ZAP AND ITS APPLICATION TO THE OPTIMIZATION OF SYNCHROTRON LIGHT SOURCE PARAMETERS*

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Abstract

The design of electron storage rings for the production of synchrotron radiation has become increasingly sophisticated in recent years. To assist in the optimization of such storage rings, a new, user-friendly code to treat the relevant collective phenomena, called ZAP, has been written at LBL. The code is designed primarily to carry out parameter studies of electron storage rings, although options for protons or heavy ions are included where appropriate. In this paper, we first describe the contents of the code itself, and then illustrate, via selected examples, how the collective effects treated by ZAP manifest themselves in the new generation of synchrotron light sources.

Introduction

There has been worldwide interest recently in the design of high-brightness synchrotron light sources, both for the VUV and X-ray regimes. Most of these facilities are intended to meet the characteristic (but conflicting) requirements of low emittance, short bunches, long lifetime, and high beam intensity. As beam dimensions decrease and beam intensities increase, of course, the influence of various collective phenomena on beam properties becomes more pronounced. To investigate the influence of these effects, a new computer code, called ZAP [1], has been written at LBL. The code is designed to facilitate parameter studies of storage rings. Such studies permit the design team to make optimum parameter choices for their particular circumstances.

Description of the Code

ZAP is an interactive Fortran code designed to run on a VAX computer. However, it was written in a manner that should not preclude its being used on other machines. A ZAP User's Manual [1] has been prepared, and is available upon request from its authors.

Inputs to the code--generally provided from a terminal--fall into three categories. The first of these involves machine parameters, e.g., circumference, momentum compaction factor, natural emittance, damping times, lattice functions. Second, there are beam parameters, e.g., energy, intensity, bunch length, momentum spread. Third, there are radio-frequency (RF) system parameters, e.g., frequency, voltage, and higher-order cavity modes.

In general, the various ZAP routines are rather loosely coupled, that is, there is no constraint in the code that the results of one routine must be used as inputs to a subsequent routine. This feature greatly facilitates parameter studies, but it does place the burden on the <u>user</u> to interpret the results of his calculations properly. (Stated another way, the code has been written to be consistent with the General Law of Computing: Garbage In, Garbage Out.)

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ZAP calculations are performed by selecting from any of nine "Main Menu" options. Options 1-6 are stand-alone options, in the sense that their inputs can all be provided from the terminal; options 7-9, however, require a table of lattice functions that has previously been written to a disk file. The individual Main Menu options are described below; details can be found in Ref. [1].

Main Menu Options

1 = SINGLE BUNCH THRESHOLDS

A table of single-bunch parameters is calculated as a function of RF voltage, based on the longitudinal microwave and transverse fast-blowup (or, if lower, transverse mode-coupling) thresholds. Included are bunch length, synchronous phase angle, synchrotron tune, (combined) resistive-wall and parasitic-mode energy loss estimates, RF bucket momentum half-height, threshold currents for both longitudinal and transverse instabilities, and the bunch current corresponding to the more severe of these.

2 = SINGLE BUNCH LONGITUDINAL PARAMETERS and ENERGY SCALING TABLES

This option comprises three different "utility" routines. The first produces a table, as a function of beam current, of longitudinal bunch parameters, based on the longitudinal microwave instability ("turbulent bunch lengthening"), the effect of potential-well distortion, or the combined effect of both phenomena.

The remaining routines produce tables of parameters needed for calculations of electron or proton storage rings, respectively, as a function of energy.

3 = LONGITUDINAL COUPLED-BUNCH INSTABILITIES

This option performs longitudinal coupled-bunch calculations for equally spaced Gaussian or parabolic bunches. The code lists the modes having the fastest growth rates and those having the largest frequency shifts. Landau damping is also considered.

4 = TRANSVERSE COUPLED-BUNCH INSTABILITIES

This option provides the same information as Main Menu option 3, but for the transverse case.

5 = GAS SCATTERING LIFETIME

This option calculates e-folding electron beam lifetimes for gas scattering. Both elastic and Bremsstrahlung processes are considered.

