SURF III – an improved storage ring for radiometry

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Abstract. The National Institute of Standards and Technology (NIST) operates the newly upgraded Synchrotron Ultraviolet Radiation Facility (SURF III) mainly as a light source for radiometry. SURF III provides continuum radiation from the far-infrared to the soft X-ray spectral range and has its peak output in the extreme ultraviolet. SURF III is a circular-orbit, weak-focusing (single dipole magnet) storage ring, a feature which is advantageous if the synchrotron radiation output is calculated. We report the improvements achieved during a recent upgrade from SURF II to SURF III and our strategy to accurately determine the magnetic flux density, radio frequency (RF), beam current, and beam size, which are the parameters necessary to characterize the source completely.

1. Introduction

The NIST synchrotron radiation source SURF II has recently been upgraded to version III in order to improve the accuracy of radiometric calibrations. The upgrade included the total replacement of the magnet system, refurbishment of the magnet power supply, improvements of the SURF vacuum chamber, a new RF transmitter, and the implementation of a software-based control system.

The single most important improvement in SURF III is clearly the total replacement of the magnet. The old magnet was optimized for pulsed synchrotron and not for continuous storage-ring operation. The new magnet poles are optimized for storage-ring operation and the gap has been reduced to increase the strength of the magnetic field, leading to higher electron energies. This new magnet considerably improves SURF's calculability as an irradiance standard and its high uniformity improves the radiometric accuracy.

2. Calculability of SURF III

If a synchrotron radiation source has been characterized carefully, its irradiance is calculable. SURF's single-magnet design simplifies this task considerably, except for the electron-beam current measurement. The irradiance is defined [1] as the radiant power passing through the area, A, at a distance r:

$$\frac{\mathrm{d}P}{\mathrm{d}A}\left(\frac{W}{m^2}\right) = \frac{\mathrm{d}P}{\mathrm{d}A}\left(\rho, E, I, A, r, \psi\right). \tag{1}$$

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For SURF III, the irradiance depends on the bending radius ρ, the electron energy E, the electron-beam current I, the aperture size A, the distance to the source r, and the angle relative to the electron orbital plane ψ. Schwinger's [2] equation is commonly used to calculate the irradiance of a synchrotron radiation source.

2.1 Orbital radius

Because of the unique single-magnet design and the resulting circular orbit, the average orbital radius can be deduced from the frequency of the driving RF field by

$$\rho_0 = \beta c n_{\mathrm{har}}/(2\pi\nu_{\mathrm{RF}}), \tag{2}$$

where βc is the electron speed (c is the speed of light in vacuum) and n_{har} the harmonic number. The harmonic number is the ratio between RF and orbital frequency, which is 2 for SURF. A measurement for SURF III delivered $\nu_{\mathrm{RF}} = 113.8456$ MHz, corresponding to an orbital radius of $\rho_0 = 838.2$ mm.

2.2 Electron energy

The energy for the SURF electron beam can be deduced from the magnetic flux density on orbit, using the following equation:

$$E = c\rho_0 eB/\beta. \tag{3}$$

Other methods of determining the electron energy, such as the resonant depolarization of electrons [3] and Compton back-scattering of laser radiation [4], are not easily applicable at SURF.

Electrons and positrons in storage rings tend to become transversely polarized because of the spin flip during synchrotron radiation emission, favouring the spin orientation of lowest energy in the external magnetic field [5, 6]. The time needed to sufficiently polarize the electrons is many hours for SURF III electron energies, for example about 4 h for 331 MeV.

Compton back-scattering at BESSY I utilizes a long, straight, interaction region, which we do not have at SURF. A multi-pass laser cavity could be a solution, but space in the SURF vacuum chamber is very limited. Therefore we have to rely on the magnetic field measurements. After the magnet was assembled the magnetic field was mapped for several weeks [7]. A computer-controlled high-precision field-mapping system was used, capable of measuring field variations of about 3 parts in 10^5. The coil-current dependence of the magnetic flux density and the magnetic field index were determined with very high precision for currents between 18.5 A and 900 A. Figure 1 shows the uniformity of the magnetic field for the new SURF III magnet in comparison with the SURF II magnet. Several field probes monitor the magnetic flux density above and below the orbit during operation. In addition, two on-orbit field probes can be moved in to determine the long-term stability of the system.

