Performance of the IBM synchrotron X-ray source for lithography

by Chas Archie

The compact superconducting synchrotron X-ray source at the IBM Advanced Lithography Facility in East Fishkill, New York has been in service to customers since the start of 1992. Its availability during scheduled time is greater than 90%, with recent months frequently surpassing 95%. Data on the long-term behavior of the X-ray source properties and subsystem performance are now available. The full system continues to meet all specifications and even to surpass them in key areas. Measured electron beam properties such as beam size, short- and long-term positional stability, and beam lifetime are presented. Lifetimes greater than 20 hours for typical stored beams have significantly simplified operations and increased availability compared to projections. This paper also describes some unique features of this X-ray source and goes beyond a discussion of downtime to describe the efforts *behind the scenes* to maintain and operate it.

Introduction

At the end of March 1991 a compact storage ring manufactured by Oxford Instruments, Oxford, England, was delivered to the IBM Advanced Lithography Facility (ALF) in East Fishkill, New York. The complete X-ray source, called Helios 1, is designed for proximity X-ray lithography [1]. A key feature of the synchrotron is the pair of superconducting dipole bending magnets. Other major components include a 200-MeV linear accelerator [2]; rf, pulsed, and dc power supplies; normal bending and focusing magnets; a 500-MHz cavity; a closed-cycle helium cryogenics system; beam diagnostics; ultrahigh vacuum equipment; and a comprehensive control system. Figures 7 and 8 from [1] show schematic views of the storage ring and injection system, respectively. Installation and commissioning of Helios 1 were complete by the end of 1991, at which point it satisfied or surpassed all performance specifications. Two beamlines are fully operational, and two more are nearing completion.

The Helios synchrotron is a strongly focusing electron storage ring with a racetrack design consisting of two 180°-bending-angle superconducting dipole magnets connected

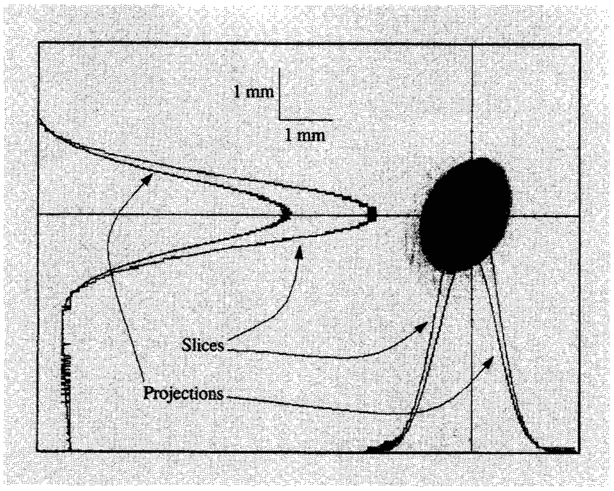

Figure 1

Cross section of the electron beam at a dipole center. Visible synchrotron light has been used to obtain a cross-sectional image of the electron beam. Both intensity information along the cross-hairs (slices) and the fully integrated intensity (projections) are presented.

Table 1 Helios 1 performance parameters.

	Specification	*Actual*
Critical wavelength		0.89 nm
Stored current		
Peak	>200 mA	297 mA
Average	>145 mA	165 mA
X-ray output power		
Peak		10.6 kW
Average	5.2 kW @ 0.89 nm	5.9 kW
Source size (FWHM)		
Horizontal	<3.5 mm	0.9–2.8 mm
Vertical	<2.6 mm	0.5–1.4 mm
Beam stability		<150 μm/day uncorrected
Beam lifetime	>5 hr @ 145 mA	18 hr @ 200 mA 48 hr @ 100 mA
Vacuum pressure		
Base	$<5 \times 10^{-10}$ torr 6.7×10^{-8} Pa	3×10^{-10} torr 4×10^{-8} Pa
Operating	$<3 \times 10^{-9}$ torr 4×10^{-7} Pa	1×10^{-9} torr 1.33×10^{-7} Pa
Injection energy	200 MeV	90 or 180 MeV
Typical injection cycle time		15 min

by two straight sections. These straight sections contain four conventional (i.e., copper windings with iron poles and yoke) quadrupole magnets, pulsed magnets for injection, a 500-MHz rf system, and beam diagnostics. In addition, there are a conventional sextupole magnet and a combination skew quadrupole/octupole magnet on the straights.

As discussed in [1], Oxford Instruments elected to produce a synchrotron light spectrum characterized by a critical wavelength in the 0.8–0.9-nm range by using 4.5-tesla superconducting bending magnets which are approximately three times stronger than conventional magnets. This results in an electron energy near 700 MeV and a magnetic bending radius of 0.52 m. The use of superconducting magnets significantly reduces longitudinal and transverse damping times for an electron beam at any given energy. Short damping times help deal with collective instabilities and assist low-energy injection.

The small bending radius affected construction and commissioning strategies. The Helios storage ring sits on one subframe. The whole unit was assembled at the Oxford factory and partially commissioned there, and was then shipped as a unit to the IBM East Fishkill facility. Over one weekend the ring was lifted from its sea shipment crate, floated on air pads into the prepared ALF vault, and placed in its final position. The final commissioning at ALF recreated the Oxford commissioning results within six weeks of injecting electrons into the storage ring. In short, the ring and supporting subsystems behaved the same in Oxford and at ALF.

