Compact Liquid-Jet X-Ray Sources

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Abstract

This thesis describes the development, characterization and optimization of compact, high-brightness, liquid-jet-target x-ray sources. Two different source types have been developed for different wavelength regions and applications.

A laser-plasma source for generating soft x-ray and extreme-ultraviolet radiation has been further developed for soft x-ray microscopy and extreme-ultraviolet lithography. This work focused on improved target stability, increased conversion efficiency and decreased debris production. For x-ray microscopy applications using carbon-containing liquid-jet-droplet targets, the droplet stability has been investigated and a method for source stabilization introduced. This source has also been optimized in terms of flux per debris with respect to target material and size. For extreme-ultraviolet lithography applications, a liquid-xenon-jet-target laser-plasma source system has been greatly improved, especially in terms of stability and conversion efficiency. This source has also been characterized in terms of, e.g., source size, angular distribution, and repetition-rate capability. For extreme-ultraviolet lithography, the possible use of tin as a target material has also been studied and conversion efficiency and debris measurements performed.

A new anode concept for electron-impact hard x-ray sources based on high-speed liquid-metal jets has been introduced. Initial calculations show that this new target concept could potentially allow more than a hundred-fold increase in source brightness compared to existing state-of-the-art technology. A low-power, proof-of-principle, experiment has been performed, verifying the basic source concept. Scaling to high-power operation is discussed and appears plausible. A main obstacle for high-power operation, the generation of a microscopic high-speed jet in vacuum, is investigated using dynamic-similarity experiments and shown to be feasible. Finally, initial medium-power experiments, approaching current state-of-the-art sources in terms of brightness, have been performed.
List of Papers

This thesis is based on the following papers:


Other Publications

The following papers and patents, contributed to by the author, are related to the work in this thesis, but are not included in it.

Papers


Patents


H. M. Hertz, and O. Hemberg, “Method and Apparatus for Generating X-Ray or EUV Radiation”, International (PCT) patent application WO 02/11499, and derivations thereof.

# List of Acronyms

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<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>BW</td>
<td>Bandwidth</td>
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<tr>
<td>CB</td>
<td>Coherent Bremsstrahlung</td>
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<td>CBS</td>
<td>Compton Backscattering</td>
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<td>CE</td>
<td>Conversion Efficiency</td>
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<td>CHR</td>
<td>Channeling Radiation</td>
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<td>CR</td>
<td>Cherenkov Radiation</td>
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<td>CW</td>
<td>Continuous Wave</td>
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<td>DUV</td>
<td>Deep Ultraviolet</td>
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<td>ECR</td>
<td>Electron Cyclotron Resonance</td>
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<td>EPL</td>
<td>Electron Projection Lithography</td>
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<tr>
<td>ETS</td>
<td>Engineering Test Stand</td>
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<tr>
<td>EUV</td>
<td>Extreme Ultraviolet</td>
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<td>EUVL</td>
<td>Extreme Ultraviolet Lithography</td>
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<td>FEL</td>
<td>Free-Electron Laser</td>
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<td>GDP</td>
<td>Gas Discharge Plasma</td>
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<td>HHG</td>
<td>High Harmonic Generation</td>
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<tr>
<td>IC</td>
<td>Integrated Circuit</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
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<tr>
<td>ITRS</td>
<td>International Technology Roadmap for Semiconductor</td>
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<tr>
<td>N/A</td>
<td>Not Applicable</td>
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<tr>
<td>NA</td>
<td>Numerical Aperture</td>
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<tr>
<td>NGL</td>
<td>Next Generation Lithography</td>
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<tr>
<td>PXR</td>
<td>Parametric X-Rays</td>
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<tr>
<td>RTR</td>
<td>Resonant Transition Radiation</td>
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<td>SASE</td>
<td>Self-Amplified Spontaneous Emission</td>
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<td>SR</td>
<td>Synchrotron Radiation</td>
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<td>TBD</td>
<td>To Be Determined</td>
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<td>TR</td>
<td>Transition Radiation</td>
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<td>UV</td>
<td>Ultraviolet</td>
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<td>VUV</td>
<td>Vacuum Ultraviolet</td>
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<td>X-Ray Proximity Lithography</td>
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Chapter 1

Introduction

Ever since Röntgen’s discovery of x-rays [1] more than a hundred years ago they have played a vital role in science, industry and medicine. There are a few basic properties of x-rays that have made them so widely used. First is their ability to penetrate normally opaque objects to give information about internal structures. Second is their short wavelength which is essential when imaging small features, as described by the Rayleigh criterion for resolution* [2]. Furthermore, the photon energy range spanned by x-rays covers a multitude of atomic resonances and they can therefore be used to probe the basic structure of matter. In the electromagnetic spectrum, shown in Fig. 1.1, extreme ultraviolet (EUV) and soft x-ray radiation (SXR) fill the spectral region between vacuum ultraviolet (VUV) and hard x-rays.

\* The Rayleigh criterion says that two incoherent point sources can be resolved at a minimum separation of $0.61\frac{\lambda}{NA}$, where $\lambda$ is the wavelength and the numerical aperture, $NA$, is defined as sin of half the maximum angle picked up by the lens.

\† The relation between vacuum wavelength and photon energy is given by 1 nm = 1239.842 eV, and 1 eV equals 1.602,177·10⁻¹⁹ J.

![Figure 1.1.](image-url) The electromagnetic spectrum between infrared (IR) and γ-rays. Electromagnetic radiation is characterized by its wavelength, or energy. Wavelength, expressed in nanometers (nm) is often used in the low energy portion of the spectrum and energy, expressed in electron volts (eV) is commonly used in the high energy range. The definitions of the different spectral regions are somewhat vague but here EUV is taken to extend between ~30 eV and ~250 eV. Soft x-rays span from ~250 eV up to several keV. Finally, hard x-rays range from a few keV up to a few 100 keV.
After their discovery, x-rays were immediately used for imaging and basic research into matter. The quick acceptance and exploitation of hard x-rays were due to two main factors. First, there were several areas in which they were immediately helpful. Secondly, the technologies required to both produce and detect them were simple and available. In comparison, the SXR/EUV range was late in being exploited, primarily due to technological difficulties, and only truly began with the advent of the synchrotron radiation light source. A primary difficulty with SXR/EUV radiation is the strong absorption in matter, where attenuation lengths can usually be measured in nanometers or micrometers compared to millimeters or meters for hard x-rays. This is a consequence of the large amount of atomic resonances in this region, something that also makes this spectral region interesting for material analysis and helped prompt the development of suitable radiation sources in the first place. For a more detailed discussion on the various general uses of x-rays see, e.g., Ref. 3 for SXR/EUV applications, Refs. 4 and 5 for medical applications, Ref. 6 for material analysis, and Ref. 7 for crystal diffraction studies.

The motivation for continued development of x-ray sources comes from the fact that most applications today are, in some way or another, limited by the source performance. A basic property of radiation sources is brightness*, which is radiated power per unit area and unit solid angle at the source. This quantity is especially important since it can not be increased but at best conserved in an optical system [8]. This means that it is not possible to concentrate the power radiated from a large divergent source into a small, well collimated beam. Hence, the maximum brightness in any optical system is given by the source brightness, which is therefore a crucial parameter. An often even more useful quantity is spectral brightness, which is simply radiated power (or number of photons) per unit area, per solid angle, per bandwidth (BW) at some energy. For line emitting sources the bandwidth of the line is a natural choice and for some applications the bandwidth of the optical system is appropriate. The brightness is, for applications involving spatial resolution, a good figure of merit for source evaluation and as such it will be extensively used throughout this text in the commonly used units of photons per s·mm²·mrad²·0.1%BW.†

* Other terms sometimes used for the same quantity are brilliance, specific intensity, and radiance depending on scientific community.

† When describing pulsed sources not only the average brightness is important but also the pulse length and the pulse repetition frequency and this is especially true for time resolved applications.
The focus of this thesis, as is evident from the title, is on compact, high-brightness x-ray sources using liquid-jet targets. Based on this target technology two rather different x-ray sources have been developed:

- A pulsed EUV/SXR source based on the emission of radiation from a hot, dense, plasma created by heating a liquid-jet target using focused, high-intensity laser pulses. This general source type is called a laser-plasma x-ray source and has applications in, e.g., soft x-ray microscopy (XRM) and EUV lithography (EUVL).
- A continuous wave (CW) hard x-ray source based on the radiation emitted when energetic electrons impact on a liquid-metal-jet anode. This general source type is called an electron-impact x-ray source, and is the most commonly used hard x-ray source with applications in, e.g., medical diagnostics and crystallography.

Both the sources developed in this work are derivations of two well known x-ray source types but they have special features and potential that merit their development. The basic physics required to understand these and other x-ray sources is briefly presented in Chapter 2. Chapter 3 is an overview of existing x-ray sources with special emphasis on brightness and is given to put the liquid-jet-target based sources in perspective and as a comparison and motivation why there is still need for compact x-ray source development although this appears a mature field. Chapter 4 is devoted to the basic theory and production of liquid-jets for targets in x-ray generation. Chapter 5 is a more comprehensive description of liquid-jet-target laser-plasma sources for EUV/SXR generation and Chapter 6 is devoted to a more detailed description of the new liquid-metal-jet anode hard x-ray source.
Chapter 2

Basic X-Ray Physics

In order to understand the different x-ray sources that will be described throughout this thesis, a basic understanding of the physics involved is required. This chapter is in no way intended as a complete treatment but is rather an introduction to, and an overview of, the physics relevant for the new x-ray sources described in Chapter 5 and Chapter 6. Here a semi-classic approach is taken, the physics phenomenologically discussed, and the main results described. A more detailed description can be found in a number of standard textbook on the subject, e.g., Refs. 3, 6, and 9-11.

This chapter will first introduce the central concepts of radiation from accelerated charges and relaxing atoms. Then photon-matter processes like ionization and scattering and resulting bulk phenomenon, like index of refraction, will be described. Electron-matter interactions are described with emphasis on bremsstrahlung, characteristic line emission, and absorption in matter. Furthermore, the special case of plasma interactions will be discussed.

2.1 Radiation from Accelerated Charges

When a charged particle is accelerated it will radiate electromagnetic radiation [12]. This is a central fact that follows from Maxwell’s equations and is the basis for most x-ray generation. The angular intensity distribution of the emitted radiation is given by the well known $\sin^2 \theta$ dipole pattern*, symmetric around the axis of acceleration, as illustrated in Fig. 2.1.a. For relativistic particles being accelerated, the angular pattern of the emitted radiation will be Lorentz shifted in the direction of motion. If the motion is parallel to the acceleration this will result in a hollow cone (Fig. 2.1.b) and if the motion is perpendicular to the acceleration it will result in a filled cone (Fig. 2.1.c). The opening angle of the cone is roughly given by $1/\gamma^\dagger$.

---

* The angle $\theta$ is measured from the acceleration.
† The Lorentz factor, $\gamma$, is given by $\gamma = 1/\sqrt{1 - \beta^2}$, where $\beta = v/c$, $v$ is the particle speed, and $c$ is the speed of light in vacuum (2.997,925·10^8 m/s). As an example, for 100 keV, 10 MeV, and 1 GeV electrons $\gamma$ becomes 1.2, 21, and 1958 and $\beta$ becomes 0.55, 0.999, and 0.999,999,9 respectively.
Figure 2.1. Conceptual representation of the radiation field from an accelerated charged particle, as viewed by a stationary observer. For a particle at rest \( \beta \sim 0 \) the angular emission is given by the well known \( \sin^2 \) dipole pattern (a) but for relativistic particles the radiation is shifted in the direction of motion. (b) shows the emission pattern from a particle where \( \beta \sim 1/3 \) and the velocity, \( v \), is parallel to the acceleration, \( a \), whereas (c) shows the pattern from a particle in a circular orbit, where \( \beta \sim 1 \) and \( v \) is perpendicular to \( a \).

The intensity of the emitted radiation is proportional to the square of the acceleration and polarized in the plane spanned by the acceleration and the emission direction. The spectrum of the emitted radiation can be found by a Fourier analysis of the acceleration \cite{12}.

2.2 Atomic Configuration and De-Excitation

Bound electrons in atoms are arranged in different subshells. The binding energies of the electrons are almost constant within each subshell and the binding energies decrease rapidly for each subshell where the inner shell is the most energetic. The shells are numbered from the inside out and called K, L, M, and so forth. The energy levels of the outermost electrons, called valence electrons, depend strongly on the atom’s chemical environment, which normally smears them to a broad continuum with almost no binding energy. The inner electrons, called core electrons, on the other hand have very well defined energy levels and higher binding energies and are only affected by the atom’s environment to a small degree. No two electrons within an atom can be identical, due to the Pauli exclusion principle \cite{13}, and there exist a complicated internal structure, including angular momentum, magnetic moment and spin, within the different principal subshells. However, this is largely outside the scope of this thesis and it is here sufficient to consider only the principal subshells. The binding energies of the inner-lying electron shells are in the x-ray range and increase with atomic number.

An excited atom is unstable and strives to return to its more energetically favorable neutral ground state. When it does, the energy surplus of the excited state will be released in the process. There are two competing processes for de-excitation: photo de-excitation and the Auger process.
2.2. Atomic Configuration and De-Excitation

Photo de-excitation occurs when an electron from a higher lying shell drops down to fill an electron vacancy and a photon is emitted. This results in well defined line emission with an energy equal to the difference in energy levels. The transitions are identified by the atom and the number of the sub shell of the vacancy and the higher lying electron, e.g., Cu K\(\alpha\) is the line emitted when a K shell vacancy in copper is filled from the L shell and Pb L\(\beta\) is the line when a L shell vacancy in lead is filled from the N shell. The photon energy* of a specific transition is given by

\[
\hbar\nu = E_{\text{initial}} - E_{\text{final}} = \hbar c R_\infty (Z - \sigma_K) \left( \frac{1}{n_{\text{final}}^2} - \frac{1}{n_{\text{initial}}^2} \right),
\]

where \(\hbar\) is Planck’s constant, \(c\) is the speed of light in vacuum, \(R_\infty\) is the Rydberg constant, \(Z\) is the atomic number of the nucleus, \(\sigma_K\) is a screening constant, and \(n\) is the shell number \([14]\).† Due to quantum mechanical considerations only transitions between certain electron configurations are allowed depending on quantum numbers and several possible transitions result in basically the same energy as the energy levels within each subshell are degenerated. The probabilities of the different transitions can be approximately calculated to give the relative line intensities. However, as a rule, the transition from the lowest possible upper shell is the most probable and the intensity ratio between K\(\beta\) and K\(\alpha\) emission varies from 0 to ~0.3 with increasing \(Z\) \([15]\). Since this emission is a spontaneous process, the radiation is isotropically distributed and not polarized.

The Auger process is very similar but instead of a photon emitted, another bound electron is ejected with a kinetic energy corresponding to the difference in energy levels minus the binding energy of the Auger electron. For low \(Z\) atoms the Auger process is more probable than photo de-excitation and for high \(Z\) atoms photo de-excitation is more probable. For K shell vacancies the cross over occurs at \(Z\sim30\) \([16]\).

Both these de-excitation processes fill a vacancy with a higher lying electron, creating a new vacancy that must now be filled and so sets off a cascade of electron rearrangements until a low energy vacancy is filled by an essentially free electron. However, most of these subsequent transitions are normally very low in energy, since only the inner shells have binding energies in the x-ray range, and thus of limited interest here.

---

* The line width essentially depends on the lifetime and is typically on the order of 10 eV for hard x-ray lines.

† The energy of a photon can be expressed as \(E=\hbar\nu=\hbar\omega\), where \(\hbar\) is Planck’s constant (4.135,669·10⁻¹⁵ eV·s), \(\hbar/2\pi\), \(\nu\) is the frequency of the radiation, and \(\omega\) is the angular frequency. The Rydberg constant \((\hbar c R_\infty = 13.605,698\) eV\) gives the ionization potential of the ground state of hydrogen.
The emphasis has here been on core vacancies in solid matter although the basic principles are true for any excited state, including excited ions, even if the energy levels are not accurately described by the simple relation in Eq. 2.1. Ions are also energetically unstable and can recombine with a free electron. For matter where the free electrons have essentially no kinetic energy this is corresponds to de-excitation from the continuum level but if the free electron has a comparatively large kinetic energy, this free-bound transition results in continuum radiation.

