7 March 1997 SRS/APN/97/123

**Daresbury Laboratory**

**SRD Accelerator Physics Group**

# SRS Apertures I: 2GeV, No Energised Insertion Devices

Hywel Owen

**Abstract**

A review of aperture theory and lifetime for the SRS is given. A theoretical model of the SRS lattice is used to calculate the expected lifetime contributions from Touschek, inelastic and elastic scattering processes in the SRS, for both multibunch and single-bunch modes of operation. The effect of the proposed restricted aperture insertion devices is considered, and a review of experimental results is compared to the theoretical model.

## 1. Introduction

The SRS upgrade requires a reduction in the storage ring apertures to allow the magnet gaps required by the proposed insertion devices. As well as a reduction in the vertical aperture, the new insertion device vacuum chambers also require a reduced horizontal aperture to properly support the chamber structure. To ensure that the machine will operate satisfactorily - i.e. that injection and ramping can take place and that the machine will maintain a satisfactory lifetime in both modes of operation - experimental studies have been performed with the storage ring collimators set to equivalent apertures to those of the proposed ID chambers. This has shown that operation should be satisfactory with the reduced aperture vessels in place. However, it is clearly useful to be able to compare these results with a theoretical study of the SRS. This is the subject of the present paper.

## 2. The SRS Aperture Model

The SRS is a fairly complicated machine to model, as it has had several major phases of operation. Many of the vacuum vessels remain from the first lattice, SRS-1, and installation of insertion devices has resulted in a complicated aperture profile around the ring for SRS-2. Since many vacuum chambers are larger than they need to be, it was suspected that limitations on the dynamic aperture of the machine may be the limiting aperture in some sections, contrary to the situation in most modern storage rings. This of course has important implications for any theoretical estimates of lifetimes.

In order to facilitate calculations, a simplified model for the apertures around the storage ring has been used. This has been chosen to reasonably approximate the machine and at the same time allow simple comparisons of the apertures before and after installation of the ID vessels.

The SRS aperture model breaks the machine up into 4 sections, broadly speaking:
1. Dipole vessel
2. DQUD vessel
3. ID vessel
4. FQUD vessel

The vacuum aperture is assumed to be of constant dimension throughout each of the vessels. In addition, a wiggler vacuum valve further restricts the aperture at one point. The aperture model is summarised in Figure 2.1 and Table 2.1.

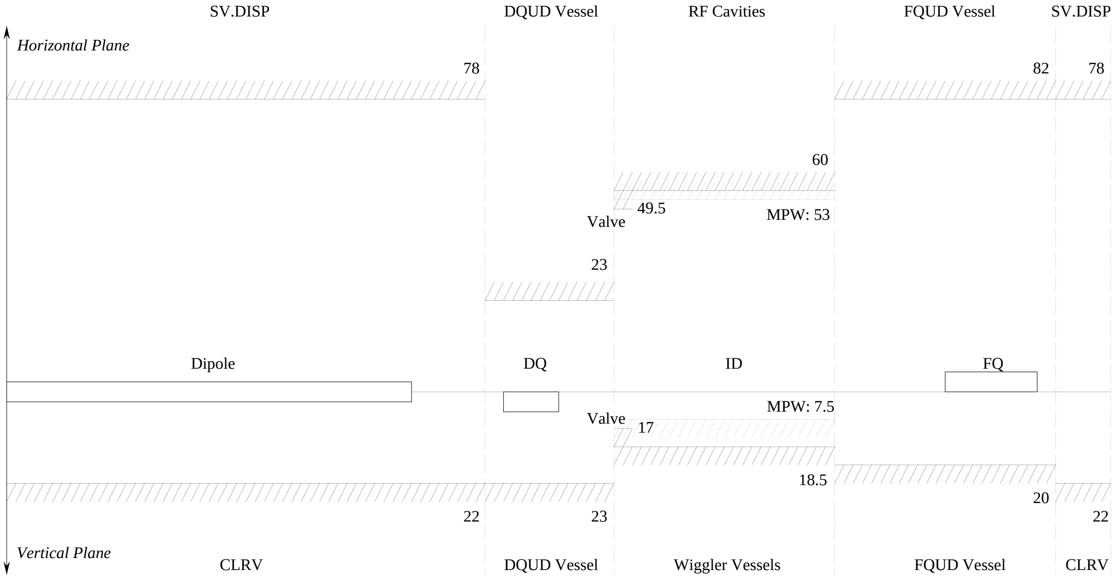


**Figure 2.1.** SRS aperture model. The new ID apertures are shown in grey.

| **Before Upgrade** | | | |
|---|---|---|---|
| **Element Name** | **Position /m** | **H Aperture /mm** | **V Aperture /mm** |
| begin | 0.0000 | 78.0 | 22.0 |
| B1 | 1.0000 | 78.0 | 22.0 |
| B2 | 2.0000 | 78.0 | 22.0 |
| B3 | 2.1880 | 78.0 | 22.0 |
| D1 | 2.5970 | 23.0 | 23.0 |
| D2 | 2.6585 | 23.0 | 23.0 |
| DQ | 2.9625 | 23.0 | 23.0 |
| D3 | 3.3220 | 23.0 | 17.0 |
| D5 | 4.0000 | 60.0 | 18.5 |
| D6 | 4.5300 | 60.0 | 18.5 |
| D8 | 5.1204 | 82.0 | 20.0 |
| FQ | 5.6146 | 82.0 | 20.0 |
| D9 | 5.7000 | 78.0 | 22.0 |
| D10/end | 6.0000 | 78.0 | 22.0 |
| **After Upgrade** | | | |
| **Element Name** | **Position /m** | **H Aperture /mm** | **V Aperture /mm** |
| begin | 0.0000 | 78.0 | 22.0 |
| B1 | 1.0000 | 78.0 | 22.0 |
| B2 | 2.0000 | 78.0 | 22.0 |
| B3 | 2.1880 | 78.0 | 22.0 |
| D1 | 2.5970 | 23.0 | 23.0 |
| D2 | 2.6585 | 23.0 | 23.0 |
| DQ | 2.9625 | 23.0 | 23.0 |
| D3 | 3.3220 | 23.0 | 7.5 |
| D5 | 4.0000 | 53.0 | 7.5 |
| D6 | 4.5300 | 53.0 | 7.5 |
| D8 | 5.1204 | 82.0 | 20.0 |
| FQ | 5.6146 | 82.0 | 20.0 |
| D9 | 5.7000 | 78.0 | 22.0 |
| D10/end | 6.0000 | 78.0 | 22.0 |

**Table 2.1.** Observation points for the aperture model and for tracking. Values which are changed after the upgrade are shown in reverse type. For the horizontal plane the minimum physical value is used (for instance in the asymmetric ID vacuum vessel).

## 3. Dynamic Aperture

Since many apertures in the machine are designed for a larger emittance lattice, it was suspected that the dynamic aperture at certain points could be smaller than the physical aperture. This has consequences for elastic gas scattering, whose scattering events make a major contribution to the overall lifetime both before and after the ID installation. To calculate the dynamic aperture, a MAD model was used with a realistic distribution of D-sextupoles (4 in the lattice).

Additionally, the dynamic aperture (maximum betatron amplitude) for off-momentum particles is also needed to calculate the momentum acceptance of the machine, which is needed to calculate the inelastic scattering lifetime and the Touschek lifetime. In this note these amplitudes for different off-momentum values will be termed the dynamic momentum acceptance. These values vary with position around the ring; conventionally, ZAP requires these values at the position in the ring of greatest dispersion, and these are the values calculated.

