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The HELIOS series of advanced, synchrotron based, X-ray sources

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Abstract. — The compact synchrotron X-ray source, HELIOS built by Oxford Instruments, was commissioned at IBM's Advanced Lithography Facility at Fishkill New York in 1991. Key features and specifications for HELIOS are described, emphasising the unique features of this storage ring X-ray source. The performance of the first machine is outlined, based on almost two years' routine operation, identifying key factors such as output flux, beam lifetime and reliability. A description of the second HELIOS and enhancements to its performance is included.

1. Introduction.

HELIOS 1 is an intense source of X-rays produced as synchrotron light. It is a compact (10.8 m circumference) superconducting racetrack synchrotron, designed to store electrons up to 700 MeV and to have a small physical 'footprint' of 6 m × 2 m. It produces 8 kW of Synchrotron radiation centred on the critical wavelength of 0.84 nm. It was built for X-ray lithography, primarily high density DRAM (Dynamic Random Access Memory) production. It also has general X-ray research applications.

Due to the cyclic nature of a storage ring operation (inject electrons, ramp them in energy, store for extended periods, decay with $1/e$ lifetime) stored electron beam lifetime is an important parameter in machine performance — a longer lifetime greatly improving performance.

Operational reliability is a key requirement in both a research and production application, particularly as a large number of beam lines can be supported. High availability is required to meet the standards required of a production tool in the semiconductor industry. HELIOS is designed to achieve this and for HELIOS 1 this has been very successfully demonstrated in the field.

A second HELIOS is under construction with a large number of enhancements and developments incorporated based on operational experience of HELIOS 1.

2. HELIOS 1.

2.1 DESIGN OF HELIOS 1. — HELIOS [1, 2] is a « racetrack » synchrotron (i.e. two 180° bends separated by two straights to make a closed loop), consisting of two superconducting dipole magnets separated by two straight sections. In total the dipoles provide 17 X-ray beam ports for lithography located every 12.5 degrees, and three diagnostics ports. The straights contain the RF (radiofrequency) cavity, vacuum components, conventional magnets for focusing the electron beam, and pulsed injection magnets. The electron beam is injected from a 200 MeV linear accelerator *via* a transport line.

Table I summarizes key design parameters compared with those achieved to date (Oct. 93) on HELIOS 1.

Table I. — *Key parameters of HELIOS 1, designed and achieved.*

Parameter	Design	Achieved
Electron Energy	700 MeV	700 MeV
Dipole (bending) field	4.5 T	4.5 T
Physical size (Ring)	6 m × 2 m	6 m × 2 m
Injection Energy	200 MeV	90 or 180 MeV
Stored Electron Current :		
at injection energy	200 mA	540 mA
at full energy	200 mA	297 mA
Beam Lifetime	> 5 h at 145 mA	22 h at 200 mA
Injection Current	10 mA	20 mA
Emitted X-ray Power	8.2 kW	10.6 kW
Source size :		
Horizontal, σ_r	< 1.5 mm	0.5-1.3 mm
Vertical, σ_v	< 1.1 mm	0.2-0.7 mm

After construction and testing at Oxford and simplified by its integrated construction, small size and light weight (about 25 tonnes), HELIOS 1 was readily transported to USA from the UK as an assembled and tested unit. This design feature was justified by rapid commissioning ; within eight weeks of its arrival in the USA, beam was stored in HELIOS at injection energy, and the specified stored beam current of 200 mA at full energy was achieved within a further two months of commissioning [3].

2.2 NORMAL OPERATIONS. — Since January 1992 HELIOS 1 has been in routine operation as a production tool for X-ray lithography. Normally it has been required to provide X-rays 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 a start-up of the injector, power supplies, and RF source. Beam is injected in a multi-shot operation (at 2 or 5 Hz) in 100 nS pulses at a chosen accumulation rate of around 4 mA/s. A beam of 200 to 250 mA is stored and ramped. The ramp lasts for three minutes and beam loss during the ramp is usually 5 % or less.

