INSTITUTE OF PHYSICS PUBLISHING METROLOGIA
Metrologia **40** (2003) S124–S127 PII: S0026-1394(03)56898-0

A SURF beamline for synchrotron source-based absolute radiometry

Ping-Shine Shaw, Uwe Arp, Howard W Yoon, Robert D Saunders, Albert C Parr and Keith R Lykke

National Institute of Standards and Technology, 100 Bureau Dr, MS 8410, Gaithersburg, MD 20899-8410, USA

E-mail: shaw@nist.gov

Published 7 February 2003
Online at stacks.iop.org/Met/40/S124

Abstract
A new source-based radiometry beamline was recently constructed at the Synchrotron Ultraviolet Radiation Facility (SURF III). The goal of this beamline is to establish a national source standard with a wide spectral range from the far ultraviolet to the infrared by using the calculability of SURF III. The new beamline is a straight-through white-light beamline with few, if any, optical components involved in delivering the radiation to the user end-station for applications such as source and irradiance intercomparisons. Due to the low tunable operating electron energy of SURF III (from 380 MeV to less than 100 MeV), the beamline is uniquely suited to work in the ultraviolet to infrared spectral range. In this paper we discuss the design of the beamline and present first results on the vertical angular distribution of the radiation determined with filtered radiometers in the ultraviolet, visible and near-infrared spectral ranges.

1. Introduction

Electron storage rings, similar to blackbody radiators, are standard calculable radiation sources that cover a broad spectral range [1]. According to Schwinger's equation [2], three parameters completely dictate the characteristics of synchrotron radiation: the magnetic flux density, the orbital radius and the current generated by the moving charged particles. Synchrotron radiation has been used in radiometric applications such as source comparisons and irradiance standards [3–6] in the spectral range from x-rays to the infrared (IR).

The Synchrotron Ultraviolet Radiation Facility (SURF) [7, 8] at the National Institute of Standards and Technology (NIST) has been involved in ultraviolet (UV) research for nearly 40 years. SURF, with a 1675 mm diameter circular orbit for electrons, has pioneered the use of synchrotron radiation for research from atomic physics [9] to measurement standards [10, 11]. Over the years, SURF has been upgraded several times. The most recent upgrade to SURF III was completed in 1998 to improve the accuracy of SURF's calculability [7, 8]. One of the major improvements for SURF III is enhanced uniformity of the magnetic field along the electron trajectory, lowering the uncertainty in the calculation of SURF III's radiation output. The electron beam stability is also improved. SURF III is unique in terms of the low and very flexible electron energies attainable, from almost 400 MeV to less than 100 MeV. The electron beam emits significantly fewer damaging x-rays in this energy range than most modern synchrotron radiation facilities with several GeV of electron energy. Varying the electron energy also provides a means to tailor the spectral distribution for specific applications. The spectral distributions for several different electron energies at SURF III are shown in figure 1. To take advantage of the

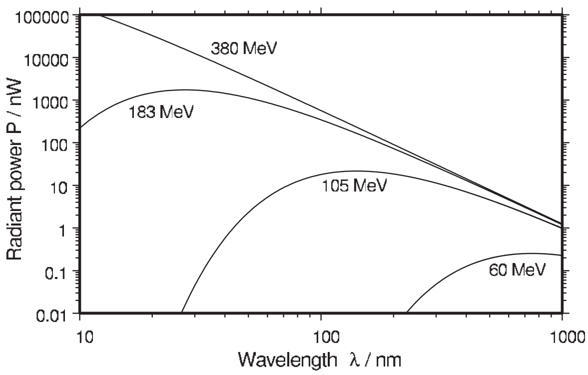

Figure 1. Spectral power distributions of SURF III at electron energies of 60 MeV, 105 MeV, 183 MeV and 380 MeV. All calculations are done for a ring current of 1 mA and a bandpass of 10 nm, assuming a 10 mm by 10 mm square aperture 6114 mm away from the source point.

improved performance of SURF III as a standard source, a new beamline was recently designed and constructed to expand our capabilities in source-based radiometry [12, 13]. Using this beamline, radiation from a test source can be characterized by comparing its radiation with SURF's output using devices such as filtered radiometers and spectroradiometers. The beamline is a white-light beamline that delivers the calculable SURF radiation to the user end-station. In addition, in the front section of the beamline an array of photodiodes monitors the electron beam current and also diagnoses electron beam conditions. To verify the calculation of the radiation in the beamline, one of the first tests was to measure the angular distribution of the synchrotron radiation in the direction perpendicular to the electron orbital plane. We describe the beamline (beamline 3) and these experimental results.

