TRANSIENT BEAM LOADING IN THE DIAMOND STORAGE RING*

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Abstract

Harmonic cavity systems have been installed on several 3rd generation light sources to lengthen the bunches and increase the Touschek lifetime. Apart from this beneficial effect, harmonic cavities are known to increase the transient beam loading in high-current machines, due to the presence of gaps in the fill pattern. The amplitude of this effect, which is substantially larger than that caused by the main RF system, can in turn produce considerable variations in bunch length and phase along the train, which result in a significant reduction of the lifetime increase.

We have developed a tracking simulation, which we have applied to the analysis of the beam loading transients in Diamond, for the case of passive superconducting harmonic cavities. The influence of beam current, gap amplitude and harmonic cavity tuning on the final lifetime have been studied, as well as the effects of different coupling factors.

INTRODUCTION

The Diamond storage ring is a DBA lattice with non-zero dispersion in the straight sections, designed to operate with a nominal emittance of 2.7 nm. It is made of 6 identical super-periods, each with three short straight sections (5.3 m) and one long straight (8.3 m), giving 24 cells total with 22 straight sections available for Insertion Devices (IDs). The Diamond storage ring has reached the commissioning phase [1] in May 2006. Tab.1 reports the storage ring main parameters.

Table 1: Diamond Ring Parameters

Beam energy $\mathbf{E_b}$	3 GeV
Ring circumference **C**	561.6 m
Beam current $\mathbf{I_b}$	500 mA
Harmonic number **h**	936
Number of bunches $\mathbf{N_b}$	624
RF frequency $\mathbf{f_{RF}}$	499.65 MHz
Energy loss $\mathbf{U_0}$	1.25 MeV/turn
Momentum compaction $\boldsymbol{\alpha}$	$1.7 \cdot 10^{-4}$
Nominal bunch length r.m.s. $\boldsymbol{\sigma_z}$ (no harmonic cavities)	2.8 mm
Nominal lifetime	10.7 h

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Extensive studies of non-linear beam dynamics have been carried out showing a Touschek lifetime in excess of 10 hours [2]. However these studies also point out some difficulty in operating with the positive chromaticity values required to counteract the resistive wall instability.

In order to improve the lifetime and to provide some Landau damping,, which would ease the chromaticity requirements, a superconducting passive third harmonic cavity will be installed on the ring. In this paper we show the results of tracking simulations, which estimate the lifetime improvement and the magnitude of the phase transient introduced by the higher-harmonic RF system.

HIGHER-HARMONIC RF SYSTEMS IN LIGHT SOURCES

Harmonic RF systems have been installed, or are under evaluation, in several third generation light sources, with various degrees of lifetime improvement [2-7]. While under ideal conditions up to a fourfold increase in lifetime can be expected, the results obtained in practice have been lower and in some cases compatibility issues between the harmonic cavities and other sub-systems (viz. bunch-by-bunch feedbacks) have been observed. Recent studies [8,9] point out how this intrinsic limitation for both superconducting and copper cavities is mainly caused by gaps, and generally asymmetries, in the fill pattern. These studies show by both experimental observations and computer simulations, that the presence of large gaps in the fill pattern changes the synchronous phase along the train and causes each bunch to experience different harmonic voltage amplitudes and phases. Several cures for the transient beam loading of harmonic systems have been proposed. Since its magnitude is strongly dependant on the R/Q of the harmonic system, there is no substantial difference between passive normal conducting and superconducting cavities, although the latter is advantageous because of the smaller number of cells required to reach the optimal harmonic voltage. Active powered cavities can in principle eliminate the transient, but only at the price of impractical power levels. Energy storage cavities have successfully been implemented [10] for reducing transients in the main RF systems and simulation show that their use would be beneficial in a higher harmonic system as well. Finally, some experiments have been carried out at the ALS and simulations also show that the beam loading transient can be controlled by tailoring the fill pattern [8], which requires the being able to target single RF buckets at injection in a controlled fashion. Due to all these complications necessary to control the transient beam loading by way of the methods listed above, it seems that the best practice would be reducing the gap length, if at all possible.