All routine operations are automated, requiring little or no operator intervention, *via* HECAMS (HElios Control and Monitoring System). Thus pre-programmed « sequences » control ramping, start-up, injection, and machine shutdown to standby at the end of operations greatly simplifying the machine operations and the workload of the operators.

2.2.1 *Lifetime performance.* — The *instantaneous* beam lifetime τ is defined by the ratio of decay rate to current :

$$\tau = -I/(dI/dt) .$$

For example, if the decay rate is proportional to current, the lifetime is a constant and equal to the time taken for the beam to decay by a factor of $1/e$.

In fact, the lifetime in HELIOS 1 is strongly current dependent. In normal operating conditions it is 22 h at 200 mA, and ≈ 50 h at 100 mA and ≈ 100 h at 50 mA.

These long lifetimes ensure that high availability can be achieved during non-stop operation, because there are fewer refills. (A refill takes about 15 min.)

2.2.2 *Lifetime improvements.* — In operation the lifetime at 200 mA is some four times above original specification, but there are still possibilities of improving it further.

Improved lifetimes are achieved at larger vertical beam sizes, which suggests that lifetime is improved with a larger bunch volume, this is the Touschek effect. Experiments are therefore planned to increase the *horizontal* beam size, to increase the bunch volume, (as this is preferred by the users) by shifting to a lower horizontal betatron tune. The change is proportionally larger in the straight sections, where the electron beam is not emitting synchrotron radiation. In this way it is anticipated that improvement of lifetime at 150 mA to nearer 40 h for the same vertical beam size, may be achieved. Figure 1 shows the improvement that should result from these experiments. These changes will lead to net decreases in brightness but these are small compared with the total brightness.

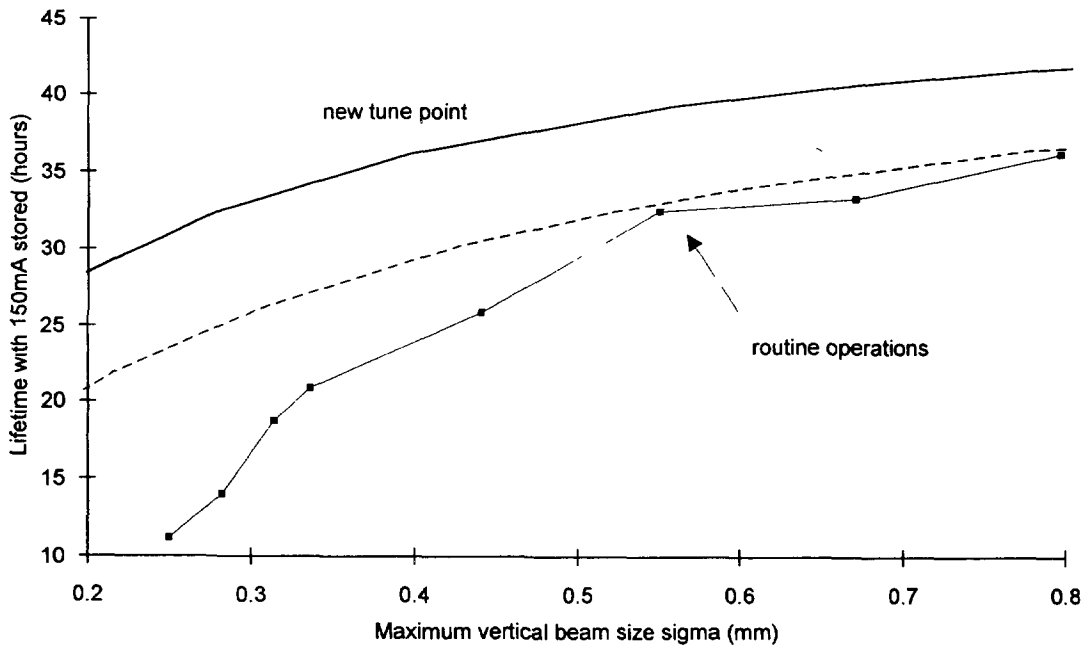


Fig. 1. — HELIOS 1 Lifetime *versus* vertical beam size ; the dashed line shows the theoretical Touschek lifetime at the normal operating point combined with a constant 50 h lifetime. The solid line shows predicted lifetimes at a lower horizontal tune.

