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HARMONIC CAVITY DESIGN CHOICE FOR LIFETIME INCREASE IN DIAMOND-II

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Abstract

The ongoing trend towards synchrotron light storage rings with ultralow emittance leads to a requirement for strong magnet gradients, which reduce the dynamic aperture and thus the Touschek lifetime of the machine. This is also the case for the planned upgrade of the Diamond Light Source. One option to increase the Touschek lifetime is to lengthen the electron bunches with a harmonic cavity operated close to a harmonic of the fundamental RF frequency. This paper presents studies of a harmonic cavity for Diamond-II with the focus on maximising the lifetime increase. It is foreseen that the ring will have to operate with a gap in the fill pattern to avoid instabilities and therefore multiparticle tracking was used to determine the effect on stability and lifetime for various cavity parameters taking into account transient beam loading.

INTRODUCTION

The planned upgrade of the Diamond Light Source to a multibend achromat lattice storage ring [1] will lead to a reduction of dynamic aperture and thus momentum acceptance and Touschek lifetime compared to the current machine. This has consequences for the frequency of top-up injections. One option to increase the Touschek lifetime is to lengthen the electron bunches with a harmonic cavity operated close to a harmonic of the fundamental RF frequency. In addition to increasing the Touschek lifetime, longer bunches also leads to reduced emittance blow-up from intrabeam scattering, reduced heating of vacuum components and increased damping of instabilities due to increased synchrotron frequency spread. All of these effects are advantageous for the operation of the machine, but so far lifetime has been the main motivation for the studies of a harmonic cavity for Diamond-II.

Due to lower complexity compared to an active cavity it is proposed to choose a passive harmonic cavity. In addition, a third harmonic cavity has been chosen as a trade-off between bunch lengthening and user requirements on the maximum bunch length. Since Diamond-II is proposed to operate at a fundamental RF frequency close to 500 MHz, the resonance frequencies of already existing harmonic cavities have also been taken into account.

The current Diamond ring is operated with a gap in the fill pattern (900 bunches out of 936) for both ion-clearing and to reduce transverse coupled-bunch instabilities. It is foreseen that a gap will also be required for Diamond-II. In addition to this, the current ring is operated a couple of weeks per year in a hybrid mode (686 bunches) for timing users with a longer gap including a 3 nC camshaft bunch. A similar mode to serve timing users will likely also be required for Diamond-II. So far the only requirement set for the hybrid mode is a maximum bunch length of 100 ps FWHM for the camshaft bunch. Gaps in the fill pattern give rise to transient beam loading in the RF cavities, which affect the effectiveness of a harmonic cavity [2]. It is therefore necessary to study the consequences of different fill patterns to determine the requirements for a harmonic cavity for Diamond-II. This paper presents multiparticle tracking simulations to predict the effects on stability and lifetime for various cavity parameters. The simulations were performed with the code *mbtrack* [3] that recently has been updated to be able to simulate arbitrary fill patterns [4]. So far, only fill patterns similar to those operated in the current ring have been considered for Diamond-II, i.e. a standard mode consisting of 900 bunches (out of 934) and a hybrid mode consisting of 685 bunches and a 3 nC camshaft bunch placed in the middle of the gap.

LATTICE AND CAVITY PARAMETERS

The Diamond-II lattice parameters of importance for the harmonic cavity simulations are shown in Table 1. The case including insertion devices (IDs) is an estimation based on preliminary parameters for fully closed IDs. For both cases, the RF voltage has been adjusted to provide 3.5% RF acceptance.

Table 1: Lattice Parameters for Diamond-II

	Bare	**Incl. IDs**
Energy [GeV]	3.5	
Circumference [m]	560.574	
Harmonic number	934	
Beam current [mA]	300	
RF voltage [MV]	1.66	2.69
Energy loss/turn [keV]	670.3	1526.0
Energy spread [%]	0.078	0.103
Momentum compaction	$1.17 \cdot 10^{-4}$	$1.16 \cdot 10^{-4}$
Long. damping time [ms]	12.01	4.67

For comparisons, different sets of harmonic cavity parameters as displayed in Table 2 were used in the simulations. The parameters for the normal conducting cases are given by the flat potential conditions (i.e. zero first and second derivative of the voltage at the synchronous phase) [5] at 300 mA current, whereas the parameters for the superconducting case are based on the Super-3HC (SLS and Elettra design) [6] cavity detuned to zero the first derivative of the voltage at

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Table 2: Harmonic cavity parameters used in simulations. The tuning angles and bunch lengths are for 300 mA current.

