv.2303.00072**

without crystal sample



with crystal sample

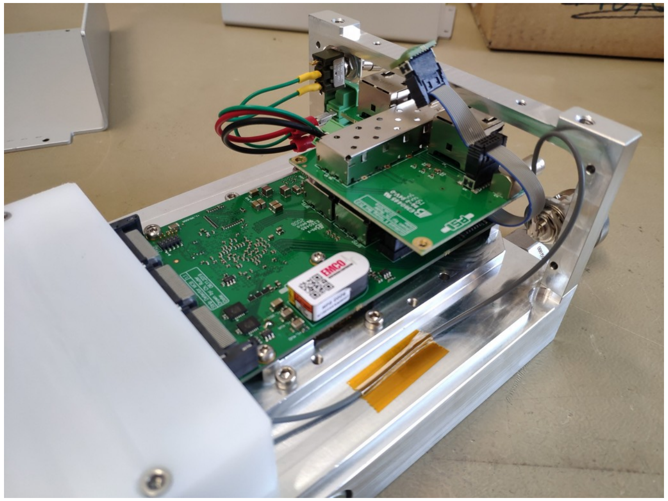
GOTTHARD-II ASIC

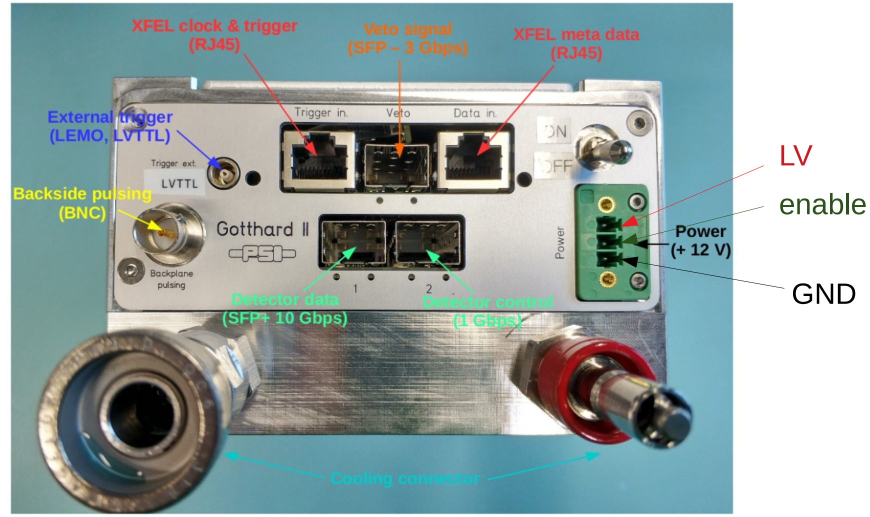


- Developed at PSI for EuXFEL
- Hybrid strip detector technology
  - 320/450 µm thick sensor wire-bonded to ASIC
- ASIC built in UMC 110 nm technology
- **Dynamic gain switching** pre-amplifier
  - Three gain stages: G0, G1, G2
  - From single photon to ~ 10^4 photons @12.4 keV

- Two sets of analog storage cells
  - ‘even’ and ‘odd’
- Four channels multiplexed to:
  - Fully differential CDS stage
  - 12 bits SAR ADC
    - ► Target: 10 bit
- Output stored in a SRAM
  - Capable **up to 2720** images per train
- 400 kHz continuous imaging

GOTTHARD-II module





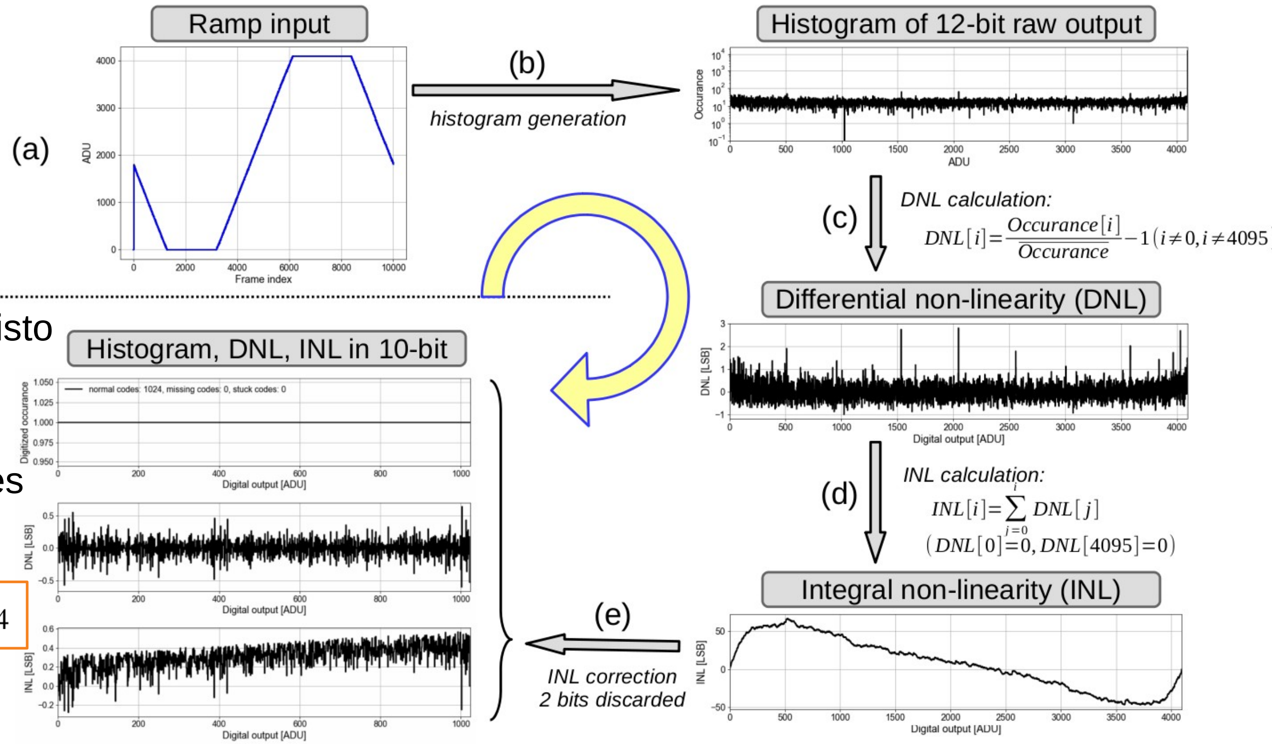
- Main board
  - +12 V external LV
    - ► Up to 500 V internally
  - FPGA Intel Cyclone 10 GX(CX)
  - x2 10 Gb/s IF
    - ► Slow control (~ 1 Gb/s transceiver)
    - ► Data out (10 Gb/s SFP+)
- Timing board
  - x2 RJ45
    - ► EuXFEL clock + train trigger
    - ► Metadata
  - x1 3.125 Gb/s SFP
    - ► VETO out
- Two versions
  - 50 µm pitch strips
    - ► 1280 strips
  - 25 µm pitch strips
    - ► 2560 strips
    - ► Readout interleaved by two boards
- Water+glycol cooled
  - Power dissipation ~ 12 W (x2 for 25 µm)
- Power:
  - +12 V LV
  - ‘Enable’ (between +2.5 V and +12 V)
- **29 detectors to be installed at EuXFEL**

