Electron-Impact Liquid-Jet Water-Window X-ray Sources

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Till farmor
Abstract

This Thesis describes the development and characterization of a soft x-ray liquid-jet-anode electron-impact source. With a water-jet target the primary emission is the O Kα line at 525 eV. This is close to the lower edge of the water-window, a spectral region lacking simple laboratory sources. In the hard x-ray regime electron-impact microfocus sources have matured and are simple, stable, reliable, and inexpensive. It would be beneficial if this source concept could be used also for soft x-ray generation.

Spectral measurements of a 120 W, 30 keV electron beam focused on a 20 μm water jet show an x-ray intensity of up to $3.2 \times 10^{12}$ ph/(s×sr×line). Combined with source size measurements up to 50 W a maximum brightness of $3.5 \times 10^9$ ph/(s×μm²×sr×line) is reported. This makes the brightness comparable to the compact discharge-plasma sources presently used for soft x-ray microscopy. The source appears to be scalable another order of magnitude which would make the brightness equal to that of the laser-plasma sources.
List of Papers

This thesis is based on the following papers:


Other Publications

The following paper, contributed to by the author, is related to the work in this thesis, but is not included in it.

<table>
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>EUV</td>
<td>Extreme-ultraviolet</td>
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<tr>
<td>eV</td>
<td>Electron volt</td>
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<tr>
<td>CW</td>
<td>Continuous wave</td>
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<td>BW</td>
<td>Bandwidth</td>
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<td>UHV</td>
<td>Ultra-high vacuum</td>
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<td>FEL</td>
<td>Free-electron laser</td>
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<td>CBS</td>
<td>Compton backscattering source</td>
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<td>CR</td>
<td>Cerenkov radiation</td>
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<tr>
<td>SXR</td>
<td>Soft x-ray</td>
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<tr>
<td>LPP</td>
<td>Laser-produced plasma</td>
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<td>DP</td>
<td>Discharge plasma</td>
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<tr>
<td>HHG</td>
<td>High-harmonics generation</td>
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<tr>
<td>HPLC</td>
<td>High pressure liquid chromatography</td>
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<tr>
<td>SDD</td>
<td>Silicon drift detector</td>
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<tr>
<td>CCD</td>
<td>Charge coupled device</td>
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<tr>
<td>FWHM</td>
<td>Full width at half maximum</td>
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Chapter 1

Introduction

Wilhelm Röntgen received the first Nobel prize in physics in 1901 for his discovery of x-rays six years earlier [1]. They have since then played an important role in science, industry and medicine through their use in spectroscopy and microscopy. X-rays are commonly classified into three regimes: Hard x-rays, with wavelengths well below one nm (above 5-10 keV); soft x-rays (SXR), with wavelengths between hard x-rays and ~10 nm (between a few hundred eV and 5-10 keV); and extreme-ultraviolet (EUV) radiation, with wavelengths between ~10 nm and ~50 nm (between a few ten eV and a few hundred eV). Because of the short wavelength compared to visible light, all three regions have potential for imaging with higher detail. As described by the Rayleigh criterion, the best attainable resolution is close to the wavelength used [2]. Out of the three x-ray types, only hard x-rays have the ability to penetrate objects usually considered opaque, to yield information about the internal structure in medical x-ray imaging and non-destructive testing.

Soft x-rays are very different from the deeply penetrating hard x-rays as they penetrate even less than visible light. One way to illustrate the large variation within the x-ray region is by considering the attenuation length of the electromagnetic spectrum in water [3–5], shown in Fig. 1.1. The variation within the x-ray spectrum by far exceeds the difference between hard x-rays and visible light. Although the exact behavior varies between materials, with most materials being opaque to visible light, the trend of very short attenuation lengths for soft x-rays and EUV radiation remains.

Right next to the oxygen absorption edge, between 2.3 and 4.4 nm wavelength (539-282 eV), is the so-called water-window regime. Here the absorption difference between carbon-rich proteins and oxygen-rich water is large, as illustrated in Fig. 1.2.a. This difference provides a natural contrast enhancement in studies of biological objects, consisting mainly of, e.g., proteins and intracellular liquid. The
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Figure 1.1: The attenuation length in water from hard x-rays to radio waves. Data from the national institute of standards and technology (NIST) [5], the center for x-ray optics (CXRO) [4] and the master’s thesis by D. J. Segelstein [3].

short attenuation length makes the water-window especially well suited for single cell studies, and the shorter wavelengths close to the oxygen edge are preferred because of the relatively low absorption. As an illustrative example of the difference in length scale and contrast compared to medical type x-rays, Fig. 1.2.b shows the attenuation length in soft tissue and bone for diagnostic imaging x-rays between 18 keV and 150 keV [6]. Here we can see that the ratio between the absorption lengths in the water-window is more than four times larger than for a medical examination with 60 keV x-rays.

Single cells have been studied by biologists since Anton van Leeuwenhoek (1632-1723) brought the microscope to their attention. From his powerful single-lens devices, microscopes have evolved into the complex instruments we have today, with modern visible-light bright-field microscopes offering a resolution of down to 0.44 times the wavelength used [2]. Although visible-light microscopy can be performed with natural absorption contrast, the small absorption of biological objects often requires enhancement techniques. These methods either use the variation in refractive index [7, 8], or rely on sample staining to achieve either higher absorption or fluorescence. Recently emerging fluoroscopy techniques [9] have demonstrated a resolution down to 16 nm [10], but the information is limited and there is always the risk of altering the specimen in the preparation process.

Although the attenuation length for hard x-rays in water is shorter, hard x-ray
microscopy has even lower contrast for single cell imaging than visible-light microscopy, due to the low absorption in all low-density materials. This makes high-resolution transmission hard x-ray microscopy of cells highly dependent on contrast agents [11]. Another complication is the low efficiency of hard x-ray optics. Diffraction-based lens-less methods have been developed to overcome these obstacles and in principle reach sub-nanometer resolution [12], but the challenges posed by the coherence requirements alongside the number of photons required [13] have only recently allowed for demonstration of hard x-ray lens-less single cell imaging [14]. At present the acquisition times involved prevent effective collection of tomographic data sets.

Lens-less imaging have recently been demonstrated with soft x-ray radiation, providing images of a yeast cell and a diatom [15, 16], but for now the complexity involved and the limited availability classifies this as instrumentation research rather than biological imaging.

