

Report on Helios: Routine Operation

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Abstract

Helios is a compact superconducting electron storage ring, intended for use as an industrial X-ray source in microchip lithography. Its compact size, thanks to the high field superconducting magnets, allows the ring to be transported intact. After commissioning in Oxford, the ring was shipped to IBM's Advanced Lithography Facility at East Fishkill, NY, USA, where it is now in routine operation. A second ring, Helios 2, is in production.

1. INTRODUCTION

Helios is a compact superconducting storage ring X-Ray source designed specifically for X-Ray lithography. The preferred spectrum for lithography requires the storage ring to produce a critical wavelength λ_c in the range 0.8 - 1.2nm; for Helios we have chosen $\lambda_c = 0.84\text{nm}$. In a conventional ring with iron magnets at 1.4T, this λ_c would imply an electron energy of 1280 MeV and a bending radius of 3.0m. With superconducting magnets running at 4.5T, the same critical wavelength is produced by electrons at 700 MeV, with a bending radius of 0.52m. This reduction in size is important for utilization in a semiconductor fabrication facility where space, especially clean space, is at a premium. It also has another very important consequence for an industrial machine: it makes it possible to transport the complete ring using normal road vehicles. This means that the ring may be commissioned and thoroughly de-bugged at the producer's factory, before being shipped intact to the customer's site, where it can be brought into service rather quickly.

2. DESCRIPTION OF HELIOS

Fig 1 shows the general arrangement of Helios, which is a racetrack ring with two superconducting 180° bending magnets. Injection is at 200 MeV from a linac manufactured by CGR MeV, via an achromatic transfer line, which has energy selecting slits located at an intermediate dispersive point. The injected beam enters via a pulsed septum magnet and there is a single fast kicker located in the opposite straight section. Adjacent to the

dipoles are four horizontally focussing conventional quadrupoles, which are enclosed by 25mm thick iron plates to screen them from the fringe field of the superconducting dipoles. Also located in the straights are a single sextupole and a combined octupole/skew quadrupole. The r.f. cavity runs at 500MHz and is electrically almost identical to the Daresbury SRS cavity.

The superconducting dipoles are air cored and provide a central field (with a gradient) of up to 4.5T. In addition, separately adjustable superconducting trim coils are provided for quadrupole, sextupole and radial (dipole) fields. The beam space and cryogenic insulating vacuum is a common vacuum space. More detail on Helios is provided in [1], [2], [3] and [4]

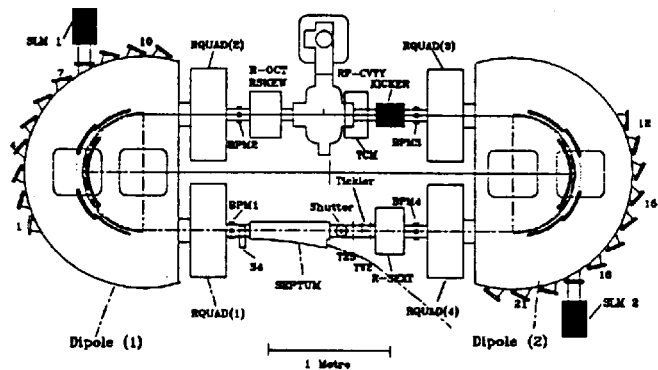


Fig 1 The Layout of Helios

3. COMMISSIONING AND TRANSPORTATION

Helios was commissioned at Oxford through the Summer/Autumn of 1990. Preliminary results were reported at the last EPAC [2]. At the conclusion of commissioning in Oxford, Helios had accumulated up to 520mA at the injection energy of 200 MeV and had ramped 100mA to the full energy of 700MeV. However the lifetime at full energy was limited to 1³/₄ hours by gas scattering. During winter/spring 91/92 the vacuum system was refurbished, principally by replacing the ion pumps, adding Titanium sublimation pumps and eliminating some

40 edge welded bellows from the dipole vacuum vessels. After this refurbishment, base pressures of $1-3 \times 10^{-10}$ mbar were achieved.

Over Easter '91, the ring was shipped from Oxford to IBM's Advanced Lithography Facility ALF at East Fishkill, NY, USA. The ring itself weighs 25 Tonnes but, because all components are mounted on a rigid steel base frame, it was moved around the factory quite easily using air skates. Electrical, gas and water services for the ring are terminated in connectors mounted on the base frame so that the ring could be quickly 'unhitched' and moved out.

