High-resolution bio-imaging with liquid-metal-jet x-ray sources

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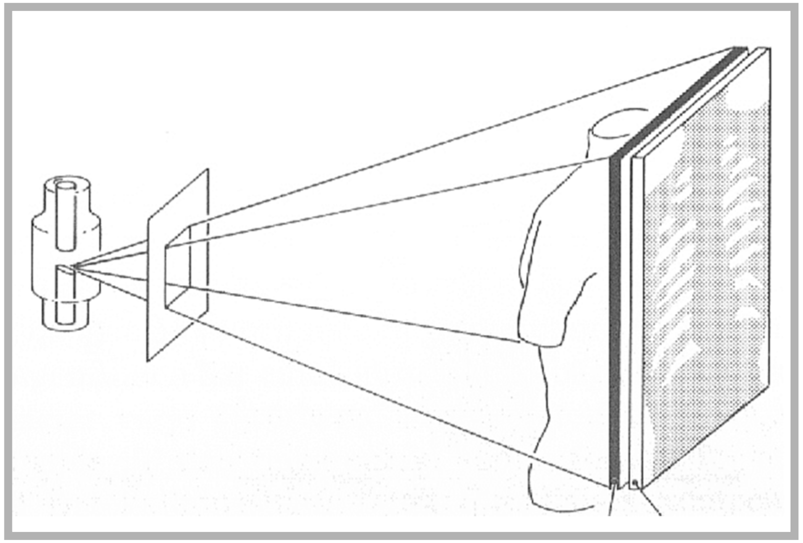
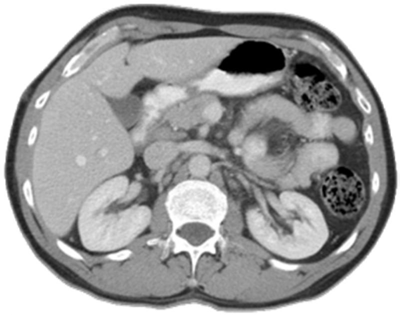
Laboratory hard x-ray imaging





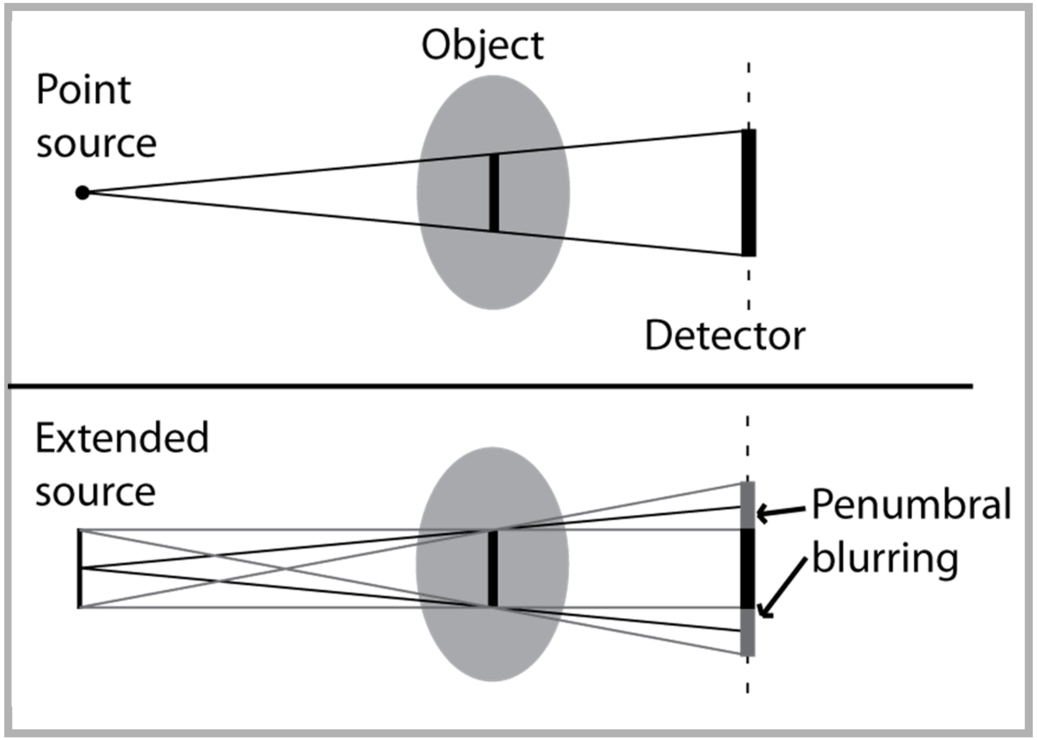
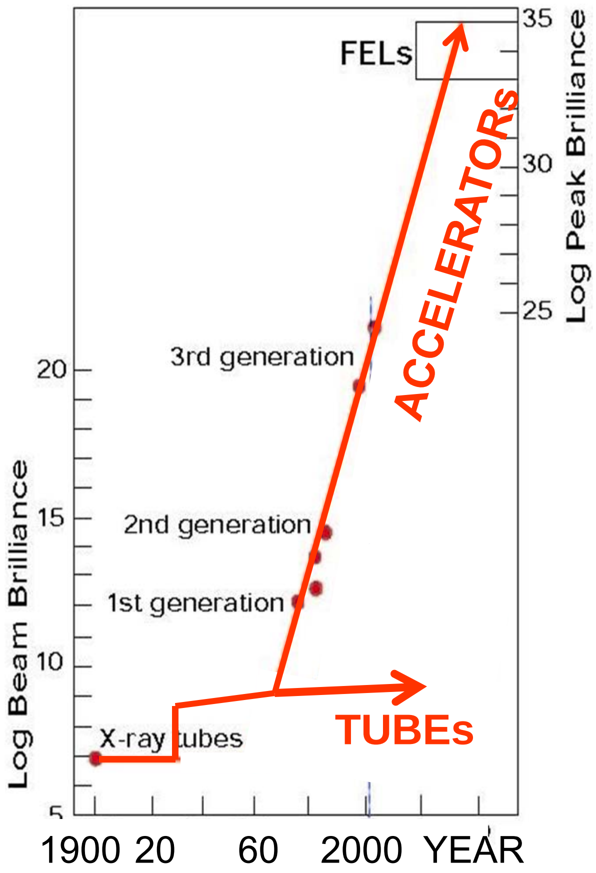