Soft x-ray transmission microscopy with water-window x-rays is therefore the standard method for high-resolution imaging of unstained single cells. Dedicated large-scale synchrotron facilities (c.f. Chapter 2) reach a tomographic resolution of below 50 nm [17], while laboratory based instruments achieve below 150 nm [18]. Although not reaching synchrotron performance, the advances in laboratory sources is paving the way for using high resolution tomography in everyday research. The short attenuation lengths pose challenges such as the requirement of good vacuum throughout the beam path and special optics. Ordinary refractive optics, i.e., lenses, are not suitable in the soft x-ray regime due to the large absorption, and normal incidence reflective optics are not suitable due to the small reflectivity for
all types of x-rays. The remaining methods are grazing incidence reflective optics [19, 20], multilayer normal-incidence reflective optics and diffractive optics [21].

The compound microscope consists of a light source, condenser optics, and imaging optics. For the laboratory water-window sources in this thesis, the photon flux is a limiting factor. This makes the main requirement on the condenser to collect as much light as possible, while the resolution is mainly determined by the imaging optics, although care must be taken to match the numerical aperture of the condenser optics and the imaging optics. Grazing incidence mirrors, multilayer mirrors and diffractive optics have all been used as condenser optics in compact water-window microscopes [22–24]. The condenser options have different pros and cons regarding, e.g., efficiency, wavelength selectivity and aberrations, but the differences are not significant enough to recommend any particular method over the other without detailed information of the source and system. The imaging optics, on the other hand, is almost exclusively a diffractive element, known as the Fresnel zone plate (although grazing incidence optics has been used [25]). Zone plates are circularly symmetric gratings whose grating frequency increases radially in such a way that the diffracted radiation is collected in a common focus. They are highly chromatic, with the focal length being inversely proportional to the wavelength, but they provide the highest attainable resolution of the three alternatives. The Rayleigh resolution limit for the zone plate is determined by the outermost zone width $\Delta r$ and zone plates with a $\Delta r$ of 12-13 nm have been developed, allowing for a theoretical resolution of 15 nm [26, 27].

As opposed to visible light, there are few natural x-ray sources. Cosmic x-ray radiation, ranging from 500 eV to 20 keV, although too faint to be used for illumination, does allow for studies of celestial objects, but due to the large atmospheric attenuation these experiments must be carried out outside the atmosphere. In this thesis a new type of continuous wave (CW) compact water-window x-ray source is demonstrated, based on the radiation emitted from energetic electrons impacting on a water jet anode. The emitted radiation is characterized spatially and spectrally and found to be a promising candidate for water-window microscopy, due to the relatively simple construction, small source size, spectral characteristics and high photon flux. In Chapter 2 the different types of existing soft x-ray sources emitting within the water window are presented. These sources, and their applications, will be used to put the new source into perspective. Chapter 3 describes the theory of electron-impact sources, the instrumentation required and the behavior of different anode materials; with a special section on the liquid-jet anode concept. Chapter 4 is devoted to a detailed description of the new electron-impact liquid-jet water-window soft x-ray source and chapter 5 provides a discussion of future improvements and applications.
Chapter 2

Water-Window Soft X-Ray Sources

This chapter describes the available water-window sources available for, e.g., transmission microscopy. The best figure of merit for monochromatic sources is the so-called brightness, which involves the photon flux, the source size and the angular distribution of the source. The brightness is expressed as photons/(s×μm²×sr), and it can at best be conserved throughout an optical system. To include the spectral distribution of polychromatic sources the spectral brightness, defined as photons/(s×μm²×sr×0.1%BW), has become the standard unit within the x-ray community.

The ongoing development of soft x-ray sources has been motivated primarily by the need for ever higher spectral brightness, but also by the desire to produce compact soft x-ray sources in order to increase the availability. Figure 2.1 shows the spectral brightness of the different x-ray sources described in this Chapter and Tab. 2.1 summarizes the more important sources. The spectral brightness stated is the average spectral brightness, which is a good figure of merit for continuous wave sources, but for pulsed sources with a relatively low pulse frequency compared to the pulse duration this does not fully describe the capacity of the source. This is especially true when the peak brightness is sufficiently high to allow for single pulse experiments.

2.1 Accelerator based sources

Acceleration of charged particles will result in the emission of electromagnetic radiation, a phenomenon that is widely used in, e.g., radio antennas. Here electrons are accelerated in a metal wire and emit radiation of a wavelength of several meters. In accelerator based x-ray sources the emitted radiation is shifted towards the x-ray
Figure 2.1: Comparison of average spectral brightness for various x-ray sources. The water window is marked as a gray band.

Table 2.1: Summary of the characteristics of the water-window x-ray sources described in this chapter, including the pulse repetition frequency (PRF) and the average spectral brightness in ph/(s×µm²×sr×0.1%BW) (Bright).
range by using relativistic electrons causing Lorentz contraction and the relativistic Doppler Effect. To achieve a sufficient wavelength shift the electrons are accelerated to a kinetic energy on the order of $10^9$ eV, corresponding to an electron speed $v = 0.999,999,999c$. At these energies the electron energy is often described by the Lorentz factor, $\gamma$, given by $\gamma = 1/\sqrt{1 - \beta^2}$, where $\beta = v/c$. For 1 GeV electrons $\gamma$ becomes 1958.

### 2.1.1 Synchrotron radiation

In synchrotrons the accelerated electrons are injected into a circular ultra-high vacuum (UHV) storage ring. Although the electron speed inside this storage ring is held constant they are subject to radial acceleration from the bending magnets used to keep them in orbit. The use of relativistic electrons will also increase the brightness by transforming the dipole radiation from the electrons into a narrow forward cone in the laboratory frame of reference as seen in Fig. 2.2.a.

![Figure 2.2](image)

**Figure 2.2**: The primary methods for synchrotron radiation: Bending magnets, wigglers and undulators

Although the concept of bending-magnet radiation is simple in nature, calculating the spectral distribution is not a trivial matter. A first approximation can be made by applying the illumination time $\Delta t$ from separate electrons to Heisenberg’s uncertainty principle, $\Delta E \Delta t \geq \hbar/2$. Because of the narrow radiation cone and the high electron speed, the illumination time is extremely short, resulting in the wide continuous spectrum seen in Fig. 2.2.a. The combination of high photon flux, narrow radiation cone, and small emitting source area all contribute to the brightness of $10^{15}$ ph/(s×μm$^2$×sr×0.1%BW) reached by bending magnets [21].