2.3 Basic Photon-Matter Processes

In the x-ray energy range photons can interact with matter through a number of different basic processes. The photon energy in this wavelength region is large compared to molecular binding energies and the interaction therefore determined by the core electrons, which are not much affected by the surrounding environment. This means that photon-matter interactions can here simply be thought of in terms of photon-atom interactions. This is, however, not true for very-low-energy photons (i.e., in the visible range), nor is it completely true close to absorption edges or if very detailed fine structures are important.

![Figure 2.2. The interaction cross section, σ, for basic photon-matter interactions between 1 keV and 3 MeV as function of photon energy for light (carbon) and heavy (lead) matter. The subscript tot stands for the total cross section, cs for coherent scattering, is for incoherent scattering, pe for photoelectric effect, and pp for pair production. Data from XCOM [17].](image)
The interactions of interest here are the photoelectric effect, coherent scattering, and incoherent scattering. The cross sections, \( \sigma \), for the different possible interactions vary with photon energy and shift significantly over the x-ray energy range, as seen in Fig. 2.2. Not only do they vary with the photon energy but also with the nuclear charge, \( Z \), of the target material.

Photo-ionization (also called photoelectric absorption or the photoelectric effect) can occur when a photon with energy \( h\nu \) impinges on an atom that has a bound electron with a binding energy, \( E_{\text{bind}} \), lower than \( h\nu \). The photon is then absorbed by the atom and an electron ejected. In order for the total energy to be conserved the ejected electron, called the photo electron, is ejected with a kinetic energy corresponding to the difference between the photon energy and the binding energy. The cross section for photo electric absorption increases with \( Z \) and roughly scales with \( E^{-3} \) in the x-ray region [17-19] although there are drastic changes in the cross section around absorption edges, where the photon energy becomes sufficient to ionize yet another electron orbital. This process leaves the atom in an exited state and it will emit radiation (fluorescence) when it relaxes to the ground state as was described in Section 2.2. Once ejected (in a forward tilted dipole), the photo electrons may themselves interact again, as will be described in Section 2.5.

Scattering occurs when a photon interacts with an electron and is deflected as a result. This process can be divided into two categories depending on whether there is an energy transfer to the scattering electron or not. If no energy is transferred the process is said to be elastic, or coherent. This is the case for Thomson scattering from free electrons and Rayleigh scattering from strongly bound atomic electrons. In coherent scattering, the scattered radiation has the same wavelength as the incident radiation and there is a definite relationship between the phases of the scattered radiation and the incident radiation. The scattered radiation can be thought of to arise as dipole emission from an electron brought to oscillate by the electric field of the incident photon. As discussed in Section 2.1, the angular distribution of the scattered radiation is then the well known dipole pattern. However, for an unpolarized photon beam the angular intensity distribution is proportional to \( 1 + \cos^2 \phi \) and the scattered radiation becomes polarized [20].

\* The interaction between two particles is generally described in terms of the cross section. This quantity essentially gives the interaction probability. The cross section has unit area and is normally measured in barns/atom where a barn is \( 10^{-24} \) cm\(^2\) but this should not be interpreted as the physical size of the particle. The total cross section for interaction is simply the sum of the cross sections for the individual processes. The cross section is related to the attenuation coefficient, \( \mu \), according to \( \mu / \rho = \sigma / u A \), where \( \rho \) is the density, \( u \) is the atomic mass constant (1.660,540·10\(^{-27}\) kg), and \( A \) is the relative atomic mass.

\* Here, \( \phi \) is the angle between the incident and scattered photon.
Compton scattering is inelastic, or incoherent, and occurs when the scattering electron is loosely bound or free and the incident photon more energetic. The electron is then recoiled by the impact and the scattering effected, since energy and momentum must be conserved. The scattered radiation is therefore shifted to a slightly longer wavelength and there is no fixed relationship between the phase of the incident and scattered radiation. The cross section for Compton scattering is almost constant in the x-ray range and to a first approximation does not scale with photon energy. Through conservation of energy and momentum, the scattering angles are related to the shift in wavelength. The angular distribution of Compton scattered radiation is similar to that of coherent scattering but become increasingly forward peaked for high energy photons. In the x-ray region the energy of the recoil electron is significantly less than that of photo electrons, and they are confined to the forward hemisphere.

Another possible interaction is pair production where a photon spontaneously converts to an electron positron pair in the presence of an electric field. This process, however, requires a minimum of $2\times511$ keV (the rest mass of the electron and the positron together) and is therefore of no consequence at the energies normally considered here although it becomes very important for higher energy interactions.

There is also a large variety of nuclear reactions that can occur when energetic photons interact with an atomic nucleus but these also require substantially higher energies than those available in the x-ray region and are therefore of no interest here. Furthermore, there are a few other, more exotic, possible reactions and some of them will be briefly discussed in Section 3.6, describing x-ray sources based upon them.

### 2.4 Index of Refraction

The bulk behavior in terms of scattering and absorption of electromagnetic radiation by an individual atom is described by the complex atomic scattering factor. This describes both the phase and magnitude of the scattered wave depending on incident wave vector, photon energy, observer position and electron distribution, and is in general too complex to handle. Fortunately, the complex atomic scattering factor simplifies greatly in the case of small angle forward scattering (or long wavelengths) where the individual electron positions are not important and can then be found tabulated [17,19,21] for a wide variety of elements and energies.*

* The complex atomic scattering factor describes the scattering relative to the free electron case. For photon energies above the atomic resonances, in the small angle approximation, it essentially reduces to the number of electrons of the atom.
As previously mentioned, the photon-matter interactions in this energy range are determined by the photon-atom interactions. Thus, the complex atomic scattering factor can be used to describe the propagation of x-rays through matter. It can be shown that there is a relation between the complex index of refraction

\[ n_i = n_r - in_i = 1 - \delta - i\beta \tag{2.2} \]

and the complex atomic scattering factor given by

\[ n_i = 1 - \frac{n_a r_e \lambda^2}{2\pi} \left[ f_1^0(\lambda) - f_2^0(\lambda) \right], \tag{2.3} \]

where \( n_a \) is the atom number density, \( r_e \) is the classical electron radius\(^*\), \( \lambda \) is the wavelength, and \( f_1(\lambda) \) and \( f_2(\lambda) \) are the real and imaginary parts of the complex atomic scattering factor where the superscript \( \theta \) denotes the small angle forward approximation [22]. The real part of the index of refraction governs the refraction and the complex part describes the absorption of an electromagnetic wave propagating through a medium.

\[ \text{Figure 2.3.} \quad \text{A schematic view of the real part of the index of refraction showing the strong variations near the IR, UV and x-ray resonances and the general tendency towards unity for higher energies where the corresponding frequencies are higher than all resonances. Adapted from [23].} \]

As can be seen from Eq. 2.3 and as shown in Fig. 2.3, the index of refraction approaches unity for short-wavelength radiation. Figure 2.4 shows \( \delta \) and \( \beta \) for two materials in the x-ray range and as can be seen, \( \delta \) is normally larger than \( \beta \) and both are normally very small and positive although they can make drastic jumps around resonances, where \( \delta \) can become negative.

\* The classical electron radius \( r_e \) is 2.817,941·10\(^{-15}\) m and the atom number density of solid matter is typically on the order of \( 10^{22} \) atoms/cm\(^3\).
This means that both the focusing power of lenses* and the reflectivity of mirrors† become very small in this region and the available optics severely limited. Refractive lenses are impossible in the EUV/SXR range due to absorption but compound refractive lenses can be made in the hard x-ray region. Grazing-incidence mirrors can be made with very high reflectivity and for EUV/SXR normal-incidence multilayer-coated mirrors‡ with high reflectivity (between ~1% and 70% depending on wavelength) can be made. Diffractive optics such as gratings (and crystals for hard x-rays) and zone plates can be used but their efficiency is low compared to traditional optics. Furthermore, capillary optics can be used although not unproblematic. X-ray optics, a complete field in itself, is largely outside the scope of this thesis and the interested reader is referred to the standard textbooks on the subject, e.g., Refs. 24-28.

![Graph of δ, β, and l for low (carbon) and high (lead) Z matter in the x-ray region. Solid line is δ, dotted is β and dashed is l. Data from CXRO [19].](image)

*The focal length, $f$, of a simple lens is proportional to $R/\delta$, where $R$ is the lens radius of curvature.

† The normal-incidence reflectivity, from a single vacuum interface is given by $R = |1 - n|^2/|1 + n|^2$.

‡ A multilayer mirror is a stack of interfaces spaced so that the reflected wave from each interface adds in phase. They are made from many (typically on the order of 100) alternating layers of high and low Z material where the thickness of each layer is $\sim \lambda/4$. As a consequence the reflectivity of these mirrors depends strongly on the angle of incidence and the wavelength. In the SXR/EUV a single layer is typically a few nanometers thick which does not correspond to many atomic layers, making manufacturing very challenging.
The intensity of a photon beam as it passes through matter decays exponentially, given by Lambert-Beer’s law [29] where the 1/e absorption length, \( l \), can be expressed using the complex part of the index of refraction according to [30]

\[
l = \frac{\lambda}{4\pi\beta}.
\]

The fact that the attenuation normally drops with increased energy and that it contains discontinuities is often used for selective filtering and hardening of radiation. The emission energy from an atomic de-excitation line is slightly below the corresponding ionization potential and absorption edge, which is often used in this respect.

### 2.5 Basic Electron-Matter Interactions

An electron incident on matter will be retarded and emit radiation, called bremsstrahlung. The Coulomb force will act between an incident electron and both the atomic electrons and the heavily charged atomic nucleus. For energetic electrons (as considered here), and especially for high Z matter, this process is completely dominated by deflection (and, thus, acceleration) in the field of the nucleus. For the simplified classical case of fast (instantaneous) electron deceleration along the axis of motion the angular emission distribution is given by a forward tilted dipole pattern, as seen in Fig. 2.5 and discussed in Section 2.1. This also results in a flat emission spectrum (the Fourier transform of a delta function is one) and polarized radiation, where the intensity is proportional to the square of the deceleration [31].

![Figure 2.5. Bremsstrahlung radiation patterns (a) for different electron velocities (\( \beta = v/c \)) and schematic intensity spectrum in energy per frequency interval (b) for an electron instantaneously decelerated along its line of motion using classical theory. Adapted from [32].](image-url)
However, this simplified picture does not agree very well with experiments on real targets. For thin targets (where there is only a single interaction) the agreement is reasonable but for thick targets it is not. The thin target spectra (as seen in Fig. 2.6) follow the simple theory but there is a sharp cut off in emission energy, which can only be explained by quantum theory, corresponding to the maximum available electron energy. The angular distribution basically follows the theory but the intensity does not fall to zero for 0° or 180°, and the polarization is only partial.

![Figure 2.6. Thin target bremsstrahlung angular distribution pattern (a) and emission spectrum (b), (c). The angular emission pattern (a) is shown for different photon energies. The emission spectrum (b) is in energy per frequency interval measured at different angles (o, and + indicate scaled measurement series data from different materials and voltages) and the number of photons per frequency interval (c) varies as 1/\( h\nu \). Adapted from [33].](image)

The deviation from the simple theory is due to the fact that the acceleration is not in line with the incident velocity nor is it constant during the interaction, which is not instantaneous. These assumptions are better for radiation close to \( h\nu_{\text{max}} \), which is why (as seen in Fig. 2.6) the results agree better here.

A thick target can be considered as a succession of thin targets where the electron energy decreases with the penetration depth. This means that photons with energy close to \( h\nu_{\text{max}} \) can only be emitted at the surface as the available electron energy and corresponding maximum photon emission energy decrease with penetration depth. The thick target spectrum, as seen in Fig. 2.7, is therefore given by a sum of flat spectra with decreasing maximum emission energy. This means that the complete spectrum has a constant slope and can be described by [31]

\[
I(h\nu) = \text{const} \cdot Z(h\nu_{\text{max}} - h\nu). \tag{2.5}
\]
Figure 2.7. Angular distribution (a) and spectra (b) of bremsstrahlung radiation emitted from a thick tungsten target. The angular distribution shows the normalized energy emission distribution for 70 keV electrons, where curve (1) is unfiltered, curve (2) filtered by 10 mm aluminum and curve (3) is the standard distribution according to Lamberts cosine law [34]. The spectra shown in (b) are for different incident electron energies. Adapted from [35,36].

As can be seen from Fig. 2.7, the angular distribution is even flatter than for thin targets and this is due to the fact that many photons are emitted by electrons that have already undergone deflection and therefore lost their initial direction. However, this does not apply for photons close to $h\nu_{\text{max}}$. In the high energy limit, the polarization is complete since the acceleration is then always parallel to the incident direction. In the low energy limit the acceleration is perpendicular to the incident velocity. However, since this radiation can also be emitted by already deflected electrons the polarization is not complete for thick targets. Between these two limits the polarization is not well defined. The total conversion efficiency between incident electron energy and bremsstrahlung is given by the integral of Eq. 2.5 and can be written as

$$\eta = \frac{\text{x-ray energy}}{\text{electron energy}} = 9.2 \cdot 10^{-10} Z V ,$$

(2.6)

where $Z$ is the atomic number and $V$ the electron acceleration voltage. This is in good agreement with empirical values, where the constant averages to about $11 \cdot 10^{-10}$ [31].

A sufficiently energetic electron incident on an atom may also lose parts of its energy by ionizing the atom, knocking out a bound electron. The ejected electron will have a kinetic energy corresponding to the difference between the incident energy and the binding energy. As described in Section 2.2, the ionized atom may relax through the emission of characteristic line radiation. The amount of characteristic line emission depends both on the ionization cross section and the probability for relaxation through a specific line.
transition, as described in Section 2.2. Using quantum theory, a semi empirical formula for the ionization cross section can be obtained that agree decently with measurements, as shown in Fig. 2.8. However, tabulated data from measurements are normally also used.

![Graph showing the relationship between energy ratio E/Ei and ionization cross section σ_{KE}^2](image)

**Figure 2.8.** Scaled total ionization cross section, σ_{KE}, for K shell ionization by electron impact as a function of electron energy, E, relative the ionization energy, E_i. Adapted from [37].

For an incident electron with energy \( E \), above the binding energy, \( E_i \), of a certain transition, the intensity of the corresponding line emission increases proportionally with \((E-E_i)^{-1.6}\), where the exponent is an experimentally determined value. For radiation emitted above the K line, the ratio between K line emission and bremsstrahlung emission is very low around \( E_i \) but rises rapidly up to \( \sim 3E_i \) where it shows a broad maximum.\(^*\) Furthermore, the ratio has experimentally been shown to vary approximately as \( Z^{-3} \) [38].

### 2.5.1 Electron Attenuation and Backscattering

All the above described processes contribute to strongly attenuate electrons traversing a medium. The attenuation of electrons is described by the stopping power [39] expressed in energy loss per path length. The attenuation can be divided into a radiative part where the loss is due to bremsstrahlung and a collisional part where the energy loss is due to ionization or excitation, as seen in Fig. 2.9.

\(^*\) Here the ratio is defined as the number of K ionizations over the number of bremsstrahlung photons with an energy equal to or greater than that of the K line. For copper this ratio reaches \( \sim 0.7 \).
The slowing-down path of electrons in matter is very complex due to multiple small-angle scatterings and occasional large-angle scatterings. The penetration depth derived from the stopping-power data is therefore not very accurate as it describes the total path length of the electrons, which can be significantly longer than the actual penetration depth.

One way to obtain the actual penetration depth is through Monte Carlo simulation of electron impacts, given accurate knowledge of the different interaction cross sections. Figure 2.10 shows such a simulation from a freely available, simple to use, program [41]. There are also a number of more sophisticated Monte Carlo simulation code packages that can accurately describe electron-matter interactions including the production of radiation but these tend to be quite complex to work with [42].
Figure 2.10. Monte Carlo simulation of 50 keV electrons incident on tin using CASINO [41]. Left hand side shows selected electron trajectories and right hand side shows energy deposition as a function of position. Scale is in micrometers.

As is evident from the simulation data shown in Fig. 2.10 a large fraction of the incident electrons are backscattered either through several small angle interactions or through single large angle scattering events.

