PERFORMANCE OF THE FAST ORBIT FEEDBACK SYSTEM WITH THE DOUBLE-DOUBLE BEND ACHROMAT INSTALLED IN DIAMOND LIGHT SOURCE

S. Gayadeen*, G. Rehm, Diamond Light Source, Oxfordshire, U.K.

Abstract

At Diamond Light Source, the Double-Double Bend Achromat (DDBA) lattice upgrade involved the conversion of one cell of the storage ring from a double bend achromat (DBA) structure to a double-DBA (DDBA). The new cell includes corrector magnets that are different in design to the DBA corrector magnets. The DDBA vacuum chamber cross section is also different from the DBA cells and includes both stainless steel and copper sections over which corrector magnets are fitted around. The performance of the Fast Orbit Feedback (FOFB) used for electron beam stabilisation with the DDBA cell installed is presented in this paper. Firstly the different corrector magnet dynamic responses are characterised and secondly the closed loop performance of the FOFB is measured and analysed for the upgraded lattice.

INTRODUCTION

Diamond Light Source has replaced one of the standard Double Bend Achromat (DBA) cells of the 561 m circumference electron storage ring with a new design consisting of two DBA cells and a straight section for an insertion device [1, 2]. This arrangement of the two DBA cells has been termed the Double-Double Bend Achromat (DDBA) cell. The DDBA cell includes 10 horizontal and vertical corrector magnets respectively on the sextupoles, 6 of which are used for the Fast Orbit Feedback (FOFB) (shown installed in the storage ring in Fig. 1). The remaining 4 of these magnets are located over copper vessels, which significantly reduces the bandwidth required for orbit correction. Additionally, 2 discrete correctors to provide adequate correction for the central insertion device source position are included which are shown Fig. 2, making a total of 6 correctors over stainless steel vessels and 2 discrete correctors over copper vessels for use in the FOFB. In the DDBA there are 8 beam postion monitors (BPM) as opposed to the 7 BPMs in the usual DBA cell. The maximum gain of the response matrix for each corrector pre- and post-DDBA cell installation is shown in Fig. 3. The gains are a little smaller pre-DDBA compared to post-DDBA, except in the DDBA cell (correctors 8-15) where the gains are smaller due to smaller beta functions.

The FOFB correction is calculated as

$$u_n = -\tilde{R}^{-1} c(z^{-1}) y_m \qquad (1)$$

where u_n is a vector of inputs to the corrector power supplies of size $n = 173$ and the beam position from $m = 172$

Figure 1: Sextupole magnet (yellow) with corrector installed on DDBA cell.

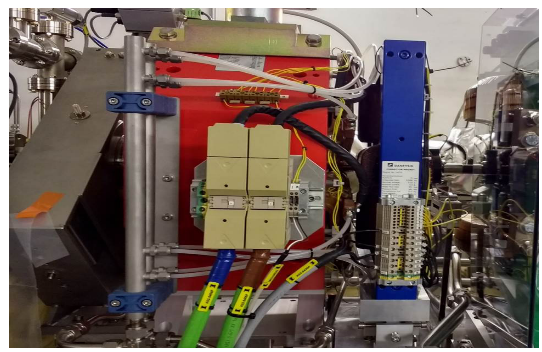

Figure 2: Discrete corrector (blue) installed on DDBA cell

BPMs is represented as the vector y_m. The beam position is multiplied by the pseudo-inverse response matrix ($\tilde{R}^{-1}$) and the output of the multiplication is then passed through an IIR filter represented by the discrete transfer function $c(z^{-1})$.

The exact inverse of the response matrix is not applied because of the presence of weakly controllable directions i.e. spatial modes associated with very small singular values resulting from the ill-conditioning of the matrix. The pre- and post-DDBA singular values are shown in Fig. 4 for each axis. While the structure of the singular values appear similar, the post-DDBA response matrix has a condition number which is a factor 1.2 greater than the pre-DDBA matrix. To avoid large (and possibly unstable) controller gains in the weakly controllable directions, the inverse singular values are filtered. The same filtering parameter has been applied to the post-DDBA response matrix as the pre-DDBA value, to achieve the same level of filtering at the modes associated with small singular values (as shown in Fig. 4).

The dynamic responses of the correctors in a DBA cell and the DDBA cell were measured using sinusoidal excitations

* sandira.gayadeen@diamond.ac.uk

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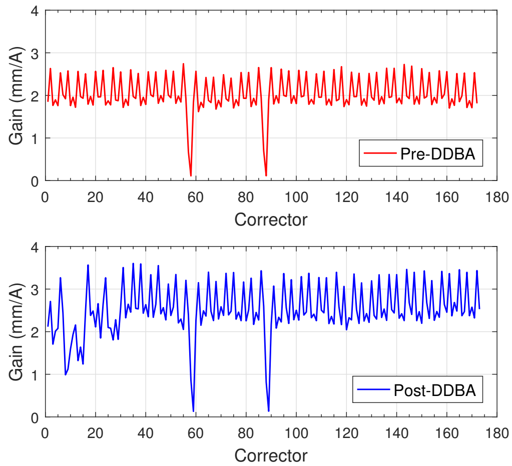

Figure 3: The top plot shows the maximum gain (mm/A) of the response matrix for each corrector pre-DDBA (–) and the bottom plot shows the same post-DDBA (–).