ADC calibration

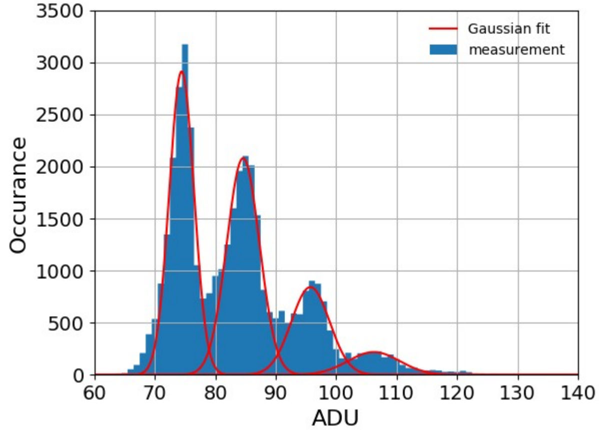
- 12-bit ADC issues:
  - Highly non linear
  - Missing/stuck codes
- ADC calibration algorithm:
  - Inject voltage ramp
    - ► Acquire images
  - Calculate DNL from output histo
  - Calculate INL from DNL
- Conversion to 10 bit
  - Solves issue of missing codes
  - **12-bit → 10-bit LUT**:

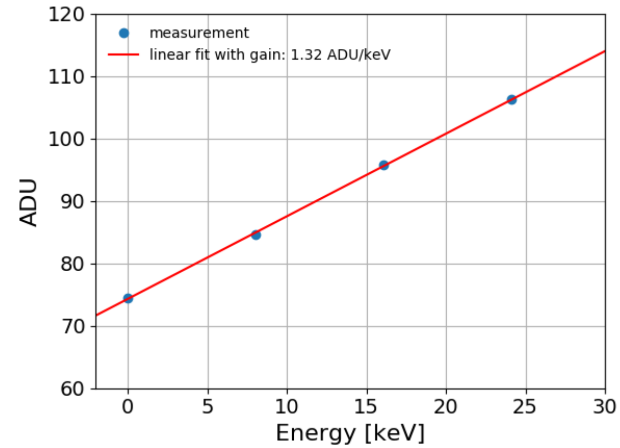
$$Dout_{10bit}[i] = (Dout_{12bit}[i] + INL[i])/4$$

- DNL and INL at 10 bit created
  - Used for further correction

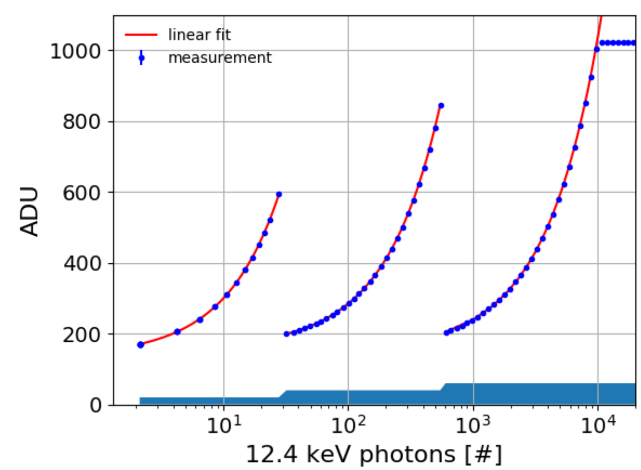


Detector calibration: gain and offset





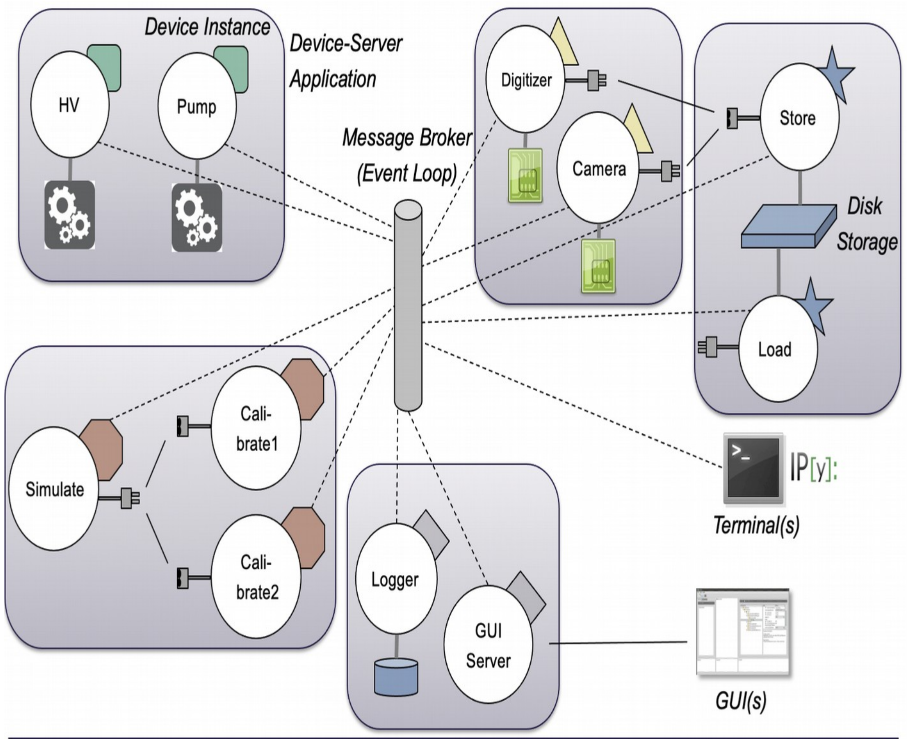
- Absolute calibration of G0
  - Monochromatic flat field (e.g. Cu fluorescence)
  - Peak fit
- Current source scan
  - Linear fit to measure gain ratios
    - ► G0/G1, G1/G2
  - **Gain conversion map** calculated for G1 and G2
- **Offset map**
  - G0 offset from dark run average
  - Offset for G1 and G2 from linear fit
  - Values stable (~ 1% variation) against temperature
    - ► Tested from 10 °C to 25 °C



More on GOTTHARD-II ASIC design and calibration:
"Design and first tests of the Gotthard-II readout ASIC for the European X-ray Free-Electron Laser",
J. Zhang et. al, 2021 JINST **16** P04015
DOI 10.1088/1748-0221/16/04/P04015

Karabo Control System Architecture

- Central message broker (control slow data)
  - Currently: OpenMQ
- Event driven:
  - Data propagates throgh the system when values change
- Content specific extensions (**devices**)
  - Run as plugins in device servers
  - C++ and Python APIs
- Device servers
  - Run as system servers via daemontools
    - ► Can be started, stopped, killed
    - ► Rolling text logs
- Karabo-GUI main access point for users

