SURF III: A flexible Synchrotron Radiation Source for Radiometry and Research

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Abstract

The calculability of synchrotron radiation (SR) makes electron storage rings wonderful light sources for radiometry. The broadband nature of SR allows coverage of the whole spectral region from the x-ray to the far-infrared. Compact low-energy storage rings like SURF III are perfect sources for radiometric applications, because the output spectrum can be custom-tailored to the user's needs: Low current operations can simulate the solar spectrum, changes to the electron energy can deal with higher-order contributions of spectrometers and monochromators, and manipulation of the source size increases the lifetime or change the radiation density. At multi-user facilities these special operational conditions are generally not possible, since many users have to be satisfied simultaneously. NIST maintains at SURF one of the best SR-based calibration programs in the world: Standard lamp calibrations, detector calibrations, and measurements of optical properties are routinely performed at SURF with great reliability and accuracy.

Keywords: Radiometry, Calibration, Space instrumentation, Vacuum ultraviolet

1. Introduction

The Synchrotron Ultraviolet Radiation Facility was one of the first dedicated synchrotron radiation sources in the world. For nearly 50 years, SURF has provided light to support basic research [1], source-based [2] and detector-based radiometry [3, 4], extreme-ultraviolet metrology (EUV) [5, 6, 7], laboratory astrophysics [8], and calibrations of space-borne instrumentation [9, 10, 11]. Over the years, SURF underwent several major upgrades, first in the 1970s it was converted from a synchrotron to a storage ring, and in the late 1990s the old synchrotron magnet was finally replaced by a DC magnet, which considerably

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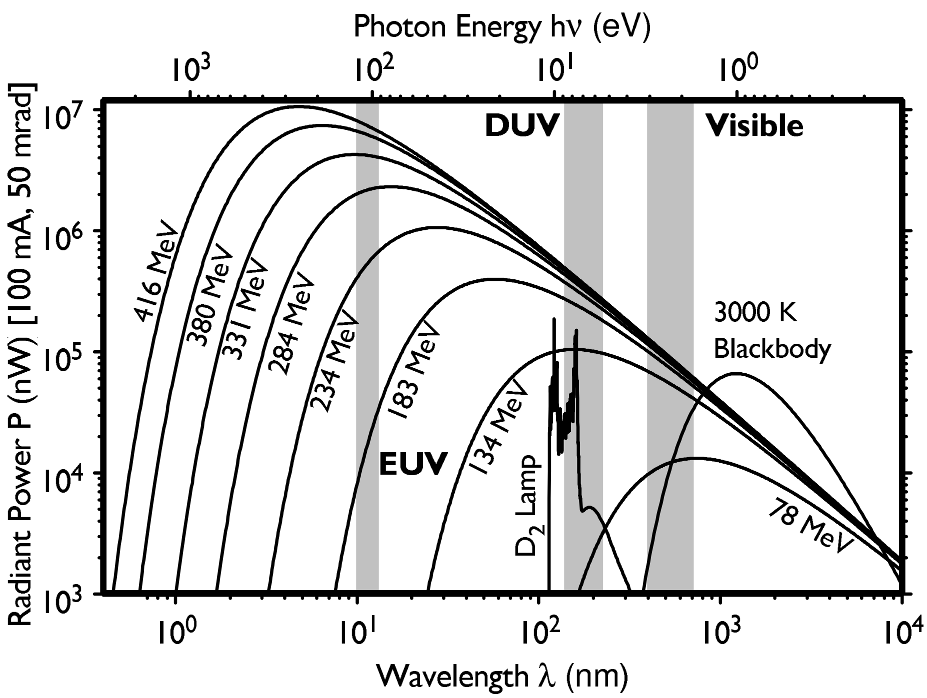

Figure 1: Calculated radiant power for SURF at several operating energies compared to a 3000 K blackbody and a 30 W deuterium lamp.

reduced the uncertainties for source-based radiometry. The SURF control system has also continuously been improved over time. Currently, the storage ring can perform autonomous injections to provide longer exposures for extreme-ultraviolet optics endurance testing. Maximum injection currents top 1 A and our maximum operating energy is around 416 MeV.

