小型リング特集

HELIOS 1 Status and HELIOS 2 Development

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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 superconducting machine. The performance of the machine is outlined, based on almost two years' routine operation, with notes on key factors such as beam lifetime and reliability. Progress notes on the construction of the second HELIOS, and a brief description of HELIOS 2, are also presented.

1. Introduction

HELIOS has been in routine operation as a production tool at IBM's Advanced Lithography Facility (ALF) since January 1992. During commissioning, after delivery in March 1991, it met or exceeded all specifications, delivering 8 kW of X-ray power centred around the critical wavelength of 8.4 Angstroms.

Reliable operation has been demonstrated, with uptime during scheduled hours averaging 94% over the first 12 months, and increasing to 99% during 1993. A recent trial of 24 hour operation has further illustrated that Helios is capable of providing the high availability required of a production tool in the semiconductor industry. Other recent work has confirmed that HELIOS operates reliably at an injection energy of 90 MeV, as well as 200MeV as originally designed.

A second ring, HELIOS 2, currently in production is designed for 100 MeV injection. Its microtron injector has been commissioned and other key components, including its superconducting magnets, are in an advanced state of manufacture or testing. Details of the current status of HELIOS 2 and its potential for X-ray research are discussed after reviewing the performance of HELIOS 1.

2. HELIOS 1

2.1 Design of HELIOS 1

HELIOS [1, 2] is a "racetrack" synchrotron, consisting of two superconducting dipole magnets separated by two straight sections. The dipoles provide 17 X-ray beam ports for lithography located every 12.5 degrees, and three diagnostics ports. The straights contain the RF (499.7 MHz) cavity, vacuum components, conventional magnets for focussing the electron beam, and pulsed injection magnets. The electron beam is injected from a 200MeV linear accelerator via a transport line.

Table 1 summaries key design parameters compared with those achieved to date.

	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 Electron Current:		
at injection energy	200 mA	540 mA
at full energy	200 mA	297 mA
Beam Lifetime	>5 hrs at 145 mA	22 hrs at 200
Injection Current	10 mA	20 mA
Emitted X-ray Power	8.2 kW	10.6 kW
Electron beam size:		
Horizontal, σ_r	<1.5 mm	0.5 - 1.3 mm
Vertical, σ_v	<1.1 mm	0.2 - 0.7 mm

By virtue of its stainless steel base frame and light weight (about 25 tons), HELIOS 1 was readily transported to USA from Oxford Instruments in 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 current of 200 mA at full energy was achieved within a further two months of commissioning[3].

Figure 1 shows HELIOS 1 being loaded on to a lorry for transport to the USA.

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 search of the shield enclosures and start-up of the injector, power supplies, and RF source. Beam is injected in a multi-shot operation (at 2 or 5Hz) in 100ns pulses at a chosen accumulation rate of around 4 mA/s. A beam of 200 to 250mA is stored and ramped. The ramp lasts for three minutes and beam loss 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.

The injection energy was originally 180MeV, but a 90 MeV mode was developed to make linac operation more reliable. Halving the energy means damping times are eight times longer, but they are naturally short in a superconducting ring because of the high bending fields. The 90 MeV injection mode has proved to be just as reliable and is now used as standard.

The HECAMS software 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. For certain operational modes, serious alarms will activate a telephone call-out system. Hence the operator may lock the control console and leave the machine effectively unmanned, knowing that in the unlikely event that there is an alarm HECAMS will page him immediately.

On site technical expertise at ALF includes three Oxford support staff, an IBM physicist and an IBM operator. Where opportunity arises, a program of machine studies is pursued. Time is roughly evenly divided between studies aimed at maintaining good and reliable performance, and those with longer term goals like further extending beam lifetime, as described below.