2.3 RELIABILITY. — An explicit goal for the IBM ALF (Advanced Lithography 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 have included a carefully planned preventative maintenance schedule and the detailed tracking and recording of all faults through a PC-based database.

Figure 2 shows HELIOS uptime as a percentage of scheduled « beam-on » time since January 1992. « Uptime » means time for which beam is stored at full energy as a percentage of that scheduled. Time lost to ALF utility failures is excluded (which are very low), as is start-up time and refill times as long as they do not occur during scheduled hours.

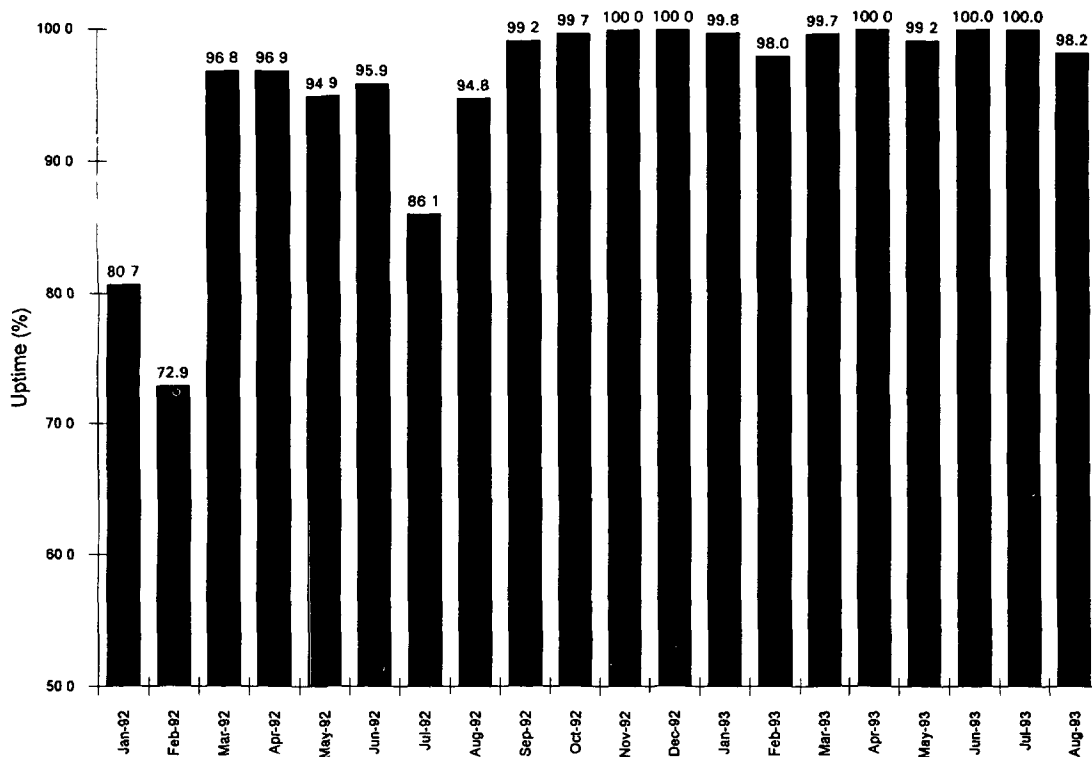


Fig. 2. — HELIOS 1 uptime during scheduled hours since routine operations started in January 1992.

The subsystem that has accounted for most of the early downtime and nearly 60 % of the total has been the injector. However, a combination of hardware modifications and improved operating procedures have greatly improved its performance since the first two months of 92, and no downtime at all has resulted from the injector in 1993. The most technically challenging part of a compact synchrotron, the superconducting dipoles and cryogenic systems, have accounted for less than 10 % of the downtime [4, 5].

