

AN UPDATED PHYSICAL DESIGN FOR THE STCF COLLIDER RINGS

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Abstract

The Super Tau-Charm Facility (STCF), proposed by the University of Science and Technology of China, is a next-generation electron-positron collider designed to achieve a luminosity exceeding $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, approximately two orders of magnitude greater than that of Beijing Electron Positron Collider II (BEPCII). Large Piwinski angle with the crab waist collision scheme is applied. However, the extremely small β_y^* ($< 1 \text{ mm}$) generates very large natural chromaticity. Local chromaticity corrections for both horizontal and vertical planes have been proposed. Touschek lifetime is very challenging due to its low-energy, low-emittance, and high-current. A two-folded lattice has been proposed for the collider rings, with the iterations of version 5. Nonlinear optimization has been carried out with Multi-Objective Genetic Algorithm (MOGA) to maximise the dynamic aperture and momentum acceptance, considering fringe fields and misalignment errors. This paper introduces the updated physical design of the STCF collider rings.

INTRODUCTION

The Super Tau-Charm Facility (STCF), proposed by University of Science and Technology of China (USTC), represents the next generation of electron-positron colliders [1, 2]. It operates over a wide collision energy range of 2 to 7 GeV, with symmetric electron and positron beam energies spanning 1 to 3.5 GeV. The design targets luminosities exceeding $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at the optimal beam energy of 2 GeV and $5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at both lowest and highest energies. To achieve these high luminosities, STCF employs a large crossing angle of 60 mrad combined with the Crab-Waist collision scheme [3-6]. The large crossing angle reduces the effective beam length at the interaction point (IP), enabling β_y^* to be compressed below 1 mm.

However, the intense focusing at the IP brings very strong nonlinear effects, resulting in significantly reduced dynamic and momentum apertures in the collider rings. These small apertures, combining high beam current and low beam emittance, leading to a very short Touschek lifetime. This short Touschek lifetime poses challenges for injector design and construction, requiring a substantially higher injection repetition frequency. The design must optimize these critical parameters to meet its performance objectives. Major changes for version 5 are as follows: i) β_x^* has been reduced from 60 mm to 40 mm to extend the high-luminosity region in response to the X-Z instability; ii) the circumference has been shortened from 860.321 m to

825.524 m due to an increase in the peak magnetic field of the damping wigglers; iii) the beta function at the IP now varies with energy; iv) the vacuum chamber aperture has been increased by 20% to reduce impedance. Table 1 summarizes the main parameters of the STCF collider rings at the optimal energy.

Table 1: Main Parameters of the STCF Collider Ring

Parameter	Value
Beam energy (GeV)	2.0
Beam current (A)	2.0
Circumference (m)	825.524
β_x^*/β_y^* (mm)	40/0.8
Coupling, $\varepsilon_y/\varepsilon_x$ (%)	1
Hor./Ver. betatron tune	28.545/31.58
Emittance (SR/DW+IBS) (nm)	8.83/3.93
Momentum compact factor (10^{-3})	1.41
Energy spread (DW+IBS) (10^{-4})	8.1
SR power per beam (MW)	1.245
RF voltage (MV)	2.5
Synchrotron tune	0.0193
Energy acceptance (%)	1.62
Bunch length, natural/IBS (mm)	7.55/9.0
Beam-beam parameter, ξ_x/ξ_y	0.003/0.1
Luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	1.02×10^{35}

OPTICS DESIGN

The STCF collider features a double-ring configuration consisting of an electron ring and a positron ring, both situated in the same horizontal plane. The circumference of each ring is 825.524 m. These rings intersect at two points: the collision point within the collision region and another intersection point diametrically opposite to it. The two beams are separated by small vertical chicane at the point opposite the IP. To accommodate the intersecting configuration, the drift lengths in the arc sections differ slightly on either side of each ring, creating distinct inner and outer rings separated by approximately 2 meters. Each ring is composed of one interaction region (with 60 degrees of bending angle), four major arc sections (60 degrees for each), and two minor arc sections (30 degrees for each), one intersection region and multiple straight sections. The straight sections serve various functions, including: injection and extraction, collimation, damping wigglers, RF, and tuning sections. Figure 1 shows the new layout and optics function of the STCF collider rings.

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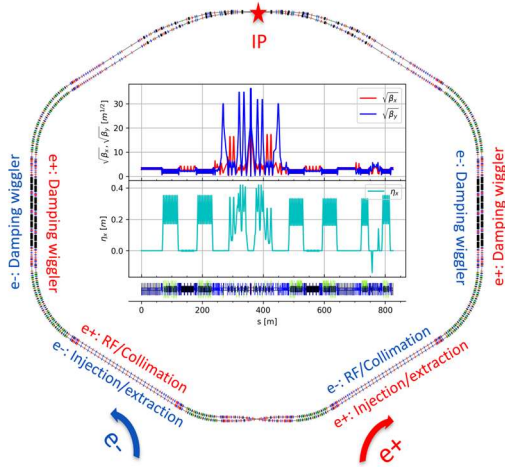


Figure 1: the new layout and optics function of the STCF collider ring (V5).

