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Synchrotron ultraviolet radiation facility SURF III

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The National Institute of Standards and Technology (NIST) has operated the Synchrotron Ultraviolet Radiation Facility (SURF) continuously since the early 1960s. The original accelerator was converted into a storage ring, called SURF II, in 1974. Then in 1998, motivated mainly by limitations in the accuracy of radiometric calibrations and the wish to extend the spectrum of the emitted synchrotron radiation to shorter wavelengths, a second major upgrade was performed. This time the whole magnet system was replaced to improve the calculability and allow for higher magnetic fields. Since the recommissioning of SURF III we have been working to improve the stability of the stored electron beam through modifications of the radio-frequency system, leading to operations with unprecedented stability and new record injection currents topping 700 mA. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1445833]

I. INTRODUCTION

The Synchrotron Ultraviolet Radiation Facility, SURF III,[1–3] is a compact storage ring operated by the National Institute of Standards and Technology, NIST. SURF is a stable source of synchrotron radiation from the infrared to the soft x-ray spectral regions, operated mainly as a light source for radiometry and applied research.[4] Currently several calibration services are provided at SURF beamlines: ultraviolet (UV) detector calibrations,[5–7] extreme ultraviolet (EUV) detector calibrations,[8,9] and measurements of optical properties in the UV[10] and EUV.[11] One beamline (BL-2),[11,12] partially supported by NASA, is open to customers for calibration of spectrometer packages based on the calculability of synchrotron radiation. Another (BL-3) is currently under development to enhance our capabilities for source-based radiometry[13,14] by reducing the uncertainty in the electron beam current determination. It will also provide additional experimental stations for the calibration of filtered detector packages and standard light sources. In addition to the magnet upgrade for SURF III, other key systems have been modified. For example, we can now operate with much higher radio-frequency (rf) power due to improvements in our rf transport line and a recently installed circulator. The circulator protects the rf amplifier from the increased reflected power during injection, when the radio-frequency is slightly detuned to suppress higher-order modes of the cavity. Also, a new pumping setup has also led to a better operational vacuum. All of these improvements translate into higher operational energies with better beam lifetime and stability. The operational stability of the beam has improved due to the use of a narrow-band frequency source instead of the previous white-noise frequency source to excite the vertical betatron oscillation. The beam size is constantly monitored and locked to a user-defined set point by feeding back on the excitation frequency. This has led to a beam stability improvement of more than 30 dB over the previous setup. The obtainable beam current was also improved in the course of the upgrade. Optimization of injection procedures has increased the average beam current to 650 mA from 120 mA. This was accomplished using a variety of techniques and improvements such as sweeping the rf frequency during injection to minimize the effects of higher-order cavity resonances. The control and management systems used in SURF III have also been upgraded to improve system performance. Currently we have full computer control of the storage ring operational parameters. These data and injection parameters are monitored and logged continuously by a computer during normal operation, and alarms are generated automatically when a problem occurs. The level of stability and brightness already obtained with SURF III opens the door to a wide range of applications such as infrared microscopy.

II. IMPROVEMENTS

A. Control system

At SURF, the electron energy is deduced using the condition[15] from the measured magnetic flux density B and radio frequency ν_{rf}:

$$E=\frac{n_{\mathrm{har}} B c^2 e}{2\pi \nu_{\mathrm{rf}}}, \tag{1}$$

where n_{har} is the harmonic number (number of bunches, or ratio of radio frequency to orbital frequency), c is the speed of light in vacuum, and e is the elementary charge. The original control software controlled the magnetic flux density via the main coil current. This resulted in a small drift of the magnetic flux density after injection. To improve operational stability, the control system was changed to keep the magnetic flux density constant instead. This was accomplished using an off-orbit Hall probe, which was calibrated with an on-orbit probe. This change greatly improved the stability for radiometric calibrations.

