

PERIODIC TRANSIENT BEAM LOADING INSTABILITY IN DIAMOND-II

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Abstract

This work demonstrates that periodic transient beam loading can affect bunch lengthening throughout the fill patterns as well as cause its time-dependent variation over dozens of synchrotron periods in Diamond-II. The instability can be eliminated by increasing the detuning of the harmonic cavity. The results suggest that introducing longer gaps in the filling pattern might eliminate the instability, but this will reduce the effectiveness of the passive harmonic cavity. Next, this study explores the option of creating a charge variation within the train of the hybrid-fill pattern. This technique can help to flatten the bunch-length variation as well as increase the bunch length in the timing bunch. Finally, the bunch-compression regime was explored using the standard-fill pattern without collective effects. It was found that the harmonic cavity can be detuned such that it shortens bunches instead of elongating them.

INTRODUCTION

As shown in Ref. [1], the periodic transient beam-loading (PTBL) instability might occur when R/Q of the harmonic cavity is not small enough or when the tuning angle is not optimal. Since the harmonic cavity for Diamond-II has been chosen to be superconducting [2], the Q -factor is relatively high ($2e8$) providing Robinson stability. However, efforts to maximise bunch lengthening increase the risk of the periodic transient beam-loading instability.

The simulation model is implemented in Elegant including the one-turn map, two *RFMODE* elements representing the main and harmonic cavities, and synchrotron radiation. Higher-order modes from the main cavity and longitudinal long-range wakes (both resistive wall and geometric components) are used as the impedance sources in the model. In most of the cases, a beam with 1000 particles per bunch is used. In this work, the case of insertion devices with minimum gaps (IDs closed) was chosen as the reference.

STANDARD-FILL PATTERN

In Diamond-II, the standard-fill pattern is composed of 5 trains, the first four consist of 180 bunches and the last one consists of 179 bunches. The bunch trains are separated by 7-bucket gaps. The nominal bunch length in the case of the standard-fill pattern at 300 mA is $\langle\sigma_t\rangle \approx 45$ ps. A developing PTBL in the standard-fill pattern can be observed in Fig. 1, which shows a snapshot of the bunch length throughout the beam distribution at the last turn of the simulation. Blue and red dots show the bunch length at the nominal 300 mA and when the beam current is increased up to 350 mA respectively. A strong asymmetry in the fill pattern indicates an

onset of the instability at 350 mA. However, PTBL is a dynamic effect, thus this snapshot is not enough to characterise the instability.

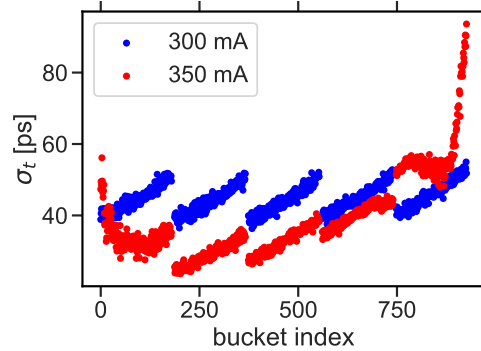


Figure 1: The bunch length throughout the standard-fill pattern at the 50000-th turn at the nominal parameters of the harmonic cavity.

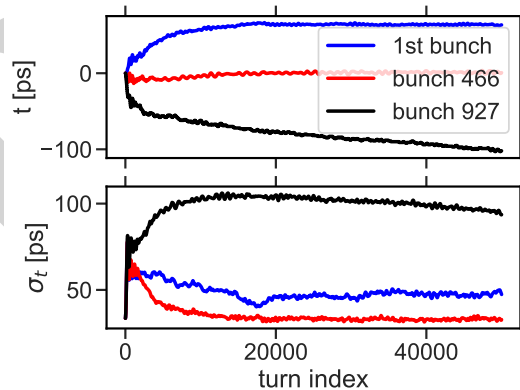


Figure 2: Synchronous time and bunch length of three selected bunches in the standard pattern at 350 mA.

Figure 2 demonstrates how the synchronous time and the bunch lengths vary from their nominal values, indicating that the beam is longitudinally unstable at 350 mA. The results were compared to the simulations with the uniform-fill pattern which was found to be stable at 300 mA and unstable at 350 mA. The results suggest that introducing relatively short gaps in the fill pattern is not sufficient to eliminate the PTBL instability.

Though the nominal current of Diamond-II is 300 mA, it is beneficial to provide strategies to increase the beam-loading safety margin by ensuring stability at 350 mA. Since the shunt impedance and the quality factor of the harmonic cavity are fixed, the only adjustable parameter is the tuning angle. The nominal value of the harmonic-cavity detuning is 57 kHz. PTBL is a dynamic effect, therefore the metric

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$\Delta\sigma_t = \text{Max}[\sigma_t(t)] - \text{Min}[\sigma_t(t)]$ (the range in the bunch length over the final 40 thousand turns) is useful in determining whether the beam is stable or unstable. At the same time, the value of the bunch length itself (averaged over the last 40 thousand turns) can be used as a good indication of a developing instability.

