Lifetime Studies in Helios 1

N.C.E. Crosland
Oxford Instruments Accelerator Technology Group,
Osney Mead, Oxford OX2 0DX, UK.

Abstract

Lifetime measurements are reported for full energy operation of the Helios 1 compact synchrotron at the IBM Advanced Lithography Facility in New York. The dependence of beam decay rate on current, beam size and other operational parameters is described. The development of lifetime with integrated ampere-hours is presented, and the relative contributions of loss mechanisms such as gas scattering and the Touschek effect are discussed and compared with theoretical models.

1. INTRODUCTION

HELIOS 1 is a compact (9.6 m circumference) superconducting racetrack synchrotron, designed to store electrons at up to 700 MeV and to have a small physical "footprint" of about 6 m by 2 m [1]. It produces up to 12 kW of synchrotron radiation centred on the critical wavelength of 0.84 nm.

Since January 1992 HELIOS 1 has been in routine use for X-ray lithography (primarily in research towards the production of high density DRAM chips) at IBM's Advanced Lithography Facility (ALF) in New York. High availability is demanded of a production tool in the semiconductor industry. HELIOS has been specifically designed to achieve this and has performed very successfully [2]. Electron beam lifetime is an important parameter in such an environment. In routine operations for a single shift (8–12 hours), the HELIOS beam lifetime is sufficient for a single fill to be retained for the whole day. In non-stop operation, long lifetimes result in reduced refill frequency, which leads to higher availability and greater ease of operation, and helps maintain high overall reliability.

2. DESIGN OF HELIOS

HELIOS 1 a racetrack synchrotron, consisting of two superconducting dipole magnets separated by two straight sections (see figure 1). The dipoles contain trim coils for adjusting field gradient, sextupole fields and radial fields. The straights contain the 499.7 MHz RF cavity and the conventional magnets: four horizontally focusing quadrupoles, a skew quadrupole and a normal sextupole. The straights also contain pulsed injection magnets (a septum and a fast kicker) and diagnostics, including a total current monitor (TCM), consisting of a magnetically shielded toroidal transformer head.

A high quality vacuum system is clearly essential to maximise beam lifetime. At low pressures the main pumping capacity is provided by ion pumps on each dipole and at the centre of each straight section. A very powerful additional pumping capacity is provided within the superconducting dipoles by the large (>3 m^2 area) 4.5 K surfaces. Vacuum monitoring is by ion gauges (both hot filament and cold cathode) near the centre of the straights and a residual gas analyser (RGA).

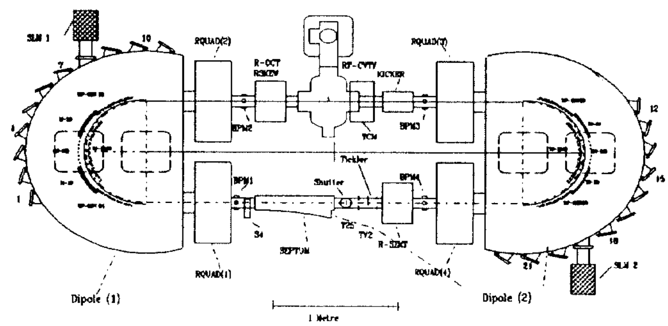

Figure 1. Schematic of Helios 1

3. LIFETIME IN HELIOS 1

3.1 Beam current dependence

Beam decay rate is a function of current. The instantaneous beam lifetime is defined by the ratio of beam current to decay rate:

$$\tau(I) = \frac{-I\,dt}{dI} \qquad (1)$$

If the decay rate is proportional to current, the instantaneous lifetime is a constant and equal to the time taken for the beam to decay by a factor of 1/e, but if it is proportional to current squared, the instantaneous lifetime is equal to the half-life.

In fact, the lifetime in HELIOS 1 shows a current dependence which is stronger than I^2. This is illustrated in figure 2, which shows reciprocal lifetime at full energy against beam current. The data are taken from three different fills in April and May 1992 The line is a fit to the data, and has the equation:

$$\frac{1}{\tau} = a_1 + a_2 I + a_3 I^2 \qquad (2)$$

The coefficients are a_1=0.0078 hr^{-1}, a_2=0.0050 $A^{-1}hr^{-1}$, a_3=1.27 $A^{-2}hr^{-1}$. The errors on the coefficients are strongly correlated, but it is clear that a_3 is non-zero (the graph is not a straight line), as it would be for a simple combination of Touschek and gas scattering lifetimes.

In summary. lifetimes are around 22 hours at 200 mA, 50 hours at 100 mA and 100 hours at 50 mA. This compares very favourably with the original HELIOS 1 specification of 5 hours at 200 mA.

