Aldo Mozzanica
for the PSD Detector Group

The *JUNGFRAU detector: beam line experience and future developments.*

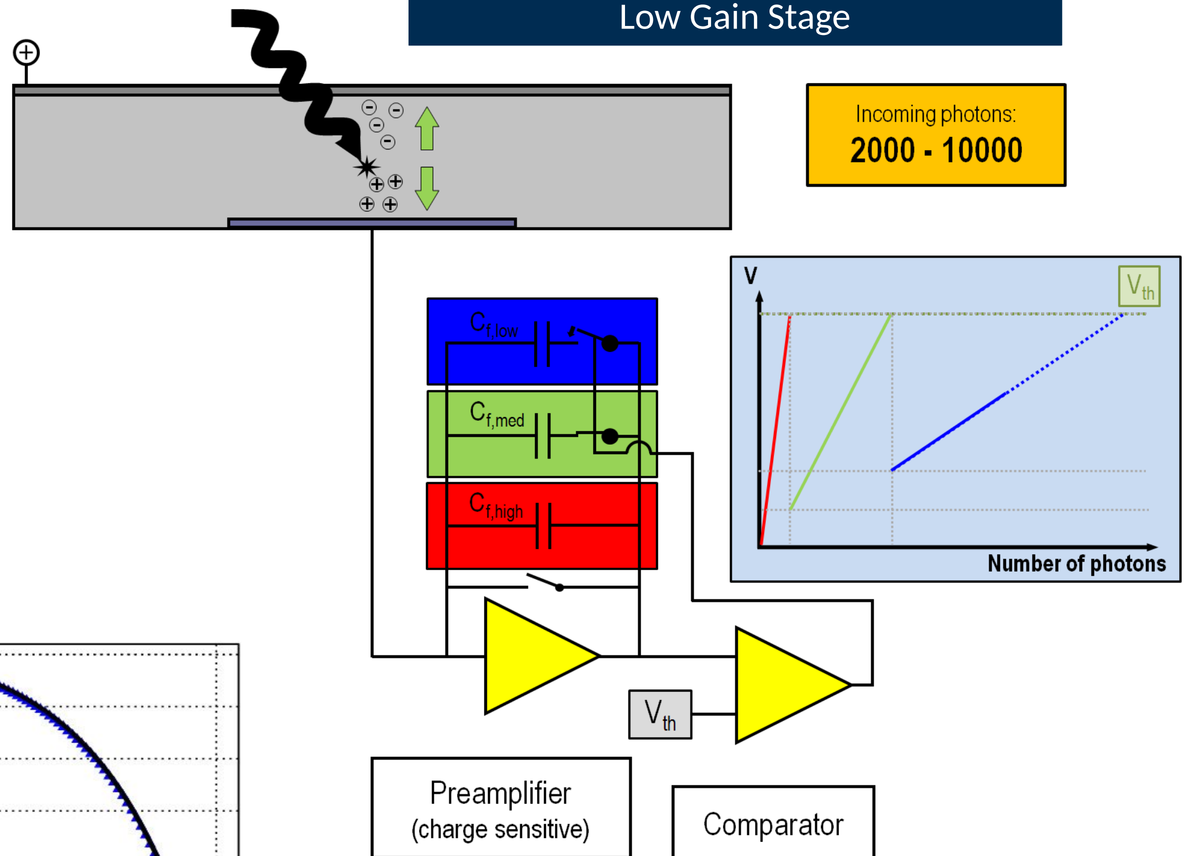
IFDEPS24, March 2024

Outlook

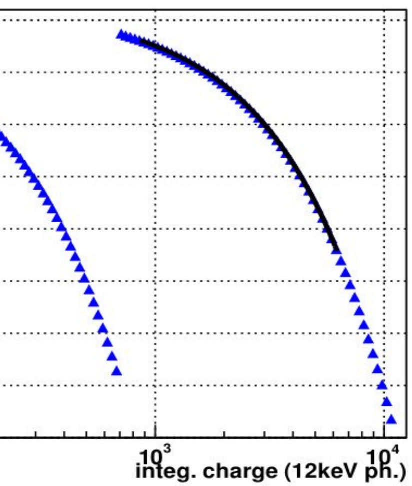
- Introduction to the JUNGFRAU detector
- Applications at FELs, Synchrotron sources, and beyond
- Problems and limitations of current system
- Plans for the near and mid term Jungfrau developments
- Conclusions

Jungfrau principle of operation

Low Gain Stage



- Used by GOTTHARD and AGIPD before Jungfrau
- Basic idea: Dynamically adding capacitors in the feedback loop of the preamplifier to adapt the gain to the number of incoming photons
- Comparator monitors preamplifier output and add capacitors if the dynamic range is ~ exceeded



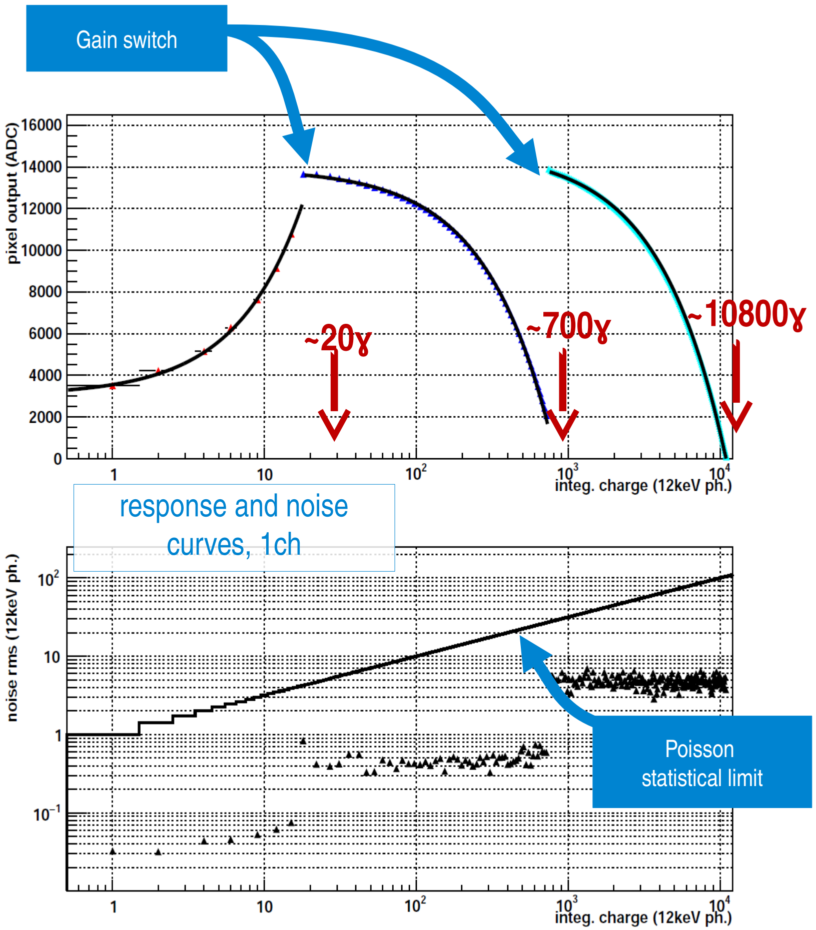
<u>Three gain:</u>

High (G0): **1 ... 20** x 12.4 keV photons

Medium (G1): *20* **... 700** x 12.4 keV photons

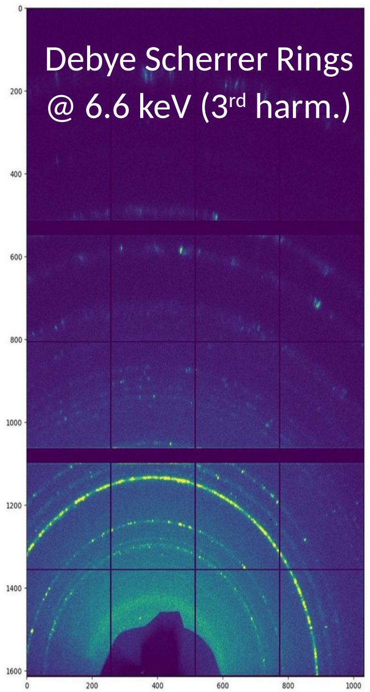
Low (G2): 700 **... <10800** x 12.4 keV photons

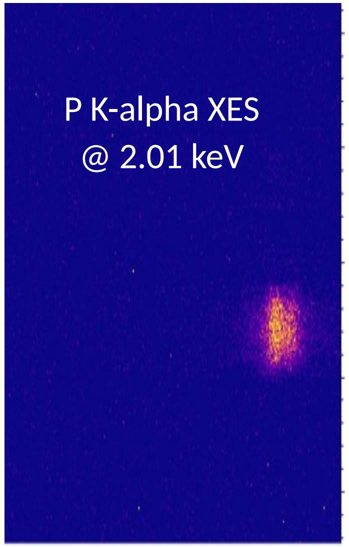
Summary of characterization results

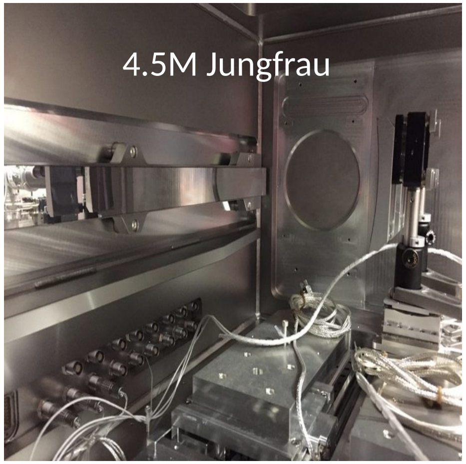


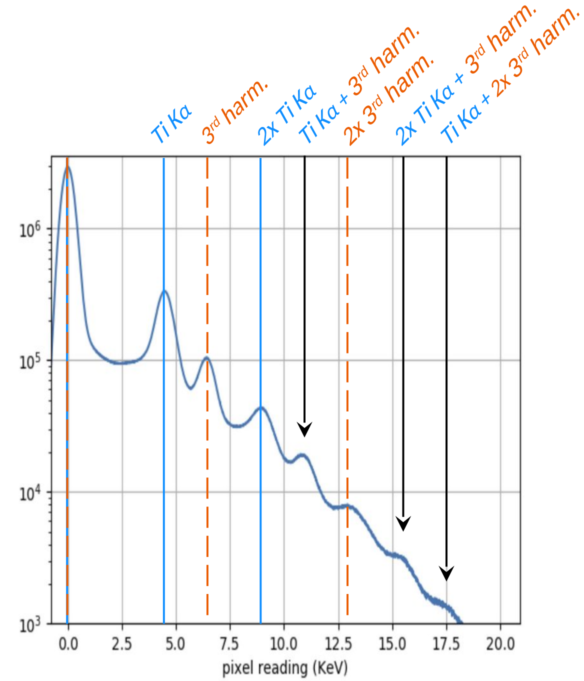
noise in G0 (@10us integration)	80±3 E.N.C. rms
noise in HG0 (low energy operation)	50±2 E.N.C. rms
min energy @ with photon detection	1.5keV
noise in G1/G2	3keV/50keV rms
nominal gain values (G0-G1-G2)	40-1.4-0.11 ADU/keV
non linearity error	<1% (w. optimal calibration)
Saturation	~11K 12keV photons per frame
Saturation flux for continous sources	12MHz/pix @ 1.13kHz,12keV 50MHz/pixel @2.4kHz,6KeV
Min integration time	500ns
Frame rate	max 2.4kHz, 1.13kHz with current FW and PCB
Min period between frames	1/frame rate (now 880us) 3us in burst mode (current FW)

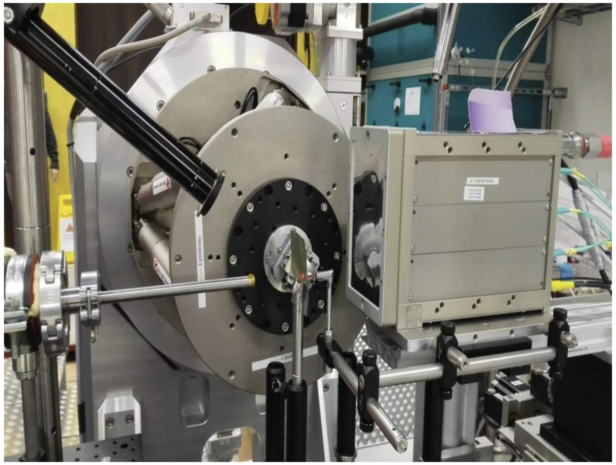
JUNGFRAU detector at SwissFEL



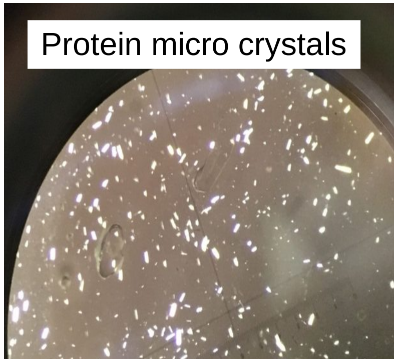


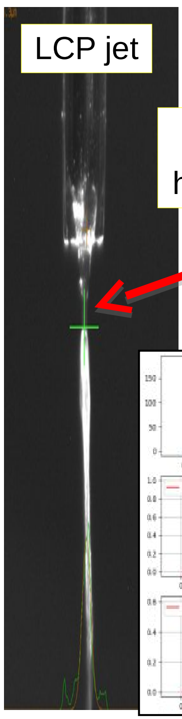


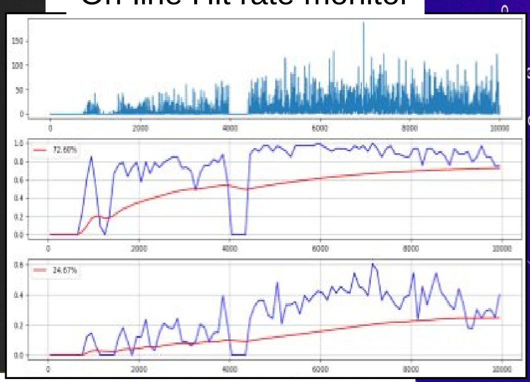


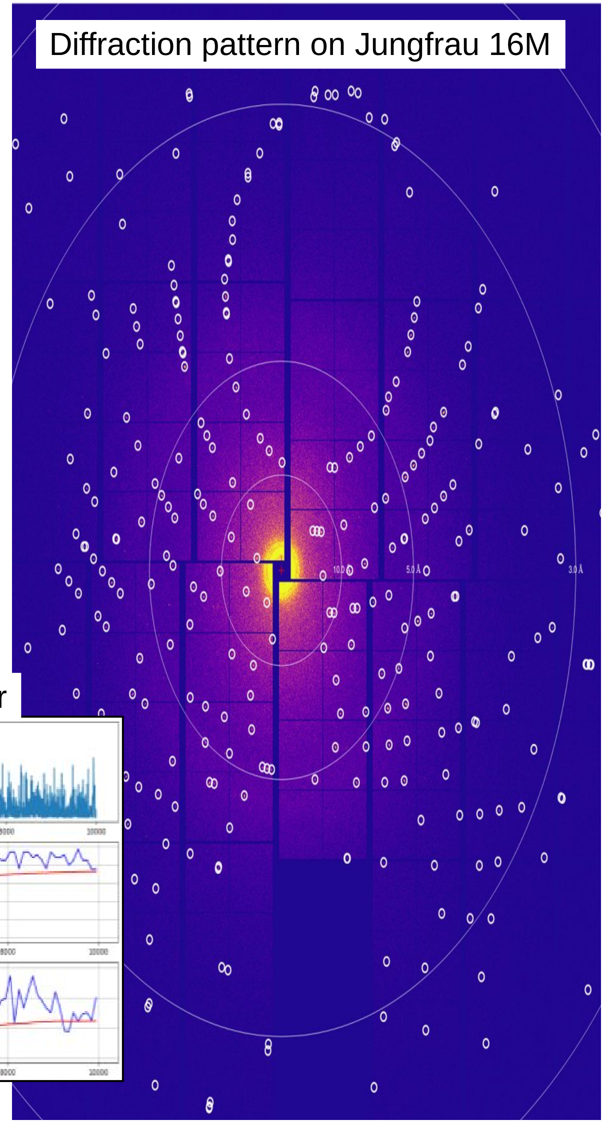


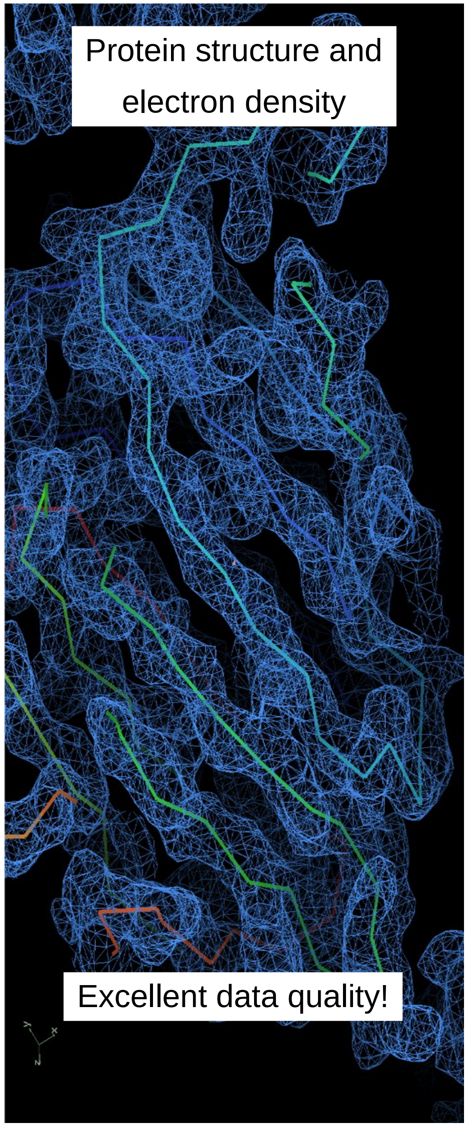
Serial protein crystallography (SFX) experiments at SwissFEL







