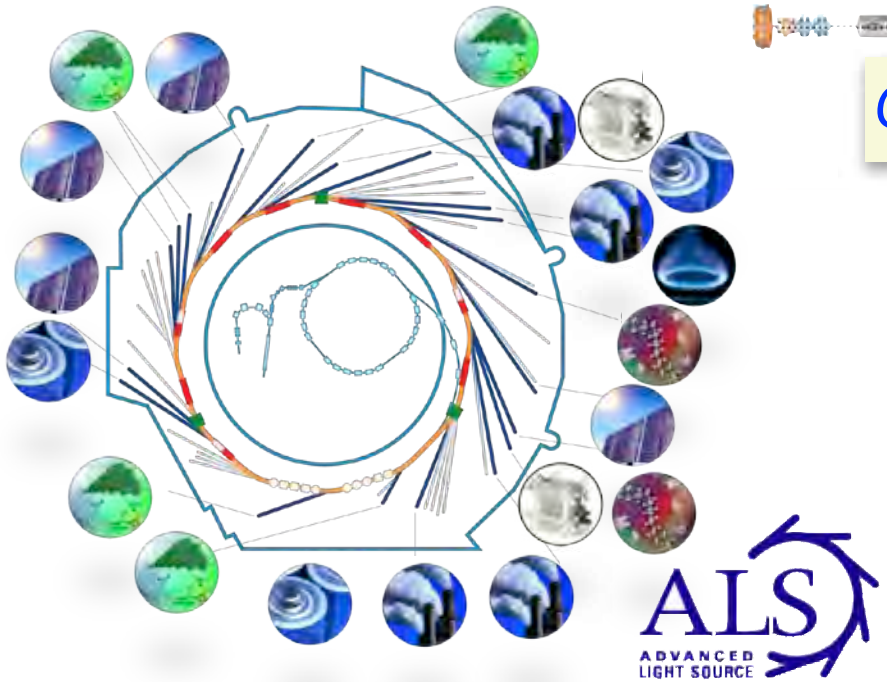
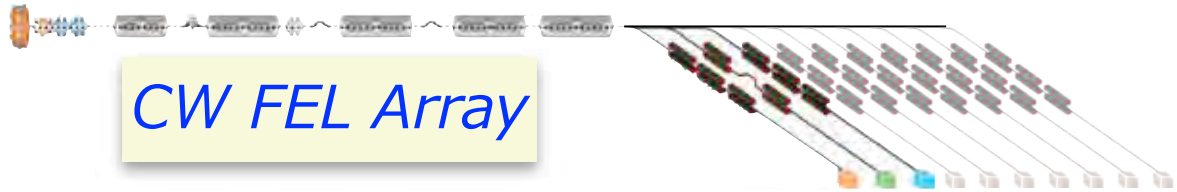
Soft X-ray Detector Developments at Berkeley

P. Denes

BERKELEY LAB
Lawrence Berkeley National Laboratory

Motivation and Activities





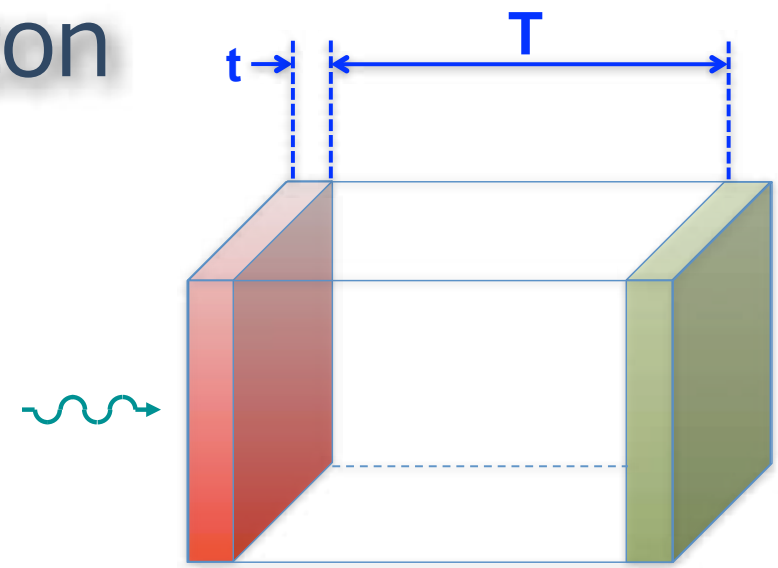
Rep Rate	**High repetition rate (≥ MHz)**
Tunability	**~250 - 1,250 eV (fundamental)**
Coherence	**Seeded operation**

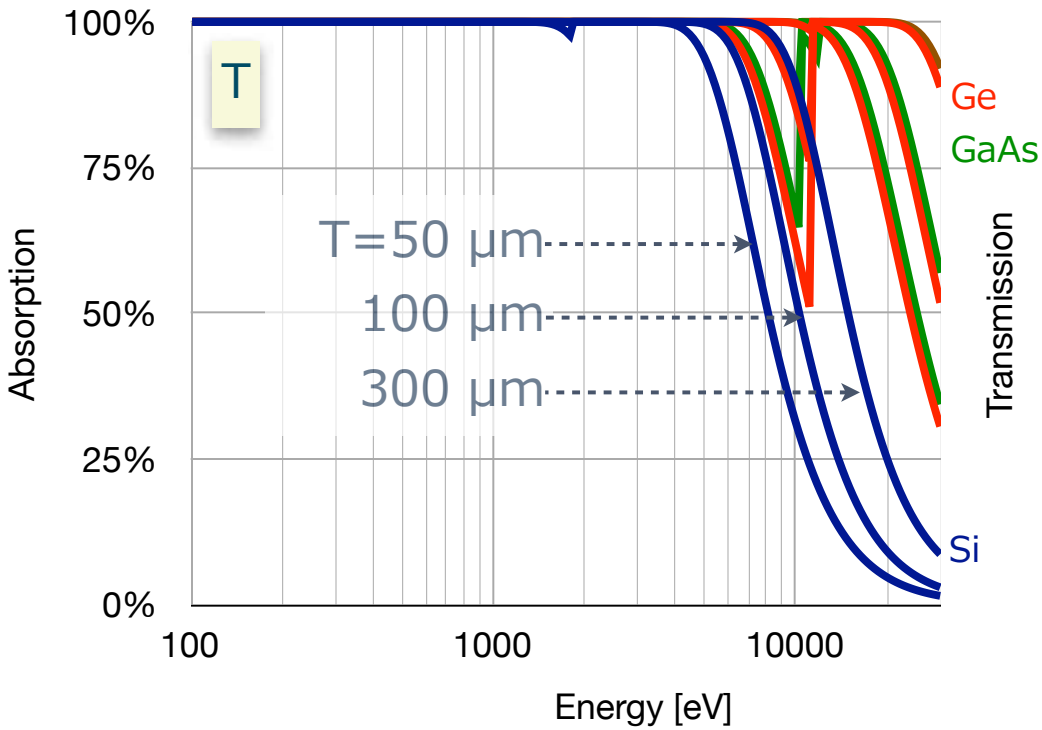
NGLS
next generation light source

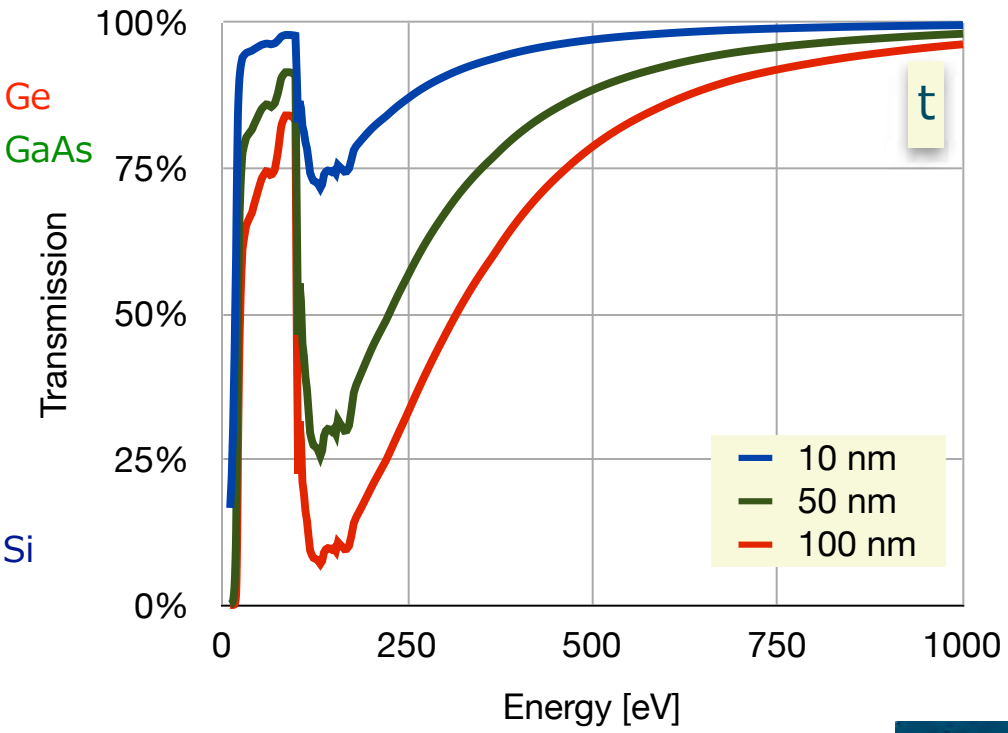
- **Soft X-ray light sources at Berkeley (Today: ALS, Tomorrow: NGLS)**
- Direct soft X-ray detection - Charge Coupled Devices
  - Emphasis on speed or special properties
- Specialized processing for soft X-ray detectors
  - Thin entrance windows, thinned sensors, laser machining, …
- Other technologies - e.g. Silicon-on-Insulator, CMOS APS, …
- Data reduction and processing

X-ray Detection in Silicon

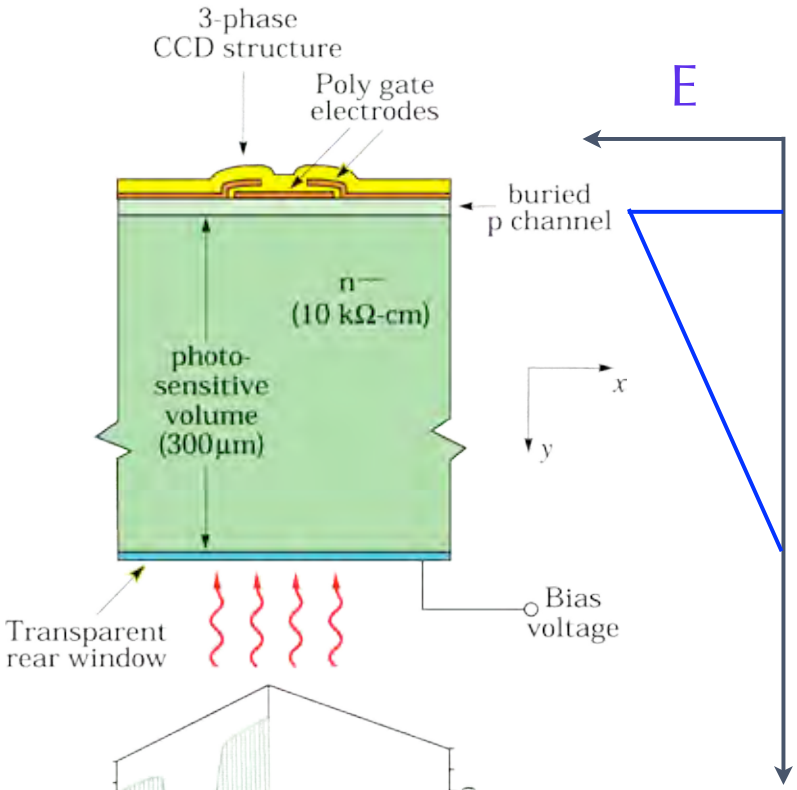
- High efficiency up to ~8 keV X-rays
- Readout noise limited for soft X-rays

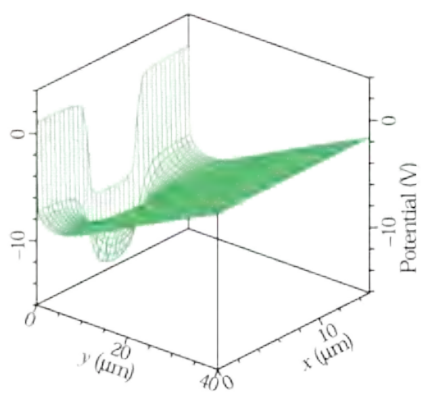






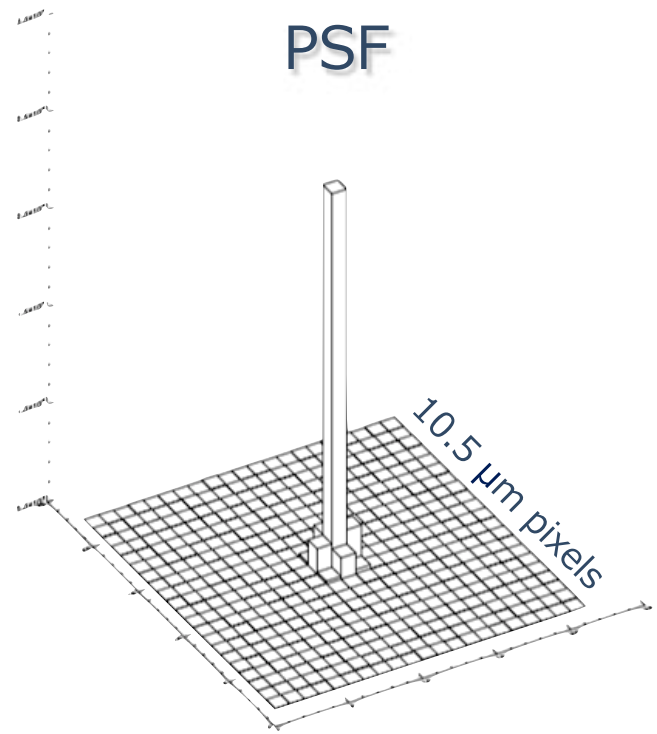
LBNL CCD





MEDICI 2-D simulation

PSF



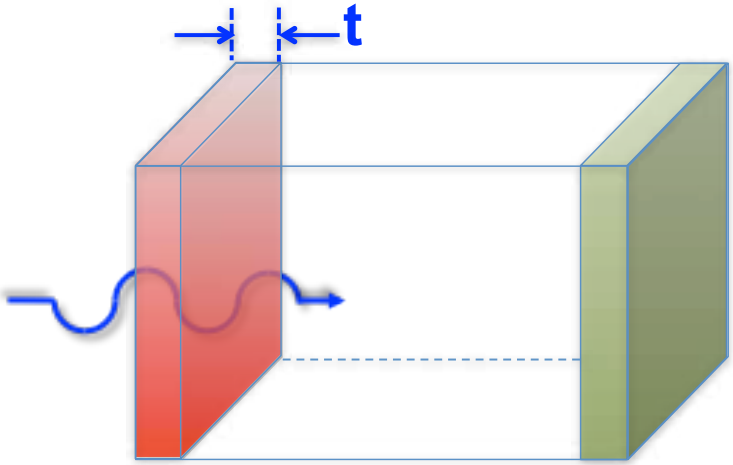
At V_{SUB} = 115 V,

σ_D = 3.7 ± 0.2 μm

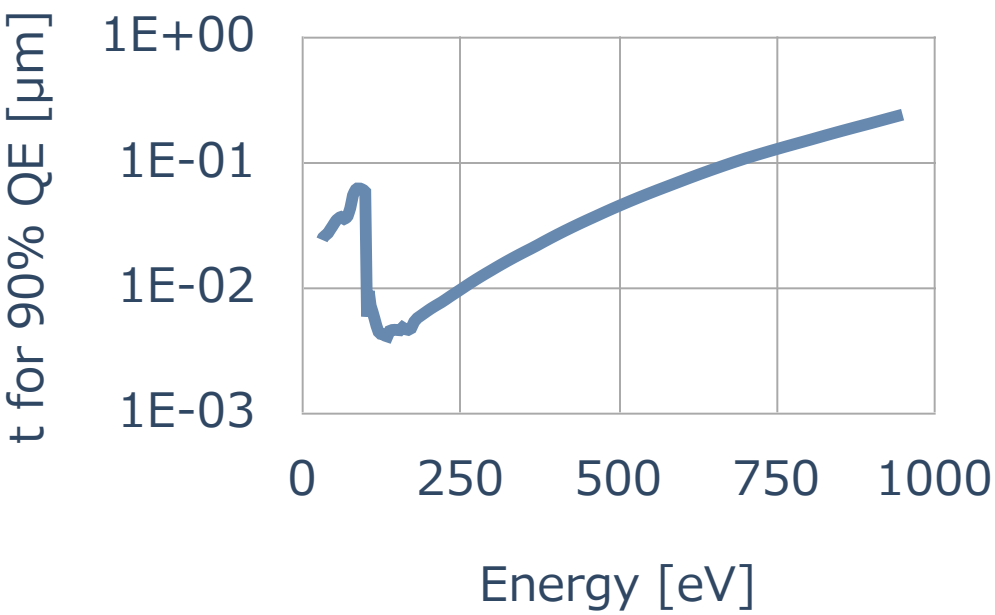
- Thick (up to 650 μm) high-resistivity Si
- Fully depleted
- Direct X-ray detection

