LIFETIME ISSUES FOR THIRD GENERATION LIGHT SOURCES

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Abstract

Achieving a long lifetime is a key issue for all new synchrotron light sources. Low horizontal emittance and small coupling limit the lifetime, even in a high energy storage ring like the ESRF, due to Touschek scattering. Instead of compromising on beam brightness by bunch density manipulations, the strategy of new projects to combat Touschek-induced lifetime limitations is to increase the momentum acceptance. Problems related to lattice optimization, hardware constraints, experimental confirmation of predicted performances as experienced at the ESRF, will be addressed.

1 BRILLIANCE CONFLICT WITH LIFETIME

The new generation of synchrotron light sources is characterized by much smaller electron beam sizes (horizontal emittance in the few nanometer range, coupling of 1 %) and insertion device gaps (leading to a beam stay-clear of 5 mm at APS, 8 mm at the ESRF for instance) than machines of the previous generation. Average brilliances in the 10^{19} to 10^{20} photons/sec/mrad^2/mm^2/0.1 % relative bandwidth can therefore be reached. The achievement of such high brilliances is often conflicting with long lifetimes: new machines suffer from gas scattering lifetime reduction due to small gap undulator chambers and from lifetime limitation due to the enhanced Touschek scattering induced by the increased density in the bunch volume.

Lifetime is therefore a key issue for machine designers and users. As a matter of fact, frequent refills due to a moderate lifetime imply:

i) changes in the thermal stability of beamline optical components which in turn is most detrimental to the quality of experiments.

ii) changes in the thermal stresses on the vacuum chamber and position of BPMs, intensity-related drifts of the electronics of the sensors which spoil the beam centre of mass stability.

The importance of the lifetime limitations is strongly related to the machine energy. Low and medium energy machines are mainly Touschek lifetime dominated. But there is also evidence from a high energy machine like the 6 GeV ESRF that, due to the low coupling, Touschek scattering gives a significant contribution to the lifetime reduction. This is illustrated in Figure 1 with typical ESRF parameters (200 mA in 330 bunches, ε_x = 4 nm, 1 % coupling, energy acceptance $\Delta p/p$ = 2.1 %).

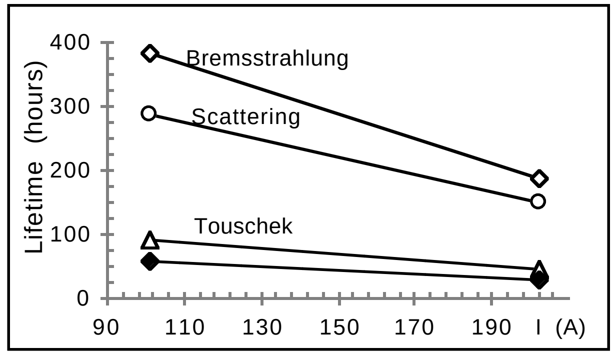

Figure 1: Contributions to the ESRF lifetime

2 COMPROMISING SOLUTIONS

2.1 Gas scattering lifetime

Even if low energy machines are Touschek dominated, small undulator gaps also affect their lifetime by reducing the beam gas scattering lifetime: for instance at ELETTRA (2 GeV), the lifetime starts to decrease for a chamber height of less than 13 mm.

Building in-vacuum undulators is one of the solutions to cope with the small beam stay-clear resulting from the reduction of the insertion device gap. This strategy has been retained by machines like Spring8 but experience has certainly to be gained before drawing conclusions.

Operating the lattice with a small vertical beta function in the straight sections is another way of minimizing the gas scattering effect. At the ESRF, by reducing β_z from 13 m down to 2.5 m, a minimum beam stay-clear of 5 mm can now be accepted instead of 7 mm for the same 20 % reduction in beam lifetime as shown in Figure 2.

