STUDY OF SINGLE BUNCH INSTABILITIES WITH TRANSVERSE FEEDBACK AT DIAMOND

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Abstract

Single bunch instability studies have been carried out at Diamond with and without the transverse multi-bunch feedback (TMBF) system. Single bunch instability thresholds were measured for zero, positive and negative chromaticity values by increasing the current till the instability onset. The bunch-by-bunch feedback system was then used to suppress the motion of the bunch centroid and the new thresholds were measured in all chromaticity regimes. The feedback loop phase of the TMBF was changed from resistive to reactive as well as intermediate to find the optimal feedback settings that maximize the single bunch instability thresholds.

INTRODUCTION

Multi or single bunch collective phenomena may limit the high current operation of storage rings. Such collective effects may obstruct performance causing longitudinal or transverse instabilities, beam quality deterioration and/or beam loss. A well-established solution to actively damp instabilities is the use of a feedback control system [1–7].

The Diamond synchrotron can store up to 936 electron bunches separated by 2 ns. The design of the TMBF allows bunch-by-bunch selectable control over feedback filters, gain and excitation with the possibility to control independently a single bunch when Diamond operates with a hybrid filling pattern [8]. The feedback system at Diamond is based on the Libera hardware platform [9] while the feedback processing is implemented in a field-programmable gate array (FPGA). The TMBF measures the position of each bunch in the train using a set of four button pick-ups, detects the betatron oscillations of each bunch, and generates a correction signal with a phase shift of 180° in the kicker striplines to suppress the transverse motion [10]. This is done via a 10-tap finite-impulse-response (FIR) filter on the bunch position [11]. The TMBF can damp up to 250 MHz coupled-bunch instabilities in both the vertical and horizontal plane allowing Diamond to reach its operational current target of 300 mA with a uniform filling pattern.

The TMBF at Diamond is also used for the continuous tune measurement on a single bunch without any visible disturbance of the user beam as well as grow-damp experiments. For the latter the beam is excited for a selected period of time, then allowed to decay or grow in transverse amplitude without feedback or further excitation and finally the beam is restored by enabling again the transverse feedback [12].

SINGLE BUNCH INSTABILITIES WITH TMBF

There has been much discussion about the effectiveness of a feedback system on the suppression of single bunch instabilities, such as the transverse mode coupling instability (TMCI) for zero chromaticity or the (weak) head-tail instabilities for non-zero chromaticity [13–18]. The majority of light sources operate with a positive chromaticity to control instabilities caused by the beam coupling impedance. In particular Diamond operates with a chromaticity of 1.5 in the horizontal and 2 in the vertical plane. A paper published by A. Burov studies the effectiveness of a feedback system theoretically and investigates the effect of gain, phase and chromaticity as to which settings are the most efficient to suppress such phenomena [19].

A set of measurements was performed at Diamond without and with the transverse feedback to investigate its effect on the TMCI threshold, the head-tail instability onset for different chromaticity values as well as the effect of the feedback gain and phase. Focus has been put on the vertical plane as the vertical machine impedance is more critical than the horizontal one.

INSTABILITY THRESHOLDS WITHOUT AND WITH TRANSVERSE FEEDBACK

Starting from low intensity, the vertical instability thresholds have been measured by injecting more and more current into a single bunch till the instability onset. The vertical chromaticity was varied between -2.5 and 2.5 in steps of 0.5. The recorded thresholds without (solid blue) and with the TMBF (dashed blue) are shown in Fig. 1.

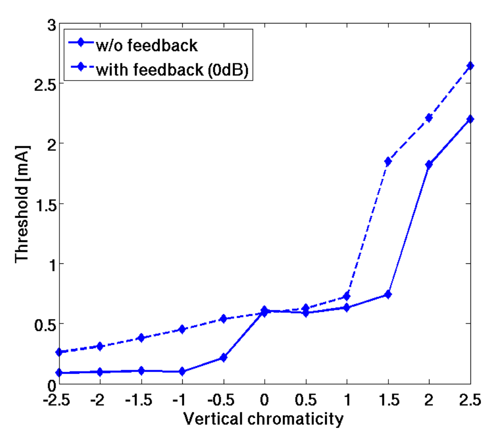

Figure 1: Vertical single bunch thresholds without and with the TMBF as a function of chromaticity.

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The TMCI threshold, caused by the coupling of modes 0 and -1 [20], is 0.6 ± 0.03 mA at zero chromaticity. During normal operation, positive chromaticity is used to achieve a higher single bunch current. This is possible as the higher-order head-tail modes have a much lower growth rate. At user time Diamond operates with a chromaticity of $Q'_y = 2$ and can deliver a single bunch current of 1.6 mA in a hybrid filling pattern [21]. Towards the negative chromaticity values, the thresholds become more severe, as it is the mode 0 that gets unstable. They can be seven times lower than the TMCI threshold.

