CALCULATION OF COLLECTIVE EFFECTS AND BEAM LIFETIMES FOR THE LBL 1-2 GeV SYNCHROTRON RADIATION SOURCE*

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Abstract

In designing a third-generation high brightness synchrotron radiation source, attention must be paid to the various collective effects that can influence beam performance. We report on calculations, performed with the code ZAP, of the bunch length, the transverse emittance and the beam lifetime (from both Touschek and gas scattering) for our 1-2 GeV storage ring. In addition, we estimate the growth times for both longitudinal and transverse coupled bunch instabilities. Bunch lengths of about 20 ps should be obtainable and intrabeam scattering emittance growth is small. For a limiting undulator gap of 1 cm and residual gas pressure of 1 nTorr, the beam lifetime is about 5 hours in the single-bunch mode; in the multibunch mode, lifetimes in excess of 6 hours are expected. These results indicate that all performance goals for the facility should be achievable.

Introduction

The beam specifications for the LBL Light Source, based on user requirements, are as follows:[1] nominal beam energy of 1.5 GeV with an energy range 0.75-1.9 GeV, average beam current of 400 mA in the multibunch configuration and 7.6 mA for the single bunch option, horizontal rms emittance less than 10^{-8} m-rad, rms bunch lengths of 10-25 ps and beam lifetime of at least 6 hours. In this paper, we examine the lattice that was selected to meet these requirements in terms of collective effects that can influence machine performance. First, we discuss the various estimated beam-storage-ring coupling impedances. This allows us to calculate the expected bunch lengths obtainable in the ring, limited by single-bunch instabilities. Effects of coupled bunch instabilities (growth rates and frequency shifts) are then calculated. The dense beam bunches specified for the Light Source make it necessary to estimate the possible growth in beam emittance due to intrabeam scattering (IBS). Calculations confirm that this phenomenon is unimportant at high energies. Finally, we estimate the beam lifetime, taking into account the combined effects of Touschek and gas scattering. All of the calculations reported here were performed with the LBL accelerator physics code ZAP.[2]

Coupling Impedances

Many elements in the Light Source storage ring will contribute to the beam-storage-ring coupling impedance. The narrow-band, high-Q impedances arise primarily from the rf cavities, through their higher order modes. These can potentially induce coupled bunch coherent modes. The shunt impedances, resonant frequencies and quality factors for the higher modes of the Light Source rf cavity are taken from experimental observations and calculations for the 500 MHz KEK rf cavity with undamped modes.[3] The broadband, low-Q impedance arises from the vacuum chamber itself, together with other elements such as diagnostic instruments, bellows, etc., and the equivalent broadband impedance arising from the many rf cavity modes. This latter rf-equivalent broadband impedance is taken to be 0.25Ω per rf cell, as obtained by appropriate summing of the higher order modes of the KEK cavity.[3] A detailed impedance inventory has not been performed yet; however, based on preliminary laboratory measurements[4] of the prototype Light Source vacuum chamber, we expect the broadband impedance contributed by the vacuum chamber itself to be much smaller than $|Z_{\parallel}/n| \simeq 2\Omega$.

With the narrow-gap insertion devices envisaged for the Light Source, there may be cavity-like resonances of the whole beam-tube volume, bounded by the narrow restrictions imposed by the undulator gap. For undulators having a 2-cm gap, microwaves at frequencies above 8 GHz will propagate through the aperture. However, between 4.5 and 8 GHz there will be many resonances (~ 750-1000), with complete overlap at the low-frequency end and isolation at the high-frequency end, within the volume of the beam tube between two insertion devices. For ten such devices, the real part of $Z_{\parallel}$, averaged over the frequency range, starts at about 40Ω at 4.5 GHz, falling off to 4Ω at 8 GHz, with a total low-frequency reactive component $(Z_{\parallel}/n)$ of about 0.3Ω. This is entirely consistent with our estimate of total impedance: $|Z_{\parallel}/n| \simeq 2\Omega$. For undulators having a 1-cm gap, this impedance pattern will extend up to 16 GHz, which is also the approximate bunch cutoff frequency. Single-bunch instability effects may begin to become significant at this stage.

