The new beamline 3 at SURF III for source-based radiometry

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The Synchrotron Ultraviolet Radiation Facility (SURF III) at the National Institute of Standards and Technology provides a unique opportunity for high-accuracy ultraviolet (UV) to infrared radiometry due to the 70-fold improvement in the uniformity of the magnetic field from the previous generation of SURF. This improvement enables the properties of the output radiation, such as spectral power, angular spread, and polarization, to be more accurately predicted based on the use of the Schwinger's equation. The radiation from SURF III is completely characterized by only three parameters, the magnetic field, the radius of the electron beam trajectory, and the electron beam current. For radiometry, the calculability of SURF III provides an important standard light source for source intercomparison. In contrast to the widely used blackbody source where the thermal radiation is completely characterized by the temperature and the emissivity of the blackbody walls, synchrotron radiation extends the wavelength range to UV and x ray which is impractical for blackbody sources. At SURF III, a new beamline, beamline 3, is constructed as a white light beamline for source-based radiometry. We describe the design of the new beamline 3 and its front-end high accuracy electron beam current monitor. This monitor not only measures one of the three fundamental parameters, the electron beam current, it also serves as an electron beam diagnostic tool. We also discuss ways to verify the calculability of SURF III using filter radiometers.
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I. INTRODUCTION

The potential of using synchrotron radiation (SR) as a calculable light source was recognized almost 30 years ago.[1] The problem of radiation emitted by a charged particle traveling in a magnetic field near the speed of light was accurately solved by Schwinger.[2] Only three input parameters in the Schwinger equation dictate the characteristics of synchrotron radiation: the magnetic field, the orbital radius, and the current provided by the moving charged particles. For radiometry, measurements of SR are completely determined by current, magnetic field, and distance measurements. This makes SR a standard source with well-defined radiation that can be used to compare and calibrate other sources.[3,4]

Other than SR, a similar calculable source that is widely used in the radiometry community is the blackbody source. Blackbody radiation is calculable by the temperature of the cavity and the emissivity of the surface. It has become an important tool in the visible and infrared for high accuracy radiometry.[5] However, the spectral distribution of a blackbody source depends solely on the temperature of the source. To reach the ultraviolet (UV), a blackbody source has to be heated to a temperature of several thousand degrees, which is difficult to reach and maintain in a normal laboratory. For SR, the broad and smooth spectral distribution, from x ray to infrared (IR), can be a great advantage over the blackbody radiation.

The Synchrotron Ultraviolet Radiation Facility (SURF III)[6,7] at the National Institute of Standards and Technology (NIST) has dedicated beamlines for radiometry in setting the national standards in radiation measurement. As opposed to most recently built synchrotrons, SURF III has a textbook style circular orbit with a highly uniform magnetic field. Because of the relatively low electron energy (up to 400 MeV), SURF III provides radiation with much less damaging high energy photons and is especially useful for improving the accuracy of UV source calibrations.

The recently constructed beamline 3 at SURF III is a white-light beamline that delivers the calculable radiation from SURF III to the end station of beamline 3 for comparing and calibrating other light sources, as well as characterizing detector systems. Because the electron beam current has the largest uncertainty of the three fundamental parameters of the Schwinger equation for the present SURF III system, instruments on beamline 3 will also accurately measure the electron beam current by monitoring the radiation from SURF III. A new current monitoring device on beamline 3 is designed to improve the uncertainty and provide redundancy for the existing SURF III current monitor. It also serves as a diagnostic tool for monitoring changes in the conditions of the electron beam. We expect this device to provide an uncertainty of less than 0.5% in the measurement of electron beam current.

