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FILL PATTERN FOR REDUCING TRANSIENT BEAM LOADING AND ION-TRAPPING IN THE DIAMOND-II STORAGE RING

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Abstract

The Diamond-II upgrade will replace the existing Diamond storage ring with a multibend achromat lattice providing higher brightness to the users by reducing the emittance and increasing the beam energy. The new storage ring will require a harmonic cavity that lengthens the bunches to increase the Touschek lifetime as well as mitigate instabilities and suppress the emittance blow up from intrabeam scattering. It is expected that the ring will have to operate with gaps in the fill pattern for ion-clearing, but that will lead to transient beam loading resulting in reduced bunch lengthening. The length and occurrence of the gaps therefore have to be determined as a trade-off between the requirements for transient beam loading and ion-trapping. This paper presents simulations of both effects for the Diamond-II storage ring to find an optimal fill pattern.

INTRODUCTION

An upgrade is planned of the Diamond Light Source to replace the existing storage ring with a multibend achromat lattice which provides higher brightness for the users by reducing the emittance and increasing the beam energy [1, 2]. The new Diamond-II storage ring is planned to operate with a passive harmonic cavity to increase the Touschek lifetime, reduce intrabeam scattering and mitigate instabilities by lengthening the electron bunches. The existing Diamond storage ring is mostly operated with a fill pattern with 900 bunches, resulting in a single gap of 74 ns for ion-clearing. It is anticipated gaps will also be required in the fill pattern for the new ring to avoid ion instabilities. Gaps however give rise to transient beam loading which when operating with a harmonic cavity results in a variation of the phase and bunch length over the bunch train as well as a reduced average bunch lengthening [3]. Previous studies for Diamond-II have shown that a similar fill pattern as the one currently operated will give rise to significant transient beam loading [4] and a new fill pattern which gives larger bunch lengthening is therefore required. This paper presents simulations of the transient beam loading and ion instabilities for the Diamond-II storage ring for different gap configurations. The purpose is to find the optimal fill pattern when considering the requirements of both effects as well as the best approach to minimise the impact on the bunch lengthening in case of issues with ion instabilities during commissioning.

This paper focuses on the fill pattern for the standard mode, but the existing storage ring is also operated for a couple of weeks per year in a hybrid mode with a 3 nC bunch in the middle of a longer gap for timing users. A hybrid mode is also under study for the Diamond-II storage ring, but depending on the gap length required by the users it will give rise to significant transient beam loading. For this mode other options for increasing the lifetime may need to be considered, such as increasing the vertical emittance or operating at lower currents. More details about the hybrid mode can be found in [1].

MACHINE AND CAVITY PARAMETERS

The machine parameters used in the simulations can be seen in Table 1. Closing all the insertion devices (IDs) reduces the equilibrium emittance [1, 5], resulting in a reduction of the horizontal emittance whereas the vertical emittance is planned to be kept at 8 pm rad with an emittance feedback. In these simulations it has been assumed that this is achieved by betatron coupling, but a new emittance feedback based on excitation at a synchrotron sideband is currently under development [6]. The effect of intrabeam scattering on the emittance has not been included. The IDs also have a significant impact on the damping times.

Table 1: Machine Parameters for the Diamond-II Storage Ring with Open and Closed Insertion Devices

	Open IDs	Closed IDs
Energy [GeV]	3.5	
Circumference [m]	560.561	
Harmonic number	934	
RF frequency [MHz]	499.511	
Tune (h/v)	54.15/20.27	
Chromaticity (h/v)	2.0/2.3	
Momentum compaction	$1.04 \cdot 10^{-4}$	
Nominal current [mA]	300	
RF voltage [MV]	1.42	2.53
Emittance (h/v) [pm rad]	153.7/8	113/8
Energy spread [%]	0.094	0.11
Energy loss/turn [MeV]	0.723	1.68
Damp. time (h/v/l) [ms]	9.7/18.1/16.0	5.7/7.8/4.8

The ring will operate with eight active normal conducting main cavities and one passive superconducting third order harmonic cavity [1]. Table 2 shows the parameters used for the cavities. The main cavities correspond to the EU HOM-damped cavities already under test in the existing Diamond storage ring [7] whereas the harmonic cavity is based on the CEA Super-3HC cavity used at SLS and Elettra [8]. As can be noted, the total R/Q of the main cavities is higher than for the harmonic cavity and they therefore dominate the transient beam loading.