Figure 2.11. Electron backscattering coefficient as a function of target material (a) and energy distribution of the backscattered electrons (b). In (a) the total backscattering coefficient is plotted and in (b) the backscattering fraction per unit energy interval is plotted as a function of the energy of the backscattered electrons (relative the energy of the incoming electrons). Both (a) and (b) are measured for 30 keV electrons but (a) is done at normal incidence and (b) at 135°. Note that the carbon curve in (b) has been multiplied by 2. Adapted from [43].
The backscattering coefficient (ratio of backscattered to incident electrons) depends only weakly on the incident electron energy (up to around 1 MeV where it begins to drop and approaches zero for tens of MeV). However, both the backscattering coefficient and the energy of backscattered electrons depend heavily on the atomic number, as seen in Fig. 2.11 [44]. The backscattering coefficient and the angular distribution of the backscattered electrons also depend on the angle of incidence, as seen in Fig. 2.12.

![Figure 2.12. Electron backscattering coefficient as a function of incidence angle for iron (a) and schematic illustration of the angular distribution for normal and grazing incidence (b). In (b) the backscattering coefficient per unit solid angle is plotted along the radius. Adapted from [45].]

2.6 Basic Plasma Physics

According to the black body theory, all matter will emit broad-band thermal radiation depending on its temperature. The peak emission energy is given by Wien’s displacement law* and is proportional to the temperature. For emission in the x-ray region the temperature must therefore be very high.† The temperature of matter is related to the average kinetic energy of the atoms and through this relation it is clear that the temperatures required for x-ray emission corresponds to an average kinetic energy well above the ionization potential of matter.‡ Significant thermal radiation in the x-ray range is therefore only possible from hot plasmas§. For high-brightness emission, the plasma must also contain a high density of radiating atoms. Plasmas required for x-ray sources are therefore hot, dense, plasmas. High temperatures imply high speeds and these plasmas

* The peak emission photon energy, is given by $h\nu = \frac{2.821,44k_BT}{3}$, where $k_B$ is Boltzmann’s constant ($8.617,385\cdot10^{-5}$ eV/K).

† Peak emission at x-ray energies of 0.1 keV and 20 keV corresponds to temperatures of ~400 kK and ~80 MK respectively.

‡ The average kinetic energy per atom in matter is given by $3k_BT/2$. The above quoted temperatures correspond to an average kinetic energy of ~50 eV and ~10 keV respectively, and the ionization energy for matter is always below 25 eV.

§ Plasma is defined as “matter in a state of partial or complete ionization” and is often referred to as the fourth state of matter.
therefore tend to rapidly expand and cool. Due to their high energy densities and expansion speeds, hot, dense plasmas tend to be small (typically sub-mm sized) and can only be sustained for short periods of time (typically ns). They also require a fast means of delivering large amounts of energy (typically on the order of joule) into a small volume and a common way to do this is through focused, high-power, laser pulses. Although many plasma processes are similar, independent of heating method, the emphasis is here on laser-produced plasmas. This section is only intended to give a phenomenological understanding of plasmas and plasma processes. For a more thorough explanation see, e.g., Refs. 46-48.

2.6.1 Plasma Processes and Properties

Before looking further into the collective behavior of laser-produced plasmas a brief description of the different microscopic processes is necessary. These short-distance processes transfer energy from particle to particle, in a somewhat random fashion, thermalizing the plasma and eradicating local differences in ionization, electron temperature, electron density, etc. They are also responsible for generating the radiation leaving a plasma.

Collisional excitation is a process in which an atom or ion is transferred to an exited state after a collision with an electron, where part of the electron’s kinetic energy is transferred to said atom or ion. The reverse process, when an electron gains kinetic energy from colliding with an exited atom or ion which is then de-excited, can of course also occur.

Collisional ionization is a process in which an electron, incident on an atom or ion, has sufficient kinetic energy to remove a bound electron. The opposite effect, also referred to as three-body recombination, occurs when two free electrons encounter an ion and one of the electrons recombines while the other gains the surplus energy.

Photo-excitation occurs when an incident photon is absorbed, raising the atom or ion to a higher energy state. This process requires a photon energy matched to an energy transition in the atom or ion. The reversed process is called photo-deexcitation and occurs when an exited atom or ion relaxes to a lower energy state by sending out a photon. This is a bound-bound process and results in emitted photons with distinct energies, corresponding to the energy difference between the two states involved, as discussed in Section 2.2.

Photo-ionization (as previously discussed in Section 2.3) can occur when an incident photon has enough energy to remove a bound electron from the atom or ion it strikes. The opposite process is called photo-recombination and occurs when an incident electron recombines with an ion and a photon is emitted. This is a free-bound transition and therefore results in continuum radiation, as mentioned in Section 2.2.
Bremsstrahlung occurs (as discussed in Section 2.5) when a free electron is decelerated in the strong electric field close to an atomic nuclei. The opposite process is simply called inverse bremsstrahlung and occurs when an incident photon is converted to increased kinetic energy of a free electron in close vicinity of an ion.

The processes discussed above are by far the most important processes in the type of plasmas used for x-ray generation. There are however other possible processes, e.g., atom/atom collisions and three wave mixing, but these are of limited interest for the plasma temperatures, plasma densities, and laser intensities of concern here.

The fact that most plasma constituents are charged result in a very different behavior than observed in a normal gas due to the strong and long-ranged electromagnetic force that makes every particle in the plasma interact with a considerable amount of its neighbors. The behavior of a plasma can thus be studied both on a large scale, where collective properties are best used and on a microscopic scale where single interactions are considered. Especially the highly mobile, low mass, electrons will behave in a collective fashion against the background of the less mobile, heavy ions. To quantify the length scale above which collective properties dominate, the Debye length [49] is introduced as

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}},$$  (2.7)

where $\epsilon_0$ is the permittivity of vacuum, $e$ is the electron charge, $T_e$ is the electron temperature and $n_e$ is the electron density.* The electron density is determined by the general density of the plasma and the average degree of ionization. The Debye length is a measure of the largest possible size over which a substantial charge unbalance can be maintained within a plasma.† Thus, for a system considerably larger than one Debye length, collective processes dominate the plasma.

The plasma expansion speed‡ [50] is given by

$$v_{\text{exp}} = \frac{Z e k_B T_e}{M},$$  (2.8)

---

* The electron density for typical laser produced plasmas for EUV/SXR generation is in the range between $10^{20}$ e/cm³ and $10^{23}$ e/cm³. The permittivity of vacuum, $\epsilon_0$, is $8.854,188 \cdot 10^{-12}$ F/m and the electron charge, $e$, is $1.602,177 \cdot 10^{-19}$ C.

† As an example, the Debye length for a 1 keV, $10^{21}$ e/cm³ plasma is $\sim 7$ nm.

‡ For a 1 keV, completely stripped, carbon plasma the expansion speed is $\sim 0.28 \mu$m/ps.
where \( Z \) is the ion charge, \( M \) is the ion mass and \( \gamma \) is 5/3. A quantity intimately coupled to the Debye length is the plasma frequency [49] given by

\[
\omega_{pe} = \sqrt{\frac{\eta e^2}{\varepsilon_0 m_e}} = \frac{1}{\lambda_D} \sqrt{\frac{k_B T_e}{m_e}}
\]

(2.9)

where \( m_e \) is the electron mass*. This is the resonance frequency for collective electron oscillations in the plasma and is very important in laser plasma applications since an electromagnetic wave can only propagate through a plasma if its frequency is higher than the plasma frequency.

![Figure 2.13. Schematic diagram of one-dimensional electron density profile and heating zone in a laser produced plasma. Adapted from [51].](image)

For laser produced plasmas this results in the creation of a, self regulating, heating zone that moves through the target as the plasma expands during the laser pulse, as seen in Fig. 2.13. During the first picoseconds of the laser pulse free electrons are created. The plasma is then formed and rapidly heated by inverse bremsstrahlung. As the plasma is heated more free electrons are created and an electron density gradient will arise. As previously stated the laser light can only penetrate the plasma if its frequency is above the plasma frequency, given by the electron density. There will be a certain electron density, the critical density,† where the laser frequency and the plasma frequency become equal and the laser light is reflected. In the under-dense region, close to the critical density, most of the

* The electron mass, \( m_e \), is 9.109,390·10⁻³¹ kg.

† For the common \( \lambda=1064 \) nm laser wavelength this occurs at a plasma density of \(~10^{21} \) e/cm³ where the plasma frequency is \(~1.8·10^{15} \) rad/s.
laser light is absorbed and thermal energy is conducted into the denser region by the electrons. This process continues through the duration of the laser pulse and when the heating ends the plasma continues to expand, rapidly cooling and recombining.

### 2.6.2 Plasma Emission Characteristics

The processes that generate photon emission in a plasma are bremsstrahlung and photo relaxation and recombination and the emission is therefore a combination of the spectra from these processes. Since the plasma basically lacks sense of direction the emission should be unpolarized and isotropic, although asymmetries are often introduced depending on the plasma heating process and target geometry. As already explained in Section 2.5, bremsstrahlung results in broadband emission depending on the electron energy and nuclear charge of the atoms. Photo relaxation, as described in Section 2.2, results in characteristic line emission. The emission characteristics are therefore mainly determined by the electron energy distribution and the ion population. However, due to the complex and non-equilibrium nature of the plasma during its short life time, calculating the electron energy distribution and the population of ionization states etc. have proven extremely difficult.

![Graph](image)

**Figure 2.14.** Schematic graph of emission from a hot and dense plasma, showing continuum radiation and superimposed line emission. Adapted from [52].

There are several different plasma models used and they all rely on describing the collective behavior of a large number of particles with distributions or averages and some assumption of an equilibrium situation [53,54]. For the pulse lengths and plasma densities normally used in SXR/EUV generation the assumption of local thermal equilibrium is a common first approximation. Although the models used are becoming more and more refined and experiments give more and more input they are far from perfect. They are very useful for, e.g., first estimates, understanding the plasma evolution, the relative effect of changing a certain parameter, and interpreting experimental data. Unfortunately, they can not yet accurately predict the quantitative emission from a laser produced plasma.
For a first estimate of the radiation emitted from a plasma it can be viewed as a blackbody radiator with a certain average electron temperature and Wien’s displacement law then gives the wavelength of maximum emission. Figure 2.14 shows a schematic distribution of the emitted radiation, where the line emission is characteristic for the material. As a rule, low Z targets have a few narrow lines and not very much continuum radiation and high Z targets have a significant continuum background and a more complex, often smeared, line structure. Often a specific line emission (or set of transitions) is coveted for a specific application and the plasma generation must then be tailored to maximize the emission of this line by optimizing the plasma temperature. A too cold plasma will not produce enough ions and a too hot plasma will completely strip the atoms, over-ionizing them. Looking at the binding energies of different electrons it is clear that the binding energy does not vary much within a shell but often changes drastically from shell to shell. This means that although the energy distribution of the free electrons is broad, with long tails, the bulk of the plasma atoms can be made to have almost the same degree of ionization, determined by a closed shell and the dominant transitions will then be to and from these states.
Chapter 3

X-Ray Sources

In this chapter several different x-ray sources will be briefly described to put the novel sources described in this thesis (see Chapter 5 and Chapter 6) into perspective. Figure 3.1 shows an overview of the energy and average spectral brightness of the most common x-ray sources. As is evident, they span a large range both in energy and brightness. Here, several x-ray sources, including some of the more exotic ones, will be phenomenologically described and state-of-the-art performance* and limitations discussed.

![Source brightness comparison graph showing state-of-the-art synchrotron based sources, laser plasmas, and electron impact x-ray sources. Adapted from [55,56].](image)

* Comparing different x-ray sources is somewhat difficult since, even using a well defined quantity like spectral brightness, the choice of bandwidth will influence the comparison. Furthermore, spectral brightness data is not always readily compiled from available source data as it requires not only flux, but spectral, angular and source size information as well. Finally it should be noted that brightness is not the best figure of merit for all applications, nor does it fully describe the source.
Chapter 3. X-Ray Sources

3.1 Electron-Impact Sources

The discovery of x-rays (in 1895) was done during the study of cathode rays and, although unintentional, the apparatus used was a primitive electron impact x-ray source. Quite a few engineering refinements have been introduced throughout the years but the basic idea has not changed. This type of x-ray source, known as an x-ray tube, is by far the most common source of x-rays used today, and it is surprisingly similar to the original. The basic idea is to bombard a solid target with accelerated electrons to produce radiation, as described in Section 2.5. This can either be done by an electron beam, as is normally done, or by a plasma as in certain pulsed systems. Electron-impact sources are normally not used for EUV/SXR generation due to the very low conversion efficiency, as described by Eq. 2.6. However, it is a very stable, clean and reliable source and there are perhaps applications where it could be useful in the EUV/SXR region [57]. From now on this section is devoted to hard x-ray generation, typically in the ~10 keV to ~100 keV range.

3.1.1 Electron-Beam Driven Sources

Figure 3.2 shows a schematic layout of a classic x-ray tube. Electrons are emitted by heating a cathode filament and are then accelerated towards a solid anode target, in a vacuum environment, by an externally applied high voltage. Except for the more efficient thermionic cathode, introduced by Coolidge in 1913, this is the same type of x-ray tube as used by Röntgen.

![Figure 3.2. Schematic view of a classic x-ray tube. Adapted from [58].](image)

The physics of electron-matter interactions was described in Section 2.5 and the most important thing to remember is that the conversion efficiency from electron-beam power to x-ray output power is very low, typically below 1%, and that the brightness of an electron-impact source is proportional to the electron beam power density on the anode. The source brightness is normally not limited by the electron beam performance but by the permissible electron beam power density, which is limited by the maximum thermal load on the anode before it melts or is otherwise damaged. Improved brightness from x-ray tubes is therefore basically equivalent to increased thermal load capability of the anode.

It is possible to calculate an anode material figure of merit accounting for both x-ray generation efficiency and thermal limitations. From this it is clear that tungsten ($Z=74$) is
the best material because of its relatively high Z and exceptional thermal characteristics. Except for certain applications where lower energy x-rays (such as 8 keV Cu $K_{\alpha}$ for crystallography or 17 keV Mo $K_{\alpha}$ for mammography) are required, tungsten is exclusively used as the anode material* [59].

![Figure 3.3](image.png)

**Figure 3.3.** Schematic view of a modern rotating anode x-ray tube, using the line focus principle. Adapted from Paper 7.

Figure 3.3 illustrates a modern x-ray tube, incorporating the two major improvements in terms of thermal management, i.e., the line focus principle and the rotating anode. Using the fact that the angular distribution of the emitted x-rays is non-Lambertian (as described in Section 2.5) it is possible to increase the apparent brightness by angled viewing of the anode. This is called the line-focus principle and was introduced in the 1920s. As the emitted radiation must penetrate more and more material there is a limit to the attainable gain set by the heel effect, as illustrated in Fig. 3.4, and also visible in Fig. 2.7.

* Modern tungsten anodes are normally alloyed with a few % of rhenium to increase their mechanical performance. Only the top layer is made from tungsten, the base is made from molybdenum on top of graphite to increase the thermal capacity per weight. Furthermore, radial slits are introduced to counter the effect of thermal gradients.
The geometric gain is proportional to $1/\sin \phi$ but this must be modified by the absorption, given by the average production depth of x-rays of a certain energy (given by the voltage and anode material) and the attenuation of these x-rays as they leave the anode. For a given line emission, the gain decreases with increasing acceleration voltage, since the production depth increases but not the attenuation length. However, for the total emission from the target the situation is more complex as the spectra, production depth and attenuation length all vary with voltage and material and that the emitted spectrum changes as a function of production depth. Normally a $l/2d$ (see Fig. 3.3) ratio around 10, corresponding to a takeoff angle of $\sim 6^\circ$ is used and as an example the geometric gain from Cu K$_\alpha$ (given $l/2d \sim 10$ and $V \sim 24$ kV) must be multiplied by $\sim 0.8$ to account for self absorption [61]. For the commonly used target materials there are semi-empirical models for the output spectra as a function of acceleration voltage and takeoff angle [62,63].

