Effect of relativistically intense laser pulses on magnetically confined fusion plasmas

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Abstract. In search for more accurate, robust and reliable methods for plasma diagnostics and control in magnetically confined fusion reactors, we study the properties and dynamic evolution of plasma wake channels produced by relativistically intense laser pulses, which are capable of expelling all electrons in their path, carving out a positively charged cavity. Scaled experiments performed with the J-KAREN-P laser [1] show the formation of a plasma channel that is several times longer than the laser's Rayleigh length and whose life time is projected to exceed 100 nanoseconds in a cold low-density gas ($\lesssim 10^{14}\,\mathrm{cm}^{-3}$). Relativistic particle-in-cell simulations are used to study such wake channels under tokamak conditions. Here, we present a brief overview of the results obtained so far, showing long-lived wake channels in the cold plasma limit, their insensitivity with respect to the laser wavelength [2], the emission of characteristic THz radiation in the magnetized case, and preliminary results concerning the effect of thermal motion, which becomes important on the nanosecond scale in a multi-keV fusion plasma.

1. Introduction

Existing methods for diagnostics and control are still insufficient to deal with the various kinds of instabilities and collective dynamics that occur in magnetically confined fusion plasmas, and this issue may have a negative impact on the ITER and DEMO projects. Using scaled laser experiments and numerical simulations, we are investigating whether short pulses (ps-fs) of a high power laser (TW-PW) may be used to address this high-priority issue. The object of interest is the electron-free positively charged plasma wake channel that is carved out by a laser pulse with relativistic intensity, which is achieved when the normalized amplitude of the laser satisfies $a_0 \sim 1$ [3]. Using the relativistic particle-in-cell (PIC) codes EPOCH [4] and REMP [5], we simulate the long-time evolution of such wake channels in the presence of a strong magnetic field ($\sim 2\,\mathrm{T}$) and a high temperature (multi-keV) as is typical for present-day tokamaks, where our predictions could be tested with existing high power laser technology.

2. Real laser channels in unmagnetized cold gas

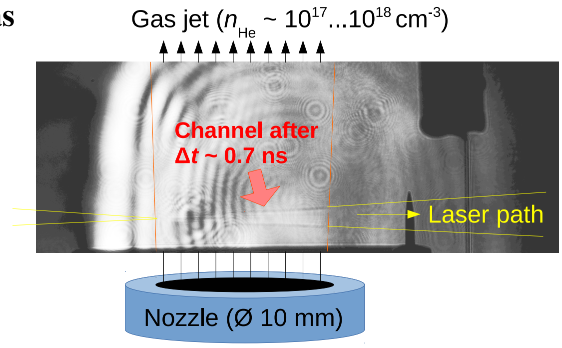

Figure 1: *Plasma channel produced in a low-density He gas jet during laser wakefield acceleration red experiments using the J-KAREN-P laser [1] in 2018. Parameters: wavelength* $\lambda_{\rm las} \sim 0.8\,\mu$m, *energy* $W_{\rm las} \sim 10$–$15\,$J, *pulse length* $\tau_{\rm pulse} \gtrsim 40\,$fs, *focal spot diameter* $d_{\rm foc} \sim 12\,\mu$m, *normalized amplitude* $a_{0,{\rm foc}} \sim 6$ *(vacuum focus, Strehl ratio* ~ 0.3*), gas pressure* 0.2–0.5 MPa. *(Note: The circular fringes should be ignored.)*

Figure 1 shows a snapshot of a shadowgraph taken about 0.7 ns after the passing of an ultra-relativistic laser pulse. Being sensitive to the second derivative of the refractive index, the shadow shows the boundaries of the plasma channel across the 10 mm wide gas jet that the laser has crossed. The contrast is quite low since these shots were performed with a relatively low gas density on the order of 10^{17}–$10^{18}\,{\rm cm}^{-3}$. The channel has been robust over hundreds of picoseconds and is likely to have remained even after this measurement, so we assume its life time to be at least on the order of $\tau_{\rm channel} \sim 1\,$ns. If one ignores thermal motion and collisions, one may assume that the channel life time is inversely proportional to the plasma frequency, $\omega_{\rm pe}\tau_{\rm channel} = {\rm const.}$, so that it scales with the electron density as $\tau_{\rm channel} \propto n_{\rm e}^{-1/2}$. This means that, in a cold gas whose density is 4 orders of magnitude lower, 10^{13}–$10^{14}\,{\rm cm}^{-3}$ as is typical for a tokamak plasma, the channel life time increases hundredfold to at least $\tau_{\rm channel} \sim 100\,$ns. This is already close to the characteristic time scale of magnetohydrodynamic (MHD) waves, such as fast magnetosonic and shear Alfvén waves, which are involved in relaxation processes that regulate magnetized plasmas.

