ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO11

CONCEPTUAL DESIGN OF COLLISION FEEDBACK SYSTEM FOR THE SUPER TAU-CHARM FACILITY*

Q. Chen, Q. Luo†, SNST, University of Science and Technology of China, Hefei, China

Abstract

The Super Tau-Charm Facility (STCF), a third-generation electron-positron collider operating in the tau-charm energy region, will be subject to mechanical disturbances and ground vibrations, which can lead to beam-beam misalignments at the interaction point (IP). Such misalignments degrade luminosity and shorten beam lifetime. To maintain an optimum beam collision condition, the development of a high-performance collision feedback system is therefore essential for suppressing orbit offsets at the IP. This study first analyzes the primary sources of orbit perturbations and evaluates the feasibility of three candidate feedback signals for monitoring IP beam offsets in the STCF collision system from the perspective of detection principles. Finally, a preliminary design of the collision feedback system is proposed based on the STCF's performance requirements.

INTRODUCTION

The STCF is a next-generation high-energy physics experiment currently under construction, designed to cover a center-of-mass energy range of 2-7 GeV with a target peak luminosity of no less than 5×10^{34} cm^{-2}s^{-1}[1]. To achieve this luminosity, STCF incorporates several advanced beam dynamics schemes, including emittance compression, the use of a large crossing angle to mitigate the hourglass effect [2], and the application of the crab-waist scheme to suppress coupling resonances induced by large-angle collisions [3]. With these designs, the final focusing (FF) quadrupoles can compress the beam size at IP to the sub-micrometer scale in the vertical direction, while effectively avoiding hourglass limitations and significantly enhancing luminosity. However, such ultra-small beam sizes make the collider highly sensitive to ground motion and mechanical vibrations, where even minute orbit perturbations can cause substantial displacements and crossing angle variations at the IP [4]. These effects severely degrade luminosity and shorten beam lifetime. Therefore, a high-performance collision feedback system with fast response and high-precision orbit control is indispensable for maintaining optimal collision conditions and realizing stable high-luminosity operation.

ORBIT DISTURBANCES

Orbit deviations at IP can lead to significant luminosity loss and therefore require correction. Such deviations may arise, for example, from vertical displacements of the FF quadrupoles induced by ground vibrations transmitted through components such as cryostats. These displacements result in closed-orbit distortions at the IP, with differing orbit drifts between the two colliding beams that cannot be fully compensated [5]. As illustrated in Fig. 1, the orbit offset at IP can be expressed as:

$$\Delta y_{IP} = \frac{\sqrt{\beta_Q \beta_{IP}}}{2\sin \pi \nu_y} = cos\left(\pi \nu_y - \left|\Delta\psi_y\right|\right) K \Delta y_Q \,, \quad (1)$$

where β_Q and β_{IP} denote the transverse beta functions at the FF quadrupoles and at the IP, respectively, ν_y is the vertical tune, $\Delta\psi_y$ is the phase advance between the IP and the FF quadrupoles, K is the quadrupole focusing strength, and Δy_Q represents the vertical displacement of the FF quadrupoles.

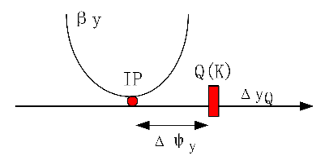

Figure 1: Change of orbit at IP by vertical displacement of the final focus magnets.

FEEDBACK SIGNALS

BPM Signal

Orbit variations induced by beam-beam interactions at IP can be measured using BPM, enabling the determination of the relative beam displacement at the IP and the implementation of orbit feedback correction [6]. Specifically, when the two beams meet each other with a small offset at the IP, the electromagnetic interaction between the beams generates a beam-beam kick proportional to the offset, which in turn causes a large-angle orbit deflection along the beam propagation direction, as illustrated in Fig. 2.

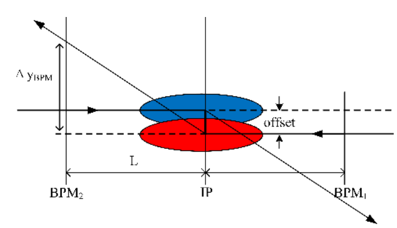

Figure 2: BPM-based principle for orbit offset detection.

