RECORD CAPTURE AND ACCELERATION EFFICIENCY IN THE SURF-II 300 MeV CIRCULAR STORAGE RING

L.R. Hughey
National Institute of Standards and Technology
Gaithersburg, MD 20899

Introduction

SURF-II is a 300-MeV, single-magnet, weak-focusing, circular storage ring. It is dedicated to the production of VUV and soft x-ray radiation for research and for absolute radiometry. The injector is a 10-MeV microtron. A single output pulse from the microtron is injected into the storage ring (SR) and accelerated to operating energy. A description of the SURF-II storage ring and the microtron injector was given at the IX Int. Conference on High Energy Accelerators [1]. Some additional improvements are described in references [2, 3 and 4]. The microtron is delivering 1-μsec long, 80-mA pulses. With multiturn capture, more than 300 mA have been accelerated to full energy. Last week (3/13/89) the average beam current was 262 mA and every beam was greater than 250 mA. This capture and acceleration efficiency is being achieved by improved transport line optics, kicker magnet pulse, the SR's magnetic field gradient and rf system.

Improved Capture

Electron capture is improved in several ways. The SR's magnetic field gradient is fine tuned. The radial betatron oscillation amplitude, at injection, is enlarged by about 60% over that used formerly. An optimum power level in the rf cavity has been found as well as better pulse shape and timing of the kicker magnet. Also the transport line optics are fine tuned for maximum capture. At injection energy, the magnetic field gradient which has led to maximum capture results in an index of .628 that is nearly constant over the radial zone occupied by the injected electrons. The inflector is positioned 3.4 cm out from the 83.82 cm equilibrium orbital radius. The betatron oscillation amplitude resulting from this position is nearly the maximum allowed by the internal dimensions of the rf cavity, the kicker magnet, the beam monitor electrode (BME) and other internal structures. The rf voltage in the cavity is set to ~1.7 kV at injection. Figure 1 shows the current pulse in the kicker magnet.

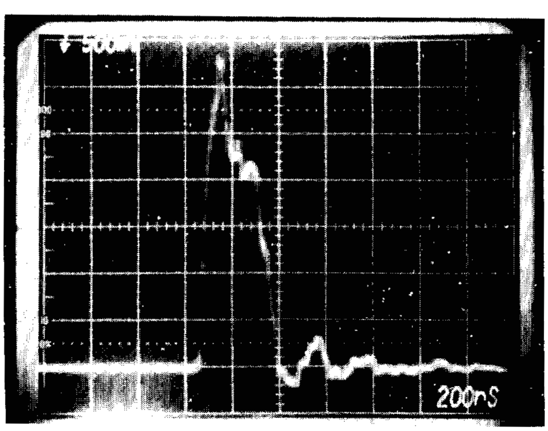

Figure 1. The kicker magnet current pulse. 1 volt corresponds to 95 amps.

As the peak current is increased to 250 A the electron capture increases. No change in capture is observed for peak current between 250-360 A. The peak current normally used is 320 A. The pulse shape is changed from the original by the addition of another capacitor and inductor in the pulse forming network. This results in a longer pulse decay time.

Figure 2 shows schematically the SR, the microtron and the transport line which connects them. There is an X & Y steering magnet pair, a quadruple focusing doublet, an insertable target, a second quadruple doublet, a second X Y steering pair, the inflector magnet (which bends the beam through 45 degrees) and a final insertable target.