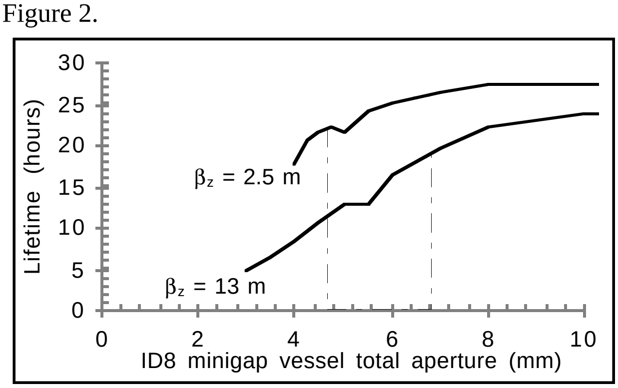

Figure 2: ESRF lifetime evolution with reduced gap

2.2 Bunch density manipulations

They provide a means (although to the detriment of the brilliance in most cases) of decreasing Touschek lifetime limitations. The available parameters are derived from the expression of the Touschek lifetime τ_T:

$$\frac{1}{\tau_T} = \frac{N r_0^2 c}{8\pi\sigma_x\sigma_z\sigma_L\beta^3\gamma^2\left(\frac{\Delta p}{p}\right)^3} f\left(\frac{\Delta p}{p}, \sigma_x\right)$$

where N is the number of particles per bunch, σ_x, σ_z, σ_L are the transverse and longitudinal beam sizes, $\Delta p/p$ the energy acceptance and γ the relative machine energy.

i) Decreasing the number of particles per bunch while keeping the same current. Table 1 summarizes the ESRF experience in that respect.

Table 1: Influence of the filling pattern on the lifetime

	1 / 3 filling	*2 / 3 filling*
I = 100 mA	65h	80 h
I = 200 mA	31 h	48 h
	16-bunch	*32-bunch*
I = 90 mA	10 h	17 h

ii) Installing a higher harmonic cavity to lengthen the bunch. This is being successfully implemented at MAX2 [1]. Another possibility used at ELETTRA [2] consists in partially exciting longitudinal coupled bunch instabilities by means of cavity temperature adjustment. The increase by a factor of 2 of the energy spread causes acceptable reduction in undulator flux while doubling the lifetime.

iii) Increasing the vertical coupling. At the ESRF, by applying some white noise, using the shaker of the tune measurement system, the vertical emittance can be increased from 30 pm to 50 pm in order to gain a few hours lifetime in the few bunch mode operation. At ELETTRA [2], the lifetime increase obtained by operating on the coupling resonance gives too much reduction in flux and noisy spectra.

3 INCREASING THE ENERGY ACCEPTANCE

Increasing the energy acceptance appears as a promising strategy to improve the Touschek lifetime since this does not compromise the brilliance. Figure 3 shows the possible gains in single bunch mode at the ESRF (I = 10 mA, ε_x = 4 nm, 1 % coupling, bunch lengthening of 3) when increasing the energy acceptance from the design value of 2 % to 4 %.

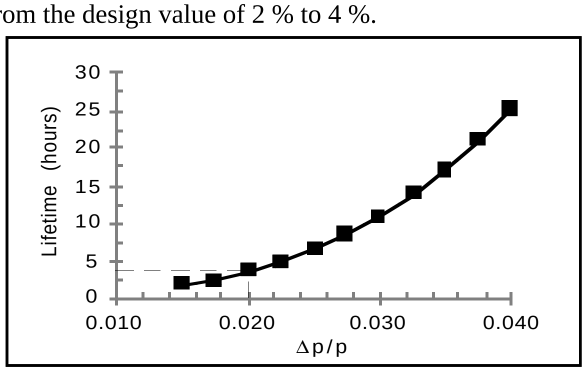

Figure 3: Single bunch lifetime increase with $\Delta p/p$

Since the energy acceptance is determined by the longitudinal acceptance given by the RF system, by the vacuum chamber physical aperture or by the dynamic aperture, the optimization of all these parameters must be tackled in parallel.