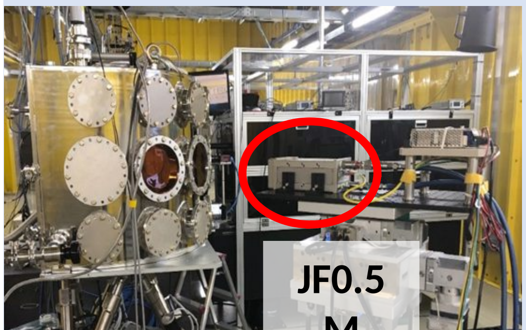


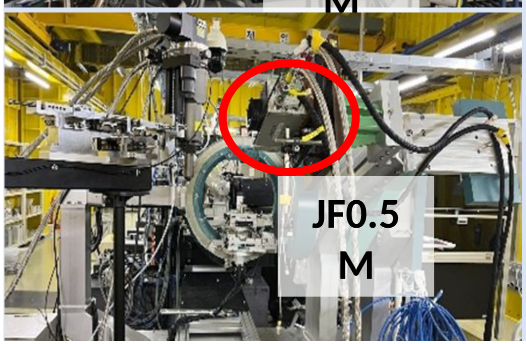


Jungfrau at PAL

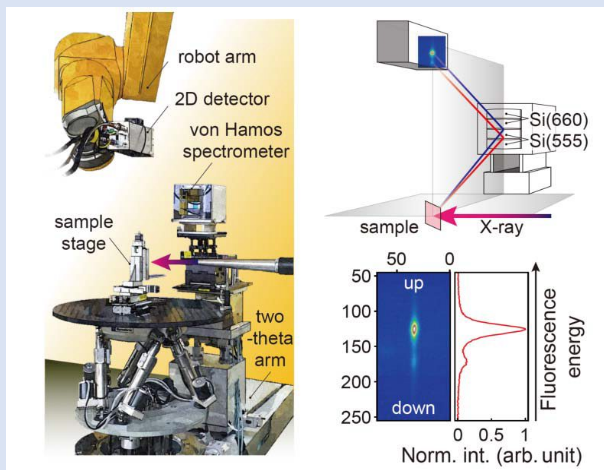
- Pohang Accelerator Laboratory is a Jungfrau early adopter, since 2018
- multiple single modules 2x4M, 1x5M one 16M (in commissioning)

X-ray Scattering





Emission spectroscopy



Tae-Kyu Choi et. al., "Resonant X-ray emission spectroscopy using self-seeded hard X-ray pulses at PAL-XFEL", J. Synchrotron Rad. (2023) 30, 1038–1047

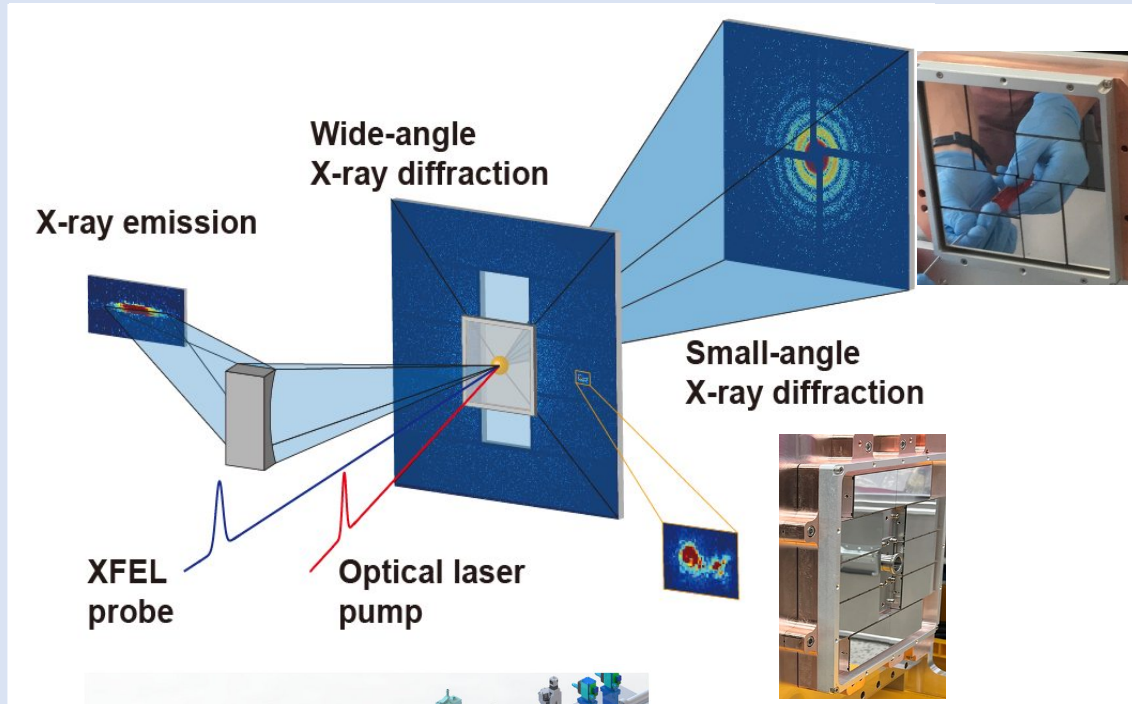
Crystallography

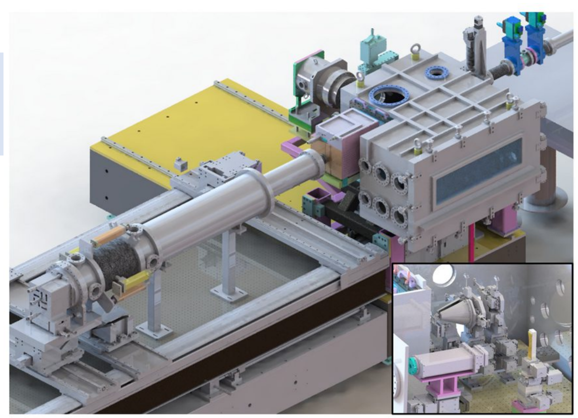
courtesy K.Kim

Jungfrau at PAL

Coherent X-ray imaging

JF5M: Wide-Angle X-ray scattering
JF4M: Small-Angle X-ray scattering
JF0.5M: emission spectrometer



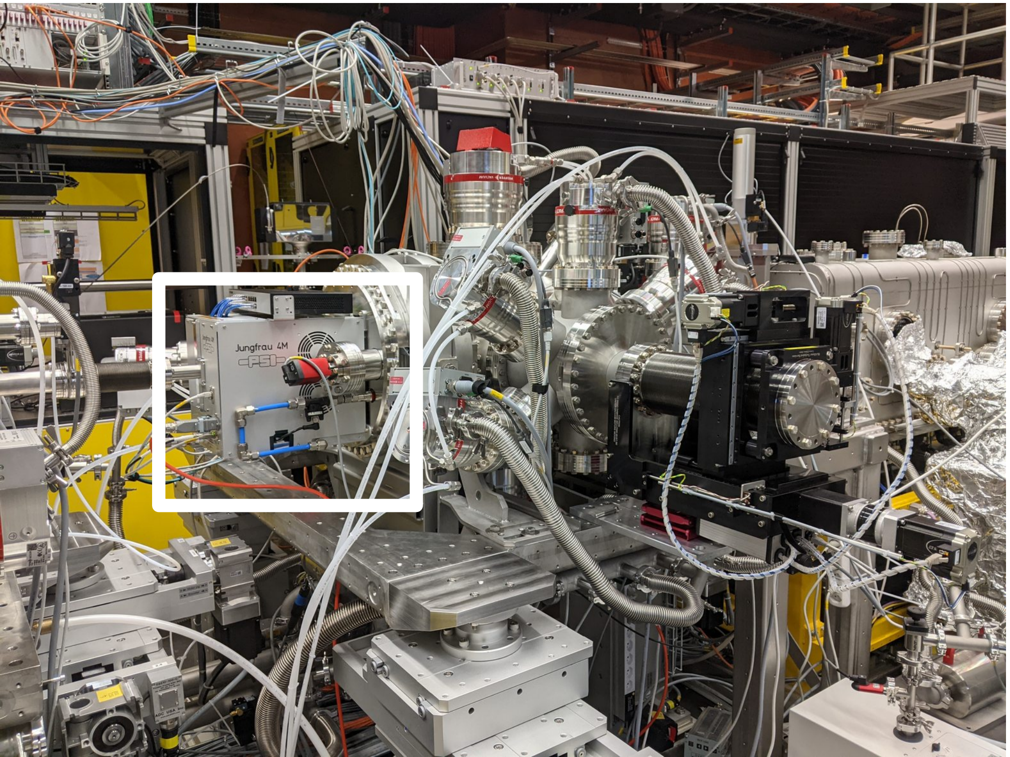


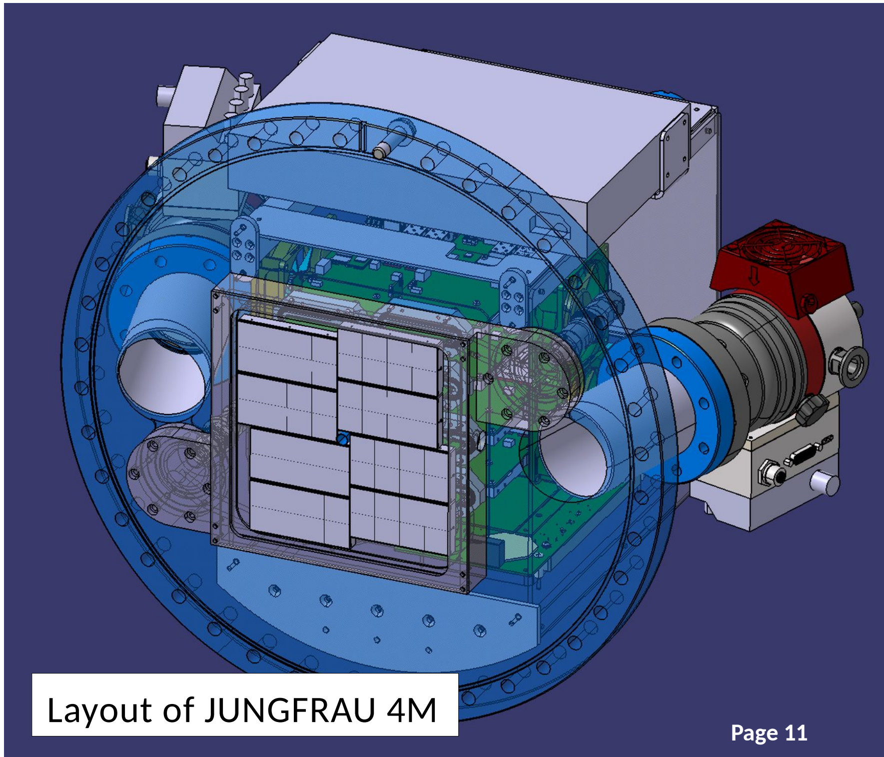
Junha Hwang et. al., "Development of Multiplex Imaging Chamber at PAL-XFEL", J. Synchrotron Rad. (Accepted 3 February 2024)

courtesy K.Kim

Jungfrau for low E: 4M at Maloja

- **Multi-purpose low-energy X-ray beamline** at SwissFEL
- **4M JUNGFRAU** installed
- 6M for larger angles in planning
- In planning for **Furka** end station
- **Commissioning** with xenon cluster target



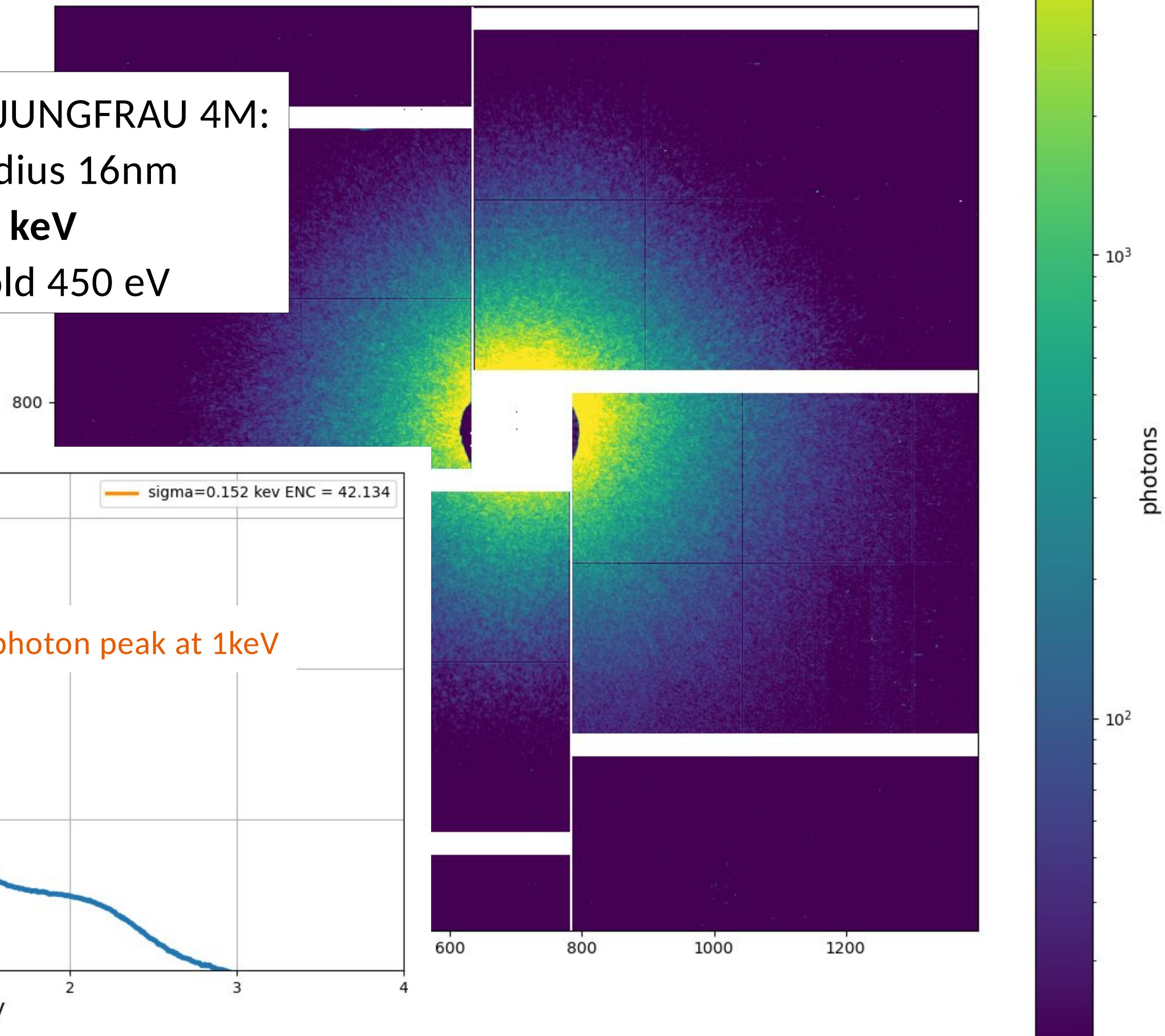


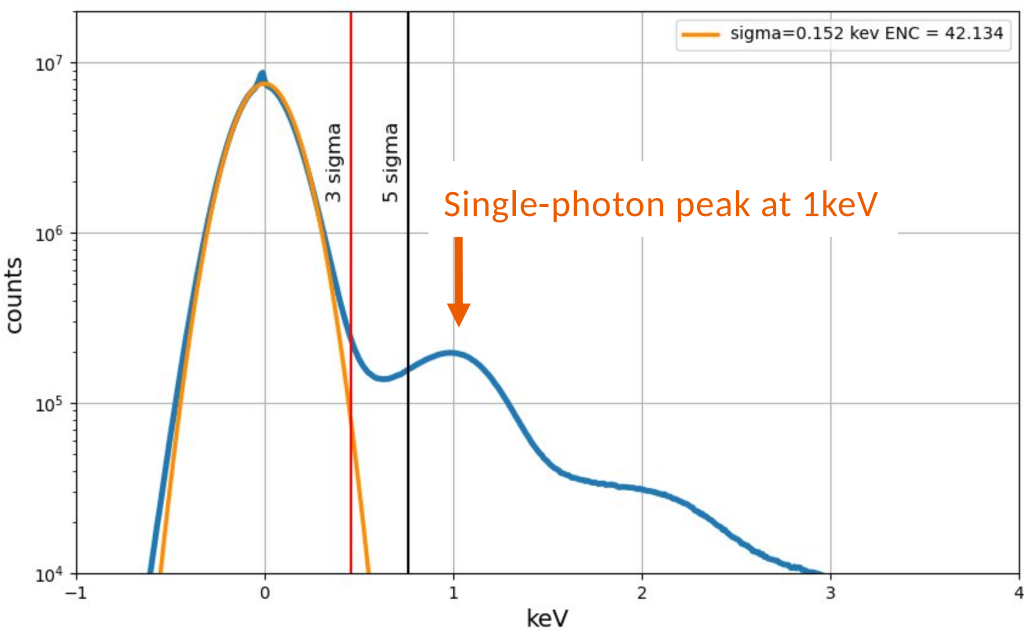
Layout of JUNGFRAU 4M

First results at Maloja

Commissioning of JUNGFRAU 4M:

- xenon cluster, radius 16nm
- **photon energy 1 keV**
- counting threshold 450 eV



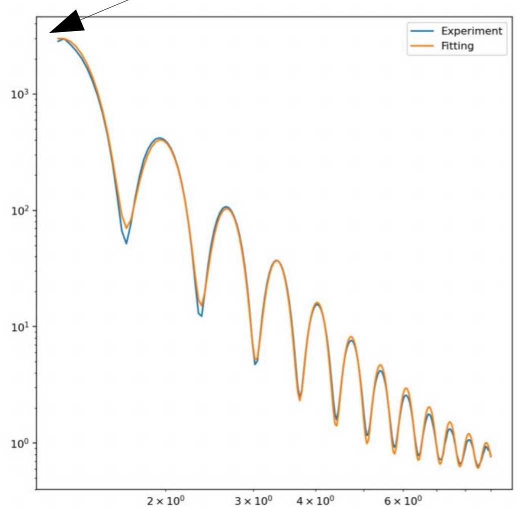


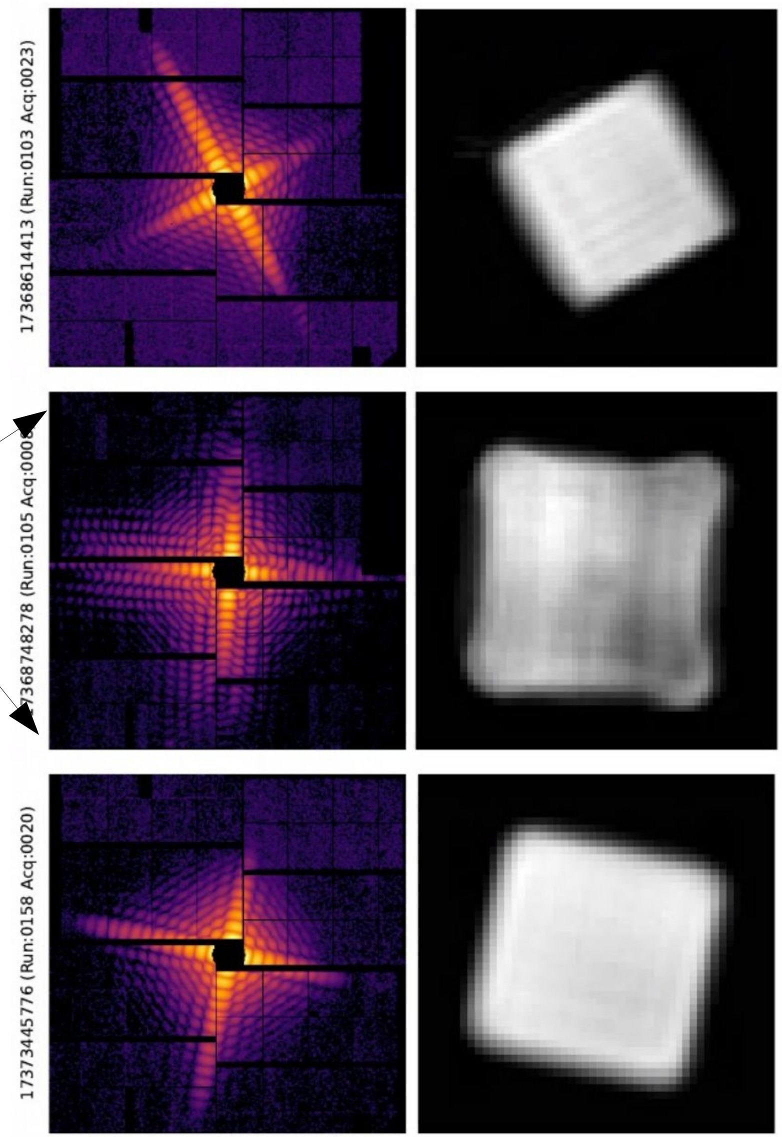
Cumulative energy spectrum in high gain (1000 frames all pixels)

