MetalJet X-ray sources for high intensity X-ray beams

NIS colloquium, X-ray induced modifications in materials: applications and challenges

Università di Torino, Italy

Ulf Lundström, 2017-04-07

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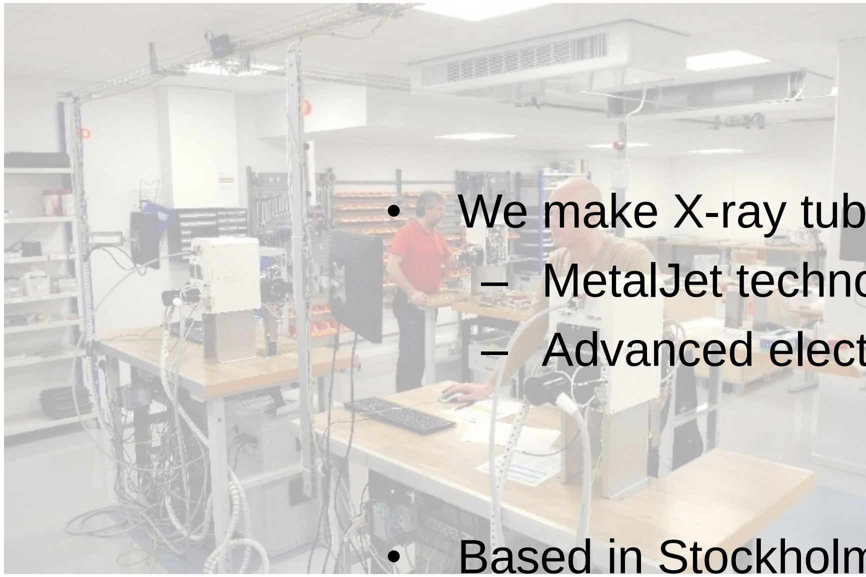
About Excillum

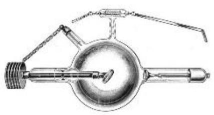


- We make X-ray tubes
  - MetalJet technology
  - Advanced electron beam technology

- Based in Stockholm, Sweden
- Founded in 2007
- Team of 19 people (and growing)

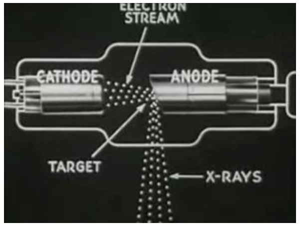
X-ray source development

~1875
Crooks
discharge
tubes



1895
Discovery
of X-rays

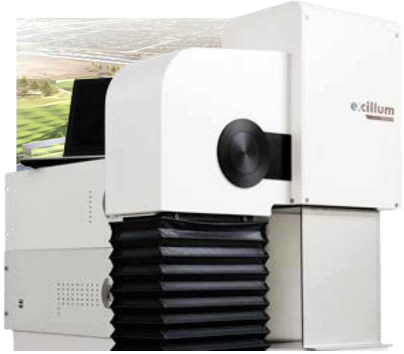
1913
Coolidge
hot cathode
tube



1929
First
commercial
rotating
anode

Synchrotron
X-ray
sources

2000
MetalJet
X-ray
source
technology



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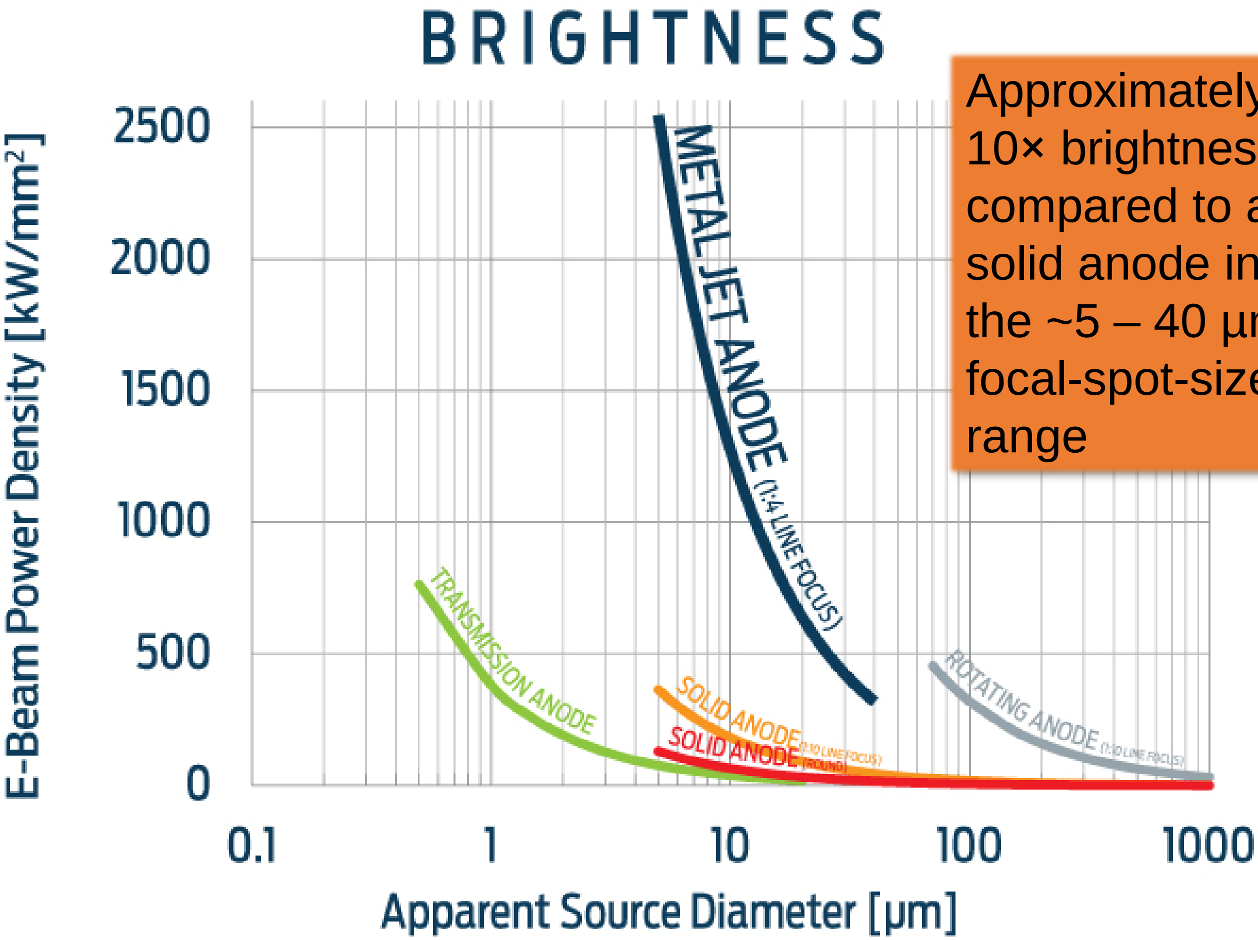
MetalJet Introduction

