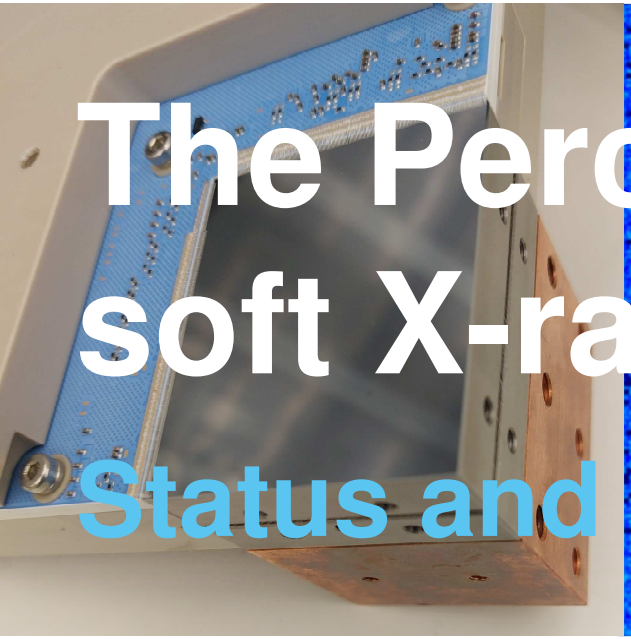
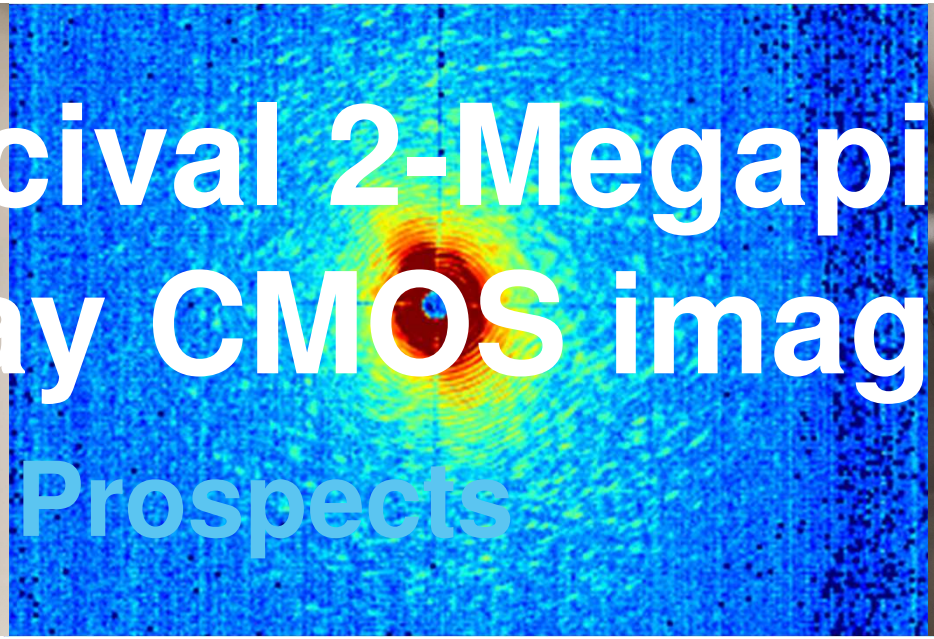
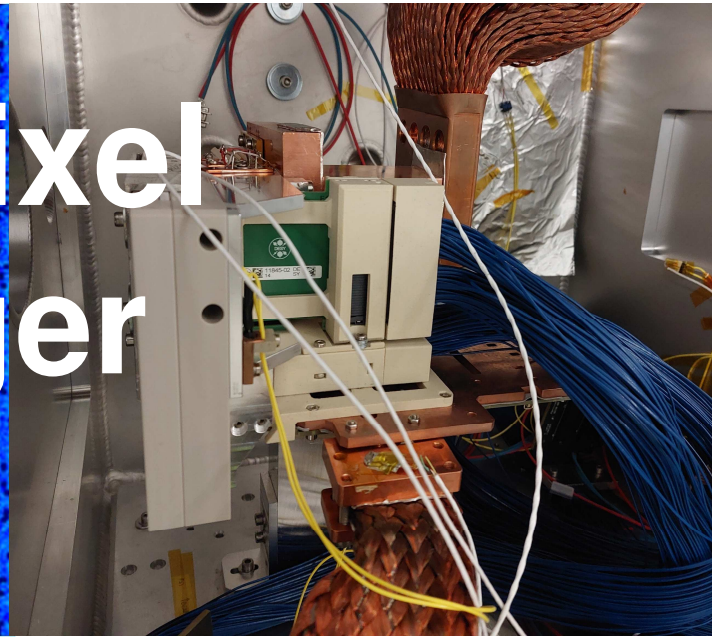




The Percival 2-Megapixel soft X-ray CMOS imager

Status and Prospects

- Percival in a Nutshell
- Percival today
- Friendly user experiments
- Outlook & Summary

Cornelia Wunderer
DESY Photon Science Detector Group
iWoRID 2022, Riva del Garda, June 28, 2022

