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A TABLETOP SOFT X-RAY SOURCE BASED ON 5-10 MeV LINACS

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Abstract

We are investigating the feasibility of a novel, tabletop, high-brightness soft X-ray source. Our approach is based on generation of inner-shell Čerenkov radiation by passing a 5-10 MeV electron beam through a thin foil. Theoretical calculations based on existing, but rather scarce, optical data predict a surprisingly large photon yield for a number of materials (e.g. Al, Si, B, C, Ti and Sc) emitting in the 2-40 nm wavelength range. The source is also characterised by a high degree of directionality and a narrow bandwidth.

1 INTRODUCTION

High-brightness sources of laboratory size in the soft X-ray region (2-40 nm) are not yet available, although there is an increasing demand in a variety of research areas. Two major applications are, for example, EUV lithography and X-ray microscopy, which are extensively discussed by Attwood [1]. We are investigating the feasibility of using a new mechanism, that is generating inner-shell Čerenkov radiation by passing a 5-10 MeV electron beam through a thin foil, for a novel, tabletop, high-brightness soft X-ray source.

It is well known that a charged particle emits Čerenkov light, when its speed exceeds the phase velocity of light c/*n* in a medium with refractive index *n*. This 'shock wave of light' is emitted at the angle of constructive interference, given by

$$\cos(\theta) = \frac{1}{\beta n(\omega)} \qquad (1)$$

with $\beta = v/c$ and v the speed of the particle.

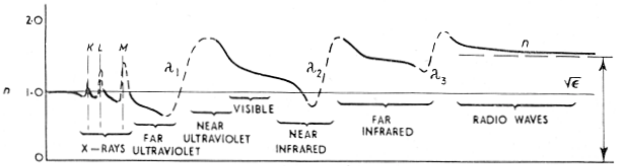

Figure 1: The dispersion curve of a typical transparent medium over the whole electromagnetic spectrum [5].

The Čerenkov radiation is limited to the frequency regions where the condition $n(\omega) \geq 1/\beta$ is fulfilled. This is mainly at near-ultraviolet, visible and longer wavelengths (see figure 1). Čerenkov radiation in the X-ray domain was excluded for a long time, because above the plasma frequency the refractive index is generally smaller than unity. The exceptions are the small regions of anomalous dispersion around absorption edges, where the refractive index may slightly exceed unity, but these regions were disregarded because of strong absorption ([2] p. 51).

Bazylev *et al.* [3] realised that efficient generation of soft X-ray Čerenkov radiation is possible around absorption edges under the condition that the coherence length (radiation formation length) is smaller than the absorption length. Bazylev *et al.* illustrated this by experiments on a carbon foil with a 1.2 GeV electron beam. Later, also Moran *et al.* [4] showed convincingly that Čerenkov radiation indeed is emitted by 75 MeV electrons in silicon around the L-edge (≈100 eV) and in carbon around the K-edge (≈280 eV). Only a few theoretical studies [5,6] have addressed the feasibility of soft X-ray radiation at the inner-shell energies.

We propose using electron beams of moderate energies (5-10 MeV) to produce Čerenkov radiation from a foil. As we show in this paper, these energies are often sufficient to produce the optimal photon flux, close to the absolute maximum value. Relatively little is gained by going to higher energies. As a consequence, small (medical) LINACs can be used resulting in a truly tabletop soft X-ray source. In this paper we discuss the promising characteristics of such a source.

2 INTRINSIC BRIGHTNESS

Spectral brightness is often used as a measure of the quality of a light source and is defined by the photon flux per unit relative bandwidth, per unit solid angle and per unit source area. The first three quantities of the spectral brightness will be discussed in separate sections below. As an illustration the equations will be applied to silicon L-edge (99.6 eV) Čerenkov radiation generated by 10 MeV electrons.

2.1 Čerenkov radiation yield

We start from the Frank and Tamm [7] expression for the Čerenkov radiation emitted per unit length by a particle of charge q:

$$\frac{dW}{dl} = \frac{q^2}{4\pi\varepsilon_0 c^2} \int_{\beta n(\omega)>1} \left(1 - \frac{1}{\beta^2 n(\omega)^2}\right) \cdot \omega \, d\omega \qquad (2)$$

The (real) dielectric constant is defined by $n(\omega)^2 \equiv \varepsilon(\omega) \equiv 1 + \chi'(\omega)$. Using the fact that around the absorption edges the susceptibility $\chi'(\omega) << 1$, and in the case that $\gamma \equiv (1-\beta^2)^{-1/2} >> 1$, we find that the N number of Čerenkov photons emitted per electron is given by

$$\frac{d^2 N}{dl \cdot d\omega} = \frac{\alpha}{c}\left(\chi'(\omega) - \gamma^{-2}\right) \qquad (3)$$

with α the fine structure constant.

