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Bright betatron X-rays for imaging applications

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Bright betatron X-rays for imaging applications

1. Introduction
2. Betatron Radiation and its applications
3. Quick Tomography of a human bone sample

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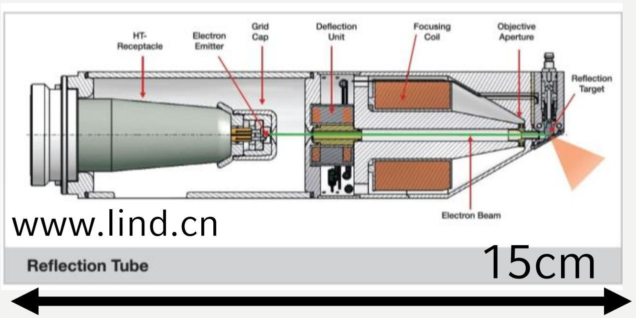
Introduction

Different X-ray sources

Costs, Beam Quality, Peak Brightness



Microfocus X-ray tube

- Incoherent
- Broadband and/or peaks from line emission
- Broad emission angle
- Small
- Cheap

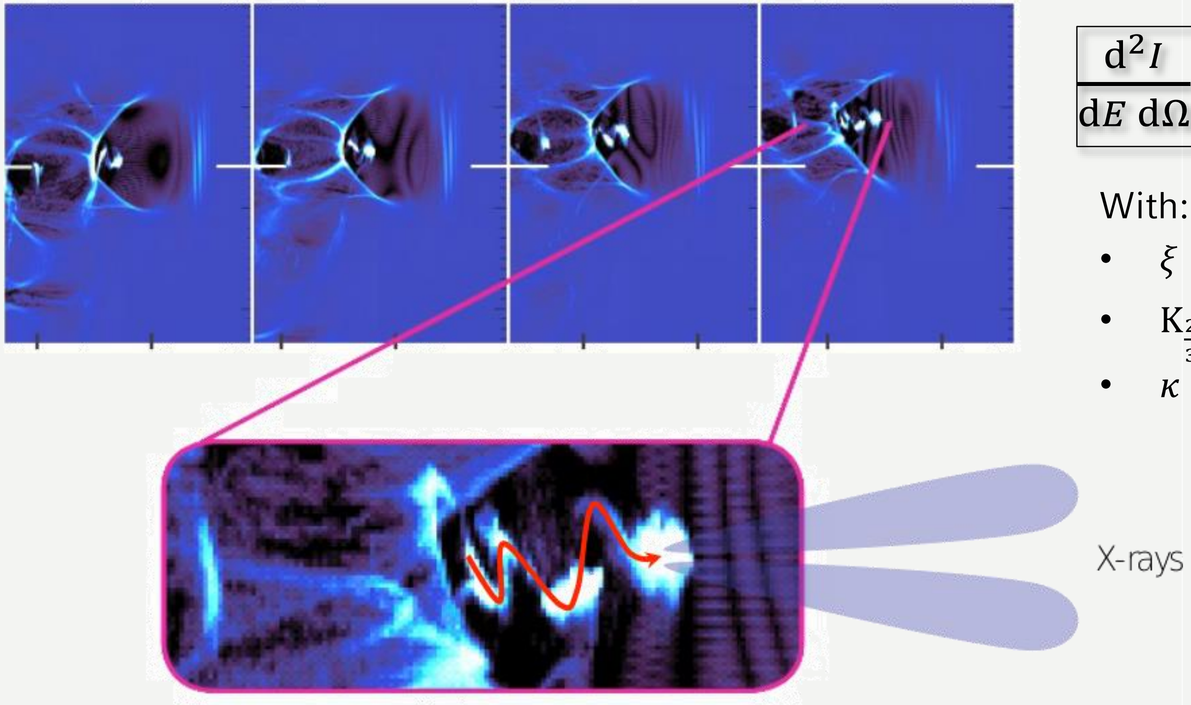
?

Synchrotron

- Broadband (W) or small (U)
- Small emission cone
- Polarized
- Pulsed
- Large
- Expensive
- Difficult to access

An X-ray source in between, i.e. relatively cheap but with synchrotron-like features would be nice!