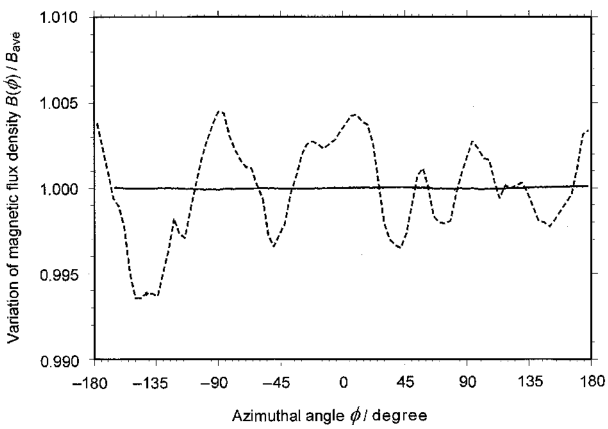

Figure 1. Magnetic flux density improvements achieved in the upgrade of SURF. Shown is the deviation from the average magnetic flux density, B/B_{ave}. SURF III at 388 MeV (solid line) versus SURF II at 303 MeV (dashed line). The relative field accuracy around the orbit is of the order of 10^{-4} for SURF III, whereas it was only 10^{-2} for SURF II.

2.3 Electron-beam current

The electron-beam current is determined through an electron counting procedure [8-10] because direct electrical measurements are difficult to perform. When less than a few thousand electrons[1] are left orbiting in SURF, the decrease in synchrotron radiation tied to the loss of individual electrons can be observed. This is done in order to determine the background of the measurement until all the electrons are gone, when the actual number of electrons can be determined through back-scaling. Because of the linearity of the silicon photodiodes and preamplifier used in this procedure, it is possible to calibrate current measurements up to the maximum ring current of a few hundred milliamperes. Hughey and Schaefer [9] estimate the uncertainty in the beam current measurement to be 2 parts in 10^3 at 100 mA [10].

2.4 Beam size

The source size can be deduced from beam imaging [11-13]. For SURF III, we set up a 1:1 imaging system with a spherical biconvex lens and a 550 nm narrowband interference filter to avoid chromatic focal shift. This system was tested and calibrated using a backlit 10 μm pinhole on an optical bench as a light source. Two main effects distort the synchrotron data: diffraction from the finite vertical aperture caused by the emission characteristics of the synchrotron radiation, and the depth-of-field when imaging a finite part of the electron orbit [14]. The latter problem can be solved by using a small vertical slit to limit the horizontal acceptance angle. A careful analysis of the data must be performed to deduce accurate beam dimensions.

For a weak-focusing storage ring such as SURF III, the horizontal electron-beam size depends on the electron energy. Table 1 lists some typical beam sizes for SURF III. The vertical beam size full-width at half-maximum (FWHM) was determined to be (32 ± 4) μm at 284.4 MeV. The values in the table are slightly larger, because no diffraction correction was performed.

Figure 2 displays beam images for different operating conditions at 284.4 MeV: without "fuzz", in full coupling, and with 12 W of "fuzz" power (see Section 2.6 for explanation).

2.5 Geometry

The solid angle and angle relative to the orbital plane are determined by experimental geometry. For source-based radiometry, these parameters have to be measured carefully. On beamline 2 at SURF III, a laser range-finder was employed to determine the distance to the tangent point with very high accuracy. Several authors [15, 16] have used triangulation with movable slits to determine the distance from the tangent point. The location of the orbital plane can be determined by utilizing the polarization properties of synchrotron radiation, because the light is horizontally polarized in this plane, whereas vertical polarization components exist outside this plane. In order to locate the orbital plane, photodetectors combined with polarizers are scanned vertically through the emitted light to determine the orbital position.