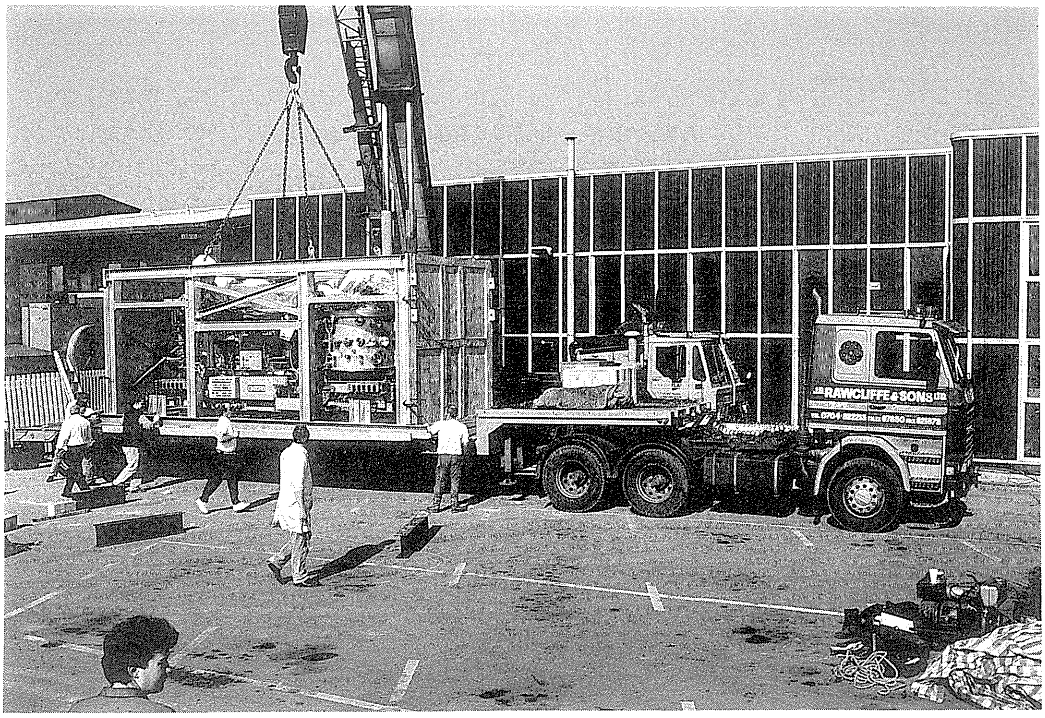


Fig.1 HELIOS 1 on lorry leaving Oxford for East Fishikill, transported as one assembled unit.

2.3.1 Lifetime Performance

The *instantaneous* beam lifetime τ is defined by the ratio of current to decay rate

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

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 hours at 200mA, and around 50 hours at 100mA and 100 hours at 50mA.

These long lifetimes ensure that high availability can be achieved during non-stop operation. This is demonstrated in **Fig.2**. The availability and ratio of average to peak current achieved in Helios is contrasted with a machine of constant 5 hour lifetime (the original specification for Helios 1), assuming 15 minute refill times. Of course, reduced frequency of refilling means not only greater availability but also tends to result in increased ease of operation and reliability.

Data from a recent trial of continuous running are presented in **Fig.3**. There were four fills in 33 hours, with refills being performed approximately every eight hours to fit naturally with shift changeovers. Average refill was 19 minutes, which is equivalent to 96.1% availability in continuous running. Averaged over the four fills, peak current was 199mA and the ratio of average to peak current was 0.86.

2.3.2 Lifetime loss mechanisms

One important beam loss mechanism is scattering off residual gas molecules. The loss rate depends on the number and type of gas molecules, which in turn depends on the beam current through photodesorption from surfaces struck by the synchrotron light. However, the cold-bore design of the Helios dipoles ensures that there is powerful cryopumping close to where the photodesorbed molecules are produced. As reported previously[4), 5)] beam lifetime rose rapidly as the surfaces receiving the synchrotron light were cleaned by the beam, from about 5 hours at 200mA to

