Megapixels & Nanobeams

High Resolution Imaging at a DLSR

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Outline

1. High Resolution Hard X-ray Imaging at the Advanced Photon Source
2. Source Criteria for High Resolution Microscopy
3. Science Case for Hard X-ray DLSR
4. Summary

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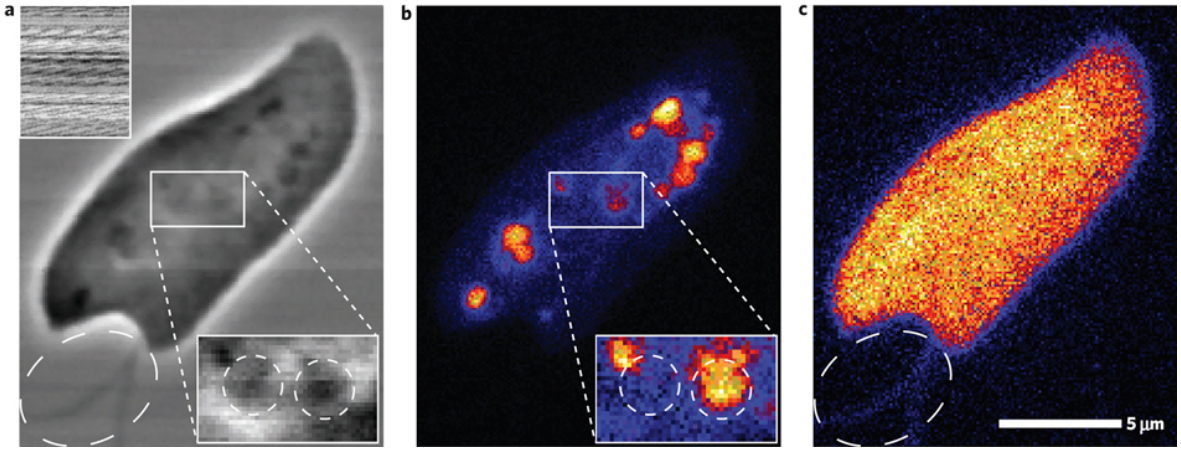
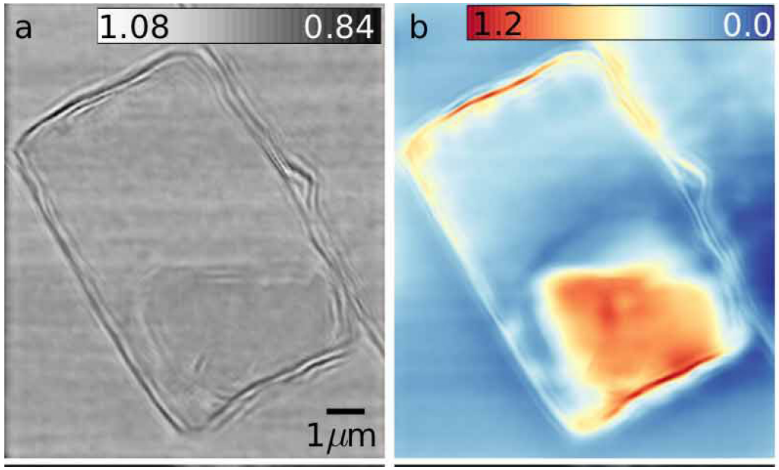
High Resolution Hard X-ray Imaging

Scanning X-ray Fluorescence & Phase Contrast Microscopy

- *Coherence required for diffraction limited focusing*



Holzner et al., *Nat. Phys.* **6** 883 2010.



Vine et al., *Opt. Exp.* **20** 18287 2012.

Coherent diffractive imaging

- *Coherence required for phase retrieval*

Criteria for High-Resolution Microscopy

Minimise focal spot
Source Image $\otimes$ Lens PSF

Phase space area

$\delta = \frac{\lambda}{2NA}$ (Abbe)
$s\Theta = s'\Theta'$ (Liouville)
$\rightarrow s\Theta = \frac{\lambda}{2}$

