Round Table

Propagation of ultra-intense laser pulses in plasma channels and related phenomena

The propagation of super-intense and ultra-short laser pulses in plasmas is a main concern in several applications of the laser-plasma interactions, from ICF to HEP. During the propagation in the plasma the light beam deeply changes its parameters, due to the onset of non-linear effects, among them the relativistic regime of the electron quivering motion. These extreme conditions are suitable for the electron acceleration in high field gradient, opening to the realization of compact secondary sources of X-gamma rays. Colleagues from the major laser infrastructures and research centers (CEA, RAL, Ecole Polytechnique, PALS, …) participating to the Round Table will consider present and future links between the different applications of such physical phenomena.

1. Introduction. The CPA (Chirped Pulse Amplification) technique (Strickland and Mourou, 1985) of mode-locked fs laser pulses opened the way for the studies of the propagation of super-intense and ultra short laser pulses propagating in plasmas in unprecedented intensity regimes, overcoming 10^{18}W/cm^2. The electric field, associated to the intensity I,

$$E[V/cm] \approx 27.5\, I^{1/2}[W \cdot cm^{-2}]$$

largely exceeds the atomic field, so producing a very fast ionization of the matter in which the laser pulse is propagating. The free electrons of the plasma so produced oscillate under the action of the electric field with relativistic quiver velocity. The relevance of the relativistic effects can be evaluated considering the relativistic parameter a, from which the Lorentz factor γ depends:

$$\gamma = \left(1 + \frac{\alpha a^2}{2}\right)^{\frac{1}{2}} \quad \alpha = 1\,(lin.\ p.)\,;\, 2\,(circ.\ pol.)$$

$$a = \frac{eE}{m\omega c} \approx 8.5 \cdot 10^{-10} \cdot I_{W \cdot cm^{-2}}^{1/2} \cdot \lambda_{\mu m}$$

The topics addressed in the **Round Table** will concern the role of the plasma channels in the interaction of super-intense and ultra-short laser pulses with the matter. In the following the major effects relevant for the Laser Plasma Acceleration (LPA) experiments and related innovative X-ray sources will be shortly considered to give some inputs to the discussion.

2. Plasma refractive index at laser relativistic intensities. The laser, propagating in a plasma, induces a quivering motion on the irradiated electrons. When the relativistic parameter a approaches or overcomes the unity in the maximum of the radial intensity distribution of the laser (bell shaped), the electrons in the center of the laser beam are more "heavy" of the ones in the margins, as a consequence of their relativistic motion ($\gamma > 1$) and the refractive index n becomes locally larger. So the laser beam bends due to the radial dependence of the refractive index on the local laser intensity. In fact, the plasma refractive index in the center of the laser beam becomes larger than in its margins, because the plasma frequency ω_{pe} depends on the Lorentz factor, related to the quivering motion of electrons in the laser electromagnetic fields.

$$n = \left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{\frac{1}{2}} \qquad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m \gamma}\right)^{\frac{1}{2}}$$

In these conditions the plasma acts as a focusing lens that, concentrating the laser radiation, increases its intensity which in turns increases the refractive index effects, so producing a positive feed-back process of beam self-focusing. The onset of this physical process (Esarey, 1997) demands to overcome the critical value for the laser power:

$$P_{cr} = \frac{mc^5\omega^2}{e^2\omega_{pe}^2} \approx 17\left(\frac{n_c}{n_e}\right) GW$$

As we can see, the critical power decreases as the plasma density increases as a consequence of the major refractive effects. Once the relativistic self-focusing take place, the laser beam can be focused over distances much larger than the Rayleigh length.

3. Self Phase Modulation of the laser radiation. Large and fast variation of the refractive index induced by an intense and ultra-short laser pulse deeply affects its spectrum and consequently the spectrum of the radiation emitted in the physical processes activated during the laser-plasma interaction, i.e., Second Harmonic Generation (SHG), Thomson

Scattering (TS) and the different parametric instabilities as, for example, the Stimulated Brillouin Scattering (SBS) and the Stimulated Raman Scattering (SRS). In fact if we consider the relation between the laser angular frequency ω and the time derivative of the refractive index:

$$\phi = kz - \omega_0 t \quad \omega = -\frac{\partial \phi}{\partial t} = \omega_0 - k_0 z \frac{\partial n}{\partial t}$$

we find, for the propagation of a laser beam in a plasma:

$$n = \left(1 - \frac{n_e}{n_c}\right)^{\frac{1}{2}} \approx 1 - \frac{1}{2}\frac{n_e}{n_c} \implies \frac{\omega - \omega_0}{\omega_0} = \frac{z}{2cn_c}\frac{\partial n_e}{\partial t},$$

where n_c is the critical density for the laser frequency and c the speed of light in vacuum.