The rotating anode was introduced in the 1930s and is also a way to increase the effective target area (from $2dl$ to $\sim 2\pi Rl$) over which the electron beam power is dissipated, without increasing the source size. After these improvements progress as regards brightness has been rather slow for compact electron-impact sources and has only been due to engineering perfection in terms of target material, heat conduction, heat storage, speed of rotation, etc. Current state-of-the-art sources now allow for 100 - 150 kW/mm$^2$ effective electron beam power densities. Typical high-end implementations are, e.g., 10 kW, 0.3×0.3 mm$^2$ effective x-ray spot size angiography systems and 1.5 kW, 0.1×0.1 mm$^2$ effective x-ray spot size fine-focus mammography systems. Low-power micro-focus sources (4 W, 5 µm effective x-ray spot diameter) have similar effective power densities (200 kW/mm$^2$) and are also limited by thermal effects. The permissible heat load also depends on the load time. The above mentioned power density values for rotating anode sources assume a
short load time and must be significantly reduced for longer exposure times. The effective electron beam power density limit of a modern rotating anode can be calculated by

\[
P = \frac{\pi l}{A_{\text{effective}}} \left( T_{\text{max}} - T_{\text{margin}} - T_{\text{base}} \right) \sqrt{\frac{j \rho c_p f R d}{4 d^2 \left( 1 + k R \frac{f d}{\pi R} \right)}}
\]

where \( A_{\text{effective}} \) is the apparent x-ray source area using the line-focus principle, \( T_{\text{max}} \) is the maximum permissible temperature before breakdown, \( \Delta T_{\text{margin}} \) is a safety margin, \( T_{\text{base}} \) is the anode starting temperature, \( \lambda \) is the thermal conductivity, \( \rho \) is the density, \( c_p \) is the specific heat capacity, \( f \) is the rotation frequency, \( t \) is the load period, and \( k \) is a correction factor taking into account radial heat conduction, heat loss by radiation and anode thickness [64]. As can be seen from Eq. 3.1, the only way to increase the power load limit is to increase the spot speed, i.e., \( f \) and \( R \). Unfortunately, even a quite unrealistic set of parameters (1 m diameter anode and 1 kHz rotation) would only result in a \( \sim6\times \) increase compared to current state-of-the-art systems [65]. It therefore seems unlikely that conventional x-ray source technology can be developed much further, even with significant engineering efforts. In terms of brightness, current state-of-the-art performance is \( \sim10^7 \) photons/(s·mm²·mrad²·0.1%BW) for the continuous radiation and up to \( \sim10^{10} \) for K line emission (integrated over the line width).

There have been many attempts to improve the brightness from x-ray tubes and these will be discussed in Chapter 6, with special emphasis on the new liquid-metal-jet anode concept.

### 3.1.2 Discharge Driven Sources

Flash x-ray generators are used for generating short x-ray pulses, typically in the range between a few and a few hundred nanoseconds, and are used for time-resolved studies. Although there are several different approaches the basic idea is to discharge stored energy to create a plasma at the cathode and then accelerate the liberated electrons towards the

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* As an example the reduction is typically \( \sim2\times \) for a \( \sim2s \) exposure. For CW systems the reduction is even greater since the limit is now determined by heat conduction away from the anode rather than heat storage capacity in the anode. As an example, for tungsten \( \lambda \) is 170 W/(mK), \( \rho \) is \( 19.3\times10^3 \) kg/m³, \( c_p \) is 133 J/(kgK), and \( T_{\text{melt}} \) is 3653 K.

† The maximum temperature is often determined by when evaporation from the anode degrades the local vacuum to a point where there is a discharge between the anode and cathode. As a rule, the maximum permissible temperature is 20% to 30% below the melting point.

‡ The disk radius is typically 5 cm and the speed of rotation around 10,000 rpm giving a focal spot speed of \( \sim50 \) m/s.
anode, usually with the same pulse as created the plasma. The damage threshold is different for these short pulses and the peak loading can be increased compared to conventional x-ray tubes. However, electrode erosion is a serious problem and the lifetime, ranging from single shot to long term operation, is determined by the load. Flash x-ray generators range between small hand-held devices where typically 1 Joule of energy is discharged at 100 kV and large installations where 100 kJ at 10 MV is discharged [66-68]. The spectral characteristics of a flash x-ray system are basically identical to that of a conventional source, with the same anode material and acceleration voltage. Typical performance for a low-voltage system [69,70] is 150 kV, 2 kA during ~70 ns in a 3 mm diameter effective spot size. This corresponds to a pulse electron beam power density of ~40 MW/mm² and the pulse brightness is therefore ~250× higher than for a comparable rotating anode source, although the average brightness is several orders of magnitude smaller.

3.2 Synchrotron Radiation Sources

As discussed in Section 2.1, charged particles will emit radiation when accelerated. Synchrotron radiation (SR) is emitted by highly relativistic ($\beta \approx 1$, as discussed in Section 2.1) particles forced to a circular orbit. This was first observed as a troublesome side effect in particle accelerators used for high-energy particle collision experiments where it limited the attainable energy. Today this side-effect is desirable and numerous dedicated synchrotron radiation facilities exist in the world. Because the power of the emitted radiation is proportional to $\gamma^4$, electrons are exclusively used in synchrotrons. They are injected into a circular, ultra-high-vacuum storage ring and kept in orbit by applied magnetic fields from bending magnets. The electron energy (on the order of GeV) is maintained by radio-frequency pumping cavities in the ring, compensating for the energy loss due to radiation. The RF pumping also orders the orbiting electrons into short, tightly packed, bunches and thus causes the emitted radiation to be pulsed. The radiation pulse length is given by the electron bunch length (typically ~100 ps) and the repetition frequency by the bunch separation (on the order of ns). This duty cycle means that the peak spectral brightness of SR sources is a few orders of magnitude higher than the average.

Synchrotrons are by far the most powerful sources of x-ray radiation known today and the golden standard to which other sources are compared. It is, however, not the most convenient source of radiation due to its high cost, large size and complexity as can be seen from Fig. 3.5, showing the layout of a small modern synchrotron facility. For more information on synchrotron radiation sources the interested reader is referred to, e.g., Refs. 3, 71, and 72.
3.2. Synchrotron Radiation Sources

3.2.1 Bending Magnets

Instead of a perfectly circular structure a synchrotron is divided into straight sections with a bending magnet at each node. This concentrates the electron acceleration and increases the radiation yield. As was described in Section 2.1, the radiation emitted by relativistic electrons in a circular orbit (the acceleration pointing inwards, perpendicular to the velocity) is concentrated in a narrow, forward directed, cone sweeping past a stationary observer, as previously shown in Fig. 2.1.c. The spectrum of the emitted radiation is quite complex to calculate accurately but a first, simple, estimate can be made from Heisenberg’s uncertainty principle, $\Delta E \cdot \Delta t \geq \hbar / 2$, applied to the radiation emitted from one particle as viewed by a stationary observer. Since the observation time, $\Delta t$, is extremely short, the energy spread will be large, resulting in a wide continuous spectrum as shown in Fig. 3.6.

The on-axis radiation is linearly polarized and bending-magnet radiation span from IR well through the soft x-ray region. State-of-the-art machines typically reach an average spectral brightness of $\sim 10^{15}$ photons/(s·mm²·mrad²·0.1%BW). Apart from the high photon flux, the exceptional brightness of synchrotron radiation comes from the well collimated nature of the radiation cone and the small emitting source area, given by the electron beam.
3.2.2 Wigglers

To further enhance the emitted radiation, a straight section of the ring can be used to introduce a periodic structure with even stronger magnetic fields. This is called a wiggler and each half period of the structure can basically be thought of as a bending magnet source but the stronger acceleration moves the spectra to higher photon energies. The periodic structure increases the flux linearly with the number of turns as the radiation adds incoherently but the large deviations result in a wider radiation cone and a larger emitting area and the brightness is therefore not increased as much. The emission from wigglers span well into the hard x-ray range and the average spectral brightness reaches \( \sim 10^{16} \) photons/(s·mm\(^2\)·mrad\(^2\)·0.1%BW).

3.2.3 Undulators

A further enhancement is the undulator in which the electrons are forced through a sinusoidally varying weak magnetic field. This results in well defined line emission (and overtones) and since the flux from each period adds coherently the flux increases as the square of periods and the radiation cone narrows. The wavelength of the emitted radiation can be tuned by changing the magnetic field strength. Undulator radiation is partially coherent and normally linearly polarized but it is possible to build more complex versions with tunable polarization. Undulator radiation is typically in the soft x-ray range and reach an average spectral brightness on the order of \( 10^{19} \) photons/(s·mm\(^2\)·mrad\(^2\)·0.1%BW).

3.2.4 Free-Electron Lasers

In an undulator, the radiation is coherent in the sense that the emission from a single electron is in phase from one oscillation to the next. However, the radiation from individual electrons is incoherent since there is no internal order in the electron bunch. If the electrons in a bunch could be structured into smaller micro bunches (considerably smaller than the wavelength) and separated by the photon wavelength the emission would be completely coherent and several orders of magnitude brighter since the flux would now
scale with the square of the number of electrons, rather than linearly. This is the next evolutionary step after the undulator and such a device is called a free electron laser (FEL). In an undulator the electron bunch will feel a modulation from the radiation field that will tend to order the bunch into correctly spaced micro bunches. In a very long undulator structure FEL conditions can be reached and self-amplified spontaneous emission (SASE) occur if a sufficiently small, well collimated and short electron pulse is used. Such pulses can only be achieved with linear accelerators and FELs have presently been realized down to the UV region. Several large-scale FEL project are currently being pursued with the goal of delivering tunable, coherent, short pulse (~100 fs) radiation in the x-ray range with an average spectral brightness of \( \sim 10^{24} \) photons/(s·mm²·mrad²·0.1%BW).

### 3.3 Plasma Based X-Ray Sources

As described in Section 2.6 plasmas are, under the right circumstances, effective emitters of x-ray radiation and in order to realize a plasma source a suitable element must be heated to an appropriate temperature. There are basically two different ways to achieve this. One is to use a focused laser beam for heating and the other is heating through an electric discharge. These have slightly different properties and will be described separately but with emphasis on laser plasmas. Both laser plasmas and discharge plasmas can be made to emit radiation from EUV to hard x-rays depending on the applied power density and resulting plasma temperature. Hard x-ray generation normally requires large facilities and tend to be single shot experiments as the enormous power input completely destroys the target system. Such systems are useful for certain experiments, e.g., backlighting in fusion research, but outside the scope of this thesis. Here the focus is on repetitive sources and the plasma sources discussed therefore mostly limited to SXR/EUV generation.

Two applications currently driving the development of compact plasma sources are x-ray microscopy (XRM) and EUV lithography (EUVL). For microscopy brightness is a good figure of merit but for lithography it is normally not. Due to the characteristics of the optical system used in EUVL the appropriate figure of merit is flux per 2%BW around 13.5 nm, given that the source étendue\(^*\) [75,76] is below a maximum limit set by the optical system. Although different figures of merit are appropriate for XRM and EUVL sources they are very similar although the average power and lifetime demands set on future EUVL sources are exceedingly demanding. Here a general description of plasma sources will be given for comparison, but in Chapter 5 the development of two specific laser-plasma sources, for XRM and EUVL, will be described in more detail.

\(^*\) The étendue is the product of area and solid angle and is conserved in classical optical systems, as is brightness. For small angles and circular apertures it can be written as \( A \cdot \pi \cdot N.A^2 \), where \( A \) is the field size. If the source étendue is larger than the étendue of the optical system only a fraction of the emitted radiation is usable.
3.3.1 Laser Plasmas

If an intense laser pulse is focused onto a solid target, a plasma is formed at the target interface. This is the basic concept of all laser plasma sources and was first utilized not for generating x-rays but rather for material analysis and basic research into laser plasma interactions. As lasers became more powerful and more available these plasmas were used as sources for short wavelength radiation for further use in applications. The basic plasma processes and properties were described in Section 2.6 and are appropriate for plasma emission in the EUV/SXR range, where the laser power densities on the target are limited \((10^{11} \text{ W/cm}^2 - 10^{15} \text{ W/cm}^2)\). When using very high intensity pulses \( (>10^{15} \text{ W/cm}^2)\) for hard x-ray generation additional processes, involving non-linear effects, become important although the plasmas are similar in many respects. As previously mentioned the focus is here on plasma sources for SXR/EUV although low-power femtosecond systems have been shown to produce an average brightness of \( \sim 10^5 \text{ photons/(s·mm}^2\cdot\text{mrad}^2\cdot\text{line)} \) at the 9 keV Ga K\( \alpha \) line [77].

![Laser-plasma spectra of a low Z material (N), and a high Z material (Xe).](figure3.7)

The average brightness of laser plasmas is proportional to the repetition rate of the driving laser and limited by the availability and price of high-average-power lasers. Since the
average brightness is also proportional to the conversion efficiency (CE) of laser energy to x-rays on a per pulse basis, this is a key parameter to maximize in laser plasma development. Although the total conversion efficiency can be large, the spectral CE is typically poor and has a complex dependence on desired wavelength, laser wavelength, power density, target material, pulse length, and pulse shape which is not fully understood. Table 3.1 shows typical data for a state-of-the-art soft x-ray laser-plasma source implementation.

Table 3.1. Typical state-of-the-art laser plasma implementation for soft x-ray generation [80].

<table>
<thead>
<tr>
<th>Target</th>
<th>Line [nm]</th>
<th>Laser λ [nm]</th>
<th>Δt [ns]</th>
<th>ΔE [mJ]</th>
<th>Power Density [W/cm²]</th>
<th>PRF [Hz]</th>
<th>Average Brightness [p/(s·mm²·mrad²·line)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>3.37</td>
<td>532</td>
<td>3</td>
<td>200</td>
<td>10¹²-10¹⁴</td>
<td>100</td>
<td>~10¹¹</td>
</tr>
</tbody>
</table>

Although laser plasmas have several great advantages they do suffer from one potentially devastating problem. The plasma will emit not only x-rays but also unwanted debris from the target material. This debris can quickly destroy sensitive optical components positioned close to the plasma to collect the radiation and severely limits the applicability of laser-plasma sources. Since there are so many advantages of laser plasmas, a vast amount of work has been put into overcoming the above mentioned limitations. The produced debris can be divided into a few different categories, as illustrated in Fig. 3.8, and much of the work on refining the basic laser-plasma source is focused on addressing these problems.

![Figure 3.8. Schematic illustration of debris production in laser-plasma sources, using a conventional solid target and a mass-limited droplet target.](image)

There are basically two different approaches to the debris problem. The first is to reduce the amount of debris produced by the plasma and the second is to mitigate the effects of the produced debris. Naturally, these are not mutually exclusive but rather used together to make the source as debris free as possible. To reduce the amount of produced debris a mass-limited target [81] can be used. If all the target material is used in the plasma
formation, no particulate debris will be produced and a minimum of atoms/ions per x-ray flux created. This requires that there is no target material in the low power wings of the laser focus and that the target material is thin enough. A liquid-droplet target, matched to the size of the laser focus, fulfills these requirements [82] as, to some extent, does liquid jet targets [83] and tape targets [84]. Another approach is to use a non-solid target such as a gas jet [85], cluster jet [86] or spray jet [87] which also reduces the debris although the target density is also lowered. The atomic/ionic debris from the plasma can be divided into two categories depending on whether or not it is harmful only when energetic or highly charged or not. A target material that is reactive or condensing will be harmful even if neutral and thermal. This basically includes all matter except the noble gases. For high repetition rate operation fresh target material must also be continuously supplied, which is also solved using a fast regenerative target system like a liquid jet.

Several different methods to mitigate the effect of produced debris have been developed. A static gas background can be used to thermalize the emitted atoms or ions [89] and a forced gas flow [90] may be able to redirect the debris away from sensitive components. Another effective method is the foil trap [88], as illustrated in Fig. 3.9. Other suggested methods include fast shutters [91], electric [92] or magnetic [93] fields for repulsion or deflection but these are only effective against charged particles. Although mitigation techniques can be quite effective (~1000× reduction for the foil trap) they always come at a price. Normally the flux is reduced (e.g., absorption in background gas or foil obstruction) and the collectable solid angle reduced. It is therefore highly desirable to have a source with intrinsically low debris production, to minimize the amount of necessary mitigation. Not only debris from the plasma itself is potentially harmful but also secondary debris generated by sputtering from components positioned close to the plasma and it is therefore also desirable to produce the plasma far away from any hardware. Chapter 5 will describe the development of such sources, based on liquid-jet targets and will also discuss the specific problems involved in high average power, long life time systems.