In this approximation the threshold condition for Čerenkov radiation is given by $\chi'(\omega)>\gamma^{2}$. From (3) it can be seen that the number of photons is proportional to the path length through the medium. This does not hold for an absorbing medium, which is the case in the soft X-ray domain. The dielectric constant of a absorbing medium is a complex number, $\varepsilon(\omega)\equiv 1+\chi'+i\chi''$, and the absorption length of the material is given by $l_{abs}(\omega)\approx c/(\omega\chi''(\omega))$. In figure 2 the complex dielectric constant is plotted versus photon energy around the L absorption edge.

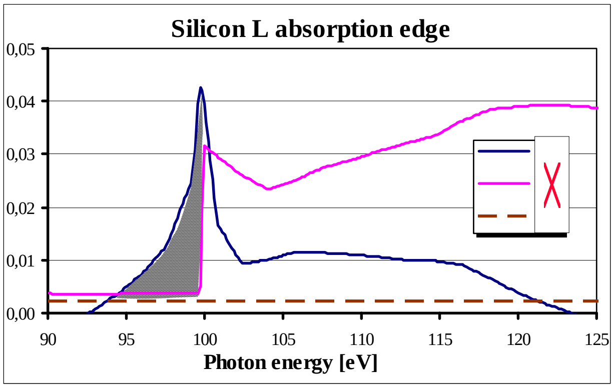

Figure 2: The complex dielectric constant around the silicon L absorption edge. The shaded area indicates the photon yield. Also is indicated γ^{-2} for 10 MeV electrons.

Generally, from a foil with a thickness of at least several absorption lengths, only those photons created effectively within one absorption length leave the surface. Integrating equation (3) over the absorption length gives

$$\frac{dN}{d\omega}=\frac{\alpha}{\omega}\left(\frac{\chi'(\omega)-\gamma^{-2}}{\chi''(\omega)}\right) \qquad (4)$$

From equation (4) it can be concluded that the criterion for a high photon yield is $(\chi'(\omega)-\gamma^{2})>>\chi''(\omega)$, which is equal to the statement of Bazylev that $2\pi l_{abs}>>l_{coh}/2$. The factor of 2π arises here because Bazylev used a different definition of the absorption length in his article. Equation (4) can be rewritten by substituting the coherence length $l_{coh}(\omega)\approx 4\pi c/(\omega(\chi'(\omega)-\gamma^{2}))$:

$$\frac{dN}{d\omega}=\frac{4\pi\alpha}{\omega}\frac{l_{abs}(\omega)}{l_{coh}(\omega)} \qquad (5)$$

If the condition $l_{abs}>>l_{coh}/4\pi$ is not fulfilled, a more thorough approach becomes necessary [3]. In figure 2 it can be seen that on the low-energy side of the Si L-edge $\chi'\approx 10\chi''$, thus the condition is fulfilled. Then, the total number of photons is given by equation (5) and is roughly proportional to the area marked in figure 2. For the silicon L-edge Čerenkov radiation, we calculate a yield of $1.7\cdot 10^{-3}$ photon/electron for a 10 MeV electron. In case a 1 mA average current 10 MeV LINAC is used, the number of photons emitted per second is about 10^{13} ph/s, i.e. 0.17 mW at 100 eV.

2.2 Čerenkov radiation line width

The anomalous dispersion around the absorption edge causes positive susceptibility in a very small wavelength band. Only in this region Čerenkov radiation is emitted, which determines the absolute line width. For the silicon L-edge with 10 MeV electrons the FWHM line width is 0.1 nm, i.e. $\Delta\lambda/\lambda\approx 0.008$.

2.3 Directionality of the Čerenkov radiation

The Čerenkov radiation is emitted at the angle θ of constructive interference given by (1), which is approximated for small angles, $\cos(\theta)\approx 1-½\theta^{2}$, small susceptibility, $\chi'(\omega)<<1$, and high electron energies, $\gamma>>1$, by

$$\theta=\sqrt{\chi'-\gamma^{-2}} \qquad (6)$$

There is a maximum angle for Čerenkov radiation corresponding to the photon energy for which χ' is maximal, which also coincides with the maximum yield in Čerenkov radiation. For the silicon L-edge with 10 MeV electrons the maximum angle of radiation is 11.5°. The associated FWHM angular width is 3.4°.