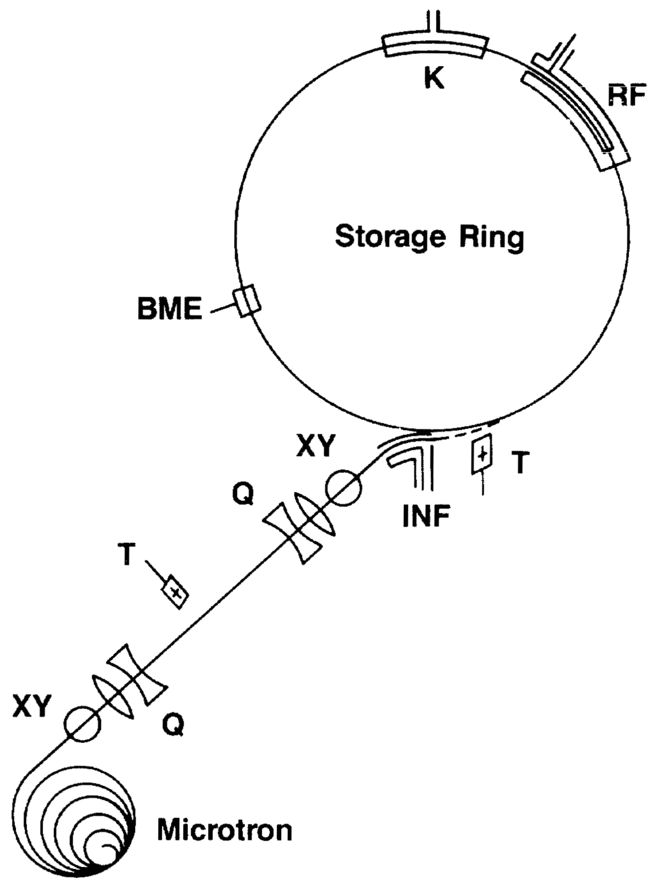

Figure 2. Schematic layout of the SURF-II storage ring, microtron and transport line. K: Kicker magnet. RF: RF cavity. BME: Beam monitor electrode. INF: Inflector magnet. T: Insertable targets. XY: Horizontal-vertical steering magnets. Q: Quadrupole doublet focussing magnets.

For initial tuning the mid-beamline target is inserted and the beam is focused to a minimum size and positioned on the cross hair. The target is removed and the target following the inflector is inserted. The second quads and steering magnets as well as the inflector current pulse amplitude are adjusted to focus the beam and position it on the second target. The beam is thus entering the SR properly. The operator then removes the target and varies the SR

CH2669-0/89/0000-0461$01.00©1989 IEEE

magnet current until a signal, which is produced by electrons passing through the BME, is observed on an oscilloscope. This signal is maximized by tuning the inflector magnet pulse and the SR's magnet current. Next, the kicker magnet is started and its timing is adjusted until electrons are captured.

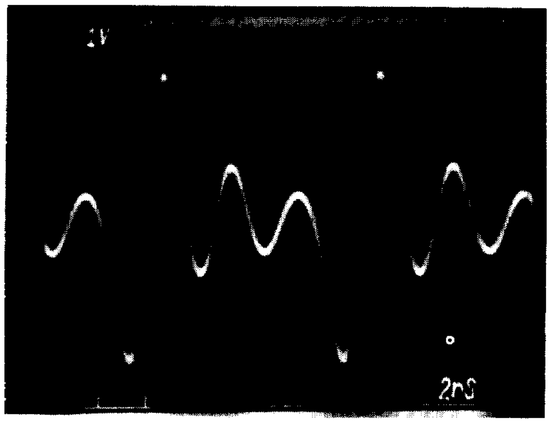

Figure 3. Beam monitor electrode signal

The waveform on the scope is shown in Figure 3. The beam is capacitively coupled to the BME and the signal is essentially the derivative of the current pulse. The operator then proceeds to maximize this BME signal by tuning the inflector current pulse amplitude, the SR magnet current, the kicker timing and all of the steering and focusing magnets in the transport line. As a final adjustment, it has been found very useful to make fine adjustments in the microtron's magnatron modulator voltage. Often we get a little more capture with slight changes in the modulator voltage. After tuning for maximum, the operator starts the ramp to operating energy. The microtron, the infector and the kicker are fired one more time and then the storage ring's magnetic field starts ramping up at ~.84 T per min. (300 MeV in SURF is 1.2T).

Energy Ramp

As the magnetic field is increased the magnetic field index is changed. As seen in Figure 4 the average index drops from .628 at 10 MeV to just over .6 at 60 MeV. At energies below 60 MeV the index shows no radial variation in that portion of the zone occupied by the electrons which we are able to measure (82.2 - 87.3 cm).

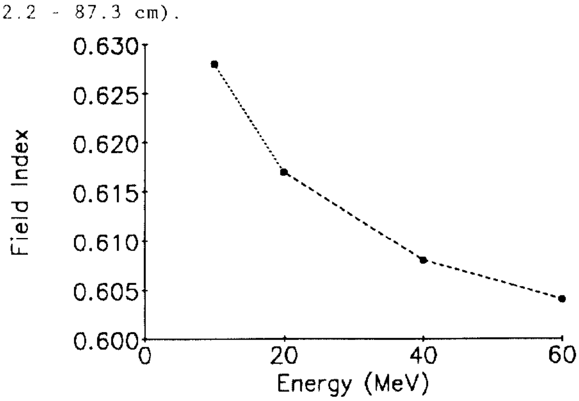

Figure 4. Magnetic field index vs. energy 10-60 MeV

As the energy is increased above 60 MeV the index becomes lower inward of the equilibrium orbital radius and larger outward thereof. Figure 5 shows the radial profile of the index at 285 MeV. The region occupied by the electrons at 285 MeV is indicated by crossed lines. At 10 MeV, the electrons traverse the 80.4 to 87.2 cm zone.

