Detector needs for imaging with high spatial and temporal resolution

P. Cloetens

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ESRF, Grenoble

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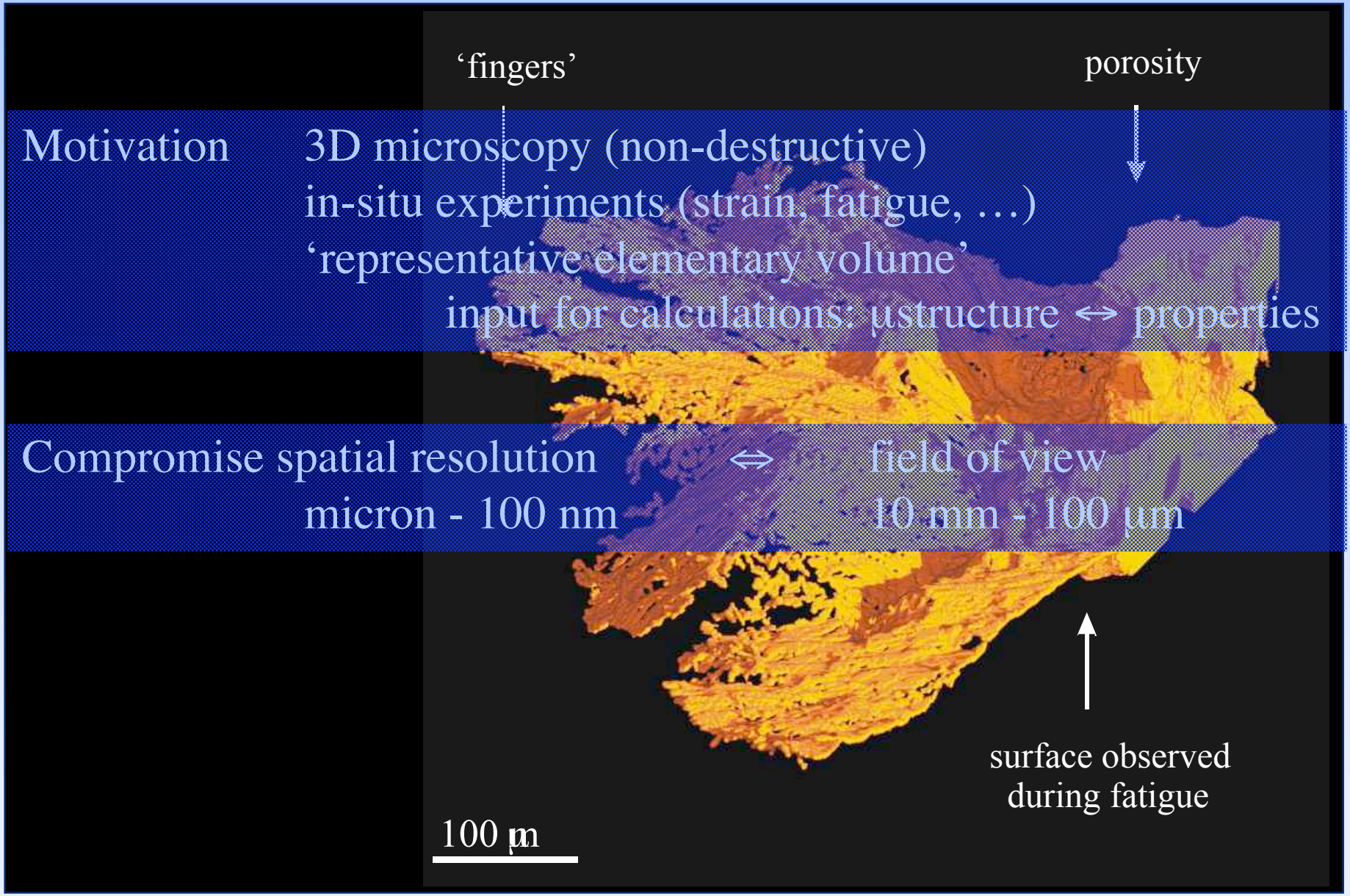
3D Imaging



Motivation 3D microscopy (non-destructive)
in-situ experiments (strain, fatigue, …)
'representative elementary volume'
input for calculations: µstructure ⇔ properties