### *3.1 Ideal Lattice*

Tracking was performed for an ideal lattice with no errors to find the dynamic limits for particle motion around the ring. After first carefully finding the limits for particles at the start of the lattice, this maximum stable amplitude was tracked and observed around the ring at points corresponding to the aperture model (Table 2.1); direct observation is performed rather than extrapolation using the betatron functions because of the phase space distortion at these amplitudes. Comparison of the values with the physical apertures confirms that at some points the dynamic aperture is significantly smaller than the physical aperture (compare Tables 2.1 and 3.1).

| **Element** | **Position /mm** | **HIQ /mm** | | | **LOQ /mm** | | |
|---|---|---|---|---|---|---|---|
| | | **H left** | **H right** | **V** | **H left** | **H right** | **V** |
| begin | 0.0000 | 74 | 58 | 36 | 75 | 73 | 40 |
| B1 | 1.0000 | 52 | 37 | 44 | 64 | 38 | 45 |
| B2 | 2.0000 | 26 | 21 | 55 | 63 | 36 | 55 |
| B3 | 2.1880 | 21 | 19 | 57 | 62 | 32 | 57 |
| D1 | 2.5970 | 18 | 17 | 64 | 63 | 32 | 63 |
| D2 | 2.6585 | 18 | 17 | 65 | 63 | 32 | 63 |
| DQ | 2.9625 | 18 | 18 | 65 | 73 | 36 | 64 |
| D3 | 3.3220 | 34 | 25 | 58 | 74 | 36 | 57 |
| D5 | 4.0000 | 54 | 38 | 47 | 100 | 57 | 45 |
| D6 | 4.5300 | 72 | 52 | 39 | 100 | 62 | 37 |
| D8 | 5.1204 | 92 | 66 | 32 | 100 | 69 | 33 |
| FQ | 5.6146 | 92 | 65 | 32 | 100 | 69 | 33 |
| D9 | 5.7000 | 92 | 66 | 32 | 100 | 70 | 34 |
| D10/end | 6.0000 | 84 | 59 | 35 | 100 | 66 | 37 |

**Table 3.1.** Dynamic aperture for the ideal lattice, in HIQ and LOQ modes. H left and H right refer to the different maximum stable amplitudes for motions to the left (inside) and right (outside) of the lattice reference orbit.

### *3.2 Errors*

The first question is whether the model lattice working points are a good representation of the real working points. Tracking performed at slightly different working points to the nominal values shows only small changes in the maximum stable amplitudes at the start of the machine (a few percent). This is assumed to carry over to the other observation points.

Secondly, an estimate of the reduction of dynamic aperture with realistic machine misalignments is necessary to see whether misalignments are significant. The set of machine errors used was that deduced by J.Clarke from vertical dispersion measurements in LOQ [1]; these are shown in Table 3.2. Using these errors in MAD gives RMS closed-orbit deviations which are of the correct order of magnitude (see Figure 3.2). With these errors, the distribution of the horizontal dynamic aperture at the start of the lattice was calculated for 40 sample sets of random errors; this is shown in Figure 3.2. The percentage reductions are shown in Table 3.3. In each case, after applying errors to the machine, the orbit, tunes and chromaticity are corrected iteratively.

The horizontal dynamic aperture at the start of the lattice is reduced to about 80% of its value with errors applied. This is used to estimate to first order the reduction of dynamic aperture at the other points in the ring both horizontally and vertically by scaling the values found in Section 3.1.

| Element | Horizontal Error /mm | Vertical Error /mm | Rotational Error /mrad |
|---|---|---|---|
| FQ,DQ | 1.5 | 1.0 | 1.0 |
| FS,DS | 1.5 | 1.0 | 1.0 |
| Dipole | 0.0 | 0.0 | 1.0 |

**Table 3.2.** Errors used in the MAD model to estimate the dynamic aperture reduction.

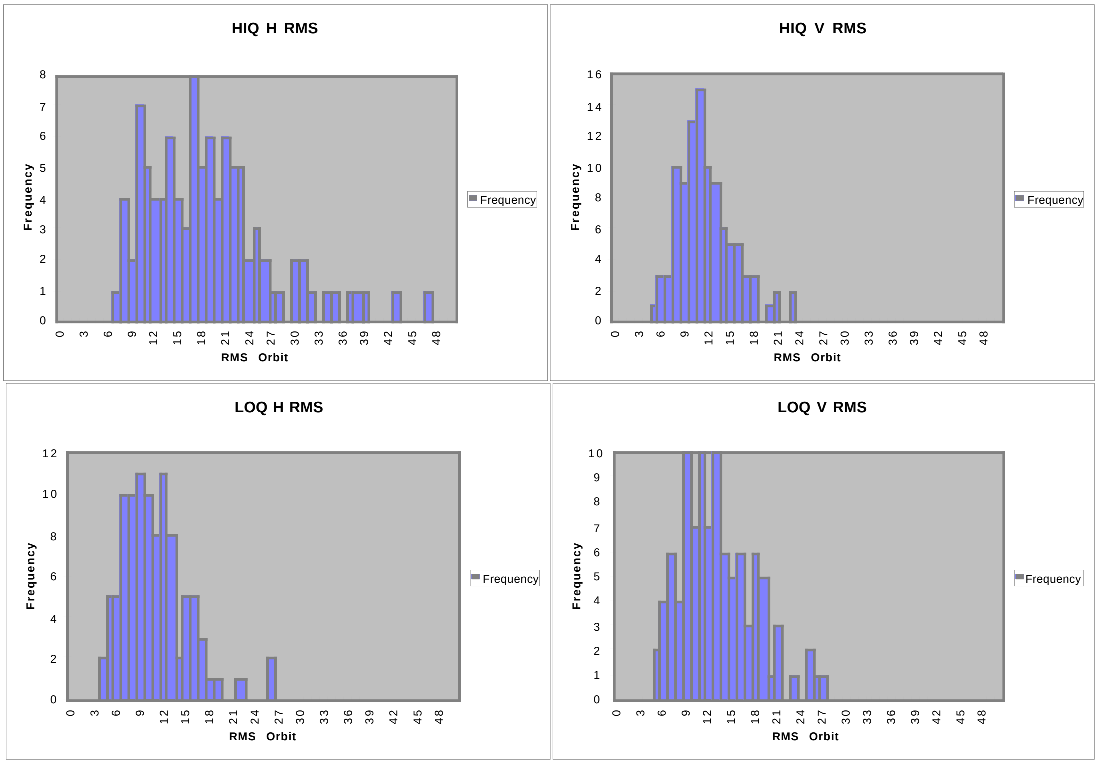


**Figure 3.1.** Distribution of RMS closed-orbit deviations in HIQ and LOQ for 40 sample sets of random errors. The order of magnitude of the RMS errors is correct, which is sufficient for a first-order calculation of dynamic aperture effects.

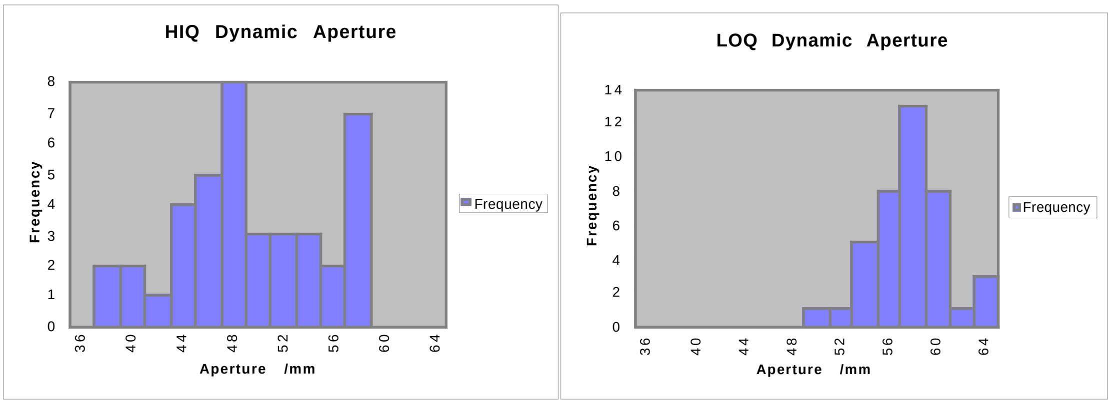


**Figure 3.2.** Distribution of horizontal dynamic apertures at the start of the lattice for 40 sample sets of random errors.

| Machine Mode | HIQ | LOQ |
|---|---|---|
| No Errors | 58 | 73 |
| With Errors | 49.0 | 57.3 |
| Fractional Reduction | 0.84 | 0.78 |

**Table 3.3.** Reduction of horizontal dynamic aperture at the start of the lattice in HIQ and LOQ with machine misalignments. The dynamic apertures are given in mm.

