BEAM-BEAM SIMULATIONS WITH SELECTED MULTI-PHYSICS EFFECTS FOR STCF

Sangya Li*[1], Ye Zou[3], Linhao Zhang[3], Tao Liu[3], Kazuhito Ohmi[2], Qing Luo†[1,3]
[1] National Synchrotron Radiation Laboratory, USTC, Hefei 230029, China
[2] High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
[3] School of Nuclear Science and Technology, USTC, Hefei 230026, China

Abstract

The Super Tau-Charm Facility (STCF) aims to achieve a peak luminosity of 1×10^{35} cm^{-2}s^{-1} utilizing the crab-waist collision scheme. While this configuration permits a high beam-beam parameter ($\xi_y \sim 0.1$), it amplifies the sensitivity of transverse beam dynamics to collective effects. This paper presents a comprehensive multi-physics investigation using a self-consistent, GPU-accelerated strong-strong simulation framework to evaluate the coupled impacts of lattice nonlinearities (LN), 3D wakefields (WK), and space-charge (SC) forces. Results show that inherent LN exacerbates the beam-beam-driven X-Z instability (XZI) via pronounced X-Y coupling. Conversely, the longitudinal wakefield provides a stabilizing effect; the induced potential-well distortion leads to bunch lengthening and synchrotron tune spread, offering Landau damping that mitigates coherent vertical beam size blow-up. Furthermore, transverse wakefields and SC forces induce dynamic tune shifts that systematically redistribute the XZI stopbands. By optimizing the horizontal fractional tune within $\nu_x \in [0.554, 0.560]$, the collider effectively maintains stable collisions against these multi-physics perturbations.

INTRODUCTION

The crab-waist (CW) collision scheme [1,2] effectively suppresses beam-beam resonances and minimizes the hourglass effect by implementing a large crossing angle and an ultra-low vertical beta function at the interaction point (β_y^*). The proposed STCF relies on this scheme to achieve unprecedented luminosity in the Tau-Charm energy region [3].

However, the extreme beam parameters demanded by the CW scheme push the beam dynamics into a highly sensitive regime. The intense and highly nonlinear beam-beam (BB) force couples strongly with lattice nonlinearities (LN) from the final focus quadrupoles and CW sextupoles, modifying amplitude-dependent tune shifts [4]. Furthermore, collective effects such as wakefields (WK) and space charge (SC) forces, which are pronounced in high-intensity machines, introduce additional dynamic tune shifts and incoherent tune spreads.

A hallmark challenge in such colliders is the coherent X-Z instability (XZI), primarily driven by synchro-betatron resonances (typically satisfying the condition $2\nu_x - m\nu_s = n$) [5]. The presence of LN, WK, and SC actively modulates the topology of these resonance stopbands. Therefore, self-consistent strong-strong simulations that encapsulate these couplings are indispensable.

Building on previous beam-beam studies [6, 7], this paper presents multi-physics simulations based on the STCF V5 lattice. Key machine parameters at the nominal 2 GeV energy are summarized in Table 1 [8]. Utilizing the GPU-accelerated code BBSCL, we systematically evaluate these coupled effects to establish a robust operational working point.

Table 1: Machine Parameters for STCF V5 at 2 GeV

Parameters	Units	Value
C	m	825.524
$2\theta_c$	mrad	60
I_b	mA	3.03
ϵ_x / ϵ_y	nm / pm	8.83 / 88.3
β_x^* / β_y^*	mm	40 / 0.8
σ_{z0}	mm	7.55
ν_x / ν_y / ν_z	-	28.545 / 31.58 / 0.0193
N_b	-	660
ξ_x / ξ_y	-	0.003 / 0.1
L	cm^{-2}s^{-1}	1.02×10^{35}

MULTI-PHYSICS COUPLING

Lattice Nonlinearities and Beam-Beam

The frequency map analysis (FMA) for the STCF V5 lattice at the nominal working point $(\nu_x, \nu_y) = (0.550, 0.580)$ demonstrates that the BB interaction significantly enhances tune diffusion (Fig. 1). This drastic expansion of the tune footprint forces large-amplitude particles to cross dense high-order resonance lines, thereby modulating the stable tune space.

