High Power Laser Grating Interaction

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1. Introduction & Motivation

In short pulse high power laser-matter interaction, one of the uttermost problems is how to transfer laser energy to the overdense plasma that is created in front of the target, when the temperature is in the range of keVs, since the collisional absorption mechanism loses efficiency due to the scaling of collisional frequency with temperature: $\nu_{ei} \propto T_e^{-3/2}$.
Other energy transfer mechanism have been found and are now well known,[1], [2],[3].

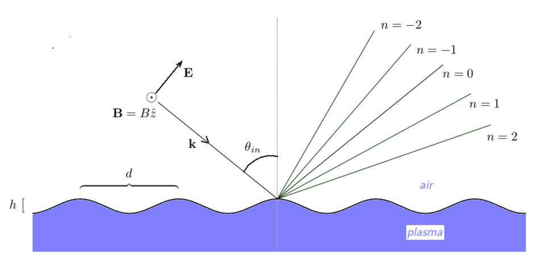
Here, we investigated the possibility to couple the laser energy to the target introducing a periodic modulation at the solid-void interface. This leads to a transfer mechanism that occurs at the solid surface and involve a collective mode excitation. In particular, we studied the influence of this surface mode on the dynamics of hot electrons by a test particle approach: at first we studied the distribution of the e.m. fields and and after the dynamics of test particles in such fields. By this approach we do not consider the self consistent fields induced by the particle motion.

Motivation of the choice:

- It is known in optics that diffraction gratings present greater energy adsorption than flat interfaces [4]
- in fully self-consistent (Particle-In-Cell) simulations it is difficult to distinguish the contribution in laser coupling coming from different transfer mechanisms [5].

2. Diffraction Gratings

Let our grating profile be described by $f(x) = \frac{h}{2}\cos(2\pi x/d)$ The geometry of the scattering problem is given in figure below:

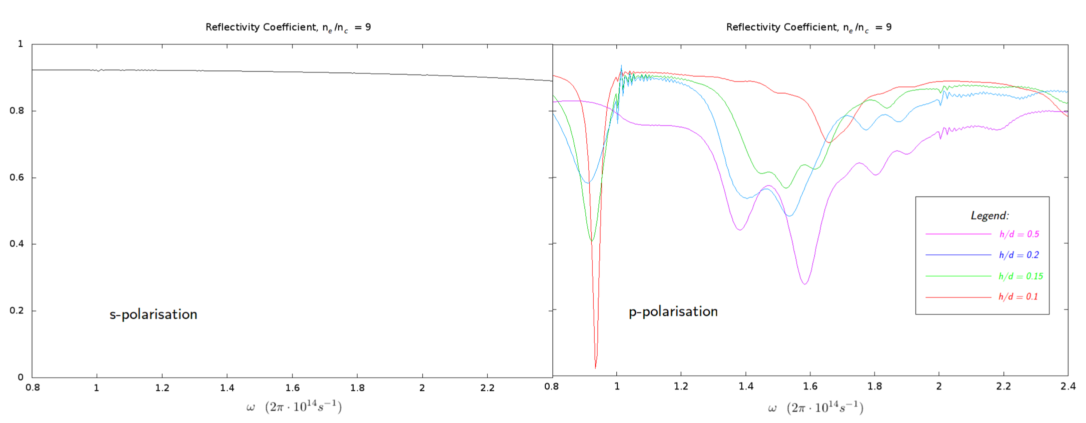


Grating formula:

$$\sin\theta_n = \sin\theta_{in} + n\frac{\lambda}{d}$$

- $|\sin\theta_n| < 1 \Rightarrow$ Propagative order
- $|\sin\theta_n| > 1 \Rightarrow$ Evanescent order

The computation of the reflectivity spectrum in S-polarisation and P-polarisation leads to very different results (fig. 2):



Why are there resonances in the p-polarisation case? The answer is:

Surface Plasmon Resonances

3. SPR excitation

Total field can be expressed by Rayleigh's expansion [6] :

$$\begin{cases} B(x,y) = e^{ik(\alpha x - \beta y)} + \sum_n B_n\, e^{ik(\alpha_n x + \beta_n y)} & \text{for } y > h/2 \\ B(x,y) = \sum_n C_n e^{ik(\alpha_n x - \gamma_n y)} & \text{for } y < -h/2 \end{cases}$$

with $\alpha_n = k_x \pm n\lambda/d$, $\beta_n = \sqrt{1-\alpha_n^2}$, $\gamma_n = \sqrt{\mathsf{n}^2 - \alpha_n^2}$.
For $h/d \ll 1$ we may assume $B_n \sim r_n$ and $C_n \sim t_n$, where r and t are the Fresnel coefficients:

$$r(\alpha_n) = \frac{\mathsf{n}^2\beta_n - \gamma_n}{\mathsf{n}^2\beta_n + \gamma_n} \qquad t(\alpha_n) = \frac{2\mathsf{n}^2\beta_n}{\mathsf{n}^2\beta_n + \gamma_n}$$