- n-type (p-channel) for enhanced radiation resistance

Soft X-rays - t not T



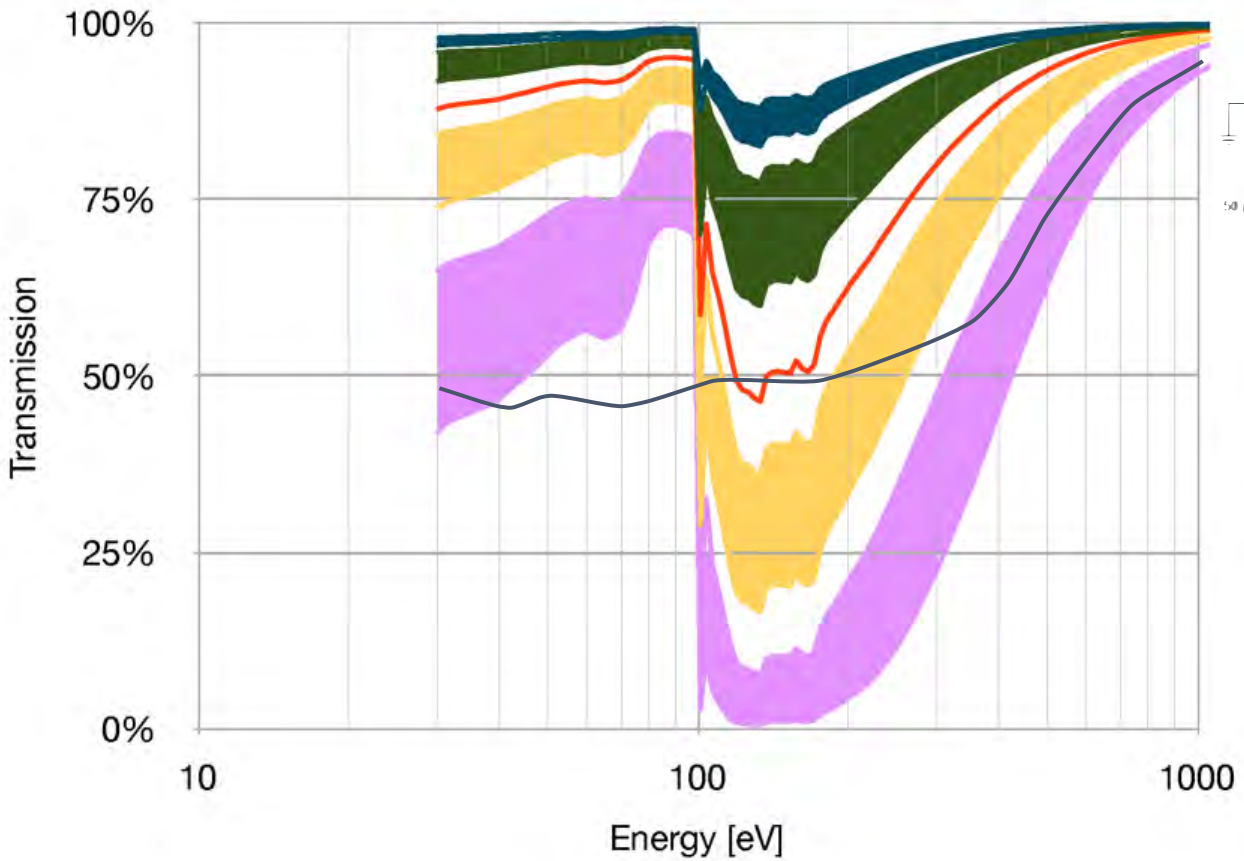
- Fully-depleted detector needs
  - High resistivity bulk
  - (thin) conductive contact
- Back illuminated

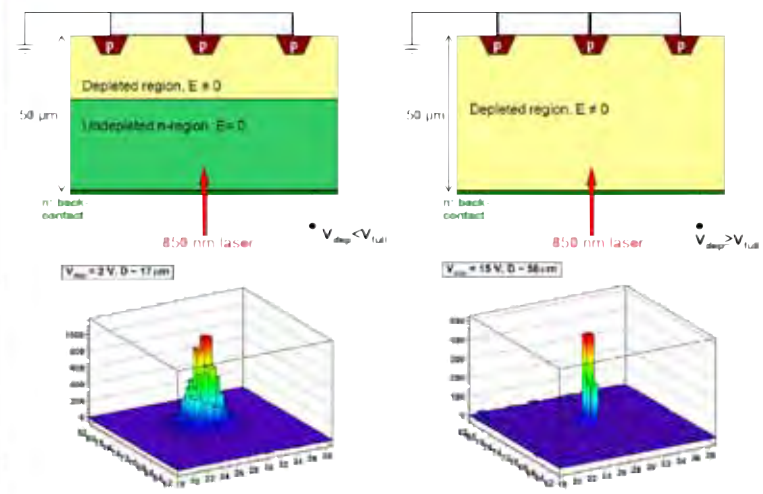


- Want low temperature implant
  - < melting point of Al interconnect
- Process (e.g. CMOS)
- Thin
- Implant

Low Temperature Thin Contact Development

Process	Window thickness	Status
Low energy implantation + 500 C annealing	1,000-2,000 Å	Process dependent, several SOI prototypes functional
Low energy implantation + laser annealing	400-700 Å	Several SOI prototypes functional after processing
a-Si contact deposition by sputtering	300 Å	Prototypes functional after processing, high leakage
In-situ doped poly (ISDP)	100-200 Å	Standard MSL process - high temperature process
Molecular Beam Epitaxy	50-75 Å	Developing in-house capability - R&D

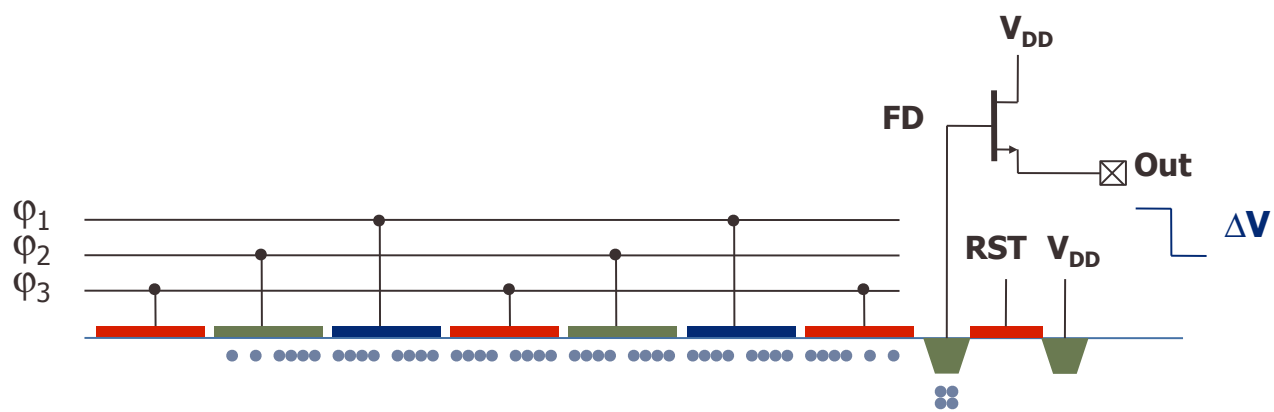




Example - 50 µm thick SOI
850 nm laser

CCDs

- Original integrated circuit scientific imager
- Noiseless, lossless charge transfer
- (Relatively) Large conversion gain with low C_{FD}, $\Delta V = q/C_{FD}$
- (Relatively) Low noise [CDS]
- Large area (wafer scale), small pixel devices possible
- But slow (parallel exposure, serial readout)



CCDs are Wonderful

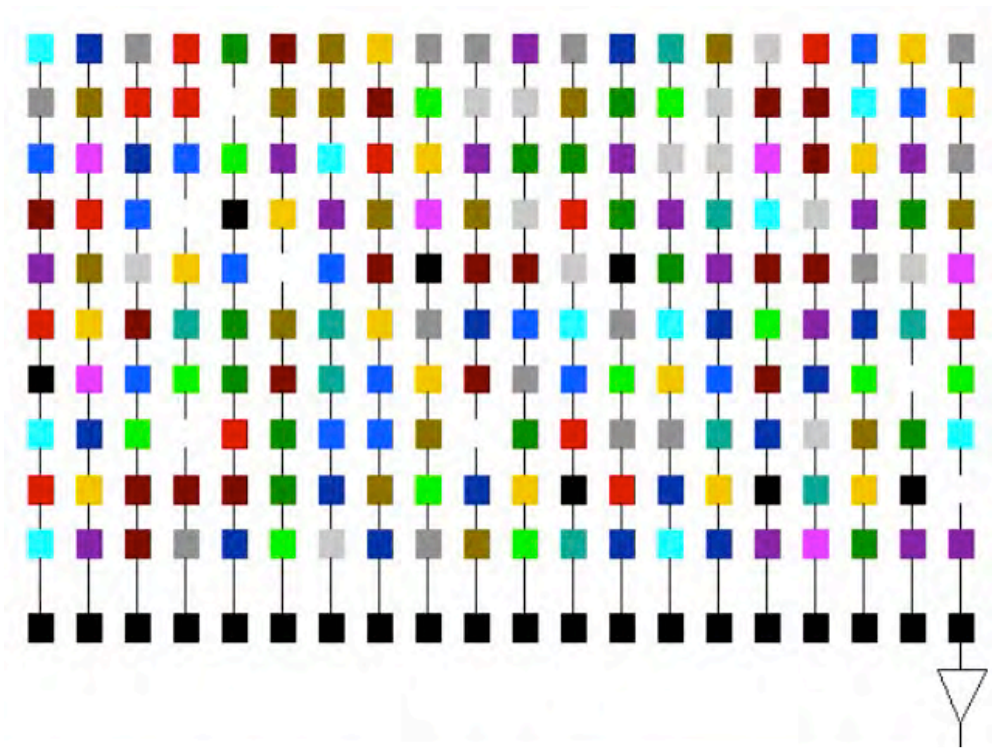
But they are slow:

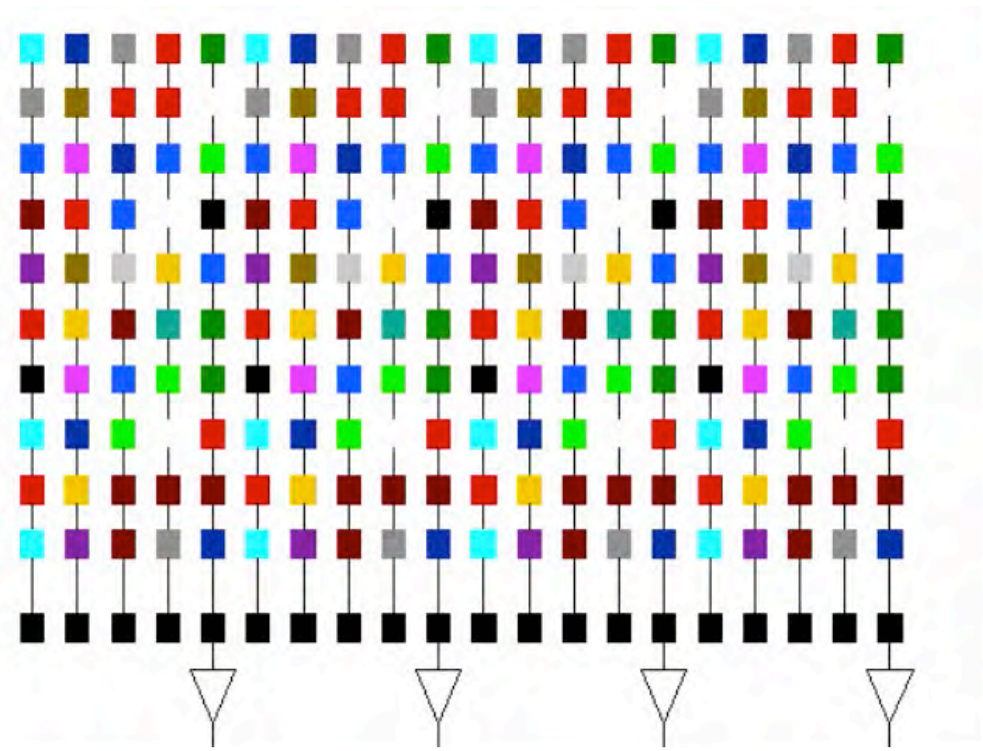
Parallel exposure

Serial readout

Solution:

