RECENT DEVELOPMENTS IN HELIOS COMPACT SYNCHROTRONS

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Abstract

HELIOS is a compact synchrotron radiation source, comprising two 180 degree, 4.5 T superconducting dipoles. The second machine, HELIOS 2, completed factory acceptance in September 1997 and is due to be shipped later this year to a purpose-built facility at the National University of Singapore. HELIOS 1 has been operating routinely at IBM's Advanced Lithography Facility in New York since January 1992. The two machines have the same magnetic lattice, but HELIOS 1 employs a 500 MHz RF system (16 bunches) whereas HELIOS 2 uses a 55MHz source (2 bunches). The performance of the two machines is described and compared. Both HELIOS 1 and 2 have stored over 600mA at full energy (700MeV), and the HELIOS 1 beam lifetime is now over 50 hours at 200mA.

1. INTRODUCTION

HELIOS is a compact, superconducting synchrotron light source with a very small physical footprint (6 m by 2 m). It is designed both for X-ray lithography and for general research use. The total X-ray power is 12 kW or more, centred on a critical wavelength of 0.84 nm (see Figure 1). This radiation is available at 20 separate beam ports, each with a horizontal opening angle of 60 mrad (see Table 1 for a summary of source properties).

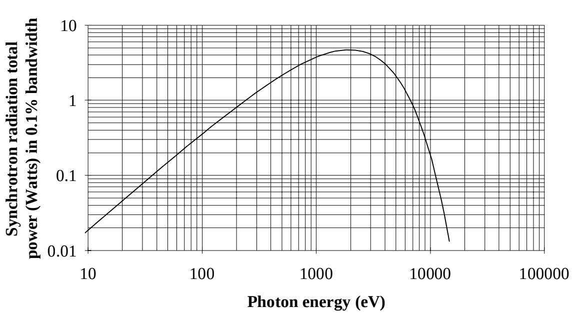

Figure 1: The power spectrum of HELIOS

HELIOS was developed by Oxford Instruments in collaboration with the CLRC Daresbury Laboratory. The first machine was delivered in 1991 to IBM's Advanced Lithography Facility (ALF) in East Fishkill, New York, where it is used primarily for research into Xray lithography for production of high density DRAM chips. The second HELIOS was commissioned in 1997 and has been purchased by the National University of Singapore. It is due to be shipped to site in late 1998, where it will become the Singapore Synchrotron Light Source (SSLS).

Table 1: HELIOS source parameters

Maximum dipole bending field, B	4.5 T
Maximum beam energy, E	700 MeV
Bending radius, ρ	0.519 m
Critical wavelength λc	0.84 nm
Critical energy Ec	1.4 keV
Number of ports	20
Horizontal port acceptance	60 mrad
Electron beam dimensions (standard tune, centre of dipole, 1 % coupling) Vertical rms electron beam size Vertical divergence (e-beam) Horizontal rms electron beam size	 0.38 mm 0.04 mrad 0.56 mm
Total Xray output power (at 300mA)	12.3 kW

Both HELIOS 1 and 2 met or exceeded all specifications, as demonstrated in Table 2. HELIOS 2 lifetime is expected to increase to HELIOS 1 levels after a year or so of operation (see Section 5).

Table 2: Primary performance indicators for HELIOS

	H1 Spec	H1 Achieved
Stored beam at injection at full energy	 200mA 200mA	 **870mA** **619mA**
Lifetime	>5 hours at 200mA	**53 hours at 200mA**
Availability	>90%	**97 %**

	H2 Spec	H2 Achieved
Stored beam at injection at full energy	 300mA 300mA	 **940mA** **600mA**
Lifetime	>10 hours at 300mA	**11 hours at 300mA**

2. OVERALL DESIGN

The overall layout is a two sector racetrack, with two 180 degree, air-cored, cold bore, 4.5 T superconducting dipoles, separated by two straight sections (see Figure 2).

The straights contain the RF cavity and conventional iron-yoked magnets. There are four quadrupoles (horizontally focusing), a normal sextupole and a skew quad. There are also vacuum components and beam diagnostics, and two pulsed injection magnets: the septum and the kicker. Injection occurs through a multishot (5 Hz), multi-turn process at 100 MeV. There is a single kicker, located opposite the injection point.

