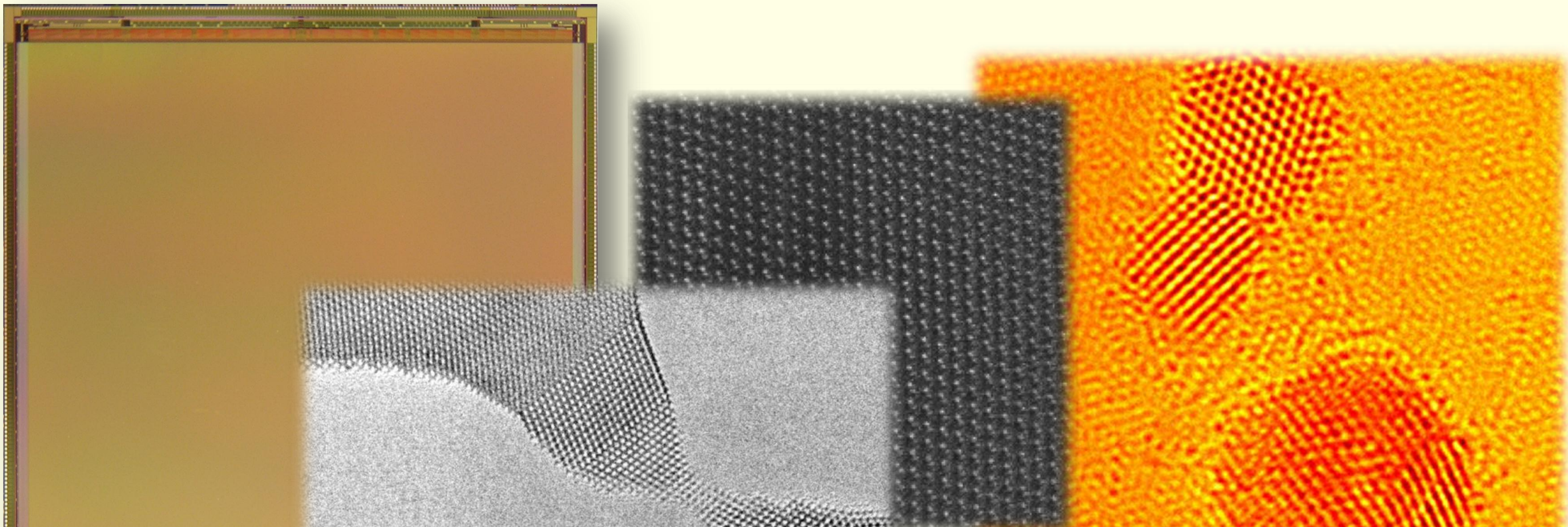
High speed, radiation hard CMOS imagers for high resolution Transmission Electron Microscopy



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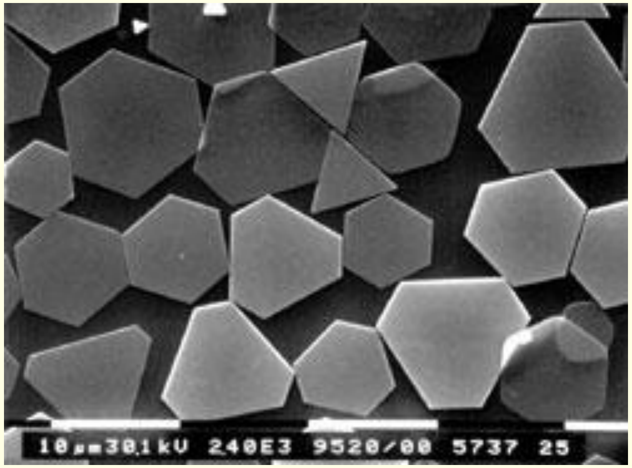
BERKELEY LAB
Lawrence Berkeley National Laboratory

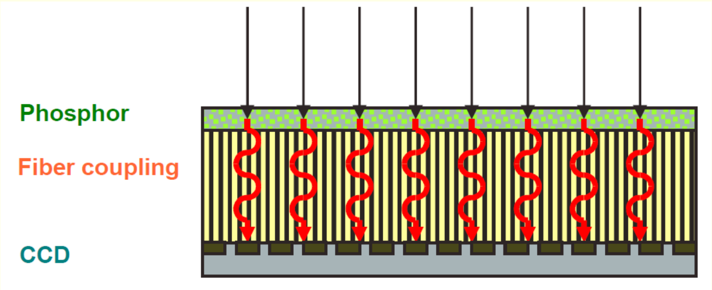
TIPP 2011
Technology and Instrumentation in Particle Physics 2011

Chicago, June 9, 2011

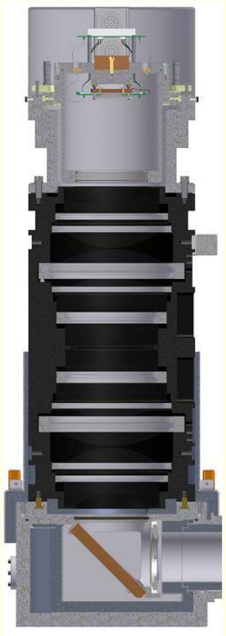
Introduction: imaging in TEM



Film



Optically Coupled CCDs



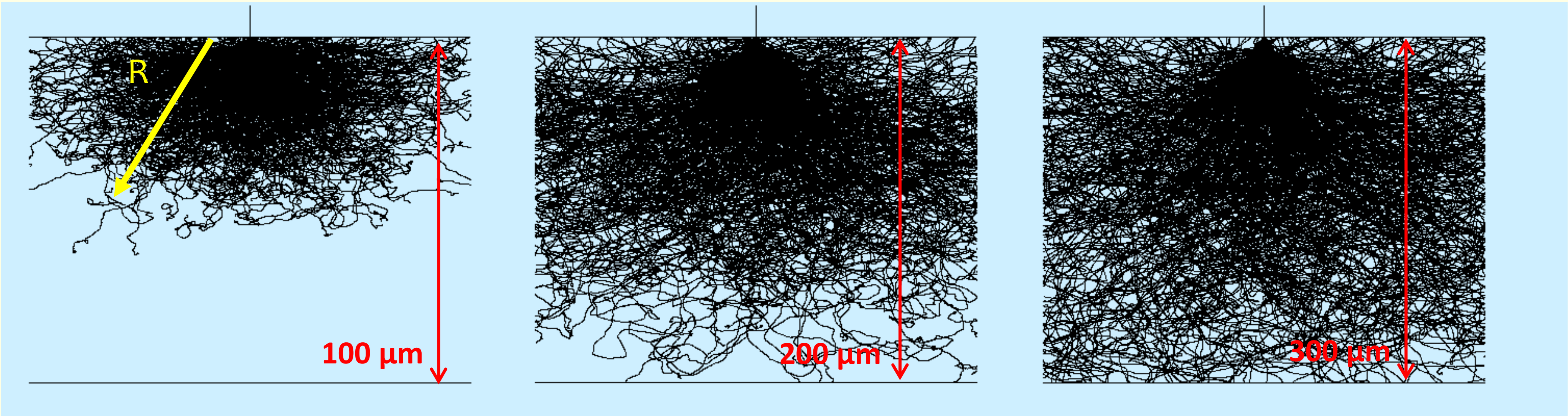
- Traditional direct detectors such as **film** or **image plates** have large area and high granularity, but are slow and do not allow fast dynamic imaging