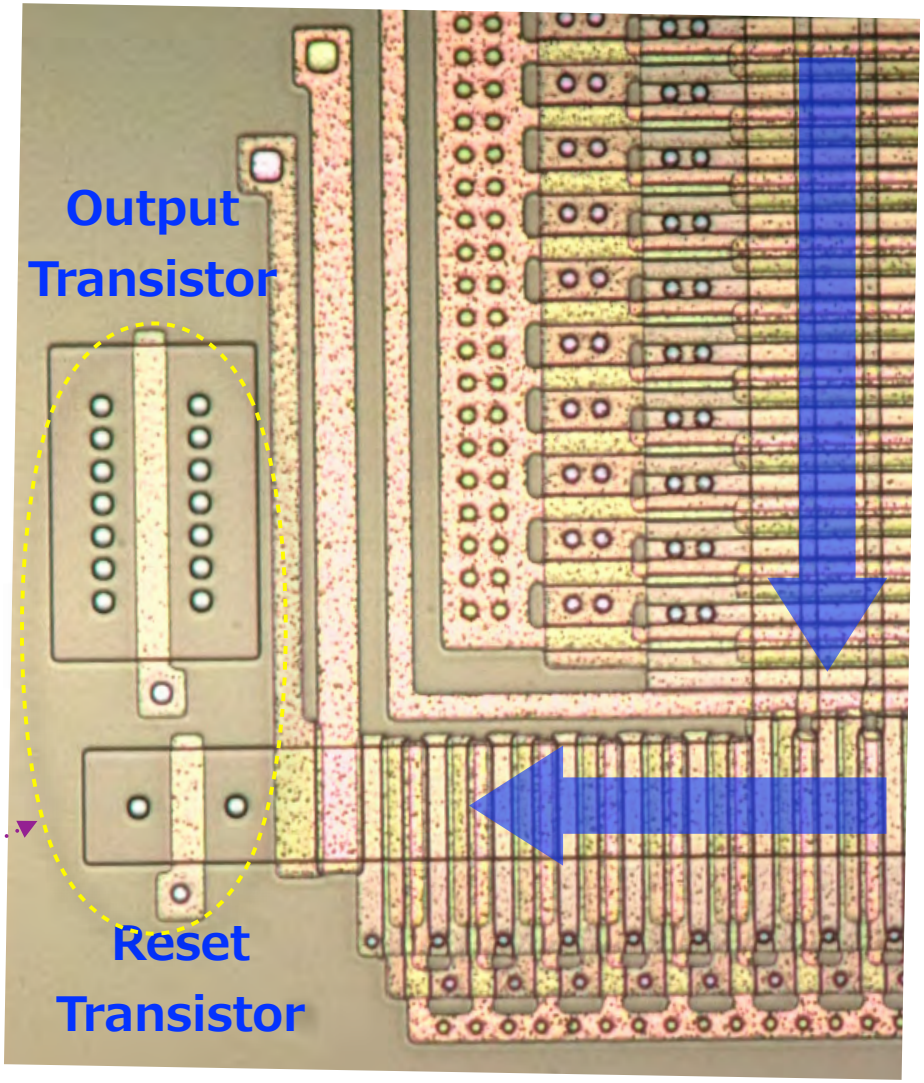
Parallel readout



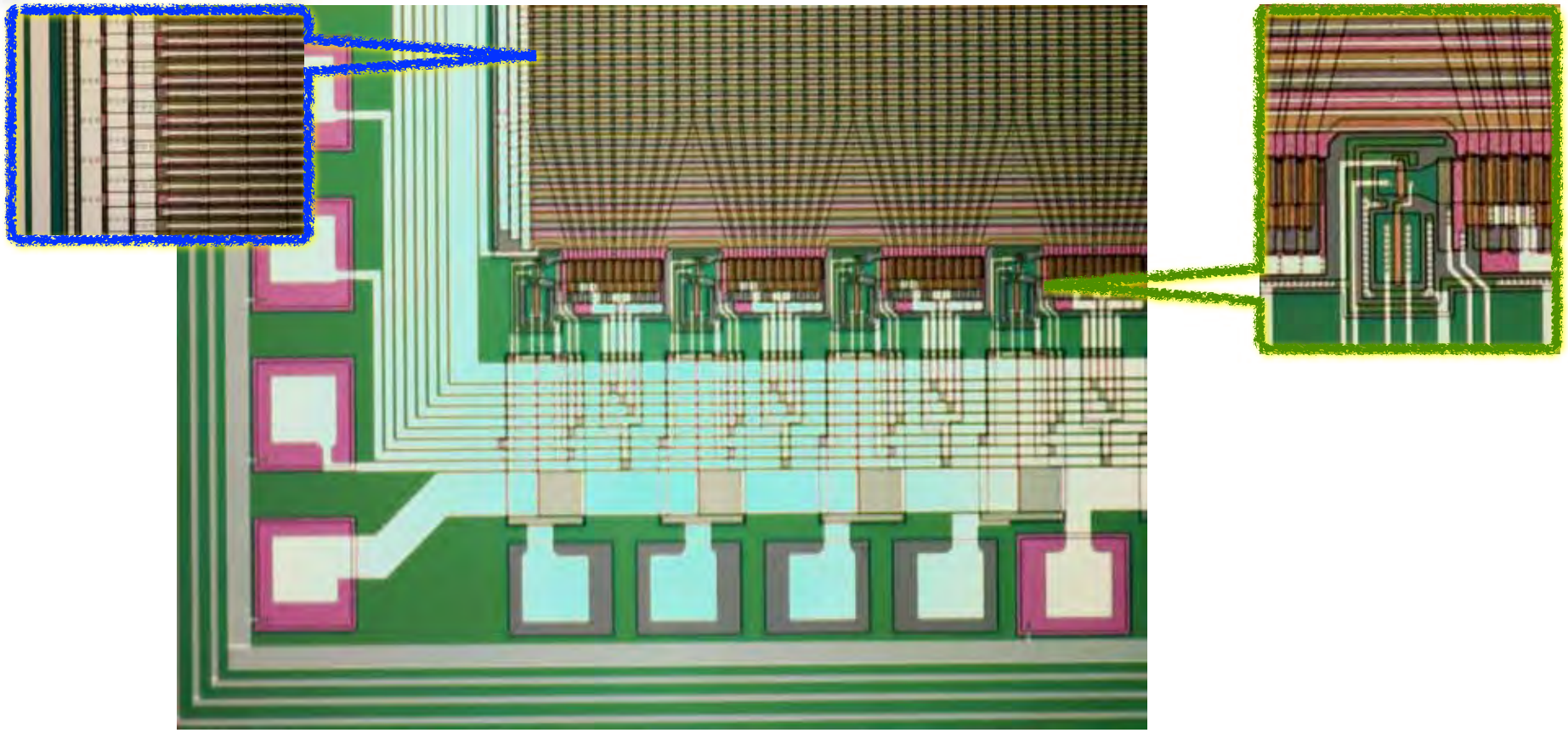


Conventional ➜ (almost) Column-Parallel CCD

- (a)CP-CCD allows:
  - keeping Source Follower
  - wire bonding (pitch)
- Need to fit multiple transistors
  - Conventionally, “outside” of imaging footprint
    - Where to put these transistors?



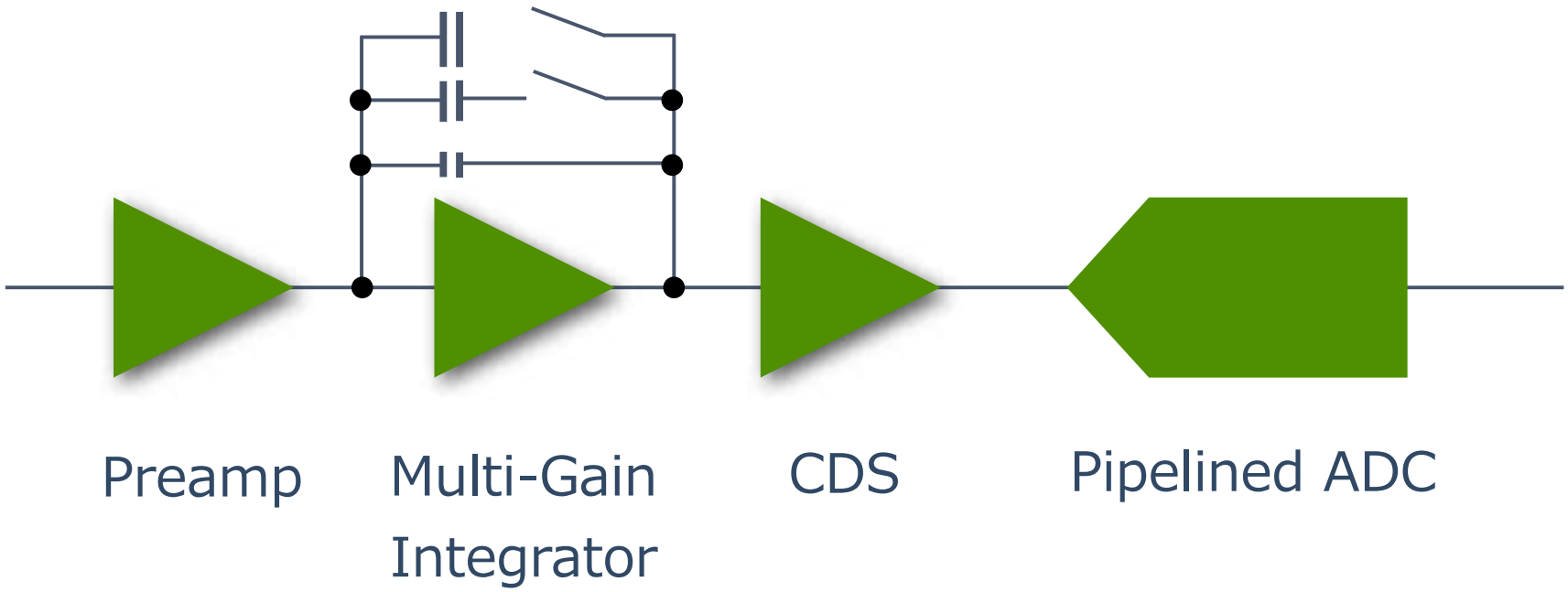
(almost) Column-Parallel CCD

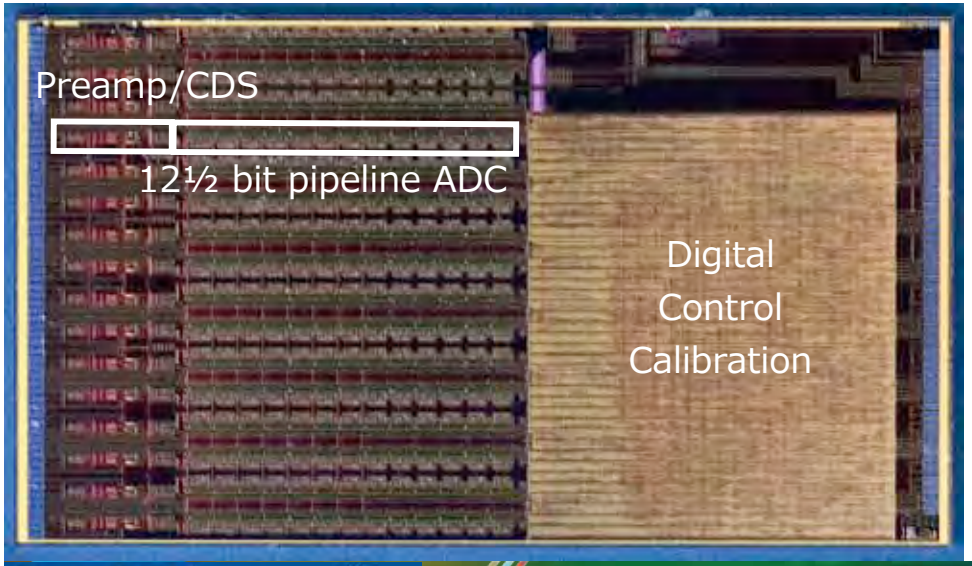


- Prototype: 480 x 480, 30 μm pixels → 96 outputs
- Constant area taper
- Metal strapping
- 300 μm output pad pitch

2006/7

16-Channel Custom Readout IC



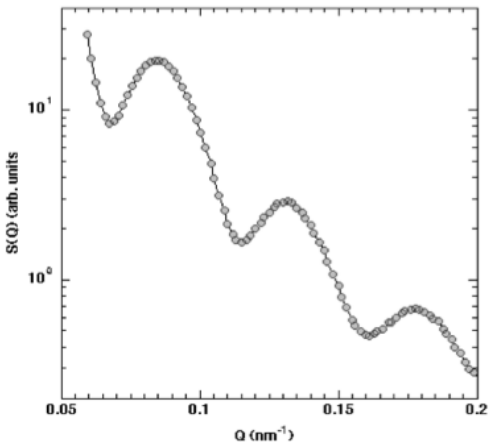


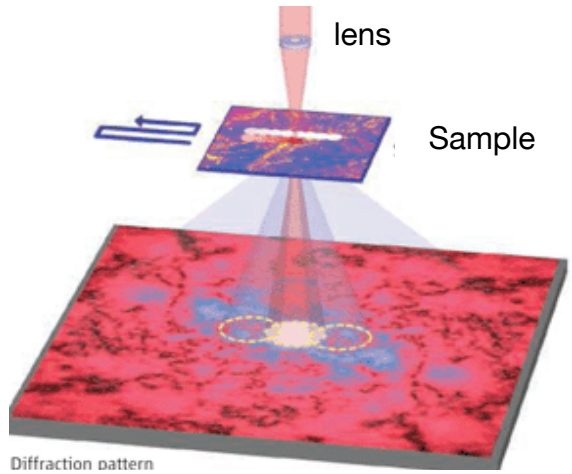
- Gain 8, 2, 1
- 12+1 bit ADC
- Covers 15 bit range
- 300 μm input pad pitch