Image quality is source limited

Electron-Impact X-Ray Sources

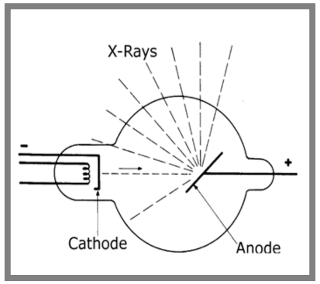
X-Ray Brightness



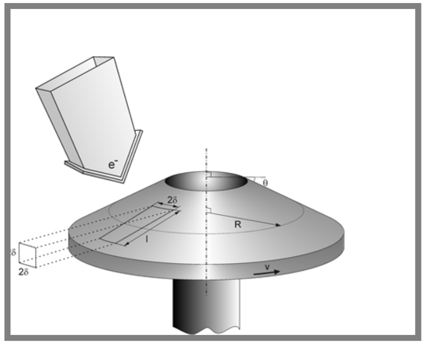
History: Electron-impact sources

E-beam power density ⇔ brightness

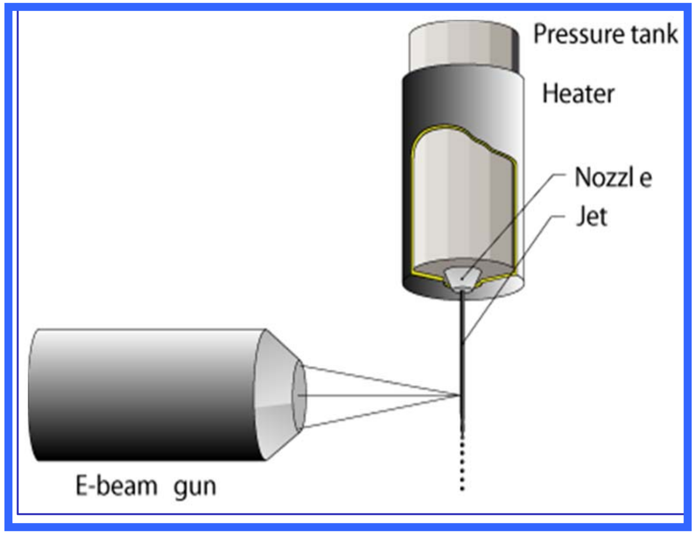
Thermally limited



Classic x-ray tube
(1895)
~1 kW/mm^2



Rotating-anode source
(1929)
~100 kW/mm^2



Liquid-metal-jet-target source
(2003)
>10 MW/mm^2

Regenerative, high speed

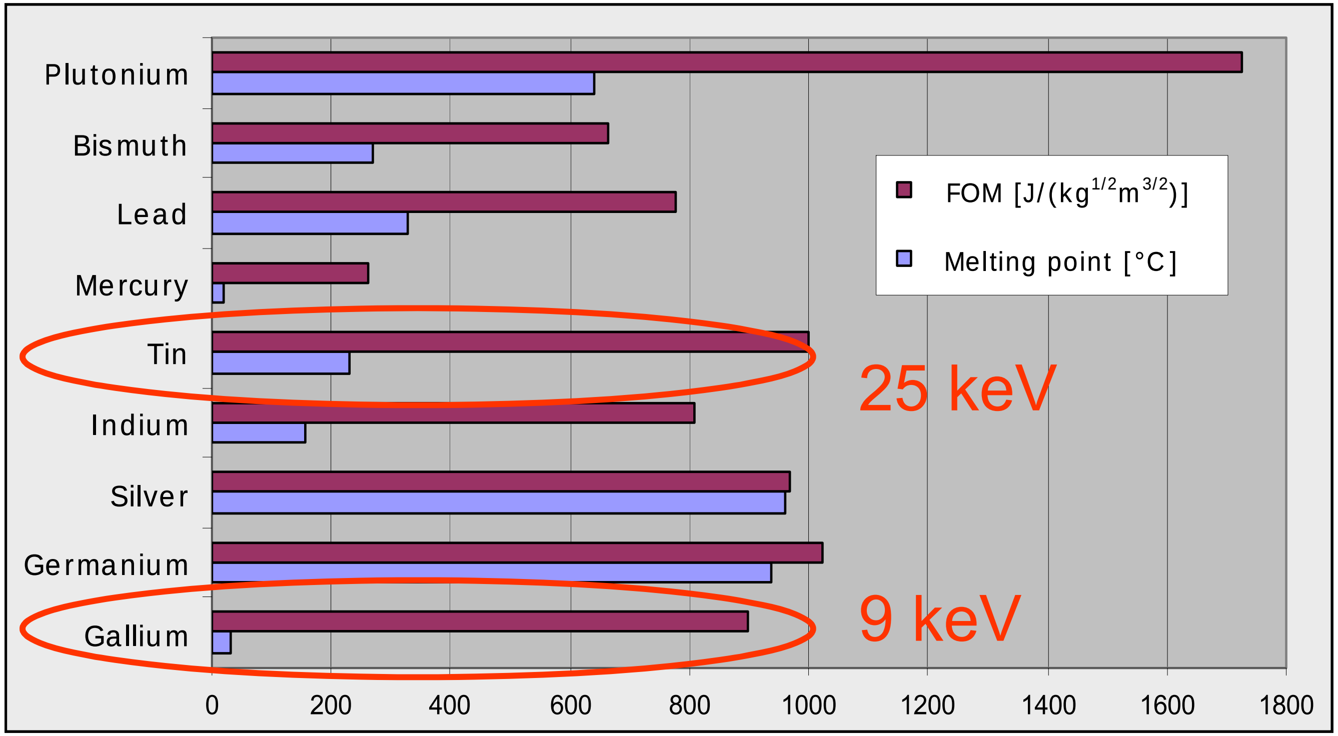
Hemberg et al, APL (2003); Hemberg et al, Opt. Eng. (2004)

The liquid-metal-jet x-ray source:

Choice of anode material

E-Beam Power Density Capacity = $v\rho(\Delta T c_p + E_{vap})$

$$FOM = Z\sqrt{\rho}\,(\Delta T c_p + \overline{E}_{vap})$$

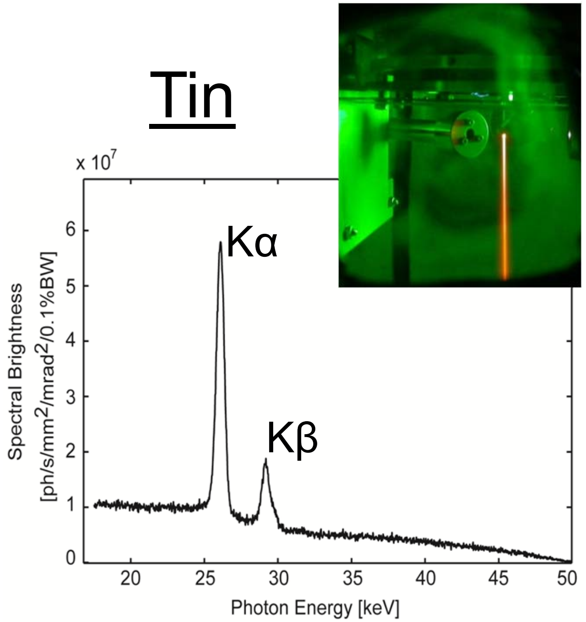


Hemberg et al, Opt. Eng. (2004)

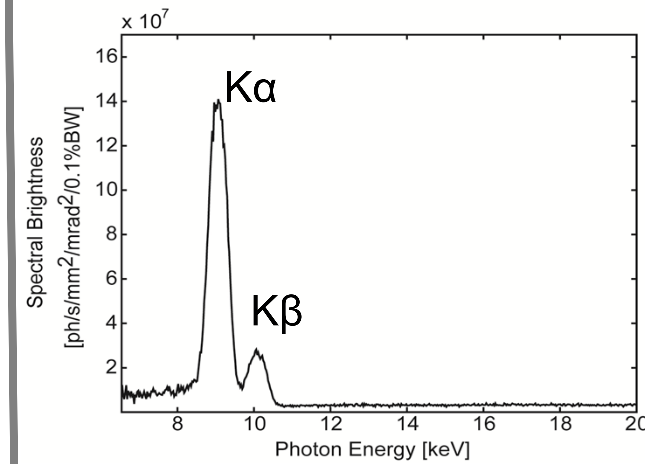
Early results (<2008):