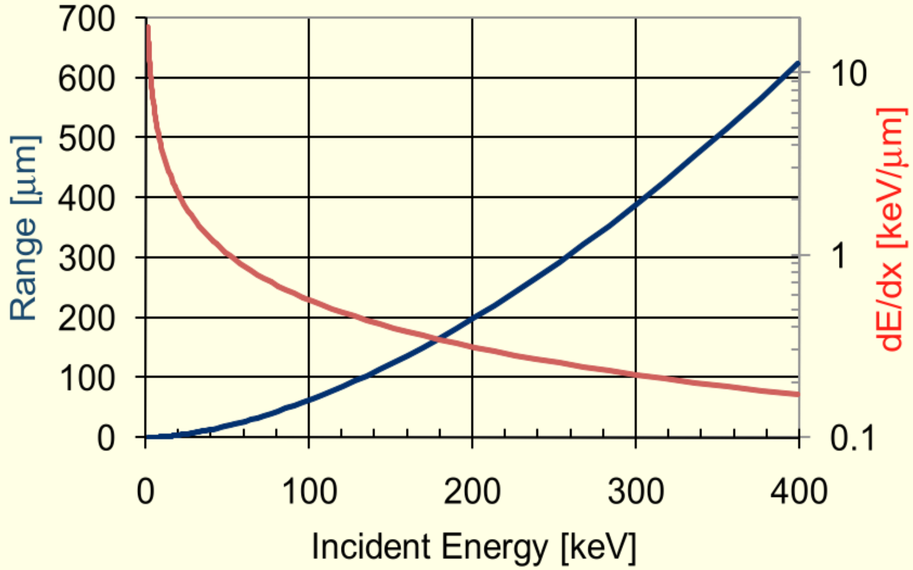
- **Optically-coupled CCDs** have limited Point Spread Function (PSF) due to the presence of the scintillator and to back-scattering from fiber optics

- **Direct semiconductor detectors** allow higher PSF and Detective Quantum Efficiency (DQE), can be high-speed, high-granularity and include processing capabilities (e.g. back-scatter discrimination) → ideal candidates for applications such as fast in-situ imaging or low-dose biological cryo-EM

Direct detectors (semiconductor)

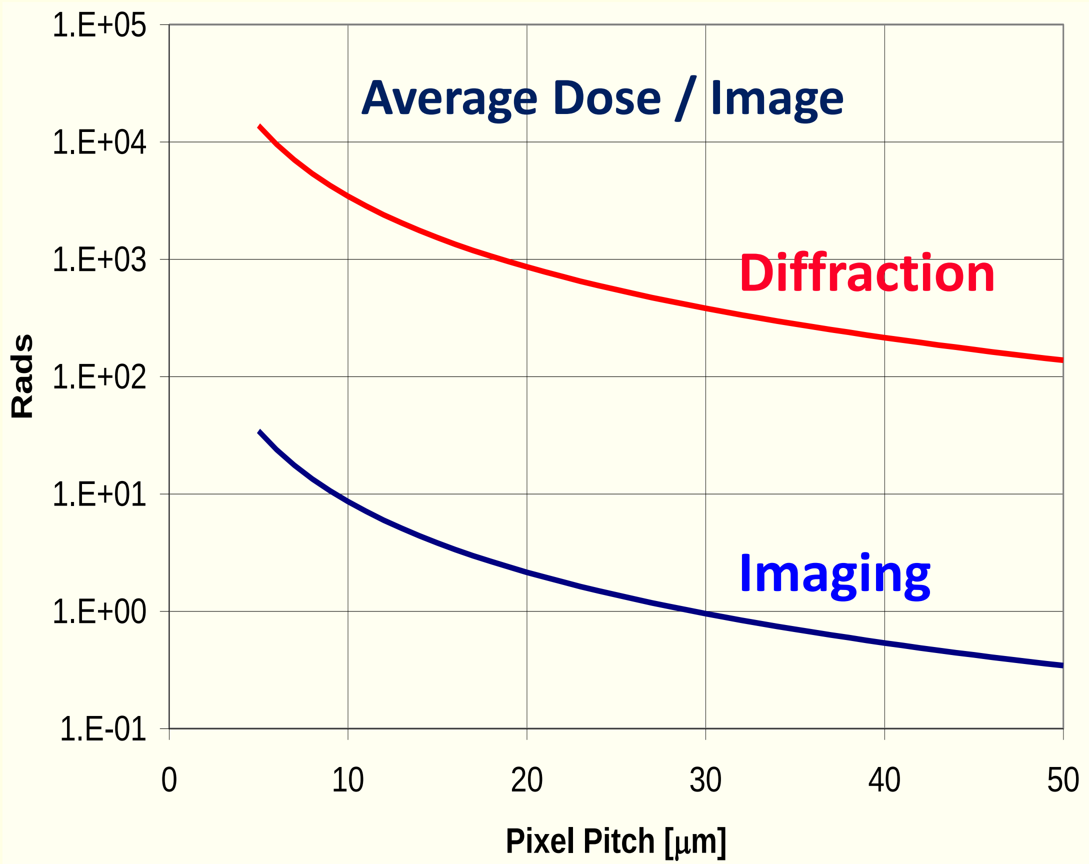
Driving detector R&D: multiple scattering

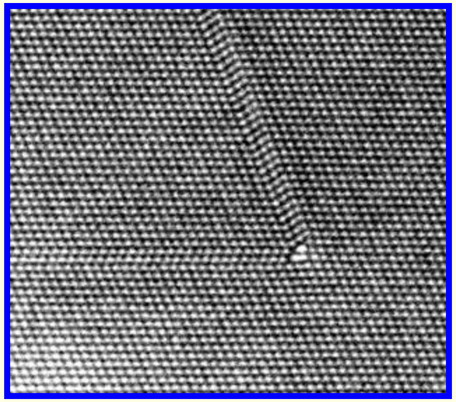




- Energies of interest to TEM: 80-400 keV
- Electron range **R [µm] ~ E [keV]**
- Energy loss **dE/dx ∝ 1/E**
- Need for a thin sensitive layer to minimize scattering contribution to Point Spread Function