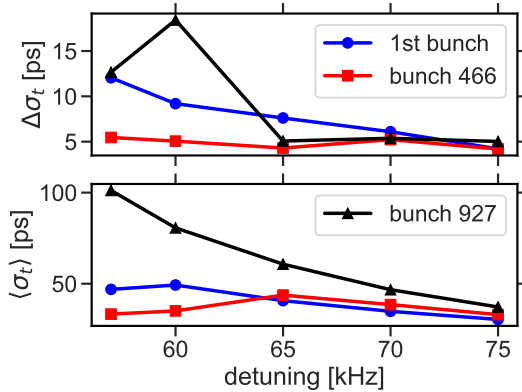


Figure 3: Bunch-length range over the last 40 thousand turns and the bunch length averaged over the same period of three bunches at 350 mA.

Blue dots, red squares and black triangles in Fig. 3 represent three selected bunches in the standard fill pattern for various probed tuning angles of the harmonic cavity. The top panel shows $\Delta\sigma_t$ whilst the bottom panel displays the bunch length itself. The results indicate that the detuning has to be increased above 65 kHz to make the beam stable at 350 mA. However, choosing a detuning higher than 75 kHz results in $\langle\sigma_t\rangle < 40$ ps. It is undesirable to operate with a reduced bunch length because it might lower the impedance-safety margin and reduce the lifetime. Therefore, the optimal detuning is slightly above 65 kHz.

STABILITY OF THE HYBRID-FILL PATTERN

There are multiple options for a hybrid operation in Diamond-II. As shown in Ref. [3], ‘static’ beam loading is the strongest when the separation between the timing bunch and the trains is the largest, namely, 100 buckets. However, the PTBL instability is absent in this case. This indicates that it is possible to mitigate the PTBL instability by introducing longer gaps (even in the case of the standard fill pattern by modifying the length of the gaps). However, this might lead to potential problems. Not only does this make the harmonic cavity less effective, but it also leads to a higher amount of charge in bunches which, in turn, might reduce the impedance-safety margin and lifetime.

As shown in Fig. 4, the hybrid-fill pattern is stable when the harmonic cavity is at its nominal detuning even when the beam current is 350 mA. This suggests that the cavity detuning can be reduced for this mode which might potentially result in a larger bunch lengthening.

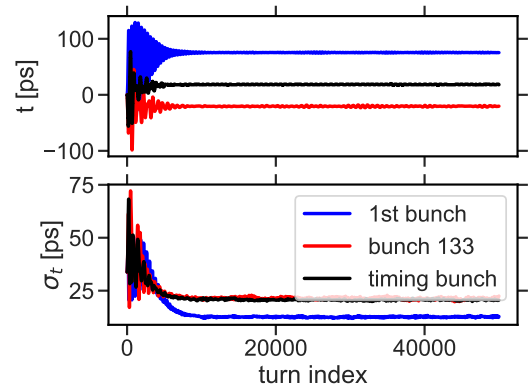


Figure 4: Synchronous time and bunch length of three selected bunches in the hybrid pattern at 350 mA, nominal detuning used.

Potential Techniques for Maximising the Harmonic-Cavity Effectiveness

The beam is stable in the longitudinal plane when the fill pattern is hybrid with longer gaps. Though the beam might become less stable when detuning decreases, the total bunch length can be enlarged. Another possible direction is reducing the main-cavity voltage. This might make the contribution of the harmonic cavity into the total RF potential larger. However, no significant progress was observed in all probed cases with the reduced main-cavity voltage.

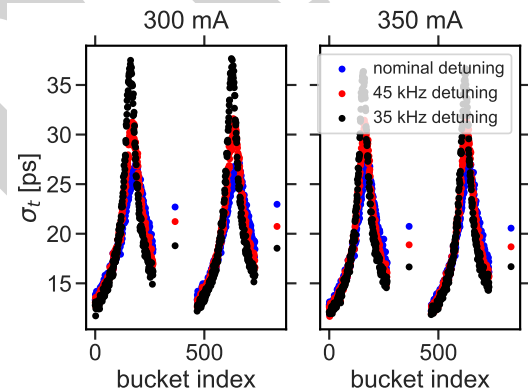


Figure 5: The bunch length throughout the hybrid fill pattern at the 50000-th turn.

Figure 5 shows the best results achieved in particle simulations. Blue, red and black dots represent three case scenarios with reducing detuning. Comparing the simulation results at 300 mA and 350 mA ensures that the beam is longitudinally stable with a good safety margin. Interestingly, the bunch length of the timing bunch is proportional to the detuning. The beam loses Robinson stability at 350 mA when the harmonic-cavity detuning is 30 kHz.

