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OPERATIONAL CHALLENGES OF THE SUPERKEKB IBUMP FEEDBACK SYSTEM*†

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Abstract

To maintain optimal beam collision conditions and luminosity performance, SuperKEKB requires a fast orbit feedback dedicated to correcting offsets at the interaction point (IP). The "iBump" feedback system calculates IP beam offset from Beam Position Monitor (BPM) measurements before and after collision and corrects by creating closed orbit bumps in the High Energy Ring (HER). This system has demonstrated robustness at stabilising IP offsets during operation. In this paper, we discuss operational aspects of the system and ongoing challenges, with a focus on the identification of vertical offset as the correction target of the iBump system. Dedicated studies on the current dependence of this feedback target as well as historical data are analysed.

INTRODUCTION

SuperKEKB is an electron-positron collider located at KEK, Japan [1, 2]. A second generation B factory, SuperKEKB utilises an asymmetric, double ring collider setup. The High Energy Ring (HER) stores 7 GeV electrons for collision with 4 GeV positrons stored in the Low Energy Ring (LER), resulting in highly boosted 10.58 GeV centre-of-mass energy collisions. SuperKEKB holds the record for instantaneous luminosity of $5.1 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ achieved in December 2024 [3]. To achieve and maintain this high luminosity the beams must be kept in collision to high accuracy.

Orbit Feedbacks at SuperKEKB

Machine imperfections during operation, such as magnet vibrations and power converter ripple, result in beam orbit variations (and other errors). To mitigate these effects, a range of feedbacks are employed. A global orbit feedback system is employed to minimise the beam orbit oscillations. This system maintains the residual of the closed orbit to about 30 µm RMS in the horizontal and vertical planes at around 0.1 Hz [4].

The tolerances at the Interaction Point (IP) are much tighter. SuperKEKB utilises the nano beam scheme [5], resulting in nano-metre scale vertical beam sizes at the IP. Dedicated IP feedback systems are therefore required to locally correct the orbit. At SuperKEKB two IP feedback systems exist [6]. A dither feedback system developed at SLAC is installed but not currently employed in operation [7]. A beam-beam deflection based system, the 'iBump' feedback system is also installed and in active use.

THE IBUMP FEEDBACK SYSTEM

The iBump feedback system was first employed at KEKB [8]. At SuperKEKB, corrections were initially calculated on CPU ('slow feedback'). Following an upgrade, an FPGA is used to calculate corrections ('fast feedback') enabling operation at 31 kHz [9]. At SuperKEKB, the iBump feedback system corrects vertical offset and vertical angle. A schematic overview is shown in Fig. 1.

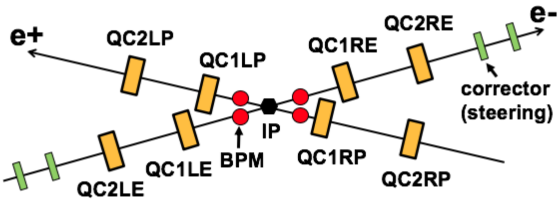

Figure 1: Schematic of the iBump Feedback System. [10]

The working principle of the iBump feedback system is beam-beam deflection. During a beam-beam interaction, each beam exerts a force on the other; a beam-beam kick is applied resulting in a change of momentum. In the regime of small offsets (feedback regime), the beam-beam kick is approximately linear as

$$\Delta a' = -\frac{2\pi}{\beta_a^*}\xi_a \Delta a, \qquad a \in x, y, \tag{1}$$

where β_a^* is the beta function at the IP and ξ_a is the beam-beam tune shift. To calculate the IP offset, the change in momentum $\Delta a'$ is calculated from centroid position measurements at four Beam Position Monitors (BPMs) and four transfer matrices between the BPMs and the IP. The BPMs are positioned 1.1 m from the IP, after a bellow and before the first Final Focus Quadrupole. Transfer matrices are obtained from an optics model in SAD [11].

A feedback correction is then applied based on a linear prediction method [10]. The orbit bump height to apply on the next feedback cycle is equal to a gain factor multiplied by the negative of the calculated offset, as

$$\Delta y_{n+1}^{\mathrm{bump}} = -G \cdot \Delta y_{n+1}, \tag{2}$$

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where G is the gain factor, and Δy_{n+1} is the predicted canonical kick in the next feedback cycle, calculated using a linear least squares method. The feedback correction is applied on the HER beam using 12 corrector magnets (4 horizontal and 8 vertical) in the interaction region. Twelve correctors are used to ensure orbit, dispersion and coupling closure.

The iBump Feedback Vertical Offset Target

The calculation of the IP offset may be subject to errors in the BPM measurements and the transfer matrices, such as: BPM misalignments, calibration errors and optics model imperfections. To account for these errors, a free parameter is used to represent the difference between the true offset and calculated offset: the 'iBump Feedback Target: Vertical Offset' (iBFBTVO).