Bunch Length

The bunch length in the Light Source must be very short: $2\sigma_T \simeq$ 20-50 ps. The attainable bunch length is determined by two things: the rf parameters and the constraint imposed by the longitudinal microwave instability. The rf parameters are taken for the nominal case of a 500 MHz system operating at 1.5 MV.[1] These parameters establish a lower limit to the bunch length. The influence of the longitudinal microwave instability is determined by the effective broadband impedance assumed for the ring. The microwave threshold in current is given by[2]

$$I_{thresh.} = \frac{\sqrt{2\pi}\ |\eta|\ (E/e)\ \sigma_p^2\ \sigma_\ell}{R\ |Z_{\parallel}/n|_{eff.}}$$

where η is the phase-slip factor, σ_p the rms relative momentum spread and R the machine radius. Extremely short bunches, as envisaged for the Light Source, will sample the high frequency component of the ring broadband impedance with significant coupling. The magnitude of the turbulent microwave bunch lengthening is very sensitive to whether or not we assume the validity of SPEAR scaling of the effective coupling impedance in this frequency range, given by:[2]

$$\begin{aligned} |Z_{\parallel}/n|_{eff.} &= |Z_{\parallel}/n|_0 & \sigma_\ell \geq b \\ &= |Z_{\parallel}/n|_0\ (\sigma_\ell/b)^{1.68} & \sigma_\ell < b \end{aligned}$$

where b is the beam-pipe radius. It is expected that the effective coupling impedance felt by the beam will be significantly reduced for short bunches, thus favoring a short bunch configuration. The unscaled broadband impedance is made up of contributions from the vacuum chamber and the rf cavities:

$$|Z_{\parallel}/n|_0 = |Z_{\parallel}/n|_{chamber} + n_{cell} \cdot |Z_{\parallel}/n|_{rf}$$

where $n_{cell} = 2$ (for V_{RF} = 750 kV/cell).

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We take $|Z_\parallel/n|_{chamber} \simeq 2\Omega$ and $|Z_\parallel/n|_{rf} \simeq 0.25\Omega$/cell as explained previously. Thus $|Z_\parallel/n|_0 \simeq 2.5\Omega$. Although SPEAR scaling can lead to very low impedance values, the extremely short bunches can never overcome the inherent free-space impedance, arising from strong coherent radiation at high frequencies even in the absence of structures. This free-space impedance, shielded by the beam pipe, is given by[2]

$$|Z_\parallel/n|_{FS} \cong 300(b/R) \ .$$

The effective broadband impedance is never allowed to fall below this free-space impedance limit, which is roughly 0.3Ω.

We illustrate the range of possibilities by performing two separate sets of calculations, one assuming no reduction in the impedance from nominal values (no SPEAR scaling) and a second assuming a reduction as given by SPEAR scaling. In Fig. 1, we show the bunch length as a function of average current for the single-bunch configuration. If the impedance reduction (in the spirit of SPEAR scaling) holds for the Light Source, there should be no problem in reaching bunch lengths of $2\sigma_T \approx 20$ ps. If not, we would expect to give up as much as a factor of two or three in bunch length. In the latter case, it does not appear practical to regain the lost bunch length by any reasonable variation of rf parameters.

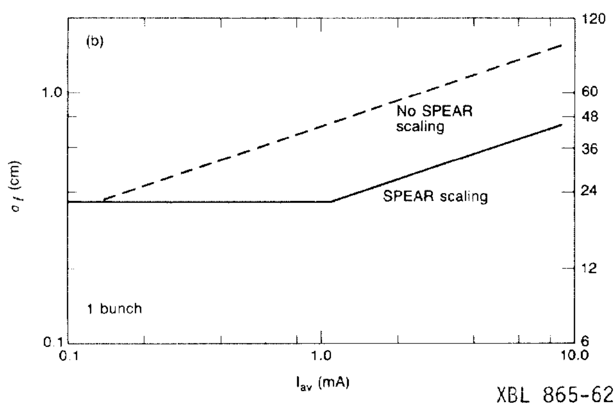

Fig. 1. Bunch length vs. current at 1.5 GeV, with and without the SPEAR scaling law.

