Experience of Routine Operation of Helios 1.

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Abstract

Experience of the first two years of routine operation of the Helios compact synchrotron at IBM's Advanced Lithography Facility (ALF) is reported. The semiconductor manufacturing setting demands maximum reliability from an X-ray source and so a quality and reliability program was devised. Its implementation and results are described, as are the efforts towards almost fully automated operation. Source properties are also discussed.

1. INTRODUCTION

HELIOS has been in routine operation as a production tool since the beginning of 1992. During commissioning, after delivery in March 1991, it met or exceeded specification on beam current and lifetime (see Table 1).

Reliable operation has been demonstrated, with uptime during scheduled hours averaging 94% over the first 12 months, and increasing to 99% during 1993.

A second ring, HELIOS 2 is currently in production. Its microtron injector has been commissioned and other key components, including superconducting magnets and the RF system, are in an advanced state of manufacture or testing. Major design changes from the first machine will be discussed.

2. DESIGN AND PERFORMANCE OF HELIOS 1

HELIOS [1] is a "racetrack" synchrotron, consisting of two superconducting dipole magnets separated by two straight sections (see figure 1). The dipoles provide 17 X-ray beam ports for lithography located every 12.5 degrees. In addition, one port on each dipole (at the 90 degree point) is dedicated to a synchrotron light monitor, which images the electron beam. The straights contain the 499.7 MHz RF cavity, vacuum components, diagnostics, conventional iron-yoked quadrupoles, a sextupole and a skew quad, diagnostics, and pulsed injection magnets. The electron beam is injected from a 200 MeV linear accelerator via a transport line which includes energy selection slits and quadrupole focusing for matching the injected beam with the ring twiss parameters.

HELIOS is built on a single, stainless steel base frame and is relatively light (about 25 tons), and so was readily transported to USA from Oxford Instruments in the UK as an assembled and tested unit. As a result, beam was stored at 200 MeV in HELIOS within eight weeks of its arrival in the USA.

Table 1. Main parameters of HELIOS 1.

	Design	Achieved
Electron Energy	700 MeV	700 MeV
Dipole (bending) field	4.5 T	4.5 T
Injection Energy	200 MeV	90 or 180 MeV
Stored current: at injection energy at full energy	 200 mA 200 mA	 540 mA 297 mA
Beam Lifetime	5 hrs at 145 mA	22 hrs at 200 mA
Injection Current	10 mA	20 mA
Emitted X-ray Power	8.2 kW	10.6 kW
Electron beam size: Horizontal, σ_r Vertical, σ_y	 <1.5 mm <1.1 mm	 0.5-1.3 mm 0.2-0.7 mm

The specified current of 200 mA at full energy was achieved within a further two months' commissioning [2]. The main efforts towards ramping large currents to full energy involved understanding how best to control the RF. A cavity volts ramp was developed that avoided synchro-betatron resonances at low energies. The algorithms that control the transparent matcher in the waveguide and tuner plunger in the cavity during the energy ramp were optimised. The aim is to detune the cavity from a perfect match to damp beam-cavity interactions, and yet protect the transmitter from reverse power and provide suitable bucket height [3].

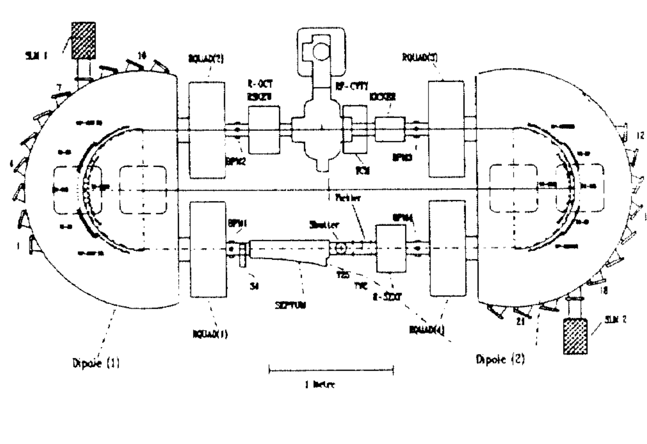

Figure 1. Schematic of HELIOS 1

3 NORMAL OPERATIONS

Since January 1992 Helios 1 has been in routine operation as a production tool for Xray lithography. Generally it has been required to provide Xrays five days a week, for between eight and twelve hours per day. The beam lifetime is sufficient for a single fill to be retained for the whole day.

