news & views

PLASMA OPTICS

Reflections off a relativistic mirror

High-order harmonics of laser pulses yield spectral components with shorter wavelength and duration and tighter focus than the original pulse. Precise spatiotemporal characterization of this radiation from a relativistic plasma mirror is relevant for ultrafast science.

Laszlo Veisz

When matter is irradiated with a high-intensity laser pulse, high-order harmonic generation takes place, creating multiples of the fundamental laser wavelength. In this way, the wavelength gets shorter and shorter, typically reaching the extreme ultraviolet regime (124 nm–10 nm) — possibly even the X-ray regime (10 nm–10 pm). The overall spectral width is also multiplied and, as the process is coherent, supports a much shorter pulse duration in the time domain, reaching the attosecond timescale. In gaseous media, this process is used to generate the shortest electromagnetic pulses possible so far. But high-order harmonics can also be produced by irradiating plasma surfaces with intense lasers[1]. This significantly different process provides higher pulse energies in a more compact setup. However, any application requires a precise characterization of these pulses, which is a challenging task — especially in a plasma. Writing in *Nature Physics*, Ludovic Chopineau and colleagues now report that they have measured the spatial and temporal properties of attosecond pulse trains generated under different conditions on plasma surfaces[2].

When a solid surface is irradiated with a laser pulse with an intensity above 10^{18} W cm^{-2}, the solid is ionized, generating a high-density plasma. The plasma electrons oscillate in the peak field of the laser with velocities near the speed of light in vacuum, which means that the plasma is relativistic. At the same time, it reflects the laser pulse in the specular direction similar to a metal surface, acting as a so-called plasma mirror. However, the nonlinear motion of the electrons leads to a mirror that oscillates with relativistic velocity and periodically Doppler shifts the laser spectrum, thus resulting in high-order harmonic generation. Accordingly, the reflected radiation including the harmonics is spectrally much broader and supports shorter pulse duration down to the 100 attosecond range.

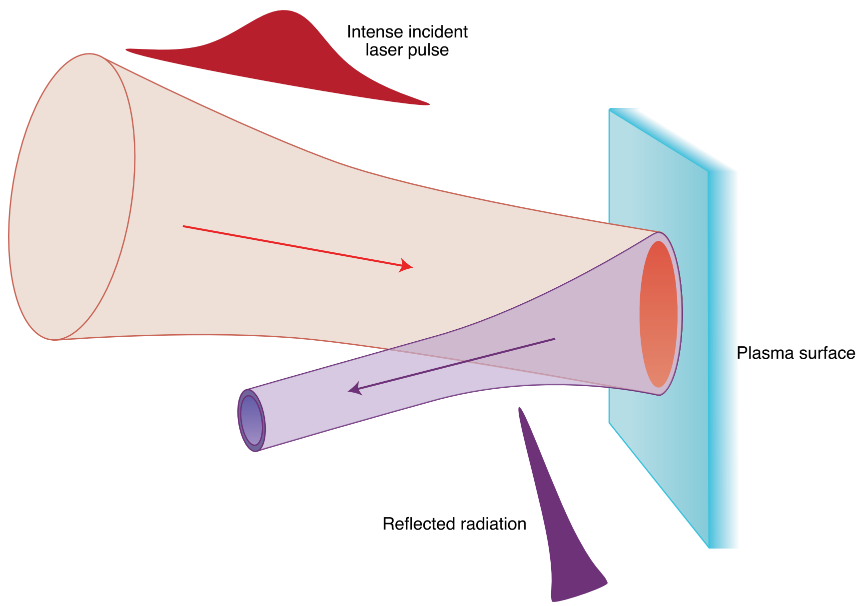

Fig. 1 | Reflection of an ultra-intense laser pulse from a relativistic plasma mirror. Due to the high-order harmonic generation process and the denting of the plasma surface by light pressure, the laser pulse becomes shorter in time and gets focused to a smaller focal spot than the incident laser pulse. The intensity is enhanced significantly — by a factor of up to 1,000 as simulated in ref. [2] — opening up an exciting potential application to approach the Schwinger limit. A detailed spatiotemporal characterization of the reflected pulses supports this intensity increase[2].

Although such experiments typically utilize conventional lasers with pulse durations of tens of femtoseconds (or longer ones), after spectrally filtering out the lowest harmonic(s), the reflection generates an attosecond pulse train in the time domain. Isolated pulses produced by intense few-cycle laser pulses have also been observed recently[3].

Various techniques allow measurements of pulses in time based on nonlinear optical processes in the visible and near-infrared spectral range, such as second harmonic generation. But these methods are not readily available in the extreme ultraviolet and X-ray regimes, especially with the low energies of the pulses from high-order harmonic generation. Harmonics from non-relativistic plasmas were characterized via autocorrelation[4], where two time-delayed replicas of the pulse generate a nonlinear signal when they overlap, thus providing information about the temporal extension. The spatial properties of high-order harmonic generation from plasma surfaces were studied with ptychography[5], a lensless microscopic imaging technique.