A systematic comparison between the ideal linear lattice (BBSS) and the real nonlinear lattice (BBSCL) in Fig. 2 reveals the shrinking of the stable luminosity window. In the unstable regime ($\nu_x < 0.554$), LN acts as an extreme amplifier for the XZI. While pure XZI primarily excites horizontal and longitudinal oscillations, the severe X-Y coupling inherent in the interaction region's sextupole aberrations channels this horizontal resonance energy directly into the vertical plane. This coupling mechanism leads to a catastrophic growth of the root-mean-square (RMS) vertical beam size σ_y.

* lisya@mail.ustc.edu.cn
† luoqing@ustc.edu.cn

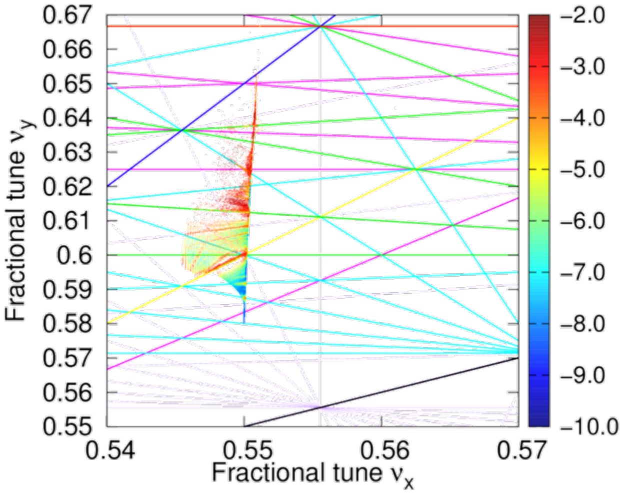

Figure 1: FMA for the STCF V5 lattice with and without beam-beam interactions.

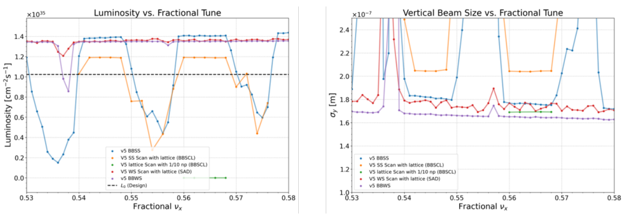

Figure 2: Luminosity and σ_y vs. ν_x for various simulation models, illustrating the vertical beam size degradation driven by lattice nonlinearities.

Furthermore, a distinct σ_y growth is observed even within the theoretically stable window. Control simulations with a reduced bunch population ($1/10N_p$) confirm that the bare lattice alone does not excite σ_y. This indicates that the intense BB interaction acts as a nonlinear pump, continuously driving core particles to larger amplitudes where lattice nonlinearities induce collective phase-space diffusion.

Transverse and Longitudinal Wakefields

We further investigated collective impedance effects using a realistic model incorporating both geometric and resistive-wall (RW) wakefields. As shown in Fig. 3, the introduction of the longitudinal wakefield (W_z) provides a vital stabilizing effect in the nonlinear lattice.

Physically, W_z induces a potential-well distortion that stretches the bunch length by approximately 6%. This longitudinal stretching not only lowers the peak charge density (weakening the horizontal BB kick) but also introduces a significant synchrotron tune spread within the bunch. This spread acts as a powerful source of Landau damping, which effectively breaks the coherent synchro-betatron resonance. By suppressing the horizontal XZI, W_z shuts off the X-Y resonance coupling channel, yielding a remarkable reduction in σ_y compared to the bare BBSCL baseline.

The inclusion of the full 3D wakefields introduces additional dynamic shifts. Specifically, the horizontal wake-

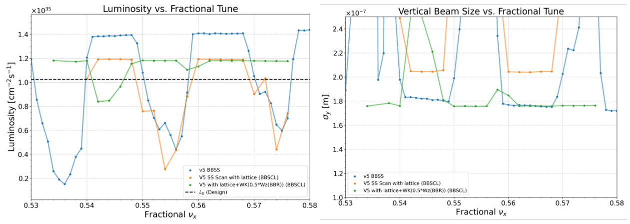

Figure 3: Comparison of σ_y for BBSS, BBSCL (LN only), and BBSCL with longitudinal wakefields (LN+WK).

field (W_x) induces an intensity-dependent coherent tune shift ($\Delta\nu_x$). This modulates the effective betatron frequency, leading to a macroscopic rightward translation of the XZI stopband onset, as observed in Fig. 4.