The liquid-(metal)-jet x-ray source

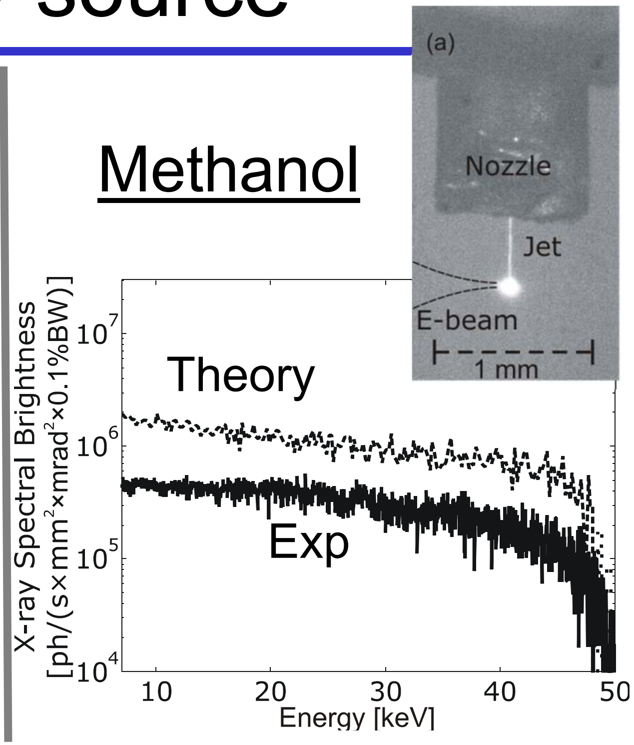
Tin



Gallium



Methanol



Present data:

Jet diameter: 15-200 μm
Jet speed: 10-100 m/s
Source size: >5 μm

Power: 50-300 W
Power density: >2 MW/mm²
(cf. ~10-100 kW/mm² existing sources)

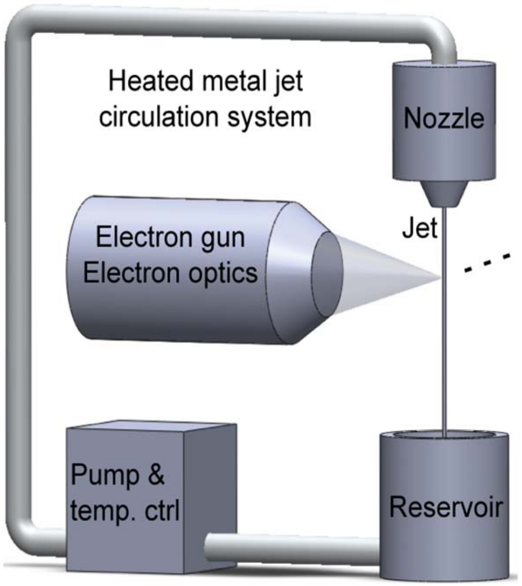
Future:

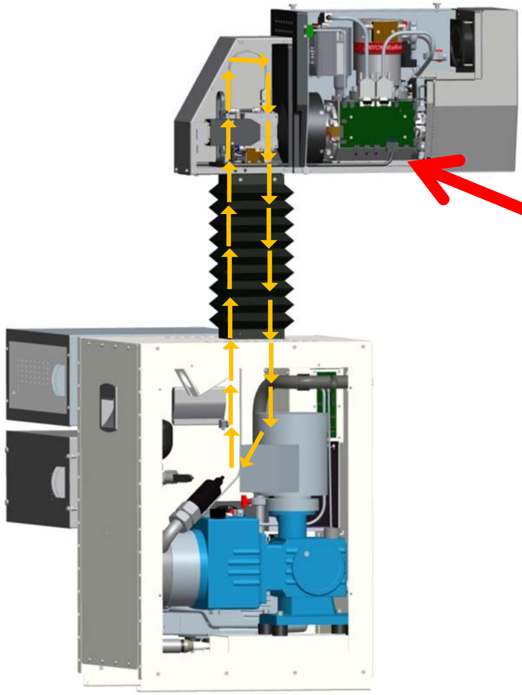
Power scalability: >100×
Power dens. scal.: >10×

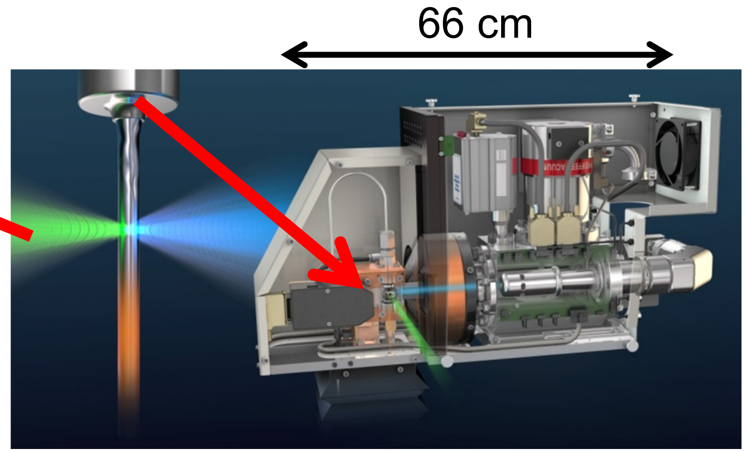
Otendal et al, Exp. Fluids (2005); Otendal et al JAP (2007); Otendal et al RSI (2008); Touhimaa et al. APL (2008)

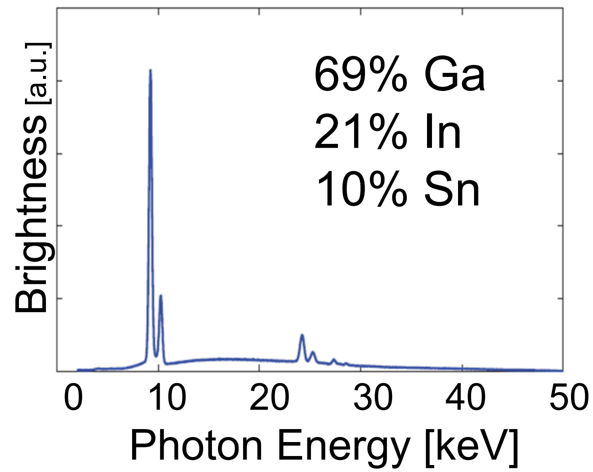
Present status:

Liquid-Metal-Jet Microfocus Sources







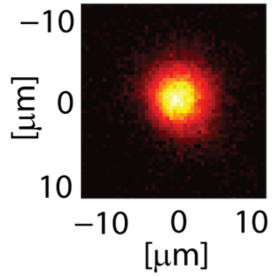


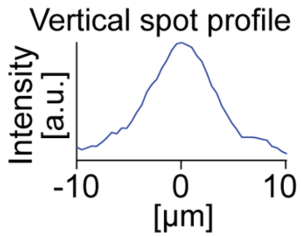
- GaInSn
- Room temp liquid metal alloy
- Metal circulation system
- 5-30 µm spot size
- 50-300 W power
- 2000 h
- Max: 15 MW/mm^2 short term

Commercialized by: eXcillum

Spot size, stability and brightness

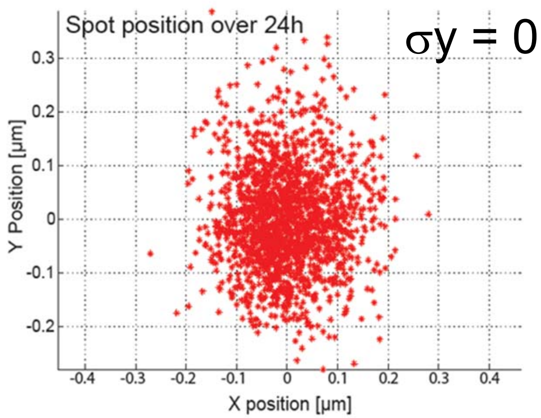
Spot size



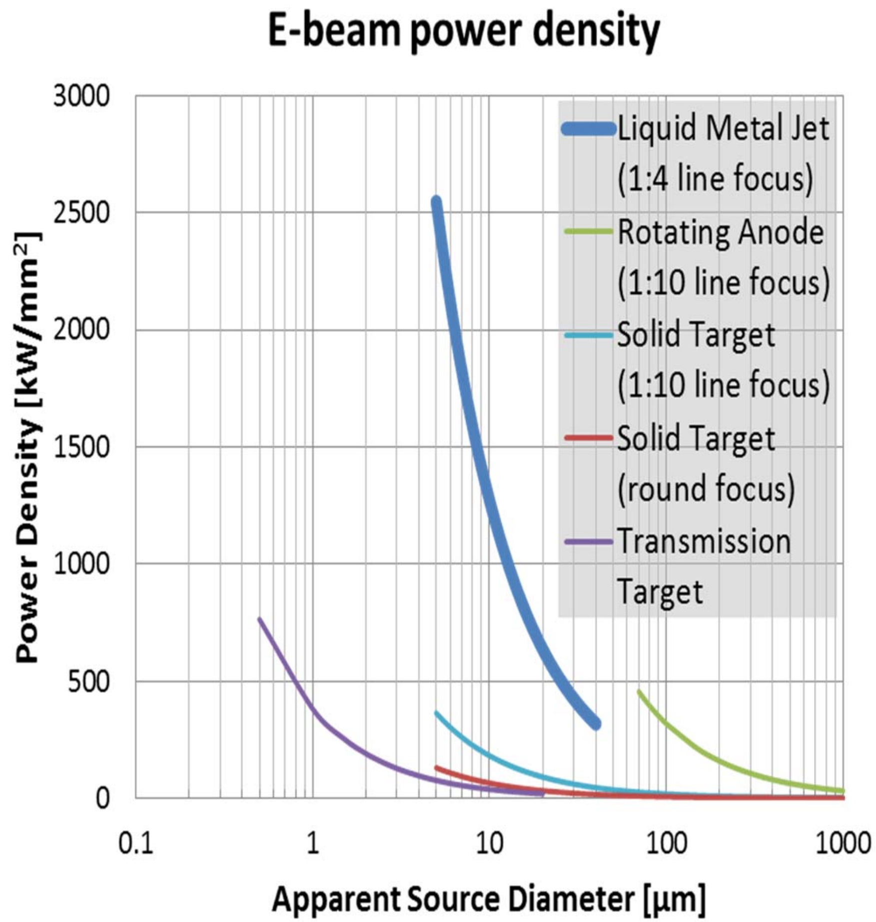


Spot stability 24 h

σx = 0.07 µm
σy = 0.09 µm



Comparison brightness



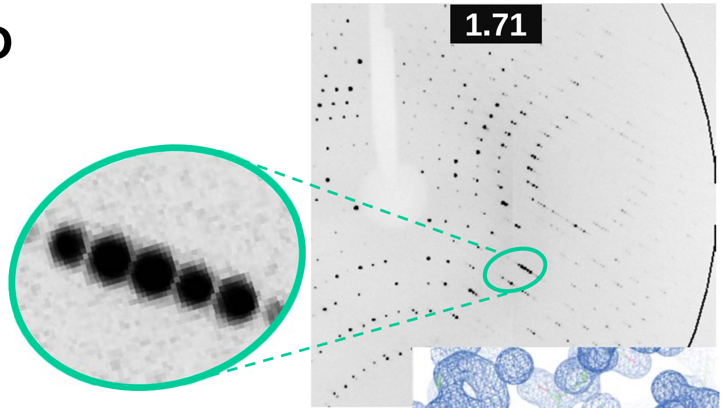
50 W/5 µm: 1×10^{11} ph/s×mm²×mrad²×line

