ELECTRON BEAM LIFETIME IN SPEAR3: MEASUREMENT AND SIMULATION[§]

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Abstract

In this paper we report on electron beam lifetime measurements as a function of scraper position, RF voltage and bunch fill pattern in SPEAR3. We then outline development of an empirical, macroscopic model using the beam-loss rate equation. By identifying the dependence of loss coefficients on accelerator and beam parameters, a numerically-integrating simulator can be constructed to compute beam decay with time. In a companion paper, the simulator is used to train a parametric, non-linear dynamics model for the system [1].

INTRODUCTION

As electrons circulate in an electron storage ring they collide within the bunch [2] and with background gas [3]. Depending on the impact parameter, they are either lost from the beam or return to the distribution core on the time scale of milliseconds. Multiple collisions are rare in most cases. The rate of particle loss can be modeled as a first-order, non-linear differential equation

$$\dot{I} = -I^2 \cdot \sigma_T - I \cdot n_g \cdot \sigma_B - I \cdot n_g \cdot \sigma_C \qquad (1)$$

where I is the total beam current, n_g is the background gas density and $\sigma_{T,B,C}$ are effective cross-sections for Touschek, Bremsstrahlung and Coulomb particle loss. If we include the dynamic pressure response $n_g = n_{go} + n'_{go} \cdot I$ and collect terms, Eq. 1 reads

$$\dot{I} = -I^2\left(\sigma_T + n'_{go}(\sigma_C + \sigma_B)\right) - I\left(n_{go}(\sigma_C + \sigma_B)\right) \qquad (2)$$

which has the form $\dot{I} = aI^2 + bI$ and is integrable [4]

$$I(t) = \frac{e^{bt}}{1 + (1 - e^{bt})\frac{a}{b}}. \qquad (3)$$

In order to account for bunch lengthening effects in σ_T the rate equation must be integrated numerically.

In general, the parametric cross-section dependencies,

$$\sigma_C = \sigma_C(y_{acc}, x_{acc})$$
$$\sigma_B = \sigma_B(V_{RF}, y_{acc}, x_{acc})$$
$$\sigma_T = \sigma_T(V_{RF}, y_{acc}, x_{acc})$$

can be modeled from experimental data and/or calculated from first principles. Correct modeling of gas pressure, bunch current, geometric and momentum aperture yields an accurate picture of beam decay. The implications for day-to-day operations, machine protection and even synchrotron radiation research are significant.

Table I summarizes the particle loss mechanisms in terms of scattering source and effective capture potential.

The most complicated beam loss mechanism is Touschek scattering because, as illustrated in Fig. 1, e^--e^- collisions can result in particle loss in any one of three dimensions [5, 6]. In SPEAR3, for instance, the electron beam lifetime increases with RF voltage up to ~3.1MV at which point the horizontal aperture starts to limit momentum acceptance. Surprisingly, however, the vertical scraper can be inserted to almost 1.0mm-rad before limiting momentum acceptance, an indication that at present non-linear coupling is *not* a dominant loss channel.

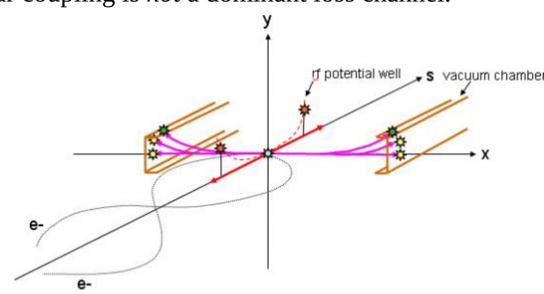

Figure 1: Touschek scattering loss mechanisms.

Table 1: Source (S) and trapping potentials (P) for particle loss. Momentum acceptance is split into RF_{acc} and lattice/chamber acceptance (A_{acc}), respectively.

	Touschek	Coulomb	Brems
I_b	S	-	-
I_t	-	S	S
RF_{acc}	P	-	P
A_{acc}	P	P	P

IN-SITU MEASUREMENTS

A systematic study of electron beam lifetime as a function of RF voltage and horizontal and vertical scraper positions has been carried out. In each case, measurements were made for a series of single-bunch and total beam currents, for both the achromatic (AC) and low-emittance optics (LE) [7].

In Fig. 2 we plot beam lifetime as a function of single bunch current for a range of RF voltages in both the AC and LE optics with similar coupling. The red curves indicate constant RF voltage scanned over a range of 1.2 to 3.2MV. Clearly the LE optics has shorter beam lifetime than in the AC mode - in part due to higher charge density driving the Touschek loss rate. The higher momentum compaction factor in the LE optics also reduces the RF bucket height (α_{LE}=0.0016 vs. α_{AC}=0.0012). The plots in Fig. 2 provide good data to model beam lifetime as a function of I_b and RF voltage.

