Commissioning of the Phase I Superconducting X-Ray Lithography Source (SXLS) at BNL*

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Abstract

The goal of the SXLS Project at BNL is to design and construct a compact storage ring as a soft x-ray source for proximity printing x-ray lithography.[1] The final ring will operate at an energy of 700 MeV and it will make use of superconducting dipoles, B_0 = 3.87 Tesla and ρ = 60 centimeters, as a source of λ_c = 10 angstrom x-rays. The project is proceeding in two phases: in Phase I low field iron dipoles (B = 1.1 Tesla) are being used to study the ring at energies of 200 MeV and below; in Phase II the low field dipoles will be replaced with superconducting dipoles. The Phase I storage ring was commissioned during the fall of 1990 and the design current of 500 ma has been exceeded. A report on the performance of the Phase I ring is presented.

1. Storage Ring Lattice

To make the ring as compact as possible (C = 8.5 m), a two superperiod gradient FODO lattice incorporating two 180° combined function dipole magnets was adopted.[2] Since the basic lattice is a "one knob" design with only horizontally focusing quadrupoles and the defocusing sextupole designed into the poleface of the dipole, two sets of poleface windings were installed on the dipoles. One winding has quadrupole symmetry to permit variation of the vertical tune and the other has dipole/sextupole symmetry to provide for tuning of the vertical chromaticity. The quadrupoles are mounted on stepping motors and can be translated by ±3 mm both horizontally and vertically to provide closed orbit correction and there are also four sets of air core dipole orbit correctors. Four 12-pole magnets are also included to provide additional tuning capability.

The basic design parameters of the Phase I SXLS ring are listed in Table 1 and the Twiss parameters are shown in Figure 1.

Table 1: SXLS Phase I Design Parameters

Energy, E [MeV]	200
Circumference, C [m]	8.503
Dipole Magnet Type	EM
Dipole Field, B_0 [T]	1.1
Bending Radius, ρ [m]	.6037
Superperiods, N_s	2
Critical Wavelength, λ_c [A]	423
Horizontal Betatron Tune, ν_x	1.415
Vertical Betatron Tune, ν_y	.415
Energy Loss Per Turn, U_0 [KeV]	.234
Uncorrected Chromaticity, ξ_x,ξ_y	-.49, -1.32
Momentum Compaction, α	.32
Natural Emittance, ε_0 [m-rad]	5.92×10^{-8}

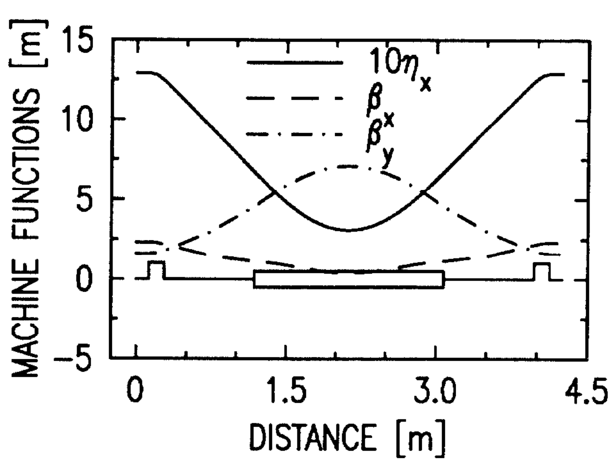

Figure 1: SXLS Optical Functions

2. Commissioning Results

The assembly of the Phase I ring was completed in late August 1990. The existing 80 MeV linac and booster ring at the NSLS serve as the injector for SXLS. A single bunch from the booster (52 MHz bucket) is injected into a 211 MHz bucket in the SXLS ring providing for 1 to 6 bunch operation. The injection system operates at 0.7 Hz. Injection rates of 2-5 ma per pulse are typical although rates of 7-10 ma per shot have been achieved quite frequently at 200 MeV operation. The novel injection scheme involves the use of a single fast kicker magnet[3], with a rise and fall time of 10 ns and a flat top of 50 ns, that gives two horizontal kicks to the stored beam and one kick to the injected beam.

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The initial commissioning of the ring was done at 200 MeV. The first turn in the ring was recorded on September 14, 1990. Stored beam was obtained one month later. By mid December 1990 the design current of 500 ma in six bunches was achieved. A maximum stored current in excess of one ampere in six bunches was accumulated with 200 MeV injection (2/91).

At present (5/91) stored currents of 600 ma in six bunches and 200 ma in one bunch are routinely obtained at an injection energy of 200 MeV. For 160 MeV injection we can routinely store 500 ma in six bunches. We have also succeeded in storing 220 ma at an 80 MeV injection energy. With our present injection system, which is optimized for 750 MeV operation of the NSLS rings, it is difficult to fully explore energies below 160 MeV as there is little damping in the booster ring at these energies. Bypassing the booster and injecting the ring directly from the linac at energies of 80 and 120 MeV will be tried in the near future.