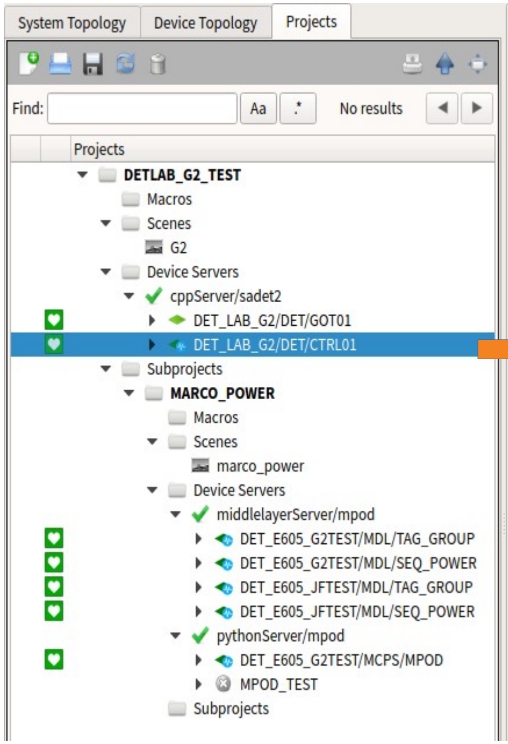


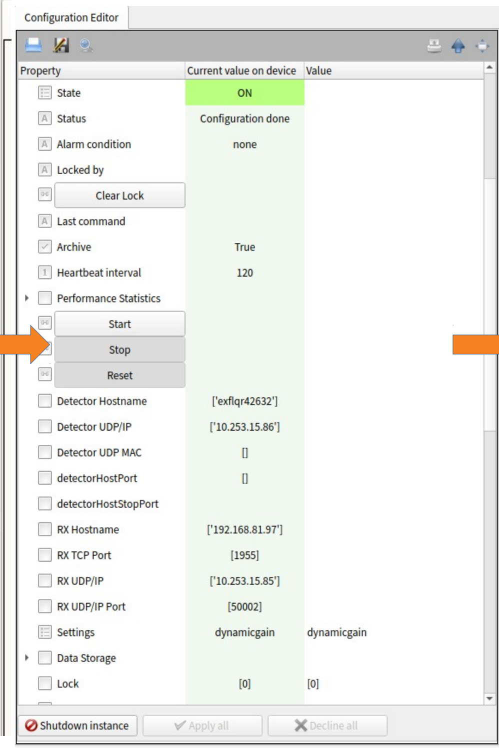
If you want to read more:
https://www.xfel.eu/organization/scientific_and_technical_groups/controls/index_eng.html

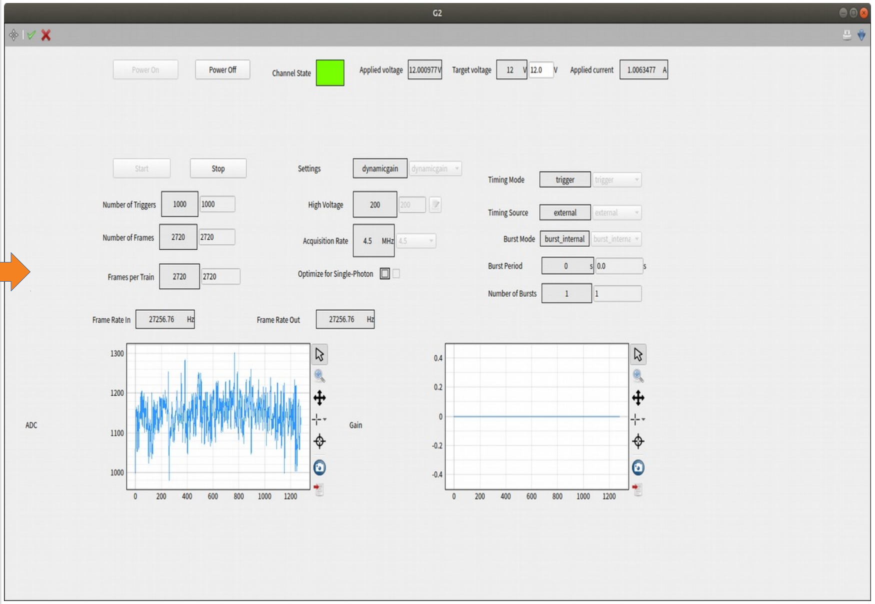
GOTTHARD-II Integration: Karabo

- Wrap slsDetectorSoftware in C++ based classes
- Same parent classes as for JUNGFRAU and GOTTHARD-I
  - CONTROL device
  - RECEIVER device for each IF
    - ► One RECEIVER for 50 µm
    - ► Two RECEIVER for 25 µm

- 16 bits per strip
  - 2 unused
  - 2 for gain stage encoding
  - 12 ADC output
    - ► on-the-fly masking
    - ► 2 images per integration gate



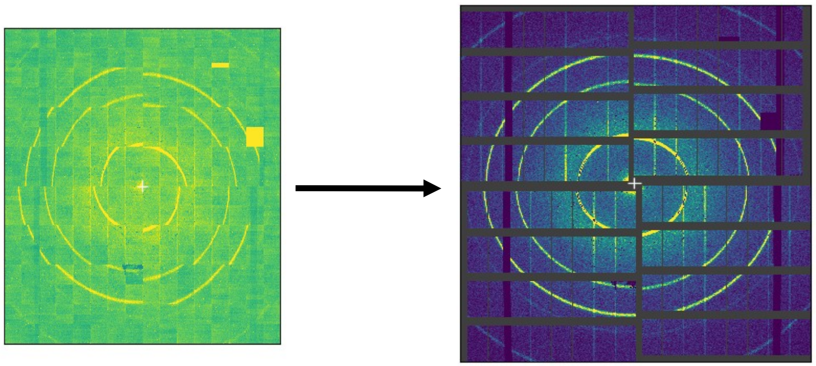




Calibration effort at European XFEL

European XFEL aims to provide facility users with a fully corrected and calibrated dataset as the primary data product.

SRN **27.4**, 35 (2014)



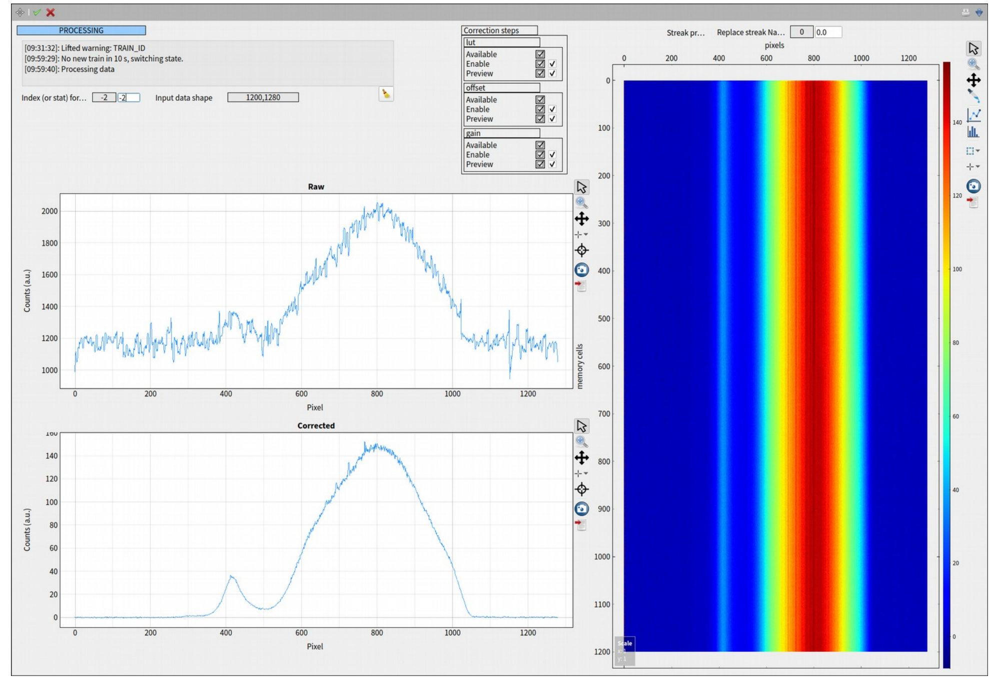
- Develop correction methods for detectors used at European XFEL
  - AGIPD, LPD, DSSC, Jungfrau, Gotthard2, pnCCD, FastCCD, ePix
- Collect and catalogue data for characterization and calibration
- Build and maintain machinery and infrastructure to apply these methods automatically and at scale

