STUDY OF BEAM COUPLING IMPEDANCE AND INSTABILITIES FOR THE SUPER TAU-CHARM FACILITY*

T. He†, W. Li, W. Liang, Z. Meng, Y. Zou, J. Tang, USTC, Hefei, China
D. Zhou, KEK, 1-1 Oho, Tsukuba 305-0801, Ibaraki, Japan

Abstract

The Super Tau-Charm Facility (STCF), a next-generation electron-positron collider in China, is designed to achieve a peak luminosity above 0.5×10^{35} cm^{-2}s^{-1} at 4 GeV in the center-of-mass frame. This paper investigates beam instability issues for the STCF, with the aim of identifying and mitigating risks from beam coupling impedance. Our work analyzes key contributors such as coherent synchrotron radiation, resistive-wall, and geometric impedances, and evaluates their role in driving both single-bunch and multi-bunch instabilities.

INTRODUCTION

The Super Tau-Charm Facility (STCF) is a proposed new-generation electron-positron collider in China, operating at center-of-mass energies from 2 to 7 GeV, with a target peak luminosity exceeding 5×10^{34} cm^{-2}s^{-1} at 4 GeV center-of-mass energy [1]. To achieve this high luminosity, the STCF requires high beam currents and low emittance, making collective effects a critical challenge. The main parameters for the collider rings at three representative beam energies (1 GeV, 2 GeV and 3.5 GeV) are summarized in Table 1.

This paper presents a preliminary study of beam coupling impedances and associated instabilities for the STCF collider rings. Key impedance sources, including coherent synchrotron radiation (CSR), coherent wiggler radiation (CWR), resistive-wall (RW), and geometric (Geo.) impedances, are modeled. The longitudinal impedance model includes CSR from dipoles, CWR from wigglers, RW with NEG coating, and geometric contributions from collimators, BPMs, bellows, etc. Since detailed geometric models for the STCF are currently unavailable, the geometric impedance is estimated by scaling existing impedance budgets from HALF [2], FCC-ee [3], and SuperKEKB [4], based on the beam pipe aperture of STCF.

The vacuum chamber cross-sectional dimensions are required for the CSR, CWR and RW calculations. The STCF vacuum chamber is divided into three typical sections: the arc, the damping wiggler (DW) section, and the interaction region. Their cross-sectional geometries are shown in Fig. 1. All chambers are assumed to be coated with a 1 μm-thick NEG film. For CSR, the impedance from the dipoles is calculated using the parallel-plate shielding model [5]. For CWR, the impedance from the wigglers is evaluated using the PP-TR model [6]. For RW, the impedance is evaluated using the IW2D code, considering NEG coating with conductivities of 10^5 and 10^6 S/m [7].

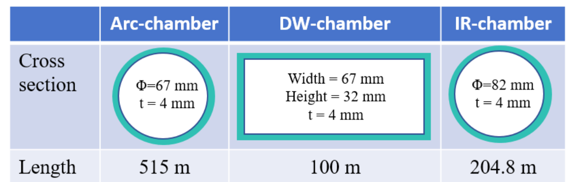

Figure 1: Typical vacuum chamber cross sections for the arc, wiggler, and interaction region.

Table 1: Key Parameters of the STCF Collider Rings for the Lattice V5 Design

Parameters	1 GeV	2 GeV	3.5 GeV
Circumference [m]	825.524	825.524	825.524
Beam current I_0 [A]	0.8	2.0	2.0
Bunch current I_b [mA]	1.21	3.03	3.03
Mom. factor α_c [10^{-4}]	13.4	14.1	14.3
Energy spread [10^{-4}]	7.16	8.12	10.02
Long. rad. damp. τ_z [ms]	21.9	8.9	6.45
Tran. rad. damp. $\tau_{x,y}$ [ms]	43.79	17.69	12.90
Harmonic number	1376	1376	1376
U_0 (total) [keV]	125.8	622.6	1494
RF voltage [MV]	0.75	2.5	6.0
Synchrotron tune (ν_s)	0.0147	0.0193	0.0228
Betatron tune (ν_x/ν_y)	28.55/33.58	28.55/31.58	28.55/30.58

IMPEDANCE MODELING

Longitudinal Impedance

Based on the modeling methods described above, the longitudinal impedance contributions from CSR, CWR, RW, and geometric sources are evaluated. Figure 2 shows the longitudinal short-range wake potential for a bunch length of 0.5 mm. The geometric wake potential is obtained via scaling, while the CSR, CWR and RW wakes are derived from their respective impedance models up to 2 THz and then Fourier transformed to the time domain. As observed from the wake potential, CSR and CWR dominate the short-range wake potential at low energies (1–1.5 GeV), highlighting their critical role in single-bunch dynamics.

