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Observation of narrow-band Si L-edge Čerenkov radiation generated by 5 MeV electrons

W. Knulst,[a)] O. J. Luiten, and M. J. van der Wiel
Applied Physics Department, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

J. Verhoeven
FOM Institute for Atomic and Molecular Physics, Kruislaan 407, 1098 SJ Amsterdam, The Netherlands

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Narrow-band Čerenkov radiation at 99.7 eV has been generated by 5 MeV electrons in a silicon foil, with a yield $\sim 1\times 10^{-3}$ photon/electron. These measurements demonstrate the feasibility of a compact, narrow-band, and intense soft x-ray source based on small electron accelerators. The observed yield and dependence of the photon spectrum on emission angle are in agreement with theoretical predictions for Čerenkov radiation based on refractive index data of silicon. [DOI: 10.1063/1.1415049]

Radiation sources based on relativistic electrons[1] have been investigated since the first accelerators were built. Among effects to generate soft x-ray radiation by interaction of electrons with a medium, e.g., coherent bremsstrahlung, channeling radiation, parametric x rays, and transition radiation, until now the well known Čerenkov effect has received little attention.

Čerenkov radiation is emitted by a charged particle if its velocity (v) exceeds the phase velocity of light (c/n) and is therefore limited to the wavelength regions where the real part of the refractive index exceeds unity ($n>1$). Since generally $n<1$ for ultraviolet and shorter wavelengths, soft x-ray Čerenkov radiation (XCR) was excluded for a long time. Bazylev *et al.*[2] realized that XCR is possible in the narrow regions of resonant anomalous dispersion at atomic absorption edges, where the refractive index may slightly exceed unity. This was experimentally confirmed by Bazylev *et al.*[3] using 1.2 GeV electrons and by Moran *et al.*[4] using 75 MeV electrons.

In this letter we report on the observation of narrow band silicon L edge Čerenkov radiation generated by 5 MeV electrons, with a yield $N\approx 1\times 10^{-3}$ photon/electron. We show, in contrast to earlier observations,[3,4] that efficient generation of XCR is possible with moderate electron energies, which can be produced by small accelerators. Using a table-top accelerator to generate Čerenkov radiation a potentially high brightness, nondebris, narrow-band, and compact source in the soft x-ray region may therefore be realized. Since XCR is generated within the wavelength regions where high-reflectivity soft x-ray multilayer (e.g., Mo/Si) mirrors operate, such a source is perfectly matched to applications using multilayer mirrors (e.g., EUV laboratory lithography). Other interesting potential applications are x-ray microscopy in the so-called water window ($\hbar\omega = 284-543$ eV) and x-ray fluorescence analysis of low Z elements.

In the soft x-ray region all materials are highly absorbing, which is taken into account by a complex dielectric constant: $n(\omega)^2 \equiv \varepsilon(\omega) \equiv 1+\chi'(\omega)+i\chi''(\omega)$, where the real part of the susceptibility, χ', describes the dispersion and the imaginary part, χ'', the absorption. Typically, the values of $|\chi'|$ and χ'' are of the same order of magnitude and much smaller than unity ($|\chi'|,\chi''\ll 1$). In the approximation of small χ' and relativistic electrons {Lorentz factor $\gamma\equiv[1-(v/c)^2]^{-1/2}\gg 1$} the well-known Čerenkov condition, i.e., $v>c/n(\omega)$, is given by $\chi'(\omega)>\gamma^{-2}$. It turns out that in the soft x-ray region χ' can be larger than zero only in narrow wavelength regions around atomic absorption edges, owing to resonance effects. In Fig. 1(a) the real and imaginary parts of the susceptibility of silicon are plotted as a function of photon energy around the L edge ($\hbar\omega = 99.7$ eV). The susceptibility data are taken from the Henke database.[5] From the maximum value of χ' ($\chi' = 0.043$ at $\hbar\omega = 99.7$ eV) follows that Čerenkov radiation is generated for electron energies larger than 2.0 MeV, which implies that small accelerators can be used. Figure 1(a) shows that for the 5-MeV-linear accelerator ($\gamma\approx 11$), which is used in our experiments, Čerenkov radiation is generated from $\hbar\omega\approx 97$ eV to 118 eV.