HELMHOLTZ

Soft X-ray CMOS Imager for FLASH and Petra III: Percival

CMOS imager to meet the combination of challenges

- Novel imager meeting key FEL challenges simultaneously, in the soft X-ray regime:
  - (at least) Megapixels in a single sensor (avoid dead area)
  - fast enough for “shot by shot” science @ today’s FELs
  - dynamically adjust to single photons & large signals
- Project initiated by DESY
- Actively invited collaboration from the community
  -> today five light sources plus RAL/STFC, DESY lead
- Sensor CMOS design at RAL
- System overall design by DESY, with contributions from partners
- Project kickoff 2011, today prototype systems at 4/5 facilities

DESY

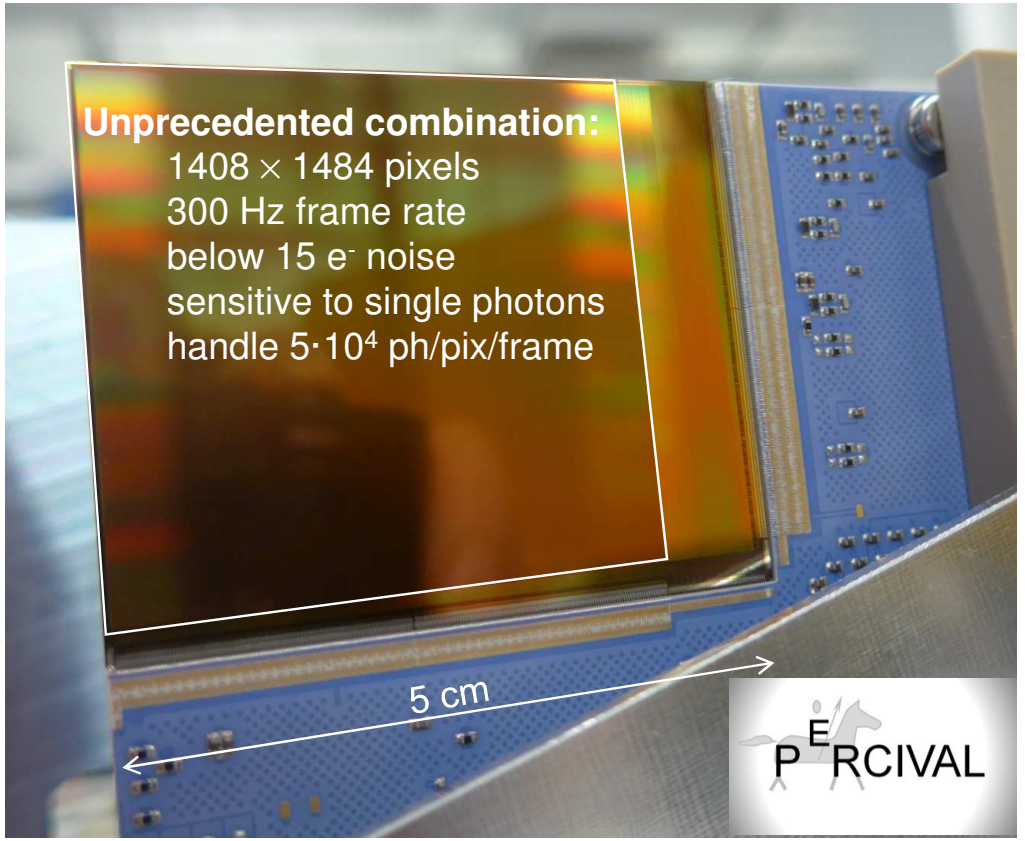
Rutherford Appleton Lab / STFC

Elettra Sinchrotrone Trieste

Diamond Light Source

Pohang Accelerator Laboratory

Soleil Synchrotron

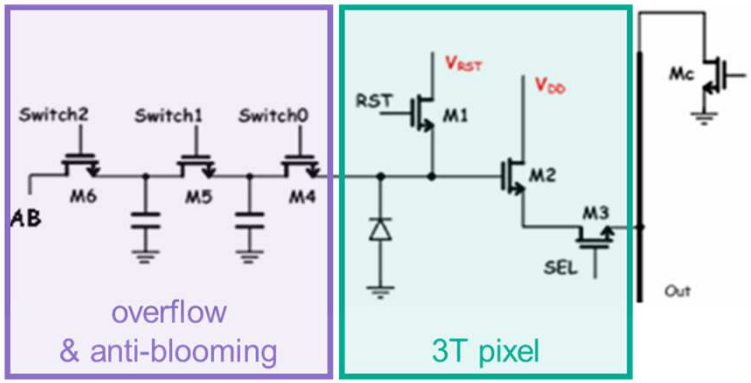


Percival 2M Sensor

Designed by partner Rutherford Appleton Lab / STFC

- CMOS imager (180nm technology)
- On-chip digitization (11520 ADCs)
- 3 auto-adjusting gain levels (per pixel, per frame, overflow)
- 1408 × 1484 pixels (+32 × 1484 ref. pixels), 27µm × 27µm
- 4 × 4 cm^2 continuous imaging area (stitched sensor)
- 3 gains to span ~15e- noise/single photons to 3.5Me-
- Primary energy range 250-1000eV
- option: 13 Megapixel imager, 120 Hz, 10 × 10 cm^2
- Data rate at full 300Hz frame rate would be 20 Gbit/s, streamed out over 45 LVDS lines (240 MHz, double data rate)
- Sensor backside-illuminated to enable soft-X-ray performance