Transverse Impedance

Figure 3 presents the transverse short-range wake potentials for a 0.5 mm bunch. The corresponding kick factors are listed in Table 2. Transverse impedance is dominated by geometric components, especially in the vertical plane. The geometric kick factors are significantly larger than the RW contribution at both 1 GeV and 2 GeV.

* Work supported by the Fundamental Research Funds for the Central Universities (No. WK2310000127) and the National Natural Science Foundation of China (Grants No. 12375324 and No. 12105284).
† htlong@ustc.edu.cn

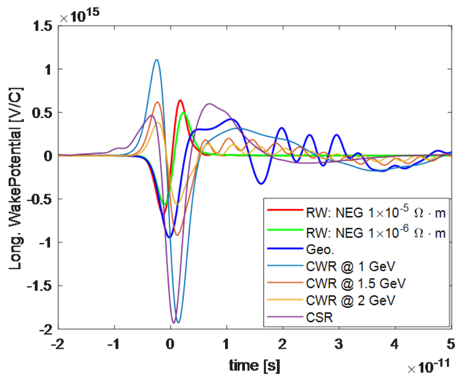

Figure 2: Longitudinal short-range wake potential for 0.5 mm bunch length.

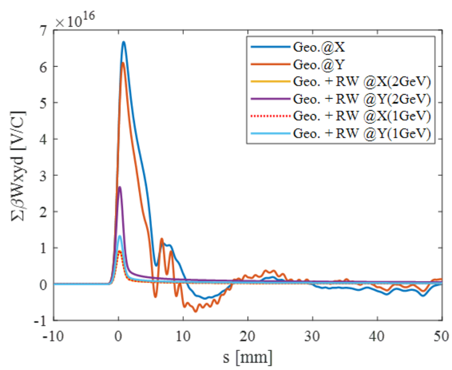

Figure 3: Transverse short-range wake potentials for 0.5 mm bunch length.

SINGLE-BUNCH INSTABILITIES

Longitudinal Microwave Instability

The microwave instability (MWI) is investigated using macroparticle tracking with the STABLE code [8] and 5 million macroparticles per bunch. We employ longitudinal wake potentials of 0.02 mm for RW, 0.2 mm for CSR, and the 0.5 mm wake shown in Fig. 2 for geometric wakes. Figure 4 shows the resulting energy spread as a function of single-bunch current. At 1 GeV, the beam becomes unstable above 1.2 mA, whereas at 2 GeV it remains stable up to the maximum simulated current of 3.0 mA. CSR and CWR are the main sources driving the instability, while the NEG conductivity has a negligible effect. Including RW has a negligible effect, whereas including geometric impedances significantly reduces the MWI threshold current.

Transverse Mode Coupling Instability

The transverse mode coupling instability (TMCI) thresholds were evaluated using both tracking simulations and analytical estimates. The tracking simulations were based on the wake potentials shown in Fig. 3, while the analytical estimates were derived from the kick factors listed in Table 2. For the analytical approach, the zero-mode tune shift is given by

$$\Delta\nu_y = \frac{eI_0}{2E\omega_0}\sum_j \beta_{yj}K_{yj}, \tag{1}$$

Table 2: Vertical Kick Factors at 1 GeV and 2 GeV

Component	**1 GeV [V/pC]**	**2 GeV [V/pC]**
RW (NEG:10^6 S/m)	984	1974
Geometric	6600	6600

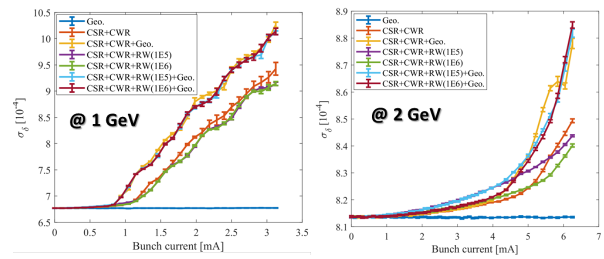

Figure 4: Energy spread vs. single-bunch current from microwave instability simulations. Nominal bunch currents are listed in Table 1.

and the corresponding tracking results are presented in Fig. 5. Assuming zero-mode tune shifts of 0.7 ν_s and 1.0 ν_s, the analytical estimates yield threshold bunch currents of approximately 6.2–8.8 mA at 1 GeV and 14.4–20.5 mA at 2 GeV, in good agreement with the tracking results. These thresholds are more than twice the nominal bunch current, indicating that TMCI is not a concern.

