A CODE FOR CALCULATING THE TIME EVOLUTION OF BEAM PARAMETERS IN HIGH INTENSITY CIRCULAR ACCELERATORS*

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Abstract

Beam emittances in a circular accelerator with a high beam intensity are strongly affected by the small angle intrabeam Coulomb scattering. In the computer simulation model we present here we used three coupled nonlinear differential equations to describe the evolution of the emittances in the transverse and the longitudinal planes. These equations include terms which take into account the intra-beam scattering, adiabatic damping, microwave instabilities, synchrotron damping, and quantum excitations. A code is generated to solve the equations numerically and incorporated into a FORTRAN code library. Circular high intensity physics routines are included in the library such as intrabeam scattering, Touschek scattering, and the bunch lengthening effect of higher harmonic cavities. The code runs presently in the PC environment. Description of the code and some examples are presented.

I. INTRODUCTION

For many years ZAP code [1] has been widely used for calculating equilibrium beam properties in high intensity circular accelerators. The code is conveniently menu-driven by an extensive inventory of menus such that the user need not have any programming skills.

In dynamic situations such as in synchrotrons, calculation of the evolution of beam parameters in a self-consistent manner in time is important. The vertical beam size is calculated self-consistently by the balancing of the damping rate with coupling and intrabeam scattering (IBS), such that the emittance ratio may be higher than the coupling ratio when intrabeam scattering is strong. The equilibrium beam parameters can be calculated naturally by letting the time run for a few damping times.

Modularization is recommended in modern programming. It is a way of unleashing the power of the routines and procedures by making them available (reusable) to other programs written by other users (client). The routines should be made as simple as possible (no fat).

Some parts of the ZAP subroutines such as the routines for calculating IBS time constants and for Touschek lifetime are used in the present FORTRAN library. New routines such as for calculating the bunch lengthening effect of third harmonic cavities are also added to the library.

Many modern accelerators demand higher beam intensities and low emittances. We found the code useful for evaluating high intensity low emittance circular accelerators such as the one contemplated for a next generation light source [2]. Our calculation showed that addition of a third harmonic cavity significantly reduces beam emittance blow up due to intrabeam scattering and at the same time increases beam lifetime.

A basic description of the code is given in section II. Some calculations are compared with measurements in section III. The modified version is particularly fast and convenient for varying certain parameters and studying how other parameters change. One such example is given in section IV.

II. THE TIME DEPENDENCE

In the present model we used the following three equations to calculate the evolution of beam parameters in time:

$$\frac{d\varepsilon_x}{dt} = -\frac{1}{\tau_x^{SR}}\left(\varepsilon_x - \frac{1}{1+\kappa}\varepsilon_x^{nat}\right) - \frac{1}{\beta\gamma}\frac{d(\beta\gamma)}{dt}\varepsilon_x + \frac{1}{\tau_x^{IBS}}\varepsilon_x \tag{1}$$

$$\frac{d\varepsilon_y}{dt} = -\frac{1}{\tau_y^{SR}}\left(\varepsilon_y - \frac{\kappa}{1+\kappa}\varepsilon_x\right) - \frac{1}{\beta\gamma}\frac{d(\beta\gamma)}{dt}\varepsilon_y + \frac{1}{\tau_y^{IBS}}\varepsilon_y \tag{2}$$

$$\frac{d\varepsilon_L}{dt} = -\frac{1}{\tau_L^{SR}}\left(\varepsilon_L - \varepsilon_L^*\right) - \frac{1}{\beta\gamma}\frac{d(\beta\gamma)}{dt}\varepsilon_L + \frac{1}{\tau_L^{IBS}}\varepsilon_L \tag{3}$$

where ε_x, ε_y and ε_L are the horizontal, vertical, and longitudinal emittances, τ^{SR} are the radiation damping times, ε^{nat} are the natural emittances, κ is the coupling coefficient, and τ^{IBS} are the intra-beam scattering (IBS) time constants [3].

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For low intensity storage rings the beam emittances are determined by the synchrotron damping and the quantum excitations [4]. which are included in the first two terms in the parenthesis on the RHS of equations (1), (2), and (3). In this case the emittances reach the equilibrium (natural) state in a few damping times, where the final emittance ratio between vertical and horizontal emittances is κ. The third term represents adiabatic damping or growth when the beam energy changes. In dynamic situations the vertical emittance is “driven” by the actual (not the natural) value of the horizontal emittance as shown in the second term in the parenthesis of equation (2). For low intensity, ε_L^* in equation (3) is interpreted as $\varepsilon_L^* = (\sigma_p^{nat}\ \sigma_L^{nat}) = \varepsilon_L^{nat}$, where σ_p^{nat} is the natural energy spread and σ_L^{nat} is the natural bunch length.