The brightness advantage



Approximately 10× brightness compared to a solid anode in the ~5 – 40 µm focal-spot-size range

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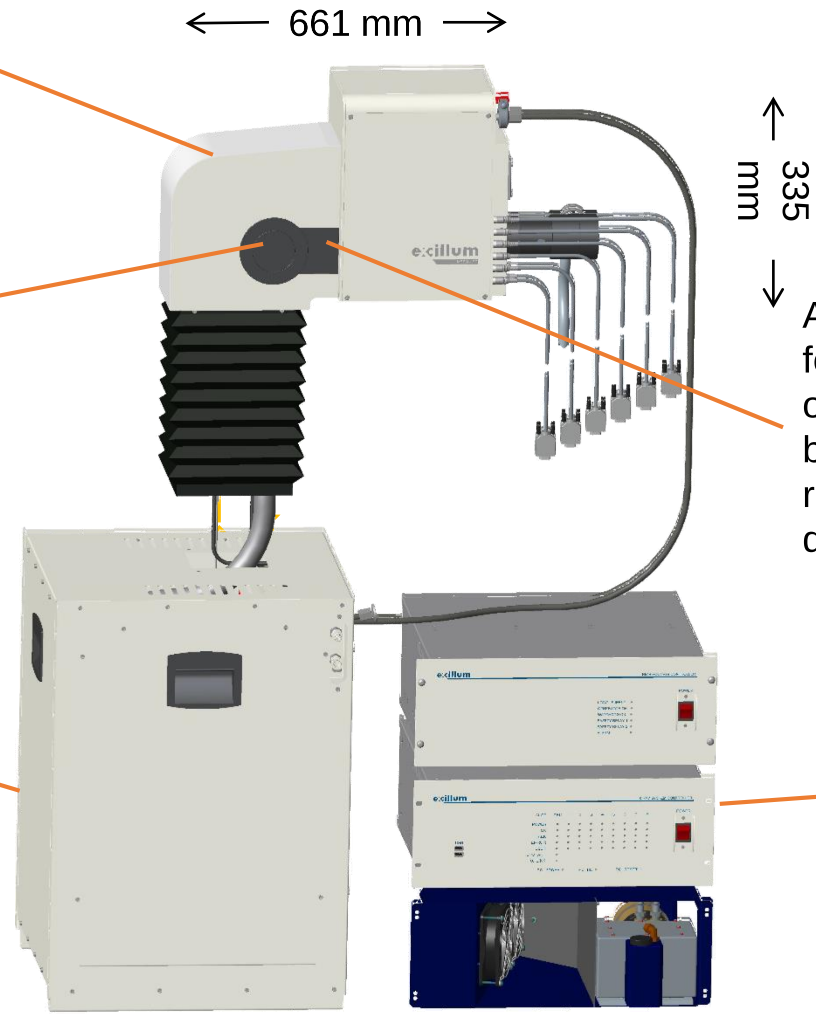
MetalJet source details

The path of the continuously recycled liquid alloy

X-rays are emitted from the interaction point between the metal jet and the e-beam



Advanced electromagnetic focusing and correctional optics together with a high brightness LaB_6 cathode results in a very high quality e-beam focus

Pumps etc. are housed in a 19” box.

Electronics is housed in two 19” boxes

Available alloys and their X-ray spectra

- Non-toxic alloys molten at or close to room temperature
- Gallium-rich alloy has emission similar to copper
  - 9.2 k
- Indium-r
  - 24.2

