Design and integration of a crab-waist interaction region for the Super Tau-Charm Facility

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Abstract

The Super Tau-Charm Facility (STCF) is a next-generation electron-positron collider being developed in China, designed to achieve a peak luminosity exceeding 5$×$10^{34} cm^(-2) s^(-1) at the optimal beam energy of 2 GeV. Achieving this goal relies on a crab-waist collision scheme with a large crossing angle-a configuration that introduces strong nonlinearities, severely constraining the dynamic and momentum apertures. This paper presents a comprehensive physics design for the STCF interaction region (IR) that systematically addresses these challenges. The design features a modular optics framework that incorporates local chromaticity correction up to the third order, exact -I transformations between chromatic sextupole pairs for nonlinear cancellation, and minimization of the dispersion invariant to improve local momentum acceptance. Optics at the crab sextupoles are optimized to reduce their strength and associated nonlinearities. When integrated into the collider ring, the design achieves a Touschek lifetime of over 300 s at 2 GeV, meeting the STCF requirement. Furthermore, fringe fields from superconducting quadrupoles are partially compensated using octupole correctors, and detector solenoid effects are fully suppressed via local anti-solenoids. The machine-detector interface layout is also optimized to avoid synchrotron radiation background at the interaction point. This IR design represents the current optimized solution for STCF and has been incorporated into the project's conceptual design report.

Full Text

Preamble

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The Super Tau-Charm Facility (STCF) is a next-generation electron–positron collider being developed in China, designed to achieve a peak luminosity exceeding (5×10$^{\{34\},\mathrm{cm}}${-2}s^{-1}) at the optimal beam energy of 2 GeV. Achieving this goal relies on a crab-waist collision scheme with a large crossing angle—a configuration that introduces strong nonlinearities, severely constraining the dynamic and momentum apertures. This paper presents a comprehensive physics design for the STCF interaction region (IR) that systematically addresses these challenges. The design features a modular optics framework that incorporates local chromaticity correction up to the third order, exact (-I) transformations between chromatic sextupole pairs for nonlinear cancellation, and minimization of the dispersion invariant to improve local momentum acceptance. Optics at the crab sextupoles are optimized to reduce their strength and associated nonlinearities. When integrated into the collider ring, the design achieves a Touschek lifetime of over 300 s at 2 GeV, meeting the STCF requirement. Furthermore, fringe fields from superconducting quadrupoles are partially compensated using octupole correctors, and detector solenoid effects are fully suppressed via local anti-solenoids. The machine-detector interface layout is also optimized to avoid synchrotron radiation background at the interaction point. This IR design represents the current optimized solution for STCF and has been incorporated into the project's conceptual design report.

Keywords: Super Tau-Charm Facility; chromaticity correction; dynamic aperture; machine-detector interface; interaction region design; crab-waist; high-order

1. Introduction

The Super Tau-Charm Facility (STCF), a new-generation electron-positron collider currently under development in China, is designed to operate at center-of-mass (CoM) energies from 2 to 7 GeV [?]. It targets a peak luminosity of at least (5×10$^{\{34\},\mathrm{cm}}${-2}s^{-1}) at the optimal CoM energy of 4 GeV—approximately 50 times that of the BEPCII (currently operating Tau-Charm factory)—making it a unique platform for precision physics studies in the tau-charm region and a potential probe of physics beyond the standard model.

To achieve the desired high luminosity, the STCF adopts the crab-waist collision scheme proposed by P. Raimondi in 2006 [?], which combines a large crossing angle with dedicated crab sextupoles. This configuration enables a drastic reduction of the vertical beta function at the interaction point (IP), thereby enhancing the luminosity, while simultaneously suppressing detrimental beam-beam resonances through sextupole-induced vertical beam waist shifts at the IP [?]. The scheme has been validated at the DAFNE ( )-factory [?] and forms the basis of all modern high-luminosity colliders, including FCC-ee [?] and CEPC [?] in the high-energy regime, SuperKEKB [?] and the earlier SuperB [?] proposal at medium energies, and tau-charm projects such as BINP's SCTF [?] and STCF [?] in the low-energy domain.

However, the crab-waist scheme introduces substantial challenges to the IR optics design [?]. The extremely low vertical beta function at the IP leads to large beta-functions at the final focus (FF) quadrupole doublets, necessitating ultra-strong FF quadrupoles that in turn generate high natural chromaticity, introduce significant fringe fields, and increase sensitivity to field errors. Additional complications arise from high-order kinematic terms of the IP drift, strict phase-advance requirements from crab sextupoles to the IP, and the need to compensate detector solenoid fields that induce horizontal–vertical coupling. Collectively, these effects degrade the dynamic and momentum apertures, limiting the Touschek lifetime—a critical issue for high-current, low-emittance operation in STCF. Experience from SuperKEKB confirms that the IR dominates the nonlinear dynamics of the ring [?], and integrating ultra-strong FF quadrupoles within a constrained machine–detector interface (MDI) further complicates the design.