1. One stored electron is equivalent to 9.12 pA ring current.

Table 1. Vertical and horizontal beam full-width at half-maximum and typical electron-beam lifetime, τ, at several different operating conditions of SURF III. Δy is the vertical displacement of the beam centroid deduced from the fit. The vertical beam sizes have not been corrected for diffraction.

E/MeV	Fuzz/W	Index n	Vertical FWHM/mm	Horizontal FWHM/mm	τ (50 mA)/h	Δy/mm
330.7	0	0.594	0.054	2.345	≈0.5	0
330.7	12	0.594	1.727	2.512	5	−0.018
284.4	0	0.594	0.100	2.090	≈0.5	−0.009
284.4	0	0.500	1.036	1.498	4	0.045
284.4	12	0.594	2.831	2.152	6.5	0.014

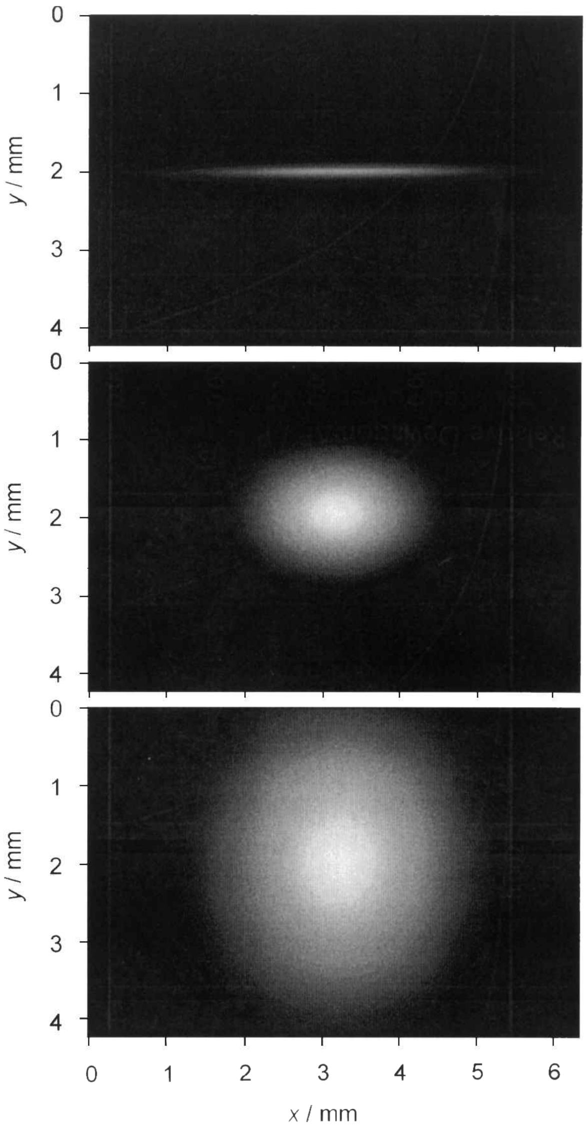

Figure 2. Beam images taken at 284.4 MeV electron energy. The images correspond to the last three results listed in Table 1. Above: no fuzz; centre: full coupling at field index 0.5; below: 12 W fuzz power (artificial excitation of the vertical betatron oscillation).

2.6 Source stability

Three main processes limit the lifetime of electrons circulating in a storage ring [17]: Touschek scattering, elastic gas scattering, and inelastic gas scattering. The Touschek scattering rate is proportional to the electron current and inversely proportional to the bunch volume. For this reason, in many synchrotron radiation sources brightness is sacrificed for lifetime and the storage ring is not operated at minimum emittance. Lengthening the bunch or increasing its transverse size increases the bunch volume. Bunch lengthening is achieved through manipulation of the RF accelerating system and has the advantage of leaving the brightness unchanged. The transverse size is enlarged either by increasing the coupling between horizontal and vertical betatron motions (Figure 2, centre) or by artificially exciting the vertical betatron motion (Figure 2, below). The latter has been the practice at SURF for the last twenty years,[2] but has been found to induce noise in the light intensity. We therefore used the alternative technique and coupled the beam completely by moving the magnetic field index,

$$n = \frac{\rho_0}{B_0} \frac{\partial B}{\partial r}\bigg|_{r=\rho_0},$$

to $n = 0.5$, making the horizontal and vertical betatron oscillation frequencies equal.

