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MEASUREMENT AND MODELING OF SINGLE BUNCH WAKE FIELD EFFECTS IN CESR*

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Abstract

Short-range wake fields have been incorporated into a Bmad-based particle tracking code to assess their contribution to current-dependent emittance growth, tune shift, and single bunch instabilities. The wakes are computed for CESR vacuum components using T3P. Simulation results are compared with measurements of bunch length, vertical beam size, and coherent tune shift. Additionally, we use movable scrapers to vary the transverse wake and measure the effect on the beam. We show that a vertical emittance increase at high current may be due to a transverse monopole wake produced by pumping slots in the beam pipe.

INTRODUCTION

The interaction of the electric field from an ultra-relativistic beam of charged particles with its environment, commonly known as its wake field, can cause a variety of problems in particle accelerators, including instabilities, distortion of the bunch's phase space, and beam loss [1]. This effect has been previously studied at the Cornell Electron Storage Ring (CESR) [2–4]. However, two recent developments at CESR have generated a renewed interest in wake field effects: the observation of a vertical emittance blowup at high single bunch current [5], and the installation of a small aperture chamber for a new undulator [6] (which is expected to have a strong transverse wake).

To investigate these effects, we have modified an existing particle tracking code designed for intra-beam scattering (IBS) studies [5] to include wakes. This paper will describe our methodology for calculating the wake fields and how their effect on the beam is simulated. It will then compare these simulations to measurements at 2.1 GeV of bunch lengthening, tune shifts, and emittance growth.

METHODOLOGY

We simulate the effect of wake fields on the beam using a particle tracking code, which makes extensive use of the Bmad software library [7]. The bunch is modeled as a distribution of macroparticles, and tracked through a realistic lattice for several radiation damping times. The single particle wake (i.e. the wake of a point charge) is added to each impedance element, and the effect on the bunch is calculated using a "pseudo-mode" formalism (described below).

Wakes for a given accelerator element are calculated using the ACE3P electromagnetic simulation suite, developed at SLAC [8]. First, the three-dimensional structure of the element is constructed using the finite element mesh toolkit CUBIT [9]. Next, the longitudinal wake for a given bunch is calculated using the time domain wake field solver T3P, which is part of ACE3P.

The primary sources of longitudinal impedance in CESR are sliding joints, horizontal separators, RF cavities, and tapers into and out of the RF sectors. Fig. 1 shows the CUBIT model of the separator. Because this element has approximate top-down and left-right symmetry, only one quarter is modeled, which saves on computation time. Fig. 2 compares the longitudinal wake calculated by T3P for each of the major CESR elements. Although the wake for a single sliding joint is small, there are approximately 100 of them in CESR, so they collectively represent the largest longitudinal impedance.

In principle, we can obtain the single particle wake by deconvolving the wake calculated by T3P from the bunch distribution. However, numerical inaccuracies will cause this calculation to diverge at high frequency, so we suppress any high frequency structure in the wake. While we verify that re-convolving our single particle wake with the bunch spectrum gives us our original wake back, the lack of high frequency information will limit the reliability of the simulation at distance scales short compared to the bunch length.

Once the single particle wake is obtained, it is decomposed as a sum of "pseudo-modes" of the form $A_i \cos(\omega_i t + \phi_i)$ where A_i, ω_i and ϕ_i are parameters of the i^{th} pseudo-mode and are chosen to best reproduce the calculated wake. During tracking, each macroparticle in the bunch adds to the amplitude of each mode, and is kicked by the wake generated by the macroparticles in front of it. By expressing the wake in terms of modes that can be added together at different phases, we avoid having to calculate the effect of each macroparticle on every other one. Thus the computation time scales linearly with the number of particles, rather than quadratically.

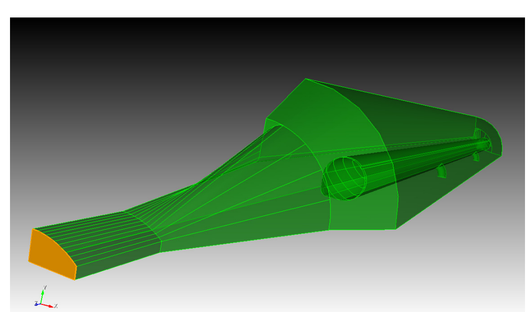

Figure 1: CUBIT quarter model of the horizontal separator.

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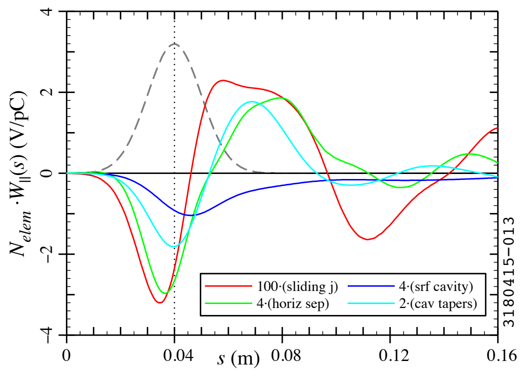

Figure 2: Longitudinal wakes calculated by T3P for a 10 mm bunch, scaled by the number of elements in CESR. The dashed grey line represents the bunch distribution.