Early STCF IR designs suffered from insufficient dynamic aperture (DA) and a short Touschek lifetime of only 35 s [?, ?]. Recent global optimizations of the collider ring improved performance to approximately 240 s [?], but the decision in 2024 to deprioritize spin polarization opened a new opportunity for a fundamental redesign of the collider lattice, including the arc and IR optics [?], with the goal of achieving a breakthrough in nonlinear performance.

This paper presents a comprehensive crab-waist IR design developed under this new paradigm. The design overcomes previous limitations through several key features: (1) a modular optics approach with minimized dispersion invariant; (2) local chromaticity correction extended to the third order; (3) exact (-I) transformation between chromatic sextupole pairs for nonlinear cancellation; and (4) integrated compensation of fringe fields and detector solenoid effects. When incorporated into the latest collider ring lattice, the design achieves a Touschek lifetime exceeding 300 s, fulfilling the STCF requirement.

This IR configuration represents the current reference design for the STCF collider ring, and has been incorporated into the STCF conceptual design report [?].

The paper is organized as follows: Section 2 details the physics-driven selection of IR key parameters. Section 3 describes the modular IR lattice design and its nonlinear properties. Section 4 evaluates the performance of the IR integrated into the full collider ring. Section 5 presents the MDI layout and physics-related design. Section 6 concludes the paper.

2. IR Key Parameter Selection: A Physics-Driven Trade-Off

The IR design is governed by several key parameters that directly influence the luminosity, nonlinear dynamics, and engineering feasibility. The selection of these parameters involves balancing competing physical effects and constraints. We focus on four primary parameters: the full crossing angle ((2 _c)), the drift length from the IP to the first FF quadrupole ((L^*)), and the horizontal and vertical beta functions at the IP ((_x^*, _y^*)). The optimized set of parameters for STCF, alongside a comparison with other new-generation (e$^{+/e}$-) colliders, is presented in Table 1 .

Crossing Angle ((2 _c)): A large crossing angle (e.g., 60 mrad) allows for a reduced (_y^*) without the hourglass effect. It also enables rapid beam separation and reduces the strength of the crab sextupoles, thereby mitigating their nonlinear impact. Furthermore, a large crossing angle lowers the horizontal beam-beam parameter ((_x)), which helps satisfy the condition (_z   _x) ((_z) is the synchrotron tune) for suppressing the coherent X-Z beam-beam instability [?, ?]. However, a larger crossing angle leads to geometric luminosity loss owing to reduced vertical beam-beam parameter ((_y)) and necessitates higher beam currents to meet the luminosity target, thereby posing greater challenges from collective effects. Therefore, the current choice of (2 _c = 60) mrad for STCF represents a trade-off between luminosity and beam-beam stability.

IP Drift Length ((L^*)): The IP drift length (L^) *affects both the chromaticity and the MDI space. A shorter (L^*) reduces the natural chromaticity of the IR, easing the requirement for chromaticity correction. However, it also constrains the space available for the detector and the dual-aperture FF superconducting quadrupoles, complicating their design and installation. With a crossing angle of 60 mrad, we have chosen (L^* = 0.9) m to provide sufficient space for the quadrupoles while maintaining acceptable chromaticity levels.

Vertical Beta Function ((_y^*)): The vertical beta function at the IP is a primary factor for achieving high luminosity. A smaller (_y^*) directly increases the luminosity but requires stronger FF quadrupoles. These stronger quadrupoles, in turn, introduce larger natural chromaticity and fringe field nonlinearities. Therefore, the choice of (_y^*) involves a trade-off between luminosity and nonlinear effects. To reach the STCF design luminosity of (1×10$^{\{35\},cm}${-2}s^{-1}) (twice the engineering goal of (5×10$^{\{34\},cm}${-2}s^{-1})), (_y^*) should be below 1 mm, considering the vertical beam-beam parameter below 0.1 and beam-intensity effects. Our current design adopts (_y^* = 0.8) mm, instead of the previously considered 0.6 mm [?], aligning with the lowest operational level achieved to date by SuperKEKB [?], to maintain high luminosity while mitigating nonlinear challenges.

Horizontal Beta Function ((_x^*)): The horizontal beta function at the IP influences the horizontal beam-beam parameter and the IR chromaticity. A smaller (_x^*) helps reduce (_x), which is beneficial for suppressing the coherent X-Z instability. However, it also increases the horizontal chromaticity and nonlinearity in the IR. After careful consideration, we have chosen (_x^* = 60) mm, revised from earlier designs that used 90 mm and 40 mm, which strikes a balance between beam-beam effects and nonlinear dynamics.

Table 1: Comparison of IR key design parameters among new-generation (e$^{+/e}$-) colliders

Parameters	STCF	SuperKEKB (LER/HER)	SuperB (LER/HER)	CEPC(Z)	FCC-ee(Z)	BINP-SCTF
(2 _c) (mrad)	60	83	60	33	30	60
(_y^*) (mm)	0.8	0.27/0.30	0.27/0.30	1.0	0.8	0.8

In summary, the selected parameters represent a carefully balanced set that optimizes the IR performance within the physical and engineering constraints of the STCF.