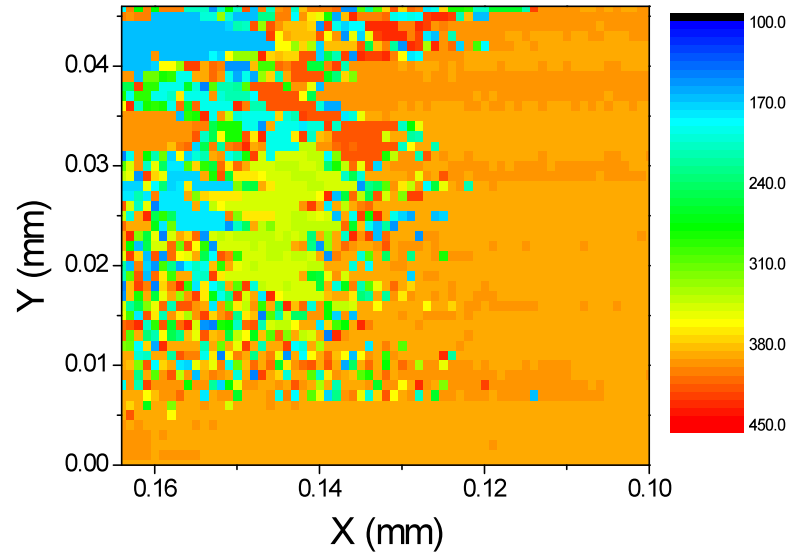
0.25 μm CMOS - 2006

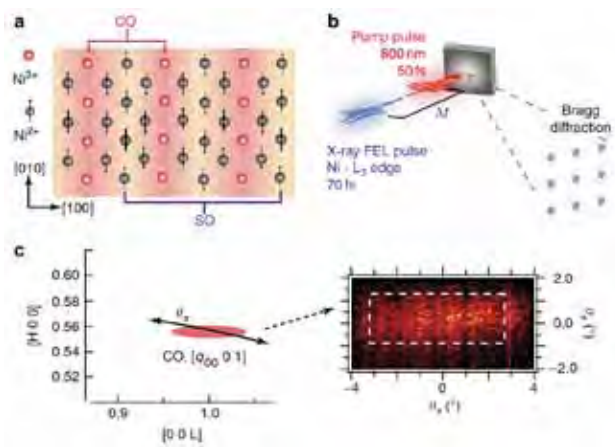
FastCCD 1.0 - 1st Demonstrations

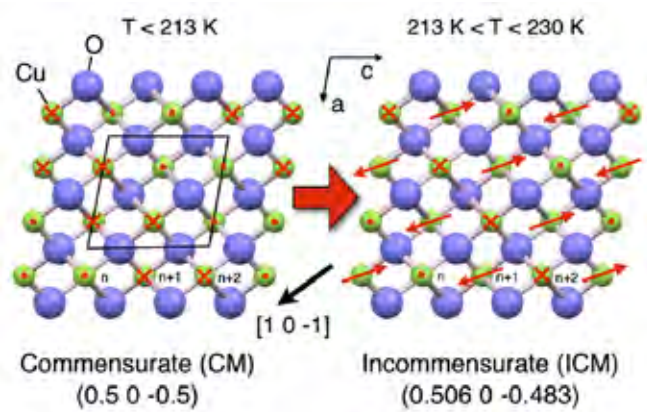
Techniques enabled or enhanced



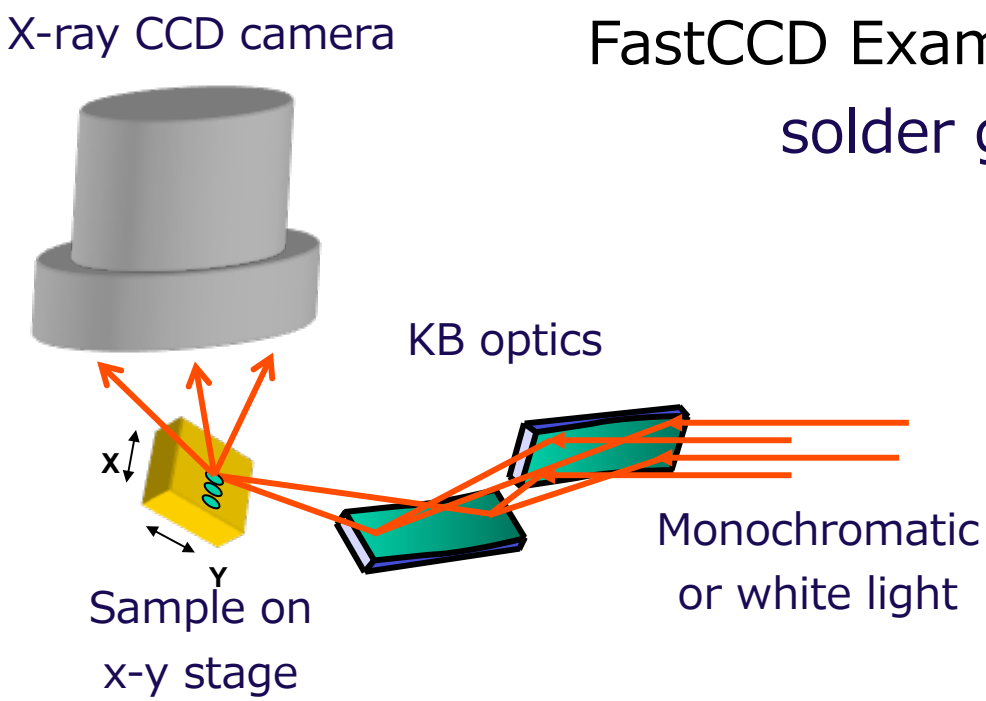




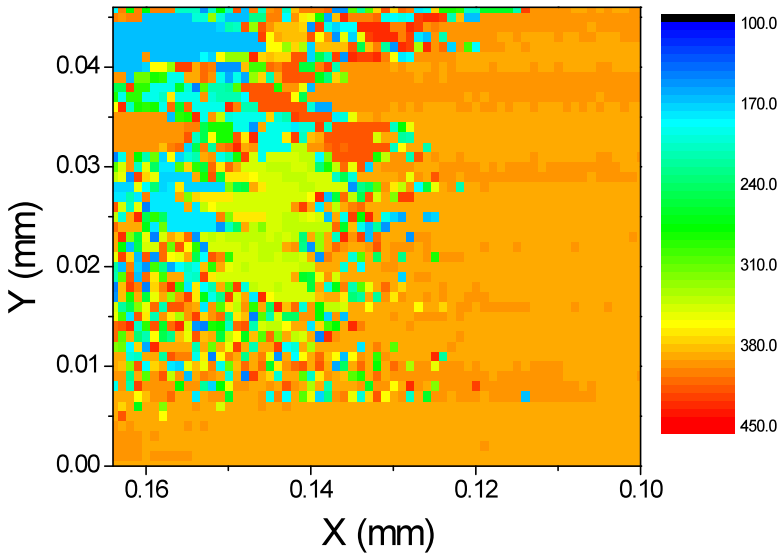




Microdiffraction - Today and Tomorrow - ALS BL 12.3.2

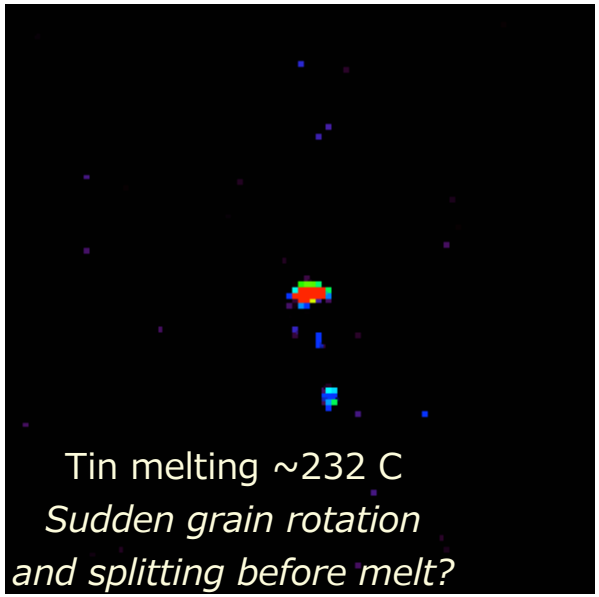


FastCCD Example:
solder grain



6.2 hrs. with conventional phosphor/CCD detector

3 orders of magnitude increase in speed at 200 fps

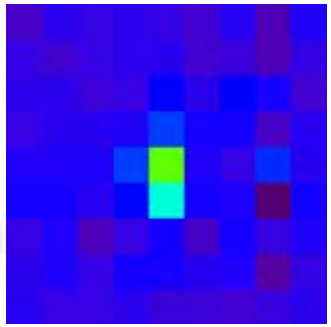


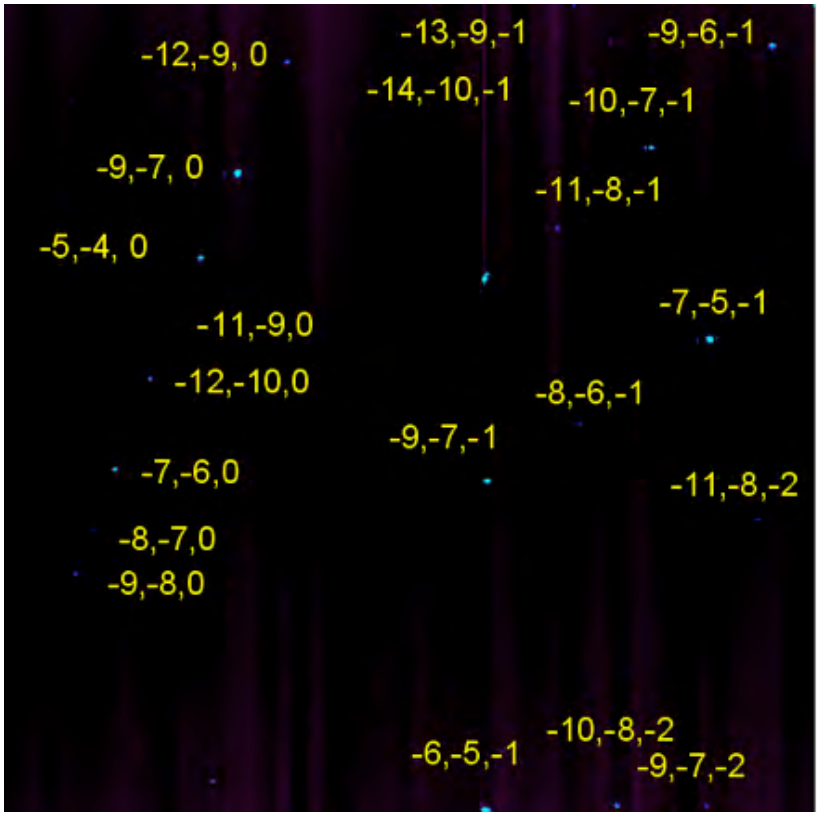
Nobumichi Tamura, Martin Kunz, Kai Chen, Rich S. Celestre, Dionisio Doering, Tae Sung Kim, Peter Denes, Patric Gruber, Andy Minor, Daniel Kiener

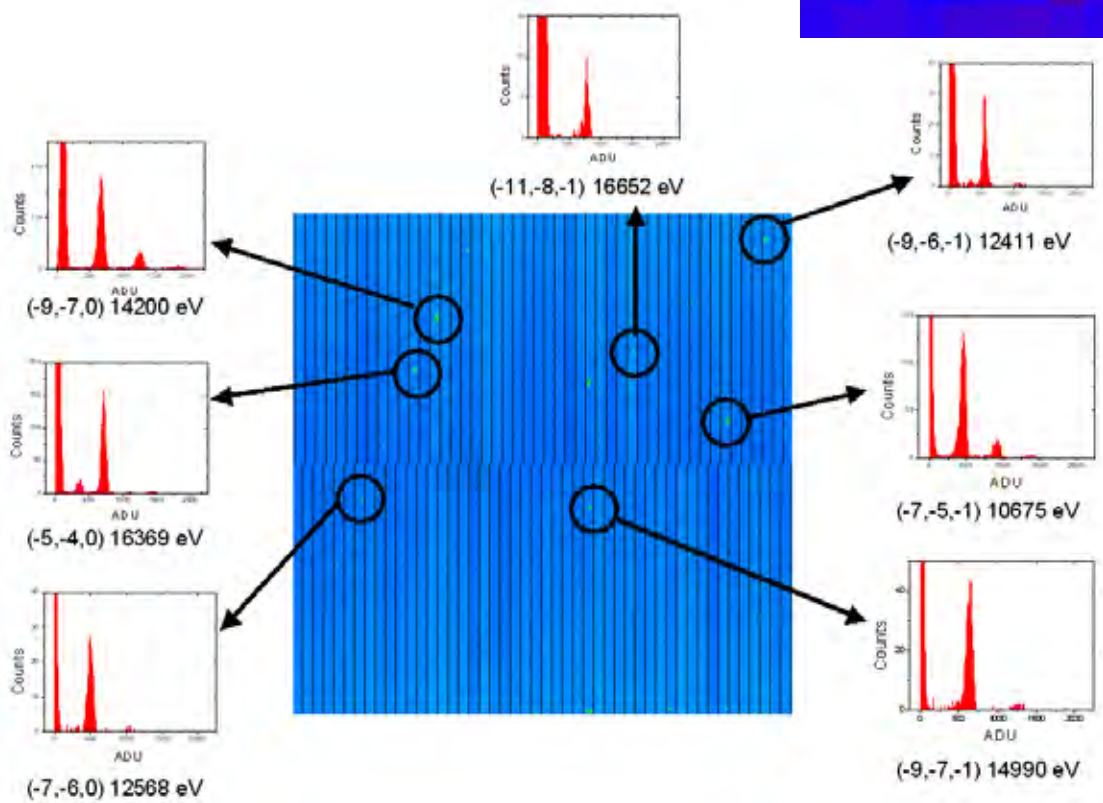
Fast Energy-resolved Laue Diffraction

- FastCCD at high readout rate → single photon counting (spectroscopy)
  - Heterogeneous samples
- Fast alternative to monochromator energy scan

Single Photon

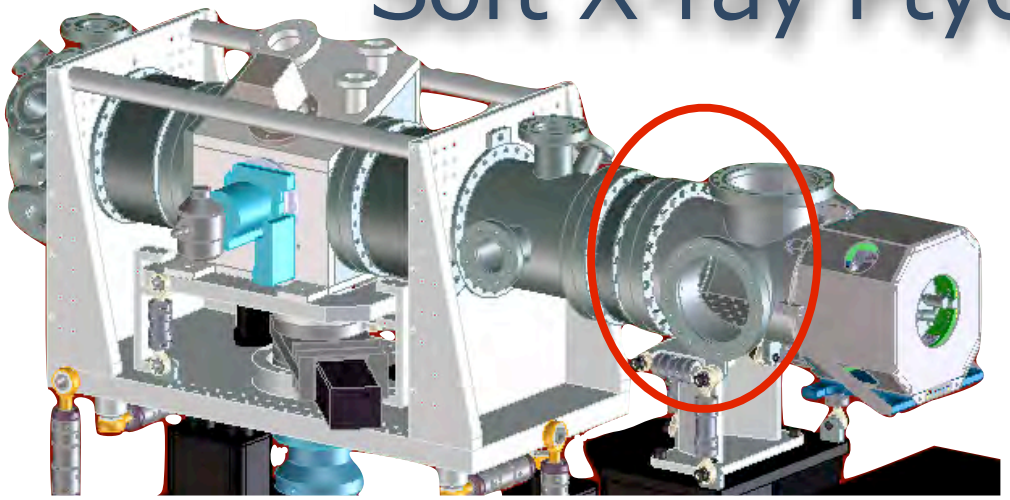




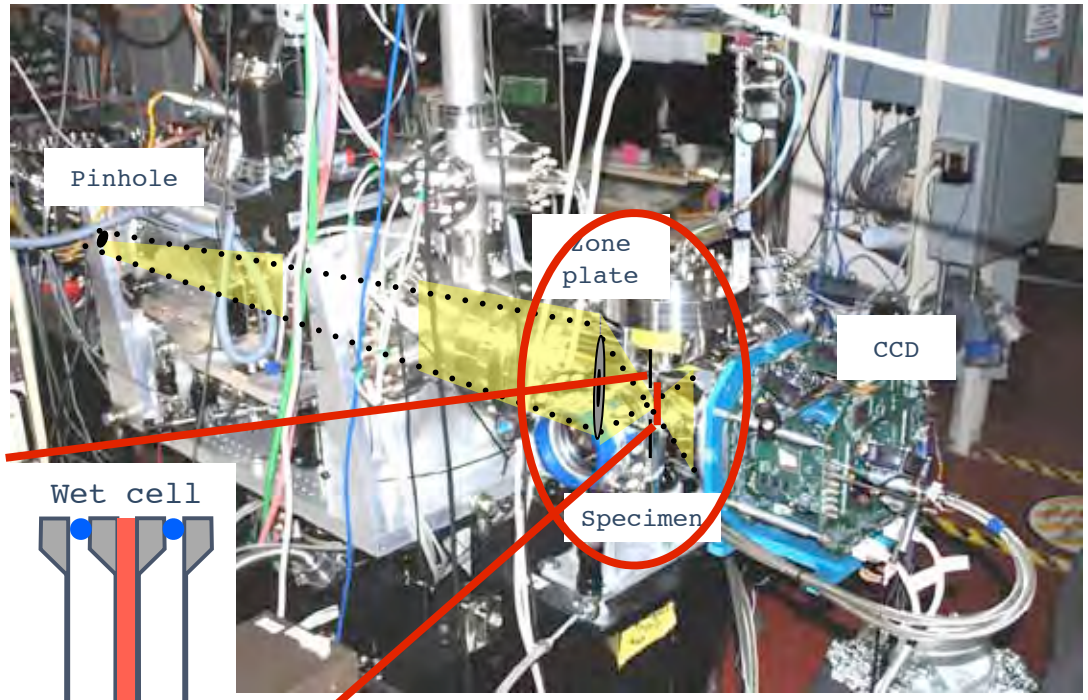


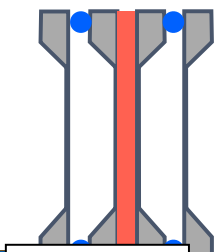
Potassium Titanyl Phosphate $KTiOPO_4$ (or KTP)

Soft X-ray Ptychography - ALS BL 9



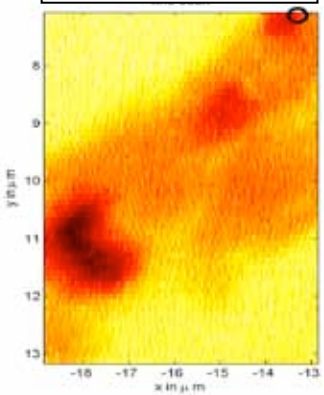
- Implemented ptychography **at 750 eV**
- wet cell
- $2x10^3$ photons/(10 nm)^3/second
- 50 MB/second 4 TB/day



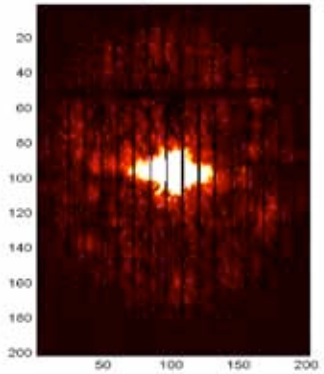


(N. Huse, LBL-UXSL)