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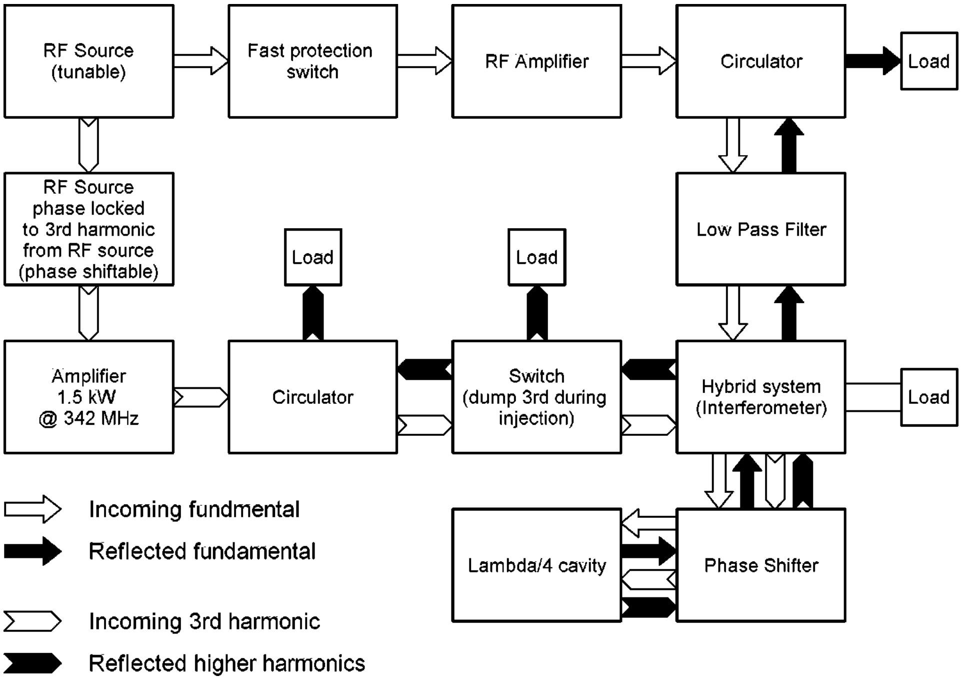

FIG. 1. The new SURF radio-frequency system.

B. Radio-frequency system

The radio-frequency system with a cavity that is resonant for all odd harmonics[16] was clearly the source of many of the stability problems at SURF. One of the greatest advantages of SURF, operability of the storage ring at any energy between the injection energy of 10 MeV and the maximum energy of 380 MeV, could not be utilized completely because of the apparent unstable electron beam at lower energies. At higher electron energies close to 380 MeV, radiation damping becomes efficient enough to make the beam stable.

The new SURF rf system is illustrated in Fig. 1. The fixed frequency oscillator was replaced by a tunable rf source, which allows us to increase the rf frequency slightly. Now at injection the radio frequency is tuned to $\nu_{\mathrm{rf}} = 114.065$ MHz and the cavity is detuned from resonance to suppress the buildup of higher harmonics in the system. Then, during the ramp to final energy, the radio frequency is swept down to 113.98 MHz. After the tunable rf source a fast protection switch was installed to protect the system in case of, e.g., arcing in the cavity or circulator. The switch is connected to an amplifier system which is followed by a circulator.[17] Power coming from the amplifier passes through this circulator undisturbed, whereas reflected power at the same frequency coming from the opposite side will be dumped into a 50 Ω load to protect the amplifier. Our next step is a hybrid system, which does not affect the fundamental, but will deflect all power in the third and fifth harmonics from the main circuit. Between the cavity and the hybrid is a phase shifter, which allows one to fine-tune the phase between the incoming and reflected power. The third and fifth harmonic coming from the cavity will pass through the hybrid and during injection will be dumped. During normal operation the third harmonic will be phase locked to the fundamental frequency and fed into the system. We have both phase and amplitude control of the injected signal with peak powers in excess of 1.5 kW. Since the rf cavity is resonant for higher harmonics,[16] we can use it to feed in the third harmonic in order to extend the bunch length to increase the electron beam lifetime.

SURF used to run with radio frequency $\nu_{\mathrm{rf}} = 113.847$ MHz, corresponding to an orbit radius of $\rho = 838.2$ mm. The orbit radius is now changed to 837.224 mm when running at 113.98 MHz.