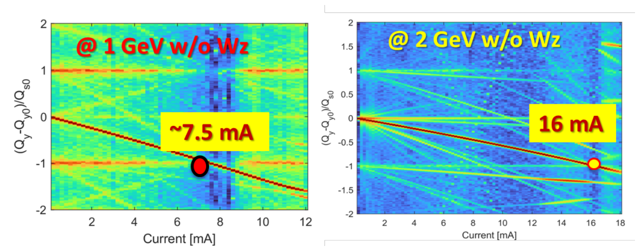

Figure 5: TMCI threshold currents from tracking and analytical methods.

COUPLED-BUNCH INSTABILITIES

Accelerating Mode

To suppress coupled-bunch instabilities driven by the accelerating mode impedance, the STCF plans to use a room-temperature 500 MHz cavity operating in the TM_{020} mode, which features strong higher-order mode damping [9]. Compared with the TM_{010} mode, the TM_{020} mode reduces the total R/Q by approximately 50% for the same cavity voltage and power requirements. Nevertheless, theoretical estimates without RF feedback, summarized in Table 3, show that low-order coupled-bunch modes, especially mode $\mu = -1$, can still be excited at 2 GeV and 3.5 GeV. Therefore, the following discussion focuses primarily on these two operating points. We find that a conventional I/Q-based PI feedback controller with proportional gain $k_p = 1$ and a loop delay of half the revolution period effectively suppresses the most dangerous mode $\mu = -1$. This may slightly increase the growth rate of mode $\mu = -2$, but it remains below the radiation damping rate [10]. Therefore, the PI feedback alone is sufficient to stabilize the accelerating-mode-driven instabilities.

Table 3: Growth Rates (s^{-1}) of Low Coupled-Bunch Modes Driven by the Accelerating Mode without and with the RF Feedback

μ	2 GeV		3.5 GeV	
	Without FB	**With FB**	**Without FB**	**With FB**
-1	412	0	562	0
-2	44	92	62	120
$1/\tau_z$	112		155	

Higher-Order Modes

Higher-order modes (HOMs) mainly originate from the RF cavity. Despite the HOM-damping design, several modes remain of concern. We used the CST wakefield solver to compute the wake potential over 100 m and extracted the longitudinal monopole and transverse dipole HOMs via the Particle Swarm Optimization (PSO) fitting algorithm [11]. The results are shown in Fig. 6. Assuming all cavities have identical HOM frequencies and that these frequencies coincide with the beam spectral lines (the worst scenario), the growth rates are estimated using the following formulas:

$$\frac{1}{\tau_{\text{HOM},\parallel}} = \frac{I_0 \alpha_c \omega_r}{4\pi \nu_s E_0/e} e^{-(\omega_r \sigma_\tau)^2} \operatorname{Re} Z_\parallel, \tag{2}$$

$$\frac{1}{\tau_{\text{HOM},\perp}} = \frac{I_0 f_0 \beta_{x/y} \operatorname{Re} Z_\perp}{2E_0/e}. \tag{3}$$

where I_0 is the beam current, α_c is the momentum compaction factor, ω_r is the angular frequency of the HOM, ν_s is the synchrotron tune, E_0 is the beam energy, e is the elementary charge, σ_τ is the rms bunch length, $\operatorname{Re} Z_\parallel$ is the real part of the longitudinal HOM impedance, f_0 is the revolution frequency, $\beta_{x/y}$ is the average beta function at the cavity location, and $\operatorname{Re} Z_\perp$ is the real part of the transverse HOM impedance.

Our analysis indicates that if the longitudinal bunch-by-bunch feedback provides at least 2 ms of damping and the transverse feedback provides at least 1 ms, all HOM-driven instabilities can be effectively stabilized.

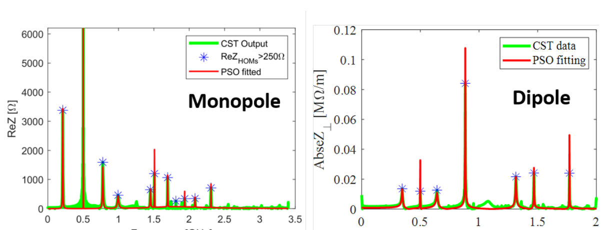

Figure 6: Longitudinal monopole (left) and transverse dipole (right) HOMs of the TM_{020} cavity.