This parameter is measured experimentally by optimising the specific luminosity and thus minimising the beam-beam offset at the IP. Details of the approach are operator dependant, with number of sample points, and time allowed for equilibration at the discretion of the operator. The scan process typically takes approximately ten minutes in good beam conditions, or longer if the initial state is far from optimal collision. A quadratic fit is applied to the measured specific luminosity profile, and an optimum value of the iBFBTVO is selected. An example optimisation scan, including the quadratic fit, is shown in Fig. 2.

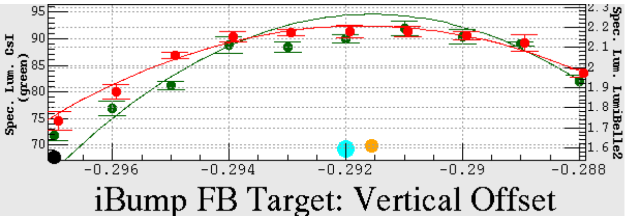

Figure 2: Example 'iBump Feedback Target: Vertical Offset' scan. The iBFBTVO is varied while specific luminosity is measured with two detectors: CsI (green) and LumiBelle2 (red) [12]. Quadratic fits are applied.

The specific luminosity shows low variance around the optimal iBFBTVO (within error bars). This indicates that the luminosity is not sensitive to minor errors in the value of the iBFBTVO with the current optics configuration.

Collision Tuning

Collision tuning typically occurs once per shift (3x per day), or following significant changes in beam conditions (abort, optics changes etc.). Collision tuning is typically the final stage of the optimisation process. Optics correction and tuning occurs on each beam independently at low current. The machine is then filled for collision tuning. Collision tuning is performed by optimisation of the iBFBTVO.

CURRENT DEPENDENCE

The experience of the operators was that the optimisation of the iBFBTVO was beam current dependent. This was tested during two machine development periods (MDs).

Machine Study: Variation with Current

The MD occurred June 4th 2024, 14:00-18:00 JST. The aim was to analyse the dependence of the iBFBTVO on beam current. Beam conditions were generally good, with one beam abort at 16:02 JST, recovered by 16:25 JST.

The iBFBTVO was scanned eleven times, yielding ten optimised values at seven currents (some repetitions pre and post abort). One scan was abandoned for inconsistency in measurement direction, while another was interrupted by the beam abort. An overview of the MD is shown in Fig. 3.

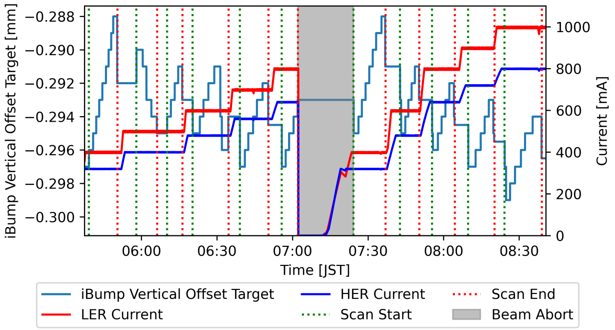

Figure 3: Overview of the Varied Current Machine Study.

A linear relationship between the iBFBTVO and beam current was observed. Results are shown in Fig. 4. A difference in the trend is observed pre-abort and post-abort, in particular for lower beam currents.

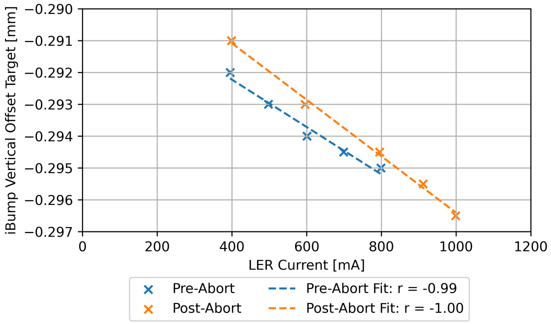

Figure 4: Current dependence of the iBFBTVO. Strong linear trends are observed, with significant discrepancy pre and post-abort.

Machine Study: Stability with Constant Current

A further MD occurred on December 11th 2024, 19:20-01:00 JST. The aim was to establish the behaviour during constant current operation by re-optimising the iBFBTVO every 20 minutes during this period. Beam conditions were generally good, with LER beam current held constant at 1200 mA. Minor RF issues were observed, where slight drops in current were observed and measurements were rejected in these periods. An overview of the MD is shown in Fig. 5.

