

Stable double-bunch beam generation for plasma wakefield accelerators via coherent synchrotron radiation-tolerant isochronous beamlines

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Beam-driven plasma wakefield acceleration represents a promising strategy for producing high-energy electron and positron beams in future accelerator facilities. A key challenge in realizing high-quality acceleration is the production of high-charge, high-stability double-bunch beams, as existing methods are often limited to low charges or suffer from significant charge loss. In this paper, we propose a coherent synchrotron radiation-tolerant beam-merging scheme using twin isochronous beamlines that share a common dipole magnet to generate a high-charge double-bunch beam with excellent stability. Numerical simulations indicate that the proposed scheme generates a 5 nC/1 nC electron double-bunch beam that exhibits no charge loss, with emittance growths of both bunches constrained to approximately 0.1 mm mrad, and an interbunch timing jitter maintained below ± 2 fs. The robustness of the scheme is evaluated, and its potential use in large-scale accelerator facilities is emphasized for supplying high-quality drive beams for plasma wakefield accelerators.

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I. INTRODUCTION

High-luminosity, high-energy electron-positron colliders are desirable for fundamental physics studies. It is envisioned that future TeV-scale colliders require electron bunches with high charge [1,2]. While rf accelerators are fundamentally limited by vacuum breakdown to gradients of up to a few hundred MV/m [3,4], plasma wakefield acceleration has emerged as a transformative technology in particle acceleration, offering acceleration gradients far exceeding those of conventional radio-frequency (rf) accelerators [5–8]. In beam-driven plasma wakefield accelerators (PWFA), an ultrarelativistic drive beam propagating through plasma excites strong wakefields, and a customized witness beam loaded at a proper phase can be accelerated with high gradient and high quality [9,10]. In PWFA, experiments have preliminarily demonstrated the potential for large energy gain [5,11] and high energy transfer efficiency from the driver to the trailing bunch [7]. This large accelerating gradient may enable a reduction in accelerator length compared to conventional rf-based designs, motivating interest in PWFA for future facilities such as the proposed Circular Electron-Positron

Collider (CEPC) [12], the hybrid, asymmetric, linear Higgs factory [13], and the 10 TeV Wakefield Collider design initiative [14].

A key challenge for PWFA is producing the driver-witness double-bunch beams with very high charge and beam quality. The two-bunch configuration requires precise control over the transverse alignment between the bunches. The optimal longitudinal separation is typically on the order of the plasma wavelength, which translates to several hundred femtoseconds (fs) [15]. To support a high-charge witness bunch, the driver must carry several to tens of nanocoulombs, with tailored current profiles to optimize the transformer ratio [16–18]. Peak currents for both bunches must reach the kiloampere level, and transverse misalignment would degrade the efficacy of the wakefield acceleration.

Various methods have been proposed to generate double-bunch beams. Critically, existing double-bunch generation methods struggle to produce high-charge (multi-nC) driver-witness pairs with the high stability and brightness. For example, schemes using a transverse mask or collimator in a dispersive beamline can split one bunch into two [19,20], but this inherently sacrifices a significant fraction of the charge. While the beam emittance can in principle be preserved with sufficiently clean masking, achieving this becomes increasingly challenging at high charge and high brightness. Similarly, transverse-to-longitudinal emittance-exchange techniques can tailor bunch profiles, but they become ineffective at very high charge [21,22]. An alternative is to generate two pulses on

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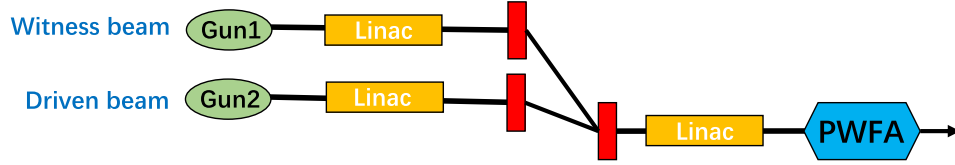


FIG. 1. Schematic illustration of the beam-merging concept proposed in this work. The driver and witness beams are generated separately in independent beamlines and merged prior to injection into a PWFA stage.

the photocathode (using a double-laser trigger), which avoids charge loss, but in practice strong space-charge forces make high-charge double-bunches difficult to compress and manipulate [23,24]. As a result, a new method capable of generating high-charge double-bunch beams with high stability and brightness is highly desired.

In this work, we introduce a novel scheme to overcome these limitations by generating the driver and witness bunches independently and then merging them into a single beam without charge loss. Specifically, the driver and witness bunches are produced from two rf injectors separately. Ideally, we would use a fast kicker magnet [25] to inject the driver bunch while leaving the accelerated bunch undisturbed. However, no kicker exists that can separate bunches at the necessary femtosecond-to-picosecond timescales [26]. Therefore, the driver and witness bunches are accelerated to different energies in their respective linacs, while their transverse and longitudinal beam parameters are individually optimized. These beams are then combined isochronously using twin beamlines that share a common dipole magnet, as illustrated in Fig. 1. This merging system avoids any physical mask or collimator, so all of the charge is preserved. It also allows precise premerge control of each bunch's length, current profile, and trajectory. This high-charge, high-brightness double-bunch beam is well suited for the requirements of future PWFA-based accelerators. After merging, the double-bunch beam can be further accelerated and modulated in subsequent beamline sections before entering the PWFA stage.

While the proposed merging scheme eliminates charge loss and enables independent optimization of the driver and witness bunches, its successful implementation for PWFA hinges on overcoming two key technical challenges. First, the temporal spacing between the two bunches must be stabilized at the femtosecond level and their transverse alignment controlled at the micrometer scale [27]. The temporal spacing is affected both by laser-rf synchronization in the accelerator and by the inevitable energy jitter and trajectory fluctuations. The former has already achieved synchronization within ~ 10 fs and is expected to improve further with advancing

technology [28,29], while the latter is the primary issue addressed in this work through an isochronous lattice design with minimal timing sensitivity. Second, efficient plasma wakefield excitation typically requires kiloampere-level peak currents. These currents are usually obtained through conventional acceleration and magnetic compression upstream of the merging section. However, such high peak currents induce strong coherent synchrotron radiation (CSR) effects in the bending magnets [30]. The CSR can significantly degrade the beam emittance and break the isochronous condition of the beamline.

This paper is organized as follows. Section II develops a comprehensive theoretical framework that quantitatively characterizes CSR effects on beam dynamics, deriving new stability criteria for emittance preservation and isochronicity maintenance under CSR conditions. Section III introduces the design principles of the isochronous merging system and the application scenarios of the specific scheme proposed in this work. Section IV demonstrates the feasibility of the proposed scheme through multi-objective genetic algorithm optimization using ELEGANT [31]. In addition to presenting the optimized performance under full CSR considerations—including fs-level timing jitter and emittance growths of both bunches limited to about 0.1 mm mrad, this section also compares optimizations performed with and without CSR effects, and examines the sensitivity of the optimized lattice to magnet field fluctuations. Section V discusses broader implications for plasma-based accelerator development and outlines implementation pathways for future high-energy physics facilities.