2. Insensitivity with respect to laser wavelength

On the basis of dimensionless scaling arguments, one may ask whether a laser with 100 times longer wavelength would be needed under tokamak conditions to satisfy $\lambda_{\rm las}/\lambda_{\rm pe} = {\rm const.}$, i.e., $\lambda_{\rm las} \propto n_{\rm e}^{-1/2}$ (related to the absorption rate). This would be problematic because relativistic amplitudes ($a_0 \gtrsim 1$) have only been achieved with laser systems that operate with wavelength between $0.8\,\mu$m (Ti:sapphire) and $10\,\mu$m (CO_2). Fortunately, our simulations indicate that there exists a parameter window where the after-glow dynamics of the magnetized wake channels are effectively independent of the laser wavelength. In particular, this is the case for highly subcritical electron densities $n_{\rm e}/n_{\rm crit} \equiv \omega_{\rm pe}^2/\omega_{\rm laser}^2 \ll 1$ [2]. This insensitivity allows us to use existing high power lasers in experiments, and it justifies the use of longer wavelengths in simulations, which reduces the computational expenses (memory and time) to the point where long-time 3D simulations become feasible [2]. This is important because charged particle dynamics are intrinsically three-dimensional in the presence of a strong magnetic field, so that 2D simulations can be used only for preliminary explorations and their results must be interpreted with care.

3. Characteristic radiation for plasma diagnostics

In our first round of PIC simulations, some of which are reported in Ref. [2], we focus on processes occurring within the first nanosecond after the passing of the laser pulse, where thermal motion and collisions can still be ignored. Besides demonstrating the insensitivity of the overall structure of the plasma wake channel with respect to the laser wavelength (discussed in the previous section), it was found in Ref. [2] that the bow waves and wake waves that form on the 1–10 ps time scale are strongly modified by the externally imposed magnetic field (here, 2 tesla along the laser path).

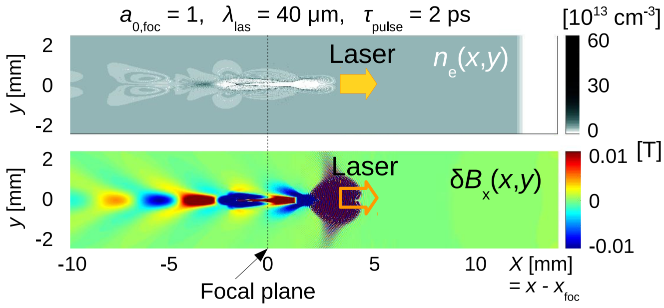

Figure 2: *Millimeter wave Terahertz radiation (b) emitted by the magnetized wake channel (a) behind a relativistically intense laser pulse (arrow, $a_{0,\rm foc} = 1$) in a deuterium plasma with background density $n_{\rm e0} = 3 \times 10^{13}\,\rm cm^{-3}$ and external magnetic field $B_{\rm ext} = 2\,\rm T$ directed along the x axis. (3D EPOCH simulation with scaled laser wavelength $\lambda_{\rm las} = 40\,\mu\rm m$ [2].)*