GOTTHARD-II Integration: Correction Pipeline

Constants loaded in DB

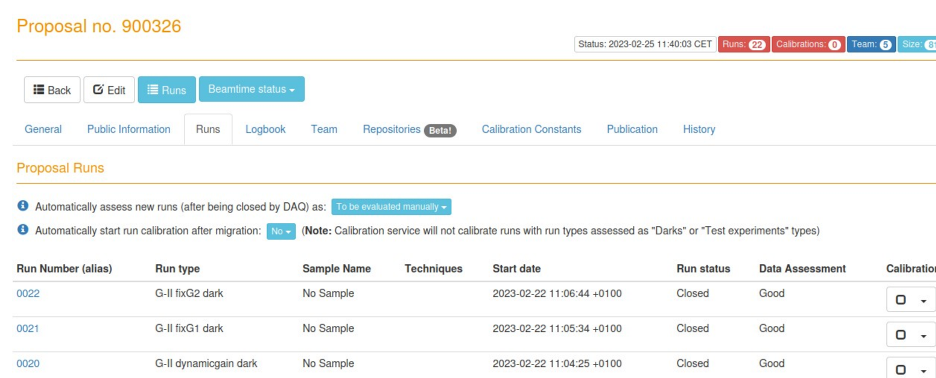
Online correction

- Implemented in Karabo devices
  - Detector class specific
  - Basic correction only
  - Code optimized for speed
  - Run on high performance machines
- Accessible from GUI
- Output corrected image



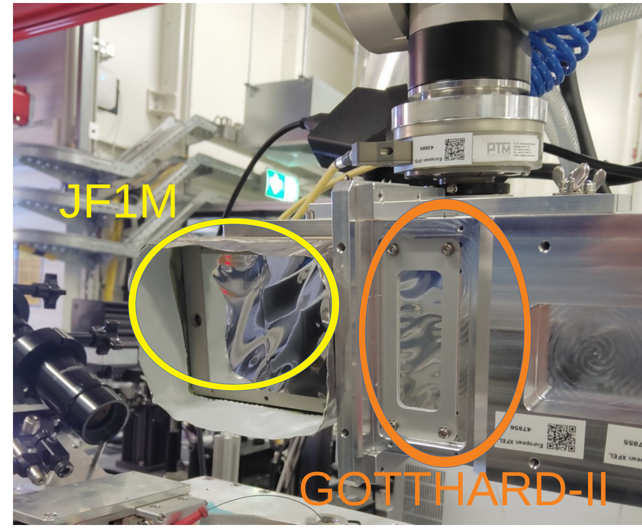
Offline correction

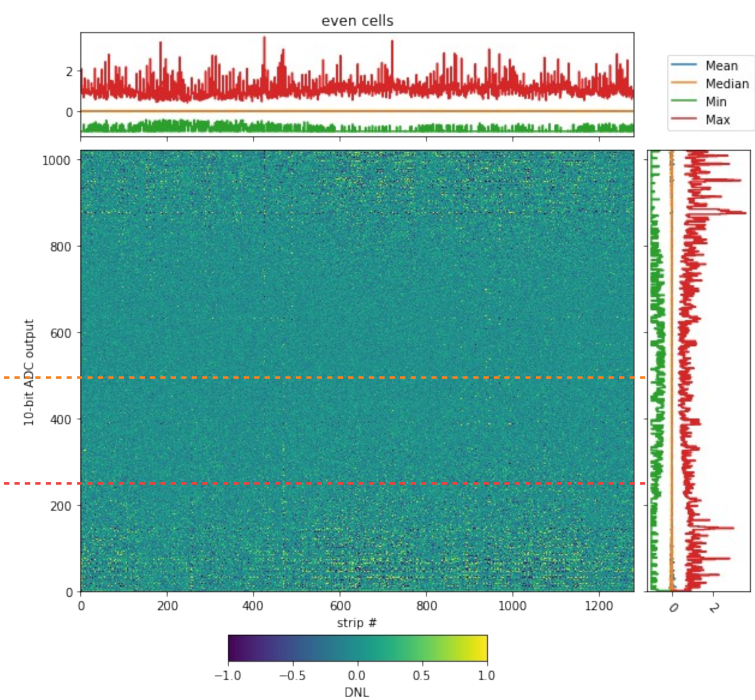
- Implemented in scripts
  - Detector class specific
  - Algorithm aims to most complete correction possible
    - ► Common mode correction
    - ► Clustering
    - ► Baseline shift compensation …
  - Code written to handle large data volumes
- Correction triggered by Metadata Catalogue
  - Scripts run a SLURM jobs on Maxwell Cluster



First test: pump and probe at FXE

- Provide end-to-end test of integration
- The detector has been mounted on the robotic arm
  - To be used in the von Hamos spectrometer
  - Co-planar with the JF1M
  - 1.5 mm slit mounted to reduce background
- Take pump-and-probe measurements
  - Compare the results of the two detectors
- ‘Single Photon’ optimized settings tested for the first time:
  - Vref of the storage cells changed to shift baseline
    - ► Optimize usage of linear region of ADC
  - CDS set to high gain
    - ► Improve S/N ratio
- Clock divider increased to run at 1.1 MHz

