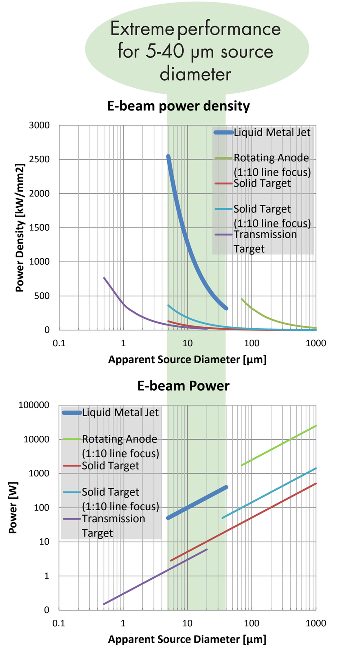
LIQUID-METAL-JET X-RAY TUBE TECHNOLOGY FOR NANOELECTRONICS CHARACTERIZATION AND METROLOGY

A conventional microfocus x-ray tube with the solid-metal anode replaced by a liquid-metal jet. The metal jet supports higher electron-beam power and can therefore generate higher x-ray flux.

Emil Espes, Björn A. M. Hansson, Oscar Hemberg, Göran Johansson,Mikael Otendal, Tomi Tuohimaa and Per Takman

DETAILS

EXTREME BRIGHTNESS



POWER LOADING CAPABILITY

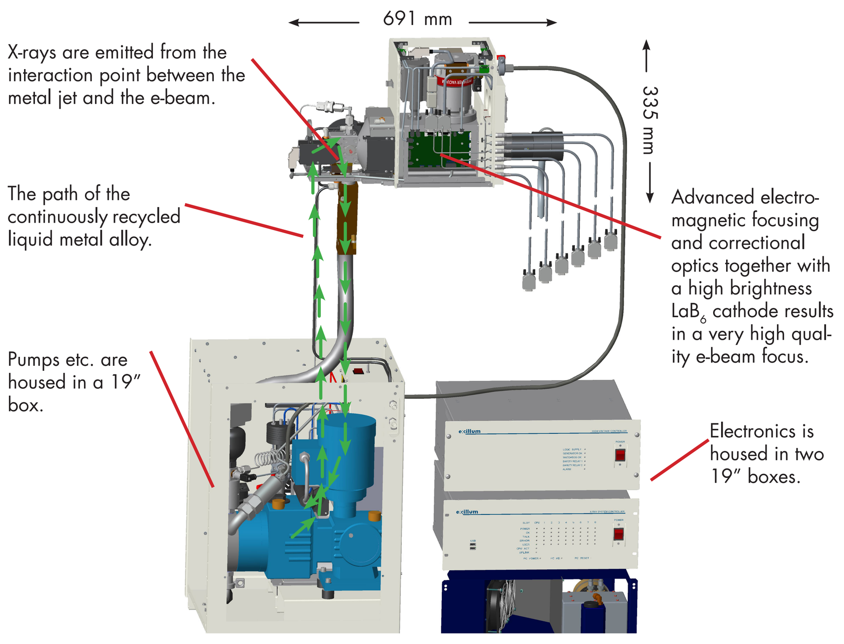
The x-ray power of all electron-impact x-ray generators is limited by the thermal power loading of the anode. In conventional solid anode technology, the surface temperature of the anode must be well below the melting point in order to avoid damage and this is fundamentally limited by the anode target material properties, primarily the melting point, the vapor pressure and especially the thermal conductivity. The liquid-metal anode is different since the limitation to maintain the target at well below melting point in removed. This is due to the fact that the material is already molten and that it is regenerative by nature, supplying new fresh target material at a rate of close to 100 m/s. This means that the electron beam and anode interaction may be destructive.

EXTREME BRIGHTNESS

Somewhat counter intuitively, the power loading capability of small-focus x-ray tubes roughly scale with the diameter and not the area of the e-beam focus. Therefore, the brightness is inversely proportional with the source diameter.

By combining extreme power loading capability and a small electron focus, a liquid-jet-source can achieve unprecedented brightness at micron spot sizes.

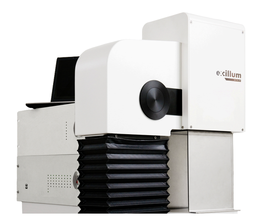
SOURCE SCHEMATICS



CURRENTLY AVAILABLE SOURCE

MetalJet D2

The MetalJet D2 is the second “off the shelf” commercially available liquid-metal-jet x-ray source. This is a fully radiation shielded dual port source with shutters. The source can be operated stand alone or is easily integrated.



