Parametric Tolerance Study of Trojan Horse plasma wakefield acceleration scheme

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Abstract

A promising scheme for plasma wakefield acceleration is the hybrid plasma acceleration mechanism, which is experimentally connected to world-wide programs at various accelerator facilities. This scheme may lead to extremely high quality electron bunches, which can be used to drive ultrabright light sources such as free electron lasers. The big challenge for plasma acceleration is to produce electron bunches with high quality in terms of low emittance, energy spread and high brightness. To overcome this challenge, the Trojan Horse scheme [1,2,3,4,5] is used for production of designer electron beams.

This work explores the Trojan Horse mechanism in a parametric study by variation of the injector laser pulse by intensity a_0, spot size w_0 and relative spatiotemporal synchronization and alignment. These parameters define output electron witness beam parameters and its quality. This sensitivity study shows a high robustness of the scheme, which is promising for a wider key prospect of the approach, namely the development of compact plasma accelerators to produce electron beams with unprecedented emittance and brightness in order to power free-electron lasers.

Introduction

The concept of Trojan Horse is based on a compact electron bunch propagating through an underdense plasma to set up the plasma blowout at low ionization threshold medium (LIT) such as hydrogen. A synchronized laser pulse is then focused at a higher ionization threshold medium (HIT) such as helium to release electrons directly inside the blowout. After that, these electrons are trapped and compressed to produce a compact witness bunch, which is then accelerated to gain energy with high tunablility.

An important part of plasma wakefield acceleration is ensuring the stability of the driver beam propagation inside the blowout by applying the beam matching formula ($r^2_{\text{matched}} = \varepsilon_n * \text{sqrt}(2) / (\omega_p/c) / \text{sqrt}(\gamma p)$) through its propagated beam with a constant radius [6]. This means that the electron driver beam transverse forces (pointing to the outside) are in equilibrium with the transverse forces produced by the electron-ion charge separation in the plasma (pointing inwards).

In this work we fixed the background of the blowout and changed the plasma photocathode laser pulse intensity and spot size, before applying the matching condition and after it was applied. This is an important step towards a full sensitivity analysis, which will be performed in the future. We start by changing w_0 and fixing a_0, as shown in Figure 1, the evolution of the transverse emittance, brightness and mean energy during propagation are plotted.

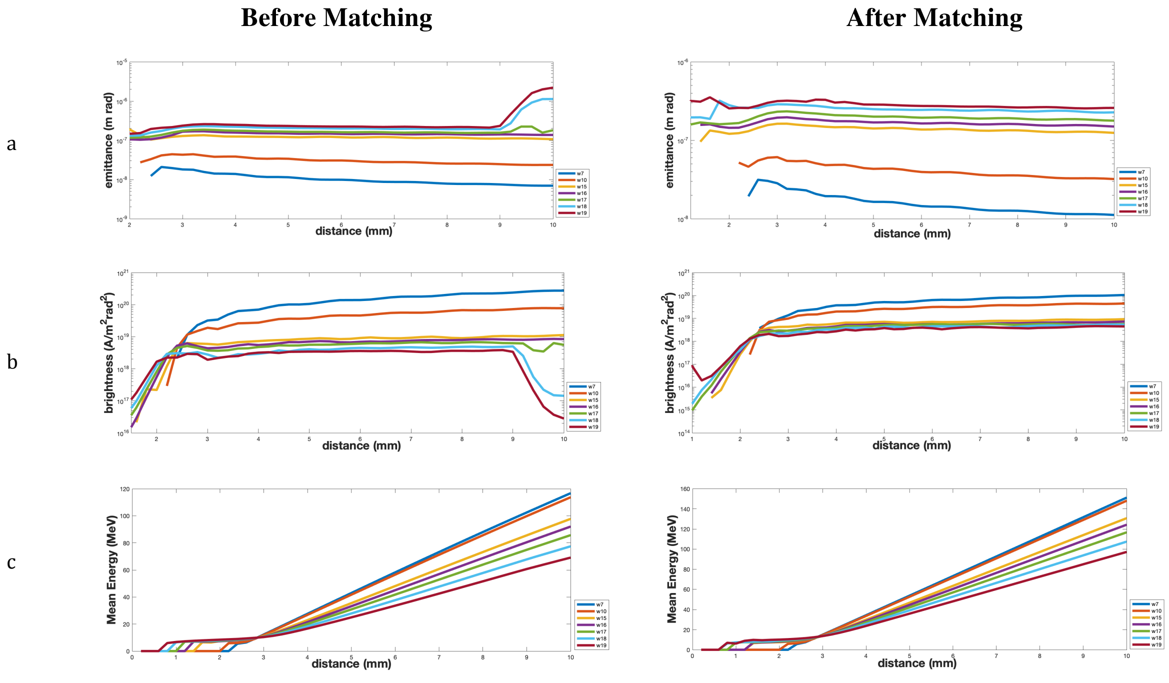


Figure 1: Evolution of the witness bunch parameters during propagation when w_0 is changed and a_0 is fixed: (a) Transverse emittance, (b) Brightness, (c) Mean energy. Where, the left side represents the scans before matching and the right side represents the scans after matching.

From the scans, emittance growth with increasing spot size is observed in the both cases from $w_0 = 7\mu m$ to $w_0 = 19\mu m$, but after matching the values are close together. On the otherhand, the witness beam has high mean energy after matching.