The horizontal closed orbit as measured on the PUEs is corrected to $x_{max} < 2$ mm using the air core trims and an outward displacement of the quadrupoles; the maximum vertical orbit deviation is $y_{max} < 0.75$ mm and this is the uncorrected orbit. The betatron tunes in the machine are nominally set at $\nu_x = 1.438$ and $\nu_y = 0.415$. The machine will store beam over a wide range of tunes; the operating point is chosen to maximize the injection efficiency. The chromaticities of the ring have been measured to be $\xi_x = +2$ & $\xi_y = +2$.

Instabilities are observed in the machine but a detailed analysis has not been performed so far. For large stored currents transverse motions of the beam can be observed on the synchrotron light monitor. There are strong synchrotron sidebands evident on the rotation and tune lines indicative of coupled bunch motion. At present we are not using any active feedback systems to stabilize the beam.

3. Vacuum System & Lifetime

The vacuum chamber straight sections are fabricated from stainless steel type 304L and the dipole chambers from INCONEL 625. An in-situ bakeout system is incorporated in the ring and has been used twice: once before commissioning started and again in Nov. 1990 after replacing a faulty vacuum window.

Vacuum pressures are monitored by ion gauges located just outside the entrance and exit of the dipole magnets. In the absence of beam the average pressure read by ion gauges is $P_{ave} \leq 1\times10^{-10}$ torr. Figures 2 & 3 display the average vacuum pressures versus current and beam current versus time respectively for several ring energies in six bunch operation. The stored beam lifetime can be obtained from Figure 3. For the data shown here it takes roughly 10-40 minutes for the current to decrease by 50%, with the longer lifetimes actually occurring at lower energies. An exact prediction of the lifetime at low energy is complicated by ion trapping, intrabeam scattering and anomalous bunch lengthening.

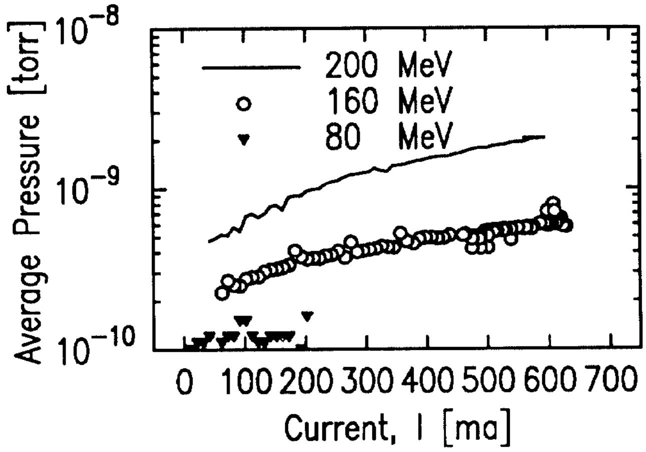

Figure 2: Pressure vs. Current [6 Bunches]

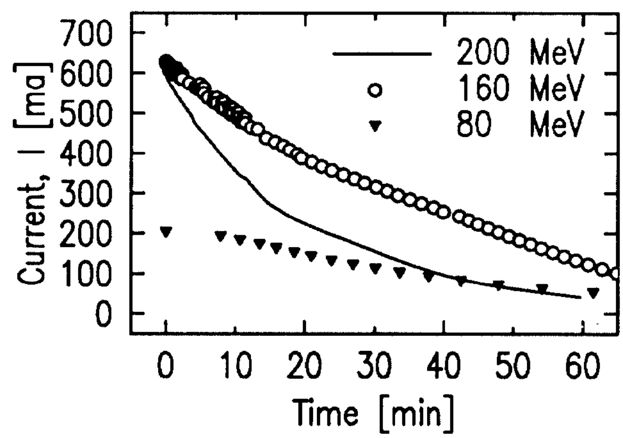

Figure 3: Current vs. Time [6 Bunches]

Major clean-up of the vacuum chamber was done by the stored beam as shown in Figure 4. About 20 amp-hrs at 200 MeV are required to finally condition the chamber during which time the ring pressure decreased by more than two orders of magnitude. To determine the recovery time from a vacuum accident a venting of the ring is planned in the near future.

4. Clearing Electrodes[4]

The vacuum chamber in the ring is equipped with fourteen clearing electrodes, five in each dipole magnet and two in each straight section. The electrodes are metal strips of approximately 20 cm in length located on the bottom of the chamber. They are terminated in their characteristic impedance by 50 Ω lossy cables and are capable of handling 5 KV.