*3.3 Dynamic Momentum Acceptance*

The dynamic momentum acceptance was calculated at the position of maximum dispersion (roughly at the centre of the F-Quadrupole in both machine modes). This was done by observing the maximum stable off-momentum amplitude for particles started at that point. These values are shown in Table 3.4 for the ideal machine, and have been scaled using the values from Section 3.2 to approximate the effects of machine errors. These values were then used in the ZAP Touschek calculations.

| dp/p /% | HIQ | | LOQ | |
|---|---|---|---|---|
| | Ideal /mm | With Errors /mm | Ideal /mm | With Errors /mm |
| -0.05 | 0 | 0 | 0 | 0 |
| -0.04 | 0 | 0 | 20 | 15.6 |
| -0.03 | 8 | 6.72 | 30 | 23.4 |
| -0.02 | 12 | 10.08 | 30 | 23.4 |
| -0.01 | 18 | 15.12 | 32 | 24.96 |
| 0.00 | 16 | 13.44 | 30 | 23.4 |
| 0.01 | 10 | 8.4 | 20 | 15.6 |
| 0.02 | 6 | 5.04 | 2 | 1.56 |
| 0.03 | 0 | 0 | 0 | 0 |
| 0.04 | 0 | 0 | 0 | 0 |
| 0.05 | 0 | 0 | 0 | 0 |

**Table 3.4.** Dynamic momentum acceptance in HIQ and LOQ for the ideal lattice and for the error reductions of Section 3.2.

## 4. Lifetime Contributions at 2GeV

*4.1 Introduction*

The total beam lifetime is given by the contributions of several effects. For the SRS at 2GeV with normal operating apertures (i.e. without scrapers in place) some of these effects are negligible and can be neglected. This is summarised in Table 4.1.

| Type | Sub-type | Process | Contributions | Significant |
|---|---|---|---|---|
| Beam-Beam | | Touschek | Phys/RF/Dyn | Yes |
| Beam-Gas | Inelastic Beam-Nucleus | B - Inelastic/ Bremsstrahlung | Phys/RF/Dyn | Yes |
| | Elastic Beam-Nucleus | C - Coulomb | Phys/Dyn | Yes |
| | Inelastic Beam-Electron | I - Inelastic Eln. | Phys/RF/Dyn | Yes |
| | Elastic Beam-Electron | E - Elastic Eln. | Phys/RF/Dyn | Yes |
| Quantum | | Quantum Effect | Phys/RF | No |

**Table 4.1.** Summary of beam loss processes in electron storage rings. Contributions can be from Physical aperture limits, RF aperture limits, and Dynamic aperture limits. Quantum lifetime effects are negligible if both the RF aperture and physical aperture have sensible values.

The nature of the processes are:

- *Touschek Scattering (T).* Single inelastic scattering of beam electrons off each other; the beam electron is lost if its momentum deviates beyond the smallest momentum aperture limit of the machine. A weighted average is calculated using ZAP.
- *Bremsstrahlung (B).* Single inelastic scattering of beam electrons off residual gas nuclei, the energy loss producing electromagnetic radiation. Again, the beam electron is lost if its momentum deviates beyond the momentum aperture limit. This process is also often called inelastic gas scattering.
- *Coulomb Scattering (C).* Single elastic scattering of beam electrons off residual gas nuclei. The beam electron is lost if its induced betatron amplitude is greater than the smallest amplitude aperture limit of the machine. Since the betatron tunes are fractional and a typical scattered beam electron executes many oscillations before synchrotron radiation damps it back to the equilibrium beam emittance, it will obtain its maximum betatron amplitude at every point around the lattice. The beam electron will be lost at the most restrictive point; this is described more fully below. For the case of dynamic aperture limitation, the appropriate aperture limit is the largest value of $x$ regardless of the value of $x'$ (see Figure 4.1). This process is also often called elastic gas scattering.
- *Inelastic Scattering (I).* Single inelastic scattering of beam electrons off electrons in the residual gas. Photons are emitted in this process.
- *Elastic Scattering (E).* Single elastic scattering of beam electrons off electrons in the residual gas. This effect is analogous to Coulomb scattering, but is of a much smaller strength.
- *Quantum Effect (Q).* The other scattering processes assume an effectively zero emittance. The quantum effect arises because of the finite emittance of the beam, which produces a Gaussian distribution of particles in phase space, both transverse and longitudinal. Particles which lie in the tails of these distributions are lost because of amplitude or momentum restrictions upon the beam, from the same effects as with the other processes, i.e. physical, RF and dynamic aperture limits. Redistribution of particles in the remaining core of the beam leads to a continuous loss of electrons. However, the loss rates from the quantum effect are vanishingly small unless the restricting apertures lie within $6\sigma$ of the beam origin position (where $\sigma$ is the standard deviation of the Gaussian distribution in the appropriate co-ordinate). The RF and momentum apertures are always much larger than this in any sensible machine, whilst the physical aperture limit is negligible unless it is extremely small (of the order of a millimetre). This effect can therefore be neglected for any sensible operating machine. Under special conditions (very small jaw experiments), however, it must be taken into account.

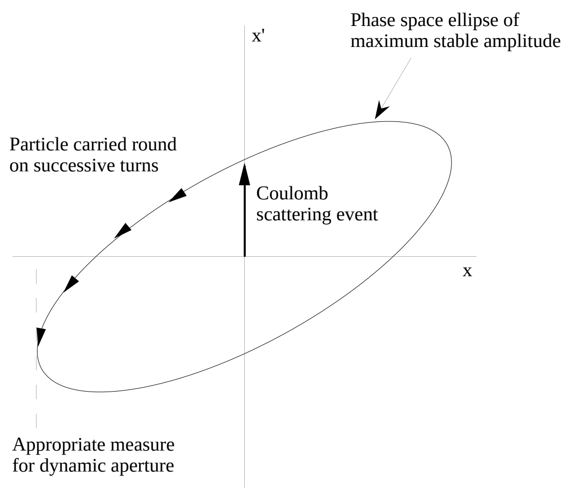


**Figure 4.1.** In a Coulomb scattering event, where the particle is scattered to its largest stable amplitude, the particle's phase space coordinate is moved vertically from an initial position approximately at the origin. Successive turns carry its coordinate around until it reaches the extremum point in $x$ shown in the figure. This is the equivalent position for a physical limit which would just obstruct a particle. This measure of the dynamic aperture is therefore the appropriate one to use to describe a dynamic limiting aperture for Coulomb scattering.

*4.2 Calculation Methods*

To calculate the B,C,I,E effects (see above), we first need a Touschek calculation using ZAP to determine the momentum aperture of the machine from its machine functions. As a reasonable approximation to the lattice, the lattice functions and apertures at the observation points of Table 2.1 were used as an input. The files are given in the Appendix.

However, to get a decent Touschek calculation we first need to know how much bunch lengthening we expect from instabilities, such as the microwave bunch lengthening, and whether in any modes there is significant emittance blow-up from intra-beam scattering (IBS). IBS comes about in bunches with high electron densities (high currents/single bunches). Multiple small-angle Coulomb scattering causes an average diffusion of the particles, which adds to the effects of quantum excitation and transverse damping to increase the equilibrium (natural) emittance. Typical equilibrium values in HIQ and LOQ modes from instabilities and IBS are necessary for a sensible estimate of the Touschek lifetime. Emittance coupling is also an important factor in estimating Touschek lifetimes.

In the following calculations, the methods used in S.L.Smith’s DIAMOND note are followed (DPG/96/48). Firstly, single bunch threshold calculations are performed, followed by a calculation of longitudinal parameters for the four combinations of microwave instability on/off and potential well distortion on/off.

*4.3 Coupling*

Coupling obviously affects both IBS and the Touschek lifetime. Since it has a variable value in LOQ single-bunch operation, assigning a ‘theoretical’ value is complicated by knowing what it is in the first place. However, ‘worst-case’ values can be readily calculated since it is known that in both HIQ and LOQ the ‘natural coupling’ far from a resonance is about 2.5%.