Driving detector R&D: radiation hardness



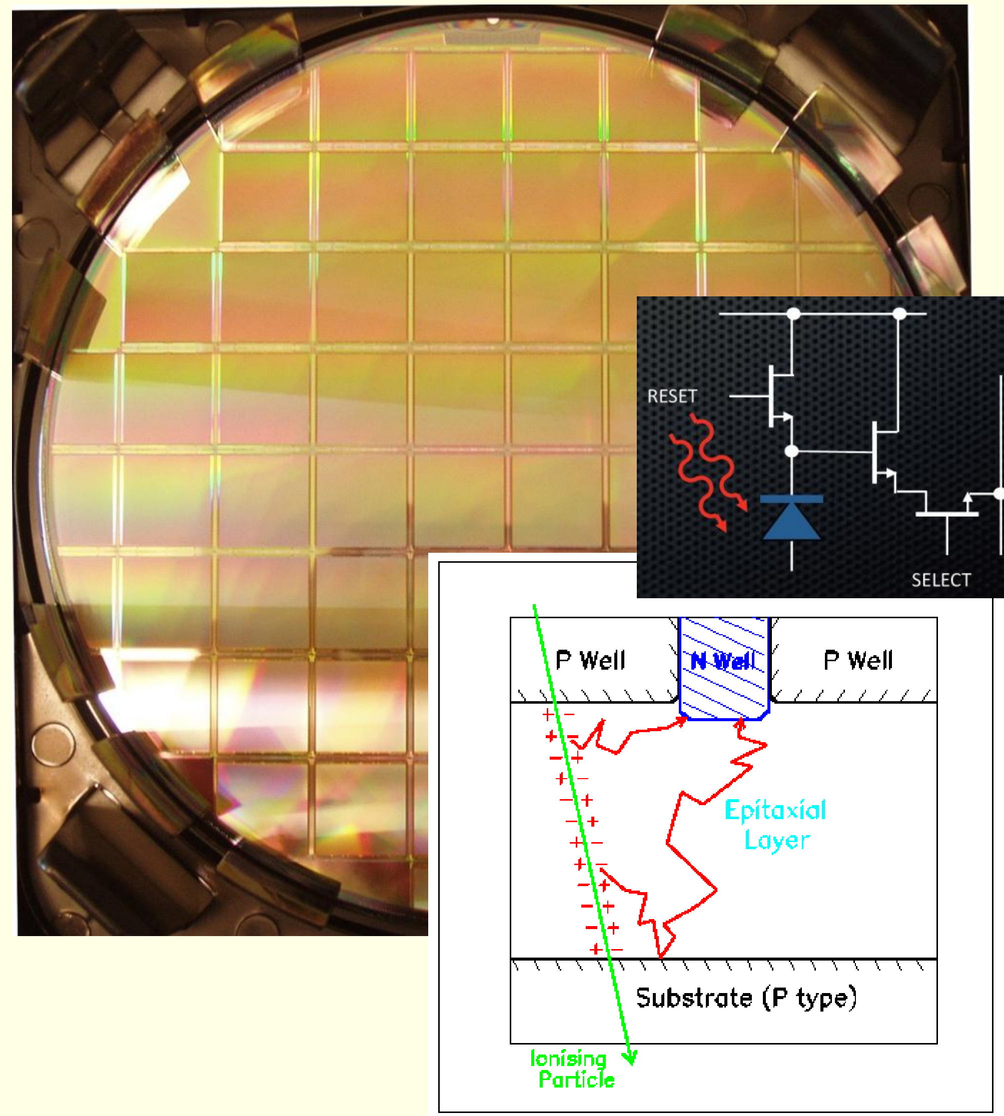


- Imaging mode: O(Mrad) ionising dose expected for typical yearly usage
- Diffraction mode: very high doses localized in bright spots
- Radiation tolerance requirements comparable with HEP applications
- Highly sensitive detectors require low node capacitance → high sensitivity to radiation → need for careful radiation tolerant design of pixel cell

CMOS imagers: new eyes for TEM

- CMOS Monolithic Active Pixel Sensors provide high resolution and low material budget particle detectors at low cost, as they are fabricated in commercial manufacturing processes

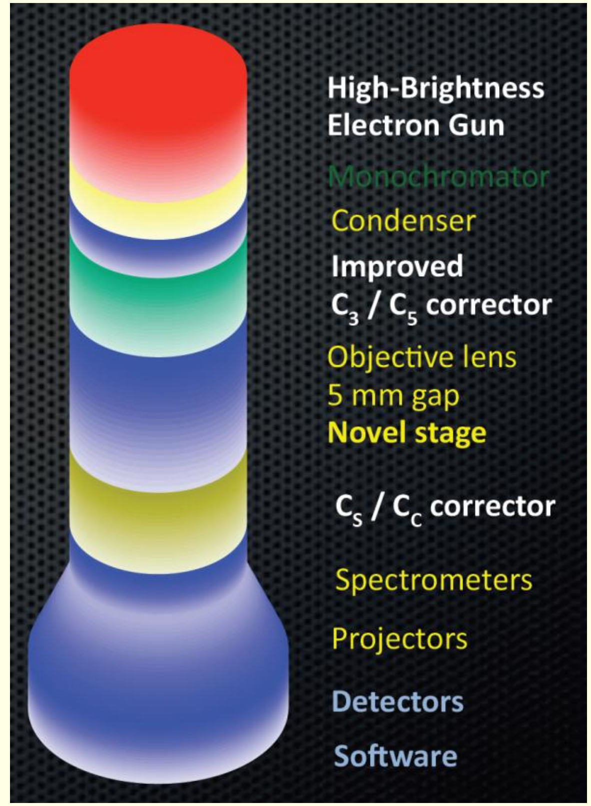
- CMOS pixels are being developed as an alternative to conventional, optically-coupled CCD cameras for TEM imaging. Advantages:
  - Single electron sensitivity from direct electron detection
  - Excellent Point Spread Function: small pixels and thin sensitive volume
  - High readout speed: several 100 frame/s achievable for Megapixel-scale imagers
  - Improved radiation hardness: lifetime of several years possible