II. THEORETICAL FRAMEWORK

In this section, we introduce the effect of CSR on the beam dynamics and derive the conditions for mitigating CSR-induced emittance growth and the achromatic and isochronous conditions in the presence of CSR. First, we review the beam transport optics without considering CSR. Assuming the six-element vector $X = [x, x', y, y', z, \delta]$ represents the coordinates of a test particle, the evolution of the particle's position can be expressed as a power series expansion of the initial phase space coordinates:

$$X_{i,f} = \sum_j R_{ij} X_j + \sum_{jk} T_{ijk} X_j X_k + \sum_{jkl} U_{ijkl} X_j X_k X_l, \quad (1)$$

where i denotes the index of the vector X and δ represents the relative energy deviation. R_{ij} , T_{ijk} , and U_{ijkl} are the first-, second-, and third-order transport matrices, respectively. As an example, consider the transverse coordinates of a particle with a relative energy deviation δ as a function of δ alone, as given by

$$x_f = x + R_{16}\delta + T_{166}\delta^2 + U_{1666}\delta^3 = x + \Delta x, \quad (2a)$$

$$x'_f = x' + R_{26}\delta + T_{266}\delta^2 + U_{2666}\delta^3 = x' + \Delta x', \quad (2b)$$

with $i = 1, 2$ and $j = k = l = 6$ following the notation of Eq. (1). The linear energy dependence, R_{16} , is the transverse dispersion, and T_{166} and U_{1666} are the second- and third-order transverse dispersions, respectively. At either end of an achromat, $R_{16} = R_{26} = 0$, and we call a lattice with $T_{166} = T_{266} = 0$ at these locations a second-order achromat, and so on. In contrast, when the beamline is not fully achromatic, a nonzero energy deviation ($\delta \neq 0$) leads to a transverse centroid displacement ($\Delta x \neq 0$), as the residual dispersion and its higher-order components couple the longitudinal momentum deviation to the transverse position.

Similarly, the first order evolution of the longitudinal coordinate z of the particle is expressed as follows:

$$\Delta z = R_{51}x_0 + R_{52}x'_0 + R_{56}\delta. \quad (3)$$

First-order isochronicity requires $R_{51} = R_{52} = R_{56} = 0$. From transfer matrix analysis, it follows that if the system is first-order achromatic ($R_{16} = R_{26} = 0$) and $R_{56} = 0$, then the arrival time becomes independent of the initial particle coordinates and energy deviation, satisfying the isochronicity condition [32]. In the absence of CSR, therefore, first-order isochronicity of an achromat is fully determined by R_{56} .

However, the presence of CSR during deflection can result in severe degradation of bunch quality, which can be significant when bunches with peak current of kA move in a curved trajectory. The effect of CSR on bunches is often investigated by employing a 1D projected model that neglects vertical influence and considers only longitudinal interactions [33]. In the 1D approximation, the effect of CSR on a particle within a bunch at location s along the beam line is to induce a relative-energy change $\delta_s(z)$ depending on the arclength coordinate s and particle longitudinal coordinate within the bunch z [34]. The relative energy deviation per unit arc length induced by CSR along a dipole of a Gaussian bunch can be estimated [35]:

$$\frac{d\delta}{ds}(z) = \frac{2r_e N}{3^{1/3} \rho^{2/3} \gamma_c} \int_z^\infty \frac{d\lambda(z')}{dz'} \frac{1}{(z' - z)^{1/3}} dz'. \quad (4)$$

In the above expression ρ is the dipole radius of curvature, N the bunch population, r_e the electron classical radius, and γ_c the relativistic factor. Significant research efforts have been dedicated to addressing the issue of emittance growth induced by CSR. Douglas and Di Mitri introduced the cell-to-cell phase matching technique [36,37], which effectively compensates for CSR kicks through the implementation of optical symmetry. Additionally, Hajima proposed a beam envelope matching approach aimed at minimizing projected emittance growth by strategically adjusting the Twiss parameters [38]. This method aligns the unperturbed beam ellipse at the exit of the beamline with the direction of the CSR kick. Furthermore, the CSR kick model [39,40] developed by Jiao offers a rigorous framework for analyzing the net coordinate deviations induced by CSR effects in individual dipole magnets. In this study, we apply the integration method developed by M. Venturini [35].

When CSR-induced energy deviations δ_{CSR} are introduced, they couple into the particle dynamics through integrals weighted by the partial transport matrices. The transverse coordinates at the exit of the beamline then become:

$$\Delta X_i = R_{i6}\delta_0 + \int_{s_i}^{s_f} R_{i6}^{s \rightarrow s_f} \frac{d\delta_{\text{CSR}}}{ds} ds, \quad i = 1, 2. \quad (5)$$

Here δ_0 and δ_{CSR} are the initial energy deviation and the CSR-induced energy deviations, respectively. The integrals represent particle coordinate offsets, while their second-order moment reflects the emittance dilution caused by CSR. Using this integral analysis method, Venturini derived the condition for eliminating CSR-induced emittance growth, under the assumption of constant bunch length [35]:

$$\int R_{i6}^{s \rightarrow s_f} ds = 0, \quad i = 1, 2. \quad (6)$$

In contrast to the extensive research on suppressing CSR-induced emittance growth, relatively few studies have addressed the impact of CSR on the longitudinal phase space. Here, we apply the same integration method to the longitudinal phase space and expand the expression for the longitudinal coordinate of a particle with an initial relative energy deviation δ_0 to second order:

$$\begin{aligned}
\Delta z &\approx R_{56}\delta_0 + \int_{s_i}^{s_f} R_{56}^{s \rightarrow s_f} \frac{d\delta}{ds} ds + T_{566}\delta_0^2 + \int_{s_i}^{s_f} T_{566}^{s \rightarrow s_f} \frac{d(\delta^2)}{ds} ds \\
&= R_{56}\delta_0 + \int_{s_i}^{s_f} R_{56}^{s \rightarrow s_f} \frac{d\delta}{ds} ds + T_{566}\delta_0^2 + 2 \int_{s_i}^{s_f} T_{566}^{s \rightarrow s_f} \delta \frac{d(\delta)}{ds} ds \\
&= R_{56}\delta_0 + \int_{s_i}^{s_f} R_{56}^{s \rightarrow s_f} \frac{d(\delta_0 + \delta_{\text{CSR}})}{ds} ds + T_{566}\delta_0^2 + 2 \int_{s_i}^{s_f} T_{566}^{s \rightarrow s_f} (\delta_0 + \delta_{\text{CSR}}) \frac{d(\delta_0 + \delta_{\text{CSR}})}{ds} ds \\
&= \int_{s_i}^{s_f} R_{56}^{s \rightarrow s_f} \frac{d\delta_{\text{CSR}}}{ds} ds + 2 \int_{s_i}^{s_f} T_{566}^{s \rightarrow s_f} \delta_{\text{CSR}} \frac{d\delta_{\text{CSR}}}{ds} ds + \left(R_{56} + 2 \int_{s_i}^{s_f} T_{566}^{s \rightarrow s_f} \frac{d\delta_{\text{CSR}}}{ds} ds \right) \delta_0 + T_{566}\delta_0^2. \quad (7)
\end{aligned}$$

