Transport and Focusing of Ultrashort Electron Bunches

Pavel Gajdos[1,2], Miroslav Krus[1]

[1] *Institute of Plasma Physics of the Czech Academy of Sciences*

[2] *Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague*

Since its proposal in 1979, laser wakefield acceleration (LWFA) has advanced significantly. Techniques such as laser pulse shaping, plasma waveguides, and injection mechanisms have enabled the production of high-quality, high-energy electron bunches in compact setups. Current facilities can generate near-monoenergetic, low-emittance, or very high-energy (up to 10 GeV [1]) bunches, though achieving all these properties simultaneously remains challenging.

Multi-stage acceleration provides a pathway to even higher energies. However, due to strong wakefield forces and small beam sizes, LWFA-accelerated bunches are highly divergent, spreading rapidly after exiting the accelerator. Efficient refocusing is essential for injection into subsequent stages. Transport can be achieved using multipole magnets or plasma lenses. Since LWFA's key advantage is its high acceleration gradient, the transport line must remain compact to avoid degrading performance. Plasma lenses, with their shorter focal lengths, offer promise, though only a small fraction of bunch charge has been successfully transported to a second stage using this approach.

While tight transverse focusing is possible even with some energy spread, preserving the ultrashort bunch length is more difficult. Large or divergent beams experience geometric dispersion—outer particles take longer paths than central ones, lengthening even monoenergetic bunches. To reduce this effect, the transport line should be positioned as close as possible to the accelerator's exit. Off-axis focusing using multiple lenses may help mitigate this dispersion.

This work investigates methods to reduce geometric dispersion and improve transport efficiency by optimizing transport line placement and using multi-lens focusing schemes.

After exiting the acceleration stage, an LWFA bunch expands transversely and longitudinally. Transverse expansion also contributes to longitudinal elongation. Using a simple geometric formula, one can estimate the time-of-flight (TOF) difference between central and outer particles. Assuming a point-like bunch at the start, the TOF difference from divergence alone is:

$$\Delta t = \frac{l}{v}\left(\frac{1}{\cos\alpha} - 1\right),$$

where l is the propagation distance, v is the particle velocity, and α is the divergence half-angle. For instance, a 100 MeV bunch with 2 mrad divergence over 50 cm produces a temporal spread of ~3.3 fs. Given LWFA bunches often show several mrad divergence, transport lines must be placed close to the acceleration stage—either to refocus or to reduce divergence. The latter has been demonstrated using passive plasma lenses that create secondary wakefields in lower-density gas [2],[3].

The same TOF equation applies to focusing with radially symmetric lenses, such as passive or active plasma lenses. To maintain the compactness of laser accelerators, the focal length of the transport line should be minimized, necessitating strong focusing fields. Plasma lenses are well-suited for this purpose due to their ability to sustain extremely high fields. However, a very short focal length can also lead to bunch lengthening, especially for bunches that have already undergone significant transverse expansion. Additionally, focusing dense electron bunches with plasma lenses can increase the energy spread due to self-induced wakefields, which may ultimately degrade the bunch quality.

Central focusing of the beam invariably leads to bunch elongation. In this work, we investigate the effect of off-axis focusing as a potential method to mitigate this issue. The concept involves using multiple lenses, but instead of aligning the bunch centrally through each lens, we introduce an intentional offset.

To compensate for the offset introduced by the first lens, a second lens is introduced in a symmetrically off-axis configuration. In this two-lens setup, the optimal position of the second lens is offset in the opposite direction relative to the first. The optimal configuration was determined by minimizing the maximum and minimum trajectory deviations across all particles in the bunch. This optimization was performed using transfer matrix calculations under the paraxial approximation, modeling quadrupole magnets and drift spaces.

Given that the bunch duration at the focal spot decreases significantly with increasing focal length, our objective was to identify a configuration that yields a shorter bunch length than central focusing (using one or more lenses), within a practical focal distance—approximately 1 meter or less. To simplify the analysis and reduce computational demands, the study was restricted to a single transverse plane. The spacing between lenses was fixed, and a uniform strength parameter was applied throughout. Two configurations were investigated: one using alternating focusing and defocusing quadrupoles, designed to

suppress beam expansion in the orthogonal plane; and the other using focusing-only matrices, modeling each lens as a FODO triplet or plasma lens, which provides symmetric focusing in both transverse planes. In both cases, the first lens was initially offset.
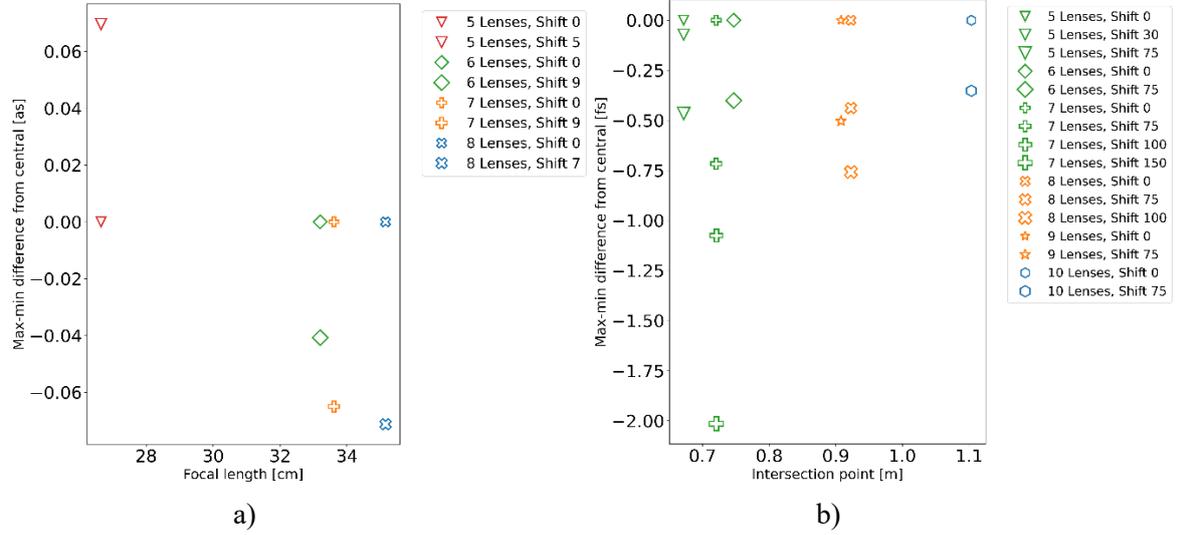

