The Design of the Helios 2 Compact Source for Operation with a Low Frequency Accelerating System

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Abstract

The compact source HELIOS 1 has a racetrack geometry with two superconducting dipoles separated by straights containing the remaining accelerator components, including a 500 MHz RF cavity. After initial commissioning at Oxford the ring was transferred to the site of the customer, IBM, where it has exceeded its design specification and is now in full operational usage as a lithography tool. Building on this success the design has been further refined to enhance its performance and a major change is the adoption of a 55 MHz RF system. The reasons for this choice and its design implications for the lattice behaviour will be discussed, together with a survey of the improved source characteristics.

1. INTRODUCTION

HELIOS is designed both for X-ray lithography and for general research use. The total X-ray output of 12 kW or more is centred on a critical wavelength of 0.84 nm and available via 20 separate beam ports.

Table 1: Main parameters for Helios 2

Maximum dipole bending field, B	4.5 T
Maximum beam energy, E	700 MeV
Bending radius, ρ	0.519 m
Nominal orbit length, C_0	10.8 m
RF frequency, f_{RF}	55.517 MHz
Critical wavelength, λ_c	0.84 nm
Injection energy, E_i	100 MeV
Number of bunches	2
Stored current at full energy	300 mA
Beam lifetime, τ	>10 hours
Emitted Xray power, P	12.3 kW
Source dimensions (dipole centre, mid tune, 2% emittance coupling):	
Vertical size	0.54 mm
Vertical divergence (e-beam)	0.05 mrad
Horizontal size	0.56 mm

HELIOS 1, the first machine in this series, is in routine operation at IBM's Advanced Lithography Facility in New York. Its performance exceeded specification in terms of beam current and lifetime, while uptime during scheduled operating hours during 1993 was greater than 99 % [1]. The design of HELIOS 2 follows the first machine quite closely, but significant changes have been made in the areas of the injector, vacuum system, control system, and particularly RF, in order to enhance performance and improve maintainability and ease of operation.

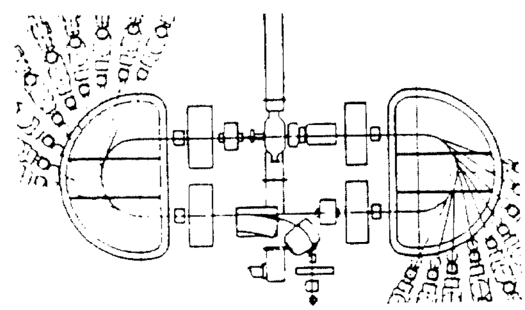


Figure 1. Schematic of HELIOS 2

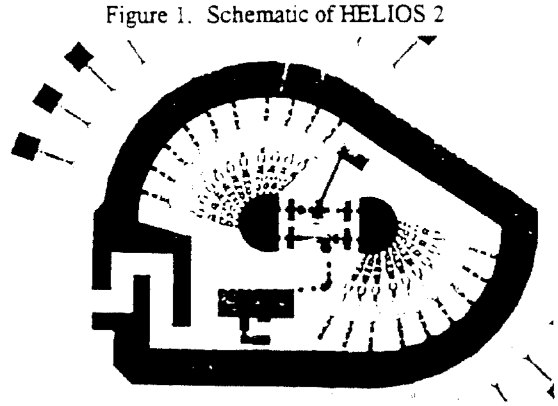


Figure 2. HELIOS and microtron inside shield enclosure.

2. OVERALL DESCRIPTION

A simplified schematic of HELIOS 2 is shown in figure 1, while figure 2 shows a compact arrangement of the ring and its microtron injector in a shield enclosure.

2.1 *Ring and lattice design*

The overall layout is a two sector racetrack, with two 180 degree, air-cored, 4.5 T superconducting dipoles. Focusing is provided by four conventional, iron-yoked quadrupoles and adjustable field gradients in the dipoles.

The minimum achievable emittance in this simple lattice is 0.4 mm mrad, although a conservative operating point is normally chosen that approximately doubles this. Lattice parameters at this mid tune point are shown in figure 3. The vertical beta function is a maximum at the dipole centres (and consequently vertical divergence is a minimum here) while β_x is a maximum at the centres of the four quadrupoles.