SURFs biggest advantage is its flexibility [12]. The storage ring can be operated in many different modes, which can be custom-tailored to the customers needs. The output spectrum can be varied by changes in the energy of the electron energy from 100 MeV to about 400 MeV (see fig. 1), effectively reducing higher orders by shifting the short wavelength cut-off. SURF can store as little as 1 electron, which is equivalent to about 10 pA ring current, or as much as $3 \cdot 10^{10}$, which is equivalent to about 300 mA. Thus we can modify the output intensity by about 10 orders of magnitude, a feature that has recently attracted interest in the calibration of photomultiplier tubes for low intensity applications [13]. We can also manipulate the electron beam size, either to maximize lifetime or increase throughput if required [14].

Table 1: Beamlines at SURF III

Beamline	Wavelength range	Purpose
1a	13 nm	EUV Optics Degradation
1b	13 nm	EUV Photoresist Properties
2	0.3 nm to 400 nm	Absolute irradiance calibrations of radiometric instrumentation
3	200 nm to 400 nm	Absolute source-based irradiance calibrations
4	140 nm to 320 nm	Detector calibrations
		Detector radiation damage
		Optical properties
5	120 nm to 400 nm	Index measurements
		Emission line sources
6		Current monitor
7	3 nm to 40 nm	Reflectance
		Optical properties
		Detector calibrations
8	13 nm	EUV Optics Degradation
9	5 nm to 50 nm	Detector calibrations
		Transmittance
10	550 nm	Beam size measurement

2. Experimental stations

Most of the beamlines (see table 1) at SURF support technological progress through advancement of measurement science, in alignment with the mission of the National Institute of Standards and Technology NIST. We are striving to constantly improve our experimental stations and the quality of the measurement services provided. Experimental stations at SURF support radiation metrology and many are operating in direct support of next-generation lithography programs. Accurate radiometry relies on stable, well characterized sources and detectors. Before the advent of synchrotron radiation, most sources in the vacuum-ultraviolet and x-ray regions had line structures and were not real continuum sources. Storage rings make excellent sources for radiometry, because their radiation output is broadband and can be calculated from first principles.

2.1. Source-based radiometry

Electron storage rings can be operated as absolute radiation sources, which makes them exceptionally useful in radiometry. To successfully use SURF as an absolute source, the magnetic flux density B, the radio-frequency ν_{rf}, and the electron beam current I_B, have to be known [2, 15]. Two beamlines at