The calculation of the Čerenkov yield from an absorbing

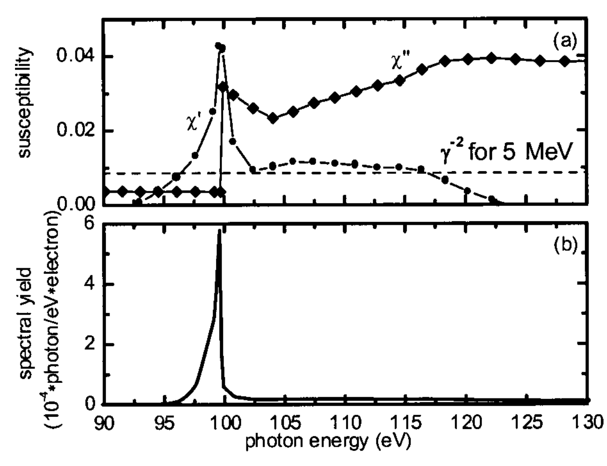

FIG. 1. (a) Real part (χ', circles) and imaginary part (χ'', diamonds) of the susceptibility of silicon as a function of photon energy around the L edge. The Čerenkov threshold for 5 MeV electrons is indicated by a dashed line. (b) Čerenkov spectral yield for 5 MeV electrons in a 10 μm silicon foil.

a)Electronic mail: w.knulst@tue.nl

foil much thicker than the absorption length ($l_{\mathrm{abs}} \approx c/\omega\chi''$) requires the Ginzburg–Frank equation[6] with a complex dielectric constant. The Ginzburg–Frank equation gives the spectral angular yield $\partial^2 N/\partial\omega\partial\Omega$, i.e., the number of photons per frequency interval and per unit solid angle, emitted from the surface of a semi-infinite medium by an electron passing through with uniform velocity. Figure 1(b) shows the spectral yield $dN/d\omega$ as a function of frequency, obtained by integrating the spectral angular yield $\partial^2 N/\partial\omega\partial\Omega$ over all angles, for 5 MeV electrons passing through a 10 μm silicon foil. The spectrum is characterized by a sharply peaked, asymmetric line, which is much narrower than the spectral region defined by the Čerenkov condition (97 eV$<\hbar\omega<$118 eV), on top of a broad, low intensity background. The background is mainly due to transition radiation. Integrating the spectral yield over the line, results in a yield $N=0.8\times 10^{-3}$ photon/electron. The main features of the Čerenkov line can be explained in terms of a simple approximate expression for optically thick foils, which neglects the contribution of transition radiation, and which holds for $\chi''(\omega) \ll \chi'(\omega) - \gamma^{-2} \ll 1$ and $\gamma \gg 1$ (Bazylev *et al.*[3]):

$$\frac{dN}{d\omega} = \frac{\alpha}{\omega}\left(\frac{\chi'(\omega)-\gamma^{-2}}{\chi''(\omega)}\right) \tag{1}$$

with α the fine structure constant. Since the absorption $\chi''(\omega)$ is approximately constant in the frequency region below the absorption edge where the Čerenkov condition $[\chi'(\omega) > \gamma^{-2}]$ holds [see Fig. 1(a)], the Čerenkov spectral yield [Eq. (1)] as a function of frequency follows the real part of the susceptibility $\chi'(\omega)$. The step in $\chi''(\omega)$ (the absorption edge) cuts off part of the spectrum generated at higher frequencies, finally resulting in a narrow, asymmetric line in front of the edge.

Čerenkov radiation is emitted in the forward direction in a cylindrical cone around the electron trajectory. The characteristic angle of emission is given by $\cos(\theta) = c/v \cdot n$, which can be approximated by

$$\theta(\omega) = \sqrt{\chi'(\omega) - \gamma^{-2}}, \tag{2}$$

for $\chi' \ll 1$ and $\gamma \gg 1$. For silicon [Fig. 1(a)] and 5 MeV electrons thus follows a maximum emission angle of 10.6° at $\hbar\omega = 99.7$ eV. Figure 2(a) shows, in addition to the full spectrum (dashed curve), two partial spectra (solid curves) obtained by integrating the spectral angular yield $\partial^2 N/\partial\omega\partial\Omega$ over two separate angular intervals of 1° width, around $\theta = 5°$ and $\theta = 10°$. The central frequencies of the spectra associated with the two emission angles are given by Eq. (2).