Figure 3.9. Schematic illustration of the foil trap debris mitigation technique. Adapted from [88].
3.3.2 Discharge Plasmas

In a discharge source the plasma is formed by an electric discharge instead of a laser. The emission characteristics of discharge plasmas are very similar to those of laser plasmas but there are some differences due to longer pulses and often lower densities. There are several different types of discharge sources but they are all based on the same principle. A very high current is driven through some target. The current heats the target and also induces a strong magnetic field that assists the formation of a hot, dense, x-ray emitting plasma by compressing the now ionized target. A more detailed description of discharge sources are given in Refs. 94 and 95.

Here the focus is on soft x-ray and EUV sources where average brightness is important, requiring high repetition rate operation which means that the discharge medium is a gas. Instead of solid wires, as normally used in single shot hard x-ray discharges. Gas discharge plasmas (GDP) have a clear advantage compared to laser plasmas in that they do not require an expensive laser. However, the conversion efficiency (here from electric energy to x-ray energy) is normally lower [96]. In terms of brightness the main problem with gas discharge sources is the large plasma size, typically several 100 µm in diameter and several millimeters long [96]. Typical state-of-the-art data is given in Table 3.2.

<table>
<thead>
<tr>
<th>Target</th>
<th>Pulse Current [kA]</th>
<th>Pulse Time [ns]</th>
<th>Pulse Energy [J]</th>
<th>PRF [Hz]</th>
<th>Average Brightness at 13.5 nm [p/(s·mm²·mrad²·0.1%BW)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>~50</td>
<td>~300</td>
<td>~10</td>
<td>1000</td>
<td>~10¹⁰</td>
</tr>
</tbody>
</table>

As mentioned in the previous section debris is a major problem for laser-plasma sources and this applies, at least as much, also to discharge plasmas sources. Using a noble gas target the problem is mainly electrode erosion and secondary debris emission from components close to the plasma as well as thermal management problems due to the plasma’s proximity to source hardware.

3.4 X-Ray Lasers

A laser in the soft x-ray and EUV region would of course be a very attractive source of radiation due to the same reasons that make lasers such superb sources of visible and UV light, i.e., high brightness, coherence, well defined wavelength, etc. Building a laser requires finding a lasing medium and, normally, constructing an optical cavity. Mirrors are very problematic in this wavelength region and almost all x-rays lasers (XRL) are therefore based on single pass self-amplified spontaneous emission (SASE) through the lasing medium. The energy transitions needed for these wavelengths are well above those of the outer electrons so highly ionized atoms must be used. The only dense source of highly ionized atoms is a hot, high-density, plasma. The plasma is normally generated by heating
with a high-power, short-pulse, laser (as in laser plasmas) although, especially for longer wavelengths, electric discharges are also used. The problems with XRLs are due to the fact that a high degree of population inversion is required for the high gain necessary for single-pass lasing and that the pumping power scales as $1/\lambda^4$, where $\lambda$ is the output wavelength. Furthermore, plasma uniformity is an issue since this affects the index of refraction and it is difficult to avoid radial density gradients.

Today only a few lasers at soft x-ray energies have been demonstrated and they are now starting to be used for applications as well as basic research. Current state-of-the-art average spectral brightness for an EUV (46.9 nm) laser operating at 4 Hz is $\sim 10^{17}$ photons/(s·mm²·mrad²·0.01%BW) with $\sim 1.5$ ns pulses [99]. For shorter wavelengths the performance is drastically decreased, the systems become far from compact (due to the large pump lasers required) and the lasing medium is often single shot, limiting the applicability beyond basic research. For a thorough review of SXR and EUV lasers, consult Refs. 100-103.

### 3.5 High-Harmonic Generation

When a very intense laser field interacts with matter, high harmonics of the fundamental laser wavelength can be produced through non-linear processes. In this process the atom absorbs $n$ photons with energy $h\nu$ and emits one photon with energy $nh\nu$. Although the physics behind this phenomenon is quite complicated a simplified phenomenologic understanding is possible. During one oscillation of the very high-intensity electric field of the incident laser beam an electron is first accelerated away from an atom and then returned. The electron is subject to a very strong, short acceleration and will emit radiation in overtones of the laser frequency, extending to very high photon energies. The harmonic generation in different atoms is in phase with respect to the laser and the intensity thus adds coherently in the direction of the pump laser, resulting in harmonic emission in a narrow (on the order of mrad) forward cone. High harmonics (100-200) may be generated and with visible pump lasers the harmonics will then extend well into the EUV (on the order of a few 100 eV). Experiments generating high harmonics typically use a very high-peak-intensity ($>10^{14}$ W/cm²) ultra-short (20-100 fs) laser pulse focused into a gas jet. The problem with this technique lies primarily in the conversion efficiency for short wavelengths (high harmonics) that so far is too low (typically between $\sim 10^{-7}$ and $\sim 10^{-10}$ depending on wavelength) to generate sufficient photon numbers for most applications. A current state-of-the-art system at $\sim 26$ nm reaches $\sim 10^{13}$ photons/(s·mm²·mrad²·line) using a 10 Hz, 200mJ, 35fs, 800 nm laser [104]. For more details on HHG the interested reader is referred to, e.g., Refs. 100 and 105.

### 3.6 Other X-Ray Sources

The sources described in this sub section are not as common as the ones described above and they are often based on more exotic electron-matter interactions at relativistic
energies. They will be briefly presented here but a more complete description is outside the scope of this thesis.

3.6.1 Electron Cyclotron Resonance

In addition to the laser plasma and GDP sources previously described, microwaves can be used to heat and sustain a gas plasma. If the microwave frequency is matched to the electron cyclotron frequency (given by their energy and the strength of a perpendicularly applied external magnetic field) the electrons are forced into circular orbits and the plasma heating becomes very efficient. This is called electron cyclotron resonance (ECR) and can be used for x-ray generation, similar to other plasmas although often a CW source [106]. The advantage of ECR sources is the simple construction, plasma confinement and high average power. The main difficulty with ECR sources in terms of brightness is the large source size. Other difficulties include wall losses and the fact that the electron mass, and thus the cyclotron criterion, changes with energy. A current state-of-the-art implementation reports up to \( \sim 10^8 \) photons/(s·mm\(^2\)·mrad\(^2\)·0.1%BW) in the region around 9 nm [107] although the emitted power is enormous (16kW of x-rays between 6 nm and 17 nm are emitted into \( 4\pi \) from a 6 cm diameter source). Plasma temperatures for hard x-ray generation can normally not be obtained and instead the plasma density is lowered and the electrons accelerated to high energies and impacted onto a solid target, much as in a conventional x-ray tube. Such a source has reached \( \sim 10^4 \) photons/(s·mm\(^2\)·mrad\(^2\)·0.1%BW) at \( \sim 20 \) keV [108]. With an added target, this is simply another way of electron acceleration and will always suffer from the same thermal limitations as a conventional x-ray tube.

3.6.2 Secondary Fluorescence

The electron-impact sources described in Section 3.1 all emit radiation in a rather broad energy band, as do many of the plasma sources. For many applications it is necessary with narrow-band radiation and the radiation used is therefore monochromatized. Naturally it would be advantageous to convert the out-of-band radiation to in-band radiation instead of simply discarding it. Using secondary fluorescence it is potentially possible to convert a polychromatic source into a quasi-monochromatic one, for certain select line emissions. Problems include the fluorescence yield and the source size. Current state-of-the-art implementations using primary radiation for electron-impact x-ray sources approach \( \sim 10^5 \) photons/(s·mm\(^2\)·mrad\(^2\)·line) at the 70 keV W K\(_\alpha\) line [109].

3.6.3 Cherenkov Radiation

Cherenkov radiation (CR) [110,111] is produced in a medium when the velocity, \( v \), of a charged particle traveling through the medium exceeds the phase velocity, \( v_p \), of light inside the medium. Cherenkov radiation will therefore be emitted by highly relativistic electrons if the refractive index of the material exceeds unity. This has been a known and widely used effect in the visible region for quite some time but has only recently been explored in the x-ray region. In the x-ray region the index of refraction is normally smaller than unity.
(as described in Section 2.4) and Cherenkov radiation can then only be generated around absorption edges where the index of refraction exceeds unity.

![Figure 3.10. Schematic illustration of Cherenkov radiation.](image)

In some ways, Cherenkov radiation (illustrated in Fig. 3.10) is analogous to the sonic shock wave created when an object supersedes the velocity of sound. The track after the electron can be thought of as a line of point emitters due to relaxation of the polarization induced by the traversing electron. If the condition for Cherenkov radiation is fulfilled, the point emitters will constructively combine to form a wave front with an angle, $\theta$, to the trajectory given by

$$\cos \theta = \frac{v_p}{v} = \frac{c}{n v}$$

and the light emitted in a forward directed hollow cone. In the x-ray region narrow-band radiation will be emitted since the refractive index only exceeds unity around sharp absorption edges and the emission angle is typically in the $1^\circ - 10^\circ$ range. Cherenkov radiation is limited in wavelength to appropriate absorption edges and in the soft x-ray range (where $n$ can be large compared to the hard x-ray region) the radiation yield is typically a few times $10^4$ photons per electron for electron energies in the few tens of MeV range. The achievable source brightness is basically limited by thermal effects in the medium and it appears feasible to scale a compact source to a few times $10^9$ photons/(s·mm$^2$·mrad$^2$·0.1%BW) [112] in the water window, although the demonstrated brightness to date is several orders of magnitude smaller.

### 3.6.4 Transition Radiation

Cherenkov light is emitted when the particle velocity exceeds the phase velocity but radiation can also be emitted at velocities smaller than the phase velocity if the phase velocity or the particle velocity changes. This happens when a particle crosses the boundary between two different media, and is called transition radiation (TR). The simplest case is a vacuum to matter interface which will be described here. Transition radiation can be phenomenologically viewed as radiation arising from a dipole formed by the particle and its mirror charge. The radiation is therefore polarized and emitted in a
narrow hollow cone with an opening angle of $2/\gamma$. The spectrum is similar to that from bremsstrahlung and is flat up to a certain cut off frequency (proportional to $\gamma$) above which it drops as $\omega^{-4}$. For a 100 MeV electron the cutoff is around 10 keV. The intensity of the transition radiation is approximately proportional to the particle energy, and the squared difference of the dielectric constants. Using a periodic stack of foils or multilayer structure the amount of emitted radiation can be drastically increased and the spectral and angular distributions narrowed due to constructive interference. This is called resonant transition radiation (RTR). The brightness is limited by thermal effects in the target and the maximum attainable brightness estimated to $\sim 10^9$ photons/(s·mm$^2$·mrad$^2$·0.1%BW) in the 0.5 - 5 keV range, although the achieved brightness to date is several orders of magnitude smaller [113,114]. For more information on TR and RTR sources see, e.g., Refs. 115 and 116.

3.6.5 Channeling Radiation

Relativistic electrons traversing a crystal along a periodic structure (axis or plane) will be restricted by the crystal planes acting as potential barriers and forced to oscillate if the angle of incidence is small enough compared to a crystal plane. This is called channeling radiation (CHR) and does not occur if the angle of incidence is too large in which case the electron will penetrate the crystal planes and the guiding effect is lost. Channeling radiation is very similar to undulator radiation, as described in Section 3.2.3 although the crystal spacing is smaller and the power limited by thermal effects. The intensity scales rather rapidly with energy ($\sim \gamma^{5/2}$) and it is therefore of most interest in the hard x-ray region. A suggested state-of-the-art channeling radiation implementation at $\sim 30$ keV would be limited to a few times $10^6$ photons/(s·mm$^2$·mrad$^2$·0.1%BW) [117]. For a more detailed description of CHR see, e.g., Refs. 118 and 119.

3.6.6 Coherent Bremsstrahlung

If the angle of incidence is above the criterion for channeling, coherent bremsstrahlung (CB) can be emitted. This occurs when the trajectory is essentially a straight line, slightly perturbed by the periodic crossing of crystal planes. For a certain crystal lattice spacing, angle of incidence and wavelength the bremsstrahlung emitted per deflection will interfere constructively and greatly increase in intensity. Coherent bremsstrahlung sources have mainly been used in the MeV range and have received little attention in the x-ray range [120]. Experimental source brightness data are difficult to find, but compared to CHR the thermal limitations are similar, the emission spectrum is harder and the spectral intensity

* Brightness data are difficult to find and this number is based on the intensity data from Refs. 113 and 114 and the thermal analysis from Ref. 111. This thermal analysis is for a thin Ti foil and a 10 MeV electron beam used in a Cherenkov source but should give an idea of the right order of magnitude for the permissible electron beam power density and associated heat load also for a foil-based RTR target.
equally lowered, typically by more than an order of magnitude. For more information regarding CB see, e.g., Refs. 121 and 122.

3.6.7 Parametric X-Rays

Parametric x-rays (PXR) are emitted when relativistic electrons pass through crystal planes. PXR is similar to Cherenkov radiation and transition radiation and can be thought of as due to polarization of the lattice atoms by the traversing electron. PXR is emitted into a small angular cone approximately satisfying the Bragg condition for x-ray diffraction. PXR is quasi-monochromatic and the photon energy can be tuned by changing the angle of incidence. The brightness is limited by thermal effects and a suggested state-of-the-art implementation could reach up to $\sim 10^{12}$ photons/(s·mm$^2$·mrad$^2$·0.1%BW) at 33 keV [123]. For more details on PXR see, e.g., Ref. 124.

3.6.8 Compton Backscattering

Compton scattering was described in Section 2.3 for the case of stationary electrons. However, the situation changes dramatically for scattering against relativistic electrons [125]. The scattered photons now have a drastically increased energy and they are concentrated to small angles relative to the initial electron motion. The gain in photon energy can be as large as $4\gamma^2$, depending on the angle. In this way, laser light can be converted to radiation well into the MeV range. For softer x-rays electron beam energies of tens of MeV is sufficient. The cross section increases as $\sim \gamma^2$ and the angular distribution as $\sim 1/\gamma$. Compton backscattering (CBS) can produce very short pulsed (~100 fs), polarized, well collimated, quasi-monochromatic, and tunable radiation although it is a quite complex, often large, source. A brightness on the order of $\sim 10^{12}$ photons/(s·mm$^2$·mrad$^2$·0.1%BW) can be reached in the 10 - 100 keV range [113,126].

3.6.9 Diffraction Radiation and Smith-Purcell Radiation

When a charged particle travels close to a structure with a different dielectric constant it will lose energy through radiation. This is a general form of transition radiation and can also be thought of in terms of dipole emission from the particle and its mirror image. Two particularly interesting cases are diffraction radiation emitted when a charged particle passes through an aperture and Smith-Purcell radiation emitted when a charged particle travels over a grating structure. The maximum separation distance and yield decrease rapidly with increasing photon energy and make the generation of this radiation difficult in the x-ray region, although conceivably rather bright [113,127,128].

3.7 Summary and Conclusions

As previously discussed average spectral brightness is an appropriate figure of merit for many applications but for time resolved applications the pulse length and repetition frequency are also important. For pulsed sources the average brightness is determined by
the peak brightness and the duty cycle, so it scales linearly with pulse repetition frequency and inversely with pulse length. Source comparison becomes even more difficult when polarization and coherence are also important and when the bandwidth is an issue. Although far from complete, Table 3.1 summarizes the key properties of the different X-ray sources described in this chapter. For electron-beam based sources with an electron energy significantly higher than the photon energy it is important to remember the necessity of radiation shielding as there will always be a photon component up to the maximum electron energy due to bremsstrahlung. Furthermore, the brightness numbers quoted in the table below and the previous sections often require quite large lasers or electron accelerators and have to be reduced for more compact systems. Naturally, a more detailed analysis than presented here must be performed when choosing an appropriate X-ray source for a given application.

