

PHYSICAL DESIGN OF THE MAIN LINAC SECTION FOR ELECTRON BEAM IN THE STCF INJECTOR

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Abstract

This paper presents the physical design of the Main Linac (ML) for the STCF, accelerating 1 GeV electron and positron beams to 1–3.5 GeV for both off-axis (1 nC) and swap-out (8.5 nC) injection. An interleaved scheme divides 36 accelerating structures into two groups, independently controlling energy gain and longitudinal phase space for each species. At the nominal 2 GeV output, simulations with ELEGANT demonstrate well-controlled energy spread and emittance. After Beam Based Alignment correction, orbit oscillation is constrained below 1 mm, with exit geometric emittances of 0.28 nm (off-axis) and 3.30 nm (swap-out), both meet injection requirements.

INTRODUCTION

The Super Tau Charm Facility (STCF) is a next-generation electron–positron collider under construction in China, operating in the tau-charm energy region with a center-of-mass energy of 2–7 GeV and a designed peak luminosity of $0.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [1]. The two orders of magnitude improvement in luminosity places higher demands on beam quality and beamline design [2].

The general layout of the STCF is shown in Fig. 1. The electron beam injection scheme is compatible with both off-axis [3] (1 nC) and swap-out [4] (8.5 nC) injection, sharing a compatible beamline. The 1 GeV electron beam from linac, and positron beam from damping ring (DR) and/or accumulate in ring (AR) at the entrance of the Main Linac (ML). They are then accelerated by the ML to the collision energy (1–3.5 GeV) and transported into the collision ring.

This paper presents the physics design of the ML for electron beams. Taking a nominal output energy of 2 GeV as the design goal, we complete the design and perform an error analysis accounting for alignment and systematic errors.

PHYSICAL DESIGN FOR ELECTRON BEAM

Layout Description

The detailed layout of the ML section is shown in Fig. 2. The accelerating section employs 36 SLAC-like standard 3-meter traveling-wave accelerating structures. A triplet consisting of three quadrupole magnets is installed between every two accelerating structures to match the transverse beam parameters. Furthermore, to correct beam orbit deviations, the Beam Based Alignment (BBA) technique [5] is required. Stripline Beam Position Monitors (SBPMs) are installed between every two accelerating structures, and in conjunction with correctors installed between each accelerating structure, they are used to achieve beam central orbit correction.

The electron beam requirements for the off-axis injection and swap-out injection schemes of the STCF are shown in the Table 1. In this paper, the physics design of the ML section is carried out using the nominal operating condition of 2 GeV as an example.

Table 1: Injection Beam Parameters

Parameters	Off-axis	Swap-out
Charge (nC)	1.0	8.5
Injection energy (GeV)	1.0-3.5	1.0-3.5
Optimal energy (GeV)	2.0	2.0
RMS Energy spread (%)	≤ 0.1	≤ 0.5
RMS Geo. emittance (nm)	≤ 6	≤ 30

In addition to energy gain, the ML modulates the longitudinal phase space (LPS) by independently optimizing the accelerating gradient and phase to compensate for distortions from space charge and longitudinal wakefields. Due to the different origins of the electron and positron beams, their initial LPS distributions may differ. Therefore, the ML operates in an interleaved mode with structures divided into two groups, each independently handling LPS modulation for one species. As shown in Fig. 2, a basic unit of four structures is repeated nine times: for electrons, the first two are powered; for positrons, the latter two. Mode switching is achieved via RF timing control.