II. BEAMLINE DESCRIPTION

Beamline 3 is a straight-through white-light beamline with minimum optical components in the optical path. SR travels down the beamline unobstructed through several apertures to reach the front end station located at 2.5 m from

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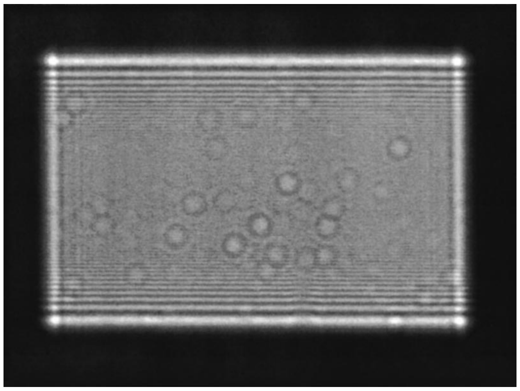

FIG. 1. Diffraction pattern from a square aperture with synchrotron radiation from beamline 3 recorded by a CCD camera with a 334 nm filter. The circular patterns are caused by diffraction from dust on the filter.

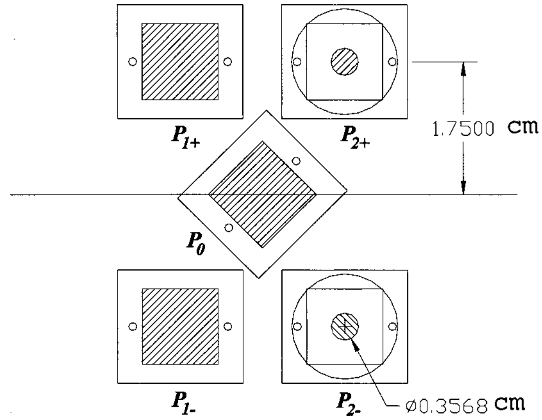

FIG. 2. Arrangement of photodiodes for the electron beam current monitor on beamline 3. P_0 is the electron counting photodiode, P_{1+} and P_{1-} are a set of photodiodes, and P_{2+} and P_{2-} are another set of photodiodes with apertures.

the tangent point on the electron orbit where the SR for beamline 3 is originated. Inside the front-end station, part of the SR is used to irradiate the high-accuracy electron beam current monitor and the rest is passed unobstructed through an aperture to the end station located 6 m from the tangent point.

The end station is constructed of stainless steel tubes with a diameter of 15 cm. This allows the mapping of the SR intensity 10 mrad above and below the electron orbital plane. Detectors used to measure SR can be mounted either inside the end-station vacuum chamber or outside (in air) viewing through a window of the vacuum chamber. For source intercomparison, the source to be compared will be mounted near the end station. A monochromator or filtered radiometer will be used at the end station to sequentially measure radiation from beamline 3 and the source being compared.

To maintain the calculability of SR, the main design considerations for beamline 3 are to reduce scattered light and diffraction effects. To reduce scattered light inside the beamline, a series of apertures and baffles are installed throughout the beamline. With the use of apertures, diffraction effects have to be considered. Diffraction effects are more pronounced in the visible and IR than in the UV and also with a smaller aperture defining the light beam. An example of the diffraction effect is shown in Fig. 1 where the SR image behind a square aperture is recorded with a charge coupled device (CCD) camera. Numerical calculations are currently being developed to model the diffraction effects for beamline 3.

III. ELECTRON BEAM CURRENT MONITOR

To fully quantify SR characteristics from SURF III, the values of three machine parameters, namely, the radius of the electron trajectory, the magnetic field, and the electron beam current, are required. The uncertainty in the calculated quantities of SR is directly related to the uncertainty in the measurements of these parameters. For SURF III, the magnetic field variation along the electron orbit is less than three parts in 10^4.[6] The radius of the electron orbit is even more accurately determined by the radio frequency (rf) of the rf cavity. As a result, the dominant contribution to the uncertainty is the measurement uncertainty of the electron beam current.[7]

Presently, the electron beam current measurement at SURF is performed optically by using a single photodiode with a variable gain amplifier.[8] The photodiode detects SR (predominantly in the visible) through a focusing lens and the signal from this detector package shows discrete steps when one or more electrons are lost from the electron beam at very low electron beam current (i.e., less than a few thousand electrons in the SURF ring—so-called electron counting). At the normal operation of about several hundred milliamperes (corresponding to about 10^{10} electrons) in the ring current, the current is extrapolated from the signal of the detector at low electron beam current where electron counting is possible.

