

PRELIMINARY STUDY ON ELECTRON CLOUD INSTABILITY IN THE SUPER TAU-CHARM FACILITY*

Zeyuan Meng^{†,1}, Weiwei Li^{‡,2}, K.Ohmi³, Ye Zou¹, Jingyu Tang¹

¹School of Nuclear Science and Technology, USTC, Hefei, Anhui, China

²National Synchrotron Radiation Laboratory, USTC, Hefei, Anhui, China

³KEK, Tsukuba, Ibaraki, Japan

Abstract

In high-intensity positron storage rings, the electron cloud instability is a significant collective effect that can deteriorate beam quality. In the Super Tau-Charm Facility (STCF) positron ring, electron cloud effects are expected to be severe. This preliminary study investigates the electron cloud build-up, the resulting single-bunch instability and detuning effects in the STCF positron ring using PyECLOUD. The single bunch instability and coherent tune shift simulation results show good agreement with analytical predictions.

INTRODUCTION

The Super Tau-Charm Facility (STCF) is a next-generation circular electron-positron collider proposed in China. At a center-of-mass energy of 4 GeV, STCF aims to achieve a peak luminosity exceeding $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, which requires a design beam current of up to 2 A [1]. The combination of high beam current and narrow bunch spacing makes collective effects a critical concern for machine performance, and the electron cloud effect in the positron ring is one of the most serious challenges. In positron rings, electron cloud build-up is predominantly seeded by photoelectrons from synchrotron radiation. When these primary electrons strike the chamber wall with energies gained from the beam, secondary emission can trigger an avalanche process if the secondary emission yield (SEY) exceeds unity. The resulting electron cloud can drive single bunch instabilities, coupled bunch instabilities, and vertical beam size blowup, severely limiting machine performance [2]. To mitigate these effects, low-SEY coatings (such as TiN and NEG coatings), antechambers to reduce photoelectron yield, and longitudinal magnetic fields from solenoids or permanent magnets have been widely adopted [3]. In this paper, we employ the PyECLOUD code to simulate both the electron cloud buildup process and the resulting single-bunch instability in the STCF positron ring, based on its design beam parameters and vacuum chamber conditions. By comparing the simulation results with the analytical estimations in terms of electron cloud build-up, single bunch instability and detuning effects, we present a preliminary assessment of the electron cloud threat to STCF and provide a basis for the design of future mitigation strategies.

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[†] ustcmzy@mail.ustc.edu.cn

[‡] liwe@ustc.edu.cn

ELECTRON CLOUD BUILD-UP

The electron cloud build-up in the STCF positron ring is simulated for operation at the nominal beam energy of 2 GeV and The main beam parameters used in the simulations are summarized in Table 1.

The vacuum chamber is modeled as a circular beam pipe with a radius of 33.5 mm. An antechamber geometry with a 16.5 mm slot is also considered for comparison. The photoelectron yield is set to 0.1 photoelectrons per photon, and the emission angular distribution follows a cosine law. For secondary emission, we adopt a peak SEY $\delta_{max} = 1.2$ at an incident electron energy of 300 eV, with a low-energy reflectivity of 0.5, which are typical values for copper surfaces. The external magnetic fields in dipole magnet of the arc sections are set to 0.77 T. The electron build-up is tracked over 102 bunch passages, which is sufficient for the electron density to reach saturation.

Figures 1 and 2 show the spatial distributions of the electron cloud. In the baseline circular chamber, electrons concentrate densely near the beam axis. In the dipole magnet case, the magnetic field constrains electrons to move along the field lines toward the chamber walls, depleting the central region. With an antechamber, the central density drops because part of the synchrotron radiation photons are intercepted before hitting the main beam wall, reducing the primary photoelectron source. These features confirm that both techniques effectively lower the electron density sampled by the beam.

We also studied the effects of low SEY materials, solenoids, quadrupole magnets, and sextupole magnets. Some of the results are shown in Table 2. Note that the effects of the solenoid field are not shown because the local electron density is reduced to a negligibly low level in the simulations, which is consistent with the results in Su-

Table 1: Beam Parameters Employed for the Electron Build-Up Simulation in the Arc Sections

Parameter	Value
Beam energy [GeV]	2.0
Circumference [m]	860.321
Hor./Ver. rms size [μm]	233/23.3
Betatron coupling	0.01
Hor./Ver./Lon. tune	30.543/34.58/0.0194
Bunch length [mm]	7.21
Bunch spacing [ns]	4
Bunch population	5.2×10^{10}

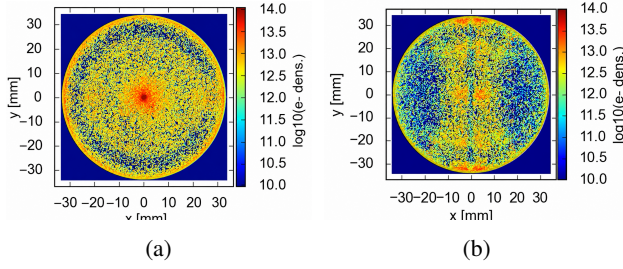


Figure 1: (a): the electron density distribution in the chamber of the arc section without external field; (b): the electron density distribution in the chamber of the arc section with dipole magnetic field.

