ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research A ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Simultaneous computation of intrabunch and interbunch collective beam motions in storage rings

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ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form
25 September 2015
Accepted 12 October 2015

Keywords:
Particle tracking code
Collective effects
Storage rings
Wakefields

ABSTRACT

We present the multibunch tracking code *mbtrack* developed to simulate, in 6-dimensional phase space, single- and multibunch collective instabilities driven by short- and long-range wakefields in storage rings. Multiple bunches, each composed of a large number of macroparticles, are tracked, allowing simulation of both intra- and interbunch motions. Besides analytical impedance models, the code allows employment of numerical wake potentials computed with electromagnetic (EM) field solvers. The corresponding impedances are fitted to a number of known analytical functions and the coefficients obtained in the fit are used as an input to the code. *mbtrack* performs a dynamic treatment of long-range resistive-wall and harmonic cavity fields, which are likely to be the two major factors impacting multibunch collective motions in many present and future ring-based light sources. Furthermore, it is capable of simulating beam-ion interactions as well as transverse bunch-by-bunch feedback. We describe the physical effects considered in the code and their implementation, which makes use of parallel processing to significantly shorten the computation time. *mbtrack* is benchmarked against other codes and applied to the MAX IV 3 GeV ring as an example, where the importance of the interplay of various physical effects as well as coupling among different degrees of freedom is demonstrated.

1. Introduction

The current trend in the design of a lepton storage ring is to achieve ultralow emittance in combination with a high beam current, since both increase the brightness or luminosity in light source rings [1] or circular colliders [2] respectively. However, ultralow-emittance optics generally require stronger quadrupole focusing with vacuum chambers of reduced apertures and this inevitably increases the coupling impedance of a machine. In addition, a low-emittance beam interacts with the coupling impedance over a wider frequency range due its short natural bunch length. Both the features above render a stored beam more sensitive to collective beam instabilities. Wakefields corresponding to geometric impedance generally affect only a single bunch due to their relatively fast decay times, while resistive-wall (RW) fields induce transverse coupled-bunch instabilities due to their long-range nature. However, to fully characterize the resistive-wall instability, one needs to understand the interplay between intra- and interbunch degrees of freedom. In most cases, the relation between the two instabilities depends significantly on the chromaticity and the filling pattern of the ring.

Numerical analysis of the beam instabilities described above, by simultaneously handling intra- and interbunch motions, is not straightforward as could be anticipated. Even though frequency domain methods, such as solving the linearized Vlasov or Sacherer equations for coupled bunches as in BBI [3], ZAP [4] and *rwmbi* [5], are capable of treating both short- and long-range forces, they are normally limited to symmetric beam fillings. Inclusion of incoherent tune spreads would also require a special effort. In fact, while single-bunch simulations simultaneously treating both the longitudinal and transverse planes were available since the mid-1980s [6], an early attempt [7] to study the influence of tune spreads generated by harmonic cavities on multibunch instabilities was limited to the longitudinal plane. By the same token, tracking of multiple bunches in time domain and including the transverse plane, such as done at BESSY [8], CERN [9] and SLAC [10] was still constrained to treating multiple bunches as point-like without any internal motion.

All of the physical and numerical background above gave the underlying motivation for the development of a macroparticle tracking code that pursues the single- and multibunch degrees of freedom simultaneously. Indeed, the code *mbtrack* was developed as a direct extension of a single bunch tracking code *sbtrack* [11,12]

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http://dx.doi.org/10.1016/j.nima.2015.10.029
0168-9002/© 2015 Published by Elsevier B.V.

that follows the evolution of a single bunch composed of a large number of macroparticles in 6-dimensional phase space under the influence of short-range wakefields. Such an extension was only possible thanks to the marked progress in the field of numerical computation in the last decade, when parallel processing became feasible relatively simply through the use of a cluster of processors and libraries such as Message Passing Interface (MPI) [13] and Parallel Virtual Machine (pvm) [14]. The code *mbtrack* is parallelized with one 'manager' task responsible for the data processing and exchange with the 'worker' tasks, each corresponding to a single bunch formed by a large number of macroparticles. The manual to *mbtrack* can be found at [15].

An important source of long-range wakefields that could be present in light source storage rings is passive harmonic cavities, introduced primarily to lengthen the bunches and increase synchrotron frequency spread. The former improves the Touschek lifetime and limits Intra Beam Scattering (IBS) and the latter generates Landau damping of coherent instabilities. While the above beneficial effects were experimentally observed longitudinally [16–20] in a number of light source storage rings, theoretically one could anticipate it to exist transversely as well. In fact, the MAX IV rings [21] seek to counteract transverse instabilities by introducing passive harmonic cavities. For studying the impact of transient beam loading during the current ramp as well as Landau damping due to the harmonic cavity potential, multibunch tracking appears to be most flexible, quantitatively accurate and reliable. A fully dynamical treatment of passive harmonic cavities has been implemented in *mbtrack* and is described in the present paper. The code can perform tracking not only of bunches placed equidistantly but also in arbitrary filling patterns.

