A COMPATIBLE INJECTION DESIGN FOR THE SUPER TAU-CHARM FACILITY COLLIDER RINGS

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Abstract

The Super Tau-Charm Facility (STCF), a new-generation electron-positron collider proposed in China, is a major international scientific facility designed to operate in the energy range of 1–3.5 GeV, with luminosity at 2 GeV beyond 5×10^{34} cm^{-2}s^{-1}. It adopts third-generation collider design concepts, including ultra-small beam size, a large Piwinski angle, and the crab waist scheme. However, these features introduce challenges such as a limited dynamic aperture and a short beam lifetime, and have imposed strict requirements on beam injection. Two injection schemes are currently under investigation. The first is off-axis injection, which is technologically mature but requires a large horizontal dynamic aperture and is characterized by larger aperture and considerable beam loss. The second is swap-out injection, with high injection efficiency and relaxed aperture constraints, but imposing stringent technical requirements and high costs on the injector system. We propose here an injection design compatible with both schemes, reserving upgrade potential from off-axis injection in Phase I to swap-out injection in future Phase II.

INTRODUCTION

The STCF is designed to explore the tau-charm energy region with high luminosity[1]. To achieve this, the collider ring employs a large crossing angle with crab waist, sub-millimeter vertical beta function at the interaction point (IP)[2], and low emittance beams. These features significantly enhance luminosity but also reduce the Touschek lifetime and limit the dynamic aperture (DA). With a beam lifetime of approximately 300 s in the low-to-medium energy range, top-up injection at high repetition rate is required to maintain stable stored beam current[3]. Injection is particularly challenging as the reduced DA complicates off-axis capture, while the short lifetime demands rapid charge replenishment. By the way, the injection scheme have to meet the requirements over the full 1–3.5 GeV energy range. A compatible injection design is proposed, combining off-axis and swap-out injection within a single straight section.

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The adoption of a compatible injection scheme also imposes specific requirements on the upstream injector. The injector must be capable of delivering two distinct types of bunches: low emittance, low charge bunches for off-axis injection, and high emittance, high charge bunches for swap-out injection. This paper mainly presents the compatible injection scheme design and the corresponding injection efficiency analysis for the STCF.

COMPATIBLE INJECTION SYSTEM DESIGN

The compatible injection system is laid out in one straight section of the STCF collider ring [4]. This straight section was selected because it provides sufficient longitudinal space to accommodate both injection schemes while minimizing impact on the arc lattice and other critical components. The layout, as shown in Fig. 1, includes a conventional four-kicker orbit bump system for off-axis injection and an ultra-fast kicker for swap-out injection, and sharing septum magnets.

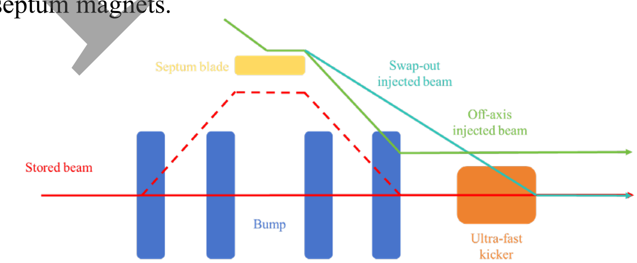

Figure 1: Compatible injection system scheme.

For off-axis injection, a local orbit bump is generated by four kickers. Since the septum position is fixed, the bump amplitude must be carefully tailored to cover the 1–3.5 GeV energy range. At high energies, the stored beam occupies a larger fraction of the dynamic aperture due to its increased geometric emittance, leaving less room for the injection bump. Consequently, the bump amplitude must be reduced to avoid beam loss. At lower energies, the stored beam is smaller, allowing a larger bump amplitude that improves beam injection capture efficiency. The optics in the injection region are therefore designed to provide a large beta function at the injection point to minimize single particle emittance increase introduced by the injected beam, while maintaining a large beta at the kicker locations to reduce the required deflection angles. This optical configuration is the result of iterative matching between the injection section and the adjacent arc cells to ensure a seamless transition and minimal beta beating outside the injection region. Figure 2 shows the optical functions for off-axis injection.