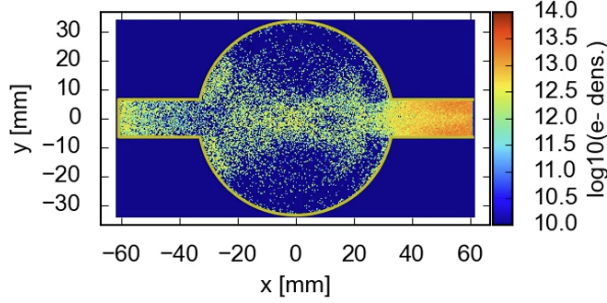


Figure 2: Electron density distribution in the antechamber of the arc section.

perKEKB [3]. The results show that the central electron density can be reduced by up to two orders of magnitude relative to the field-free drift case, consistent with observations at other machines, such as SuperKEKB [3, 4] and BEPCII [5].

SINGLE BUNCH INSTABILITY

The threshold electron density for the single-bunch instability driven by the electron cloud is given by (with the coasting beam assumption):

$$\rho_{e,th} = \frac{2\gamma v_s \omega_c \sigma_z / c}{\sqrt{3KQr_e \beta L}}, \quad (1)$$

where,

$$\omega_c^2 = \frac{2\lambda_b r_e c^2}{\sqrt{2\pi} \sigma_z \sigma_y (\sigma_x + \sigma_y)}, \quad (2)$$

and $K = \frac{\omega_c \sigma_z}{c}$, $Q = \min(Q_{nl}, \omega_c \sigma_z / c)$. The electron cloud acts as a short-range wake field that couples the head and tail of the bunch, leading to rapid vertical emittance growth when

Table 2: Local electron cloud density at the beam position (10^{12} m^{-3}). The fractional values indicate the remaining fraction of the local electron cloud density after applying the corresponding mitigation measures.

Sec.	Circ.	Ante.	Coat.	Dip.	Quad.	Sext.
Arc	15	1/2	4/5	1/3	1/10	1/30
Wiggler	25	1/6	4/5	1/4	-	-

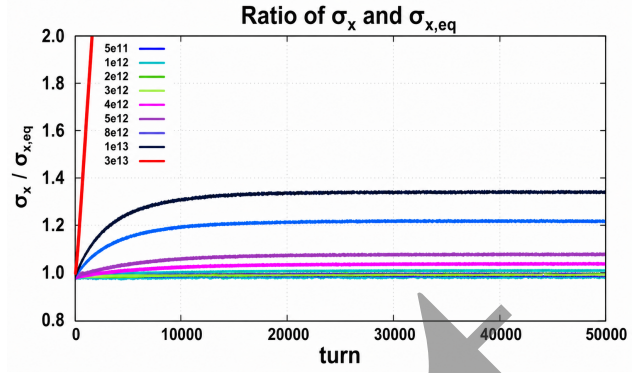


Figure 3: Evolution of the ratio of the horizontal beam size and the equilibrium horizontal beam size $\sigma_x / \sigma_{x,eq}$.

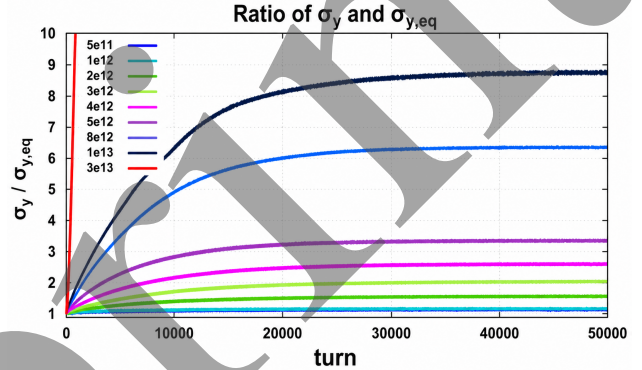


Figure 4: Evolution of the ratio of the vertical beam size and the equilibrium vertical beam size $\sigma_y / \sigma_{y,eq}$.