At larger coupling values, the Touschek lifetime is estimated from the coupling derived from beam size measurements; from this can be derived a table of values for different bunch currents and coupling. This is most conveniently expressed in terms of the current-lifetime product for different coupling strengths.

*4.4 LOQ Calculations at 2GeV*

The 2 GeV calculation is fairly straightforward as the effects of potential well distortion (PWD), microwave bunch lengthening (MBL) and IBS are small.

In LOQ, the bunch length is insensitive to both PWD and MBL for wide ranges of bunch currents, the natural bunch length of 20.4 mm being unaffected by any significant amount up to 80mA of bunch current. Instability thresholds are similarly very high. IBS has little effect at an assumed coupling of 2.5%, and so will be negligible at larger coupling values. The use of apertures determined assuming errors has no effect upon the momentum aperture calculations, and lifetime calculations are therefore fairly straightforward. Touschek lifetimes are shown for single-bunch and multibunch cases in Tables 4.2 and 4.3. Current-lifetime products for these cases are shown in Table 4.4.

| **Current /mA** | **LOQ Multibunch Touschek Lifetime /Hours** |
|---|---|
| 50 | 1263 |
| 100 | 631 |
| 150 | 421 |
| 200 | 316 |
| 250 | 253 |
| 300 | 210 |

**Table 4.2.** Multibunch Touschek lifetimes in LOQ. Note that these assume 2.5% emittance coupling. Larger coupling, such as in the real machine at an operational working point, will give larger Touschek values.

| Current /mA | LOQ Single-Bunch Touschek Lifetime /Hours |
|---|---|
| 5 | 78.9 |
| 10 | 39.5 |
| 20 | 19.7 |
| 30 | 13.2 |
| 40 | 9.9 |
| 50 | 7.9 |
| 60 | 6.6 |
| 70 | 5.6 |
| 80 | 4.9 |
| 90 | 4.4 |
| 100 | 3.9 |

**Table 4.3.** Single-Bunch Touschek lifetimes in LOQ. Note that these assume 2.5% emittance coupling. Larger coupling, such as in the real machine at an operational working point, will give larger Touschek values.

| Mode | Current-Lifetime Product /mAHours |
|---|---|
| LOQ Single-Bunch | 394 |
| LOQ Multibunch | 63140 |

**Table 4.4.** Current-Lifetime products for the Touschek lifetimes in LOQ single-bunch and LOQ multibunch. Note the multibunch value is 160 times the single-bunch value (the harmonic number).

To calculate the effect at different coupling values, ZAP is again used. Remembering that the vertical and horizontal emittances are given by

$$\varepsilon_y = \frac{\chi\varepsilon}{1+\chi}, \quad \varepsilon_x = \frac{\varepsilon}{1+\chi} \tag{4.1}$$

where $\varepsilon$ is the natural emittance and $\chi$ is the emittance coupling, the Touschek current-lifetime products are readily calculated, and are shown in Table 4.5.

| Coupling /% | Current-Lifetime Product /mAHours |
|---|---|
| 1 | 244 |
| 2.5 | 383 |
| 5 | 524 |
| 10 | 703 |
| 20 | 900 |
| 50 | 1090 |
| 100 | 1100 |

**Table 4.5.** Touschek current-lifetime products for varying emittance coupling.

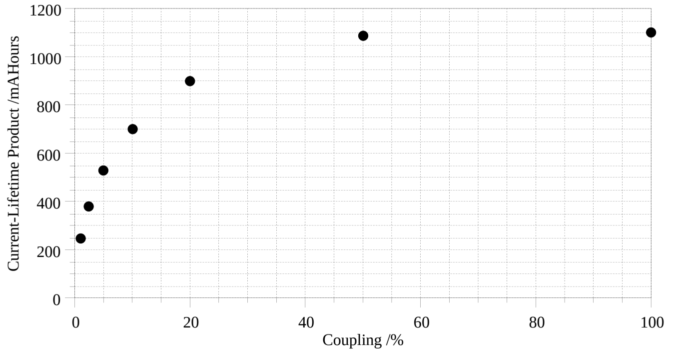


**Figure 4.2.** Touschek current-lifetime products for varying emittance coupling.

To calculate the B,C,I,E beam-gas scattering effects, the momentum aperture calculated using ZAP is used; the appropriate value is the lower of the RF aperture and the dynamic momentum acceptance. In LOQ, the dynamic momentum acceptance has a value of 1.13% whilst the RF provides 0.56% at 1.3MV; the latter value is therefore used. Using Microsoft Excel the four contributions were calculated for a range of machine pressures. These results are summarised in Figure 4.3. What is surprising is the significant effect of scattering from electrons in the residual gas, whose lifetime is smaller than expected. Typically the scattering from electrons is neglected in an estimation of the beam-gas lifetimes, but these calculations show that it should be taken into account.

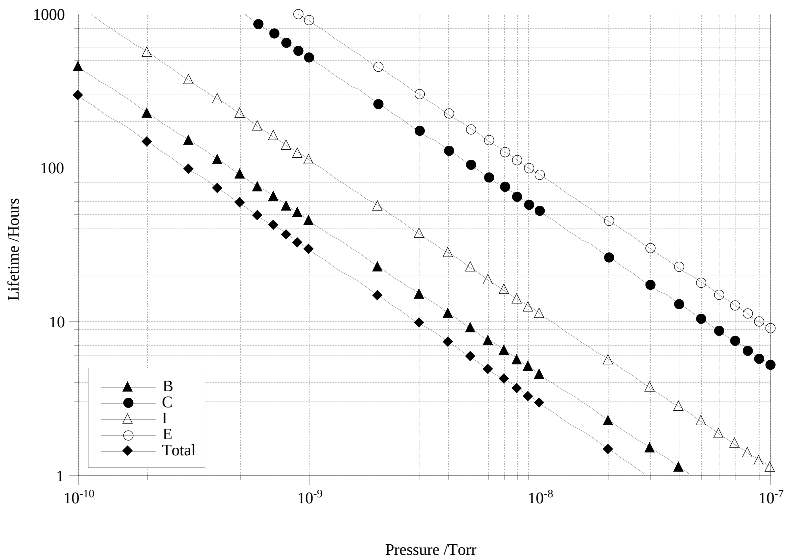


**Figure 4.3.** Beam-gas lifetime contributions at 2GeV in LOQ. At 1 nTorr, for instance, the total predicted lifetime from beam-gas scattering is 29.5 hours.

*4.5 HIQ Calculations at 2GeV*

The HIQ 2GeV case is simpler than LOQ: firstly, single-bunch calculations are unnecessary, and secondly, the emittance coupling is effectively constant (again at around 2.5%). However, the assumption of the errors above does reduce the dynamic momentum acceptance calculation, reducing it from 0.757% to 0.646%; since the RF aperture from 1.3MV is 0.80% in HIQ, this affects the overall momentum aperture for beam-gas scattering. This translates to a small reduction in the beam-gas lifetimes; for instance, at 1nTorr, the lifetime from Bremsstrahlung reduces from 49 to 47 hours.

In HIQ, the bunch length is again insensitive to both PWD and MBL for a wide range of bunch currents, although the bunch current limits before modification occurs are lower than in LOQ. In multibunch, the effect is small up to well over 400mA of current. Touschek lifetimes are shown in Tables 4.6 and 4.7.

| **Mode** | **Current-Lifetime Product /mAHours** |
|---|---|
| HIQ MB No Errors | 29050 |
| HIQ MB With Errors | 22700 |

**Table 4.6.** Current-Lifetime products for the Touschek lifetimes in HIQ multibunch, with and without errors.

| Current /mA | HIQ No Errors /Hours | HIQ With Errors /Hours |
|---|---|---|
| 50 | 581 | 452 |
| 100 | 290 | 226 |
| 150 | 194 | 151 |
| 200 | 145 | 113 |
| 250 | 116 | 91 |
| 300 | 97 | 75 |
| 350 | 83 | 65 |
| 400 | 73 | 57 |

**Table 4.7.** Multibunch Touschek lifetimes in HIQ, with and without machine errors included. Note that these assume 2.5% emittance coupling.