As shown in fig 2, Helios was lifted by means of a frame, which bolts directly onto the base frame of the ring. This same frame also formed the box which protected the ring from damage during transit. In just one day, Helios was packed, loaded onto an air ride lorry and driven from Oxford to the transatlantic 'roll-on-roll-off' ferry at Liverpool. Two weeks later it arrived at East Fishkill. Most other parts of the installation were transported by air freight. An advance party had already been working on the site for some months previously to install cabling etc in the IBM shield vault. As a result of this preparatory work, stored beam was achieved in East Fishkill just 2 months after the ring arrived on site. Through the summer of 1991, the stored beam at full energy was progressively increased from the 100 mA achieved at Oxford to values comfortably in excess of the specified 200mA. The highest stored beam recorded so far is 294mA at full energy. The primary factor in achieving this progressive improvement was our growing understanding of the r.f. system and its interaction with the beam, covered separately later in this

conference [5]. Table 1 summarizes the specified and achieved performance.

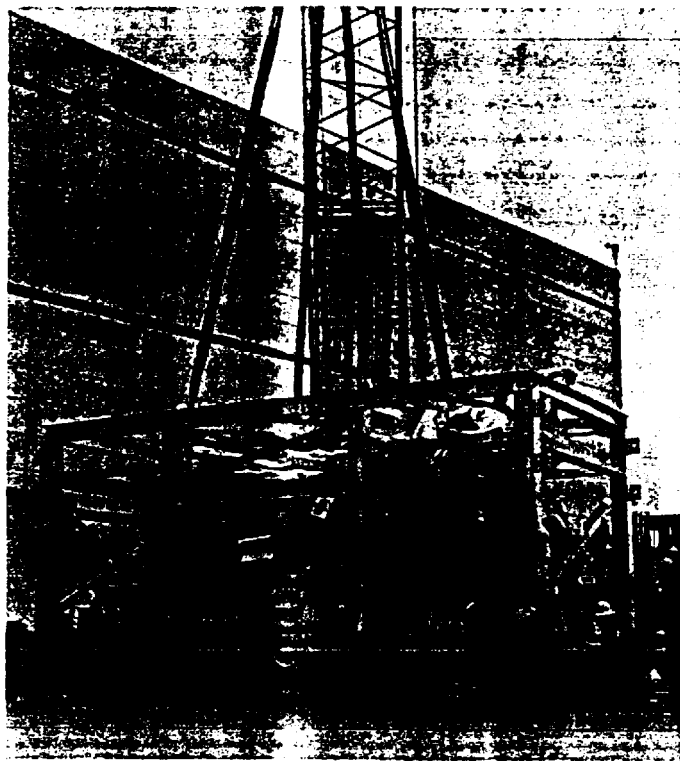


Fig 2 Helios being lifted off the air ride lorry after transportation from Oxford to East Fishkill.

Table 1: Main Parameters of Helios

PARAMETER	SPECIFIED	ACHIEVED
Maximum electron energy	700MeV	700MeV
Maximum dipole field	4.5T	4.5T
Critical wavelength	0.84nm	0.84nm
Bending Radius	519mm	519mm
Stored beam current (peak)	200mA	294mA
Stored beam current (8 hr av)	145mA	175mA
Lifetime at 200mA	5 Hours	11.5 Hours
Base vacuum pressure	5×10^{-10} mbar	3×10^{-10} mbar
Vacuum pressure with beam	3×10^{-9} mbar	3×10^{-9} mbar
Horizontal source size σ_x	< 1.5mm	0.4mm-1.2mm
Vertical source size σ_y	< 1.1mm	0.2-0.4mm

4. ROUTINE OPERATION

At the end of 1991 Helios 1 had completed all phases of the detailed acceptance procedures agreed some 4 years earlier between Oxford and IBM. As well as the technical specification summarized in Table 1, these procedures included running the ring for 5 days at an average current in excess of the specified 145mA and operation 'from cold' by IBM staff previously unfamiliar with storage rings. Since January 92, Helios has been in routine operation, providing X-ray beams for lithography development. Fig 3 shows two of these beamlines up to the point where they pass through the IBM shield wall into the lithography area.

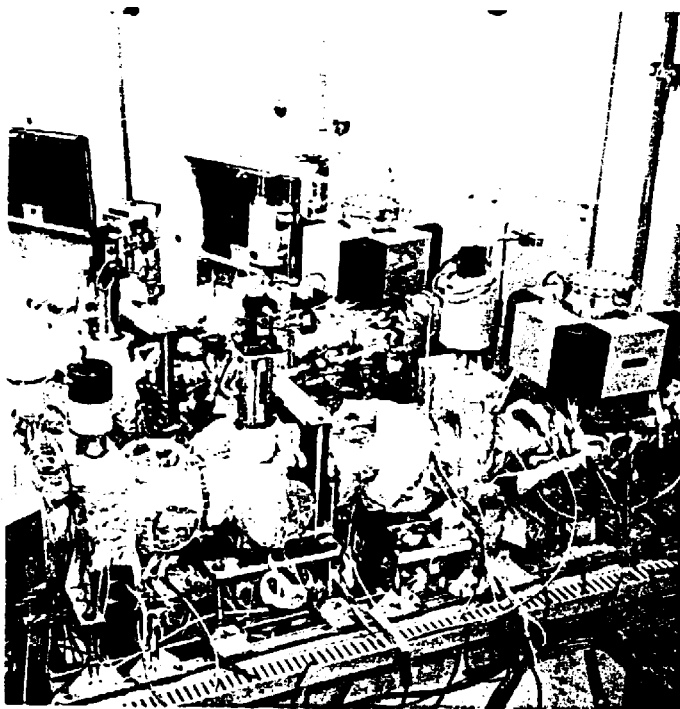


Fig 3. X-ray beamlines at the IBM Advanced Lithography Facility.