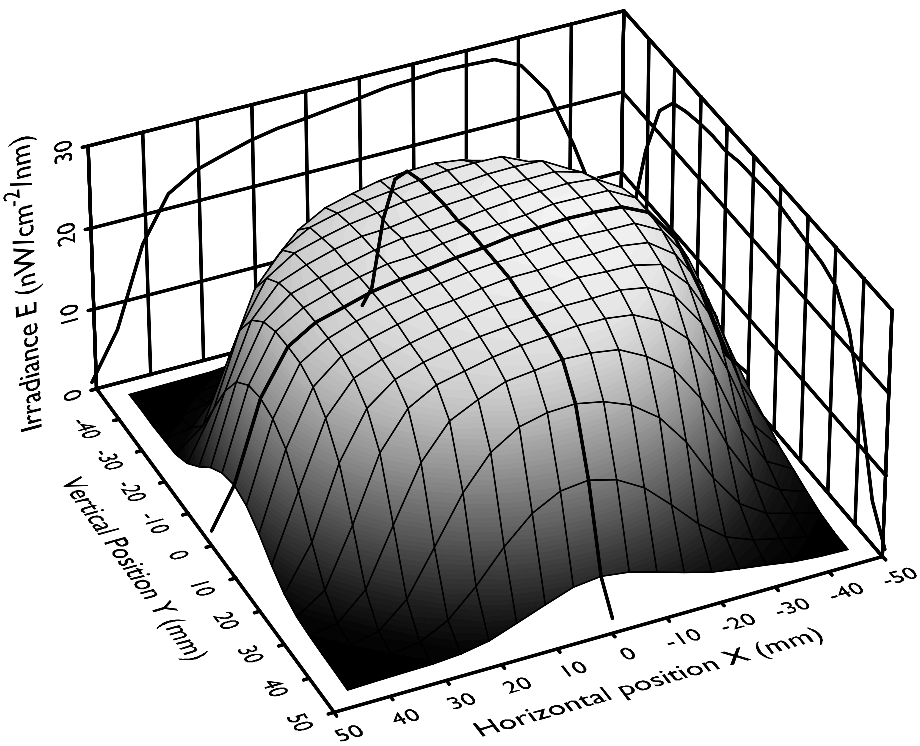

Figure 2: Spatial irradiance map of a deuterium lamp at $\lambda = 230$ nm as measured at BL-3.

SURF operate in this way: BL-2 is used to calibrate detector packages used in solar extreme-ultraviolet observations, like most recently the instruments on the Solar Dynamics Observatory (SDO) [10]; and BL-3 is mainly used to calibrate ultraviolet sources, like deuterium lamps [16] (see figure 2 for an example of a spatial irradiance map), but also has been used to perform absolute calibrations of energy dispersive x-ray detectors.

2.2. Detector-based radiometry

Several beamlines at SURF have been used to calibrate transfer standard detectors, like *e.g.* photodiodes. These calibrations are based on absolute detectors, either electrical substitution cryogenic radiometers [3, 7] or ionization chambers [17, 18]. To perform reliable detector calibrations, the employed light-source has to be stable over time and should not have any spectral features. Early on, scientist at National metrology institutes realized the potential of using synchrotron radiation for these applications. Recently, we started to calibrate photomultiplier tubes for low intensity applications, taking advantage of the simple scaling of the output intensity with the stored electron beam current [13].

2.3. Optical properties

Several experimental stations are used to determine optical properties, like reflectance, transmittance, absorbance, or luminescence efficiency. BL-4 is routinely used to collect absorbance and reflectance data in the ultraviolet spectral region. Most recently in a collaborative effort with the Jet Propulsion Laboratory, we installed an experimental chamber that allows studies of cryogenically grown ices with relevance in planetary science. Both BL-7 and BL-9 are used to measure optical properties in the EUV. BL-9 was used recently to determine the transmission of filters used in the solar overvations [18].

2.4. Extreme-ultraviolet lithography

Extreme-ultraviolet lithography (EUVL) is a leading contender in the race to replace current chip manufacturing technology. SURF supports EUVL at several experimental stations, providing EUV reflectometry at BL-7 [19, 20], optics endurance testing at BL-1 [21] and BL-8 [5], and photoresist related research at BL-1 [6]. Recently, BL-1 was rebuild to allow simultaneous research on photoresists and multilayer optics by splitting the beam.

2.5. Space weather related calibrations

The total solar irradiance varies by about 0.01 % over the solar cycle. However, in the extreme-ultraviolet spectral range, the solar irradiance varies up to 10 % on the same time scale. Monitoring the EUV output of the sun helps improving space weather forecasts, which have implications for a wide range of activities on earth ranging from radio communications to air travel. The strong EUV variability of the sun is also suspected to play an important role in climate forcing on earth. Many experimental stations contribute to this research, as summarized here [18].

3. Conclusion

SURF III is a powerful radiation source for radiometry and applied reseach in the wavelength range from the ultraviolet to the soft x-ray. The well understood output characteristics allow the operation of SURF III as an absolute source, which can be used to calibrate other radiation sources or detection systems. The structure-free broadband nature of synchrotron emission makes it an ideal source for experiments using monochromators to determine optical properties or detector responses. SURF has helped to advance science and radiometry for nearly 50 years and continues to be a highly useful source of ultraviolet radiation.

References

[1] R. P. Madden, K. Codling, Phys. Rev. Lett. 10 (1963) 516–518.

[2] P.-S. Shaw, U. Arp, R. D. Saunders, D.-J. Shin, H. W. Yoon, C. E. Gibson, Z. Li, A. C. Parr, K. R. Lykke, Appl. Opt. 46 (2007) 25–35.

