Microfocus electron-impact x-ray sources are gaining importance for a number of applications such as nondestructive testing, microtomography, phase contrast imaging, hard-x-ray microscopy, and x-ray diffraction. Recently, microfocus electron-impact sources based on liquid-metal-jet anodes have demonstrated superior performance compared to conventional microfocus sources. To date, predominantly high-Z metal-jet anodes with a low melting point have been employed, thus limiting the range of characteristic line radiation available. In the present paper, we extend this class of jet-based sources by demonstrating stable operation of a nonmetallic anode at useful power levels. In addition, the performance limit of this class of anodes is investigated by simulating the x-ray emission with Monte Carlo techniques.

Conventional microfocus x-ray sources are limited in performance by the thermal properties of the anode with typical maximum e-beam power loads being in the range of 0.4–0.8 W per electron-beam diameter in micrometers. In order to increase the x-ray brightness, liquid-metal-jet anodes have been proposed. They are attractive due to their higher thermal load capacity, regenerative nature, and the higher brightness achieved. E-beam loading capacities of >8 W/μm² have been demonstrated in continuous operation, more than an order of magnitude higher than what is achievable with conventional electron-impact technology.

Extending the jet anode concept to nonmetallic liquids would greatly increase the number of possible target elements giving access to numerous characteristic x-ray fluorescence lines. In an early low-power experiment directed toward soft-x-ray fluorescence emission, instabilities between a water jet and an e-beam at 10 keV occurred at powers above 0.6 W. In the present paper, we show stable operation of a fully evaporated nonmetal (methanol) jet with significant hard x-ray emission. Methanol was chosen due to its high vapor pressure and low-conductivity properties, making it a good anode candidate for evaluating the limiting properties of low-Z, nonmetallic anode materials. Furthermore, methanol has the additional advantage of generating vapor emission products that can be pumped away from the source area. This might be a problem for metal-jet anodes, where metal vapor is potentially deposited on all exposed surfaces, making a debris mitigation system necessary at high-power operation.

The experimental results are compared with Monte Carlo simulations using the PENELOPE code. By adapting the simulations to the cylindrical geometry of the jet, the theoretical limits for the x-ray emission from this class of anodes may be investigated.

The x-ray source with its nozzle arrangement for producing the methanol jet anode was situated in a vacuum chamber pumped with a 500 l/s turbo drag pump down to a base pressure of ~10⁻⁷ mbar. By applying up to 40 bars of nitrogen backing pressure a stable ~70 m/s, ~10 μm diameter liquid-methanol jet was injected into the vacuum chamber via a tapered glass nozzle. The e-gun was based on a custom-made 50 μm diameter LaB₆ cathode with energies ranging from 10 to 50 keV and a maximum power of ~75 W. The beam was focused by a magnetic lens onto the methanol jet resulting in a high-brightness x-ray spot. The gun was optimized for operation at 50 keV and the Gaussian e-beam diameter (FWHM) at the focus was estimated to be 4–5 μm at 60 W and 50 keV from simulation results. Thus, the electron gun operated at 60 W and 50 keV could ideally achieve >12 W/μm² e-beam power loading, corresponding to approximately 2 MW/mm² e-beam power density at the target, more than enough to melt and permanently damage any conventional anode.

Differential pumping of the gun with a separate 250 l/s turbo drag pump kept the base pressure in the gun at ~10⁻⁸ mbar when the jet was not running. The gun and jet chamber were separated by a 2.5 mm diameter aperture in the gun and a 6 mm aperture in the magnetic lens. Due to the high vapor pressure of methanol and the heating of beam, the pressures in the gun and jet chamber rose to ~10⁻⁵ and ~10⁻⁷ mbar, respectively. This was still good enough to get adequate transmission of the electron beam and the x rays produced in the interaction with the methanol jet. The complete system was carefully grounded to avoid charging phe-
nommena and subsequent electron beam instabilities. An x-ray charge-coupled device (CCD) detector (Photonic Science VHR) was used for imaging in a projection geometry and a CdZnTe diode (Ref. 17) was employed for spectral flux measurements. The instruments operated at 45° and 90°, respectively, relative to the e-beam direction, thus enabling simultaneous recording of the spectrum and source size. The x-ray source size, needed for the absolute brightness calibration of the spectra, was determined via modulation measurements using a custom-made resolution object based on a 50 μm thick silicon substrate with 10 μm high gold structures. Lines down to 3 μm half-period, corresponding to ~160 LP/mm² were available on the resolution target. The experimentally measured modulation could then be used to calculate the source size by comparing to simulated modulation curves using an adaptation of the code described in Ref. 6.