CDI with JUNGFRAU at Maloja

Single particle CDI
photon energy 1 keV

Measurements profit
from detector:
High DR – Large Area



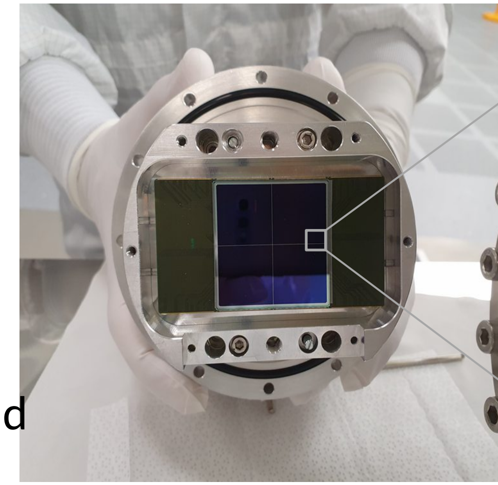


courtesy A.Colombo

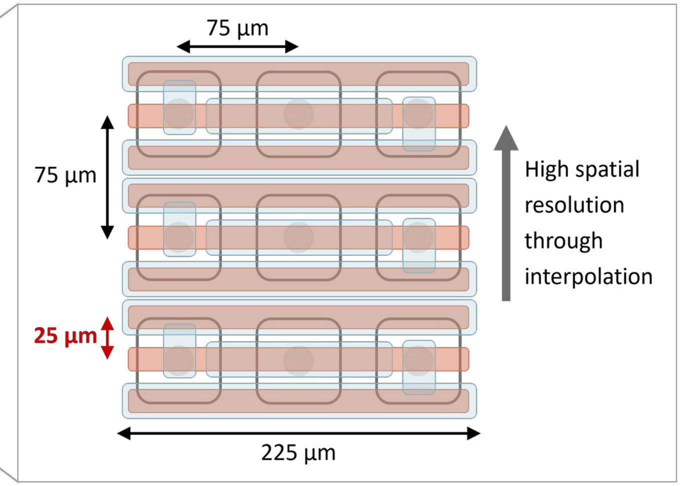
JUNGFRAU for RIXs

- High resolution with strixsel geometry
- Low noise with iLGAD sensors*
- Tested at Furka and hRIXS (EU-XFEL)

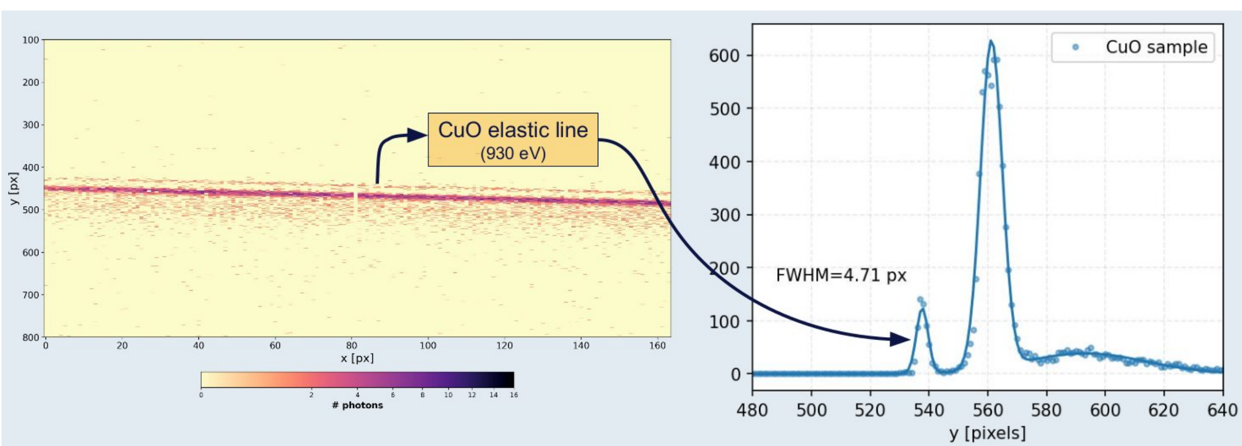
JUNGFRAU-iLGAD module



Rectangular pixels ("strixels")



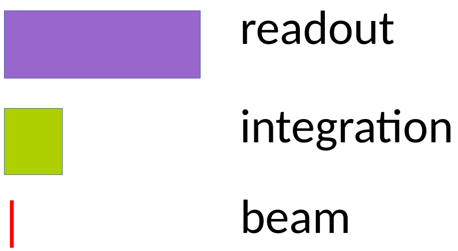
** see Talk from J.Zhang*

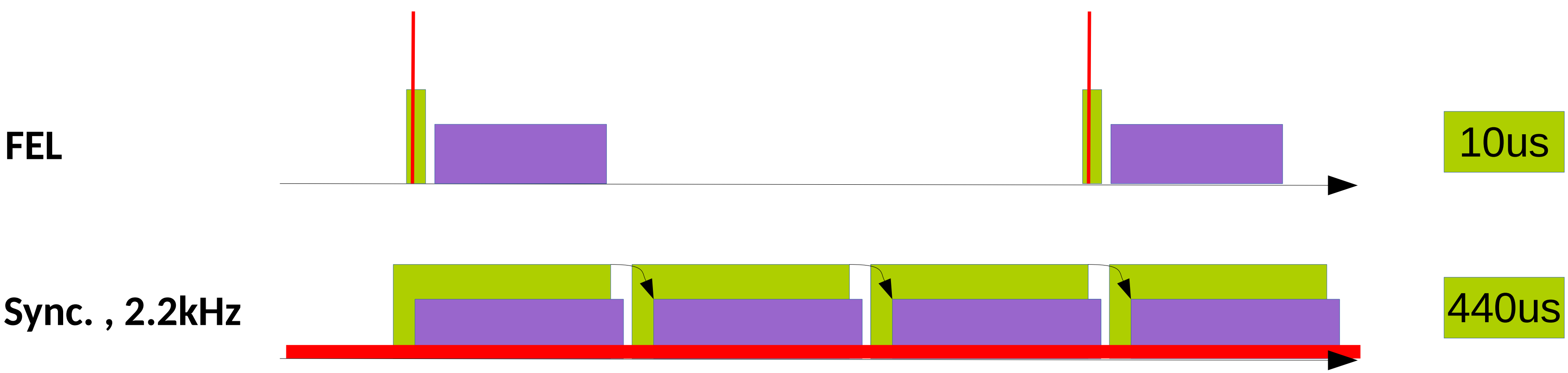


courtesy N.Duarte

JUNGFRAU at Syncrotrons

- Working with a continuous source requires long integration times: cooling to reduce leakage current, noise.
- Forced to work at full speed
- Readout during integration: 96% duty cycle
- As a plus, rate capabilities scale with frame rate
- Noise at 840us integration goes up to 160-200e- r.m.s.
   3keV single photon sensitivity should be possible

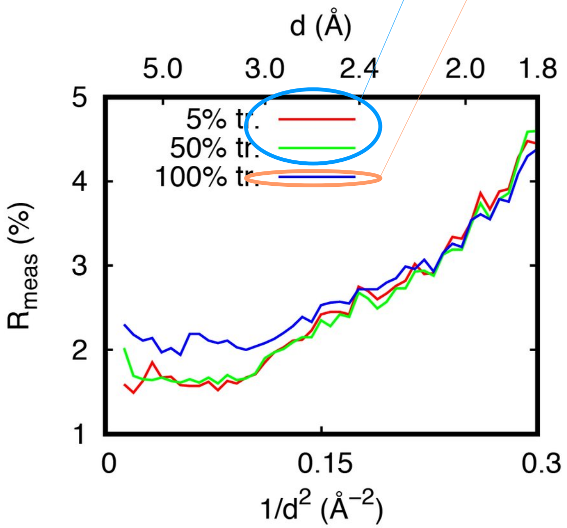




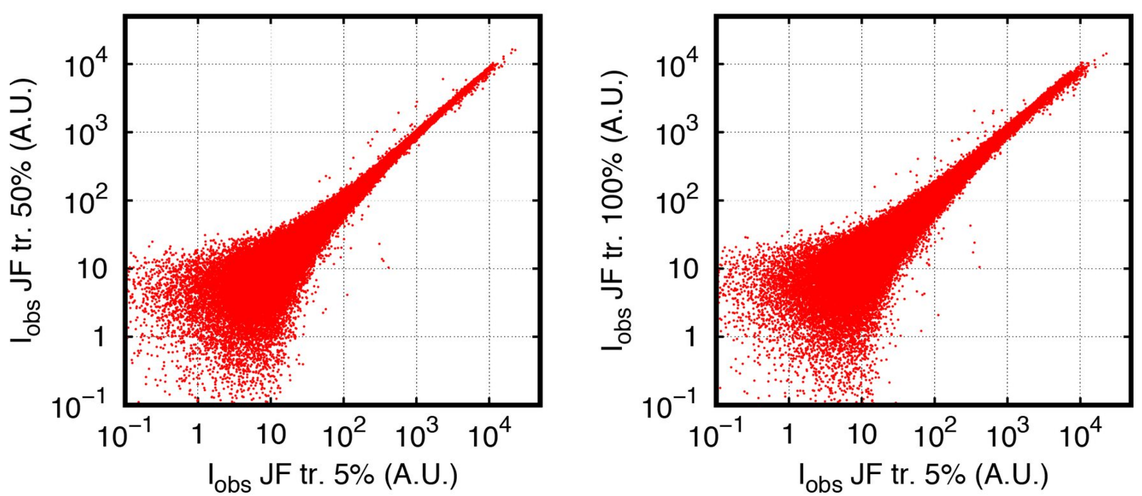
JUNGFRAU at SLS PX

- data quality compares very well with state of the art PC detectors
- It allows fast data collection with strong beam

Data consistency



Integrated intensities



5% transmission with 5 deg/s = 36 second
50% transmission with 50 deg/s = 3.6 second
100% transmission with 100 deg/s = 1.8 second

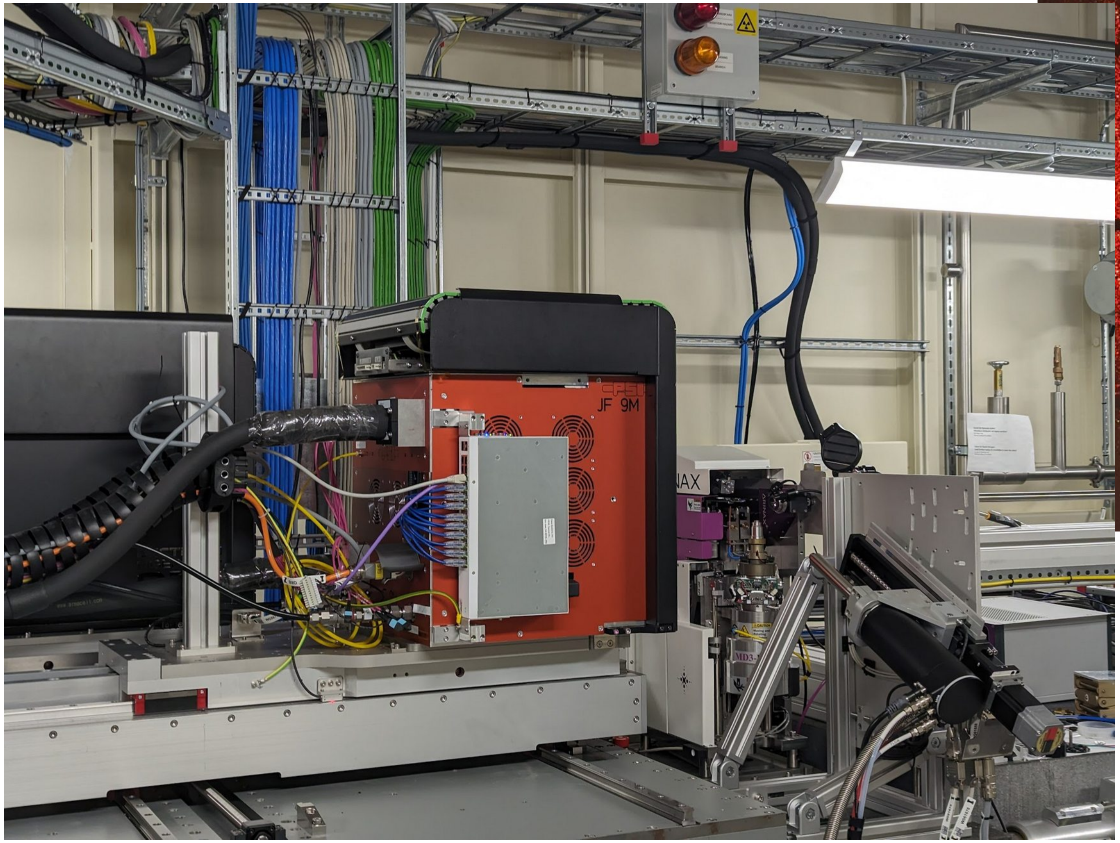
"JUNGFRAU Detector: Accurate Data for Macromolecular Crystallography",
10.1038/s41592-018-0143-7