Several vertical and horizontal beam sizes are listed in Table 1, as well as lifetimes for a ring current of 50 mA. Under normal operating conditions the centroid of the beam does not move by more than a micrometre on a timescale of a few microseconds.

In the microwave region, coherently enhanced synchrotron radiation has been observed [18, 19]. To ensure calculability of the emitted synchrotron radiation, one has to ensure that coherent effects do not contribute to the radiation. We performed experiments in near-UV to near-IR spectral regions, but did not find any evidence of coherent synchrotron radiation. Recent experiments have also shown that with increasing electron energy the coherent microwave emission disappears, ensuring calculability of SURF III.

In addition, all instabilities have threshold currents between 10 mA and 20 mA ring current, depending on the electron energy. Below this threshold current, we have a highly stable and noise-free synchrotron radiation source, independent of the operating conditions. It should be pointed out that in full coupling of the

2. At SURF this is called applying "fuzz" to the beam.

horizontal and vertical betatron motion, even at fairly high beam currents, the source is very stable.

2.7 Uncertainty budget

For irradiance calculations the accuracy with which the necessary parameters can be determined is very important. The magnetic flux density has been determined to be uniform within 1 part in 10^4, leading to the same uncertainty in the electron energy. Figure 3 illustrates the influence of uncertainties in power measurements. At wavelengths longer than 100 nm, the small uncertainties of SURF III in the bending radius and the electron energy have negligible influence on the intensity. The biggest contribution clearly comes from the electron-beam current measurement, which, in our case, has an uncertainty of 2 parts in 10^3. We are currently working on ways to improve the determination of the electron-beam current.

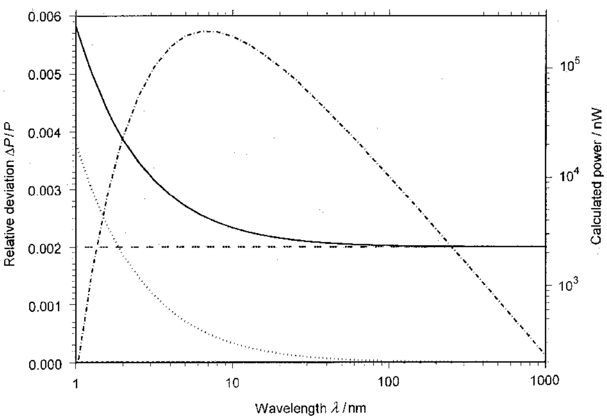

Figure 3. Total calculated optical power (dashed-dotted line) for SURF III at 330.647 MeV, 100 mA ring current, bending radius 838.214 mm, on orbit ($\psi = 0$), distance from source $r = 10$ m, and aperture size $A = 10$ mm^2. The dotted line is the relative error introduced by an uncertainty of 1 part in 10^4 in the electron energy, the triple-dotted-dashed line shows the error arising from an uncertainty of 2 parts in 10^3 in the electron current, and the dashed line (hardly visible on the baseline) represents the relative error caused by an uncertainty of 1 part in 10^6 in the radio frequency. The solid line is the combined uncertainty.

3. Conclusions

SURF III has been successfully upgraded, implementing a new magnet optimized for storage ring operations. The characterization of SURF III is being carried out in parallel with the commissioning of beamlines. All beam diagnostics show that SURF behaves fully as expected from fundamental accelerator physics. The excitation of vertical betatron oscillations to increase the electron-beam lifetime has been found to cause intensity noise under certain conditions, but we have found a cure for this by operating the machine in full coupling.

The SURF upgrade has generated a much more stable and better-characterized light source for radiometry.

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