Another potential way to increase the effectiveness of the harmonic cavity is to modify the fill pattern itself. The idea is to redistribute the charge within the train, so the power transferred from the beam to the harmonic cavity is increasing towards the tail of the train slower or faster. For example, if the timing bunch should have a larger bunch

length, it is preferable to increase the charge towards the tail of the train.

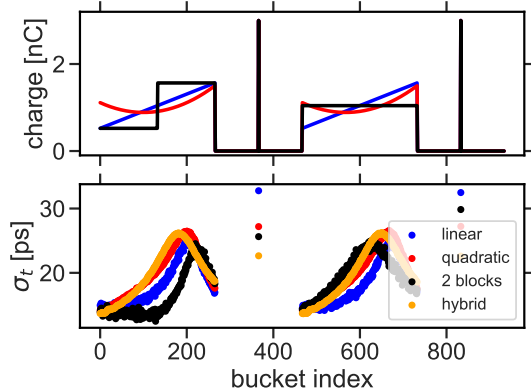


Figure 6: Modified hybrid-fill pattern and the bunch length at the 10^5 -th turn for all probed cases.

The number of modification options is unlimited. As shown in the upper panel of Fig. 6, the simplest options include trapezoid and parabolic fill patterns corresponding to the blue and red curves. However, the most practical might be just combining two blocks in one train which is represented by the black line. The blue, red and black dots in the lower panel represent the linear, quadratic and 2-blocks modifications compared to the hybrid-fill pattern. The results show that it is possible to significantly increase σ_t of the timing bunch. However, flattening σ_t throughout the fill pattern remains challenging. Varying the charge only in the first train changes the bunch length in the second train also. The second timing bunch in the case of two blocks has a larger bunch length compared to the first timing bunch, though the charge variation was created only in the first train.

BUNCH COMPRESSION

Another potential way of using the harmonic cavity is to create the RF potential which can result in bunch shortening. This section explores potential ways of achieving bunch shortening (compression) if such regime is requested by the users. The simulation setup is identical to what is described above, using the standard fill pattern in particle tracking. As shown in Fig. 7, it is possible to detune the harmonic cavity in the opposite way to ensure bunch compression. As expected, this technique is less effective when the absolute value of the detuning is larger. Also, the average bunch length is smaller when the beam loading is larger at the harmonic cavity (higher beam current). Interestingly, the bunch-length variation within the trains is minimal and is potentially caused by the noise in the simulations. More simulations are required to estimate the lifetime and to find the thresholds of the microwave and head-tail instabilities in this RF configuration.

SUMMARY AND CONCLUSIONS

This study demonstrates that periodic transient beam loading can affect bunch lengthening as well as cause its variation

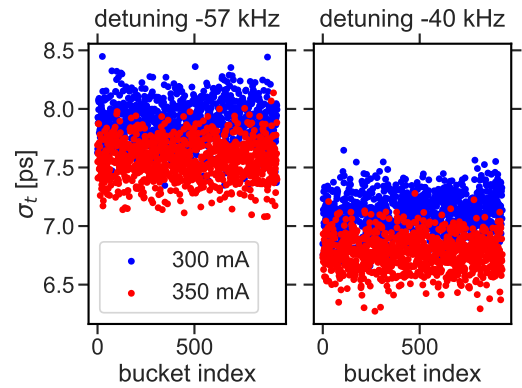


Figure 7: The bunch length of the standard fill pattern at the 10^5 -th turn when the HHC is compressing the bunches.

over ≈ 30 synchrotron periods ($\approx 50 \cdot 10^3$ turns) in Diamond-II. The beam is found to be stable under nominal conditions. However, if the total beam intensity is increased to 350 mA, additional PTBL mitigation techniques are required. It was demonstrated that the instability can be eliminated by increasing the detuning of the harmonic cavity. The optimal detuning at 350 mA is slightly above 65 kHz ensuring that the bunch lengthening is not completely lost. The simulation results suggest that introducing short gaps in the filling pattern is insufficient to eliminate the instability. However, the hybrid fill pattern with a 100-bucket half-gap is stable in a wider range of probed tuning angles of the harmonic cavity than the standard fill pattern.

The options for increasing the harmonic-cavity effectiveness with the hybrid-fill pattern were explored. It was possible to achieve a higher peak bunch length throughout the train (which also translates into a larger average bunch length) by reducing the harmonic cavity detuning. It was found that even at 30 kHz detuning the beam is stable at 300 mA, and the bunch length is the largest in this case. The choice of 35 kHz might be optimal, because the beam is stable also at 350 mA. The option of creating a charge variation within the train was tested. This technique can help flatten the bunch-length variation throughout the fill pattern as well as significantly increase the bunch length in the timing bunch.

Finally, the bunch-compression regime was explored using the standard fill pattern without the short-range wakes. It was found that the harmonic cavity can be detuned so that it shortens bunches instead of elongating them. If the absolute value of detuning is small, the harmonic cavity is more efficient. There is almost no variation of the bunch length throughout the fill pattern. The effect can be intensified by loading the harmonic cavity by increasing the total current.

REFERENCES

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