Beam-gas scattering is affected by whether or not machine errors are taken into account, as the momentum aperture is larger in the ideal machine. Beam-gas scattering lifetimes are shown in Figure 4.4.

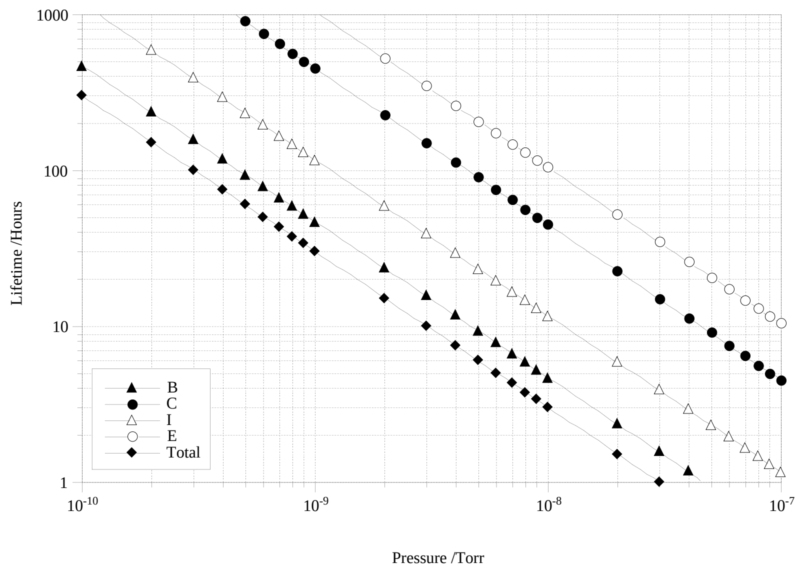


**Figure 4.4.** Beam-gas lifetime contributions at 2GeV in HIQ; there are only small differences between the cases of with and without errors (with errors is shown). At 1 nTorr, for instance, the total predicted lifetime from beam-gas scattering is 30.5 hours (with errors assumed).

### *4.6 2 GeV Conclusions*

The calculations above allow a prediction of the beam lifetime for different beam conditions. The first thing to note is that the Touschek contribution to the lifetime is important even in multibunch operation, and that dynamic apertures have a significant effect upon it. If dynamic aperture limits are not included in HIQ, for example, the Touschek lifetime rises to 100 hours at 300mA multibunch current. Even more important is the effect upon momentum acceptance: in HIQ, dynamic aperture limits the momentum acceptance to around 0.7 %, in comparison to the 2.49% acceptance provided by the vacuum apertures and 0.8% provided by the RF. This of course has an effect upon the beam-gas scattering lifetimes; for instance, at 1nTorr, the lifetime from beam-gas scattering is reduced from around 45 hours to 30 hours. In LOQ the effect is masked by the RF aperture being the limiting aperture.

## 5. Prediction of Effect of Reduced Aperture ID Vessel Upon 2GeV Lifetime

### *5.1 Calculations*

The reduced aperture of the new ID vessels has two effects. Firstly, the horizontal aperture reduction reduces the Touschek lifetime and reduces the momentum aperture of the machine (affecting the B,I,E beam-gas lifetimes). Secondly, the vertical aperture reduction reduces the Coulomb Scattering lifetime.

In the SRS aperture model, the horizontal aperture is assumed to reduce in all places around the ring when the IDs are installed, when in reality the maximum number will be 3. Since the Touschek lifetime is calculated as a weighted average around the ring, this should be taken into account. However, since the starting model is a broad approximation anyway, the errors in it far outweigh the assumption that the reduced aperture is only present in some straights of the ring. What this means for calculations is that the real Touschek lifetime would be expected to be larger than the value which is calculated. For beam-gas scattering calculations, it is irrelevant whether the reduced apertures are present in all or only several of the straight sections - the effect will be the same.

Repeating the ZAP calculations of the previous section, it is found that the reduction of the horizontal aperture by the introduction of IDs has no effect upon either the Touschek lifetime or the momentum acceptance, also meaning that the B,I,E lifetimes will remain constant. Therefore, *the only effect upon the lifetime from the new IDs at 2GeV will be due to the reduced vertical aperture of the vacuum chamber*. This confirms what had been thought previously.

The change in the Coulomb scattering contribution is easily calculated; the results are summarised in Figures 5.1 to 5.4.

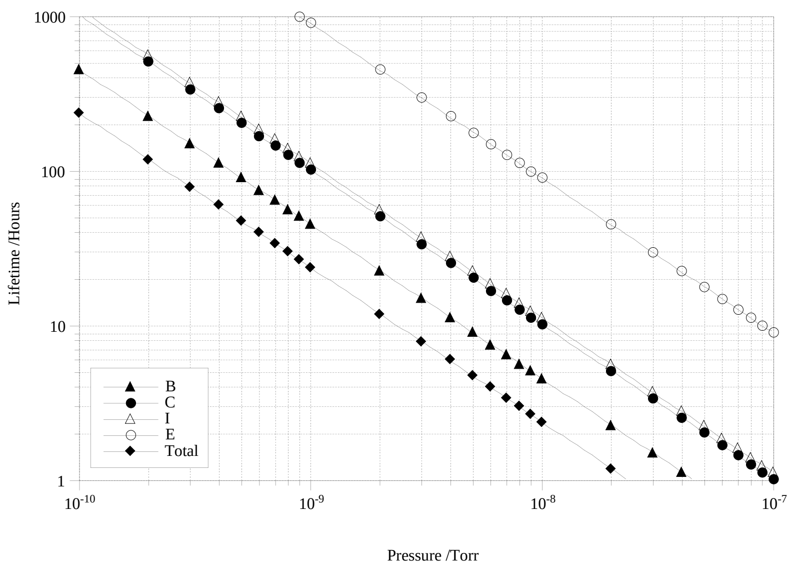


**Figure 5.1.** Beam-gas lifetime contributions at 2GeV in LOQ after the ID vacuum chamber installation. At 1 nTorr, for instance, the total predicted lifetime from beam-gas scattering is 24.0 hours.

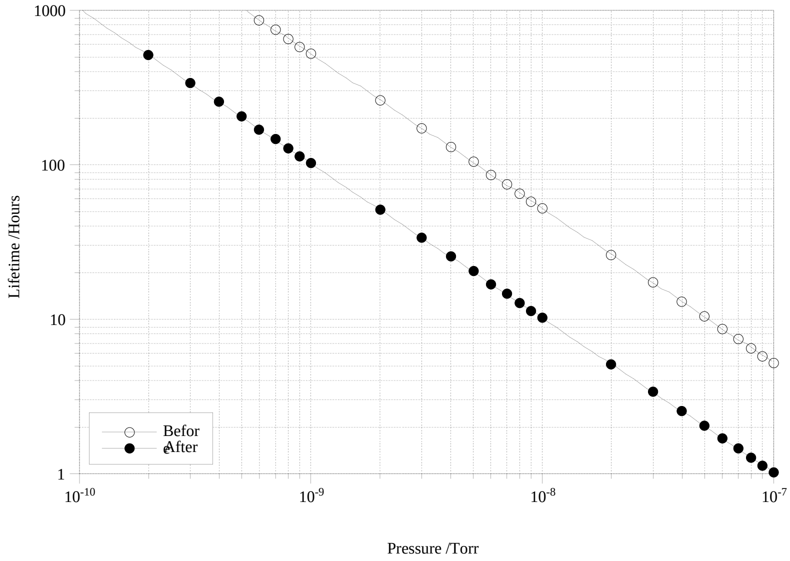


**Figure 5.2.** Coulomb scattering contributions to the lifetime at 2GeV in LOQ before and after the ID vacuum chamber installation. At 1 nTorr, for instance, the total predicted lifetime from Coulomb scattering drops from 524 hours to 102 hours. Although this sounds alarming, it simply signifies that the Coulomb scattering has become significant after the ID installation.