LONGITUDINAL RESULTS

With wakes and IBS included, the particle tracking code was used to model bunch lengthening due to potential well distortion. Fig. 3 compares the result with a measurement made with a streak camera [10]. The combination of the two effects gives approximately the correct result for bunch length as a function of current. Both data and simulation show no additional energy spread, which suggests that we are below the microwave instability threshold.

TRANSVERSE WAKE CALCULATION

Transverse wakes can be derived from longitudinal wakes using the Panofsky-Wenzel theorem [11]. The dipole transverse wake is calculated by running T3P with a displaced bunch and a conducting boundary at the midplane of the chamber. Fig. 4 compares the transverse wakes for the major CESR elements; again, the sliding joints provide the largest impedance.

Because the CESR vacuum chambers are not axially symmetric, we must also include a quadrupolar or “detuning” wake [12]. This is calculated by post-processing the output from T3P, with an on-axis drive bunch and an off-axis witness particle.

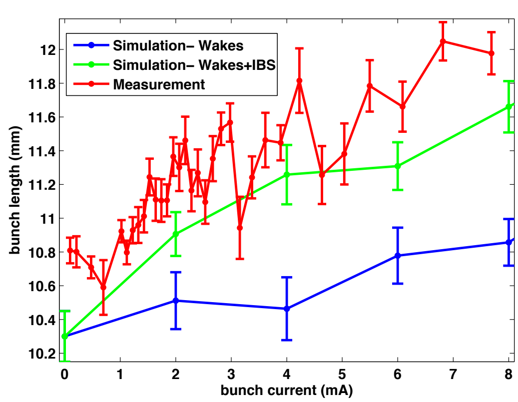

Figure 3: Simulated bunch length as a function of current, compared with a streak camera measurement.

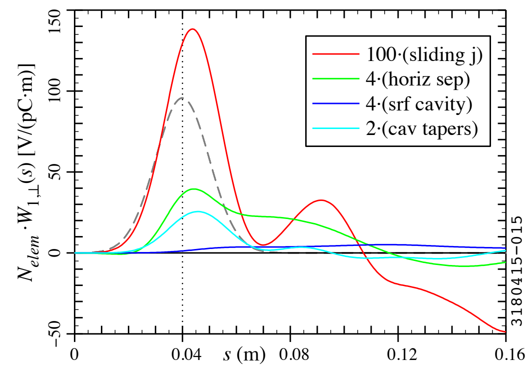

Figure 4: Transverse vertical wakes calculated with T3P for a 10 mm bunch, scaled by the number of elements in CESR.

Vertical Tune Shift

The transverse dipole wake causes a current dependent coherent tune shift, while the quadrupolar wake causes an incoherent tune spread. With both types of wake included, the total vertical tune shift predicted by the simulation is about −160 Hz/mA at beam energy 2.1 GeV, well below the measured value of −500 Hz/mA. At the moment the source of this discrepancy is unclear; probably additional impedance elements, including resistive wall, will need to be included to match the measured tune shift.

Undulator Chamber

Recently, an undulator chamber with a 5 mm vertical aperture was installed in CESR [6]. The chamber is 3.38 m long with 17.5 cm long tapers from the nominal 5 cm CESR aperture. Measurements before and after installation of the chamber showed a ∼ 50% increase in the current dependent tune shift (measured at beam energy 2.1 GeV), indicating a similar increase in the vertical impedance. Efforts to incorporate the undulator chamber into our impedance model are currently underway.

TRANSVERSE MONOPOLE WAKE

In the above analysis, we have assumed the chambers were top-down and left-right symmetric. If a chamber lacks one of these symmetries, there can be a term in the longitudinal wake that depends linearly on the transverse position of the bunch. This leads to a transverse wake that is independent of transverse position [13], i.e. a transverse monopole wake.

The monopole wake produces a kick on the beam particles that depends only on their longitudinal position. If the tunes lie on a synchro-betatron resonance ($f_\beta \pm m f_s = M f_0$), the kicks will add coherently, and the emittance will increase linearly with time, until it is balanced by damping [14]. Even away from resonance, the kicks can add together for several turns (depending on the relative values of the synchrotron and betatron tunes), resulting in an increased emittance.