Spatial coherence

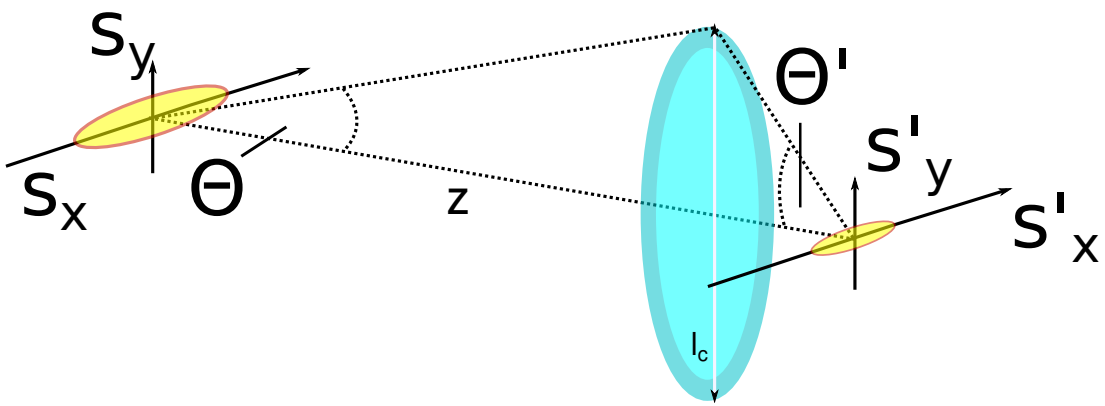
$s\Theta = \frac{\lambda}{2}$
$s\frac{l_c}{2z} = \frac{\lambda}{2}$
$\rightarrow l_c = \frac{\lambda z}{s}$

Temporal coherence

$\rightarrow l_t = \frac{\lambda^2}{\Delta\lambda} > \lambda N_F$

Coherent Volume

$V_c = (l_c)^2 l_t = \frac{z^2}{s_x s_y}\frac{\lambda}{\Delta\lambda}\lambda^3$



Single phase space cell[a]

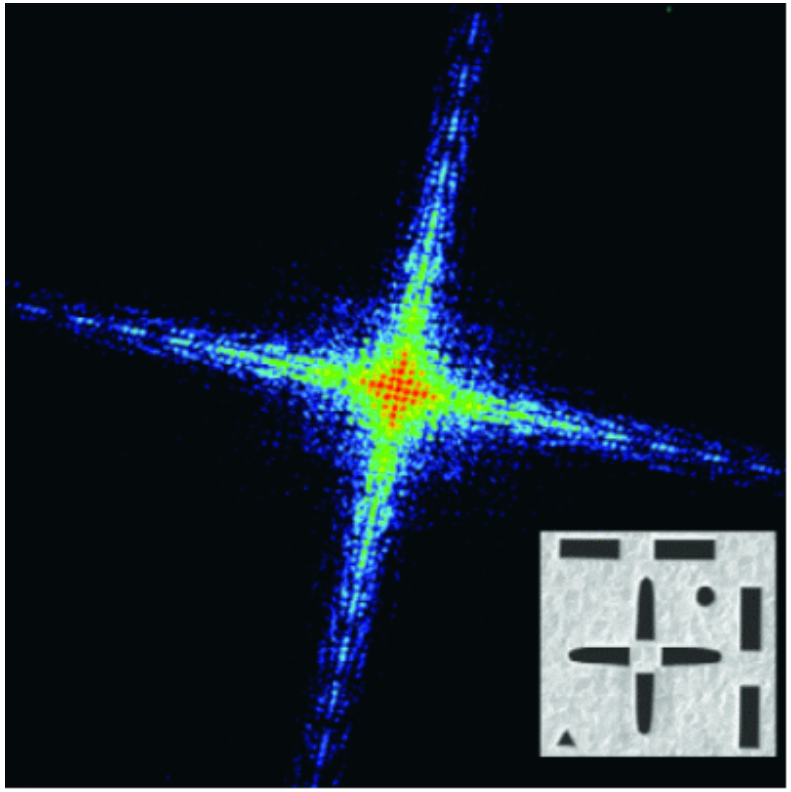
$\Delta x \Delta y \Delta z \Delta p_x \Delta p_y \Delta p_z = h^3$
$\Delta p_x = \Delta p_y = \frac{h}{\lambda}\sin\Theta$, $\Delta p_z = h\frac{\Delta\lambda}{\lambda^2}$
$\Delta p_x \Delta p_y \Delta p_z = \frac{s_x s_y}{z^2}\frac{\Delta\lambda}{\lambda^4}h^3$

$\rightarrow \Delta x \Delta y \Delta z = V_c$

- $\Delta x \Delta y \Delta z$ - volume of space in plane of optic
- $\Delta p_x \Delta p_y \Delta p_z$ - geometric and bandwidth constraints
- Coherence volume is the region of source from which photons occupy a single mode

[a] Mandel & Wolf

Criteria for High Resolution Ptychography



Porod's Law: $I \propto q^{6-D}$.

