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# High-brightness, narrowband, and compact soft x-ray Cherenkov sources in the water window

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Narrowband, soft x-ray Cherenkov radiation at energies of 453 and 512 eV has been generated by 10 MeV electrons in, respectively, titanium and vanadium foils. The measured spectral and angular distribution of the radiation, and the measured total yield ( $\approx 10^{-4}$  photon per electron) are in agreement with theoretical predictions based on refractive index data. We show that the brightness that can be achieved using a small electron accelerator is sufficient for practical x-ray microscopy in the water-window spectral region. © 2003 American Institute of Physics.

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Recently, there has been much progress in the development of laboratory-sized, high-brightness soft x-ray sources in the water-window spectral region. The water window lies between the carbon-*K* absorption edge at 284 eV (4.47 nm) and the oxygen-*K* absorption edge at 543 eV (2.36 nm) and is the ideal spectral region for x-ray microscopy.<sup>1</sup> Promising sources are laser-produced plasmas<sup>2,3</sup> and high-harmonic generation with femtosecond laser pulses.<sup>4,5</sup> Unfortunately, the former suffers from debris and both lack monochromaticity. In this letter we present clean, high-brightness soft x-ray line sources within the water window based on Cherenkov radiation generated by 10 MeV electrons passing through titanium (454 eV or 2.73 nm) and vanadium (512 eV or 2.42 nm) foils. We claim that this Cherenkov source is suitable for soft x-ray microscopy.

Cherenkov radiation is a well-known phenomenon in the visible spectral region and is, for example, often used for high-energy particle identification.<sup>6</sup> However, in the soft x-ray region it was excluded for a long time. Cherenkov radiation is emitted by a charged particle when its velocity  $v$  in a medium with refractive index  $n$  exceeds the phase velocity of light  $c/n$ . In the soft x-ray region this condition is generally not fulfilled, because the refractive index is smaller than unity. Bazylev *et al.*,<sup>7</sup> however, realized that due to resonant behavior of the refractive index at absorption edges it is possible to generate Cherenkov radiation in narrow spectral regions. This effect was demonstrated for carbon at the *K* edge using 1 GeV electrons<sup>8</sup> and later also for 75 MeV electrons.<sup>9</sup> Efficient generation of soft x-ray Cherenkov radiation, however, does not require such ultrahigh energy electrons. This was recently demonstrated<sup>10</sup> by using 5 MeV electrons to generate silicon *L*-edge (99.7 eV) radiation. In the present letter we show that for a variety of materials Cherenkov radiation can even be generated in the water window, using a 10 MeV electron accelerator.

In the extreme ultraviolet (EUV) and soft x-ray spectral

region all materials are highly absorbing and therefore the electromagnetic interaction is described by a complex refractive index ( $\tilde{n} = n + ik$ ). The real part of the refractive index ( $n = 1 - \delta$ ) describes the phase propagation of waves (which is mainly dominated by atomic scattering properties), while the imaginary part ( $k$ ) represents the absorption. At atomic absorption edges, corresponding to the binding energies of inner-shell electrons, the real part of the refractive index shows resonant behavior associated with bound electrons in that shell. This anomalous resonance dispersion can be so strong that the real part  $n$  exceeds unity, whereas for photon energies in the EUV range and higher it is generally smaller than unity. From a thorough analysis of strong resonance effects by Smith *et al.*,<sup>11</sup> we find that such resonances only occur in the soft x-ray region (30 eV–1 keV) for low- $Z$  elements ( $Z < 30$ ) in the solid state. These are therefore in principle suitable materials for generating soft x-ray Cherenkov radiation. As an example Fig. 1(b) shows the refractive index of titanium<sup>12</sup> around the *L* edge (453 eV). The real part peaks well above unity, which enables generation of Cherenkov radiation with 10 MeV electrons.