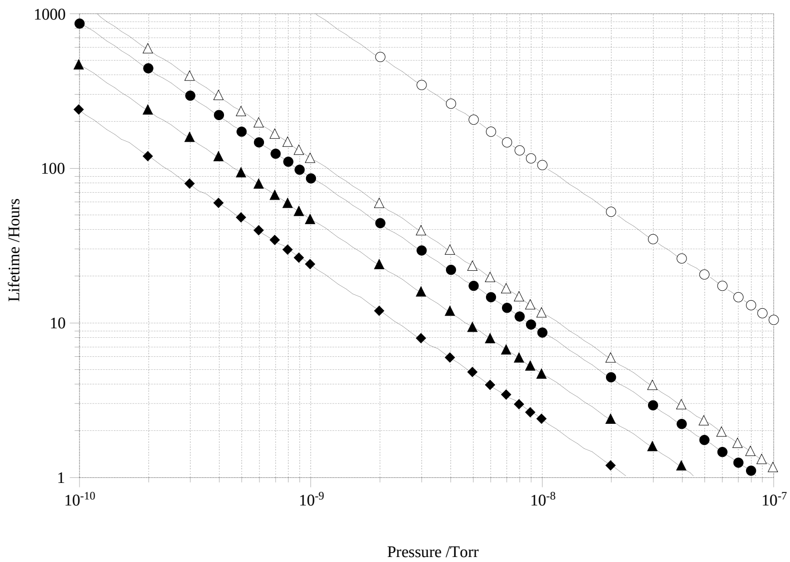


**Figure 5.3.** Beam-gas lifetime contributions at 2GeV in HIQ after the ID vacuum chamber installation. At 1 nTorr, for instance, the total predicted lifetime from beam-gas scattering is 23.7 hours (with errors assumed as in the previous section).

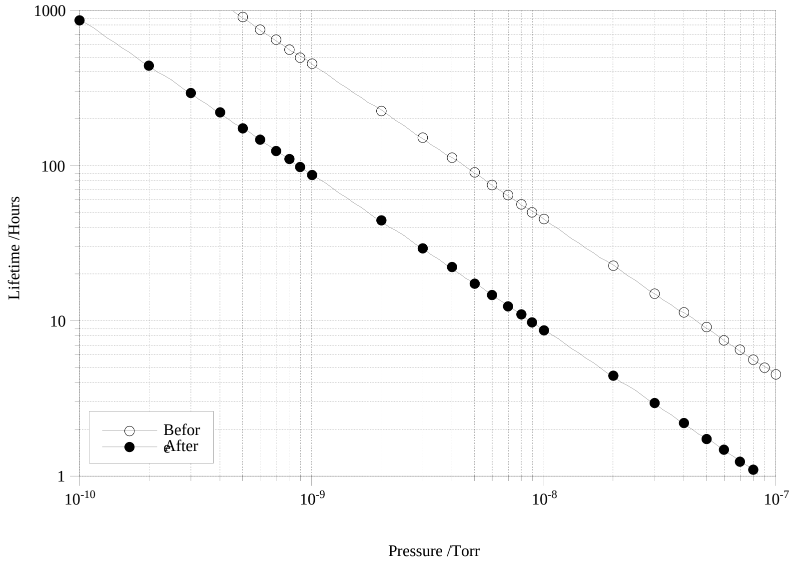


**Figure 5.4.** Coulomb scattering contributions to the lifetime at 2GeV in HIQ before and after the ID vacuum chamber installation. At 1 nTorr, for instance, the total predicted lifetime from Coulomb scattering drops from 451 hours to 88 hours. Again, this signifies that the Coulomb scattering has become significant after the ID installation.

*5.2 Conclusions*

Overall, the above calculations allow us to predict the total beam lifetime given the machine pressure, assuming that the beam is steered to be flat. The results are summarised in Tables 5.1 and 5.2.

| Mode | Before | After |
|---|---|---|
| **LOQ** | 29.5 | 24.0 |
| **HIQ** | 30.5 | 23.7 |

**Table 5.1.** Total beam-gas lifetimes before and after ID installation at a machine pressure of 1nTorr. It is assumed that the beam orbit is flat.

| Mode | Multibunch | Single Bunch |
|---|---|---|
| **LOQ** | 63140 | 390 |
| **HIQ** | 22700 | - |

**Table 5.2.** Touschek current-lifetime products for different modes, assuming 2.5% machine coupling. The lifetimes before and after ID installation are the same, assuming the beam orbit is flat.

The predicted total lifetimes as a function of pressure (at a fixed current) and as a function of current (at a fixed pressure) are shown in Figures 5.5 to 5.11. Representative values of 200mA multibunch current, 25mA single bunch current, and 1nTorr pressure have been used in the calculations. 2.5% coupling is assumed throughout.

As expected, the predicted reductions in 2GeV lifetimes correspond well with what has been observed experimentally, i.e. the reduction is at about the 15% level.

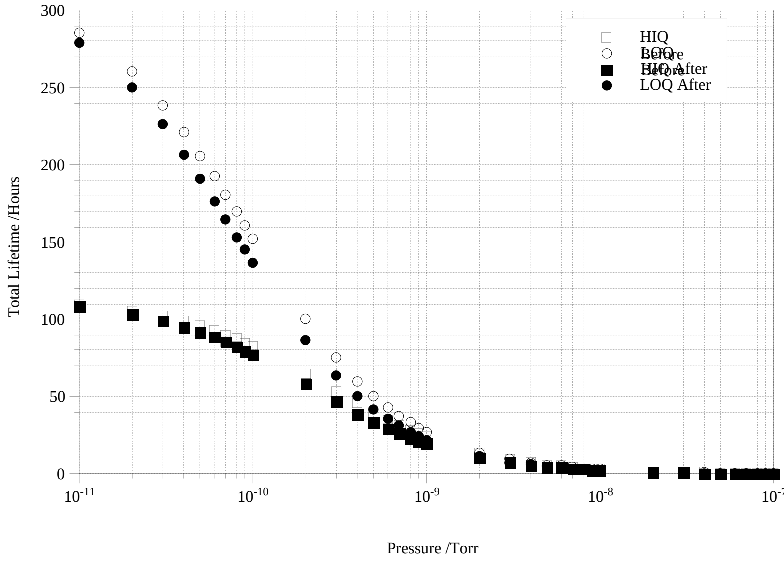


**Figure 5.5.** Predicted lifetime as a function of pressure in multibunch mode, in HIQ and LOQ before and after the ID installation. 200 mA current is assumed. The total lifetime tends to the value of the Touschek lifetime at low pressures.

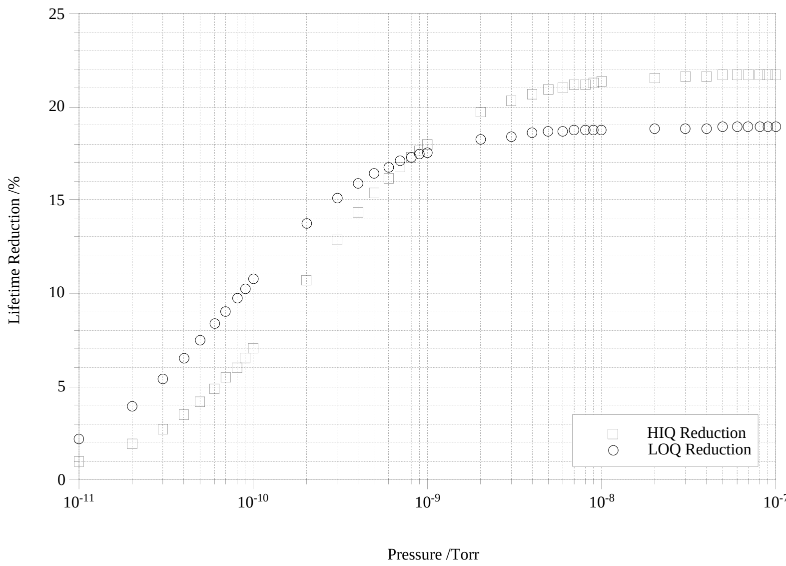


**Figure 5.6.** Predicted percentage reduction in lifetime due to the ID installation, as a function of pressure in multibunch mode (HIQ and LOQ). 200 mA current is assumed. Since the lifetime at low pressures is Touschek-dominated, the reduction tends to zero in this limit. At high pressures, the reduction tends to a constant value determined by the ratio of limiting vertical apertures. Since the vertical beta-functions are similar in HIQ and LOQ, these have a similar value.