Table 3.3. Summary of X-ray source characteristics and maximum achievable brightness. Data from this chapter and references herein.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SR B. M.</td>
<td>0.5 - 8 GeV</td>
<td>&lt;100</td>
<td>cont.</td>
<td>1/γ</td>
<td>100 ps</td>
<td>M-G</td>
<td>~10^{15}</td>
</tr>
<tr>
<td>SR Wiggler</td>
<td>0.5 - 8 GeV</td>
<td>&lt;100</td>
<td>cont.</td>
<td>&gt;1/γ</td>
<td>100 ps</td>
<td>M-G</td>
<td>~10^{16}</td>
</tr>
<tr>
<td>SR Und.</td>
<td>0.5 - 8 GeV</td>
<td>&lt;10</td>
<td>1%</td>
<td>1/10γ</td>
<td>100 ps</td>
<td>M-G</td>
<td>~10^{19}</td>
</tr>
<tr>
<td>FEL</td>
<td>1 - 50 GeV</td>
<td>0.01 - 100</td>
<td>10^{-3} - 10^{-5} μrad</td>
<td>100 fs</td>
<td>M-G</td>
<td>~10^{24}</td>
<td></td>
</tr>
<tr>
<td>Tube (BS)</td>
<td>20 - 200 keV</td>
<td>5-100</td>
<td>cont.</td>
<td>4π</td>
<td>N/A</td>
<td>CW</td>
<td>~10^{7}</td>
</tr>
<tr>
<td>Tube (line)</td>
<td>20 - 200 keV</td>
<td>5-100</td>
<td>10^{-3}</td>
<td>4π</td>
<td>N/A</td>
<td>CW</td>
<td>~10^{19}</td>
</tr>
<tr>
<td>LPP (soft)</td>
<td>N/A</td>
<td>0.1-1</td>
<td>1-10^{-3}</td>
<td>4π</td>
<td>1 ns</td>
<td>k</td>
<td>~10^{11}</td>
</tr>
<tr>
<td>GDP (soft)</td>
<td>N/A</td>
<td>0.1-1</td>
<td>1-10^{-3}</td>
<td>4π</td>
<td>100 ns</td>
<td>k</td>
<td>~10^{19}</td>
</tr>
<tr>
<td>ECR (soft)</td>
<td>N/A</td>
<td>&lt;0.5</td>
<td>1-10^{-3}</td>
<td>4π</td>
<td>N/A</td>
<td>CW</td>
<td>~10^{8}</td>
</tr>
<tr>
<td>XRL</td>
<td>N/A</td>
<td>&lt;0.1</td>
<td>10^{4}</td>
<td>few mrad</td>
<td>0.1 - 1 ns</td>
<td>1</td>
<td>~10^{7}</td>
</tr>
<tr>
<td>HHG</td>
<td>N/A</td>
<td>&lt;0.05</td>
<td>10^{-3}</td>
<td>few mrad</td>
<td>&lt; fs - 100 ps</td>
<td>k</td>
<td>~10^{13}</td>
</tr>
<tr>
<td>CR</td>
<td>10 - 100 MeV</td>
<td>0.1-1</td>
<td>10^{-2} - 10^{-3}</td>
<td>few &quot;</td>
<td>1 ns - 1 μs</td>
<td>k</td>
<td>~10^{14}</td>
</tr>
<tr>
<td>CHR</td>
<td>10 - 200 MeV</td>
<td>1-100</td>
<td>10%</td>
<td>1/3γ</td>
<td>1 ns - 1 μs</td>
<td>k</td>
<td>~10^{14}</td>
</tr>
<tr>
<td>(R)TR</td>
<td>50 - 500 MeV</td>
<td>0.1-50</td>
<td>50%</td>
<td>1/γ</td>
<td>1 ns - 1 μs</td>
<td>k</td>
<td>~10^{14}</td>
</tr>
<tr>
<td>PXR</td>
<td>10 - 500 MeV</td>
<td>1-50</td>
<td>1%</td>
<td>few mrad</td>
<td>1 ns - 1 μs</td>
<td>k</td>
<td>~10^{28}</td>
</tr>
<tr>
<td>CBS</td>
<td>10 - 200 MeV</td>
<td>1-100</td>
<td>10%</td>
<td>1/3γ</td>
<td>100 fs</td>
<td>k</td>
<td>~10^{12}</td>
</tr>
</tbody>
</table>

* The average spectral brightness is given in the conventionally used units of photons/(s·mm²·mrad²·0.1%BW).

For line emitting sources the amount of photons per line is given, as long as the line width does not significantly exceed 0.1%. However, it should be noted that this BW choice is unfavorable for sources with a narrower intrinsic linewidth. Furthermore, it should be remembered that the quoted brightness number can usually not be achieved independent of the other source parameters.

$ These values are based on suggested source designs and the currently achieved brightness is typically several order of magnitude smaller.

† Can be increased using periodic stacks.

‡ Depending on accelerator type.

As previously mentioned synchrotron radiation sources are outstanding in terms of brightness and will continue to improve with the development of FELs. Although massive installations, synchrotron facilities are motivated by the numerous applications currently only possible there. This also motivates the development efforts of more compact
substitutes. For applications requiring hard x-rays and compact sources x-ray tubes are currently the best option. For applications that do not require high photon energies, XRL and HHG sources are becoming more attractive as the performance is increased and the size and complexity decreased. However, for applications that do not require coherence, but slightly higher energies or larger photon fluxes laser plasmas and GDP are commonly used. CBS is an excellent source, but still quite complex and not very compact. Although work is currently being done on Cherenkov [111] and PXR sources [129] most of the unconventional sources described in this chapter have found limited use as x-ray sources for applications.

Summarizing this section on different x-ray sources it is clear that conventional hard x-ray tubes and SXR/EUV laser plasmas are very competitive sources for many applications and that further improvement of these in terms of brightness, power and lifetime is highly desirable as they are well proven, relatively simple and compact sources. Chapter 5 describes the development of an improved EUV/SXR laser plasma source and Chapter 6 summarizes the development of a new x-ray tube.
Chapter 4

Liquid Jets

4.1 Introduction and Motivation

As has briefly been mentioned and as will become apparent in Chapter 5 and Chapter 6, liquid jets are very attractive targets both for laser plasmas and in x-ray tubes. The liquid-jet targets employed in this thesis span a wide range of materials, diameters and speeds depending on application.* Furthermore, jets broken up into droplets are also used. A prerequisite for stable x-ray generation is stable target generation, requiring an understanding of liquid jets in vacuum. This chapter, which to a large extent is based on the work described in Papers 1-9, will describe the basic theory, from an engineering point of view, of liquid jets in vacuum and experimental work towards stable target generation. For a more complete treatment of conventional liquid-jet theory see, e.g., Refs. 130-135.

4.2 Liquid Jet Basics

A liquid jet is formed when a pressurized liquid is discharged through a nozzle orifice. For certain parameters this will result in a stable, well collimated jet that will eventually break up into droplets due to minimization of surface energy. This is called Rayleigh breakup and normally occurs if the pressure is above some lower limit where the liquid simply drips out of the nozzle and some upper limit where other breakup mechanisms dominate (c.f. below). Liquid-jet targets are normally operated in the Rayleigh regime, since the jet is here collimated and well-behaved. Furthermore, this is the region where liquid droplet operation is possible. The jet is energetically unstable and small initial disturbances grow exponentially until they are comparable to the jet radius and droplets form. In the Rayleigh regime the drop formation distance is proportional to the jet speed and is given by†

\[
L = \ln\left(\frac{d}{2\delta_0}\right) \cdot \nu \cdot \left(\sqrt{\frac{\rho d^3}{\sigma}} + \frac{3d\eta}{\sigma}\right),
\]

(4.1)

* The liquid jets considered here range in diameter from ~10 µm to ~100 µm and in speed from ~10 m/s to ~500 m/s. Typical “normal” liquids used are water and ethanol, but also liquid metals (e.g., tin) and liquid noble gases (e.g., xenon) are used.

† As an example, the breakup length for a 10 µm, 50 m/s water jet is typically 2 mm.
where $d$ is nozzle diameter, $\delta_0$ is an initial disturbance, $v$ is the average jet speed at the exit, $\rho$ is the density, $\sigma$ is the surface tension, and $\eta$ is the dynamic viscosity [136]. The initial disturbance factor can only be determined experimentally, but the logarithmic expression is normally $\sim 10$ [136]. The average spontaneous drop formation frequency, $f$, is given by

$$f = \frac{v}{4.51 \cdot d}$$

and results in an average drop diameter of $1.89 \cdot d$ [137]. The drop formation can be controlled, and equally sized and spaced droplets may be produced. This is done by applying an external disturbance, that dominates over the spontaneous initial disturbance, with a frequency close to the resonance frequency of drop formation, as seen in Fig. 4.1.

The speed, $v$, of the liquid jet depends, as a first approximation, only on the applied pressure, $p$, and the liquid density, $\rho$. Conservation of energy gives [138]

$$v = \sqrt{\frac{2p}{\rho}},$$

assuming a negligible pressure in the exit region as well as a static fluid reservoir. However, there are always losses in the nozzle due to, e.g., viscous friction and turbulence,

* As an example the material data for water at room temperature and pressure are $\rho = 977$ kg/m$^3$, $\eta = 1.04 \cdot 10^{-3}$ Ns/m$^2$, and $\sigma = 73 \cdot 10^{-3}$ N/m.

† Typical pressures used are between $\sim 1$ bar and $\sim 200$ bar, resulting in jet speeds between $\sim 1$ m/s and 100 m/s depending on liquid and nozzle.
4.2. Liquid Jet Basics

that will generally depend on both nozzle geometry and fluid parameters. The loss fraction, i.e. the ratio of the actual jet exit speed and the theoretical exit speed, is called the nozzle discharge coefficient, $C$. $C$ normally range from ~0.6 almost up to unity [139]. As the jet leaves the nozzle it contracts (the diameter contraction ratio is typically 0.9) and since the mass flow is constant the speed is increased [140]. For laminar flows, as assumed in the Rayleigh regime, the viscous losses can be expressed using the Hagen-Poiseuille equation [141] and the actual speed can in principle be determined. However, as is shown in Paper 2, the calculation of the viscous loss is extremely sensitive to the nozzle geometry and normally a semi-empirical model must be used. For a given nozzle geometry it is possible to calibrate the model and accurately predict the jet speed as a function of pressure, density, viscosity and surface tension.

Liquid flows are conventionally described by a set of dimensionless fluid-dynamic parameters that describe the interplay of different forces: [142]

\[
\text{Reynolds number, } \text{Re} = \frac{\text{inertia forces}}{\text{viscous forces}} = \frac{rd\rho}{\mu}, \tag{4.4}
\]

\[
\text{Weber number, } \text{We} = \frac{\text{inertia forces}}{\text{surface tension}} = \frac{v^2 d\rho}{\sigma}. \tag{4.5}
\]

It has been shown that the transition from laminar flow to turbulent flow depends on the Reynolds number and that this transition occurs above some critical value. In tubes, the flow is always laminar for $\text{Re} < \sim 1000$, but laminar flows can also be sustained at much higher $\text{Re}$ if the experimental conditions are correct, e.g., when there is nothing to promote turbulence [143,144]. The stability and Ohnesorge diagrams, shown in Fig. 4.2, are normally used to describe the behavior of liquid jets.

\* Evidently the jet diameter and speed change in the region just after the nozzle orifice, but here we will ignore this fact and use $d$ and $v$ without finer distinction.
Jet Breakup Length
Jet Speed
Dripping flow
Laminar flow
Transition region
Turbulent flow
Spray zone

Figure 4.2. Schematic illustration of jet stability diagram and Ohnesorge diagram. Ohnesorge number, $Oh=\sqrt{We/Re}$, describes ratio of viscous to surface tension forces. Adapted from [145].

The transition zone is due to interactions between the jet and the surrounding atmosphere. Aerodynamic pressure effects and viscous friction cause and amplify wind-induced instabilities and promote jet breakup. In the turbulent zone, the jet starts to spray although it is often coherent for some distance before it disintegrates. The behavior of the jet (the nature of the breakup) and the scaling of the jet length in the transitional and turbulent region do not follow any simple rules but differ from system to system. The wind-induced breakups depend on the surrounding pressure and can be described by the atmospheric Weber number*, $We_A$. The onset of wind-induced breakups normally occurs around $We_A \sim 1$ and the spray zone starts at a $We_A$ on the order of 10 [130]. Figure 4.3 shows different breakup phenomenon that typically occur when the jet speed is increased outside the Rayleigh region.

Figure 4.3. Typical jet breakup in the transition zone (top) and in the turbulent spray region (bottom). Adapted from [144].

* In addition to the Weber number of the jet there is also a Weber number associated with the atmosphere, describing the influence of the surrounding gas.
The jet stability and breakup tendency also depend on the nozzle design, as shown in Fig. 4.4. Two important aspects are surface roughness and flow profile. Reduced surface roughness means smaller initial disturbances that can be amplified and smooth nozzle surfaces are therefore desirable. Other than rough surfaces, sharp corners should be avoided since they promote the formation of eddies. Furthermore, the exit flow profile should be as flat as possible, without any radial velocity components, to minimize the required flow profile rearrangement after the nozzle exit [136].

![Figure 4.4. Influence of nozzle design on jet stability. Images show a 2.54 mm diameter 20 m/s glycerol-water jet with a Re of 4750 injected into air from increasingly long nozzles. The exit flow profile becomes more parabolic with longer nozzles, increasing the required velocity profile rearrangement. Adapted from [136].](image)

### 4.3 Liquid Jets in Vacuum

When injecting a liquid jet into vacuum, conventional wind-induced breakup does not occur and the classic stability and Ohnesorge diagrams cannot readily be applied. In vacuum the jet breakup is determined by the nozzle and jet parameters, i.e., internal turbulence and flow profile relaxation [146-148]. This means that it should be possible to operate a collimated jet in vacuum at Reynolds numbers far exceeding what is possible in atmosphere, as will be discussed more in Section 4.6.

Another consequence of the vacuum environment is evaporation. Most liquids have a significant vapor pressure and will therefore evaporate once injected. This evaporation leads to cooling of the jet through mass loss [149]. As is shown in Paper 1, this evaporative cooling reduces the temperature of the nozzle and thus the liquid prior to

---

* As an example, the water vapor pressure at 20 °C is ~25 mbar.
ejection, and effects the jet speed through the temperature dependence of the viscosity. For liquid jet-targets this is not a significant problem but for liquid-droplet operation, where accurate drop position is crucial, a shift in jet speed results in a shift in drop position. The demands on droplet position stability are quite strict (a fraction of a drop diameter) and cannot easily be achieved by temperature control of the nozzle, but requires that the drift in drop position can be compensated for by some other means. Such a system is presented in Paper 1.

4.4 Cryogenic Liquid Jets

As mentioned in Section 3.3.1, noble gases are attractive target materials. However, liquid-jet formation requires cryogenic operation since the boiling point is very low. The vapor pressures of cryogenic gases are very high, as is the associated evaporation and this leads to a number of phenomena. The very rapid cooling in combination with the small liquid temperature span mean that the jet freezes before it can form droplets. Furthermore, the extreme cooling causes stability problems due to freezing at the nozzle orifice. Paper 4 analyses the behavior and cooling of cryogenic liquid jets in vacuum and also presents a solution to this instability problem. The work in Paper 5 uses an improved cryogenic liquid-jet system with accurate temperature control.

Figure 4.5. Rupture of a superheated liquid-nitrogen jet injected into vacuum. Adapted from [150].

A further complication resulting from the vacuum environment is cavitation. Since the vacuum pressure is normally below the vapor pressure the liquid jet is superheated and prone to cavitation [151]. This is most prominent for cryogenic liquid jets and Fig. 4.5 shows the rupture of a superheated cryogenic liquid-nitrogen jet. However, it is normally possible to avoid this by minimizing the number of nucleation sites (particles or bubbles) and operating at the lowest possible temperature, as discussed in Papers 4 and 9.

---

* As an example, xenon is liquid between approximately 161 K and 165 K at atmospheric pressure and the vapor pressure of a liquid-xenon jet at injection is ~1 atm.

† As an example, the calculated freezing length of a 10 µm, 40 m/s liquid-xenon jet injected at 170 K is ~0.4 mm, compared to the minimum drop formation point of ~1.8 mm.
4.5 Liquid-Metal Jets

Liquid-metal jets are in principle not different from other liquid jets and their low vapor pressures* means that they do not suffer from the extra difficulties described in the previous section. The melting point of most metals is far above room temperature and the problems associated with liquid-metal jets are more of the engineering type. These include the fact that liquid metals are quite reactive and that once filled, a liquid-metal pressure system is very difficult to inspect and clean. Papers 6-9 are based on a liquid-metal-jet system originally developed in Paper 6 and more thoroughly described in Paper 7.

4.6 High-Speed Liquid Jets

For certain applications the jet speed is crucial. As mentioned in Section 3.1 the key figure of merit for the target in an x-ray tube is the heat load handling capability. For a liquid-metal-jet target, as will be discussed in Chapter 6, this is proportional to the jet speed. Furthermore, high-repetition-rate operation of laser plasmas, as investigated in Paper 5, requires a high-speed jet for continuous target supply.