2. Beamline description

A diagram of the new radiometric beamline is shown in figure 2 (top view). The synchrotron radiation from the storage ring propagates unobstructed to a user's end-station centred 6100 mm from the tangent point where the radiation originates. This long distance to the end-station is critical in achieving better uniformity of the radiation over the area of a user's detector because the distribution of synchrotron radiation is highly dependent on angle. The end-station is constructed of stainless steel tubes with a diameter of 150 mm. This allows the mapping of the synchrotron radiation intensity 10 mrad above and below the electron orbital plane. This mapping is particularly important in finding the orbital plane of the electron beam and aligning detectors with it.

2.1. Baffle system

Also shown in figure 2 are several baffles installed throughout the beamline. These baffles are not used as defining apertures but instead are applied to reduce the amount of scattered light reaching the end-station. Without the baffle system, we observed significant scattered light caused by grazing incidence reflections from the vacuum stainless steel walls. All baffles were designed as wedged cavities for trapping light and were coated with a layer of graphite particles to reduce reflectance.

2.2. Electron beam current monitor

An electron beam current monitor is located 2473 mm from the tangent point in a ultra-high-vacuum chamber. The electron beam current is one of the three fundamental parameters, along with the radius of the electron beam orbit and the magnetic field, that fully characterize the synchrotron radiation. At SURF, the magnetic flux density and radiofrequency are used to determine the orbital radius and electron energy. The magnetic flux density is measured using an on-orbit magnetic field probe while the electron beam current is at present measured optically, by a photodiode monitoring the synchrotron radiation [14]. The absolute electron current is determined by counting electrons in the storage ring when the electron current is reduced to fewer than a few thousand electrons. The higher electron current is then extrapolated from the signal induced by a single electron in the storage ring. Of the three parameters, the electron beam current has the highest uncertainty. Therefore a new current monitoring system was included in the beamline. The electron beam current monitor in the new beamline is designed to improve the linearity of the existing current monitor and to provide lower uncertainty to supplement the existing unit. In addition, the new current monitor also serves as a diagnostic tool for electron beam conditions such as changes in position and size. A detailed discussion of the design and preliminary measurement results are presented in [12].

2.3. End-station

At present, the end-station is used to measure the irradiance of the synchrotron radiation using filter radiometers. The detectors are mounted on an arm of a motorized linear motion feedthrough, such that they can scan the radiation in the direction perpendicular to the electron orbital plane. For the measurements described in this paper, several filtered radiometers were mounted in the same vertical position on the linear motion feedthrough and simultaneously scanned in the vertical direction. A computer-controlled motor translated the linear motion feedthrough, and the currents from the two filtered radiometers during the scanning were recorded.

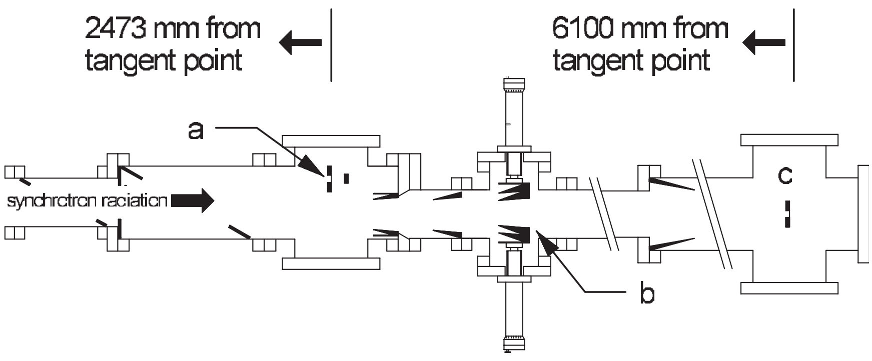

Figure 2. Schematic top view of the beamline baffle system along with (a) the SURF electron current measurement device, (b) adjustable horizontal and vertical aperture pairs (only one pair shown) and (c) user detectors in the end-station arrangement of photodiodes for the electron beam current.