There are approximately 100 ion pumps in CESR, connected via longitudinal slots in the bottom of the beam pipe (Fig. 5), which clearly lack top-down symmetry. As shown in Fig. 6, this leads to a strong linear term in the dependence

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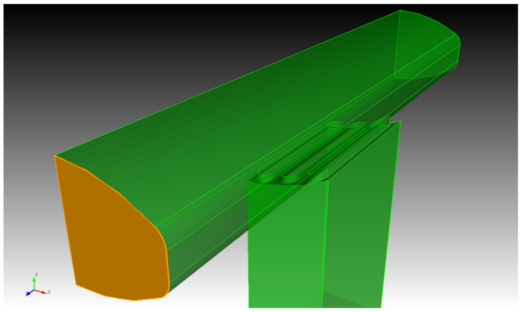

Figure 5: CUBIT half model for the pumping slots.

of the longitudinal wake on vertical position, and hence produces a transverse monopole wake.

Emittance Growth

During IBS studies at CESR, above a threshold current (typically 3 to 4 mA), the measured vertical emittance increased with current much faster than predicted by IBS theory. Simulations with dipole and quadrupolar wakes did not show this effect. However, as shown in Fig. 7, when the transverse monopole wake from the pump slots is included, the simulation does show emittance growth above a threshold current. With the wake amplitudes obtained from T3P, quantitative agreement with the data is poor. A simulation with the amplitudes increased by 50% fits the data better, again suggesting we are missing some source of impedance in our model. Further study is needed to better understand this effect, in particular its dependence on the betatron and synchrotron tunes.

In December 2014, we studied the effect of impedance on the emittance blowup by inserting a set of vertical scrapers (which are known to have a large transverse impedance). No change in the beam size was observed with both scrapers inserted. However, when only the bottom scraper was inserted, we observed a strong vertical blowup, as shown in Fig. 8. The increased emittance could be due to the strong monopole wake created by the asymmetric scraper configuration. A small orbit distortion (on the $\sim 100\mu m$ level) was

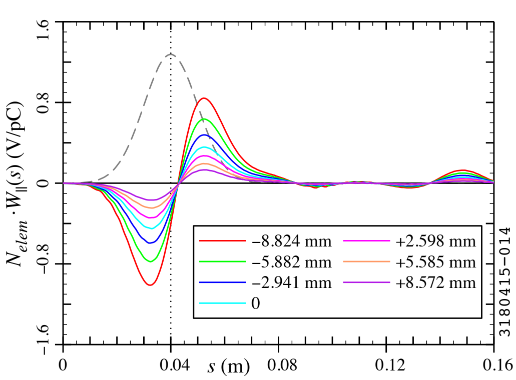

Figure 6: Longitudinal wake of the pumping slots for different vertical displacements.

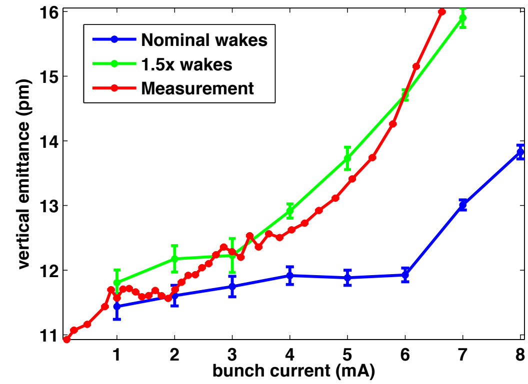

Figure 7: Vertical emittance in tracking simulation, with transverse monopole wakes included, compared to a measurement made with an x-ray beam size monitor [15].

observed, but this is not enough to attribute the blowup to coupling from sextupole magnets.

CONCLUSION

A particle tracking code has been developed to study wake field effects in CESR. When combined with intra-beam scattering, the code accurately models current dependent bunch lengthening. The current dependent vertical tune shift predicted by the simulation is smaller than observed. The simulation strongly implies that the high current blowup observed in low emittance conditions is due to a transverse monopole wake caused by asymmetric vacuum chamber elements (such as pump slots). This hypothesis was strengthened by a measurement in which we observed increased blowup with asymmetric positioning of vertical scrapers, but not with symmetric insertion of the scrapers.

These results suggest that current and future accelerators aiming for low emittance beams should be aware of the transverse monopole wake, and minimize vacuum chamber asymmetries.

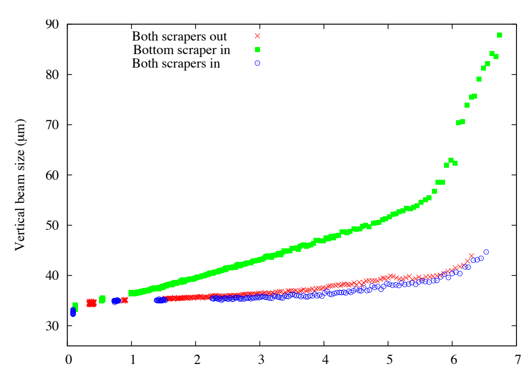

Figure 8: Vertical beam size vs current, with different scraper configurations. There is a strong beam size blowup when only the bottom scraper is inserted.

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