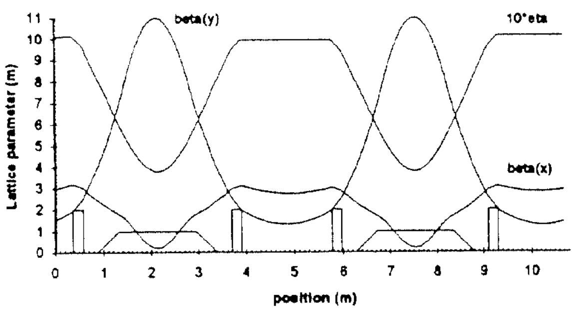


Figure 3. Lattice parameters around the ring

Detailed magnetic field measurements around the dipoles, including higher order terms, are incorporated into lattice modelling codes. The tracking routines were specially modified to include additional terms arising from the fact the amplitude of betatron oscillations is not negligible compared with the bending radius [2]. In modelling a compact source it is also necessary to take proper account of the extended fringe fields of the bending magnets, unlike the more common "hard-edged" simulations. Tracking studies were then performed to identify the best operating points and determine dynamic apertures.

The equilibrium orbit is calculated from a 3-D magnetic finite element analysis. The vertical closed orbit is particularly sensitive to the dipole alignment errors because of the large value of β_y here. The effect of dipole positions and angles on the closed orbit have been calculated in detail. For example, the effect of a dipole being 1 mm *high* is modelled in DIMAD by translating the beam down 1 mm at the dipole entrance and up 1 mm at the dipole exit. Practical experience has verified the accuracy of these models and enabled rapid correction of alignment errors once the first closed orbit measurements are made. Radial field trims built into each dipole provide fine tuning of the vertical orbit and correction for any radial field errors.

Further superconducting trim coils provide a normal sextupole field to adjust the vertical chromaticity. The conventional sextupole in the injection straight affects both vertical and horizontal chromaticities. Therefore, the chromaticities in both planes can be zeroed or, as in HELIOS 1, set slightly positive to damp the head-tail instability.

The orbit length has been increased from 9.6 m in HELIOS 1 to 10.8 m to allow the insertion of vacuum valves at the end of the straights to facilitate servicing.

2.2 *Injector*

The new injector is a 100 MeV, 10 mA Scanditronix racetrack microtron, replacing the earlier 200 MeV linac. 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.

The microtron injector allows a small overall footprint (which is especially useful in industrial settings) and provides a high quality output beam with small emittances (0.1 mm mrad specified) and energy spread (0.1 %).

Injection occurs through a multishot (up to 10 Hz), multiturn ($\approx$3) technique. A single kicker, located opposite the injection point, provides a half sine-wave, 300 ns pulse.

3. THE RF SYSTEM

RF power is provided by a 55 MHz tetrode source. The number of electron bunches is 2 (instead of 16 in HELIOS 1). The choice of a lower frequency source was motivated by the following factors:

1. The low bunch count reduces the number of possibly dangerous coupled bunch modes. It also reduces the tendency for ions to be trapped.
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 longer because of the increased energy acceptance and the longer bunches.
4. The 55 MHz tetrode amplifier is very tolerant to reverse power. Also, a lower voltage (and so lower RF power) is required.

4. BEAM LIFETIME AND CAVITY VOLTS

Beam lifetime considerations are an important factor in determining the required range of cavity volts. Long lifetimes at full energy increase machine availability and ease of operation, while at injection lifetimes of up to half an hour are useful during commissioning. The ramp from 100 to 700 MeV takes less than 3 minutes, so intermediate energy lifetimes are not crucial.

The principal loss mechanisms are gas scattering and the Touschek effect.

4.1 *Touschek lifetime*

The Touschek loss mechanism is a single, large angle, Coulomb scattering event which results in an electron's longitudinal momentum exceeding the momentum acceptance of the machine. The lifetime increases with increasing bunch volume and momentum acceptance, but is inversely proportional to the number of electrons per bunch.

Current-dependent instabilities (microwave instability, intrabeam scattering...) are very important at low energies. For a beam current of 300 mA at 100 MeV, bunch length and emittance are enhanced by factors of 6 and 35 respectively over their natural values, according to ZAP [3]. The corresponding increase in bunch volume leads to significant beneficial effects on injection energy Touschek lifetime.

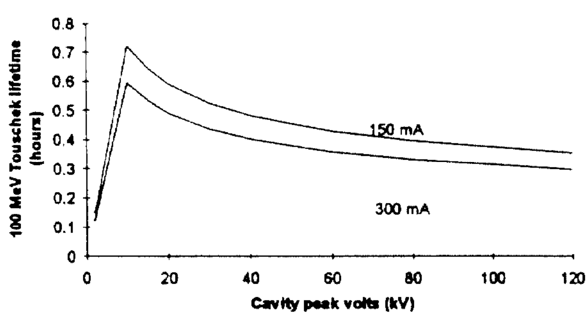
The assumption in the ZAP lifetime calculation that transverse momentum is non-relativistic (i.e. $\gamma\sigma_x' \ll 1$) is not valid in HELIOS at 700 MeV. However, a fully relativistic calculation has been incorporated into the Daresbury code ORBIT using the method outlined in [4].