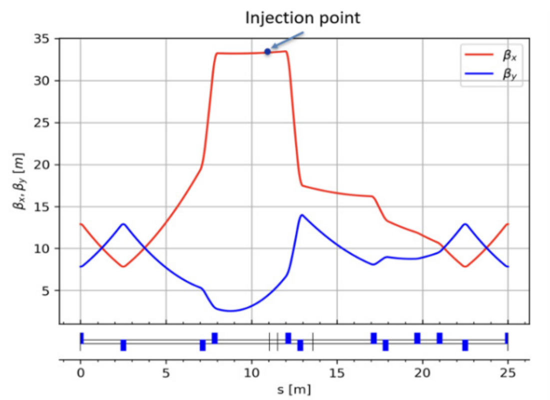

Figure 2: The optics function of off-axis injection schemes.

For swap-out injection, the ultra-fast kicker replaces a stored bunch with freshly injected one on-axis[5]. The key to the physics design of the bunch swap-out injection scheme lies in arranging the components in a geometrically rational layout to ensure the injected bunch enters the closed orbit of the collider rings accurately, minimizing disturbance to other stored bunches and reducing the required deflection angle of the kicker[6]. To accommodate the large emittance of the injected bunch in this mode, the beta function at the kicker is deliberately reduced to avoid beam loss on the narrow-gap kicker. Figure 3 shows the optical functions for swap-out injection.

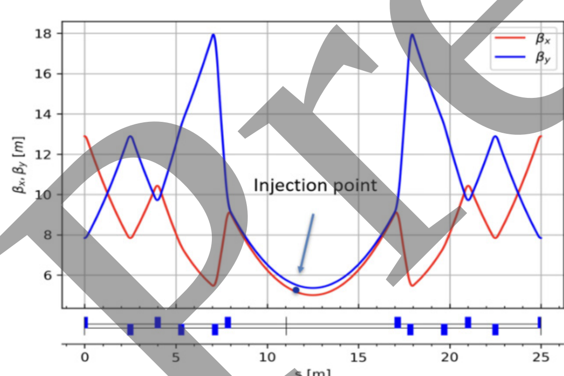

Figure 3: The optics function of swap-out injection schemes.

The compatible design enables a clear two-phase construction strategy. In Phase I, the STCF can begin operation with the conventional off-axis injection scheme using a single damping ring injector design, requiring no accumulator ring. This allows early commissioning and physics runs while minimizing initial technical risks and costs. In Phase II, the system can be upgraded to the swap-out injection scheme by adding an accumulator ring to the injector complex and installing the ultra-fast kicker system. Crucially, this upgrade requires no modifications to the collider ring itself, as both injection schemes share the same straight section and septum magnets. This phased approach preserves full operational flexibility over the STCF's energy range.

INJECTION EFFICIENCY ANALYSIS

For injection simulation, the storage ring lattice is based on the STCF design version 5, with the working point near the half-integer resonance and crab waist implemented. Synchrotron radiation damping and quantum excitation are included. Identical PIC parameter (10,000 macro-particles) and machine apertures are used for both injection schemes. Table 1 summarizes the bunch parameters of injection bunch for simulation.

Table 1: Injection Bunch Parameters

Parameter	Off-axis Injection			Swap-out Injection		
Energy(GeV)	1	2	3.5	1	2	3.5
Hori. Emit.(nm·rad)	12	6	4	30	30	20
Vert. Emit.(nm·rad)	3	1.5	1.5	10	8	8
Energy Spread(10^{-3})	2	1.5	1.5	4	2	2

Injection efficiency is defined as the fraction of particles surviving after 3000 turns of tracking. The injection point horizontal jitter is considered as the dominant error source, while the vertical jitter effects are negligible as the vertical acceptance is sufficiently large and the vertical emittance is small. Table 2 summarizes the ideal injection efficiency at 1-3.5GeV.

Table 2: Injection Efficiency at 1-3.5GeV in Ideal Simulation

Parameter	Off-axis Injection			Swap-out Injection		
Energy(GeV)	1	2	3.5	1	2	3.5
Injection Efficiency（%）	99.13	99.96	98.7	99.42	99.46	100

Gaussian-distributed transverse position and angle errors (rms of ±20% σ_x and ±20% σ_x') are introduced at the injection point in the horizontal plane. For off-axis injection, horizontal jitter shows a clear impact on efficiency due to the finite dynamic aperture required for injection, especially at high energy end of 3.5 GeV. As the jitter amplitude increases, the injected beam approaches the acceptance boundary, resulting in particle loss. Figure 4 shows the off-axis injection efficiency as a function of horizontal position and angle jitter at 1/2/3.5 GeV.