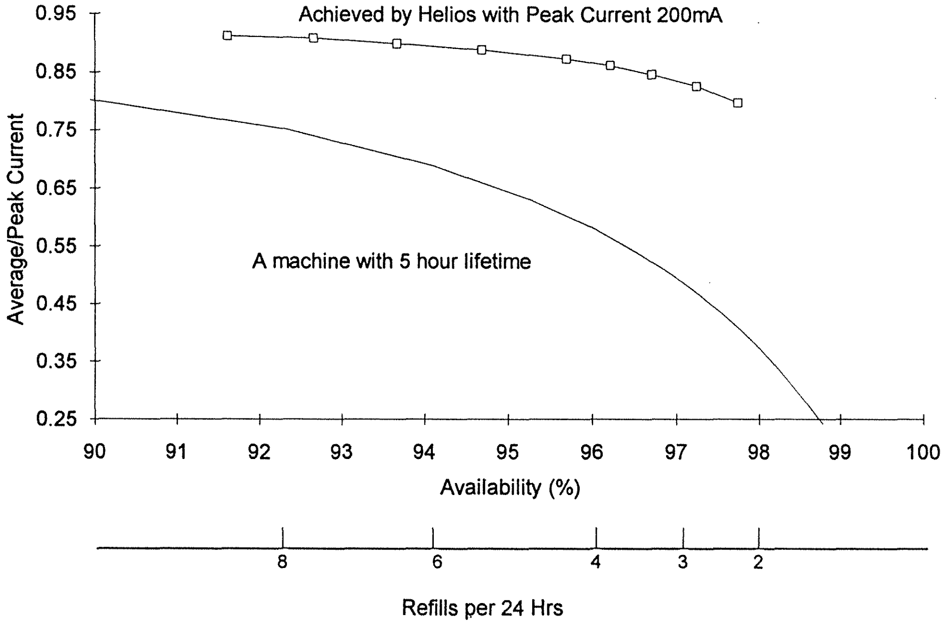


Fig.2 HELIOS 1 Tradeoff between average current and availability for various stored beam periods, assuming a 15 minute refill period. Comparison is made with a hypothetical machine of 5 hour lifetime.

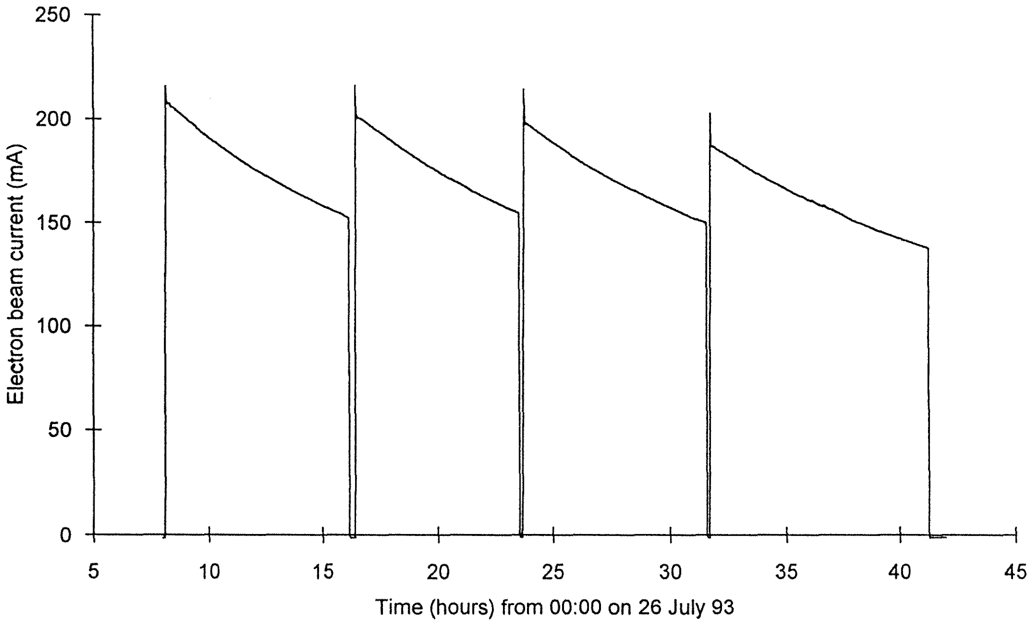


Fig.3 HELIOS 1 Performance during a trial run of continuous operation.