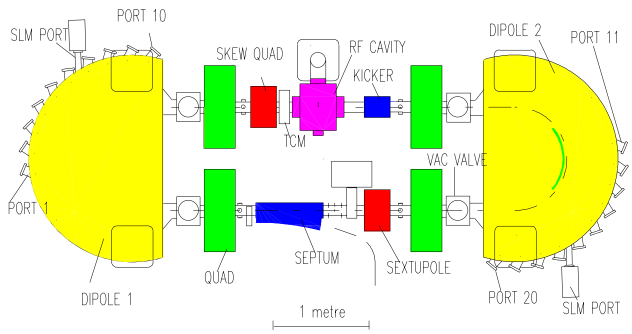

Figure 2. Schematic of HELIOS 2

In addition to the conventional quadrupoles, focusing is provided by adjustable field gradients in the dipoles. Further superconducting trim coils provide a normal sextupole field to adjust the chromaticity and radial fields for fine adjustment of the vertical closed orbit.

The minimum emittance in this simple lattice is 0.4 mm mrad. However, ALF users prefer bigger beams, and at the standard operating point the emittance is three times larger. Lattice parameters at the standard tune point are shown in figure 3. A suitably large vertical beam size is chosen by setting the skew quad current to provide an emittance coupling of about 8%.

The machine is built on a single stainless steel base frame and is relatively light (about 25 tons) and so is readily transported as an assembled and tested unit on the back of a lorry, so reducing on-site installation time.

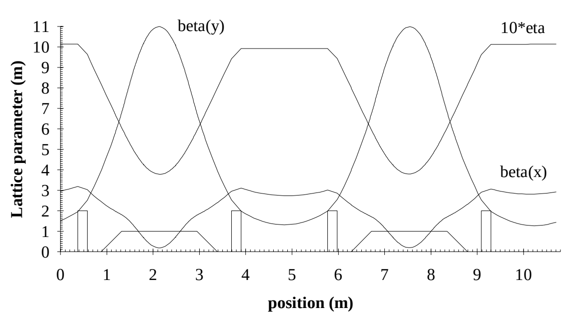

Figure 3: Lattice parameters around HELIOS

3. CHANGES IN HELIOS 2

HELIOS 2 has been designed to retain the proven performance of HELIOS 1, but significant changes have been made in the areas of the injector, vacuum system, computer controls and the RF system (see Table 3).

The new injector is a 100 MeV, 10 mA Scanditronix racetrack microtron, replacing the 200 MeV linac used in HELIOS 1. Injection in HELIOS 1 is just as reliable at 100 MeV as at 200 MeV, and the lower energy is employed in all routine operations. Good injection up to 500mA has also been demonstrated at energies as low as 72 MeV. Damping times are naturally short in a compact ring, ranging from 0.2 s (longitudinal) to 1.0 s (radial) at 100 MeV at the standard tune point.

Table 3: Comparison of Helios 1 and Helios 2

	HELIOS 1	HELIOS 2
Nominal orbit length	9.6 m	10.8 m
RF frequency, f_{RF}	499.2 MHz	55.54 MHz
Number of bunches	16	2
Injector	Linac	Microtron

The microtron injector permits a small overall footprint and provides a high quality output beam with a low emittance and small energy spread (0.1 %).

Several design modifications were made to improve access and ease of maintenance. Most significantly, vacuum valves were added to the ends of the straights to enable servicing of a straight without affecting the vacuum in the rest of the machine. As a result, the overall orbit length is increased from 9.6 m to 10.8 m.

However, the principal design change is in the RF system. RF power is provided by a 55 MHz power tetrode amplifier, instead of the 500 MHz klystron (TV transmitter) in HELIOS 1. The 55 MHz source feeds the cavity via a copper coaxial feed and a loop coupler. The cavity is electrically a 1/4 wave resonator, which is capacitively loaded to reduce its overall length to 430 mm (internal dimension).

The consequence of changing from 500 to 55 MHz is that the number of electron bunches is reduced from sixteen to two. The choice of a lower frequency was motivated by the following factors:

1. The low bunch count reduces the number of possibly dangerous coupled bunch modes.

2. The synchrotron tune is much lower (typically 0.004 instead of 0.02) which reduces the influence of synchrotron and synchro-betatron resonances.

3. The Touschek lifetime is predicted to be longer because of the increased energy acceptance and the longer bunches [1]. It has not yet been possible to confirm this prediction experimentally.

4. The 55 MHz tetrode amplifier is very tolerant to reverse power (up to 15kW). Also, a lower voltage (and so lower RF power) is required.

These factors allowed more rapid commissioning of the energy ramp in HELIOS 2. However, in terms of beam current and lifetime the performance of the two machines is very similar.

4. HELIOS 1 AVAILABILITY

The semiconductor manufacturing setting demands maximum reliability from the X-ray source and an explicit goal for the ALF facility was to demonstrate the reliability of a synchrotron in an industrial environment [2]. The reliability has been carefully measured using the semiconductor industry standards (SEMI-E10).