Laser driven X-ray sources – Generation of Betatron radiation in LWFAs



$$\boxed{\frac{d^2 I}{dE\, d\Omega} \propto \gamma^2 \xi^2 K_{\frac{2}{3}}^2\left(\frac{\xi}{2}\right) \quad \text{for } \kappa \gg 1}$$

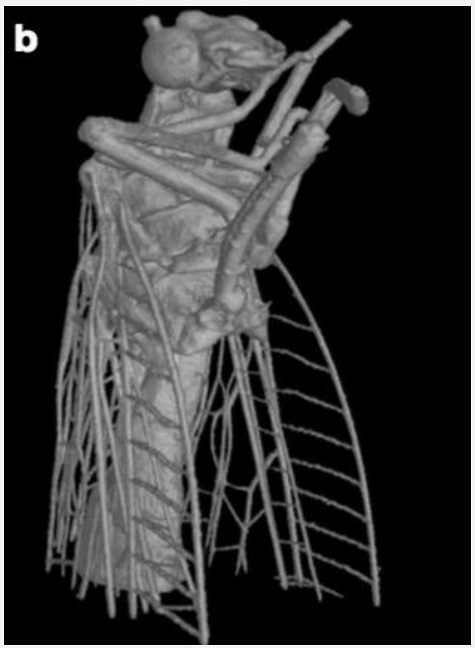
With:

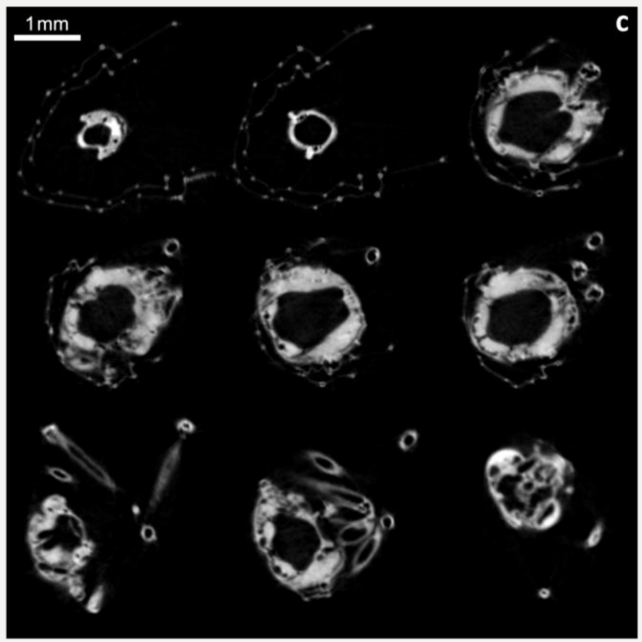
- $\xi = \frac{E}{E_{crit}}$
- $K_{\frac{2}{3}}$ modified Bessel fct. of 2nd kind
- $\kappa = \gamma k_\beta r_\beta$ (Betatron strength parameter)

Strong transverse focusing fields force the electrons to oscillate transversally
=> betatron oscillations => betatron x-rays

Applications of Betatron Radiation – Proof of Principle

Thin samples - e.g. fly



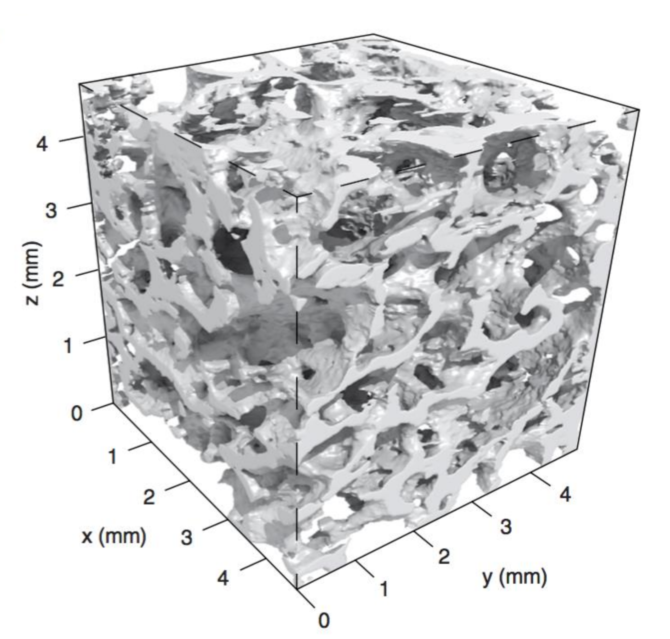


- Tomography of a green lacewing
- 360° with 1° step size
- 1487 shots @ 0.1 Hz repetition rate

J. Wenz et al. Quantitative X-ray phase-contrast microtomography from a compact laser-driven betatron source. Nature Communications (2015)