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Table 2: Cavity Parameters

	Main	Harmonic
Number of cavities	8	1
Cavity harmonic	1	3
Shunt impedance [Ω]	$3.944 \cdot 10^6$	$1.768 \cdot 10^{10}$
Q factor	33 000	$2 \cdot 10^8$
R/Q per cavity [Ω]	119.5	88.4
Total R/Q [Ω]	956	88.4

TRANSIENT BEAM LOADING

Simulations of the transient beam loading have been conducted in `Elegant` [9,10] including RF feedback in the main cavities, beam loading in both main and harmonic cavities and longitudinal broadband impedance [11]. The simulations were done using 10 000 particles per bunch and the beam tracked until it had reached equilibrium. With a superconducting harmonic cavity it is not possible to achieve the commonly used flat potential conditions where both the first and second derivative of the total voltage are zero at the synchronous phase [12], but the cavity can still be tuned to achieve similar bunch lengthening. This nominal tuning has been found using the method presented in [13]. For the main cavities, the power coupling and detuning have been used which minimise the reflected power [14]. Figure 1 shows the time shift over the bunch train, bunch length and lifetime gain as a function of the number of gaps for the case with closed IDs and the nominal 300 mA current. Similar results are found for the bare lattice. The lifetime gain is calculated compared to a bunch of 0.6 nC charge (corresponding to a uniform fill) which has the natural bunch length. The results show that operating with a single gap in the fill pattern which is commonly done today at many synchrotron light sources gives the strongest transient beam loading. Increasing the number of gaps helps to increase the lifetime gain up to a point where the bunch length no longer increases and the lifetime gain instead starts to decrease due to the increased bunch charge. The optimal is to operate with the shortest gaps possible and with 2-3 gaps depending on the gap length. Then the transient beam loading is drastically reduced compared to operating with the existing fill pattern (900 bunches, 1 gap).

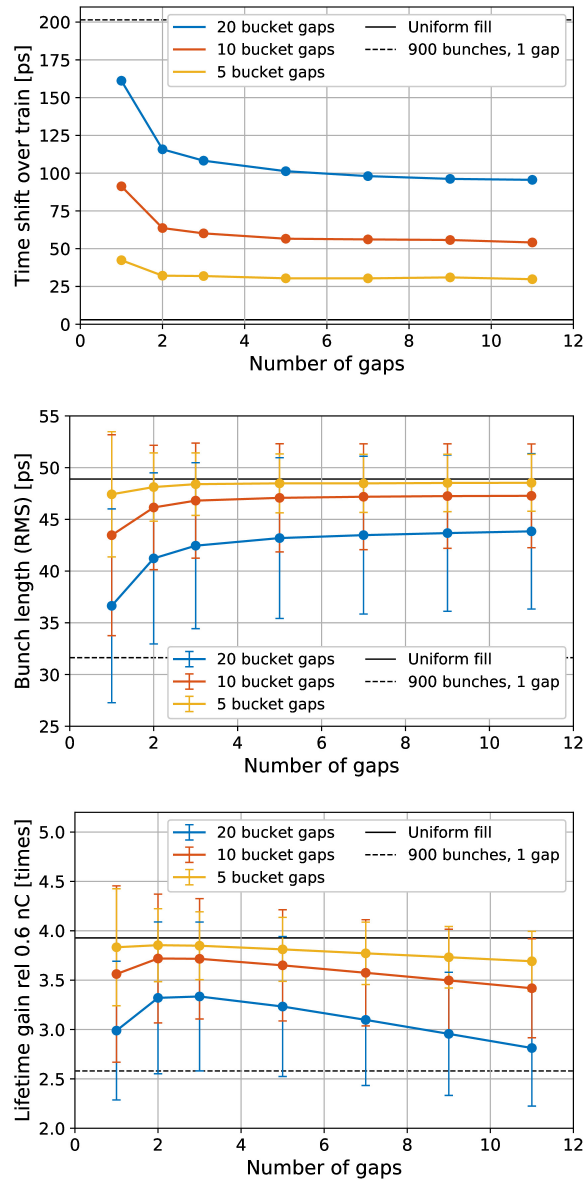

Figure 1: Time shift over the train, bunch length and lifetime gain for different gap lengths as function of the number of gaps for the case with closed IDs and 300 mA current. The lifetime gain is calculated relative to a 0.6 nC bunch with the natural bunch length.

ION INSTABILITIES

Simulations of ion instabilities were also conducted in `Elegant`. In this simulation the electron beam is modelled using macroparticles tracked in 6D along the ring whereas the ion beam is modelled as macroions generated at specified interaction points representing the ion line density for the section between two points. Also in this simulation 10 000 particles were used per electron bunch, but it was sufficient to only generate a single macroion per bunch pass through an interaction point. The simulations were performed for 97 interaction points along the lattice chosen based on the variation of the ion critical mass number [15] which describes how the ion-trapping is distributed along the ring. The vacuum pressure was included as a s-dependent pressure profile based on vacuum calculations assuming 100 Ah conditioning time and unsaturated NEG coating. The mean pressure for the four gases included in the simulation can be seen in Table 3. The generation of different ion species depends on their ionisation cross sections, which are dependent on the electron energy. Ionisation cross sections are usually only measured up to the keV scale, but a formula exists to extrapolate to higher energies [16, 17]. The ionisation cross sections used in the simulation can also be seen in Table 3. In the simulation both the kick from the ions to the electron

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beam and the corresponding kick from the electron beam to the ions are calculated. So far, the kick has been calculated assuming that the charge distribution is Gaussian in both transverse planes for both the electrons and the ions.

