Probing the dynamics of under-dense plasma expansion with ultra-short electron bunches

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An ultra-short, intense laser pulse propagating through an under-dense plasma produces a wakefield behind it, with the electrons oscillating around their mean position in a uniform ion background. In this picture, the ions are generally considered immobile and do not contribute to the dynamics. When the wakefield becomes strongly non-linear and/or electrons are injected into the wakefield at the back of the bubble, a strong electron density spike is formed. This starts to attract the ions to the centre of the wakefield where the electrons and the ions interact with each other, redistributing and dissipating energy from the plasma.

To study the fields that are formed during this dynamic, we used an ultrashort, timed electron probe beam created by another laser wakefield accelerator. After passing through the electro-magnetic fields of the plasma, the probe beam gains a local transverse momentum. As the probe beam undergoes a drift, the structure of the fields through which it passed through are imprinted on its spatial intensity modulations. These intensity modulations are then imaged outside the chamber with a scintillating screen.

The experiment consisted of two parts, one in which the probe beam was transversely incident onto the under-dense plasma and the second in which the probe electrons were co-propagating with the laser. Particle-in-cell simulations revealed a strong density spike in the electron density at the back of each of the bubbles of the wakefield. This starts to attract the ions towards the axis creating a strong increase in the ion density, called an ion filament. The ion density builds up over a few plasma periods after which the ion filament then coulomb explodes, with the ions closer to the axis moving faster than the ones off-axis. This leads to a further pileup of ions off-axis which again undergoes coulomb explosion. Such an interplay occurs multiple times weakening the ion and electron density spikes and dissipating energy from the non-linear wakefield. A similar observation was predicted in simulations by K. I. Popov et. al.[1].

We present the first experimental results, obtained with the electron probe, showing these electron and ion dynamics in an under-dense plasma. Our experiments, along with new simulations, reveal the formation of a strong non-linear wakefield behind the laser which is surrounded by a linear wakefield. The linear wakefield, since it does not interact strongly with the ion background, is observed to have a longer lifetime. This governs the electron probe images obtained when a transverse probe is used on a time scale of a few picoseconds after the laser. On the other hand, using an electron probe that co-propagates with the laser, we observe oscillations in the transverse momentum of the probe beam on pico-second time scales. This characteristic behavior suggests the initial evidence of the coulomb explosion of the ion filament formed behind the wakefield, providing a direct measurement of the ion dynamics.

References

[1] K. I. Popov, W. Rozmus, V. Yu. Bychenkov, N. Naseri, C. E. Capjack, and A. V. Brantov, Phys. Rev. Lett. **105**, 195002 (2010)