Resistive-Wall Driven Instabilities

Because β_y is significantly larger than β_x, the RW-driven transverse coupled-bunch instability is more severe in the vertical plane. Using the analytical formula of growth rate and the β-weighted sum impedance, we evaluated the instability growth rates at 2 GeV for different chromaticities. The results are shown in Fig. 7. At zero chromaticity, the fast-mode growth rate reaches 1643 s^{-1}. Increasing chromaticity to +3 reduces it only slightly to 1583 s^{-1}, which is still far above the radiation damping rate of 56.5 s^{-1}. Therefore, a fast transverse feedback system with a damping time below 0.6 ms is required to suppress this instability.

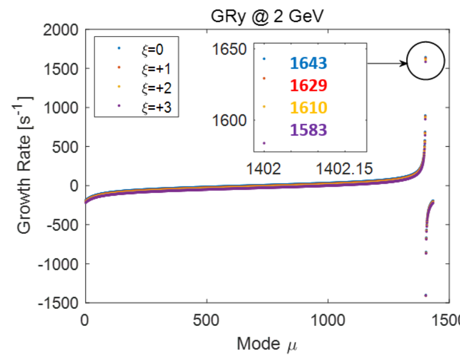

Figure 7: RW-driven instability growth rate as a function of coupled mode number.

SUMMARY

A preliminary impedance model has been developed for the STCF, including CSR, CWR, RW, and geometric contributions. The main findings are summarized as follows:

- MWI is only a concern at 1 GeV, where its threshold falls below the target current; it is dominated by CSR and CWR, while NEG conductivity has a negligible effect.
- TMCI thresholds are safe, exceeding twice the nominal bunch current at both energies of 1 GeV and 2 GeV.
- The accelerating mode driven instability can be fully suppressed with a simple PI feedback.
- HOM-driven instabilities require active feedback, with damping times of about 2 ms longitudinally and 1 ms transversely.
- Transverse RW instability demand fast feedback systems (0.4–0.6 ms).

These results provide a basis for further impedance reduction and feedback design for the STCF.

REFERENCES

[1] X.-C. Ai *et al.*, “Conceptual design report of the Super Tau-Charm Facility: the accelerator”, *Nucl. Sci. Tech.*, vol. 36, p. 242, 2025. doi:10.1007/s41365-025-01833-x

[2] T. He *et al.*, “Beam coupling impedance modeling for the Hefei Advanced Light Facility”, in *Proc. IPAC’26*, Normandy, France, May 2026, paper THP5645, this conference.

[3] Impedance/Wake Model of the Future Circular Collider (FCC), https://github.com/ImpedanCEI/fcc_ee_IW_model

[4] T. Ishibashi, “Impedance budget and single-bunch collective instability simulations for SuperKEKB low energy ring with a nonlinear collimation system after a first long shutdown”, presented at eeFACT’25, Tsukuba, Japan, Mar. 2025, unpublished.

[5] R. L. Warnock, “Shielded coherent synchrotron radiation and its effect on very short bunches”, Stanford Linear Accelerator Center, Stanford, CA, USA, Rep. SLAC-PUB-5375, 1990.

[6] T. He *et al.*, “Impact of coherent wiggler radiation impedance in Tau-Charm factories”, *Phys. Rev. Accel. Beams*, vol. 28, p. 101002, 2025. doi:10.1103/yqdj-r617

[7] N. Mounet, ImpedanceWake2D (IW2D), https://gitlab.cern.ch/IRIS/IW2D

[8] T. He and Z. Bai, “Graphics-processing-unit-accelerated simulation for longitudinal beam dynamics of arbitrary bunch trains in electron storage rings”, *Phys. Rev. Accel. Beams*, vol. 24, p. 104401, 2021. doi:10.1103/PhysRevAccelBeams.24.104401

[9] Y. Wei *et al.*, “Preliminary design of a 500 MHz normal-conducting cavity for main rings of Super Tau-Charm Facility”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 1467–1469. doi:10.18429/JACoW-IPAC2024-TUPR23

[10] W. Liang, T. He *et al.*, “Beam instability induced by the RF cavity accelerating modes and its suppression in the Super Tau-Charm Facility”, submitted for publication.

[11] H. Yao, T. He *et al.*, “Particle swarm optimization fitting of long-range wake potentials for trapped-mode parameter characterization in the HALF storage ring”, submitted for publication.