In six bunch operation the clearing electrodes are necessary to reach stored currents in excess of 300 ma. Voltages in the range of 200-700 volts applied to six of the electrodes provides adequate clearing although powering only a single electrode enhances the achievable stored current. Ion clearing currents of 3 nanoamperes/100 ma

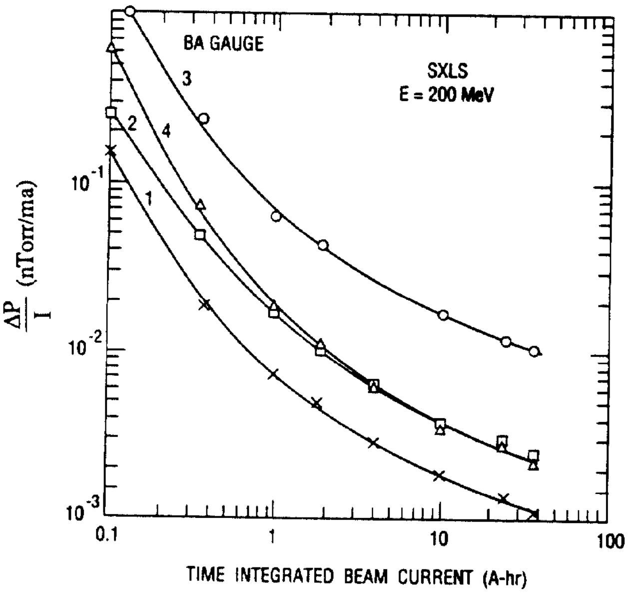

Figure 4: Normalized Pressure Change vs. Beam Dose

have been measured at ring energies of 100 MeV. Preliminary results on the effects of ions on the betatron tunes and the beam size are reported in reference [4].

5. RF System

The 211 MHz RF system is a single gap, capacitively loaded accelerating cavity driven in the TM01 mode and capable of producing a peak gap voltage of 50 kV. Figure 5 displays the measured synchrotron tune as a function of the RF voltage for 200 MeV operation. Gap voltages of 45 KV have produced the best injection rates. Transient beam loading from injecting up to 10 ma per shot has not been a problem. Throughout the commissioning the cavity has been the largest measurable source of outgassing.

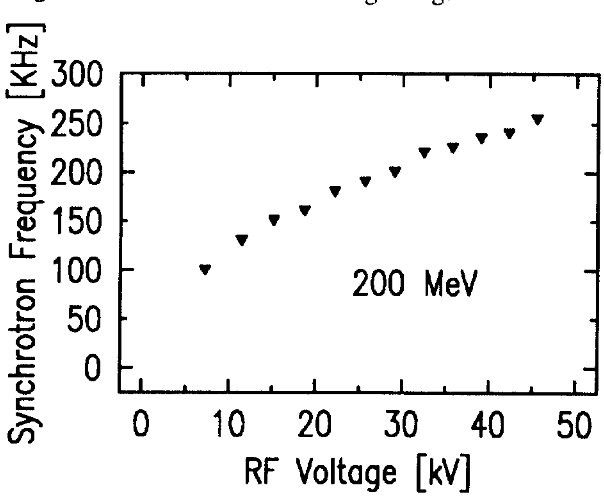

Figure 5: Measured Synchrotron Tune vs V_{RF}

6. Diagnostics

There are four fluorescent flags in the ring for establishing the injection orbit. Pick-up electrodes (PUE) have been built into the vacuum chamber to provide beam position information at six points around the ring. There is a set of four horizontal and vertical PUEs at each end of the two straight sections and a set of two PUEs (hor.) in each dipole. Beam positions in a single turn around the ring are determined by processing the PUE signals with hybrid networks and a Giga-sample/sec digitizing oscilloscope (LeCroy 7200). With stored beam the closed orbit is measured at a 5 Hz rate with dedicated beam position monitors. In addition to the PUEs, two sets of stripline electrodes have been provided, one for "kicking" the beam and the other for monitoring.

Beam current is determined by peak-detecting a rotation harmonic in a PUE sum signal. Transverse dimensions of the electron beam are measured by imaging the beam with a telescope on a CCD TV camera using the synchrotron light coming out of one of the dipole ports. During normal operations, the beam image is continuously displayed on a video monitor and can also be stored to disk with a frame grabber for further processing. Tune measurements are made using a 500 MHz network analyzer (HP 4195A), a wideband RF power amplifier and the striplines. Electronics for damping longitudinal beam instabilities is in the process of being commissioned.

7. Closing Remarks

The successful commissioning of the Phase I storage ring lays a solid foundation on which to build the Phase II superconducting dipole based ring. Ion clearing electrodes have been essential to storing large currents (I > 300 ma) in the ring. Studies will continue on the Phase I ring over the next year to enhance our understanding of the machine and to continue to lower the injection energy.

8. Acknowledgements

The SXLS group gratefully acknowledges the contribution of the NSLS operators, technicians & staff to the commissioning of the machine.

9. References

[1.] J.B. Murphy, et. al., Proc. 2nd EPAC, p. 1828 (1990).

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[3.] R. Heese & T. Romano, this proc. (1991).

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