Besides the beam instabilities arising from the coupling impedance, simulation of the Fast Beam-Ion Instability (FBII) was implemented in *mbtrack*. Bunch-by-bunch transverse feedback including Finite Impulse Response (FIR) filters has also been introduced and this helped to better understand the mechanism of beam losses occurring at SOLEIL at high beam current as a consequence of a non-trivial interplay among the resistive-wall instability, FBII and the transverse feedback [22]. This paper is organized as follows: in the following section, we cover the theory and equations describing the different single- and multibunch effects treated in the code. In Section 3, we describe the code structure, in particular, the parallelization of computation, communication and implementation of the various physical effects. Then, in Section 4, we benchmark the code and apply it to the case of the MAX IV 3 GeV ring as an example in Section 5. Finally, a summary is given in Section 6.

2. Theory

When circulating in an accelerator beam pipe, charged particles create and leave behind wakefields that can be short-range, as in the general case of geometric impedance, or long-range, such as those arising from the finite wall conductivity and high Q cavities. These fields may affect the trailing particles and lead to beam energy losses and the onset of various beam instabilities. Another phenomenon causing beam instability is the interaction of the circulating beam with ions created and trapped in the storage ring vacuum chamber.

To pursue possible consequences of exposing a beam to wakefields and ions, one can perform phase space transformations according to the machine optics in the presence of the above mentioned effects.

2.1. Basic single particle transformations

The position of every macroparticle in phase space is described by the 6-vector $(x, x', y, y', \tau, \delta)$. x and y are the horizontal and vertical positions, $x' = \frac{dx}{ds}$ and $y' = \frac{dy}{ds}$ are the transverse momenta at longitudinal position s, and $\delta = \frac{\Delta E}{E_0}$ is the energy deviation relative to the reference particle's energy E_0. The longitudinal coordinate τ is the arrival time with respect to the reference particle.

Basic optics transformations are done once per turn with the revolution period T_0. First, we shall describe the transformations in the longitudinal plane.

The energy deviation at turn $i+1$ can be found from that at the previous turn i, the relative energy gain in the RF cavities ϵ and the synchrotron radiation losses U_{rad}

$$\delta_{i+1} = \delta_i + \epsilon_i - \frac{U_{rad}}{E_0}. \tag{1}$$

The longitudinal coordinate is transformed as follows:

$$\tau_{i+1} = \tau_i + \delta_i T_0 \alpha_c \tag{2}$$

with α_c being the momentum compaction factor. The relative energy gain from the RF cavities is determined as

$$\epsilon_i = \frac{e}{E_0} V_{RF} \sin(\omega_{RF}\tau_i + \phi_s) \tag{3}$$

where V_{RF} is the peak voltage, ω_{RF} is the angular RF frequency, ϕ_s is the phase of the synchronous particle and e is the electron charge. Besides the main RF frequency the system may include additional cavities that may be at higher harmonics of the main RF. The total energy gain is then

$$\epsilon_i = \frac{e}{E_0} V_{\sum}(\tau_i) = \frac{e}{E_0}[V_{RF} \sin(\omega_{RF}\tau_i + \phi_s) + \sum \hat{V}_j \sin(n_j \omega_{RF}\tau_i + n_j \phi_j)] \tag{4}$$

where $\hat{V}_j$ is the peak voltage of the j-th harmonic cavity with angular frequency $\omega_j = n_j \omega_{RF}$ and phase $n_j \phi_j$ where n_j is a positive number.

A bunch lengthening harmonic cavity can be represented with the help of the second term in Eq. (4). In fact, it can be shown [23] that an increase of the bunch length as well as of the incoherent synchrotron frequency spread is achieved if the first and second-order derivatives of the potential function are both zero at the synchronous phase (flat-potential conditions Eq. (5))

$$\left.\frac{\partial V_{\sum}(\tau)}{\partial \tau}\right|_{\tau=0} = \left.\frac{\partial^2 V_{\sum}}{\partial \tau^2}\right|_{\tau=0} = 0. \tag{5}$$

In the case of a single higher harmonic, for which these conditions are satisfied, the total energy gain is

$$\epsilon = \frac{e}{E_0} V_{RF}[\sin(\omega_{RF}\tau + \phi_s) + k \sin(n\omega_{RF}\tau + n\phi_h)] \tag{6}$$

with n being the harmonic number and the following parameters:

$$k = \sqrt{\frac{1}{n^2} - \frac{U_{rad}^2}{e^2 V_{RF}^2} \frac{1}{n^2 - 1}} \tag{7}$$

$$\tan(n\phi_h) = \frac{1}{n} \tan(\phi_s) = -\frac{nU_{rad}/(eV_{RF})}{\sqrt{(n^2-1)^2 - (n^2 U_{rad}/(eV_{RF}))^2}}. \tag{8}$$

The synchronous phase is now expressed as

$$\sin\ \phi_s = \frac{n^2}{n^2 - 1} \frac{U_{rad}}{eV_{RF}}. \tag{9}$$

In both transverse planes, the beam particles perform betatron oscillations, which are commonly described using Twiss parameters $\alpha_{x,y}$, $\beta_{x,y}$, $\gamma_{x,y}$ and a phase advance per turn $\Psi_{x,y}$. This phase advance for particles with $\delta = 0$ can be expressed in terms of the

Please cite this article as: G. Skripka, et al., Nuclear Instruments & Methods in Physics Research A (2015), http://dx.doi.org/10.1016/j.nima.2015.10.029