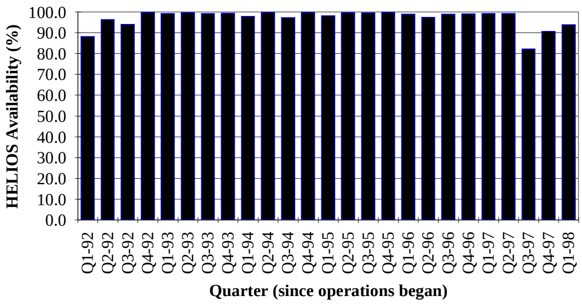

Figure 4. HELIOS 1 Availability by Quarter

Figure 4 shows HELIOS "Availability" since January 1992, by Quarter. Availability represents the time when beam is stored at full energy as a percentage of the scheduled operating hours. Time lost to building utility failures (mains power etc...) is excluded, as are start-up times and refill times *if* they do not occur during scheduled hours. *Scheduled* downtime (e.g. for preventative maintenance) is also excluded. The average quarterly availability through the six years is 97.3 %.

5. LIFETIME

Good beam lifetime implies that refills are required less often, which is important as refills result in downtime and disruption to the Users. Reducing refill frequency also leads to greater ease of operation, and helps maintain higher reliability. HELIOS 1 is often left unattended with stored beam at full energy, both overnight and even over weekends. The beam lifetime is good enough for there to be useful photon flux several *days* after the beam was first stored.

The key to the HELIOS lifetime is the high quality vacuum system. There are ion pumps on each dipole and at the centre of each straight section, but because of their "cold-bore" design there is very powerful additional cryo-pumping in the dipoles by the extensive 4.5 K surfaces.

Beam decay rate is a strong function of current. The decay rate can be fitted to:

$$\frac{-\mathrm{d}I}{\mathrm{d}t} = b_0 I + b_1 I^2 \qquad (1)$$

The instantaneous beam lifetime τ is then defined by:

$$\tau = \frac{-I\mathrm{d}t}{\mathrm{d}I} = \left(b_0 + b_1 I\right)^{-1}$$

Recent fits of HELIOS 1 lifetime give b0=0.004 /hr and b1=0.000075/hr/mA. Hence, for example lifetime is 38 hours at 300 mA, 53 hours at 200 mA and 87 hours at 100 mA.

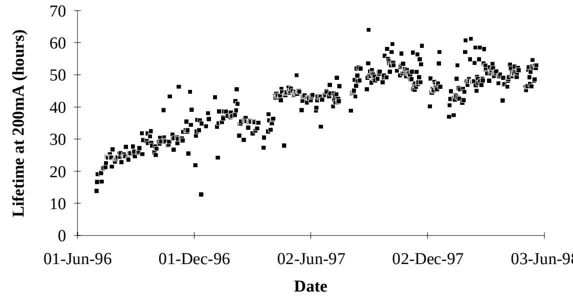

Figure 5: Change in HELIOS 1 lifetime with Date

The dependence of beam decay rate on current *squared* is due partly to the Touschek effect but primarily to the fact that the residual gas density rises linearly with stored beam. This beam induced pressure rise is caused by photodesorption which results when the Xrays strike internal water-cooled copper absorbers. The process is usually mediated by photoelectron production, which implies that the number of desorbed gas molecules is proportional to the number of incident photons, and so to beam current and energy. Significantly, desorption takes place close to where the powerful cryo-pumping is available. The probability of photodesorption reduces with integrated stored current, which means that lifetime improves significantly with time. This is demonstrated in Figure 5, which shows the HELIOS 1 lifetime since the machine was vented for a dipole upgrade to permit higher beam currents. The plot represents some 2000 Amp-hours, where 1 Amp-hour corresponds to a dose of about 10^{27} photons/m^2 incident on the absorbers.

6. SUMMARY

HELIOS 1 and HELIOS 2 have similar primary performance indicators, even though one system uses 16 bunches and the other 2. Both systems have exceeded specification for beam current and lifetime.

HELIOS 1 has been operating routinely for more than 6 years with an average availability of 97 %. HELIOS 2 has completed factory acceptance and will shortly become the Singapore Synchrotron Light Source (SSLS).

Work has begun on the design and manufacture of HELIOS 3.

7. ACKNOWLEDGEMENTS

Many more individuals at Oxford Instruments and CLRC Daresbury Lab have contributed to the success of the HELIOS project than can be listed in this paper, but their efforts are gratefully acknowledged.

8. REFERENCES

[1] N.C.E.Crosland et al "The Design of the Helios 2 compact source with a low frequency RF system", EPAC 94.p624.

[2] V.C.Kempson et al "Experience of Routine Operation of Helios 1", EPAC 94,p594.