In order to establish silicon L edge XCR, we have measured the yield at emission angles of 5° and 10°. Figure 3 shows a schematic overview of the experimental setup. Electrons from a 5-MeV linear accelerator pass through a foil chamber. For our experiments we have used a 10 μm foil of undoped single-crystal silicon (Virginia Semiconductors Inc.). After the foil chamber a 90° dipole magnet bends the electron beam into a dump, where the current is measured. Part of the full Čerenkov cone passes through the bending magnet vacuum chamber into the detection section. The observation angle of the detection section is fixed at either 5° or 10°. The detector subtends an angle of 0.93° in the plane of the electron beam.

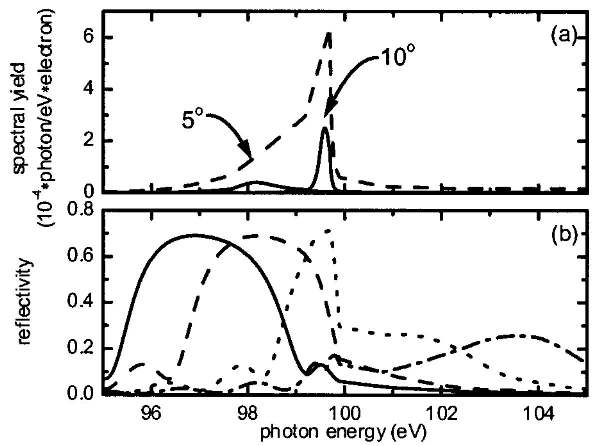

FIG. 2. (a) Theoretical spectral yield emitted within the angular ranges 0°–15° (dashed line), 4.5°–5.5° (solid line), and 9.5°–10.5° (solid line). (b) Reflectivity of the Mo/Si multilayer mirror as a function of photon energy for various angles of incidence: 88.5° (solid), 80° (dashed), 74° (dotted), and 70° (dot-dashed).

The detection section consists of two elements, a Mo/Si multilayer mirror and a photodiode, in a "θ–2θ" configuration. The main purpose of this configuration is to prevent hard x rays from reaching the photodiode, because these may lead to a spurious background signal. In addition, the limited wavelength dispersive capability of the multilayer mirror is used to obtain crude spectral information. The multilayer mirror[7] (supplied by the FOM-Institute for Plasma Physics, The Netherlands) consists of 101 alternating layers of silicon and molybdenum. The reflectivity is 68.2% for $\hbar\omega = 96.72$ eV (i.e., $\lambda = 12.82$ nm) at an angle of incidence of 88.5°. The reflectivity is a strong function of frequency and angle of incidence, as shown in Fig. 2(b). The typical width of the reflection curve is 3 eV. The reflection curve shifts to higher frequencies for a decreasing angle of incidence. The radiation reflected from the multilayer mirror is detected by an absolutely calibrated XUV silicon photodiode (IRD Inc.). The diode is supplied with a thin film consisting of 100 nm silicon and 200 nm zirconium, which acts as a bandpass filter around $\hbar\omega = 100$ eV. This bandpass filter very efficiently blocks any visible or ultraviolet light that is reflected by the multilayer mirror. In addition a 150 nm Zr foil bandpass filter (Luxel Corp.) can be put into the beam to check whether visible and ultraviolet light are sufficiently suppressed.

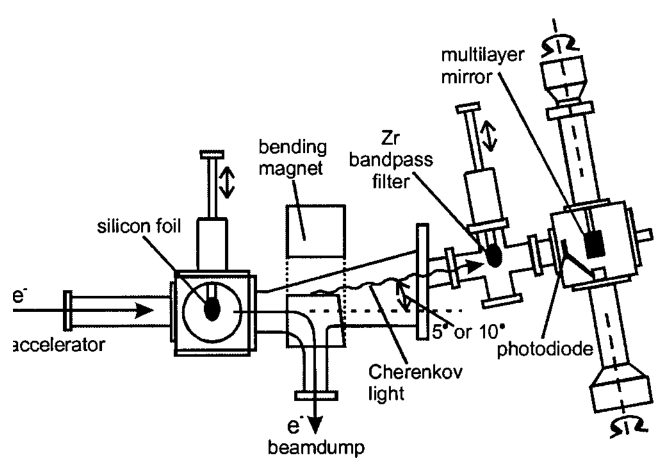

FIG. 3. Schematic overview of the experimental setup.

