IMPEDANCE COMPUTATION AND MEASUREMENTS IN MODERN STORAGE RINGS

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Abstract

Recent progress in the evaluation of machine impedance and instability thresholds are reviewed, and comparisons made between measurements and predicted impedance in some of the modern storage rings including those recently commissioned.

INTRODUCTION

Modern accelerators are always pushed for a higher beam current, as the latter scales linearly with brightness and luminosity in light source storage rings and high energy physics rings respectively, while for linac-based FEL machines, the bunch current is to scale quadratically with the peak brightness explored. Higher the beam current, stronger will be the collective beam interaction with its self-induced electro-magnetic (EM) fields, namely the wake fields, whose frequency contents are described by the impedance. It likely results in beam quality degradation, instability, as well as vacuum components heating, spoiling the performance. Study of impedance and instability is therefore of critical importance in constructing a new machine.

Specifically, the nature of wakes well differs according to the type of machines. In light sources, the presence of many low gap chambers for insertion devices generally keeps the vertical aperture small in the rest of the ring, resulting in distributed impedance composed of tapers, resistive-wall (RW), and numerous 3D discontinuities. In high energy physics rings, the impedance may be localised, consisting of collimators, injection and extraction kickers, and metallic coated ceramic chambers. Due to their large circumference, low frequency wakes may be important in multibunch fillings. In linac-based FEL machines, the shortness of bunches raises the importance of high frequency wakes beyond the known range, of components such as tapers, collimators, long accelerating cavities and surface roughness, as well as of CSR wakes. Confronted impedance issues motivate studies and developments in the related areas such as time domain numerical wake field computations, analytical wake field studies, simulation of collective beam dynamics, and measurement of impedance, outcomes of which are often useful in other types of machines. In the following, we shall overview the progress above, as well as comparisons between measurement and expectation in some of the modern storage rings including those recently commissioned.

TIME DOMAIN NUMERICAL WAKE FIELD COMPUTATIONS

Wake fields in a general structure may be most accurately obtained via numerical solution of Maxwell's equations. Since the '80s, the first 2D and 3D codes were developed, such as *TBCI*, *MAFIA*, *ABCI*, *NOVO*, and *XWAKE*. Newer rings, in particular light sources, which appeared since the '90s, having flat chambers and shorter bunches, required more powerful computations in 3D geometry, with smaller mesh and longer integration time, as trapped modes are often encountered. Linac-based FEL machines are confronted to wakes of even shorter bunches in the sub mm range over long structures. Facing this situation, major breakthroughs are being made in EM solvers, which are all beneficial for storage rings.

The first of such may be *parallelisation* using a cluster of cpu's, which is implemented in several codes [1-3]. In *GdfidL* [1], the required memory is initially greatly reduced with *linked lists* that store discretised 3D EM arrays of non-conducting materials alone. The computational volume is divided into many sub-volumes leaving only a small non-conducting volume, which is distributed to different cpu's. The scheme developed in *PBCI* [3] makes efficient decomposition (recursive orthogonal bisection) of the computational volume with load balancing.

The second effort consists in *suppressing numerical grid dispersion errors* in solving discretised Maxwell equations. A major interest behind this elaboration may be the use of "moving mesh" technique [4] that greatly reduces the memory and cpu time, which would best work in the absence of dispersion errors. Several different approaches have been developed, which are compatible with parallelisation (i.e. *explicit* integrations), such as *Mesh rotation* [5], *TDBEM*: (Time Domain Boundary Element Method) [6] and *Split-Operator* methods [3].

Another important step forward may be the recently achieved generalisation of Napoly integration to 3D structures [7-8]. The Napoly integration concerns numerical treatment of beam pipe boundaries due to wakes requiring a long time to catch up relativistic bunches after discontinuity. The scheme in Ref. 7 involves integration of TM and TEM fields along transverse direction at given longitudinal positions, while in Refs. 3, 8 integrations are made via 2D eigenmode decomposition of the excited fields at longitudinal boundaries. In particular, the pure frequency domain approach in the latter [3] allows avoiding integration between two structures connected by a long beam pipe, resulting in a significant saving of the computation time.

ANALYTICAL WAKE FIELD STUDIES

Looking firstly from the geometrical impedance, improved taper impedance models in the inductive regime were derived by B. Podobedov et al. [9-10]. In their studies, the existing formulae by Yokoya and Stupakov were identified as the leading terms in their perturbation expansion; an extension was made to elliptical cross sections; good agreement was found between theory and numerical calculations (*ABCI*, *GdfidL* and *ECHO*); the obtained formulae were used to optimise nonlinear tapering, where more than a factor of 2 of reduction in the inductive impedance was achieved for large minimum and maximum gap ratios (~20).