Modern synchrotrons are made up from bending nodes and straight sections where devices with periodic magnetic structures are inserted. In the case of strong magnetic fields this is referred to as a wiggler. The wiggler ideally behaves like a series of independent bending-magnet nodes, as seen in Fig. 2.2.b, and the intensity therefore increases linearly with the number of magnetic structures. For soft x-rays the
average spectral brightness reach $10^{16} \text{ph}/(s \times \mu m^2 \times \text{sr} \times 0.1\% \text{BW})$ [21]. Both bending magnets and wigglers are considered old techniques, especially for soft x-rays, and proposed wigglers are usually aimed towards hard x-rays due to the possibility of using strong magnetic fields.

For an electron beam with a sufficiently small cross-section and energy variation, a wiggler can be turned into a so-called undulator by reducing the field strength. This is shown in Fig. 2.2.c. Although this will reduce the photon flux, the spectral brightness will increase with several orders of magnitude due to the smaller deviations of the electron beam. Instead of having a series of short pulses sweeping past the sample, something that will lead to broad-band emission, the sample will be continuously illuminated and thus the radiation will be collected in a narrow-band spectrum. Furthermore, since the flux from each period will add coherently, the flux increases with the square of the number of periods instead of linearly. These properties have made undulator emission in the water-window reach an average spectral brightness on the order of $10^{20} \text{ph}/(s \times \mu m^2 \times \text{sr} \times 0.1\% \text{BW})$ [28], with simulated performance improvement of the new facilities, i.e. the Max IV in Lund [29], of another order of magnitude within a couple of years.

To compensate for the radiative energy loss in synchrotrons, radio-frequency pumping cavities are used to maintain the kinetic energy of the circulating electrons. These cavities also serve to order the electrons into tightly packed bunches which cause the emitted synchrotron radiation to be non-continuous. Although this means that the peak spectral brightness is a few orders of magnitude higher than the average brightness, the photon flux from a single pulse is usually too low to allow for single-pulse experiments with synchrotron radiation.

2.1.2 Free-electron lasers

With a sufficiently long undulator and well prepared electron beam a phenomenon known as free-electron laser (FEL) instability will occur [30, 31]. The electron bunches will, through interaction with the emitted undulator radiation, divide into so-called micro bunches. These micro bunches, having a size substantially smaller than the generated x-ray wavelength, will be separated by exactly one wavelength. This way the emission will turn completely coherent and thus scale with the square of the number of electrons, rather than linearly. The first FEL facilities reached the EUV region in 2006 [32] and now both the LCLS at Stanford and FLASH are producing x-ray photons at each edge of the water-window with a brightness of up to $10^{22} \text{ph}/(s \times \mu m^2 \times \text{sr} \times 0.1\% \text{BW})$ [33, 34]. The planned facility at the European XFEL aims towards another three orders of magnitude by 2014, mainly by increasing the repetition rate [35].

The large increase in brightness for the FEL increases the potential for single pulse imaging. This opens up whole new opportunities since the radiation within one
2.2. LABORATORY SOURCES

Pulse is not only completely coherent, but the pulse is also considerably shorter. Due to the more confined electron bunches in a FEL, the x-ray pulses reach down to the femtosecond range rather than the picoseconds range found in undulators. The spectral brightness within one pulse, the so-called peak spectral brightness, has so far reached \(3 \times 10^{31} \text{ph/(s}\times\mu\text{m}^2\times\text{sr}\times0.1\%\text{BW})\) [33] at 800 eV.

2.1.3 Other sources

A few other accelerator based sources should be mentioned, although they do not yet meet the requirements for high-brightness water-window generation. Compton backscattering sources (CBS) are based on interaction between relativistic electrons and intense laser light. Relativistic effects will shift scattered photons into the x-ray region and CBS have been successfully demonstrated in the hard x-ray regime [36]. Although water-window x-ray emission has been reported [37, 38], the average spectral brightness is still too low to allow for most types of experiments.

Cerenkov radiation (CR) is produced when charged particles are passed through a material with a speed larger than the material’s phase velocity of light. Water-window CR sources have been proposed [39] and although sufficient brightness seems feasible with a CW electron beam without melting the material, the pulsed nature of linear accelerators has so far been limiting the performance of water-window sources [40].

2.2 Laboratory sources

Although synchrotron radiation has become the standard tool for water-window x-ray generation, the scientific impact would be higher if laboratory systems could be operated with sufficiently short exposure times. In this section some compact systems are presented with special emphasis on laser-plasma sources and discharge-plasma sources, since these are the only systems that currently provide enough brightness for water-window microscopy.

2.2.1 Laser-plasma sources

By heating a suitable target to a sufficiently high temperature it can become an effective x-ray emitter [21]. One way of doing this is by focusing a high power laser onto the target, with laser parameters and target material tailored to meet the desired spectrum. This source is referred to as a laser-produced plasma (LPP). Nanosecond pulses from CO\(_2\) and Nd lasers are typically used to generate the high temperatures required for SXR/EUV spectra. The rapid processes involved
implies that the size of the x-ray emitter is roughly given by the size of the laser focus, with a diameter on the order of $10 - 20 \, \mu m$. Elements with low atomic number, such as nitrogen or carbon, are chosen since they generate soft x-rays within the water window at temperatures where the line emission from bound electron transitions dominates. This combination of small source size and narrow linewidth gives the LPP the high average spectral brightness. The liquid-nitrogen-jet target laser-plasma [41] has been used in soft x-ray microscopy [24] since it is regenerative and generates a sufficiently small amount of debris. It currently operates at 2.5 nm wavelength with an average spectral brightness of $2 - 4 \times 10^{10}$ ph/(s×μm²×sr×0.1%BW).

2.2.2 Discharge-plasma sources

Another way of creating a plasma is through a very high current from an electric discharge, referred to as a discharge-plasma (DP) source. The conversion efficiency from electric energy to x-ray energy is a couple of orders of magnitude higher than for the laser plasma, where the electric energy is first converted to laser energy, but the plasma is several hundred μm in diameter and several millimeters long. The combination of these two differences makes recent discharge-plasma sources achieve an average spectral brightness of $4 \times 10^9$ ph/(s×μm²×sr×0.1%BW) [22].

2.2.3 High-harmonics generation

By propagating a high-intensity laser through a gas cell it can, through non-linear processes, be made to reproduce pulses of very high (>100) harmonics of the original wavelength. The pulsed nature of these sources makes generation of coherent attosecond x-ray pulses, containing enough photons to reach nanometer resolution, perhaps the ultimate goal for compact x-ray imaging. In recent years, progress has been made in the EUV region allowing for single shot imaging of high-absorption test objects achieving 120 nm spatial resolution and 50 fs temporal resolution [42]. Water-window sources have so far only reached a brightness of $10^6$ ph/(s×μm²×sr×0.1%BW) [43].