Another aspect of the use of superconducting magnets in Helios was the decision by Oxford Instruments to use a *cold-bore* design. The electron beam in the dipole magnets is surrounded (except for the synchrotron light exiting slot) by liquid-helium-temperature surfaces. From the point of view of performance, the benefits of this design are twofold. First, gas scattering effects on the stored electron beam are greatly reduced by the close-proximity cryopumping. Second, the absence of additional hardware to make a room-temperature beam enclosure allows the superconducting coils to be closer to the electron beam, thereby allowing the production of stronger magnetic fields.

One intent of this paper is to present the actual performance of the Helios X-ray source in order to elaborate on many of the ideas presented in this introduction. The next section describes properties of the source. After that, the performances of major subsystems are detailed. In the final section, the operations program is briefly discussed, with respect to the resources required to operate and maintain this X-ray source.

X-ray source characteristics

Key performance parameters for the Helios X-ray source are presented in **Table 1**. There was no explicit IBM specification for the critical wavelength; rather, an acceptable X-ray band was specified with a corresponding

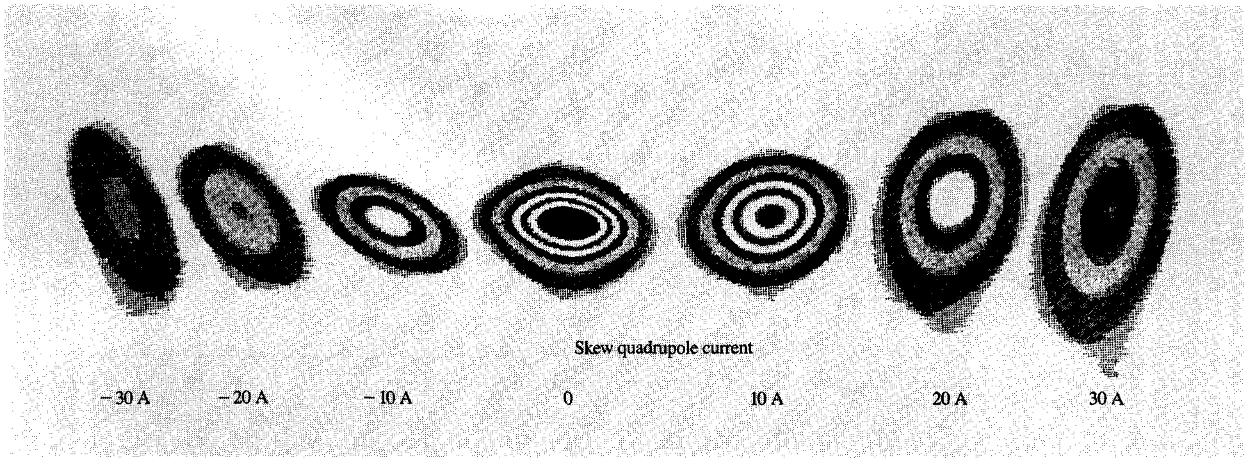

Figure 2

Effect of skew quadrupole on the electron beam. Beam cross-sectional images for different skew quadrupole magnet currents are shown here. The minimum vertical extension corresponds to about 4 A, while the normal operating point is 20 A. Note that 20 A corresponds to a field gradient of 0.6 T/m over an effective magnet length of 0.18 m.

curve of average output power versus X-ray wavelength. Oxford Instruments elected to build and commission Helios for 0.89-nm and 5.2-kW operation. Since this average power (stored-current) specification included averaging over any refill time during an eight-hour interval, an explicit refill cycle time requirement was not needed. Several of the parameters are discussed further in the following subsections.

• *Source size*

On each of the two superconducting dipole magnets there are eleven X-ray beam ports. The ports are located every 12½ degrees, with the eighth port on each dipole at the 90° position. Currently these 90° ports are dedicated to synchrotron light monitors (SLMs) that use the visible light portion of the spectrum to image the electron beam. The first fully developed beamlines are located on ports near the SLMs. However, during ALF commissioning last year these SLMs were temporarily moved to other ports in order to provide additional size measurements of the electron beam.

Figure 1 shows an image of a cross section of the electron beam from one of the SLM cameras. Superimposed on this image are crosshairs along which the light intensity has been read and displayed. These profiles are approximately Gaussian, characterized by full widths at half maximum of 1.4 mm vertically and 1.2 mm horizontally.

The tilt of the image is a real effect caused by the skew quadrupole magnet. This, in effect, is a normal quadrupole magnet rotated by 45° which produces a 0.05-milliradian horizontal (vertical) kick for a 1-mm vertical (horizontal) electron deviation from the design orbit for 20-A magnet current. In **Figure 2** SLM images are displayed for a number of different settings of the current in this magnet. The primary effect is to vary the vertical extent of the beam, but the tilt of the major axis changes as well. A skew quadrupole magnet introduces linear coupling between the small transverse horizontal and vertical motions of the electrons in the beam, i.e., the betatron oscillation modes. In fact, it is these motions induced by the quantum nature of synchrotron light emission that are responsible for the horizontal emittance. The tilt results from the new normal modes for transverse excitation being linear combinations of synchronized vertical and horizontal motions [3]. In normal operations, the skew quadrupole magnet is energized to 20 A to increase the vertical extension of the beam. Empirically this has been found to increase the beam lifetime (discussed in the next subsection).

