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ABSTRACT The interactions of ultra-intense laser pulses with underdense plasmas are studied in a new regime in which the longitudinal spatial extent of the pulse duration is close to both the laser focal spot size and the plasma wavelength.

The interaction of ultrashort, high-intensity laser pulses with underdense plasmas is of fundamental interest, relevant to relativistic optics, laser and plasma based accelerators and radiation sources, and ICF fast ignition scheme. However, most previous studies used laser pulse durations with their longitudinal spatial extent much greater than the focal spot size or the plasma wavelength. We will present results in a new regime, in which the pulse's longitudinal spatial extent is close to, or shorter than, both the focal spot size and the plasma wavelength. The results include the generation of a resonant, longitudinal laser wakefield, the observation of relativistic filamentation, and the emission of megaelectronvolt (MeV) electrons which are strongly correlated to the relativistic filamentation.

The experiments were performed with a multi-terawatt, ultrashort Ti:sapphire laser system that delivered 10 Hz pulses at 810 nm [2]. The pulse shape and beam quality of the output beam were well characterized. Usually, the pulse duration was 29 fs in full width of maximum (FWHM) with 93% laser energy contained from ±38 fs to the peak. At ±200 fs from the peak, the intensity contrast was 10^{-5}. Under optimized condition, the pulse duration could be as short as 24 fs. With an f/4.5, 45-degree off-axis metallic parabola, the 4-cm-diamter beam was focused into a spot of r_0= 8 μm, containing 50% laser energy inside the first minimum. A supersonic gas jet was used to produce a flat-top-profile gas plume, which was found necessary for the high-intensity laser interactions with underdense plasmas.

A physics picture is introduced to unify the two concepts, relativistic self-focusing and relativistic filamentation. The theoretically predicted filament size is given by $4\pi c/\omega_p a_0$ [1]. If the laser focal spot size is r_0, the necessary condition for relativistic filamentation is given by $4\pi c/\omega_p a_0 \tilde{<} 2r_0$, where "~" applies to relativistic self-focusing. Note that relativistic self-focusing is the special case of relativistic filamentation.

The evolution from relativistic self-focusing to relativistic filamentation is observed from energy transmission measurement and optical microscopic imaging [3]. It is found that with increasing laser power, the laser energy transmission loss becomes larger. An inflection point of the transmission loss occurs at incident laser power P · P_c, where P_c is the power for relativistic self-focusing. When P~5P_c, the transmission loss becomes apparent. The apparent transmission loss is verified and caused by the growth of relativistic filamentation, which scatters the laser beam out of its vacuum propagation angle.

Along with the growth of relativistic filamentation, MeV electrons are observed. The electrons are emitted as a collimated beam in the forward direction. It is interesting to note that, possibly due to the filamentation, the electron beam has a divergence angle of only 1^0 in FWHM, the narrowest ever observed from a laser-plasma generated MeV-electron beam. A mechanism has recently been proposed for electron acceleration by a propagating short ultraintense laser pulse [4], which may be the physical cause for the strong correlation of the MeV electron emission to the filamentation process.

An important issue of the interaction studies is the generation of a large-amplitude, resonant laser wakefield driven by the ultrashort pulse. Different from previous wakefield results that the transverse wakefield was dominant, the one-dimensional resonant wakefield is explored in this work. The latter means that the longitudinal wakefield is dominant. Experimental results indicate density resonance, which is consistent with theoretical predictions for a one-dimensional resonant laser wakefield. The wakefield amplitude and the duration are measured. Some new features are observed. The details will be presented.

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