MetalJet D2 TECHNICAL SPECIFICATIONS

Cathode	LaB_6	**Min. focal spot size**	~5 μm
Target Material[1]	Ga or In rich alloy	**Emission stability**[3]	< 1%
Max current	4.3 mA	**Position stability**[3]	< 1 μm
Voltage[2]	10 - 70 kV / 160 kV	**Min. focus-object distance**[4]	18mm
Power	0 - 300 W / 1000 W	**Beam angle**	13° or 30°

1) The room temperature liquid metal alloys supplied for the MetalJet source consist mainly of gallium, indium and tin. They have low reactivity and low toxicity but should be handled according to their safety data sheets and local regulations.
2) Depending on source version
3) Standard deviation
4) Without a shutter

PERFORMANCE EXAMPLES (Exally G1, 70kV)

Spot size[5] [μm, FWHM]	E-Beam Power [W]	Ga Kα Flux [Photons/(s·mrad²·line)]	Ga Kα Peak Brightness [Photons/(s·mm²·mrad²·line)]
5	50	3.0×10^{6}	1.0×10^{11}
10	100	6.0×10^{6}	5.2×10^{10}
20	200	1.2×10^{7}	2.6×10^{10}

5) Actual e-beam spot has a 1:4 aspect-ratio line focus, but the projected spot dimension is essentially circular. True round focal spots for, e.g., large-angle imaging can typically generate ¼ power compared to the numbers above.

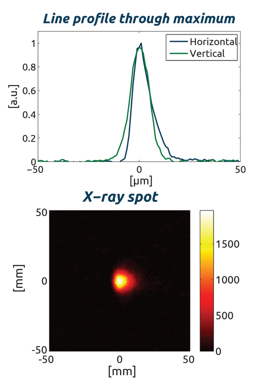
SPOT SIZE AND STABILITY

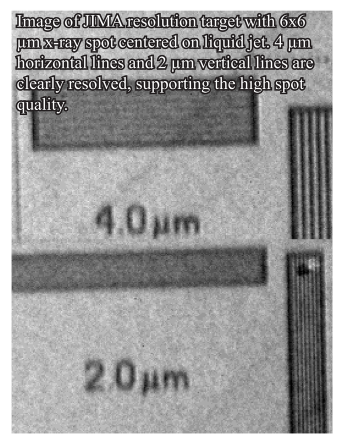
SPOT QUALITY

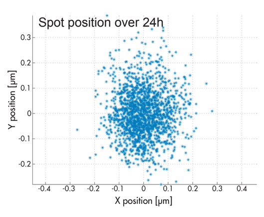
Thanks to advanced electromagnetic focusing and correctional optics together with a high brightness LaB_6 cathode, a high quality e-beam focus is achieved. Together with a continuously generated smooth liquid target surface, the source produces x-ray spots of very high quality.

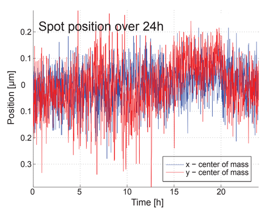
TUNABLE SIZE

Both the spot size and the aspect ratio can be tuned freely.









SOURCE STABILITY

The spatial stability of the source is very high. The images to the left illustrate a spot centroid standard deviation of < 0.1 μm over 24 hours, as taken with pinhole camera mechanically coupled to the source.

X-RAY SPECTRA

X-RAY SPECTRA OF LIQUID METAL

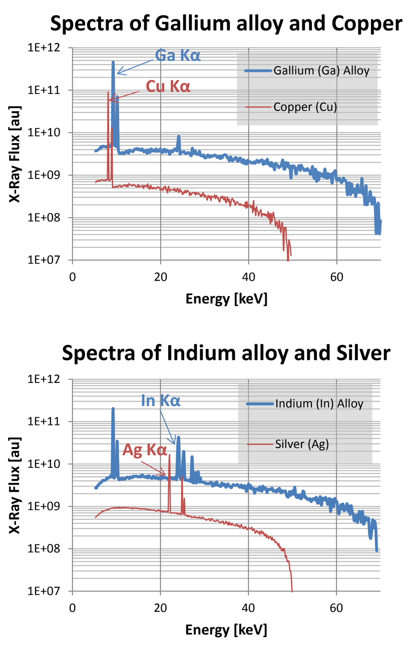
In order to reach different x-ray emission lines, different metal alloys are used. First generation metal-jet sources feature metal alloys that are molten at more or less room temperature. Still, several alloys have emission characteristics similar to regular solid anodes. Future upgrades can also include alloys with higher melting points.