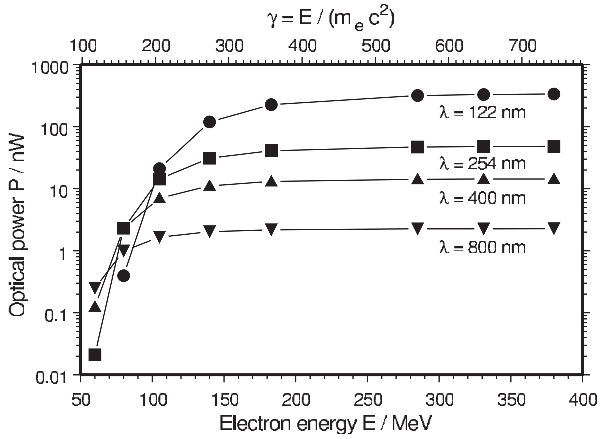

Figure 3. Calculated electron energy dependence of the optical power output for four wavelengths: 122 nm, 254 nm, 400 nm and 800 nm. A square of aperture 10 mm by 10 mm was assumed to be at a distance of 6114 mm from the tangent point. The bandpass of all filters was assumed to be 10 nm.

3. Results from filtered radiometers

In figure 3 we show the dependence of the optical power on the electron energy for four different wavelengths.

As a first test of the performance of the beamline, we used filtered radiometers to scan the intensity distribution of the photon beam in the vertical direction. The filtered radiometers consisted of a precision aperture, a defusing quartz plate, an interference filter and a silicon photodiode. The filtered radiometers have a nominal spectral bandpass of 5 nm to 10 nm and are centred at wavelengths of 254 nm, 400 nm and 800 nm. The apertures are 3.5 mm in diameter. We measured the vertical intensity distribution of the beam at several different SURF electron energies. Figure 4 shows the results at electron energies of 380 MeV, 183 MeV and 105 MeV. The estimated relative uncertainties in these measurements are less than 0.5%. Preliminary analysis shows good relative agreement between the measurements displayed in figure 4 and calculations using the procedure described in [13].

At an energy of 380 MeV, the measured vertical distribution shows the classic double-peak structure, observable at radiation wavelengths much longer than the characteristic wavelength, which is $\lambda_c = 8.52$ nm at 380 MeV. This is consistent with the predictions from Schwinger's theory [2]. The radiation collected in the central valley is linearly polarized in the plane of the electron orbit. The increase in intensity towards the two peaks results from the increasing contribution of vertically polarized light. Also, the width of the distribution is wavelength dependent and is wider at longer wavelengths. At 183 MeV the characteristic wavelength becomes $\lambda_c = 76.36$ nm and the double-peak structure disappears at wavelengths of 254 nm and 400 nm. The intensity is also reduced, as expected from figure 3.

When the electron energy is reduced to 105 MeV, the characteristic wavelength is increased to $\lambda_c = 404.22$ nm. This causes the double-peak structure to completely vanish for radiation of wavelengths 254 nm, 400 nm and 800 nm. Just as calculated in figure 3, the intensity is reduced even further. Note that these measurements were performed with filtered radiometers directly exposed to the synchrotron radiation. With electron beam currents typically less than 50 mA in the storage ring for the measurement, we observed no noticeable degradation of the filtered radiometers, even at 380 MeV. Therefore, this beamline provides an irradiance standard with a relative uncertainty below 0.5% that is accessible for use with typical radiometers. The irradiance responses of the 400 nm and 800 nm filtered radiometers were recently measured at the NIST facility for spectral irradiance and radiance responsivity calibrations using uniform sources (SIRCUS) [15] with an uncertainty of ≈0.1%. The irradiance response of the 254 nm filtered radiometer was measured using beamline 4 at SURF [16]. We are in the process of using these response measurements, along with the electron beam current and distance measurements, to quantitatively confirm the calculability of the SURF III radiation.