As we can see, in the case of further ionization induced by the laser beam during its propagation in a partially ionized plasma,

$$\frac{\partial n_e}{\partial t} \rangle 0$$

and blue shift of the laser radiation is produced due to the Self Phase Modulation (SPM) effects; while during the plasma channel formation, produced for example under the action of ponderomotive forces or relativistic self-focusing related to the beam intensity distribution, being

$$\frac{\partial n_e}{\partial t} \langle 0$$

the frequency shift, due to the SPM, is towards the red. The SPM of laser pulses can produce a very large modification of the original laser radiation. Let consider, i.e., the case of an intense pulse ($\tau = 40 fs$) of a Ti:Sapphire laser inducing, while it is propagating in a plasma extending for $\approx$5mm, a variation of the electron density $\Delta n_e \approx 10^{17} cm^{-3}$; the corresponding frequency variation is in this case quite large:

$$\frac{\omega - \omega_0}{\omega_0} \approx 1 .$$

4. Anomalous plasma transparency. The relativistic motion of the electrons in the electric field of the laser decreases the value of the plasma frequency by a factor $\sqrt{\gamma}$, allowing the propagation of the radiation at densities exceeding the critical one for the laser wavelength (Predhiman, 1998). In fact the condition to be fulfilled by the frequency for the laser propagation become in this case:

$$\omega > \frac{\omega_{pe}}{\gamma^{\frac{1}{2}}} = \frac{\omega_{pe}}{\left(1 + a^2\right)^{\frac{1}{4}}} .$$

For example, an intense pulse of a Ti:Sapphire laser, at $I = 10^{21} Wcm^{-2}$, can propagate in a plasma up to the maximum electron density of $n_e \approx 2.6 \times 10^{22} cm^{-3}$, i.e. more than one order of magnitude higher than the maximum electron density in which the same laser can propagate at sub-relativistic intensities. Another "anomalous" propagation can onset in plasmas when the super-intense laser beam interacting with the target produces very intense magnetic fields (Giulietti, 1997). In fact in presence of a static magnetic field B_0, perpendicular to the laser wave-vector and parallel to the oscillating magnetic fields of the electromagnetic wave, the light can propagate through an over-dense magnetized plasma as an extraordinary mode, provided that:

$$n_e < n_c \left(1 - \frac{\Omega}{\omega}\right)$$

where $\Omega = \frac{eB_0}{mc}$ is the cyclotron frequency (Predhiman, 1998).

5. Hole-boring and channel formation. An even more important phenomenon is the "ponderomotive hole-boring", due to its consequences in some applications of the laser-plasma interaction at high intensities, as the electron laser-plasma acceleration and the related betatron radiation. In fact the ponderomotive force:

$$\langle U_q \rangle = \frac{e^2 E^2}{4m\omega^2} \rightarrow F_p = -\nabla\langle U_q \rangle = -\frac{2\pi e^2}{mc\omega^2}\nabla\langle I \rangle$$

that in the relativistic regime of the laser radiation reduces to the expression

$$\langle U_q \rangle = mc^2(\gamma - 1) \quad \rightarrow \quad F_p = -mc^2 \nabla \gamma \approx -mc^2 \nabla a = -\frac{e\sqrt{8\pi c}}{\omega} \nabla \langle I \rangle^{\frac{1}{2}}$$

produces an electron density depletion along the laser path as a consequence of the intensity gradient related to the laser pulse. When this process takes place, the local density distribution can be described with fairly good approximation as

$$n(r) = n_0 + \Delta n \cdot \left(\frac{r}{r_{ch}}\right)^2.$$

In this case it is easy to show that the spot size to match the optical guiding condition in the pre-formed plasma is:

$$w_0 = \frac{r_{ch}^2}{(\pi r_e \Delta n)^{1/4}}.$$

The previous equation relates the plasma channel density profile with the laser spot size to match the optical guiding. It means that pulses focused in spots smaller than w_0 can be refractive-guided in such plasma channels (Gamucci, 2006).