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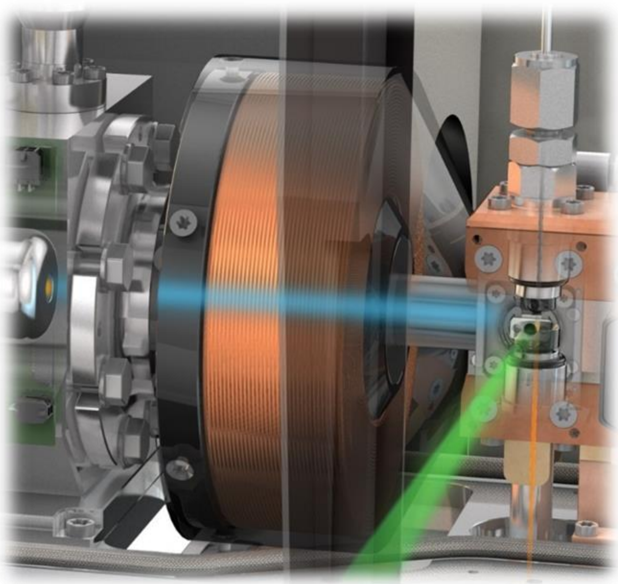
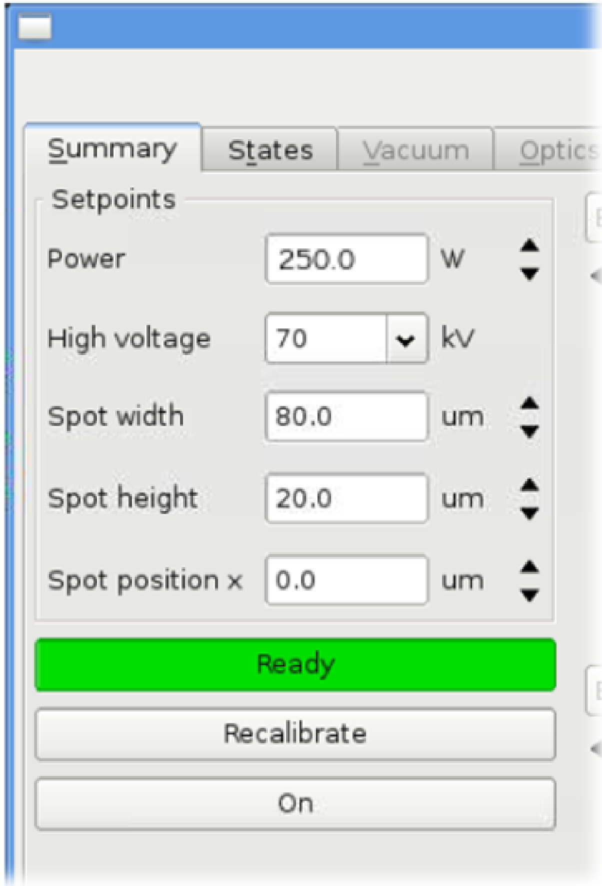
Small high quality e-beam spot

- Thanks to advanced electromagnetic focusing and correctional optics together with a high brightness LaB_6 cathode, a high quality near Gaussian source distribution is achieved.
- Both the spot size and the aspect ratio can be tuned freely and are characterized internally.





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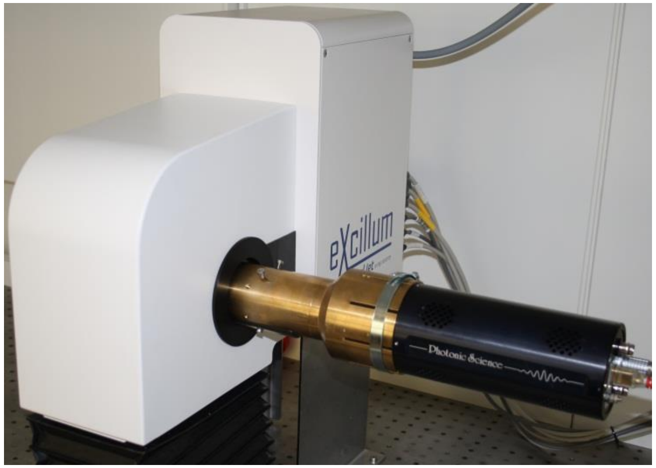
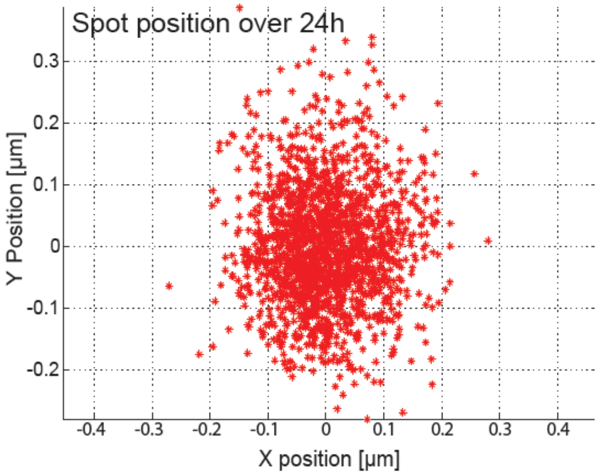
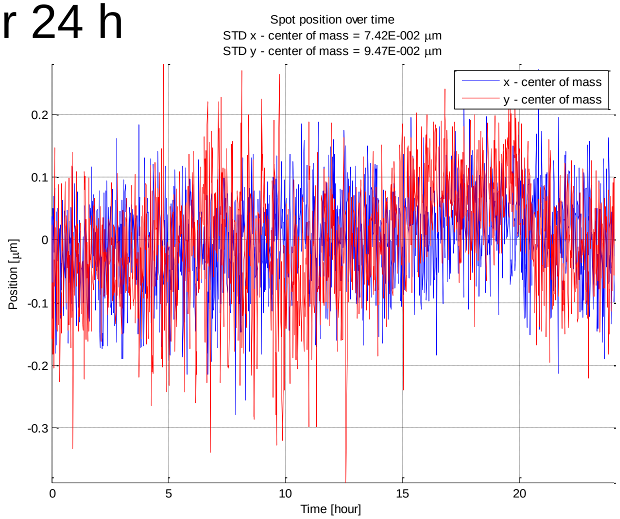
Operates stable and unattended 24/7

- The positional stability of the spot is measured over 24 hours with a pin-hole camera bolted to the source
  - STD x center of mass = 0.07 µm
  - STD y center of mass = 0.09 µm