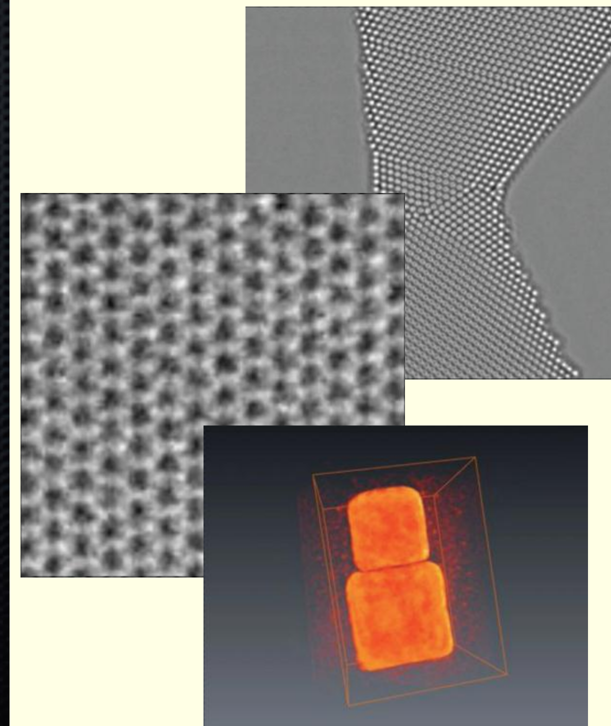


The TEAM project

TEAM: Transmission Electron Aberration-corrected Microscope

http://ncem.lbl.gov/TEAM-project/index.html



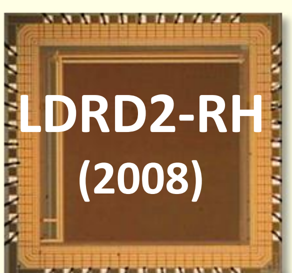


- Funded by the US Department of Energy, Office of Science, Basic Energy Sciences
- 80-300 keV electron energy, 0.5Å spatial resolution TEM/STEM, 0.1 eV δE
- Major advances in electron optics and aberration correction to obtain excellent spatial resolution
- Capabilities for 3D tomography and in-situ experiments; development of novel stage for atomic-scale tomography and novel detector for in-situ/dynamics studies
- Project completed 09/2009, now national user facility

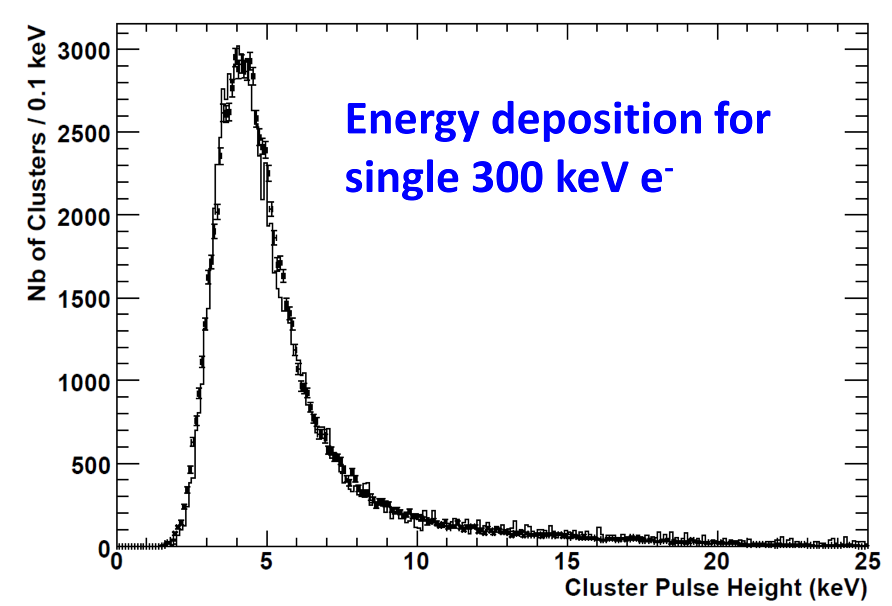
U.S. DEPARTMENT OF ENERGY
Office of Science
U.S. Department of Energy

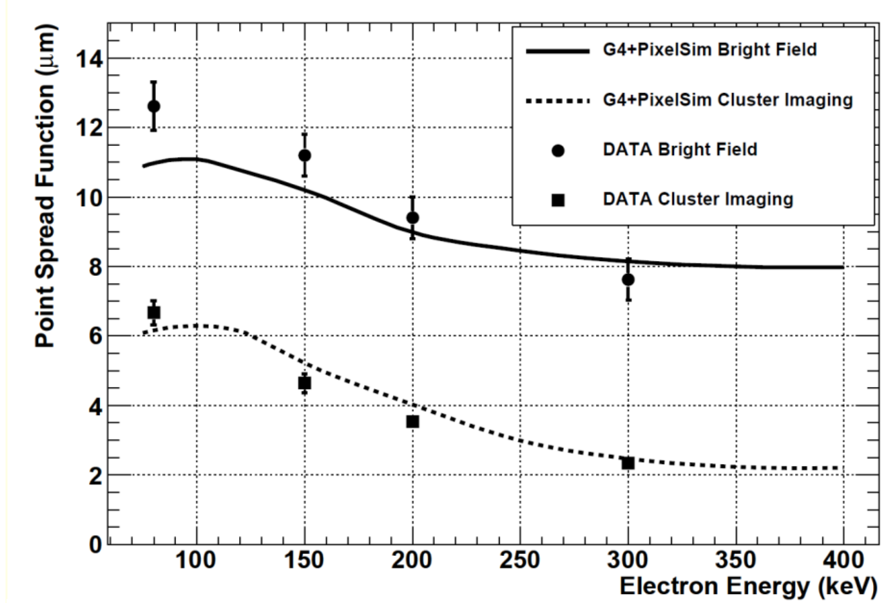
The TEAM detectors

- CMOS imagers manufactured in commercial 0.35 μm CMOS process
- 9.5×9.5 μm^2 pixels, 50 μm thin, single image exposure time of 2.5 ms; rad-hard pixel layout selected from small scale prototype
- TEAM1k detector deployed as 400 frames/s direct detector for the TEAM I microscope
- TEAM2k covers full CMOS reticle (2×2 cm^2), to be commissioned on TEAM I in 2011