In **Figure 3** the vertical and horizontal beam sizes throughout a dipole are presented for the standard operating conditions. The azimuth coordinate measures distance along the electron orbit starting at the dipole center. The curves are calculated on the basis of measured dipole and quadrupole fields and the measured betatron tune operating point of $\nu_v = 0.63$ and $\nu_h = 1.43$, assuming a coupling such that the vertical emittance is 3.5% of the horizontal emittance. The measurements which come from placing the SLMs on various ports on the two dipoles are well described by calculation. Vertical lines show the locations of X-ray beam ports. It is noteworthy that the horizontal beam size changes by more than a factor of two

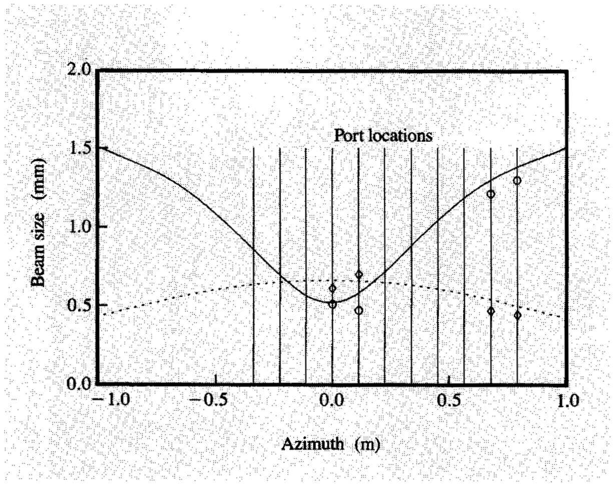

Figure 3

Electron beam size as a function of X-ray beam port for normal operation conditions. Measurements at different ports were gathered over time by moving the synchrotron light monitors during scheduled downtimes. The beam sizes are expressed as Gaussian sigmas, where $\sigma = 0.425$ FWHM. Circles and diamonds are horizontal and vertical measurements, respectively. The solid curve is the calculated horizontal beam size. The calculated vertical beam size (dashed line) assumes 3.5% coupling.

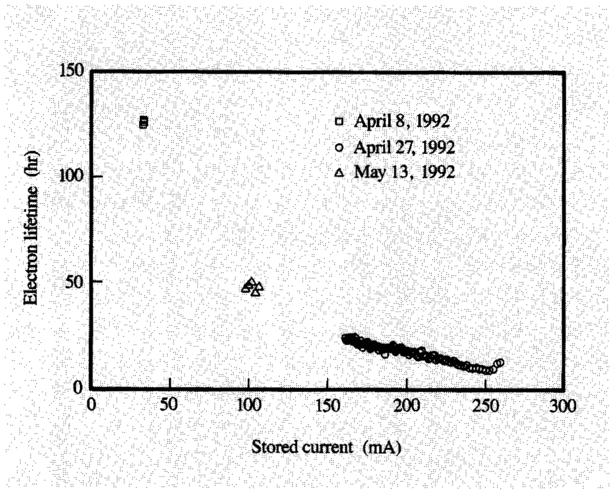

Figure 4

Electron beam lifetime versus stored current.

in going from the beam ports near the dipole center to the outermost one. The vertical size shows much less variation.

• *Electron beam lifetime*

The electron beam lifetime is a key property in the determination of the ultimate availability possible from this X-ray light source. As displayed in Table 1, the measured beam lifetime for Helios is considerably better than the original specification. The instantaneous beam lifetime τ is defined as

$$\tau \equiv -\frac{I}{\frac{dI}{dt}}. \tag{1}$$

If the loss mechanisms were independent of the electrons themselves, the decay would be exponential and τ would be a constant independent of current. In **Figure 4** the actual electron beam lifetime is presented as a function of beam current. As part of its routine duties, the Helios control system logs the beam current and calculates and logs the beam lifetime. Presented data come from different days, because on a day in which 250 mA is injected into the ring, the current only decays to 160 mA by the end of the day. To obtain lifetime information at lower currents, data were used from days of user-requested low current. Clearly the current decay is nonexponential. The data are empirically fit to

$$\frac{1}{\tau} = \frac{1}{\tau_0} + c_1 I + c_2 I^2, \tag{2}$$

where

$\tau_0 = 326$ hr,

$c_1 = 0.103$ (hr-A)$^{-1}$,

$c_2 = 0.766$ (hr-A^2)$^{-1}$.

Common loss mechanisms that do depend on the beam current include intrabeam electron scattering (Toushek effect) and gas scattering from synchrotron-light-induced desorbants. There is evidence that both effects are significant. During commissioning it was observed that longer lifetimes resulted from energizing the skew quadrupole magnet which spreads the beam vertically. This implicates the Toushek effect, which depends on the electron density [4]. The calculated Toushek lifetime contribution increases from 45 hours with 1% coupling for 200 mA to 90 hours with 4% coupling in fair agreement with observation.

Synchrotron-light-induced gas desorption is implied by **Figure 5**. In this figure the lifetime at 200 mA is plotted as a function of time during part of this year. The steady but gradual improvement in lifetime during the early part of the year suggests that beam cleaning of the surfaces receiving synchrotron light is playing a role.

It is therefore argued that the long lifetime is partially the result of the cryopumping stemming from the cold-bore design of the Helios superconducting magnets. Gauges on the storage ring do not directly measure the vacuum of the cold regions, since they are at room temperature. The pressures reported in Table 1 are considered gross overestimates for the state of the vacuum in the dipoles. Evidence for outstanding vacuum in the dipoles comes from clearing electrode currents around the ring. These high-voltage electrode structures are intended to sweep away ions in the vacuum pipe. Energizing the electrodes on the straights has several observable effects on the electron beam, and these draw approximately 1 mA of current when the storage ring is at full energy with 200 mA of stored current. By contrast, energizing the dipole-clearing electrode has little effect on the electron beam, and virtually no current is drawn. It is calculated that a *ring-circumference-averaged* pressure of one nanotorr of carbon monoxide (a common residual gas in stainless steel UHV systems) would produce a gas scattering lifetime contribution of 23 hours at 200 mA of stored current, a result roughly consistent with observation.