GALLIUM ALLOY

A gallium (Ga) rich alloy is available. It’s 9.2 keV Kα emission line is close to the copper (Cu) Kα emission line.

INDIUM ALLOY

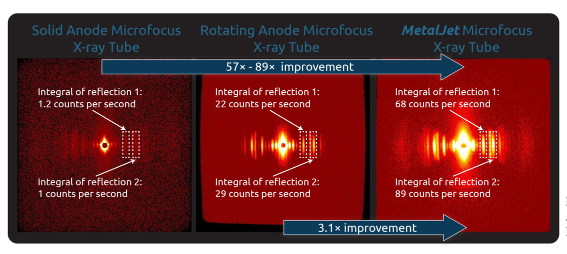
An indium (In) rich alloy is also available. It’s 24.2 keV Kα emission line is close to the silver (Ag) Kα emission line.



SMALL ANGLE SCATTERING

STATE OF THE ART HOME LAB SCATTERING

The MetalJet-technology is very well suited for Small Angle X-ray Scattering (SAXS), due to the small spot-size and high brightness. This has been proven in traditional SAXS, and in the figure below, you will find an comparison of different X-ray tubes, where rat tail tendon was studied.



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

CRITICAL DIMENSION-SAXS

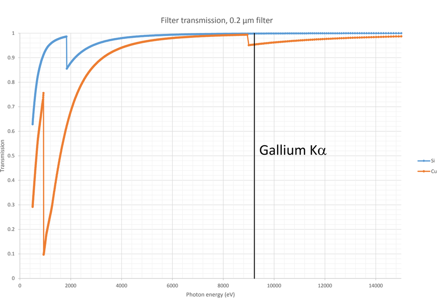
Research on critical dimension small angle X-ray scattering (CD-SAXS) [1] have identified that lab-based X-ray sources with higher brightness than previously available, at energies higher than 20 keV are needed for non-synchrotron CD-SAXS. The MetalJet source technology with indium K-α emission at 24 keV show great promise towards meeting the requirements.

1. R. J. Kline, D. F. Sunday, D. Windover and W. Wu, ‘Bringing CD-SAXS to the Fab’, SEMICON West 2014, 2014.

X-RAY MICROSCOPY

Traditionally the MetalJet-technology has been used extensively for phase-contrast imaging, both in propagation- and grating-based x-ray phase contrast imaging. The MetalJet-technology is very well suited for this type of imaging due to the fine spot-size and very high-brightness.

More recently, a growing interest in using the MetalJet-technology for imaging of nanoelectronics has emerged. The highest available resolution in lab-based X-ray microscopes is achieved with zone-plate based projection microscopes [2]. Such microscopes, however, typically use Cu Kα (~8 keV) radiation which is not so well suited to see copper structures in silicon due to poor contrast between copper and silicon at that energy. As illustrated by the graph to the right, the Kα of gallium, which is used in MetalJet sources, is just above the K-absorption edge of copper [3] and thus much better suited to create a sufficient contrast between copper and silicon.



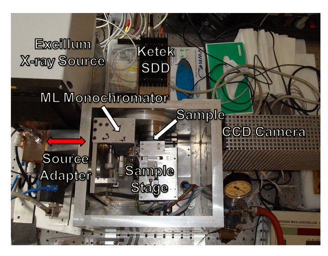
2. T. Beetz, ‘High-resolution X-ray Tomography Imaging Systems’, CHESS Users’ Meeting Ithaca, NY, 2008.
3. E. Gullikson, *Filter transmission*, http://henke.lbl.gov/optical_constants/filter2.html, visited on 2015-03-24.

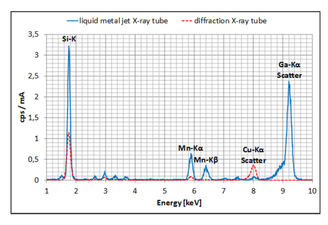
TXRF USING METALJET

Total reflection X-ray spectroscopy (TXRF) is a powerful analytical technique for qualitative and quantitative analysis of trace and ultra-trace elements in a sample. Historically several different x-ray sources has been used for this technique. A. Maderitsch et al. from Atominstitut, Vienna University of Technology, has performed TXRF-measurements with the MetalJet technology [4].