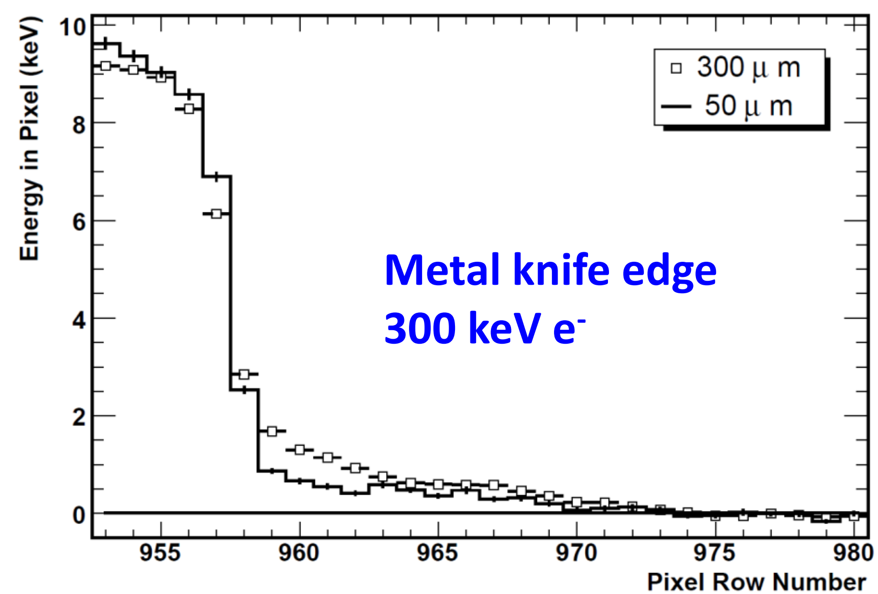


Performance of the TEAM detectors



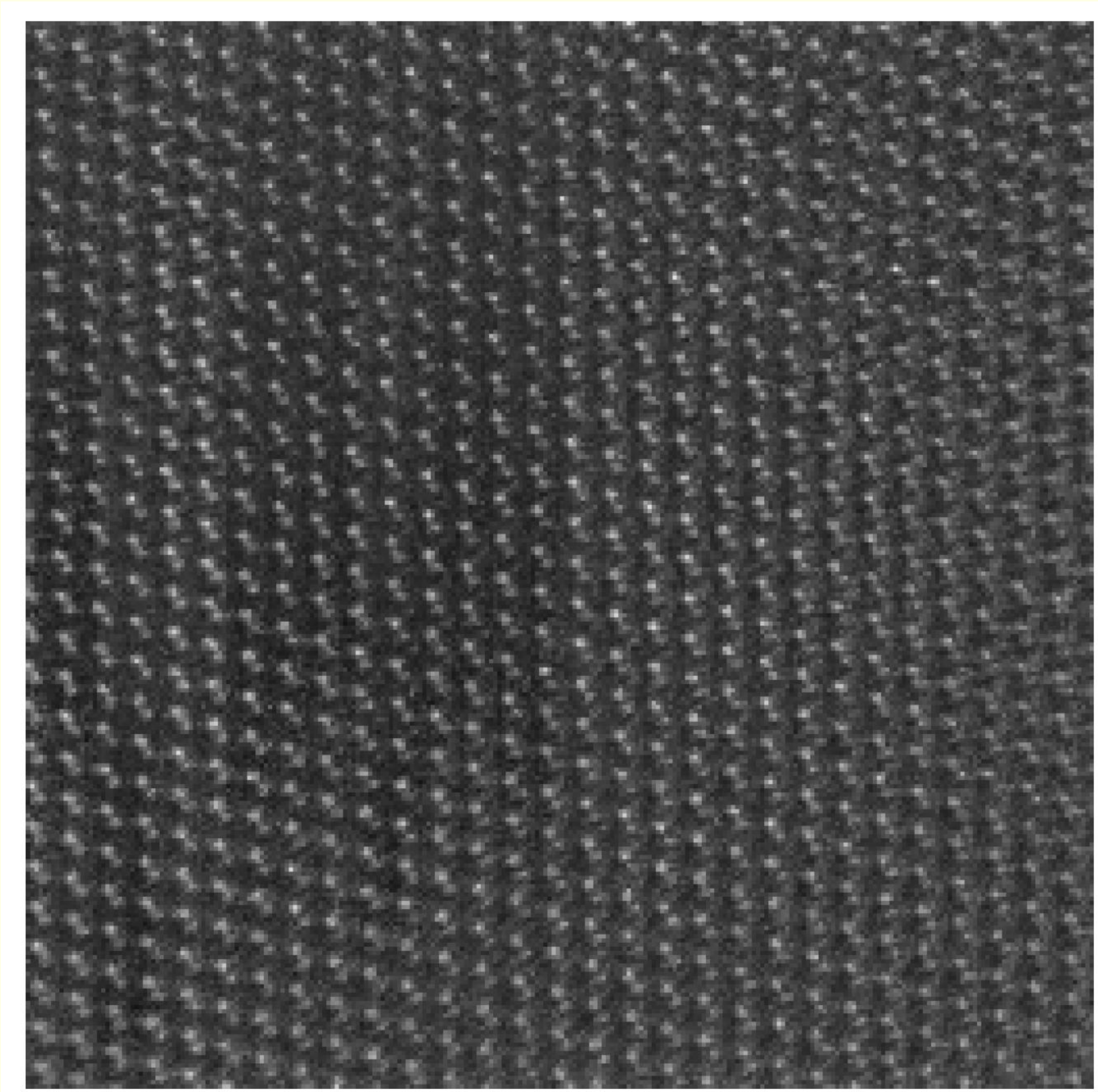


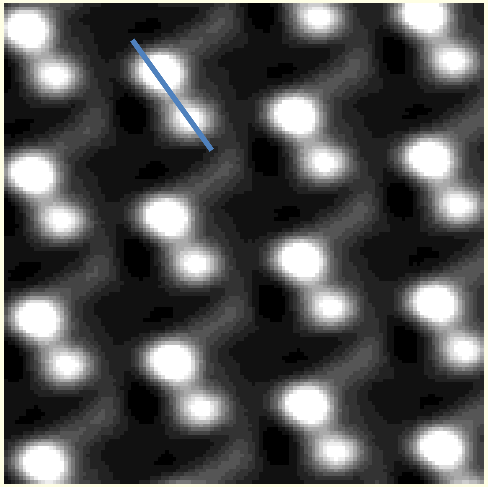
- Single electron sensitivity with low pixel noise (30 electrons) and <S/N>~15-20
- Sensor thinning to 50 μm improves Line Spread Function (LSF), thanks to reduction of back-scattering from detector substrate
- LSF can be dramatically improved by reconstructing the impact position of each single electron and reconstructing the image from the superimposition ("cluster imaging")
- Very good agreement of data with simulation



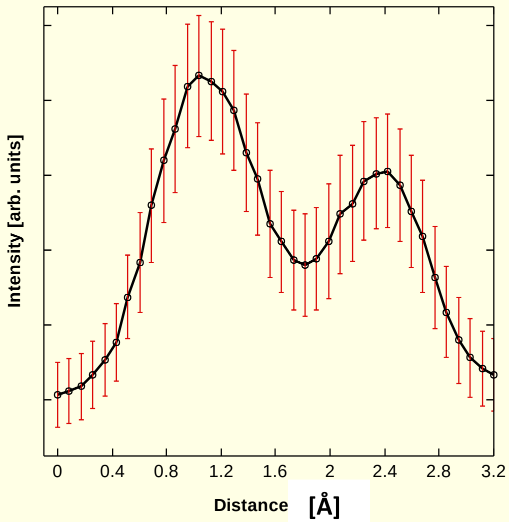
[M. Battaglia et al., Nuclear Instruments and Methods A 622 (2010) 669]