3 OPTIMAL ELECTRON ENERGY

It is not necessary to have very high electron energies for efficient production of Čerenkov radiation. The threshold value γ_{th} is given by

$$\gamma_{th}=(\chi'_{\max})^{-1/2} \qquad (7)$$

If $\gamma>>\gamma_{th}$, then the maximum Čerenkov photon yield is achieved, because then equation (4) is independent of γ. But for an optimal Čerenkov photon yield it is already sufficient for γ to be a few time γ_{th}. The threshold electron energies for a few materials that have absorption edges with anomalous dispersion in the soft X-ray domain are between 2 and 8 MeV. This means that LINACs of 5, 10 or 25 MeV are sufficient to produce Čerenkov radiation from a foil with promising characteristics. These accelerators are compact enough to develop a tabletop soft X-ray source. For these moderate electron energies the yield is slightly lower than in case of high-energy electrons. In table 1 this effect is illustrated for the silicon L-edge.

Table 1: The characteristics of the source when different LINACs are used as electron source.

	5 MeV	**10 MeV**	**25 MeV**	**1.2 GeV**
N [#ph/el]	$8.5\cdot 10^{-4}$	$1.7\cdot 10^{-3}$	$2.1\cdot 10^{-3}$	$2.2\cdot 10^{-3}$
$\Delta\theta$ FWHM	62 mrad	63 mrad	67 mrad	67 mrad
$\Delta\lambda$ FWHM	0.09 nm	0.15 nm	0.17 nm	0.17 nm

3 SOFT X-RAY ČERENKOV EMITTING MATERIALS

In the literature two materials, silicon and carbon, have been shown to emit soft X-ray Čerenkov radiation at respectively the L-edge (99.6 eV) and K-edge (288 eV).

3.1 Refractive index throughout the periodic table

What can be predicted for other materials? There exists little experimental data on the anomalous dispersion of materials in the soft X-ray domain. Direct measurements of the real part of the refractive index, that is necessary at the absorption edges, are extreme difficult and therefore scarce. One of the most recent measurements of the refractive index at the carbon K-edge by interferometry has been done by Joyeux *et al.* [9]. They compared their experimental data to the two most accurate databases available [10,11]. For the carbon absorption K-edge they have measured positive values of the susceptibility and the CXRO database was quantitatively most comparable to these measurements.

Smith *et al.* [8] discussed the sign reversal of the susceptibility of silicon and aluminium at the L-edge and made predictions for other materials. They presented a few conditions for atoms to have likely sign reversal in the soft X-ray domain. First, the element must have a strong absorption edge with a sharp onset. Second, the edge must be sufficiently isolated that the high-energy absorption tails of transitions at lower energies are small. These conditions favour edges originating from levels that are filled with a large number of electrons, such as $L_{II,III}$ in the third period and $M_{IV,V}$ in the fourth period. Exceptions are the K-edges of the elements in the second period (e.g. C), because they lack a well-developed L-shell.

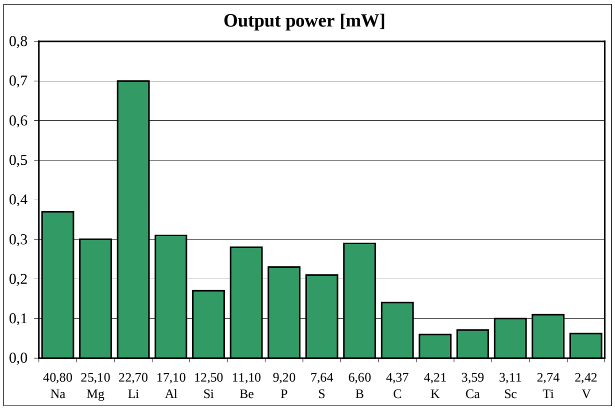

Figure 3: The output power [mW] of several elements at the given wavelength [nm] with a 1 mA average current 10 MeV LINAC.

With this knowledge the CXRO database [10] has been used to investigate the periodic table on potential Čerenkov emitters. Although this database consists of data calculated by Henke from mass absorption coefficients using the Kramers-Kronig relations, the quantitative agreement with the data of Smith is striking enough to use it for predictions. In figure 3 an overview of elements is shown that potentially emit in the 2-40 nm soft X-ray wavelength region. The output power per element is calculated by using equation (4).

4 CONCLUSION

The investigation throughout the periodic table, summarised in figure 3, predicts a variety of Čerenkov radiation emitters in the soft X-ray region. It is based on simple calculations by using equation (4) and the CXRO database. The presented values are based on 10 MeV electron energy, which is sufficient to produce an optimal yield, while enabling a tabletop soft X-ray source. Higher electron energies are not necessary, because the yield will not be significantly enhanced.

Besides the promising output values, the source is also characterised by a relatively small bandwidth in the order of 10^{-2}. Together with the fact that the radiation is emitted in a cone with a small angular spread of a few degrees, the source has got promising optical characteristics.

Our first experiments focus on the measurement of L-edge Čerenkov radiation from a 10 μm silicon foil. We use a 5 MeV medical LINAC with an average current up to 100 μA, as electron source.

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