Interaction Region Design

The interaction region lattice design employs a modular functional design, which includes the final focus telescope for compressing the beta function at the IP to a very small value, the vertical/horizontal local chromaticity correction sections, the dispersion suppression section, and the crab sextupole section.

The final focus telescope employs a doublet focusing structure, consisting of two groups of superconducting quadrupoles which are used to achieve an extremely low vertical beta function at the IP. Local chromaticity correction section needs to form the $-I$ transformation required for the sextupole pair to cancel nonlinear effects [7]. The phase advances between crab sextupole and IP are $\mu_x = 6\pi$, $\mu_y = 5.5\pi$. Additionally, at the crab sextupole, a large β_y is chosen to reduce the strength of the crab sextupole and thereby minimize its nonlinear effects. Figure 2 shows the optics function of the interaction region.

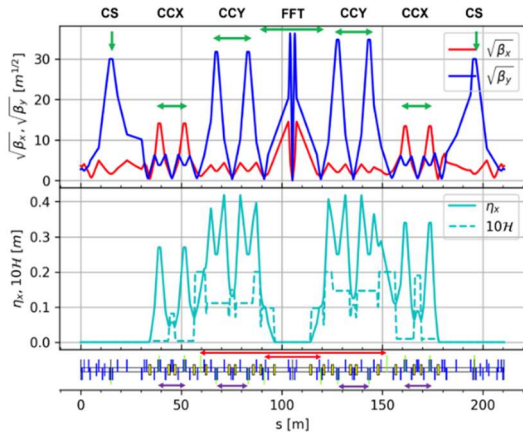


Figure 2: The optics function of interaction region. (CS: Crab Sextupole, CCX: Chromaticity Correction in horizontal, CCY: Chromaticity Correction in vertical, FFT: Final Focusing Telescope)

Arc Section Design

The arc section in the lattice of version 5 is almost the same as version 4. Each ring has four major and two minor

arc sections, both of which employ the same standard FODO cell. Each FODO cell is 4.7 meters long, with a deflection of 6 degrees, and a phase shift of 90 degrees. Each cell contains four 0.8-meter-long drift spaces mainly for sextupoles. The large arc section consists of 9 FODO cells, totalling 57.184 meters in length and providing a 60-degree deflection, while the small arc section consists of 4 FODO cells, totalling 33.684 meters in length and providing a 30-degree deflection.

Damping Wiggler Section Design

Each ring includes two damping wiggler (DW) sections to reduce damping time and adjust the emittance at different energy points. The DW has a length of 3.6 m with the period length of 0.6 m. Every two DWs are located in an 8.4 m long drift section to eliminate the trajectory shift after one DW. Each section consists of 8 DWs in 4 pairs. Triplet structure is selected as the primary lattice configuration for this segment due to its flexibility, enabling the formation of longer drift sections to accommodate DWs. A certain number of quadrupole magnets are placed at both ends of the damping wiggler segment to match the optics function to the arc. Figure 3 shows the optics function of damping wiggler section.

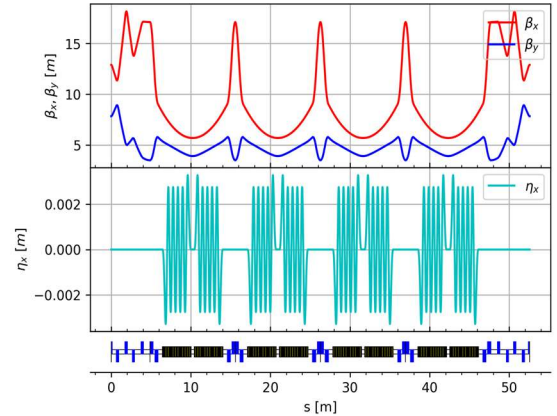


Figure 3: The optics function of DW section.

BEAM DYNAMICS

The design goal of the transverse beam dynamics in the collider ring is to achieve sufficiently large dynamic aperture and momentum acceptance to meet requirements such as high injection efficiency and long beam lifetime.

The arcs adopted an interleaved $-I$ transformation scheme, which cancels the first-order geometric aberrations. While higher-order geometric terms cannot be eliminated, the use of more sextupole families reduces the strength of individual sextupoles, thereby minimizing residual higher-order terms.

The dynamic aperture and momentum acceptance are primarily limited by the interaction region (IR), which contributes the majority of the ring's nonlinearities. Due to the presence of numerous factors with significant nonlinear effects in IR, such as the fringe field effects of FF quadrupoles, high-order kinematic effects in the IP drift section, contributions from chromaticity correction sextupoles, and

crab sextupoles, comprehensive analytical analysis of these nonlinear effects becomes very challenging.

To optimize the dynamic aperture and momentum acceptance, multi-objective optimization algorithms (MOGA) are employed for the overall nonlinear optimization with the crab sextupole strength kept active throughout the process. The collider ring utilizes a total of 48 groups of sextupoles as tuning variables, with which 40 groups in the arc and 8 groups in the IR.