This interleaved strategy decouples energy gain and LPS modulation for both beams under the 2 GeV nominal con-

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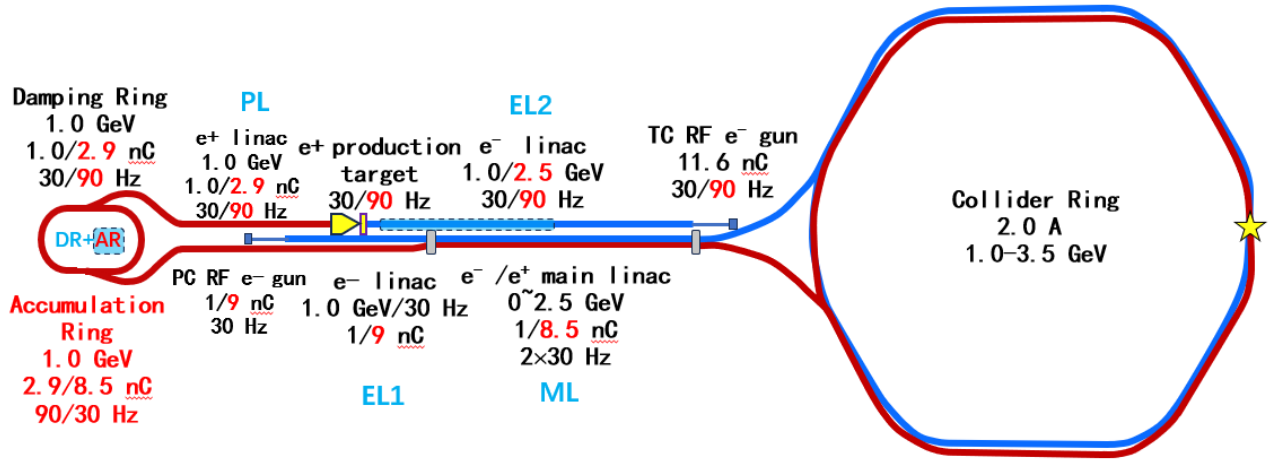


Figure 1: STCF compatible injection scheme.

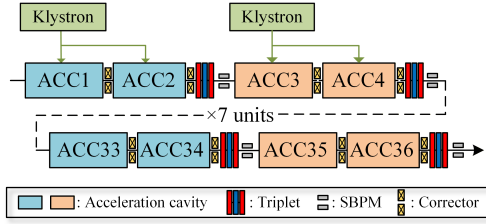


Figure 2: Detailed layout of the STCF ML section.

dition, while preserving the capability for 3.5 GeV extreme operation.

The following presents the electron beam output under the two injection modes with the ML operating at 2 GeV. Initial bunch distributions were taken from colleagues' prior calculations, and the ML optimization was performed using ELEGANT [6].

Off-Axis Scheme (2 GeV, 1 nC)

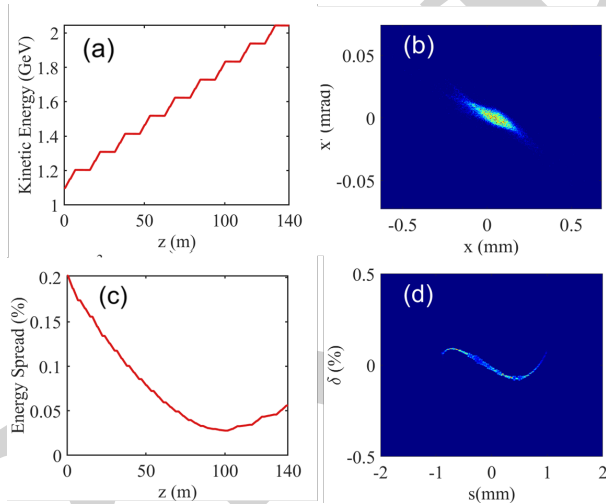


Figure 3: Off-axis: (a) energy gain, (b) Trans. phase space, (c) energy spread, (d) Longi. phase space.

Figure 3(a) shows the stepwise energy gain under interleaved acceleration. At low charge, unpowered structures act

as drift spaces with negligible wakefield degradation, and the energy spread decreases steadily as shown in Fig. 3(c).