Ptychography works as follows. A small portion of a microscopic object is irradiated by light and the angular distribution of scattered radiation is measured. This is then repeated many times by shifting the object a little to irradiate different but partially overlapping areas. An algorithm reconstructs the spatial amplitude and phase of the object and the irradiating beam from the diffraction patterns. However, neither a detailed temporal measurement nor a relativistic source characterization has so far been realized using any of these techniques.

Chopineau and colleagues report a striking extension of ptychography, which they call dynamical ptychography, to measure the spatial as well as temporal properties of the reflected radiation. This is achieved by utilizing a weak perturbation beam with second harmonic frequency near the intense main beam that generates the attosecond pulses. The interaction between the two beams produces a known running interference pattern that influences the angular properties of the reflected radiation at different wavelengths in a way that provides information also about the temporal dimension.

With dynamical ptychography, Chopineau and colleagues managed to overcome previous limitations: they characterized a relativistic plasma mirror source and obtained for a relativistic case a temporal train of attosecond pulses with a duration of 450 attoseconds that is further focused in space after the generation.

Although the technique is very powerful, it determines the spatial properties only in one dimension. However, it can be extended in principle to two dimensions, as is discussed by Chopineau and colleagues. Another limitation is that it is only applicable at the position of the harmonic generation and does not give information on what happens after additional optics or filters. Furthermore, it assumes that all pulses in a train are identical, but it would work well to characterize an isolated attosecond pulse.

Apart from this immediate use, this work opens up a potential application of plasma mirrors in the more distant future. As the laser focus has a radially decreasing intensity from its centre, the associated light pressure pushes the plasma differently in and the plasma mirror surface becomes dented. This focuses the reflected radiation to a smaller focal size than that of the original laser pulse. An ultra-intense laser pulse reflected from a plasma mirror is thus shorter and gets focused to a smaller focal spot (Fig. 1), which leads to a significant increase in intensity[6]. This may enable approaching the Schwinger limit requiring intensities of the order of 10^{29} W cm^{-2}, where electron–positron pairs are produced by the laser in vacuum, or test other fundamental predictions of quantum electrodynamics[7,8]. ❐

Laszlo Veisz ✉
Department of Physics, Umea University, Umea, Sweden.
✉*e-mail: laszlo.veisz@umu.se*

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Competing interests

The author declares no competing interests.

SQUEEZED VIBRATIONS

More speed out of the quantum gate

Quantum gates on trapped ions may be quicker and more reliable owing to squeezing of their vibrational motion. A threefold drop in operation time shows potential for applications in quantum technologies.

Klaus Mølmer

Ion-trap quantum computers use the vibrational mode of atomic ions to mediate interactions between qubits stored in their internal electronic states[1]. This coupling is key to achieving fast and reliable quantum gate performance, but implementing the protocol with strong enough interactions is an ongoing challenge. Now, writing in *Nature Physics*, Shaun C. Burd and colleagues report that they have achieved a more than threefold reduction in the gate time needed to produce a maximally entangled Bell state in a trapped-ion system[2]. To do so, they applied a periodic modulation of the trapping forces, which led to squeezing — and antisqueezing — of the external position and momentum degrees of freedom, in turn modifying their coupling to the internal qubit states.

Using modulation of physical parameters to amplify the dynamics of a physical system has a long history. For classical oscillators, for example, the mechanical vibrations under double-frequency driving were theoretically investigated by Lord Rayleigh[3]. The process has favourable noise properties, giving rise to the parametric amplifiers introduced for (classical) electronic signals in the 1950s.

For quantum systems, a particle must occupy a Gaussian-shaped wave function to attain the equality sign in Heisenberg's uncertainty relation for position and momentum. These wave functions include the ground state and coherent states of a harmonic oscillator, all of which have equal uncertainty, and squeezed states, which have different uncertainty in these variables. The latter can be achieved by perturbing a harmonic oscillator Hamiltonian with a modulation of the confinement potential. That perturbation, when modulated at twice the original harmonic trap frequency, couples the states separated by two quanta of energy, and hence can efficiently squeeze the state of the oscillator. Squeezing of quantum systems has many applications, including the noiseless parametric amplification of the response of quantum sensors to external influences, which has been used in the detection of gravitational waves[4].

Along with the idea of noiseless signal amplification, it has been proposed more recently that squeezing can also be employed to amplify the coherent coupling of field or mechanical oscillators to other quantum systems[5–7]. The strength with which a physical observable couples to the oscillator position can be rescaled with respect to a squeezed position variable, thus allowing one to explore the strong interaction regimes of the coupling.

In a special implementation with bichromatic fields[8], the position and momentum phase space variables of a vibrational eigenmode of the trapped ions