The orbit variations of positrons and electrons detected by the BPM can be expressed as:

$$\begin{aligned} \Delta y_{BPM,e} &= L \cdot \Delta y_e'^{*} = -L \frac{2\pi}{\beta_y^*} \xi_y \left(y_e^* - y_p^*\right), \\ \Delta y_{BPM,p} &= L \cdot \Delta y_p'^{*} = L \frac{2\pi}{\beta_y^*} \xi_y \left(y_e^* - y_p^*\right). \end{aligned} \quad (2)$$

$\Delta y_{e,p}^*$ represents the beam-beam kick experienced by the electron and positron beams, and $y_{e,p}^*$ denotes their vertical positions at the IP. According to Eq. (2), by monitoring BPM signals upstream and downstream of the IP,

* Work supported by National Key R&D Program of China (2022YFA1602201).
† luoqing@ustc.edu.cn

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO11

together with ξ_y, β_y^*, and the transfer matrix between the IP and the BPMs, the orbit offset at the IP can be accurately reconstructed. This technique was originally developed for the Stanford Linear Collider (SLC) at SLAC and has been successfully applied for many years in circular colliders such as KEKB and SuperKEKB [7].

ξ characterizes the strength of the beam–beam interaction. For STCF, a large ξ_y makes the beam–beam kick a sensitive observable for monitoring collisions, which can be effectively tracked using BPM signals. In contrast, when ξ_x is relatively small, BPM signals alone are insufficient to support collision feedback.

Beamstrahlung Signal

When the two beams collide at IP, synchrotron radiation, referred to as beamstrahlung (BS), is generated due to the strong electromagnetic field of the opposing beam [8]. The power and angular distribution of the BS signal provide a direct measure of the state of the opposing beam, making it a relatively straightforward diagnostic tool. Simulations for FCC-ee indicate that the BS power is highly sensitive to vertical orbit offsets, while being largely insensitive to horizontal offsets due to the large crossing angle and the beam length being longer than σ_x [9, 10]. The STCF's physical design exhibits the same characteristics, suggesting that BS signals could be used for vertical orbit feedback. However, since the beam density at STCF is significantly lower than at FCC-ee, the resulting BS power is much weaker, and effective acquisition of the BS signal requires further investigation.

Luminosity Signal

As the ultimate performance metric of a collider, luminosity provides a direct indication of orbit offset and can be used for collision feedback via luminosity monitors. However, this approach has two inherent limitations. First, the luminosity function is symmetric, making it difficult to directly determine the direction of the offset when a luminosity drop is observed. Second, fluctuations in beam parameters, such as variations in beam size or current, introduce low-frequency luminosity disturbances that can obscure the identification of orbit drifts.

Since luminosity is a scalar signal, it does not directly provide directional information required for orbit correction. A dithering system can resolve this limitation by modulating one beam with a sinusoidal oscillation of known amplitude and frequency f [11-13]. When the beams are perfectly aligned, the luminosity signal decreases symmetrically around its peak, and dominated by the second harmonic . When an offset is present, a primary component emerges at the fundamental frequency, whose amplitude is proportional to the beam displacement, while the phase of the signal indicates the offset direction. However, this active orbit modulation approach incurs a partial luminosity loss.

COLLISION FEEDBACK

The main advantage of an orbit feedback system based on BPM signals lies in its ability to accurately determine both the direction and magnitude of the required orbit correction. If the BPMs possess sufficient resolution, the system can maintain optimal collision conditions with minimal luminosity loss. A preliminary design of a beam–beam deflection feedback system based on BPM signals has been carried out. The key design parameters required for this system are summarized in Table 1.

Table 1: Design Parameters of STCF

Parameters	Value	Units
Beam energy, E	2	GeV
Crossing angle, 2θ	60	mrad
Hor. emittance, ε_x	4.63	nm
Ver. emittance, ε_y	46.3	pm
Hor. beta function at IP, β_x^*	60	mm
Ver. beta function at IP, β_y^*	0.8	mm
Hor. Beam size at IP, σ_x^*	16.67	µm
Ver. Beam size at IP, σ_y^*	0.19	µm
Hor. Beam-beam parameter, ξ_x	0.005	
Ver. Beam-beam parameter, ξ_y	0.095	

Using Beam-Beam Weak-Strong (BBWS) simulations, the degradation of luminosity due to both slow and fast orbit offsets at the IP was quantitatively analyzed. The simulation results indicate that a closed-orbit deviation of $0.5\sigma_y^*$ at the IP leads to approximately a 10 % reduction in luminosity, as shown in Fig. 3. Accordingly, to limit the luminosity loss to within 1 %, the tolerance for vertical orbit offsets was set: the orbit must be controlled within $0.05\sigma_y^*$, corresponding to a maximum allowable offset between the two beams at the IP of $0.05\sigma_y^*$.