3.1 RF system

In the new machines, using active superconducting cavities is envisaged to provide a high accelerating voltage and the resulting large energy acceptance (for instance $\Delta p/p = \pm$ 6 % with V_{RF} = 4 MV at SOLEIL). At the ESRF, the recent installation of a third RF unit [3] gives an energy acceptance of ±5.5 % instead of the initial ±3.2 % (12 MV instead of 8 MV).

3.2 Physical aperture

Particles that are Touschek scattered in dispersive sections experience a sudden change in energy which results in an induced betatron amplitude around the machine. Large horizontal vacuum vessel apertures are therefore required to provide the necessary betatron acceptance. The energy acceptance resulting from a limiting horizontal aperture X_S is given by:

$$\left(\frac{\Delta p}{p}\right)_{max} = \frac{X_S}{\eta_S + \eta_A\sqrt{\frac{\beta_S}{\beta_A}}}$$

where η and β are the horizontal dispersion and betatron function at the location of maximum dispersion (index A) and at the location of the restricted aperture (index S)

In most machines, the injection septum gives the transverse limitation. This is illustrated in Figure 4 for the ESRF. The measuring technique consists in recording the lifetime evolution as a function of the RF voltage with a 5 mA single bunch. The lifetime increases with the RF voltage to the point where transverse limitations take over. It can be seen that, when moving the septum by 5 mm outwards, the energy acceptance increases from 2.4 % to 3 % instead of the expected 3.7 %. The saturation in the lifetime increase with the RF voltage likely comes from a dynamic aperture limitation. The unexpected limitation of the physical aperture induced by damaged RF fingers also shows up with the reduction of the energy acceptance down to 2.3 %.

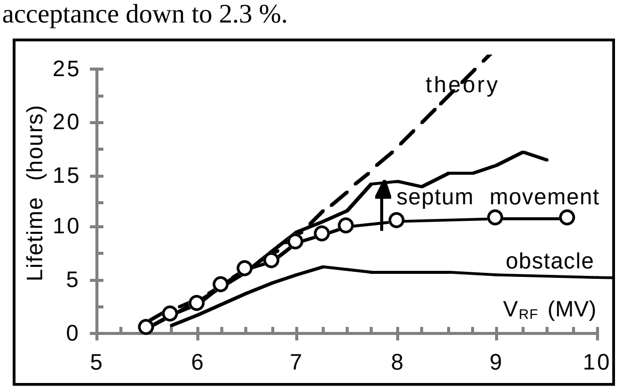

Figure 4: Effects of a physical aperture limitation on the lifetime

3.2 Large energy acceptance lattices

The procedures for optiziming low emittance lattices with large momentum acceptance consist in minimizing low order resonance strengths, adjusting the tune shifts with amplitudes and flattening the dependence in $\Delta p/p$ of tunes [4], [5]. Promising examples of energy acceptances up to ± 6 % are reported for machines being designed. At the ESRF, simulations show that dynamic apertures for momentum deviations up to ± 5 % are still larger than the physical aperture (Figure 5).

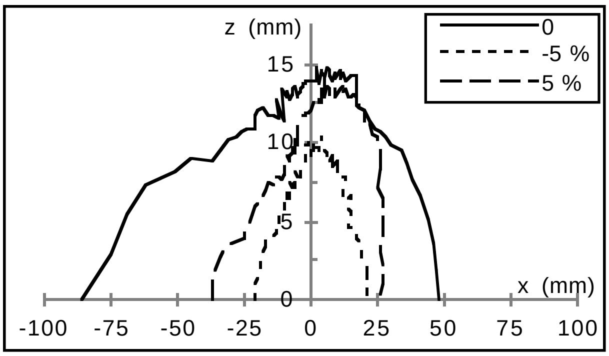

Figure 5: ESRF dynamic aperture for $\Delta p/p \neq 0$

However, ESRF experimental measurements of the effective $\Delta p/p$ acceptance show that achieving large energy acceptances might set problems mostly linked to hardware constraints. A few examples are reviewed hereafter.