Here δ denotes the total energy deviation, δ_0 the initial energy deviation, and δ_{CSR} the energy deviation induced by CSR. In our analysis, we consider the regime $|\delta_0| < 0.1\%$ and assume that δ_{CSR} is independent of δ_0 . Under this assumption, the first two terms in the last line of Eq. (7) can be treated as constants with respect to δ_0 . We notice that, instead of R_{56} , the linear dependence of the longitudinal coordinate on the initial energy deviation can be described by an effective R_{56} , defined as

$$R_{56,\text{eff}} = R_{56} + 2 \int_{s_i}^{s_f} T_{566}^{s \rightarrow s_f} \frac{d\delta_{\text{CSR}}}{ds} ds. \quad (8)$$

The additional contribution to $R_{56,\text{eff}}$ originates from the composition of the second-order longitudinal transport term T_{566} with the CSR-induced energy variation accumulated along the beamline. As the energy deviation evolves continuously due to CSR emission, the quadratic longitudinal dispersion effectively feeds down to a linear term. This resembles the feed-down effect caused by sextupoles when the beam does not pass through their center. Misalignment can cause a feed-down effect [41], which means that a magnet of given order will also exhibit lower-order terms; a transversely displaced sextupole will give a quadrupole kick. However, this effect arises purely from CSR-induced energy offsets and can occur in the absence of sextupoles within the beamline. The same reasoning applies to T_{566} and U_{5666} , and this coupling can extend to higher-order terms, which are neglected here.

Similar modifications occur for R_{16} and R_{26} , meaning that both achromatic and isochronous conditions are CSR-dependent:

$$\begin{aligned}
R_{16,\text{eff}} &= R_{16} + 2 \int_{s_i}^{s_f} T_{166}^{s \rightarrow s_f} \frac{d\delta_{\text{CSR}}}{ds} ds, \\
R_{26,\text{eff}} &= R_{26} + 2 \int_{s_i}^{s_f} T_{266}^{s \rightarrow s_f} \frac{d\delta_{\text{CSR}}}{ds} ds. \quad (9)
\end{aligned}$$

Therefore, achieving effective isochronicity in the presence of CSR requires satisfying not only the conventional $R_{56} = 0$ but also nullifying the CSR-induced terms. While analytical insights can guide lattice design, full fidelity

requires numerical simulation due to the higher-order couplings and beam distribution complexity. In this work, we use these theoretical insights to inform the CSR-resilient merger lattice design.

III. LATTICE DESIGN

To numerically demonstrate the effectiveness of the proposed merging method, we designed two isochronous beamlines under a conceptual PWFA injector framework, as illustrated in Fig. 1. In this scenario, the driver and witness bunches are generated from two separate rf guns (typically producing ~ 100 A peak currents), independently accelerated in conventional rf linacs to different energies, and longitudinally compressed using magnetic chicanes to reach kiloampere-level peak currents. The two bunches are subsequently merged at moderate energies (hundreds of MeV) using the isochronous system proposed in this work. After merging, they are further accelerated to multi-GeV energies, during which the energy difference between the bunches can be exploited for compression before entering the PWFA stage. This overall framework is conceptually similar to the CEPC plasma injector design [12]. The present work focuses on the beam merging method itself, while techniques for further acceleration and modulation are discussed in other studies [12].

The choice of beam parameters follows the need to balance CSR suppression, charge preservation, and practical accelerator constraints. The driver bunch carries a charge of 5 nC and is accelerated to 400 MeV, while the witness bunch carries 1 nC at 200 MeV. These energies are chosen as a compromise between minimizing CSR-induced energy deviations—which scale as γ^{-1} —and avoiding the introduction of excessive energy spread to the final driver-witness double bunch. The energy difference also facilitates subsequent longitudinal compression of the merged beam. Each bunch has an rms length of 0.3 mm, an uncorrelated rms energy spread of 0.1%, and normalized emittances of 2 mm mrad (witness) and 10 mm mrad (driver), respectively, consistent with the parameters summarized in Table I. Both beams are assumed to have Gaussian longitudinal profiles truncated at $3\sigma_z$. For simplicity, the driver and witness bunches are

TABLE I. Parameters of the ELEGANT simulation.

Parameter	Witness	Driver	Unit
Bunch charge	1	5	nC
Bunch length	0.3	0.3	mm
rms energy spread	0.1	0.1	%
Normalized emittance	2	10	mm mrad
Beam energy	200	400	MeV

assumed to have same durations in this study, although this is not a fundamental requirement of the scheme.

The Twiss parameters of each bunch are treated as adjustable variables. This flexibility allows the CSR-induced emittance growth to be minimized according to the suppression condition mentioned in [38]. Practically, this corresponds to matching the beam envelope at the entrance to the optical response of the lattice, ensuring that the CSR kick at each dipole is optically compensated downstream.

The merging system design is based on quadruple bend achromat (QBA) [42]. This configuration is selected for its ability to suppress CSR-induced emittance growth while preserving achromaticity and parallel beam trajectories. This symmetry simplifies the dual-beamline layout and facilitates precise spatial and temporal alignment of the driver and witness bunches. The lattice configuration and the parameters of the driver and witness bunches are constrained by CSR effects.

Preliminary suppression of CSR effects can be realized through the combination of optical symmetry and small beta functions in the bending magnets. The symmetry of the QBA lattice ensures that the dispersion function and its derivative vanish at the entrance and exit of the section, thereby eliminating first-order chromatic distortions. In our design, each beamline consists of four dipoles and a sequence of quadrupole and sextupole magnets arranged symmetrically about the central plane. This configuration guarantees that the two beams emerge parallel to the incoming trajectory, simplifying downstream transport and recombination. The quadrupole magnets between the dipoles are tuned to control the betatron phase advance and to satisfy the desired R_{16} , R_{26} , and R_{56} conditions as given in Eq. (6). Two sextupoles are placed near the first and second quadrupoles, where the horizontal dispersion is relatively large. Their function is to compensate for second-order chromatic aberrations and to maintain isochronicity in the presence of CSR, as illustrated in Eq. (7).