4.1 Injection

A typical injection fill rate in daily operation is 3mA/sec, although higher rates can be achieved. Fig 4 shows a typical sequence of a beam dump, re-injection and ramping, the whole process taking about 10 minutes.

4.2 Beam Lifetime

Fig 4 also shows instantaneous beam lifetime τ (middle trace) of the stored beam current I (upper trace). The plot is generated by assuming that the instantaneous rate of decay follows the relation $\frac{dI}{dt} = -\frac{I}{\tau}$, ie $I = I_0 e^{-t/\tau}$. The time

base for the calculation of the displayed beam lifetime can be set manually or automatically.

The whole decay is fitted rather well [6] by:

$$\frac{dI}{dt} = b_0 I + b_1 I^2$$

where

$$b_0 = -1.40 \times 10^{-3} \text{ hour}^{-1}$$

$$b_1 = -4.32 \times 10^{-4} \text{ hour}^{-1} \text{ mA}^{-1}$$

$$\tau = -\frac{1}{b_0} \cdot \frac{1}{\left[1 + \frac{b_1 I}{b_0}\right]} = \frac{716}{(1 + 0.31I)}$$

thus $\tau = 11.4$ hours at 200mA
 $= 22.4$ hours at 100mA.

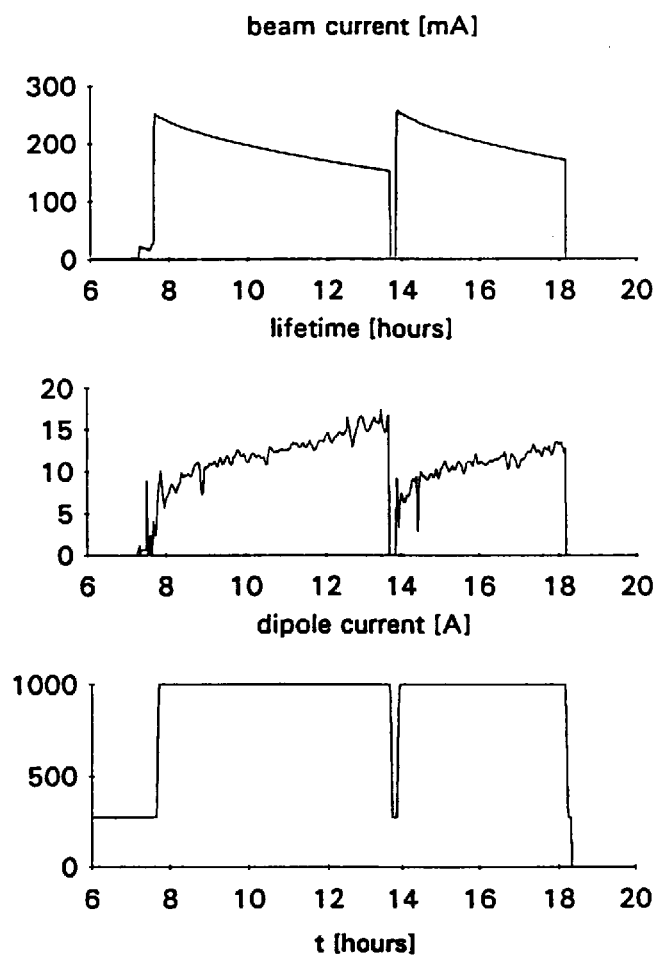


Fig 4. A typical fill and ramp sequence.