Compromise spatial resolution ⇔ field of view
micron - 100 nm 10 mm - 100 µm

Frontiers in 3D Imaging

Sensitivity

Attenuation
Phase Contrast } Quantitative

Speed

Real-time Tomography
In-situ Experiments

3D X-ray imaging

Resolution

Nano-Tomography

Rich Probes

Fluorescence
Diffraction

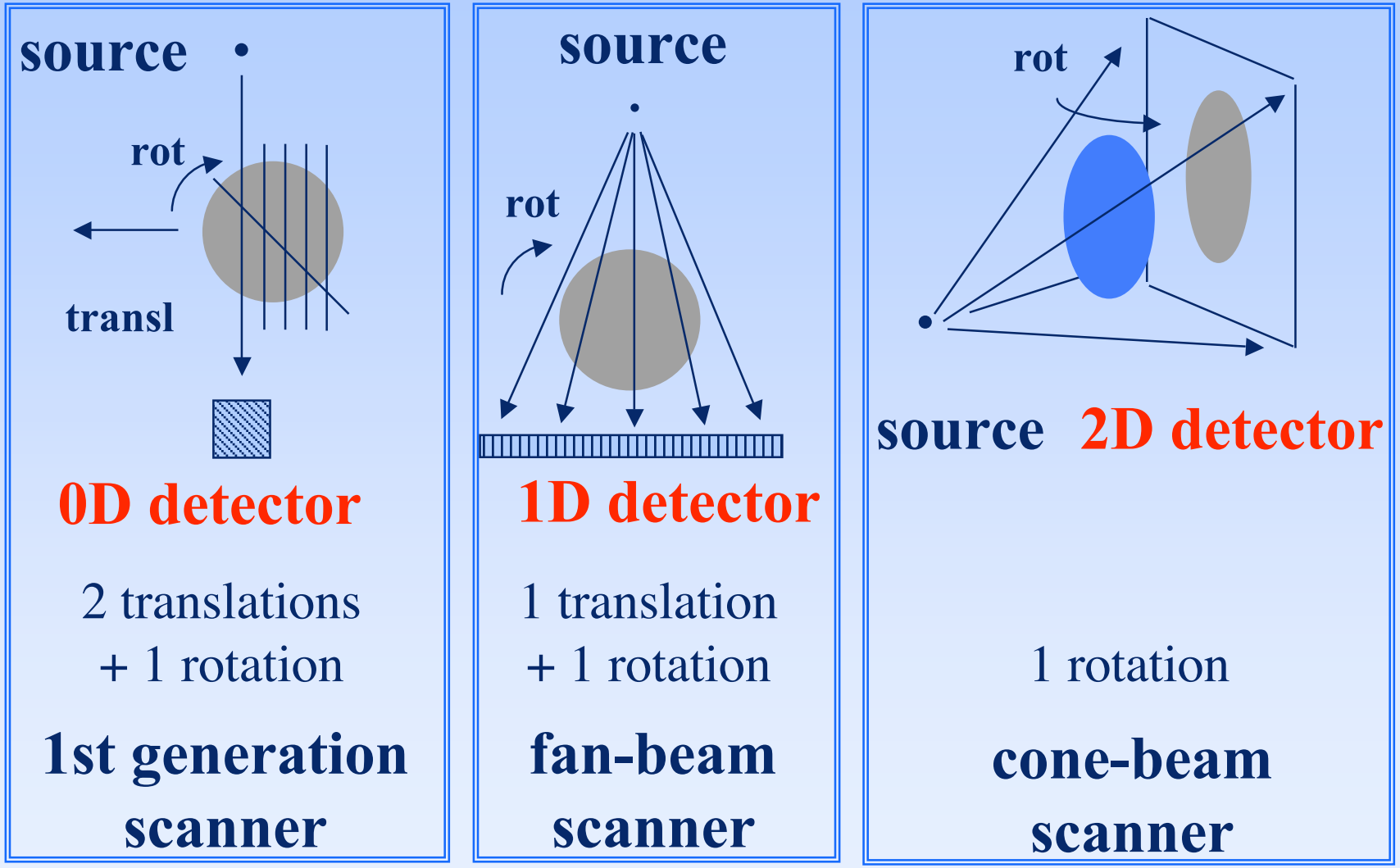
Damage

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



1 datapoint | 10^3 datapoints | 10^6 datapoints

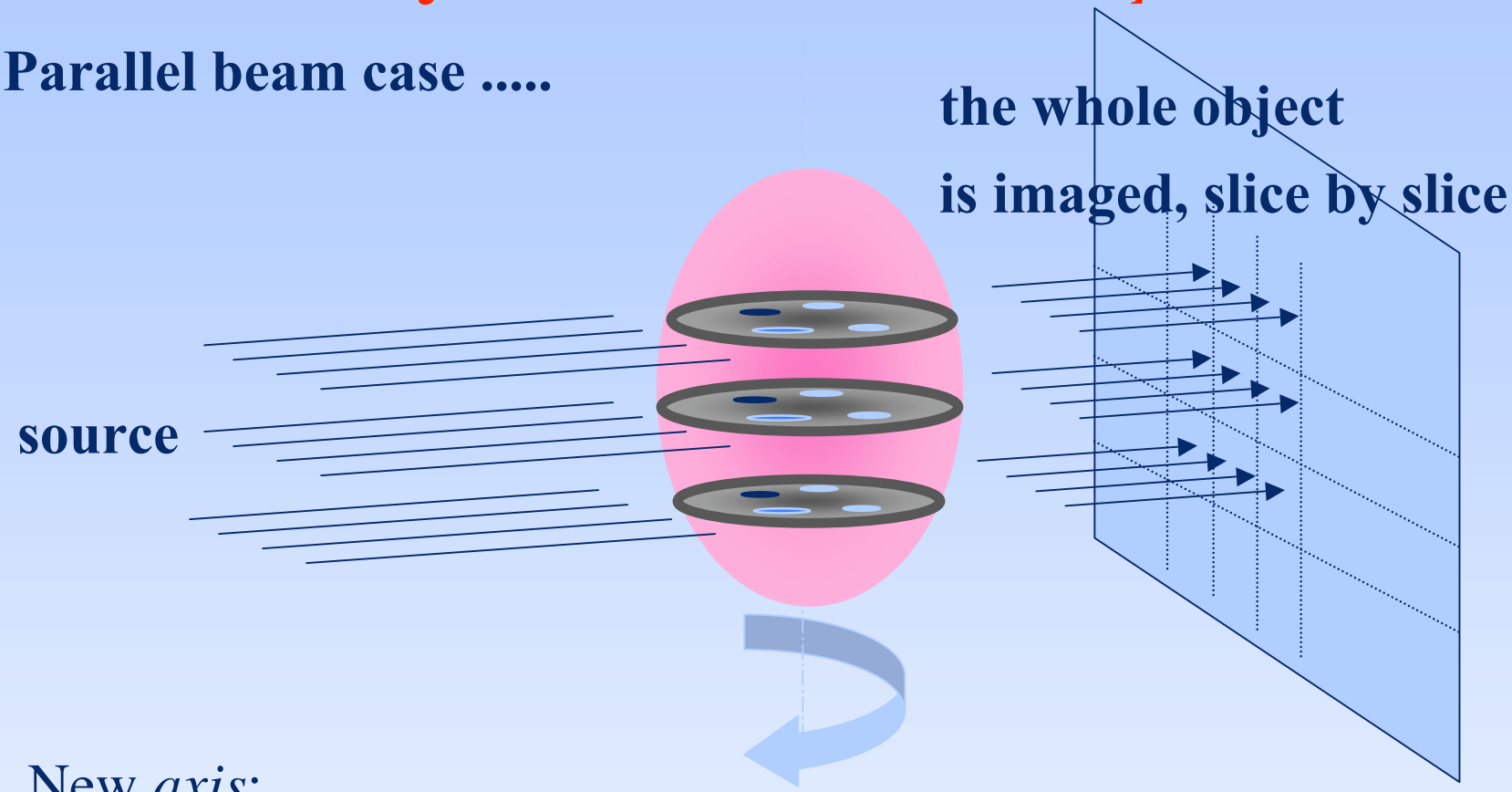
G. Peix (INSA-Lyon)

Synchrotron based in μCT

Parallel beam case .....

the whole object

is imaged, slice by slice



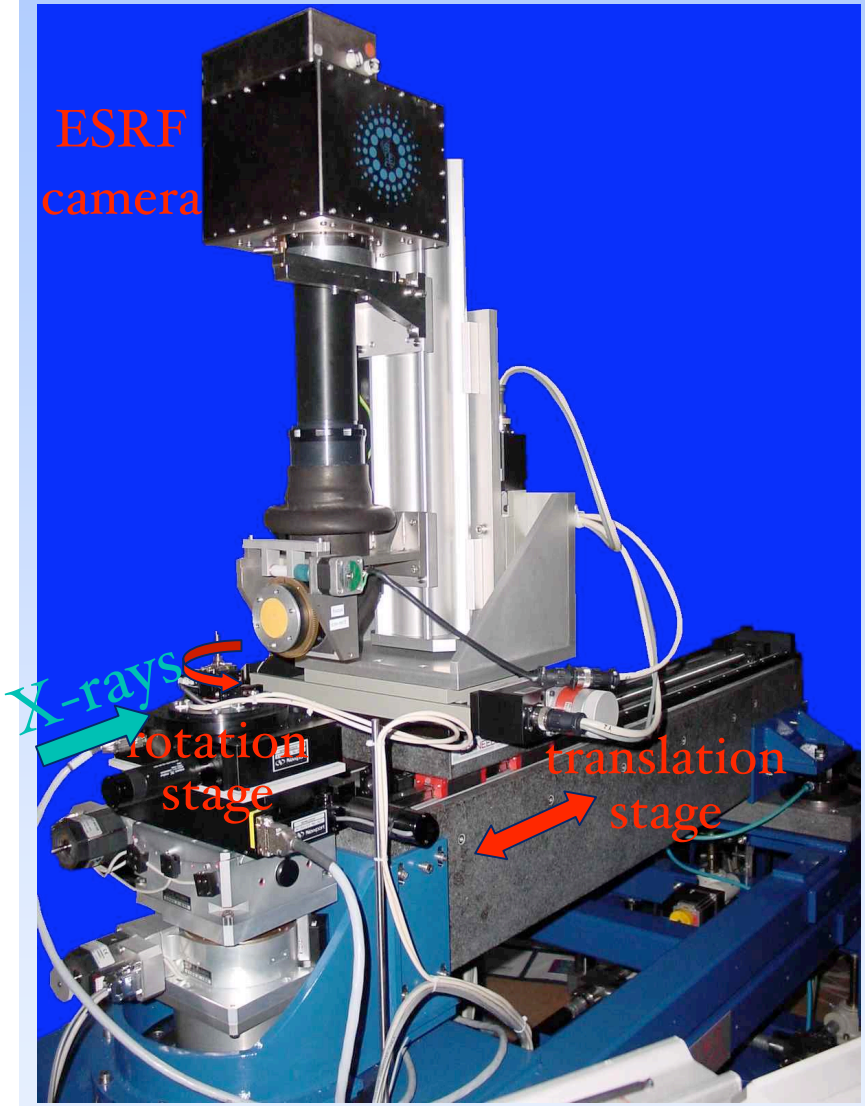
New *axis*:

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

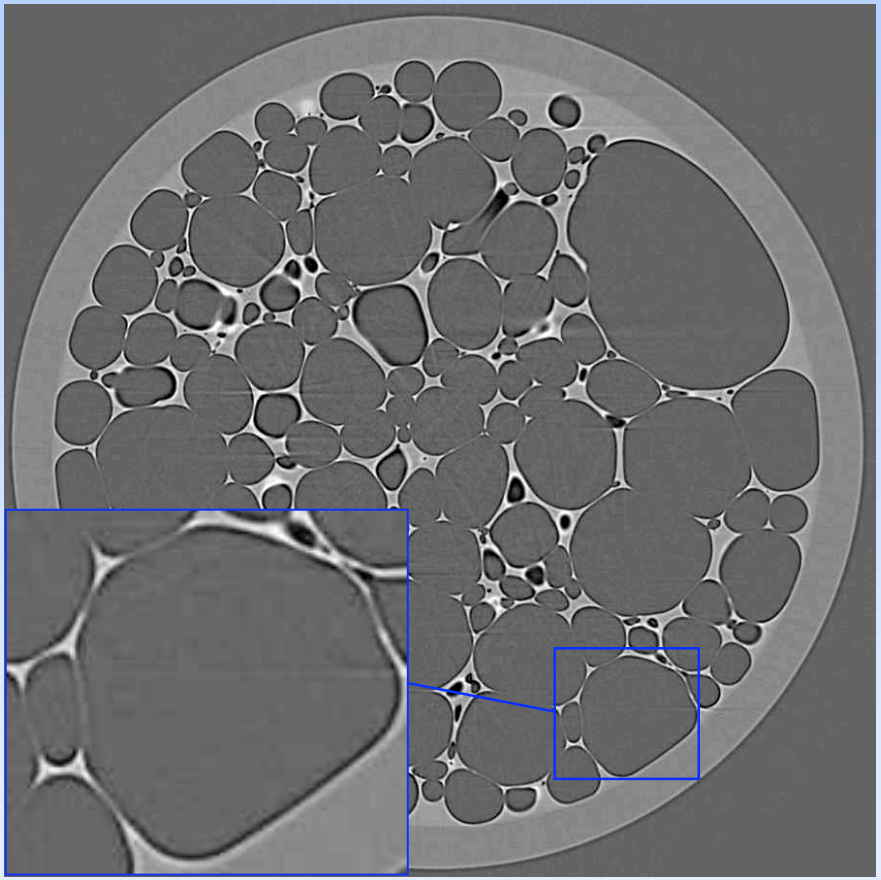
1K x 1K, 13.5 bits CCD, 60 ms/frame

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



2 minutes/scan (2GB data)

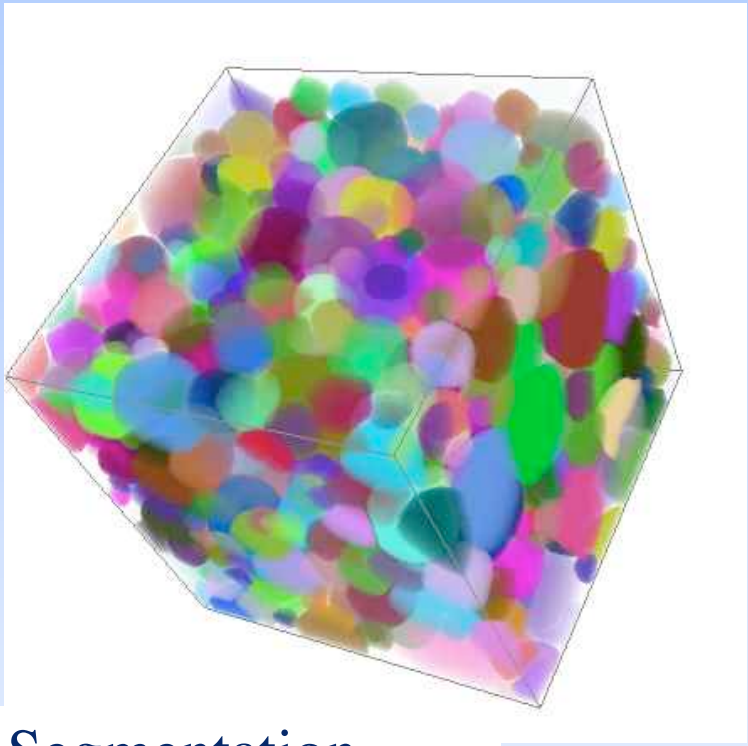
⇒ 3D Growth Law: volume individual bubbles in time

but also grain growth, sintering (ID15), bread (BM05), metallic foams, …

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

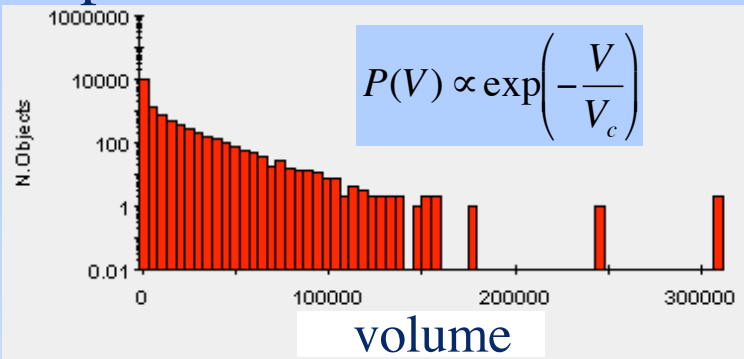
Fast Tomography: Liquid Foams

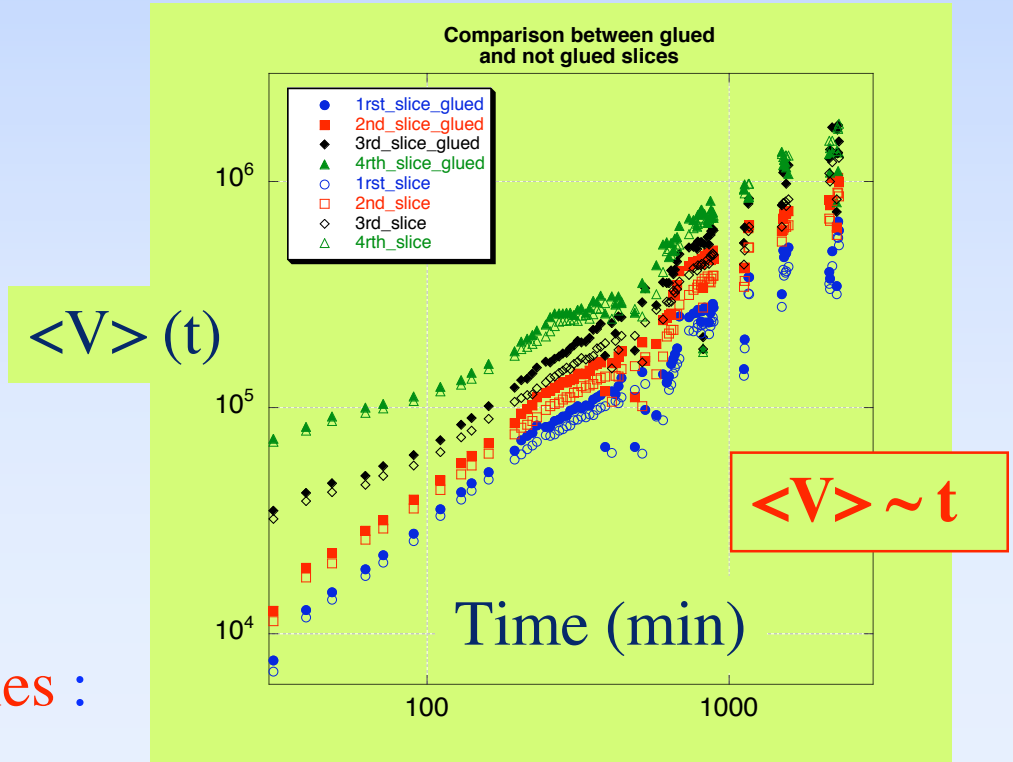
Data Analysis



Segmentation
+ labelling
individual bubbles

Exponential size distribution





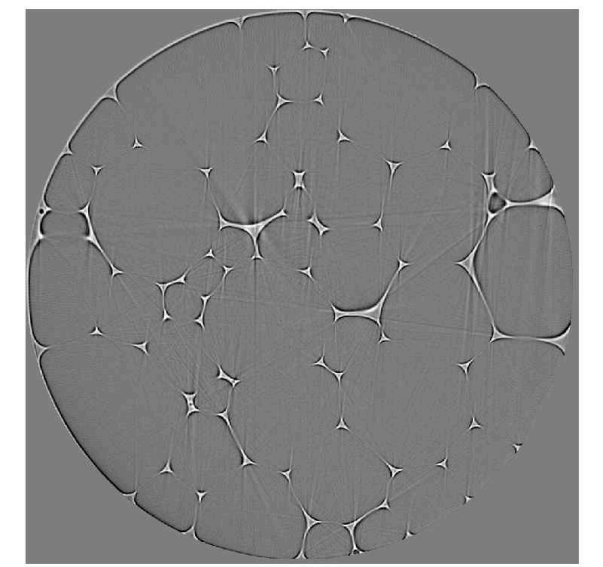
Behaves ~ as dispersed bubbles :
cf. LSW mean field theory