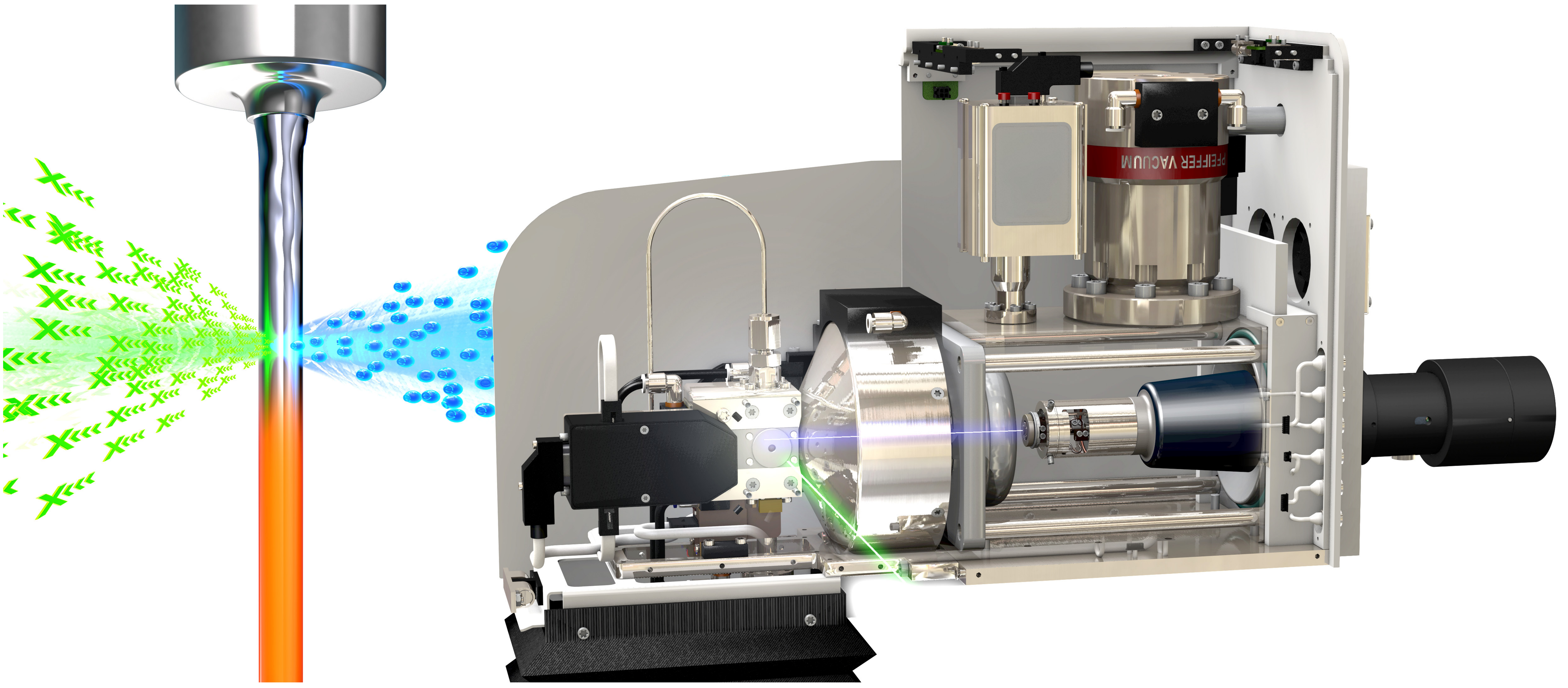
A TXRF spectrometer designed at the Atominstitut was adapted to the MetalJet, and several measurements were performed. As a reference, the same spectrometer was used with a 2 kW diffraction long fine focus x-ray tube (Cu-Kα). For comparison, the measurements were normalized to the x-ray tube current and to the counts per second (cps). The results are presented in the spectrum to the right.

The high brilliance of the MetalJet gives a great yield of the primary photons. Also, the normalized Mn signal is higher with the MetalJet, even though the excitation of Mn is better with Cu-Kα radiation.





4. A. Maderitsch, S. Smolek, P. Wobrauschek, C. Streli and P. Takman, Feasibility study of TXRF using a liquid metal jet X-Ray tube, Spectrochimica Acta Part B: Atomic Spectroscopy, TXRF2013 special issue



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