For high intensity circular accelerators, the intra-beam scattering (IBS) represented by the fourth (the last) terms is important. In the final equilibrium state, damping is balanced by quantum excitations and growths due to IBS.

If the intensity is above the threshold for the micro-wave instability (MWI) the energy spread and the bunch length increase above the natural values. In the present model this increase is treated in the same way as the quantum excitations and the value of ε_L^* in equation (3) is interpreted as $\varepsilon_L^* = (\sigma_p^{mwi}\ \sigma_L^{mwi}) = \varepsilon_L^{mwi}$.

Equations (1), (2), and (3) are coupled nonlinear equations, with τ^{IBS} depending on the beam emittances. A program is written to solve them numerically and is included in the Circular-High Intensity Physics Code library.

Most of the ZAP subroutines are rewritten into smaller modules and incorporated into the code library.

III. TESTS

The code was tested by comparing the calculated beam parameters with the measured beam parameters in the following two experiments.

In the first experiment, electrons are cooled in the ALS booster synchrotron [5] in which the 50 MeV electrons were injected into the booster, accelerated to 650 MeV and cooled for about 330 msec, decelerated to about 200 MeV, and extracted. The calculated emittances agreed well with the measurements within the experimental errors.

In the second experiment, the ALS storage ring beam sizes were measured at the diagnostics beam line [6]. Beam size should grow with current as a result of IBS and more rapidly at lower energies where IBS is stronger. The beam size at the source point was measured indirectly by measuring the spot size of synchrotron radiation on a scintillator screen. Measurements were done at two beam energies, 1100 MeV and 1522 MeV. The results are summarized in Figures 1 an 2.

Figures 1 and 2 shows that beam sizes are larger at higher currents compared to the zero current beam sizes. Beam size grows more rapidly for 1100 MeV beam.

Measurement and calculation errors may come from several systematic and random sources. Systematic errors may be caused by the optical distortion in the diagnostics beam line, saturation in the target, calculation of the magnification, calculated lattice functions, etc., and estimated to be about ± 10%. Random errors errors from unknown sources appear to be about ± 10%. Calculated beam sizes agree with the measured values within the experimental error.

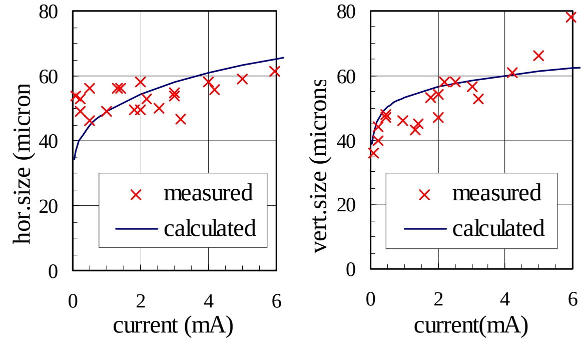

Figure 1. Measured and calculated beam sizes in the ALS for beam energy of 1100 MeV. Coupling was assumed to be 3 %.

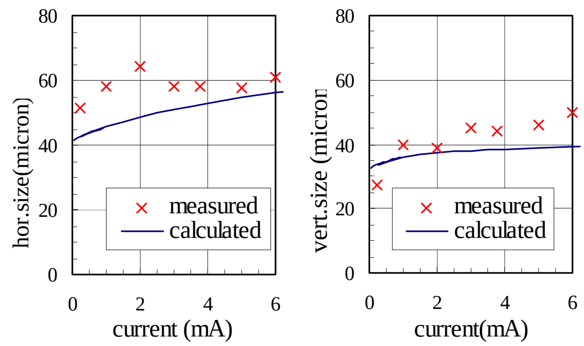

Figure 2. Measured and calculated beam sizes in the ALS for beam energy of 1522 MeV. Coupling was assumed to be 1.5 %.