In this study, it is assumed that the dipole magnet is a sector bending magnet with an arc length of 0.4 m and a bending angle of 20° for the witness beam and 10° for the driver beam, primarily constrained by the spatial layout of the beamline. The magnetic lengths of the quadrupole and sextupole magnets are both set to 0.2 m, and the drift between the last dipole and the adjacent sextupole is

designed to exceed 2.8 m, ensuring that the center-to-center distance between the nearest sextupoles in the two beamlines exceeds 0.48 m. This separation enables effective magnetic shielding to prevent fringe fields from one beamline from influencing the other.

IV. SIMULATION RESULTS

A. Performance of matrix-based design

To evaluate the necessity of CSR-tolerant optimization, we first consider a baseline isochronous design optimized without considering CSR effect. The corresponding lattice layout is shown in Fig. 2. In this scenario, the first- and second-order transport coefficients (R_{16} , R_{26} , R_{56} , and T_{566}) are minimized to satisfy achromatic and isochronous conditions.

When CSR are ignored in the simulation, this standard design performs well. For the witness bunch, the horizontal emittance increases from 2 to 2.027 mm mrad. For the driver bunch, the horizontal emittance increases from 10 to 10.94 mm mrad. The TOF jitter is successfully constrained within ± 2 fs, as demonstrated in Fig. 3.

However, when CSR is included in the tracking simulations, the performance of solution I degrades significantly. In particular, the linear correlation between energy deviation (δ) and TOF jitter increases due to the CSR-induced $R_{56,\text{eff}}$ modification discussed in Sec. II, pushing the TOF jitter beyond 4 fs for the witness bunch and 6 fs for the driver bunch. More critically, the CSR-induced emittance growth becomes severe. As summarized in Table II, the witness bunch horizontal emittance increases to 3.852 mm mrad, and the driver bunch horizontal emittance reaches 13.112 mm mrad.

These results demonstrate that although a matrix-based isochronous optimization can achieve excellent performance in the absence of collective effects, it is not robust when CSR is present. The observed degradation in both timing stability and emittance preservation originates from CSR-induced centroid shifts and effective dispersion modifications, which are not captured by a transport-matrix-only optimization strategy.

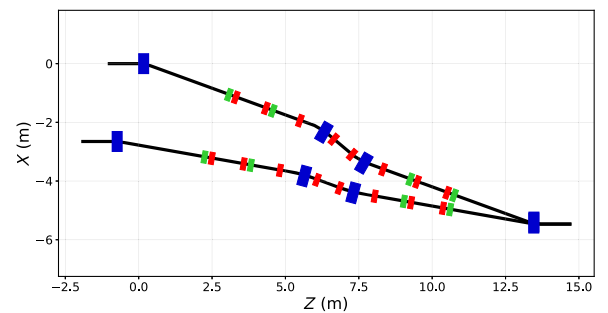


FIG. 2. Layout of the baseline design optimized without considering CSR effect. Blue rectangles are dipoles, red rectangles are quadrupoles, and green rectangles are sextupoles.

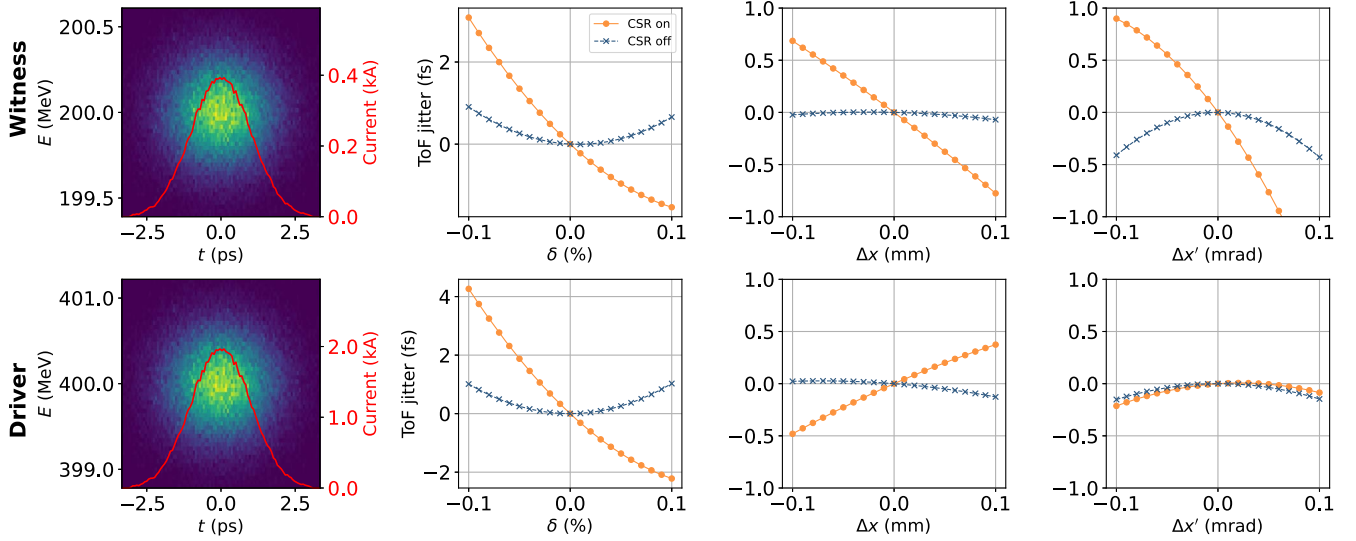


FIG. 3. Longitudinal phase spaces, current profiles, and time-of-flight jitters of the witness (top row) and driver (bottom rows) bunches under δ , x , and x' perturbations in solution I.

B. CSR-tolerant optimization and lattice performance

Motivated by the clear limitations of the matrix-based optimization discussed above, we now turn to a CSR-tolerant optimization strategy. Building upon the established QBA-based layout, numerical simulations and optimizations were performed. The beamlines for the witness and driver were optimized separately using the Elegant framework [31] with a multiobjective genetic algorithm (MOGA). The objective functions include the normalized emittance growth and the time-of-flight (TOF) jitter under perturbations of beam energy, transverse coordinates, and divergence. The incoming energy jitter was set to $\pm 0.1\%$, the transverse offsets were ± 0.1 mm, and the divergence jitter was ± 0.1 mrad for both driver and witness beams. Collective effects, including CSR and longitudinal space charge, were fully incorporated. From the resulting Pareto fronts for each beamline, a representative solution was selected that balances emittance preservation and timing stability for both bunches [43]. The corresponding lattice layout is shown in Fig. 4.

