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BEAM LOADING SIMULATIONS IN PYAT FOR THE ESRF

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Abstract

The Extremely Brilliant Source (EBS) at the European Synchrotron Radiation Facility (ESRF) is a 4th generation light source operating with a horizontal emittance of 135 pm. This low horizontal emittance reduces the lifetime in filling modes with high current per bunch. This will be alleviated in the future with an active 4th harmonic cavity. In order to simulate the effect of the 4th harmonic cavity on the EBS performance, beam loading needed to be included to PyAT (Python – Accelerator Toolbox). Here, we introduce the beam loading model and show the benchmarking simulations with theory.

INTRODUCTION

The ESRF-EBS has been commissioned and is currently in operation, delivering high brilliance and high spatial coherence x-rays to the users [1–4]. The EBS lattice has a significantly reduced horizontal emittance (reducing from 4000 pm to 135 pm) which causes a large reduction of the Touschek lifetime [5]. This reduction is most visible for the high current per bunch modes (timing modes). As an example, for the same total current and vertical emittance, the EBS is approximately a factor 2 smaller in lifetime than the old SR. A table of EBS storage ring and main cavity parameters can be found in Table 1.

Table 1: Parameters of the ESRF-EBS Storage Ring and Main RF Cavities

	units	
Energy	GeV	6
Circumference	m	843.977
Max. number of bunches		992
Momentum compaction factor	10^{-5}	8.512
Momentum spread (@0 mA)	10^{-3}	0.9356
Bunch length (@0 mA)	mm	3.06
Energy loss/turn	MeV/turn	2.533
RF Voltage	MV	5.5-6.5
Synchrotron Tune	10^{-3}	3.490
Number of cavities		13
Q_0		37500
β_c		2.8
R/Q per cavity	Ω	145

A harmonic cavity would provide bunch lengthening which would utilise the longitudinal plane to make the beam less dense and increase the Touschek lifetime, improving the operational performance of the timing modes [6]. Active harmonic cavities are more appropriate for use with beams with high current per bunch, as they do not need high total current to generate the appropriate harmonic voltage. This means that less cavities are needed, which reduces their total R/Q and reduces their susceptibility to transient beam loading effects. However, there are questions on the stability of active harmonic cavities in the presence of beam loading. Sophisticated feedback loops may be needed to ensure beam stability. In order to begin this simulation study on the EBS machine, multiple developments were required in PyAT; parallelised multi-bunch collective effects [7] and a generalised beam loading module.

COLLECTIVE EFFECTS DEVELOPMENTS IN PYAT

PyAT is now able to track multi-bunch collective effects. OpenMPI is used for parallelisation and there is no restriction on the number of cores that can be used for the parallelisation. For example, a 48 bunch simulation can be spread over 47 cores or over 100 cores, the only restriction is that each core must have a number of macroparticles that is an integer multiple of the number of bunches.

The module also includes some standardised wake elements that may be added to the AT lattice. Among them are elements for Longitudinal and Transverse Resonators, as well as Resistive Wall wake fields. Multiple benchmarks have been made for both longitudinal and transverse cases, agreeing well with theory in all cases. Wake tables can be provided, and interpolation is automatically applied when providing multiple files. Combining the new wake elements, the parallelised multi-bunch tracking and the fast ring module which reduces a full lattice into 3 lattice elements, the amount of CPU time needed for tracking in the presence of collective effects is significantly reduced.

Reference [7] contains an overview of these developments.

BEAM LOADING

This section will introduce the basic concepts of beam loading and its compensation [8].

When the beam passes through the cavity, a voltage V_b builds up over time which acts at a phase θ_b. The desired V_c is defined to give an energy kick to recover the energy loss per turn U_0 at the synchronous phase ϕ_s. The generator voltage and phase must therefore be computed such that the following condition is fulfilled,

$$\tilde{V_g} = \tilde{V_c} - \tilde{V_b}. \quad (1)$$

where the tilde refers to a time varying quantity. When strong beam loading is present, the interaction between the beam and the generator creates a reduction of the coherent oscillation frequency. A full derivation of this interaction can

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be found in Ref. [9]. The main results will be summarised here. The unperturbed synchrotron frequency is given by

$$\omega_{s0} = \sqrt{\frac{eV_c f_0 \omega_{rf} \alpha \cos(\pi - \phi_s)}{E}} \tag{2}$$

where e is the elementary charge, V_c is the main cavity set point, α is the momentum compaction factor, E is the beam energy, f_0 is the revolution frequency, $\omega_{rf} = 2\pi h f_0$, h is the harmonic number and $\phi_s = \pi - \sin^{-1}(eU_0/V_c)$.