The beneficial effects of accumulated operating experience and a reliability enhancement program are clearly seen in the upward trend in the uptime figures during 1992. Averaged over the whole of 1992 HELIOS uptime was 94 % of scheduled hours. In the first eight months of 1993 average uptime was over 99 % (less than 8 h have been lost). This is a substantial achievement and clearly demonstrates the success and applicability of a synchrotron X-ray source in industrial applications.

3. HELIOS 2.

3.1 OVERALL DESCRIPTION. — The second HELIOS has been designed to retain the proven performance of HELIOS 1, whilst refining some features to ensure long term reliability and enhanced performance in some areas. Changes include the injector, RF system, vacuum system, sub frame, and controls. Figure 3 shows a layout of HELIOS 2, complete with its microtron injector, inside a proposed shield enclosure, showing 19 of the 20 beamlines in use in this configuration.

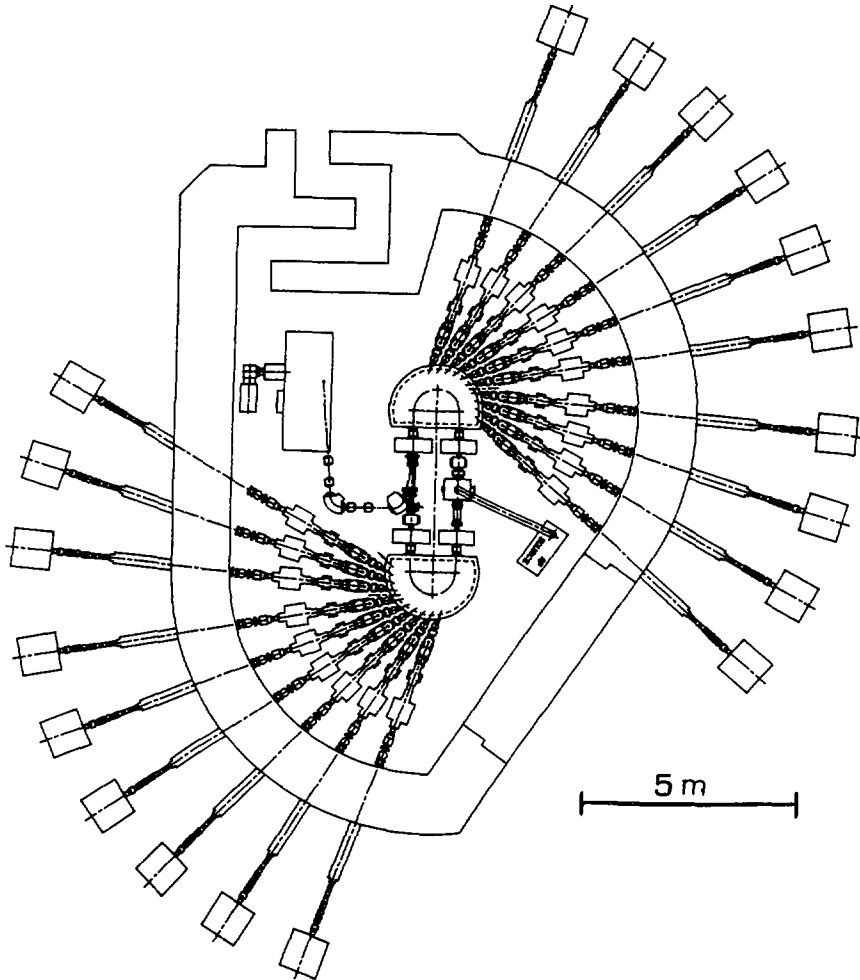


Fig. 3. — HELIOS 2 proposed overall layout with beamlines. The microtron injector and RF transmitter are also within the shield enclosure.

3.2 HELIOS 2 INJECTION. — Successful extended operation of HELIOS 1 at 90 MeV injection has confirmed that the 200 MeV injection design was too conservative, and 100 MeV is chosen for HELIOS 2. This offers several advantages ; primarily, the overall size of the installation is considerably reduced.