- *Electron beam stability*

The positional stability of the electron beam has been monitored for the short and long term by using the synchrotron light monitors. The SLM reference is a scribe mark on the inner wall of the electron beam space inside the dipole. A framegrabber program which monitors a selected SLM has a routine which periodically reads the intensity profiles along the crosshairs, fits these data to quadratic form around the intensity maximum, adjusts the crosshairs to the new image maximum, and logs the new position. The precision of the tracking is typically better than one hundredth of the beam size, i.e., 10 μm. A typical day's data and longer-term behavior are shown in **Figure 6**. The electron beam experiences slow random drifts within a 150-μm band vertically and a 50-μm band horizontally on a daily basis. Superimposed on these drifts are quasiperiodic oscillations with 5–10-minute periods and amplitudes of 30 μm vertically and 10 μm horizontally. These quasiperiodic oscillations have been seen in the X-ray beam vertical position in the beamlines as well. It is believed that thermal oscillations in cooling water or room temperature are ultimately responsible.

The bottom graph of Figure 6 shows the long-term stability over several months. The vertical beam position again shows much more apparent movement than does the horizontal position. The magnitudes of these drifts do not yet warrant corrective action. When necessary, correcting the electron orbit vertically by using vertical steering trims in the dipole magnets is possible. Investigation continues into the root cause(s) of these apparent drifts.

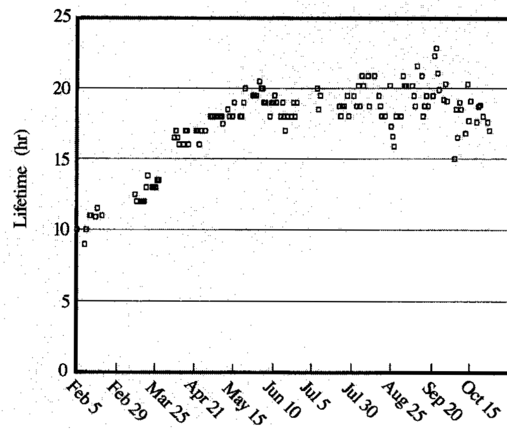

Figure 5

Measured lifetimes for 200 mA of stored beam, showing increase of electron beam lifetime with time.

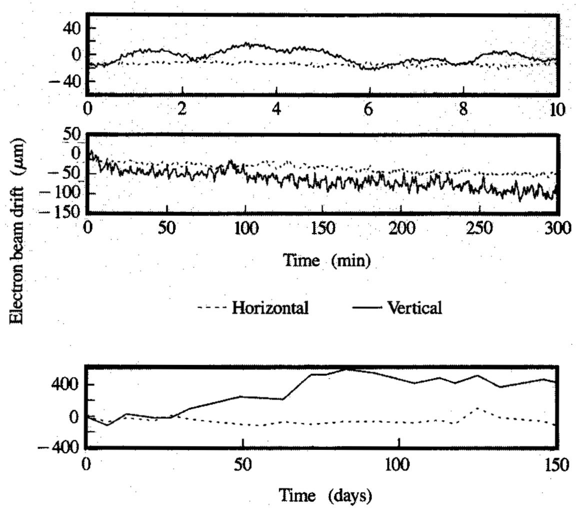

Figure 6

X-ray source positional stability over time.

Performance of major source subsystems

Presented in **Figure 7** are the 1992 monthly and total year uptime averages for the ALF X-ray source from the users' point of view. Downtime is defined as scheduled time during which any fault made X-rays unusable for lithography. **Figure 8** shows the downtime distribution by major categories. Many of the Helios subsystems can occasionally fail in ways that do not directly affect facility uptime; these failures are not part of uptime accountability. Also, some subsystems by their very nature