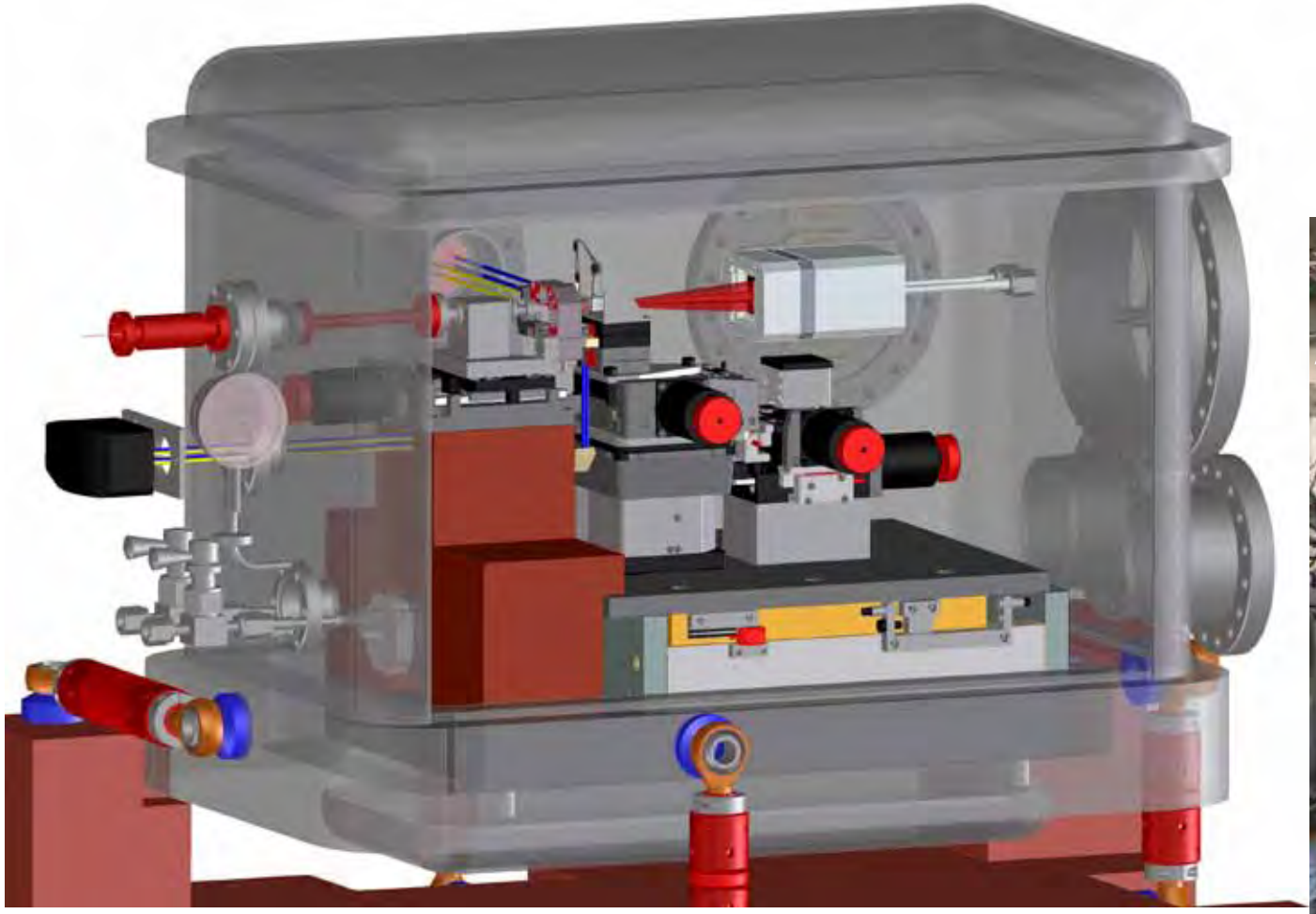
Scanning

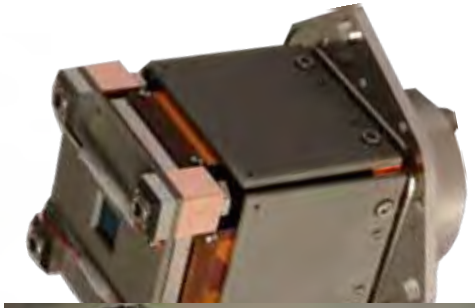


Diffraction

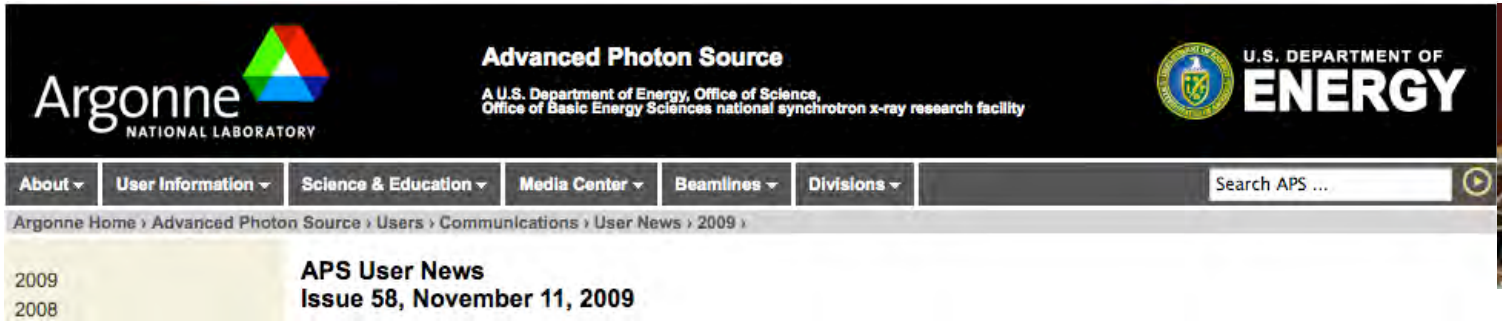


Nanosurveyor - *COSMIC*

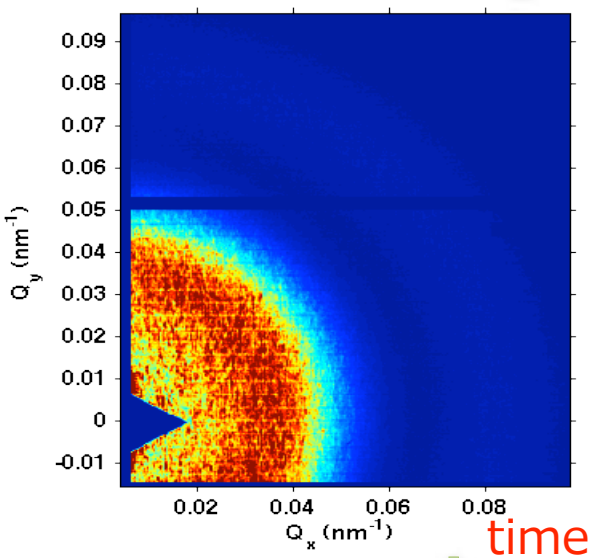


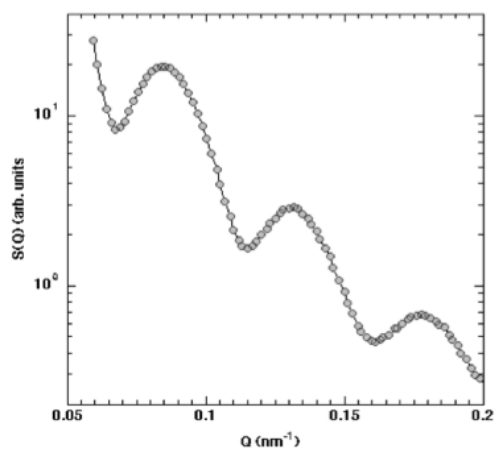


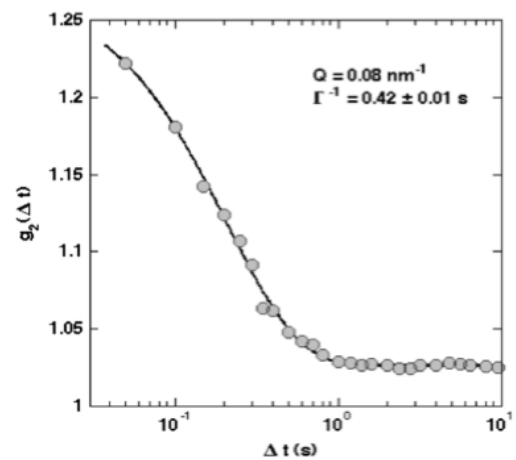
Photon Correlation Spectroscopy - APS BL 8-ID



time autocorrelation





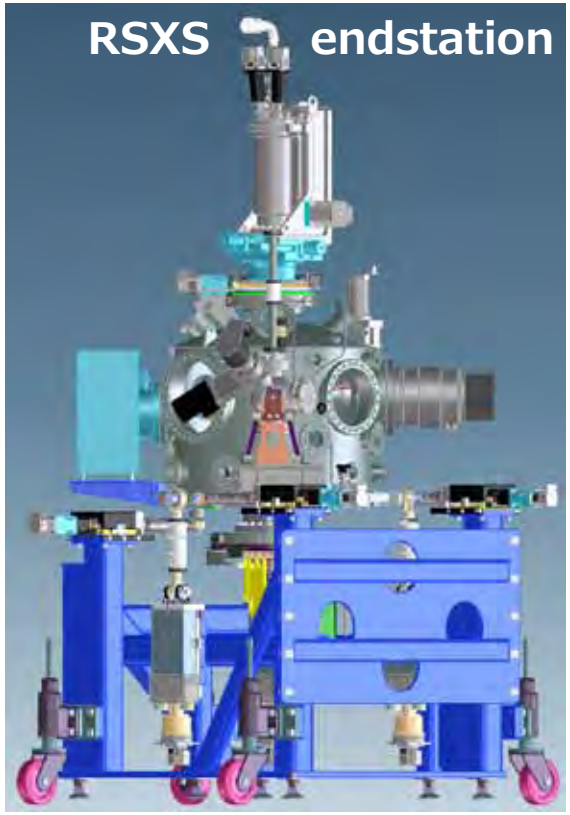


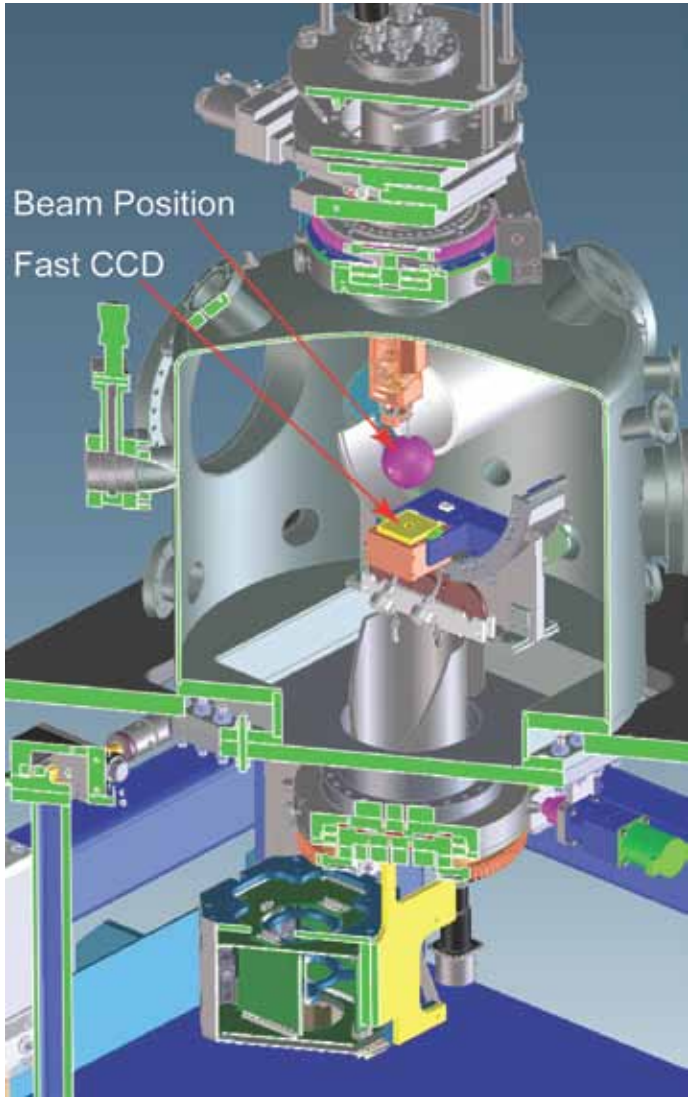
10 ms exposures

time average

XPCS Example – 71nm radius latex spheres in glycerol at ~-20 deg C
(Data courtesy of Suresh Narayanan and Alec Sandy)

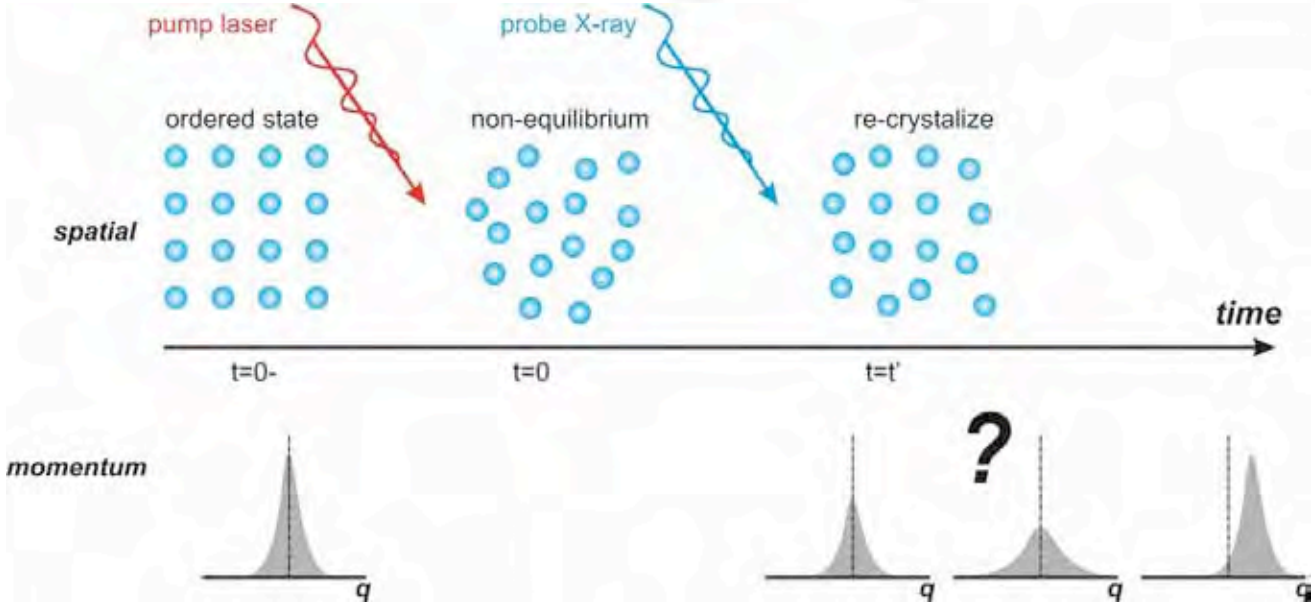
RSXS system for ALS/LCLS



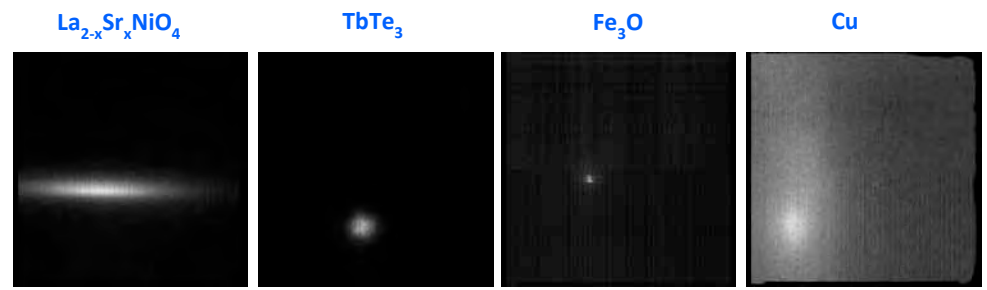


- 360 degrees rotation in horizontal scattering plane
- 90 degrees rotation in vertical scattering plane
- -30 degrees operating temperature (water cooling)
- ~480X480, 30μm square pixels
- 200fps (max) readout