After selecting the representative solutions from the Pareto fronts, we evaluated the temporal stability of the optimized beamlines. Figure 5 summarizes the TOF jitter of

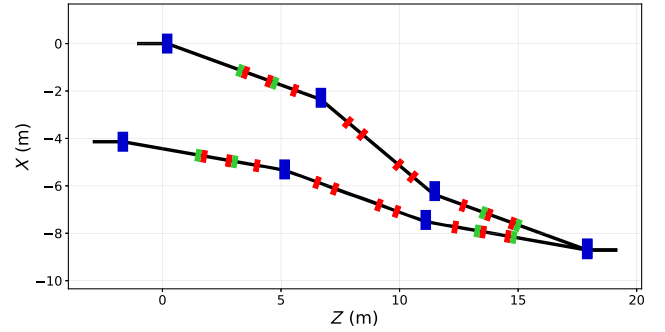


FIG. 4. Overview of the geometry of the two quadrupole bend achromats in the isochronous merging system. Blue rectangles are dipoles, red rectangles are quadrupoles, and green rectangles are sextupoles.

the witness and driver bunches under representative perturbations, including energy deviation (δ), initial transverse position offset (Δx), and divergence offset ($\Delta x'$). The figure also displays the corresponding longitudinal phase spaces and current profiles, showing peak currents of approximately 400 A for the witness and 2 kA for the driver.

TABLE II. Summary of emittance growth and transport matrix of solution I.

Parameter	Witness	Driver	Unit
Initial normalized emittance ϵ_{nx}	2.000	10.000	mm mrad
Final normalized emittance ϵ_{nx} without CSR	2.027	10.935	mm mrad
Final normalized emittance ϵ_{nx} with CSR	3.852	13.112	mm mrad
R_{16}	-2.745×10^{-6}	-4.153×10^{-6}	m
R_{26}	5.480×10^{-5}	9.590×10^{-5}	rad
R_{56}	4.836×10^{-5}	5.210×10^{-5}	m

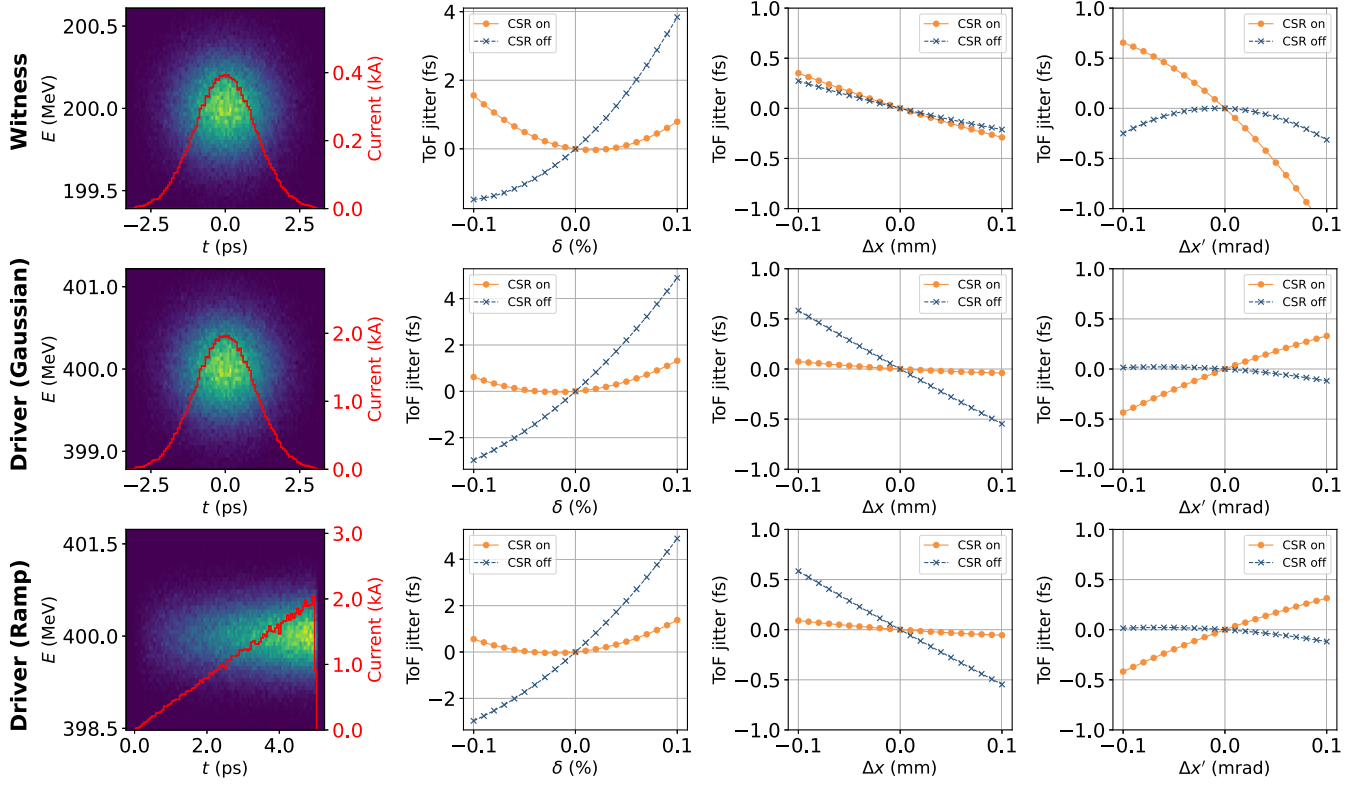


FIG. 5. Longitudinal phase spaces, current profiles, and time-of-flight jitters of the witness (top row) and driver (middle and bottom rows) bunches under δ , x , and x' perturbations in solution II.

Simulations with CSR enabled (orange circles) and disabled (blue crosses) clearly demonstrate that CSR introduces additional contributions to the isochronicity beyond the pure energy dependence, consistent with the theoretical analysis in Sec. II. These CSR-induced effects modify the TOF jitter profiles in all perturbation cases. Nevertheless, the optimized beamlines successfully constrain the TOF jitter within ± 2 fs, confirming that the optimization effectively suppresses timing fluctuations.

To further test the robustness of the design, we repeated the simulations using ramp-type current distributions

relevant for PWFA driver bunches, with a total charge of 5 nC and peak current maintained at 2 kA. The resulting TOF jitters remained nearly identical to those obtained with Gaussian bunches, indicating that the design performance is largely insensitive to the initial current profile.