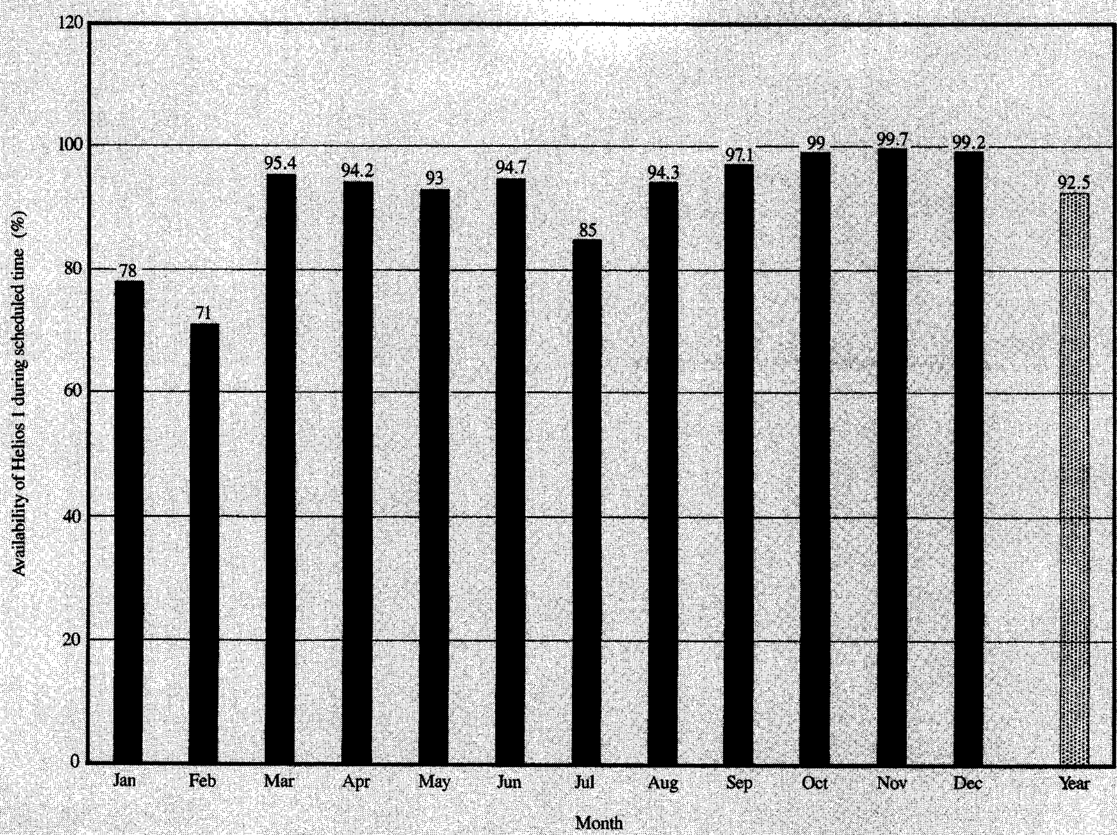

Figure 7

X-ray source monthly uptime averages for 1992.

require significant routine staff support; a case in point is the cryogenics. This section, therefore, goes beyond discussing explicit downtime incidents to cover the actual effort associated with many of the Helios subsystems.

The most complicated operations of the X-ray source are the electron injection process and the energy ramp of the stored beam. Injection involves all major subsystems. In particular, the pulsed 3-GHz microwave systems of the linear accelerator and the pulsed injection magnets on the storage ring come into play briefly during this operation. During the five-minute energy ramp, the synchrotron light output power changes rapidly, so the dynamics of the beam as well as the loading of the 500-MHz rf system change radically over a short period of time. These pulsed systems are discussed in more detail following the next section, on the control system.

- *Control system*

The Helios control system, HECAMS, is based on a database-oriented control system from the Stanford Linear Accelerator Center. This system runs on a minicomputer with two identical operator workstations, each with a touch screen and trackerball for input and a graphics screen for display of current values and trending. The interface to the hardware is through CAMAC, an industry standard for computer-aided monitoring and control. Oxford Instruments extensively expanded the capabilities of the control system.

Many of the procedures developed during commissioning have been incorporated into the control system by the use of the *Sequence* facility. This fairly flexible program uses lists of simple commands from text files to perform multiple tasks in a coordinated way.

The sequence files were largely constructed during commissioning last year. Frequently used sequences do the following: 1) make the linac ready for operation; 2) bring transport line and storage ring power supplies from standby to injection energy output levels; 3) turn on and adjust the 500-MHz storage ring rf system; 4) conduct the electron fill, pausing occasionally for operator action, and then ramp the electron beam to full energy; 5) dump the stored beam at full energy and ramp the system to injection conditions; and 6) take all subsystems from injection condition to overnight standby.

In terms of the impact on facility downtime, the only major incident was one lasting 45 minutes in September, when HECAMS falsely reported the stored beam current to the X-ray steppers. The cause was traced to a full storage disk, and corrective action was taken.

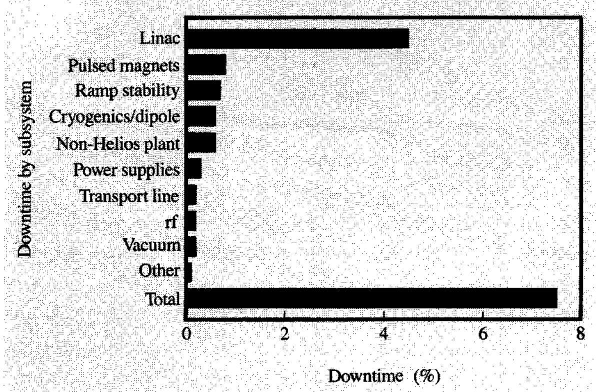

Figure 8

Downtime distribution for 1992.

• *Linac*

The linear accelerator typically produces an ~100-ns-long stream of 180-MeV electrons with a peak current of 20 mA. The repetition rate can be as high as 10 Hz. The major parts include a triode gun, a 500-MHz prebuncher cavity, a 3-GHz buncher, two nominal 100-MeV accelerating sections, each powered by a pulsed 3-GHz modulator and klystron, and a computer controller. To better match the electron beam energy spread to the energy acceptance of the storage ring, the beam is sent through an energy selection transport line: A bending magnet first spreads the beam horizontally (bending depends on energy), and tungsten slits then accept 180-MeV electrons with a ±0.5% spread. This scheme helps to localize the radiation hazard resulting from electron loss. The energy-selected beam has 10-mA peak current.

A typical refill operation involves dumping the beam at full energy, ramping storage ring magnets and rf parameters to injection conditions, injecting a 180-MeV electron beam into the storage ring, and ramping the beam energy to 686 MeV. These actions are largely accomplished by HECAMS sequences. Generally, during each filling episode, the phase of the microwave power for the second accelerating section relative to that for the first section and the common high-voltage source for the two klystrons must be adjusted by the operator to maximize the output through the energy selection slits. It should be clear that during these operations the X-ray source is not available, and such operations should be minimized both in duration and frequency of occurrence. A typical refill time from dumping the beam to achieving full energy with a new stored beam is 15 minutes.