Imaging Si[110] dumbbells in 2.5 ms



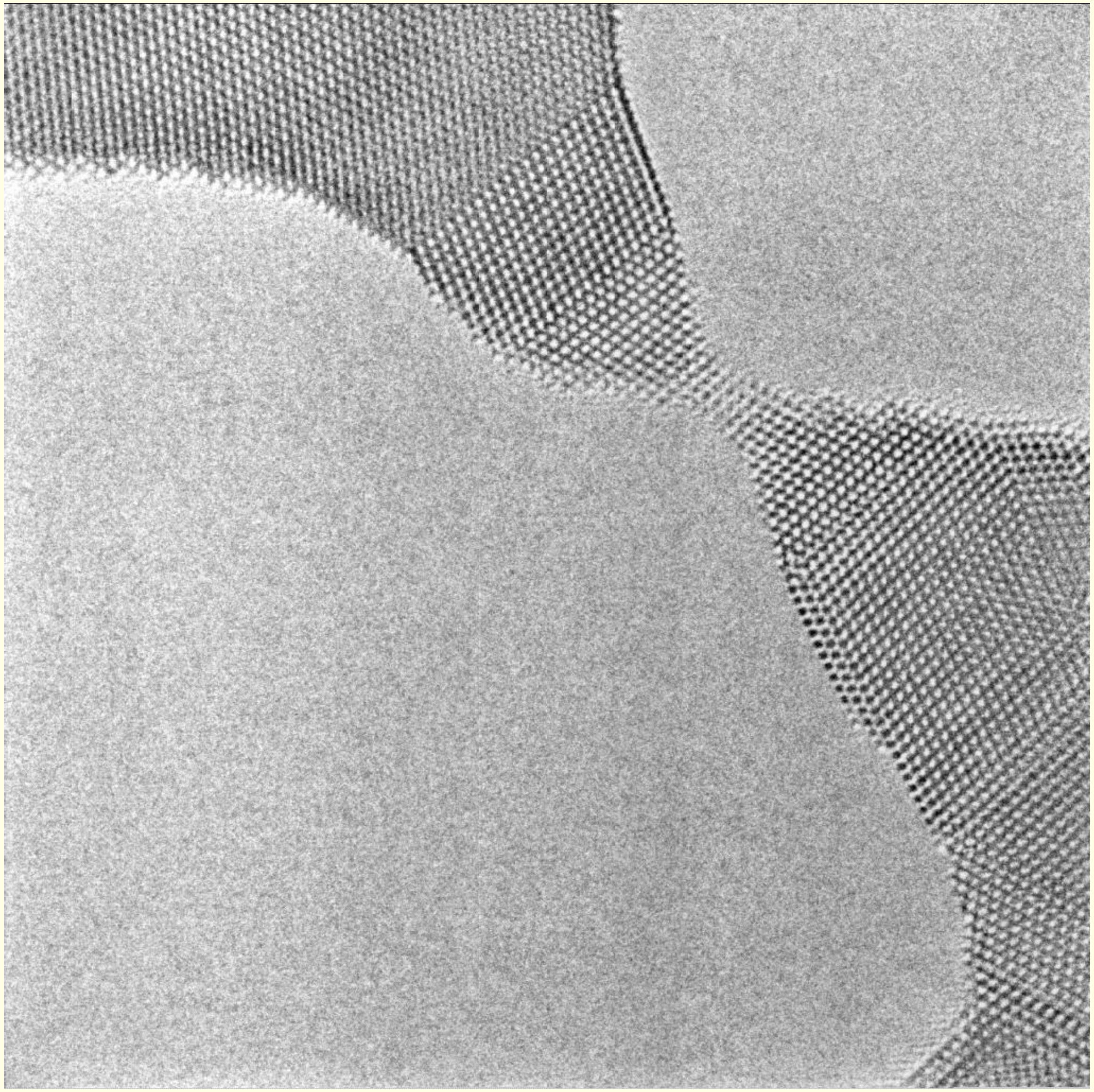


Line profile across dumbbell in averaged image



300 keV e^-, 1024×1024 pixels (TEAM1k chip); single, raw, unprocessed 2.5 ms exposure

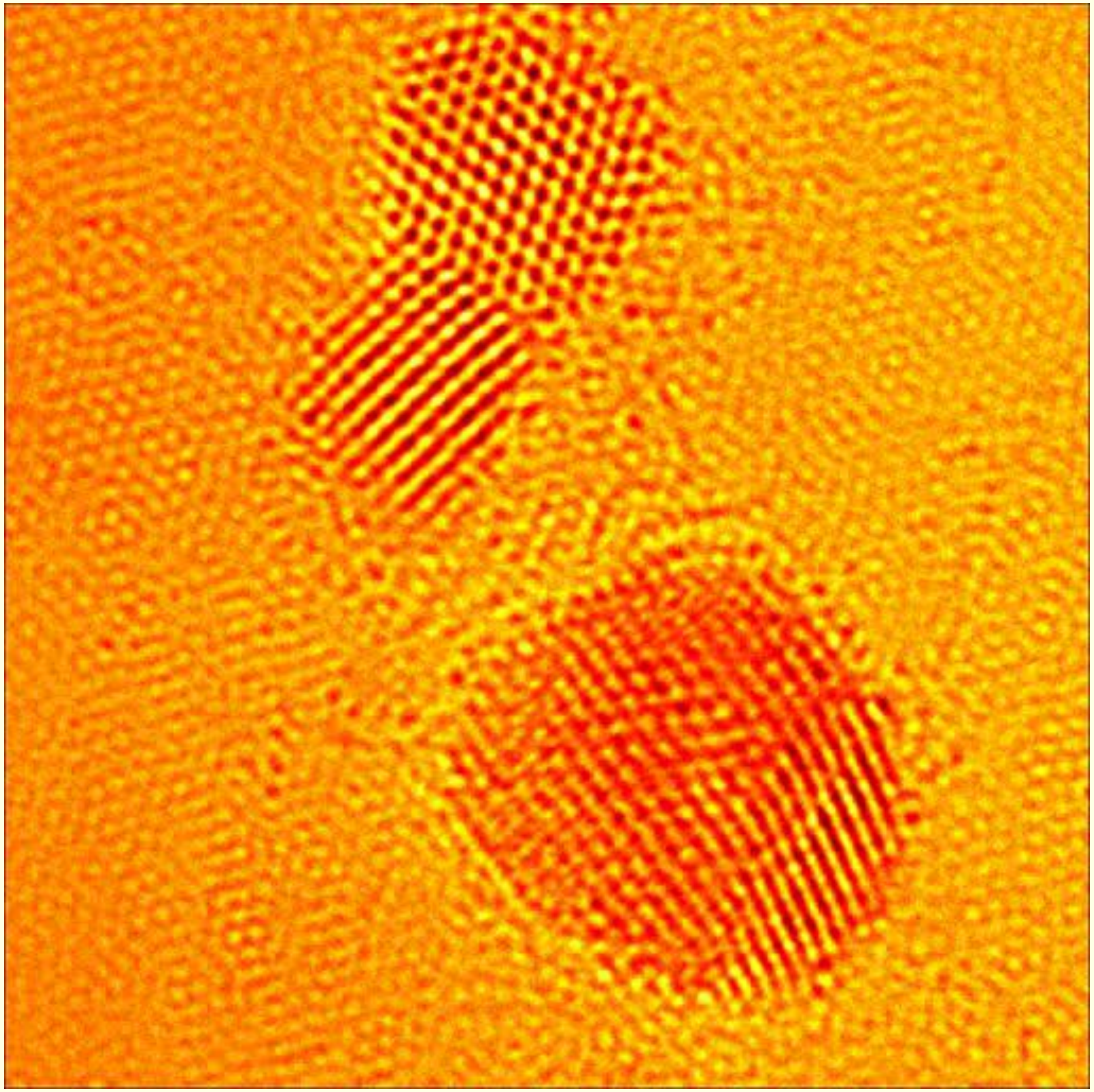
Au nanobridge (300 keV)