6 = FREE ELECTRON LASER FORMULAE

This option evaluates the FEL performance of a ring. For a specified wavelength and undulator gap, parameters for the required undulator are calculated, as are values for the FEL gain parameter and e-folding length. The degradation in performance due to the finite beam momentum spread is also evaluated.

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7 = INTRABEAM SCATTERING

This option calculates beam growth rates (in all three dimensions) due to the effects of intrabeam scattering (IBS). If non-zero synchrotron radiation damping rates are provided (for electrons), ZAP iterates to obtain the equilibrium emittance based on the balance among quantum fluctuations, IBS, and radiation damping. Otherwise, IBS rates at the specified beam emittance are evaluated. Overall rates are weighted averages of those calculated point by point throughout the lattice.

8 = TOUSCHEK SCATTERING

This option evaluates the Touschek scattering half-life as a weighted average over the lifetimes calculated point by point throughout the lattice. The momentum acceptance at any given lattice point is based on the minimum value of the RF acceptance, the physical or the dynamic aperture. If the equilibrium emittance has been calculated (for electrons) in option 7, this value is automatically utilized in the Touschek calculation. Thus, beam blowup from IBS is taken into account in a consistent manner.

9 = ION TRAPPING FORMULAE

This option evaluates parameters relevant to the effects of ion trapping (for electrons). Critical masses for trapping are calculated, along with the limiting ion density, the neutralization factor, the equivalent ion "pressure," and the ion-induced tune shifts (all assuming full neutralization).

Examples of Parameter Optimization

To illustrate how the code can be utilized, we select several representative cases. First, we examine a series of candidate lattices that were invesigated [2] during the early design phase of the LBL 1-2 GeV Synchrotron Radiation Source. Such a parameter study is typical of that employed to evaluate the suitability of a particular lattice design for a synchrotron light source. Next, we consider the design of a storage ring optimized for use as a high-gain FEL [3]. Finally, we explore the issue of low energy injection into a storage ring. This issue has particular relevance at present because of its importance to the design of compact synchrotron radiation sources for use in x-ray lithography [4].

1-2 GeV Light Source Design

Performance issues considered here are bunch length, emittance growth, and beam lifetime. We take as a starting point a set of requirements specified [5] by the potential users of such a facility. Five different lattices were investigated: the "original" Chasman-Green ALS lattice [6], designated "CG"; an expanded Chasman-Green structure [7] in which the central quadrupole of the achromat is replaced with two empty FODO cells, designated "ECG"; a triple-bend achromat structure [8], designated "TBA"; and two FODO structures [9], one with two and one with three cells per achromat, denoted "FODO2" and "FODO3," respectively.

Bunch Length. Our requirement [5] is for very short bunches, $2\sigma_\tau \approx$ 20-50 ps. The attainable bunch length is determined by the RF parameters and the constraints of the longitudinal microwave instability. For RF parameters, we take a 500-MHz system operated at 3 MV; these parameters were selected to provide very short bunches. The influence of the longitudinal microwave instability depends upon the effective impedance of the ring. In particular, the magnitude of the bunch lengthening is very sensitive to whether or not we assume SPEAR scaling [1]. A value of 2 ohms is taken for the vacuum chamber broadband impedance; the RF cavity is assumed to have an impedance (per cell) of 0.25 ohms.

In terms of bunch length, the five lattices all show essentially identical behavior. The influence of SPEAR Scaling is demonstrated in Fig. 1. At higher currents, the bunch length is reduced by a factor of 2-3. Without SPEAR scaling, achieving a bunch length of 20 ps with a reasonable single-bunch current is clearly difficult.

