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Impedance computations and beam-based measurements: A problem of discrepancy

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ABSTRACT

High intensity of particle beams is crucial for high-performance operation of modern electron–positron storage rings, both colliders and light sources. The beam intensity is limited by the interaction of the beam with self-induced electromagnetic fields (wake fields) proportional to the vacuum chamber impedance. For a new accelerator project, the total broadband impedance is computed by element-wise wake-field simulations using computer codes. For a machine in operation, the impedance can be measured experimentally using beam-based techniques. In this article, a comparative analysis of impedance computations and beam-based measurements is presented for 15 electron–positron storage rings. The measured data and the predictions based on the computed impedance budgets show a significant discrepancy. Three possible reasons for the discrepancy are discussed: interference of the wake fields excited by a beam in adjacent components of the vacuum chamber, effect of computation mesh size, and effect of insufficient bandwidth of the computed impedance.

1. Introduction

High intensity of particle beams is crucial for effective and high-performance operations of modern electron–positron storage rings, both colliders and light sources. One of the significant limiting factors of beam intensity is the beam's interaction with electromagnetic fields induced in a vacuum chamber by the beam itself (collective effects of beam dynamics). This interaction can result in serious troubles affecting accelerator operations, such as overheating of vacuum chamber components or instability of beam motion, leading to deterioration of the beam quality or limitation of the beam intensity. The interaction of a particle beam with its surroundings is described using the concept of impedance. Basically, the interaction intensity is proportional to the product of the impedance and the beam current.

For a new accelerator project, computation of the impedance budget is an essential part of the accelerator design. The impedance must be minimized to achieve the design beam intensity and quality. Beam-based measurement of the impedance is an important part of machine commissioning. Comparisons of impedance computations and beam-based measurements show significant discrepancies for many machines, a factor of two or even more is not something unusual. There are many publications describing thorough calculations of impedance budgets, where finally the total impedance is multiplied by a "safety factor" of two. However, there are operating machines, which have not achieved their design beam currents because the collective effects nave not been predicted correctly at the design stage. Thus, the accuracy of impedance computation seems to be not adequate for engineering design of modern accelerator facilities, which are extremely complex and expensive. For such rough estimates, there is no need for comprehensive computer simulations, approximate formulae are sufficient. Since the accuracy of impedance budget computations is not sufficient, understanding the reasons for this discrepancy is important if we want to improve the impedance computations and predict stability conditions for a high-intensity particle beam in future accelerators.

In this article, results of comparative analyses of impedance computations and beam-based measurements are presented. For 15 electron–positron storage rings, the impedance budgets are taken from articles published before commissioning. For the same machines, the broadband impedances were estimated from beam parameters measured experimentally using beam-based techniques during commissioning and operations. Possible reasons for the observed discrepancy between the computed and measured impedances are discussed: (1) interference of the wake fields excited by a beam in adjacent components of the vacuum chamber; (2) effect of computation mesh size; (3) effect of insufficient bandwidth of the computed impedance.

2. Wake fields and impedances

Fundamentals of the theory of collective effects and impedances are described, for instance, in [1,2]. The concept of the wake function is

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used to describe the interaction of relativistic charged particles with the wake fields. The wake function is a time-domain response of a vacuum chamber to a point-charge excitation; in an ultra-relativistic case, it is determined only by the geometry and electromagnetic properties of the chamber, and it is independent of the beam parameters. The wake function is defined as a normalized integral of the Lorentz force that acts on a test particle moving behind a leading particle which excites the wake fields. To analyze the beam stability in most practical cases, it is enough to consider only the monopole longitudinal $W_\parallel$ and dipole transverse $\mathbf{W}_\perp$ wake functions. The longitudinal wake function is obtained by integrating the electric field component E_z, which is parallel to the velocity $\mathbf{v}$ ($|\mathbf{v}| = c$) of the particles moving on the same trajectory [2]:

$$W_\parallel(\tau) = -\frac{1}{q}\int_{-\infty}^{\infty} E_z(t,\tau)\,\mathrm{d}t\,, \tag{1}$$

where q is the charge of the leading particle, $\tau = s/c$, s is the distance between the leading and trailing particles, c is the speed of light. The dipole transverse wake function is determined similarly to the longitudinal one as an integral of transverse electromagnetic forces normalized by the dipole moment qr of the leading particle (r is the transverse offset); it is a vector with horizontal and vertical components:

$$\mathbf{W}_\perp(\tau) = -\frac{1}{q\,r}\int_{-\infty}^{\infty} [\mathbf{E}(t,\tau) + \mathbf{v}\times\mathbf{B}(t,\tau)]_\perp \mathrm{d}t\,. \tag{2}$$

The longitudinal and dipole transverse wake functions are related to each other by the Panofsky–Venzel theorem [2,3].

For a beam with arbitrary charge distribution, its interaction with wake fields is described by the wake potential V, which is a convolution of the wake function W and the longitudinal charge density $\lambda(t)$:

$$V(\tau) = \int_0^{\infty} W(t)\lambda(\tau - t)\mathrm{d}t\,, \tag{3}$$

where $\lambda(t)$ is normalized as $\int_{-\infty}^{\infty}\lambda(t)\mathrm{d}t = 1$.

In the frequency domain, each part of the vacuum chamber is represented by a frequency-dependent coupling impedance. Longitudinal $Z_\parallel$ and transverse $Z_\perp$ impedances are defined as Fourier transforms of the corresponding wake functions. The major contributors to the total impedance are: finite conductivity of the walls (resistive-wall impedance), steps and tapered transitions, high-order modes of accelerating RF cavities, electrostatic pickup-electrodes, strip-lines, flanges, bellows, synchrotron radiation ports, and other non-uniform sections of the vacuum chamber.