Applications

Thick samples – e.g. human bone

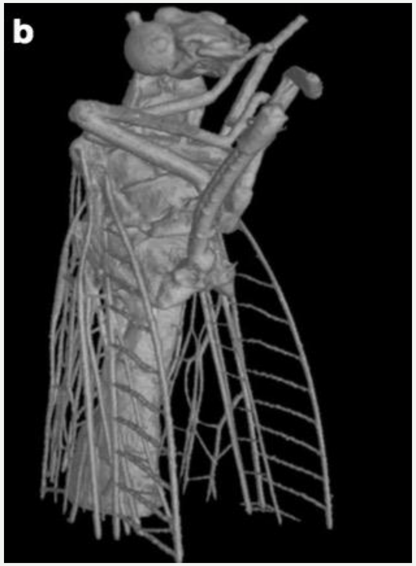


- Tomography of a human bone sample
- 180° with 1° step size, 180°-360° with 12° step size
- 235 shots @ 0.025 Hz

J. Cole et al. Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone. Scientific Reports (2015)

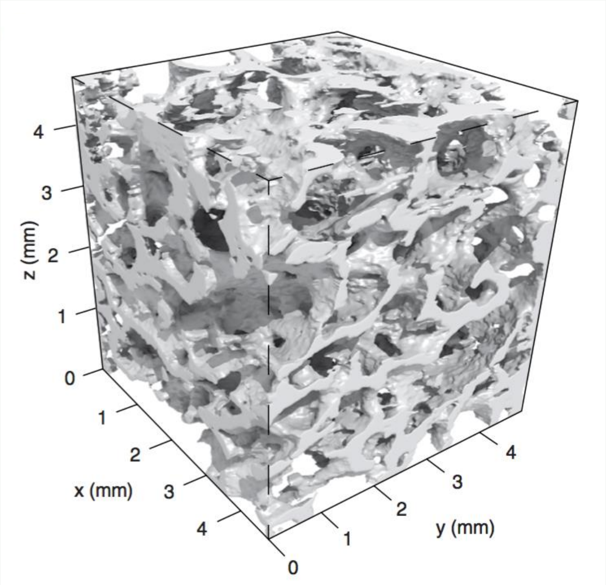
Applications

Why still not in biomedical use today?



How to **reduce the acquisition time**?

- Increase *laser shot frequency*
- Increase *vacuum pump capacity*
- Decrease *camera readout time*



1487 shots @ 0.1 Hz repetition rate

~ 5 hours

Acquisition time limited by:

- Readout time of x-ray camera
- gas load in vacuum chamber

235 shots @ 0.025 Hz repetition rate

~2.5 hours

Acquisition time limited by:

- laser

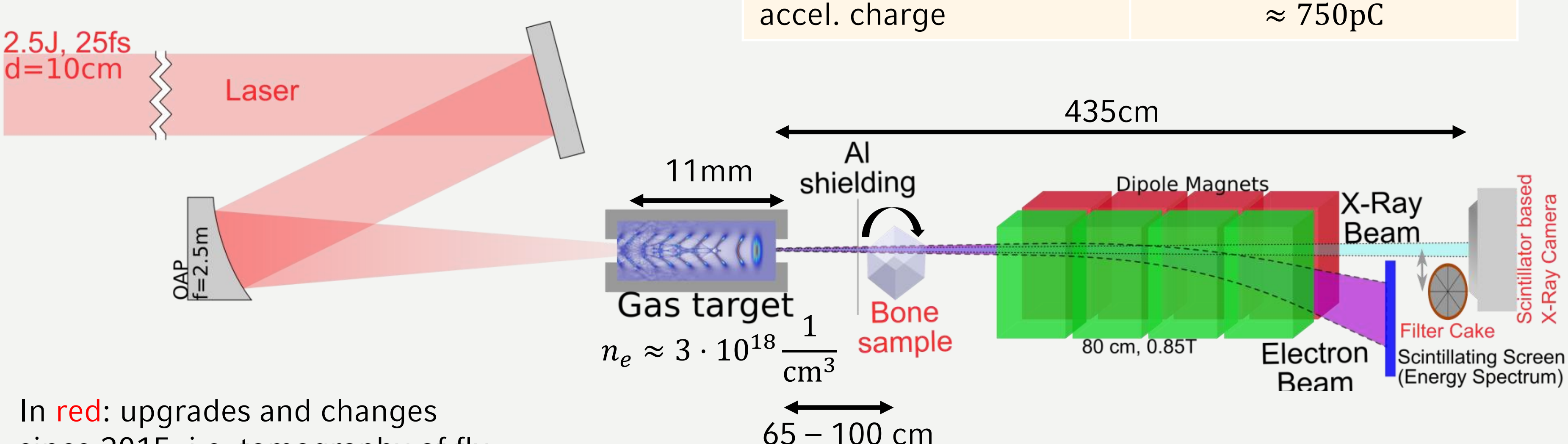
Quick Tomography

Experimental Setup for quick tomography of a bone sample

Operating @ 1Hz

(upgraded vacuum system, i.e. now limited by readout time of camera)