- increase flux by 2-3 orders of magnitude
- increases resolution by 1 order magnitude
- no increase in scan time

Resolution limited by dose, not optics

- $F_c = Br \cdot \lambda^2 \cdot \frac{\Delta E}{E}$
- $\Phi_c = \frac{F_c}{A}$
- $\rightarrow$ Increase coherent flux
- $\rightarrow$ Match illumination to (nano-)ROI
- Schropp & Schroer, New J. Phys. **12** 035016 (2010)

An assessment of the resolution limitation due to radiation-damage in x-ray diffraction microscopy

M. R. Howells,[1,*] T. Beetz,[1] H. N. Chapman,[2] C. Cui,[3] J. M. Holton,[3] C. J. Jacobsen,[3,1] J. Kirz,[3] E. Lima,[1] S. Marchesini,[2] H. Miao,[1] D. Sayre,[1] D. A. Shapiro,[3,1] and J. C. H. Spence[3,4]

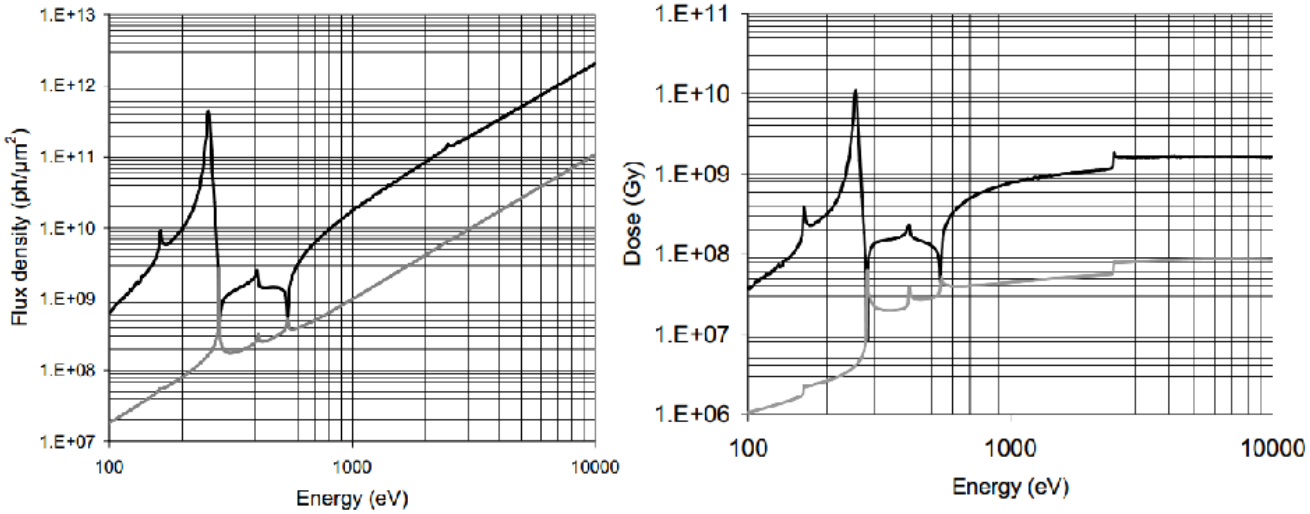
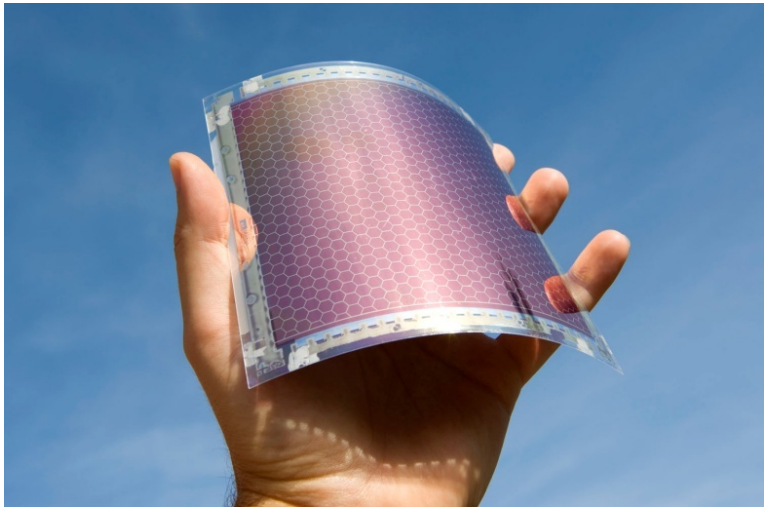