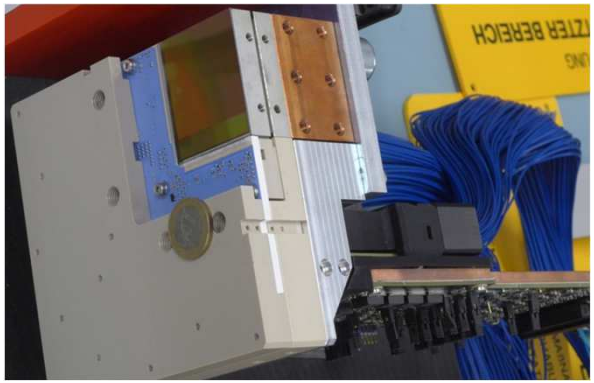
Keep in mind:
A single 250eV photon deposits 69e- on average in Si,
and has an absorption length of 92 nm in Si (cxro database)
(lowest attenuation length is 40nm, around 125eV)

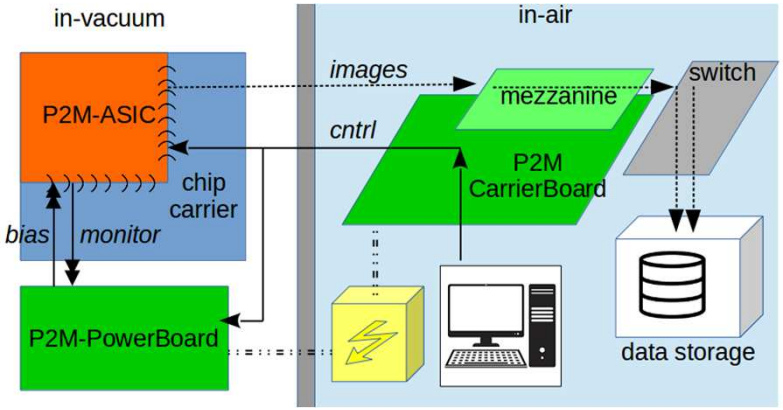


Percival System

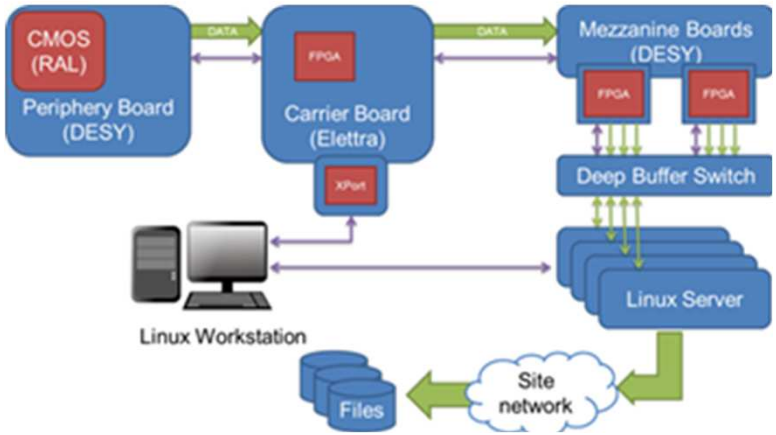
Design driven by the desire to allow as flexible in-vacuum use as possible (long cables, movable, …)

- Signal redistribution & biasing in vacuum
- 2-side buttable, enable cloverleaf





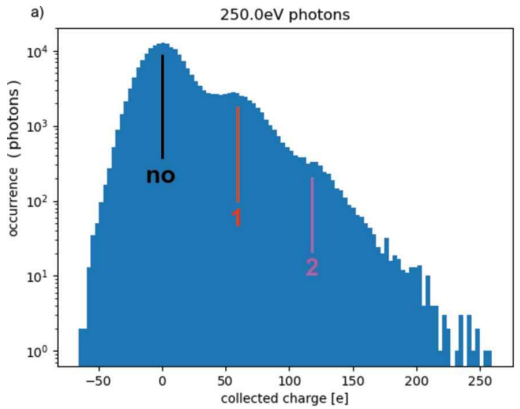
- Carrier board hosts FPGA for sensor finite state machine, and mezzanine preparing data for streamout
- 20 Gbit/s at full frame rate
- Save to disk in standard hdf5 format, incl system metadata
- Designed for interfacing to standard control tools at beamlines



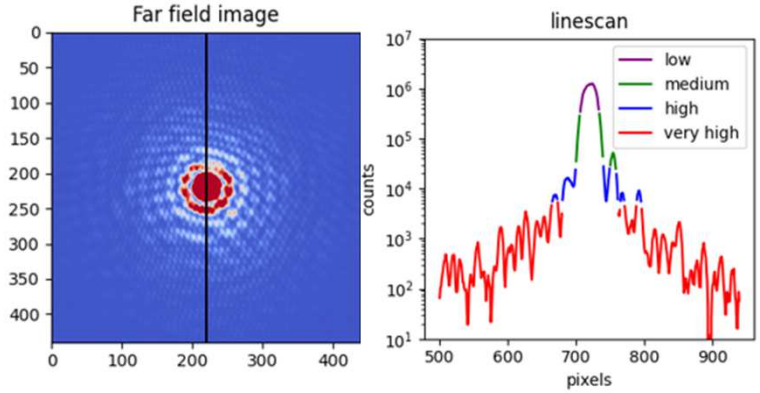
Percival Today

Sensor & System Performance

- 14 e- noise demonstrated (crosstalk suppression mode)
- Dynamic range single photons at 250eV to 3.6 Me- (50k photons)