Time Evolution of Charge / Spin Ordering

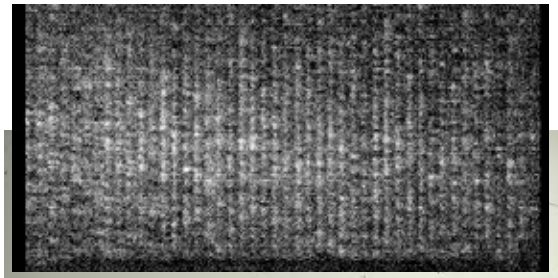


Qualify samples on ALS BL 8.0

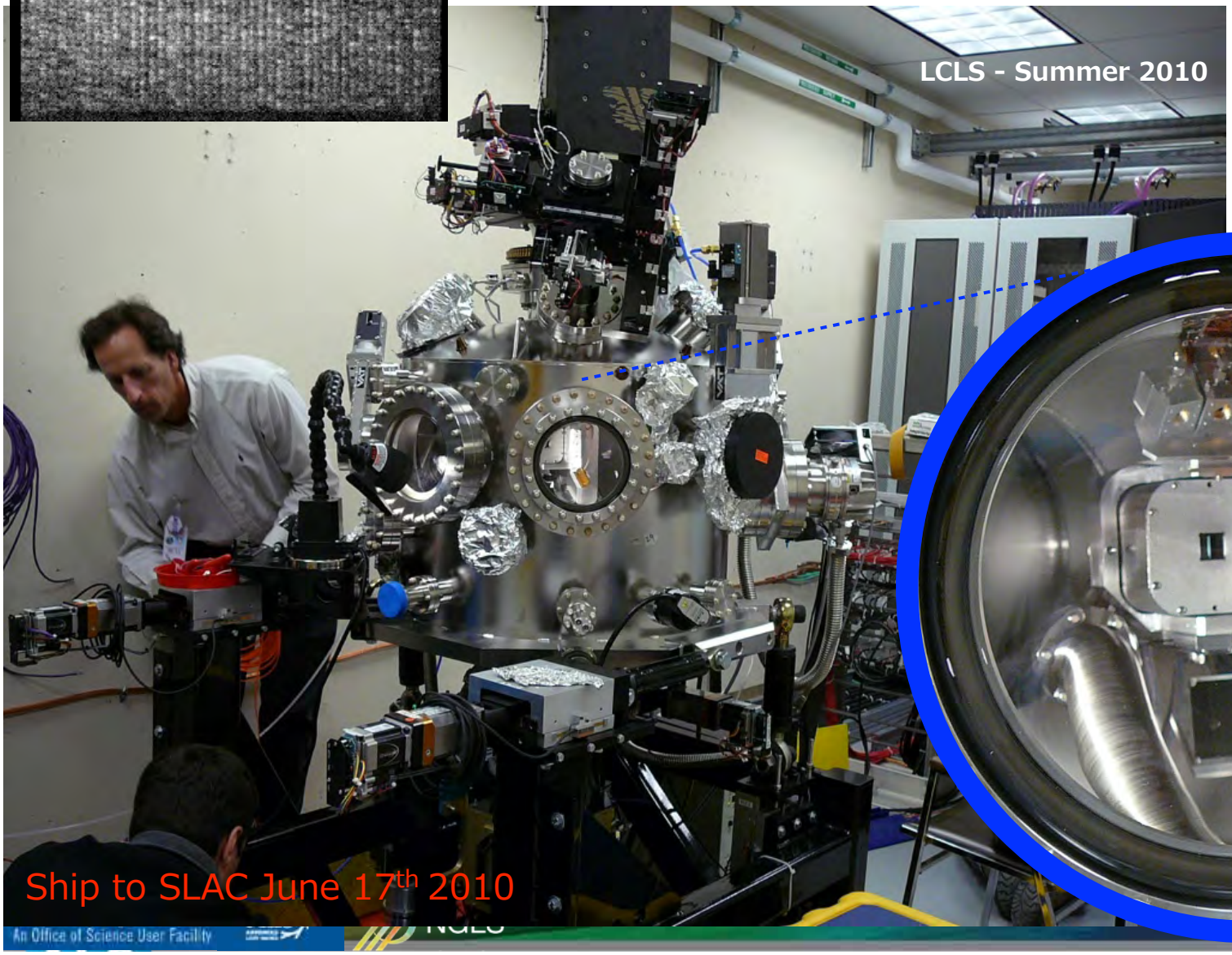


Photon energy = 854 eV | 1240 eV | 720 eV | 930 eV

cFCCD - RSXS Endstation



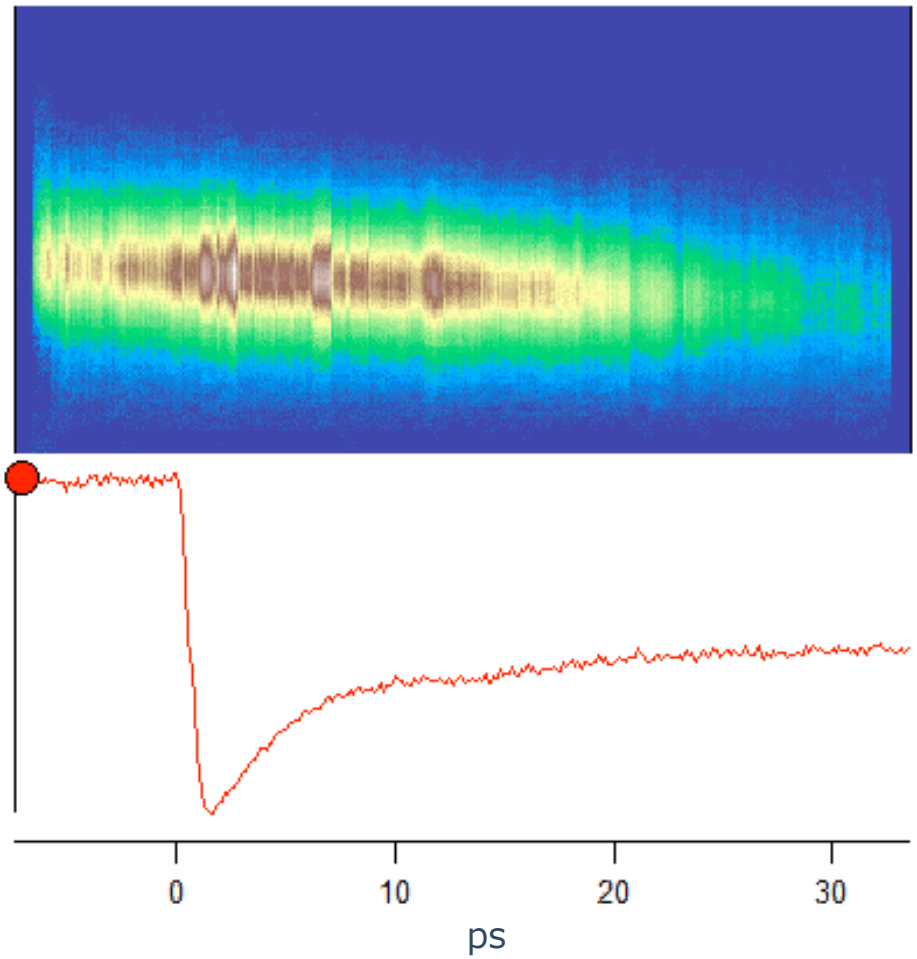
1st light - Jul. 2010

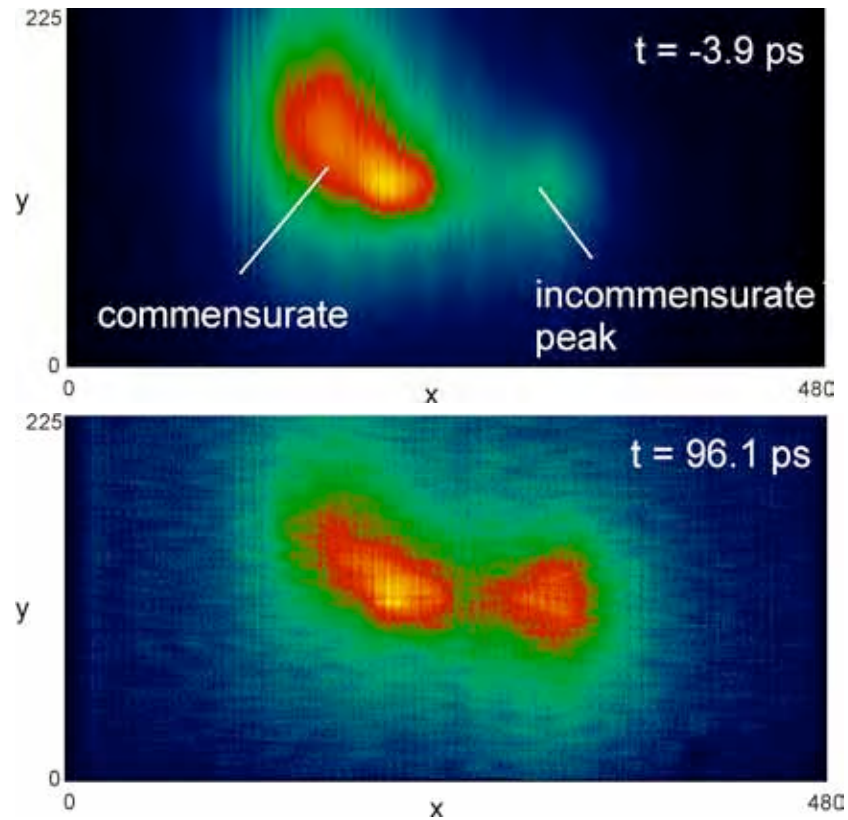


Ship to SLAC June 17th 2010

Spin Ordering (SO) – The Movie

Fast melting and slow recovery of spin ordering around 50K
(shot-by-shot readout to correct time jitter and intensity fluctuation)





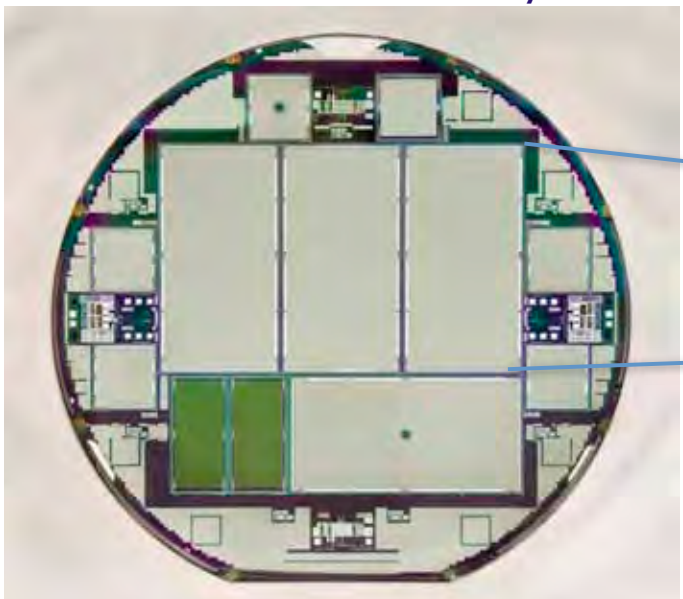
Aug. 2010 - 28 mJ/cm^2

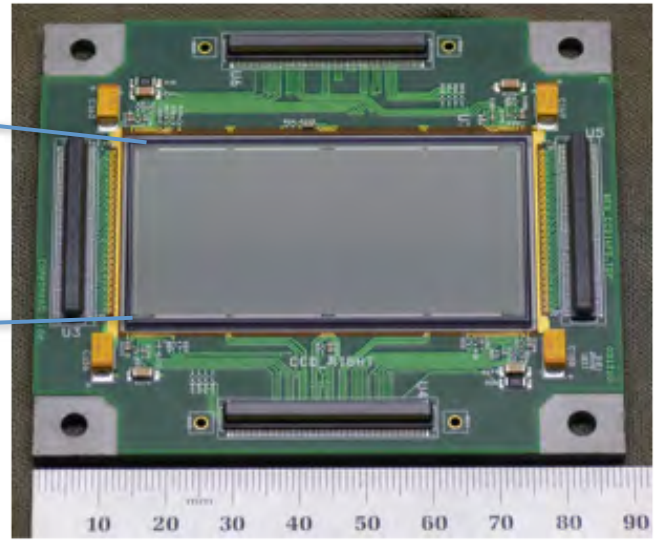
FastCCD 2.0 -1k Frame Store

- 1,920 x 960 30 μm pixels
- Can operate as 2k CCD
- Or 1k CCD with electronic shutter
- 200 fps
- <500 μs shutter

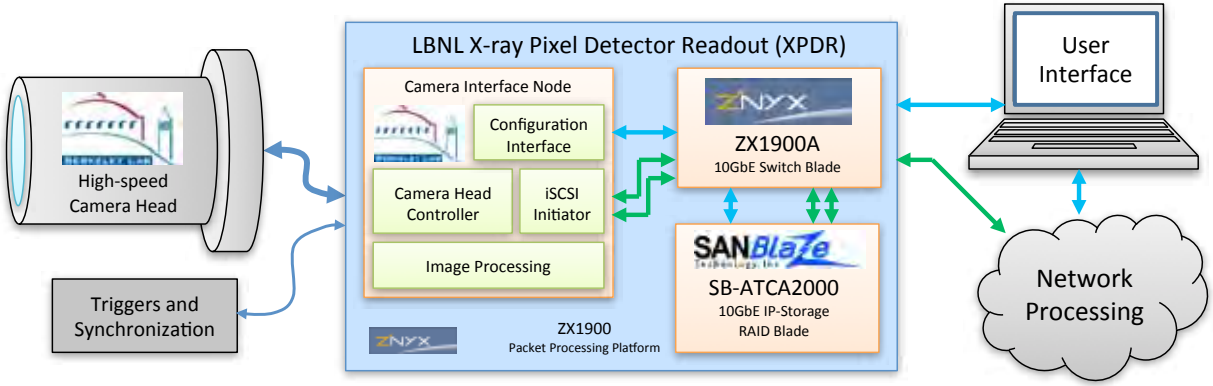
1K Frame Store FastCCD Systems

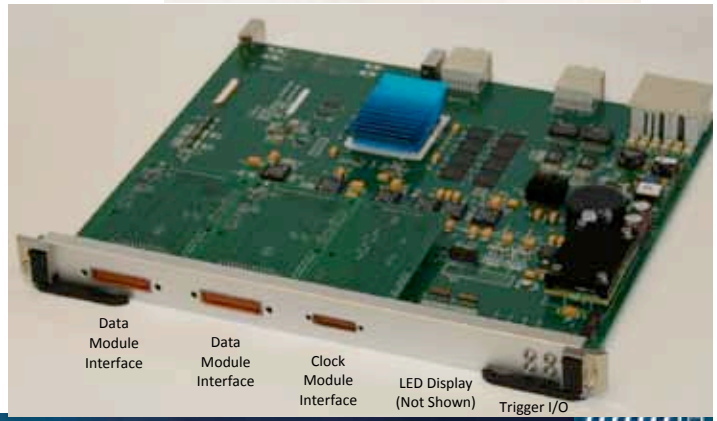
~dozen systems for ALS and APS (XFEL, LCLS and NSLS-I/II)