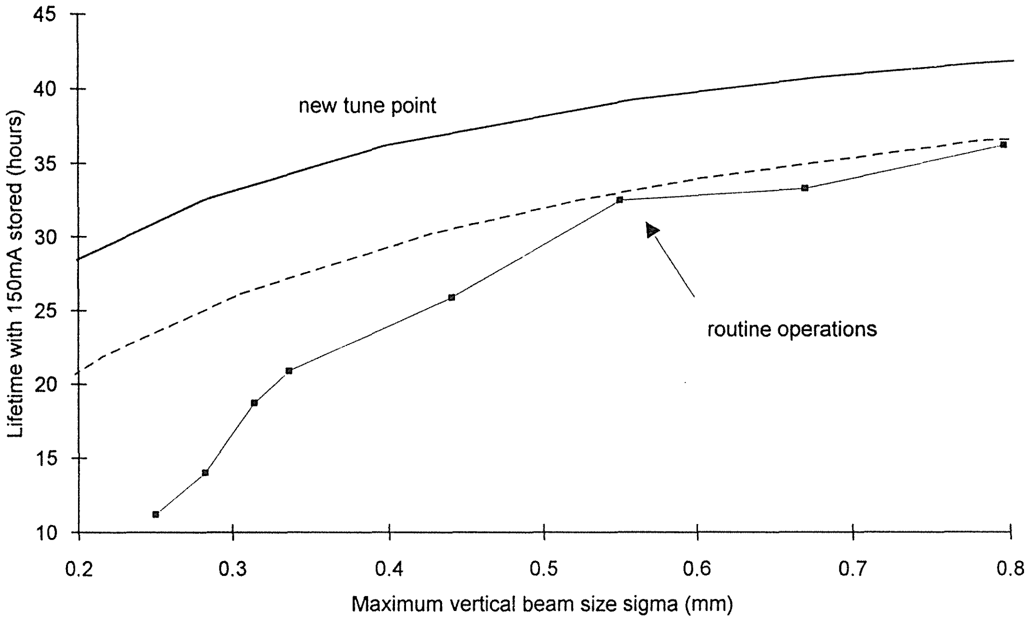


Fig.4 HELIOS 1 Lifetime versus vertical beam size; the dashed line shows the theoretical Touschek lifetime at the normal operating point combined with a constant 50 hour lifetime. The solid line shows predicted lifetimes at a lower horizontal tune where the maximum horizontal beam sigma is 2.4mm instead of 1.7mm.

nearly 20 hours after 150 Ampere-hours.

A second significant loss mechanism is thought to be the Touschek effect, where Coulomb scattering between electrons in the same bunch causes an electron to exceed the momentum acceptance of the machine. The loss rate is proportional to the electron density in the bunch.

In **Fig.4** measured lifetimes at 150mA are plotted against maximum vertical beam size (which·is easily controlled using a skew quadrupole). The theoretical curve represents the combined effects of a constant 50 hour gas scattering lifetime and the calculated Touschek lifetime (from the Daresbury code ORBIT which is novel in having the fully relativistic treatment required⁶⁾).

The beam size in routine operations is indicated. Better lifetimes are achieved at larger vertical beam sizes, which suggests that lifetime is improved with a larger bunch volume. Experiments are therefore planned to increase the horizontal beam size by shifting to a lower horizontal betatron tune. In this way we hope to improve lifetime at 150mA to nearer 40 hours for the same vertical beam size, as shown by the upper curve in **Fig.4**.