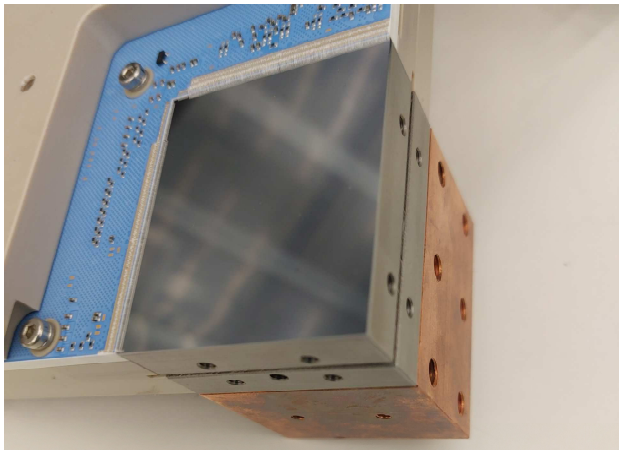


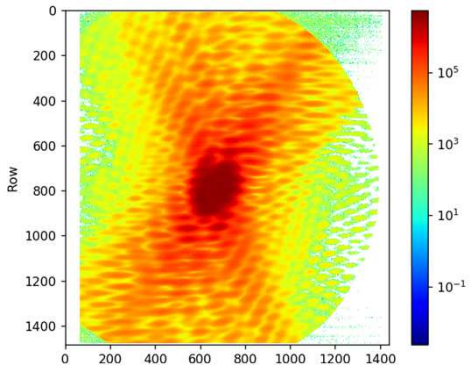
Finger plot showing individual 250eV photons. Data recorded in highest gain, maximal crosstalk suppression



Percival's multiple gains & resulting dyn. range (central region only, from holography beamtime, intensity in e-)

- 2 Megapixels in a monolithic sensor
- Used at DESY's soft X-ray FEL FLASH down to 92 eV





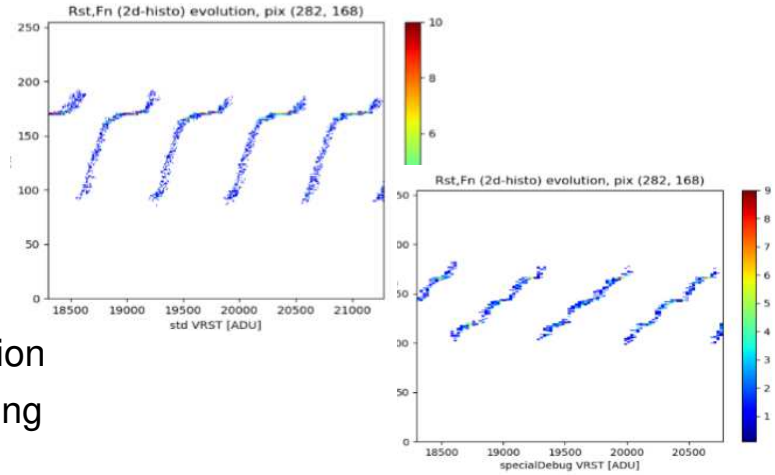
Diffraction image of 10um pinhole from single FEL 91.85eV pulse. Scale in e-.

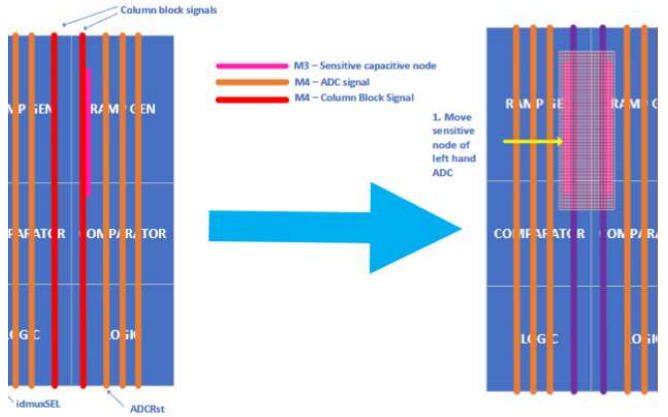
1st-version Shortcomings of Sensor & Remedies

to be addressed in respin (submission fall 2022)

Crosstalk

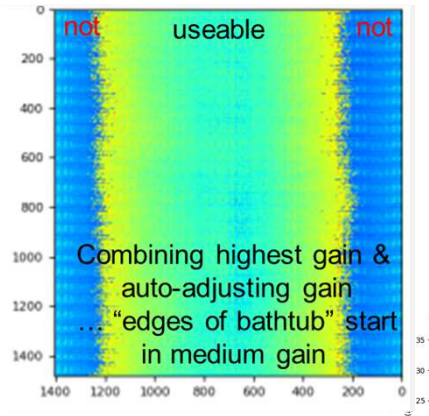
- Design: 3 phases in parallel: read pixel, ADC, streamout
- Pixel commanding & ADC
- Streamout & ADC
- Workaround: temporal separation
- Respin: shielding, change routing