2.2.4 X-ray lasers

So far, light amplification by stimulated emission of radiation (LASER) has been successfully realized down to 13.9 nm with an average spectral brightness of $10^{14}$ ph/(s×μm²×sr×0.1%BW) [44], but high-brightness x-ray lasers in the water-window region are not yet available as laboratory systems.
Chapter 3

Electron-Impact X-Ray Sources

Like the soft x-ray sources previously discussed, the original electron-impact x-ray source used by Röntgen can produce high-brightness soft x-rays under the right conditions. Figure 3.1.a shows a schematic view of the original electron-impact x-ray source while 3.1.b depicts a modern high-brightness configuration. Both types are based on the generation of free electrons at the cathode. These are accelerated towards the anode by applying a voltage of several kilovolts. At the anode, x-rays are finally generated by deceleration of the electron beam and ionization of the anode material.

![Schematic images of a) a primitive electron-impact x-ray source and b) a modern microfocus configuration. Adapted from [45].](image)

Section 3.1 describes the design of modern hard x-ray high-brightness systems and their typical performance and limitations. The liquid-jet concept, developed to overcome the brightness limitation of hard x-ray sources, is briefly described in Sec.
3.2. Section 3.3 deals with the generation and manipulation of the electron beam, suitable electron emitters and focusing components. This subject is particularly important for high-brightness x-ray sources, since the spectral brightness is inversely proportional to the source size, which is typically only a few µm larger than the e-beam focus. Section 3.4 describes the x-ray emission process and how the target can be chosen to tailor the wavelength of the emitted radiation, finally also with the added complexity of molecular targets.

3.1 Conventional electron-impact sources

The relatively simple design has made electron-impact sources widely used in science, medicine, and industry, and they have therefore come to be known as x-ray tubes [46]. Since conventional hard x-ray imaging is based on shadow projections, large brightness leads to high spatial resolution and/or decreased exposure times, and is therefore desirable in, e.g., medicine [47]. For a given acceleration voltage, the brightness is proportional to the electron beam power and inversely proportional to the size of the electron focus. This ratio is called power density and is usually expressed as W/mm$^2$. Since it is often used to describe the performance of x-ray tubes, it will be used for a large part of this Chapter instead of the emitted x-ray brightness.

When an electron reaches the anode, typically $0.5 - 1\%$ of the kinetic energy is converted to x-rays, while the remaining energy heats the target. This heat load limits the power density. To increase the effective power density, the line focus principle and the rotating anode were introduced in the 1920s. A rectangular e-beam focus and angled viewing are used for radial distribution of the generated heat while maintaining a small effective spot size, and rotating the anode distributes the heat load over a larger area. This way the whole cone surface can be used for heat conduction. Typical high-end sources, used where short exposure times are important to reduce motion artifacts, now have an effective power density of 100-150 kW/mm$^2$, e.g., angiography systems with 10 kW distributed over a $0.3 \times 0.3$ mm$^2$ effective spot size.

For applications where high resolution is desired, rather than short exposure times, low-power microfocus sources have been developed. Typical systems (4 W, 5 µm diameter) have a much lower photon flux, but since they can be used with a higher power density, and thus reach higher brightness, they will serve as comparison for the source developed in this Thesis. For microfocus systems the maximum power density scales not with the area of the electron beam focus, but rather with the diameter. In order to avoid permanent damage to the anode the maximum power density is $0.4 - 0.8$ W/µm [48], and considering the many improvements made to the x-ray tube it is unlikely that this limit will increase much hereafter [49–51].
3.2 Liquid-Metal-Jet Anode X-Ray Sources

To overcome the power density limit due to thermal effects in conventional microfocus sources the liquid-metal-jet anode source has been developed [52]. The regenerative nature of these anodes allows for a power density of $> 6 \text{ W/} \mu \text{m}$ [53, 54], with experimental non-metal jets reaching an on-target power density of $> 8 \text{ W/} \mu \text{m}$ [55].

3.3 Electron emitters and focusing optics

Assuming that the heat load can be managed, e.g., by the use of liquid-metal jet anodes, the other limiting factor of the x-ray brightness is the brightness of the electron beam. For high-brightness systems more advanced electron guns must be constructed. As illustrated in Fig. 3.1.b these contain a high-brightness electron-emitting cathode, a short acceleration gap and an optical column for manipulation of the e-beam.

Most x-ray tubes use thermionic cathodes that emit electrons as they are heated. All metals can be made to emit electrons if heated to high enough temperatures [56] and tungsten is the most common cathode material. The single crystal LaB$_6$ cathode, however, is robust and can deliver a high e-beam brightness with sufficiently high beam current, properties that have made it useful in microfocus x-ray tubes [57]. The acceleration gap is usually below 10 mm with a hole in what would otherwise become the target, making the electrons propagate at constant speed towards the anode. This way the high-voltage part of the e-gun, including the cathode that requires ultra-high-vacuum ($< 10^{-7}$ mbar) to ensure a long lifetime (>1000 h), is separated from the rest of the source and components for manipulation of the e-beam can be inserted. Good quality e-beam focusing optics are needed since the x-ray spot always will be at least as large as the e-beam focus. The $> 6 \text{ W/} \mu \text{m}$ power density mentioned in the previous section was accomplished at 50 keV with a single magnetic lens focusing the e-beam from a 50 $\mu \text{m}$ diameter LaB$_6$ crystal down to a 6.5 $\mu \text{m}$ e-beam spot [54]. A dual lens system for achieving sufficient focusing with 30 keV electrons will be described in Chapter 4.

3.4 Electron-target interaction

When the accelerated electrons reach the anode, x-rays are generated through two processes: Electron deceleration and ionization of the anode material.

The deceleration creates a continuous x-ray spectrum, since the electron can either come to a sudden stop, and emit all kinetic energy as a single x-ray photon, or
emit several lower-energy photons as the speed is gradually reduced. The total conversion efficiency, summarized over the whole spectrum, is

\[
\eta = \frac{\text{x-ray energy}}{\text{electron energy}} = 9.2 \cdot 10^{-10} \text{ ZV},
\]

where \( Z \) is the atomic number and \( V \) is the acceleration voltage [58]. A typical number would thus be, e.g., 100 keV electrons on a tungsten anode \((Z=72)\), giving a conversion efficiency of 0.7%.