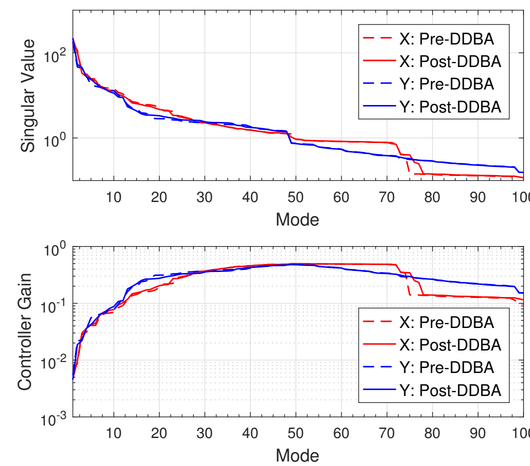

Figure 4: The top plot shows the singular values pre-DDBA for the X-axis (- -) and Y-axis (- -) compared to the singular values post-DDBA for the X-axis (–) and Y-axis (–).

to the current inputs to the magnet power supplies [3] and are shown in Fig. 5 for the vertical plane. The DBA correctors have a bandwidth of 700 Hz, whereas the correctors installed on sextupoles in the DDBA cell have a bandwidth of the 1 kHz (due to thinner stainless vacuum vessel). These DDBA cell correctors are referred to as "fast" correctors. The discrete correctors that are placed over the copper vacuum vessel have a significantly lower bandwidth of 10 Hz and are referred to as "slow" correctors. This represents a challenge for the FOFB since the controller dynamics, $c(z^{-1})$ is designed based on the dynamics of the DBA correctors i.e. the control action is calculated based on a 700 Hz bandwidth system.

In this paper, the effect of the DDBA upgrade on the FOFB performance is presented. Firstly, the robustness of the closed loop is assessed and secondly, disturbance rejection capability of the closed loop is assessed.

STABILITY OF THE CLOSED LOOP

Robustness to differences in the gain and phase of the actual system dynamics compared to the design dynamics can be expressed in terms of the gain and phase margins, which are determined directly from the frequency response plots of the forward loop ($L_n(z^{-1})$) given by

$$L(z^{-1}) = G(z^{-1})RC(z^{-1})\tilde{R}^{-1} \quad (2)$$

where $G(z^{-1})$ is the matrix of open loop dynamics. The gain margin is the factor by which the gain can be raised before instability results i.e. how much increase in system gain can the controller accommodate. A gain margin > 1 is required for stability and > 3 is considered good practice. Likewise, the phase margin is the amount by which the phase lag can be increased before instability results i.e. how much extra delay in the system can the controller accommodate. A positive phase margin is required for stability. The first mode

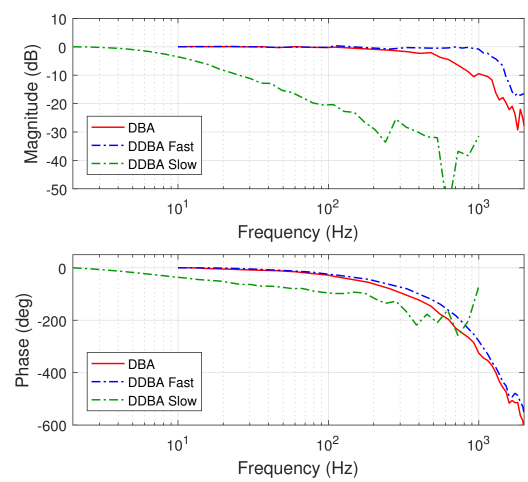

Figure 5: Measured vertical frequency responses of a DBA corrector magnet (–), a fast DDBA corrector (·–) and a slow DDBA corrector (- -).

(associated with the largest singular value) has the smallest gain margin and phase margin and for the vertical system the gain margin is 3.7 and the phase margin is 73.5 deg. The measured forward loop frequency response for each corrector type is shown in Fig. 6 and for each frequency the gain and phase margins of the DDBA correctors compared to the design dynamics is not exceeded. Therefore the closed loop is stable even in the presence of the different dynamics of the DDBA correctors.