The beam from the microtron injector, has a naturally small energy spread (0.1 %) and size (specified emittances are 0.1 mm mRad). These characteristics allow a relatively simple design of transport line and offer the prospect of easy set up of injection and relatively low external radiation. Typical beam current is 12 mA, with 100 nS pulse lengths and repetition rates up to 10 Hz. Acceptance trials at Oxford have confirmed exceptional ease of operation, with fast turn-on, excellent reliability and repeatability, and easy integration into the HELIOS 2 control system.

3.3 HELIOS 2 VACUUM. — The experience gained with HELIOS 1 of good beam lifetime from low vacuum pressures has shown the value of careful vacuum design to achieve the best possible vacuum throughout the ring. Distributed NEG (Non-Evaporable Getter) pumps have been added to maximise the pumping in the straights when combined with ion pumps. The aim of this is to take full advantage of the inherently large cryopumping in the dipoles offered by their coldbore design. The NEG electrodes are combined with ion clearing electrodes, to make best use of the available space in the vacuum vessels.

Monitoring is improved so that both straights and both dipoles will be fitted with an RGA head and an ion gauge.

3.4 HELIOS 2 MAINTAINABILITY. — 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.

3.5 HELIOS 2 CONTROLS. — The computer control system has been revised to incorporate modern workstation-based operator stations, whilst keeping the key features of HELIOS 1 — e.g. automated sequences, standard modular components and independent fail-safe interlocks. The commercially available « VISTA » software package, which provides windows-based displays, is used as the basis of the control system, in place of the SLAC (Stanford Linear Accelerator Laboratory) package used for HELIOS 1.

3.6 HELIOS 2 RF. — The RF system has been revised by lowering its operational frequency from 500 MHz to 55 MHz to provide longer Touschek lifetimes and reduced likelihood of « coupled bunch instabilities » that can lead to beam loss by lifetime reduction, total beam loss or a reduction in the maximum achievable current that can be stored.

The RF source driving the rf cavity consists of a high power tetrode output stage, rather than the klystron tube used for HELIOS 1. The ring RF cavity is a cylindrical, disk-loaded, cavity with a tuner plunger.

Another advantage of the lower frequency is the ability to employ fast feedback on the cavity voltage. This enables a wider choice of stable cavity voltage settings for more flexible injection and ramping.

3.7 HELIOS 2 STATUS. — HELIOS 2 is currently at an advanced stage of manufacture and several key components have been tested. The 100 MeV microtron injector has been extensively tested and integrated with the main HELIOS control system. The superconducting dipole magnets are almost finished. The test results confirm the magnetic performance and have demonstrated that a fast ramp-rate, about 100 seconds to full field, can be used to minimize refill times. The ring straight section containing the RF cavity is being assembled, while the injection straight is complete and under vacuum (at 1.6×10^{-10} mbar). Many items of plant equipment are complete.

4. X-ray research with HELIOS.

Although originally designed for use in X-ray lithography, HELIOS 2 is equally suitable for general research use [6]. The X-ray power spectrum of HELIOS 2 (operating at its full energy of 700 MeV) is shown in figure 4, with spectra from Daresbury laboratory (UK) and Max 1 (Lund Sweden) for comparison. The total power output of HELIOS 2 is 12.3 kW for a 300 mA stored beam. The critical wavelength (defined as the half power point in the continuous spectrum produced by synchrotron sources) is 0.84 nm (1 465 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).