C. Beam size measurement and control

The transverse electron beam size and position at SURF is permanently monitored using an imaging system similar to the one described in Ref. 18. The synchrotron radiation emitted by the electrons stored in SURF is imaged using a spherical lens, narrow-band interference filter and a charge coupled device (CCD) camera. The signal from the CCD camera is fed into a frame grabber and the captured images are analyzed using particle detection functions and nonlinear curve-fitting routines. The software also adjusts the gain on the camera for full use of the dynamic range of the 8-bit frame grabber. Without manipulation the vertical beam cross section at SURF is very small,[18] resulting in very short electron beam lifetimes, limited by electron–electron scattering within the beam. To increase the lifetime the vertical betatron oscillation is excited.[19] This used to be done using a broadband noise generator, which was found to introduce noise into the beam[20,21] and subsequently replaced by a narrow-band frequency generator. The excitation frequency of this instrument is controlled by the same program that performs the beam size measurement and the frequency is adjusted over time to keep the vertical beam size constant. In standard operating mode the beam is excited to have a vertical full

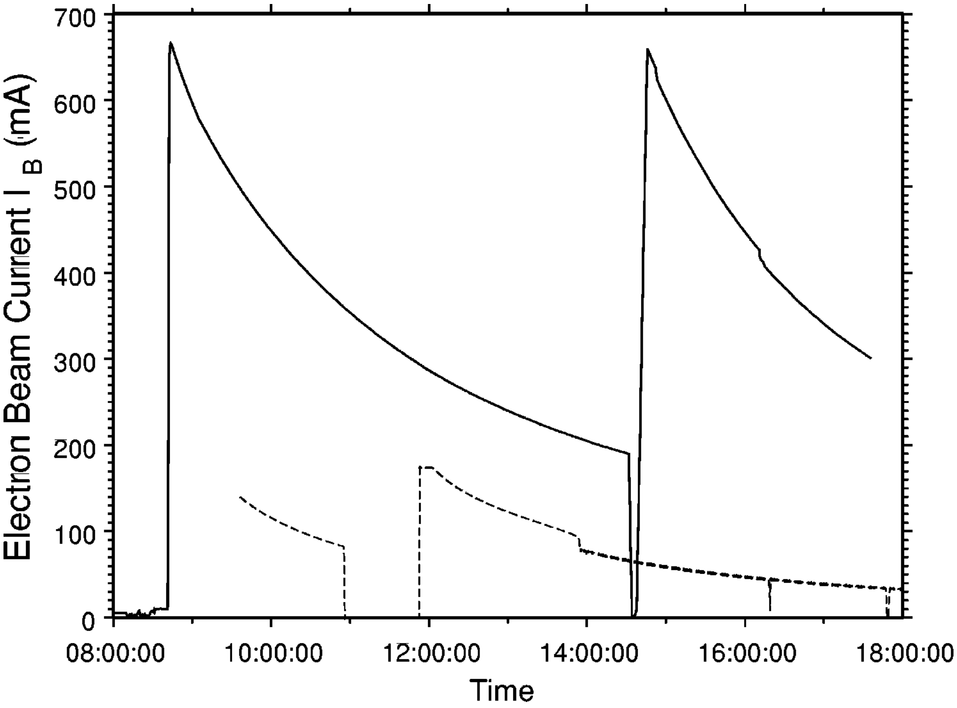

FIG. 2. Increase in injection currents at SURF from January 10, 2000 (dashed line) to January 9, 2001 (solid line).

width at half maximum of about 1 mm, leading to electron beam lifetimes of several hours.

D. Injection currents

In the first days of SURF III, injection currents remained well below 200 mA on average. As shown in Fig. 2, the injection currents increased considerably during calendar year 2000 and are now in excess of 700 mA on a good day. The displayed beam currents were collected with a logging program, which collects data on all major storage ring parameters, allowing easy access to performance data.

III. CONCLUSION

The overall performance of SURF III has been improved considerably since it was commissioned in the fall of 1998. Increased injection currents have made SURF a competitive synchrotron radiation source in the spectral region from the extreme ultraviolet to the far infrared. A completely refurbished rf system should allow for increased beam stability at all operating energies. First tests of this system have been very promising, but because of its complexity the tuning procedure is not completely understood yet. The automatic beamsize measurement and control system improved the overall beam stability as well, as shown elsewhere.[21] Given all these improvements, we plan to implement some new beamlines in addition to existing ones, making full use of the improved capabilities of SURF.

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