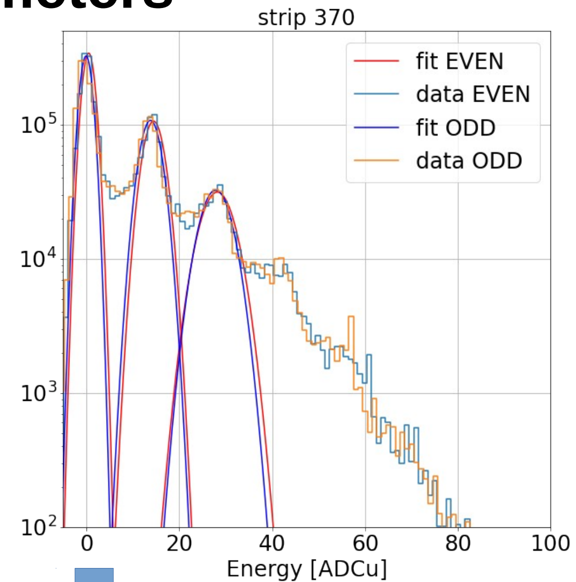




‘single photon’ pedestal level

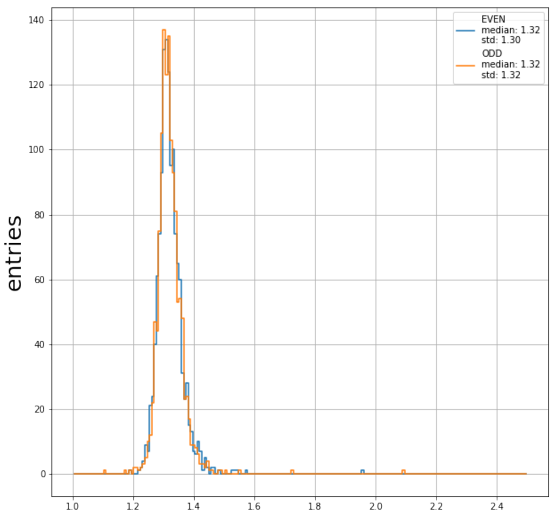
normal pedestal level

Test at FXE – Detector operational parameters

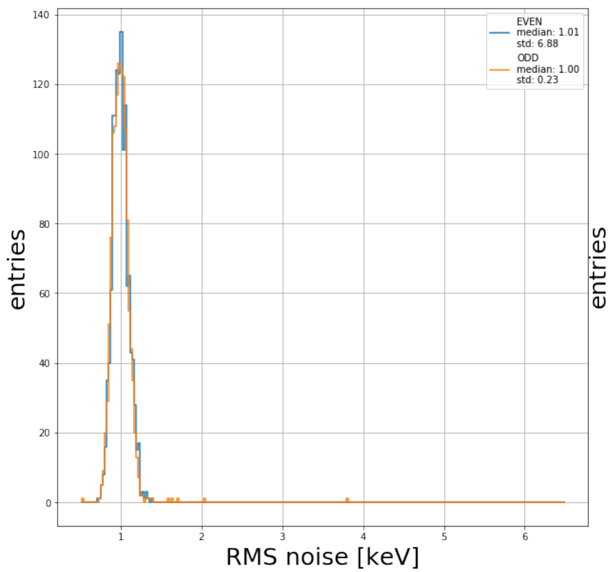


- End-to-end test successful
- Comparison with basic operation mode
- Characterization in 1.1 MHz, 'single photon' mode
  - Single photon Cu K_α spectra
    - ► Gain in G0 CDS high ~30% higher
  - Noise comparable
    - ► Pedestal gaussian fit variance
    - ► Exposure time x4 larger at 1.1 MHz
  - ~30% improvement on S/N

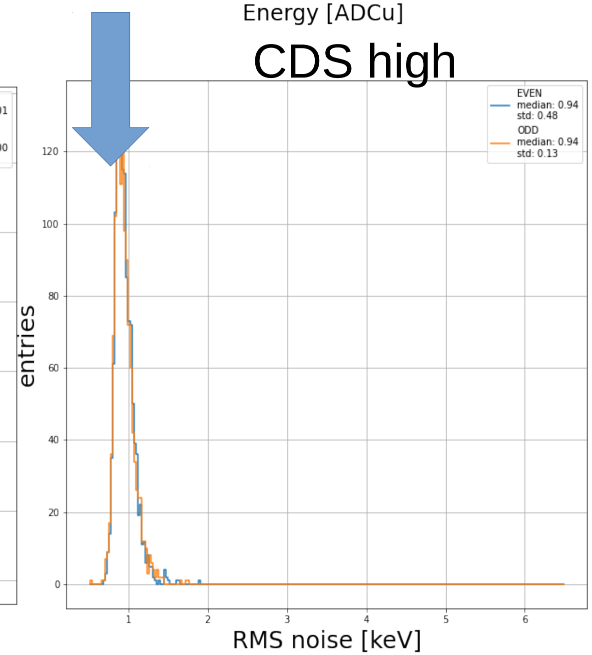
Gain ratio



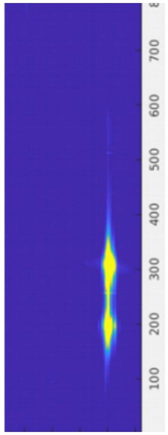
CDS low



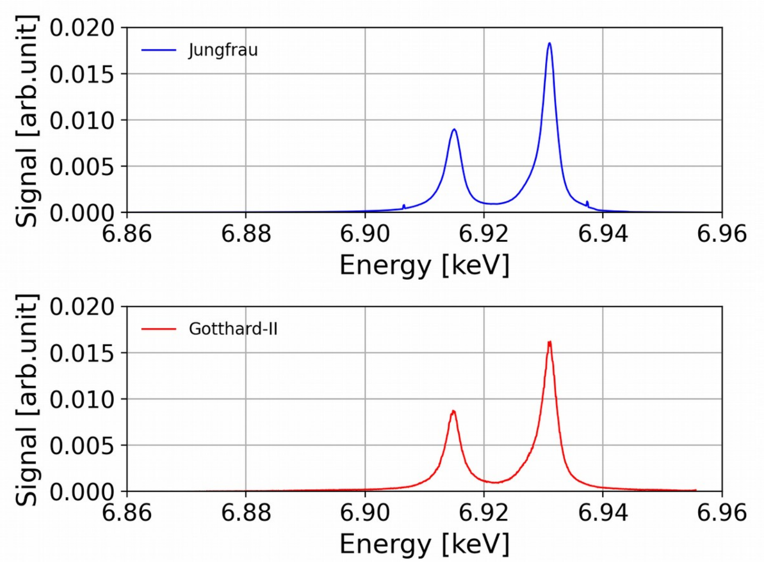
CDS high

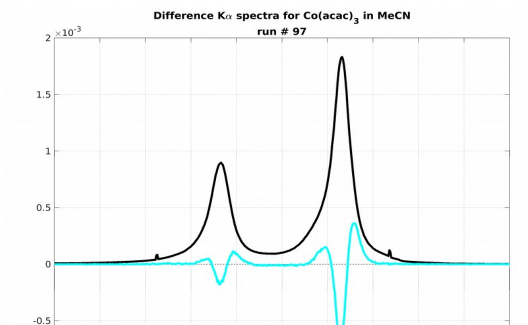


Test at FXE – Pump and probe

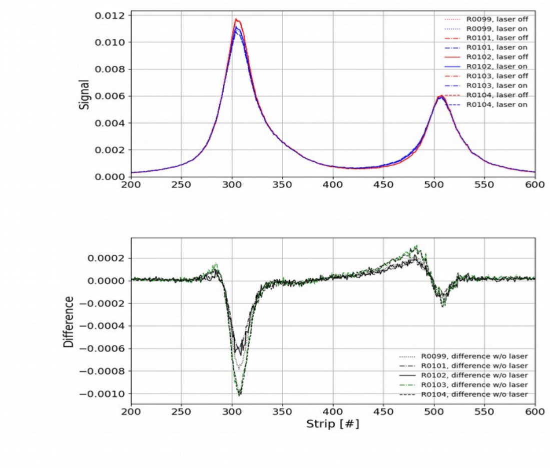


- Energy dispersive measurement
- Detector in 1.1 MHz, ‘single photon’ mode
- Different combinations of X-ray and laser rep. rates
  - Compare the JF signal difference with G-II
    - ► Some difference in results
    - ► Slightly different spot shape
    - ► Further investigation