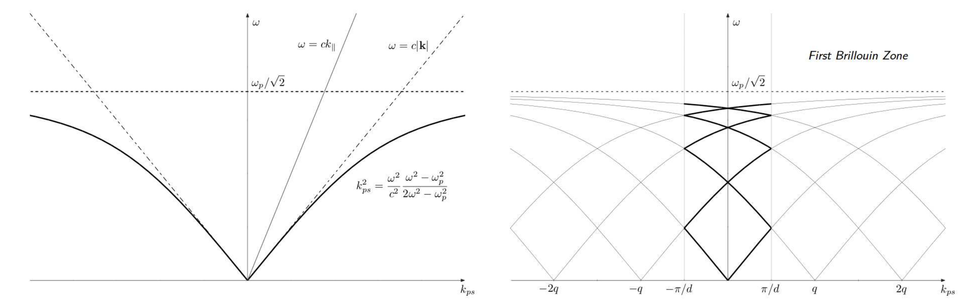
- If $\Re\{\mathsf{n}^2\} < 0 \implies$ Poles in the denomitators of Fresnel coefficients
- This corresponds to a solution of *homogeneous* Maxwell Equations $\Rightarrow$ Maxwell equations **eigenmode**
- Characterized by $\alpha_n > 1$, $\beta_n \in \Im \Rightarrow$ Localization near the interface: ***surface mode***!

Relation dispersion of the so-called Surface Plasmon Resonance (SPR) is :

$$k_{sp}^2 = \frac{\omega^2}{c^2}\frac{\varepsilon}{1+\varepsilon} \implies \underbrace{k_{sp}^2 = \frac{\omega^2}{c^2}\left(\frac{\omega^2 - \omega_p^2}{2\omega^2 - \omega_p^2}\right)}_{\text{for a Drude metal}}$$

4. Resonant e.m. fields

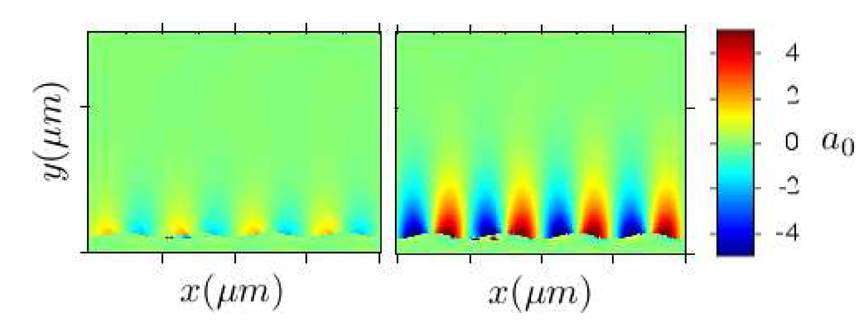
- With NO grating, matching condition $k_{sp} = k_x < 1 \Rightarrow$ no way
- With grating, "reflection" at Bragg planes give: $k_{sp} = k_x + nq$



At normal incedence, SPRs are excited for:

$$\omega_n^2 = \frac{\omega_p^2}{2} + n^2q^2 - \sqrt{\frac{\omega_p^4}{4} + n^4q^4}$$

Comparison between resonant and not resonant cases:



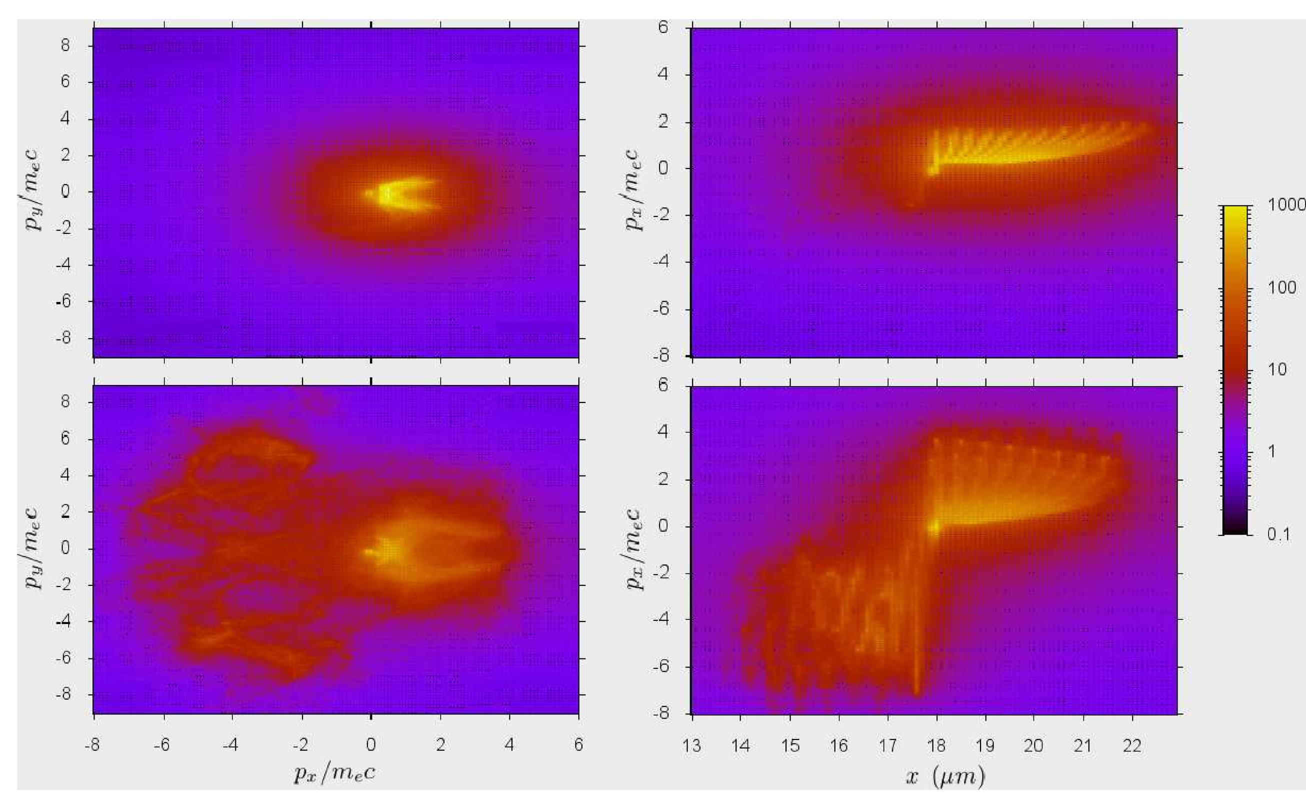
5. Particle dynamics

Dimensionless motion equation solved numerically:

$$\frac{d\mathbf{p}_{i,m}}{dt} = \mathbf{E}(\mathbf{x}_{i,m}, t, \phi_m) + \frac{\mathbf{p}_{i,m}}{\gamma_{i,m}} \times \mathbf{B}(\mathbf{x}_{i,m}, t, \phi_m)$$

where $\mathbf{p} = \mathbf{p}_e/m_ec$, $\mathbf{x} = \mathbf{r}/\lambda$, $\mathbf{E} = a_0\frac{qE}{m_e\omega c}$, $\mathbf{B} = a_0\frac{qB}{m_e\omega c}$, $a_0 = \frac{q|\mathbf{A}|}{m_ec^2}$, $\phi_m = \omega m\Delta\tau$ and $\Delta\tau = t_{end} - t_0$.

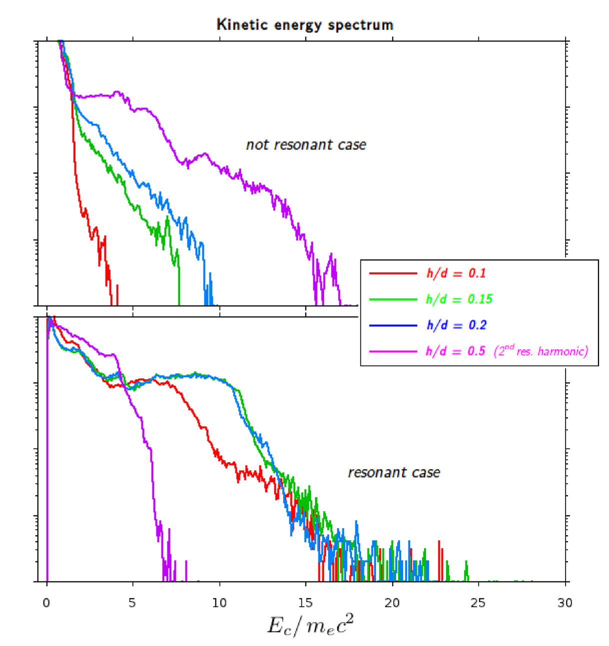
- i = labels particle initially at the interface: $(x_i, y_i) = (i\,d/N, f(i\,d/N))$, $(v_{x,i}, v_{y,i}) = (0, v_{th})$, with N = # particles
- m = labels temporal delay after which a bunch of N particles is initialized : $\phi_m = m\,(t_{end} - t_0)/T$, with T = # samples



Upper figures: not resonant case. Lower figures: resonant case. Simulation parameters: $N = 200$,$T = 1000$, $\omega t_{run} = 5$, $n_e/n_{cr} = 9$, $a_0 = 1$. We recall that in practical units, $a_0 = 0.85\left(\frac{I\lambda^2}{10^{18}\text{ W cm}^{-2}}\right)^{1/2}$

6. Results

Simulations with different depth profiles show a general enhancement of the kinetic energy acquired by the accelerated test particles when the plasmonic resonance is excited, as can be observed in figures below. It should be noticed that in the case $h/d = 0.5$ we are totally out of the approximations that allow us to take as relation dispersion the exact curve of the flat case, and replicate it according to the grating periodicity.



All cases refer to $a_0 = 1$.

7. Conclusions & Future Work

We have demonstrated that the introduction of a modulation at the target surface leads to field enhancement and to the possibility to excite plasmonic resonances (also at *normal* laser incidence) which greatly enhance electron acceleration near the surface.

Further work:

- Study of non linear effects for $a_0 > 1$
- Phase interval between re-initialisation should be dependent on fields intensity

References

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