The daily cycle begins with start-up of the injector, power supplies, and RF source. A 90 MeV beam (with energy selection ±0.5 %) is injected in a multi-shot operation (usually 2 Hz) in 100 ns pulses (i.e. over 3 turns). The linac gun current is chosen to provide a convenient stack rate (say, around 4 mA/s). Beam is stored momentarily at injection energy and then ramped. The ramp lasts for three minutes, with beam loss usually 3 % or less.

All routine operations are automated, requiring little or no operator intervention, via HECAMS (Helios Control and Monitoring System). Pre-programmed "Sequences" control start-up, injection, ramping, refilling, and machine shutdown to standby at the end of operations.

The linac is capable of accelerating electrons to 200 MeV, but a 90 MeV injection mode was developed and is now used as standard. This makes linac operation more reliable and reproducible as only one of the two accelerating sections is required.

HECAMS includes a "Survey" facility which notifies the operator immediately if any power supply, cryogenic variable etc... goes out of tolerance, or if an interlock is tripped. If desired, serious alarms will activate a telephone call-out system, so the operator may lock the control console and leave the machine unmanned, knowing that if there is an alarm HECAMS will page him.

The lifetime is strongly current dependent. In normal operating conditions the instantaneous lifetime (current divided by decay rate) is 22 hours at 200 mA, 50 hours at 100 mA and 100 hours at 50 mA.

A short trial of continuous running was performed in 1993. There were four fills in 33 hours, with refills being performed every eight hours to fit naturally with shift changeovers. Average refill time was 19 mins, which is corresponds to 96.1 % availability in continuous running. Averaged over the four fills, peak current was 199 mA and the ratio of average to peak current was 0.86.

Long lifetimes imply reduced frequency of refill. This leads to greater availability, and also increased ease of operation and greater reliability.

4. RELIABILITY

An explicit goal for the ALF facility is to demonstrate the reliability of a synchrotron in an industrial environment, and a on-going reliability program has been pursued to monitor and maximise HELIOS availability. Key elements of this program include a thorough preventative maintenance (PM) schedule and the detailed tracking and recording of all faults and fault repairs through a computer database.

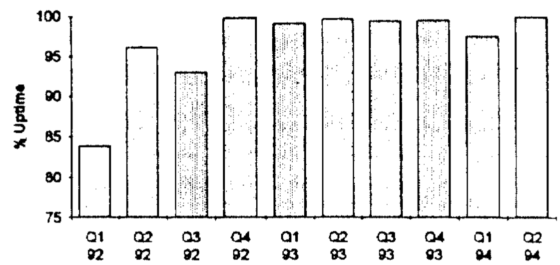

Figure 2. HELIOS Uptime by month as a percentage of scheduled hours

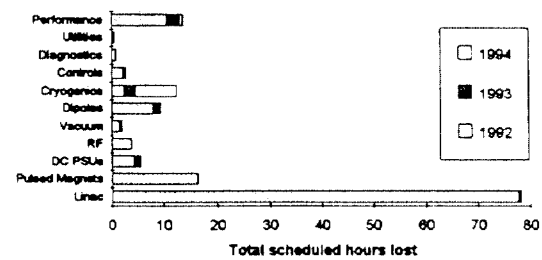

Figure 3. HELIOS downtime hours by system

Figure 2 shows HELIOS uptime as a percentage of scheduled "beam-on" time since January 1992, by quarter. "Uptime" is defined as time for which a significant beam is stored at full energy. Time lost to ALF utility failures (mains power etc.) is excluded, as are start-up times and refill times as long as they do not occur during scheduled hours. Scheduled downtime is also excluded. This includes one day per month of PM and a week-long PM shutdown twice a year.

The downtime hours attributed to different sub-systems is shown by calendar year in figure 3. As can be seen, the linac accounted for the majority (nearly 60 %) of downtime. A combination of hardware modifications and improved operating procedures have greatly improved its performance, and linac downtime since the first quarter of 1992 has been negligible.

"Pulsed Magnets" downtime was due to initial problems with overheating of the kicker power supply. No faults have occurred the last two years.

"Performance" faults were generally caused by long term drifts in betatron and synchrotron tune, which affected injection and ramping efficiency. These faults have since been avoided by improved procedures (e.g. better hysteresis cycles for the iron-yoked magnets and regular power supply recalibration), and by hardware modifications to eradicate the drifts.