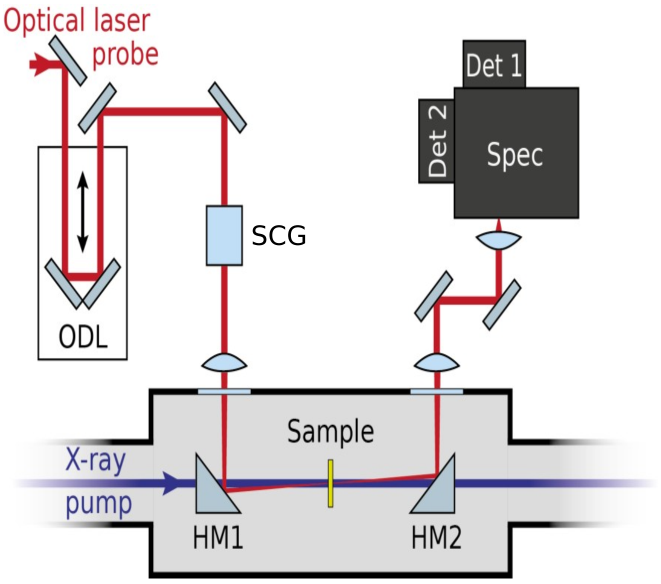
picture by D. Khakhulin

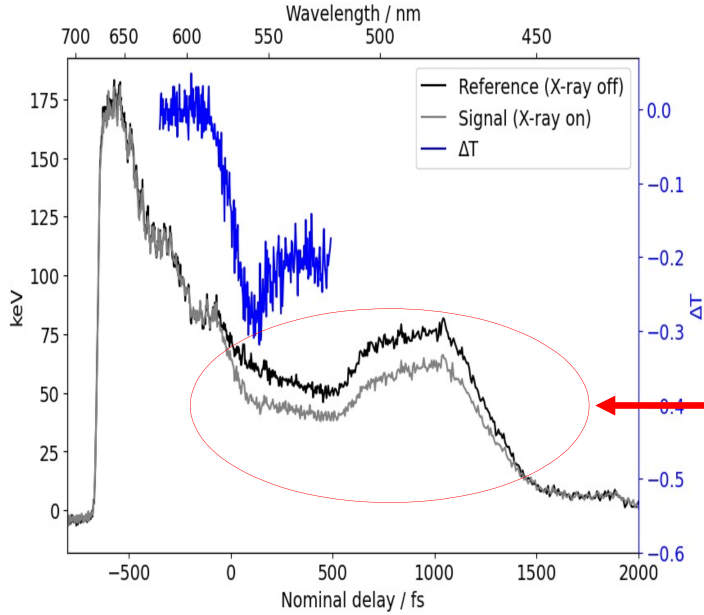


Photon arrival time measurement with spectral encoding

Slide courtesy of T.Sato, R. Letrun, J. Koliyadu, J. Liu

- X-ray induces change in optical properties of dielectric material
- Relative arrival time of X-ray/optical laser information mapped to optical laser spectrum





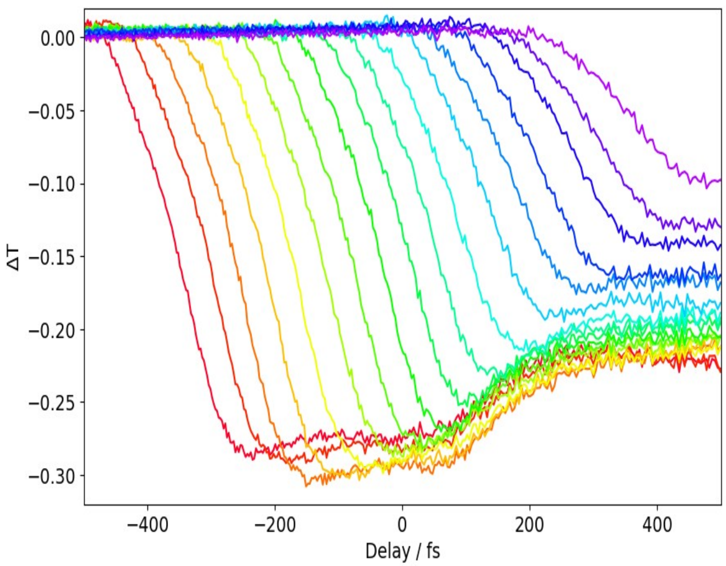
X-ray induced change in optical transmission:
ΔT = Signal /Reference - 1

Bionta et al., Opt. Express 19, 21855–21865 (2011)
Koliyadu et al., J. Synchrotron Rad. 29, 1273–1283 (2022)

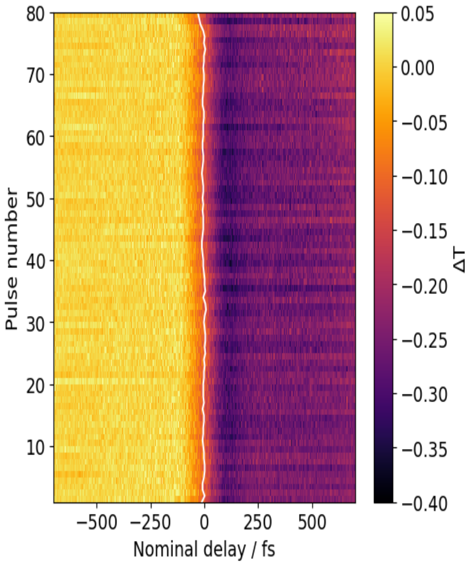
GOTTHARD II for photon arrival time measurement at SPB/SFX

Slide courtesy of T.Sato, R. Letrun, J. Koliyadu, J. Liu

Delay scan, average of 100 shots



Single shot data within a train



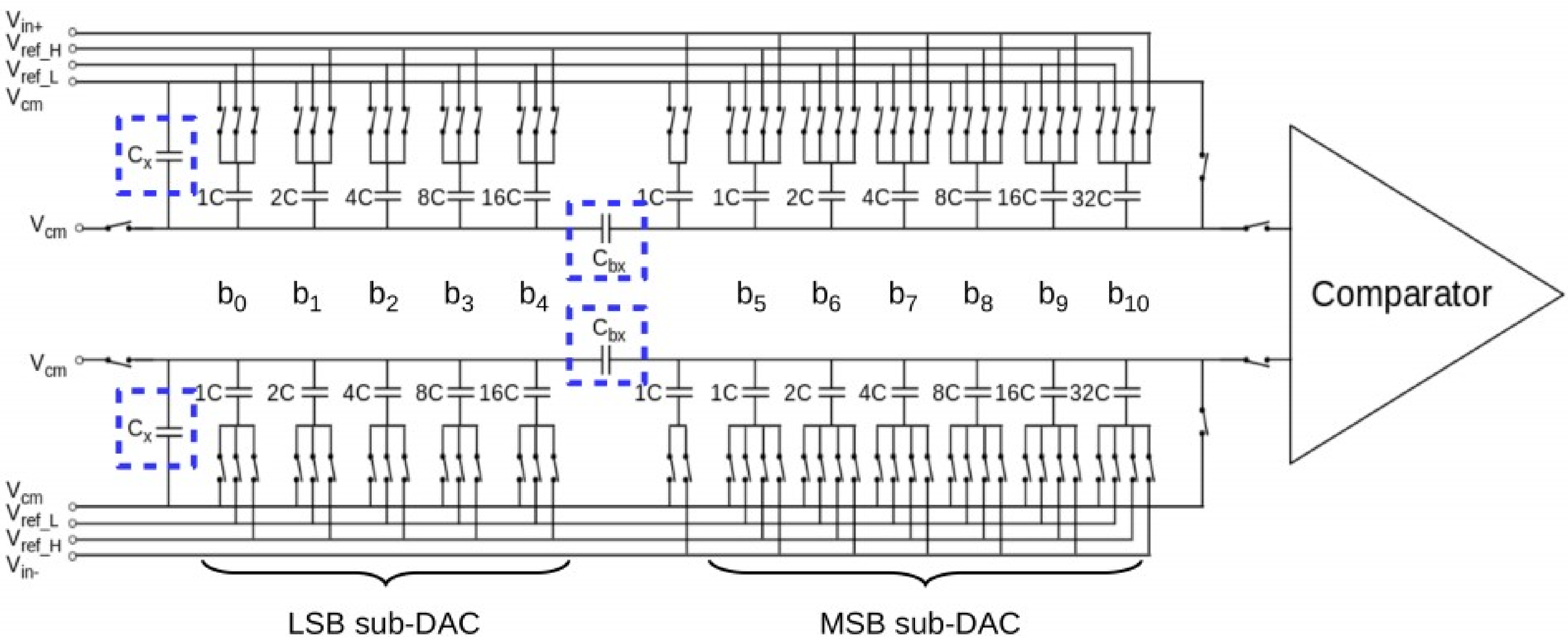
- Interleaved X-ray at 2.25 MHz
  - Optical laser reference at 4.5 MHz
- Time resolution comparable with GOTTHARD-I
  - Experimental conditions not optimized yet
- Previous setup:
  - GOTTHARD-I
    - ► Maximum 282 kHz X-ray repetition rate
    - ► Max ~60 X-ray pulses