Very high-speed liquid jets (~1000 m/s) are currently found in the water-jet cutting industry where the demands on jet coherence are less strict [152]. Fortunately, a vacuum environment should enable the stable operation of a collimated high-speed jet. Paper 9 analyses the possibility of high-speed liquid-metal jets in vacuum through dynamic-similarity experiments and finds that a 30 µm diameter liquid-tin jet operating at 500 m/s, as required in Chapter 6, is feasible although it would require a driving pressure on the order of $10^4$ bar.

---

* As an example the vapor pressure of liquid Sn is $\sim 10^{-19}$ mbar at 300 °C, $\sim 1$ mbar at 1500 °C, and reaches 1 atm at the boiling point of $\sim 2800$ °C.
Chapter 5

Liquid-Jet-Target Laser-Plasma X-Ray Sources

5.1 Introduction and Motivation

The physics of laser plasma x-ray sources was described in Section 2.6 and general aspects of laser plasma x-ray sources discussed in Section 3.3.1. As mentioned there, two key issues of laser-plasma x-ray sources are conversion efficiency (CE) from laser pulse energy to in-band x-ray energy and the production of harmful debris. As previously mentioned, the use of mass-limited targets, such as liquid droplets or jets, greatly reduces the amount of produced debris and allows almost $4\pi$ sr geometric access to the plasma as well as uninterrupted, high-speed, target supply. Here, the development of two different laser plasma source systems based on liquid jet/droplet targets will be described.

5.2 A Laser-Plasma Soft X-Ray Source for Microscopy

In the so called water-window,\(^*\) there is a natural contrast between water and protein which can be used for high resolution SXR microscopy of individual cells\(^†\) in their natural aqueous environment without the need for staining. SXR microscopy can also be used for other applications, e.g., material science, and is normally performed at synchrotrons [153]. However, in terms of accessibility for the applied scientist, a table-top system would be beneficial and Fig. 5.1 shows the layout of a laser plasma based, full field, water-window soft x-ray microscope [80,154]. This microscope is designed to operate at a $\lambda=3.37$ nm C\(^+6\) plasma emission line and the multilayer mirror designed for this wavelength. The resolution is determined by the outermost zone width of the zone plate\(^‡\) used for imaging the sample onto the CCD and the useful source size is $\sim 20$ µm. The resolution is currently

\(^*\) The water window is the spectral range between the oxygen ($\lambda \approx 2.3$ nm) and carbon ($\lambda \approx 4.4$ nm) absorption edges and the difference in absorption length is here $\sim 10\times$. The water $1/e$ absorption length span from $\sim 10$ µm at the oxygen edge down to $\sim 2$ µm at the carbon edge.

\(^†\) The radiation dose delivered to the sample during exposure is orders of magnitude above a lethal dose but structural changes do not necessarily occur on the time scale of a single exposure.

\(^‡\) A zone plate lens is a circular grating with decreasing line widths, so that the diffracted radiation from each zone is in phase at the focal point. The properties of a zone plate are such that $NA=\lambda/2\Delta r$ where $\Delta r$ is the width of the outermost zone and this means that the Rayleigh criterion for resolution reduces to $1.22\Delta r$. 

53
on the order of 50 nm and the exposure time typically a few minutes. The relatively long exposure time (synchrotron radiation based systems have an exposure time on the order of 10 s) is due to the limited brightness of the laser-plasma source and the low photon economy of the system.* Other problems include mirror degradation due to source debris and positional stability† of the plasma. The source is based on a ~10 μm liquid ethanol jet and can be operated both in liquid jet or droplet mode. The plasma is generated by a frequency doubled λ=532 nm Nd:YAG laser delivering ~200 mJ per ~3 ns pulse at 100 Hz. Although the use of an ethanol-jet-target reduces the debris deposition a factor ~10^3 compared to a low debris tape target [90], carbon deposition is still an issue. The source is described in more detail in Refs. 83, 155, and 156.

* The condenser collection angle is ~0.03 sr, the effective reflectivity (including flare) is only 0.05%, the zone plate efficiency is ~5% while filters and sample substrate remove another 70%. As a first approximation, this means that of the ~10^{11} photons/(pulse·sr·line) emitted from the source, not counting sample absorption, only ~2·10^4 reach the detector plane, which is ~0.02 photons per pixel per pulse.

† The condenser mirror images (1:2) the source onto the sample and for efficient illumination a positional stability of a few μm is required.
Given the long exposure times and debris issues, the microscope would benefit from any possible source improvements. Paper 1 describes an analysis of the source stability when operating in droplet mode and also presents an automatic control system to compensate for the droplet-position drift and allow stable, long term, operation. Paper 3 describes an optimization of the source with respect to target material and target size showing that the effective debris (carbon) deposition can be decreased $\sim 2\times$ and the flux simultaneously increased $\sim 3\times$ compared to previous operating practice.

Although instrument development continues, compact laser plasma based soft x-ray microscopy has been developed to a point where the focus is shifting towards applications. With the introduction of more powerful lasers and better optics the exposure times will be reduced and the resolution increased in future systems.

5.3 A Laser-Plasma EUV Source for Lithography

Integrated circuits (IC), e.g., computer processors and memory, are manufactured in an optical projection lithographic process where the circuit pattern is imaged (and demagnified) from a mask onto a silicon wafer. Naturally the IC production process involves many more steps, but here the discussion will be limited to the lithographic part. For a more detailed description of microfabrication of ICs, see, e.g., Refs. 158-160. The continued demand for better electronics has pushed the IC industry to roughly double the number of transistors per area every second year [161]. This empirical fact is called Moore’s law and is predicted to continue for the foreseeable future.

As mentioned in Chapter 1, the resolution of an optical system, like a projection-lithography system, is determined by the Rayleigh criterion. However, the smallest printable semiconductor feature is not the same as the optical resolution and for lithographic purposes, a modified relation is used:

$$\text{smallest feature} = k_1 \frac{\lambda}{NA}, \quad (5.1)$$

where $k_1$ is a process specific parameter [162]. From the above equation it is clear that there are only three ways to decrease the smallest feature size: Increased $NA$, decreased $k_1$, or decreased $\lambda$. To keep up with Moore’s law, all the above parameters have continuously improved over the years. $NA$ has gone from 0.3 in 1982 to 0.85 in current state-of-the-art

* A projection lithography system for semiconductor manufacturing is normally referred to as a stepper.
systems [163,164]. At the same time, $k_1$ has gone from ~0.8 to almost 0.4* [165,166] and the wavelength has decreased from 435 nm (Hg arc lamps) to 193 nm (DUV ArF eximer lasers). [163,164] Although there is still some room for improvement, the physical or economical limit for 193 nm lithography is approaching and alternatives are needed for the future.

The most straightforward way is to move to yet a shorter laser wavelength, and 157 nm lithography using F$_2$ lasers and CaF$_2$ optics is one such alternative [167]. However, there are several difficulties with this approach and the gain in resolution is moderate. Another possibility is immersion lithography, where a high-index-of-refraction liquid is used between the objective and the wafer [168]. This has been used in high-resolution optical microscopy for decades and reduces the effective wavelength by the index of refraction. Immersion is not a new idea in lithography but has gained renewed interest due to the problems of 157 nm lithography together with the fact that immersion using water at 193 nm would outperform conventional 157 nm lithography.

Although the use of conventional optical lithography has been extended far longer than first anticipated, and might still be extended for some time, it will eventually run out of steam, requiring new lithographic schemes [169]. Methods under consideration are EUV projection lithography (EUVL), x-ray proximity lithography (XPL) [170], electron projection lithography (EPL) [171], ion projection lithography [172], imprint lithography [173], and different maskless technologies [174]. All of these have their different strengths and weaknesses but a thorough discussion of this topic is outside the scope of this thesis. At the last Next Generation Lithography workshop† in 2001 [175] the future alternatives were down-selected to EUVL and EPL, where EUVL was vastly favored for the 45 nm node‡, scheduled for insertion in 2007. However, EUVL is currently targeted at the 32 nm node scheduled for insertion at 2013 according to the ITRS§ [169] and 2009 by Intel.

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* Further improvements can be made through extensive use of off-axis illumination, phase-shifting masks, optical-proximity corrections, and partial coherence factor.

† The Next Generation Lithography workshops were organized by International Sematech, a global consortium of leading semiconductor manufacturers involved in pre-competitive cooperative efforts.

‡ A node is named after the 1/2 pitch of the smallest printable dense lines and spaces with that technology and the industry basically advances one node at a time, currently the 90 nm node is being put into full scale production.

§ The International Technology Roadmap for Semiconductors is an industry wide cooperative assessment of the semiconductor field for the next 15 years.
The prime enabler of EUVL is the ability to make high-reflectivity mirrors in the EUV wavelength region* [177], allowing for reflective projection optics with mask reduction. In this respect EUVL is very similar to conventional optical lithography although reflective rather than refractive optics are used and the entire system must be operated in vacuum due to absorption. Figure 5.2 shows the reflectivity of near normal incidence Mo/Si multilayer mirrors developed for EUVL, where the wavelength of choice is ~13.5 nm [76]. To date, only one full field EUVL stepper, shown in Fig. 5.3, has been built and it is a low throughput technology demonstrator system that has successfully printed 70 nm lines [178].

* The highest normal incidence peak reflectivity has been achieved using either Mo/Be or Mo/Si multilayer stacks in the wavelength region just above the Be and Si absorption edges at 11.1 nm and 12.4 nm.
As previously discussed, not only wavelength but also $NA$ is important for resolution. Although the wavelength is drastically decreased in EUVL the limitations imposed by all-reflective optics make high $NA$ systems difficult to design and manufacture. Furthermore, the ~70% reflectivity per mirror means that the number of surfaces must be minimized. Current designs for the projection optics have 6 aspheric mirrors* and an $NA$ of 0.25 [179,180]. Working back from the wafer throughput demand of ~100 per hour, resist sensitivity (~2-5 mJ/cm$^2$), transmission of the optical system, etc, it is possible to estimate the in-band power that the source must deliver to the illumination optics. Further demands on the source include limited out-of-band radiation, life time†, stability, size, etc. The source demands, commonly agreed upon by the large stepper manufacturers, are summarized in Table 5.1.

---

* The required mirror surface finish varies with spatial frequency but is on the order of 0.1 nm rms for high spatial frequencies (surface roughness), mid spatial frequencies (flare) as well as low spatial frequencies (figure error).

† The collector life time is normally defined as the time to a irreversible 10% loss of reflectivity.
Table 5.1. The commonly agreed upon source requirements. Data from [181,182].

<table>
<thead>
<tr>
<th>Source Characteristic</th>
<th>Requirement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>13.5 nm</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>115 W</td>
<td>2% BW, at the intermediate focus (IF)</td>
</tr>
<tr>
<td>Pulse Repetition Frequency</td>
<td>&gt; 7-10 KHz</td>
<td>Design dependent</td>
</tr>
<tr>
<td>Energy stability</td>
<td>±0.3%, 3σ</td>
<td>Averaged over 50 pulses, at the IF</td>
</tr>
<tr>
<td>Source cleanliness:</td>
<td>≥ 30,000 h</td>
<td>System after the IF</td>
</tr>
<tr>
<td></td>
<td>&gt; ~1 year</td>
<td>Collector lifetime, cost dependent</td>
</tr>
<tr>
<td>Etendue of source output</td>
<td>≤ 1 - 3.3 mm²sr</td>
<td>Design dependent</td>
</tr>
<tr>
<td>Max solid angle input to illuminator</td>
<td>0.03 - 0.2 sr</td>
<td>Design dependent</td>
</tr>
<tr>
<td>Spectral Purity:</td>
<td>% of in-band EUV power</td>
<td></td>
</tr>
<tr>
<td>130 - 400 nm (DUV/UV)</td>
<td>≤ 7%</td>
<td>Design dependent</td>
</tr>
<tr>
<td>≥ 400 nm (IR/Vis.)</td>
<td>TBD</td>
<td>Design dependent</td>
</tr>
</tbody>
</table>

The requirements in Table 5.1, especially the EUV power, are extremely demanding and currently no source can fulfill them although several candidates are being developed. One promising possibility is a liquid-xenon-jet based laser-plasma source. Figure 5.4 schematically shows such a source system [183-185] and a possible future configuration to reach the power specification of Table 5.1. The current system typically uses a $\lambda=1064$ Nd:YAG laser with 350 mJ per ~5 ns pulse. The best achieved CE is $0.95\%/ (2\%$BW·$2\pi$sr) at 13.5 nm and the best EUV pulse-to-pulse output stability has been measured to ±8.4% ($3\sigma$) operating 50 mm from the nozzle.

![Potential configuration to reach the future source power requirements](image)

Figure 5.4. Schematic view of the liquid-xenon-jet laser-plasma EUV source system described in Paper 5 and a possible future system configuration to reach the required source power specification assuming that no lossy spectral purity filter or debris mitigation will be needed and that a 5 sr collector is used [186].
The future need for a high average power drive laser presents enormous thermal problems and stable operation far from the nozzle, as shown in Fig. 5.5, is essential for both thermal management and reduced secondary debris production. Paper 4 analyses the stability of liquid-xenon jets in vacuum and presents a method for improved angular stability. Paper 5 presents a thorough review of several important source parameters, e.g., out-of-band emission, source size and shape, maximum repetition rate, and debris. It shows that the liquid-xenon-jet laser-plasma source system could potentially fulfill the source requirements of Table 5.1.

![Figure 5.5. Image of the xenon-liquid-jet laser-plasma EUV source during operation. Adapted from [183].](image)

To limit the required laser drive power an increased CE would be highly beneficial. A possible alternative to xenon as a target material is tin. As shown in Fig. 5.6, the emission from tin is spectrally better suited for the Mo/Si mirrors used. However, as discussed in Section 3.3.1 the use of condensing target material severely increases the debris problem. Paper 9 presents the first EUV measurements on a liquid-tin-jet target including debris measurements. A CE of $2.5\%/\text{(2\%BW}\cdot 2\pi\text{sr})$ at 13.5 nm is demonstrated but the use of tin is questioned since an estimated debris mitigation efficiency of $\sim 10^8$ would be necessary.
It appears very probable that EUVL will eventually be put into production although the insertion year is still unclear. What source will actually be used remains an open question with pros and cons for both laser plasmas and GDPs. However, it seems feasible for a liquid-xenon-jet laser plasma source to meet the requirements.

Figure 5.6. EUV emission from xenon and tin laser plasmas where the gray line indicates the \(~2\%\) BW of a Mo/Si optical system. From Paper 8.
Chapter 6

The Liquid-Metal-Jet Anode X-Ray Tube

6.1 Introduction and Motivation

The physics of electron-impact x-ray sources was described in Chapter 2 and general aspects of current state-of-the-art x-ray tubes were discussed in Section 3.1.1. As mentioned there, the main factor limiting the brightness is the power-loading capability of the anode.

There are many applications currently utilizing x-ray tubes, which would benefit from an increased brightness, either in terms of exposure time, resolution, or dose. These include important applications such as medical imaging [4,5]. Furthermore, such an increase in brightness could allow applications currently only possible at synchrotrons to be performed with a compact source. X-ray phase imaging [187-189] is one such application that appears very promising for, e.g., future medical diagnostics.

With the clear benefit of increased source brightness, several attempts have been made to improve the conventional electron-impact x-ray tube [65,190,191] which is now close to engineering perfection. Most notable of these attempts are different uses of liquid anodes. Use has been made of a stationary liquid anode [192], a liquid flowing across a surface [193] as well as behind a thin window [194]. However, their advantages have been severely limited by the intrinsically low flow speeds, and associated poor heat-load capacities, of such systems.

This chapter describes the development of a new anode concept, based on a high-speed liquid-metal jet, that could potentially increase the attainable brightness in compact electron-impact x-ray sources a factor $10^2$ to $10^3$.

6.2 Source Description

The use of a liquid-metal-jet anode is advantageous since it can withstand a higher electron beam power density than a conventional anode. In short, the reason for this can be summarized as:

- The energy required to heat a metal target from liquid to boiling is higher than what is required to go from room temperature to 20% below the melting point.
• The speed of a liquid-metal jet can be significantly increased compared to the speed of a rotating anode.
• In contrast to a rotating target, the liquid-metal jet is not reused and the electron beam power density can thus be increased beyond the damage threshold.