Swap-Out Scheme (2 GeV, 8.5 nC)

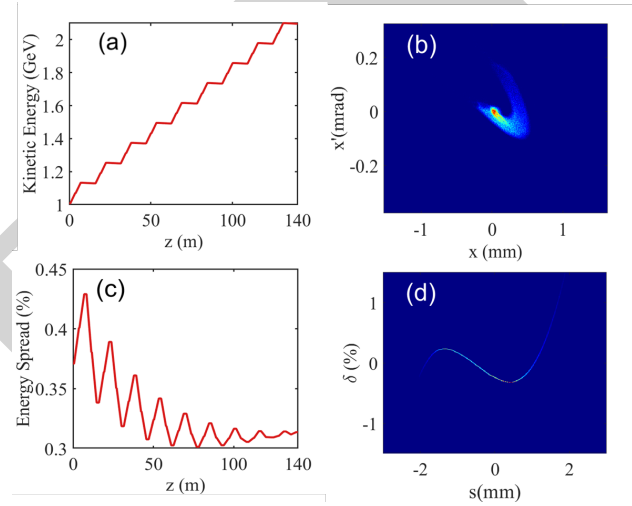


Figure 4: Swap-out: (a) energy gain, (b) Trans. phase space, (c) energy spread, (d) Longi. phase space.

For the 8.5 nC swap-out bunch, severe wakefields are compensated by a strong negative chirp in each unit. Consequently, the energy spread oscillates within each unit—first increasing, then decreasing—while maintaining an overall downward trend as shown in Fig. 4(c).

ERROR ANALYSIS AND CORRECTION

Error Analysis

In the numerical simulation, the systematic errors listed in Table 2 were introduced, with values set according to the engineering capabilities of the STCF construction. To calibrate and eliminate these transverse errors, a global BBA correction algorithm is employed in ELEGANT. Once the transverse beam trajectory is effectively corrected, the emittance growth caused by transverse wakefields is effectively limited.

Table 2: The Error Settings in the Simulation

Parameters	$\Delta x/\Delta y$ (μm)	$\Delta\theta$ (mrad)	FSE(%)
ACCs	100	-	0.04
Quadrupoles	100	1.0	0.1
SBPMs	100	-	-
Correctors	100	-	-

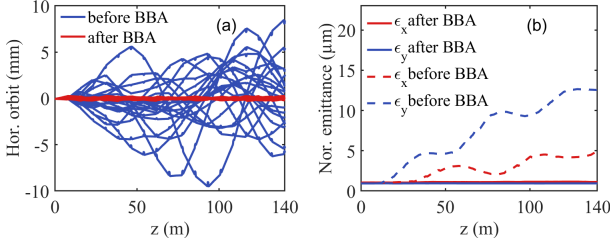
Off-Axis Scheme (2 GeV, 1 nC)

Figure 5: Off-axis: (a) Hor. Orbit, (b) Nor. emittance.

Figure 5(a) compares the beam central orbit before and after BBA correction. BBA constrains the trajectory oscillation from a maximum of 10 mm to less than 1 mm. Since this deviation is the main cause of transverse wakefield effects, normalized transverse emittance growth is effectively suppressed, as shown in Fig. 5(b). The geometric emittance at the ML exit is 0.28 nm, meeting the injection requirements listed in Table 1.

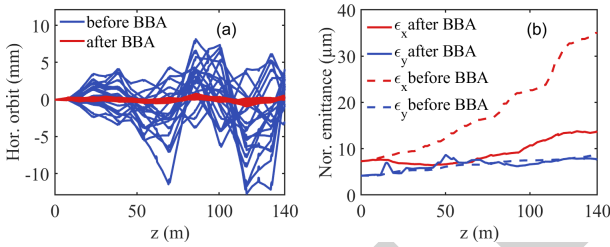
Swap-Out Scheme (2 GeV, 8.5 nC)

Figure 6: Swap-out: (a) Hor. Orbit, (b) Nor. emittance.

As shown in Fig. 6(a), BBA provides an equally effective correction as well. Due to the larger bunch charge and initial

emittance, the Nor. emittance still grows along the beamline, but the overall growth remains acceptable after correction. The exit geometric emittance is 3.30 nm, satisfying the injection requirements.

CONCLUSION AND DISCUSSION

The ML physics design for STCF electron beam is completed, featuring an interleaved scheme for independent e^-/e^+ control. Optimized simulations with error corrections meet injection requirements. The positron beamline remains under optimization, but half of the structures can support positrons without compromising electron performance.

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