3. Modular Optics Design and Nonlinear Properties

3.1 Design Philosophy and Evolution of Crab-Waist IRs

In new-generation crab-waist colliders, the pursuit of extremely low (_y^*) (millimeter scale and even sub-millimeter) substantially amplifies the natural chromaticity, necessitating more powerful local chromaticity correction systems. Furthermore, a central challenge lies in integrating the crab sextupoles (CS), whose prescribed phase advances and strengths—derived for on-momentum particles using a linear transfer map (see Ref. [?] or the Appendix)—are perturbed by momentum deviation (= p/p_0). This introduces chromatic-dependent Twiss functions (/) at the CS location and phase advances between the CS and the IP, which degrade the off-momentum dynamic and momentum apertures. This challenge has led to two predominant optics design philosophies for the crab-waist IR:

Separated Correction Scheme: This scheme, exemplified by the designs for SuperB [?], FCC-ee (by P. Raimondi) [?], CEPC [?], and BINP-SCTF [?], features dedicated vertical and horizontal chromaticity correction sections, with the crab sextupoles placed in the ensuing achromatic regions at the outer ends of the IR. This configuration aims to provide a near-transparent optical environment for the crab sextupoles, minimizing their off-momentum nonlinear impact, though it generally results in a longer IR. A. Bogomyagkov previously proposed placing the crab sextupole closer to the IP for the FCC-ee IR [?], an approach subsequently tested in the BINP-SCTF IR [?]. While this configuration improved the on-momentum dynamic aperture, it led to a significant reduction in the full 6D dynamic aperture when the crab sextupoles were activated. Consequently, the BINP-SCTF design ultimately reverted to the conventional layout with crab sextupoles outside the dedicated chromatic correction sections [?].

Integrated Correction Scheme: Pioneered by K. Oide for FCC-ee [?] and employed in SuperKEKB [?], this scheme aims for a more compact IR while providing the crab-waist effect at the IP. It integrates the crab sextupole into the second magnet of the vertical chromatic sextupole pair. This yields a more compact IR but requires stronger sextupoles and leaves horizontal chromaticity between the crab sextupole pair uncorrected, potentially compromising off-momentum dynamics performance. Particularly, SuperKEKB has residual dispersion at the crab sextupole location, which may further limit the off-momentum DA [?].

The STCF IR design adopts the separated correction scheme as its foundational architecture to ensure performance robustness and mitigate CS-induced nonlinearities. Building upon this foundation, our work introduces several key optimizations in the linear optics design to further suppress these inherent nonlinear sources.

3.2 Modular Optics Design and Key Features of the STCF IR

The STCF IR lattice is architected around a modular framework, as illustrated in Fig. 1 [Figure 1: see original paper]. The design strategy proactively minimizes nonlinearities by embedding three core principles: (1) implementing exact (-I) transformations between chromatic sextupole pairs for geometric aberration cancellation; (2) minimizing the dispersion invariant (H_x) along the IR to enhance the local momentum aperture (LMA) [?]; and (3) optimizing the beta functions at the CS locations to reduce their strength and associated nonlinearities.

A half-IR of the STCF consists of the following modules: the final focus telescope (FFT), vertical chromatic correction (CCY), horizontal chromatic correction (CCX), crab sextupole section (CS), and multiple matching sections (MCY, YMX, XMC, and MS).

FFT Section: This module compresses the ( )-function at the IP using the superconducting doublet, followed by a normal-conducting doublet that forms the first IP mirror point with (_x = _y = 0) and phase advances to IP (_x = _y =) [?]. This configuration allows IP optics tuning by adjusting the mirror-point ( )-functions without modifying internal components. A weak bending magnet (B0), positioned 8.5 m from the IP to reduce synchrotron radiation background, is inserted between the two doublets to generate local dispersion for the subsequent placement of high-order chromaticity correction sextupole at the first IP image point.

FFT-to-CCY Matching Section (MCY): Comprising a FODO-like cell starting with a defocusing quadrupole, this section ensures the required Twiss parameters ((_x, _y, _x, _y)) at the first vertical chromaticity correction sextupole (S1Y). Moreover, the vertical phase advance from S1Y to the first FF quadrupole (QD1) is set near ( ) [?], allowing fine-tuning for second-order chromaticity correction. Dipoles B1 and B2 enhance dispersion at S1Y, reducing its required strength and mitigating associated nonlinearities, while aiding in control of (H_x).

CCY Section: This module implements an exact (-I) transformation between the S1Y sextupole pair to cancel sextupole-induced nonlinearities—a specific case of the general cancellation conditions detailed in Ref. [?]. The CCY section consists of two mirror-symmetric FODO-like cells, each designed with (/2) phase advances in both planes and (_x = _y = 0) at the section midpoint. Drift lengths are carefully tuned to achieve the exact (-I) condition. Dipoles B3 and B4 create a symmetric dispersion distribution across the CCY and further refine (H_x) control.