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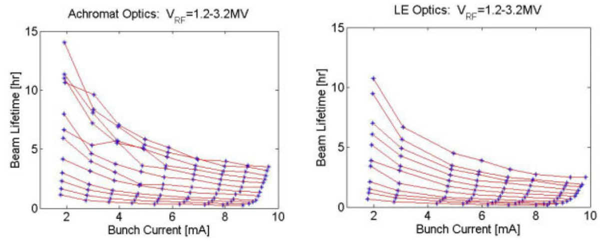

Figure 2a,b: Lifetime vs. I_b for AC and LE optics. Red curves indicate constant RF voltage.

In Fig. 3a we plot beam lifetime as a function of vertical scraper position for both AC and LE optics and 3.2MV RF voltage. Both lattices have β_y=3.7m at the scraper position. The solid lines (100ma in 280 buckets) have relatively low charge/bunch and can be used to estimate the vertical acceptance (~4.5mm-mrad) at the knee of the curves. For the dashed lines (100ma in 20 buckets), the high Touschek loss rate masks the knee yielding a false result for the vertical chamber acceptance.

Figure 3b shows a plot of normalized lifetime vs. horizontal scraper acceptance in a highly Touschek-dominated regime (25ma/bunch). From this data we see the impact of a smaller RF-bucket height and smaller value of curly-H in the LE optics, i.e., the x-scraper must be inserted further into the chamber to impact beam lifetime for a given RF voltage: $\sqrt{\mathrm{H}}\delta_{RF} > \frac{x^2}{\beta}$.

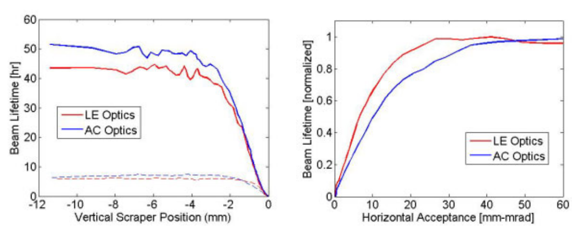

Figure 3a,b: Beam lifetime as a function of vertical scraper (position) and horizontal scraper (acceptance).

To further study this effect, we measured lifetime as a function of RF voltage for a series of horizontal scraper settings positioned to give the same physical acceptance in both optics. In each case the scraper is in a region of zero dispersion. Figure 4 shows the bifurcation points occur at lower RF voltage in the LE optics for a given acceptance defined by the horizontal scraper. Beam conditions in both cases were set to 100ma in 20 bunches to reach a Touschek-dominated regime.

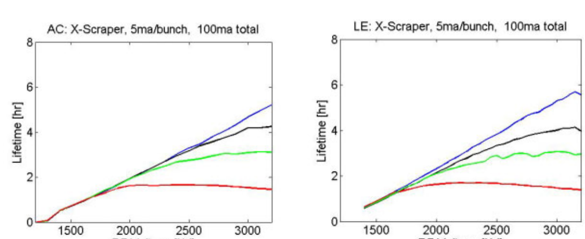

Figure 4a,b: Lifetime vs. RF voltage for different values of horizontal acceptance: 60, 9.7, 4.8 and 1.6mm-mrad.

Similarly, to test the impact of the vertical aperture on momentum acceptance, the vertical scraper was inserted to progressively smaller radii while scanning the RF voltage for each lattice [8]. Again we filled 100ma in 20 bunches to monitor non-linear coupling of intra-beam scattering events into the vertical plane. Note that while low vertical acceptance values of [1.2, 0.7 and 0.1mm-mrad] have only a small impact on momentum acceptance, the same apertures, under normal operating conditions (280 bunches) would cause unacceptable Coulomb loss (see Fig. 3).

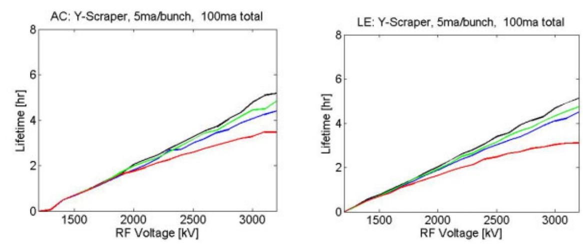

Figure 5a,b: Beam lifetime vs. RF voltage for different y-scraper positions (retracted, 2.1, 1.6 and 0.6mm).

SIMULATOR - MODEL COEFFICIENTS

By using beam lifetime measurements to model the cross-section parameters in Eq. 1, it is possible to develop a non-linear *macroscopic* model parameterized by RF voltage, scraper position and bunch current. The rate equation can then be used as a model for predictive analysis of different operational modes. A parallel project seeks to use the first-principles model in the framework of a Parametric Universal Nonlinear Dynamics Approximation (PUNDA) [1]. In this section we briefly describe construction of the model.

