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An External Injected Driver-witness Bunch Pair Merge System with Femtosecond Timescale Jitter

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Beam-driven plasma-wakefield accelerators (PWFA) rely on the precise energy transfer from a leading drive bunch to a trailing witness bunch, with the separation between the two typically on the order of 100 fs. To achieve high transformer ratios and maintain long-distance acceleration, it is crucial to precisely control this separation. We propose and demonstrate a novel system that merges two bunches from separate beamlines using a common dipole magnet. Through optimized parameter sets, we show that the energy jitter-induced separation time jitter can be reduced to femtosecond levels, while accounting for coherent synchrotron radiation (CSR) and longitudinal space charge (LSC) effects. Furthermore, we address emittance growth during beam merging, incorporating design strategies to mitigate its impact and preserve beam quality. Our system is compatible with other longitudinal modulation methods and can utilize the initial energy difference between bunches for further beam compression in high-energy accelerators.

INTRODUCTION

To ensure efficient energy transfer in Beam-driven plasma-wakefield accelerators (PWFA), the double-bunch structure must meet three key requirements:

- precise temporal separation of around 100 fs with fs-level tof jitter control
- longitudinal alignment of both bunches along the same axis
- controlled emittance to minimize growth, especially from CSR.

Existing methods to generate such a structure include splitting a single bunch with a mask, which causes emittance degradation and charge loss, and generating two bunches at the photocathode , which faces challenges in achieving high charge and precise timing.

In our scheme, two bunches with energies of 200 MeV and 400 MeV are transported through two separate beamlines into our designed system and are ultimately merged into a double-bunch structure via a single dipole magnet, which avoids charge loss and enables high-charge (nC-level) bunch generation.

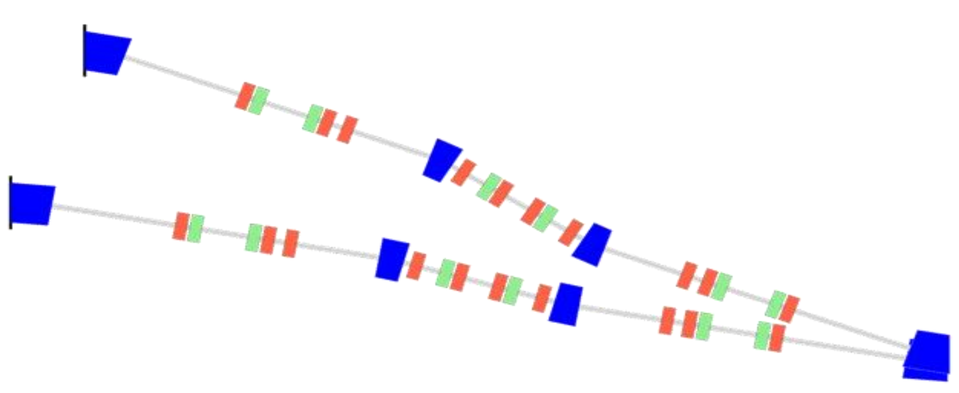

Figure 1:layout of the merge system

SYSTEM DESIGN AND PRINCIPLES

To reach our goal, we have to take energy variation induced by CSR and LSC into consideration. By introducing the energy variation terms into the transport matrices, we notice that the higher order transport matrix element can contribute to residual dispersions.

$$\Delta x = R_{16}\delta \quad \Delta x' = R_{26}\delta \quad \Delta z = R_{56}\delta$$

Emittance growth (red box) — Modified Dispersions (blue box)

$$\Delta x = \int_{s_1}^{s_f} R_{16}^{s\to s_f}\frac{d\delta}{ds}ds + \left(R_{16} + 2\int_{s_i}^{s_f} T_{166}^{s\to s_f}\frac{d\delta}{ds}ds\right)\delta$$

$$\Delta x' = \int_{s_i}^{s_f} R_{26}^{s\to s_f}\frac{d\delta}{ds}ds + \left(R_{26} + 2\int_{s_i}^{s_f} T_{266}^{s\to s_f}\frac{d\delta ds}{ds}\right)\delta$$

$$\Delta z = \int_{s_i}^{s_f} R_{56}^{s\to s_f}\frac{d\delta}{ds}ds + \left(R_{56} + 2\int_{s_i}^{s_f} T_{566}^{s\to s_f}\frac{d\delta}{ds}ds\right)\delta$$

Equation 1:Modified transportation equations

Table 1: Witness/Driver parameters

Energy	200/400 MeV
Charge	1/5 nC
Beam length	0.3/0.3 mm
Energy spread(rms)	0.1/0.1 %
Emittance(normalized)	20/20 μm