The vertical feedback was used with nominal settings corresponding to a resistive system that damps the coherent betatron oscillations. The thresholds with nominal TMBF settings are shown in Fig. 1 with the dashed blue line. In the case of zero chromaticity the use of feedback with nominal settings did not alter the TMCI threshold significantly. This can also be seen from the normalised tune shift slope versus single bunch current in Fig. 2, where the tune shift slope of mode 0 with resistive feedback (red) is very close to the slope without feedback (black), with the difference being less than 8%.

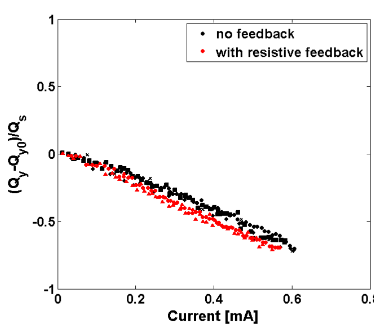
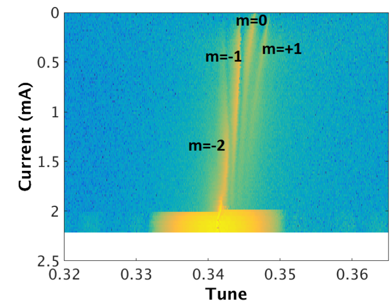


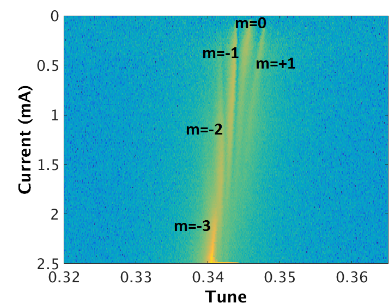
Figure 2: Normalised vertical tune shift versus single bunch current without (black) and with (red) the TMBF at zero chromaticity.

For slightly positive chromaticity there is a small increase of the head-tail instability thresholds when the feedback is on. For high positive chromaticity values $Q'_y >= 1.5$ the increase is much more pronounced, as shown in Fig. 1. As an example, in Fig. 3 an increase by a factor 1.2 is observed on the achievable single bunch current when the TMBF is on and for $Q'_y = 2.5$.

For negative chromaticity values a significant increase in stored current is accomplished when the feedback is on, as seen in Fig. 1. This is because it is the mode 0 that becomes unstable, which can be damped by a resistive bunch-by-bunch feedback to some extent. A resistive feedback damps the betatron oscillations by acting on the bunch centroid and thus it is the most effective when the chromaticity is negative. In the case of Diamond the current is increased up to a factor 4.5. Figure 4 shows an example of negative chromaticity $Q'_y = -2.5$ without and with the bunch-by-bunch feedback. The current stored is increased by a factor 3.5 when the TMBF is used. However, from an operational point of view,

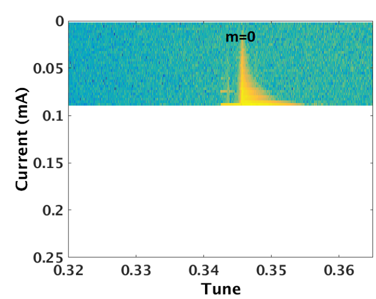


(a) Without feedback, maximum current at 2.1 mA.

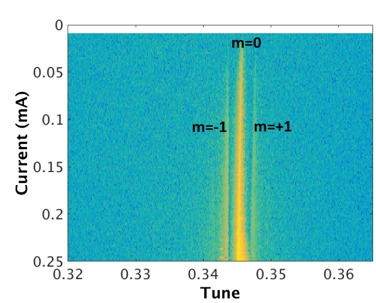


(b) With resistive feedback, maximum current at 2.5 mA.

Figure 3: Tune-shift versus single bunch current for $Q'_y = 2.5$. The threshold is 2.1 mA without the TMBF and is limited by the mode -2 (top plot). The threshold is pushed to 2.5 mA when the TMBF is used and mode -3 causes the instability (bottom plot).



(a) Without feedback, maximum current at 0.07 mA.



(b) With resistive feedback, maximum current at 0.25 mA.

Figure 4: Tune-shift versus single bunch current for $Q'_y = -2.5$. The threshold is 0.07 mA without the TMBF and is limited by the mode 0 (top plot). The threshold is pushed to 0.25 mA when the TMBF is on (bottom plot).

the achievable beam current with feedback on and negative chromaticity is still far from the desired value and what can be normally achieved when operating the synchrotron with positive chromaticity.