To improve the accuracy of the electron current measurement, we designed a multiple photodetector array system for the front-end station of beamline 3. There are three sets of Si photodiodes with a total of five photodiodes arranged as depicted in Fig. 2. The first consists of an electron counting photodiode located on the orbital plane of the electron beam. The electron counting photodiode is attached to an amplifier with a gain of 10^{10} V/A and is used only in low light condition for electron counting. A shutter blocks the photodiode at higher electron beam current to avoid radiation damage to the photodiode. The second and third sets of photodiodes each consist of two 1 cm×1 cm Si photodiodes positioned 7 mrad above and below the orbital plane. The third set of photodiodes also has an aperture with an area of 10 mm^2 mounted on top of the photodiodes.

Each of the three sets of photodiodes is responsible for the measurement of a range of the electron beam current. The electron counting photodiode has the highest response to the electron beam current because of its on-plane position as compared to the out-of-plane position for the other two sets of photodiodes. For a normal electron beam current of a few hundred milliamperes, the last set of photodiodes with apertures is used to monitor the electron beam current because of its lowest response to electron beam current.

To calibrate the response of the photodiodes to the electron beam current, the measurement of each photodetector can be bootstrapped to other photodetectors to cover a wide range of electron current. This reduces the problem with lin-

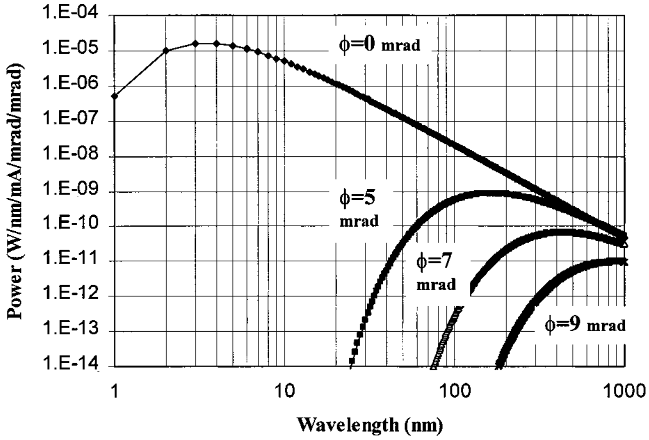

FIG. 3. Calculated spectral power distribution for SURF III with out-of-plane angle ϕ at 0, 5, 7, and 9 mrad. The electron energy used for this calculation is 360 MeV.

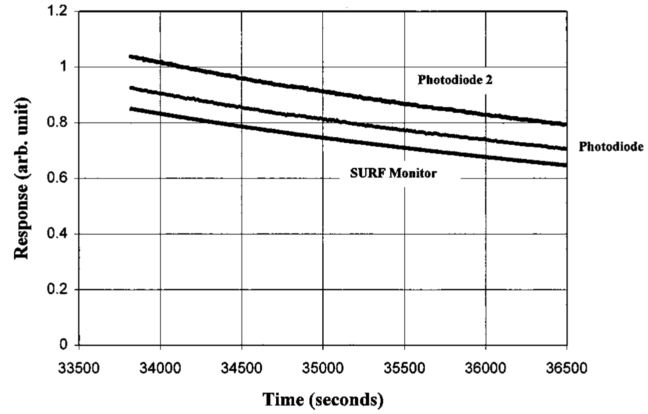

FIG. 4. Monitoring of SURF III electron beam current by two photodiodes with apertures on beamline 3 and the signal from the existing SURF current monitor as a function of time.

earity when only one photodiode is used. The response of the photodiodes for the current setup is eventually tied to the electron counting photodiode and the actual current in the SURF III ring when the electron current is lowered.

