§41. Relativistic Compression of a Laser Pulse Reflected from a Moving Plasma

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A generation of ultra-short (attosecond) light and relativistic particle bunches is of importance in various applications [1)]. We consider a general problem of a linear reflection of a time-dependent EM (laser) pulse (Dirac's- $\delta(t)$) from a plasma half-space moving at the relativistic velocity. The incident electric field (S- polarization) with incident angle θ_i, is in the time domain represented by inverse Fourier transformation.

$$\begin{aligned} E_{yi} &= (1/2\pi)\int_{-\infty}^{+\infty} E_0 \exp\left[j\left(\omega_i t - \mathbf{k}_i \mathbf{r}\right)\right] d\omega_i \\ &\equiv E_0 \delta\left(t - (x/c)\sin\theta_i + (z/c)\cos\theta_i\right), \quad (1) \end{aligned}$$

The rest frame of the moving plasma is K'. Making use of the Lorentz transformations, covariance of Maxwell's equations and the principle of phase invariance to transform between the K-rest (laboratory) frame and the moving K'-frame;

$$\omega_i' = \gamma\left(1 - \mathbf{k}_i\mathbf{v}/\omega_i\right)\omega_i, \quad \gamma = \left(1 - v^2/c^2\right)^{-1/2}, \quad (2)$$

$$\mathbf{k}_i' = \mathbf{k}_i - \gamma\omega_i\mathbf{v}/c^2 + (\gamma - 1)\left(\mathbf{k}_i\mathbf{v}\right)\mathbf{v}/v^2, \quad \text{and} \quad (3)$$

$$E_0' = \gamma\left(1 - \mathbf{k}_i\mathbf{v}/\omega_i\right)E_0, \quad (4)$$

with $\exp\left(j\omega_i' t'\right)$ time dependence suppressed, frequency domain reflected field is

$$\mathcal{E}_{yR}' = \frac{1 - N'}{1 + N'} E_{01}' \exp\left(-j\mathbf{k}_r'\mathbf{r}'\right), \quad (5)$$

with cold plasma index of refraction in K',

$$N' = \left|1 - \left(\omega_p'/\omega' \cos\theta_i'\right)^2\right|^{1/2}, \quad \omega_i' = \omega_r' = \omega_t' \equiv \omega'.$$

After transforming back from K' to K, time domain reflected field is found by the standard method of contour integration [2)], as

$$E_{yR} = -\left(2E_0\alpha_0/\xi\right) J_2\left(\alpha_1\xi\right) U(\xi), \quad (6)$$

$$\alpha_0 = \gamma^2\left(1 + 2\beta\cos\theta_i + \beta^2\right), \ \alpha_1 = \left|\omega_p/\gamma\left(\beta + \cos\theta_i\right)\right|,$$

$$\xi = \alpha_0 t - (x/c)\sin\theta_i - (z/c)\gamma^2\left|\left(1 + \beta^2\right)\cos\theta_i + 2\beta\right|,$$

where $U(\xi)$ is the Heaviside unit step function; $J_2(x)$ is the Bessel's function of the first kind of second order.

The plasma motion ($\mathbf{v} = \mathbf{e}_z v$) strongly modifies both the amplitude and the oscillatory phase of the reflected field (6); with a departure from the classical Snell's law ($\theta_i \neq \theta_r$). From above one calculates: $\tan\theta_r = \sin\theta_i/\gamma^2\left|\left(1 + \beta^2\right)\cos\theta_i + 2\beta\right|$, which for large $\beta > 0$, predicts $\theta_r < \theta_i$, i.e. the reflection angle close to normal incidence. The time delays in terms of the inverse plasma frequency of the maximum positive and negative reflected amplitude, as a function of plasma velocity β, deduced from Fig. 1 are shown in Fig. 2. Large compression and amplification of the reflected pulse (factor $\sim 2\gamma$) at relativistic plasma motion reveals a remarkable potential of this linear mechanism for ultra-short (attosecond) pulse generation by low intensity high-rep-rate femtosecond laser pulses scattering at counter-propagating relativistic electron beams [3)]. For example, a short green laser light pulse ($\lambda \sim 0.5$ microns) reflected from 5MeV electrons ($\gamma \sim 10$) at critical density gives a main reflected pulse width of around 60 attoseconds. An important point is that the reflected pulse width is basically determined by the relativistically upshifted electron plasma frequency which can be high in laser-solid density plasmas.

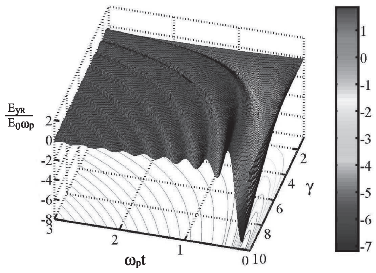

Fig. 1. Reflected EM field in time as a function of the plasma velocity γ.

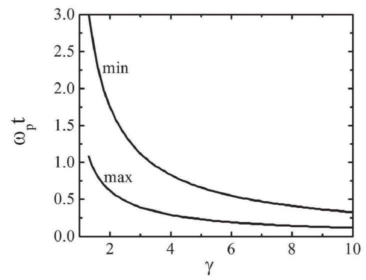

Fig. 2. Time period of the first and second peak in the reflected wave versus (γ).

1) Stanić, B., Škorić, M. M., J. Phys. D**7**, (1973) L137
2) Mourou, G. et al., Rev. Mod. Phys. **78**, (2006) 309
3) Nikolić, Lj., Škorić, M. M. et al., J. Phys. E (2008)