Figure 1. Max-min trajectory difference (bunch duration) between off-axis and central focusing for a) short offsets range and only focusing lenses and b) for larger offsets and alternating focusing, Shift in the label means the offset of the first lens. The bunch duration varies from 4 to 9 fs.

   Results are presented in Figure 1. The initial beam had a diameter of 2 mm (a) and 4 mm (b) to ensure measurable TOF differences. The figure compares TOF spread for off-axis and central focusing across various lens counts and offsets. Larger offsets in (b) yield shorter final bunch durations with off-axis focusing. With finer lens placement, even greater compression may be achievable.

   In practical systems, electron optics magnets have limited apertures, typically only a few millimeters, restricting usable offsets. The large-offset case primarily illustrates that off-axis focusing can slightly mitigate geometric dispersion.

   Assuming a 100 MeV monochromatic beam allowed us to isolate path length differences. This is reasonable since LWFA routinely generates quasi-monochromatic bunches at several hundred MeV. Beams with significant energy spread would require sextupoles and spatial chirping for focal spot optimization.

   We also examined active plasma lenses using 2D PIC Smilei simulations, modeling the lens as an electron stream traveling with the bunch. These lenses, typically up to 500 μm in diameter [4], were tested with an initial beam radius of 60 μm. At this scale, geometric dispersion had limited impact. Figure 2 shows evolution of bunch parameters—size, emittance, energy, and energy spread.
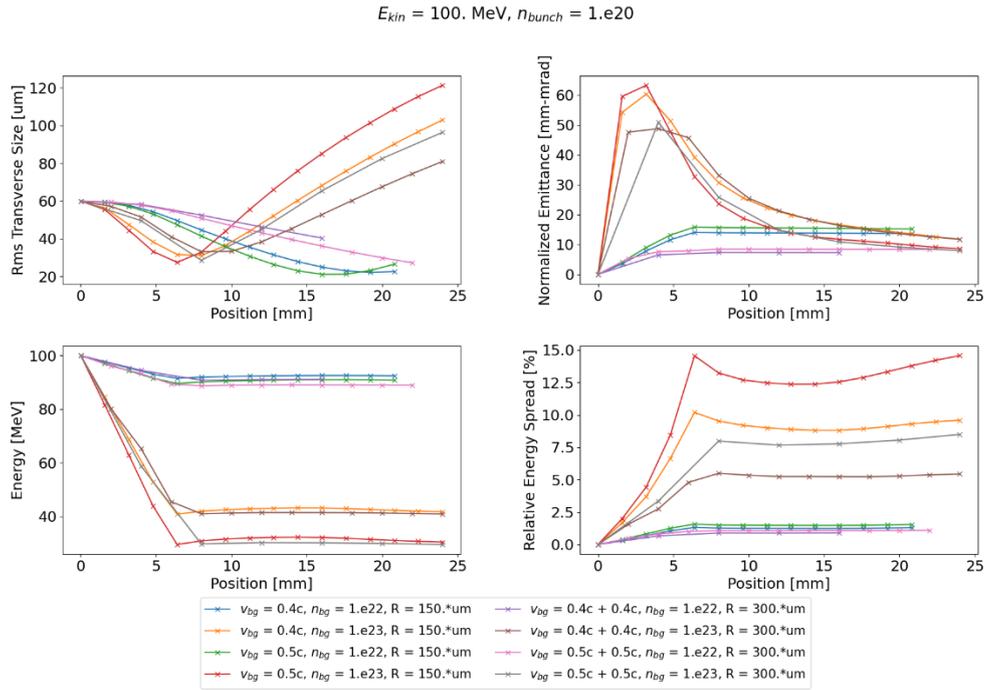
Figure 2. The evolution of the bunch parameters for off-axis (3+3 mm) and central (6 mm) focusing. E_{kin} is the kinetic energy of bunch electrons, n_{bunch} its density, v_{bg} is the speed of background electrons forming a plasma lens, n_{bg} is their density and R is the plasma lens radius.

The issue of geometrical dispersion cannot be easily corrected using off-axis, at least not for offset small enough to fit dimensions of convectional electron optic magnets. However, it might be useful to decrease the loss of energy, energy spread and emittance.

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