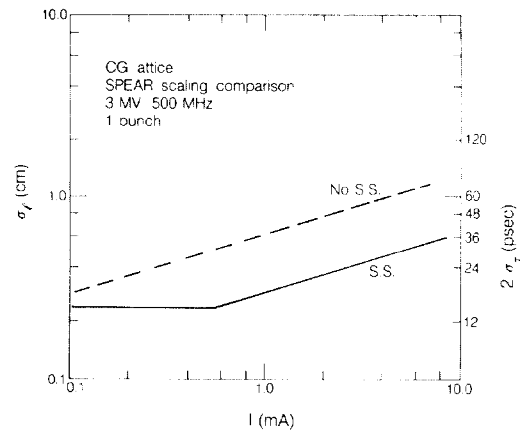

Fig. 1 Comparison of predicted bunch length with and without SPEAR scaling.

Emittance Growth. In general, the severe effects of IBS diminish rapidly as the beam energy increases. However, for lattices where the natural emittance and natural bunch length values are (by design) very small, we might expect to see some emittance blowup even at rather high energies. Because the IBS phenomenon is a single-bunch effect, the most severe problems will occur in the (high current) single-bunch scenario and for the smallest coupling. In Fig. 2 we show the emittance growth for a representative case. It is negligible at high energies and is only about a factor of 3 beyond the natural emittance at 1000 MeV. Due to the resultant higher beam density, the SPEAR scaling case leads to more growth. For all lattices investigated, the emittance growth does not compromise user requirements [5].

Beam Lifetime. Beam lifetime is limited by a combination of two effects: Touschek scattering and gas scattering. Touschek scattering is most severe for bunches having high current, short bunch length, low emittance, and weak coupling. These properties are (unfortunately from this viewpoint) just those we are striving for. Touschek lifetime is also strongly influenced by the momentum acceptance of the lattice. For these lattices, the limiting acceptance at low energies is always transverse. Touschek lifetimes have been calculated for all lattices for the cases of 400 mA in 250 bunches and 7.6 mA in 1 bunch. For both single- and multi-bunch cases the calculated pattern is about the same but, on the average, the single-bunch lifetimes are about half those for the multi-bunch case.

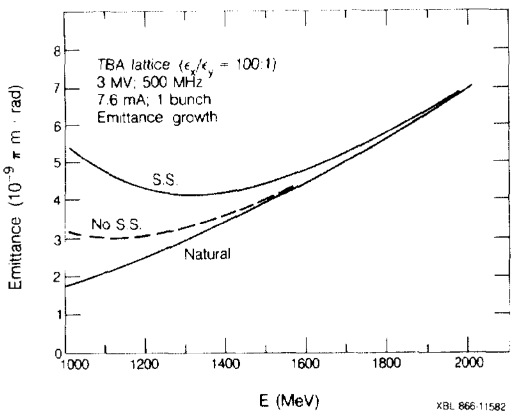

Fig. 2 Predicted emittance growth from IBS for TBA lattice.

Gas scattering lifetimes have been calculated for each lattice, assuming a pressure of 1 nTorr of nitrogen gas and a ring acceptance limited by an undulator (full) gap of 8 mm. Resultant lifetimes lie in the range of about 5-20 hours; all lattices exhibit fairly similar behavior.

Overall beam lifetimes for the five lattices are collected in Table I. Lifetimes in excess of 6 hours should be achievable in most cases. It is important to remember, however, that the lifetimes will decrease at lower beam energies.

Table I

Beam Half-Life at 1500 MeV[a)]
(10:1 emittance ratio; 3 MV; 500 MHz)

Lattice	τ_g[b)] (hrs)	400 mA; 250 bunch S.S. τ (hrs)	400 mA; 250 bunch no S.S. τ (hrs)	7.6 mA; 1 bunch S.S. τ (hrs)	7.6 mA; 1 bunch no S.S. τ (hrs)
CG	12.9	6.8	9.5	4.0	6.8
ECG	15.5	7.1	11.8	4.6	9.6
FODO2	15.0	8.4	12.3	6.0	10.0
FODO3	14.2	7.5	11.7	7.3	9.9
TBA	10.5	8.0	9.6	6.4	8.9