CCY-to-CCX Matching Section (YMX): This section transitions the Twiss parameters from S1Y to the first horizontal chromaticity correction sextupole (S1X). The horizontal phase advance from S1X to the second FF quadrupole (QF2) is set near (3) to support second-order chromatic correction. A second IP mirror point is formed with (_x = _y = 0). Dipoles B5 and B6 are added to enhance dispersion at S1X, lowering sextupole strength requirements while maintaining (H_x) control.

CCX Section: Similar to the CCY section, this module implements an exact (-I) transformation between the S1X sextupole pair, with dipoles B7 and B8 providing symmetric dispersion while preserving (H_x) control.

Dispersion Suppression Section (XMC): Dispersion is suppressed at the crab sextupole location using dipole B9.

CS Section: Six quadrupoles are used to satisfy the precise phase advance constraints from the crab sextupole to the IP as (_x = m , _y = n + /2), while maintaining (_y = 900) m, (_x = 2.8) m at the crab sextupole. A key design feature is the minimization of CS strength by ensuring (_y _x), with (_x) kept as small as possible but greater than 1. This configuration mitigates undesired nonlinear effects from the CS (see Appendix). The current design adopts (_y = 900) m and (_x = 2.8) m at the crab sextupole, yielding an integrated gradient field of approximately 3.39 m(^{-2}).

Matching Section (MS): This section employs several quadrupoles to match the (/) functions to the long straight section while adjusting phase advances between the IR and the adjacent arc.

The three design principles for nonlinearity mitigation have been fully integrated into the linear optics design. The resulting optical functions for the STCF IR are shown in Fig. 2 [Figure 2: see original paper]. A notable achievement is the maintenance of a low (H_x) ((0.02) m) throughout the IR, which enhances the LMA by reducing the nonlinear momentum dependence of particle trajectories. Strategic placement of dipoles—all standardized to 1 m length for cost efficiency—enables this control while preserving the required 1.5–2 m separation between the two rings. The total bending angle across the IR is 60°, consistent with the collider ring's geometric layout. To accommodate the 60 mrad IP crossing angle, an asymmetric 30 mrad split is applied: the outer-ring half-IR bends 30 mrad more, and the inner-ring half-IR 30 mrad less, resulting in an asymmetric dispersion profile across the IR.

3.3 High-Order Local Chromaticity Correction

To achieve a Touschek lifetime exceeding 200 s, essential for minimizing beam loss and ensuring high injection efficiency, the STCF requires a momentum acceptance of approximately ($\pm 1.5\%$). Furthermore, to mitigate adverse effects of crab sextupoles on the momentum aperture, the IR optics must exhibit minimal chromatic dependence at the CS locations. These objectives necessitate a systematic local chromaticity correction strategy extending to third order [**?**, **?**].

The correction methodology is structured as follows:

First-Order Correction: Vertical and horizontal chromaticity is corrected using the main sextupole pairs S1Y and S1X, respectively, located in dispersive regions with exact (-I) transformations. This configuration simultaneously corrects linear chromaticity and cancels geometric aberrations induced by the sextupoles.

Second-Order Correction: Second-order chromaticity is suppressed by optimizing the phase advances from the S1Y and S1X sextupoles to the FF quadrupoles QD1 and QF2, respectively. Fine-tuning of quadrupole strengths in the MCY and YMX matching sections enables this correction without introducing additional nonlinear elements. Proper phase advance selection also minimizes leakage of the chromatic beta function amplitude induced from the FF quadrupoles into the arc sections [**?**].

Third-Order Correction: Third-order chromaticity is compensated using additional sextupoles (S3Y and S3X), known as Brinkmann sextupoles [**?**], positioned at the first and second IP image points where the beta functions reach local minima. This optics configuration enhances their effectiveness in correcting higher-order chromatic effects while limiting nonlinear side effects.

This hierarchical correction strategy aligns with methodologies adopted in other new-generation ($e^{+/e}$-) colliders [**?**, **?**, **?**, **?**, **?**]. Following third-order correction in the STCF IR, the off-momentum optical behavior—described by the Montague W functions [**?**]—is well controlled at both the IP and the CS locations, as shown in Fig. 3 [Figure 3: see original paper]. Particularly, the sharp decline in (W__y) at S1Y and (W__x) at S1X in Fig. 3 indicates strong decoupling between horizontal and vertical planes, confirming the orthogonality of the corrected optics.

Despite these improvements, residual second-order dispersion outside the IR may still influence off-momentum dynamics. In addition, the residual second-order vertical chromaticity remains non-negligible, ultimately limiting the achievable momentum acceptance. These observations identify key areas for further refinement in future optimizations.

3.4 Nonlinear Analysis via Resonance Driving Terms

To quantitatively evaluate the effectiveness of the nonlinear suppression strategy after local chromaticity correction in the STCF IR, we computed the distribution of resonance driving terms (RDTs) [**?**, **?**] along the IR using E. Forest's FPP/PTC code [**?**], as shown in Fig. 4 [Figure 4: see original paper].