Coupled Bunch Instabilities

We have calculated the growth rates and the coherent frequency shifts for the first few fastest-growing coupled bunch modes in the Light Source. The resonance parameters for the higher order modes of the rf cavity were taken from the undamped values of these parameters for the similar KEK 500 MHz rf cavity.[3] The broadband impedance for the ring was taken as $|Z_\parallel/n|_{chamber} = 2\Omega$ and, to obtain the effect of resistivity, we include the contributions of the aluminum vacuum chamber wall. All calculations were done using Gaussian bunch shapes. For the sake of conservativeness, we have used a current of 1.6 mA per bunch (consistent with our multibunch operating mode with 250 bunches), with a completely filled 328-bunch configuration. The bunch lengths and momentum spreads used in the calculation are $\sigma_\ell = 0.86$ cm and $\sigma_p = 16.5\times10^{-4}$, respectively, without SPEAR scaling and $\sigma_\ell = 0.42$ cm and $\sigma_p = 8.0\times10^{-4}$, respectively, with SPEAR scaling, at 1.5 GeV.[1]

A summary of the results is given in Table I for the first few fastest-growing longitudinal and transverse modes for the SPEAR-scaled bunches at 1.5 GeV.[1] Results for bunches without SPEAR-scaled lengths are similar. Modes with synchrotron mode numbers higher than a = 2 longitudinally and a = 1 transversely are all effectively Landau damped by the synchrotron frequency spread in the beam. No betatron tune spread was assumed in the calculations. The coherent tune shift comes mainly from the rf modes themselves in our case, with a small component from the ring broadband impedance. Consequently, reducing the storage ring broadband impedance will not help stabilize the beam via Landau damping for the low-order synchrotron modes (dipole a = 1, and quadrupole, a = 2, longitudinally, and rigid dipole, a = 0, and nonrigid dipole, a = 1, transversely). The calculated growth rates are high, especially the longitudinal ones. Synchrotron radiation damping is of little help, since the radiation damping times are ~ 10-20 ms, much longer than the instability growth times. Consequently, the storage ring design includes both higher order mode-suppression schemes for the rf and feedback systems.[1]

TABLE I.

	Synchr. Mode No. a	Growth Time τ(ms)	Tune Shift $\lvert\Delta\nu\rvert_{coh.}$	Landau Damping
Long.	1 2 3	0.13 17.2	2.82×10^{-3} 1.33×10^{-4}	U U Stability Border
Trans.	0 1 2,3,...	1.76 551	1.42×10^{-4} 6.83×10^{-6}	U U D

Emittance Growth

We have estimated the final emittance of the beam resulting from the equilibrium among intrabeam scattering, synchrotron radiation damping and heating due to quantum fluctuations, as calculated by ZAP.[2] Confidence in such an estimate is established by reasonable agreement between ZAP predictions for the Aladdin storage ring and experimental results at low energies.[5]

In general, the severe effects of intrabeam scattering diminish rapidly as the beam energy increases. However the very high density in the Light Source bunches warrants such a calculation even at higher energies. Because intrabeam scattering is a single-bunch effect, the most severe problems are expected to occur in the (high-current) single-bunch scenario.

In Fig. 2, we show the growth in equilibrium emittance from the natural value at a 10:1 horizontal-vertical emittance ratio, for a single-bunch scenario. There is a noticeable emittance growth at the lower end of the energy range (about a twofold increase over the natural emittance at 1 GeV), but it does not limit the performance of the machine. The emittance growth is negligible at high energies. For a larger emittance ratio (smaller coupling), the beam density is higher and the low energy emittance growth becomes more pronounced.[1] However the operating specifications of the machine are not compromised even then.

Beam Lifetime

Beam lifetime is limited by a combination of Touschek scattering and background gas scattering.