NEXT: 15 MW/mm² @ 8 µm for 2000 h

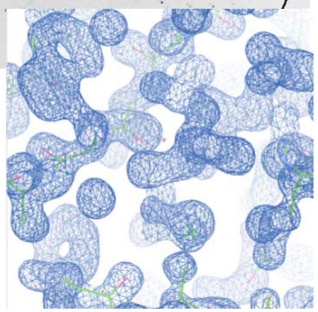
Applications: XRD and SAXS

LMJ source with
Montel optics

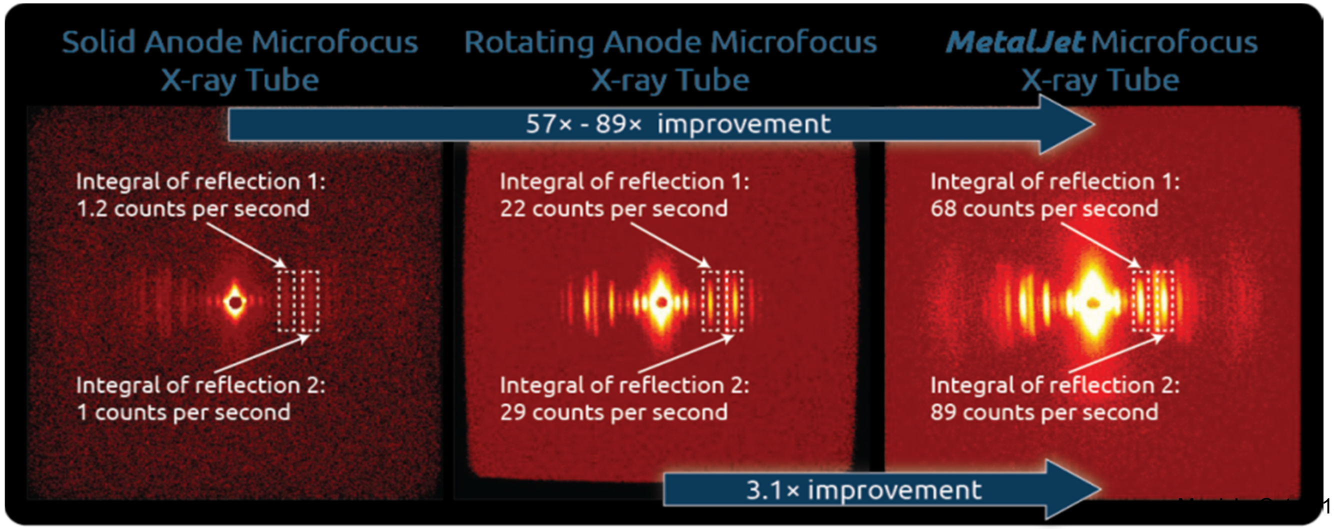
S-SAD XRD
Theumatin



Crystal: 0.18×0.20×0.22 mm
Exp. time: 4 hours
Resol: 1.7 Å
Data cut off at 2.6Å

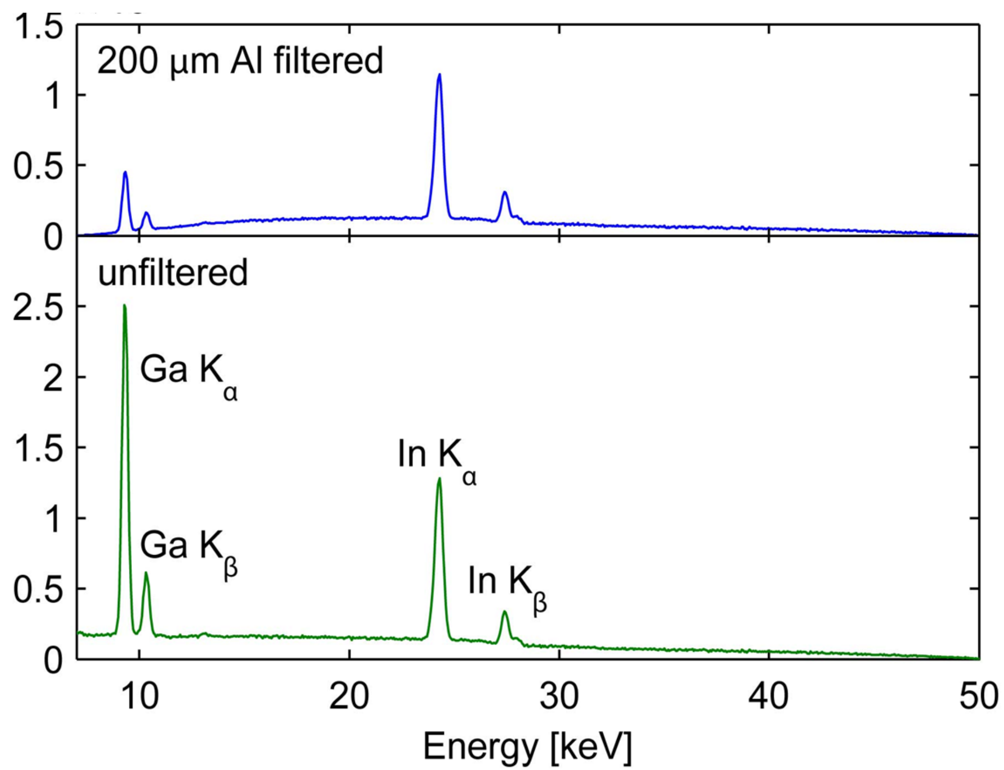


SAXS
Rat tail tendon
(67 nm period)



In/Ga anode

for higher energy and thick-object imaging

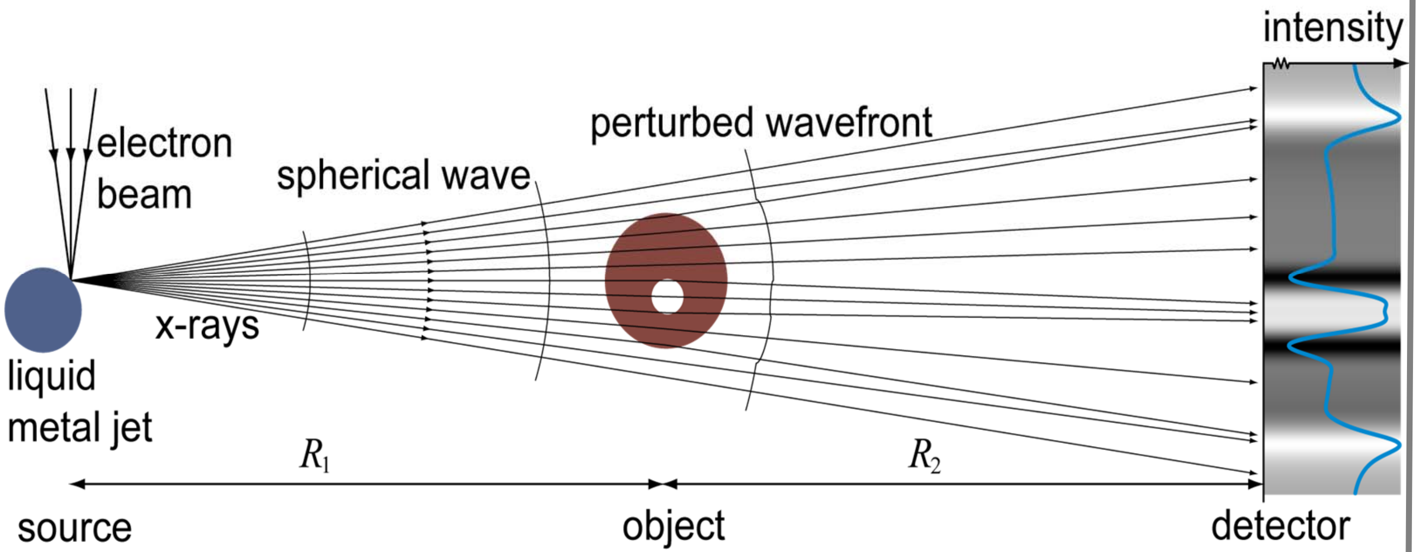


- Higher In content (65%)
  - → more 24 keV emission
  - → better penetration through e.g., mouse
- Al filtering for reduced dose
- Elevated temp operation

Larsson et al, RSI (2011)

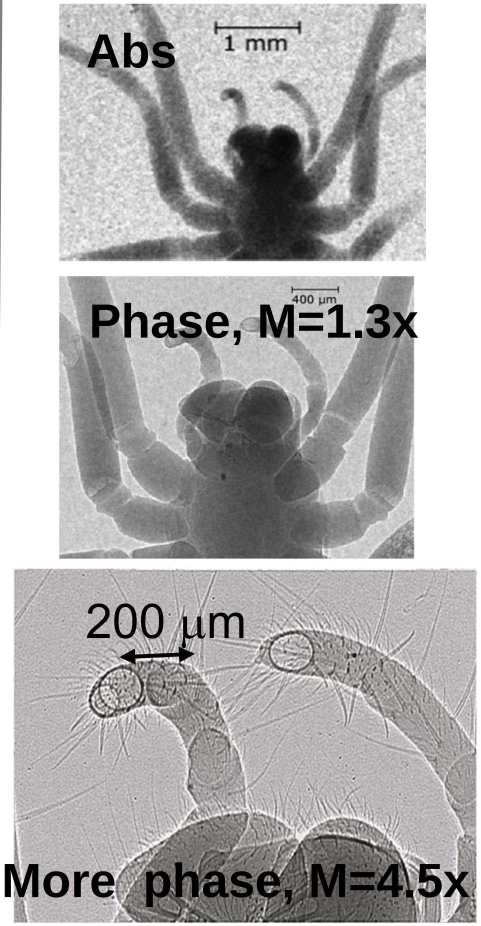
X-ray in-line phase-contrast imaging
with liquid-metal-jet sources