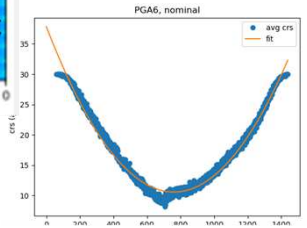


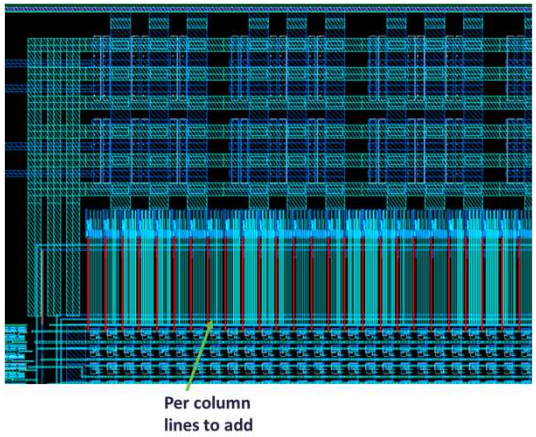


‘Bathtub’

- Too-high resistance of pixel source-followers towards gnd indirectly affects bias current;
  → non-constant behavior over sensor area
- Workaround: ignore edges of ‘tub’ in high gains
- Workaround: highest amplification used only fixed-gain
- Respin: improved pixel matrix gnd connections







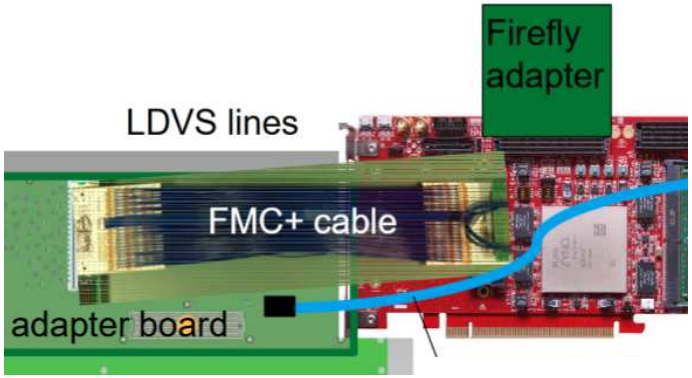
Yield (stitched, large sensor …)

1st-version Shortcomings of System & Remedies

2nd-generation DAQ 2023, revised system ~ 2024

- DAQ firmware not fast and flexible enough, today limits sensor readout speed (83 Hz) & modes
- 2nd generation – based on modern Xilinx Zynq eval board – expected ready-to-use early 2023

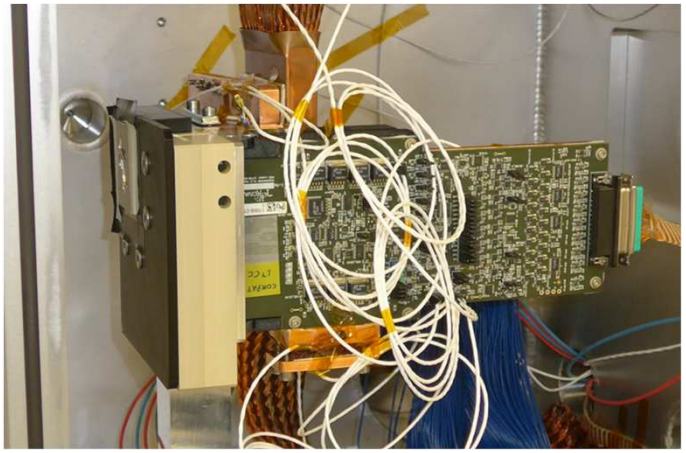
Mezzanine shared with 1st-generation AGIPD and LAMBDA systems

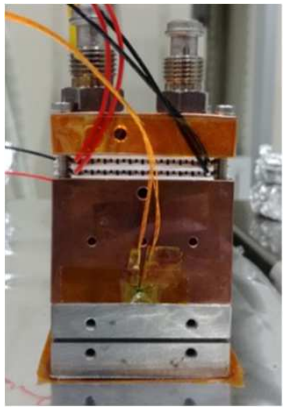


2nd-generation DAQ development based on Xilinx Zynq Ultrascale eval board

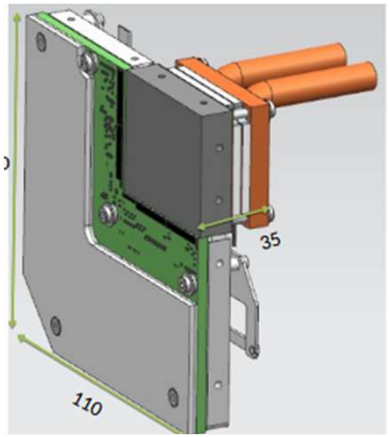
- Cumbersome
- Long cooling & warmup times with Cryotiger-based setup
- Experts required to operate