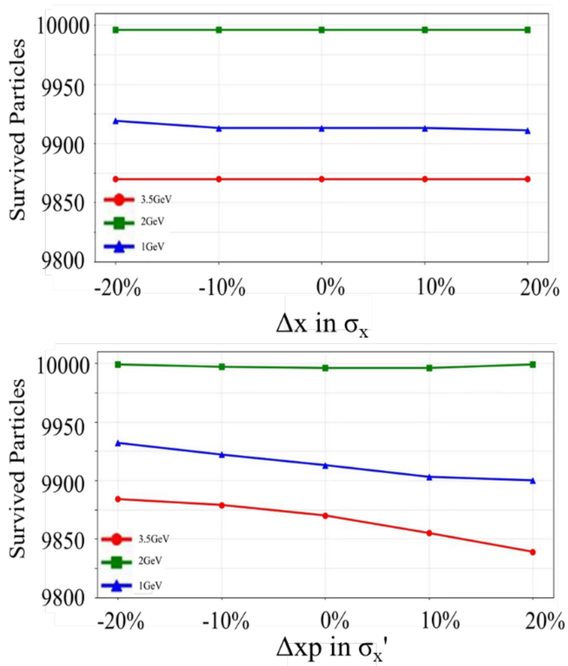

Figure 4: Off-axis injection efficiency with x plane jitter.

Swap-out injection, being an on-axis scheme, is significantly less constrained by dynamic aperture limitations, exhibiting broader tolerance to transverse errors. Figure 5 shows the corresponding efficiency for swap-out injection.

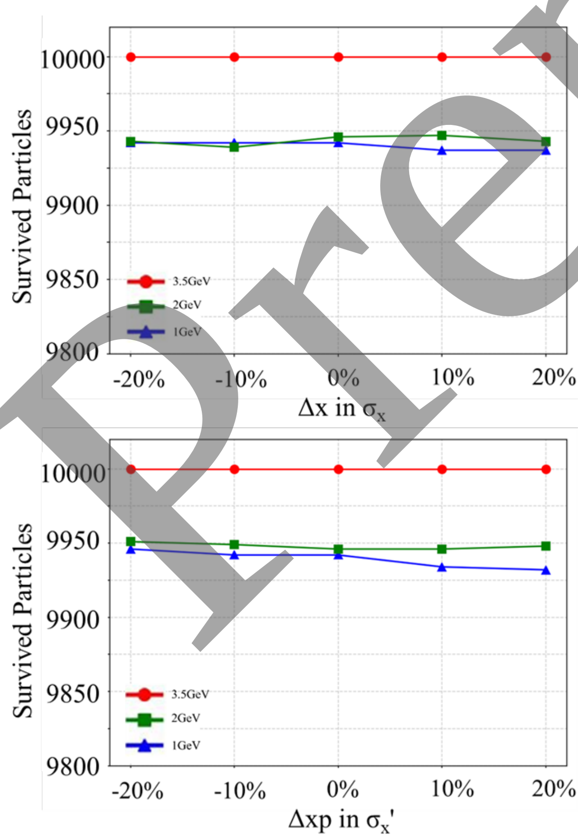

Figure 5: Swap-out injection efficiency with x plane jitter.

The simulation results confirm that: (1) off-axis injection performs well at low-to-medium energies but the sensitivity to horizontal jitter increases with energy, as the larger geometric emittance of the stored beam at higher energy consumes the available DA. The overall efficiencies are high if beam matching is well done; (2) Swap-out injection is robust across all energies and is particularly suited for high-energy operation.

CONCLUSION

A compatible injection scheme integrating off-axis and swap-out injection has been designed for the STCF. The system provides operational flexibility across the 1–3.5 GeV energy range and preserves a clear upgrade path from conventional off-axis injection in Phase I to swap-out injection in Phase II. Simulation results confirm that the compatible design meets the diverse injection requirements of STCF and supports its phased upgrade strategy. Future work will focus on more detailed design and simulations, such as septum leakage field, injection bunch twiss match and so on.

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