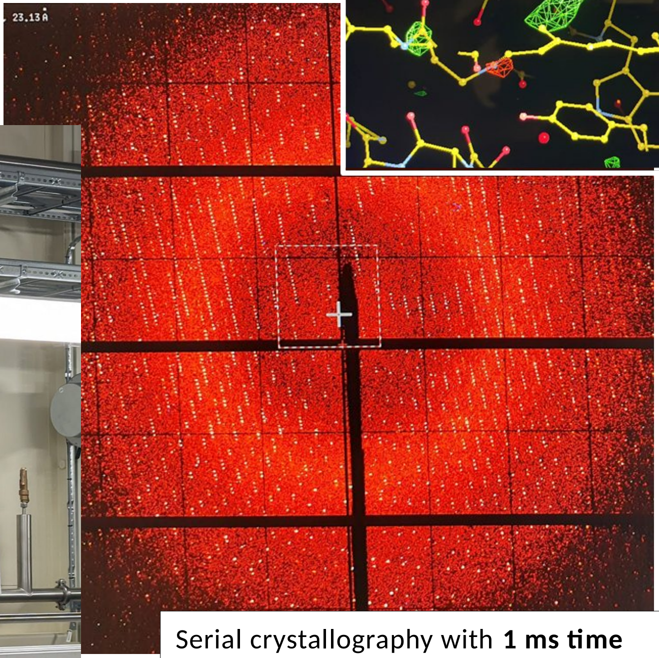
thanks F.Leonarski

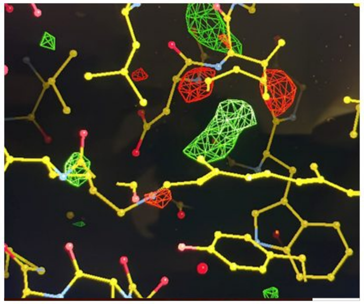
JUNGFRAU 9M at SLS PX*

*temporarily at MAXIV

- 9M detector with isolated dry chamber and warm/cool dual water loop





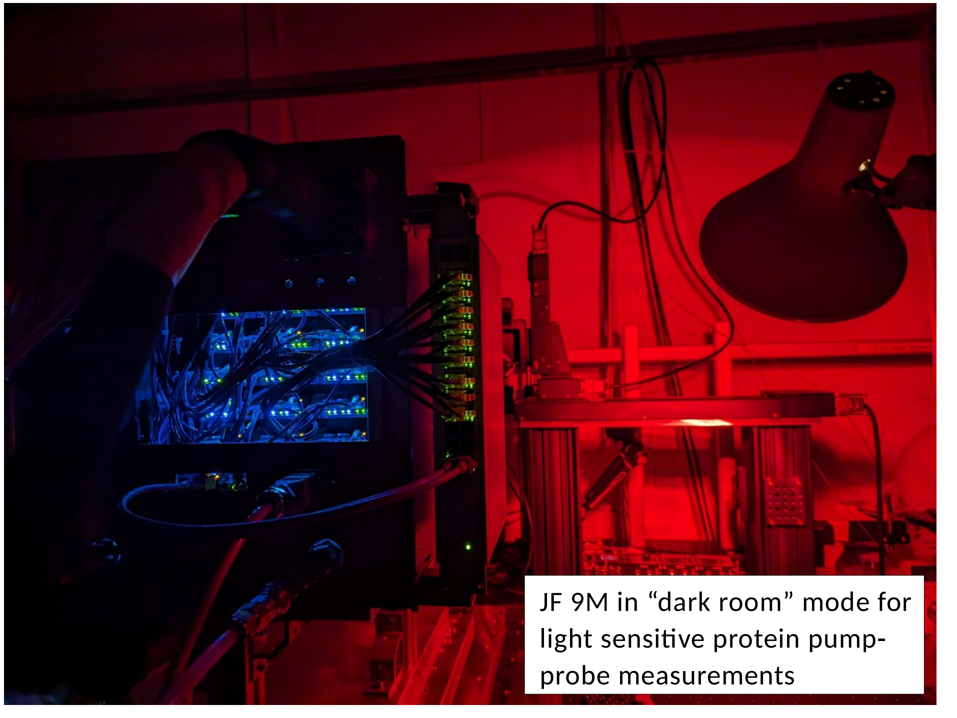


Serial crystallography with **1 ms time resolution** at MAX IV MicroMAX beamline

thanks F.Leonarski
J. Duan

JUNGFRAU 9M at SLS PX

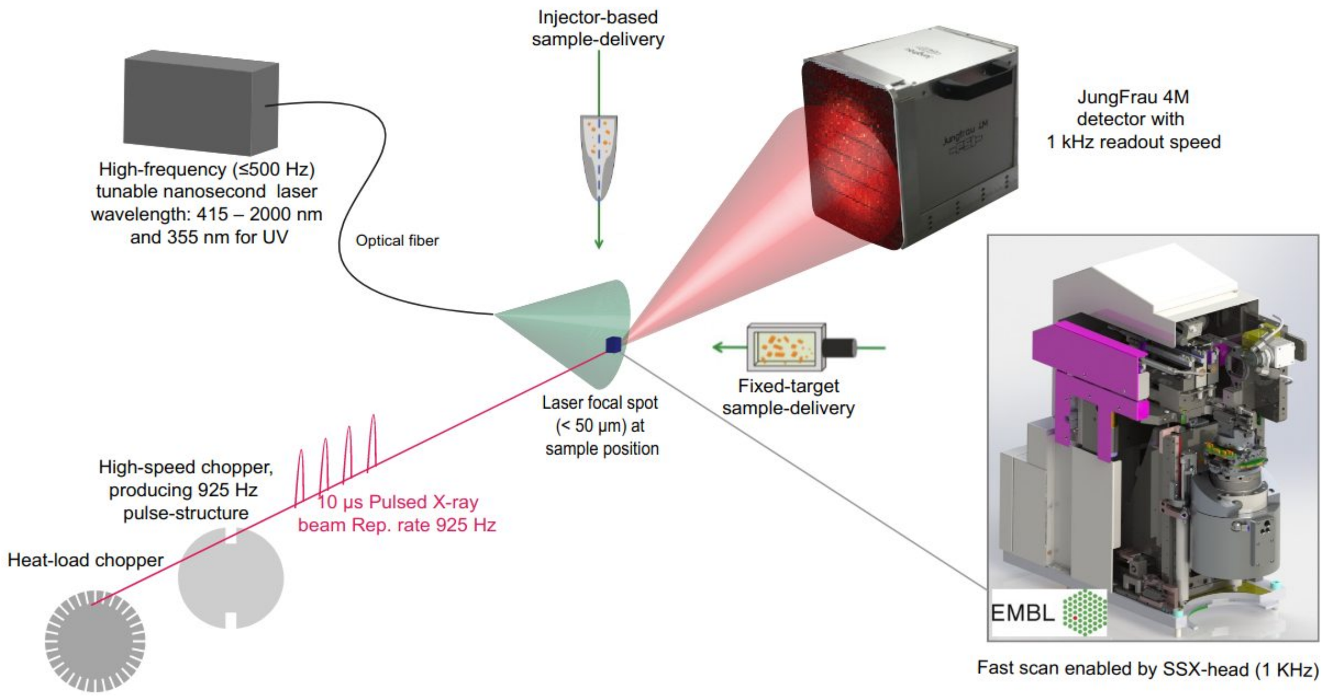
- High rate capabilities allow (with frame rate) to measure structural changes with 500us time resolution at high flux beamlines
- For even higher time resolution storage cell mode has been used



JF 9M in “dark room” mode for light sensitive protein pump-probe measurements

thanks F.Leonarski

JUNGFRAU 4M at ESRF ID29

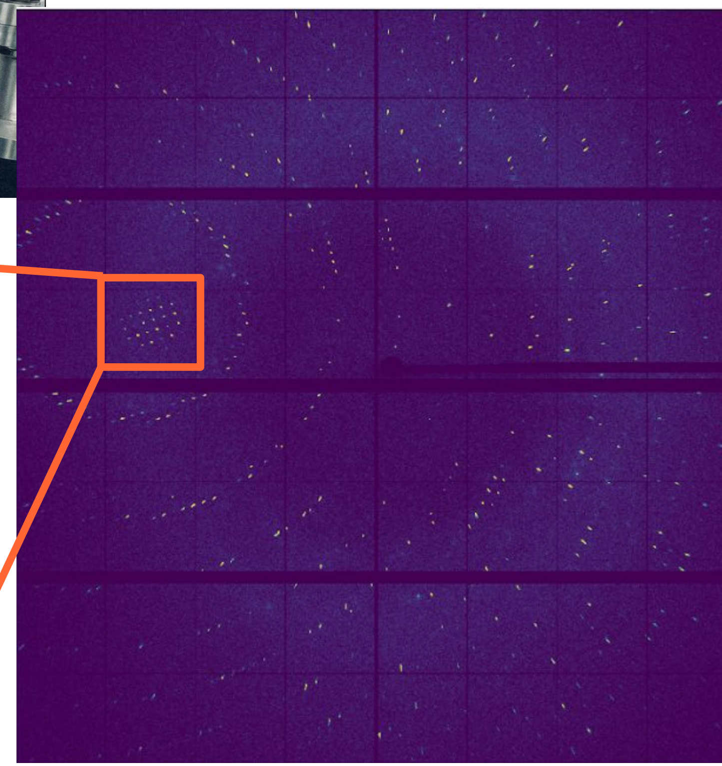


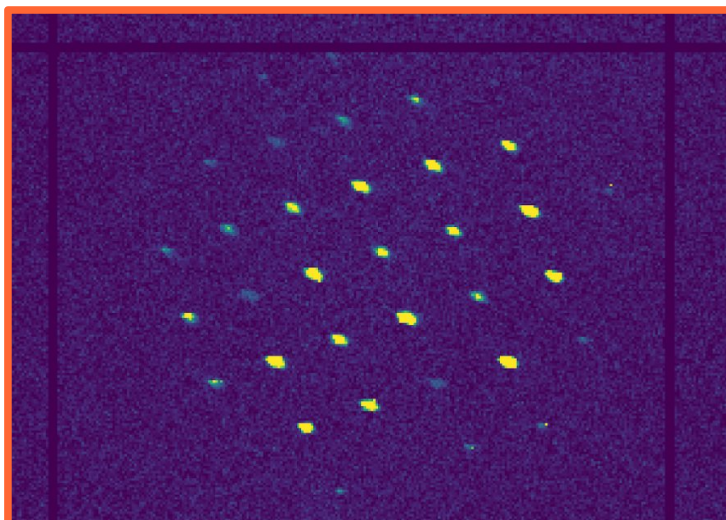
- The **first world beamline** dedicate to Time-resolved Serial crystallography at room temperature
- A completely new way to perform experiment and **novel beam characteristics**
- The beam is pulsed at **231.25 hz**
    - limited by **data transfer rate** and live analysis, sample refreshing
    - Pulse length of **90 us** (**30 - 20 - 10 us**)
    - Beamsize ~ 4 x 2 um
    - ~ **3 x 10^15 ph/s** (~3E11 per Pulse)
- Standard energy is 1**1.56 keV with 1 % bandwidth** and 1.6 Å resolution

thanks D.de Sanctis

JUNGFRAU 4M at ESRF ID29

- JUNGFRAU 4M in operation since 2022

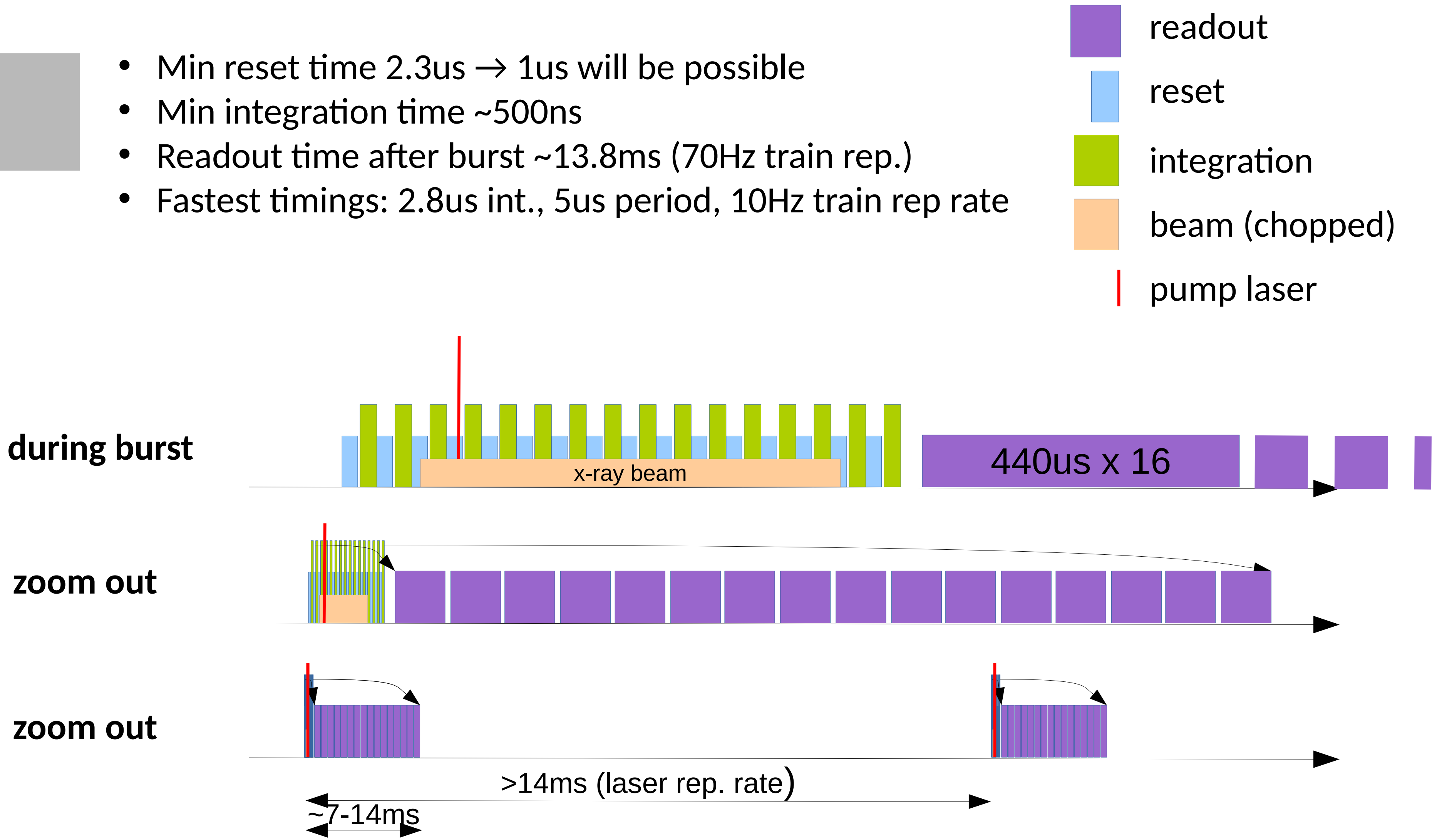




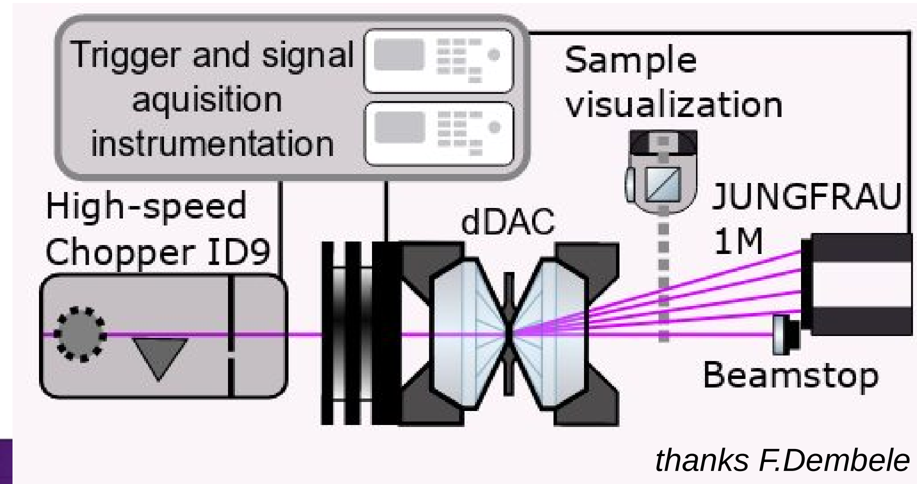
thanks D.de Sanctis

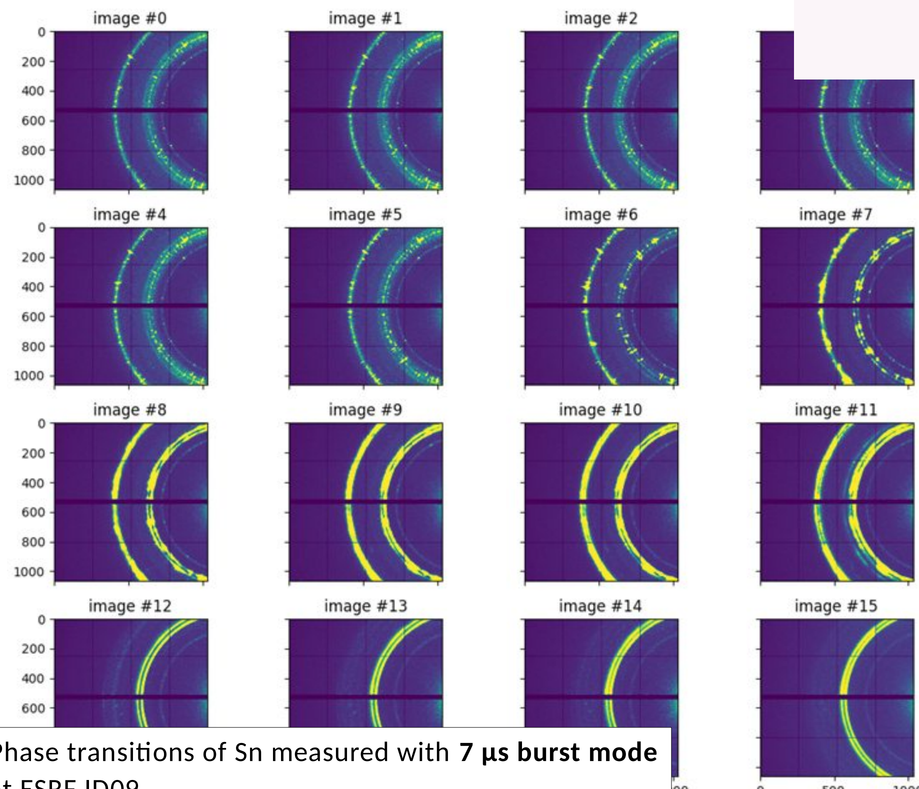
Measuring with storage cells

- Min reset time 2.3us → 1us will be possible
- Min integration time ~500ns
- Readout time after burst ~13.8ms (70Hz train rep.)
- Fastest timings: 2.8us int., 5us period, 10Hz train rep rate



Measuring with storage cells



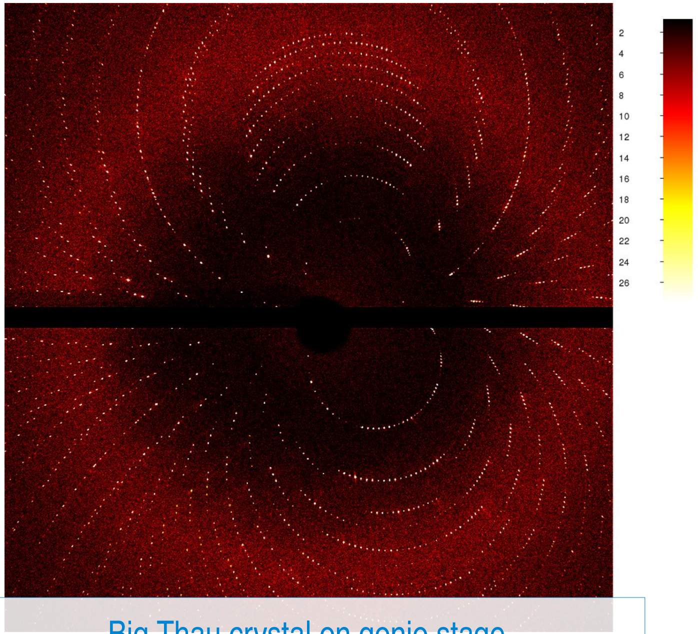


Phase transitions of Sn measured with **7 µs burst mode** at ESRF ID09

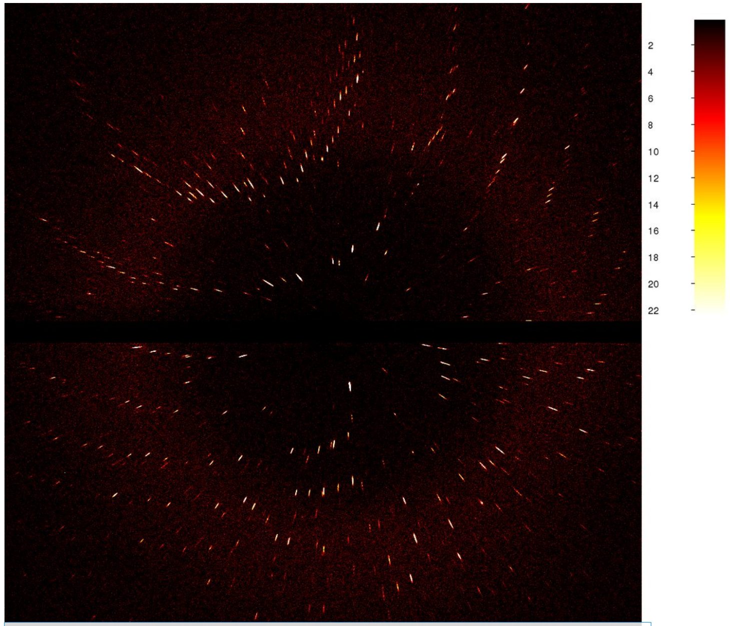
JUNGFRAU with pink beam (chopper)

First serial Xtallography with JF

- Pink beam at APS BioCARS beamline
- full beam transmission
- chopped down to single bunch (or few)
- <10 um beam size
- Makes liquid jet experiments possible at SYNs



Big Thau crystal on gonio stage



Small Lyso crystals in liquid jet

JUNGFRAU with pink beam (chopper)