Figure 4 shows that HELIOS fills the middle region of the spectrum, in between Daresbury and Max 1. To obtain the photon flux into a given beamline it is necessary to scale figure 4 by the spectral range and the horizontal angular width accepted by the beamline. For example, in the spectral range 900 to 1 100 eV, a beamline of acceptance 50 mrad will receive :

$$50 \times 4.1 \times 10^{12} \times (200 \text{ eV}/1\,000 \text{ eV})/(0.1 \%) = 4.1 \times 10^{16} \text{ photons per s.}$$

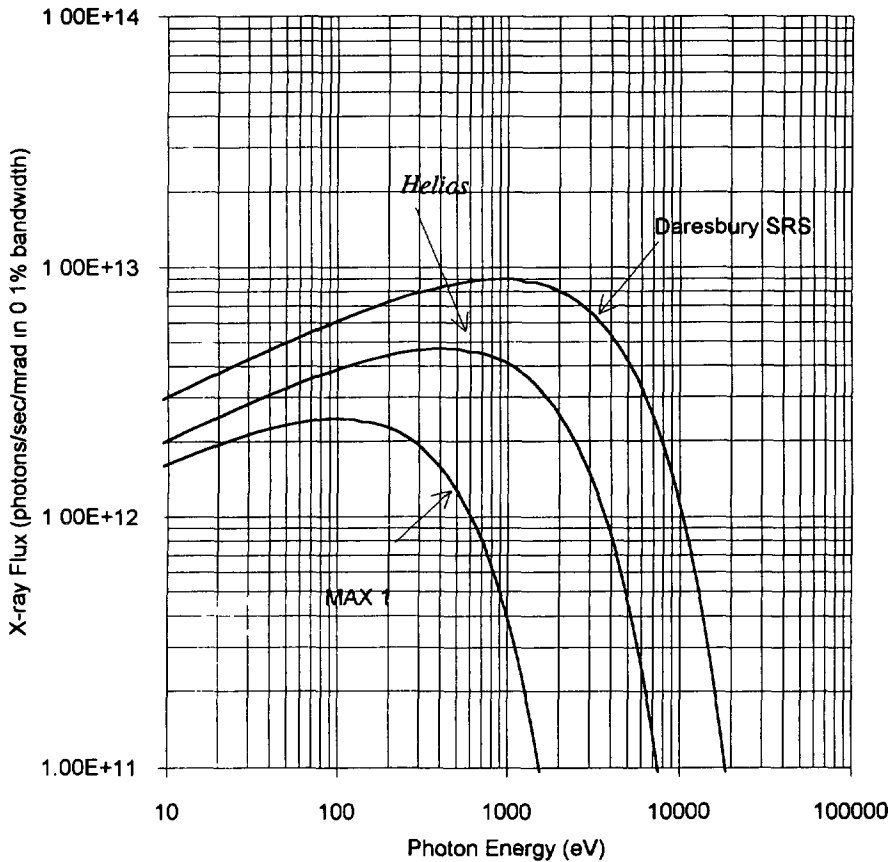


Fig. 4. — Spectral power from HELIOS 2 compared with two large conventional rings at National facilities.

The source (electron beam) dimensions may be easily varied over a large range. The vertical beam size is determined by the setting of a skew quadrupole, which controls the emittance coupling between the horizontal and vertical phase spaces. The horizontal beam size is determined by the setting of conventional focusing quadrupoles, which control the horizontal betatron tune.

HELIOS 2 provides for the attachment of up to 10 Beam lines on each of the two dipoles (Fig. 3) giving 20 in all (one of the 20 is not used in this specific configuration), diagnostic ports are additional. Unused ports can be closed using a blanking plate and water cooled absorbers. Each port is designed to transmit a horizontal fan of radiation 60 mrad wide giving an X-ray power to the line of 115 W.

5. Summary.

HELIOS 1 has exceeded specification in both stored current and beam lifetime, and its uptime during scheduled hours for the last 12 months has been over 99 %.

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

Extremely intense Synchrotron based X-ray sources, producing continuous radiation using synchrotron light have been demonstrated as practical sources for industrial applications. HELIOS performance is comparable with a number of national light facilities and is suitable for a range of research applications requiring intense X-rays.

Acknowledgements.

Many individuals at Oxford have contributed to the success of HELIOS 1 and the design and construction of HELIOS 2. We are also pleased to acknowledge the contributions from staff at the Daresbury Laboratory and IBM.

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