The analytical optimum for the cavity tuning angle is given by

$$\psi = \tan^{-1}\left(\frac{-2I_{tot} R_s \cos(\pi - \phi_s)}{(1+\beta_c)V_c}\right) \tag{3}$$

where I_{tot} is the total beam current, R_s is the main cavity unloaded shunt impedance and $\beta_c = Q_0/Q_L - 1$ is the cavity coupling factor, with Q_0 as the unloaded cavity quality factor and Q_L as the loaded cavity quality factor.

Setting

$$K = \frac{\alpha e f_0 I_{tot}}{E} \frac{R_s}{(1+\beta_c)}, \tag{4}$$

gives a reduced synchrotron frequency of

$$\omega_s = \sqrt{\omega_{s0}^2 + K\omega_{rf} \sin 2\psi}. \tag{5}$$

In order to correctly compensate the beam loading, the amplitude and phase of $\tilde{V}_g$ is modified to ensure that $\tilde{V}_c$ remains constant. To compute the correct correction, an accurate computation of the beam induced voltage must be made. In PyAT, two methods were provided for this computation, the phasor and the wake model.

Phasor

To compute the beam induced voltage using the phasor model, the beam (single or multi bunch) must be sliced, and the centroid position and total current of each slice must be computed. The total number of slices is given by $N_{s,tot} = N_s N_b$ where N_s is the number of slices per bunch and N_b is the number of bunches. The iterative formula applied each turn, n, is given as

$$\tilde{V}_{b,n} = \tilde{V}_{b,n-1} e^{-\omega_c t_0/2Q_L} + \sum_{sl=0}^{N_{s,tot}} 2V_{b0} e^{i\omega_{rf} dt} e^{-\omega_c dt/2Q_L} \tag{6}$$

where dt is the elapsed time between the current slice and the slice before (this must include the rest of a full turn when considering the first slice) and

$$V_{b0} = k_l \frac{I_{sl}}{f_0} \tag{7}$$

is the beam self kick with $k_l = \omega R_s/2Q_L$ the usual resonator loss parameter definition [10]. The total kick applied to each slice is the sum of all previous slices plus V_{b0}. Whereas the voltage deposited is $2V_{b0}$ due to the fundamental theorem of beam loading.

Wake

The real longitudinal resonator wake function is given as [11]

$$W_r(t) = 2R_s \alpha_R e^{\alpha_R t}(\cos(\bar{\omega}t) + \frac{\alpha_R}{\bar{\omega}} \sin(\bar{\omega}t)) \tag{8}$$

and the imaginary longitudinal resonator wake function can be approximated as

$$W_i(t) = 2R_s \alpha_R e^{\alpha_R t}(\sin(\bar{\omega}t) - \frac{\alpha_R}{\bar{\omega}} \cos(\bar{\omega}t)) \tag{9}$$

with $\bar{\omega} = \sqrt{\omega_r^2 - \alpha_R^2}$ where $\alpha_R = \omega_r/2Q_L$

A similar summation to the Phasor model can be found, where each turn the amplitude and phase of the beam induced voltage is computed. In PyAT, the number of turns for the wake memory must be provided and it has to be large enough to include all of the decay of the wake function. This makes the history of the slice centroid positions and currents available to the AT pass method which means that for each slice the full voltage can be reconstructed. This method is slower than the phasor implementation and can only be used for moderate Q values (with number of turns in the wake memory around 30-100) as any higher than this results in unacceptably long simulations, but nonetheless offers a potential alternative to the usual phasor implementation, and a good test for benchmarking.

With both of these methods, the amplitude and phase of the beam induced voltage can be computed. The amplitude and phase of the two methods are compared with the analytical expectations in Fig. 1.

COMPARISON

Having implemented the beam loading module, a variety of benchmarking tests can be performed to ensure it is working as expected. A simple way of testing if the beam loading is well compensated, is to check that the coherent frequency, or the frequency of all bunches oscillating together, is reduced compared to the oscillation frequency of only one bunch, or the incoherent frequency, which should continue to oscillate at ω_{s0}. Figure 2 shows the coherent spectrum (obtained by kicking all bunches together) alongside the incoherent spectrum (obtained by kicking only one bunch).

If the machine is filled asymmetrically, transient beam loading effects are expected. As only the average V_b in one turn is used to compensate the beam loading, it is expected that some bunches will be better compensated than others. One manifestation of this effect is a change in the synchronous position. Figure 3 shows a comparison of uniform filling vs 350 bunches placed at the beginning of the ring.