JF at Synchrotrons: pro and cons

Cons

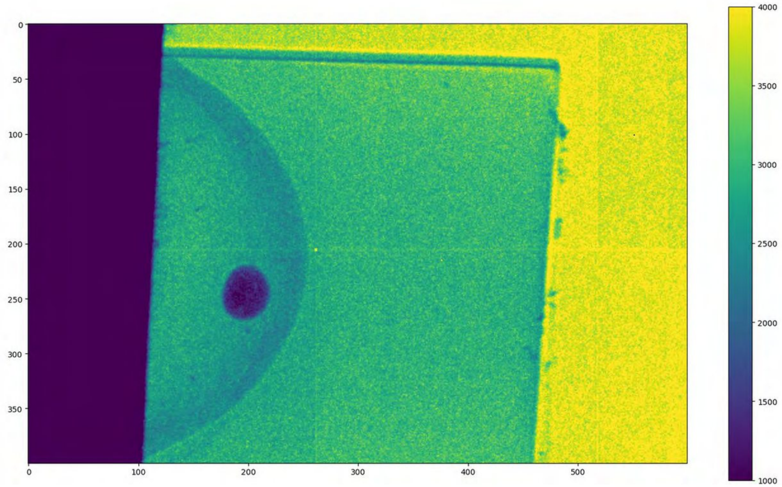
- huge data rates : we have to run full speed, always
    - save raw data not a good strategy on the long run
    - online conversion will require IT resources
- Calibration is more complex
- Pedestals are essential: “frequent” dark collection and temperature control – moderate cooling (<0C) is required
- **Fluorescence suppression at medium/high rates not possible**

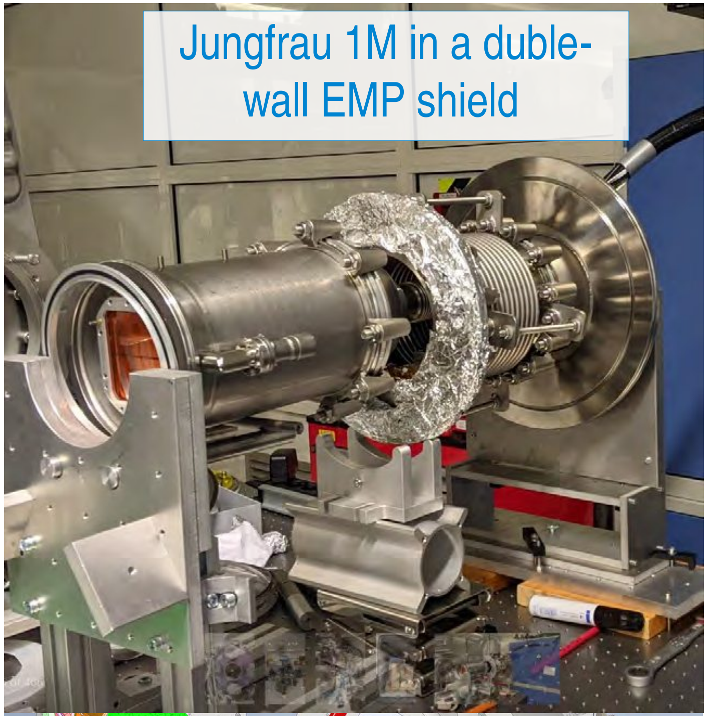
Pros

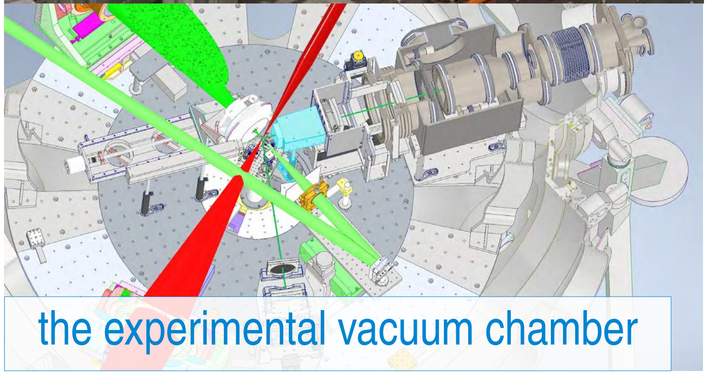
- very high count rate limit: 24Mcps @ 12.4keV, 40Mcps at 8keV
    - can be extended 10x with a DR extension method
    - or even higher if dead time is acceptable
- No “corner effect”
- low energies: single photon resolution at 2.5keV (or lower for short int. times)
- at low flux, JF gives energy information, without Th scan.
- works with strong single bunches, suitable for serial pink beam crystallography

Jungfrau at laser facilities (LULI/PHELIX)

- PW class Laser (rep rate O(1/h)) on W or Cu wire as source, split beam as "pump"
- Sample projects image onto detector
- Strong EMP produced – shielding required (Be entrance window)
- Signal can be strong, 100s ph./pulse middle gain
- Game changer with respect to image plates!



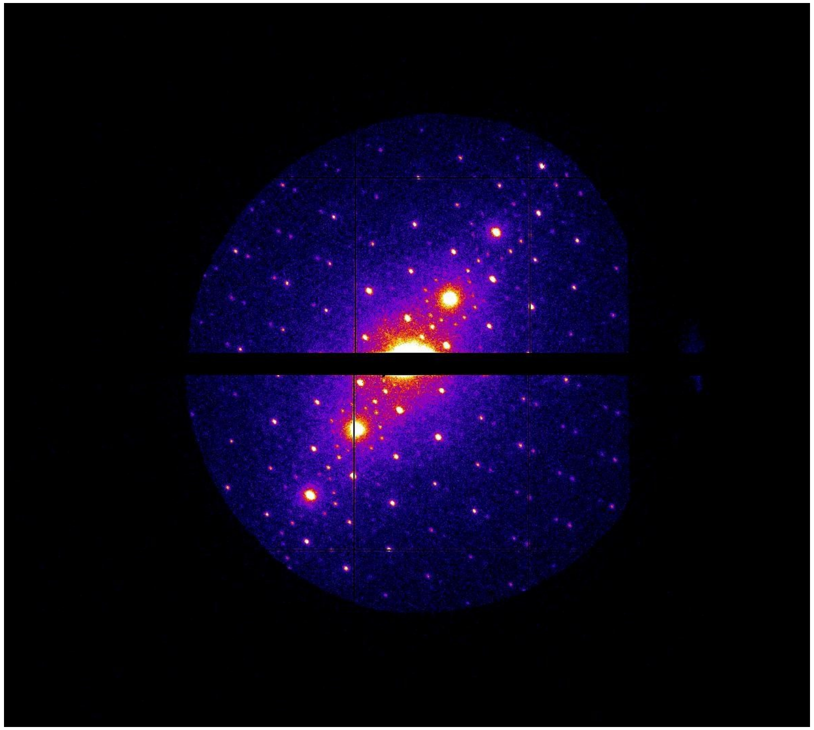


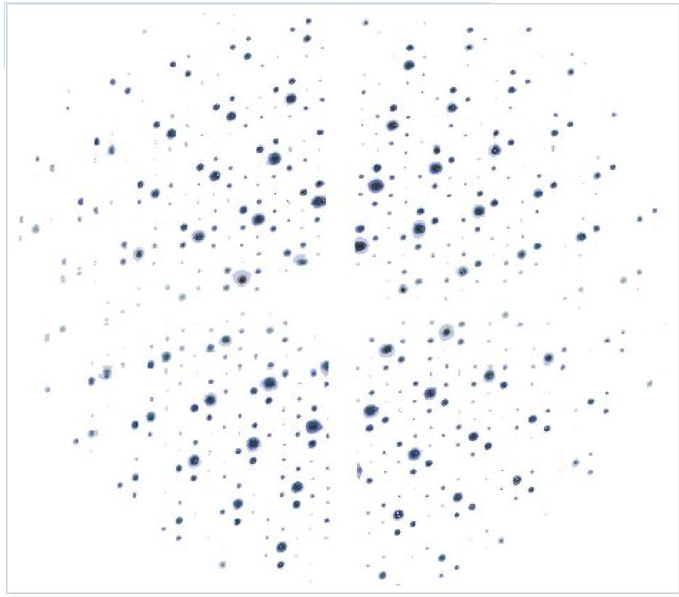


courtesy S.Schreiner 10.1063/5.0160120

JUNGFRAU at electron facilities

1M vacuum JUNGFRAU System installed
at REGAE facility,
DESY, Hamburg
Diffraction from 3MeV electrons.





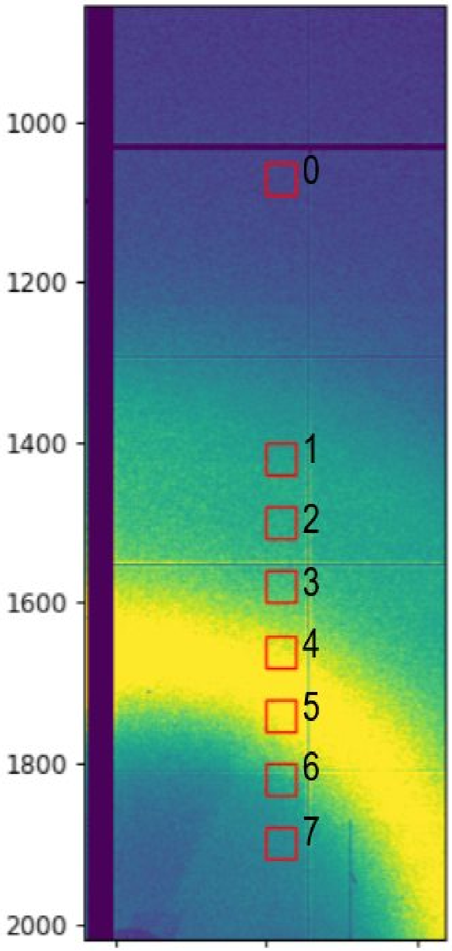
3D reciprocal space representation of the hexagonal 1T-TaS_2 super lattice from REGAE diffraction data (a= 12.1 Å, c=17.6 Å).

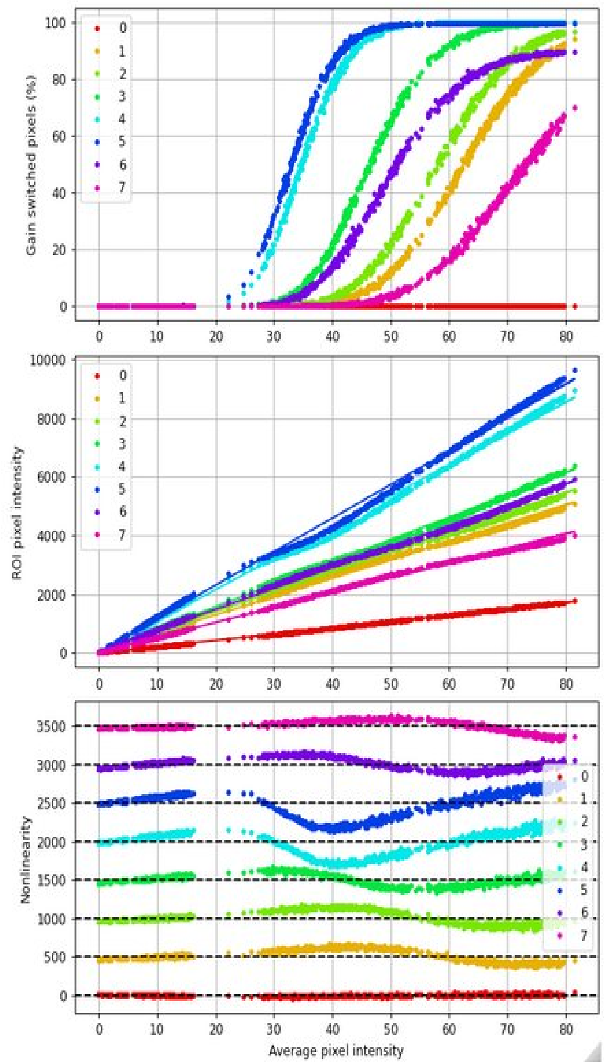
courtesy A.Meents

A perfect detector?

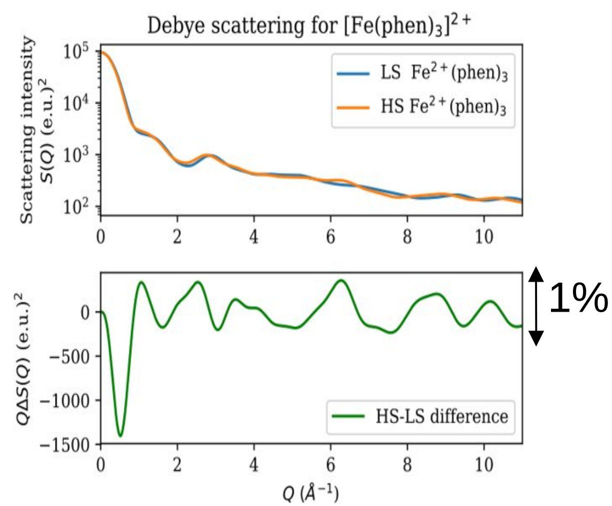
courtesy A.Meents

JUNGFRAU non-linearities at switching points





- data from SwissFEL Bernina enstation
- Intensity fluctuations up to 100%
- Small changes (<1%) within an intense diffuse signal
- Non-linearities at the switching point prevent proper data collection
- Fixing gain 1 as stop-gap solution

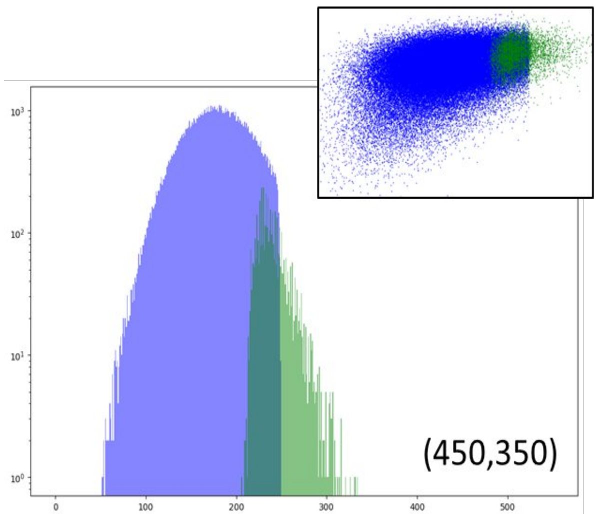


JUNGFRAU non-linearities at switching points

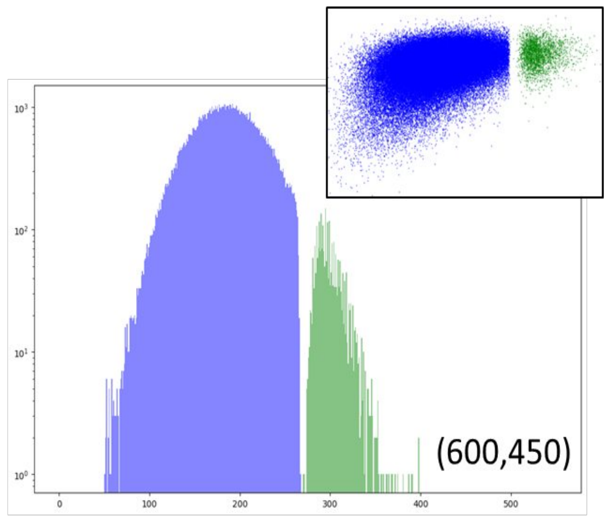
JUNGFRAU Anomaly

- **Linearity issue in gain switching region**

  - need to correct the offsets

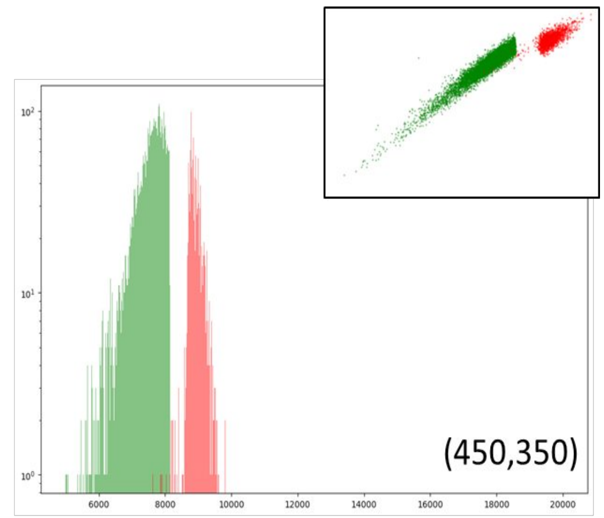


Calibrated ADU of JUNGFRAU



Calibrated ADU of JUNGFRAU

High – Medium gain switching

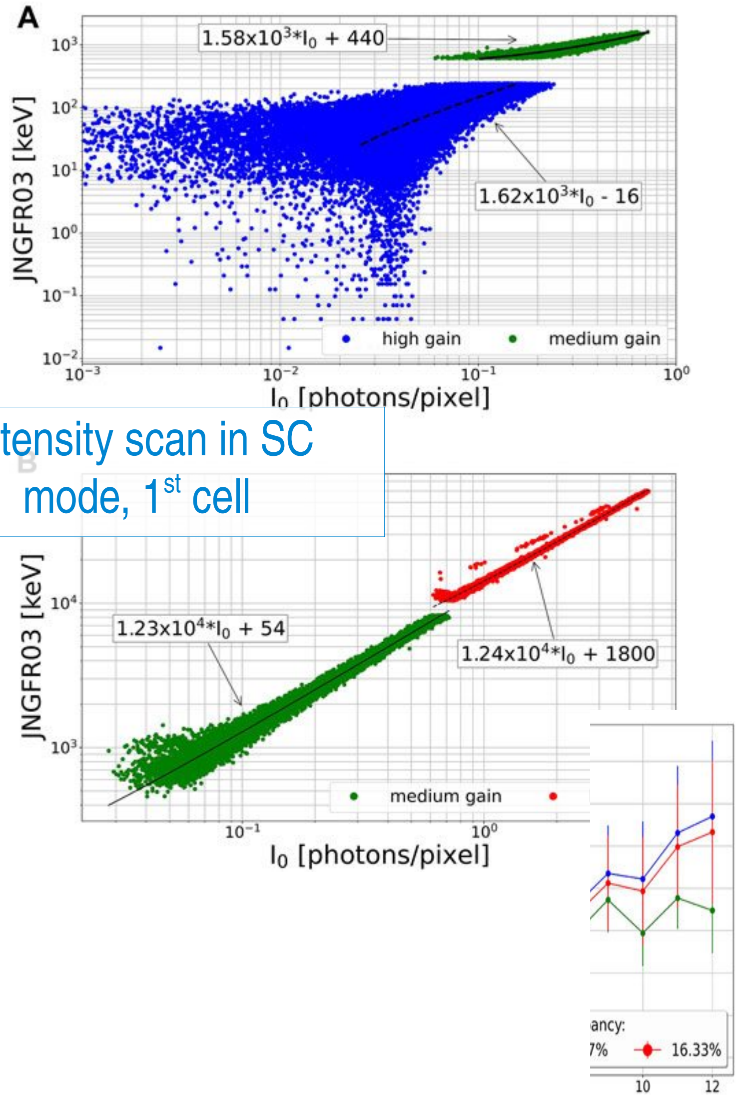


Calibrated ADU of JUNGFRAU

Medium – Low gain switching

courtesy K.Kim

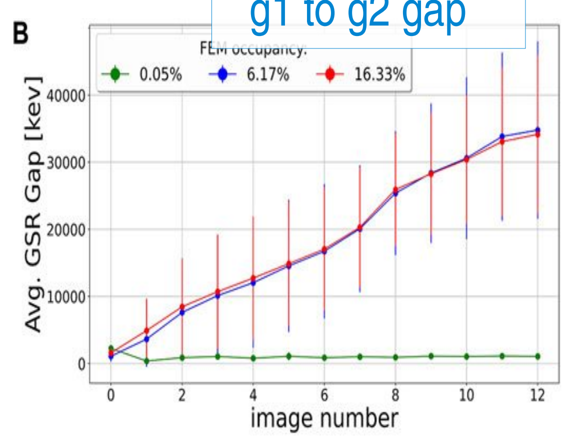
JUNGFRAU storage cell issues@EU-XFEL



intensity scan in SC mode, 1st cell

- in storage cell mode the gaps are more pronounced
- effect changes with occupancy
- without close loop correction data is unusable
- Fixed gain1 proved to be a workaround in many cases.

g1 to g2 gap



10.3389/fphy.2023.1303247

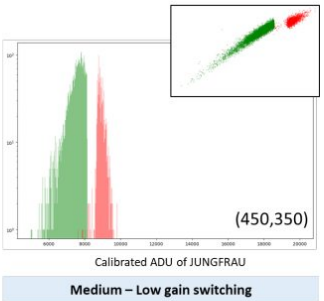
courtesy M.Sikorski, M.Ramilli

we are not alone..