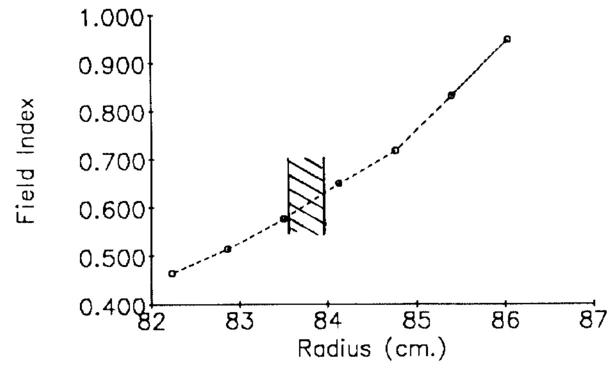

Figure 5. Field Index vs Radial Distance at 285 MeV.

By the time the energy has been ramped up to 50 MeV, radiation damping has reduced the betatron amplitudes to ~600 nm radially and ~40 nm vertically. In a weak-focusing, circular storage ring σ_y' and σ_r' are directly proportional to σ_y and σ_r, respectively. For small σ the emittance becomes very low and the Touschek loss rate can be very large. Therefore, the vertical and radial betatron oscillations are stimulated deliberately to increase the emittance and thereby the lifetime. The vertical oscillation is enlarged by applying an rf voltage to a pair of vertical defection plates in the SR. This rf has a center signal of 13 MHz which is the difference frequency of the 57 MHz orbital frequency and the vertical betatron frequency. The source of this signal is a white noise generator with a 300 kHz bandwidth, 13 MHz center frequency filter. This broad band vertical deflection signal provides for variation in betatron frequency during the ramp and drift in the index during the lifetime of the stored beam. Little power is needed at low energy as the beam isn't very stiff, but as the energy increases more power is required to provide the same oscillation amplitude. This is accomplished by using a voltage controlled transmission filter between the noise generator and the power amplifier.

Even though σ_r is fairly large, we have found a means to increase it by about a factor of 2. A mechanical device has been built and installed in the rf power cable which can vary the length (phase angle) of the cable. The phase can be varied by as much as 182°. We have found a phase angle (a cable length) which allows self-stimulated radial and longitudinal oscillations that enlarge the beam and increase the lifetime. The phase angle which we found first for this effect worked fine at all energies, but as we began getting better capture efficiency and therefore more electrons during the energy ramp we began noticing small incremental, periodic losses during the ramp. It was found that these losses were avoided by increasing the phase angle ~8° during capture and most of the ramp. Since this phase angle gave a significantly poorer lifetime at high energies the phase angle was shifted back to the former "good" angle above about 200 MeV. We have since found an even better phase angle 6° larger yet, which is good for injection, ramping and full energy. It gives even better lifetime at full energy (300 to 150 mA takes almost 2 hours).

Figure 6 shows the beam monitor electrode signal processed by a spectrum analyzer. It shows the 114 MHz fundamental and the harmonics up to 1 GHz. The amount of beam current and the phase angle for each

(a) (c)

(b) (d)