Finally, a comparison of the synchrotron frequency variation with total current can be made. Measurements of the coherent oscillation frequency of the EBS machine were able to be made during topup injection in uniform filling. The

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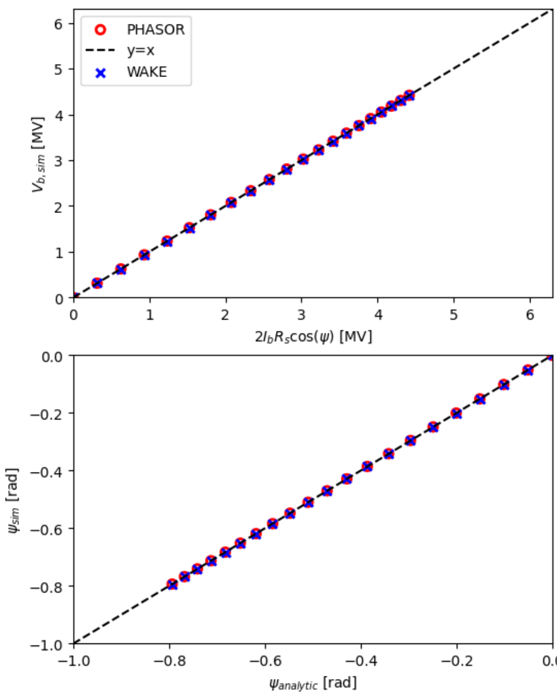

Figure 1: A comparison of the beam induced phase and voltage for the wake and phasor methods with the expected analytical results. A range of currents between 0 and 200 mA are provided for the various points.

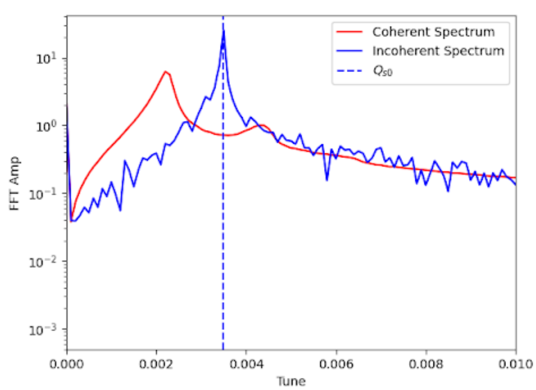

Figure 2: A comparison of the coherent vs incoherent spectra for uniform filling mode.

injection bump currently in use at the EBS produces a transverse kick which grows over approximately 50 turns, this also causes some path lengthening. When the final bump is quickly removed, a longitudinal kick is also created, allowing an observation in the horizontal frequency spectrum of the frequency of the longitudinal coherent oscillation. During these measurements, 2 out of 3 of the solid state amplifiers were suffering problems, so $N_{cavs} = 11$ with $V_c = 5.5$MV. For the simulations, $N_s = 1$ was used with 1 macroparticle per bunch. Figure 4 shows a comparison between the two computational models of PyAT, Eqs (2)-(5) for the coherent

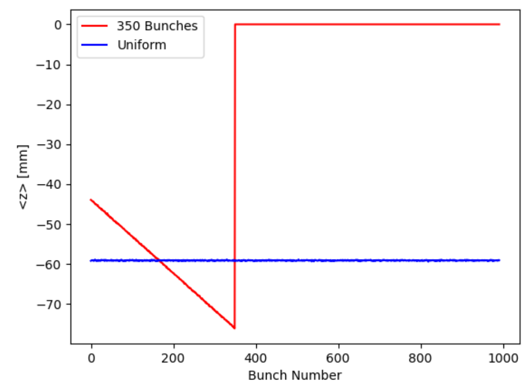

Figure 3: An example of transient beam loading due to asymmetric filling. Uniform filling in blue is compared with only the first 350 buckets filled in red.

frequency in the presence of beam loading and measurement in the EBS machine. In this example, $V_c = 5.5$MV, $N_b = 992$, $N_s = 1$ and $N_{cav} = 11$. Excellent agreement is seen for all 4 cases.

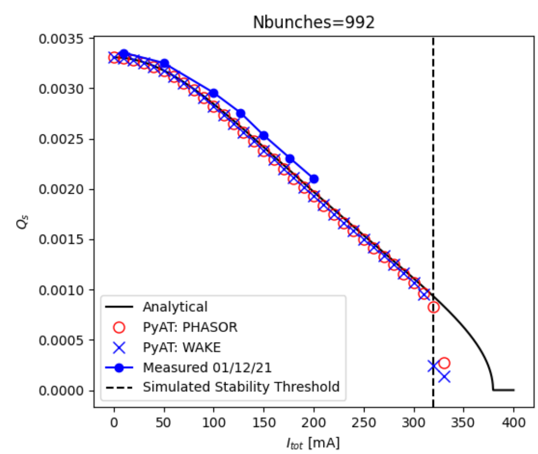

Figure 4: A comparison of the reduced synchrotron frequency with the simulation output using the wake and phasor models, the analytical expression and machine based measurements.

CONCLUSIONS

Significant developments in PyAT have been made that now allow full multi-bunch, parallelised, collective effects simulations in the presence of beam loading. The new beam loading module has been introduced and fully benchmarked, with excellent agreement with theory in all cases.

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