2.3.3 Summary

Due to the excellent vacuum the lifetime at 200mA is some four times above original specification, but there are still hopes of improving it further. Lifetimes are predicted to be still longer in HELIOS 2. Although the number of electrons per bunch will be greater (there will be two bunches instead of 16) the bunch length and momentum acceptance will be larger, and predicted Touschek lifetimes are more than doubled. Gas scattering lifetime should be improved in HELIOS 2 as a result of more distributed pumping in the straights (see section 3.3).

Long lifetimes greatly increase machine availability and overall ease of operation.

2.4 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 have included a carefully planned preventative maintanence schedule and the detailed tracking and recording of all faults through a PC-based database.

Figure 5 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. Time lost to ALF utility failures is excluded, as are start-up time and refill times as long as they do not occur during scheduled hours.

The subsystem that has accounted for most of the downtime (nearly 60%) has been the linear accelerator. However, a combination of hardware modifications and improved operating procedures have greatly improved its performance since the first two months, and no downtime at all has resulted from the linac 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), 7)].

The beneficial effects of accumulated operating experience and the reliability 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 hours have been lost).

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 6** shows a layout of HELIOS 2, complete with its 100MeV microtron injector, inside its shield enclosure.

3.2 HELIOS 2 Injection

Successful extended operation of HELIOS 1 at 90

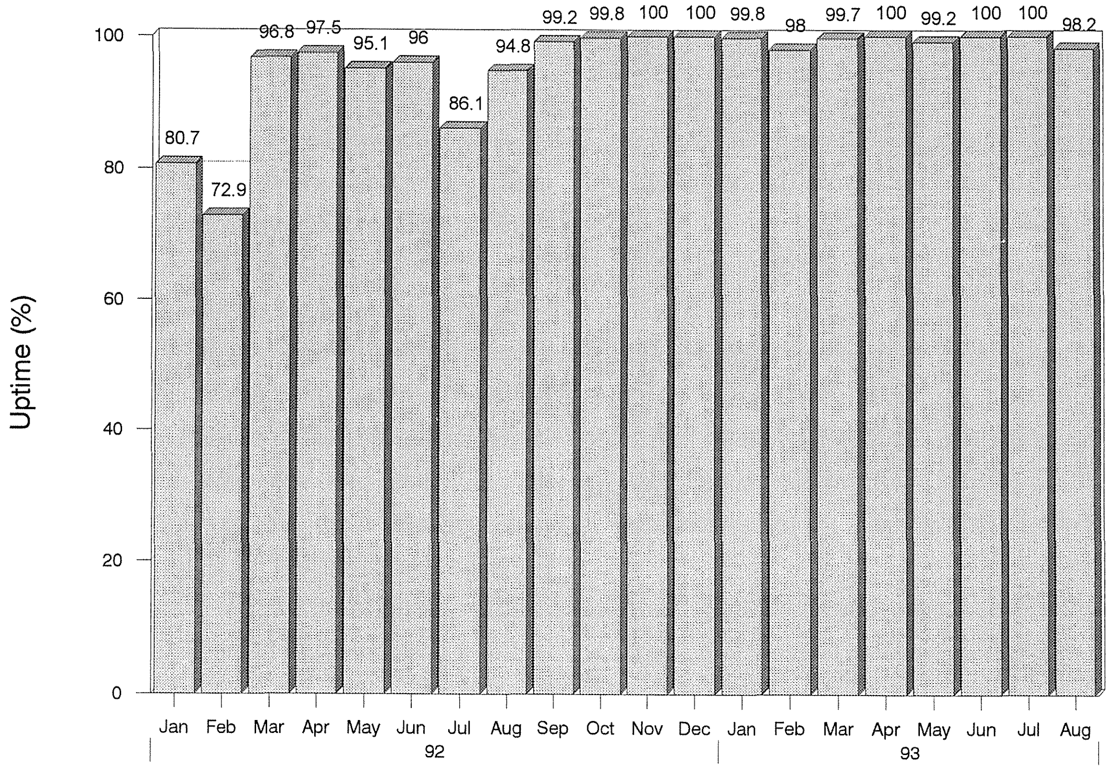


Fig.5 HELIOS 1 Uptime during scheduled hours since routine operations started in January 1992.