Figure 2 illustrates the underdense photocathode process based on particle-in-cell (PIC) simulations with VSim code [7]. The driver generates the plasma blowout within the low ionization threshold medium (LIT), and the laser pulse releases He electrons around its focus with ultralow emittance. These electrons are then trapped and create a witness bunch with high quality at the end of the blowout, thus profiting from maximized energy gain.

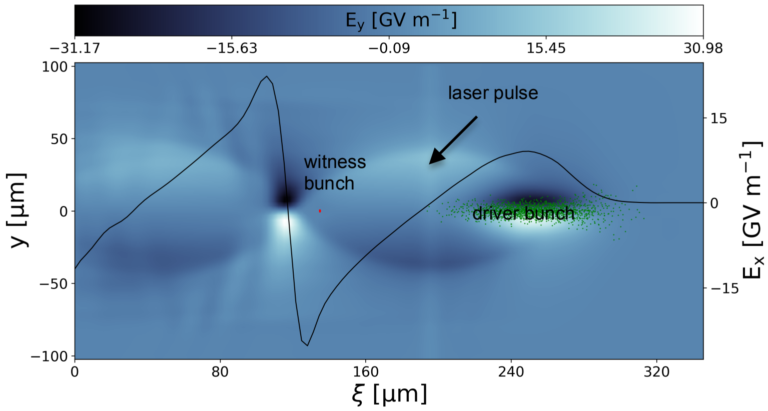
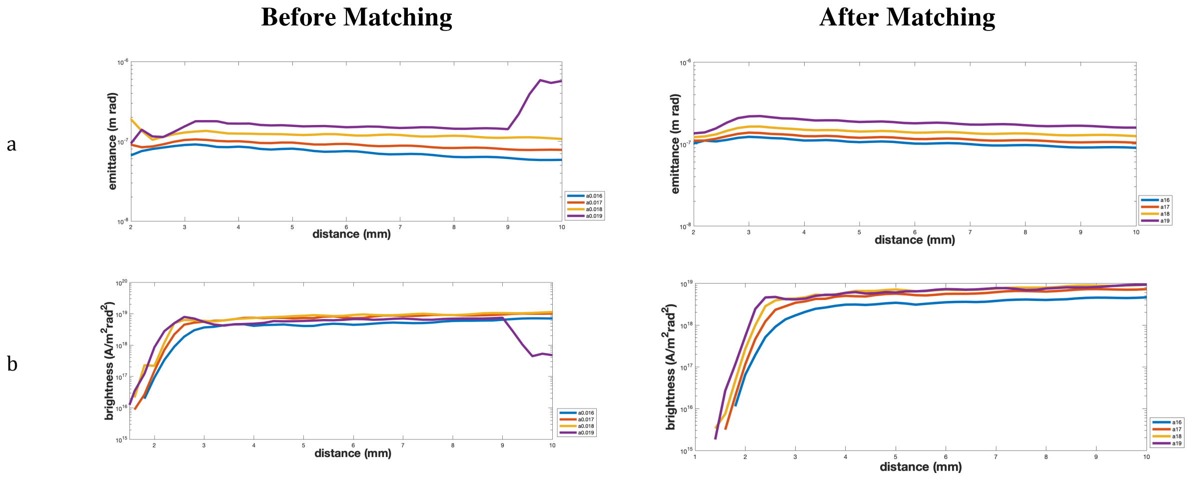


Figure 2: PIC simulation of the release, trapping and acceleration of He electrons inside the plasma blowout, with a_0=0.018 and w_0=7 µm (after matching). The He electrons (red) are tunnel ionised by the laser pulse resulting in the formation of the witness bunch, which undergoes compression and further acceleration.

After that, a_0 was changed and w_0 was fixed. These changes have a profound impact on emittance and brightness and are experimental knobs, which can be used to tune the obtainable electron beam quality. The brightness increases as the laser intensity increases from a_0 = 0.016 to a_0 = 0.019 due to a strongly increased current caused by higher charge being released as laser intensity increases. Nevertheless, the emittance and mean energy decrease as laser intensity increases. This is depicted in Figure 3 for both cases.



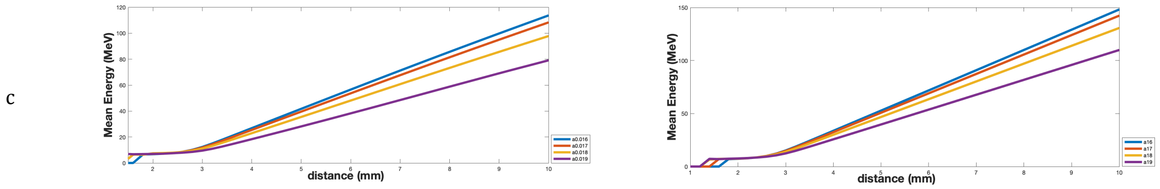


Figure 3: Evolution of the witness bunch parameters during propagation when a_0 is changed and w_0 is fixed: (a) Transverse emittance, (b) Brightness, (c) Mean energy. Where, the left side represents the scans before matching and the right side the scans after matching.

Conclusion

The laser pulse must be adjusted accurately to produce a high quality witness bunch which strongly depends on the properties of the laser pulse such as laser spot size and laser intensity. Furthermore, the beam matching is a critical part in accelerators because it minimizes the instabilities inside the plasma and increases the mean energy of the witness bunch. These considerations guide the experimental parameter range which is required to realize future experimental implementations, with major long-term applications such as a plasma-based free-electron-laser via ultrahigh brightness beams produced through Trojan Horse technique.

Acknowledgments

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