Touschek scattering, which is large-angle single Coulomb intrabeam scattering, is most severe for short, high-current bunches with low emittance and a large coupling ratio -- precisely the properties we are striving for in the Light Source. In addition, Touschek lifetime is

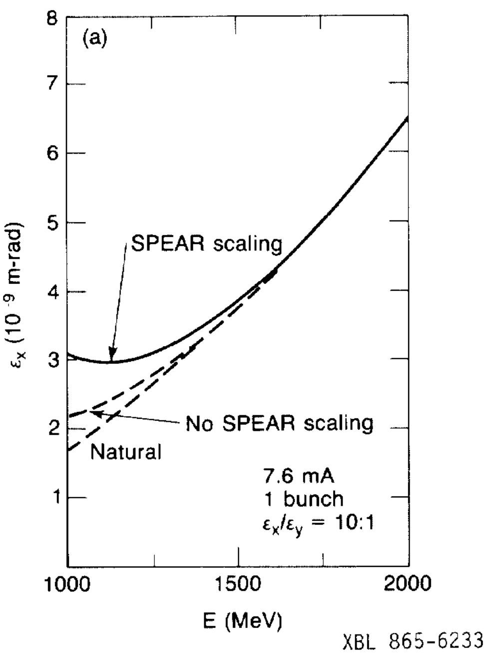

Fig. 2. Predicted emittance growth from intrabeam scattering for 7.6 mA in a single bunch.

strongly influenced by the momentum acceptance of the lattice.

The momentum acceptance limit of the lattice can be either longitudinal (i.e., the rf bucket height) or transverse (i.e., the physical or dynamic aperture). For the transverse limit, we specified a pair of values that give the maximum momentum acceptance in the dispersive and nondispersive regions of the lattice. The values for the transverse momentum aperture used in our study--based on tracking results--are 4.0% in the dispersive region and 5.0% in the nondispersive region. At energies above about 1.2 GeV, however, the rf (longitudinal) aperture (3.5% at 1.5 GeV) is the limiting one.[1]

Compared with the case of no SPEAR scaling, Touschek lifetimes are shorter (by a factor of two or three) for SPEAR-scaled bunch lengths, due to their higher particle density (by the same factor).[1] Touschek half-lives for multibunch and single-bunch scenarios, with the SPEAR scaling assumption and for an emittance ratio of 10:1, are in the range of 20 and 8 hours, respectively. Increasing the emittance ratio to 100:1 reduces the Touschek lifetimes by about a factor of three.[1] The Touschek lifetime can also be affected by the rf parameters. At 1.5 GeV, the lifetime for a higher rf voltage of 3 MV increases almost twofold, despite the increased bunch density.[1] At low energies, with the transverse limit dominating, however, the increased rf voltage affects the beam lifetime adversely.[1]

Gas scattering lifetimes were calculated including contributions from both elastic and inelastic (Bremsstrahlung) scattering, assuming a pressure of 1 nTorr of nitrogen gas and a ring acceptance limited by undulator vacuum chambers with full apertures of 2 cm and 1 cm. The lifetimes for a 2-cm gap lie in the range of about 20-35 hours. The lifetime degradation for a gap of 1 cm is substantial, about a factor of two.

Overall beam lifetimes (at an aperture of 1 cm) are shown in Fig. 3 for the various beam scenarios. Multibunch lifetimes remain in excess of 6 hours even with a 1 cm gap, although the single bunch case yields lifetimes of only 4-5

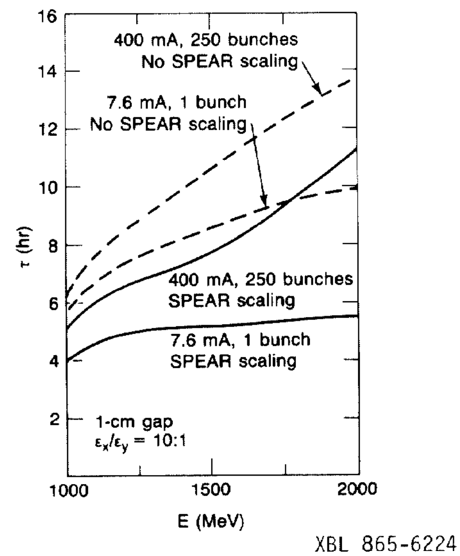

Fig. 3. Predicted overall beam lifetimes for single-bunch and multibunch scenarios.

hours. Given the ability to fill the storage ring rapidly, this should still lead to acceptable experimental conditions.

Summary

We have used the code ZAP to calculate the various collective effects that can influence beam performance in the LBL 1-2 GeV Synchrotron Radiation Source. The results indicate that the performance goals of short bunch length, long lifetime and small transverse emittance for the facility are achievable. Potential coupled bunch instabilities call for both higher order mode suppression schemes for the rf and feedback systems.

References

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