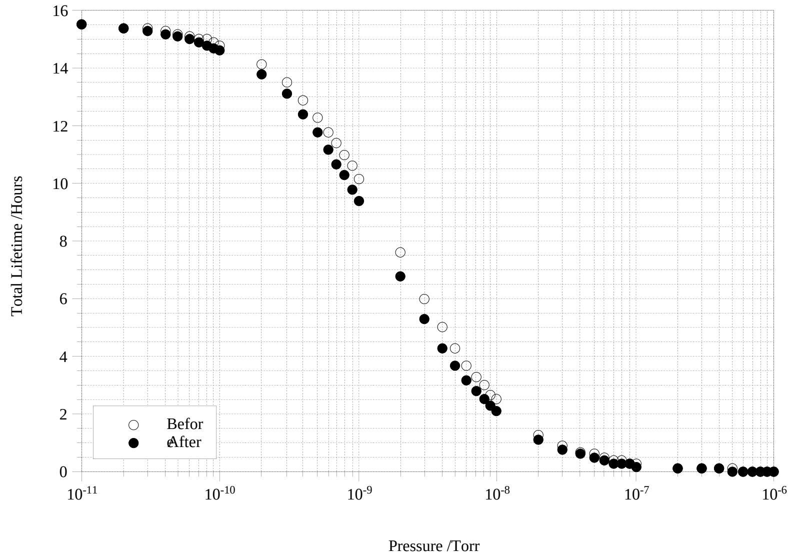


**Figure 5.7.** Predicted lifetime as a function of pressure in single bunch mode, before and after the ID installation. 25 mA current is assumed. At low pressures the total lifetime tends to the Touschek lifetime as gas scattering becomes small.

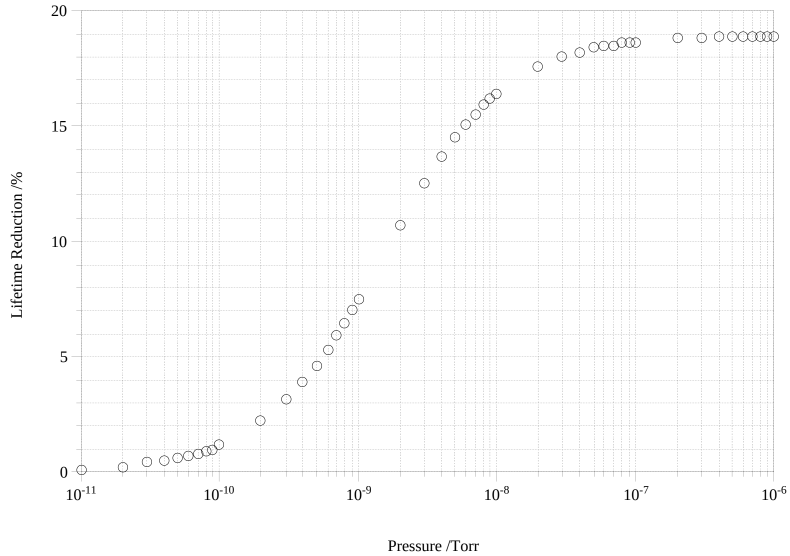


**Figure 5.8.** Predicted percentage reduction in lifetime due to the ID installation, as a function of pressure in single bunch mode. 25 mA current is assumed. As in multibunch, since the lifetime at low pressures is Touschek-dominated, the reduction tends to zero in this limit. At high pressures, the reduction tends to a constant value determined by the ratio of limiting vertical apertures.

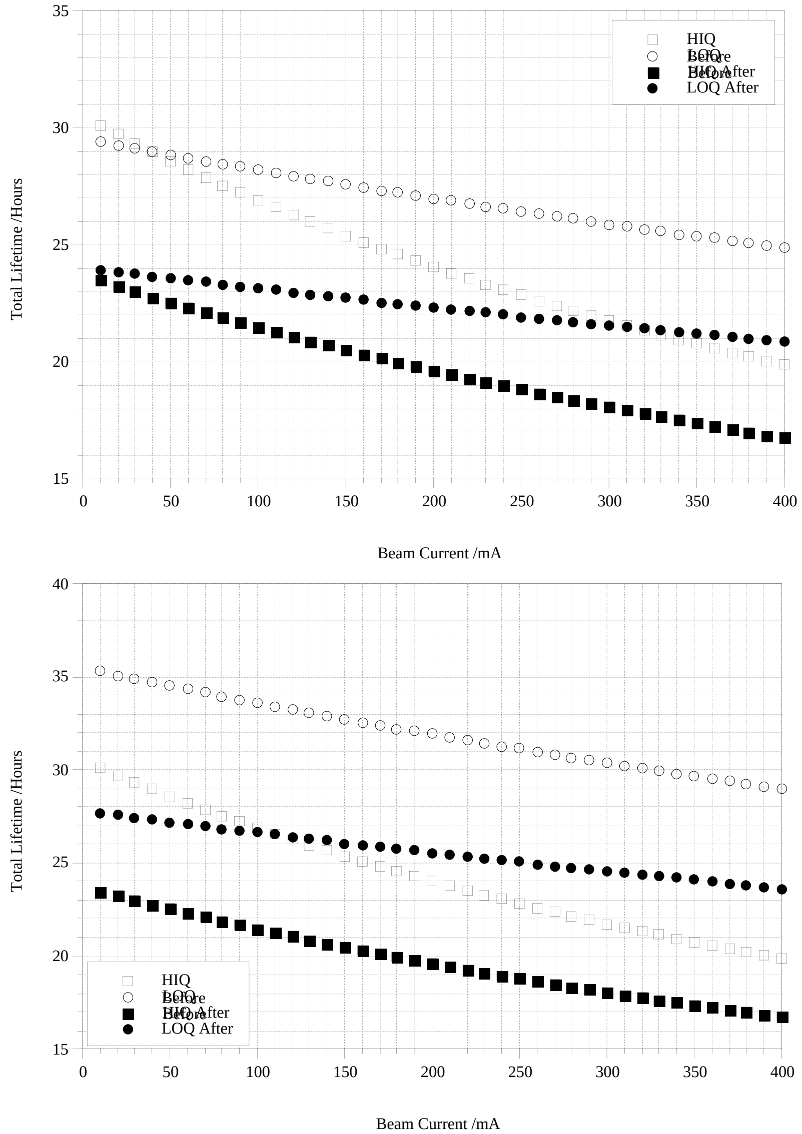


**Figure 5.9.** Predicted lifetime as a function of current in multibunch mode, in HIQ and LOQ before and after the ID installation. 1nTorr pressure is assumed. Lifetime reductions vary between about 15% and 20% The lifetime reduces at higher currents due to the decrease in the finite Touschek lifetime.

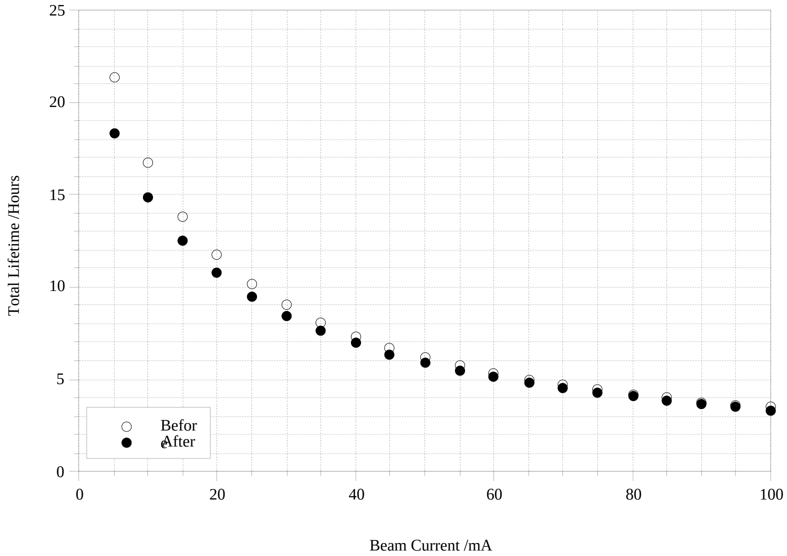


**Figure 5.10.** Predicted lifetime as a function of current in single bunch mode before and after the ID installation. 1nTorr pressure is assumed. The shape of the curves is determined by the variation in Touschek lifetime.