Spot position stability over 24 h





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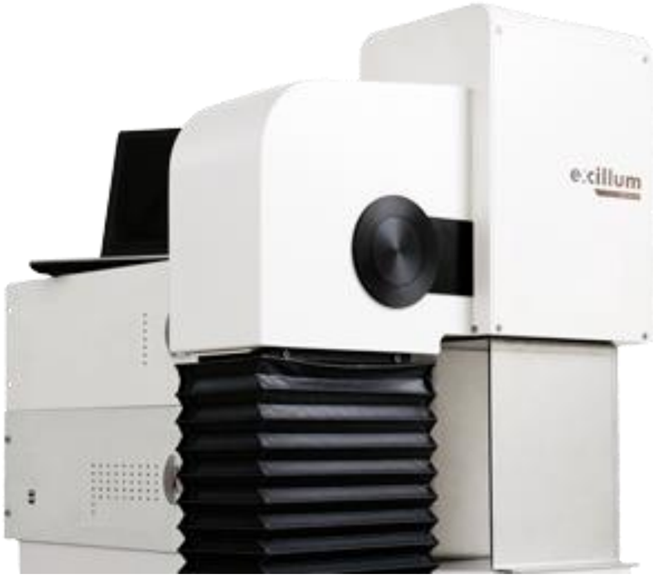
MetalJet D2+

Technical Specification

Target Material	**Ga or In rich alloy**
Acceleration voltage	Up to 70 or 160 kV
Power	250 W @ 20 µm
Min focal spot	~ 5 µm
Min. focus object distance	18 mm
Beam angle	13° or 30°



Performance Example (ExAlloy-G1, 70 kV)

Spot Size [µm, FWHM]	E-beam power [W]	Gallium Kα (9.2 keV) peak brightness [photons/(s·mm²·mrad²·line)]
10	125	6.5×10^{10}
20	250	3.3×10^{10}

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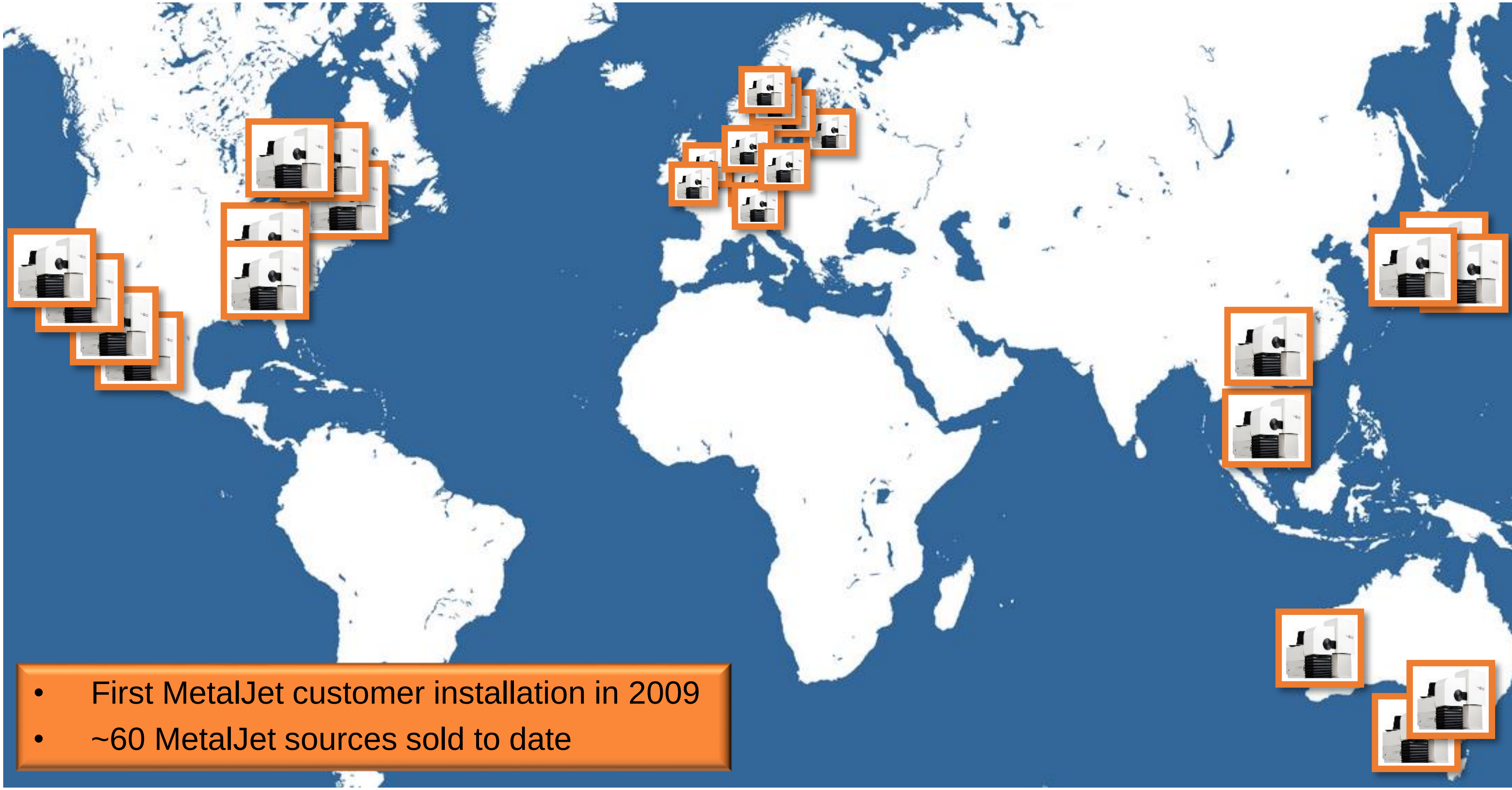
Spread over the world



- First MetalJet customer installation in 2009
- ~60 MetalJet sources sold to date