The optimized beamlines exhibit excellent beam quality preservation, with normalized emittance growths of 0.105 mm mrad for the witness bunch and 0.072 mm mrad for the driver bunch in the x direction, well within the tolerance required for PWFA injection [27]. Table III summarizes the emittance growth and key transport matrix

TABLE III. Summary of emittance growth and transport matrix of solution II.

Parameter	Witness	Driver	Unit
Initial normalized emittance ϵ_{nx}	2.000	10.000	mm mrad
Final normalized emittance ϵ_{nx} without CSR	2.053	10.065	mm mrad
Final normalized emittance ϵ_{nx} with CSR	2.105	10.072	mm mrad
Final rms energy spread σ_δ	0.153	0.220	%
Final mean relative energy deviation C_δ	-1.852×10^{-3}	-3.287×10^{-3}	
R_{16}	8.634×10^{-5}	1.963×10^{-4}	m
R_{26}	7.291×10^{-4}	1.691×10^{-3}	rad
R_{56}	9.249×10^{-4}	1.214×10^{-3}	m
$R_{56,\text{eff}}$ computed from simulations with CSR	-1.160×10^{-4}	1.058×10^{-4}	m
$R_{56,\text{eff}}$ computed from Eq. (8)	1.195×10^{-5}	8.229×10^{-5}	m
T_{566}	3.537×10^{-1}	2.886×10^{-1}	m

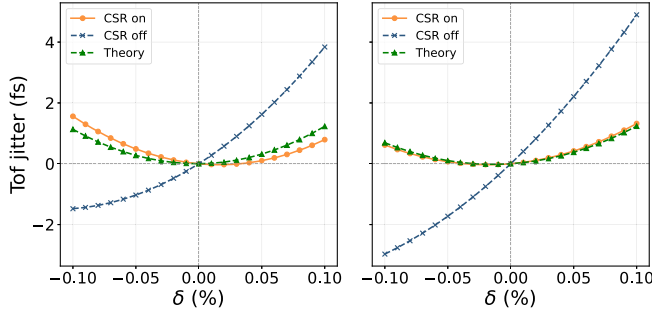


FIG. 6. TOF jitter as a function of energy deviation (δ) for the witness (left) and driver (right) bunches. Simulations with CSR enabled (orange circles) and disabled (blue crosses) are compared to the theoretical prediction (green triangle), incorporating a first-order CSR correction.

elements, including values directly obtained from matrix multiplication, from ELEGANT simulations with CSR enabled, and from the analytical expressions in Eq. (7). The close agreement among these values confirms the consistency between theoretical and numerical evaluations of the beam transport.

To further validate the theoretical model developed in Sec. II, the simulated TOF jitter is compared with the analytical prediction of Eq. (9), as shown in Fig. 6. The figure presents the TOF jitter as a function of energy deviation (δ) for both the witness and driver bunches, with CSR-enabled (orange circles) and CSR-disabled (blue crosses) results plotted alongside the theoretical curve (green triangles) incorporating the first-order CSR correction in Eq. (7). Excellent agreement is observed between the corrected theoretical prediction and the CSR-on simulation results, confirming the validity of the first-order model within the relevant parameter range. The remaining small discrepancies are attributed to higher-order CSR effects and feed-down contributions from off-axis trajectories. Overall, these results verify that the optimized design achieves both isochronicity and emittance preservation under realistic collective effects.

The transverse centroid (C_x) and divergence ($C_{x'}$) responses to energy deviation are shown in Fig. 7 for both the witness (top) and driver (bottom) beamlines. A clear global offset can be observed in both C_x and $C_{x'}$ when CSR is included, consistent with the discussion in Sec. II, where such centroid shifts were identified as the source of emittance growth through their second-order moments. In addition, the slope of the C_x - δ dependence exhibits a noticeable change, indicating a CSR-induced modification of the effective dispersion function. Despite these effects, the centroid jitter remains within $\pm 2 \mu\text{m}$ and the angular jitter within $\pm 2 \mu\text{rad}$, both well below the $10 \mu\text{m}$ PWFA alignment tolerance [27]. These results confirm that the optimized beamlines maintain excellent achromaticity and transverse stability, ensuring reliable wakefield excitation and efficient witness acceleration in

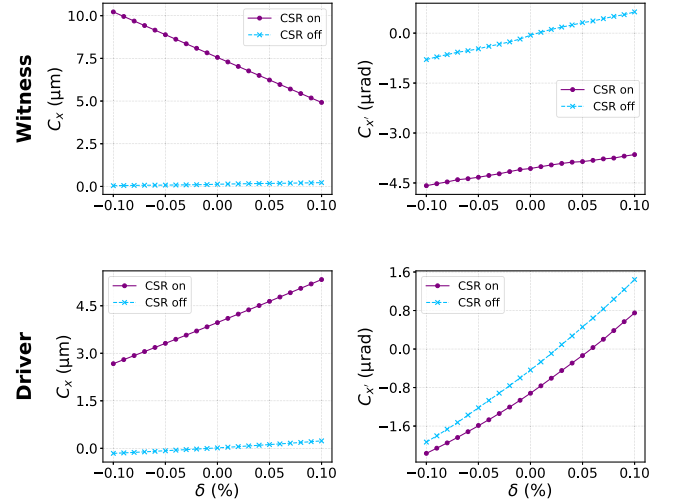


FIG. 7. Transverse centroid and divergence offsets at the beamline exit as functions of relative energy deviation (δ). The upper panel shows the witness bunch and the lower panel the driver bunch.

subsequent stages. In practical implementations, maintaining the required beam overlap may impose stringent timing and alignment tolerances. The fs-level timing jitter and micron-level alignment tolerances quoted in this work correspond to the specific parameter set considered here and should not be interpreted as general requirements for all PWFA-based accelerator systems.

To evaluate the applicability range of the optimized lattice, additional simulations were performed by varying the bunch charges while keeping the lattice parameters fixed. The witness charge was varied from 0.5 to 3 nC and the driver charge from 3 to 9 nC.

As the bunch charge increases, the CSR-induced energy deviation becomes stronger, leading to larger time-of-flight jitter for both beams, as shown in Fig. 8. This behavior reflects the charge dependence of the effective transport parameter $R_{56,\text{eff}}$ discussed in Sec. II. For sufficiently high charge, the residual jitter increases noticeably for both witness and driver beams.

The normalized emittance evolution is shown in Fig. 9. For both beams, the emittance growth increases with charge due to enhanced CSR effects. The witness beam exhibits stronger sensitivity, whereas the driver beam

TABLE IV. FWHM of the TOF jitter under 30 ppm magnet power supply errors.