Table 3: Mean Pressure Values Extracted from S-dependent Pressure Distribution after 100 Ah Conditioning Assuming Unsaturated NEG Coating and Ionization Cross Sections at 3.5 GeV Electron Energy

Gas	Mean pressure [mbar]	Ionisation cross section [Mb]
H_2	$3.37 \cdot 10^{-10}$	0.369
CO	$0.84 \cdot 10^{-10}$	1.81
CO_2	$0.67 \cdot 10^{-10}$	2.88
CH_4	$1.19 \cdot 10^{-10}$	2.11

Figure 2 shows the maximum average ion line density over the ring and the maximum vertical oscillation after 1000 turns as function of the number of gaps for the case with closed IDs and the nominal 300 mA current. Similar results are found for the bare lattice despite the difference in horizontal emittance since the ion-trapping is dominated by the much smaller vertical beam size. In these simulations the nominal chromaticities have been used and neither impedance or harmonic cavity been included. Since the growth rate of the ion instabilities varies with time due to the interaction between the ions and the electron beam it is non-trivial to fit an exponential growth rate which accurately describes the growth and therefore the maximum amplitude after 1000 turns is used here instead as a measure of the growth rate. It can be seen that the existing fill pattern (900 bunches, 1 gap) actually gives rise to a larger vertical oscillation after 1000 turns than fill patterns with a shorter single gap despite lower average ion density. This is showing the characteristics of ion instabilities where a strong instability can have a reduced growth rate with time because of the effect on the electron beam. The results show that it is preferable to operate with many short bunch trains rather than fewer longer trains. Especially, the results show that for a fill pattern with the same number of bunches better ion-clearing can be achieved with several short gaps instead of a single long one.

CONCLUSION

The simulations show that operation with a single gap in the fill pattern which is commonly done today in many synchrotron light sources is not optimal for neither reducing the transient beam loading or the ion-trapping. Instead, operating with several shorter gaps can provide both good lifetime gain and ion-clearing. A fill pattern of 5 gaps of 7 buckets has therefore been chosen for the standard mode of the Diamond-II storage ring. This leads to 4 trains of 180 bunches and 1 train of 179 bunches which fits well with the maximum bunch train achievable from the Diamond-II booster. This fill pattern provides a lifetime gain around 3.8 times while keeping the growth rate of the ion instabilities

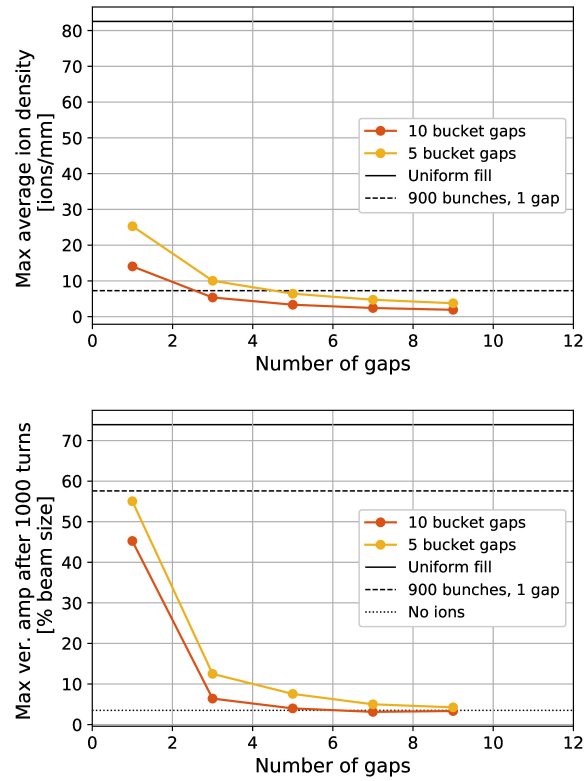

Figure 2: Maximum average ion line density and vertical oscillation for different gap lengths as function of the number of gaps for the case with closed IDs and 300 mA current.

within a magnitude expected to be possible to damp with multibunch feedback. The simulations also show that in case of issues with ion instabilities during commissioning it is favourable for the bunch lengthening to add additional gaps rather than making them longer.

FUTURE WORK

Further studies of the ion instabilities including charge variation, impedance and multiple ionisations are planned. In addition, studies using a bi-Gaussian model in both transverse planes for the ion distribution are also planned, especially with focus on studying the effect on the emittance in addition to just the centroid motion. Also studies of other currents, other pressure conditions and including a transverse multibunch feedback are planned.

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