J. Lambert (Univ. Rennes)

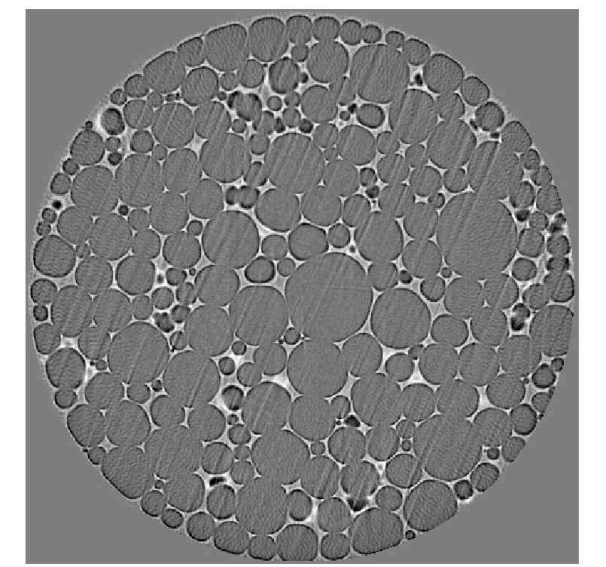
Fast Tomography: Liquid Foams

Towards the Dry Foam limit (liquid fraction → 0)

Liquid foams

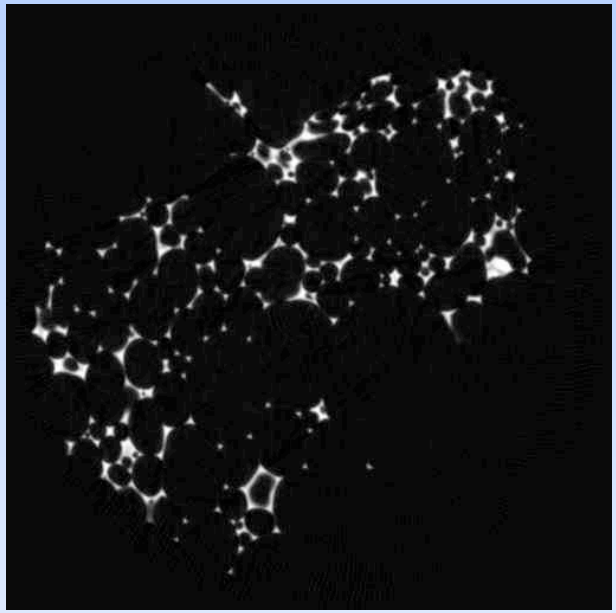


Scan time ~ 20 sec
1024^2 ; 500 proj.
40 ms / projection



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

Lava (RT)



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)

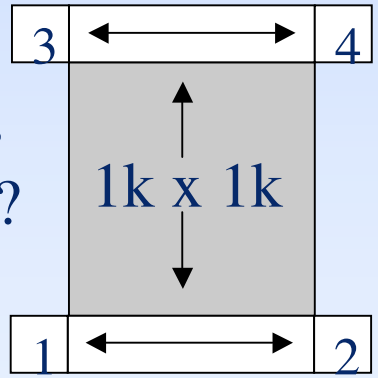
Fast Tomography

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

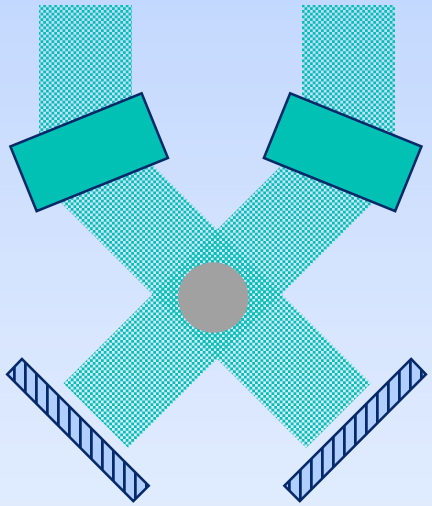


Fast Tomography

New experimental arrangements

cf 5th, 6th generation CT: no rotation!

Multiple 2D beams / 2D detectors



Multiplexing of the angle

Compact optical / detector design?

N beams: 180/*N* angular range, acquisition time divided by *N*

Combined approach: full 3D datasets in *ms* time range

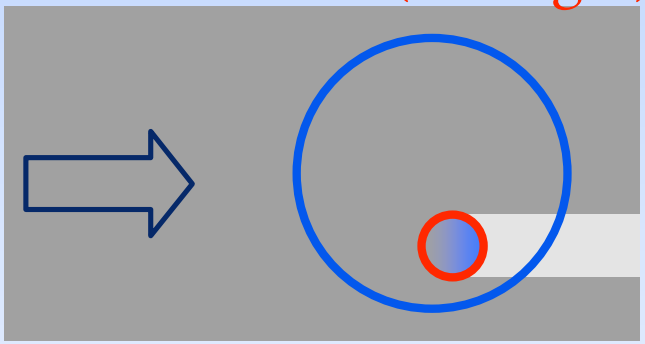
Afterglow issues!

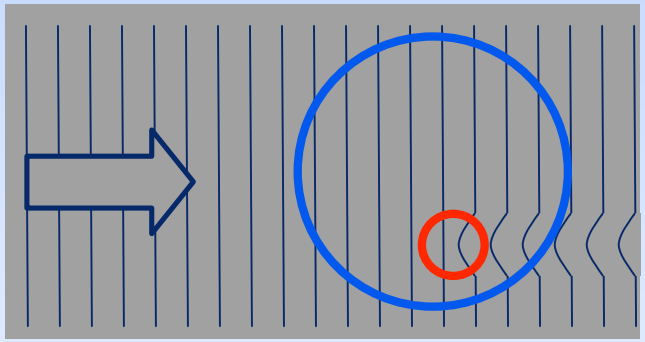
Phase Contrast

Dream 1: Sensitivity

Absorption contrast too low high spatial resolution
light materials
similar attenuation: C-C, Al-Si, Al-Al_2O_3

Dream 2: Zero Dose (damage!)





0.1% shrinkage ⇔ 2 voxels motion (N=2048)

Phase Contrast

- Increase the energy
- Dose and Attenuation contrast drops
- Replaced by Phase Contrast ☺
- DQE drops ☹

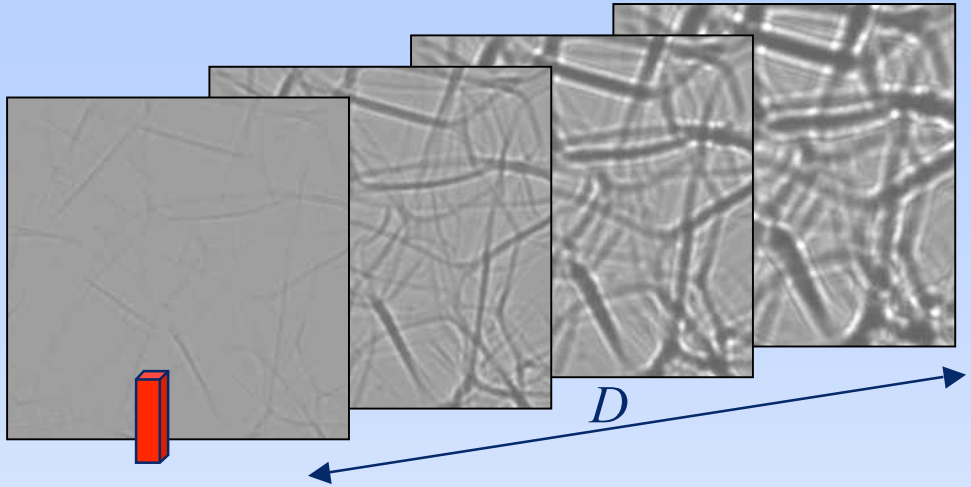
DQE limited by attenuation in scintillator

