Thomson Scattering Imaging From Ultrashort Ultraintense Laser Interaction With Gas

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Abstract—**Laser–plasma acceleration can provide acceleration gradients which are thousands of times stronger than conventional electron accelerators. The laser propagation length is a crucial parameter that must be extended to achieve high-energy electrons. Here, we show that color images of the laser–plasma interaction region taken from the direction perpendicular to the polarization plane are a powerful tool to discriminate between Thomson scattering and plasma self-emission, leading to a precise measurement of the propagation length.**

Index Terms—**Plasma accelerators, plasma diagnostics, plasma waves, power.**

THE LASER WAKEFIELD ACCELERATOR (LWFA) [1] is one of the most promising techniques for the acceleration of electron bunches that takes advantage of the high electric fields supported by electron plasma waves. In the LWFA, the electrons trapped in the plasma wave are accelerated to the phase velocity of the wave that can be very close to the speed of light. Recent experiments [2], [6], [7] and simulations [3] show that, in the so-called bubble regime of the LWFA, quasi-monoenergetic electron bunches can be accelerated from the background population of electrons up to high (> 100 MeV) energies.

In general, in laser–plasma acceleration experiments, the measurement and the control of the propagation length of the focused laser are crucial to determine the ultimate acceleration gradient to achieve high-energy electrons. Depending on the laser intensity, several mechanisms can give rise to the scattering of radiation in the optical domain and can be used to follow the propagation of the laser pulse in the gas. At moderate laser intensities, the so-called Thomson scattering gives rise to laser radiation emitted in the direction perpendicular to the polarization of the laser electromagnetic wave. At higher laser intensities, nonlinear mechanisms arising from laser-driven instabilities like the stimulated Raman scattering [4] can account for the additional significant scattering of laser light. Here, we focus on the moderate intensity regime where the Thomson scattered radiation is dominant. In this regime, the motion of plasma electrons will move in the direction of the oscillating laser electric field, resulting in electromagnetic dipole radiation. The scattering can be described in terms of the emission coefficient ε, where $\varepsilon\ dt\ dV\ dW\ d\lambda$ is the energy spectral density scattered by a volume element dV in time dt into solid angle dW between wavelengths λ and $\lambda + d\lambda$. In our case, with the collection optics placed perpendicularly to the polarization field, the emission coefficient is

$$\varepsilon = \frac{\pi\sigma}{2} I n_e$$

where σ is the Thomson differential cross section, n_e is the electron density, and I is the incident laser flux. This result simply shows that the Thomson scattering provides combined information on the laser intensity and electron density. When knowledge on the plasma density can be derived independently, for example, from the plasma interferometry, Thomson scattering can be used to derive information on the laser intensity.

Here, we show the results of Thomson scattering imaging of a laser–plasma acceleration experiment in which a 120-mJ 65-fs FWHM duration laser pulse was focused onto a 4-mm-wide and 1.2-mm-thick gas jet, consisting of N_2 at a backing pressure of up to 50 bar. Several diagnostics were used to study the laser–target interaction and the accelerated electrons as described in Fig. 1. A full account of the experiment can be found elsewhere [5]. Thomson scattering was set up to study the propagation of the laser pulse through the gas and the plasma formation via ionization. An F/10 achromatic doublet was used

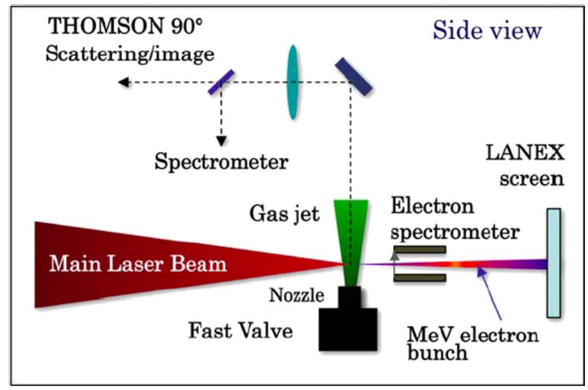

Fig. 1. Schematic setup used for detection of Thomson scattered radiation in a laser–plasma acceleration experiment.