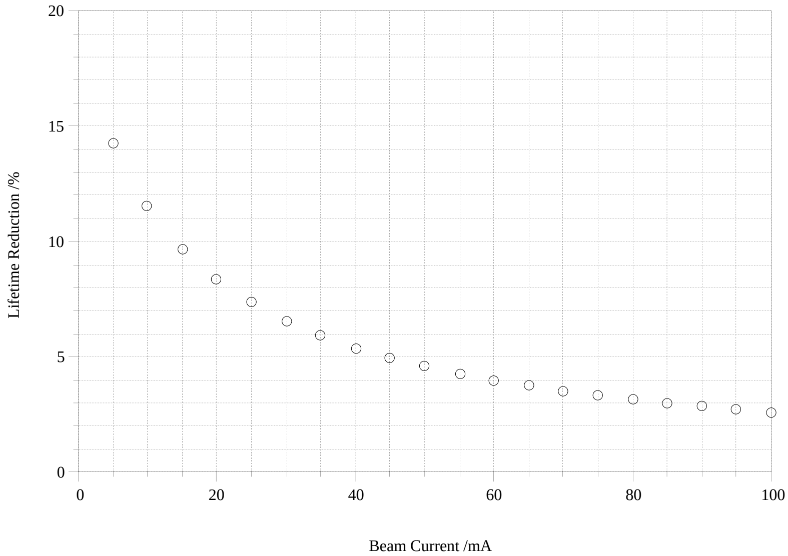


**Figure 5.11.** Predicted percentage reduction in lifetime due to the ID installation, as a function of current in single bunch mode. 1nTorr pressure is assumed. As the current increases, the lifetime becomes Touschek-dominated and the reduction is smaller.

## 6. Comparison with Experimental Results

Of course, the calculations above are only predictions. To give some confidence in the calculations, a comparison with experiment is obviously needed. This is done in SRS/APES/95/89 for multibunch beams. In LOQ single bunch, the theoretical data has been compared with the most complete set of lifetime vs. coupling data available, that from SRS/APES/96/04. The comparison is shown in Figure 6.1, using pressure values obtained during the shift. For the case of horizontal aperture restrictions, SRS/APES/96/48 confirms the prediction that the proposed reduction caused by the reduced ID aperture will have no effect upon the 2GeV lifetimes.

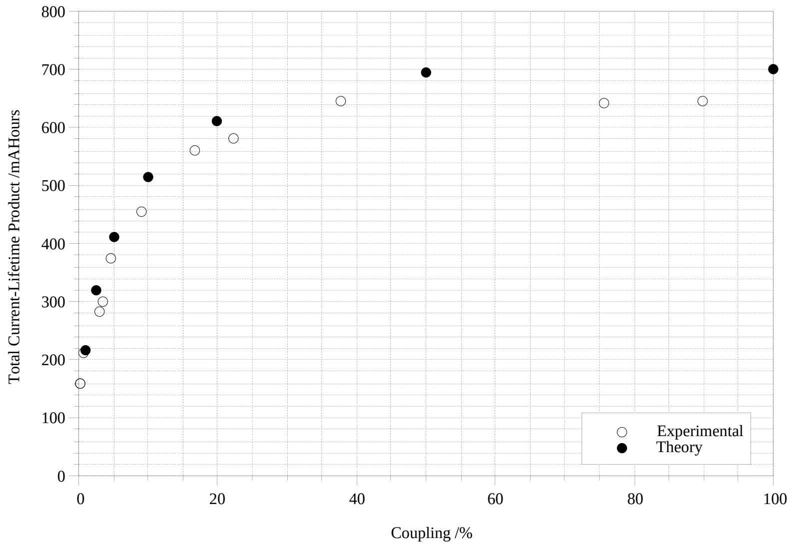


**Figure 6.1.** Comparing the total current-lifetime products from theoretical calculations with the data of SRS/APES/96/04. With an approximate pressure of 0.5nTorr, the agreement is good.

Broadly speaking, the 2GeV predictions are borne out by what is actually observed. This gives confidence in two things: firstly, the validity of certain measured parameters, such as the indicated machine pressure (SV.AVPR.01) and the RF voltage (at 2GeV). Secondly, it is believed that the modelling method is reasonable.

Presently, the calculations of dynamic aperture, and hence the momentum aperture, are theoretical, based upon estimates of errors in the machine. To refine the predictions, and to confirm that the momentum aperture calculations are reasonable, a measurement of the momentum aperture for different machine conditions would be useful.

## 7. Conclusions

The calculations given in this note predict the expected total lifetimes for the SRS at 2GeV, for a range of conditions both before and after the SRS upgrade. Comparison with experiment shows a reasonable agreement with theory for the state of the machine before the upgrade, and with measurements made with reduced apertures. This gives confidence in the predictions of the effect of the reduced ID apertures which are made.

## Appendix

*A.1 Useful Formulae*

ZAP input requires the number of particles per bunch. This is given by the simple formula

$$N = \frac{CI}{ehc}. \tag{A.1}$$

In the SRS, a handy formula is

$$N \approx 2\times 10^{12}\frac{I}{n_h}, \tag{A.2}$$

where $n_h$ is the number of bunches filled. Remember that $I$ is in A, not mA. For instance, a single bunch beam current of 10mA gives $N \approx 2\times 10^{10}$.

*A.2 Beam-Gas Scattering Cross-Sections*

Most calculations of lifetimes in the literature are based upon J.LeDuff's paper [1], which in turn is based upon J.Haïssinski's thesis [2]. For the B,C,I,E processes (see above), the corresponding total cross-sections for beam electron loss are:

$$\sigma_B = \frac{4r_e^2Z^2}{137}\frac{4}{3}\ln\frac{183}{Z^{1/3}}\left(\ln\frac{1}{\varepsilon_a}-\frac{5}{8}\right), \tag{A.3}$$

where $\varepsilon_a$ is the machine energy (momentum) acceptance.

$$\sigma_C = \frac{4r_e^2Z^2}{\gamma^2}\frac{\pi}{2}\langle\beta_i\rangle\left(\frac{\beta_i}{a_i}\right)_{s_0}, \tag{A.4}$$

where loss occurs in the $i = x, y$ plane, and the aperture $a_i$ is calculated at the point of loss. The plane used is the one which is most restrictive.

$$\sigma_I = \frac{4r_e^2Z}{137}\frac{4}{3}\left(\ln\frac{2.5\gamma}{\varepsilon_a}-1.4\right)\left(\ln\frac{1}{\varepsilon_a}-\frac{5}{8}\right) \tag{A.5}$$

$$\sigma_E = \frac{2\pi r_e^2Z}{\gamma}\frac{1}{\varepsilon_a} \tag{A.6}$$

The corresponding lifetime $\tau$ for each of these processes is given by

$$\frac{1}{\tau_i} = -\frac{1}{N}\frac{dN}{dt} = \sigma_i cn \tag{A.6}$$

where $n$ is the residual gas number density. Other symbols have their usual meaning.

*A.3 Modelling Files*

A combination of programs was used to perform the modelling, mainly MAD, ZAP and EXCEL. The modelling files are available with this note on ELROS, and the AP_Common directories on ELROS and srasv1.

## References


1. J.LeDuff, *Nucl.Instr.Meth.* **A239**, 83 (1985)
2. J.Haïssinski, *Thèse, Laboratoire de l'Accélérateur Linéaire*, Orsay (1965)