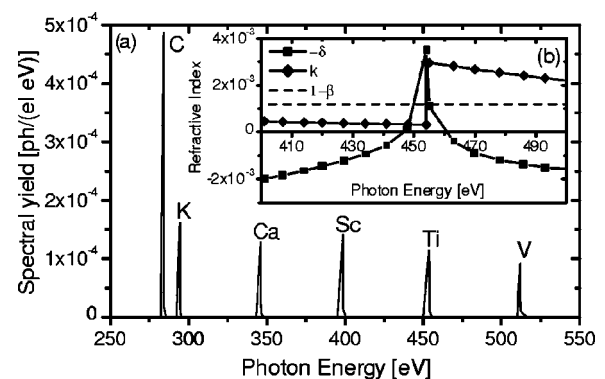


FIG. 1. (a) The Cherenkov spectral yield in the water window for different materials using 10 MeV electrons, predicted on basis of refractive index data of Ref. 12. (b) The real part ( $n - 1 = -\delta$ ) and the imaginary part ( $k$ ) of the refractive index of titanium around the *L* edge (454 eV). The dotted line indicates the  $1 - \beta$  threshold for Cherenkov emission for 10 MeV electrons.

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The available number of data points for the refractive index at absorption edges is limited. Nevertheless, it is sufficient to discuss in some detail two characteristic properties of soft x-ray Cherenkov radiation, i.e., (i) its narrow bandwidth and (ii) its narrow angular distribution. (i) The Cherenkov condition  $n \geq 1/\beta$ , with  $\beta = v/c$  the relative velocity of the electron, limits the generation of Cherenkov radiation to a small spectral range. Due to the step in absorption at the edge the width of the Cherenkov spectrum is even further narrowed to a few electron-volts. (ii) The angle of emission  $\theta$  is given by the Cherenkov angular relation  $\cos(\theta) = 1/(n\beta)$ . Because  $n$  and  $\beta$  are close to unity, the radiation is concentrated in a hollow cone in the forward direction. Within that cone, the Cherenkov angular intensity<sup>13</sup> is maximal at  $\theta_{\max}$ , determined by  $n_{\max}$ , e.g.,  $\theta_{\max} = 3.9^\circ$  for titanium using 10 MeV electrons.

On the basis of refractive index data from Ref. 12 a number of materials can be identified as suitable Cherenkov emitters in the water window. To calculate the Cherenkov yield for these materials a code is used that numerically evaluates the Ginzburg–Frank equation,<sup>14</sup> which gives the number of photons per electron, per unit frequency, and per unit solid angle. By integrating over all emission angles the spectral yield is obtained. Figure 1(a) shows the result of such a calculation using 10 MeV electrons. All materials emit Cherenkov radiation with a typical full width at half maximum (FWHM) of about 1.5 eV and a yield of a few times  $10^{-4}$  photons per electron.

We have verified the above predictions by experiment. For the first experiments titanium and vanadium were selected, because both metals are readily available in micron-thick foils. The experimental setup is designed to measure the Cherenkov radiation as a function of emission angle. The 10 MeV electrons are generated by a medical linear accelerator (M.E.L. SL-75). After the electron beam has passed through the foil a 90°-dipole magnet bends the beam into a dump, where the current is measured. The detector unit is placed at the end of a 1 m long arm that can be rotated in the vertical plane from  $-20^\circ$  to  $+20^\circ$  with respect to electron beam. To analyze the emitted radiation a soft x-ray charge coupled device (CCD) camera is used, which has been developed by Space Research Organization Netherlands for x-ray astronomy<sup>15</sup> and is capable of measuring the energy of individual photons with a high quantum efficiency ( $>80\%$ ). Photon energies between 280 eV and 15 keV can be resolved spectrally. The FWHM spectral resolution is 165 eV at 1.5 keV and scales with the square root of the photon energy. In front of the CCD chip a thin aluminum–carbon filter (layer thicknesses of 150 and 27 nm) with a diameter of 16 mm (Luxel corp.) is mounted to block any visible light. This limits the detection solid angle to  $2.2 \times 10^{-4}$  sr.