i) Despite the fact that special care in minimizing the field errors and non-identity of magnets had been taken at the design and construction stages, non-systematic resonances are excited and lead to a dynamic aperture and lifetime reduction. This is experienced at the ESRF where the correction of the quadrupolar and sextupolar resonances close to the working point is routinely performed to mininize resonance widths (Figure 6). For quadrupolar resonances, individual powering of quadrupoles is another way of improving the situation.

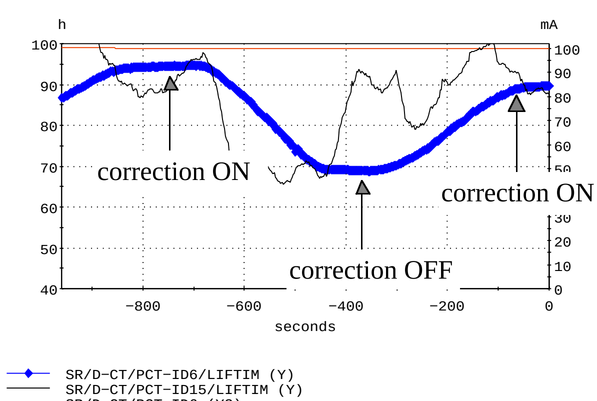

Figure 6: Impact of the correction of $3\upsilon_x = 109$ on the lifetime

ii) A large energy acceptance is conflicting with the overcompensation of the chromaticity often used to stabilize the beam against resistive wall instability which worsens with the increasing number of narrow gap vessels. As shown in Figure 7, in the case of the ESRF with chromaticities of $\Delta\upsilon_x/(\Delta p/p) = 4$, $\Delta\upsilon_z/(\Delta p/p = 7)$, numerous resonances are on the path of Touschek scattered particles and affect the lifetime. The experimental energy acceptance is measured using an RF frequency scan. The energy acceptance computed from the RF frequencies giving zero lifetime stands at -2.4 % / +3.7 %. The limitation on the negative side comes from the crossing of a node of third-order resonances. The solution consists in implementing a feedback system and/or using low resistivity materials for the vacuum vessels.

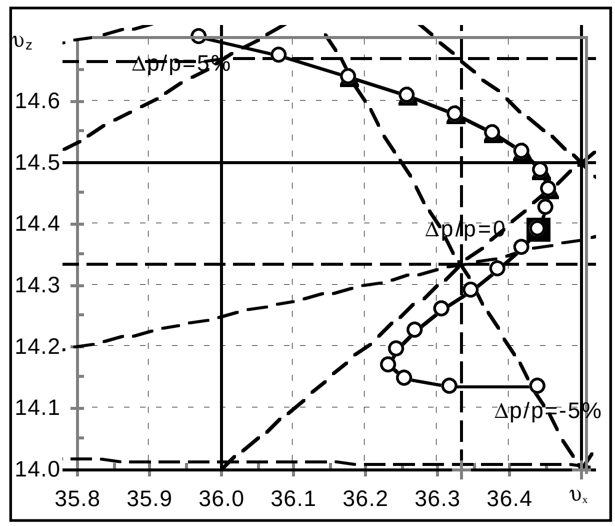

Figure 7: Predicted tune path for off-momentum particles

4 CONCLUSIONS

Since design goals in terms of horizontal emittance and coupling have been achieved for third generation light sources, the current challenge consists in increasing the lifetime without compromising the brilliance. In that respect, the key parameter is the energy acceptance. The ESRF experience shows some discrepancies between the large predicted acceptances and measured figures. This needs to be understood for future machines.

The possibility of permanent injection (top-up) is considered at different places (APS, SLS,...) to compensate for short lifetimes. Practical implications on cost, safety have still to be analyzed.

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