Laser + Electron Parameters	
focus size (FWHM)	$\approx 30\ \mu\mathrm{m}$
peak intensity (30% within FWHM)	$\approx 4.5 \cdot 10^{18}\,\frac{\mathrm{W}}{\mathrm{cm}^2}$
normalized vector pot.	$a_0 \approx 1.4$
accel. charge	$\approx 750\mathrm{pC}$



In red: upgrades and changes since 2015, i.e. tomography of fly

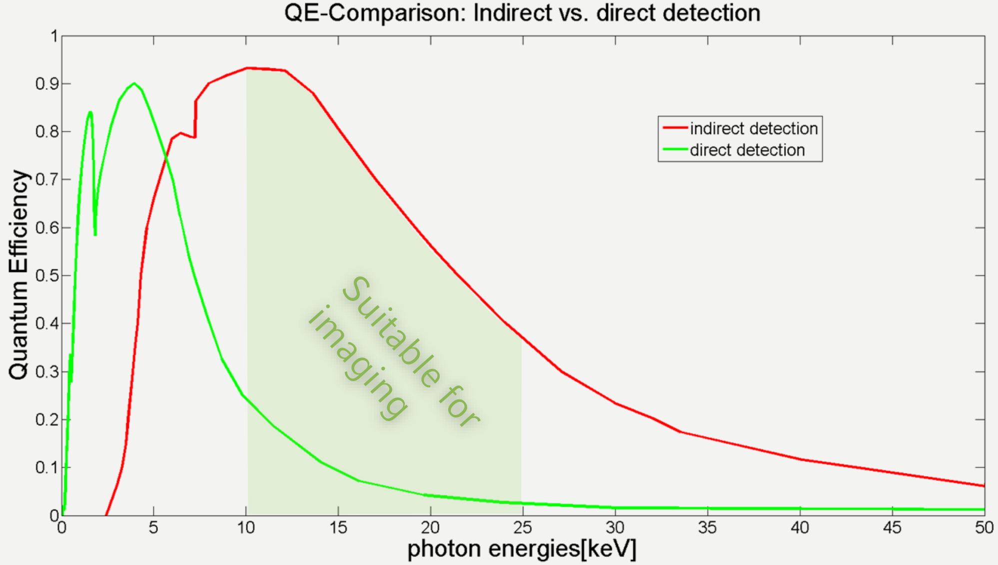
Details of the x-ray camera and spectrum reconstruction

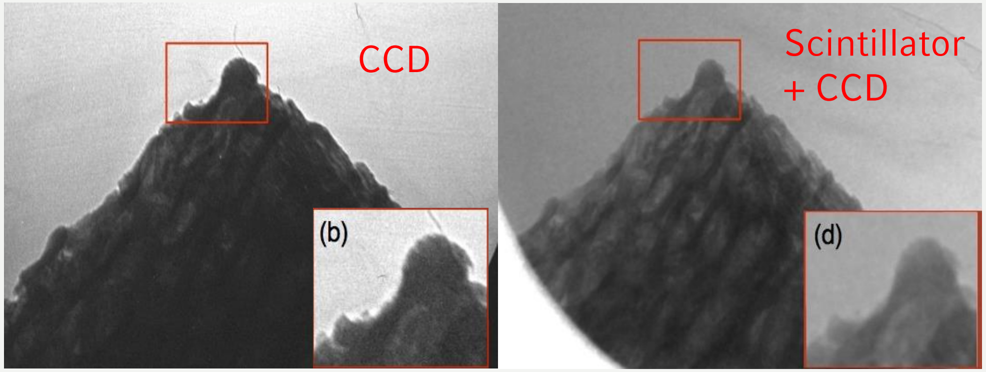
X-ray energy [keV]	Tenth-value thickness for canc. bones [mm]
5	0.1
10	0.6
20	1.3
30	17

Difficulties in imaging “thicker“ samples:
- Tenth-value thickness increases drastically
- X-ray energies beyond 15keV cannot be detected directly, since they just pass through the CCD

⇒ ***Indirect detection*** necessary:
A scintillator converts the incident X-rays into photons of visible wavelengths. These are then intensified and recorded by a CCD.

=> X-rays beyond 50keV still detectable.