In Figs. 2(a) and 2(d) pulse height spectra are shown of the radiation generated by 10 MeV electrons passing through 10- $\mu\text{m}$ -thick foils (Goodfellow) of, respectively, titanium and vanadium, both measured at an observation angle of  $4^\circ$ . Both pulse height spectra contain two peaks: The strong peak on the low-energy side is interpreted as Cherenkov radiation, as will be discussed in detail in the following, and the weaker peak on the high-energy side is identified as fluorescence radiation, which will be used for energy calibration.

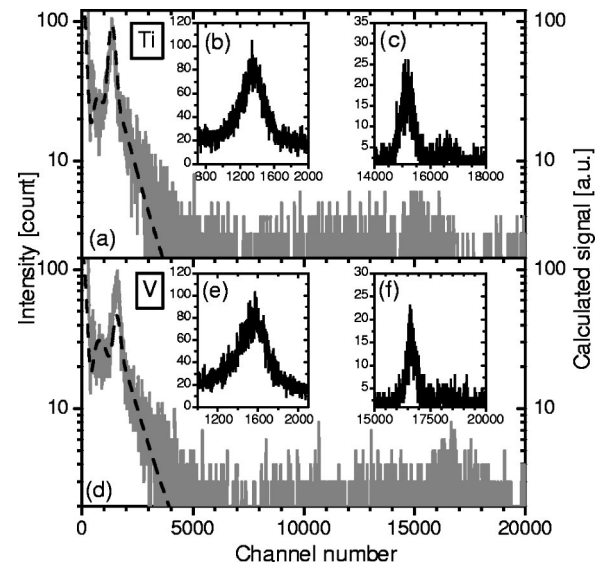


FIG. 2. Pulse height spectrum of the radiation produced by 10 MeV electrons in titanium (a) and vanadium (d) at an observation angle of  $4^\circ$ . The dotted curve indicates the calculated yield taking the CCD response into account. (b), (e) Enlargement of the Cherenkov peak. (c), (f) Enlargement of an additional measurement of the fluorescent lines measured at an observation angle of  $10^\circ$  and much higher beam current.

Figures 2(b) and 2(e) zoom in on the Cherenkov peak. Note that the measured width of, for example, the titanium peak (96 eV FWHM) is completely determined by the spectral resolution of the CCD camera. The theoretical width of 2.0 eV thus implies that the real amplitude is approximately 50 times higher. The background under the Cherenkov peaks is a low intensity, continuous spectrum of transition radiation<sup>16</sup> that is decreasing with photon energy and has its maximum intensity at an emission angle of  $1/\gamma$  ( $\gamma$  is the Lorentz contraction factor), i.e.,  $2.8^\circ$  for 10 MeV electrons. The enlarged spectra in Figs. 2(c) and 2(f) show additional measurements of the  $K_\alpha$  and  $K_\beta$  fluorescence lines, which are measured at an observation angle of  $10^\circ$  and with much higher electron beam current.

The photon energy of the Cherenkov lines can be obtained from the spectra by fitting the peaks to a Gaussian line profile. The linear calibration of the channel numbers was obtained by using the titanium and vanadium  $K_\alpha$  lines (the resolution of the CCD camera is too low to resolve  $K_{\alpha 1}$  and  $K_{\alpha 2}$ ) and a third  $K_\alpha$  line obtained from an aluminum foil. Based on this calibration the Cherenkov peak energies are experimentally determined at  $459 \pm 2$  eV for titanium and at  $519 \pm 3$  eV for vanadium, while theoretically the peak energies should be at their respective  $L$  edges, i.e., 453 and 512 eV. The fact that we measure the peaks at slightly higher photon energies can be explained by a precise analysis of the theoretical Cherenkov spectrum (using the Ginzburg–Frank equation) convoluted with the CCD spectral response as is indicated by the dotted line in both spectra [Figs. 2(a) and 2(d)]. At an energy a few electron-volts below the  $L$  edge the quantity  $\delta = 1 - n$  goes through zero, so at this energy Cherenkov radiation and the transition radiation background are both absent. The resulting dip in the radiation spectrum shifts the peak of the convoluted spectrum to slightly higher energies: the resulting theoretical peak energy is 458 eV for titanium and 522 eV for vanadium. The measured peak energies