- Improved readout chip – fCRIC2
- New buffer chip – for higher speed





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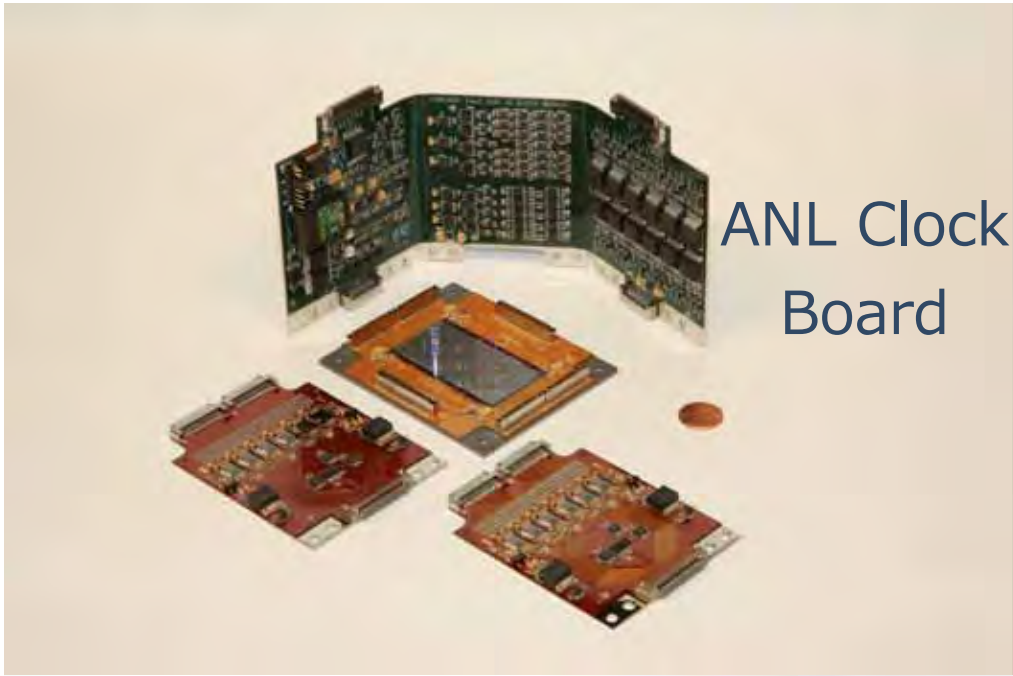
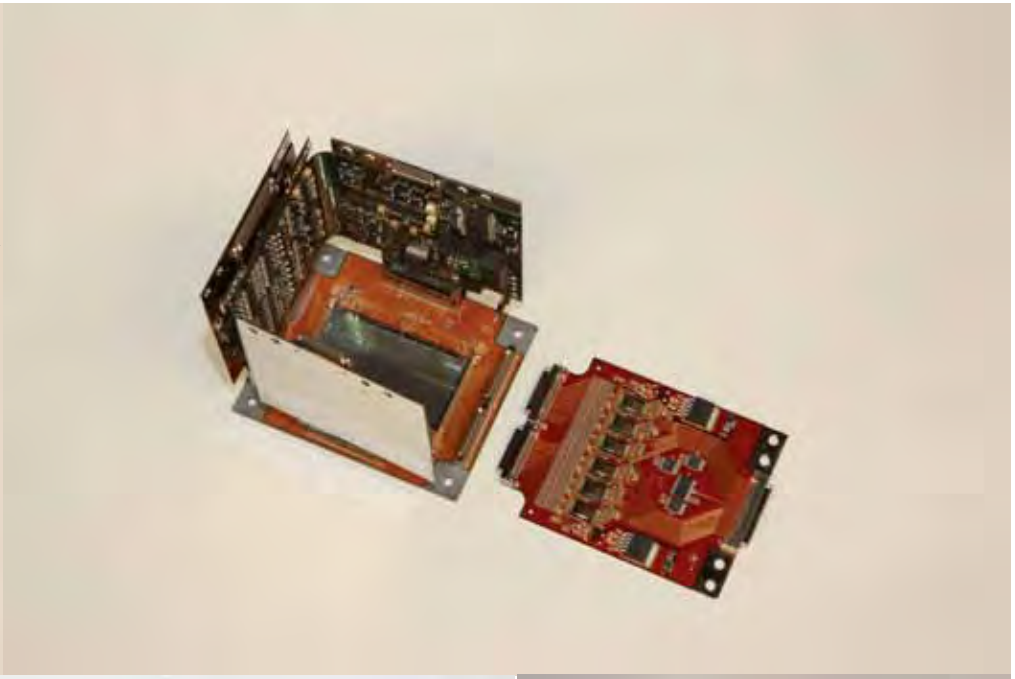
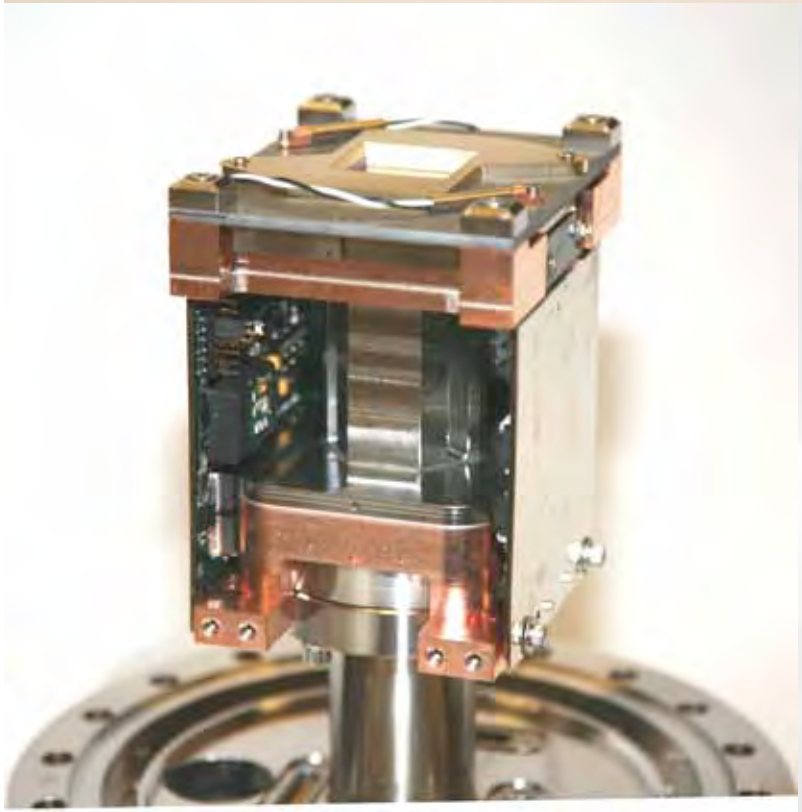
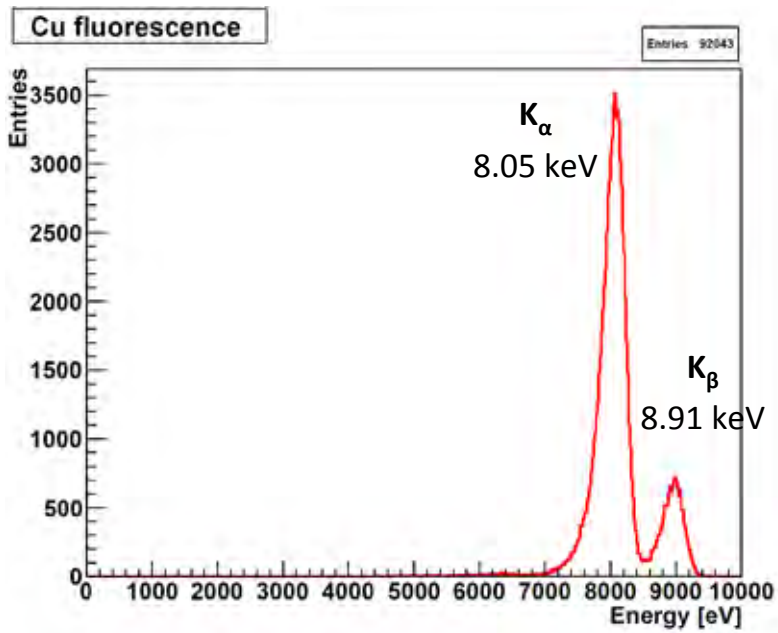
ANL Clock Board

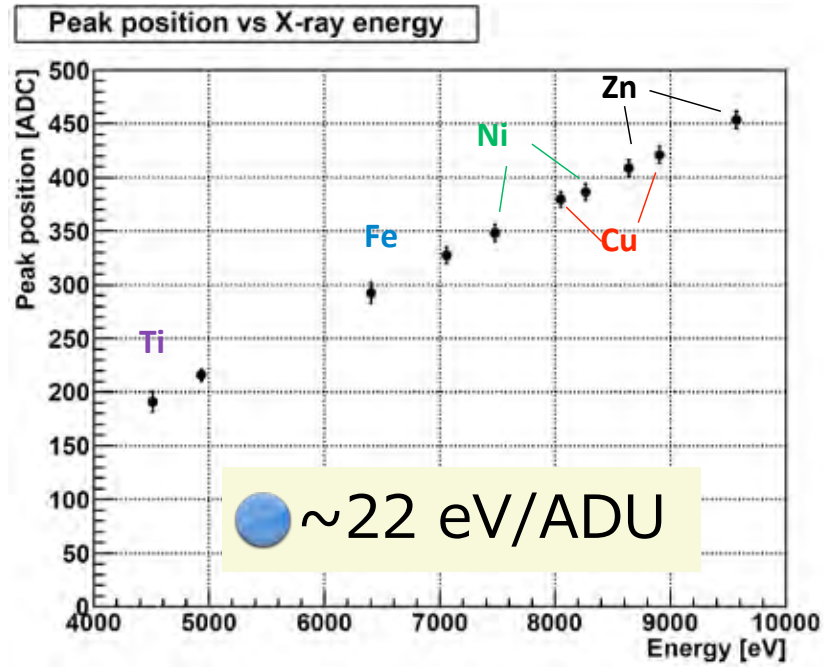




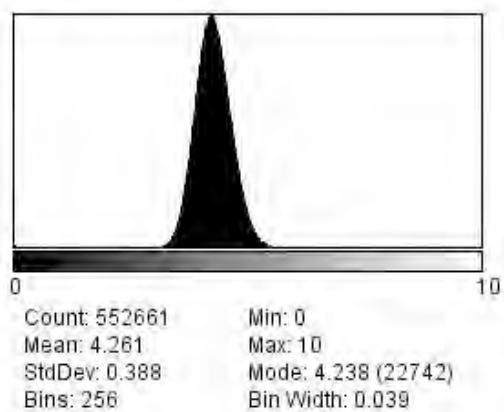


Performance (ALS BL 5.3.1)





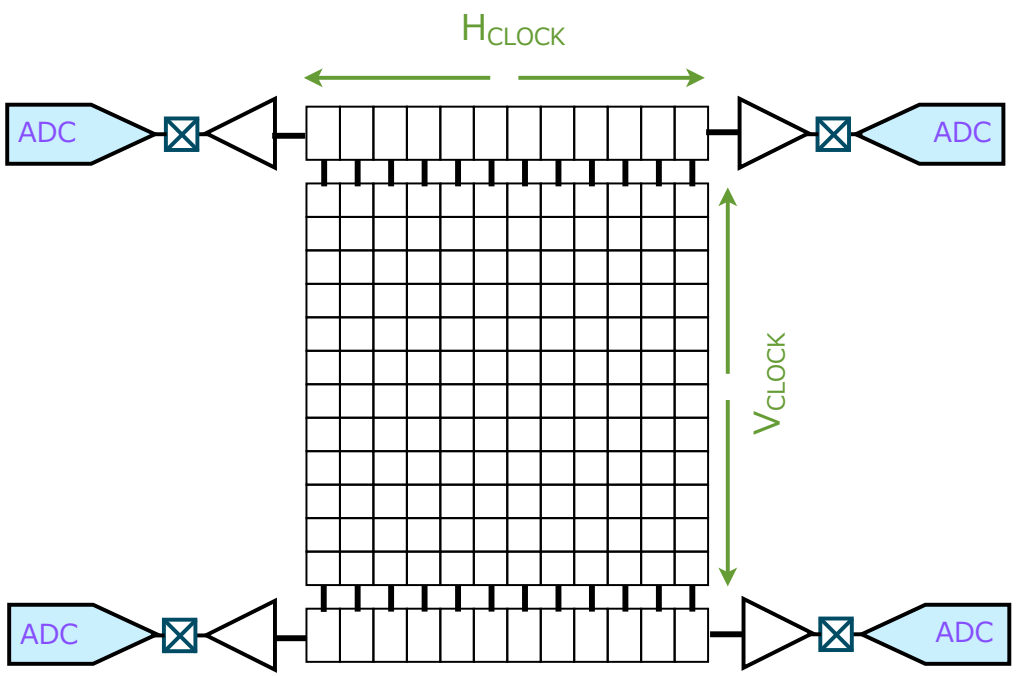
BEAMLINE 5.3.1	
Femtosecond Phenomena	
GENERAL BEAMLINE INFORMATION	
Operational	Yes, but not open to users
Source characteristics	Bend magnet
Energy range	1,000 - 13,000 eV
Monochromator	Si(111) double crystal, W/B4C ML
Flux (1.9 GeV, 400 mA)	~1 x 10^{12} photons/s/3x10^{-4}BW
Resolving power (E/ΔE)	1,200 at 5,000 eV
Spot size at sample	100 x 300 μm
Endstations	Detector testing, KB optics development
Sample format	Crystals, foils
Sample environment	10^{-6} Torr vacuum or air



Noise distribution:
<Noise> = 90 eV
(25 electrons)

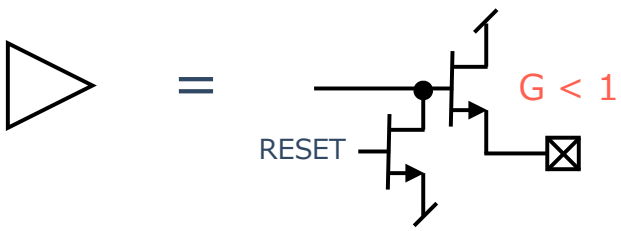
T = -50°C, exposure time = 20 ms, V_{SUB} = 50 V.
All spectra for single pixel events