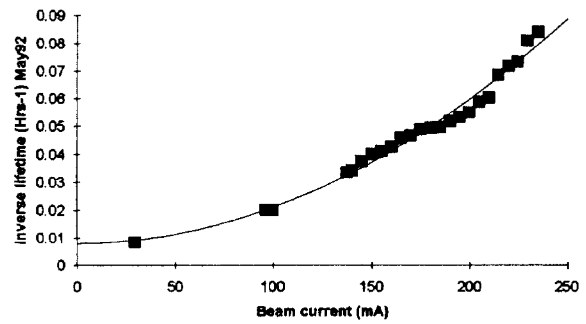

Figure 2. Instantaneous lifetime against beam current

3.2 Touschek effect

An important loss mechanism is the Touschek effect, where Coulomb scattering between electrons in a single bunch causes an electron to exceed the longitudinal momentum acceptance of the machine. Touschek lifetime is inversely proportional to the bunch density; so it is proportional to the bunch dimensions (longitudinal and transverse) and inversely proportional to the beam current.

The beam size depends on the betatron tune (primarily the radial tune), which affects both the lattice parameters and the equilibrium emittance. The minimum emittance at 700 MeV in this simple lattice is 0.4 mm mrad, but at the normal operating point the emittance is around double this. Higher emittance tune points have higher Touschek lifetimes. Intensity dependent emittance blow-up due to intrabeam scattering is significant only at low energies.

Vertical beam size is determined by the coupling between the two transverse phase spaces. Its natural value is about 1 % but it can be varied over a large range by energising the skew quadrupole. Close to a coupling resonance (i.e. where $\Delta=\nu_y-\nu_x-p\cong0$, where p an integer) the vertical beam size and divergence increase uniformly with the skew quad current.

Lifetime is a strong function of the vertical beam size, as shown in figure 3. This shows the instantaneous 150 mA lifetime against the one sigma vertical beam size at the dipoles' centre (which is where σ_y is a maximum). The solid line indicates the theoretical prediction at this tune point, assuming (arbitrarily) a constant 50 hour gas scattering lifetime. The beam size chosen during routine operations (corresponding to about 4 % coupling) is also shown.

Increasing vertical beam size and divergence causing some reduction in source brilliance. However, the Xray beam vertical divergence (usually the most important parameter) is almost unaffected. In normal operations the *maximum* electron beam vertical divergence with 4 % coupling is 0.32 mrad, which is smaller than the rms synchrotron radiation opening angle of about 0.43 mrad at the critical wavelength.

The theoretical Touschek lifetime calculations are made with the Daresbury tracking code ORBIT, which contains a fully relativistic treatment [3]. The predicted lifetimes are some 20 % shorter than those derived from computer codes which assume a non-relativistic transverse momentum (i.e. that $\gamma\sigma_x'<<1$). The agreement with experiment is quite good except at small beam sizes.

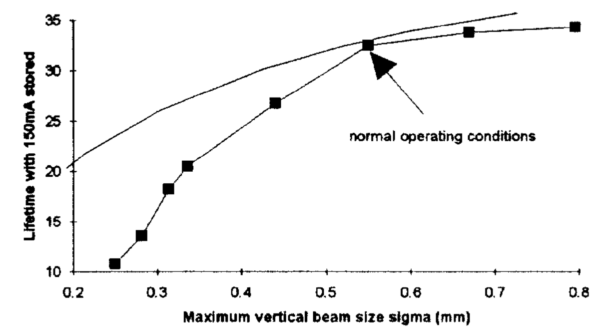

Figure 3. Instantaneous lifetime against maximum vertical beam size.

3.3 Gas scattering

Beam loss due to scattering off residual gas molecules varies with stored current and over time because there is a beam induced pressure rise.

The beam decay rate depends on the number density and type of gas molecules. The present day total pressure at the centre of the straights is estimated to be $1-1.5\times10^{-9}$ mbar for 200 mA stored beam, with $0.3-0.5\times10^{-9}$ mbar base pressure. RGA scans indicate that the base pressure is virtually all hydrogen in HELIOS 1, while with stored beam the residual gas is 10% carbon monoxide. However, by virtue of its relatively high nuclear charge, CO is around 200 times more destructive to lifetime than hydrogen.

The pressure rise is caused by synchrotron radiation induced photodesorption. 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. X-rays produced in HELIOS strike water-cooled copper absorbers. Significantly, any desorption takes place close to where the powerful cryopumping is available.

When gas scattering is the dominant loss mechanism, it follows that inverse lifetime should increase linearly with gas pressure and beam current. This was seen quite clearly in the course of the first beam cleaning runs during commissioning (figure 4). The data were collected over 5 days during which the integrated current was about 12 Ahrs. The slope of the best fit line is $0.043\ (\text{hr pbar})^{-1}$, compared with the calculated value for CO alone of $0.097\ (\text{hr pbar})^{-1}$.