Spectrum reconstruction

5cm

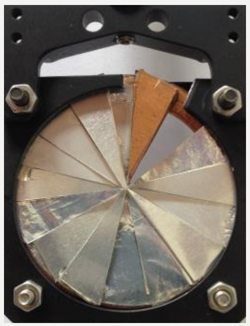
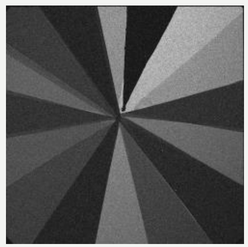
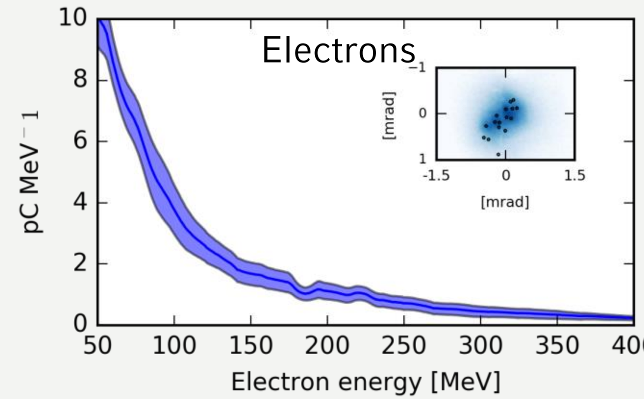
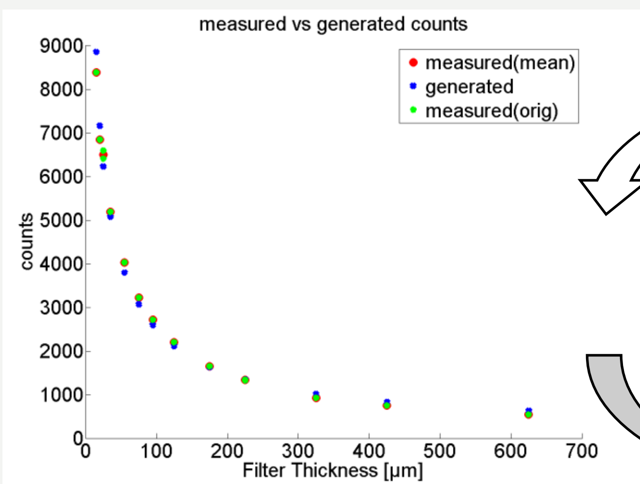


Image of filter on camera

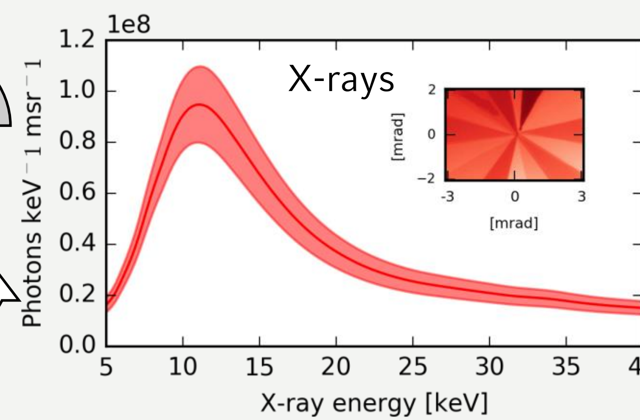


filter cake:
16 wedges with different Al thicknesses (5µm-610µm)





Iterative Algorithm



X-ray characteristics

Typical betatron parameters	
E_{crit}	$\approx 15\text{keV}$
divergence	$\approx 5\text{mrad} \cdot 15\text{mrad}$
source size	typically $\approx 1 - 2\mu\text{m}$
no. of photons on camera	$\approx 7 \cdot 10^7$
no. of photons per shot	$= 1.2 \pm 0.3 \cdot 10^9/\text{msr}$
average photon flux (@ 1Hz)	$\approx 1.2 \cdot 10^9 \dfrac{1}{\text{s} \cdot \text{msr}}$