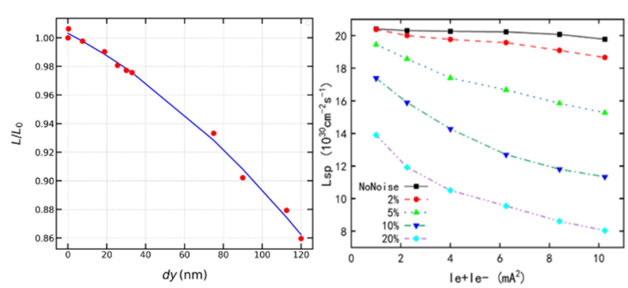

Figure 3: Closed orbit offset at IP (left) and turn by turn noise (right).

To improve measurement accuracy, the system plans to install four BPMs at equidistant positions relative to the IP, ideally located between the Y-type chamber of the interaction region and the QD0 quadrupoles, as illustrated in Fig. 4. In this configuration, only a drift section separates the IP and the BPMs, and the positions of the electron and positron beams can be independently monitored via separated orbits. The most stringent case occurs when a BPM is placed at the entrance of the Y-type chamber, 63 cm from the IP, where Eq. (2) yields a required resolution of 4.5 µm. This specification is within the capability of existing BPM

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO11

designs, ensuring the orbit offset at the IP can be confined within 5 % of the beam size.

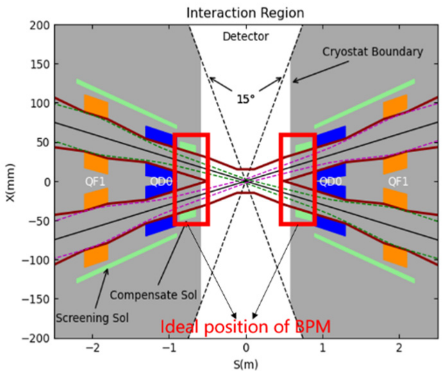

Figure 4: Ideal position of BPM.

However, due to the limited space in the STCF interaction region, it is not feasible to install two sets of BPMs at the ideal positions. Consequently, the BPMs are moved downstream of the QD0 quadrupoles. While this simplifies installation, it introduces magnetic field errors and positional deviations from QD0, reducing measurement accuracy. To address this, two sets of common BPMs with eight electrodes each are planned closer to the IP to achieve limited orbit separation between the two beams. The preliminary BPM layout in the interaction region is shown in Fig. 5.

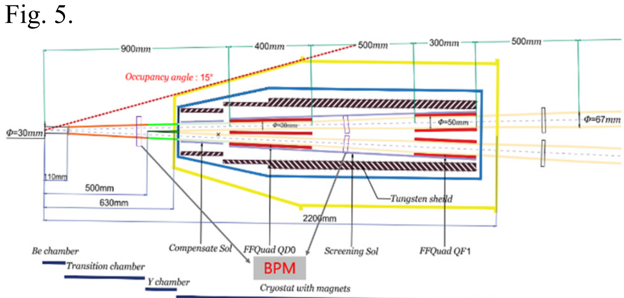

Figure 5: STCF IR BPM.

Once BPM signals are successfully acquired and the IP orbit offsets are sensitively monitored, a feedback loop must be established to correct the orbit. Figure 6 shows the simulation model of the collision feedback loop. Different closed-loop transfer functions correspond to different system delays, i.e., the time elapsed from BPM signal acquisition to the response of the fast corrector. This delay directly affects the feedback bandwidth of the system.

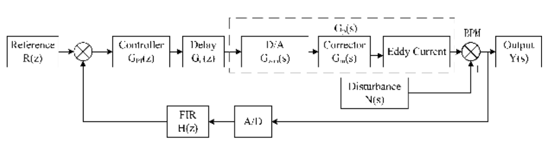

Figure 6: Feedback loop.

Before designing the feedback loop in detail, the maximum allowable total delay should be determined based on the required effective feedback bandwidth. The control loop was simulated using Simulink, and Fig. 7(a) illustrates the effect of different delays on disturbance attenuation under fixed PI parameters: while the attenuation gain remains constant, the overshoot increases with delay. Further, by optimizing the PI parameters using Simulink PID Tuner, a balance between control performance and robustness can be achieved under the total delay constraint. Fig. 7(b) presents the results of PI tuning for different delays. Simulations indicate that to achieve a feedback bandwidth of 100 Hz, the total delay of the feedback loop must not exceed 1.41 ms.