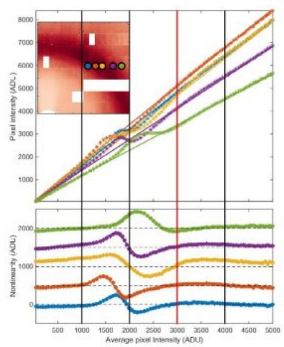
Detector anomalies (gain switching, etc.) **-Discussion outcome**

Detectors continue to be a challenge, despite a decade of XFEL use.
Gain-switching is particularly challenging. Gain-selection > Gain-switching but may not be viable for higher repetition rates. Necessary for high dynamic range to address the extremely diverse science cases.

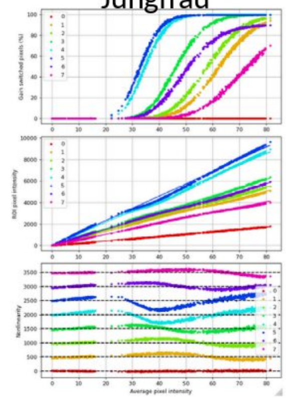
PAL-FEL
Jungfrau



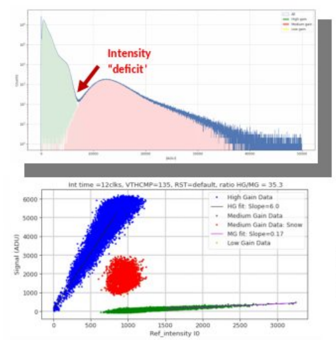
Eu-XFEL
LPD



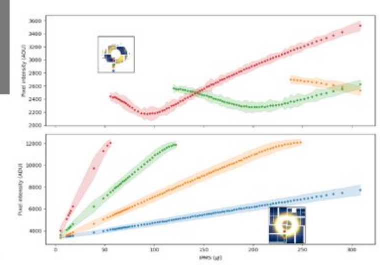
SwissFEL
Jungfrau



Eu-XFEL
AGIPD



LCLS
ePix10k2M

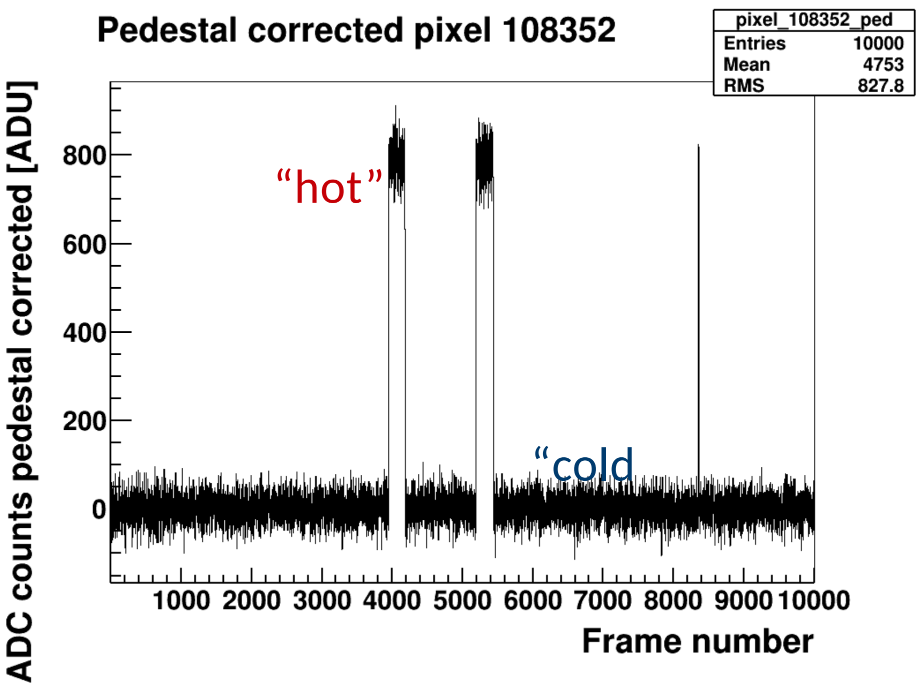


Representatives:
Tim van Driel (LCLS)
Kyung Sook Kim (PAL-XFEL)
Marcin Sikorski (EuXFEL)
Takaki Hatsui (SACLA)
Jakub Vonka (SwissFEL)

Summary slide presented at 5way meeting last summer.
Courtesy Tim van Driel (LCLS)

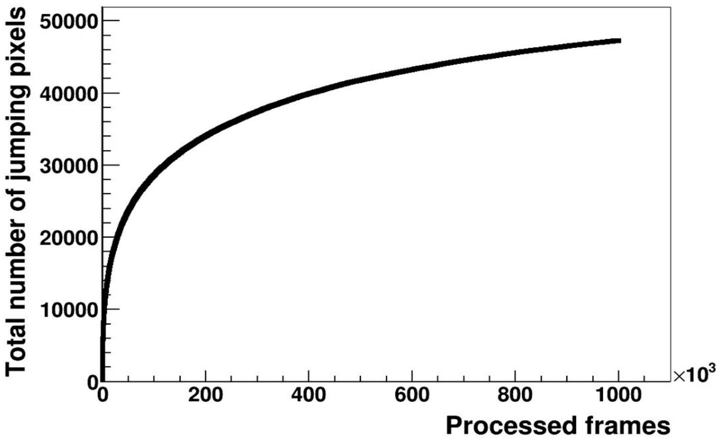
„Jumping“ pixels

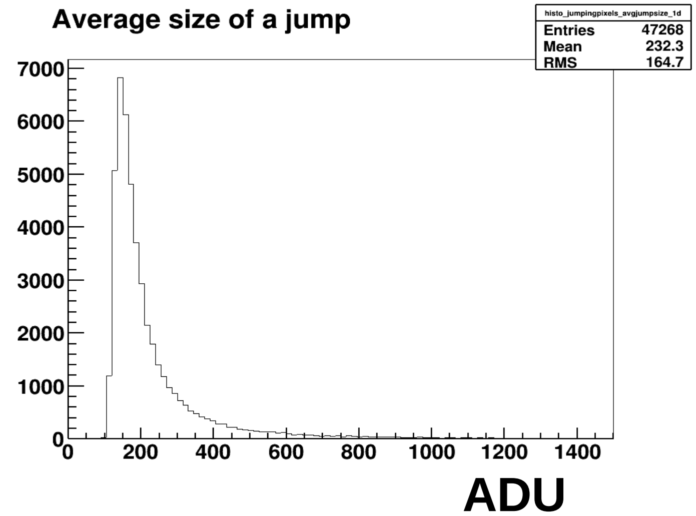
- a few pixels (<1%) show this long term 2 step behavior
- Step size continuously distributed
- Step size scales with integration time – plot for 1ms
- step size scales with amplifier gain
- Does not improve with temperature (but occupancy of “hot” and “cold” might changed)
- In the (extreme) case of this plot the step corresponds to two 12keV photons and a current ~pA at pre input.

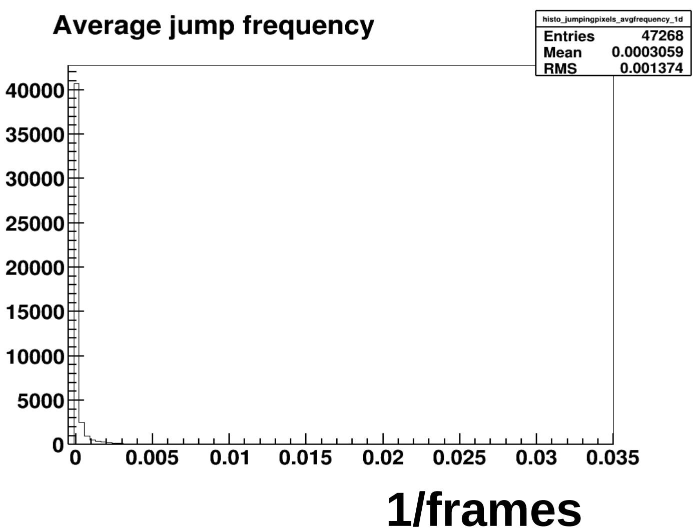


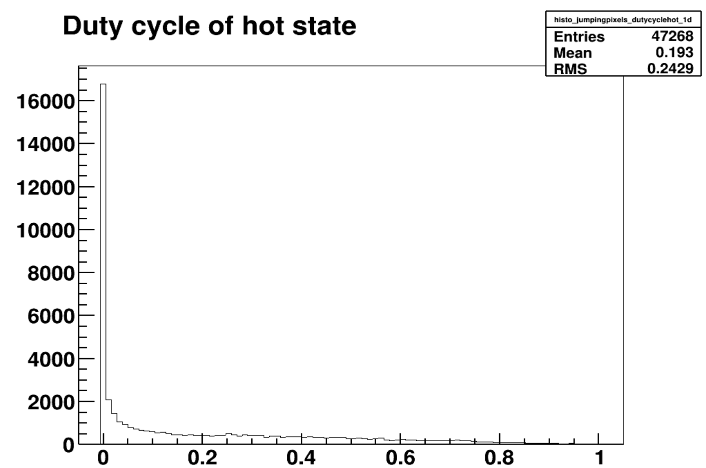
- Mitigation: pixel mask
- at FEL timings (expose<100us) this is completely negligible

„Jumping“ pixels – statistics for a 4M









How can we improve – JF 1.2

- many problems we see can be interpreted as deviation from linear behavior of the amplifier references and of the readout chain
- deviations become bigger when ASIC is operated at boundary conditions, e.g. pedestal g1/g2 collection

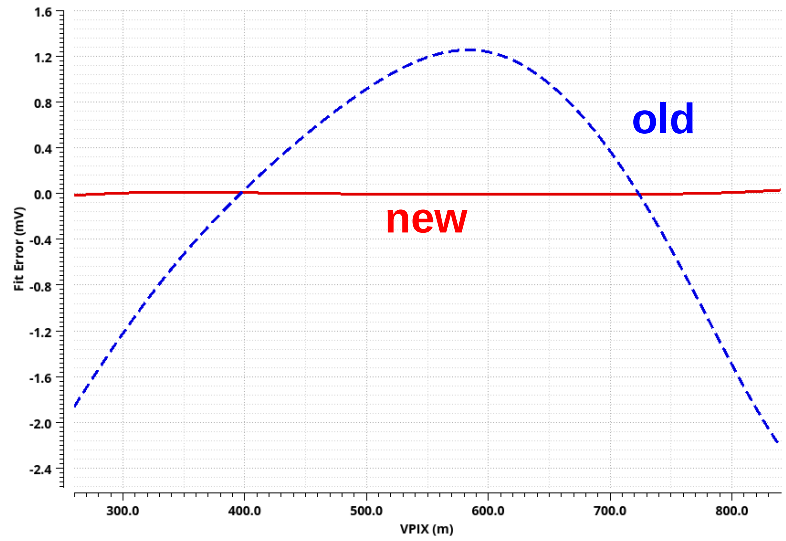
- the readout chain has been completely reworked
- more robust voltage delivery: buffers buffers buffers!

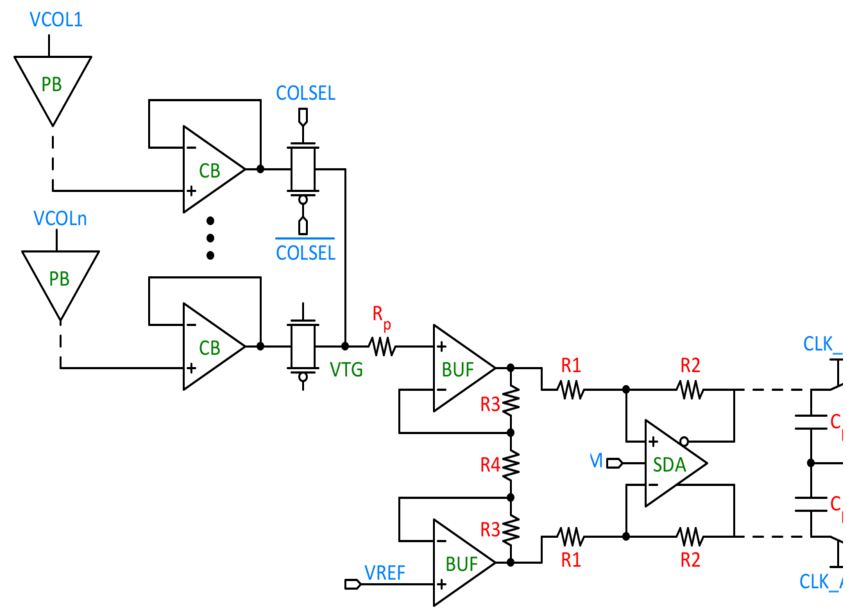
Bonus: improving linearity simplifies gain calibration and improve calibration data quality

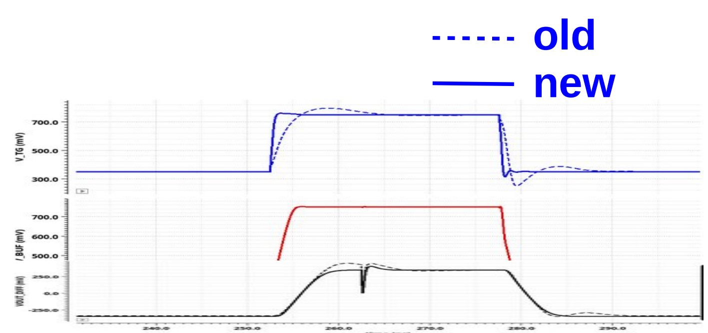
JF 1.2 vs JF1.0: Linearity

- Readout chain linearity massively improved
- dynamic performance at 40MHz also improved. Settling time allow (theoretical) 65MHz
  - this simplify the ADC phase window setting at system level

non linearity of readout chain







off chip transient at 40MHz, full swing

JF 1.2

Additional improvements

- low noise mode as JF1.1
  - 35e- rms expected
- (unoptimized) electron collection mode
- 16 storage cells
- digital comparator disable (avoids late switching)
- internal current source strength can be selected
- flexible

JF 1.2 ASIC ready for tape out

JF 2.0 towards higher frame rate

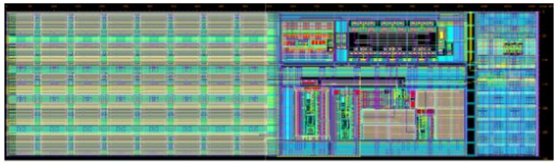
- 10kHz frame rate target
- On chip ADCs
  - preliminary specs:
  - 12b 10Ms/s
  - every 8 columns

- High speed serializers and transceivers for off chip communication
  - 1.5 GHz PLL
  - 3.125 Gb/s
  - 64/66b encoding

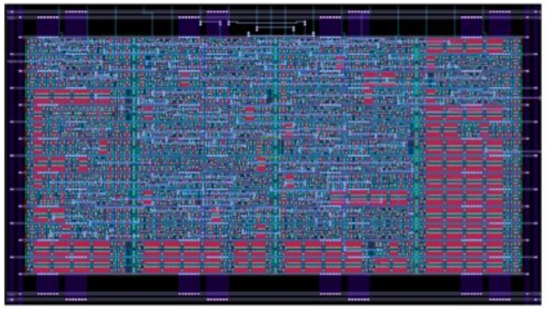
- Requires complete back end and DAQ redesign → Matterhorn readout board.