Summary

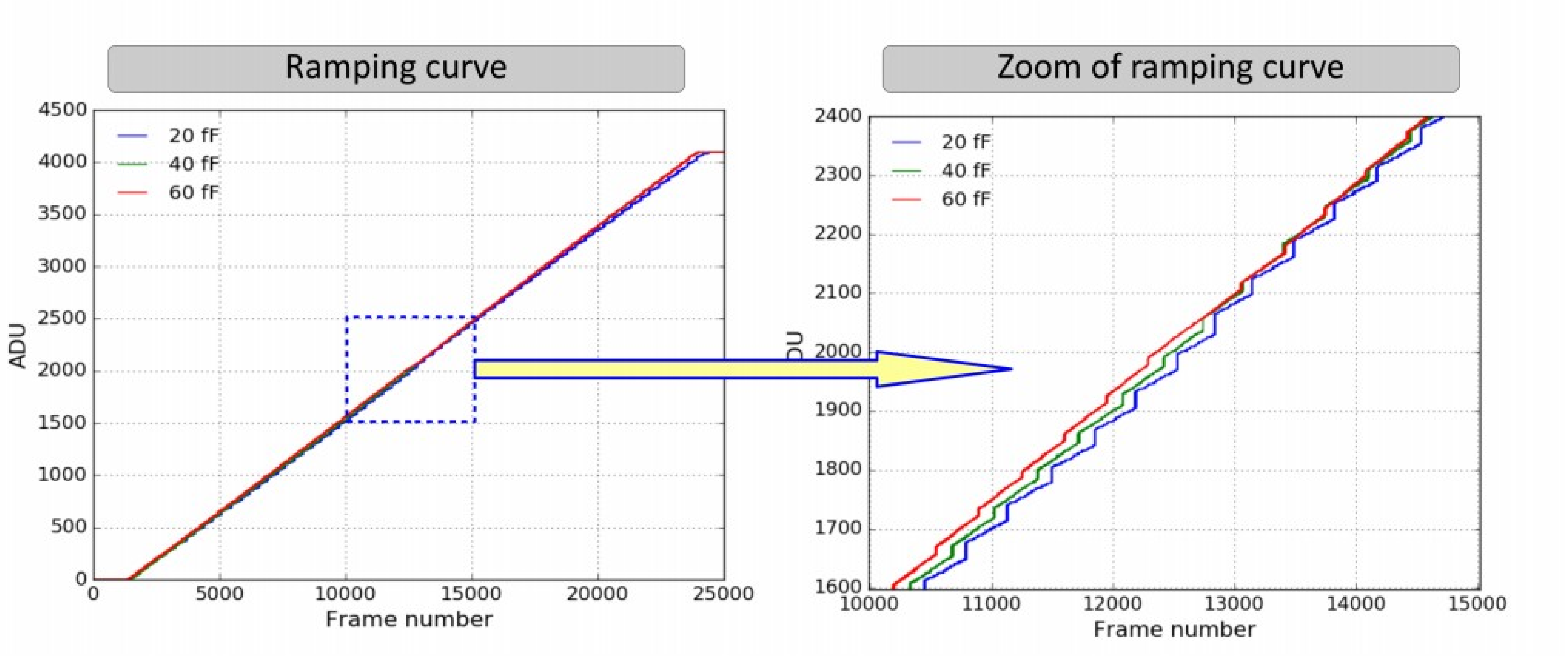
- GOTTHARD-II is hybrid strip detector developed at PSI
  - Fast on-chip ADC
    - ► 4.5 MHz frame rate in burst mode
    - ► 2720 images/train
  - Dynamic gain switching pre-amplifier
  - Two versions:
    - ► 50 µm pitch, 12 detector delivered at EuXFEL
    - ► 25 µm pitch, first delivery summer 2023
- Successfully integrated 50 µm pitch in EuXFEL control system and correction pipeline
- First tests performed
  - X-ray sensitive 50 µm detector in von Hamos spectrometer at FXE
    - ► First test in EuXFEL environment
    - ► Assessed status of integration
    - ► Verified high CDS, 1.1 MHz operation
  - Visible light 50 µm detector in pulse arrival monitor at SPB/SFX
    - ► Allows pulse arrival timing at 2.25 MHz X-ray pulse rate
- Upcoming installations:
  - MHz-TOMOSCOPY setup at SPB/SFX
    - ► Spring 2023
  - HIREX spectrometer
    - ► Summer 2023

