Detector needs for imaging with high spatial and temporal resolution

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**3D Imaging**

<table>
<thead>
<tr>
<th>Motivation</th>
<th>3D microscopy (non-destructive) in-situ experiments (strain, fatigue, …) ‘representative elementary volume’ input for calculations: structure ↔ properties</th>
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<tbody>
<tr>
<td>Compromise spatial resolution</td>
<td>micron - 100 nm ↔ field of view 10 µm - 100 µm</td>
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</table>

‘fingers’ porosity

Surface observed during fatigue
Frontiers in 3D Imaging

Sensitivity
- Attenuation
- Phase Contrast
- Quantitative

3D X-ray imaging

Resolution
- Nano-Tomography

Speed
- Real-time Tomography
- In-situ Experiments

Rich Probes
- Fluorescence
- Diffraction

Damage
- Ultimate Limit
- Dose efficient approaches
Frontiers in 3D Imaging

- Sensitivity, Speed, Resolution, Rich Probes, Dose

- Synchrotron Radiation is crucial

- Detector often equally important
Role of detector in CT

0D detector
- 2 translations + 1 rotation
- 1 datpoint
- 1st generation scanner

1D detector
- 1 translation + 1 rotation
- 10^3 datapoints
- Fan-beam scanner

2D detector
- 1 rotation
- 10^6 datapoints
- Cone-beam scanner

G. Peix (INSA-Lyon)
Synchrotron based in $\mu$CT

Parallel beam case ..... the whole object is imaged, slice by slice

source

New axis:
- **distance**: holotomography, 3DXRD
- **energy**: edge CT, XANES, fluorescence

New ‘3D detector’ to replace 1 more axis: distance, energy or ‘angle’
Experimental Set-up

Source:
- ID19: 1 wiggler, 2 undulators
distance to source: 145 m (coherence)

Monochromator:
- double Si crystal ($\Delta\lambda/\lambda=10^{-4}$)
  or multilayer ($\Delta\lambda/\lambda=10^{-2}$)

Sample stage
- rotation stage (tomography)
- sample environment

Detector
- fluorescent screen - lens - CCD
  pixel size: 0.28 µm - 40 µm
  FReLoN cameras
  1K x 1K, 13.5 bits CCD, 60 ms/frame
  2K x 2K, 13.5 bits CCD, 240 ms/frame

Single camera covers nearly all applications from ms to minutes
Fast Tomography: Liquid Foams

Coarsening: pressure driven growth or disappearance of bubbles

⇒ 3D Growth Law: volume individual bubbles in time
but also grain growth, sintering (ID15), bread (BM05), metallic foams, …

F. Graner (UJF), J. Lambert, P. Cloetens

2 minutes/scan (2GB data)
Fast Tomography: Liquid Foams

Data Analysis

Segmentation + labelling individual bubbles

Behaves \( \sim \) as dispersed bubbles: cf. LSW mean field theory

Exponential size distribution

\[
P(V) \propto \exp\left(-\frac{V}{V_c}\right)
\]

Comparison between glued and not glued slices

\( <V> (t) \)

\(<V> \sim t\)
Fast Tomography: Liquid Foams

Towards the Dry Foam limit (liquid fraction $\rightarrow 0$)

Scan time ~ 20 sec
$1024^2$ ; 500 proj.
40 ms / projection

Scan time ~ 6 sec
$512^2$ ; 300 proj.
20 ms / projection

Scan time ~ 3 sec
$512^2$ ; 300 proj.
10 ms / projection

DALSA camera (12 bits): 60 images/s (1024) or 110 images/s (binned)
cf. ID15 High Energy beamline (M. Di Michiel)
Fast Tomography

Today: 3D volume ~ second time range (monochromatic beam)

Faster CCD’s
keep in mind the full story:
e.g. DALSA is faster compared to FRELON
but sensitivity is 5 times lower, QE 2.5 times

Further multiplexing + frame transfer:
Parallel read-out: 4 channels → 32 channels
custom designed CCD (1 M$ development)?
adapted to needs of SR community
Fast Tomography

New experimental arrangements
cf 5th, 6th generation CT: no rotation!

*Multiple* 2D beams / 2D detectors

Compact optical / detector design?
*N* beams: 180/*N* angular range, acquisition time divided by *N*

Combined approach: full 3D datasets in *ms* time range
Afterglow issues!
Dream 1: Sensitivity
Absorption contrast too low
high spatial resolution
light materials
similar attenuation: C-C, Al-Si, Al-Al$_2$O$_3$

Dream 2: Zero Dose (damage!)

$0.1\%$ shrinkage $\Leftrightarrow$ 2 voxels motion $(N=2048)$
Phase Contrast

- Increase the energy
- Dose and Attenuation contrast drops
- Replaced by Phase Contrast 😊
- DQE drops 😞
  - DQE limited by attenuation in scintillator

Potential Phase Contrast still largely unused due to low DQE at higher energies
Holo-tomography

1) phase retrieval with images at different distances
cf. Focus Variation Method

2) tomography: repeated for ≈ 1000 angular positions

3D distribution of $\delta$ or the electron-density
improved resolution
straightforward interpretation
processing

In-situ imaging of organic tissue

In situ 3D imaging of a seed of an Arabidopsis plant

wet sample, no preparation

R. Mache (UJF, Grenoble)
In-situ imaging of Arabidopsis

Holotomographic approach
Four distances
E = 21 keV

Seed of Arabidopsis

Tomographic Slices

30 µm

R. Mache (UJF, Grenoble)
In-situ imaging of Arabidopsis

Seed of Arabidopsis

Tomographic Slice

- tegumen
- protoderm
- intercellular spaces
- organites (protein stocks)