While the deceleration creates a broad-band spectrum, the ionization process creates narrow-band emission with element-specific photon energies. This process happens in two steps, as shown in Fig. 3.2.a. First the incoming electron knocks out an inner shell electron from the atom and thereafter an outer shell electron falls down to fill the vacancy (after \( 10^{-11} \) s) and either another outer shell electron is ejected, a so-called Auger electron, or an x-ray photon is emitted. The energy of this photon will be equal to the difference in binding energy between the two electrons, and complete tables can be found in the literature [21]. In Fig 3.2.b, the most energetic K transitions and the less energetic L transitions are shown.

The probability that an incoming electron will create an x-ray photon is dependent on the energy of the incoming electron and has been formulated as \( N = \xi(E_0 - E_X)^n \) [59], where \( \xi \) is a material constant, \( n \) is a fundamental constant of 1.63, \( E_0 \) is the electron beam energy and \( E_X \) is the binding energy of the electron. This relationship can also be expressed as \( N = \zeta(U_0 - 1)^n \), with a different material constant \( \zeta \) and \( U_0 = E_0/E_X \). A more thorough analysis has shown that the exponent \( n \) is also a material constant, with values ranging from 0.33 to 2.49 [60]. These expressions are only approximations and do not take self absorption into account, but they can be useful as a first approximation.

\( \xi \)
\( n \)
\( E_0 \)
\( E_X \)
\( U_0 \)
\( \zeta \)

Figure 3.2: a) The fluorescent line emission process from a high-Z material. b) The allowed K and L transitions.
3.4. ELECTRON-TARGET INTERACTION

For a more thorough analysis of the emitted spectrum, various Monte Carlo simulation packages are available, such as CASINO [61], NISTmonte [62] and PENELOPE [63, 64]. PENELOPE has been extensively used for simulations of x-ray emission from both solid anodes and liquid-jet anodes since it can be used with all combinations of electron energies, materials and geometries [65]. As can be seen in Fig. 3.3, simulated x-ray emission is in excellent agreement with measured spectra from the liquid-metal-jet sources and PENELOPE will therefore be used for simulations of x-ray emission throughout the rest of this Thesis.

![Figure 3.3](image.png)

**Figure 3.3:** Measured (black) and simulated (blue and red) spectra from the a) tin and b) gallium liquid-metal-jet anode sources. It can be seen that while the emission is correctly simulated, care should be taken with the simulated source size. Adapted from [65].

### 3.4.1 Water-window x-ray generation

Although not shown in Fig. 3.3, all electron impact sources generate bremsstrahlung in the soft x-ray regime. This bremsstrahlung is not very bright, so instead the line radiation should be used as it is several orders of magnitude stronger. High-brightness soft x-ray line radiation can either be generated with $L_\alpha$ radiation from high-Z materials or with $K_\alpha$ radiation from low-Z materials. Within the water window the available spectral lines, and the corresponding photon energies, are $L_\alpha$ from scandium (395 eV), titanium (452 eV) and vanadium (511 eV); and $K_\alpha$ from nitrogen (392 eV) and oxygen (525 eV). The estimated yield in Sec. 3.4 shows that the $K_\alpha$ radiation yield is more than an order of magnitude higher than the $L_\alpha$ radiation yield and although a water-window titanium-anode microscope has been constructed [66], the low photon flux requires up to one-hour exposure times despite the lens-less projection mode used.

The choice would therefore be either nitrogen or oxygen, with the latter being preferred since the oxygen $K_\alpha$ peak is just inside the water window. Amongst
the various oxides available an anode with 64% mass oxygen and minimal self-absorption could be made from beryllium oxide [40], as it also has thermal properties close to those of copper and tungsten. For comparison between a BeO x-ray tube and the LPP in Chapter 2, PENELOPE simulations have been carried out with a source size of 15 $\mu$m and at a power density of 1 W/$\mu$m. The simulated brightness for a 30 keV e-beam is $4.5 \times 10^9$ ph/($s \times \mu m^2 \times sr \times line$) or, by including the spectral width of 1.2 eV, $2 \times 10^9$ ph/($s \times \mu m^2 \times sr \times 0.1\%BW$). This makes the spectral brightness at the power density limit an order of magnitude lower than for the LPP source. Hence this concept seems unlikely to ever reach LPP exposure times. The other option is to expand the liquid-jet concept to the soft x-ray regime and choose water ($H_2O$) as anode material. It has 89% mass of oxygen and is a suitable candidate due to its thermodynamical properties. This source will be thoroughly described in Chapter 4.

### 3.4.2 Non-homogenous targets

PENELOPE doesn’t take molecular structure into account but only considers the density and, in the case of compounds, the fraction by weight of the different elements used. For this reason, changes in photon energy caused by energy difference between molecular and atomic electron orbitals are not accounted for. To add this information simulations done with quantum chemistry theory, where the Schrödinger equation [67] for molecules is solved numerically using the Hartree-Fock method [68], have been done for water [69]. This shows that the linewidth is 2.2 eV, compared to the <0.24 eV for pure oxygen [70]. The molecular orbitals and the corresponding spectrum simulation is shown in Fig. 3.4 and it is in good agreement with previous measurements [71].

![Molecular orbitals and spectrum simulation](image)

**Figure 3.4:** a) The three oxygen $K_\alpha$ transitions of $H_2O$. b) Simulated emission spectrum from water vapor and liquid water. Adapted from [69]
Chapter 4

Liquid-Jet Electron-Impact Water-Window Sources

The consequence of the power density limit for electron-impact microfocus sources with solid anodes is that the required exposure times would be more than an order of magnitude longer compared to, e.g., LPP sources. Therefore this chapter is concerned with the implementation of a stable liquid-jet anode for high-brightness electron-impact soft x-ray generation. To date, liquid-jet anodes have been successfully implemented for high-brightness hard x-ray generation (10 keV range). Work has primarily been on tin [52] and gallium [53] jet. However, work on methanol jets [55] for bremsstrahlung emission has demonstrated the potential for expanding the liquid-jet concept to non-conducting low-Z target materials and that such jets can be stably operated at high electron-beam intensities. These materials are less suitable for generation of bremsstrahlung, as is apparent from the Z-dependence given in Eq. 3.1. In the present Chapter this concept will be used for high-brightness generation of oxygen line emission in the water-window using a water jet anode. Early attempts on water jets by Buijsee were terminated due to jet instabilities limiting the brightness to to $5 \times 10^8$ ph/(s×sr×μm$^2$×line) [72].