a) $\frac{1}{\tau} = \frac{1}{\tau_g} + \frac{1}{\tau_T}$

b) N_2 gas; P = 1 nTorr

High-Gain Free-Electron Laser Design

A promising approach to the production of coherent radiation in the XUV region is the so-called high-gain FEL [3], in which the interaction of the beam with the undulator occurs in a single pass and no mirrors are required. Because of the disruptive effect on the beam (in terms of energy loss, energy spread, and gas scattering lifetime), the FEL undulator is placed in a special bypass section, through which the stored beam passes periodically. The beam requirements for this purpose include a high peak current, a low emittance, and a small energy spread; these requirements place severe demands upon the storage ring design. To study the trade-offs inherent in such an application, a series of lattices was investigated [3].

Peak Current. For low momentum spread, the peak current limitation arises from the longitudinal microwave instability. To gain in peak current, then, the momentum spread of the beam must increase. Unfortunately, the gain of the FEL itself degrades with increasing momentum spread [3] quite rapidly, so the actual effect of the increase in momentum spread is to decrease the gain parameter and increase the e-folding length. Thus, a smaller momentum spread is favored, despite the penalty in peak current.

Lifetime. For the bypass scenario considered here, the beam lifetime is determined by Touschek scattering. The required high bunch density and relatively low beam energy make this a serious concern. Because the Touschek lifetime is a strong function of the momentum acceptance of the ring, we determined with ZAP the momentum acceptance necessary to achieve a Touschek lifetime in excess of one hour. For all the lattices studied, this value turns out to be about 3%.

Emittance Growth. There is significant emittance growth for the high peak current, low energy regime of interest for FEL purposes; this growth is generally about a factor of two beyond the natural emittance value at 750 MeV.

Optimum Beam Energy. The final issue of concern is the choice of beam energy. Issues that must be considered (simultaneously) include the threshold current for bunch lengthening, emittance growth from IBS, and Touschek lifetime. Using ZAP to sort out the rather complicated interplay among these phenomena, we obtain the results shown in Fig. 3. In this example, the best energy appears to be somewhere between 750 and about 1000 MeV.

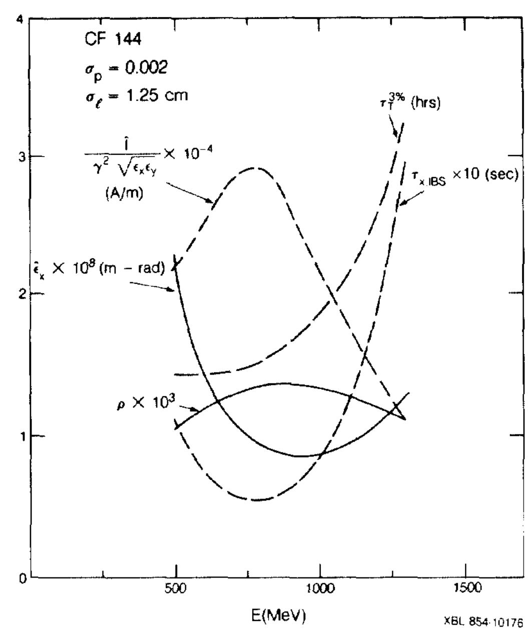

Fig. 3 Energy dependence of the following parameters: Touschek lifetime for 3% RF bucket height, $\tau_T^{3\%}$; intrabeam scattering lifetime τ_x; equilibrium emittance ϵ_x; bunch volume density $I/\gamma \sqrt{\epsilon_x\epsilon_y}$; FEL parameter ρ.

Low Energy Injection

The topic of low energy injection is an important one for electron storage rings, especially the so-called "compact" devices being designed in many places to serve as photon sources for x-ray lithography [4]. The issue, of course, is not whether a low energy injection scheme can work--it can and does--but to assess the consequences of such a technique on the required beam aperture and beam lifetime.