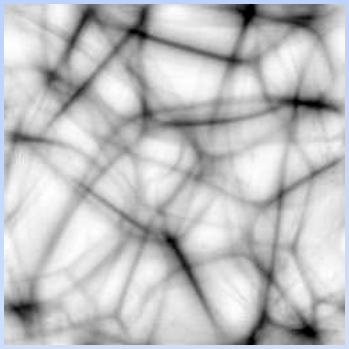
Potential Phase Contrast still largely unused due to low DQE at higher energies

Holo-tomography

1) phase retrieval with images at different distances

cf. Focus Variation Method

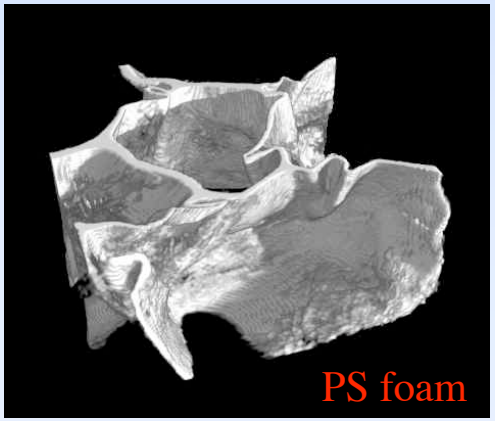




Phase map

2) tomography: repeated for ≈ 1000 angular positions

3D distribution of δ or the electron-density
improved resolution
straightforward interpretation
processing



P.Cloetens et al., Appl. Phys. Lett. 75, 2912 (1999)