Backup

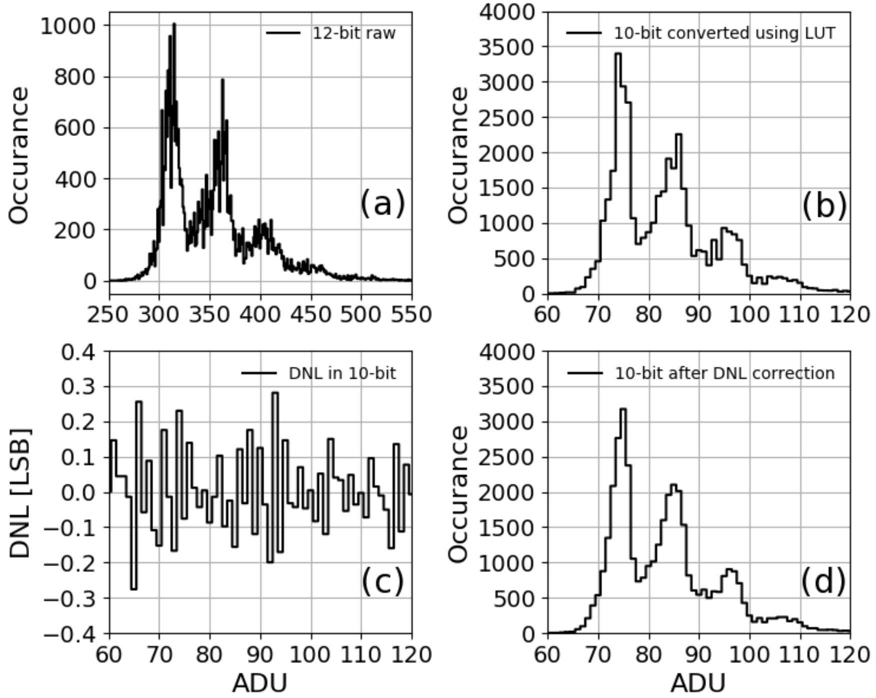
ACD schematics



Missing codes



ADC output correction



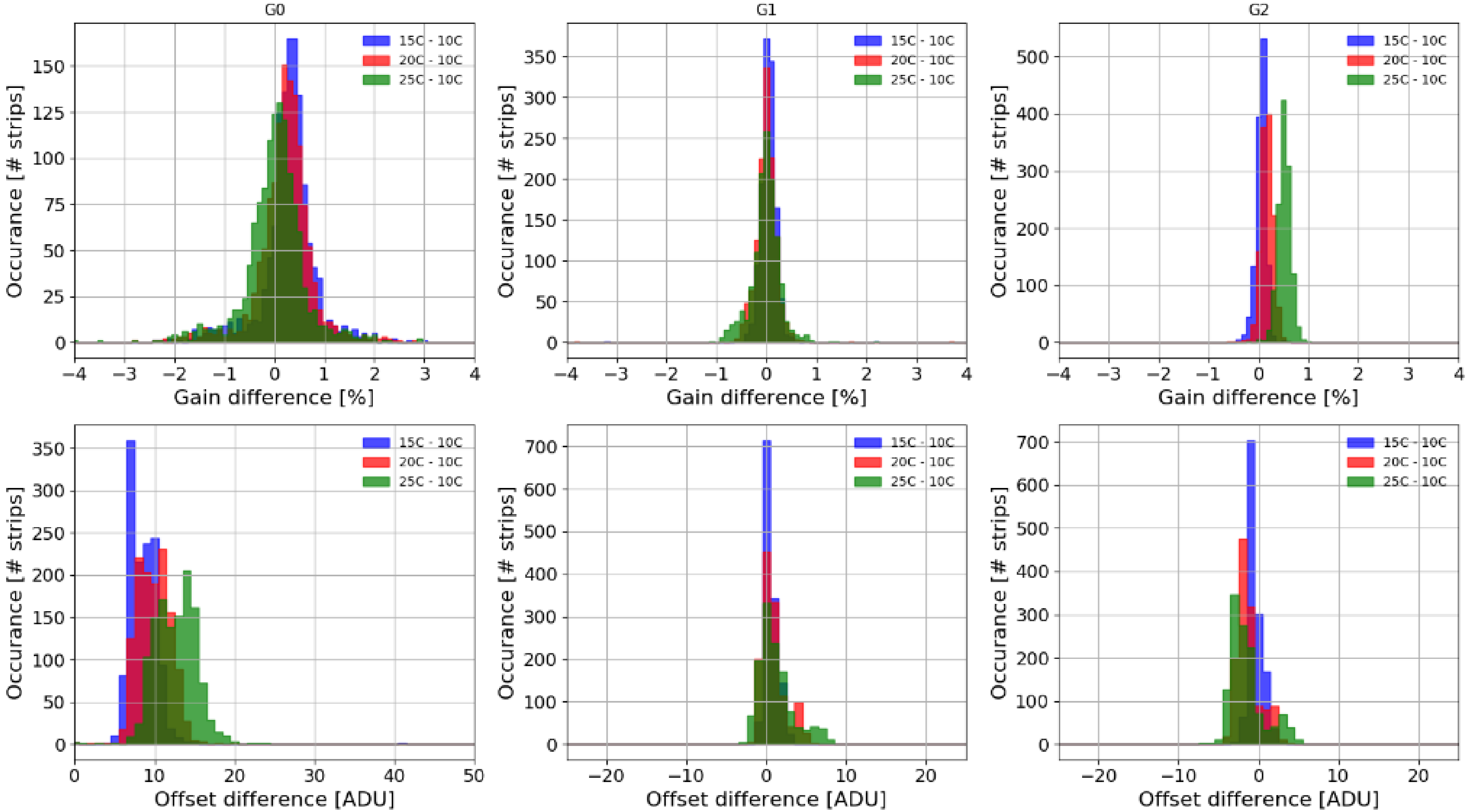
- Raw 12-bit ADC output
  - LUT 12 bit → 10 bit
- DNL at 10 bit within+/- 0.5
  - Not critical for imaging
  - Relevant for spectroscopic information
- Energy calibration requires correction:

$$N_{10bit,corr}[i] = \frac{N_{10bit}[i]}{DNL_{10bit}[i] + 1}$$

300 ns exposure time to settle pulser input signal

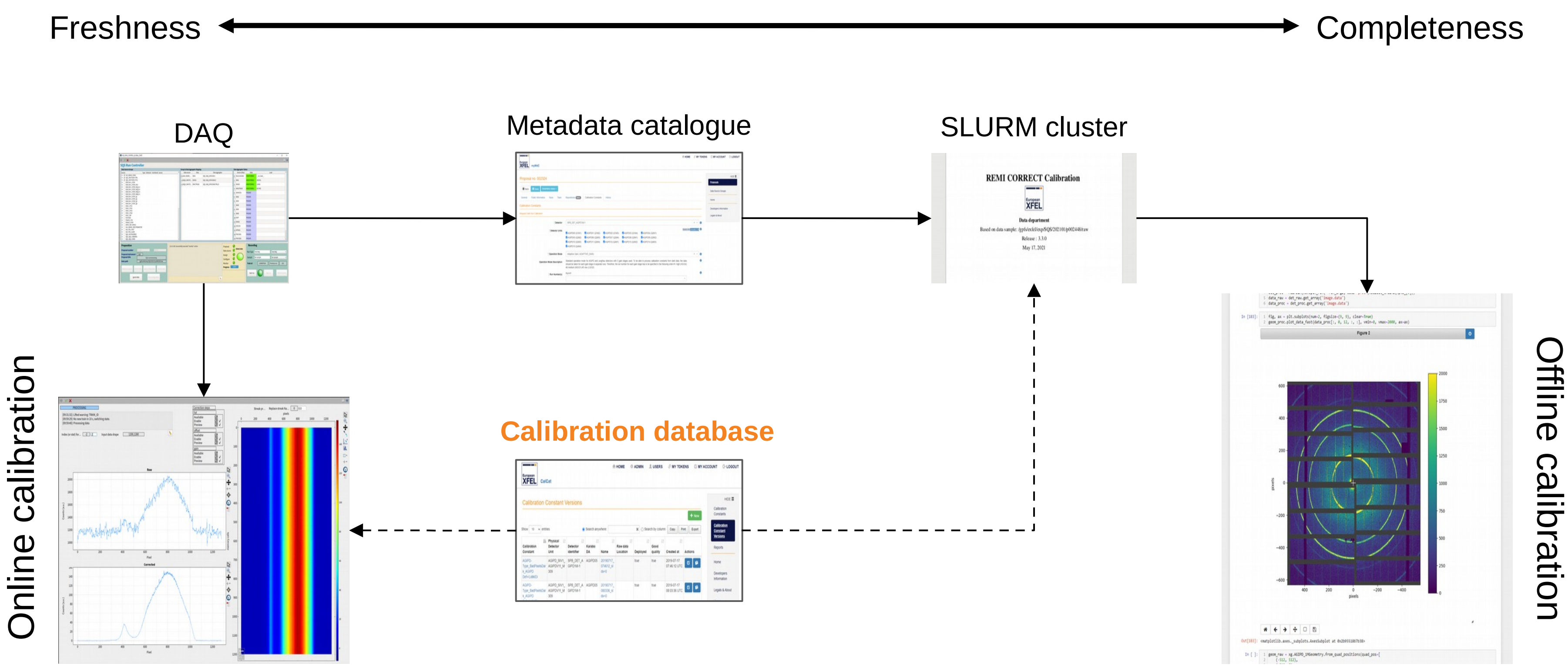
Dynamic range - 3: Statistics for all strips

- Temperature dependence of G0, G1, and G2 as well as offsets for "even/odd"



Gain difference within 1-2% in the measured temparature range for all strips!

Calibrated detector data at European XFEL



GOTTHARD-II Integration: Offline Correction

- First version of Offline Correction (by K. Ahmed)
  - So called ‘semi-online’
- Constants *not* in the CalCat:
  - Constants retrieved from files on the online cluster
    - ► Expert needed to change constants
  - /proc folder also on the online cluster
- Performs offline:
  - 12bit → 10 bit conversion via LUT
  - Offset subtraction
  - Gain correction