FIG. 2: (a) The flux density and (b) the dose required to visualize a 10 nm cubic voxel of protein of empirical formula $H_{50}C_{30}N_9O_{10}S_1$ and density 1.35 gm/cm^3 against a background of water (black) and vacuum (gray) according to the Rose criterion.

Nano-structure of roll-to-roll coated polymer solar cells

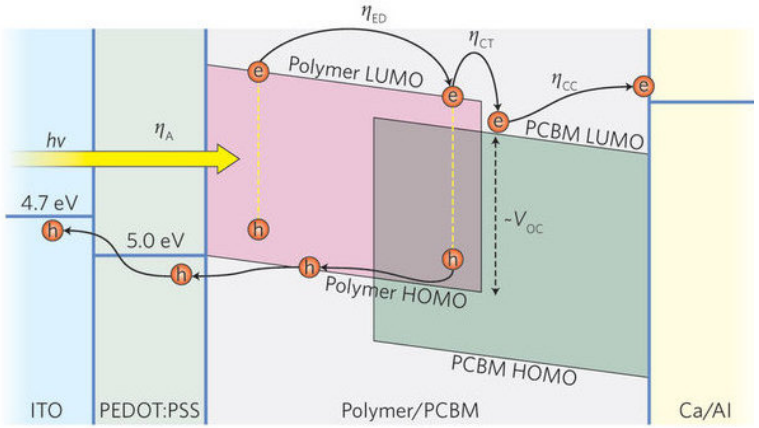
- Efficiency $\sim$ 9%
- Low cost materials & manufacturing
- Flexible
- Semi-transparent
- Collaboration with Andreasen Group, DTU

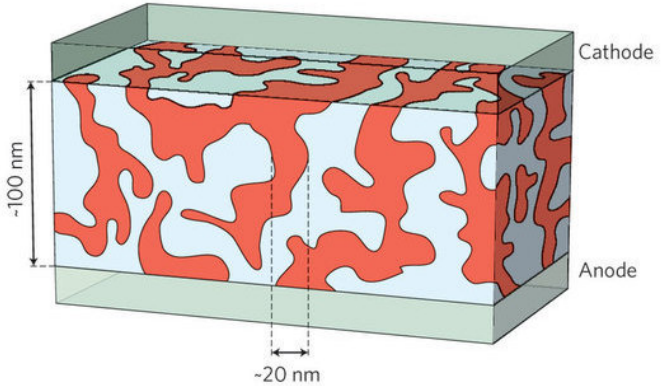


Galagan & Andriessen, Third Generation Photovoltaics

Nano-structure of roll-to-roll coated polymer solar cells

- Blended polymer
- Can attain 100% internal quantum efficiency
- 3D bulk nanostructure is unknown!
- Challenging to image intermeshed polymers with similar density