The liquid-metal-jet anode concept and initial work, including basic thermal calculations, proof-of-principle experiments, and high power scaling possibilities, are described in Papers 6 and 7. Here, a short summary will be given for completeness and as an introduction to the yet unpublished results of electron gun simulations and medium-power experiments described in the following sections.

The power required to evaporate a liquid jet is given by

\[ P = \frac{\pi d^2}{4} \rho v \left[ \Delta T c_p + E_{\text{vap}} \right] \]

where \( d \) is the jet diameter, \( v \) is the speed, \( \rho \) is the density, \( \Delta T \) is the temperature span from liquid to boiling, \( c_p \) is the specific heat capacity, and \( E_{\text{vap}} \) the heat of vaporization. With the use of Eqs. 4.3 and 2.6 a material figure of merit can be calculated and Sn is found to be a top candidate. In addition, Sn has a \( K_\alpha \) line at 25 keV, a low melting point, is decently harmless and readily available. Assuming a 30 µm diameter, 600 m/s liquid-tin-jet heated according to Eq. 6.1 by a 30 µm diameter electron beam the power density would be \( \sim 12 \) MW/mm\(^2\), roughly a factor 100 above current state-of-the-art systems. With the use of a flat jet and a perpendicular line focus this could potentially be improved almost another order of magnitude.

**Figure 6.1.** Schematic setup of the proof-of-principle liquid-metal-jet electron-impact hard x-ray source system. Adapted from Paper 7.
A first proof-of-principle experiment has been performed using a \( \sim 100 \text{ W}, 50 \text{ keV}, \sim 150 \mu\text{m} \) FWHM electron beam incident on a \( 50 \text{ m/s}, 75 \mu\text{m} \) diameter liquid-solder jet (Sn63Pb37), as shown in Fig. 6.1. Although the achieved electron-beam power density of \( \sim 3 \text{kW/mm}^2 \) is far below current-state-of-the-art, it did confirm the basic principle of the liquid-metal-jet anode and the measurements agreed with calculations. As reported in Paper 6 and 7, also spectra, liquid-jet stability and the electron-beam focus size were measured.

Scaling the source to very high power (and brightness) operation is of course not unproblematic. It will require the generation of a stable, well collimated, microscopic \( \sim 500 \text{ m/s} \) liquid-metal jet in vacuum. Paper 9 explores this and finds that, although challenging in terms of engineering, it should be feasible. Furthermore, it will require a 10-100 kW, \( \sim 100 \text{ kV} \) electron beam focused down to \( \sim 30 \mu\text{m} \). Although also challenging, this appears possible and similar electron beams with larger foci, but also larger working distances, are found commercially in electron-beam welders.

A perhaps more fundamental problem lies in the electron beam and liquid-metal jet interaction. Although no instabilities have yet been observed it is difficult to foresee the behavior of the interaction, when the liquid-metal jet is pumped with enough energy to evaporate it during a \( \sim 50 \text{ ns} \) transit time through the electron beam. It is, however, clear that there will be a vacuum issue due to the fact that the jet is brought to evaporate. Other problems include heating uniformity and the limited electron penetration depth, as shown in Fig. 2.10. Possible solutions to these problems are discussed in Papers 6 and 7.

### 6.3 Electron Gun Simulations

The electron gun used in the current system was designed for 500 W, 50 kV CW operation into a \( \sim 50 \mu\text{m} \) focus at a working distance of \( \sim 10 \text{ cm} \). This is a simple, source limited, low perveance* design based on a 1.78 mm diameter flat single crystal LaB\(_6\) cathode. The central part of the electron gun is shown in Fig. 6.2. The electric field is essentially flat in the 50 keV acceleration gap between the cathode and anode and the electron trajectories should therefore be basically straight. However, the anode exit aperture acts as a negative lens and produces a virtual point source. This point source is then imaged by the electromagnetic lens and small deflection coils are used to move the focal spot in the focal plane. The electron beam focus is intentionally steered of axis to minimize the amount of ions backstreaming to the cathode. The small anode and lens apertures allow the electron

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* The perveance, \( p \), is defined as \( I/V^{3/2} \) and used to characterize electron beams. The current electron beam has perveance of \( \sim 1 \text{nP} \), where space charge effects are essentially negligible. An initially parallel electron beam will diverge under the influence of space charge effects and will double its initial diameter, \( r_0 \), after traveling a distance \( \sim 0.013r_0/p^{0.5} \). Space charge effects can also limit the minimum achievable focal spot size.
gun to be differentially pumped by its own 250 l/s turbo-drag pump, and a vacuum better than 10^{-7} mbar (required by the cathode) is maintained although the main chamber is in the 10^{-4} to 10^{-5} mbar range.

![Figure 6.2. Layout of the original electron-beam gun. Dimensions are in mm. From [195].](image)

Although simple in design, and simulated using a standard electron gun simulation package (EGUN2) prior to construction, the performance of the electron beam has not reached the design specifications. The electron beam originally suffered from two main problems: the spot size was in the range of a few hundred microns instead of ~50 µm and the transmission through the gun was ~50% limiting the maximum sustainable power due to anode heating and vacuum issues.

![Figure 6.3. Simulated electron trajectories between the anode and cathode, showing the divergent trajectories from the edge of the cathode. The even more divergent emission from the cathode side is not shown here.](image)
To better understand and hopefully correct the electron beam problems a new electron beam simulation package was developed. In contrast to the existing EGUN package [196] this system uses an easy-to-operate graphical user interface and a variably sized polygonal mesh. This is important as the required geometric simulation accuracy is not constant in the gun and the use of a sufficiently fine, constant mesh, is difficult due to computer limitations. For more details of the FEMLAB based electron simulation package, see Ref. 197. Based on the new, high-resolution simulations, the cathode was redesigned to avoid edge emission, as shown in Fig. 6.3, and the system transmission is now typically 99% allowing full power (600 W) operation over extended periods. However, the spot size is still larger than the simulated values of ~50 µm, typically ~150 µm, and the reason for this is currently unclear. For more information on electron guns and optics see, e.g., Refs. 198-203.

### 6.4 Recent Medium-Power Experiments

Recently, a series of promising medium-power experiments have been performed using the improved electron beam system and a ~25 µm diameter, up to 70 m/s liquid-tin jet. However, the following results are still preliminary [204]. Figure 6.4 shows an image of the liquid-metal jet and electron beam interaction during medium-power operation.

![Figure 6.4](image.png)

**Figure 6.4.** Photograph of the liquid-tin jet and electron beam interaction point during operation with the 600 W, 50 kV electron beam focused to ~150 µm FWHM on a ~20 µm diameter, ~30 m/s liquid-tin jet.
A 9 µm diameter pinhole camera was used to image the x-ray source at an angle of 45º relative the electron beam, and normal to the Sn jet and the spot (shown in Fig. 6.5) was approximately found to be a ~25 µm wide center cutout of a ~150 µm FWHM 2D Gaussian distribution, corresponding to the electron beam and liquid-metal jet overlap. The source positional stability, also shown in Fig. 6.5, was measured by a series of pinhole camera images and the standard deviation found to be ±8 µm vertically and ±1 µm horizontally. The electron beam spot stability was measured to ±2 µm on the static beam dump and the above mentioned horizontal uncertainty was mainly caused by angular instabilities of the liquid jet. However, since no signs of electron beam induced directional instabilities have yet been detected, and the current angular/positional stability of the jet is limited by the mechanical design of the system, it should be possible to significantly improve the x-ray spot stability.

![Figure 6.5. X-ray pinhole camera image of the source (a) and positional stability measurements (b). The stability measurements were done by a series of 50 images, each with an exposure time of 3 s, and the center of gravity calculated for each frame. In (b) each star is the center of mass for a single exposure and the bars indicate the standard deviation. The electron beam was operated at 250 W, 50 kV, ~150 µm FWHM, and the tin jet had a diameter of ~25 µm and a speed of ~50 m/s.](image)

The spectrum was measured under the same conditions as the pinhole camera images in Fig. 6.5, and in the same direction. The source spectrum, shown in Fig. 6.6, has been corrected for detector efficiency, filter losses, spot size, measurement geometry, etc. to give the average spectral source brightness within the FWHM, using a 250 W, ~150 µm FWHM electron beam.
Figure 6.6. Emission spectrum from the initial medium-power experiments. The spectrum has been calculated using the previously measured source size and was recorded using a ~25 µm jet with the electron beam operating at 250 W. With the above mentioned jet and electron beam dimensions, approximately 12% of the total electron beam power hits the jet within the FWHM of the x-ray spot. The spectrum was measured through the pinhole (in a 100 µm thick Ta disc) normally used for imaging but has not been corrected for the transmission through the disc. Although this could bias the spectrum the total transmission through the Ta disc is only ~10% of the transmission through the pinhole.

The maximum achieved electron beam power density on the jet in this experiment was ~8 kW/mm² (within the ~25×150 µm² spot), but using a 600 W electron beam and a 9.5° takeoff angle the effective source size becomes ~25×25 µm² and the effective electron beam power beam density ~110 kW/mm², in parity with current state-of-the-art sources.

6.5 Summary and Conclusions

A new anode concept in compact electron-impact x-ray sources has been introduced. Calculations indicate that this new anode concept could potentially increase the attainable brightness 2-3 orders of magnitude compared to existing compact state-of-the-art electron-impact x-ray sources. This is supported by a first proof-of-principle experiment and preliminary medium-power results that confirm the basic viability of the concept. Although significant challenges remain in developing a high-power source, the positive initial results and the benefit of such an increased brightness certainly warrants further work.
Summary of Papers

This thesis is based on the 9 papers listed below. They are all directed towards the development of compact, high-brightness x-ray sources based on liquid-jet targets. The author has been the main responsible for Papers 1, 2, 6, and 7. In the other papers the author has been actively involved in the planning, preparation and performing of the experiments. However, the author was not actively involved in the out-of-band or ion/sputtering measurements reported in Paper 5.

Paper 1
In this paper a longitudinal droplet position drift in an ethanol-target laser-plasma soft x-ray source for microscopy is analyzed. The drift is found to be the result of an evaporation-induced cooling, influencing the liquid’s viscosity and, thus, the jet speed. A phase-delay droplet-to-laser synchronization, based on real time imaging of the plasma symmetry, is also presented and long-term, stable, source operation demonstrated.

Paper 2
In this paper a semi-empirical model of the jet speed from a tapered glass capillary nozzle is presented. The model takes pressure, density, viscosity and surface tension into account and is found to be accurate to ~5% within the parameter space in which it was developed and tested.

Paper 3
In this paper a carbon-based liquid-jet laser-plasma source for microscopy is optimized in terms of debris per flux by tuning the target liquid and the target size. It is found that the flux can be increased ~3× while decreasing the debris ~2×. An unexpected variation in debris deposition as a function of target material is reported and an oxygen etching mechanism identified as the probable reason.

Paper 4
This paper analyzes the stability of cryogenic liquid jets in vacuum and introduces a method for directional stabilization by heating of the nozzle tip. The evaporation-induced cooling is modeled and the effect of improved jet stability on the emission stability from a laser-plasma source is measured.
Paper 5
This paper describes in-depth quantitative characterization of a liquid-xenon-jet laser-plasma source based on the requirements of a future EUV lithography source. It details the non-EUV emission, size and stability of the in-band emitting plasma as well as size scalability, maximum repetition rate estimates, conversion efficiency, ion emission, and sputtering.

Paper 6
This paper introduces a new liquid-metal-jet anode concept for electron-impact sources. Initial calculations show that this new concept could potentially increase the attainable brightness in compact x-ray tubes by more than a factor 100. The new anode concept is demonstrated in a low power, proof-of-principle experiment verifying the basic concept.

Paper 7
This paper is a more extensive description of the liquid-metal-jet anode concept and the low-power demonstration system. A material figure of merit depending on thermal properties and x-ray conversion efficiency is developed and the system details are described. High-power scaling and source limitations are also discussed.

Paper 8
This paper reports on the first liquid-tin jet laser-plasma EUV source. The conversion efficiency is measured as function of laser pulse energy and power density and a maximum CE of 2.5% into $2\pi\cdot\text{sr}\cdot2\%\cdot\text{BW}$ at 13.5 nm is reported. Quantitative debris measurements as well as maximum repetition rate estimates are also presented.

Paper 9
This paper investigates the hydrodynamics of microscopic high-speed liquid-metal-jets in vacuum through dynamic-similarity experiments using water. It is shown that the vacuum environment prevents the normally limiting wind-induced breakups and that generation of a 30 µm diameter, 500 m/s liquid tin jet in vacuum should be possible.
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Bibliography


[16] D. Attwood, Chapter 1.2 - Basic Absorption and Emission Processes, pp. 5-10, in [3].

[22] D. Attwood, Chapter 3.1 - The Wave Equation and Refractive Index, pp. 56-61, in [3].
[23] D. Attwood, Figure 3.1, pp. 58, in [3].
[32] B. K. Agarwal, Figure 1.14 and 1.15, pp. 20 and 23, in [6].
[33] B. K. Agarwal, Figure 1.20 and 1.16, pp. 25 and 23, in [6].
[35] E. Krestel, ed., Figure 3.2, pp. 62, in [4].
[36] H. Haken, and H. C. Wolf, Figure 18.5, pp. 311, in [11].
[37] B. K. Agarwal, Figure 2.9, pp. 62, in [6].
[38] B. K. Agarwal, Chapter 2 - Characteristic X-Rays, pp. 51-104, in [6].


[44] W. R. Leo, Chapter 2.5.2 - Backscattering of Low-Energy Electrons, pp. 48, in [18].

[45] J. I. Goldstein, and H. Yakowitz, eds., Figure 3.7, pp. 62, in [43].


[50] D. Attwood, Chapter 6.4.4 - Plasma Expansion, pp. 211-213, in [3].

[51] C. E. Max, *Physics of Laser Fusion vol. 1 - Physics of the Coronal Plasma in Laser Fusion Targets* (Lawrence Livermore National Laboratory, Livermore, 1982), Figure 1, pp. 3.

[52] D. Attwood, Figure 6.1, pp. 192, in [3].

[53] D. Attwood, Chapter 6.4 and 6.5 on Plasma models and simulations, pp. 197-238, in [3].

[54] I. C. E. Turcu, and J. B. Dance, Chapter 4.4 and 4.5 on Plasma Equilibrium Models and simulations, pp. 142-157, in [47].


[56] D. Attwood, Figure 5.24, pp. 169, in [3].


[58] H. Haken, and H. C. Wolf, Figure 18.1, pp. 309, in [11].


[60] J. Beutel, H. L. Kundel, and R. L. Van Metter, eds., Figure 1.8, pp. 12, in [5].


[74] G. Johansson, *Compact Soft X-Ray Microscopy*, Ph.D. Thesis (Royal Institute of Technology, Stockholm, 2003), Figure 2.2, pp. 7.


[94] J. A. Samson, and D. L. Ederer, eds., Chapter 4 - Hollow cathode, Penning, and Electronbeam Excitation Sources, pp. 65-81, in [27].


[106] J. A. Samson, and D. L. Ederer, eds., Chapter 3.5 - Electron Cyclotron Resonance Sources, pp. 52-54, in [27].


[118] A. W. Sáenze, and H. Überall, eds., Chapters 4 through 7 on Channeling, pp. 61-194, in [115].


[121] A. W. Sáenze, and H. Überall, eds., Chapters 2 and 3 on Coherent Bremsstrahlung, pp. 5-60, in [115].


[125] P. Rullhusen, X. Artru, and P. Dhez, Chapter 4 - Compton Scattering of Laser Light, pp. 89-98, in [113].


[137] A. H. Lefebvre, Chapter 2 - Basic Processes in Atomization, pp. 27-78, in [130].


[142] R. D. Blevins, Chapter 4 - Dimensional Analysis, pp. 8-18, in [133].


[145] A. H. Lefebvre, Figure 2.8 and 2.10, pp. 45 and 49, in [130].


[157] G. Johansson, Figure 6.1, pp. 40, in [74].


[164] TWINSAN SCAN XT1250 193 nm Stepper from ASML Holdings NV, the Netherlands, information available online at http://www.asml.com.


[166] H. J. Levinsson, Chapter 8 - Overcoming the Diffraction Limit, pp. 257-283, in [162].


[204] O. Hemberg, M. Otendal, T. Tuohimaa, and H. M. Hertz, work in progress.