… 2nd-generation system in planning, scope TBD





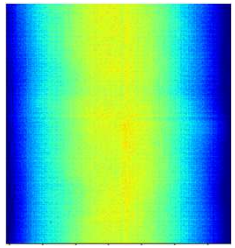
Peltier prototype @ PAL



a compact design sketch

“Dry Numbers” – Achieved vs Aims, today

- **Frame rate today: 83 Hz**
  - Limited by today’s readout periphery
  - Work in progress …
- **Dynamic range**
  - 13-14e- noise for part of pixels today, 24e- for all (expect ~ 14e- for all pixels with revised firmware)
  - 3Me- with dynamic gain & overflow, 3.6Me- if fixed
- Today’s system has significant **performance variations over chip area**
  (dynamic range per gain level, noise, …
  this also hampers full use of dynamic gain)



- **Soft X-ray QE**
  - We have seen 250eV photons without evidence of higher harmonics at P04, same for 92eV at FLASH
  - No QE numbers yet for P2M full-size chip

- **Design: 300 Hz, proportionally faster for partial readout**
  - Some of this recoverable w/o respin (not all)
  - Firmware issues keep us from trying faster (yet)
- **Design dynamic range**:
  - single photons at 250eV / <15e-,
  - 50k Photons at 250eV (3.5Me- for 100% CCE)
- **Uniformity to be addressed in respin**
  (improved grounding;
  should also enable combining <15e- noise in highest gain with dynamic-gain operation)
- **Soft X-ray QE**:
  using NASA JPL’s delta-doping BSI process for ultrathin entrance windows (~ 5nm) and soft X-ray QE > 85%

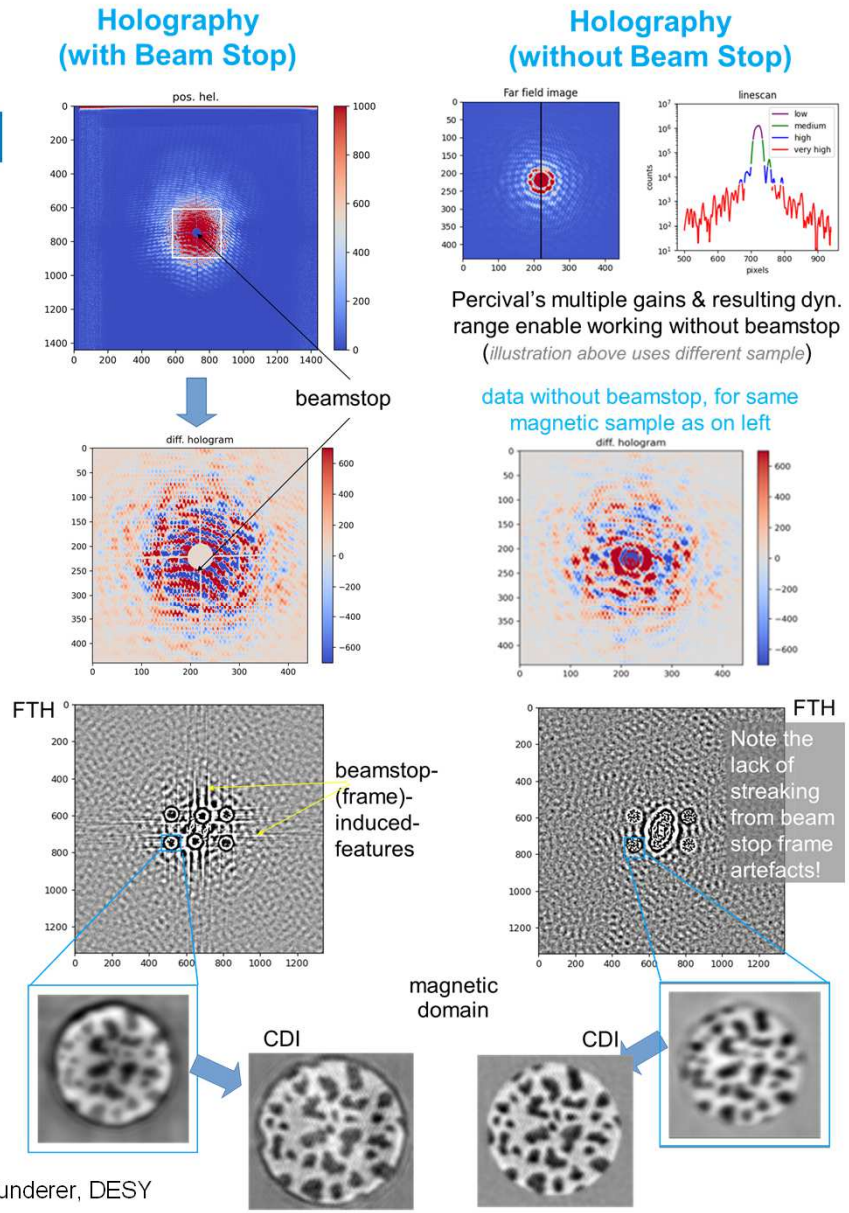
Percival
Friendly User Experiments

First very-friendly-user experiment: Petra III

P04, July 2020

- Skirmions reconstructed successfully from Percival data
- Total dynamic range achieved was appreciated