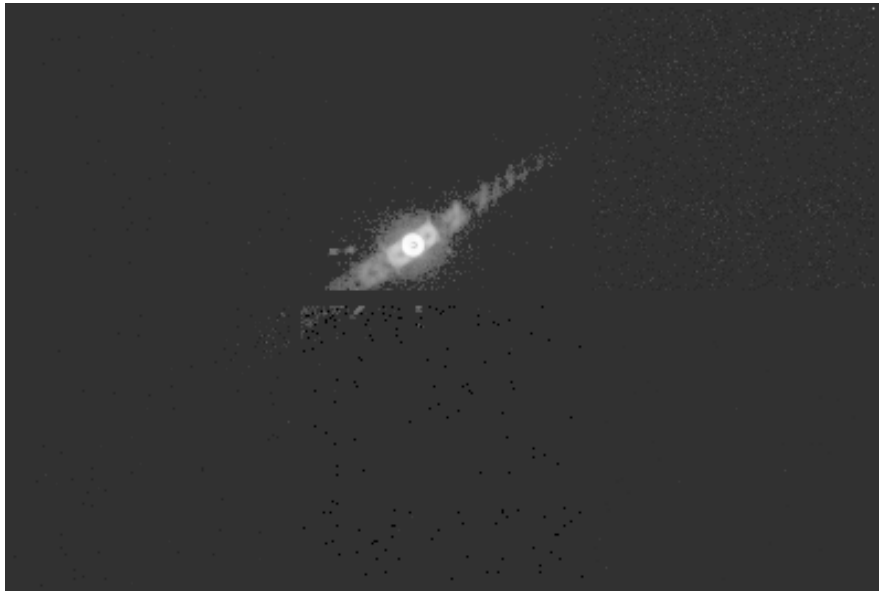




Li *et al.*, Nat. Photon., **6** 153 (2012)

XFM Ptychographic Nanotomography - Experimental Methods

- Beamline 2-ID-B
  - 2.5keV
  - 150nm focused beam
- Gruner/Cornell MMPAD Detector
  - 266$\times$396 150μm pixels
  - Max 1kHz frame rate
  - Single photon sensitive at 2.5keV (S Kα)
- Per projection
  - $9(h) \times 4(v)\mu m^2$
  - 129 $\times$ 58 point cartesian scan
  - 7482 diffraction patterns
  - 6nm real space pixel size
- Complete dataset
  - 449k diffraction patterns
  - 176GB raw data



- Measurement Time
  - 100msec per point
  - 18m per projection
  - 21h per tomogram
- Reconstruction
  - 50 iterations
  - 10m per iteration
  - 12d reconstruction (24 cores)
  - 308 single processor compute days

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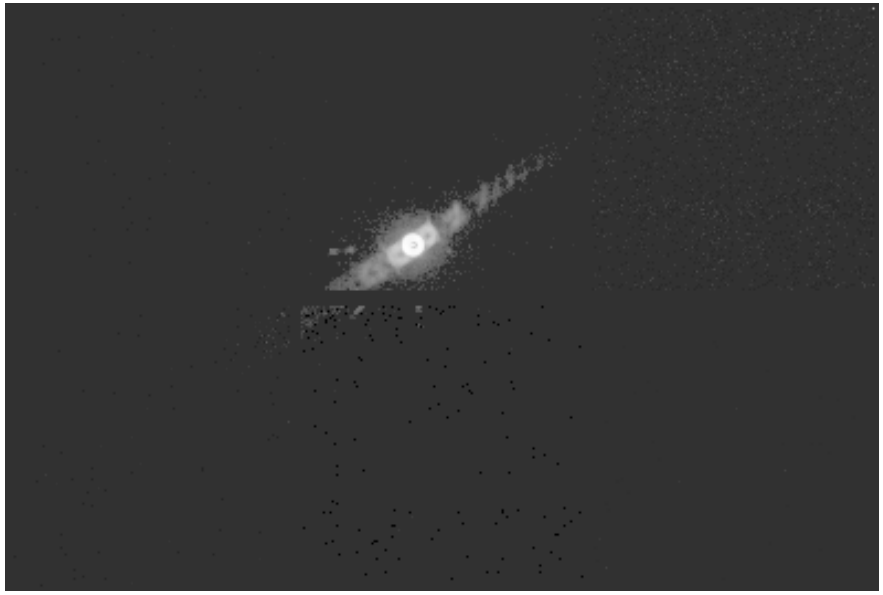