ρ_e exceeds $\rho_{e,th}$. For the STCF parameters at 2 GeV (as illustrated in Table 1), Eq. (1) yields $\rho_{th} \approx 4 \times 10^{12} \text{ m}^{-3}$. The single-bunch instability driven by electron cloud is studied using a combined simulation approach with PyECLLOUD and PyHEADTAIL [6]. To simplify the model while capturing the essential physics, the following assumptions are adopted. The ring is represented by 10 equally spaced electron cloud interaction points, all with the same beta function. At each interaction point, the electron cloud is initially distributed uniformly over a transverse region much larger than the beam size. Before each bunch passage, the electron cloud distribution is reset to the initial uniform distribution so that the beam interacts with a fresh electron cloud at every interaction point. Figures 3 and 4 show the evolution of the horizontal and vertical beam size with turn number for different electron densities respectively. Below the threshold, the beam size remains close to the equilibrium value. Above the threshold, a pronounced blowup develops, signaling the onset of the single-bunch instability.

COHERENT TUNE SHIFT

The coherent tune shift in the vertical plane can be estimated as (the coherent dipole mode) [7]:

$$\Delta \omega_{\beta,coh} = \frac{\omega_b^2}{2\omega_{\beta 0}} \frac{c}{2\omega_e \sigma_z} \sin\left(\frac{2\omega_e \sigma_z}{c}\right), \quad (3)$$

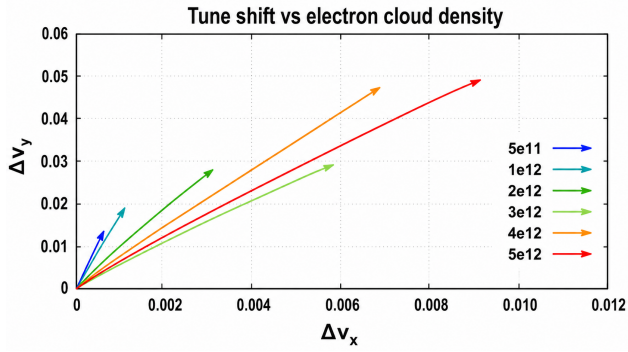


Figure 5: Coherent tune shift simulation results obtained with PyECLoud for different local electron densities.

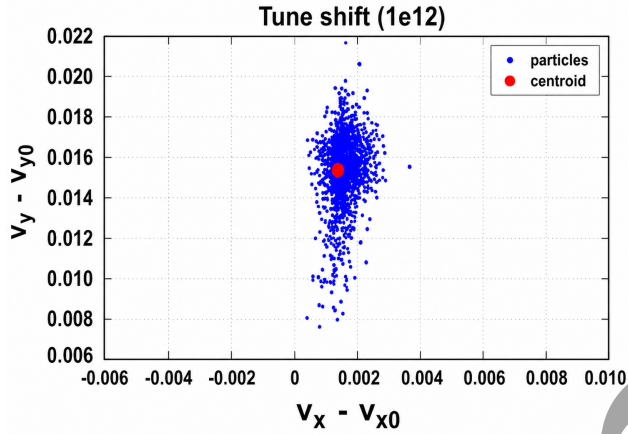


Figure 6: Tune spread effects in the simulation results with the local electron density equaling $1 \times 10^{12} \text{ m}^{-3}$.

where,

$$\omega_b^2 = \frac{\lambda_e r_e c^2}{\gamma \sigma_y (\sigma_x + \sigma_y)}, \quad (4)$$

where λ_e is the electron line density and γ is the Lorentz factor.

The tune footprint in Fig. 5 shows that as the electron cloud density increases, the tune shift grows significantly, and the simulation results agree well with the analytical predictions (~ 0.03 with $\rho_{e,local} = 1 \times 10^{12} \text{ m}^{-3}$). Besides, we also observe the occurrence of tune spread (as illustrated in Fig. 6), with an inverse direction compared with the space-charge effect, which is consistent with the theoretical expectation.

SUMMARY AND DISCUSSION

In this paper, we investigated the electron cloud effects in the STCF, including the single-bunch instability and co-

herent tune shift induced by the electron cloud. The simulation results show good agreement with the analytical predictions. The results indicate that the local electron cloud density should be controlled below $1 \times 10^{12} \text{ m}^{-3}$ in order to avoid significant beam quality degradation. Such a requirement is considered feasible, since an electron density of approximately $1.1 \times 10^{11} \text{ m}^{-3}$ has already been achieved in SuperKEKB [8], and our build-up simulations also demonstrate that effective mitigation techniques can substantially suppress the electron cloud density in the STCF positron ring. In addition, a non-monotonic behavior of the tune spread effect is observed as the electron density increases, which mainly originates from the sinusoidal term in the analytical model of Eq. (3). These results provide a preliminary evaluation of the electron cloud effects in the STCF and offer a basis for future optimization of mitigation strategies and beam operation conditions.

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