MeV 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 microton injector, supplied by Scanditronix, 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 12mA, with 100ns pulse lengths and repetition rates up to 10Hz. 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 cold-bore 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 maintanence. Cables and cooling pipework have been rearranged, the baseframe has been simplified, and

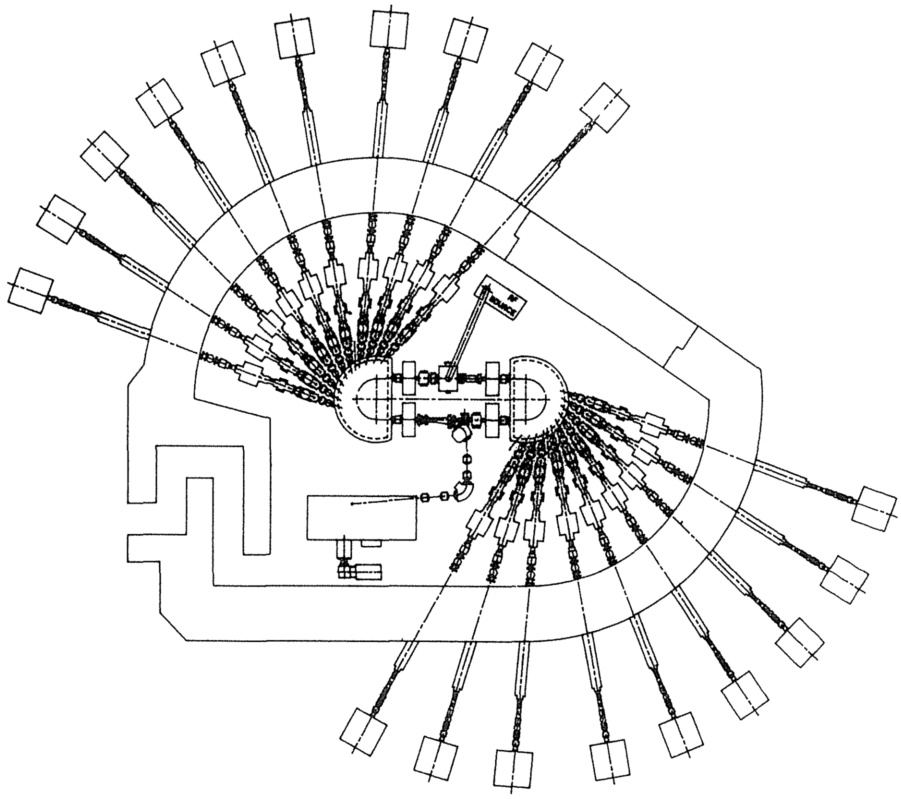


Fig.6 HELIOS 2 Overall layout with beamlines. The microtron injector and RF transmitter are also within the shield enclosure.