There can be substantial growth in the beam size at low energies under the influence of IBS, whose rate depends strongly on the phase-space density of the electron bunch. Because of the quadratic dependence of the beam emittance values (horizontal, vertical, and longitudinal) on beam energy, the relative rates of IBS at the natural emittance values for a ring (i.e., the emittance values obtained solely from the influence of synchrotron radiation emission) scale as roughly E^{-9}. Clearly, the rates associated with an injection energy of, say, 1/10 of the full energy of a ring can be very large, even if the IBS effects at full energy are essentially negligible. The mechanism that "controls" the growth rate, of course, is radiation damping. The damping rate is also strongly energy dependent, increasing as E^3 . Thus, at low energies, where little synchrotron radiation is emitted, damping times of seconds--in contrast to the millisecond damping times typical at full energy--are the rule. As a result, the situation during low energy injection can be one in which the growth rates are large and the damping rates small, leading to equilibrium emittance values from IBS that are very much larger than the natural values. Because ZAP solves for the equilibrium emittance in the presence of both synchrotron radiation and IBS, it can be used to estimate the magnitude of this growth. As examples, we discuss two rings that utilize low-energy injection and calculate the resultant effects on beam size and lifetime.

Aladdin. Aladdin is a 1 GeV electron storage ring operated by the University of Wisconsin. Its injection system is a nominally 100 MeV microtron. Because of problems during the commissioning phase of the machine, a study was carried out to investigate its behavior.

At low energies, the predicted [10] effects of IBS on the beam emittance, both longitudinal (Fig. 4) and transverse, are quite large. Thus, the beam size at injection is much larger than that given by the natural emittance of the storage ring. This is evident in Fig. 5, which shows the predicted energy dependence of the effect. It is clear that low-energy injection can lead to substantial growth, which must be taken into account in the design of the injection system. These predictions have been verified experimentally [11], with the results shown in Table II. The observed emittance is more than a factor of 100 larger than the natural emittance at injection energy, and the beam size at injection is larger than that at an operating energy of 800 MeV. It is worth noting, however, that the Touschek lifetime--which would otherwise be very low at 100 MeV--is considerably enhanced by this emittance blowup because of the concomitant lowering of the bunch density.

MAX. Another synchrotron radiation facility utilizing low-energy injection is the 550 MeV MAX ring at the University of Lund [12]. The injection scheme for this facility is similar to that at Aladdin. Predicted emittance growth (Fig. 6) is similar to that in Fig. 5, with an emittance blowup of a factor of 100 at a beam current of 50 mA.

The predicted Touschek lifetime, shown in Fig. 7, mirrors the effect of the emittance blowup, that is, the lifetimes at low energies increase substantially from what they would be in the absence of the IBS growth.

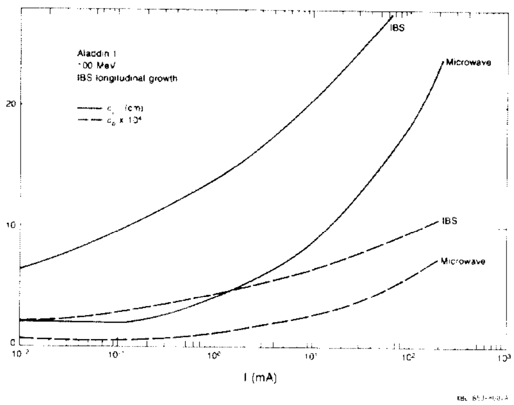

Fig. 4 Equilibrium bunch length and momentum spread as a function of beam intensity.

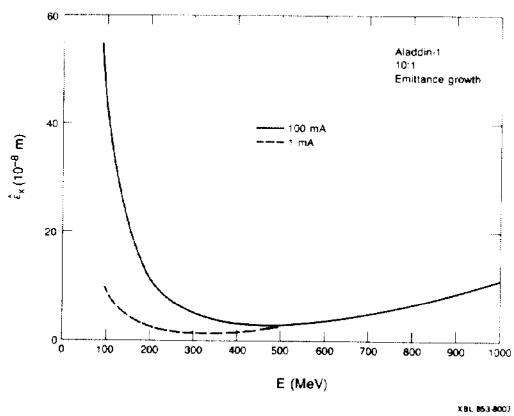

Fig. 5 Energy dependence of equilibrium transverse emittance for Aladdin.