In addition to monitoring the electron beam current, there are two additional advantages with the positioning of the out-of-plane photodiodes. First, these photodiodes are exposed to SR with decreased number of high-energy photons, which results in much less radiation damage and more stability in photodiode response. This is demonstrated in Fig. 3 where the calculated spectral distribution is plotted for several out-of-plane angles. Second, the SR from SURF III changes rapidly as a function of angle at the 7 mrad angle where two photodiodes are positioned. This makes the arrangement of two photodiodes above and below the plane very sensitive to any change in the position and direction at the tangent point of the electron orbit for beamline 3. This is an important diagnostic tool to identify measurement errors for source intercomparisons caused by a change in SURF III electron orbit.

Finally, the electron beam current monitor is mounted on a motorized vacuum manipulator. This allows accurate positioning of the device with respect to the electron orbital plane.

IV. MEASUREMENTS WITH THE ELECTRON BEAM CURRENT MONITOR

The electron beam current monitor on beamline 3 was constructed recently and preliminary measurements were conducted and compared to the existing SURF monitor. Shown in Fig. 4 are the signals from two of the apertured photodiodes monitoring the SR on beamline 3 and also the signal from the existing SURF monitor. The decay of all the curves resulted from the decay of the electron beam current in the storage ring.

The signals from the photodiodes of the electron current beam monitor were used to study changes in the electron orbit. The ratio of the signals from two photodiodes above and below the orbital plane was used to study orbital plane stability. The stability of the orbital plane can be affected by a number of factors like the electron energy, the fuzz level, the phase angle, and even the electron beam current. As an example, we found that as the energy of electrons changes, the ratio shows a distinct change. This is shown in Fig. 5. Independent measurements on another beamline by scanning the angular distribution showed movement of the electron beam to be a fraction of a millimeter over the electron energy range. Figure 5 demonstrates the sensitivity of the electron beam current monitor on beamline 3 to the stability of the electron orbit. We are currently studying other factors that could change the electron orbital plane.

V. FUTURE WORK

We will continue the measurements using the electron beam current monitor to determine the SURF III electron beam current. Before actual source calibration using beamline 3, we plan to verify the calculability of SURF III using a series of calibrated filtered radiometers from the UV to the IR to measure the spectral irradiance of SR while varying the electron beam energy from as low as 50 MeV to the normal operation energy of 380 MeV. The spectral irradiance responsivities of these filtered radiometers are calibrated at the NIST Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources Facility[9] to an uncertainty less than 0.1%. Measurements of SR with these filtered ra-

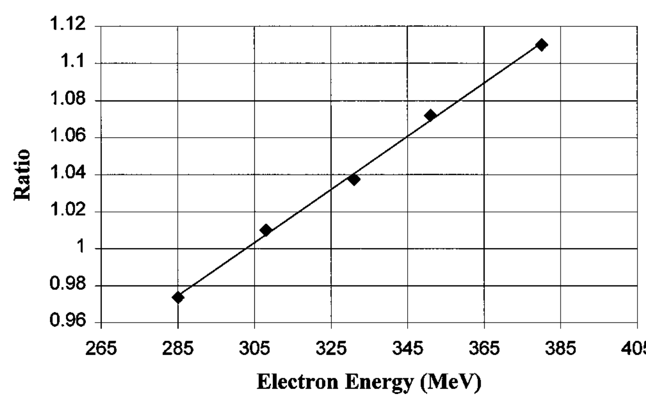

FIG. 5. The ratio of signals from two photodiodes with apertures as a function of the SURF III electron energy. The solid line is a best-fit line.

diometers will independently confirm the electron beam current and the electron beam energy and verify the overall uncertainty of beamline 3 for source intercomparison.

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