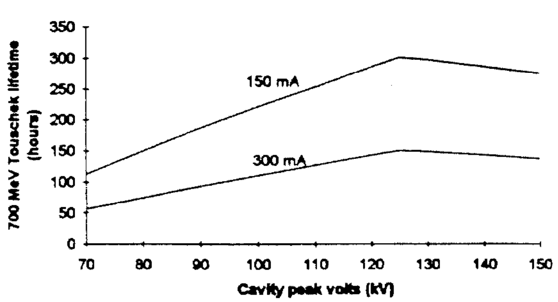
Radial apertures (physical or dynamic) present important limitations, especially at low energies. The RF bucket height is proportional to $1/\sqrt{f_{RF}}$, and so is much larger in the 55 MHz system. For high voltages, momentum acceptance is limited not by the RF voltage but by the available radial aperture. The threshold is around 10 kV at 100 MeV and 125 kV at 700 MeV, corresponding to a minimum momentum acceptance of 1.1 % Increasing cavity volts above these thresholds reduces the natural bunch length (which scales as $1/\sqrt{V}$) but does not affect the momentum acceptance, and so reduces the Touschek lifetime.

Touschek lifetime at 100 MeV against cavity volts is shown in figure 4. The data are calculated at the mid tune point referred to above, although longer Touschek lifetimes are predicted at higher emittance tune points. Emittance coupling of 5 % is assumed.

A similar graph of Touschek lifetimes at 700 MeV is given in figure 5. The value at 120 kV with 300 mA stored is 143 hours. In fact, at both injection and full energy the calculated Touschek lifetimes in are in the region of 2½ times those in HELIOS 1.

The natural emittance coupling ($\varepsilon_y/\varepsilon_x$) in HELIOS 1 at full energy is about 1 %, but it may be increased substantially using the skew quadrupole. Touschek lifetime scales as $\sqrt{\varepsilon_y}$, but practical beamlines may put an effective upper limit on vertical electron beam divergence.





Figures 4 and 5. Touschek lifetime against RF volts at 100 and 700 MeV (5% coupling, standard tune)

4.2 Gas scattering

Gas scattering primarily occurs off the *nuclei* of the residual gas, with a rate proportional to square of the atomic number. The loss mechanism is primarily elastic scattering at injection, but elastic and inelastic scattering contribute almost equally at full energy. The inelastic scattering cross-section decreases slowly with increasing energy acceptance. All cross-sections are independent of beam current, but the residual gas pressure will initially depend on beam current as a result of Xray induced photodesorption.

The ZAP calculated gas scattering lifetime at 700 MeV for 0.1 nTorr Carbon Monoxide is 80 hours. Note however that the residual gas pressure varies widely around the ring. Significantly the "cold-bore" design of HELIOS, in which cryogenic and electron beam vacuum spaces are common, provides powerful cryopumping in the dipoles, where the photodesorption takes place. Pumping in the straights has been enhanced in HELIOS 2 by adding distributed NEG (non-evaporable getter) strips.

5. Cavity Volts at Injection

Studies using Monte-Carlo techniques and single particle tracking predict an optimum injection efficiency at around 10 kV, but greater than 10 % efficiency up to 120 kV at 10 Hz injection rate. An efficiency of 10 % corresponds to a stack rate of 30 mA/s, assuming a 10 mA pulse is injected at 10 Hz over 3 turns.

With high beam currents and low cavity voltages (e.g. 300 mA, 20 kV) the beam induced voltage is dominant, and calculations indicate that Robinson type instabilities may be encountered [5]. Consequently, fast feedback electronics have been developed to allow the cavity to be operated stably at low voltages.

A linear ramp from 16 kV at 100 MeV to 120 kV at 700 MeV would maintain a constant synchrotron tune of 0.004.

6. Summary

Although HELIOS 1 is exceeding its original specifications, HELIOS 2 has been redesigned with a 55 MHz RF system, in particular to enhance performance at high beam currents. Beam trials on the new machine are scheduled to commence in mid 1995.

7. References

[1] V.C.Kempson et al "Experience of Routine Operation of Helios 1", these proceedings.

[2] C.N.Archie, J.A.Uythoven "Tracking studies for the Oxford Instruments Compact Electron Synchrotron", Proceedings of IEEE Particle Accelerator Conference 1991 (San Francisco), p1594.

[3] M.S.Zisman et al "ZAP User's Manual" Version 1-Dec-86.

[4] R.P.Walker "Calculation of the Touschek Lifetime in Electron Storage Rings" Proceedings of IEEE Particle Accelerator Conference 1987, p491.

[5] G.Saxon, private communication.