- On the FE side, we are evaluating:
  - lower noise at long exposure times
  - higher DR for FELs (4x higher)

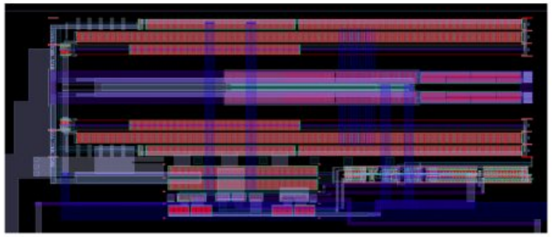
PLL



Serializer



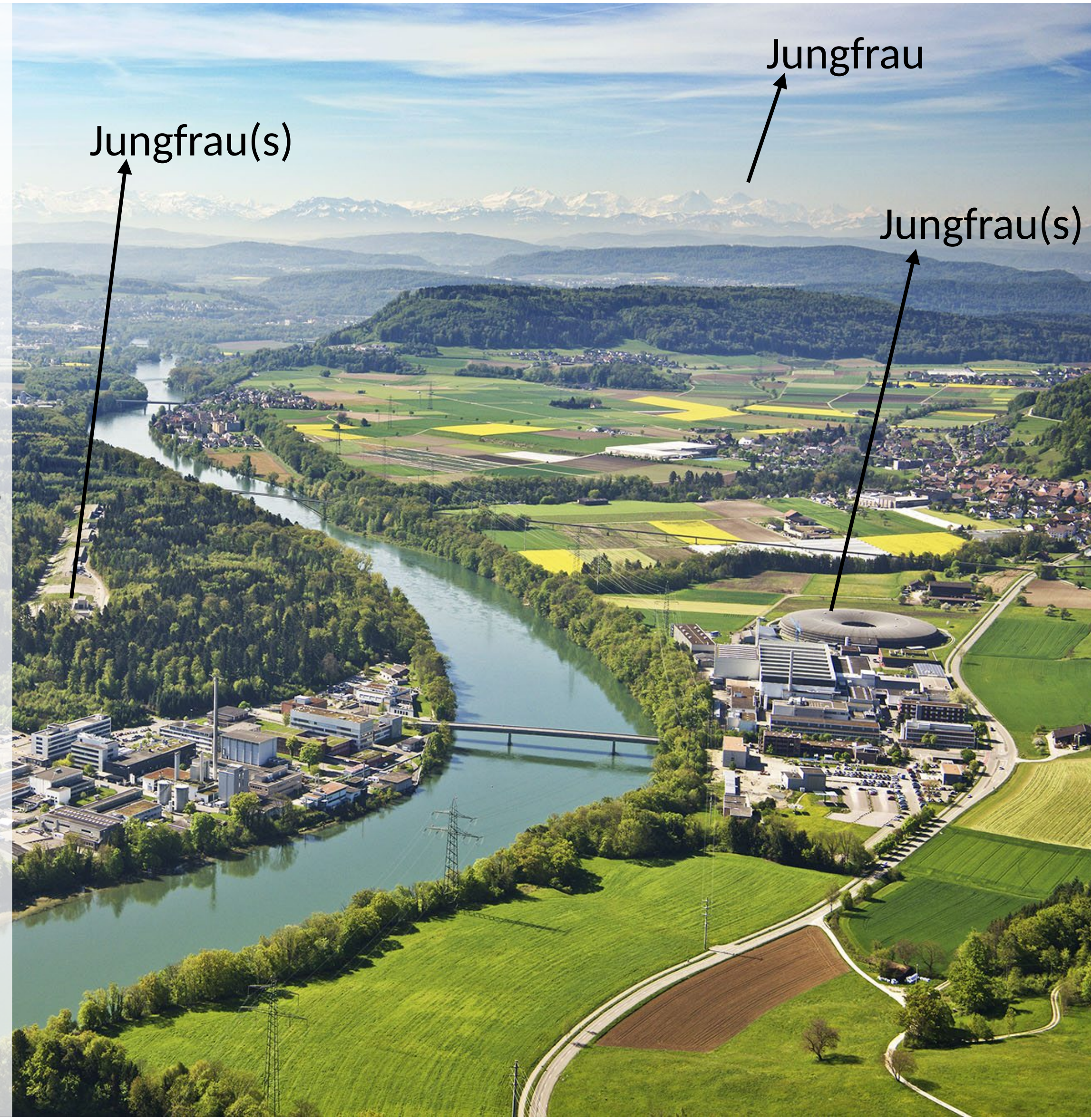
CML driver



Conclusions

- the JUNGFRAU pixel detector developed for SwissFEL, is in use at FELs and Synchrotrons worldwide

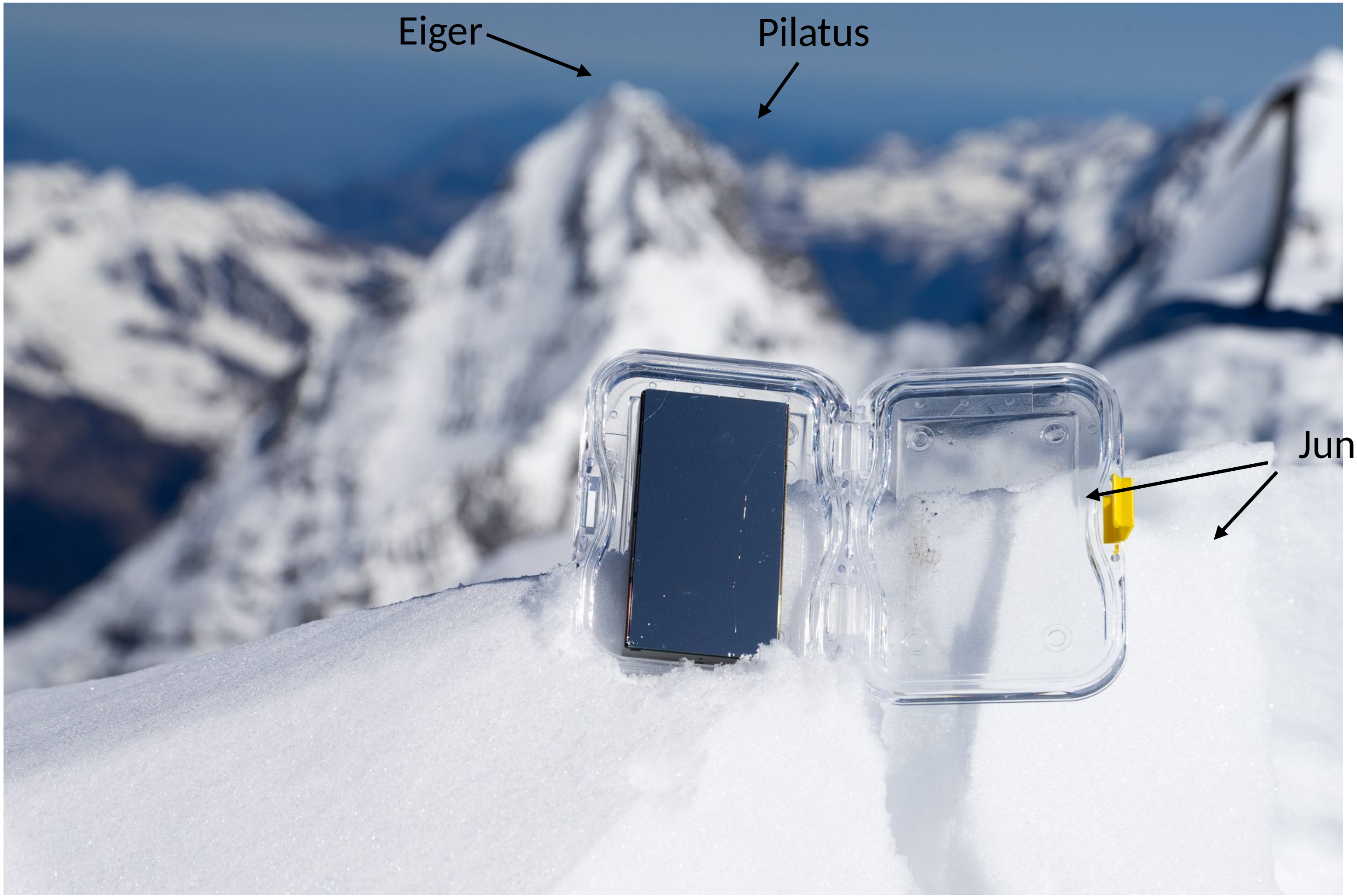
- ASIC and system issues which mostly impact users have been identified and (mostly) understood
- A new ASIC addressing these issue is under way.
- Higher frame rates will be achieved down the road



Acknowledgements

Back: **Marie Ruat**, Bernd Schmitt, **Sophie Redford**, **Aldo Mozzanica**, Erik Fröjdh.
Middle: Jiaguo Zhang, **Carlos Lopez**, Marie Andrae, Rebecca Barten, **Martin Brueckner**, **Christian Ruder**, Dominic Greiffenberg, **Seraphin Vetter**.
Front: Xintian Shi, **Dhanya Thattil**, Gemma Tinti, Anna Bergamaschi, Marco Ramilli, Roberto Dinapoli, Davide Mezza.
Not in pic: Sabina Chiriotti

Jungfrau on top of Jungfrau



Backup Slides

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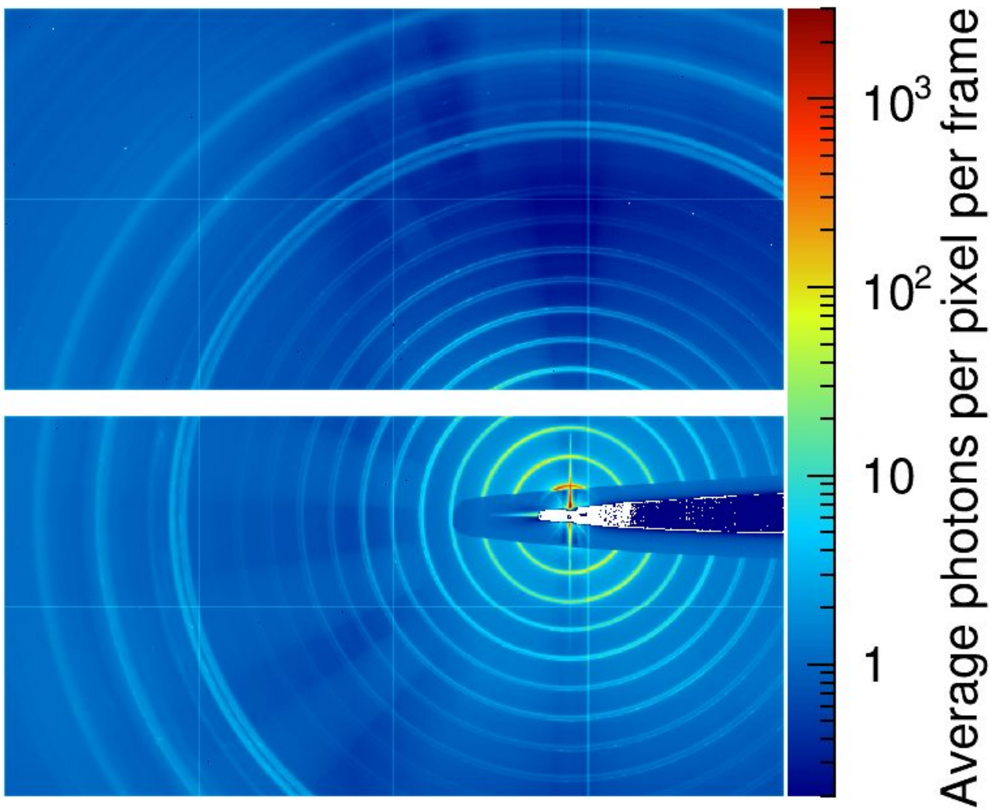
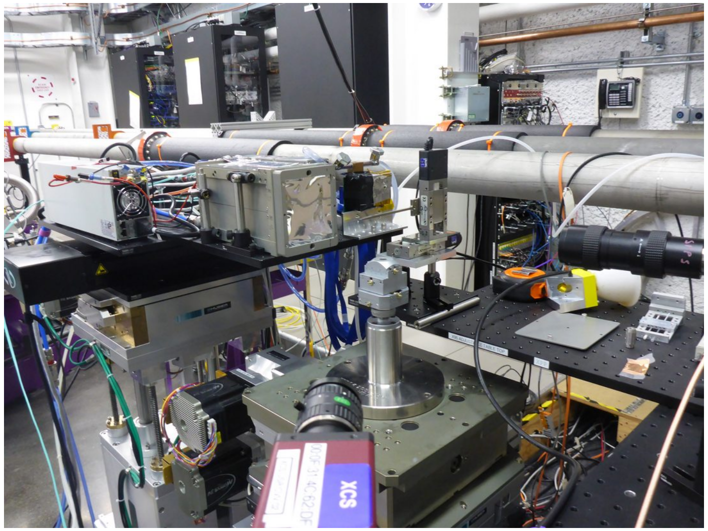
Specification summary

ASIC technology	UMC110nm
mudule pixel count	525k
mudule size	80x40 mm^2
sensor thickness	320-500 μm
pixel size	75x75 mm^2
dynamic range	up to 10^4 12keV photons
noise r.m.s.	50 e.n.c.
min Energy	1.5 keV
linearity	better than 1%
point spread function	1 pixel
dead time	<500ns
ext. power consumption	30 W /module
cooling	liquid @ e.g. 10^0C
readout time = 1 / frame rate	2.4kHz with 2x10GbE
rate capability @ syncrotron (with 10GbE)	10^4 x 2.4 10^3 = 2.4x10^7 photons per ch. per s

JUNGFRAU at LCLS - September 2016

Silver behenate (AgBe) powder measurement
- full beam transmission
- 9.5 keV photons
- 10-15 um beam size



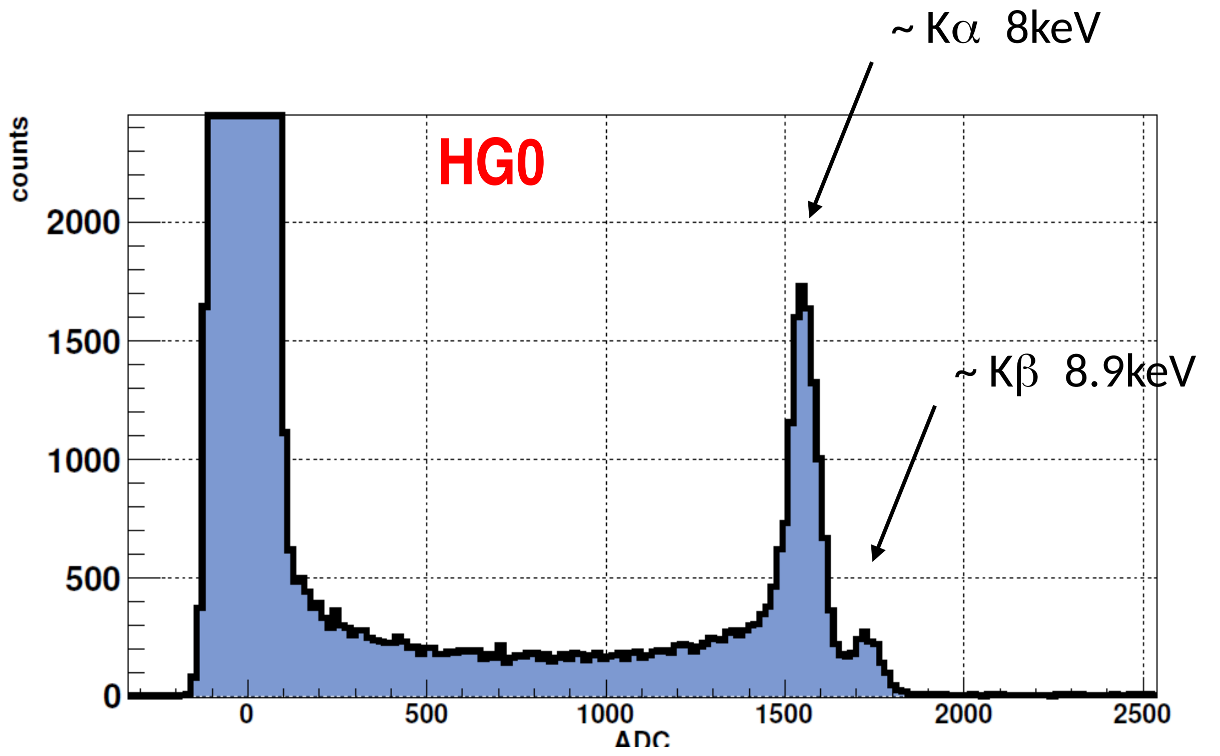


Two JUNGFRAU modules
- 1 MPixel in total
- 36 pixel-width gap
- 10 μs integration time
- 200 V bias
- dynamic range

~10^4 9.5 keV photons
- central ring pixels are in the middle of low gain

Single photon measurements

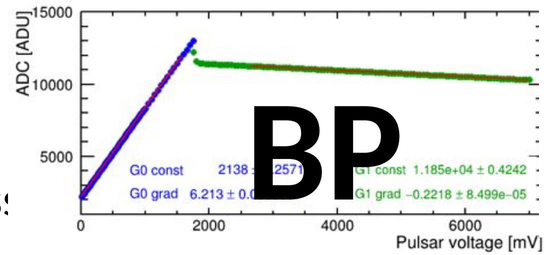
- X-Ray tube, W anode
- Cu Fluorescence target
- 10μs integration time
- **HG0**
- HV=200V
- Readout at 500-700Hz
  - limited by prototype firmware
  - 20MHz ASIC readout

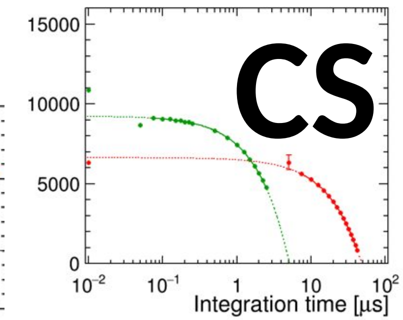


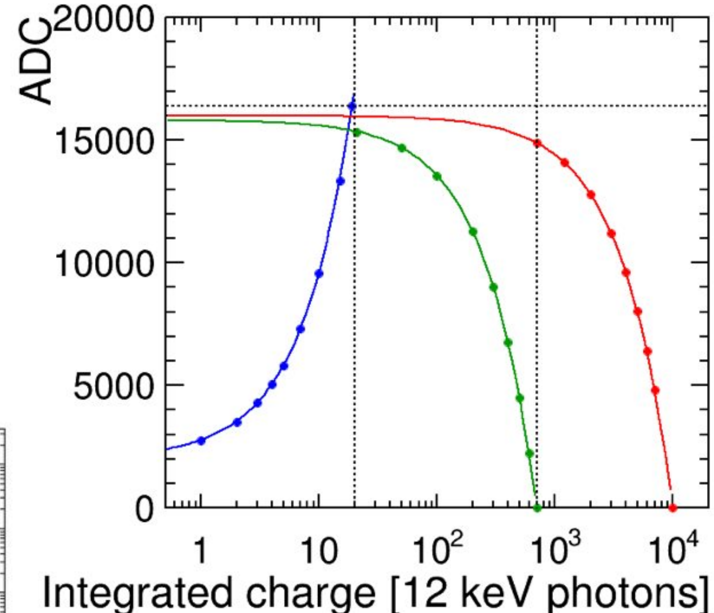
JUNGFRAU calibration procedure(s)

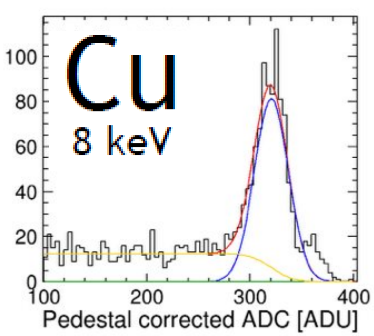
Second version of calibration procedure established for JUNGFRAU

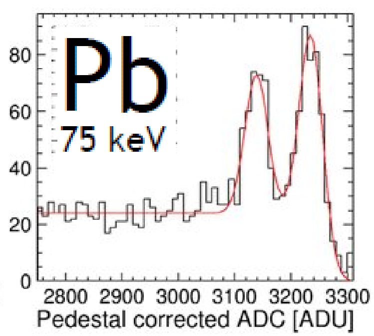
- Single or multi photon peaks for G0 (absolute)
- Backplane Pulsing (BG) for G1/G0 cros calib.
- Internal Current Source (CS) for G2/G1 cross calib.
- Calibration uncertainty <<1% for G0 and G1, order 1% for G2
- Validation of procedure on SLS and LCLS data ongoing