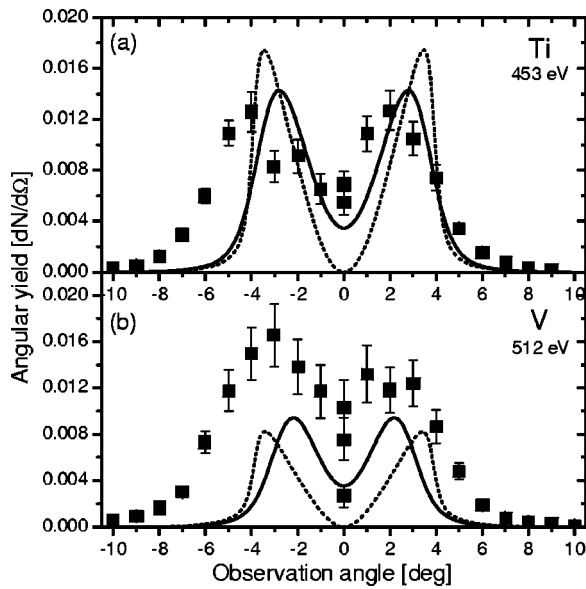


FIG. 3. Measured Cherenkov angular yield [ph/(el sr)] as a function of detector angle generated by 10 MeV electrons in titanium (a) and vanadium (b). The dotted curves are the theoretical angular yields for an ideal beam. The solid curves take elastic scattering of the electron beam in the foils into account as well.

agree with these values within the experimental error.

Similar spectra have been obtained both for titanium and vanadium at observation angles ranging from  $-10^\circ$  to  $+10^\circ$ . The resulting Cherenkov angular yields of titanium and vanadium (number of photons per electron and per unit solid angle) as a function of observation angle are shown in Figs. 3(a) and 3(b). Clearly the typical angular behavior of Cherenkov radiation is seen, which is a symmetric profile that has a maximum associated with the maximum value of the refractive index  $n$  and drops rapidly to zero for larger angles. The dotted curves represent the emission profile of Cherenkov radiation for a perfectly parallel beam, which is calculated by integrating the Ginzburg–Frank equation over the narrow spectral region where the Cherenkov condition is fulfilled. Due to the fact that the electrons undergo small-angle elastic scattering when passing through the foil, the angular profile is broadened as is indicated by the solid curve. The measured angular profile is also shifted with respect to the theoretical curve, which is probably due to a small misalignment of the electron beam.

Integrating over all emission angles we find a total yield of  $3.5 \times 10^{-4}$  photons/el for titanium and  $4.3 \times 10^{-4}$  photons/el for vanadium. For titanium this is slightly higher than the theoretical value of  $2.4 \times 10^{-4}$  photons/el. For vanadium the experimental value is even a few times higher than the theoretical value of  $1.4 \times 10^{-4}$  photons/el. The latter can be explained by assuming that the resonance dispersion at the vanadium  $L$  edge is slightly broader than according to the refractive index data of Ref. 12.

Given the measured yields per electron, we can now evaluate the potential of this Cherenkov-radiation-based

compact source for soft x-ray microscopy. Using a high-power, but laboratory-sized, 10 MeV accelerator of 1 mA average current the total output is  $2.2 \times 10^{12}$  photons/s (0.16 mW) for titanium and  $2.7 \times 10^{12}$  photons/s (0.22 mW) for vanadium. The corresponding brightness is  $2.7 \times 10^9$  photons/( $s \mu\text{m}^2 \text{sr} 0.1\% \text{ BW}$ ) for titanium and  $4.9 \times 10^9$  photons/( $s \mu\text{m}^2 \text{sr} 0.1\% \text{ BW}$ ) for vanadium, assuming a  $100 \mu\text{m}$  electron-beam spotsize. These fluxes are comparable to the values obtained from laser-produced plasma<sup>2</sup> [ $1 \times 10^{10}$  photons/( $s \mu\text{m}^2 \text{sr} 0.1\% \text{ BW}$ ) using high-power lasers] and high-harmonic generation<sup>4</sup> [ $5 \times 10^7$  photons/( $s \mu\text{m}^2 \text{sr} 0.1\% \text{ BW}$ )]. We emphasize that in contrast to the situation in these sources, the Cherenkov spectrum consists of only a single, isolated peak and that no debris formation occurs.