As described in Sec. 3.4, the line emission is strong enough to make this type of electron-impact emission an alternative, but the low e-beam absorption in a low-Z jet presents additional challenges. Although the on-target power density of the methanol jet was > 8 W/μm, the absorption was only estimated to ~10% due to the combination of high e-beam energy (50 keV) and a small jet diameter (10 μm) [55]. This stresses the importance of selecting not only a suitable jet material, but also the optimum e-beam energy when designing a high-brightness electron-impact liquid-jet water-window source.

$K_\alpha$ radiation from either oxygen or nitrogen have been found to be two possible alternatives for a high-brightness water-window source. Since the lower absorption
in the high-energy side of the water window (∼500 eV) results in a higher signal on the detector while maintaining a high contrast, the line radiation from oxygen is preferred over nitrogen. Water (H₂O) is a stable and non-toxic liquid with high oxygen content and excellent thermodynamical and hydrodynamical properties, but the molecular structure of water described in Sec. 3.4.2 creates a ten-fold line broadening compared to pure oxygen. A high-resolution spectrum, included in Paper I, confirms this line broadening. Therefore an estimation of the achievable brightness from a cryogenic liquid-oxygen jet is mentioned in Sec. 4.3.2.

4.1 Liquid jets

A thorough analysis of liquid-jet anodes can be found in the literature [73, 74], but two important characteristics of liquid jets are the jet velocity and the jet breakup length. The first is especially important since the maximum power density for liquid-jet-anodes is proportional to the jet velocity, while the latter limits the working distance from the nozzle to the x-ray source.

4.1.1 Jet velocity

The nozzle is a high aspect-ratio converging duct that converts high pressure and low velocity into low pressure and high velocity. Bernoulli’s equation is commonly used to describe liquid jets in vacuum and by assuming an ideal transformation of the pressure energy on an incompressible fluid into kinetic energy, it becomes

\[
\frac{\rho v_1^2}{2} + p_1 + g \cdot z_1 = \frac{\rho v_2^2}{2} + p_2 + g \cdot z_2,
\]

where \( g \cdot z \) is the gravitational force, \( v \) is the fluid velocity, \( \rho \) is the density of the liquid, and \( p \) is the static pressure. This expression can be simplified further since we assume a low initial velocity \( (v_1 \approx 0) \), a low final pressure \( (p_2 \approx 0) \), and negligible gravity effects. On the other hand, to account for a non-ideal energy transformation, with losses caused by fluid friction and turbulence, a correction factor called the discharge coefficient, \( c_v \), must be introduced. The discharge coefficient is given by the ratio between the measured flow rate and the ideal flow rate, and the final expression for the jet velocity can thus be written as

\[
v = c_v \sqrt{\frac{2p}{\rho}}
\]
4.1.2 Breakup length

When applying the backing pressure a continuous jet is ejected from the nozzle, but since this is unfavorable from an energy perspective it will eventually break up into droplets [75, 76]. The distance $L$ from the nozzle to the onset of droplets is referred to as the breakup length and is given by

$$L = \ln \left( \frac{d}{2\delta_0} \right) v \left( \sqrt{\frac{\rho d^3}{\sigma}} + \frac{3d\eta}{\sigma} \right),$$  \hspace{1cm} (4.3)

where $d$ is the jet diameter, $\delta_0$ is an initial disturbance factor, $\sigma$ is the surface tension, $\eta$ is the dynamic viscosity of the liquid, $\rho$ is the density, and $v$ is the jet velocity [76]. $\delta_0$ can be determined experimentally, but as a rule of thumb the logarithmic expression is usually $\sim 10$ [76]. For the nozzle design used in this thesis it has been measured to 9.5 for 10 $\mu$m diameter nozzles [77].

The relationships in Eqs. 4.2 and 4.3 are based on the assumption of incompressible fluids. This is valid if the ratio between the jet velocity and the speed of sound in the liquid, the so-called Mach number, is smaller than $0.25 - 0.3$ [78].

4.2 Differential pumping

To maintain the required vacuum of $< 10^{-7}$ mbar at the cathode, while injecting a non-metal-jet into the vacuum chamber, the vacuum system has to be carefully designed. It is particularly important to avoid contaminating the cathode with $O_2$ since this is known to affect the lifetime of the cathode [79, 80]. This problem has been solved in environmental scanning electron microscopy (ESEM), where samples with a background pressure of up to 1 mbar are being imaged with a low-current e-beam, with a vacuum of $10^{-9}$ mbar maintained at the cathode by implementing differential pumping [81].

Differential pumping is achieved by dividing the vacuum chamber into individually pumped compartments, separated by small apertures, as seen in Fig. 4.1. The principle is conceptually similar to electric circuits with apertures of different shapes and sizes giving different gas conductance. The gas flow between two compartments is given by $q = L \cdot \Delta p$, where $\Delta p$ is the pressure difference and $L$ is the conductance [82]. The pressure in each compartment is then given by $p = q/S$, where $S$ is the volume flow rate of the vacuum pump. Some algebra gives the vacuum levels in a vacuum system consisting of two chambers as

$$p_1 = \frac{Q}{S_1}, \quad p_2 = \frac{QL}{S_1S_2} \left( \frac{1 + \frac{L}{S_2}}{S_2} \right),$$  \hspace{1cm} (4.4)
where \( S_1 \) and \( S_2 \) is the respective volume flow rate of each vacuum pump, \( L \) is the conductance of the aperture, and \( Q \) is a constant load in the primary chamber. For a typical differential pumping system with a small turbomolecular vacuum pump and a mm-sized aperture, the ratio \( L/S_2 \) is \( \sim 10^{-3} \), which makes the vacuum improvement \( p_2/p_1 \approx L/S_2 \).

\[
p_2/p_1 \approx L/S_2
\]

**Figure 4.1:** The layout of the differential vacuum pumping system described in Eq. 4.4.

### 4.3 The electron-impact liquid-jet water-window source

By considering the spectral line of oxygen and the properties of liquid water, a high-brightness water-window source based on electrons impacting on a water jet seems as an interesting alternative to the LPP source. Implementation of the differential vacuum pumping system described in Sec. 4.2 is required to meet the demand for ultra-high vacuum (<\( 10^{-7} \) mbar) at the cathode. To allow for the use of standard soft x-ray microscopy components the source is designed to have a size close to the \( \sim 20 \mu m \) diameter used in the LPP microscope. This section will describe the different components necessary for implementation of this source, i.e., the e-beam system, the differential pumping system and the high-speed water jet.