6. Extending the acceleration length. Among the several drawbacks of the Laser Plasma Acceleration (LPA) schemes the limited acceleration length L_{acc} is one of the major concerns facing researchers. In fact even if this innovative acceleration technique allows accelerating fields several thousands of times higher than the ones used in the conventional accelerators, the maximum energy gained by the electrons is still far lower, due to the difficulty to maintain the high laser intensity over distances exceeding the Rayleigh length of the focusing optics and the two most important effects limiting the acceleration length, i.e. the pump depletion and the dephasing length. The dephasing length consists in the relativistic electrons slipping on the accelerating wave until they outrun the plasma wave and fall in a decelerating region. Considering that the phase velocity of the plasma wave is determined by the group velocity of the laser pulse, the dephasing length comes out to be

$$L_{deph} \approx \gamma_p^2 \lambda_p$$

where λ_p and $\gamma_p \approx \dfrac{\omega}{\omega_{pe}}$ are respectively the Langmuir plasma length and the Lorentz factor related to the phase velocity of the accelerating plasma wave. As we can see the dephasing length scales as $(n_e)^{-1.5}$, so in the LPA experiments the plasma density have to be low enough to guarantee the condition $L_{acc} < L_{deph}$ is fulfilled.

Much more difficult is to contrast the reduction of the acceleration length related to the depletion of the laser pulse propagating in the plasma. In fact to hold up the plasma wave and counterbalance the depletion losses along the acceleration length a minimum laser intensity I_0 is required. In the optimistic case of a high quality diffraction limited focusing optics, we get:

$$L_{acc} \approx 2Z_R = \frac{2\pi w^2}{\lambda} \approx \frac{2E_L}{\tau \lambda I_0}$$

where Z_R, w, E_L, t are the Rayleigh length, the laser beam waist, the laser pulse energy and its duration respectively. It is easy to verify that a few millimetres acceleration length would require a PW class laser !

7. Betatron radiation. The propagation of the super-intense and ultra-short laser pulses in plasmas in the so called "bubble regime" (Pukhov, 2002) is one of the most interesting acceleration scheme, due to the high energy and relatively low energy spread that can be obtained. In this physical process the accelerated electrons, moving along a region depleted by the electron density, suffer a restoring force towards the bubble axis due to the unbalanced positive ion charges. The transverse electric field due to space charge separation:

$$E = \frac{n_e e r}{2\varepsilon_0}$$

induces an oscillatory motion on the electrons having a velocity radial component :

$$\mathbf{v} = \mathbf{v_r} + \mathbf{v_z} \qquad tg(\theta) = \frac{v_r}{v_z} \approx \frac{v_r}{c}$$

$$\gamma m \frac{\partial^2 r}{\partial t^2} = -\frac{n_e e^2 r}{2\varepsilon_0} \quad \Rightarrow \quad r(t) = r_0 \cos(\omega_b t)$$

$$\omega_b = \frac{\omega_{pe}}{\sqrt{2\gamma}}$$

where w_b and w_{pe} are the betatron and electron plasma frequencies, respectively and g the Lorentz factor of the accelerated electrons. The electron trajectory:

$$r(z) = r_0 \cos(k_b z)$$

is characterized by the spatial period:

$$k_b = \frac{\omega_b}{c} \quad , \quad \lambda_b = c\frac{2\pi}{\omega_b}$$

The transversal oscillation of the relativistic electron accelerated in the bubble produces an intense X-ray emission along the same direction of the laser pulse and the accelerated electrons. The so called "betatron radiation" shows several analogies to the Free Electron Laser physical mechanisms .
The radiation emitted by the electrons will have the divergence:

$$tg(\theta) \approx \theta = k_b r_0$$

with a strength parameter, in analogy with the FEL emission:

$$K = \gamma\theta = \gamma k_b r_0 = 1.33 \cdot 10^{-10} \sqrt{\gamma n_e (cm^{-3})} \ r_0(\mu m)$$

For K<<1 the radiation detected in the laboratory frame will be:

$$\omega_f = \omega_b 2\gamma^2 = \sqrt{2}\omega_{pe}\gamma^{\frac{3}{2}}$$

which corresponds to the betatron frequency, Doppler shifted in the laboratory reference frame. For K>1 the amplitude of the electron transversal motion increases, the plasma channel acts as a wiggler and high harmonics are radiated in a broad frequency band centred at

$$\omega_c = \frac{3}{4c}\gamma^2\omega_{pe}^2 r_0$$

References

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