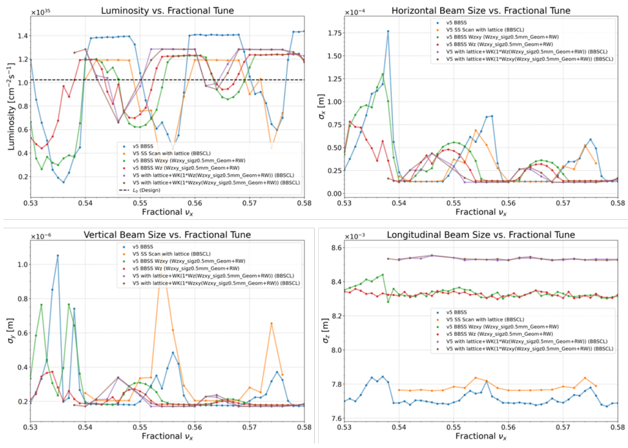

Figure 4: Simulated luminosity and beam sizes vs. ν_x, comparing cases with W_z only and full 3D wakefields ($W_{x,y,z}$).

Interplay with Space Charge Effects

Space charge (SC) forces exert a continuous perturbation along the entire circumference of the collider. In our strong-strong simulations, the primary dynamic consequence of SC is the induction of a negative incoherent tune spread ($\Delta\nu_x \sim -0.004$, $\Delta\nu_y \sim -0.04$).

Because SC introduces a negative tune shift, the core particles require a higher nominal machine tune to hit the identical resonance conditions. Consequently, this translates the overall topology of the XZI stopbands rightward in the macroscopic tune scan (Fig. 5).

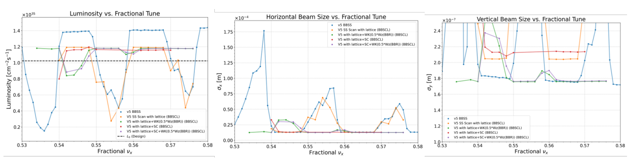

Figure 5: Impact of space charge (SC) effects. SC causes a global rightward shift of the resonance stopbands. Data within the severe XZI stopbands are smoothed due to catastrophic particle loss.

Within the stable operational regions, SC induces only a marginal increase in σ_y, leaving the peak luminosity virtually unaffected. In these regimes, core particles experience a predominantly linear SC force, contributing mainly to tune shift rather than chaotic diffusion. However, inside the XZI stopbands, particles are driven to large amplitudes where they simultaneously experience the highly nonlinear tail of the SC force and the extreme fringe fields of the lattice sextupoles. This resonance overlap completely destroys the dynamic aperture, leading to massive particle loss and confirming that SC significantly intensifies the lethality of the beam-beam instability in the unstable regime.

CONCLUSION

Utilizing the self-consistent BBSCL code, we systematically evaluated the beam-beam interaction in the STCF under complex multi-physics coupling effects. Our simulations demonstrate that lattice nonlinearities exacerbate the vertical beam size blow-up by channeling the horizontal XZI energy into the vertical plane via severe X-Y coupling.

Conversely, the longitudinal wakefield provides a critical stabilizing mechanism. The induced potential-well distortion lengthens the bunch and generates a synchrotron tune spread, offering Landau damping that suppresses the XZI. Meanwhile, transverse wakefields and distributed space charge forces induce coherent and incoherent tune shifts, respectively, resulting in a global macroscopic translation of the resonance stopbands.

Despite the complex dynamic resonance shifts introduced by these coupled effects, the STCF V5 lattice design exhibits substantial robustness. Our integrated simulations indicate that carefully optimizing the horizontal fractional tune within the range of $\nu_x \in [0.554, 0.560]$ provides a sufficiently wide and stable operational window to successfully maintain the design luminosity.

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