To study the high frequency wakes excited by sub-mm bunches in future linac-based FELs, the evaluation of which would not be easy even numerically, the existing theory was extended by the SLAC and DESY groups to what was named as the *optical regime*, where diffraction no longer exists. The developed theory was applied to collimators [11-12]. Interesting experiments were also made, measuring the kick factors of different kinds of geometric impedance dominated collimators prepared in the SLAC linac, to compare with theory and numerical calculations (*MAFIA* and *ECHO*) [13]. There was good overall agreement, particularly between measurement and calculations, to 20-30% levels, while the theory disagreed up to nearly a factor of 2 in some cases.

Several theoretical models of the surface roughness impedance were developed in the last decade, again primarily in view of its possible impact on short bunches. While it was found that a collection of uncorrelated μm-level bumps on the surface may bring about a significant effect [14], a more precise evaluation of an actually measured well finished surface in the *small angle approximation* led to a much weaker effect [15]. Numerically, it was found that excited wakes resemble that generated by a periodically corrugated beam pipe [16]. An excellent review is found in Ref. 17. As what may be related to the roughness impedance, it was observed in Elettra in a repetitive manner that NEG coated chambers generate coherent tune shifts which are nearly double of non-coated ones [18]. Since these tune shifts were much larger than what was estimated from the resistivity of the coating itself, at SOLEIL it was decided to decrease the thickness of the NEG coating by a factor of 2 to 0.5 μm for precaution, as nearly a half of the ring is NEG coated.

Many of the recent studies on RW wakes addressed their deviations from the classical formula, such as at low frequencies, at very short range, due to non-circular cross section, finite wall thickness, and the presence of different material layers. In a representative work by Burov and Lebedev [19], general analytical impedance formulae were derived for circular and flat chambers with arbitrary layers, with correct low frequency behaviour. A detailed theoretical explanation on the incoherent tune shifts observed in several machines due to the RW of non-circular chambers was given by A. Chao et al., including the evaluation of diffusion time of the excited field in a finite thickness wall [20]. At the ESRF, single turn contributions of the tune shift were measured by differentiating between the head and tail of a bunch train, as well as following the tune shift in single bunch, finding good agreement with theory [21].

At CERN, studies of the RW impedance of collimators to be used in LHC led to revelation of a new physical regime. Although the skin depth at the first betatron line (~8 kHz) of around 2 cm is still thinner than the collimator thickness of ~2.5 cm, it was found that the real part of the impedance is actually roughly 2 orders of magnitude smaller than that given by the classical formula [22-23]. The physical interpretation given is that when the skin depth is much larger than the distance between the beam and the wall, the effective aperture increases as the image current flows deep inside the wall. Another interesting study came from measuring the LHC collimator impedance in the SPS ring, where the measured coherent tune shifts were smaller than expected by nearly a factor of 2. Being in the regime where the beam size is comparable to the gap size, the theory was extended to include nonlinear wakes, both coherent and incoherent wise, by keeping the correct time dependence, which well explained the observed discrepancies [24].

SIMULATION OF COLLECTIVE BEAM DYNAMICS

We shall review below some recent progress in the beam tracking, namely the time domain simulation, in which more works appear to exist as compared to the frequency domain approach. This may reflect better adaptability and flexibility of the former in describing complicated collective dynamics.

The first noted elaboration may be the use of more realistic impedance models, namely the outputs of what discussed in the previous two sections, instead of simplified models such as a single broadband resonator or purely inductive impedance scaled to reproduce some measured collective effects. A list of examples includes; - Direct use of wake potentials numerically obtained (with *GdfidL*) for short bunches in *Pelegant* (parallelised *elegant*) at APS [25], - 2D and 3D *MAFIA* results fitted to analytical impedance models (inductive, resistance and cavity-like) in *CISR* and *SISR* at SPring-8 [26], - Use of a collimator RW wake function and electron clouds outputs of *ECLOUD* in *HEADTAIL* at CERN [27]. At SOLEIL, wake potentials numerically obtained with *GdfidL* were transformed to impedances, which were decomposed into components whose wake functions are analytically known, enabling wake potentials to be constructed for any bunch distributions. Machine files comprising piecewise RW information, along with machine optics, were prepared for accurate evaluation of RW effects [28].

Inclusion of different sources of instability to study their combined effects, as well as simultaneous treatment of short and long range forces may be another marked step forward. In *HEADTAIL*, a broadband resonator, RW, space charge, electron clouds, and dipole and quadrupole wakes are included [27]. Wake fields were included in space charge oriented codes such as *ORBIT*, *TRANFT* and *SIMPSONS* [29-31]. In *elegant*, wake fields, space charge, the coherent synchrotron radiation (CSR) impedance, as well as intra-beam scattering (IBS) are treated [32]. A multibunch tracking code *MULTI-TRISIM* was developed at CERN to simulate RW-induced coupled-bunch instability in high energy proton rings such as LHC in arbitrary bunch filling [33]. However, each bunch is treated as a macro-particle and no bunch internal motions are taken into account. The code *mbtrack* developed at SOLEIL is a direct extension of a single bunch tracking code *sbtrack* to multibunch, which keeps the full 6-dimensional bunch internal motions in treating long-range inter bunch forces [28].