10 µm
Fast radiography

Pressure

Trigger (19.2 Hz)

intratracheal pressure during exposure

1 mm

TL Wasserthal, R. Fink (Erlangen)
High Resolution Imaging
Without X-ray magnification

- 25 µm thick scintillator → 2 µm resolution → up to 40 keV
- 5 µm thick scintillator → 1 µm resolution → up to 20 keV
- 1 µm thick scintillator → 0.5 µm resolution
Detector efficiency

Scintillator is semi transparant

$\rightarrow$ use several detectors in parallel

Multiplexing of the distance

Practical issues:
medium resolution: 4 distances over 8 m
high resolution: 4 distances over 100 mm
on-line data-analysis
Detector efficiency

\[ \text{depth of focus } \propto \frac{\text{resolution}^2}{\lambda} \]

Converter thickness and efficiency is limited by depth of focus for visible light

Visible light

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<tr>
<th>5 ( \mu m )</th>
<th>1 ( \mu m )</th>
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X-rays (coherent case)

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<th>2000 ( \mu m )</th>
<th>1 ( \mu m )</th>
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Other schemes than fluorescent screen - lens - CCD
Detector Efficiency

1D KI crystal in C nanotube
R. Meyer et al.
University of Cambridge
Science, 2000
Nano-Tomography Project

Motivation:
Materials Science: relevant scale 0.1-10 \( \mu \text{m} \)
Nano-technology/fabrication: 50 nm scale and below
Cell biology, colloids: complete cell < 20 \( \mu \text{m} \)

Strategy:

*Dedicated 3D microscope*
*State-of-the-art in-house / commercial products*

**Optics**

KB Optics Group

**Mechanics / metrology**

Sample preparation

**Goal:** *routine CT with \(~50\text{ nm}\) spatial resolution*

combine *micro-structure and micro-analysis*

P. Cloetens
J. Susini
O. Hignette
Combine Configurations

**Projection Microscopy:**
Structure
Dose efficient, fast
Phase contrast

**Fluorescence mapping:**
Nano-analysis
Slow
Rich, trace elements
Phase contrast

**Full-field microscope:**
Structure
Dose inefficient, fast
Absorption + phase
Detection and Nano-imaging

- Signal-to-noise ratio
  interacting volume ↓

- Radiation damage
X-ray magnification using lenses

Full field microscope: FZP’s
60 nm spatial resolution at 4 keV
Zernike PhC with phase ring

U. Neuhaeusler, W. Ludwig,
ID21; G. Schneider, D.Hambach

Fresnel Zone Plate technology:
limited field of view (~ 50 µm)
large focal distance (~ 20 mm)
little energy tuneability
needs good monochromaticity: \( \Delta \lambda / \lambda < 10^{-3} \)
→ will not solve all detector issues

25 nm image pixel with 100 µm pixel detector: 80 m path length!
Keep the detector pixels as small as possible
Kirkpatrick-Baez focusing

< 300 mm

50 mm

focus

mirror

150 m

source

Mirror Efficiency: reflectivity towards 1 (0.6)
No chromatic aberration: large bandwidth possible
Large NA
Tuneable focus

O. Hignette, G. Rostaing
Kirkpatrick-Baez focusing

*Multilayer* coated first mirror

Gain in **flux** > 100

Gain in **vertical acceptance**

$\Delta E/E \approx 10^{-2}$ (3rd harmonic undulator)

Working Distance: 50 mm
The New Units

Photon Density on Sample:
5 \(10^{11}\) ph/s in 90 nm x 90 nm spot

6 \(10^{13}\) ph/s/\(\mu m^2\)  Old units

6 \(10^{7}\) ph/s/nm\(^2\)  New units

A Nano-Probe for hard X-ray nano-science
Projection Microscopy

Towards focus

D = 225 mm  
M = 17

D = 175 mm  
M = 22

D = 125 mm  
M = 31

D = 45 mm  
M = 87

E = 20.5 keV

Exposure time = 1 s (16-bunch)

No X-ray optics behind the sample  ⇒ dose efficient

P. Cloetens, W. Ludwig
Projection Microscopy: Phase Retrieval

5 distances

Mass → Quantitative Fluorescence
Are single atom x-ray experiments possible?

cf. D. Bilderback (Cornell)

- Cu: $\sim 4 \text{ nanogramme/cm}^2 - 1 \text{ ag (10 s)}$ (S. Bohic)
- 300 ms:
  sensitive to $cc < \text{ppm}$ for Cu, Zn, …
- $10^4$ atoms
- Detection angle fluorescence: $3 \times 10^{-2} \text{ sr}$

- Detection efficiency to be improved
  Careful with scattered radiation, collimators, angle resolved
- No longer that unlikely
Data handling

Memory:
database TomoDBII
MIS

Data storage:  NICE (backup???)

Data processing:

PyHST (scisoft, A Mirone, R Wilcke)
on linux mini-cluster (10 cpu’s)

Multiplexing of the processing

Data analysis???
Conclusions

- 3D detectors: multiplexing of distance, energy, …
- Detector is crucial element for the resolution, the speed and the sensitivity
- Improvement in efficiency is necessary for applications in soft condensed matter, biology
- CCD-based detectors will be hard to beat for full-field imaging evolution possible: e.g. custom designs
- Pixel detectors with small pixels (~ 10 µm)?
- Large gains possible in fluorescence imaging
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