The results indicate that first-order geometric terms are fully canceled outside the crab sextupole pairs, while transverse coupling terms such as (h_{10110}), (h_{10200}), and (h_{10020}) persist at the IP. This is consistent with the intentional crab-waist effect generated by the (xy^2) Hamiltonian component of the crab sextupole [**?**, **?**]. Owing to the exact (-I) transformation applied between the CCY and CCX sextupole pairs, amplitude-dependent tune shifts (ADTs) and second-order geometric terms are also largely canceled outside these sections. It is worth noting that a sextupole pair separated by a (-I) transformation can, in principle, compensate for geometric aberrations—both second-order and higher-order—introduced during chromaticity correction [**?**]. However, this result is strictly valid only under the thin-lens approximation and for on-momentum particles. When accounting for the finite sextupole length or off-momentum beam conditions, the ideal (-I) transformation is perturbed, leading to residual nonlinearities. For instance, certain RDTs such as (h_{00220}) and (h_{00310}) are not completely canceled outside the CCY sextupole pair due to finite-length effects, as seen in Fig. 4, though their magnitudes remain small. This indicates that, in the case of STCF, the impact of finite sextupole length is not severe.

Nonetheless, in the off-momentum case, chromatic-geometric terms and chromatic ADTs remain only partially compensated due to the breakdown of the (-I) condition in both CCY and CCX sections. This results in relatively large residual driving terms at the IR exit, potentially limiting the off-momentum dynamic aperture. These findings highlight an important area for future local optimization of chromatic RDTs within the IR, potentially via decapole pairs near chromatic sextupole pairs [**?**].

4. Performance Evaluation of the STCF IR Integrated into the Collider Ring

This section presents a comprehensive performance evaluation of the optimized IR design within the full STCF collider ring lattice. The assessment validates the design's robustness by demonstrating: (1) excellent integrated dynamics performance with minimal degradation from the crab sextupoles; (2) conclusive evidence of the crab-waist effect; and (3) effective mitigation of realistic perturbations from fringe fields and the detector solenoid.

4.1 Global Dynamics Performance of the Collider Ring with the Integrated IR

To evaluate performance under realistic operating conditions, the optimized IR design was integrated into the full STCF collider ring lattice. The ring features a quasi-two-fold symmetric structure comprising one IR, four 60° arcs, two 30° arcs, and multiple straight sections for injection, extraction, damping wigglers, RF cavities, and collimation. The arcs employ standard 90° FODO cells—replacing the earlier HMBA design [**?**]—to achieve a target emittance of ~5 nm · rad while improving the momentum compaction factor, minimizing the dispersion invariant (H_x), and enabling more flexible sextupole configuration.

Chromaticity outside the IR is corrected using an interleaved (-I) transformation sextupole scheme, reducing individual magnet strength while canceling first-order geometric aberrations. Global nonlinear optimization was performed using PAMKIT [**?**] integrating multi-objective algorithms with 48 sextupole families (8 in IR, 40 in arcs). During optimization, crab sextupoles remained active and IR chromatic sextupole strengths were allowed slight variations from nominal values.

Figure 5 [Figure 5: see original paper] shows optimized Montague function and second-order dispersion along the ring. The Montague function remains well-controlled within the IR, while second-order dispersion exhibits relatively large global perturbations due to leakage from the IR into the arcs. Figure 6 [Figure 6: see original paper] presents the tune shift with momentum for the full ring (left) and the variation of phase advance for the IR only (right), indicating a momentum acceptance of approximately (±1.5%)—meeting the Touschek lifetime requirement. The similarity between full-ring tune shift and IR-only phase shift confirms that the momentum acceptance is primarily limited by residual vertical second-order and horizontal third-order chromaticity originating in the IR.

The 6D DA simulations using the SAD code [**?**], including synchrotron motion, synchrotron radiation, quantum fluctuations, tapering, and high-order kinematic terms (depending on high powers of transverse momentum [**?**]), reveal that activating the crab sextupoles causes only a slight reduction in both on-momentum and off-momentum DA compared with the CS-off case, as shown in Fig. 7 [Figure 7: see original paper]. This small impact indicates that the IR design strategies—namely the CS optics design, high-order local chromaticity correction, and nonlinear cancellation via (-I) transformations—have successfully suppressed the IR inherent nonlinearities. The resulting Touschek lifetime with CS active reaches 350 s at (0.94 $\times10^{\{35\},\mathrm{cm}}${-2}s^{-1}) and 2 GeV, satisfying the STCF design goal. Performance under more realistic conditions, including Maxwellian fringe fields and detector solenoid effects, is addressed in

Sections 4.3 and 4.4.

RDTs across the full ring, shown in Fig. 8 [Figure 8: see original paper], confirm that nonlinear contributions from the arcs remain small, with the IR remaining the primary source of nonlinearities—highlighting the importance of rigorous local chromaticity correction and nonlinear suppression. Additionally, crab sextupoles introduce first- and second-order chromo-geometric terms and chromatic amplitude-dependent tune shifts for off-momentum particles (see Figs. 4 and 8), further justifying global nonlinear optimization with CS activated.