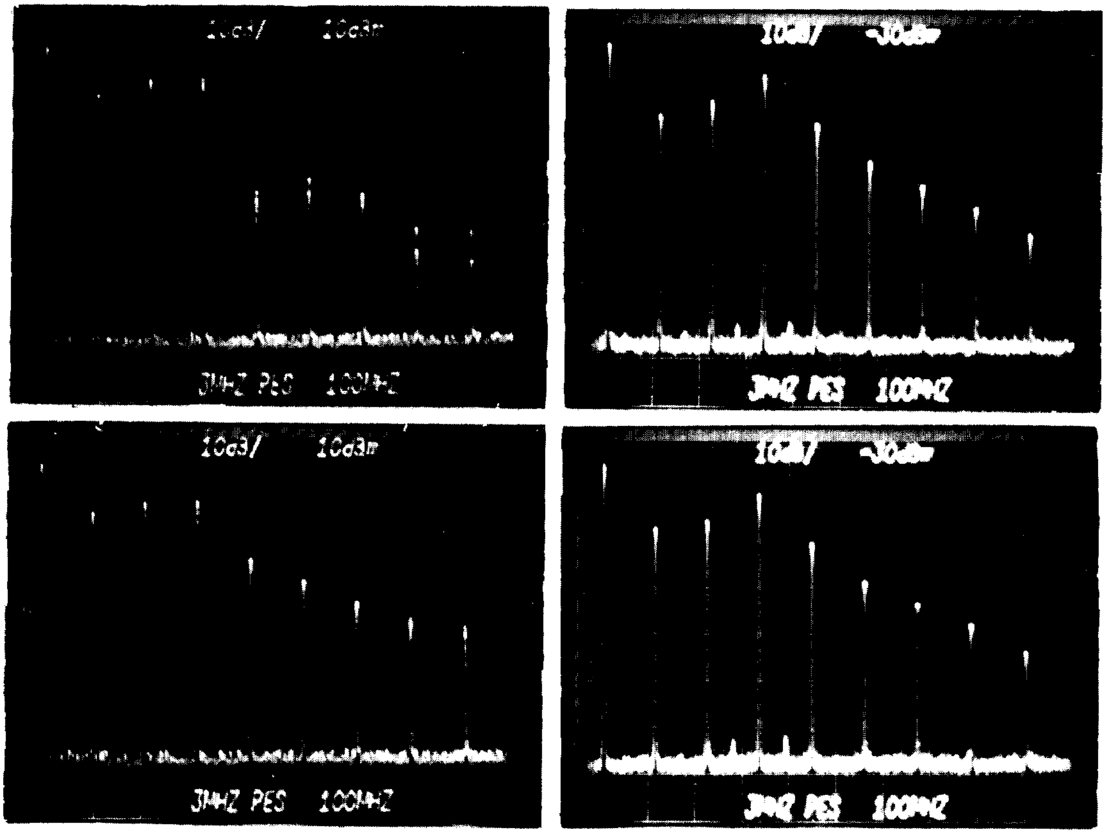

Figure 6. Harmonic spectra of beam monitor electrode signal showing harmonics up to 1 GHz. (a) 150 mA, $\theta = 144°$, (b) 150 mA, $\theta = 138°$, (c) 190 μA, $\theta = 144°$, (d) 190 μA $\theta = 138°$.

photo is indicated. The recently found optimum phase angele is 144° and 138° is the former good angle for ramping. Note in the two spectra on the left the distinct difference in the 4th - 8th harmonics. Both of the spectra were obtained with 150 mA of beam current. During a low current run the spectra for the same two phase angles are seen on the right side and show no obvious difference. They were taken with 190 μA of beam current. In all 4 cases the beam energy was 285 MeV.

In many storage rings the beam current is increased by stacking. We have found that cycling from high energy to fairly low energy and back to high energy does not result in gross losses. We have started with 270 mA at 285 MeV and ramped to 93 MeV and back to 285 in 3 minutes. Fourteen percent of the beam was lost. Subsequent cycles over the same energy range resulted in 5% lost starting with 230 mA and a 2% loss when starting with 219 mA. These cycles were made with no attempt at optimizing index, rf voltage or anything else except the phase angle was shifted to 131° (the former "good" angle) from 144°. Whereas 144° seems to be best for the injection to full energy ramp, it results in bad losses when ramping back down.

Lifetime

We find that the coherent synchrotron-relaxation oscillation discussed by G. Rakowsky at the 1985 Particle Accelerator Conference [5] does not occur with the 144° phase angle we are using. This oscillation is found by shifting the phase to 125°, i.e., shortening the rf cable by about 1/20 of a wavelength. The beam lifetime with the 125° phase angle is not as good as it is with 144°. At the present time the beam current-lifetime product at SURF-II is about 500 mAHr.

References

[1] E.M. Rowe, et.al., The Conversion of the NBS 180 MeV Electron Synchrotron to a 240 MeV Electron Storage Ring, Proc. IX Int. Conf. on High Energy Accelerators, Stanford, CA (1974), pp. 689-692.

[2] G. Rakowsky and L. Hughey, SURF's Up at NBS: A Progress Report, 1979 Particle Accelerator Conference, San Francisco, CA, IEEE Trans. Nucl. Sci., NS-26 (June 1979) pp. 3845-3847.

[3] G. Rakowsky, NBS SURF-II: A Small Versatile Synchrotron Light Source, 1980 Conference on the Application of Accelerators in Research and Industry, Denton, TX, IEEE Trans. Nucl. Sci., NS-28 (April 1981) pp. 1519-1521.

[4] G. Rakowsky, SURF-II Upgrade Features Magnet and RF System Enhancements, 1983 Particle Accelerator Conference, Santa Fe, NM, IEEE Trans. Nucl. Sci., NS-30 (August 1983) pp 3444-3446.

[5] G. Rakowsky, Coherent Synchrotron Relaxation Oscillation in an Electron Storage Ring, 1985 Particle Accelerator Conference, Vancouver, BC, Canada, IEEE Trans. Nucl. Sci., NS-32, pp. 2377-2379