#### 4.3.1 Simulations of the brightness

To maximize the emitted radiation the e-beam has to be completely absorbed in the jet. An acceleration voltage of 30 kV is appropriate since these electrons will be totally absorbed in 17 \( \sim 18 \mu m \) of water. Simulations with PENELOPE have therefore been done with a 30 keV e-beam focused to a 5 \( \mu m \) Gaussian spot on a 20 \( \mu m \) water jet. The resulting x-ray intensity per watt of e-beam power is \( 9 \times 10^{10} \text{ ph}/(\text{sr} \times \text{line} \times \text{W}) \). Assuming a 15 \( \mu m \) diameter source the brightness per watt would become \( 5 \times 10^{8} \text{ ph}/(\text{sr} \times \mu m^2 \times \text{line} \times \text{W}) \). In order to achieve LPP brightness \( \sim 100 \text{ W} \) of e-beam power would be required.
4.3. THE ELECTRON-IMPACT LIQUID-JET WATER-WINDOW SOURCE

4.3.2 The water jet

To estimate the jet speed required for withstanding the e-beam power, the thermodynamical properties of water have to be considered. This is done using the same method that has been used for estimation of bremsstrahlung generation from liquid-metal-jet anodes [83]. Assuming that we allow for total jet vaporization, the required backing pressure according to Eq. 4.2 can then be calculated as

\[
p = \frac{P^2}{2\rho \pi r^2 (c_p \Delta T + \Delta H_{vap})^2}, \tag{4.5}
\]

where \( P \) is the e-beam power, \( \rho \) is the liquid density, \( r \) is the jet radius, \( c_p \) is the specific heat capacity, \( \Delta T \) is the temperature difference between melting point and boiling point and \( \Delta H_{vap} \) is the enthalpy of vaporization. Calculating this number for water gives a required backing pressure of 69 bars to create a jet that would withstand 100 W of e-beam power before total vaporization. As comparison the required backing pressure for a cryogenic jet of liquid oxygen is > 1000 bars due to the low enthalpy of vaporization.

The 20 \( \mu \)m diameter water jet is created with a tapered glass capillary nozzle pressurized by a high pressure liquid chromatography (HPLC) pump capable of up to 690 bars of backing pressure. Since this is an order of magnitude higher than the estimated requirement the jet vaporization will be significantly reduced. According to Eq. 4.2, this would correspond to a jet speed of up to 370 m/s for an ideal nozzle. This gives a Mach number of 0.23, which means that we are fulfilling the requirement for incompressible fluids. The flow rate is measured for several nozzles and the actual jet speed is calculated by considering the nozzle diameter of 20 \( \pm \) 2\( \mu \)m. The results from three different nozzles are shown in Fig 4.2. The breakup length, as described in Eq. 4.3, is \( \sim \)30 mm at a jet speed of 300 m/s.

![Figure 4.2: By measuring the flow rate and knowing the nozzle diameter of 20 \( \pm \) 2\( \mu \)m, the jet speed is calculated for three different nozzles. The dotted line shows the theoretical jet speed with an ideal nozzle and the solid line shows the jet speed with a \( c_v \) of 0.9.](image)

\[ v = (2p/\rho)^{0.5} \]
\[ v = 0.9 \times (2p/\rho)^{0.5} \]
CHAPTER 4. LIQUID-JET ELECTRON-IMPACT WATER-WINDOW SOURCES

4.3.3 The electron beam and focusing system

A single-lens system was used in a low-power proof-of-principle experiment with a 100 $\mu$m diameter LaB$_6$ cathode. This experiment was limited to 7.8 W of e-beam power by the increasing pressure at the cathode, as described in Paper I. However, even without the vacuum problem, aberrations in the magnetic lens would have limited the absorbed e-beam power. Because of the increased emission angle of the e-beam at higher powers, due to thermal effects and space charge effects at the cathode, spherical aberrations would eventually have made the e-beam focus larger than the jet diameter. This effect is present in all e-beam systems, but it is more pronounced when using relatively low acceleration voltages and long e-beam propagation distances.

When focusing a high e-beam power onto the jet the aberrations in the optical column therefore have to be mitigated. A dual-lens optical column with a magnetic condenser lens and a magnetic focusing lens, as seen in Fig 4.3, will reduce the spherical aberration, as the condenser lens will decrease the beam expansion. To select the optimal performance and how it will be reached, simulations have been done with MATLAB and Lorentz-2D [84]. Figure 4.4 shows the results from these simulations for a single-lens and a dual-lens system with a 150 $\mu$m diameter LaB$_6$ single crystal cathode. It follows that for this configuration a dual-lens system is required to focus the e-beam on 20 $\mu$m diameter jet. While single-lens systems can be used, they require a small cathode, which limits the maximum e-beam power, and a short propagation distance, which limits the possibility of implementing differential vacuum pumping. The experiments on the methanol jet were therefore limited to an e-beam power of 70 W and resulted in a cathode chamber vacuum of $\sim 10^{-5}$ mbar [55].

![Figure 4.3](image)

**Figure 4.3:** The cathode, the anode hole and the dual-lens e-beam focusing column. The dotted line shows the vacuum pumped volume.

Since a 100 $\mu$m diameter crystal is easier to focus while the e-beam power can still be up to 200 W using an acceleration voltage of 30 kV, this size is a good compromise for high-power experiments.
4.3. THE ELECTRON-IMPACT LIQUID-JET WATER-WINDOW SOURCE

4.3.4 The differential pumping system

A three-stage differential vacuum pumping system is used to achieve a sufficient pressure difference between the nozzle chamber and the cathode chamber, as shown in Fig. 4.5.a. By choosing a tube between the two lens chambers instead of an aperture it can be made with a larger diameter while maintaining a high differential pumping capacity. This way a larger diameter e-beam can pass through. For instructions on how to calculate the conductance for various shapes see, e.g., [82]. The nozzle chamber is pumped by a 20 ℓ/s rotary vane pump, while the three differential pumping chambers are pumped by 60 ℓ/s turbo pumps. Because of conductance losses the effective pumping speed is reduced, as seen in Fig. 4.5.b, but a cathode chamber vacuum of <10^{-7} mbar can still be maintained while having a vacuum of almost 10 mbar in the nozzle chamber. This would be equivalent to total vaporization of a 500 m/s, 20 µm diameter water jet. The geometry of this differential pumping system is described in more detail in Paper II.