4.2 Validation of the Crab-Waist Effect for the Integrated IR

The critical question of whether the crab sextupoles function as intended is addressed through the following validation approaches:

Hamiltonian and RDT Analysis: The (xy^2) term in the Hamiltonian of a crab sextupole induces the desired crab-waist effects at the IP (see Appendix). From the perspective of RDTs, this (xy^2) component generates driving terms including (h_{10110}), (h_{10200}), and (h_{10020}) [**?**, **?**]. As shown in Fig. 8, these terms propagate to the IP and remain non-zero, consistent with the RDTs analysis in Section 3.4, confirming that the crab sextupoles can effectively introduce the intended crab-waist effects.

Beam-Beam Simulation with Lattice: Beam-beam simulations incorporating the full collider ring lattice and realistic beam parameters (e.g., bunch charge and emittance) provide the most direct validation of the crab-waist effect, as luminosity is its ultimate performance metric. The simulation results [**?**] demonstrate that the luminosity with CS on is significantly higher than with CS off. This gain arises because the CS suppresses detrimental betatron beam-beam resonances that would otherwise broaden the beam tune spread and increase the beam envelope.

Multi-Particle Tracking: Multi-particle tracking offers direct visualization of the crab-waist effect via the beam density distribution at the IP. Figure 9 [Figure 9: see original paper] displays the beam density distribution at the IP after single-pass tracking, with two distinct scenarios: with CS off, the (z)-(x) plane shows normal density distribution; with CS on, clear density modulation emerges, confirming the vertical beam waist shift induced by the crab sextupole.

4.3 IR Fringe Field Compensation

Fringe fields in all magnets introduce additional nonlinearities that degrade the dynamic aperture. Unlike high-energy colliders such as FCC-ee, where fringe field effects are relatively minor [**?**], the STCF—operating at lower energy—is more susceptible to such effects. Simulations using the SAD code, incorporating Maxwellian fringe fields from dipoles, quadrupoles, and sextupoles, identify the ultra-strong final focus superconducting quadrupoles as the dominant source of DA degradation, as illustrated in Fig. 10 [Figure 10: see original paper].

To mitigate this effect, we implement a compensation strategy based on the mathematical similarity between the Hamiltonian of a quadrupole fringe field and that of a thin octupole magnet [?]. Octupole coils are installed at the IP-opposite ends of the FF quadrupoles QD1 and QF2, with strengths optimized as part of the global nonlinear tuning process with crab sextupoles active.

The compensation proves particularly crucial when considering the interference between fringe fields and crab sextupoles. Without octupole correction, the combined nonlinear effects cause a severe drop in DA compared with the case considering only FF quadrupole fringe fields but CS off. With optimized octupoles, a clear recovery is achieved, though not complete restoration—indicating the challenging nature of this compensation. The resulting configuration maintains a Touschek lifetime of approximately 300 s at (0.94 $\times 10^{\{35\},\mathrm{cm}}${-2}s^{-1}) and 2 GeV, meeting the STCF design target despite these substantial nonlinear perturbations.

4.4 Detector Solenoid Field Compensation

The detector solenoid field presents another critical perturbation, potentially increasing vertical emittance through two mechanisms: horizontal-vertical coupling from the longitudinal (B__z) component, while the radial (B__r) fringe field generates vertical dispersion due to the crossing angle. To suppress these effects, STCF implements local perfect compensation using anti-solenoids, requiring complete cancellation of the integrated (B__z) field between the IP and the pole face of QD1 and zero (B__z) field inside QD1 and QF2 quadrupoles. A step-function solenoid model similar to FCC-ee [?] is adopted for evaluation: a detector solenoid field of 1 T extends from (-0.5) m to (+0.5) m around the IP, while an anti-solenoid field of (-1.25) T covers (±0.5) m to (±0.9) m.

As shown in Fig. 11 [Figure 11: see original paper], with perfect local compensation, both the vertical dispersion and vertical closed orbit are effectively confined near the IP, with no significant leakage into outside regions. The apparent sharp change in the horizontal closed orbit observed in Fig. 11 is not physical but arises from the coordinate system transition from the beam axis to the solenoid central axis in the SAD simulation when the beam enters the solenoid field. The integrated (B__z) field cancellation eliminates horizontal–vertical coupling, while the resulting vertical emittance growth from the combined effect of the anti-solenoid fringe field and the crossing angle is below 1 pm—negligible compared to the STCF ring's design vertical emittance of about 50 pm. This substantial margin contrasts sharply with high-energy colliders like FCC-ee and CEPC, where the sub-2 pm design vertical emittance imposes far stricter constraints on solenoid-induced distortions [?]. The weak optics focusing effect introduced by the solenoids is corrected by fine-tuning the strengths of FF quadrupoles to restore the ring tunes, with negligible impact on the beta functions and only minor, acceptable perturbations in the horizontal dispersion. Most significantly, the dynamic aperture is fully recovered under perfect solenoid compensation, as shown in Fig. 12 [Figure 12: see original paper]. These results confirm that the fully local anti-solenoid compensation approach effectively eliminates the adverse solenoid effects without introducing new nonlinearities, making it well-suited to the STCF collider.