Experimental arrangement



- Simple: no optics, no gratings
- Variations in density cause refraction
- Refraction cause edge enhancement
- Good at high spatial frequencies
- Requires:
  - small x-ray spot
  - a high-resolution detector

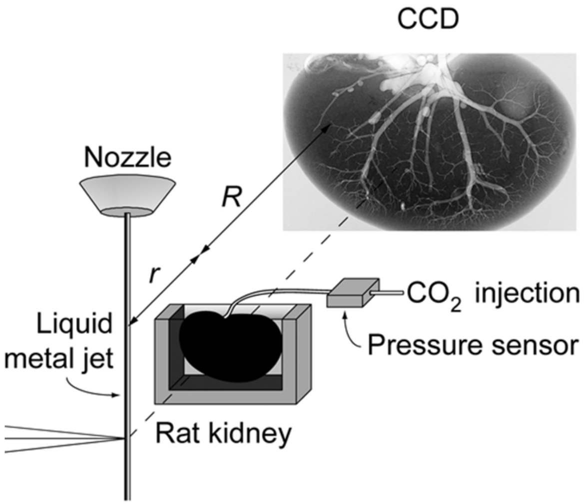
Test object

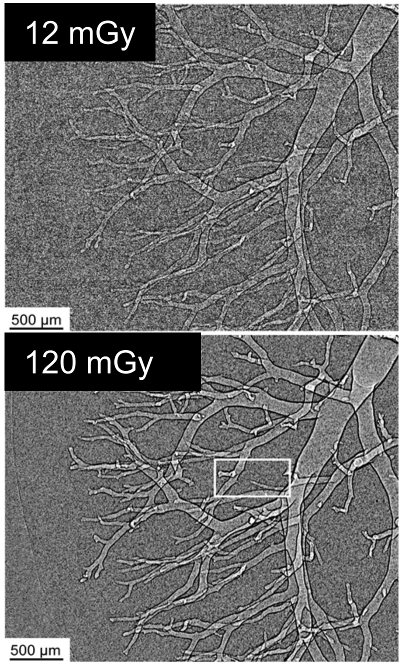


Tuohimaa et al, APL (2007)

Phase-contrast for enhanced CO_2 micro-angiography

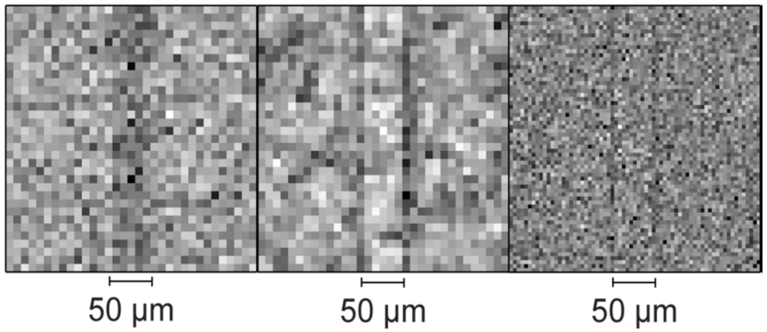
Rat kidney vasculature



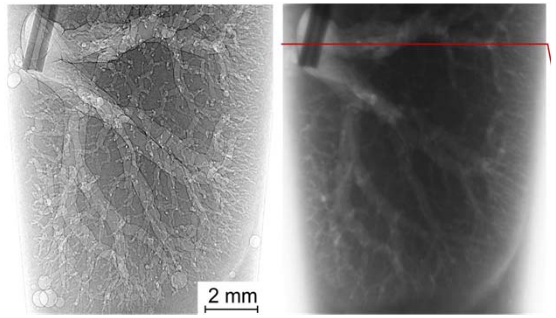


SNR^2 = 25 for 50 µm vessel in rat kidney

Perfect absorption with Iodine 677 mGy	Present phase with CO_2 8.6 mGy	Perfect phase with CO_2 0.09 mGy



Phase retrieval

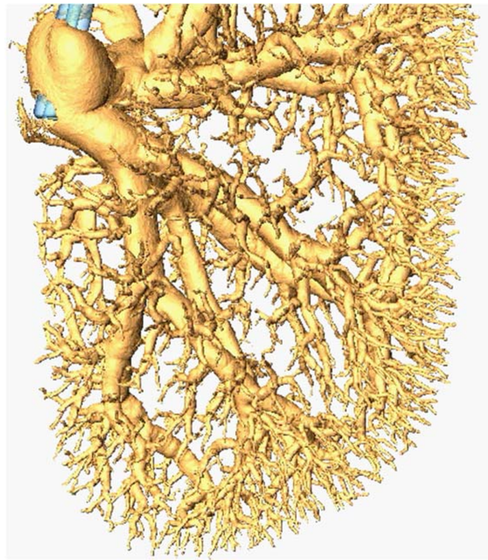


Phase contrast image

Projected density

Burvall et al, Opt. Express (2011)

Tomography



Data: 360x14 sec
Power: 40 W
Dose: 160 mGy
Observe: 50 μm vessles

Lundström et al, PMB (2012b)

Quantitative detectability

How?

Ideal observer signal-to-noise ratio (SNR):

$$\mathrm{SNR}^2 = \iint \frac{|\Delta G(\mathbf{u})|^2}{W(\mathbf{u})} \mathrm{d}^2 u$$

u: spatial frequency

Δ*G* : Fourier transform of the signal difference

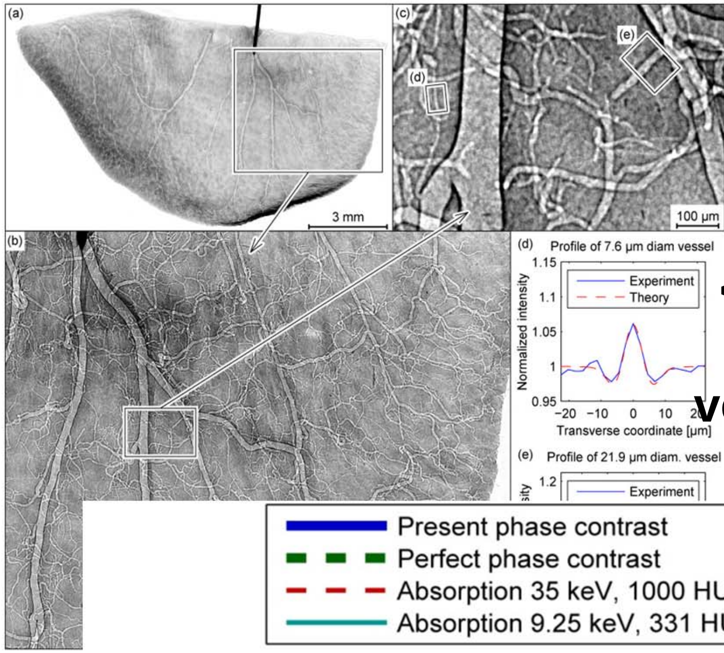
W : noise power spectrum.