TEAM I
300 keV
Single image
20 ms exposure
(raw data, 2010)

[A. Gautam, NCEM]

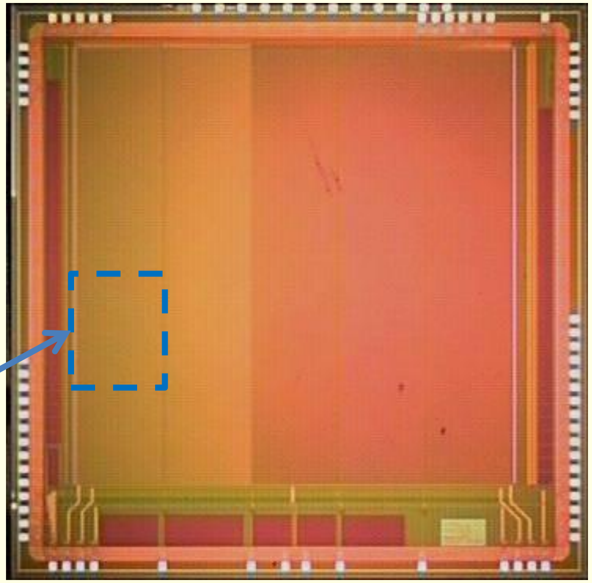
Au/FeO on graphene nanobridge (80 keV)



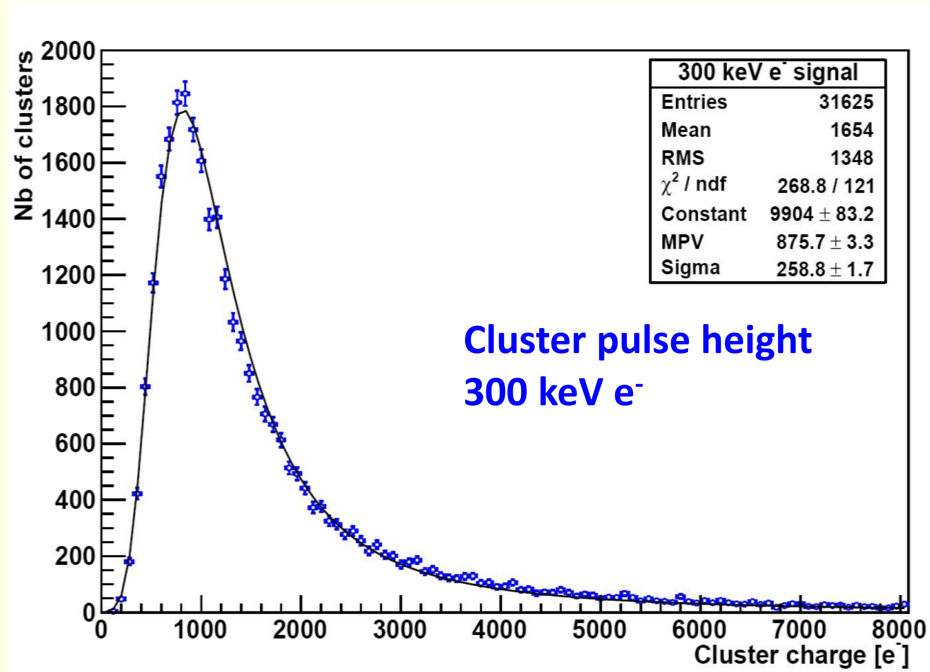
TEAM I
80 keV
Average of 40
2.5 ms images
(raw data, 2010)

[P. Ercius, C. Ophus, V. Radmilovic, NCEM]

Scaling down to 0.18 µm process



152 x 192 pixel section with best layout (0.76 x 0.96 mm²)



- Prototype chip funded by Howard Hughes Medical Institute (HHMI)
- 0.18 µm commercial CMOS process
- 760×768 pixels of 5 µm pixel pitch, 50 µm thin
- 12 pixels layouts, best architecture selected from radiation hardness performance as baseline for reticle size camera
- Detection performances comparable with TEAM sensors
- 0.18 µm w.r.t 0.35 µm process shows higher gain, lower leakage but reduced dynamic range

Fabrication process [µm]	Conversion Gain [µV/e⁻]	Noise (@ RT) [e⁻]	Leakage current [fA]	Well depth [e⁻]
0.35	9.4	30	10	90000
0.18	15.5	35-40	4	23000

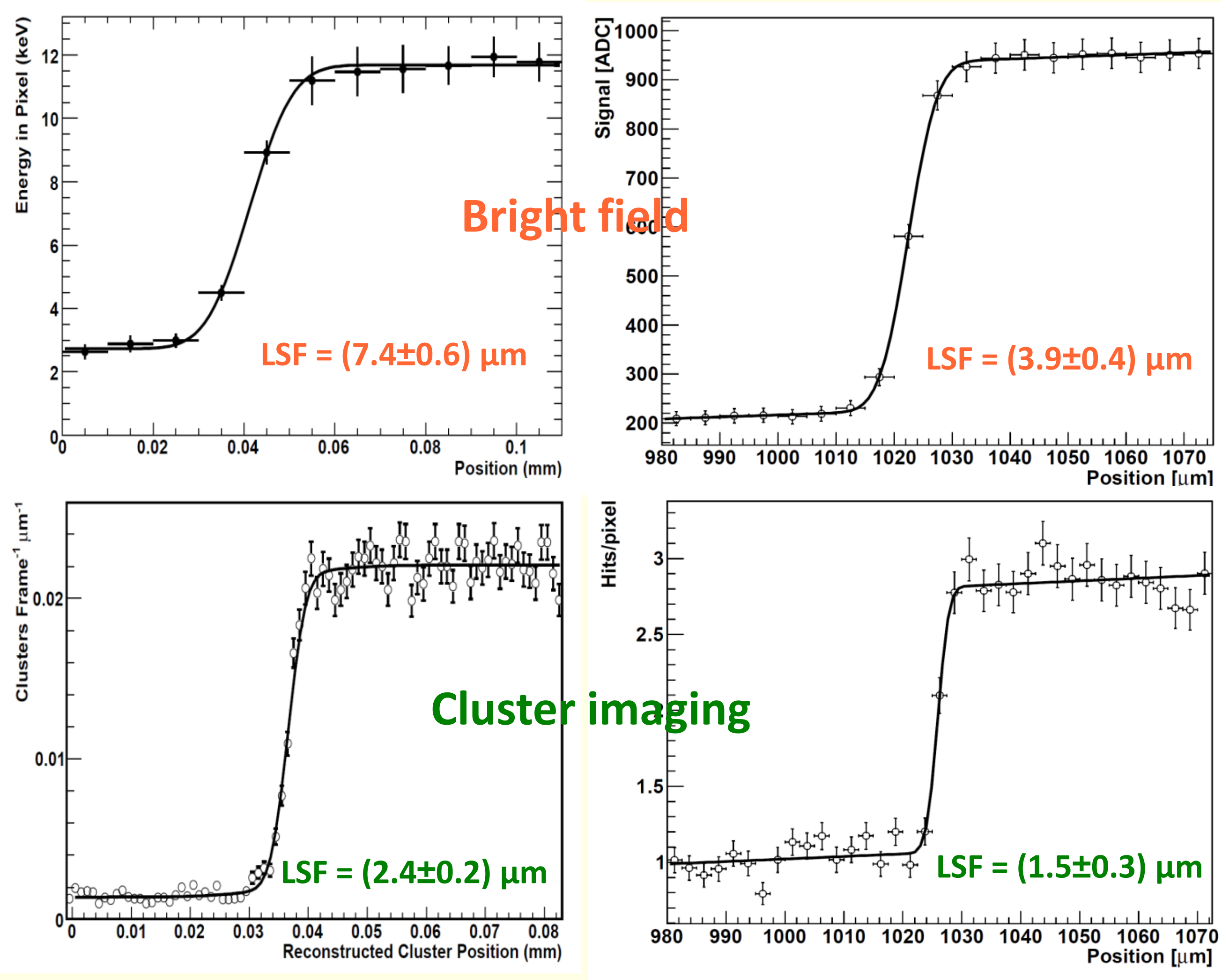
[D. Contarato et al., NIMA A 635 (2011) 69]