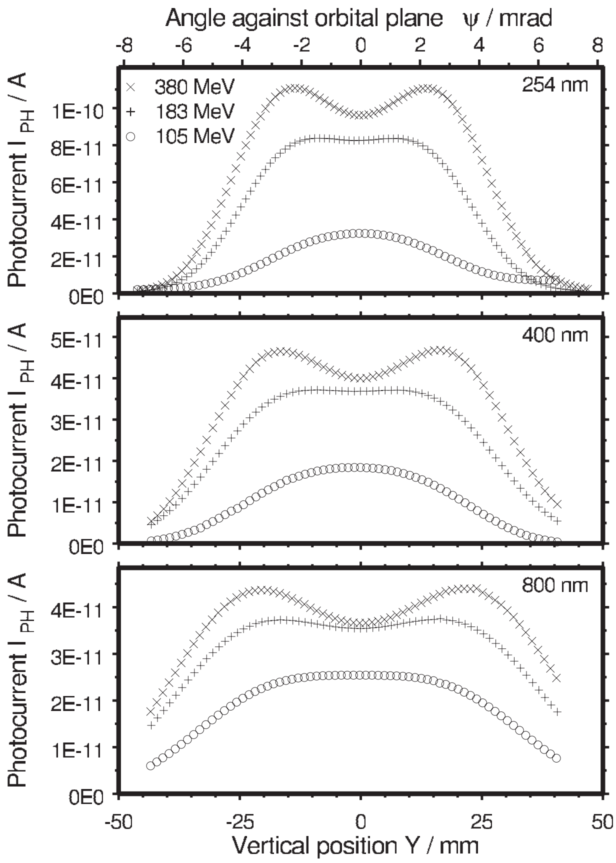

Figure 4. Measured intensity distributions at wavelengths of 254 nm (top), 400 nm (middle) and 800 nm (bottom). The data were taken at electron energies of 380 MeV (×), 183 MeV (+) and 105 MeV (○).

4. Conclusions

A new beamline has been constructed at SURF III for source-based radiometry. Applications of this beamline include source calibrations and irradiance standards in the ultraviolet to infrared regions. Our first measurements using filtered radiometers at 254 nm, 400 nm and 800 nm qualitatively confirmed the angular distribution and total intensity of SURF radiation deduced from theoretical calculations.

Acknowledgments

Continuing support by Alex Farrell, Mitch Furst and Edward Hagley is gratefully acknowledged.

References

[1] Ederer D L, Saloman E B, Ebner S C and Madden R P 1975 *J. Res. Natl. Inst. Stand. Technol.* **79A** 761–74
[2] Schwinger J 1949 *Phys. Rev.* **75** 1912–25
[3] Ulm G and Wende B 1995 *Rev. Sci. Instrum.* **66** 2244–7
[4] Hollandt J, Jans W, Kühne M, Lindenlauf F and Wende B 1992 *Rev. Sci. Instrum.* **63** 1278–81
[5] Thornagel R, Klein R and Ulm G 2001 *Metrologia* **38** 385–9
[6] Scholze F, Thornagel R and Ulm G 2001 *Metrologia* **38** 391–5
[7] Bosch R A *et al* 2000 *Synchrotron Radiation Instrumentation: Eleventh US National Conf. (Stanford, California, 1999)* ed P Pianetta, J Arthur and S Brennan (Melville, NY: American Institute of Physics) pp 383–90
[8] Arp U, Friedman R, Furst M L, Makar S and Shaw P S 2000 *Metrologia* **37** 357–60
[9] Madden R P and Codling K 1963 *Phys. Rev. Lett.* **10** 516–18
[10] Codling K and Madden R P 1965 *J. Appl. Phys.* **36** 380–7
[11] Canfield L R, Johnson R G, Codling K and Madden R P 1967 *Appl. Opt.* **6** 1886–8
[12] Shaw P S, Shear D, Stamilio R J, Arp U, Yoon H W, Saunders R D, Parr A C and Lykke K R 2002 *Rev. Sci. Instrum.* **73** 1576–9
[13] Arp U 2002 *J. Res. Natl. Inst. Stand. Technol.* **107** 419–23
[14] Schaefer A R, Hughey L R and Fowler J B 1984 *Metrologia* **19** 131–6
[15] Brown S W, Eppeldauer G P and Lykke K R 2000 *Metrologia* **37** 579–82
[16] Shaw P S, Larason T C, Gupta R, Brown S W, Vest R E and Lykke K R 2001 *Rev. Sci. Instrum.* **72** 2242–7