- Gain transitions caused issues
  - Changing noise levels
  - Accompanying non-linearities in linearly corrected data

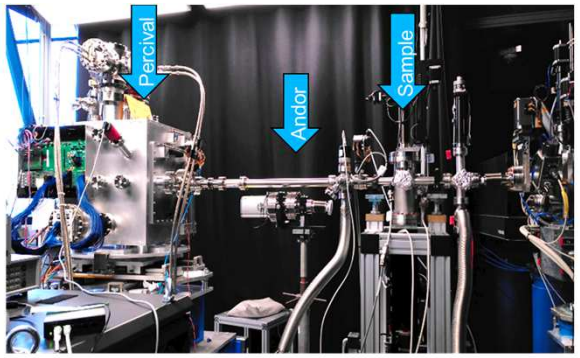


First very-friendly-user experiments: FLASH

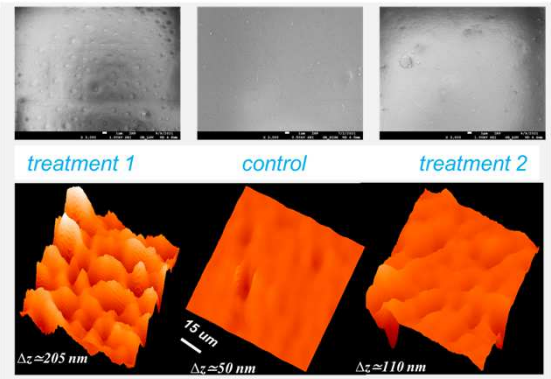
November 2020, FL24 beamline, Ptychography

- side-by-side use of user's Andor (iKon-M SO BEN) camera, and Percival
- Comparison somewhat hampered by fluctuations in beam behavior of FEL

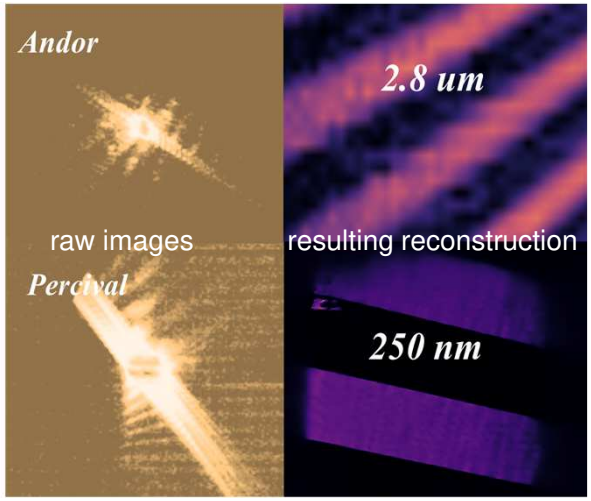
- Recorded diffraction patterns from single FEL pulses down to 91.85 eV
- Plasma-treated polymer surfaces could be imaged



Experimental set-up at the FL24 beamline in Dec 2020



Comparative characterization of plasma-treated polymer surfaces (top: SEM images, bottom: X-ray ptychography)



Comparison of the resolution obtained for segments of a Siemens star, recorded in multi-shot (scanned) Ptychography with Percival and the more conventional Andor camera
Percival's primary advantage: larger dynamic range.

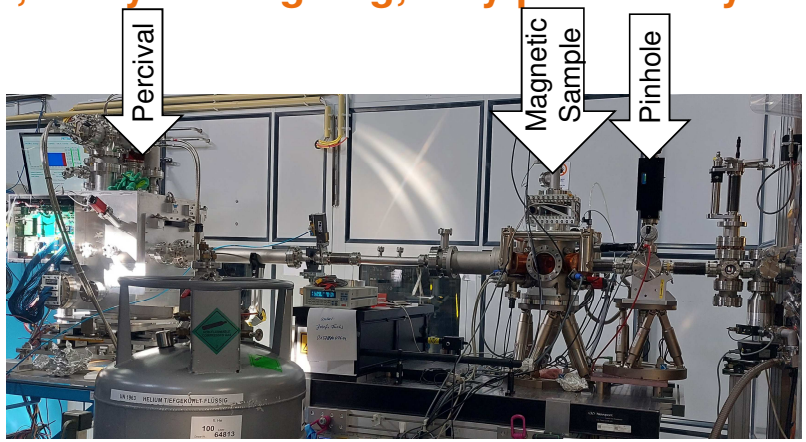
User feedback:

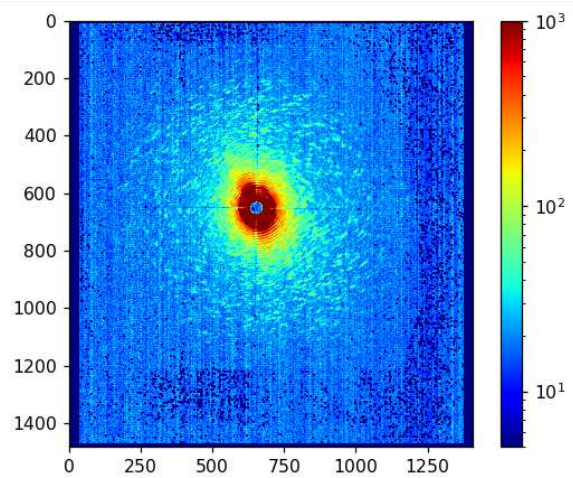
"I would prefer the PERCIVAL due to the bigger chip size and dynamical range."