Point spread function improvement by clustering

- For low electron rates (< 0.05 e^-/pixel), clusters of pixels interested by signals generating from single electron interactions can be distinguished
- Electron impact positions can be reconstructed with larger accuracy w.r.t. pixel pitch, e.g. by interpolating the charge distributed among the pixels in the cluster (technique widely used in HEP)
- The "cluster imaging" technique composes higher resolution images from the superimposition of many frames with sparsified electron hits
- Point spread function of O(1 µm) possible with pixel pitches of O(10 µm)

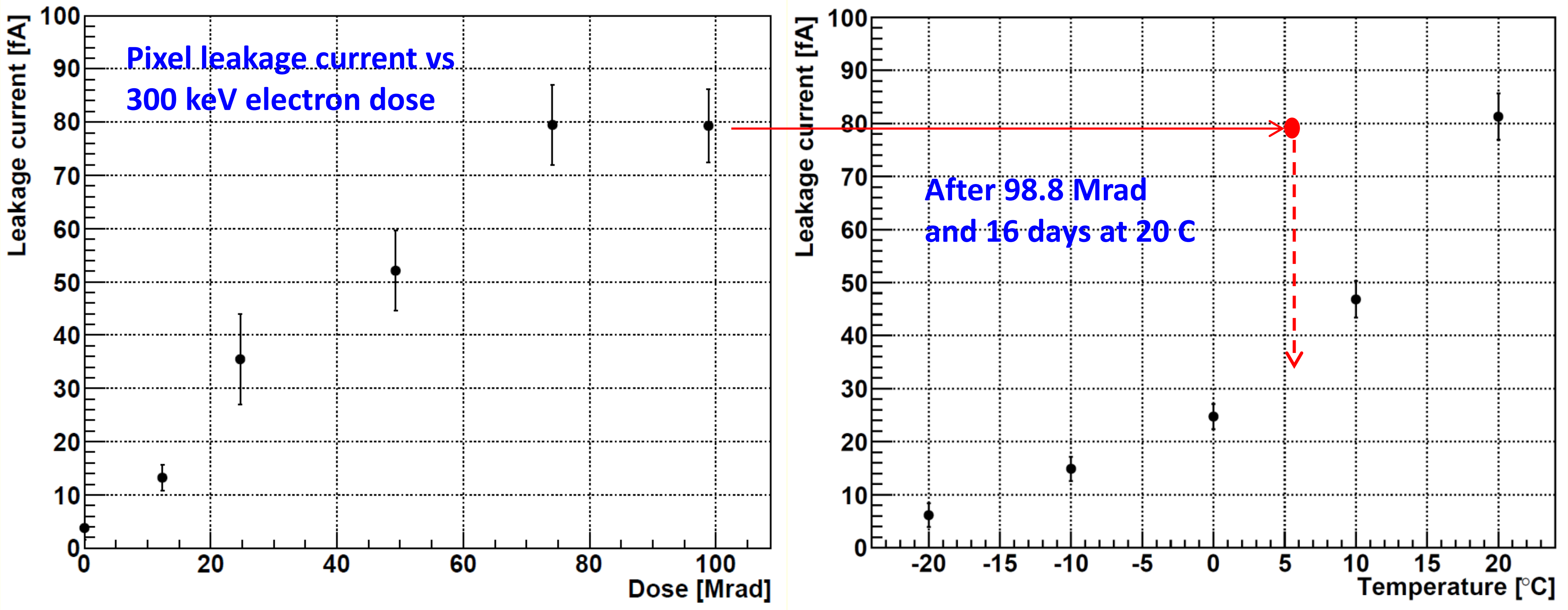
[M. Battaglia et al., NIM A 608 (2009) 363]
[M. Battaglia et al., NIMA A 622 (2010) 669]
[D. Contarato et al., NIMA A 635 (2011) 69]

TEAM1k, 9.5 µm pixels | **HHMI, 5 µm pixels**



Gold wire edge, 300 keV e^-

Radiation hardness: leakage current



- Irradiations performed with 300 keV electrons, T = +5°C
- Dose rate 4300 rad/s, 6.25 MHz clock frequency (integration time ~10-20 ms)
- Moderate leakage current increase with dose that results in increased noise and loss of dynamic range (50% full well at 100 Mrad); leakage current can be reduced 4x by running the sensor at 25 MHz
- Strong dependence of radiation-induced leakage current on temperature: pre-irradiation dynamic range can however be recovered by cooling to -20°C

[D. Contarato et al., NIMA A 635 (2011) 69]

Summary & Conclusions

- CMOS pixel sensors have been successfully developed and deployed as direct detectors for high resolution and fast imaging in Transmission Electron Microscopy; direct detection on a thin sensor layer benefits both position resolution and detective quantum efficiency

- Sub-pixel pitch Line Spread Function demonstrated on 10 µm pitch pixels; the successful architecture demonstrated in the TEAM chips (0.35 µm process) has been ported to a 0.18 µm process with 5 µm pixel pitch, yielding µm-level PSF and radiation hardness to electron doses close to 100 Mrad

- The reconstruction of single electron hit positions and the build-up of images from the superimposition of centroids yields a dramatic improvement in resolution and quantum efficiency; high quality images can thus be obtained from electron counting at high frame rate and reduced electron dose

- Stemming from this development, a camera system with a 16 Mpixel, 400 frames/s, 5 µm pitch direct CMOS sensor and integrated hardware processing for cluster imaging will be commercialized in 2011