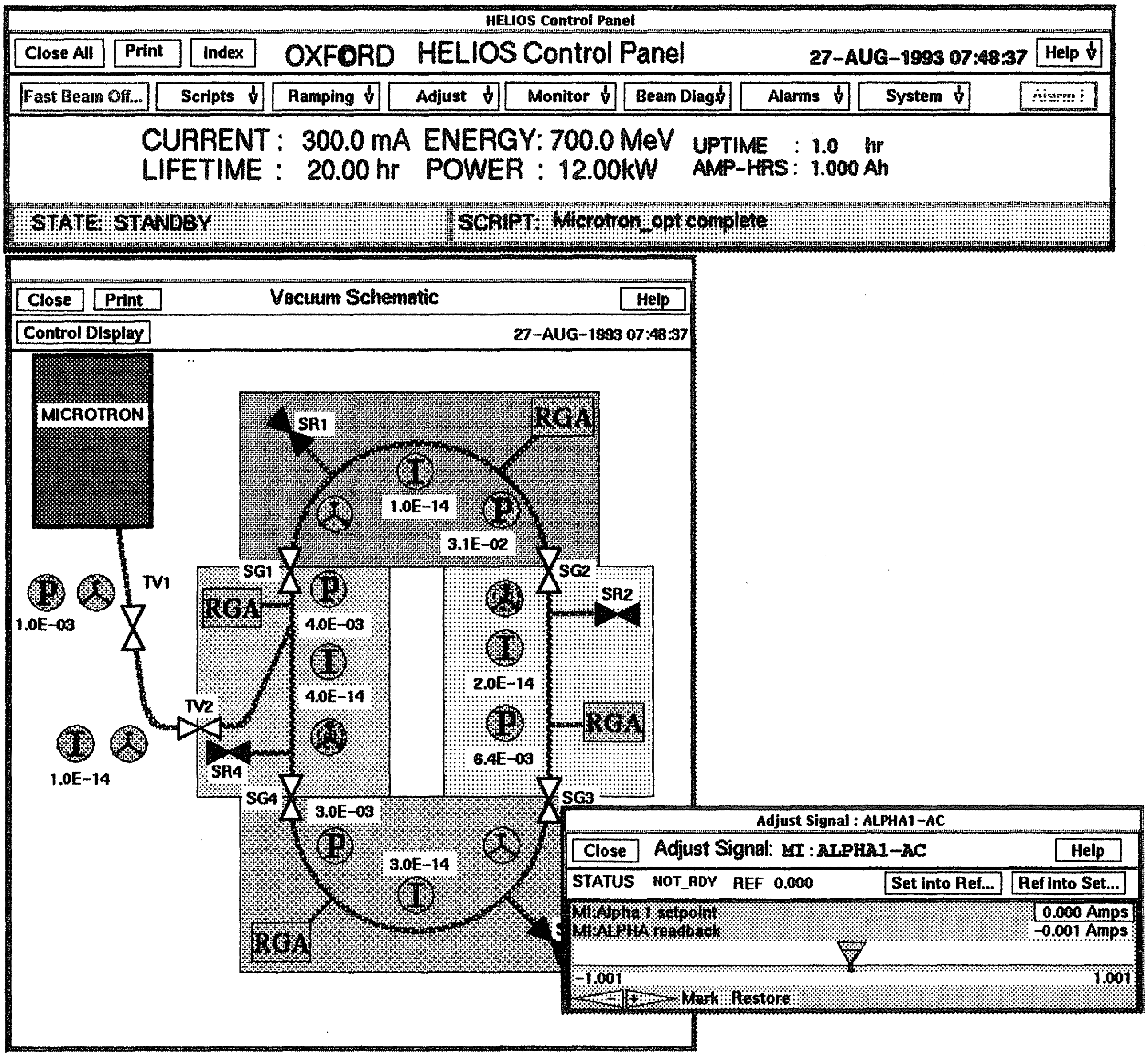
some components have been moved from the ring to the plant area.

Vacuum valves have been added at the ends of the straights to enable servicing and baking a straight without affecting the rest of ring.

3.5 HELIOS 2 Controls

The computer control system has been revised to incorporate modem workstation-based operator stations, whilst keeping the key features of HELIOS 1-e.g.automated sequences, standard modular components (CAMAC etc.) 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 package used for HELIOS 1. **Figure 7** illustrates a typical operator display with three windows: "Status", "adjustment" and a vacuum schematic.

Ethernet is used to link CAMAC interfaces for plant controls, as well as providing a direct link to the microtron's local controller. Two control racks contain the CAMAC interfaces to all the storage ring



HELIOS Control Panel

OXFORD HELIOS Control Panel　27-AUG-1993 07:48:37

CURRENT: 300.0 mA ENERGY: 700.0 MeV UPTIME : 1.0 hr

LIFETIME : 20.00 hr POWER : 12.00kW AMP-HRS: 1.000 Ah

STATE: STANDBY　SCRIPT: Microtron_opt complete

Vacuum Schematic　27-AUG-1993 07:48:37

Adjust Signal : ALPHA1-AC

Adjust Signal: MI : ALPHA1-AC

STATUS NOT_RDY REF 0.000

MI:Alpha1 setpoint　0.000 Amps

MI:ALPHA readback　-0.001 Amps

-1.001　1.001

Fig.7 HELIOS 2 Control screen showing control and status windows, and a vacuum system schematic.

and transport line units, as well as providing a centralised interlock system and pulsed timing control. Ramping is initiated from the main computer (VAX workstation), but a CAMAC PC module is responsible for the lower level ramping of the magnet setpoints.