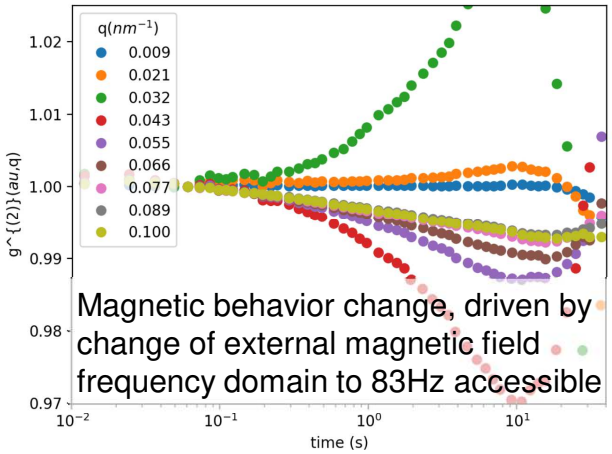
First very-friendly-user experiments: Petra III XPCS

P04, May 2022 – i.e. hot off the press, analysis on going, very preliminary

- Aim: XPCS of magnetic domains (708 eV)
- Percival ‘the’ detector used
- Interim step: holography of magnetic domains and skyrmions
- Unfortunately, various issues: beam stability, ring stability, sample thermal stability ….
- Detector itself performed well, judging from “first glance at images”
- Detailed quantitative analysis in progress







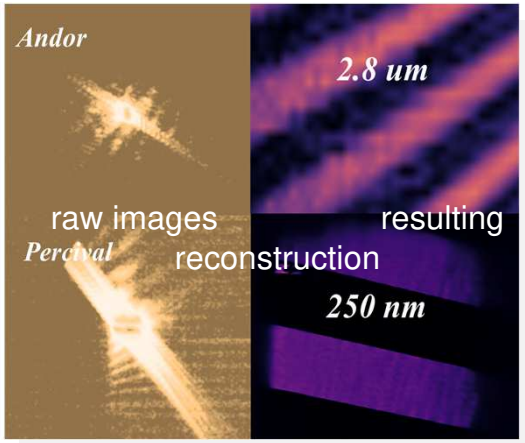
Magnetic behavior change, driven by change of external magnetic field frequency domain to 83Hz accessible

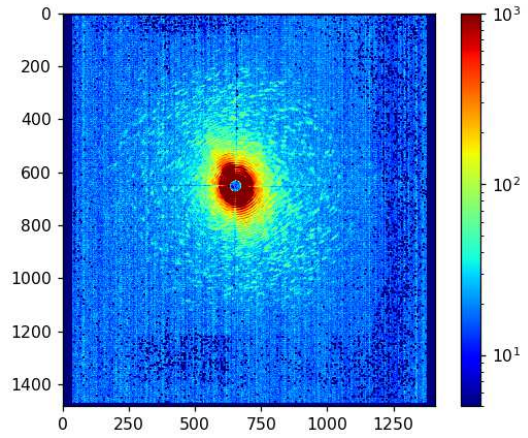
Holographic image of magnetic domain

Percival
Summary and Outlook

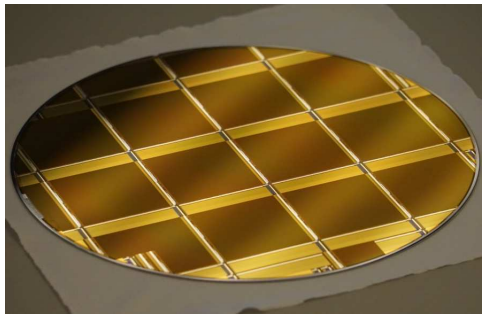
Summary and Outlook

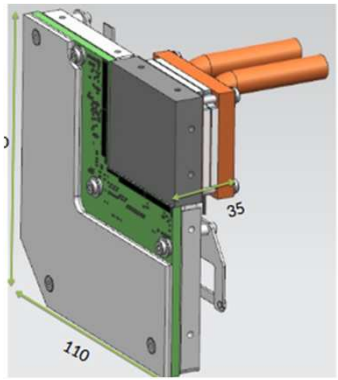
- Successful experiments at soft X-ray synchrotrons & FELs
- Users appreciate in particular high dynamic range and high frame rate (even 83Hz is ‘a lot’)
- Systems operational today at 4 collaborator sites, BSI sensor yield limiting factor here





- **Respin** submission 2022
  fix crosstalk, fix bathtub
  - full speed at 15e- noise performance,
  - full images,
  - Link highest gain with dynamic gain switching
- New-generation **DAQ hard-and firmware** 2023
  - Full speed, use all operation modes & noise-reduction tools
- **Revised system** 2024
  - Compact, Peltier-cooled, user-friendliness





Thank you for your Attention –

and thanks to the whole Percival Collaboration

and the Experiment teams

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Vahagn Vardanyan *(now XFEL)*
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