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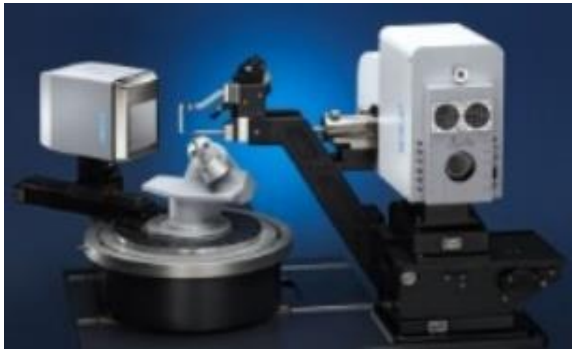
Applications of the MetalJet

- Small-angle X-ray scattering
  - For material science, biology and semi
  - Normally brightness limited, so MetalJet has large advantage
  - Most sources sold to integrators
- Single crystal diffraction
  - Both for small-molecule and macromolecular crystallography
  - Largest advantage for small crystals
  - Most sources sold to integrators
- X-ray imaging
  - Mainly for phase-contrast X-ray imaging
  - Most sources sold to universities

Single crystal X-ray diffraction



MetalJet D2 installed in a Bruker Single Crystal Diffraction System

	Conventional Sealed Tube	Air-cooled Microfocus Tube	“Traditional“ Rotating Anode	Microfocus Rotating Anode	**Liquid Metal Jet Anode**
Power (W)	1200	30	4000	2500	**200**
Anode spot size (mm^2)	0.4 x 8	< 0.05 x 0.20	≤ 0.3 x 3	< 0.1 x 1.5	**≤ 0.02 x 0.08**
Power density (kW/mm^2)	0.5	> 5	> 5	> 20	**> 150**
Typical Intensities ($ph/s/mm^2$)	> 2 x 10^8	0.7 - 2 x 10^{10}	0.7 - 2 x 10^{10}	0.2 - 2 x 10^{11}	**> 4 x 10^{11}**

Data courtesy of Jürgen Graf, Incoatec

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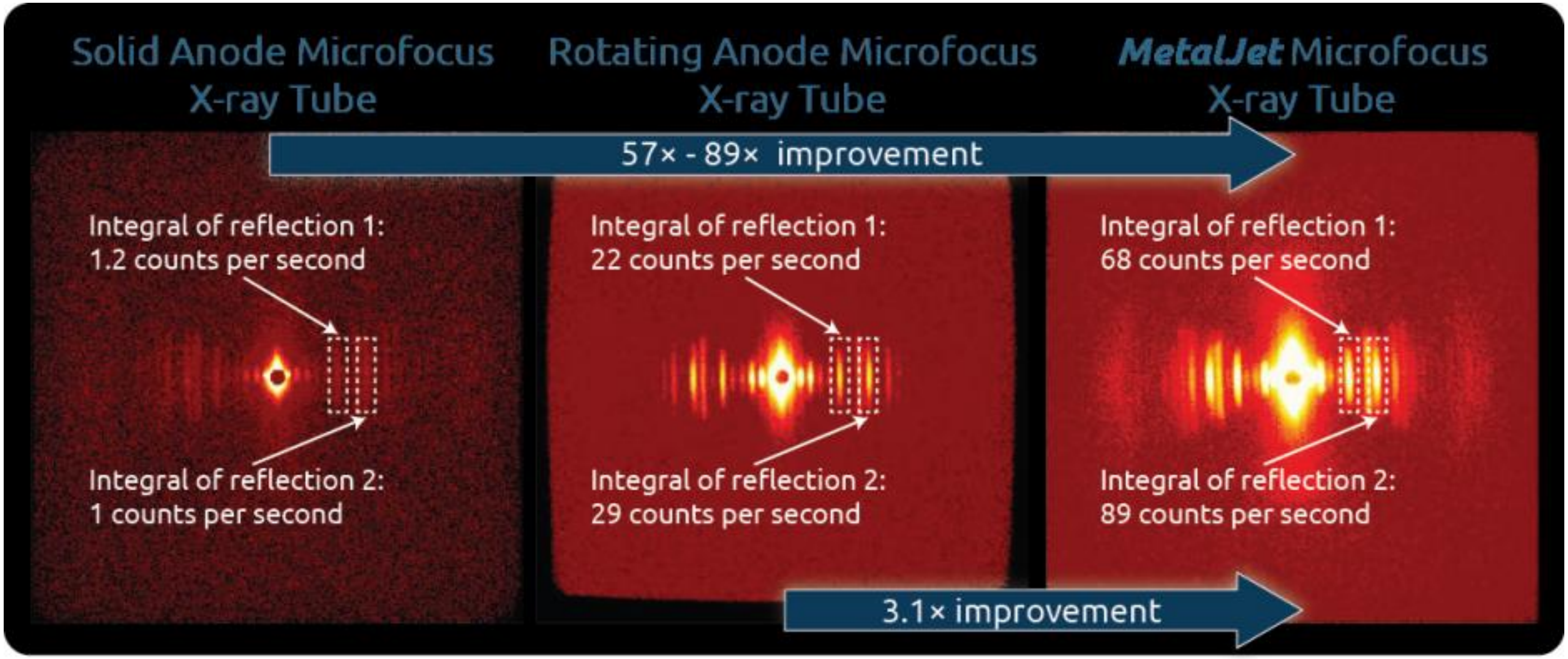
Small-angle X-ray scattering

- SAXS measurements on rat tail tendon, a standard sample with 67 nm periodic structure.
- 57× - 89× stronger signal compared to solid anode microfocus tube
- 3.1 × stronger signal compared to state-of-the-art rotating anode



Data courtesy of J. Lange, A. Schwamberger and K. Erlacher of Bruker-AXS.