Start-up from the overnight standby state involves several additional steps that are not part of a refill operation. The operators conduct searches of both accelerator vaults for reasons of personnel safety and machine protection. HECAMS sequences are run to prepare the system for injection; this includes waiting for klystron and thyratron filaments to stabilize thermally, and for a mild reconditioning of the linac accelerating sections. Typically it takes one hour to achieve full-energy stored beam in the morning.

As noted in Figure 8, the linac has been the major source of downtime this year. It is useful to partition linac difficulties into three general categories. The first includes hardware failures in one of the two klystron/modulator systems. In February, first one klystron and then later the other failed to operate by tripping out on several interlock protections. The failures were traced to the instability of a rack of power supplies providing currents to focusing coils in the two klystrons. The remedy has been to greatly modify the rack in terms of additional air and water cooling and to upgrade several electronic components. Furthermore, preventative maintenance has been expanded to check routinely for possible drifts in these power supplies.

In August two diodes failed in the high-voltage/high-power modulator circuitry driving one of the klystrons. A 3-GHz preamplifier for one of the klystrons failed once. The replacement preamplifier required tuneups over several weeks before stabilizing. Commissioning an alternative mode of injection (to be discussed) has minimized the downtime impact of this category of problems.

The second category is failures in *one-of-a-kind* hardware. The linac gun had occasional failures of control integrated circuits in February, and a 5-V power supply common to gun-control circuitry failed in December. While these faults involved inexpensive *off-the-shelf* items, they were particularly troublesome, since the time required to identify and repair them resulted directly in facility downtime. Fortunately, such failures have been few.

The third area of linac downtime is associated with minor adjustment problems in maximizing the output current—these are control-room adjustments made by the operator in the setup of injection. This resulted in some late starts, if only by a couple of minutes.

The reliability of the linac has improved steadily. Not only have hard failure rates been dropping, but the degree of operator adjustment has been decreasing as well. As mentioned previously, only two controls are generally adjusted now to maximize the electron beam output at the desired energy, and the time needed for this is usually less than two minutes. It is believed that this improvement stems from the greater stability of key power supplies achieved during the year.

The downtime associated with drifts in the power supplies for the klystron focusing coils was minimized by a rapid commissioning of a low-energy injection mode for Helios. It was first demonstrated during the factory commissioning that the linac could produce a nominal 90-MeV energy beam with fair efficiency by disabling the second accelerating section. This mode was recommissioned in February and used while klystron problems persisted.

As discussed in [1], conventional injection becomes increasingly difficult as the energy is lowered, because the excited beam damping times increase. At the normal injection energy of 180 MeV, the horizontal damping time is 100 ms and the beam lifetime is slightly less than two hours. At the newly commissioned injection energy of 90 MeV, that damping time increases to one second. A longer damping time makes the beam more susceptible to beam loss by collective instabilities. This low-energy injection mode requires more study before it can be made as repeatable as 180-MeV injection, but it may eventually become the normal injection process for two reasons: It requires less output from the pulsed injection magnet power supplies, thereby increasing their reliability, and it immediately generates for the facility a backup 3-GHz klystron modulator system to minimize downtime for the first category of linac difficulties.

- *Injection magnets*

The process of injection requires the time-critical pulsing of two magnets on the storage ring: the kicker and septum magnets. Normally HECAMS operates these magnets without operator adjustment. The septum power supply has performed flawlessly this year. The power supply for the kicker magnet, however, has been responsible for some downtime. In one incident, a connector for the cable supplying the timing signal broke. More recently, a new kicker power supply (replacing a prototype) failed because of overheating. Source operations continued after a return to the prototype. Since then, the new supply has been modified to eliminate the overheating and is again installed on the storage ring, operating without problems.

- *Superconducting magnets and cryogenic system*

In normal operations the superconducting magnets behave similarly to conventional magnets. On the other hand, during the initial start-up of Helios last year special attention had to be paid to these magnets. First, the liquid helium can that separates the superconducting coils (some of which are potted in epoxy) from the electron beam space cannot be baked like the rest of the UHV chambers and devices. The cryogenics controller (discussed in greater detail later) has a special mode of operation for preventing significant temperature rise of the helium can above room temperature while the outer vacuum chamber is baked. The cryogenics controller has another mode for controlled cooling of the helium cans to liquid helium temperature in order to avoid severely thermally stressing the coils.

At this point, the superconducting magnets must be *trained*. Training is the practice of ramping the current to the magnet until the magnet *quenches*; ramping is repeated until no further significant improvement in maximum current occurs or until specification is achieved. Quenching is the phenomenon that occurs when an operating superconducting magnet undergoes a sudden transition to the normal resistive state; this causes the magnet to discharge its inductive energy rapidly. During training it is usually caused by the small movement of an individual turn within the winding under the effect of the electromagnetic forces.

As reported earlier [5], it was found during commissioning last year that substituting the third production dipole (Dipole 3) for the first production dipole (Dipole 1) allowed the ring performance to exceed expectations significantly. (IBM had ordered the third dipole as a spare.) This increased performance is due to the fact that Oxford Instruments' dipole development program has resulted in a continuous improvement in the quenching performance of the dipoles.

The main coils of Dipole 3 have never quenched in ALF. Corrective trims did require some training. Dipole 2 trained to specification with two quenches for its main coils and had trim training similar to that for Dipole 3. Total training required a couple of days during the initial cooldown of this pair on the storage ring.