Over the full period of six hours, the optimal iBFBTVO was observed to be stable. As the iBFBTVO accounts for

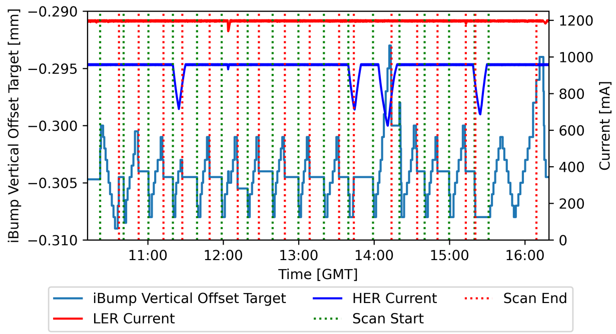

Figure 5: Overview of the Constant Current Machine Study.

errors in the BPM positions and transfer matrices, this implies that with stable beam conditions the variation of these errors is low.

During one current drop (due to the RF issue), a scan was continued. A significantly larger optimal iBFBTVO was measured, aligning with the dependence observed during the varied current MD. The magnitude was not measured, as the beam current was varying during measurement, so no equilibrium was reached.

The final scan was repeated twice in the forward direction and once in reverse. The measurement was observed to be reproducible, regardless of the direction.

Historical Data

In addition to dedicated MD periods, analysis has been performed on historical data to consider longer time periods. Data from 2022 operation and the 2024ab machine runs have been analysed and the dependence of the iBFBTVO with current are shown in Fig. 6. In contrast to the MD results, there is no clear trend with current. As the iBFBTVO addresses errors in BPM positions and transfer matrices, these are likely to change upon a change of machine optics. Furthermore, it was observed during the varied current MD that aborts produce hysteretic shifts in the machine state. Therefore, over extended operation periods it is not possible to predict the optimal iBFBTVO from just the current. Collision tuning is required upon each abort and optics change.

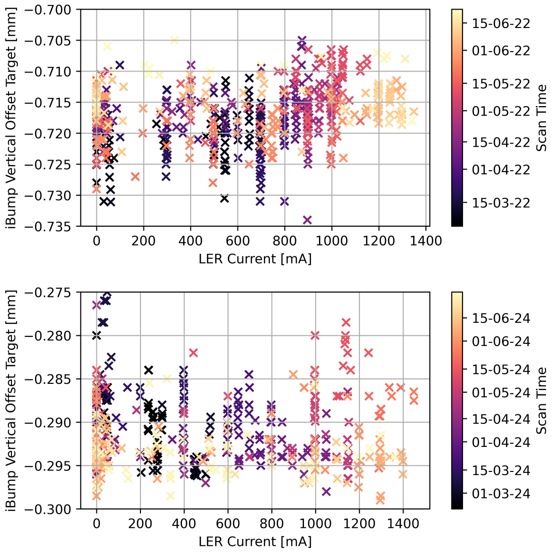

Figure 6: Feedback Target vs Current historical data plot (2022 and 2024ab).

CORRELATION WITH OTHER PARAMETERS

In addition to the current dependence of the iBFBTVO, other correlations were tested during the varied current MD period. Many strong correlations were observed with Pearson Product Moment Correlation Coefficients greater than 0.95. Correlations were observed for variables associated with luminosity, current, beam-size, temperature, Final Focus Quadrupole (FFQ) offsets and IP feedback aspects.

Of particular note were parameters that showed strong correlations both pre and post abort, but not over all data. This indicates a strong hysteretic effect of the abort. Three variables showed this particularly strongly, all related to the separation between the cryostat containing the FFQs and the Belle-II detector Central Drift Chamber (CDC). These are measured using ‘gap sensors’ to calculate the relative displacement [13]. The correlations are shown in Fig. 7.

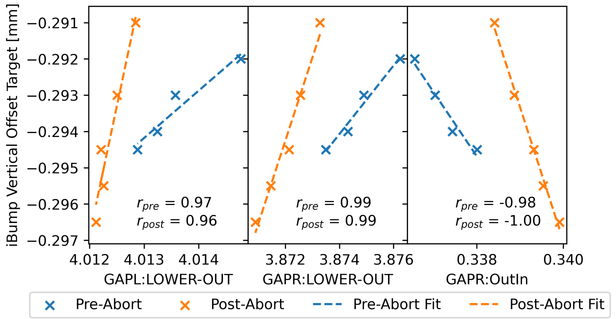

Figure 7: Parameters observed to show strong correlations pre and post abort, but with a discontinuity during abort. Parameters relate to the offset between the Belle-II CDC and the FFQ cryostats, labelled as the EPICs variables.

Sudden FFQ motion was directly observed at the abort, and one proposed explanation is that the rapid drop in beam current results in a rapid temperature change and thus sudden quadrupole motion.

CONCLUSION AND OUTLOOK

The iBump system is effective at maintaining luminosity during SuperKEKB operation. The system is not fully automated and still relies on the input of skilled operators. As SuperKEKB pushes to reach design parameters the performance of the system will be enhanced further.

ACKNOWLEDGEMENTS

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