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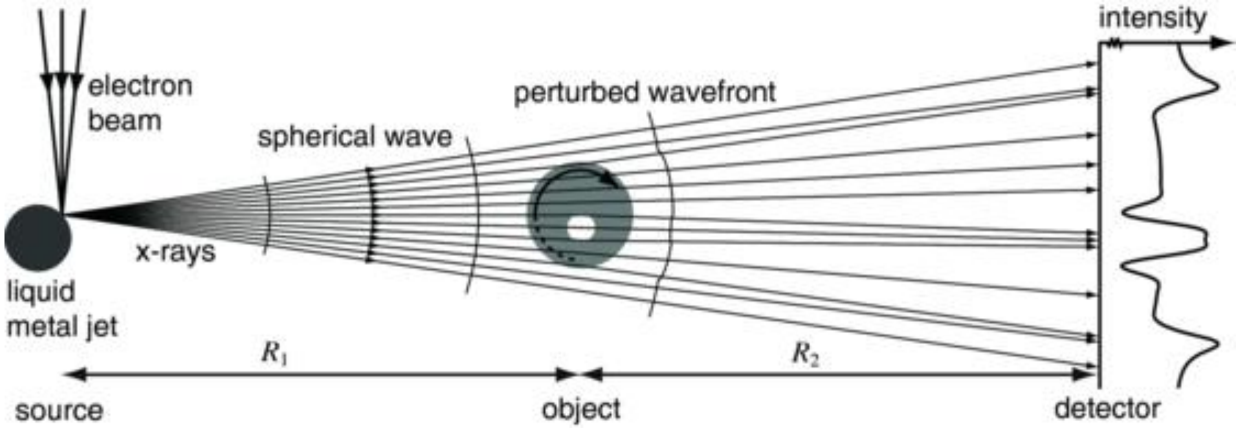
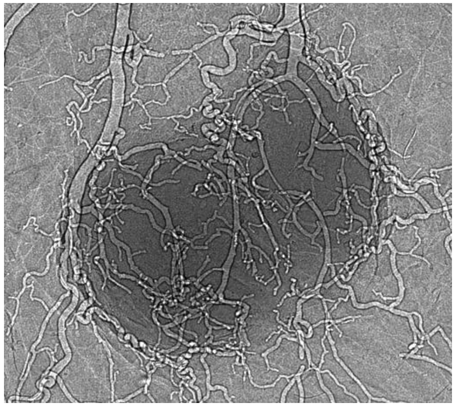
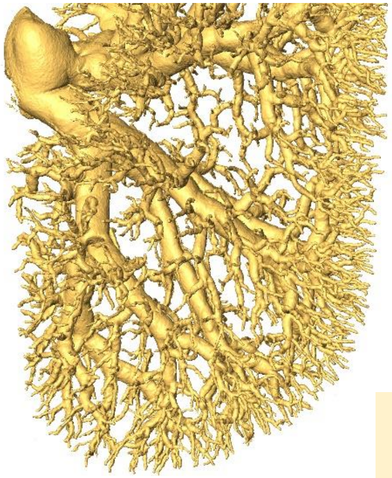
Propagation-based X-ray phase contrast imaging



Small animal angiography showing <10 µm vessels in mouse tumors





U. Lundström et al., "X-ray phase contrast for CO_2 microangiography", *Phys. Med. Biol.* **57**, 2603 (2012).

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X-ray optics for micro-focus X-ray tubes

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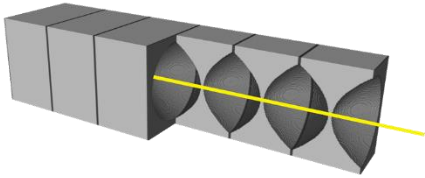
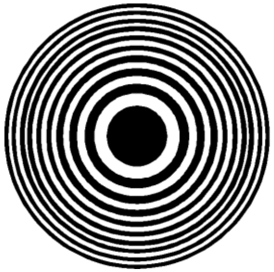
Focusing X-rays optics

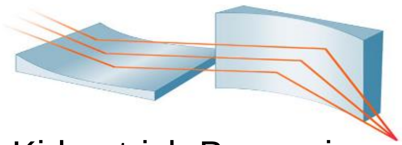
- Many different techniques
  - Refractive optics (lenses), zone plates, KB mirrors cannot collect enough x-rays
  - Montel mirrors (multilayer-coated elliptical mirrors) are widely used for crystallography and small-angle X-ray scattering on x-ray tubes
  - Polycapillary optics are often used for spectroscopy
  - Monocapillary optics might be really good
  - Doubly curved crystals gives a narrow bandwidth