$\mathrm{SNR}^2 = 25$ is required to detect a vessel

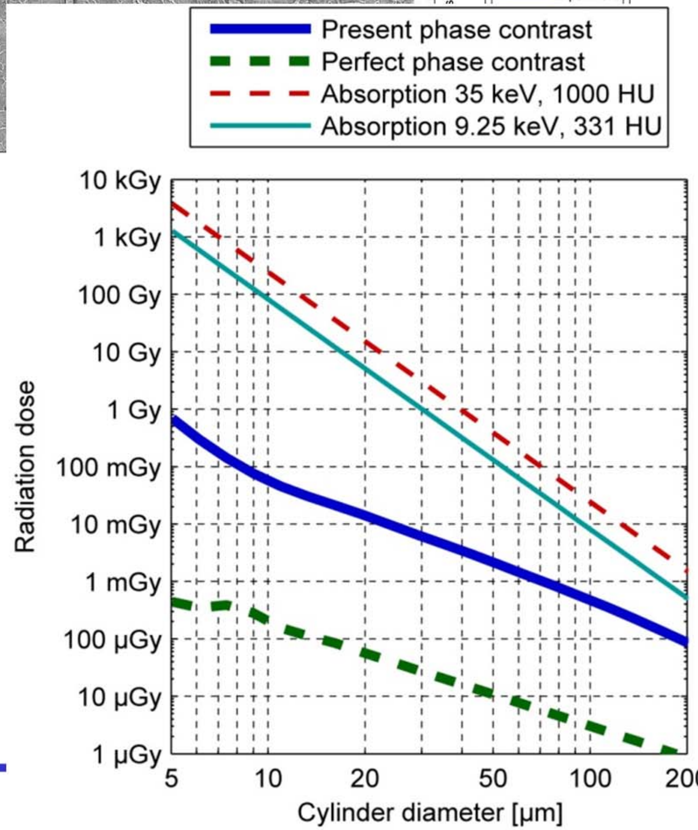
Adjust dose to give $\mathrm{SNR}^2 = 25$

Lundström et al, PMB (2012a)

Mouse ear



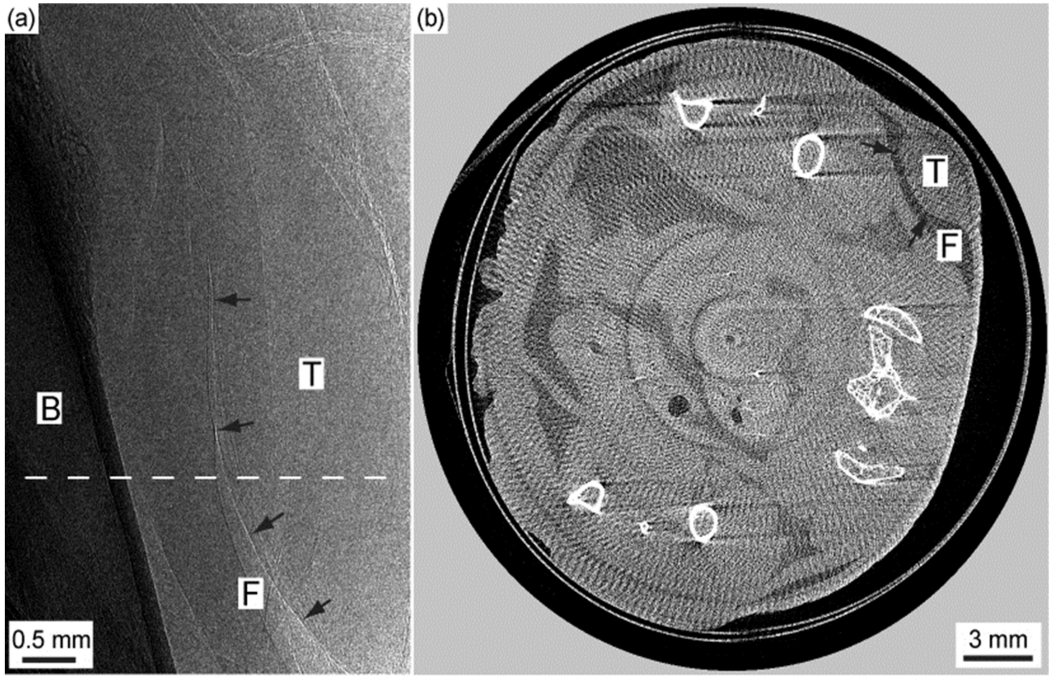
<8 µm diam vessles!



Tumours:

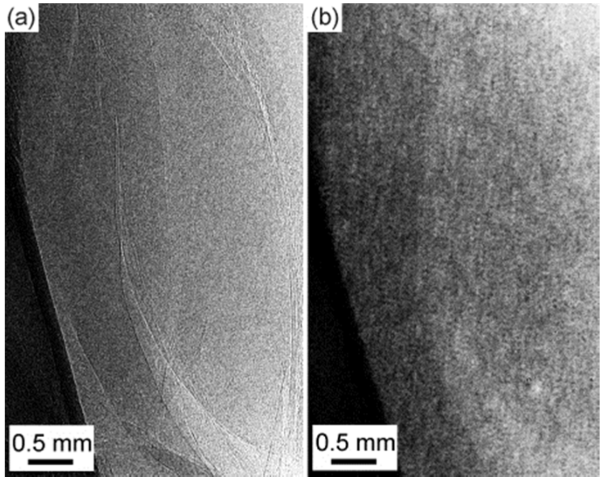
Natural-contrast tumour demarcation in mouse

Natural contrast
Absorption vs phase-contrast



Phase-contrast
19 mGy

Absorption CT
1.3 Gy

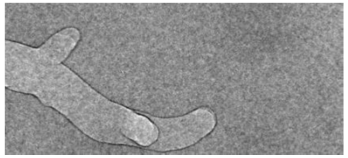


Phase-const **Abs contr**
Same dose ≈19 mGy

Larsson et al, Med Phys (2013)

Phase-contrast CO_2 microangio:

Limitations



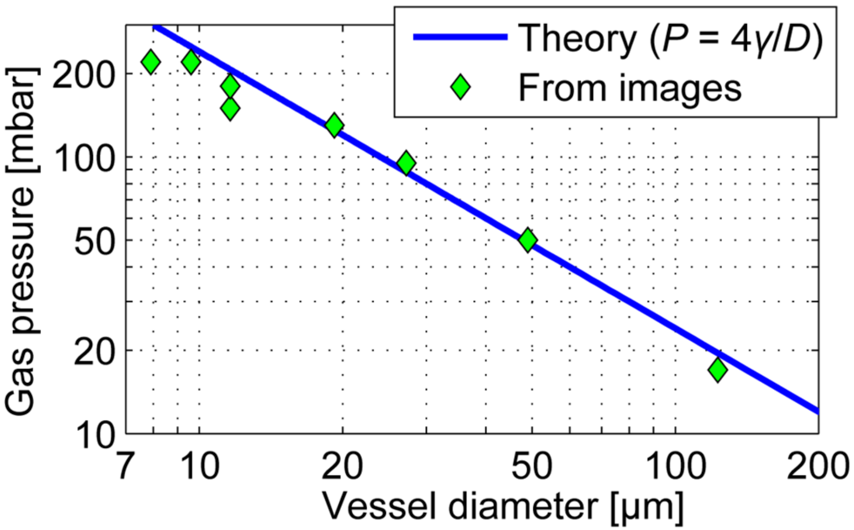
Gas filling

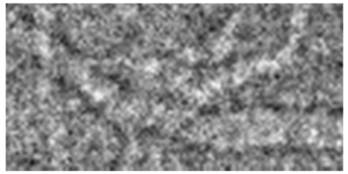
- Depends on gas pressure
- Required pressure is

  $P = 4\gamma/D$,

  D = diameter of vessels

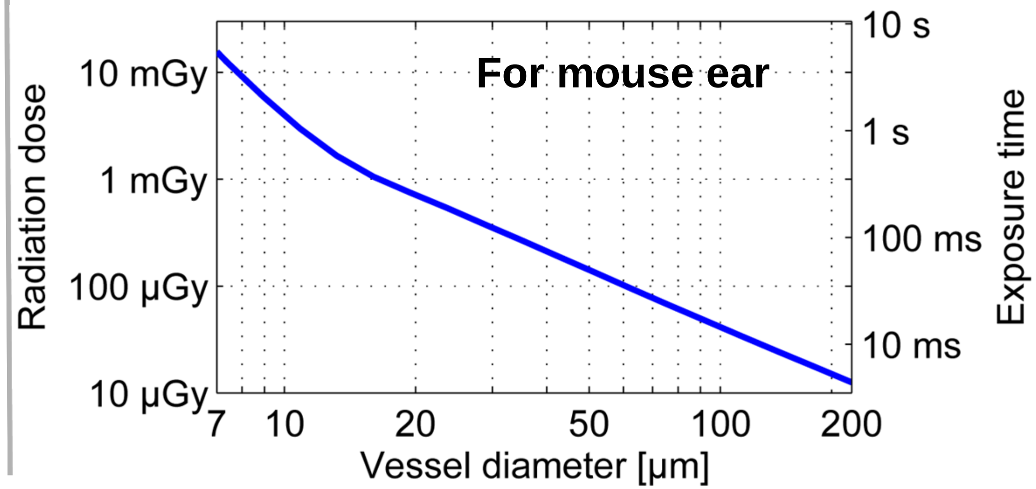
  γ = surface tension





Photon noise

- Depends on
  - Exposure time
  - Radiation dose
  - Imaging distances
  - X-ray source and detector



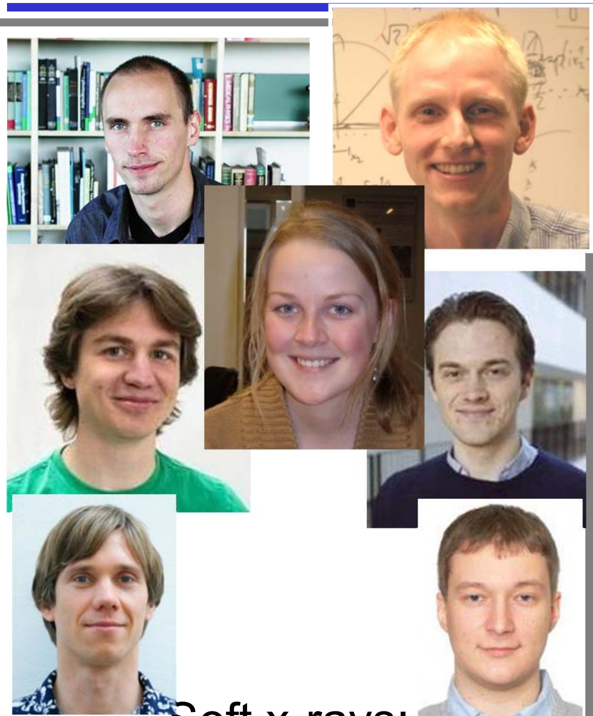
Lundström et al, PMB (2012b)

Summary & Future

- Liquid-metal-jet sources promise 100× higher brightness
  - High-spatial resolution imaging
  - Spatial coherence for strong in-line phase contrast
- Phase-contrast imaging
  - Micro vasculature imaging with CO_2
  - Single-cell-size detail
  - Dose levels acceptable for small-animal studies.
- Next
  - Source:
    - Higher power, higher brightness, shorter exposure times
  - In-line CO_2 micro angiography:
    - Tumor angiogenesis studies
    - Plaque
  - Comparison between propagation-based and grating-based phase-contrast imaging

Biomedical & X-Ray Physics group

Thanks!

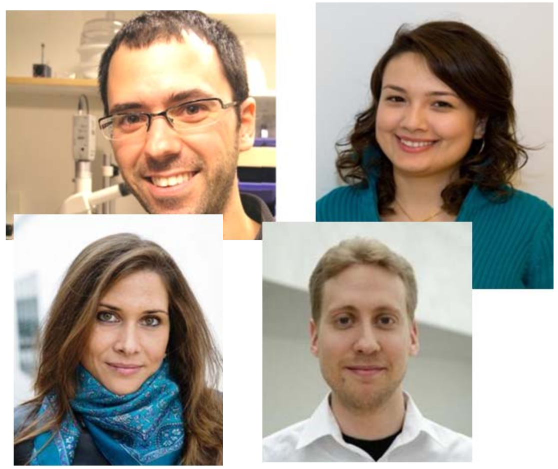


Soft x-rays:

Sources, optics, & microscopy

Hard x-rays:

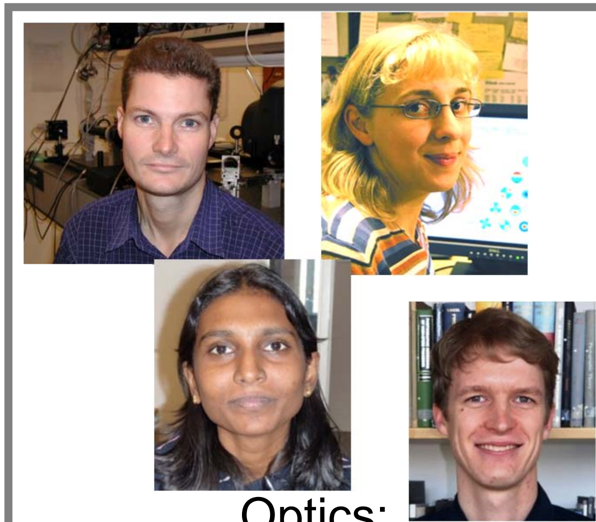
Sources, optics & imaging



Ultrasonics & μ-fluidics:

Bio-analytics and cell biol.

Teaching & technical



Optics:

Peripheral vision