The beneficial effects of accumulated operating experience and the reliability program are seen in the general upward trend in the uptime figures. In total 129 hours of scheduled beam time were lost in 1992, as against 8.8 hours in 1993 and 9.13 hours in 1994 (up until the end of May).

5. Source Properties

The X-ray flux spectrum of HELIOS (operating at its full energy of 700 MeV) is shown in figure 4, with spectra from MAX1 and the Daresbury SRS for comparison. The total power output is 8.2 kW for a 200 mA stored beam. The "critical" wavelength (the wavelength that divides the power spectrum in two equal halves) is 0.84 nm (1465 eV), but the range of useful wavelengths extends from the visible to the edge of the hard X-ray region at about 5 keV.

The critical wavelength may be increased by terminating the ramp at a lower energy. This has the effect of reducing the power emitted at the higher photon energies.

The source dimensions may be easily varied over a large range. Vertical beam size and divergence is varied by energising the skew quad, which controls the coupling between the horizontal and vertical phase spaces. Horizontal beam size is mainly determined by the radial betatron tune, which affects the equilibrium emittance and the lattice parameters. Beam has been successfully injected, ramped and stored at a wide range of radial tunes.

6. Helios 2

The second HELIOS has been designed to retain the proven performance the first machine, while redesigning certain components to enhance performance in some areas and improve ease of operation and maintainability. Changes include the injector, RF system, vacuum system, sub frame, and controls [4].

In the light of HELIOS 1 experience, an injection energy of 100 MeV has been chosen for the second machine. A racetrack microtron injector, supplied by Scanditronix, has been purchased and commissioned. This offers several advantages over a 200 MeV linac. Primarily, the overall size of the installation is considerably reduced. The microtron exit beam has a small emittances (0.1 mm mrad specified) and energy spread (0.1%), which allows a simple design of transport line, and offers the prospect of easy set-up of injection and low external radiation. Microtron acceptance trials at Oxford have confirmed exceptional ease of operation, fast turn-on, excellent reliability and repeatability, and easy integration into the HELIOS 2 control system.

Significant modifications have been made to the ring support frame to improve access and ease of maintenance. Cables and cooling pipework have been rearranged, the baseframe has been simplified, and some components have been moved from the ring to the plant area. Vacuum valves have been added at the ends of the straights to enable servicing and baking a straight without affecting the rest of the ring.

The computer control system has been revised to incorporate current generation workstation-based operator stations, whilst keeping the key features of HELIOS 1, e.g. automated sequences, standard modular components (CAMAC etc.) and independent fail-safe interlocks. The commercial "VISTA" software package, which provides windows-based displays, is used as the basis of the control system, in place of the SLAC package used for HELIOS 1.

One principal design change is the introduction of a 55 MHz RF system. The revised RF system and its impact on the accelerator physics of HELIOS 2 is described in an accompanying paper [5].

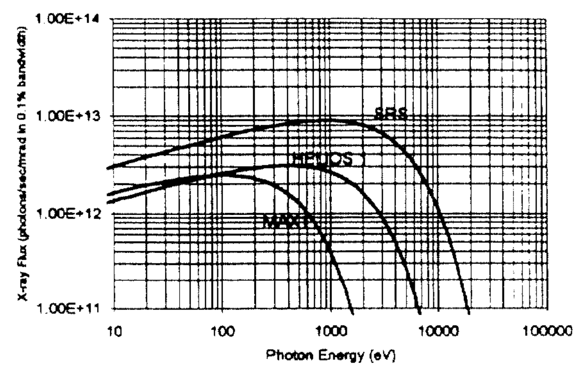

Figure 4. The Xray power spectrum of HELIOS for a 200 mA stored beam

7. Summary

HELIOS 1 has exceeded specification in both stored current and beam lifetime, and its uptime during 1993 was over 99%.

Using experience from the first machine, HELIOS 2 has been designed to provide higher stored currents and lifetimes, with improved ease of operation and maintainability, while retaining the same high standards of reliability.

8. Acknowledgements

Many individuals at Oxford Instruments have contributed to the reliable operation of HELIOS 1, especially the other resident engineers at ALF, R.Palmer, and R.Webber. We are also pleased to acknowledge the contributions from staff at the Daresbury Laboratory and IBM in design, operation and commissioning of HELIOS.

9. References

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