There is an approximate relation between the longitudinal $Z_\parallel(\omega)$ and dipole transverse $Z_\perp(\omega)$ impedances (conclusion of the Panofsky–Venzel theorem):

$$Z_\perp(\omega) \approx \frac{2c}{b^2\omega} Z_\parallel(\omega)\,, \tag{4}$$

where b is the vacuum chamber aperture. This equation is exact for a round pipe with resistive walls, b is the pipe radius.

3. Impedance computation and beam-based measurement

There are several approximate analytical formulae used to calculate impedances of sections with simple geometry, such as pillbox cavities or step transitions. A useful collection of the formulae is published in [4]. To compute the impedance of vacuum chamber components with complex geometry, 3D simulation codes are used, e.g. GdfidL [5] or CST Particle Studio [6]. These codes solve Maxwell equations with boundary conditions determined by the chamber geometry. The fields are excited by a model bunched beam with pre-defined charge distribution. The simulation code output is the wake potential (3) which is a convolution of the wake function and the longitudinal bunch profile. Taking into account that a convolution of two time-domain functions is equivalent to a product of their Fourier transforms, the impedance is calculated as

$$Z(\omega) = \frac{\tilde{V}(\omega)}{\tilde{\lambda}(\omega)}\,, \tag{5}$$

where $\tilde{V}$ and $\tilde{\lambda}$ are the Fourier transforms of the wake potential and the longitudinal charge density, respectively. So the bandwidth of the impedance derived from the simulated wake potential is limited by the bunch spectrum width, which is inversely proportional to the bunch length defined for the simulation. The mesh size of the solver is essential, it should be small enough to get reliable results for a given bunch spectrum. For a typical bunch length of few millimeters, full 3D simulation of wake fields in a big and complex structure is quite difficult because huge memory and processor time are required.

For beam stability analysis, the total impedance of a vacuum chamber can be approximated by a finite number of equivalent resonators with proper frequencies, shunt resistances and quality factors. Since narrow-band oscillation modes are more long-living than broadband modes, we can assert that the narrow-band impedance causes the bunch-by-bunch interaction and can result in multi-bunch instabilities, whereas the broadband impedance causes the intra-bunch particle interaction and can cause single-bunch instabilities. The beam–impedance interaction manifests itself in several effects of beam dynamics, some of these effects can be measured quite precisely using modern beam diagnostic instruments and measurement techniques, and the measured data are used for the impedance estimation.

3.1. Longitudinal broadband impedance

For the longitudinal broadband impedance, the measurable single-bunch effects are: current-dependent bunch lengthening, synchronous phase shift, and energy spread growth due to the microwave instability. These effects are dependent on integral parameters combining the impedance and the bunch power spectrum: the effective impedance and the loss factor. If the bunch length is much shorter than the ring average radius, the normalized effective impedance $(Z_\parallel/n)_{\mathrm{eff}}$ is defined as

$$\left(\frac{Z_\parallel}{n}\right)_{\mathrm{eff}} = \frac{\int_{-\infty}^{\infty} Z_\parallel(\omega)\frac{\omega_0}{\omega}h(\omega)\mathrm{d}\omega}{\int_{-\infty}^{\infty} h(\omega)\mathrm{d}\omega}\,, \tag{6}$$

where $Z_\parallel(\omega)$ is the frequency-dependent longitudinal impedance, $n = \omega/\omega_0$ is the revolution harmonic number, $\omega_0 = 2\pi f_0$ is the revolution frequency, $h(\omega) = \tilde{\lambda}(\omega)\tilde{\lambda}^*(\omega)$ is the bunch power spectrum, $\tilde{\lambda}(\omega)$ is the Fourier transform of the longitudinal charge density $\lambda(t)$. For a Gaussian bunch, $h(\omega) = e^{-\omega^2\sigma_t^2}$, where $\sigma_t = \sigma_z/c$, σ_z is the bunch length. The effective impedance (6) will be used in the next section to compare computations and beam-based measurements of the longitudinal broadband impedance.

The loss factor $k_\parallel$ characterizes the coherent loss ΔE of the beam energy caused by the beam–impedance interaction

$$\Delta E = k_\parallel q^2\,, \tag{7}$$

where q is the bunch charge. The loss factor can be expressed in terms of the wake potential $V_\parallel$ or of the impedance $Z_\parallel$:

$$k_\parallel = \int_{-\infty}^{\infty} V_\parallel(t)\,\lambda(t)\mathrm{d}t = \frac{1}{2\pi}\int_{-\infty}^{\infty} Z_\parallel(\omega)\,h(\omega)\mathrm{d}\omega\,. \tag{8}$$

If the bunch is not very short, the measurable single-bunch effects can be described with reasonable accuracy using a simple broadband resonator model. For longer bunches, even the simplest inductive model $Z_\parallel/n = const$ is acceptable.

Interaction of a bunched beam with the broadband impedance deforms the longitudinal bunch profile $\lambda(t)$, which is Gaussian for a zero-intensity beam. The bunch profile can be measured directly using a streak-camera or a dissector tube; the bunch length can be measured indirectly by measuring the bunch spectrum width using a pickup electrode. At small beam currents (below the microwave instability threshold), the energy spread of a relativistic beam is independent of its intensity, and $\lambda(t)$ as a function of the average bunch current $I_b = qf_0$ can be described by the Haissinski integral equation [7]:

$$\lambda(t) = K\lambda_0(t)\exp\left(\frac{I_b}{\omega_s\sigma_\delta\frac{E}{e}}\int_{-\infty}^{t}\mathrm{d}t''\int_{-\infty}^{\infty}\mathrm{d}t' W_\parallel(t''-t')\lambda(t')\right), \tag{9}$$