In-situ imaging of organic tissue

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

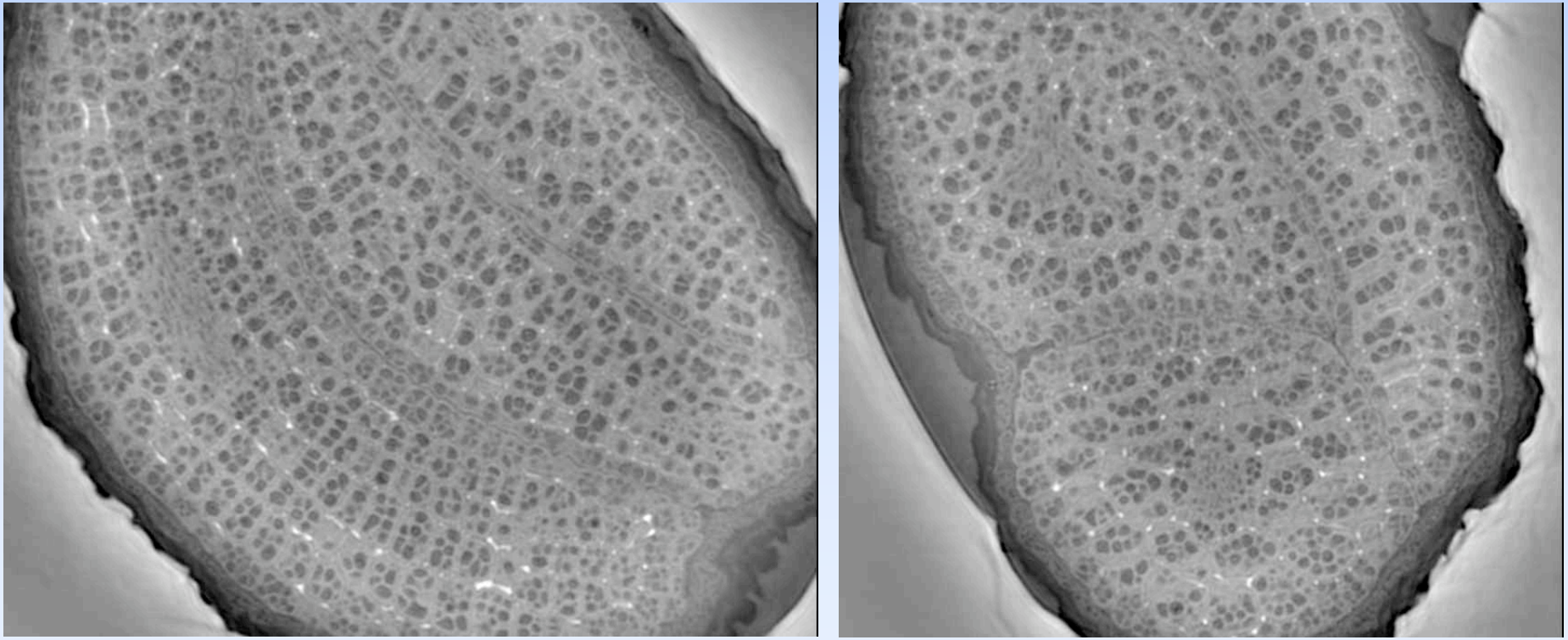
↳ wet sample, no preparation

In-situ imaging of Arabidopsis

Holotomographic approach
Four distances
E = 21 keV

Seed of Arabidopsis

Tomographic Slices



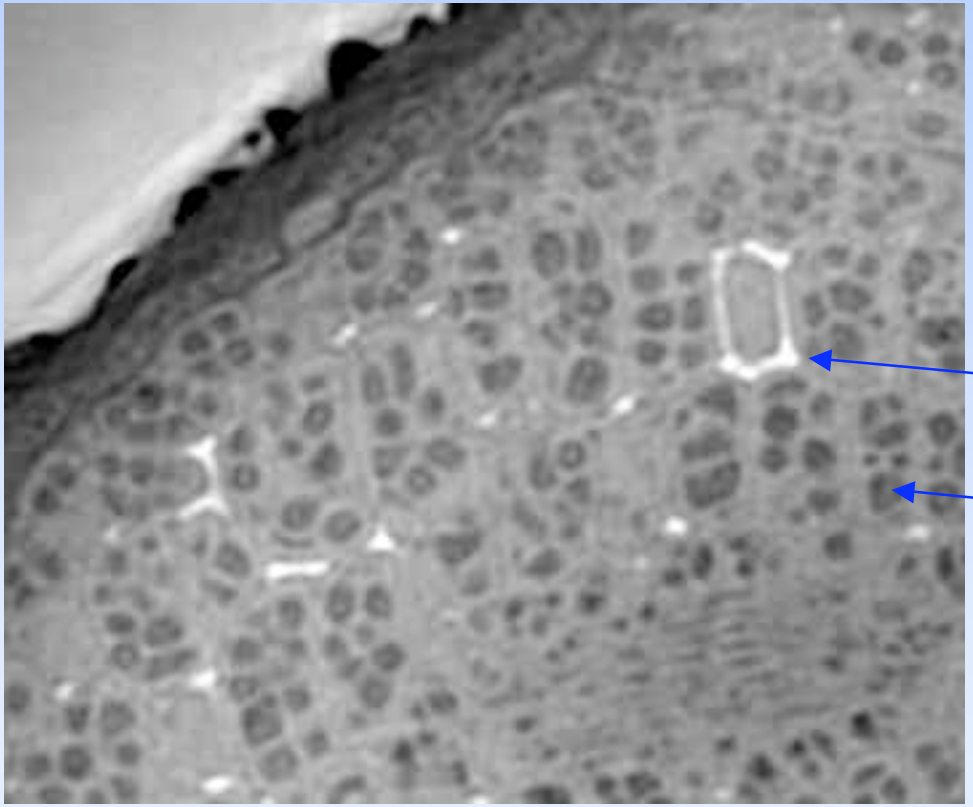
30 μm

R. Mache (UJF, Grenoble)

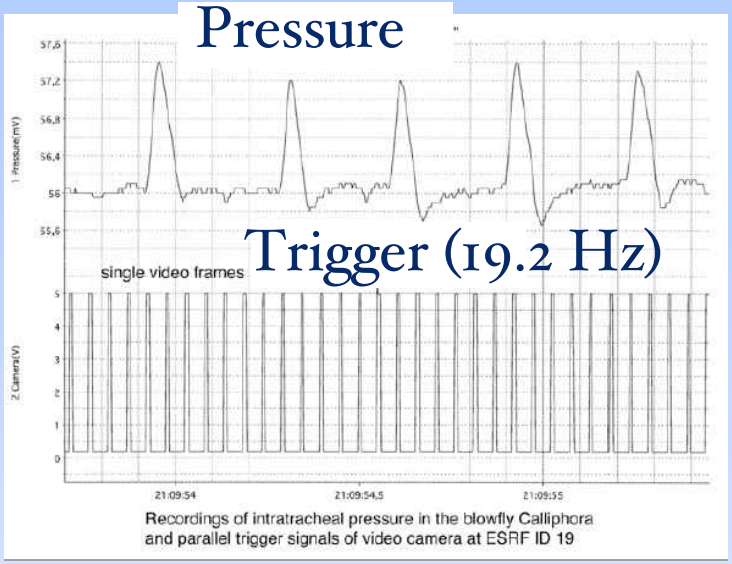
In-situ imaging of Arabidopsis

Seed of Arabidopsis

Tomographic Slice



Fast radiography



intratracheal pressure during exposure

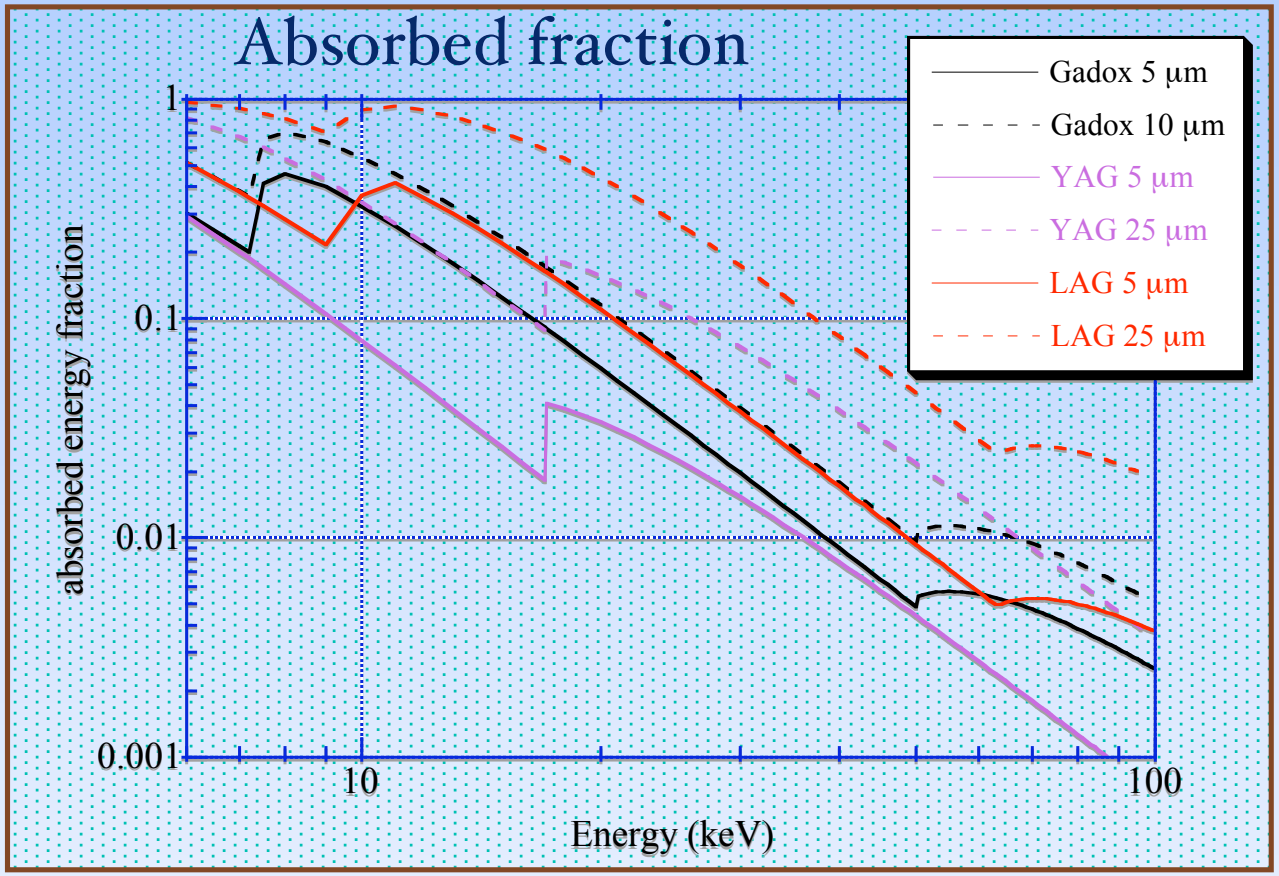
fruitfly
Drosophila

1 mm

TL Wasserthal, R. Fink (Erlangen)

High Resolution Imaging

Without X-ray magnification



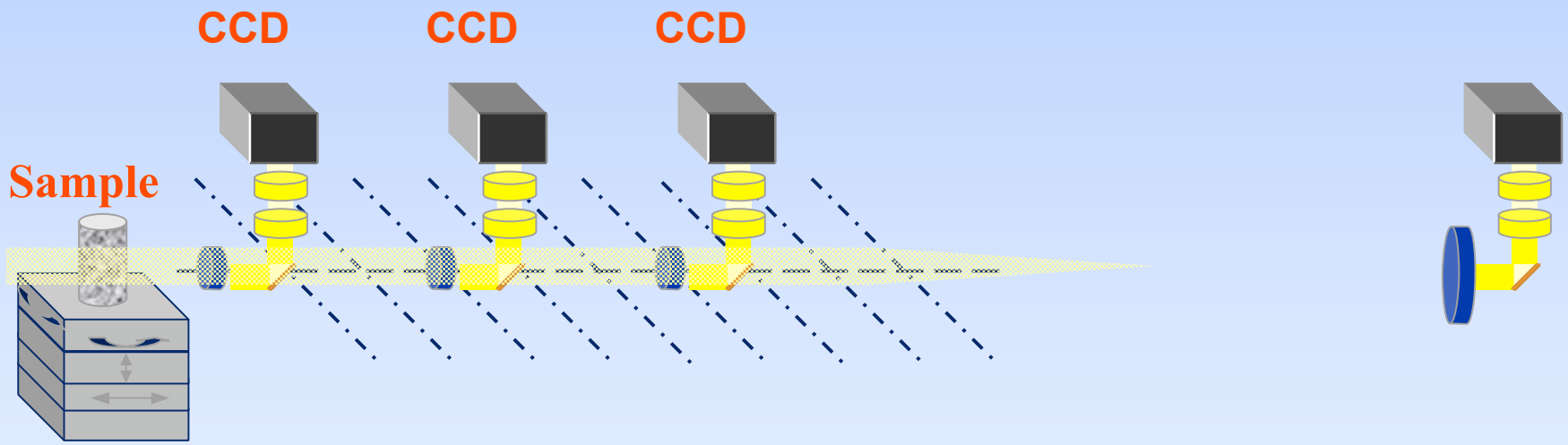
- 25 μm thick scintillator → 2 μm resolution → up to 40 keV
- 5 μm thick scintillator → 1 μm resolution → up to 20 keV
- 1 μm thick scintillator → 0.5 μm resolution

Detector efficiency

Scintillator is semi transparant

→ use several detectors in parallel

Multiplexing of the distance



Practical issues:

medium resolution: 4 distances over 8 m

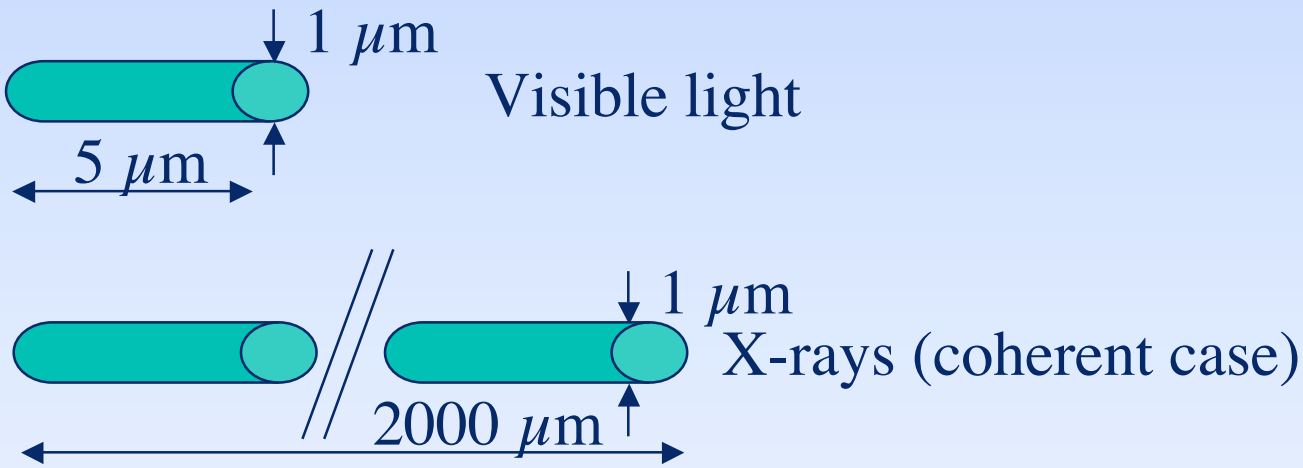
high resolution: 4 distances over 100 mm