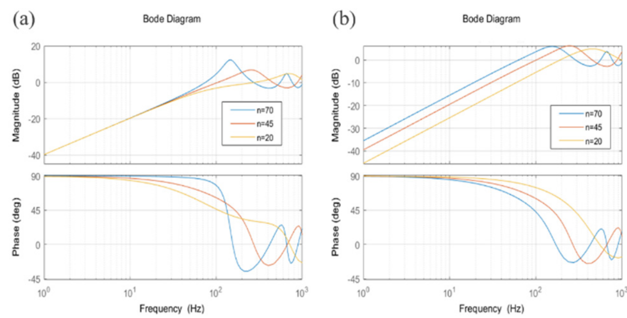

Figure 7: Different delays on disturbance attenuation response (a) and attenuation response with PI tuning (b).

CONCLUSION

In this work, a preliminary design study has been conducted for a beam-beam deflection feedback system based on BPM signals. Future work will focus on refining key aspects, such as further optimization of the eight-electrode BPMs and the design of the feedback electronics. In addition, the acquisition of the other two types of feedback signals and the development of their corresponding feedback systems will continue to be explored, with the aim of comprehensively enhancing the collision stability and overall performance of STCF.

ACKNOWLEDGEMENTS

We thank the Hefei Comprehensive National Science Center for their strong support on the STCF key technology research project.

REFERENCES

[1] H. P Peng, Y. H. Zheng, and X. R. Zhou, "Super tau-charm facility of China", *Physics,* vol. 49, no. 8, pp. 513-524, 2020. doi:10.7693/wl20200803

[2] SuperB collaboration, "SuperB: A high-luminosity asymmetric e+ e- super flavor factory. Conceptual design report", Sep. 2007, arXiv:0709.0451 [hep-ex]. doi:10.48550/arXiv.0709.0451

[3] P. Raimondi, D. Shatilov, and M. Zobov, "Beam-beam issues for colliding schemes with large Piwinski angle and crabbed waist", Feb. 2007, arXiv:physics/0702033 [physics.acc-ph]. doi:10.48550/arXiv.physics/0702033

[4] Y. Funakoshi *et al.*, "Interaction Point Orbit Feedback System at SuperKEKB", in *Proc. IPAC'15,* Richmond, VA, USA, May 2015, pp. 921-923. doi:10.18429/JACoW-IPAC2015-MOPHA054

[5] M. Serluca *et al.*, "Vibration and luminosity frequency analysis of the SuperKEKB collider", *Nucl. Instrum. Methods Phys. Res. A,* vol. 1025, p. 166123, 2024. doi:10.1016/j.nima.2021.166123

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO11

[6] P. Bambade and R. Erickson, “Beam-beam deflections as an interaction point diagnostic for the SLC”, *in Proc. LINAC'86,* Stanford, CA, USA, Sep. 1986, paper TH3-16, pp. 475-477.

[7] Y. Funakoshi *et al.*, “Orbit feedback system for maintaining an optimum beam collision”, *Phys. Rev. Spec. Top. Accel. Beams,* vol. 10, p. 101001, 2007. doi:10.1103/PhysRevSTAB.10.101001

[8] A. Hofmann and E. Keil, “Synchrotron radiation caused by the field of the other beam”, CERN, Geneva, Switzerland, Rep. CERN-LEP-70-86, 1978. https://cds.cern.ch/record/443445

[9] M. Boscolo and A. Ciarma, “Characterization of the beamstrahlung radiation at the future high-energy circular collider”, *Phys. Rev. Accel. Beams,* vol. 26, p. 111002, Nov. 2023. doi:10.1103/PhysRevAccelBeams.26.111002

[10] J. Salvesen, F. Zimmermann, and P. Burrows, “First studies on error mitigation by interaction point fast feedback systems for FCC-ee”, in *Proc. IPAC'24,* Nashville, TN, USA, May 2024, pp. 3322-3325. doi:10.18429/JACoW-IPAC2024-THPG31

[11] L. Hendrickson *et al.*, “Luminosity optimization feedback in the SLC”, in *Proc. ICALEPCS`97*, Beijing, China, Nov. 1997, paper ID126.

[12] A. S. Fisher *et al.*, “Commissioning the Fast Luminosity Dither for PEP-II”, in *Proc. PAC'07,* Albuquerque, NM, USA, Jun. 2007, paper FRPMS066, pp. 4165-4167. doi:10.1109/JACoW-PAC2007-4440072

[13] M. Masuzawa *et al.*, “Early Commissioning of the Luminosity Dither Feedback for SuperKEKB”, in *Proc. IBIC'18,* Shanghai, China, Sep. 2018, pp. 328-331. doi:10.18429/JACoW-IBIC2018-TUPC13