As it is done for EM field solvers, parallelisation has been introduced in some codes to shorten the cpu time. *Pelegant* is parallelised on the level of single particle, for which wake potential convolution (i.e. histogramming) is conflicting. However, the advantage of parallelisation is enhanced for a larger number of particles [34]. In *mbtrack*, each bunch composed of many particles is handled by a different processor. The *master* intervenes to collect and distribute the information of other bunches, for each bunch to take into account inter-bunch forces over multiple turns [28]. Besides parallelisation, the FFT convolution technique is used in several codes such as *TRANFT* [30] to reduce the number of particles squared dependence of wake or space charge convolutions.

Lastly, efforts of benchmarking different instability codes have been made in the last years in view of the rapid and diverse progress in simulations and increasing needs of consistency checks among different codes. See for example a summary found in Ref. 35.

MEASUREMENT OF IMPEDANCE AND INSTABILITY IN STORAGE RINGS

As conventionally performed, analysis of measured beam instability provides information on the global impedance of a ring. Characterisation in terms of beam current, amplitude growth rate, synchronous phase shift, energy spread widening (via dispersion function) and beam spectra relates etc. deduces the effective real part of the impedance, while coherent tune shift (detuning) and bunch lengthening at low beam current relate themselves to the effective imaginary part. Diagnostic tools available nowadays such as a wide band BPM, stripline, pinhole and streak cameras, along with the standard analog and digital signal processors provide accurate means to measure the observables above [36-37].

In contrast to the global measurement, the fact that the transverse (inductive) impedance behaves like a *pseudo defocusing quadrupole* allows it to be measured locally, either as a local change of focusing, or as a dipolar kick by shifting the closed orbit at its location. The distribution of impedance around a ring can therefore be studied and even ultimately the impedance of a single element, depending upon the diagnostic system. Below we shall review some of the schemes developed along this line, along with their obtained results. Analysis made in LEP (CERN) using turn by turn BPMs would be the first such attempt [38]. By exciting a betatron oscillation and measuring the beam position over one thousand turns, the betatron phase $\mu(I)$ was deduced at each BPM for a given beam current. The slope $d\mu/dI$ was then extracted and plotted additively around the ring. The result impressively showed two discrete steps at the location cavities, confirming their large contribution. The turn by turn measurement method was re-utilised recently in SPS (CERN) [39]. To increase the precision, the focusing strengths were fitted to reproduce the measured phase distortion (beating) with respect to the model optics globally, by solving a set of linear equations via SVD. The obtained solutions well reproduced measured phase slopes and exhibited several large peaks around the ring, some of which well coincided with kicker locations.

The alternative kick measurement was attempted successfully around the same time at APS and BINP [40, 41]. An extensive study was later performed at the ESRF, measuring different types of low gap chambers [42]. The developed scheme makes a closed bump at low beam current, with care to eliminate both unphysical orbit readings and hysteresis effects. The measurement is then repeated with a high current single bunch, attributing the changes in the orbit to current-dependent kicks. The scheme was later extended to take into account the impedance sources outside the bump region. The measured precision was estimated to be 5-20%. Another scheme recently developed at APS looks for focusing errors as in LEP and SPS, but via orbit response matrix that can be measured accurately to few μm [43]. The measured matrix is fitted with the existing quads to extract the slopes $d\mu/dI(s)$ at BPMs, which are then fitted with virtual quads representing the impedance. The result obtained well reproduced the expected impedance distribution, with agreement with the expectation at 10-20% level for the two major types of low gap chambers. The estimated errors of the measurement were roughly at the same level as in the ESRF case.

It is worth mentioning that a bunch by bunch transverse feedback system, capable of measuring the instability growth rate bunch by bunch, opens new possibilities to instability and impedance analysis. It allows measuring the phase difference between adjacent bunches, amplitude distribution along a bunch train and reconstructing unstable beam spectra etc. For example, it turned out very useful at SOLEIL in investigating the transverse instability driven by RW and ions [44]. It should also be added that bench measurement provides another independent and effective means to measure the vacuum chamber impedance. It consists in simulating the beam with a wire (longitudinal) or with a twin-wire (transverse), and measuring the scattering coefficients (S_{21} and S_{11}) for the reference chamber and *DUT* (Device Under Test). Many such measurements have been performed recently for high intensity proton rings, such as LHC, SNS and, J-PARC to evaluate the impedance of kickers and ceramic TiN coated chambers, which make large contributions to the total budget. Particular efforts have been made to improve the accuracy at low frequencies. A. Mostacci et al. improved the measurement sensitivity of the coil and the choice of the reference structure, to obtain good agreement at low frequencies with theory (referred to earlier) for a circular steel tube [45]. A review on recent developments can be found for example in Ref. 46.