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<sup>1</sup>C. Jacobsen, Trends Cell Biol. **9**, 44 (1999).

<sup>2</sup>G. A. Johansson, A. Holmberg, H. M. Hertz, and M. Berglund, Rev. Sci. Instrum. **73**, 1193 (2002).

<sup>3</sup>R. Lebert, G. Schriever, T. Wilhein, and B. Niemann, J. Appl. Phys. **84**, 3419 (1998).

<sup>4</sup>C. H. Spielmann, N. H. Burnett, S. Sartania, R. Koppitsch, M. Schnürer, C. Kan, M. Lenzner, P. Wobrauschek, and F. Krausz, Science **278**, 661 (1997).

<sup>5</sup>Z. Chang, A. Rundquist, H. Wang, M. M. Murnane, and H. C. Kapteyn, Phys. Rev. Lett. **79**, 2967 (1997).

<sup>6</sup>C. Grupen, *Particle Detectors* (Cambridge University Press, Cambridge, 1996).

<sup>7</sup>V. A. Bazylev, V. I. Glebov, E. I. Denisov, N. K. Zhevago, and A. S. Khlebnikov, JETP Lett. **24**, 371 (1976).

<sup>8</sup>V. A. Bazylev, V. I. Glebov, E. I. Denisov, N. K. Zhevago, M. A. Kumakhov, A. S. Khlebnikov, and V. G. Tsinoev, Sov. Phys. JETP **54**, 884 (1981).

<sup>9</sup>M. J. Moran, B. Chang, M. B. Schneider, and X. K. Maruyama, Nucl. Instrum. Methods Phys. Res. B **48**, 287 (1990).

<sup>10</sup>W. Knulst, O. J. Luiten, M. J. van der Wiel, and J. Verhoeven, Appl. Phys. Lett. **79**, 2999 (2001).

<sup>11</sup>D. Y. Smith and J. H. Barkyoumb, Phys. Rev. B **41**, 11529 (1990).

<sup>12</sup>B. L. Henke, E. M. Gullikson, and J. C. Davis, At. Data Nucl. Data Tables **54**, 181 (1993).

<sup>13</sup>J. V. Jelley, *Cherenkov Radiation and Its Applications* (Pergamon, London, 1958).

<sup>14</sup>M. L. Ter-Mikaelian, *High-Energy Electromagnetic Processes in Condensed Media* (Wiley, Toronto, 1972), Chap. 4.

<sup>15</sup>J. W. den Herder, A. C. Brinkman, S. M. Kahn, G. Branduardi-Raymont, K. Thomsen, H. Aarts, M. Audard, J. V. Bixler, A. J. den Boggende, J. Cottam, T. Decker, C. Erd, H. Goulooze, M. Güdel, P. Guttridge, C. J. Hailey, K. Al Janadi, J. S. Kaastra, P. A. J. de Korte, B. J. van Leeuwen, C. Mauche, A. J. McCalden, R. Mewe, A. Naber, F. B. Paerels, J. R. Peterson, A. P. Rasmussen, K. Rees, I. Sakellidou, M. Sako, J. Spodek, M. Stern, T. Tamura, J. Tandy, C. P. de Vries, S. Welch, and A. Zehnder, Astron. Astrophys. **365**, L7 (2001).

<sup>16</sup>B. Lastdrager, A. Tip, and J. Verhoeven, Phys. Rev. E **61**, 5767 (2000).