DISTURBANCE REJECTION CAPABILITIES

The effect of the different dynamics on the ability of the closed loop to reject beam disturbances (i.e. the sensitivity function) is shown in Fig. 7. The DBA correctors

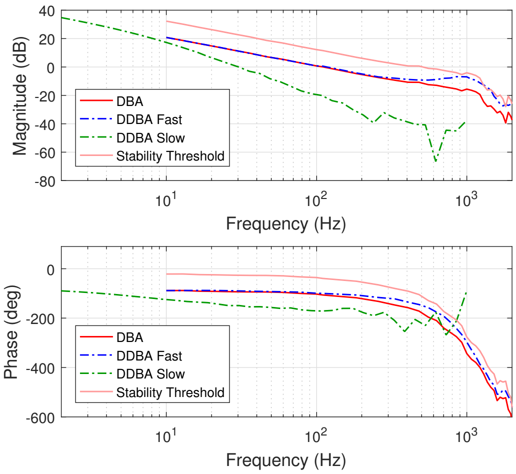

Figure 6: Measured vertical frequency responses of the forward control loop for a DBA corrector magnet (–), a fast DDBA corrector (·–) and a slow DDBA corrector (- -). The gain and phase margins are also shown (–).

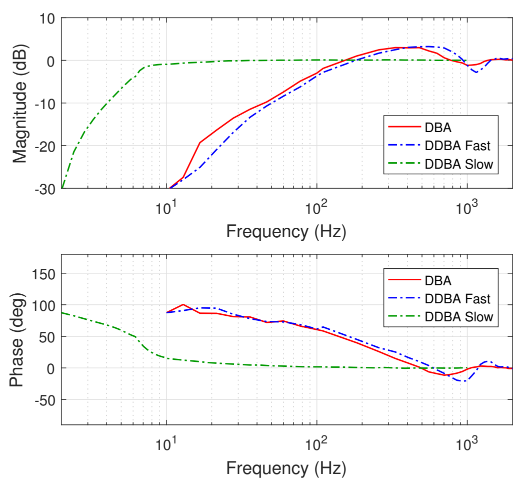

Figure 7: Measured vertical sensitivities of a DBA corrector magnet (–), a fast DDBA corrector (·–) and a slow DDBA corrector (- -).

and DDBA fast correctors have similar sensitivities i.e. 30 dB suppression at 10 Hz is achieved and no suppression is achievable above 145 Hz. However the slow DDBA correctors provide just 1 dB suppression at 10 Hz and no attenuation of disturbances above 20 Hz. Therefore the slow correctors have limited bandwidth and strength to correct disturbances as well as the DBA and fast DDBA correctors.

The performance of the FOFB is assessed mainly from the integrated vertical beam motion up to 100 Hz which is shown in Fig. 8 for the pre- and post-DDBA storage ring observed at all BPMs. The uncorrected integrated motion shows that beam motion is greater at all locations with the exception of the DDBA cell (BPMs 8-15). However,

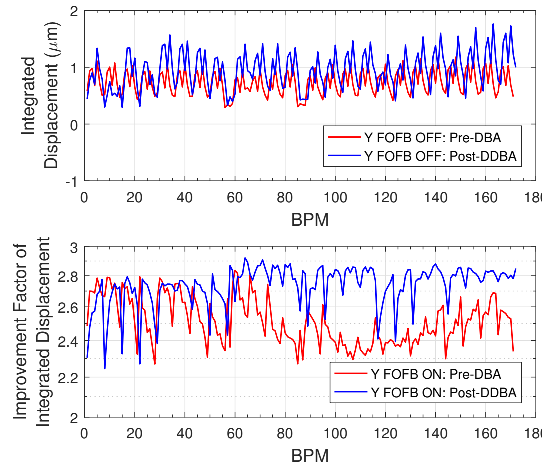

Figure 8: The top plot shows the integrated vertical beam motion (μm) up to 100 Hz pre-DDBA (–) and post-DDBA (–). The bottom plot shows the factor by which the integrated beam motion was suppressed with FOFB pre-DDBA (–) and post-DDBA (–).

with FOFB correction applied, pre-DDBA correction was non-uniform around the ring and achieved on average 2.5 times suppression of integrated beam motion. Post-DDBA, the correction factor is increased in the DDBA cell and is less at other sections of the ring. However on average the suppression is now 2.7 times. Therefore the FOFB achieves a similar level of beam motion suppression globally.

CONCLUSION

The DDBA cell installation has introduced several challenges to the FOFB system. Mainly the introduction of corrector magnets with different dynamics and a redistribution of the disturbances observed by the BPMs. However, despite the changes to the storage ring, it was not required to re-tune the FOFB controller to achieve the same level of disturbance suppression as achieved prior to the DDBA cell installation. Moreover the FOFB controller was robust enough (i.e. had sufficient gain and phase margin) to accommodate the changes to the corrector magnet's responses affecting the FOFB system.

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