The number of desorbed gas molecules created per incident photon falls with total photon dose D, so there is an improvement in lifetime and vacuum pressure with integrated stored current. For example, the pressure rises in figure 4 fit well an assumed decay of $\Delta p\propto D^{-q}$, with q=0.4.

The development of beam lifetimes at 160 mA and 190 mA with integrated current in Amp-hours (with beam stored at full energy) during the first eight months or so of normal operations are shown in figure 5. The lifetimes have been almost constant since the last point. One amp-hour in HELIOS at full energy corresponds to 10^{24} photons/m, or a dose of about 10^{27}photons/m^2 on the copper absorbers.

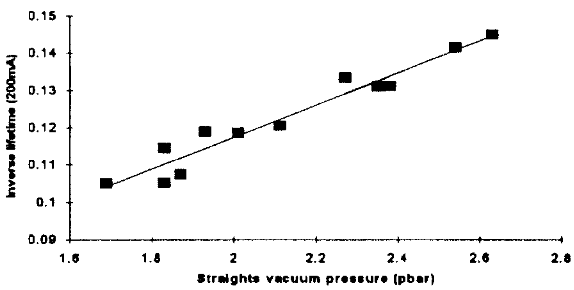

Figure 4. Development of lifetime and pressure during first period (5 days) of high current running.

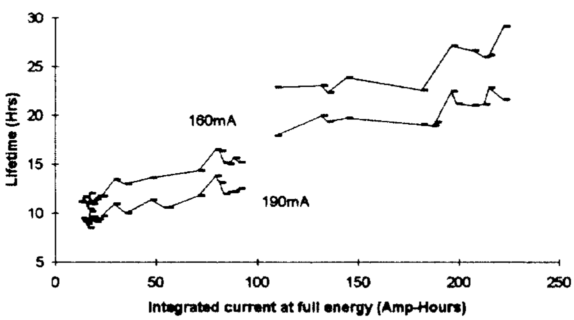

Figure 5. Development of lifetime with integrated current during first nine months of normal operations

A 50% increase in lifetime occurred following a partial warm-up of the superconducting dipoles performed during the first shutdown period (after around 100 Ahrs). This increase seems to have been the result of releasing gas molecules cryopumped on to the LHe temperature surfaces.

3.4 Ion effects

Electrons may also interact with ions captured by the beam.

Ion clearing electrodes are used in the straights. Electrodes fitted in the dipoles drew no current, probably because of the low residual gas density there. In normal conditions the lifetime is insensitive to ion clearing volts above a threshold voltage (of 200 V), and the current drawn is proportional to beam current and beam energy.

4. HELIOS 2

4.1 Vacuum system design

Because of the powerful cryopumping in the dipoles, it is believed that the gas scattering lifetime is limited by the pressure in the straights. Therefore, distributed NEG (non-evaporable getter) pumps have been added in HELIOS 2.

The NEG material, SAES St707, is used in strip form. It is built into the straight sections on electrical isolators that allow it to be baked by resistive heating and allow the strips to be used also as ion clearing electrodes (to make best use of the available space in the vacuum vessels). Six strips are used, each having a surface area of 219 cm^2.

The pressure distribution along the two straights has been modelled using a specially developed spreadsheet (EXCEL) based molecular flow model. The distributed nature of the NEG and the fact there are no conductance limitations produce a factor 5 improvement in peak pressure for reactive gas species. The improvement is greatest towards the ends of the straights, which is where the horizontal beta functions are greatest and close to where the photodesorption occurs.

4.2 RF System Design

HELIOS 2 has been designed for operation with a 55 MHz RF system, instead of the 500 MHz system used in the first machine [4].

There will be two electron bunches instead of 16. Although there are more electrons per bunch, both the bunch length and the RF bucket height are greater in the low frequency system. For a peak cavity voltage of 120 kV the RF bucket height is comparable with the energy acceptance defined by the available radial aperture (around 1.1 %).

This results in Touschek lifetimes which are a factor of 2.5 longer than those in HELIOS 1, both at injection and full energy.

The low bunch count also reduces the tendency for ions to be trapped.

5. Summary

HELIOS 1 exceeds specified 200 mA beam lifetime by a factor of more than 4. Using experience from the first machine, HELIOS 2 has been designed with the aim of achieving still longer lifetimes.

6. Acknowledgements

My thanks to the resident Oxford engineers responsible for operations and studies on HELIOS 1: A.Weger, R. Palmer and R.Webber.

7. References

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