Shifting the focus to the cryogenics, this system manages the flow of two cryogens, liquid helium and liquid nitrogen, within Helios. There are two programmable logic controllers (PLCs), one dedicated to running the helium liquefier and the other to managing the liquid helium levels in a 3500-liter buffer dewar and in the two dipoles. This second PLC also controls the liquid nitrogen for the dipoles' protective shields. Normal operation is a closed helium cycle. A backup mode takes the liquefier off line and continues to maintain liquid helium levels in the dipoles by supplying from the buffer dewar; this mode can operate for more than two days before draining the buffer dewar. In fact, the backup mode could continue indefinitely if the liquid helium were replenished through outside purchase. The backup mode has not been used this year.

The cryogenics has not significantly affected downtime. The major downtime event was associated with an interruption of power to the facility which caused sufficient disruption that the cryogenics needed a half day to recover. Actually, the recovery could have been considerably faster if a critical low-temperature valve had closed properly—tracing that problem took much of the time. It should be noted, however, that significant attention is paid to this system by the source staff on a routine basis. Optimizing performance requires considerable patience, since understanding the full implications of modifying a part of the system, say a control loop, requires monitoring for hours or perhaps days. This system has been the major source of facility alarms overnight and during weekends. (HECAMS can telephone designated engineers when selected signals are out of tolerance.) This is not surprising, since the cryogenics is the only system which is as active during nonworking hours as during light-producing operations.

These *behind-the-scenes* failures can be divided into two types: those associated with broken equipment and those due to fluctuations in thermal and pressure control loops. In one instance, a heater failed in a boiler which ensures that exhaust nitrogen is at room temperature before release. While waiting for a replacement, the facility continued to operate with frosty pipes. In another episode, the helium liquefier system tripped out repeatedly because of excessive oil accumulation at separators between the compressor output and the liquefier input. Fortunately, this problem never occurred during scheduled operations. (Of course, if it had, the backup dewar supply mode could have been used to continue operations.) The solution was to modify the oil-recovery plumbing.

Through the course of the year the cryogenic control loops have been optimized to eliminate major thermal and pressure excursions. As a consequence, the incidence of HECAMS telephone calls has dropped from about two per month at the start of the year to zero—none since June.

- *Other subsystems*

The other major subsystems of Helios are the storage ring rf system, the normal magnets and magnet power supplies, various beam diagnostics, and the vacuum system.

The storage ring 500-MHz system consists of a rack of control electronics; a 60-kW transmitter; a waveguide and coaxial delivery system with filters and a HECAMS-controlled phase matcher; and, of course, the rf cavity, with an rf pickup and a HECAMS-controlled tuner. There are forward and reverse power pickups in the waveguide system. A water-cooled ceramic window separates the UHV cavity from the waveguide system, which is at atmospheric pressure. Significant efforts in the commissioning of Helios involved learning to control this system while ramping large currents to full energy. Important considerations are the sudden loading of the rf cavity from the electron beam during the energy ramp, and the need to protect the transmitter from significant reverse power (approximately 1 kW). A HECAMS program which controls the matcher and tuner was improved by a number of upgrades [6]. Also, the interplay between natural modes of collective excitation for the electron beam and higher-order rf modes in the cavity must be understood in order to avoid beam loss. Finding robust operating points in the betatron and synchrotron tune spaces at injection, during ramping, and at full energy defined major missions of the commissioning.

During this year of operations, minor problems have occurred in the rf system. A couple of water flow failure interlock trips for the cavity window temporarily stopped operations. Apparently some metal and plastic shavings were accidentally introduced into this cooling loop. Repair included flushing and introducing a second filter specific to the window cooling channels.

Occasional minor adjustments to the rf system control programs in HECAMS have been necessary to maintain good ramping efficiency. Typically less than 5% of the beam is lost during the ramp. It was not necessarily the rf that had drifted in all cases requiring intervention, but rf parameter modification has been very successful at quickly curing the immediate problem. The stability of the electron beam links the rf system with the dipole and quadrupole magnets as well as with the state of the vacuum. Changes in one system can often be compensated by changes in another. On such occasions, improving ramping efficiency acquires a high priority in the beam studies program. The energy ramp details have been modified approximately a dozen times during the year.

Beam diagnostics on Helios include two Faraday cups, three scintillators, and three capacitive beam position monitors (BPMs) on the transport line, and one scintillator, four BPMs, and two SLMs on the storage ring. Also on the storage ring is a toroidal current monitor (TCM). Failures in these items have not directly caused downtime.

The TCM provides measurement of the electron beam current with better than 1% accuracy. This information is electronically provided to the X-ray steppers to determine the duration of lithography exposure. Its calibrations are checked frequently, and so far no unscheduled recalibration has been necessary.

The BPMs share common electronics. An electronic unit which switches among the sensors has required repair on a couple of occasions. Also, the calibration of the sensors on the storage ring has been the objective of several beam study sessions this year. In refining the model for the closed orbit of the electron beam in the storage ring, the factory calibration of these devices became suspect. While this situation did not interfere with normal operations, it required clarification if substantially larger stored currents were someday desired. The study technique was to individually change slightly the currents to the four quadrupole magnets on the ring and note the BPM output changes. This measurement determines how far the actual electron closed orbit is from the magnetic centers of the quadrupole magnets. Along with careful survey of the locations of magnets and diagnostics on the ring, this information determines the actual closed orbit and the zero offset calibrations of the BPMs.

The dc magnet power supplies have operated with few faults. On two occasions a water hose in the main dipole power supply developed a leak that stopped operations for several hours, and several other water leaks have occurred. Preventative maintenance has been modified to increase the frequency of hose inspections. The long-term solution includes replacing many power supply and magnet hoses with a more robust design. On another occasion, drifts in power supplies for the superconducting quadrupole trims adversely affected the efficiency of the injection and ramping processes. Preventative maintenance has been expanded to check the stability of critical power supplies more frequently.