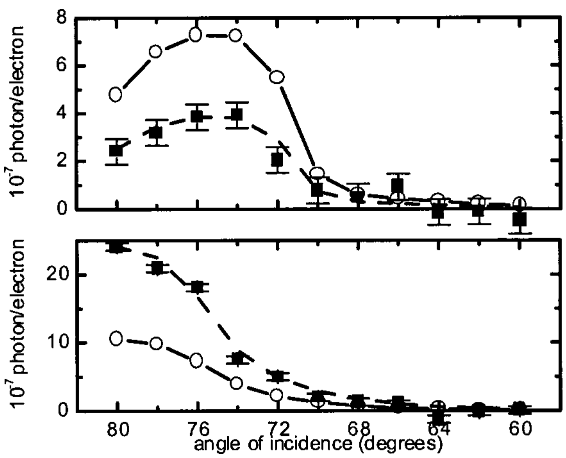

FIG. 4. Measured (squares) and calculated (circles) detector signal as a function of angle of incidence on the multilayer mirror at an observation angle of 10° and 5°. The dashed curve is the theoretical curve (solid line) multiplied by a factor of 2.4 at 5° and by a factor of 0.6 at 10°.

Figure 4 shows the experimental data. The detector signal, from which a background signal has been subtracted, is plotted as a function of angle of incidence on the multilayer mirror for observation angles of 5° and 10°. The signal cannot be measured for angles of incidence higher than 80°, because then the photodiode blocks the light path from the foil to the multilayer mirror. The maximum of the 10° detector signal curve occurs at a smaller angle of incidence than the maximum of the 5° detector signal curve. This implies that higher photon energies are emitted at 10° than at 5°, which is in agreement with the theoretical expectations of Čerenkov radiation [Fig. 2(a)].

To enable an accurate comparison of theory and experimental data, we have calculated the detector signal as a function of angle of incidence by using the theoretical spectral yield emitted within the detector solid angle [Fig. 2(a)], the accelerator current (typically 8.2 μA average current), the complete solid angle (1.0 cm^2 photodiode area at 62 cm) and the reflectivity curves of the multilayer mirror [Fig. 2(b)]. Figure 4 shows the calculated detector signal curves, indicated by solid lines. There is a very good agreement between the shapes of the calculated and the measured detector signal curves. This is illustrated by the dashed curves, which are obtained by multiplying the calculated detector signal curves by a factor 0.6 at 10° and by a factor 2.4 at 5°. The total yield, integrated over all angles, has not been measured. The measurements of the partial yields around 5° and 10° indicate however that the total yield should be of the order of 1×10^{-3} photon/electron, roughly in agreement with the theoretical expectation.

To explain the remaining discrepancy between theory and experiment, we would like to point out that the calculation of the Čerenkov spectral yield requires detailed knowledge of the optical constants in a very small frequency range in front of the L edge. Our calculation is based on only four data points available from the Henke database (Fig. 1), which are subject to large uncertainties.[8] Minor adjustments of the optical data are sufficient to explain the observed discrepancies. In fact, the sensitivity of the Čerenkov yield to the exact values of the optical constants suggests an interesting new tool to determine optical constants at absorption edges.

In conclusion, we have shown that narrow band 99.7 eV Čerenkov radiation can be generated by 5 MeV electrons in a single-crystal silicon foil with a yield of about 1×10^{-3} photon/electron. This implies that using a commercially available 5 MeV, 1-mA linear accelerator a total output power of 0.1 mW (6×10^{12} photon/s) can be produced. The Čerenkov effect may thus be employed for the development of compact, narrow-band, high-brightness soft x-ray sources. In addition, the Čerenkov effect may be used to probe optical constants in the frequency regions just below absorption edges.

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