# Intense Laser Pulses Propagation in Overdense Plasmas

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# LASER propagation in plasmas up to the **critical density**

$$\omega_L^2 = \omega_P^2 + k_L^2 c^2 \qquad \omega_P = \sqrt{\frac{n_e e^2}{\varepsilon_0 m}}$$

$$v_g = c\left(1 - \omega_P^2/\omega_L^2\right)^{1/2} \qquad v_\phi = c\left(1 - \omega_P^2/\omega_L^2\right)^{-1/2}$$

$$critical\ \ density\ (n_c) \rightarrow \omega_L = \omega_P$$

$$n_c = \frac{m\omega_L^2\varepsilon_0}{e^2} \qquad = 1.1\times 10^{21}\ \lambda_L^{-2}\left(\mu\mathrm{m}\right)\ \mathrm{cm}^{-3}$$

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# PONDEROMOTIVE HOLE-BORING

$$Ponderomotive\ \ force$$

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

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

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# Relativistic Intensities (1)

$$I = u v_g = \varepsilon_0 E^2 c \cdot n$$

$$for \quad n \approx 1 \qquad E_{V/cm} \approx 27.5 \; I_{W\cdot cm^{-2}}^{\frac{1}{2}}$$

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

$$\gamma = \left(1 - \beta^2\right)^{-\frac{1}{2}} \qquad \beta = \frac{v}{c}$$

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

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

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# Relativistic Intensities (2)

$$for\ 6J,20\,fs\ \ @\,\lambda \approx 0.815\mu m\ laser\ pulse$$

$$focal\ spot\ \phi \approx 5\mu m$$

**Relativistic intensities a ≈ > 1**

$$I \approx 10^{21}\,W \cdot cm^{-2}$$

$$E \approx 10^{12}\,V/cm >> E_{at} \approx 5 \cdot 10^{9}\,V/cm$$

$$B \approx 10\ GGauss$$

$$P = \frac{I}{c} \approx 6.6 \cdot 10^{16}\,N/m^{2} \approx 660\ GBar$$

$$a \approx 22 \Rightarrow \gamma \approx 15.5 \Rightarrow E_{cin} = mc^{2}(\gamma - 1) \approx\ 7MeV$$

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# Relativistic self-focusing

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

$$Example: for\ \lambda_0 = 0.815\mu m\ and\ n_e = 10^{18} cm^{-3} \Rightarrow P_{cr} \approx 29\ TW$$

The laser pulse can be self-focused over distances much larger than the Rayleigh length

$$Z = \frac{\pi w_0^2}{\lambda_0}$$

where $w_0$ is the laser pulse waist at the focus.

# LASER propagation in plasmas at relativistic intensities

$$n_c^* = \frac{m\omega_L^2\varepsilon_0}{e^2}\gamma$$

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# Relativistic trasparency

$$condition\ \ for\ \ relativistic\ \ transparency\quad \omega > \frac{\omega_{pe}}{\gamma^{\frac{1}{2}}} = \frac{\omega_{pe}}{\left(1+a^2\right)^{\frac{1}{4}}}$$

$Example:$

$$\lambda_0 = 0.815\mu m;\ a << 1\ \rightarrow\ n_c = 1.66\times 10^{21}cm^{-3}$$

$$I = 10^{21}Wcm^{-2}\ \rightarrow\ \ a \approx 22\ ,\ \ \gamma \approx 15.5\ \rightarrow\ n_c^* = 2.6\times 10^{22}cm^{-3}$$

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# Magnetically Induced Optical Transparency

Laser light can propagate through an overdense magnetized plasma as an extraordinary mode provided that:

$$n_e < n_c \left(1 - \frac{\Omega}{\omega}\right) \quad where \quad \Omega = \frac{eB_0}{mc} \quad is\ the\ cyclotron\ frequency$$

$$and\ B_0\ is\ a\ static\ magnetic\ field\ perpendicular\ to\ the\ wavevector$$

$$and\ parallel\ to\ the\ oscillating\ magnetic\ field$$

$$Example: \lambda_0 = 0.815 \mu m; \frac{n_e}{n_c} \approx 50 \quad \Rightarrow \quad B_0 \geq 1 GGauss$$

*D. Giulietti et al, Observation of Solid-Density Laminar Plasma Transparency to Intense 30 Femtosecond Laser Pulses, PRL,**79**, 17, 3194, 1997*

# CONCLUSIONS AND PERSPECTIVES

The propagation of intense 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, inducing at the same time the relativistic regime of the electron quivering motion.

These extreme conditions are suitable for the electron acceleration in high field gradients, opening to the realization of compact secondary sources of radiation (X-gamma rays ) and particles (ions, e+, ….)