5. Machine-Detector Interface Design

5.1 Integrated MDI Layout and Spatial Optimization

The machine-detector interface design for STCF embodies a philosophy of co-design, where accelerator components and detector systems are optimized as an integrated system rather than separate entities. The fundamental constraint driving the MDI layout stems from the detector's requirement to maximize the solid angle for physics coverage, confining all IR accelerator elements within a stringent 15° conical region centered on the IP. This spatial limitation, combined with the demanding optical requirements for ultra-low (__y^*) achievement, creates one of the most compact and challenging MDI environments among new-generation colliders.

Figure 13 [Figure 13: see original paper] illustrates the integrated half-MDI layout within (±3.5) m of the IP, detailing the spatial arrangement of detector boundaries, beam pipe assembly, superconducting magnet systems, and support structures. The compact cryostat design incorporates two superconducting quadrupoles (QD1/QF2), multiple compensating and screening solenoids, beam position monitors (BPMs), corrector magnets, and tungsten shielding. Particularly noteworthy is the compensation solenoid arrangement, essential for preserving beam optics quality: the compensating solenoid located IP-upstream of QD1 cancels the integrated longitudinal magnetic field of the detector solenoid between the IP and QD1; the screening solenoid ensures zero net (B__z) field within the quadrupole regions; a second compensating solenoid located QF2-upstream counteracts the long-range fringe field of the detector solenoid.

The central beam pipe employs an IP beryllium section at the center (215 mm length) with gold coating to mitigate synchrotron radiation background and beam impedance. Its 30 mm inner diameter is optimized to avoid higher-order mode capture. The transition section, fabricated from tantalum with copper coating, evolves from a 30 mm round profile to a racetrack-shaped cross-section (60 mm wide (×) 30 mm high), gracefully accommodating the transition to dual-aperture configuration while balancing impedance control.

The Y-chamber (remote vacuum connector, RVC) represents a key junction between the single-aperture and dual-aperture beam pipes. An eight-button BPM installed at this location provides potential for real-time beam position monitoring near the IP.

Electromagnetic simulations using the CST code indicate total beam power losses of approximately 587 W in the central beam pipe, with only 40 W deposited in the critical beryllium section—well within thermal limits. Ongoing optimization of the Y-chamber geometry focuses on further reducing capture-mode losses and impedance contributions.

5.2 Synchrotron Radiation Management

Control of synchrotron radiation background is achieved through strategic lattice design and component placement. Our analysis identifies the upstream bending magnet B0 as the primary radiation source entering the MDI region. Through deliberate lattice optimization, this magnet is positioned 8.5 m from the IP with a minimal bending angle of 1°, yielding critical energies of 0.31 keV at 2 GeV and 1.66 keV at 3.5 GeV—significantly reducing the high-energy photon flux.

The strategic combination of beam-pipe transition design and outer-ring beam incidence provides an elegant solution to the radiation challenge. As shown in Fig. 14 [Figure 14: see original paper], simulations confirm that synchrotron radiation from B0 does not strike the central beryllium pipe when beams enter the IP from the outer ring, owing to effective shielding by the transition beam pipe. This configuration simultaneously addresses accelerator operational needs (compatible with injection layout) and detector performance requirements (minimized background).

Further analysis under extreme conditions, including closed orbit deviations of 1 mm and angular deviations of 1 mrad at B0, confirms the robustness of this approach. Even in these scenarios, no synchrotron radiation hits the beryllium chamber. Additionally, radiation generated in the FF quadrupoles remains negligible, assuming closed orbit deviations within 200 m—well above the alignment tolerance of 30 m specified for these components.

We further calculated the line power density distribution of synchrotron radiation from B0 along the beamline under beam energy of 3.5 GeV and beam current of 2 A, see Fig. 15 [Figure 15: see original paper], with power loss in different regions explicitly indicated. These results provide essential input for the thermal and mechanical design of the MDI's vacuum chambers, as well as for mask shielding (if required).

5.3 MDI Beam Stay-Clear Region

The definition of beam-stay-clear (BSC) regions represents a critical intersection of beam dynamics and engineering design. For STCF, we adopt a hybrid approach that synthesizes established practices from previous colliders [**?**] with advanced stability requirements of modern facilities. Figure 16 [Figure 16: see original paper] illustrates the BSC boundaries at beam energies of 2 GeV and 3.5 GeV, where the dashed magenta and green lines represent the positron and electron beam envelopes, respectively.

At 2 GeV, the horizontal BSC is defined as (22 _x + 2) mm (or (24 _x)), and the vertical BSC as (22 _y + 2) mm (or (26 _y)). At 3.5 GeV, the larger natural emittance permits a more aggressive definition: (9.5 _x + 2) mm (or (11.5 _x)) horizontally and (9.5 _y + 2) mm (or (10.5 _y)) vertically. These values assume a horizontal emittance of 5 nm at 3.5 GeV and 27 nm at 2 GeV, with vertical emittance set to be 5% of the horizontal value. The reduced BSC at 3.5 GeV can be relaxed by increasing beta functions at the IP (e.g., (_x^*): 60 (→) 150 mm, (_y^*): 0.8 (→) 1.6 mm), with acceptable luminosity trade-offs (reduced by 24%) for high-energy operation.