COMPUTER SIMULATION OF HARMONIC RF SYSTEMS

We refer to transient beam loading only in the context of a steady-state condition arising from an asymmetric fill pattern and not to transient effects from perturbations of an equilibrium condition such as during beam injection. Most main RF systems have been studied by way of linear models of the interaction between cavity and beam, which can estimate the level of transient effects. Because the intrinsic nonlinearities in the longitudinal beam dynamics of a harmonic RF system we developed a computer tracking code to find the steady-state main and harmonic voltages and phases in correspondence of each RF bucket. Using these values we then compute the corresponding bunch shape and lifetime increase for each bunch. Our code is illustrated with much detail in Ref. [6]. Each bunch is first treated as a macroparticle to calculate its energy and phase deviation from the nominal equilibrium parameters turn-by-turn from the difference equations:

$$\begin{cases} \varepsilon_{i+1} = (1 - 2\lambda_{rad})\varepsilon_i + \frac{1}{E}\left[eV_g(\phi_i) + eV_b(\phi_i) - U_0 \right] \\ \phi_{i+1} = \phi_i + 2\pi\alpha h \varepsilon_i \end{cases} \quad (1)$$

where V_g and V_b are the sums of the generator and beam-induced voltages in the main and harmonic RF systems and U_0 and λ_{rad} are the radiation damping rate and the radiation loss per turn respectively. The beam voltages for both cavities are found from the difference equation

$$\tilde{V}_{b,i+1} = \tilde{V}_{b,i} e^{(j\omega_r - \omega_r/2Q)\Delta t} - 2kq \quad (2)$$

where $k = \omega_r R_s / 2Q$ and Δt is the time separation between the current and the previous bunch and q its charge.

TRANSIENT BEAM LOADING CALCULATIONS FOR THE DIAMOND LIGHT SOURCE

Using our FDTD code we tracked the bunches circulating in the Diamond storage ring for tens of thousands of turns, until a steady-state distribution of voltages and phases is reached.

Table 2: RF Parameters

RF voltage $\mathbf{V_{RF}}$	3.3 MV GeV
Number of cells	2
R/Q	90 Ohm
Q_0	$5 \bullet 10^8$
R/Q_h (harmonic cavities)	85
$Q_{0,h}$	$2 \bullet 10^8$
Optimal detuning δ_h (est.)	60 kHz

Nominal parameters

Our first results were calculated for the machine nominal parameters, with a 33% gap and a main RF voltage of 3.3 MV. In the absence of transients a 60 kHz detuning of the harmonic cavities provides the required $V_{RF}/3$ voltage.

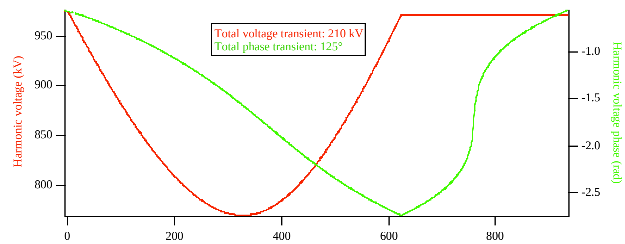

Figure 1: Harmonic voltage and phase (33% gap).

Fig. 1 shows harmonic voltage amplitude and phase as calculated by our code. One can appreciate how the desired voltage is reached only at the beginning and at the end of the bunch train. On the other hand, the ideal phase of about (~π rad) is achieved only in the central portion of the train, where the voltage is instead lower. The combination of these two factors substantially reduces the overall gain in lifetime, as we will see.

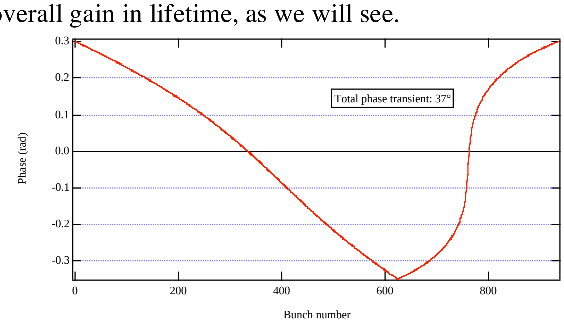

Figure 2: Synchronous phase along the bunch train (33% gap).

Figure 2 shows instead the synchronous phase variation along the train. This is critical for all those sub-systems that work based on the exact arrival time of a bunch. The 37 degrees reported in figure 2 are equivalent to as much as one tenth of the total length of an RF bucket in Diamond. In such cases the use of a fixed clock is often problematic and the timing information has to be extracted by the beam itself.

Half-length gap

To better show the influence of the gap length on the lifetime increase, we also ran our code with the nominal Diamond parameter, except for the number of bunches which was increased to 780, thus halving the gap length.