	Normal conducting		Super conducting	
	Bare	Incl. IDs	Bare	Incl. IDs
Shunt impedance $\left(P = \frac{V^2}{2R}\right)$	5.41185 MΩ	4.92679 MΩ	17.68 GΩ	17.68 GΩ
Tuning angle	99.647°	105.447°	90.00301°	90.00453°
Bunch length (RMS) when tuned in (uniform fill)	43 ps	46 ps	46 ps	53 ps

the synchronous phase. In addition to this, Diamond-II is proposed to operate with eight normal conducting main cavities similar to the ones recently installed in the current ring for redundancy [7]. For these cavities a shunt impedance of 3.9435 MΩ and a Q factor of 33000 were assumed. In all simulations, the main cavities were assumed to operate with optimal power coupling and detuning.

ROBINSON STABILITY

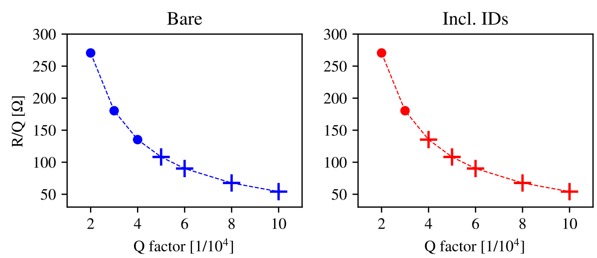
Bunch lengthening from a harmonic cavity requires to detune the cavity on the Robinson unstable slope of the cavity impedance. This can to some extent be compensated by the detuning of the main cavities, but this puts constraints on the parameters and operation of them. Figure 1 displays a comparison of the stability in tracking simulations as function of the Q factor of the harmonic cavity. The simulations show that common Q factors for normal conducting cavities (20 000 – 30 000) are too low to avoid Robinson instability when the harmonic cavity is fully tuned in due to the resulting R/Q. Stability can, however, be obtained for a superconducting cavity ($Q \sim 2 \cdot 10^8$) tuned to achieve similar bunch lengths. This is also the case when not taking the damping from the main cavities into account, which allows for flexible operation of them.

EFFECT OF TRANSIENT BEAM LOADING

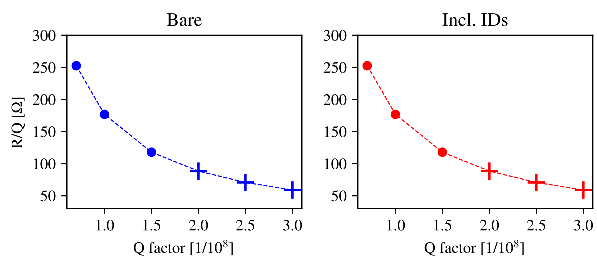
Transient beam loading gives rise to a variation of the amplitude and phase of the harmonic voltage over the bunch train. This leads to a variation of the synchronous phase of the bunches and a reduction of the average bunch lengthening, as well as a variation of the bunch length over the bunch train [2]. The variation of the synchronous phase can affect the bunch-by-bunch feedback systems used to control instabilities and the injection efficiency. For Diamond-II no issues are expected for the feedback systems due to sufficient phase range, but so far a maximum time deviation of 100 ps over the bunch train has been estimated from injection studies. The Touschek lifetime increase from a harmonic cavity taking into account the modification of the longitudinal bunch profile can be estimated according to

$$\frac{\tau_{\mathrm{hc}}}{\tau} = \frac{\varepsilon_{\mathrm{hc}}^2}{\varepsilon^2} \frac{\int \rho^2(z)dz}{\int \rho_{\mathrm{hc}}^2(z)dz}, \tag{1}$$

where τ, ε and $\rho(z)$ are the Touschek lifetime, momentum acceptance and longitudinal bunch profile without harmonic



(a) Normal conducting



(b) Superconducting

Figure 1: Stable (+) and unstable (•) harmonic cavity parameters in tracking simulations for 300 mA current, the settings in Table 2 and a uniform fill (934 bunches) including Robinson damping from the main cavities.

cavity and τ_{hc}, $\varepsilon_{\mathrm{hc}}$ and $\rho_{\mathrm{hc}}(z)$ the corresponding values including the cavity. Simulations show that the effect of the change in momentum acceptance is of the order of $\sim 5\%$ and can therefore be neglected.

Figure 2 shows the time shift and lifetime increase over the bunch train for the two fill patterns using the parameters of the Super-3HC cavity and the bare lattice. In these simulations the transient beam loading in the main cavities has not yet been included to be able to study only the effect of the harmonic cavity. However, it is already evident that the estimated requirements for Diamond-II are not fulfilled since the time deviation over the bunch train is >100 ps for both fill patterns. The lifetime increase is also reduced from 4.6 times for a uniform fill to 3.1 ± 0.4 times and 2.0 ± 0.3 times, for the standard and hybrid mode, respectively. Including the transient beam loading reduces the lifetime increase further to 2.1 ± 0.3 times and 1.3 ± 0.1 times, whereas the time deviation over the train increases from 126 ps and 190 ps to 228 ps and 298 ps, respectively.