Evolution of CCD Readout

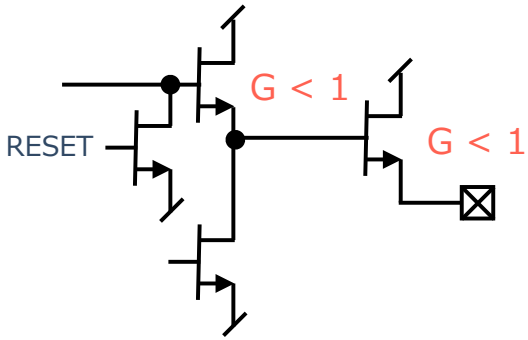


Conventional CCD
4-port
Commercial readout
10^0 fps

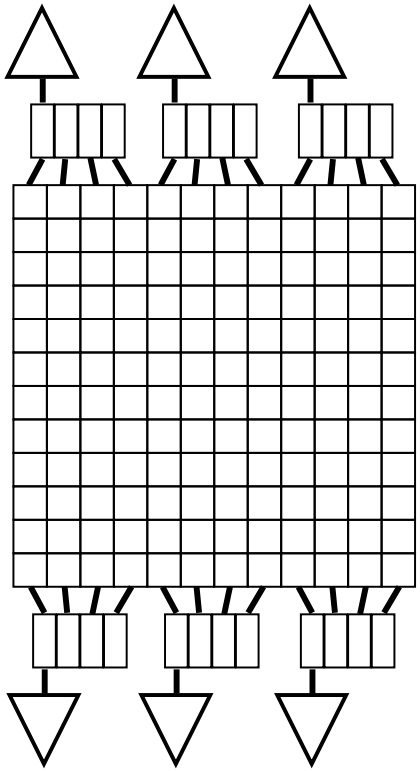
- Slow V_{CLOCK}
- Fast H_{CLOCK}
- Fast ADC
- Multi-stage CCD output



or



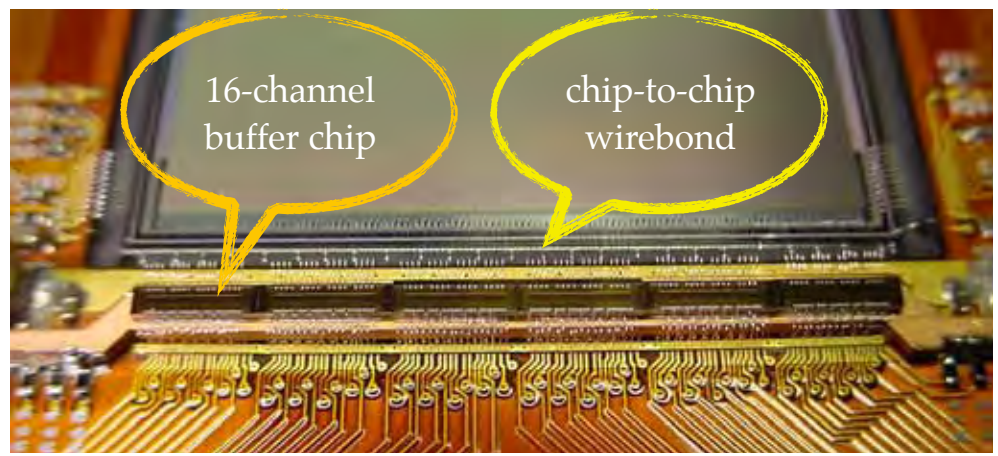
Evolution of CCD Readout - (a)CP-CCD



- Slow V_{CLOCK}
- Fast H_{CLOCK}
- Fast ADC (ASIC)
- Single-stage output

- Buffered output
  - t_R ~100 ns → ~ns
  - Gain ~30% signal

FastCCD
(almost)Column Parallel
fCRIC (custom 0.25 µm CMOS readout IC)
10^2 fps

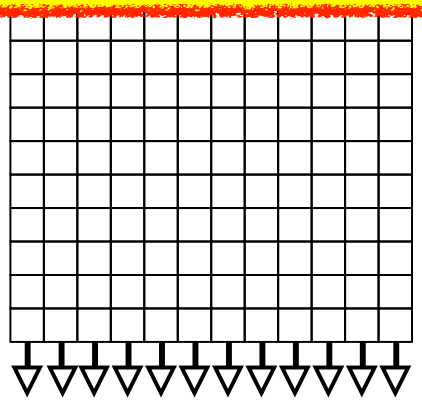


0.35 µm HVCMOS - 2011

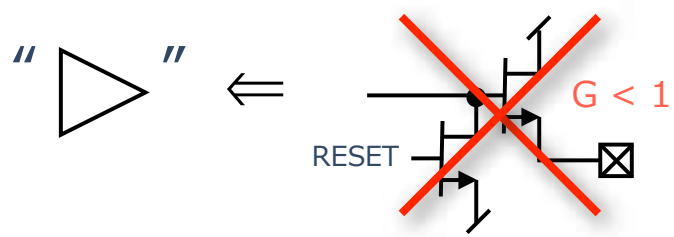
Evolution of CCD Readout - CP-CCD

Challenge: Fast V_{CLOCK} with reasonable power

- Fast V_{CLOCK}
- Faster H_{CLOCK}
- Faster ADC (ASIC)
- No SF Output

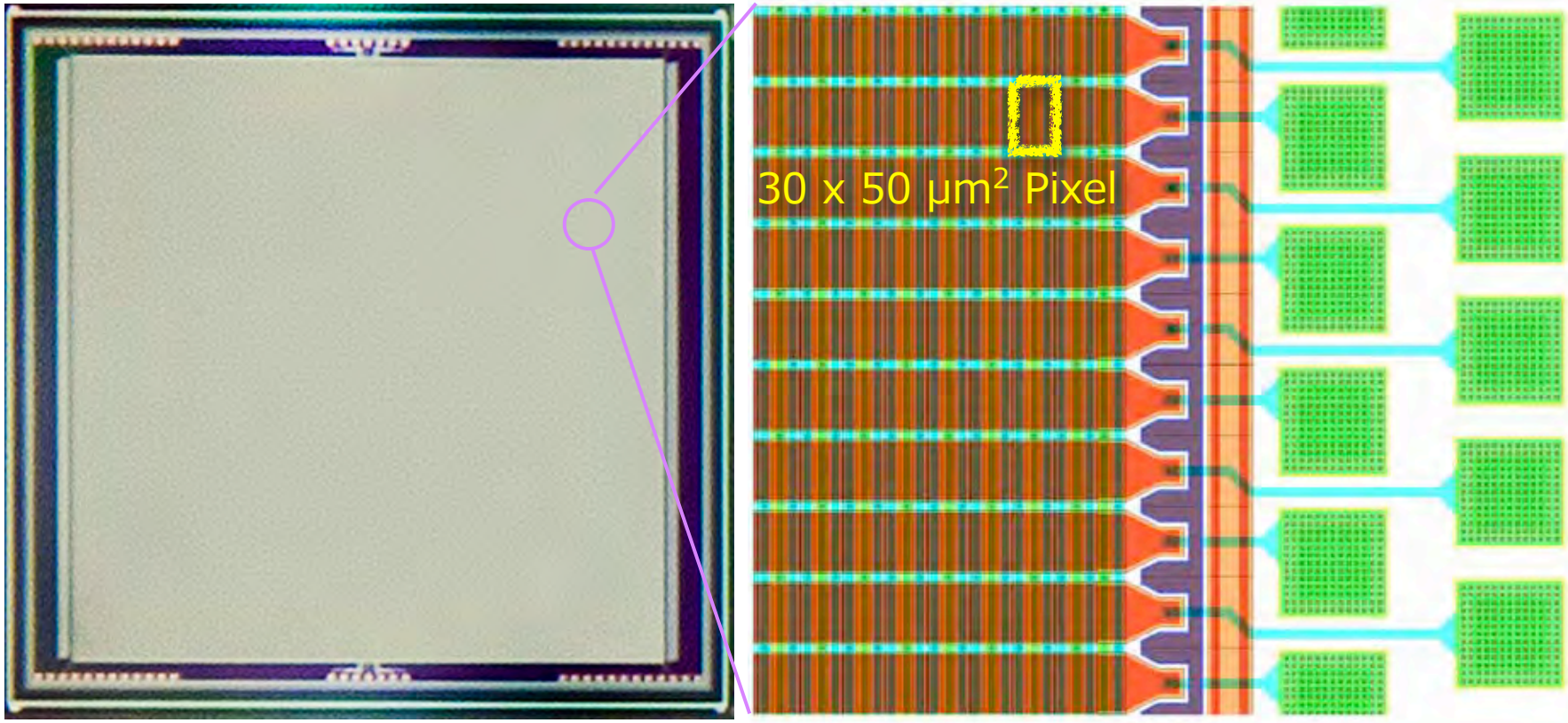


Highly parallel digitizers



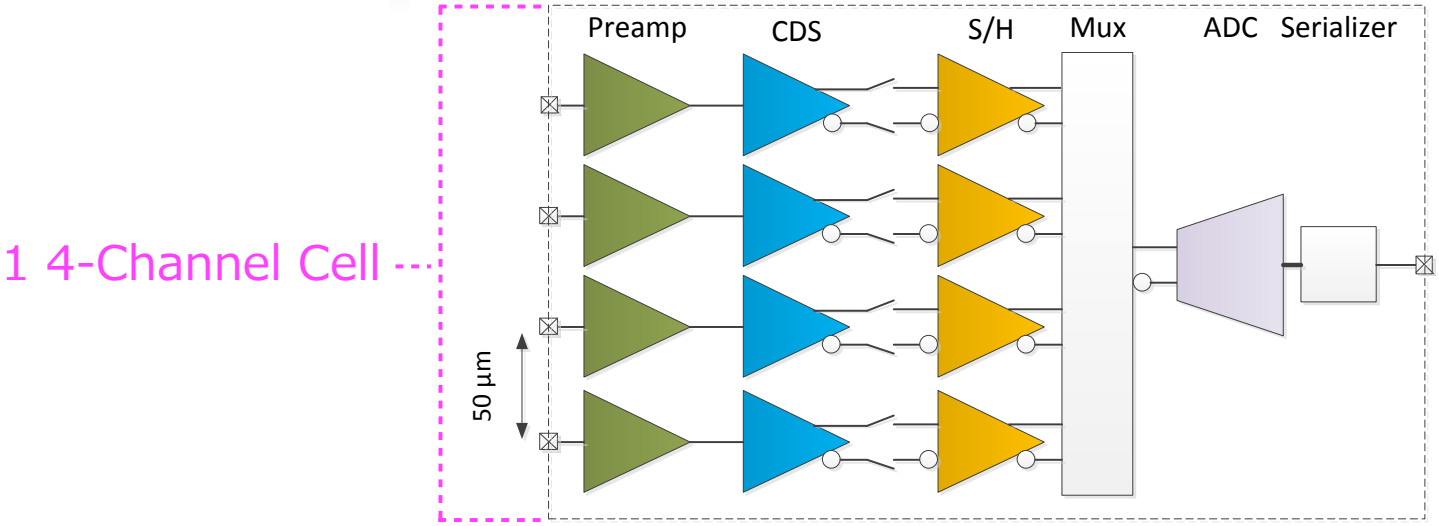
Very FastCCD
Column Parallel
HIPPO (custom 65 nm CMOS readout IC)
$>10^{3\text{-}4}$ fps

VFCCD - CCD



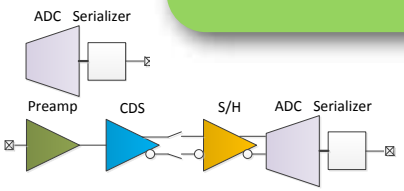
- 50 μm pitch for chip-to-chip wire bonding
- Aim for 10,000 MPix / s

HIPPO High-Speed Image Pre-Processor with Oversampling



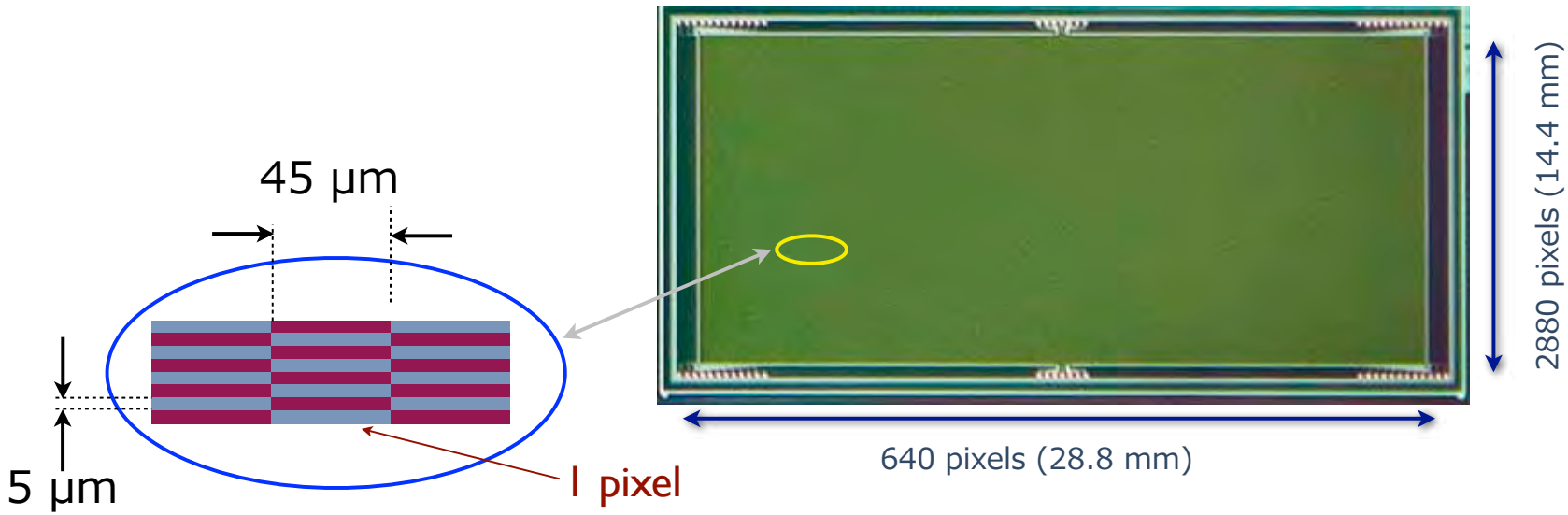
Requirement	Value	Units	Comment
Resolution	12	Bits	
Sampling Rate	80	MS/s	
Full Scale	1	Volts	V_{pp}-differential
Noise (ADC)	200	µV-rms	LSB is 250 µV
Noise (Full)	1.4	LSB	
Linearity	10	Bits	Differential
Circuit Pitch	50	µm	match CCD
Serial Output	480	Mb/s	dual data rate

10 MHz
x 4 (40 MHz)
+ CDS (80 MHz)



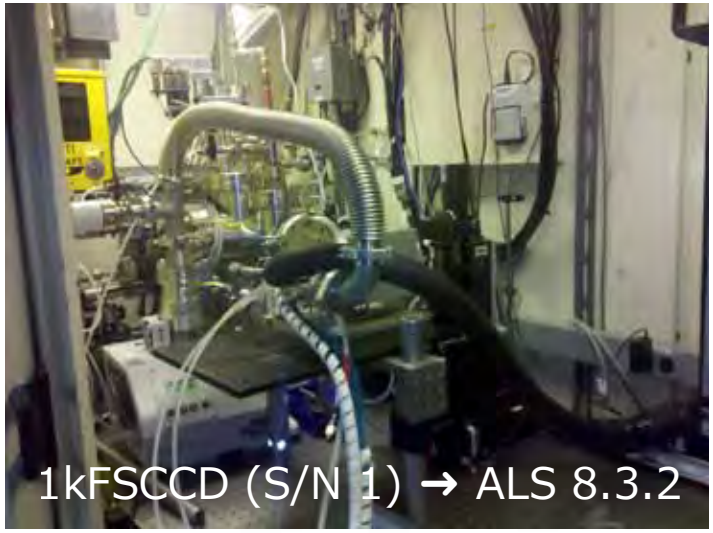
65 nm CMOS - 2011

Fine-pitch CCD for Spectroscopy



- "Conventional" 4-port CCD
- Anticipate <4 e– noise can be obtained at 50 - 100 kHz readout
  - 2880 x 640 = 1.8 x 10^6 pixels
  - 4 ports ➜ 4.6 x 10^5 pixels / port
  - ~5 (10) second readout at 100 (50) kHz

Summary



- Fully-depleted, thick CCDs as X-ray detectors
  - Obtain speed by parallelism
- Thin contacts required
  - Low temperature process required post metalization

- Other monolithic structures we work on:
  - Bulk CMOS APS (thinned, implanted) for SXR
  - Silicon-On-Insulator

- Data volumes will grow immensely
  - Eu XFEL, NGLS, further developments at storage rings
  - Compression and “pre-analysis” becoming part of detector development

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Together with:
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ALS Scientific Support Group
APS Beamline Technical Support Group
National Center for Electron Microscopy

Engineering Division
- Electronic Systems Group
- Integrated Circuit Design Group
- Microsystems Laboratory

Physics Division