The beam lifetime has actually improved fairly steadily since the ring was last vented in Nov 91. Fig 5 shows a plot of a lifetime at 100mA against number of days since venting

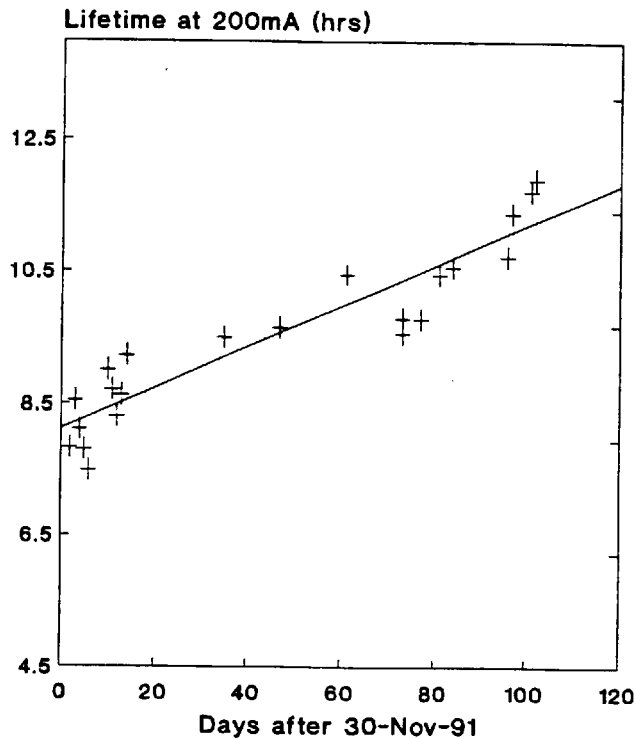


Fig 5. Improvement of beam lifetime from the effects of beam cleaning.

4.3 Control Sequences

As an industrial machine, it is important for Helios to be easily operable in a routine way making minimum demands on the operator. To this end the Helios Control and Monitoring System HECAMS [7] provides a selection of programmed control sequences which take the machine through all normal daily operations with minimal intervention by the operator.

Only five sequences are needed for normal operation. In the morning, the system is switched from the overnight standby state to the operational state by the sequences READY-ON and LINAC-ON. Injection and ramping are performed by the sequence FILL. The stored beam may be dumped by DUMPREP, after which the ring may be refilled by FILL. At the end of the day, the system is switched to its overnight state by the sequence READY-OFF.

The most important and comprehensive sequence is FILL which, starting from all systems in the ready state, takes the ring through the complete injection and ramping sequence to produce a stored beam at full energy. The sequence first checks that all transfer and ring magnets are set to their reference values, that the septum and kicker are

on (waiting to be triggered by the linac) and that the ring RF is on. The MATCHER sequence is called to ensure that the RF matcher is correctly set up for injection.

Before starting the linac beam, FILL switches off the bending magnet downstream of the energy slits in the transport line to dump the beam. FILL then sets the console scope to monitor the beam pick up sensors situated between the energy slits and the beam dump point. The sequence suspends at this point, leaving the operator to check the linac beam and, if necessary, optimize the energy as indicated by transmission of beam through the slits.

The sequence is then reactivated and immediately sets the downstream transfer line magnet to its reference value, at which point accumulation in the ring starts. As the specified current (usually 250mA) is approached, the linac current is reduced to avoid overshoot. At the specified current, the linac beam is switched off, the reference RAMP file is activated and the MATCHER software is put into automatic control. Once ramping is under way, the linac, kicker and septum are switched off. At peak energy, the console display switches to the beam current and lifetime and the STATUS display is updated.

These five sequences are the only ones normally used by the operators. In addition, there are several other sequences, such as the RF matcher software, which are called by the main sequences, but which may also be used alone. For major shut-down periods, there is also a set of sequences which take each system to and from the cold state.

5. HELIOS 2

With Helios 1 now finished, Oxford is well into the production of Helios 2. The design will follow Helios 1 quite closely, but several improvements have been made in the light of experience so far.

Helios 2 will be injected at 100MeV. Experiments on Helios 1 now lead us to believe that this energy is quite sufficient to accumulate the required currents of 200 - 300 mA and that our original choice of 200MeV was too conservative. Instead of the present linac we shall use a microtron as this is more compact and has better momentum definition. The microtron is now nearing completion at Scanditronix AB, Uppsala, Sweden; it has already produced currents of 15mA, comfortably in excess of the specification.

Vacuum pressures along the straights should be significantly improved by our planned use of distributed NEG pumps. The NEG strips will be mounted such that they can also be used as ion clearing electrodes. To minimize the effect of possible vacuum accidents and also facilitate Hmaintenance, vacuum valves will be fitted at each end of each straight, thereby dividing the ring into 4 sectors.

Many detailed improvements have been made in the interests of improved accessibility and maintainability. For example it will be possible to remove either of the straights

from the ring as a complete module. All key components are readily accessible.

The trend of these and other refinements to Helios 2 stem from our perception at Oxford that the physics performance of compact rings is already sufficient for the needs of the semiconductor industry. The main challenge for the future is to achieve the highest possible levels of availability and productivity, requiring up-times of 95% or better, far higher than achieved in existing storage rings.

6. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the contributions of many IBM staff at East Fishkill to the installation and commissioning process. The accelerator physics design of Helios was worked out by staff at the Daresbury Laboratory, who also made strong contributions to the commissioning. Many staff at Oxford, in addition to the authors have contributed to Helios.

7. REFERENCES

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