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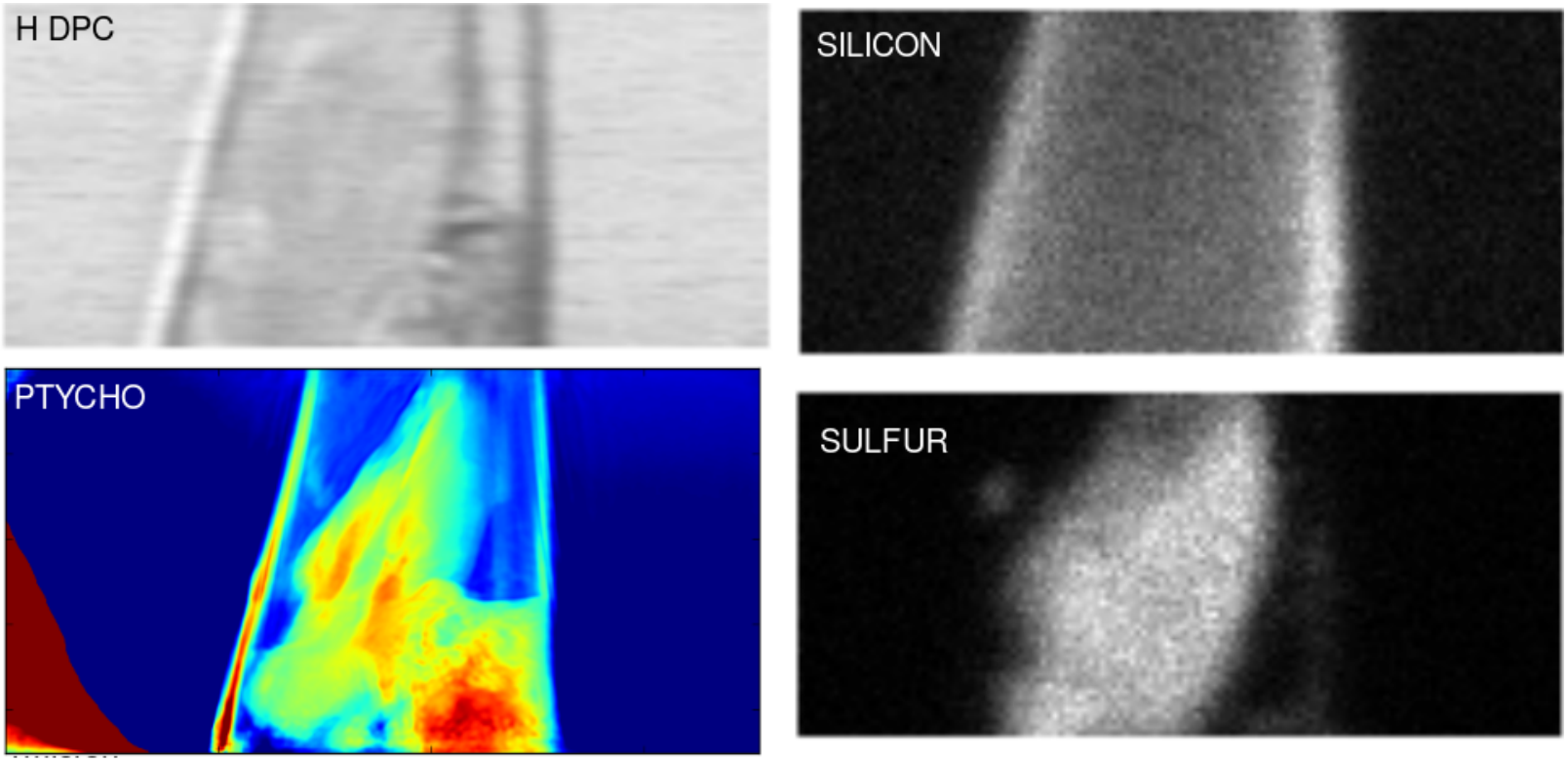
Reconstruction of Single Projection



Fast X-ray Microscopy with a Diffraction Limited Storage Ring

Spatial resolution:

- Now: optics limited (ZP, KB)
- Soon: dose & time limited (MLL)

Resolution vs Scan Time

Source	δ [nm]	# Pix [MPix]	Scan Time
APS	100	0.25	9m
APS	5	4	55h
APS	10	60*	833h
DLSR	100	0.25	5s
DLSR	5	4	0.6h
DLSR	10	60*	8h

$10 \times 10\mu$m area, constant dose (0.5 vs 50ms dwell). * Tomography

Summary

- XFEL is not the ultimate source for all applications
  - Need Joules to roast chicken...
  - But you don't cook a chicken with dynamite!
- High resolution imaging demands:
  - High Brilliance Sources
  - High Coherent Flux