The most critical BSC limitation occurs in the FF quadrupoles, where the combination of minimal physical aperture and large beta functions creates a particle loss hotspot. This region proves particularly vulnerable to losses from Touschek scattering and injection processes, posing risks of superconducting magnet quenches and elevated detector background. Our mitigation strategy employs strategic collimator placement at distances ( )15 m from the IP (outside the MDI core), effectively localizing particle loss away from sensitive regions.

5.4 Preliminary Estimation of Detector Background

Comprehensive collaborative accelerator-detector simulations identify Touschek scattering and beam-gas Coulomb scattering as the dominant background sources in STCF's low-energy regime. With optimized collimation, Touschek losses in the IR are reduced to less than 1% of ring-wide total losses—an order-of-magnitude improvement over the un-collimated scenario. The same collimator settings effectively control injection losses without compromising injection efficiency.

With effective Touschek suppression, beam-gas Coulomb scattering emerges as the primary background source, driving the requirement for ultra-high vacuum conditions ((10^{-7}) Pa in MDI region, (10^{-8}) Pa elsewhere). Synchrotron radiation and beam-gas bremsstrahlung represent secondary but non-negligible background contributions. Synchrotron radiation primarily contributes to the thermal load on beam pipes, though its high-energy components at 3.5 GeV require careful assessment. Beam-gas bremsstrahlung becomes increasingly relevant at higher energies, reinforcing the need for the specified ultra-high vacuum conditions.

These findings establish the foundation for ongoing optimization of vacuum systems, collimator configurations, and background suppression strategies, ensuring the STCF will achieve its physics goals while maintaining operational robustness.

6. Conclusions and Outlook

This paper presents a complete physics design for the STCF crab-waist interaction region, successfully addressing the challenge of managing strong nonlinearities in a low-energy, high-luminosity collider. The integrated approach—encompassing parameter optimization, modular optics design, nonlinear dynamics control, and MDI optimization—provides a robust foundation for achieving the project's ambitious performance targets.

Key IR parameters, including the crossing angle (2 _c), the IP drift length (L^*), and the IP beta functions (_{x,y}^*), were selected through a balanced consideration of luminosity performance, nonlinear dynamics control, and engineering constraints. These choices fundamentally shape both the optical design and mechanical integration while ensuring compatibility with detector requirements.

A central achievement of this work is the development and validation of a modular crab-waist IR optics that strategically decomposes the complex nonlinearity into manageable components. By implementing exact (-I) transformations for chromatic sextupole pairs, minimizing the dispersion invariant to enhance local momentum acceptance, optimizing beta functions at crab sextupole locations, and extending local chromaticity correction to third order, we have designed a practical IR structure that balances high luminosity, adequate beam lifetime, and operational robustness against fringe fields and solenoid effects. Integrated into the full ring, the design can achieve a momentum acceptance of (±1.5%) and a Touschek lifetime exceeding 300 s at (0.94 $\times 10^{\{35\},\mathrm{cm}}${-2}s^{-1}) and 2 GeV, thereby meeting the STCF performance goal.

This study yields insights applicable beyond the STCF context. First, explicit control of the dispersion invariant proves to be a powerful strategy for alleviating local momentum acceptance bottlenecks, particularly relevant for low- to medium-energy colliders where enhanced local momentum acceptance is essential for achieving adequate Touschek lifetime. Second, we demonstrate that a systematic local compensation approach—utilizing octupoles for fringe field correction and anti-solenoids for detector field cancellation—can effectively restore dynamic aperture against realistic perturbations.

Looking forward, several strategic directions are identified for further enhancement. Correction of residual second-order vertical and third-order horizontal chromaticity offers immediate gains in momentum acceptance. Compensation of chromo-geometric terms arising from the breakdown of (-I) transformations for off-momentum particles—e.g., via dedicated decapole pairs near chromatic sextupoles [**?**]—could further extend off-momentum dynamic aperture. Tailored dipole settings may also help optimize second-order dispersion, while higher-order correctors (octupoles or decapoles) at IP image points may open routes to fourth- and fifth-order chromaticity control [**?**].

The design methodology established here—systematic management of nonlinearities in crab-waist IR configurations—offers a valuable reference for other colliders in comparable energy regimes. The demonstrated integration of advanced optics design with practical engineering constraints marks a critical step toward the STCF technical design phase. As the design evolves, continued co-optimization of IR optics, final focus magnets, and machine-detector interface will be essential to further refine the balance among performance, technical feasibility, and cost-effectiveness. This work thus lays a solid foundation for realizing the full potential of the STCF collider ring.

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Note: Figure translations are in progress. See original paper for figures.