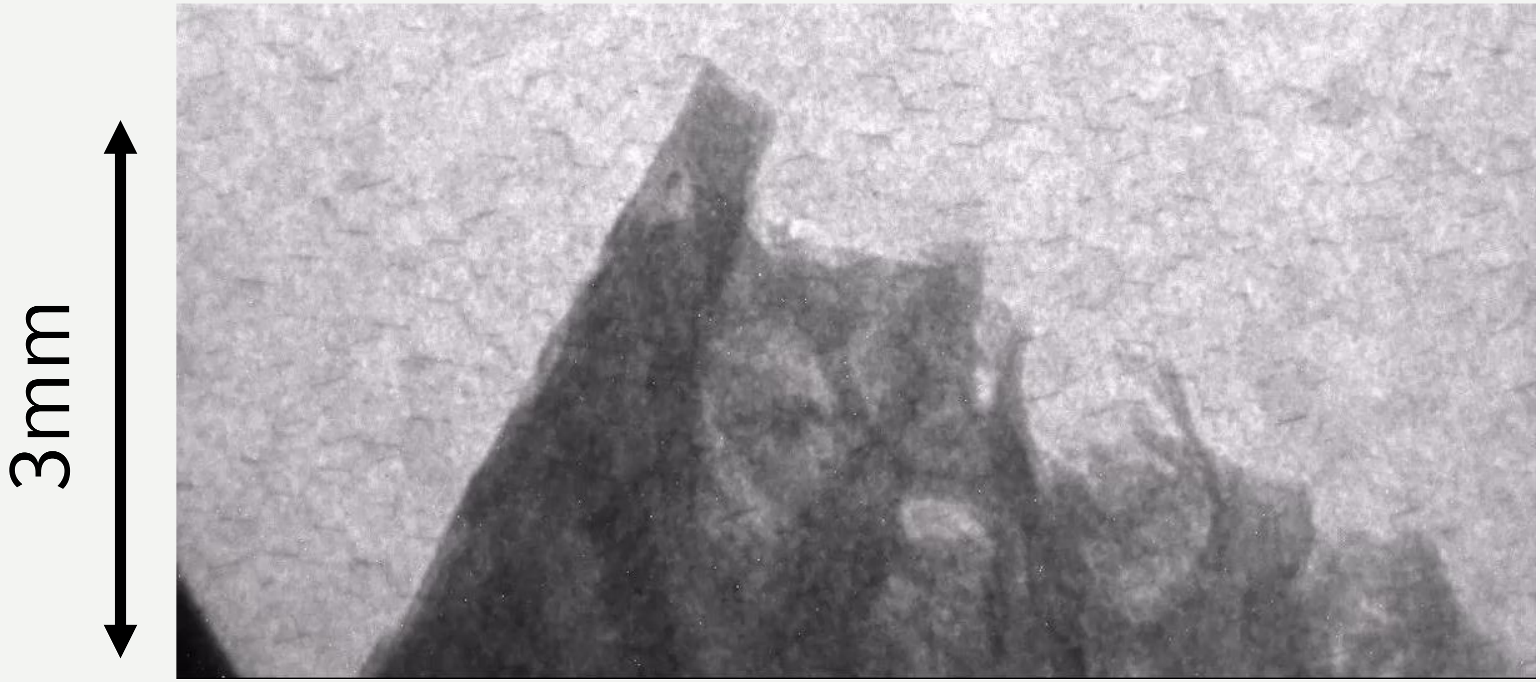
First scan: Setup optimization

Goals:
- decrease readout time of camera as far as possible
- find reasonable number of shots per angle
- determine appropriate angular step size

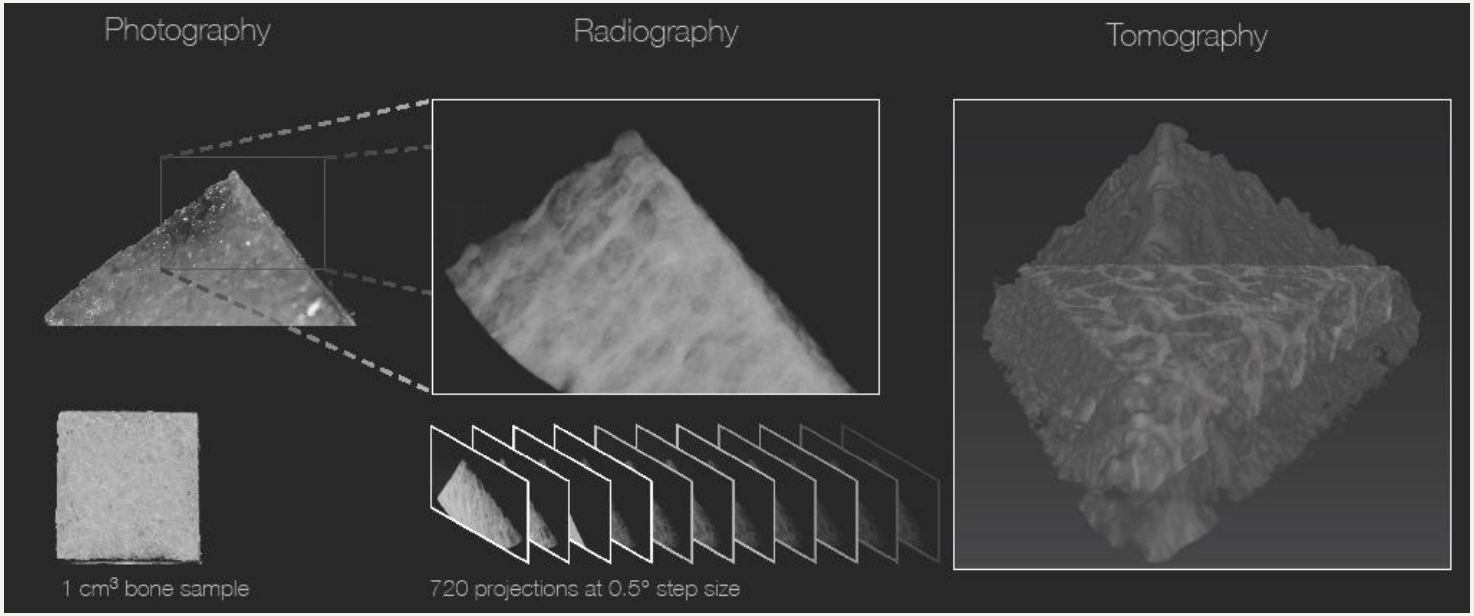
~3000 shots @ 0.5-1Hz repetition rate
~**1h**