[3] P.-S. Shaw, K. R. Lykke, R. Gupta, T. R. O'Brian, U. Arp, H. H. White, T. B. Lucatorto, J. L. Dehmer, A. C. Parr, Metrologia 35 (1998) 301–306.

[4] P.-S. Shaw, K. R. Lykke, R. Gupta, T. R. O'Brian, U. Arp, H. H. White, T. B. Lucatorto, J. L. Dehmer, A. C. Parr, Appl. Opt. 38 (1999) 18–28.

[5] U. Arp, I. Ermanoski, C. Tarrio, S. Grantham, S. Hill, P. Dhez, T. B. Lucatorto, in: Choi, JY and Rah, S (Ed.), Synchrotron Radiation Instrumentation, Pts 1 and 2, volume 879 of *AIP Conference Proceedings*, pp. 481–484.

[6] C. Tarrio, J. Res. Natl. Inst. Stand. Technol. 114 (2009) 179–183.

[7] C. Tarrio, R. E. Vest, S. Grantham, K. Liu, T. B. Lucatorto, P. S. Shaw, in: Warwick, T and Arthur, J and Padmore, HA and Stohr, J (Ed.), Synchrotron Radiation Instrumentation, volume 705 of *AIP Conference Proceedings*, pp. 608–611.

[8] M. S. Gudipati, L. J. Allamandola, Astron. J. 615 (2004) L177–L180.

[9] J. S. Evans, D. J. Strickland, D. R. M. W. K. Woo, S. P. Plunkett, R. A. Viereck, S. M. Hill, T. N. Woods, F. G. Eparvier, Sol. Phys. 262 (2010) 71–115.

[10] T. Woods, F. Eparvier, R. Hock, A. Jones, D. Woodraska, D. Judge, L. Didkovsky, J. Lean, J. Mariska, H. Warren, D. McMullin, P. Chamberlin, G. Berthiaume, S. Bailey, T. Fuller-Rowell, J. Sojka, W. Tobiska, R. Viereck, Sol. Phys. (2010) 1–29.

[11] L. Didkovsky, D. Judge, S. Wieman, T. Woods, A. Jones, Sol. Phys. (2009) 1–27.

[12] U. Arp, in: J. L. Duggan, I. L. Morgan (Eds.), 17th International Conference on the Application of Accelerators in Research and Industry CAARI 2002, AIP, Woodbury, New York, 2003, pp. 530–533.

[13] L. Hum, P.-S. Shaw, Z. Li, K. R. Lykke, M. L. Bishop, volume 7304, SPIE, 2009, p. 730410.

[14] U. Arp, R. Friedman, M. L. Furst, S. Makar, P.-S. Shaw, Metrologia 37 (2000) 357–360.

[15] U. Arp, C. W. Clark, A. P. Farrell, E. Fein, M. L. Furst, E. W. Hagley, Rev. Sci. Inst. 73 (2002) 1674–1676.

[16] P. Sperfeld, Metrologia 45 (2008) 02002.

[17] R. E. Vest, L. R. Canfield, in: Pianetta, P and Arthur, J and Brennan, S (Ed.), Synchrotron Radiation Instrumentation, volume 521 of *AIP Conference Proceedings*, pp. 104–107.

[18] R. E. Vest, Y. Barad, M. L. Furst, S. Grantham, C. Tarrio, P.-S. Shaw, Adv. Space Res. 37 (2006) 283–296.

[19] C. Tarrio, T. B. Lucatorto, S. Grantham, M. B. Squires, U. Arp, L. Deng, in: D. A. Tichenor, J. A. Folta (Eds.), Soft X-Ray and EUV Imaging Systems II, volume 4506, SPIE, Bellingham, WA, 2001, pp. 32–38.

[20] S. Grantham, C. Tarrio, M. B. Squires, T. B. Lucatorto, in: R. L. Engelstad (Ed.), Emerging Lithographic Technologies VI, volume 4688, SPIE, Bellingham, WA, 2002, pp. 348–353.

[21] C. Tarrio, S. Grantham, Rev. Sci. Inst. 76 (2005) 056101–1–056101–3.