Gas Pressure

To first order, Coulomb and Bremsstrahlung loss scale linearly with background gas density. In SPEAR3, the dynamic pressure scales as

$$<P> = \frac{1}{L}\int P\beta ds \sim 0.375 + 0.0016 \cdot I \ \ [\mathrm{nT}]$$

so we use $n_{go} = 0.375$ and $n_{go}^{'} = 0.0016$ in Eq. 2 to produce the correct pressure scaling law.

Gas Scattering

In order to model the σ_C term in Eq. 2, we assume Coulomb loss scales with chamber acceptance, so

$$\sigma_C \propto C_1\beta_x / x^2 + C_2\beta_y / y^2 .$$

where for simplicity the machine acceptances x/y_{acc} are taken in a physically aperture-limited regime.

For Bremsstrahlung collisions, again the scattering rate is proportional to pressure but this time as a weak function of momentum acceptance, $\sigma_B \propto B_1 \log(p/dp)$.

Touschek Scattering

Touschek scattering is the dominant loss term for most light sources and the most difficult to model. Not only is the parametric dependence on V_{RF}, x_{acc} and y_{acc} complicated by the non-linear dynamics inherent in the momentum aperture, the bunch volume scales with lattice, RF voltage, charge, and coupling. Furthermore, the oscillation amplitude following an e^--e^- scattering event is a non-linear function of optics [5] so many strong-focusing machines see non-linear coupling of oscillations into the vertical plane. For purposes of the PUNDA study, the Touschek loss σ_T was modeled as a function of RF voltage and single-bunch charge with bunch-lengthening.

Lifetime Contributions in SPEAR3

As an example of using beam lifetime data to determine the separate contributions to beam lifetime, measurements were taken at I_t={25,50,75,100}mA with fill patterns including {20,40,80,140,280}bunches. The data was then fit to

$$\frac{1}{\tau} = a + bI_t + cI_b \quad (4)$$

where the $a+bI_t$ contribution is due to gas scattering and the cI_o term is due to intrabeam scattering. The fitted coefficients for both optics are listed in Table 2. At 500ma with 280 bunches in the AC and LE optics for example, the estimated beam lifetime is 12.2hr and 9.5hr.

Table 2: Fitted coefficients to Eq. 4 for AC and LE optics.

	a	b	c
AC	5.5×10^{-3}	4.4×10^{-5}	3.1×10^{-2}
LE	4.5×10^{-3}	5.1×10^{-5}	4.2×10^{-2}

By fitting lifetime vs. vertical scraper data for the 100ma, 280 bunch fill pattern, the Coulomb scattering component was separated from the combined inelastic and intra-beam scattering components. The Touschek lifetime is given by the third term in Eq. 4. Knowing the Touschek lifetime one can then solve for the Bremsstrahlung component, and finally the Coulomb component. Using this technique, estimates for all three beam loss contributions are listed in Table 3 both the AC and LE optics in the 100ma, 280bunch fill pattern.

Table 3: Lifetime contributions for LE and AC optics [hr].

	τ_C	τ_B	τ_T
AC	275	160	90
LE	240	200	65

Beam Decay Model Interface

A beam loss model with gui interface allows in interactive control of the simulated electron beam parameters (I_t, I_b) scraper positions, RF voltage, gas pressure coefficients, beam loss cross-sections $\sigma_{T,B,C}$ and a bunch lengthening coefficient. Once the beam parameters are entered, lifetime is calculated using Eq. 3 (no bunch-lengthening) and numerically integrated to take bunch-lengthening into account. Figure 6 shows an example of beam decay for a 100ma beam in 20 bunches over an 8hr period with- and without bunch-lengthening effects.

The simulator was constructed so that the computation engine can be run remotely for batch calculations of beam lifetime vs. scraper position, etc.

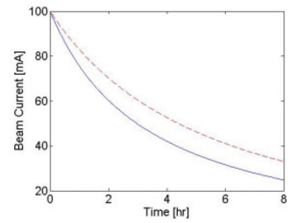

Figure 6: Example beam decay profile with bunch-lengthening (red dash) and without (solid blue).

SUMMARY

Measurements of electron beam lifetime as a function of x- and y-scraper position, RF voltage, beam fill pattern and machine optics have been made to characterize beam dynamics and the interaction of the beam with the physical environment in SPEAR3. In parallel, an interface has been developed to solve the beam-loss rate equation in closed form or with a numerical integrator to model bunch lengthening. A companion paper utilizes a commercial software package to construct a non-linear, parametric model of the beam lifetime data [1].

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