3.6 HELIOS 2 RF

The RF system has been revised by lowering the frequency from 500MHz to 55MHz to provide longer Touschek lifetimes and reduced likelihood of coupled bunch instabilities.

The RF source will consist of a power tetrode output stage, rather than the klystron tube used for HELIOS 1. This is simpler and more tolerant of reverse power, so the HELIOS 1 system of dynamic matcher and waveguide are not required. The ring RF cavity consists of 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 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 minimise 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). Certain items of plant equipment are complete, including the main dipole (1125A) power supply.

4. X-ray research with Helios

Although originally designed for use in X-ray

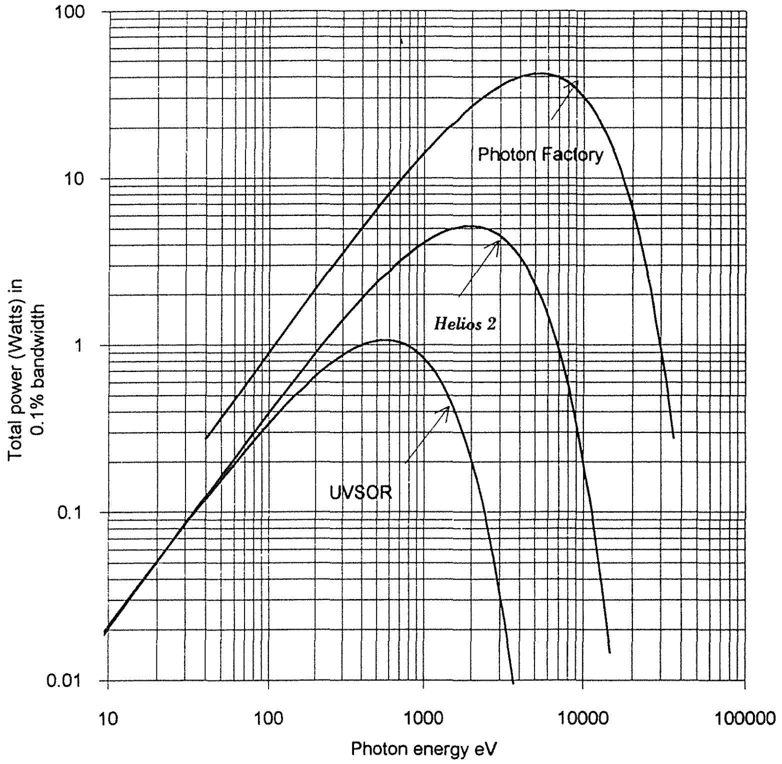


Fig.8 Spectral power from HELIOS 2 compared with two large conventional rings.

lithography, Helios 2 is equally suitable for general research use [9]. The X-ray power spectrum of Helios 2 (operating at its full energy of 700MeV) is shown in **Figure 8**, with spectra from UVSOR and the Photon Factory for comparison. The total power output is 12.3kW for a 300mA stored beam. The critical wavelength is 0.84nm (1465 eV) but the range of useful wavelengths extends from the visible to the edge of the hard X-ray region at about 5keV. 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 (electron beam) dimensions may be easily varied over a large range. The vertical beam size is determined by the energisation of the skew quadrupole, which controls the emittance coupling between the horizontal and vertical phase spaces. The horizontal beam size is determined by the energisation of the conventional focusing quadrupoles, which control the horizontal betatron tune.

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.

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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