The role of hysteresis in the normal and superconducting magnets is better understood this year. The normal quadrupole magnets on the storage ring become slightly nonlinear at full energy operation because of slight saturation of the iron poles. As a consequence, the field current relationship is history-dependent. In order to have repeatable performance during injection and ramping, it has been found that recovery from nonstandard values for these magnets requires a ramp/deramp cycle (hysteresis cycle).

The main superconducting magnets are slightly nonlinear in the dependence of their dipole and quadrupole fields on power supply current for a different reason. The large magnetic forces generated in these magnets cause structure straining. This strain is well within material limits, but because the multicoil structure is a layered structure, there is some relative sliding during deformation, and this is hysteretic. This hysteresis is also corrected after nonstandard operating conditions by doing a hysteresis cycle.

In normal operations the vacuum equipment for Helios requires very little attention. In fact, it was demonstrated during the factory acceptance tests for the superconducting dipole structures that the cold surfaces cryopump sufficiently well to allow the ion pumps on these structures to be turned off. The vacuum actually improved!

Besides six ion pumps on the storage ring, there are two titanium sublimation pumps, which are regenerated approximately monthly by flashing a new layer of titanium. The base pressure seems to be improved by this procedure. However, this does not seem to affect the electron beam lifetime. As in most UHV stainless steel systems, the dominant residual gas is hydrogen, followed by carbon monoxide. Very likely, flashing the TSPs primarily affects the partial pressure of hydrogen, which as a low-atomic-number element causes little scattering of the electron beam.

Operations

The operating experience for this first year of service at ALF as discussed in the preceding section is helpful in explaining the composition of the source operations team and how their duties are divided among normal operations, studies, preventative maintenance, and repair. The operations team consists of three engineers, two technician-level operators, and an occasional third operator. This team is largely responsible for maintaining the readiness of Helios and providing synchrotron X-rays five days a week, between eight and twelve hours per day.

Normal operation requires full operator attention during start-up, refill, and shutdown. Typically start-up from overnight standby takes an hour; refills take 15 minutes, and shutdown requires half an hour. It has proved practical to staff two people for the day shift, during which start-up and possibly refills occur, but only one person during the evening. One engineer and one operator are typically assigned for the day shift.

Currently, one day per month is dedicated to preventative maintenance (PM). On this day, actions which require a shutdown are performed. PM items consistent with normal operation are conducted at other times. All staff members including the operators participate in this. PM extends to daily and weekly duties for the day shift in that during the quiet hours of operation, measurements of sensitive equipment are made to discover drifts or other changes, hopefully before they become a downtime problem. These checklists are evolving on the basis of experience.

There is a regular program of source studies typically using a four-hour block, one evening per week. Sometimes physicists from Oxford Instruments or IBM participate in these sessions, but the studies are generally conducted by some of the staff engineers. These studies are devoted to extending performance but, as the need arises, the time is spent retuning the machine to regain lost performance. In the latter category were studies to improve ramping when the efficiency dropped below 90% and to develop nominal

90-MeV injection when one of the linac klystrons failed to operate. Enhancement studies have included tweaking the cryogenic control loops to reduce thermal and pressure fluctuations. Of course, many studies, such as the positional stability of the electron beam, are carried out concurrent with normal operation.

Summary

Since the start of regular service of Helios in the IBM Advanced Lithography Facility, considerable performance data have been gathered, including the requirements for operating the facility. The source has surpassed specifications in all major categories. The full year uptime availability is 92.5% for 1992.

Though the linac has been the main cause of downtime this year, there has been considerable progress in understanding the root causes of the difficulties and correcting them. Linac operation has been made more robust by commissioning a nominal 90-MeV injection mode for Helios. Oxford Instruments is sufficiently confident in this injection mode that it is considering 100-MeV injection as standard for Helios 2, now under construction.

The beam lifetime specification of five hours has been considerably surpassed. This has allowed a single fill in the morning to meet the facility's needs for eight hours of operation with an average current exceeding the specification of 145 mA. Furthermore, the refill operation has become more reliable and rapid, typically lasting 15 minutes from old to new stored beam at full energy. The cold-bore design of the Oxford superconducting magnets is believed to be responsible for the long beam lifetime of Helios. The resulting reduced frequency of linac use has played a role in achieving good uptime performance for the source this year.

The measured vertical and horizontal electron beam sizes are better (smaller) than specification at all usable X-ray ports, and the long-term positional stability is acceptable even without periodic adjustment. The effect of the skew quadrupole on the source shape, though initially surprising, is now understood and is quite acceptable.

The engineering staff has been able to spend roughly 40% of their time doing studies this year. As a consequence, a number of improvements have been achieved: The HECAMS sequences governing coordinated operations of Helios have been crafted to simplify operator actions. The cryogenics, once a subsystem requiring frequent attention though not a major downtime contributor, has stabilized to relatively trouble-free performance. Preventative maintenance procedures have been tested and revised in light of real experience.

In short, the first year of normal operation for Helios at ALF has been a tremendous success. The actual performance should help convince observers that this is a reliable technology for a semiconductor manufacturing setting. The indications are that the coming years will see continuing improvements in source operations as well.

Acknowledgments

The author wishes to remind the reader that he is largely reporting on the work of others. Clearly many at Oxford Instruments and at IBM are responsible for the performance of Helios at ALF this year, but deserving of special mention are Oxford Instruments' resident engineers, A. J. Weger, R. Palmer, and R. Webber, and the regular IBM operators, C. Schneider and B. Hill.

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