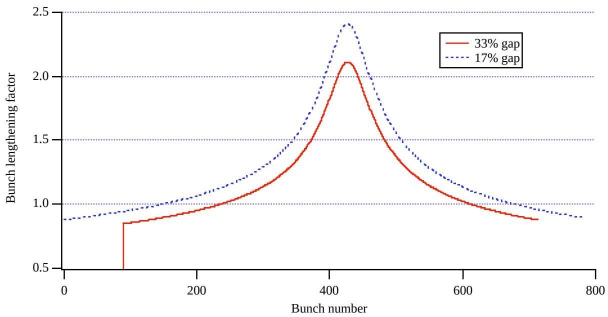

Figure 3: Bunch lengthening factor for the nominal gap (33%) and a halved gap (17%).

In Fig.3 we show the calculated bunch lengthening factor for each bunches with the nominal gap and the reduced length gap. In both cases the bunches at the center of the train (which correspond to the ideal harmonic voltage phase) are at least doubled in length.

Table 3 shows how, due to the dominant effect of those bunches at the train edges, which are actually shortened, the actual increase in lifetime is only 12% for the 312-bucket gap. The short gap fares a little better, but the 45% increase in lifetime is partly due to the lowered bunch current, which accounts for a 25% improvement in lifetime.

Table 3: Half gap effects summary

Gap length	**33%**	**17%**
$\Delta\phi$	37°	34°
avg. V_h (kV)	870	940
ΔV_h (kV)	210	180
$\Delta\phi_{\square}$	125°	107°
avg. lengthen. factor	1.19	1.26
total lifetime increase	1.12	1.45

Higher main RF voltage

Since it was apparent from our simulation that pursuing the highest harmonic voltages is in fact less advantageous than obtaining a reduced variation in the voltage phase, we analyzed the system with an increased main RF voltage

Table 4 shows our results for several voltages, up to 5.2 MV. It is evident from the reduction in the total harmonic phase transient $\Delta\phi_{\square}$ that the harmonic cavity, maintained at a fixed detuning of 60 kHz, works closer to ideal conditions and the bunch lengthening is more uniform along the train. Even though the third harmonic voltage gets farther away from the design value ($V_{RF}/3$) the increase in lifetime is more strongly dependant on the reduced phase transient and the lifetime increase reaches values in excess of 40%. Although, when we take into account that the higher RF voltage decreases the "natural" bunch length (i.e. with no harmonic cavities), the final lifetime increase is only of about 17% with respect to the 3.3 MV case.

Table 4: Code output for a harmonic system at different main RF voltages

V_{RF} (MV)	**3.3**	**4.0**	**4.4**	**4.8**	**5.2**
β	11000	7500	6500	5500	4500
$\Delta\phi$	37°	25°	20°	16°	13°
avg. V_h (kV)	870	980	1010	1030	1040
ΔV_h (kV)	210	150	120	100	90
$\Delta\phi_{\square}$	125°	89°	73°	61°	52°
σ_{z0} (mm)	2.77	2.48	2.36	2.25	2.16
avg. lifetime. increase	1.12	1.29	1.37	1.42	1.43
total lifetime increase	1.12	1.15	1.17	1.15	1.12

CONCLUSIONS

Using a FDTD tracking code, we have examined a proposed third harmonic RF system for the Diamond light source storage ring. Our results point out that, like in other installations of such a system, the overall effect on the beam lifetime is limited by the transient beam loading in the harmonic cavities introduced by a large gap in the bunch train. The resulting large excursion of the harmonic voltage phase, up to values that actually shorten some bunches, needs to be addressed in order to maximize the benefits in terms of lifetime increase. There are several possible strategies and our code is a valuable tool for identifying the best solutions.

REFERENCES

[1] R. Walker, these proceedings.
[2] R. Bartolini, these proceedings.
[3] M. Georgsson, . Å. Andersson, *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **416**, 465 (1998).
[4] J. M. Byrd, S. De Santis, *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **455**, 273 (2000).
[5] M. Georgsson, D. Kramer, *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **469**, 373 (2001).
[6] A. Gallo, *et al.*, in *Proc. of the EPAC 2000*, Vienna (2000).
[7] C. Wang, *et al.*, in *Proc. of the 1997 PAC*, Vancouver (1997).
[8] J. M. Byrd, S. De Santis, *et al.*, Phys. Rev. ST-AB, **5**, 092001 (2002).
[9] G. Penco and M. Svandrlik Phys. Rev. ST-AB, **9**, 044401 (2006).
[10] T. Kageyama, K. Akai, *et al.*, in *Proc. of the EPAC 1996*, p. 2008-2010, Sitges (1996).