The fringe field exists in all magnets and is one of the sources of nonlinearity that leads to a reduction in dynamic aperture. Results show final-focusing superconducting quadrupole magnets play the most important role on the fringe field effects. Octupole coils are installed outside the FF quadrupoles to correct the fringe fields effect, allowing the dynamic aperture to be largely restored. Figure 4 shows the on- and off-momentum dynamic aperture w/ and w/o errors and with fringe fields effect and corrections. It shows that the on-momentum DA can reach $20\sigma_x$ and $50\sigma_y$ with errors and fringe fields effect. The off-momentum DA can reach $15\sigma_x$ at $10\sigma_\delta$. Figure 5 shows the frequency map analysis (FMA) with errors and fringe fields effect which show no danger resonances within DA. Figure 6 shows the local momentum acceptance (LMA) w/ and w/o errors and with fringe fields effect and corrections. The Touschek lifetime can reach at least 300 s at the optimal beam energy, taking into account the misalignment errors and fringe fields effect and corrections.

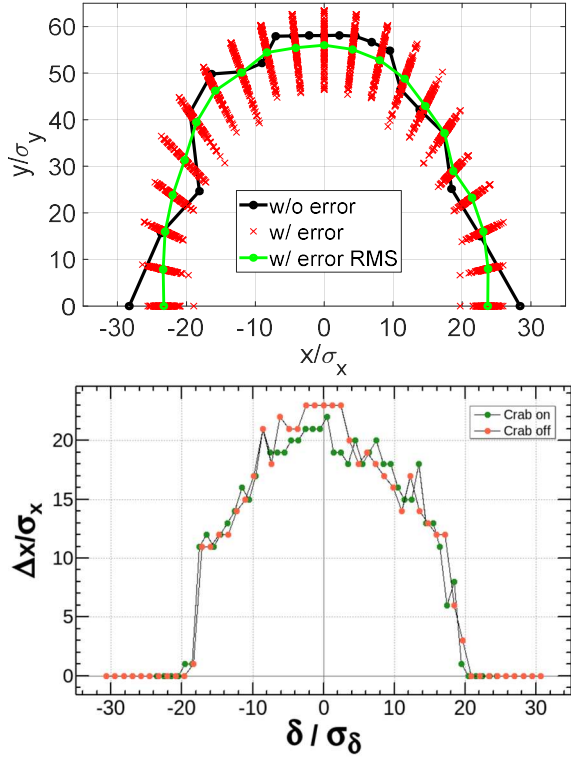


Figure 4: The on-momentum (Upper) and off-momentum (Lower) dynamic apertures of the STCF collider ring w/ and w/o errors and with fringe fields and corrections.

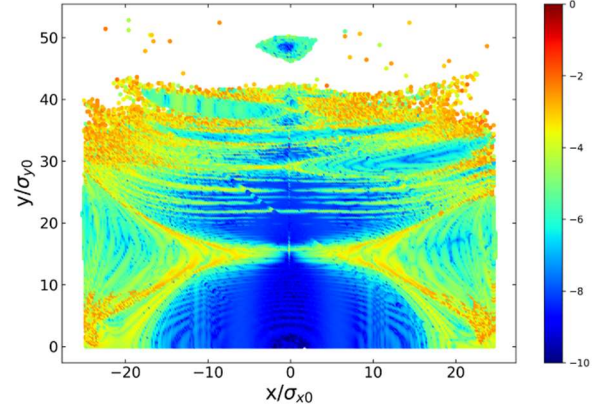


Figure 5: The on-momentum (Upper) and off-momentum (Lower) dynamic aperture of the STCF collider ring with Fringe fields of final focus quadrupoles and correct.

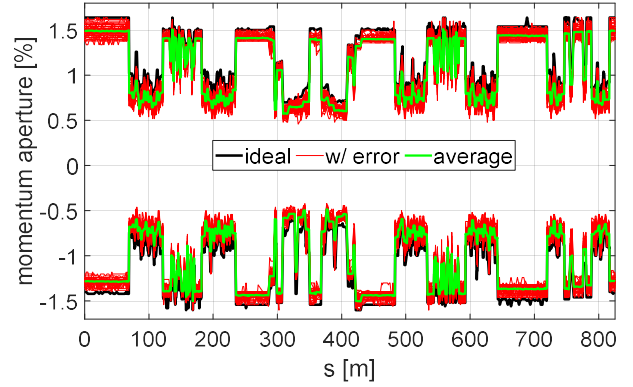


Figure 6: Local momentum acceptance w/ and w/o errors and the average values.

CONCLUSIONS

This paper introduces an updated physical design of the STCF collider rings. With the new lattice design, the luminosity can reach $1.02 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, and the Touschek lifetime can reach more than 300s, considering misalignment errors and fringe fields effect. Detailed studies on beam collimation, beam-beam effects, and instabilities based on this lattice are still ongoing.

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