The general-purpose Monte Carlo code system PENELOPE was used for simulation of x-ray spectra. PENELOPE is applicable to all materials and covers the energy range from 50 eV up to 1 GeV. The code implements databases with reliable interaction cross sections and relaxation data for the elements. In particular, bremsstrahlung cross sections are used to calculate the source size by comparing to simulated modulation curves using an adaptation of the code described in Ref. 6.

Spectra were measured for e-beam energies ranging from 20 to 50 keV, all at a constant e-beam current of 0.8 mA. Figure 3 shows a calibrated bremsstrahlung spectrum, recorded with a 50 keV, 40 W (~4 W deposited) electron beam with a peak spectral brightness of ~5.4 × 10⁵ photons/(s × μm² × sr × 0.1% BW) at 10 keV. Although more power could be absorbed in the jet for low keV e-beams and the measured x-ray flux increased, the e-beam focus got larger resulting in x-ray spot growth and hence slightly lower values for the spectral brightness at lower e-beam energies (20–40 keV). The average spectral brightness was (3.6 ± 1.3) × 10⁵ photons/(s × μm² × sr × 0.1% BW) for the investigated acceleration voltages in the range of 20 to 50 keV. Characteristic line emission was not visible in the 10–50 keV energy interval due to the low-Z composition of methanol.
The Monte Carlo simulated spectrum, plotted with a dashed line in Fig. 3, has a spectral brightness of \( \sim 1.6 \times 10^6 \text{photons/(s}\times \mu m^2\times sr\times 0.1\%\text{BW)} \) at 10 keV. The brightness calculations for the simulated spectra were made using experimentally measured source sizes. The shape of the simulated spectrum is in good agreement with the experimental data, although the overall brightness is a factor of \( \sim 2–3 \) higher. This is thought to be due to the modeling of the jet as a nonmoving cylinder neglecting all thermodynamic phenomena such as jet boiling and subsequent density gradients that reduce x-ray production. Therefore the simulations give an upper limit for the x-ray brightness set by the input parameters and are valuable for understanding the ultimate performance of jet-based anodes with very high velocities.

To conclude, we have demonstrated stable x-ray operation of a nonmetallic liquid-jet anode at power levels sufficient to completely evaporate the jet in the e-beam focus. The maximum x-ray performance was found to be limited by the total evaporation of the jet material which occurred at \( \sim 6 \) W of absorbed e-beam power for the fastest jet used in the experiment. Larger and/or faster jets would overcome the present limit because of their inherently higher heat load capacities. We have previously shown that liquid jets can in principle be operated in a stable manner at much higher speeds in a vacuum environment.\(^{21}\) If the technological difficulties of increasing the jet speed could be overcome, the liquid-jet-anode concept would be an interesting alternative to existing compact x-ray sources, both for the hard and soft x-ray ranges. As an example, a water jet anode could be used to emit K-shell x-ray radiation at 525 eV, making it a potential alternative to existing laser plasma\(^{22}\) or gas discharge sources.\(^{23}\) To achieve this goal, further experimental work is necessary to investigate the long term stability and power scaling of such systems, in particular the lifetime of electron gun cathodes exposed to elevated gas loads.

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\(^{1}\)See, e.g., MicroXCT, nanoXCT (www.xradia.com).


\(^{15}\)See, e.g. (http://www.a-p-tech.com/grcathodes.htm).

\(^{16}\)LORENTZ2EM v.6.2 (www.integratedsoft.com).

\(^{17}\)XR-100T-CZT (www.amptek.com).