[0:0.5:90]: 10 images at each angle
[90:0.5:360]: 1 image at each angle
[20:10:80]: 100 images at each angle

Raw data (350 shots, 60fps)



Sample reconstruction – Setup optimization scan

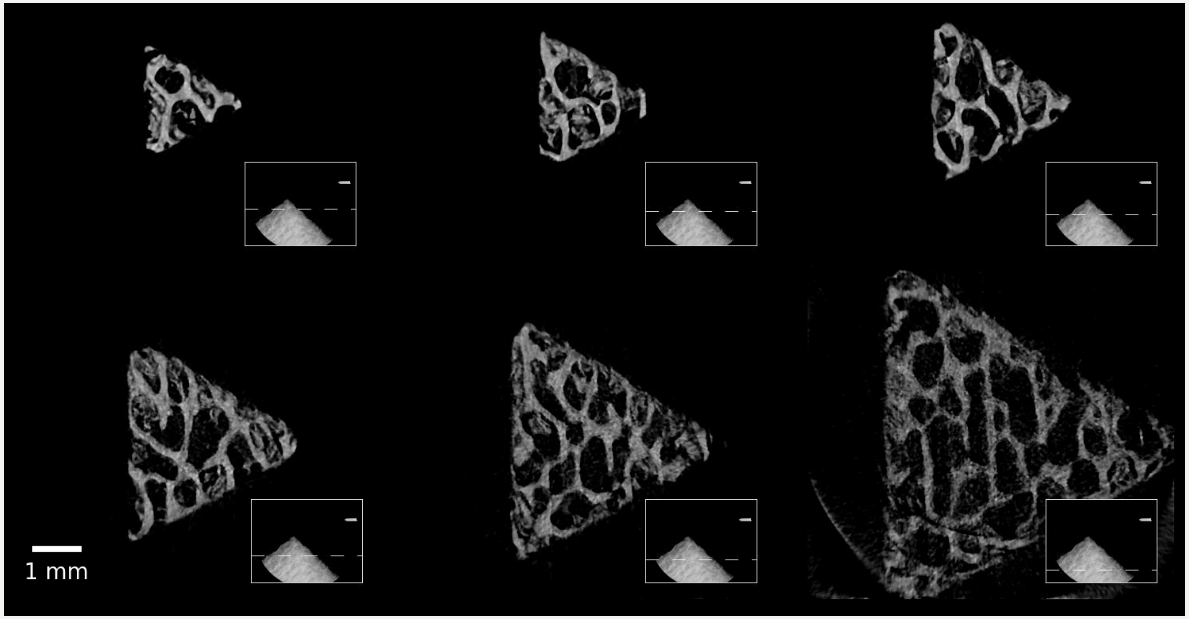


3 step for reconstruction:

- Flat field correction => removes CCD artifacts (sensitivity variations, dust, ...)
- Static fiducial => corrects for small pointing fluctuations
- Advanced reconstruction algorithm: **Statistical iterative reconstruction (SIR)**

Sample reconstruction – SIR algorithms

SIR: iteratively improves reconstructed image
+ removes reconstruction artifacts
+ regularization reduces noise
+ weighting factors emphasize regions with good signal
+ powerful for small data sets
- High computation time