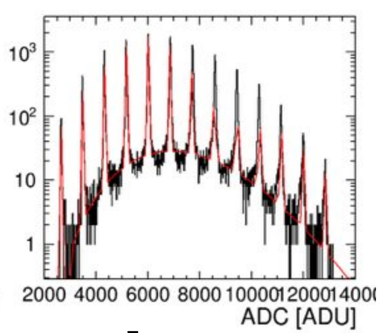






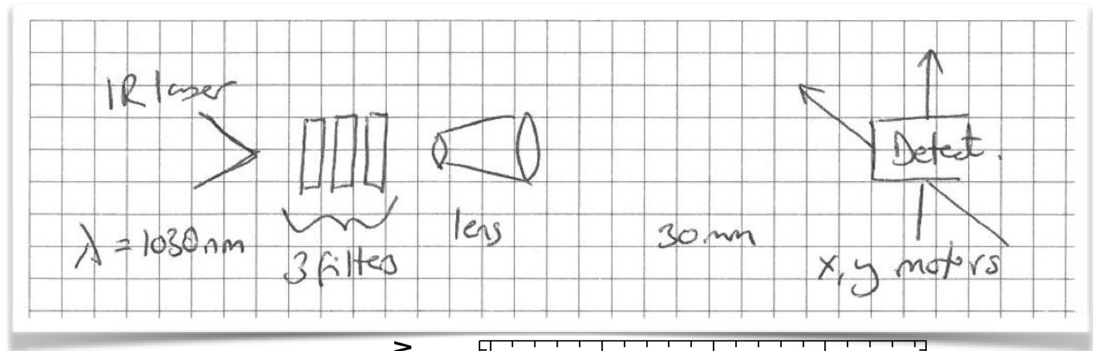






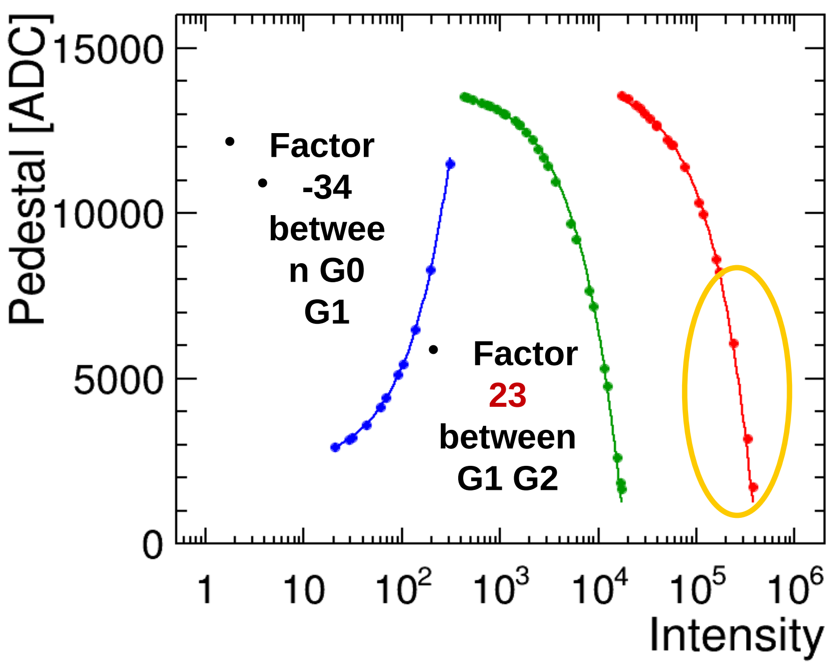
20keVxN

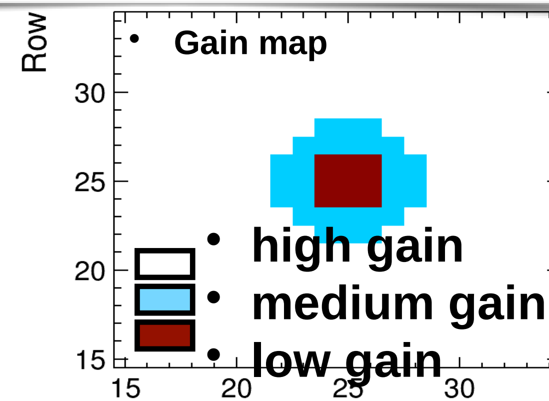
Cal. Validation with IR laser

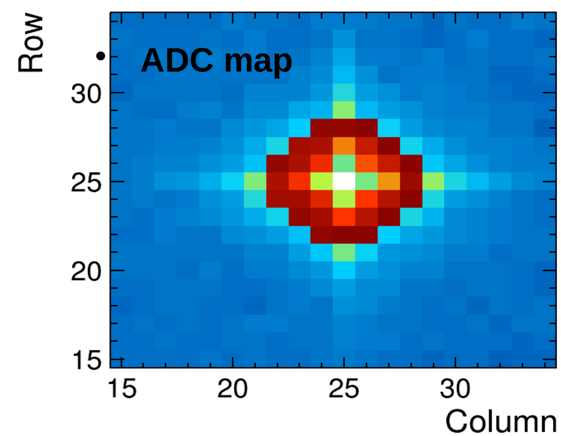


IR laser calibration

- targets individual pixels
- scan intensity with filters
- access all gain stages
- significant charge loss to neighboring pixels at high intensity
- reflected in gain ratio between G1 and G2







JF at Synchrotrons: pro and cons

Cons

- huge data rates : we have to run full speed, always
  - save raw data not a good strategy on the long run
  - online conversion will require IT resources
- Calibration is more complex
- Pedestals are essential: “frequent” dark collection and temperature control – moderate cooling (<0C) is required
- **Fluorescence suppression at medium/high rates not possible**

Pros

- very high count rate limit: 24Mcps @ 12.4keV, 40Mcps at 8keV
  - can be extended 10x with a DR extension method
  - or even higher if dead time is acceptable
- No “corner effect”
- low energies: single photon resolution at 2.5keV (or lower for short int. times)
- at low flux, JF gives energy information, without Th scan.
- works with strong single bunches, suitable for serial pink beam crystallography

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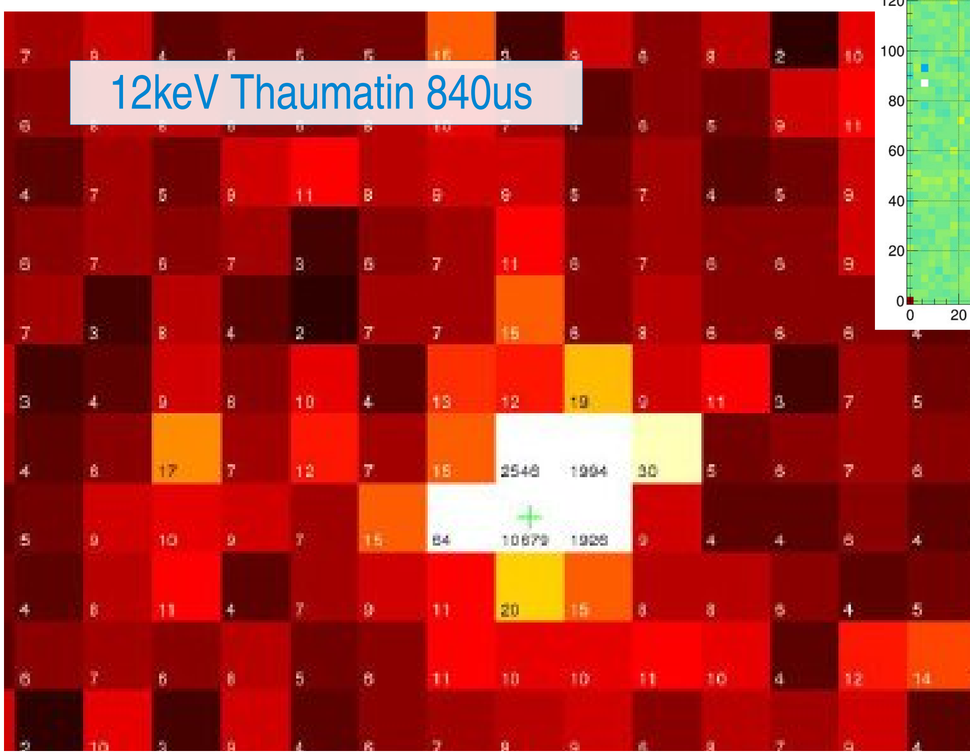

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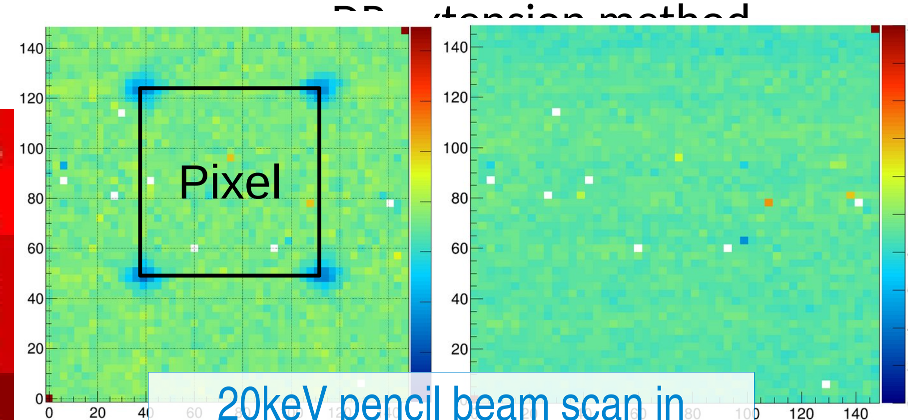

20keV pencil beam scan in photon counting(L) and integrating mode (R)

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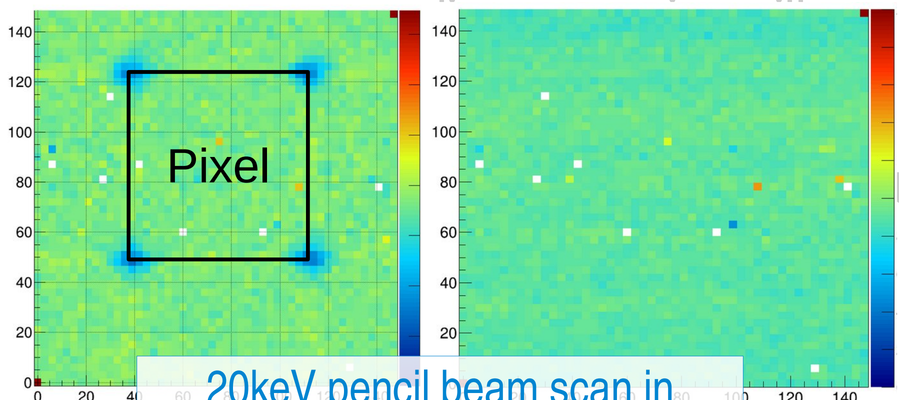

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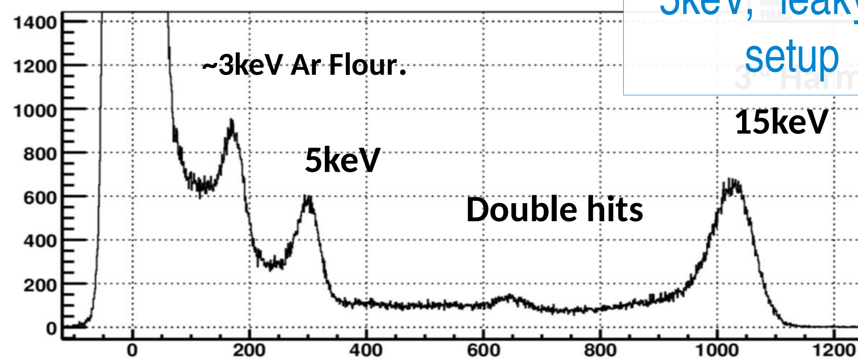
JF at Synchrotrons: pro and cons

Beam energy 5keV, “leaky” He setup



Cons

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  full speed, always
  - save raw da … with a
    strategy on
  - online conv … time
    require IT resources … is acceptable

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“frequent”

perature

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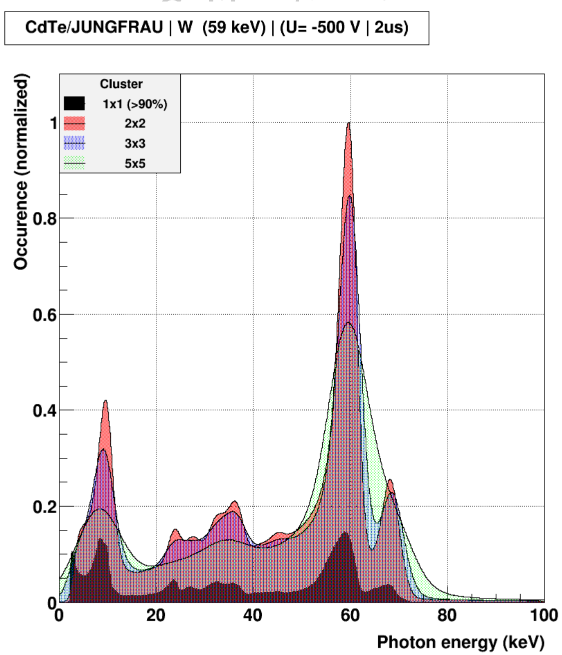

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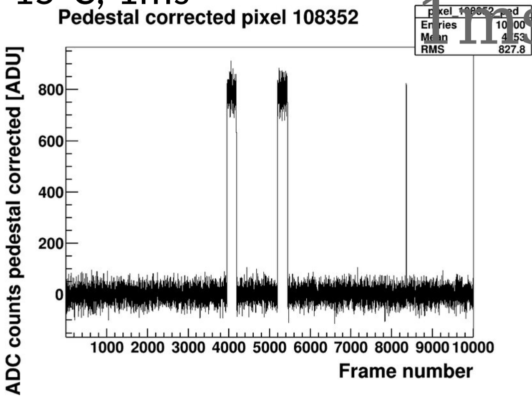
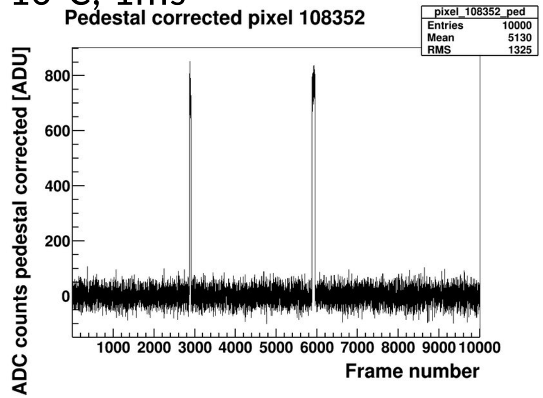
Pixel 108352 – varied temperature @ 1ms

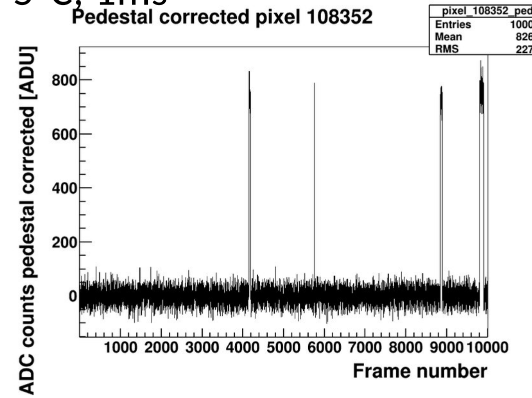
-15°C, 1ms



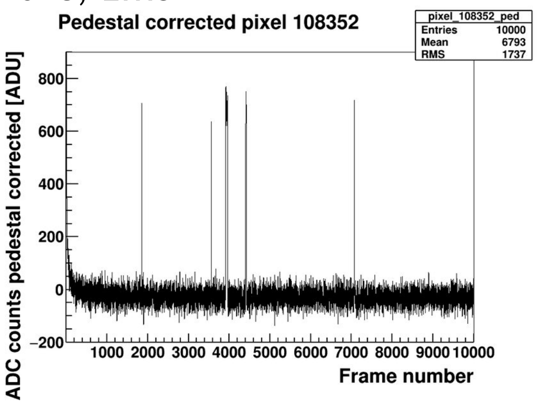
-10°C, 1ms



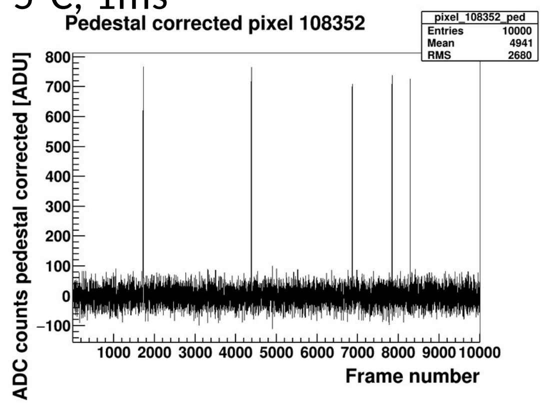
-5°C, 1ms



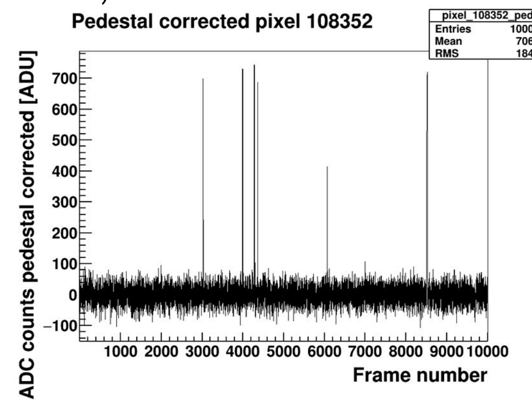
0°C, 1ms



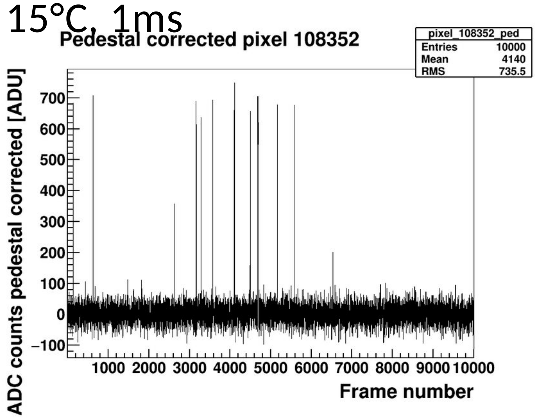
5°C, 1ms



10°C, 1ms



15°C, 1ms



20°C, 1ms