Table II

Emittance Data

100 MeV

I (mA)	$\varepsilon_x^{meas.}$ a) (10^{-8} m-rad)	ε_x^{ZAP} b) (10^{-8} m-rad)	$\sigma_\ell^{meas.}$ (m)	σ_ℓ^{ZAP} b) (m)	$\sigma_\ell^{\mu wave}$ b) (m)
7.6	23.7 ± 7.3	11.2	1.0	1.5	1.0
4.9	23.7 ± 7.3	12.1	1.0	1.4	0.84
1.1	10.6 ± 3.9	6.9	0.84	1.1	0.51
0.5	6.6 ± 2.8	4.5	0.75	0.93	0.40
		200 MeV			
4.0	4.4 ± 2.5	2.9	1.1	0.96	0.79
2.0	4.6 ± 2.4	2.5	1.1	0.88	0.63
1.0	4.3 ± 1.9	2.0	0.9	0.80	0.50
0.5	4.4 ± 1.6	1.8	0.78	0.73	0.41

a) Assumed errors are: $\sigma_{x,y}$, 10%; $\beta_{x,y}$, 10%; D, 10%; σ_ℓ, σ_p, 20%.

b) Based on a broadband impedance of 13 Ω.

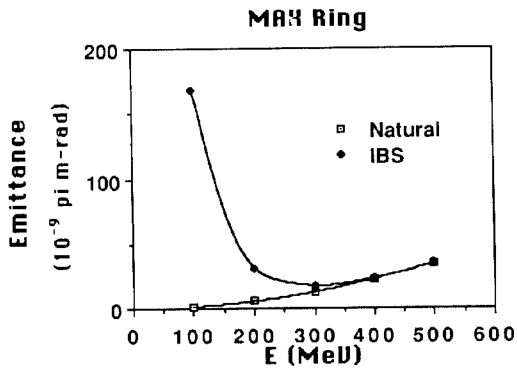

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Fig. 6 Equilibrium transverse emittance for MAX ring at a beam current of 50 mA and 10% emittance coupling.

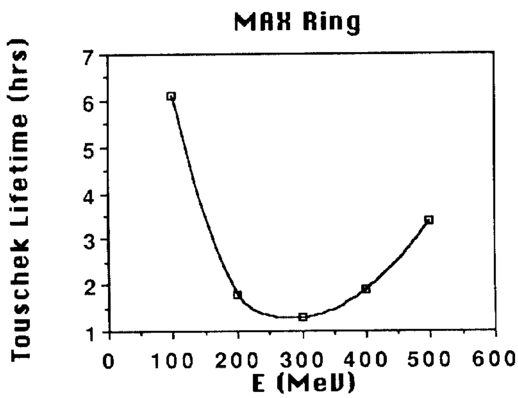

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Fig. 7 Touschek lifetime for MAX ring at a beam current of 50 mA and 10% emittance coupling.

Compact Synchrotrons. It is clear from the above results that the growth in beam size at low energies is an important issue. For the design of compact synchrotrons, fortunately, things tend to be somewhat improved. The reason is that the bending radius is much smaller, which--for a given injection energy--enhances the radiation damping process. Although the qualitative features of emittance growth are similar to those shown in Figs. 5 and 6, the growth tends to be smaller. In cases examined up to now, the emittance at 100 MeV is typically comparable to that at an operating energy of about 600 MeV. Thus, the beam size at injection energy is unlikely to greatly complicate the filling process. On the other hand, of course, the smaller beam size implies that the Touschek lifetime may be more of a problem.

Summary

A new accelerator physics code, ZAP, has been written at LBL. The code is designed for systematic studies that can elucidate the often complicated trade-offs implicit in various parameter choices. The examples contained here give some indication of how the code can be used to good advantage in the design of electron storage rings. In particular, the ability of the code to calculate the equilibrium emittance, including the effect of IBS, is very beneficial in making realistic performance evaluations.

Acknowledgments

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