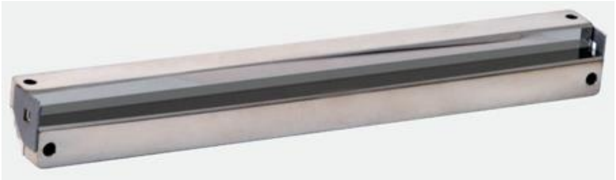
Compound refractive lens



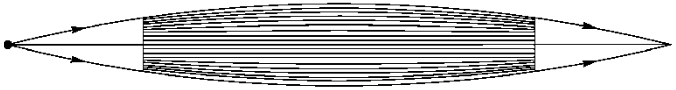
Zone plate



Kirkpatrick-Baez mirrors



Montel mirror



Polycapillary optic

Monocapillary optic

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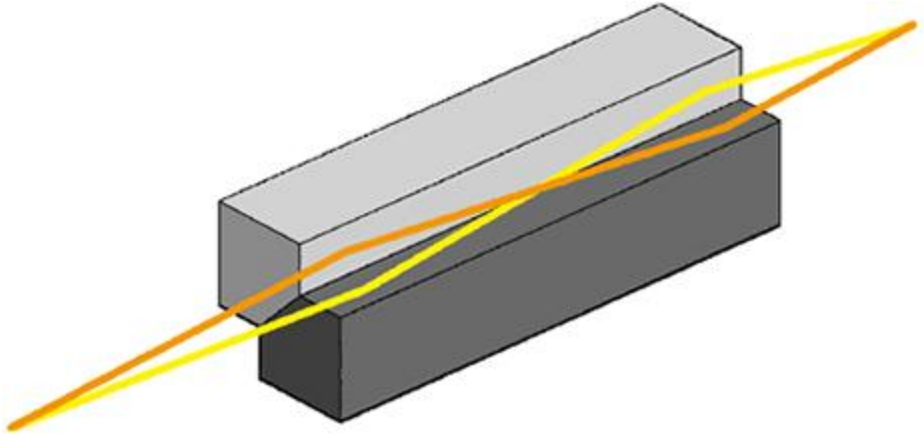
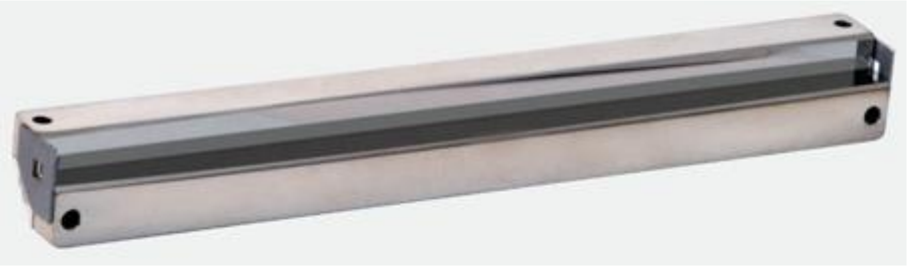
Montel mirrors, background

- Montel mirrors are curved in one direction
- Two mirrors side by side are used to focus in two directions
- Surface is elliptical with source in one focal point and the x-ray focus in the other
- Surface has multilayer coating to increase reflectivity for one wavelength
  - Typically tuned to emission line of the x-ray tube
  - Layer thickness varies along the mirror
- Gives monochromatic beam
- Widely used for crystallography and small-angle x-ray scattering





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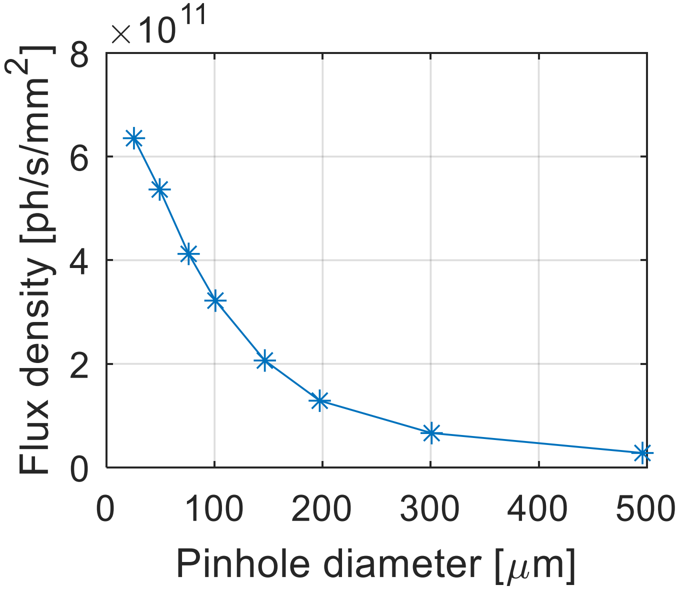
Montel mirrors, measurements

- We offer mirrors with the source
- Parameters of standard crystallography mirror
  - Length L = 150 mm
  - Source-to-focus distance 500 mm
  - Source-to-mirror distance d_1 = 30 mm
  - Collection angle Φ = 39 mrad = 2.2°
  - Convergence angle = 7.5 mrad = 0.43°
- Measurements with calibrated diode and various pinholes in focus
  - Focus size 70 µm FWHM
  - Focused flux 5.6×10^9 ph/s at 9.2 keV (Ga Kα)
  - Peak flux density 6.4×10^{11} ph/s/mm^2
- Smaller focus size with almost the same total flux should be doable with an increased convergence angle



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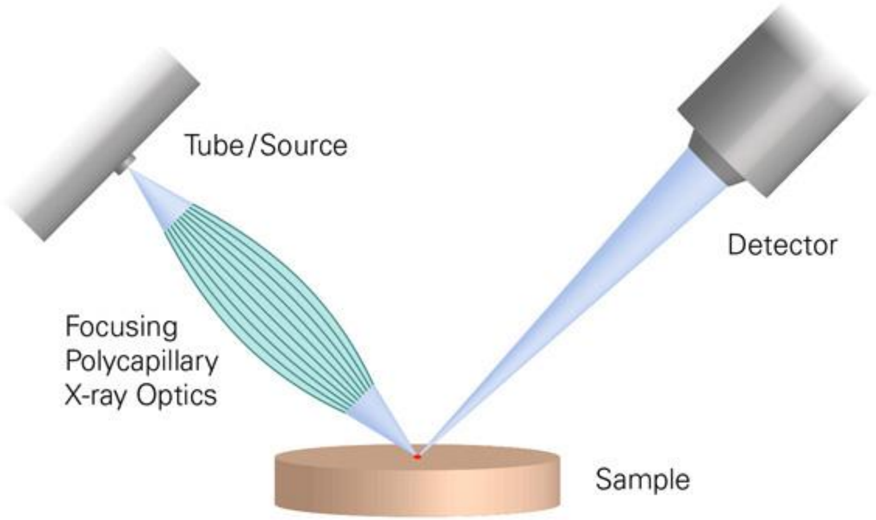
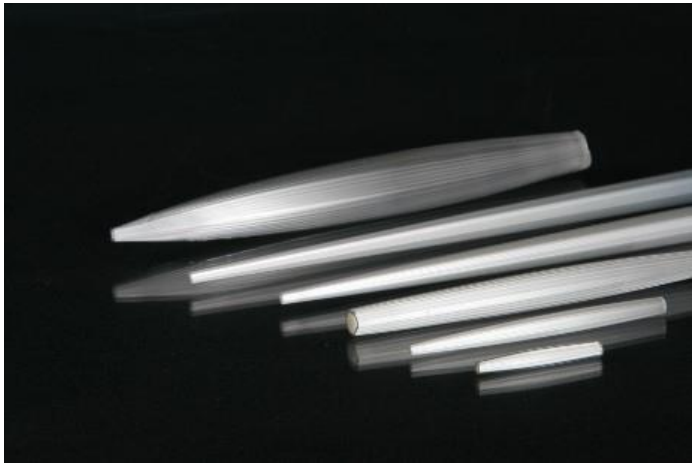
Polycapillary optics, background

