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Characterization of the preplasma scale length using time-resolved reflection spectroscopy

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Current research on laser-driven proton acceleration is focusing on the interaction of relativistic-intensity laser pulses with sub-micrometer-thick targets, aiming for advanced acceleration mechanisms. Despite very positive estimates delivered by numerical simulations, a significant discrepancy exists between theory and experimental realization so far, motivating further investigations. The predicted mechanisms rely on well-defined plasma conditions at the time of the maximum laser intensity. In the laboratory, target pre-heating and pre-expansion occur in a mostly uncontrolled manner, because of the non-perfect temporal profile of the laser pulse. This causes an uncertainty in the preplasma conditions. During the interaction of the laser with the plasma, the critical plasma density reflects a part of the laser pulse. The Doppler shift of the reflected light, due to the motion of the critical plasma surface during the holeboring or plasma expansion phases, modulates the incoming laser spectrum. The interplay between these effects is intimately related to the plasma density gradient in the vicinity of the reflection point as well as the plasma temperature. A shallow plasma gradient will favor holeboring, leading to an increased acceleration into the plasma and higher holeboring velocity, whereas a steep plasma gradient will reduce this dynamic. We have performed 2D simulations using the particle-in-cell code EPOCH, with parameters as close as possible to the experiment, including a pre-expanded target. We varied the scale length and temperature of the plasma and monitored its effect on the reflected laser pulse. With decreasing scale-length below 1 µm, a transition from a red shifted to a blue shifted spectrum at even higher gradients is visible. To explain this behavior, we developed an analytical description of the holeboring velocity in the presence of a plasma density gradient, which is in very good agreement with numerical simulations. To verify these findings, an experimental campaign was conducted at the PHELIX facility, which utilized an improvement of the temporal contrast to achieve different preplasma conditions. The experiment shows that the behavior is similar to the simulation results and the analytical holeboring description allows the determination of the preplasma scale length, picoseconds prior to the arrival of the peak intensity. We believe that this method can deliver some estimates on the preplasma expansion on a sub-micrometer scale, a spatial range that is challenging for other experimental methods like shadowgraphy or transverse interferometry.

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