OPTIMIZATION RESULT

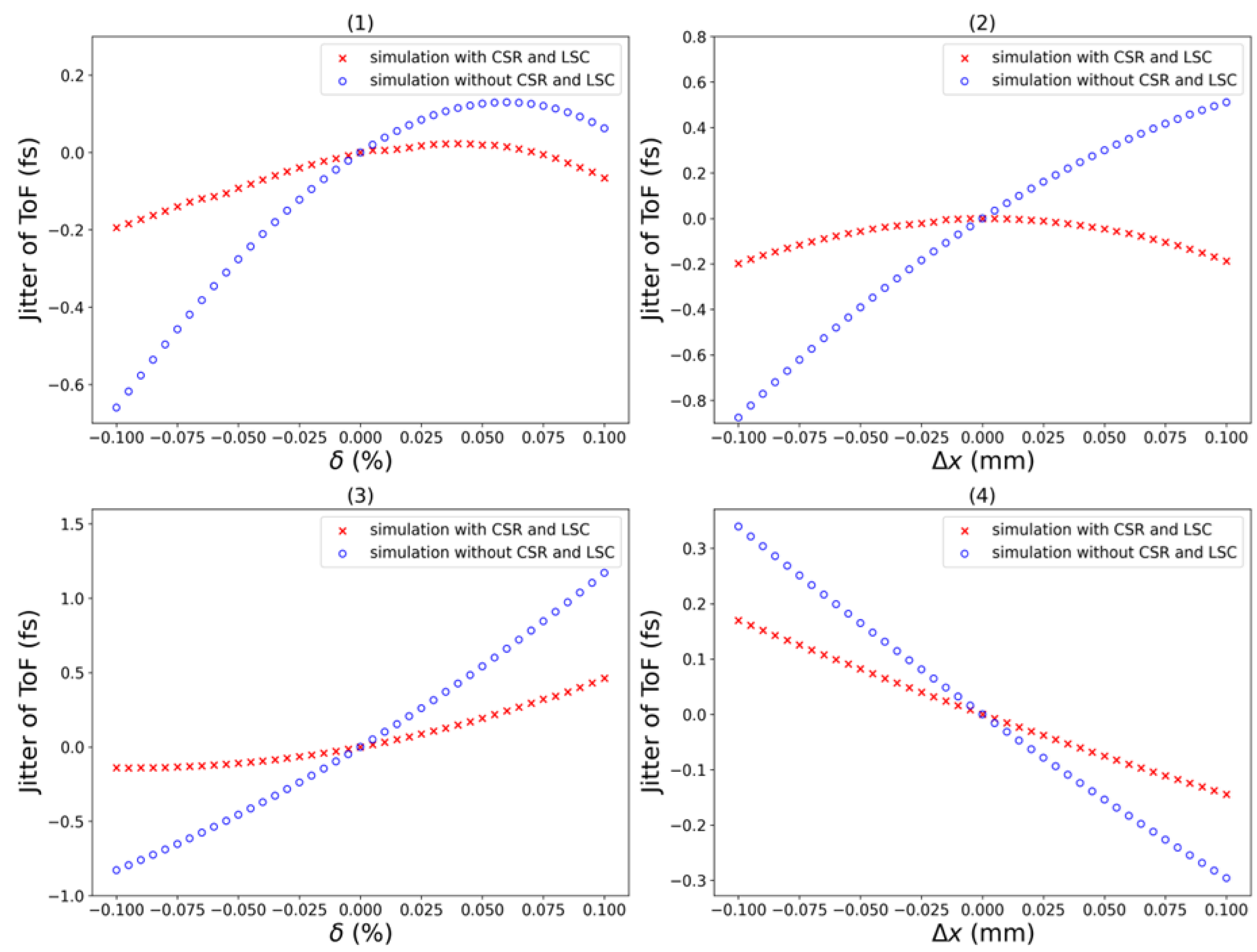

Figure 2: tof jitter induced by energy jitter and initial x offset

By simulation of ELEGANT, we optimize both beamlines, controlling the tof jitter below 1fs with 0.1% energy jitter and 0.1 mm transverse offset at the entrance. Also the effect of the magnetic field error caused by power supply of dipoles are considered.

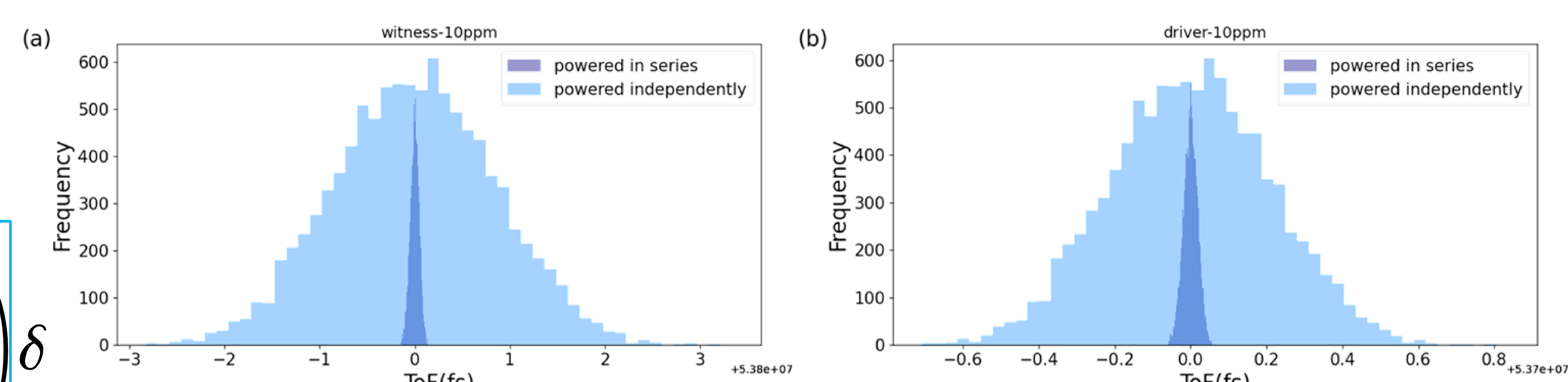

Figure 3: tof jitter induced by power supply error of the dipoles

CONCLUSION

This study propose a design which effectively merges two high-charge bunches with energies of 100 MeV and 200 MeV, achieving femtosecond-level timing stability and minimal emittance growth, making it a highly suitable solution for advanced PWFA applications and compatible with other longitudinal modulation methods.

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