on-line data-analysis

Detector efficiency

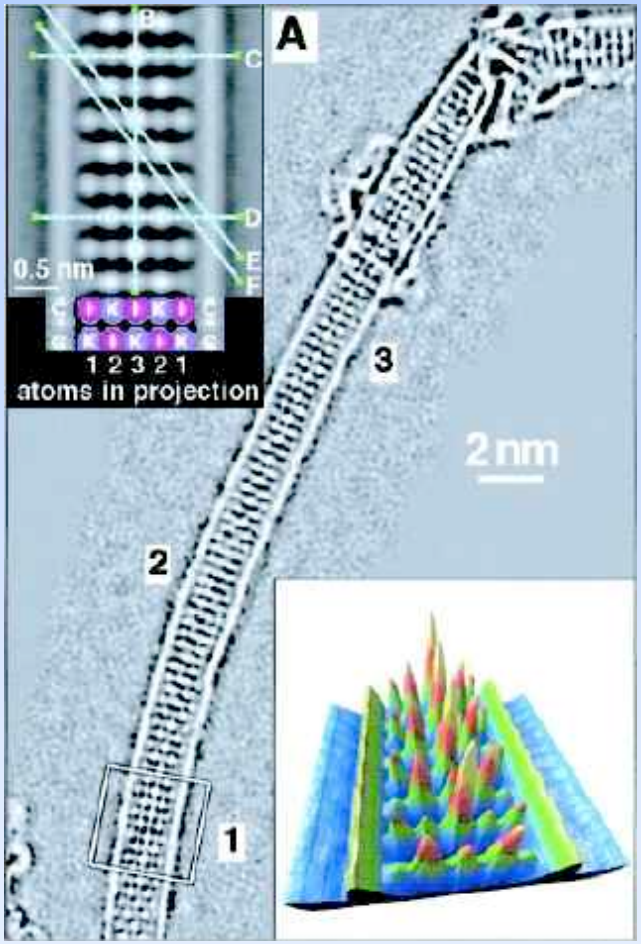
$$\text{depth of focus} \propto \frac{\text{resolution}^2}{\lambda}$$

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



Other schemes than
fluorescent screen - lens - CCD

Detector Efficiency



1D KI crystal in C nanotube
R. Meyer *et al*.
University of Camebridge
Science, 2000

Nano-Tomography Project

Motivation:

Materials Science: relevant scale 0.1-10 μm

Nano-technology/fabrication: 50 nm scale and below

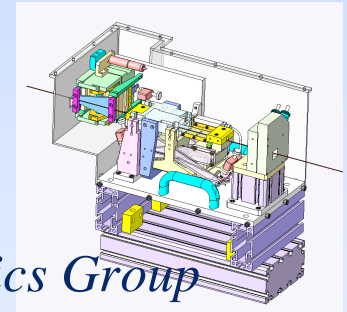
Cell biology, colloids: complete cell < 20 μm

Strategy:

Dedicated 3D microscope

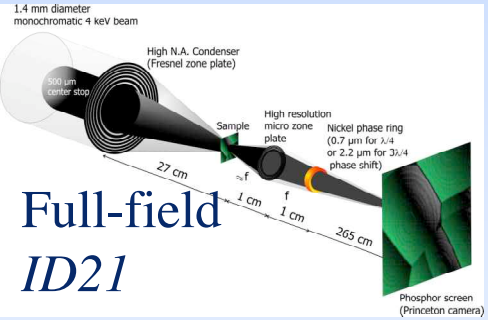
State-of-the-art in-house / commercial products

Optics



KB

Optics Group



Full-field

ID21

Mechanics / metrology

Sample preparation

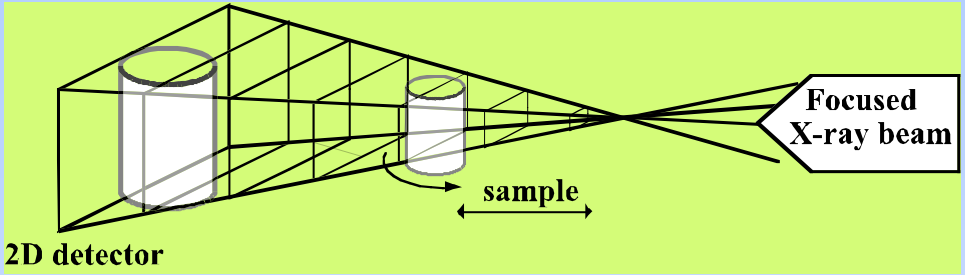
Goal: *routine* CT with ~ *50 nm* spatial resolution

combine micro-structure and micro-analysis

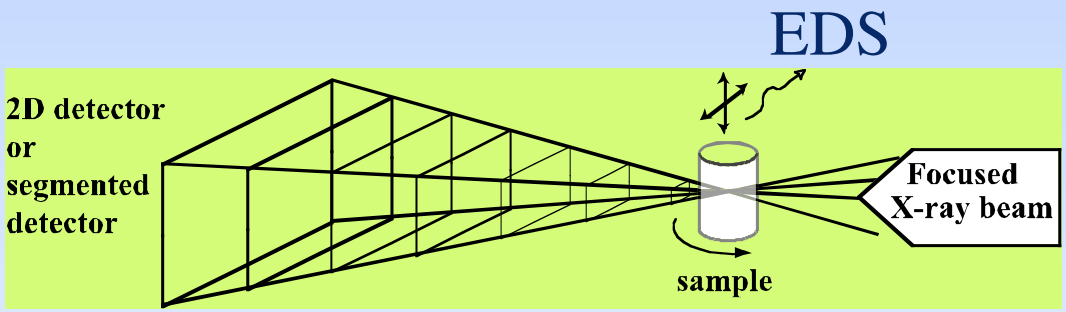
P. Cloetens
J. Susini
O. Hignette

Combine Configurations

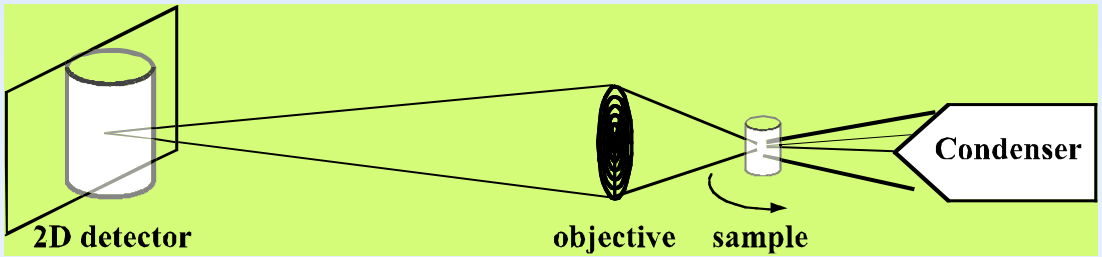
Projection Microscopy:
Structure
Dose efficient, fast
Phase contrast



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:

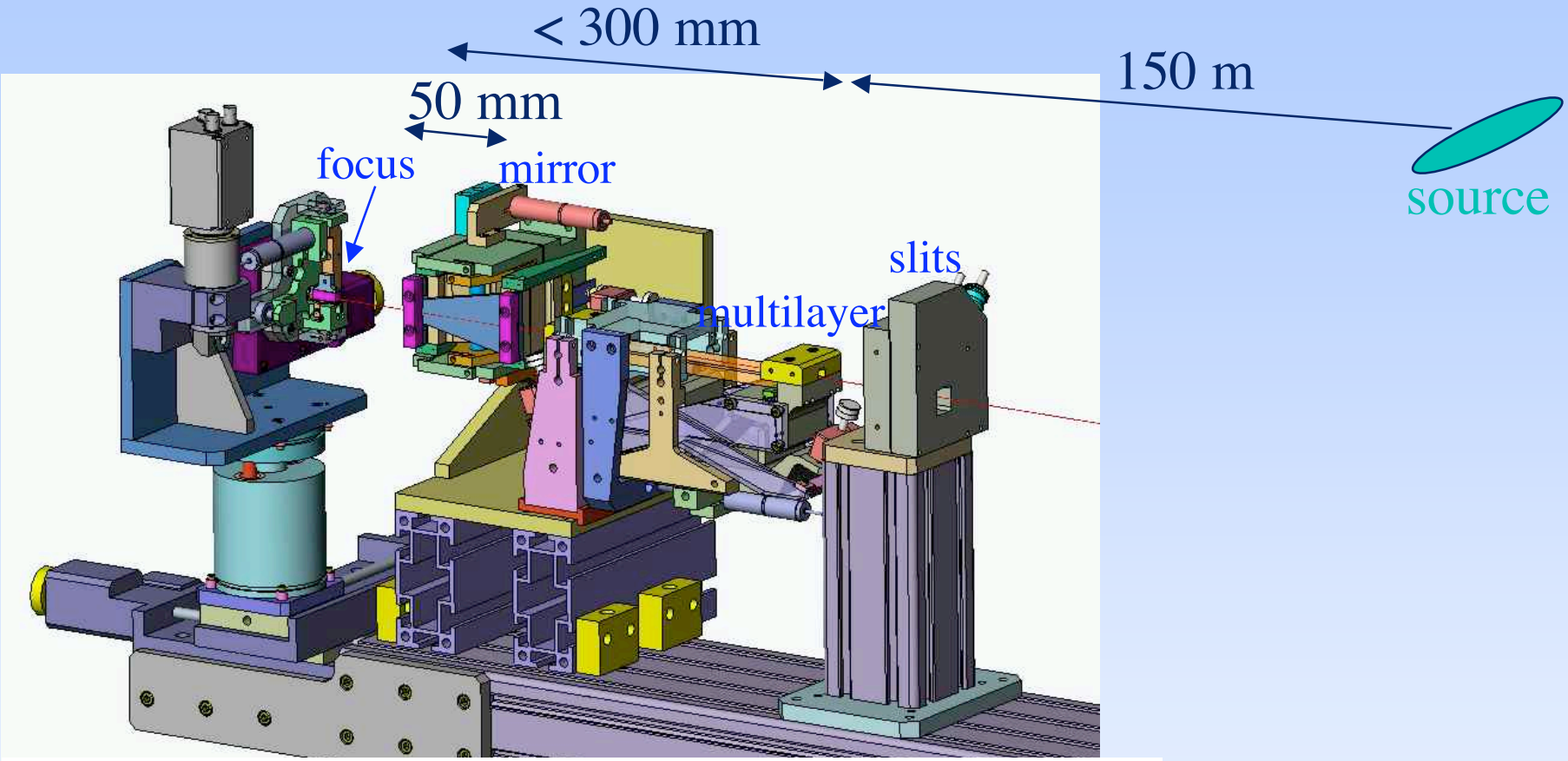
- limited field of view (~ 50 μm)
- large focal distance (~ 20 mm)
- little energy tuneability
- needs good monochromaticity: $\Delta\lambda/\lambda < 10^{-3}$

→ 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



Mirror Efficiency: reflectivity towards 1 (0.6)

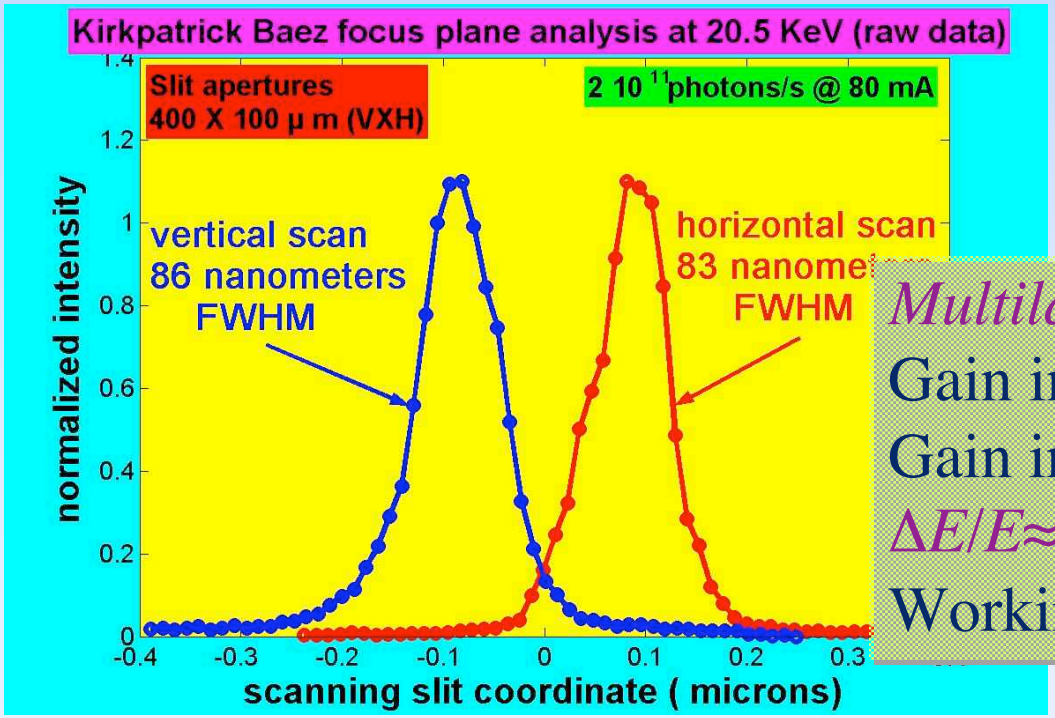
No chromatic aberration: large bandwidth possible

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/μm^2 Old units

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

A *Nano-Probe* for hard X-ray nano-science

Projection Microscopy

D = 225 mm
M = 17

D = 175 mm
M = 22

D = 125 mm
M = 31

D = 45 mm
M = 87

E = 20.5 keV

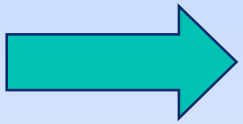
Exposure time = 1 s (16-bunch)

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

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

Data handling

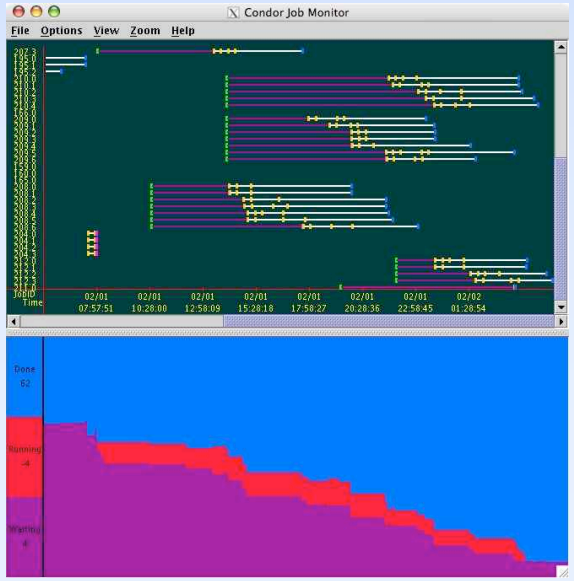
Memory:

database TomoDBII

MIS

Data storage: NICE (backup???)

Data processing:



PyHST (scisoft, A Mirone, R Wilcke)

on linux mini-cluster (10 cpu's)

(CS, WD Klotz, G Foerstner)

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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Lab. Louis Néel, Grenoble M. Schlenker
Plant cell imaging

■Zoologie I, Univ Erlangen L.T. Wasserthal
Phys. Chemie II, Univ. Erlangen R. Fink
Insect Imaging

■Univ. Bordeaux 1 R. Ortega, G. Deves
Cellular mapping of metals

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