The source point and the coupling were used as fitting parameters for calculating the beam sizes. The source point is the point where the beam line meets tangent to the electron orbit in the bending magnet. We achieved the best fitting if we assume that the source point is at 5.2 meters from the center of the straight section where β_x=0.39 m, β_y=20.6 m, and η_x=0.030 m. The source point could move as much as 5 cm if the orbit moved by 10 milliradians, which could give us better fittings for the two energies. However, it is not likely that we will have such a large orbit distortions in ALS [7]. The coupling were assumed to be 3 % for 1100 MeV and 1.5% for 1522 MeV in the calculation. Coupling in ALS is thought to be caused by magnet misalignments and orbit distortions. The orbit at 1100 MeV had a larger closed-orbit distortion which can explain why the coupling is larger at this energy.

IV. AN EXAMPLE

In order to illustrate the capability of the code we present the following example where the variation of beam parameters were studied as functions of the coupling coefficient. Parametric dependency studies can be done conveniently in "DO-LOOPs". Subroutines, such as the IBS routine, can be called in a do-loop repeatedly while other parameters can be varied systematically.

In the present example, the coupling coefficient was varied in a do-loop while in each do-loop the time is let run for a few damping times to calculate the equilibrium emittances, bunch length, and the lifetime for each value of the coupling. This calculation also serves a practical purpose for improving the ALS beam brightness by reducing the coupling. The calculation results are summarized in Figures 3 and 4.

The calculation was done for the normal ALS operating condition with beam energy 1522 MeV, current 400 mA, and the number of bunches 288. The beam current is just below the measured microwave instability threshold of 2 mA per bunch [8]. The half bucket height was assumed to be 2.67 % and $\nu_s = 0.0076$.

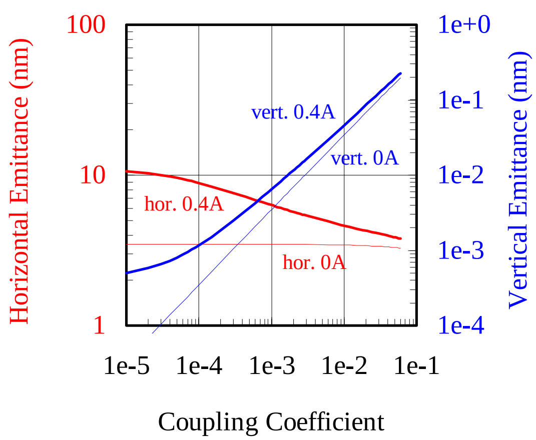

Figure 3. Horizontal and vertical emittances are plotted as functions of the coupling coefficient. The differences between the zero current and the 400 mA plot are due to the intrabeam scattering.

Some physics can also be learned. As the coupling coefficient becomes very small (κ < 0.1 %), the vertical emittance decreases until the IBS rate becomes large enough to balance the radiation damping rate. The increased intrabeam scattering rate will, in turn, cause the horizontal emittance and the bunch length to grow dramatically and reduce the beam lifetime as shown in Figures 3 and 4.

If there was no coupling (only a theoretical possibility), beam parameters equilibrated at the following values: $\varepsilon_x = 1.1 \times 10^{-8}$ m -Rad, $\varepsilon_y = 4.2 \times 10^{-13}$ m - Rad, $\sigma_L = 6.0$ mm, and $\sigma_p = 0.0009$, vertical tune shift = 0.011, and a beam lifetime of 40 minutes

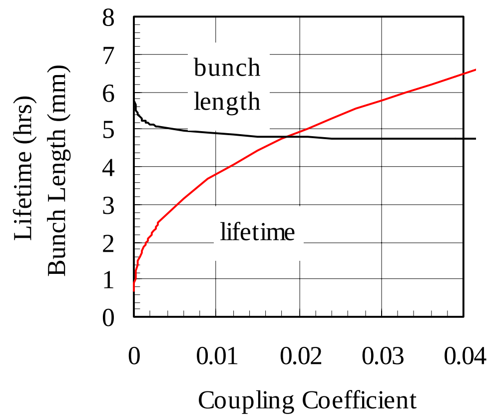

Figure 4. Bunch length and beam lifetime as functions of the coupling coefficient.

V. SUMMARY

A FORTRAN code library for circular high intensity physics is created which is used for calculating evolution of beam parameters in time in a self-consistent manner in the presence of strong intrabeam scattering. We have compared the calculated values using the library with experimentally measured values with good results.

The code runs in the PC environment using FORTAN90 in the Microsoft Development Studio©.

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