- A polycapillary contains many hollow glass tubes guiding the x-rays to a common focus
- Total external reflection on inside of the capillaries
- Can focus a wide x-ray spectrum
- Relatively large collection angle
- Often used for scanning fluorescence imaging and spectroscopy





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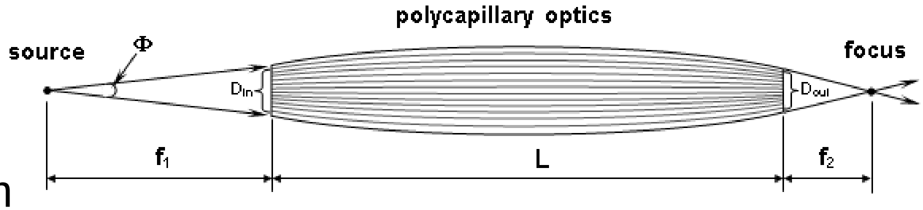
Polycapillary optics, measurements

- We have recently done measurements on a polycapillary optic together with a MetalJet D2+ x-ray source
- Polycap parameters:
  - Input focal distance f_1 = 27.5 mm
  - Length L = 20.9 mm
  - Output focal distance f_2 = 3.4 mm
  - Collection angle Φ = 84 mrad = 4.8°



- Focus size measured with an edge scan
  - Between 12 and 14 µm depending on photon energy
- Flux measured with a medipix photon-counting camera
  - 3.3×10^9 ph/s with energy > 5 keV
- Flux density of 2.0×10^{13} ph/s/mm^2
- Collection efficiency drops quickly with photon energy
  - 24% at 5-8 keV and 0.7% at 14-17 keV

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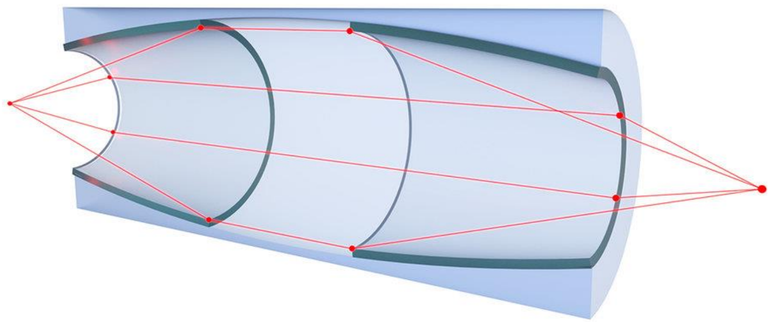
Monocapillary optics, background

- A hollow glass tube is drawn to get an elliptical or parabolic inner surface
- Total external reflection on the inner surface is used to focus the x-rays
- Inner surface can be coated with high density material to increase reflectivity
- X-rays can be reflected once or twice depending on design



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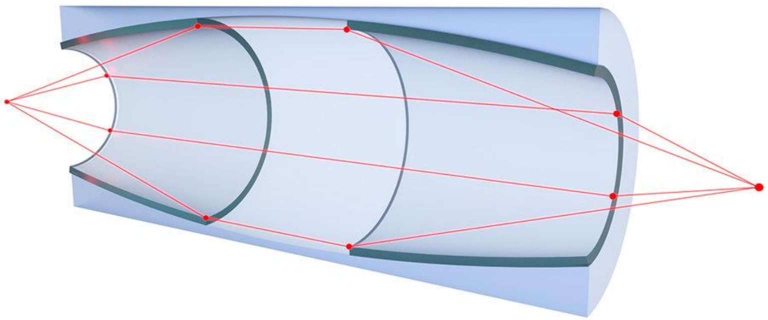
Monocapillary optics, calculation

- Collection angles up to 4 times the critical angle of platinum
  - For Ga Ka at 9.25 keV this is 35 mrad or 2.0 degrees
  - Beam stop has an angle of 40% of this, blocking 20% of the x-rays
- Point spread function can be small enough to preserve brightness of a 20 um x-ray spot
- Transmission efficiency ~80%
- MetalJet X-ray source with 20 um spot has peak brightness of 3.3×10^{10} ph/(s mm^2 mrad^2) in the Ga Ka line
- With 1:1 imaging we would then expect a flux density of 2.6×10^{13} ph/s/mm^2 and total flux of 1.0×10^{10} ph/s
- Somewhat higher flux density probably possible with demagnification, a smaller source size and including the brehmstrahlung



Thank you for listening!

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