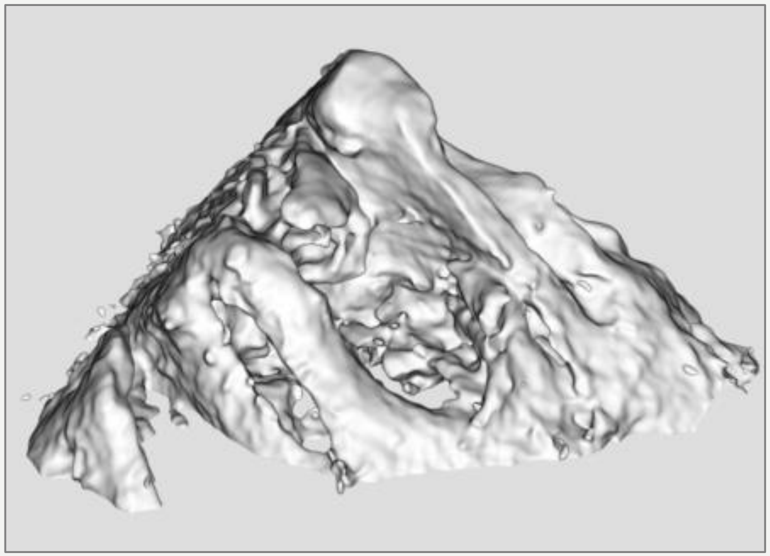
Resolution:
1388x1038 px.
Pixel size: 29µm
Magnification: 4.35
=> Voxel size: $(6.7\mu m)^3$

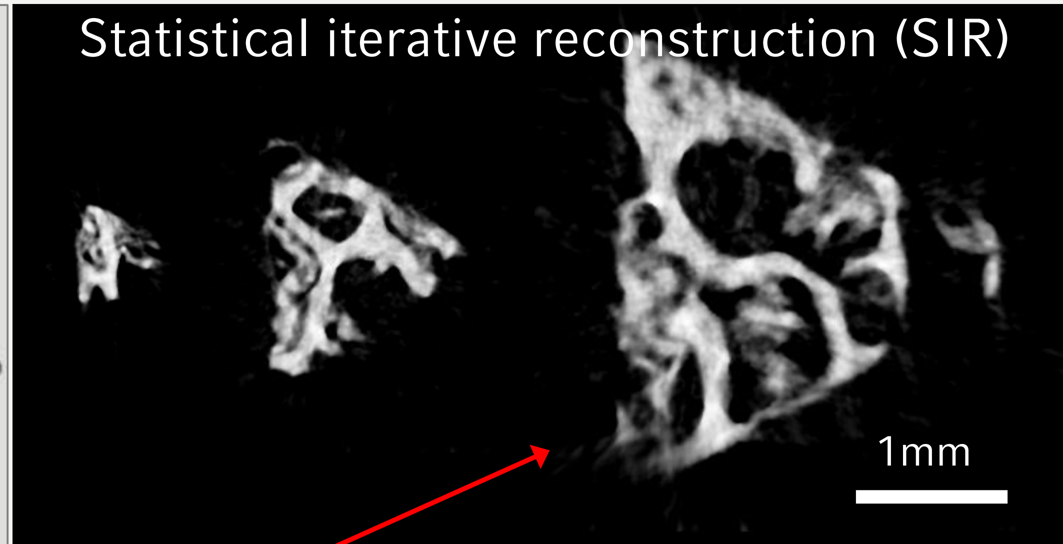
Experimental Setup - Findings:

- 1Hz repetition rate works
- [0°:1°:180] suffices for full 3D reconstruction
- at least 1 image per angle (i.e. 180 images in total) necessary for successful reconstruction
- static fiducial can be omitted (subsequent alignment via algorithm)

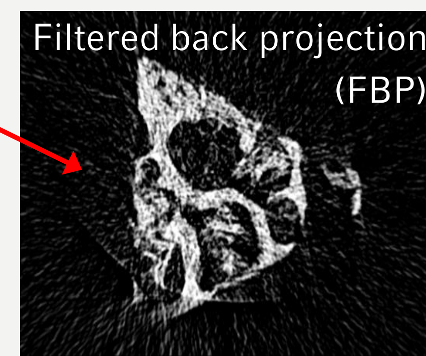
Quick Tomography

Quick tomography: 180 images [0°:1°:180°], **3min**





SIR proves to be superior to FBP



Conclusion: Microtomography of thicker objects is feasible within minutes

A. Döpp et al. Quick X-ray microtomography using a laser-driven betatron source. (in submission)

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Thank you for
your attention