Error source	Witness	Driver	Unit
Dipole (powered independently)	3.53	0.94	fs
Dipole (powered in series)	0.41	0.22	fs
Quadrupole	0.47	0.22	fs
Sextupole	1.52	0.8	as

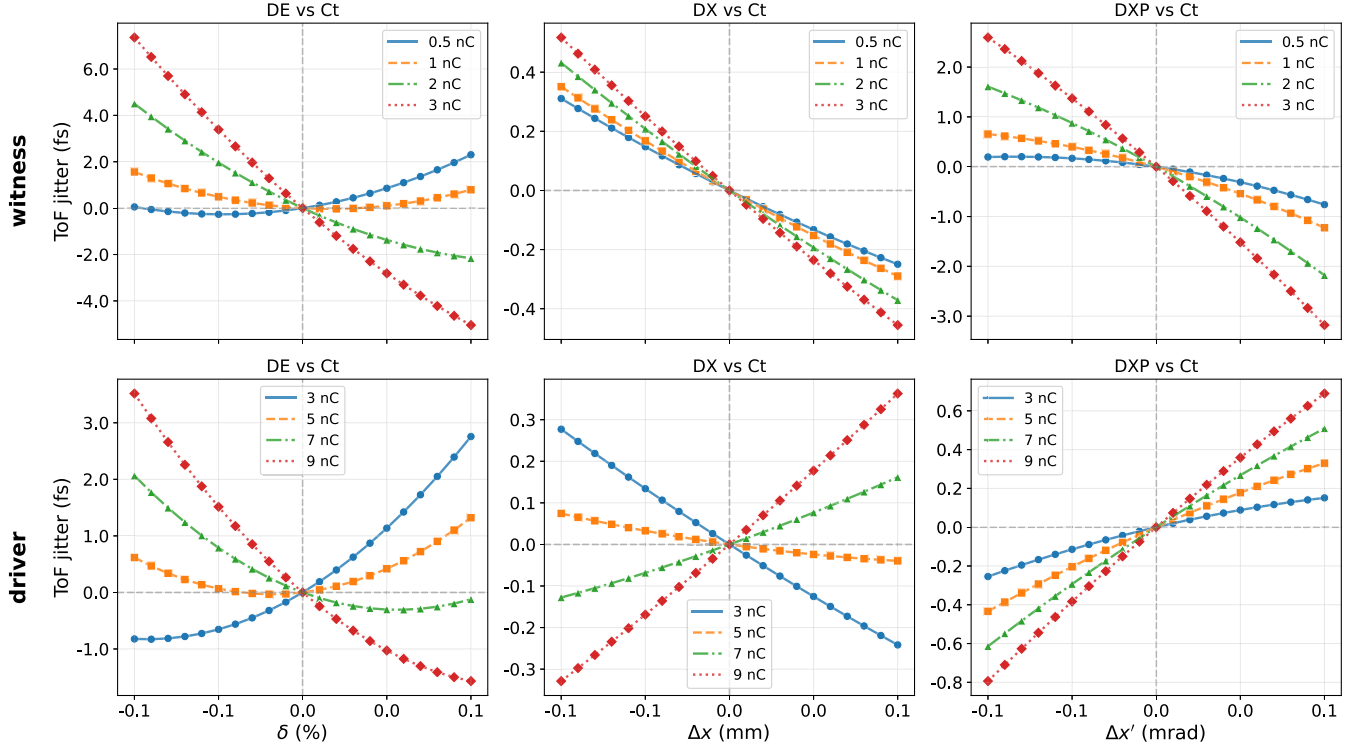


FIG. 8. Time-of-flight jitter of the witness (top) and driver (bottom) beams for different bunch charges with the lattice parameters fixed.

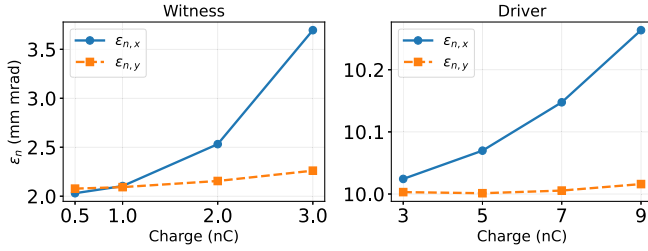


FIG. 9. Normalized transverse emittance of the witness and driver beams with different bunch charges.

remains comparatively less affected owing to its higher energy and smaller bending angles.

These results indicate that the proposed lattice effectively suppresses CSR-induced degradation within a given charge range, but the optimal compensation is charge dependent. For substantially different bunch charges, re-optimization of the lattice parameters is required. However, it should be noted that this optimization is primarily parametric and does not require layout adjustments, making it relatively straightforward.

C. Impact of magnet field fluctuations

The performance of the double-bunch beamline is sensitive to dynamic errors, primarily arising from temporal instabilities of the power supplies that drive the beamline

magnets. Such fluctuations can perturb the magnetic field strengths and alter the isochronicity of the transport system, leading to timing jitter between the witness and driver bunches.

Dynamic errors in the dipole magnets were first analyzed, as these elements play a crucial role in maintaining the isochronous condition. Power supply jitter levels of 30 ppm, representative of modern accelerator standards, were simulated over 1000 random error configurations. Two powering configurations of the four identical dipoles were compared: independent powering and series powering. As shown in Fig. 10, independent powering leads to full width at half maximum (FWHM) TOF jitters of 3.53 fs for the witness bunch and 0.94 fs for the driver bunch. In contrast, series powering synchronizes the magnetic field variations among all dipoles, preserving the beamline symmetry and reducing the jitter to 0.41 fs for the witness and 0.22 fs for the driver bunch. This subfemtosecond timing stability ensures precise control of the bunch separation, essential for effective wakefield excitation in PWFA.

We further evaluated the influence of quadrupole and sextupole power-supply fluctuations, both at 30 ppm. Quadrupole jitter introduces TOF variations of 0.47 fs (witness) and 0.22 fs (driver), while sextupole jitter results in smaller variations of 1.52 and 0.8 as, respectively. All these values, as presented in Table IV, remain well below 1 fs, confirming that the beamline exhibits excellent robustness against dynamic magnetic field instabilities.

