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

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

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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
- **2000**: Synchrotron MetalJet X-ray source technology

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exillium
MetalJet Introduction
The brightness advantage

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

Pumps etc. are housed in a 19" box.

Advanced electromagnetic focusing and correctional optics together with a high brightness LaB$_6$ cathode results in a very high quality e-beam focus

Electronics is housed in two 19" boxes

661 mm

335 mm
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 keV / 1.3 Å
• Indium-rich alloy has emission similar to silver
  • 24.2 keV / 0.51 Å

Spectra of gallium and silver
Small high quality e-beam spot

- Thanks to advanced electromagnetic focusing and correctional optics together with a high brightness LaB₆ 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.
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
MetalJet D2+ Technical Specification

<table>
<thead>
<tr>
<th>Target Material</th>
<th>Ga or In rich alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration voltage</td>
<td>Up to 70 or 160 kV</td>
</tr>
<tr>
<td>Power</td>
<td>250 W @ 20 µm</td>
</tr>
<tr>
<td>Min focal spot</td>
<td>~ 5 µm</td>
</tr>
<tr>
<td>Min. focus object distance</td>
<td>18 mm</td>
</tr>
<tr>
<td>Beam angle</td>
<td>13° or 30°</td>
</tr>
</tbody>
</table>

Performance Example (ExAlloy-G1, 70 kV)

<table>
<thead>
<tr>
<th>Spot Size [µm, FWHM]</th>
<th>E-beam power [W]</th>
<th>Gallium Kα (9.2 keV) peak brightness [photons/(s·mm²·mrad²·line)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>125</td>
<td>6.5 × 10¹⁰</td>
</tr>
<tr>
<td>20</td>
<td>250</td>
<td>3.3 × 10¹⁰</td>
</tr>
</tbody>
</table>
Spread over the world

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

<table>
<thead>
<tr>
<th></th>
<th>Conventional Sealed Tube</th>
<th>Air-cooled Microfocus Tube</th>
<th>&quot;Traditional&quot; Rotating Anode</th>
<th>Microfocus Rotating Anode</th>
<th>Liquid Metal Jet Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (W)</td>
<td>1200</td>
<td>30</td>
<td>4000</td>
<td>2500</td>
<td>200</td>
</tr>
<tr>
<td>Anode spot size (mm²)</td>
<td>0.4 x 8</td>
<td>&lt; 0.05 x 0.20</td>
<td>≤ 0.3 x 3</td>
<td>&lt; 0.1 x 1.5</td>
<td>≤ 0.02 x 0.08</td>
</tr>
<tr>
<td>Power density (kW/mm²)</td>
<td>0.5</td>
<td>&gt; 5</td>
<td>&gt; 5</td>
<td>&gt; 20</td>
<td>&gt; 150</td>
</tr>
<tr>
<td>Typical Intensities (ph/s/mm²)</td>
<td>&gt; 2 x 10⁸</td>
<td>0.7 - 2 x 10¹⁰</td>
<td>0.7 - 2 x 10¹⁰</td>
<td>0.2 - 2 x 10¹¹</td>
<td>&gt; 4 x 10¹¹</td>
</tr>
</tbody>
</table>

Data courtesy of Jürgen Graf, Incoatec
Small-angle X-ray scattering

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

Data courtesy of J. Lange, A. Schwamberger and K. Erlacher of Bruker-AXS.
Propagation-based X-ray phase contrast imaging

Small animal angiography showing <10 µm vessels in mouse tumors

X-ray optics for micro-focus X-ray tubes
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
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
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 $\Phi = 39$ mrad $= 2.2^\circ$
  - Convergence angle $= 7.5$ mrad $= 0.43^\circ$
- Measurements with calibrated diode and various pinholes in focus
  - Focus size $70$ µm FWHM
  - Focused flux $5.6 \times 10^9$ ph/s at $9.2$ keV ($\text{Ga K}\alpha$)
  - Peak flux density $6.4 \times 10^{11}$ ph/s/mm$^2$
- Smaller focus size with almost the same total flux should be doable with an increased convergence angle
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
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 $\Phi = 84$ mrad $= 4.8^\circ$

- Focus size measured with an edge scan
  - Between 12 and 14 $\mu$m depending on photon energy

- Flux measured with a medipix photon-counting camera
  - $3.3 \times 10^9$ ph/s with energy $> 5$ keV

- Flux density of $2.0 \times 10^{13}$ ph/s/mm$^2$

- Collection efficiency drops quickly with photon energy
  - 24% at 5-8 keV and 0.7% at 14-17 keV
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
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 $3.3 \times 10^{10}$ ph/(s mm$^2$ mrad$^2$) in the Ga Ka line
• With 1:1 imaging we would then expect a flux density of $2.6 \times 10^{13}$ ph/s/mm$^2$ and total flux of $1.0 \times 10^{10}$ 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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