Although the sub-nanosecond dynamics of laser-induced wake channels are not expected to have any significant effect on the stability of a tokamak plasma, the substantial charge separation on the order of 100% that is caused by a relativistically intense laser pulse and the ensuing strong plasma oscillations that are modified by the local magnetic field may be used for plasma diagnostics. As an example, Fig. 2 shows the structure of the magnetized wake channel in terms of (a) the perturbed electron density $n_{\rm e}$ and (b) the axial component of the perturbed magnetic field δB_x in the x-y plane ($z = 0$) of a 3D EPOCH simulation. In (a), one can see the electron-free cavity (white area) as well as "singluar" multi-flow cusps [6] with localized electron density peaks reaching $n_{\rm e} \sim 60 \times 10^{13}\,\rm cm^{-3} = 20 \times n_{\rm e0}$ here (and even larger values with higher spatial resolution). In (b), one can see that the magnetized wake contains a strong axial magnetic field perturbation δB_x induced by the rapid gyration of charged particles around the channel axis. The sign of δB_x alternates with a wavelength of about $\lambda_{\rm wake} \approx 4\,\rm mm$, which is consistent with that of an upper-hybrid wave $c\omega_{\rm UH} = c(\omega_{\rm Be}^2 + \omega_{\rm pe}^2)^{1/2}$ for the present plasma parameters [2].

Since these laser-induced fluctuations depend on the local strength of the external magnetic field $B_{\rm ext}$ via the cyclotron frequency $\omega_{\rm Be} = eB_{\rm ext}/m_{\rm e}$ and on the electron density $n_{\rm e}$ via the plasma frequency $\omega_{\rm pe}$, it may be possible to infer the local values of these quantities by measuring the radiation that is emitted from the wake channel due to the alternating $\boldsymbol{v} \times \boldsymbol{B}$ acceleration. This radially propagating electromagnetic wave can be seen in Fig. 2(b) as diagonal stripes emanating up- and downward. The emitted wave intensity in this simulation is about $\mu_0^{-1} \times 10^{-3}\,\mathrm{T} \times 0.3\,\mathrm{V}\,\mu\mathrm{m}^{-1} = 24\,\mathrm{kW\,cm}^{-2}$ at a radial distance $r = \sqrt{y^2+z^2} = 1\,\mathrm{mm}$ from the channel axis. The signal intensity a few meters away would then be $\sim 10^{-3}\,\mathrm{W\,cm}^{-2}$, which is easily measurable with a THz imaging system.

4. Effect of thermal motion

A few 100 ps after the laser pulse has passed, the ion response produces a large perturbation in the deuteron density, $n_\mathrm{D}/n_\mathrm{D0} \sim 100\%$, and this ion channel is robust on the nanosecond scale when thermal motion is ignored [2]. Since presently available lasers can produce only narrow channels with diameters $d_\mathrm{ch} \lesssim 0.5\,\mathrm{mm}$ [2], the first threat to the channel's survival is the radial influx of ions, which move at thermal speeds $v_\mathrm{th,D} \sim 0.5\,\mathrm{mm/ns}$ on large gyroorbits with radii $\rho_\mathrm{BD} \sim 5\,\mathrm{mm} \gg d_\mathrm{ch} > \rho_\mathrm{Be} \sim 0.1\,\mathrm{mm}$ in a 3 keV Maxwellian plasma magnetized with 2 tesla. Figure 3(a) shows that the channel would be eliminated within 1 ns if there was no magnetic field, whereas it remains robust on the nanosecond scale in the magnetized case shown in Fig. 3(b). The effect of thermal motion on longer time scales ($\sim 10\,\mathrm{ns}$) is currently under investigation.

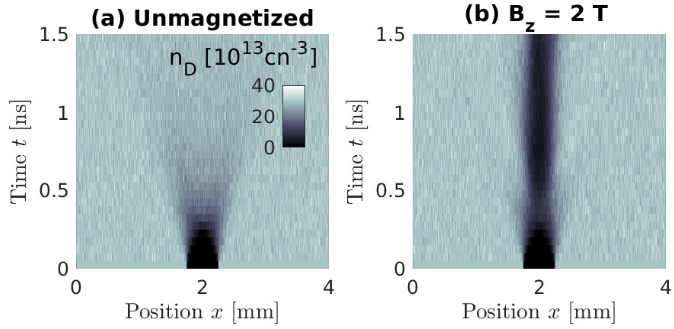

Figure 3: *Thermal collapse of a circular density hole in a 2D Maxwellian plasma slab with initial background density* $n_\mathrm{D} = 30 \times 10^{13}\,\mathrm{cm}^{-3}$ *and temperature* 3 keV. *(a): Unmagnetized case. (b): Magnetized with* $B_z = 2\,\mathrm{T}$. *(Preliminary results of a 2D REMP simulation without laser.)*

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