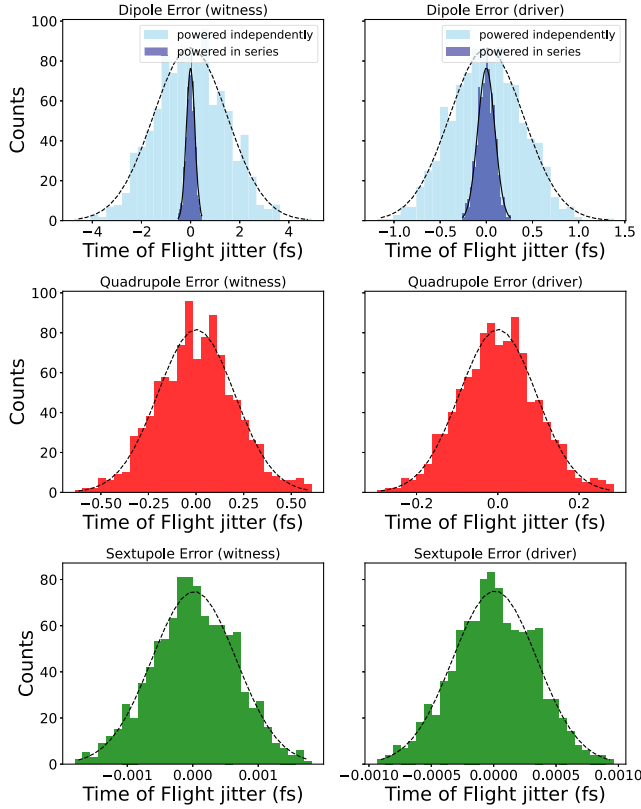


FIG. 10. Histogram of the arrival time jitter for the witness (left) and driver (right) bunches under 30 ppm dipole magnet power supply errors, across 1000 random error configurations.

Overall, the results demonstrate that the optimized double-bunch transport system maintains excellent temporal stability even under realistic magnet power-supply fluctuations. The strong suppression of timing jitter—down to the subfemtosecond level—validates the robustness of the QBA-based design and ensures reliable bunch synchronization for high-gradient PWFA experiments.

V. CONCLUSION

In this work, we have developed and demonstrated a novel double-bunch generation and transport scheme for beam-driven plasma wakefield acceleration, based on twin isochronous beamlines sharing a common dipole magnet. The design enables precise and stable combination of a high-charge driver (5 nC) and a lower-charge witness (1 nC) bunch with femtosecond-level temporal synchronization.

By incorporating CSR effects into an extended isochronicity framework, we have revealed a CSR-mediated modification to the transport matrix and established a self-consistent theoretical model describing its impact on timing and emittance. Multiobjective optimization using the ELEGANT-MOGA workflow yields a CSR-resilient lattice that simultaneously minimizes emittance growth and time-of-flight jitter. The optimized design maintains

femtosecond arrival-time stability under realistic power-supply fluctuations, confirming its robustness against dynamic magnetic errors. These results provide a validated approach for synchronized high-charge double-bunch delivery in PWFA injector systems.

While this work has demonstrated the beam-merging and transport process at moderate beam energies (hundreds of MeV), the proposed beam-merging concept provides a broader framework that can be further developed in several directions. Future studies will investigate the acceleration and compression of the merged double bunches in complete PWFA injector systems and examine its applicability to other scenarios, including direct PWFA injection after merging and electron-positron beam merging. The CSR-tolerant isochronous transport methodology developed here may also be relevant to beam transport between PWFA stages, where synchronization and beam quality preservation are essential. Experimental verification and more detailed CSR modeling will be pursued to further evaluate the performance and operational robustness of the proposed scheme.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX: THE LATTICE PARAMETERS

This appendix provides the detailed lattice definition of the isochronous merging system shown in Fig. 11. The magnet layout and ordering in the table follow exactly the sequence illustrated in Fig. 11. The parameters of the elements are presented in Table V. Here, D0 denotes the drift section between a sextupole and its adjacent quadrupole.

The witness and driver beamlines share the same magnetic layout and ordering, while the corresponding magnet strengths and drift lengths differ slightly to account for their different beam parameters. Both beamlines are designed to be centrosymmetric with respect to the midpoint of the lattice.

The current profiles of the driver and witness beams shown in Fig. 11 are adopted from Ref. [27], where they were optimized for plasma wakefield acceleration. They are included here to illustrate that the present lattice design is intended to support PWFA-oriented beam parameters. These profiles are not used as input distributions in the beam dynamics studies presented in the main text.

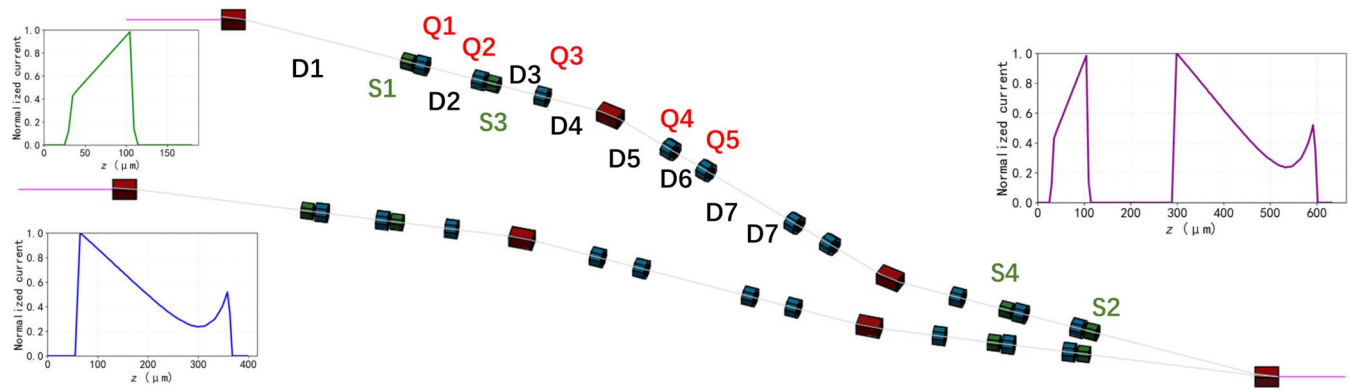


FIG. 11. The lattice structure of the isochronous merging system and the magnet layout.

TABLE V. Parameters of the lattice.

Parameters	Witness	Driver	Unit
Quadrupole length	0.2	0.2	m
Q1 strength	4.437	4.443	m ⁻²
Q2 strength	-6.001	-6.062	m ⁻²
Q3 strength	3.426	3.395	m ⁻²
Q4 strength	-4.527	-4.598	m ⁻²
Q5 strength	3.581	3.586	m ⁻²
Sextupole length	0.2	0.2	m
S1 strength	9.323	13.249	m ⁻³
S2 strength	-9.323	-13.249	m ⁻³
S3 strength	5.952	0.869	m ⁻³
S4 strength	-5.952	-0.869	m ⁻³
D1 length	2.884	2.885	m
D2 length	0.853	0.859	m
D3 length	0.695	0.750	m
D4 length	0.951	0.927	m
D5 length	1.024	1.079	m
D6 length	0.594	0.594	m
D7 length	0.888	0.890	m
D0 length	0.05	0.05	m

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