COMPARISON BETWEEN MEASUREMENT AND EXPECTATION

SNS (ORNL) ring was commissioned in 2006. Efforts were made to suppress instability with TiN coated chambers against electron cloud build-up and reduction of extraction kicker impedance [47]. Three kinds of transverse instabilities were observed due to RW, extraction kickers and electron clouds, at distinct frequency ranges, ~200 kHz, ~6 MHz and 60-80 MHz, respectively in agreement with expectation. The measured real part of the impedance for the first two cases was also in good agreement with expectation: 34 kΩ/m versus 39 kΩ/m calculated for RW, while 28 kΩ/m versus 22-30 kΩ/m of bench measurement for extraction kickers.

In TEVATRON (FNAL), large efforts were made to reduce the impedance in the entire complex, increasing the luminosity by more than an order of magnitude [48]. In the TEVATRON ring, the measured growth rate indicated that the RW impedance of laminated Lambertson magnets is larger than expected by about a factor of 4. Removal and shielding of these magnets managed to reduce the impedance accordingly. In the recycler ring, the measured growth rate of the most unstable head-tail mode excited by RW gave 10-20% agreement with expectation.

SSRF (Shanghai Synchrotron Radiation Facility) ring was commissioned starting from the end of 2007. Geometric calculations were made with *ABCI* and *MAFIA*, and RW analytically [49]. Longitudinally, $(Z/n)_{eff}$ of 0.22 ~ 0.30 Ω measured against 0.2 Ω calculated. Vertically, $(Z_{\perp})_{eff}$ of 98 ~ 136 kΩ/m was deduced from the coherent tune shift, being nearly a factor of 2 above expectation. The measured RW instability threshold was ~64 mA at zero chromaticity and increased above 100 mA for chromaticity larger than 0.5.

At SOLEIL, which was commissioned in 2006, a piecewise evaluation of the impedance budget was made, with *GdfidL* and *ABCI* for the geometric impedance and analytically for the RW, as stated earlier. In single bunch, the measured effective impedance turned out to be nearly a factor of 2 larger in all three planes, the reason of which is yet to be understood. Both measurement and expectation showed no substantial energy spread widening up to 20 mA. In multibunch, the RW threshold at zero chromaticity agrees well with expected [44].

Lastly, interesting comparisons come from two large-scaled light sources operating since more than 10 years. At APS (ANL), the impedance database was constructed twice, initially with *MAFIA* by taking σ_z of 5 mm (*IDB*-1). To reproduce the measured bunch lengthening and energy spread, Z/n of i0.1 Ω had to be added manually. To find the missing 0.1 Ω, the impedance was recalculated with a much shorter bunch of σ_z = 1 mm (*IDB*-2) with *GdfidL. IDB-2* turned out to well reproduce the measurement without any modification. In the vertical plane, RW not included in *IDB-1* was mainly responsible for the remaining discrepancy [25]. At SPring-8, the impedance model was constructed with *MAFIA* (2 and 3D) for the geometric part by taking σ_z of 1 mm and analytically for RW. To be noted is that numerically obtained wake potentials for a 1 mm bunch were directly used in simulations for *macro particles* in a bunch, assuming that they have the same shape profile. The simulated bunch lengthening, phase shift and energy spread widening are all in impressively good agreement with the measured ones. In the vertical plane, the calculated TMCI threshold was 3 mA against 3.5~4 mA measured. At chromaticity of 4, the calculated threshold was 10 mA, while the measured was above 16 mA [50].

CONCLUSION

Remarkable progress in the numerical and analytical evaluation of wake fields, many of them driven by needs in future accelerators. Instability simulations are getting steadily closer to reality, both in terms of wake fields and beam dynamics. There is large progress in measuring the impedance locally in a storage ring. Most measurements agree with expectation to within a factor of 2.

ACKNOWLEDGEMENT

The author is grateful to the help of F. Zimmermann (CERN), YC. Chae, K. Harkay (ANL), YH. Chin, T. Ieiri, T. Toyama (KEK), V. Danilov (ORNL), A. Burov (Fermilab), T. Nakamura (SPring-8), Z. Zhao (SSRF), W. Bruns (Tech. Univ. Berlin), R. Bartolini (DIAMOND), R. Dowd (ASP), M. Thomasset, N. Béchu (SOLEIL) in preparing this talk.

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