EFFECT OF FEEDBACK PHASE

Further studies were carried out investigating the effect of the feedback phase. In the measurements above the feedback was used in resistive mode with its-phase being -180° relative to the measured phase of the bunch oscillation, as in normal user multi-bunch operation. The feedback phase can be changed from resistive to reactive as well as any intermediate value by changing the phase of the feedback inside the FIR filter [11]. A reactive feedback shifts the coherent betatron frequency either up or down. A purely reactive feedback corresponds to a phase of ±90°.

An example is given in Fig. 5 where the normalised vertical tune shift slope is compared for a case without feedback (black), with a purely resistive feedback with -180° phase (red), and with an intermediate phase of -120° (magenta). For an intermediate phase, the mode 0 line is prevented from shifting down with increasing current, as it would normally do without the TMBF. This it true up to a certain current. Eventually, however, it starts to shift down till it merges with mode -1, causing a TMCI instability at 0.74 mA. The purely reactive phase has a similar result and rises the instability onset to 0.71 mA.

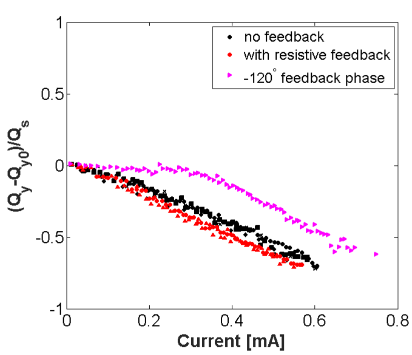


Figure 5: Normalised vertical tune shift versus single bunch current without (black) and with resistive TMBF with a phase of -180° (red). A comparison is shown with an intermediate feedback phase of -120° (magenta).

Additional Feedback Gain

In order to test the best performance of the feedback two more steps were made. First, it was ensured that the beam would pass through the electric center of the TMBF pick-up. This was achieved by placing an orbit bump of 350 μm. Secondly, the back-end amplifier gain was increased to its maximum value. These two steps provided an additional feedback gain of 6 dB.

Vertical single bunch thresholds were measured for various phases with the additional feedback gain, and are compared to the thresholds without feedback and with nominal resistive feedback in Fig. 6. In the TMCI regime at zero chro-

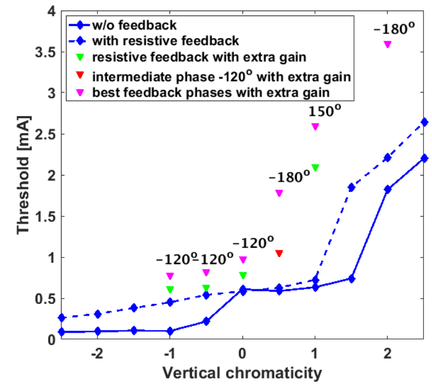


Figure 6: Vertical single bunch thresholds without TMBF (solid blue) and with nominal settings of the TMBF operating in resistive mode (dashed blue) as a function of chromaticity. In the same plot are included the measured thresholds with the TMBF with the extra gain operating in fully resistive mode (green) and at an intermediate phase of -120° (red). The highest achieved thresholds are noted at each chromaticity along with the feedback phase (magenta).

maticity both a resistive and an intermediate feedback phase increase the threshold when additional gain is provided to the feedback, with the latter outperforming the former. For other chromaticity values, it was observed that the phase that allows the maximum stored current varies. In most cases, an intermediate phase was found to be best without a unique answer as to which phase is the most effective in all chromaticity regimes.

For Diamond operation, although it has been possible to increase the TMCI threshold, the highest single bunch current can still be achieved with positive chromaticity. At its working point of $Q'_y = 2$, Diamond provides a 1.6 mA single bunch current in the hybrid filling pattern. The possibility to control a single bunch independently of the rest of the train, would allow a 3.6 mA single bunch current in a hybrid filling pattern as demonstrated in Fig. 6.

CONCLUSION

Measurements of single bunch instability thresholds versus chromaticity, and tune shift versus current have been made without and with transverse feedback. Switching on the nominal resistive feedback had a beneficial effect on the instability thresholds for both negative and positive chromaticity values. It was found that by adjusting some of the feedback settings one can maximize performance and increase the TMCI threshold. Changing the feedback phase from resistive to reactive and intermediate allowed us to find the maximum achievable currents. There is no unique phase that works best in all chromaticity regimes. Further studies need to be done with a realistic feedback model in a macro-particle simulation code and the effect of the injection oscillations on the stored beam must be included as they cause early-on saturation of the feedback system.

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