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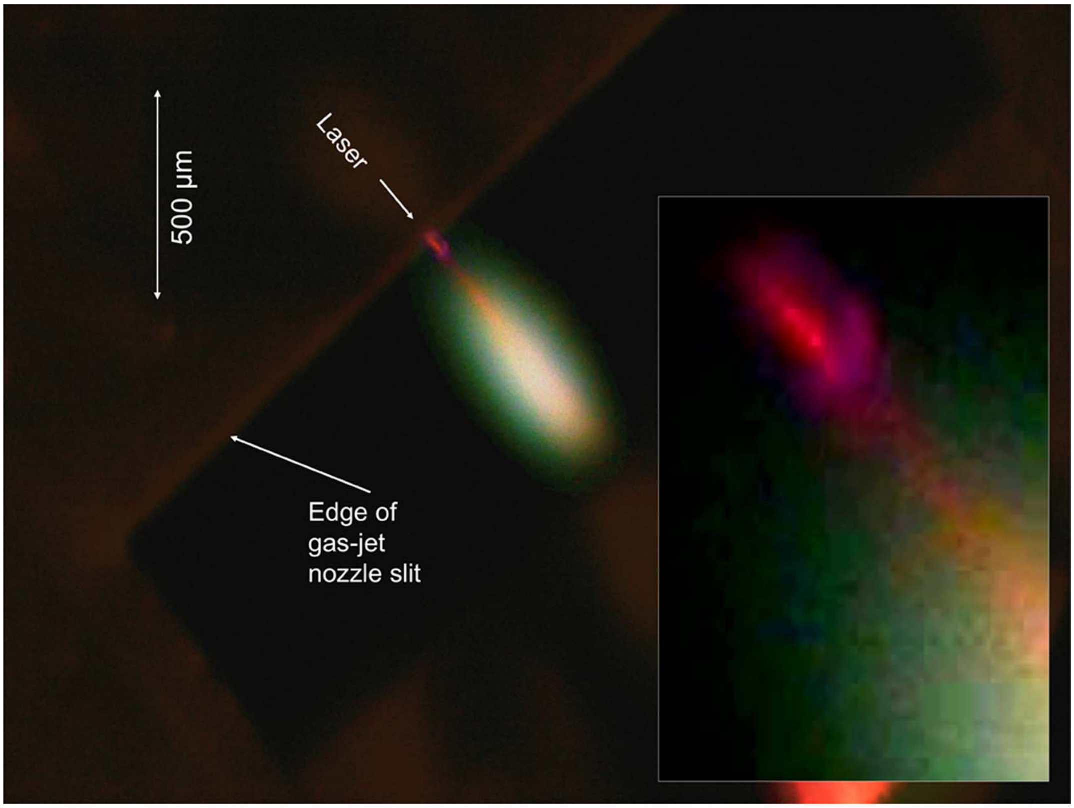

Fig. 2. Typical top-view image of the gas-jet nozzle obtained by the Thomson scattering diagnostic channel showing the main features of the interaction. The waist of the laser beam is placed on the edge of the gas jet where Thomson scattering radiation is clearly visible (red in color image). Beyond that point, the laser beam expands, and the emission visible in the image is dominated by white light plasma self-emission. The insert in the top-right side of the image shows the magnified region of Thomson scattered radiation.

to produce a 10× magnified image of the interaction region. Monochrome images of the plasma with appropriate filters are customarily used to discriminate between different sources of optical emission. In our case, a color CCD detection system was used instead.

Fig. 2 shows a typical Thomson image of the entire interaction area showing the nozzle, the interaction region, and the plasma emission. According to this image, the laser pulse propagates over a channel of more than 200 μm long showing longitudinal spatial modulations of approximately 15-μm scale length, most likely due to oscillating self-focusing [5]. Beyond that point, the laser beam expands, and the emission visible in the image is dominated by plasma self-emission. According to the image of Fig. 2, the length of the channel is approximately twice the depth of focus (Rayleigh length) of 100 μm expected for the focusing optics used in our experiment. This observation suggests that laser pulse channeling is taking place which significantly extends the length of the interaction region. Also visible in the magnified insert of Fig. 2 is the detailed structure of the Thomson scattering emission along the laser propagation direction. Images like the one shown in Fig. 2, obtained using a color CCD detector, clearly show that the different contributions to the emission from the laser–plasma interaction region can be easily detected and identified.

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