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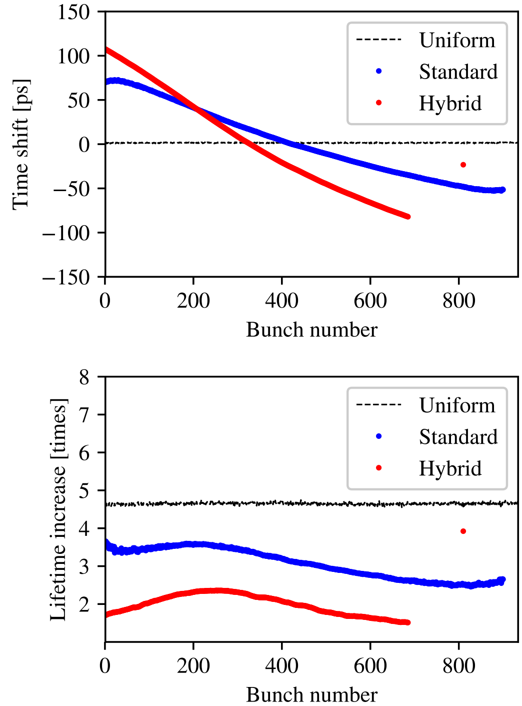

Figure 2: Time shift (top) and lifetime increase (bottom) over the bunch train for 1.66 MV voltage, 300 mA current, the bare lattice and the Super-3HC harmonic cavity tuned according to Table 2. The results for a uniform fill are displayed for comparison. In these simulations the transient beam loading in the main cavities has not been included.

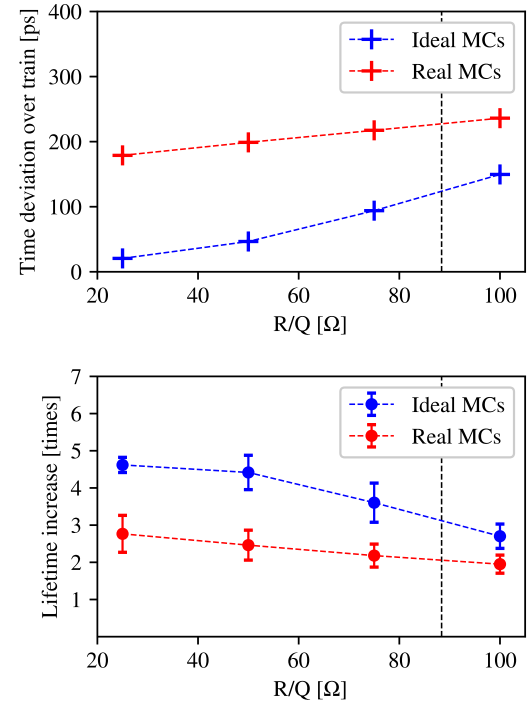

Figure 3: Time deviation (top) and lifetime increase (bottom) as function of harmonic cavity R/Q for the standard mode for 1.66 MV voltage, 300 mA and the bare lattice. The R/Q of the Super-3HC harmonic cavity is marked (black dashed). Results are shown for both ideal main cavities and when including the transient beam loading in them.

Figure 3 shows the time deviation over the bunch train and lifetime increase as function of harmonic cavity R/Q for the standard mode both for ideal main cavities and including the transient beam loading in them. The results show that a reduction of the harmonic cavity R/Q would improve the situation, but also that the contribution from the main cavities is significant and efforts to reduce the R/Q of the harmonic cavity would be in vain unless a feedback can be implemented to reduce the transient in the main cavities. However, the situation for the hybrid mode would be more severe and most likely difficult to improve by only these means.

CONCLUSIONS

Tracking simulations show that a superconducting harmonic cavity is required to achieve Robinson stability for Diamond-II. A superconducting cavity also have other benefits such as the possibility to achieve long bunches already at low current, which could be of importance during commissioning, and a lower R/Q which helps to reduce the effect of transient beam loading.

Due to the time and cost requirements to design and prototype a superconducting cavity it is preferable to choose an existing harmonic cavity design. However, simulations show that parameters for existing cavities do not fulfil the requirements for Diamond-II for the two current fill patterns. To be able to operate these fill patterns with satisfactory performance, both reduced R/Q of the harmonic cavity and feedback to reduce the transient beam loading in the main cavities would be required. To avoid this, it is preferable to study options for operating different fill patterns in Diamond-II compared to those operated in the current Diamond ring.

FUTURE WORK

Studies of options for new fill patterns for Diamond-II has been initiated. The aim of these studies is to develop a standard mode which meets the requirements of maximum 100 ps time deviation over the bunch train and average lifetime increase of 4 times for existing harmonic cavity designs by utilizing several short gaps for ion-clearing instead of one long gap. Discussions about requirements and solutions for the hybrid mode have also begun.

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