![Figure 4.4: Simulations of the optimal performance of the focusing column in Fig 4.3 when a) using only the focusing lens and b) using both lenses. The cathode diameter is assumed to be 150 µm.](image)

![Figure 4.5: a) The geometry of the three-stage differential pumping system. b) The measured volume flow rate of the turbopumps.](image)
CHAPTER 4. LIQUID-JET ELECTRON-IMPACT WATER-WINDOW SOURCES

4.4 Performance characteristics

The brightness of the source is calculated by measuring the x-ray emission and the source size. The emission is measured with a single-photon-counting spectrometer and the source size is measured by imaging the source onto a soft x-ray charge coupled device (CCD) with a zone plate. The average brightness within the central 12 \( \mu \text{m} \) diameter spot is calculated to allow for direct comparison with the LPP source [41].

The relatively large linewidth of the source will affect the spectral brightness. Since the \( \sim 70 \text{ eV} \) bandwidth of the spectrometer is much larger than the expected width of the \( \text{K}_\alpha \) peak of water, the quantitative flux measurements are combined with measurements from a high-resolution grating spectrometer to determine the spectral brightness. Although the spectrometer bandwidth (\( \sim 3 \text{ eV BW} \)) will cause some broadening, an estimation of the spectral brightness is provided. The details of these measurements are given in Paper I.

4.4.1 X-ray intensity

Figure 4.6.a shows the total emitted soft x-ray intensity at 525 eV for e-beam powers up to 120 W. There are several possible explanations for the saturating behavior shown. One possibility is that the increasing e-beam size causes partial absorption of the e-beam in the differential pumping apertures or that it creates focusing aberrations due to misalignment of the electron-optical column. It could also be caused by electron absorption and scattering due to the locally higher pressure arising from increasing the power loading more than the jet speed, an effect that is manifested as a bright line on the left hand side in the 120 W jet image in Fig. 4.6.b.

![Graph showing x-ray intensity vs. e-beam power](image)

**Figure 4.6**: a) The emitted x-ray intensity with increasing e-beam power. b) Microscope images showing stable operation of high speed jets with up to 120 W of e-beam power. a) and b) from Paper II.
4.4.2 Spot size

Figure 4.7.a. shows the $21 \times 17 \, \mu m^2$ full width at half maximum (FWHM) intensity distribution from the interaction between a 50 W e-beam and a 125 m/s water jet, taken with a 0.5 s exposure time. From the spectral measurements it is not surprising to see that the spot size in Fig. 4.7.b is growing with increased e-beam power and this will also limit the achievable brightness.

![Figure 4.7:](image)

4.4.3 Source brightness

By combining the spectral and spot size measurements the brightness can be calculated. The combination of a saturating x-ray intensity and a growing spot size give a maximum measured brightness of $3.5 \times 10^9 \, ph/(s \times \mu m^2 \times sr \times line)$ at 50 W, as seen in Fig. 4.8.a. To confirm the linewidth broadening caused by the molecular structure, and calculate the average spectral brightness for the $K_\alpha$ peak of the electron-impact liquid-jet water-window source, the brightness is combined with a high-resolution spectrum. The resulting FWHM linewidth is measured to 3 eV, which is consistent with the spectrometer resolution and Fig. 4.8.b shows an average spectral brightness of $4.5 \times 10^8 \, ph/(s \times \mu m^2 \times sr \times 0.1\% BW)$ at 50 W.

4.5 Comparison to other compact water-window sources

The measured spectral brightness is not as high as for existing compact water-window sources, i.e., the laser-plasma and the discharge-plasma sources, due to the molecular linewidth broadening. In soft x-ray tomography a relative bandwidth
Figure 4.8: a) The brightness of the electron-impact water-window liquid-jet source up to 50 W. b) The spectral brightness at 50 W.

\[ \lambda/\Delta \lambda \text{ of 200, which is similar to the performance described here, might give improved resolution since this would create a larger depth of focus [85]. In that case the full line can be used and a better figure of merit is the line brightness, which is already in the range of the discharge-plasma sources, despite the difficulties with e-beam focusing. If the brightness can be increased another order of magnitude, e.g., by improved e-beam focusing or increased e-beam power, it seems possible to reach the brightness of laser-plasma sources. Future prospects, with improved e-beam focusing and increased e-beam power, looks promising indeed.} \]
Chapter 5

Summary and Outlook

This Thesis describes the development of a new type of high-brightness electron-impact soft x-ray source, emitting at the edge of the water-window, making it a potential candidate for soft x-ray microscopy. Because of the simple and reliable design of electron guns, this can be a relatively stable and inexpensive alternative to existing compact sources.

By implementing a three-stage differential pumping system, a dual-lens electron-optical column and a liquid-jet system delivering jet speeds $>300$ m/s, the source has reached the same brightness as discharge-plasma sources, which are currently used for soft x-ray microscopy. The relatively large bandwidth reduces the spectral brightness, but might be an advantage for soft x-ray microscopy since it increases the depth of focus.

The present limiting factor is spot enlargement with increasing e-beam power. To increase the brightness further the electron beam focusing and the vacuum in the jet chamber must be improved. Simulations suggest that a small focus can be maintained up to 200 W. It seems possible to increase the brightness another order of magnitude and thereby approach the brightness of laser-plasma sources.
Summary of Papers

The two papers included in this Thesis are part of the implementation of a high-brightness electron-impact liquid-jet water-window x-ray source. The first paper describes the implementation of a proof-of-principle low-power experiment and the second paper addresses the improvements needed for upscaling the brightness towards existing compact water-window sources. The author was the main responsible researcher for both papers.

**Paper I** is a demonstration of the water-jet anode concept and a low-power demonstration system. The initial results are in good quantitative agreement with Monte Carlo simulations and show the potential of scaling the source towards the brightness of existing compact water-window sources, e.g., the discharge-plasma and the laser-plasma sources. Vacuum pumping and jet stability are determined to be the most important limiting factors.

**Paper II** is a higher-power implementation of the source concept. With upgraded vacuum pumping, improved jet stability and a new electron beam focusing system the power loading is increased 15 times from Paper I. A more thorough investigation of the spatial characteristics of the source shows that the brightness is equivalent to the discharge-plasma source. The electron beam focusing at high power is now the limiting factor for reaching the brightness of the laser-plasma source.
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