

Laser interaction with nano-cluster in the few-cycle regime

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1 Importance of laser-cluster interaction

Very efficient laser-energy coupling

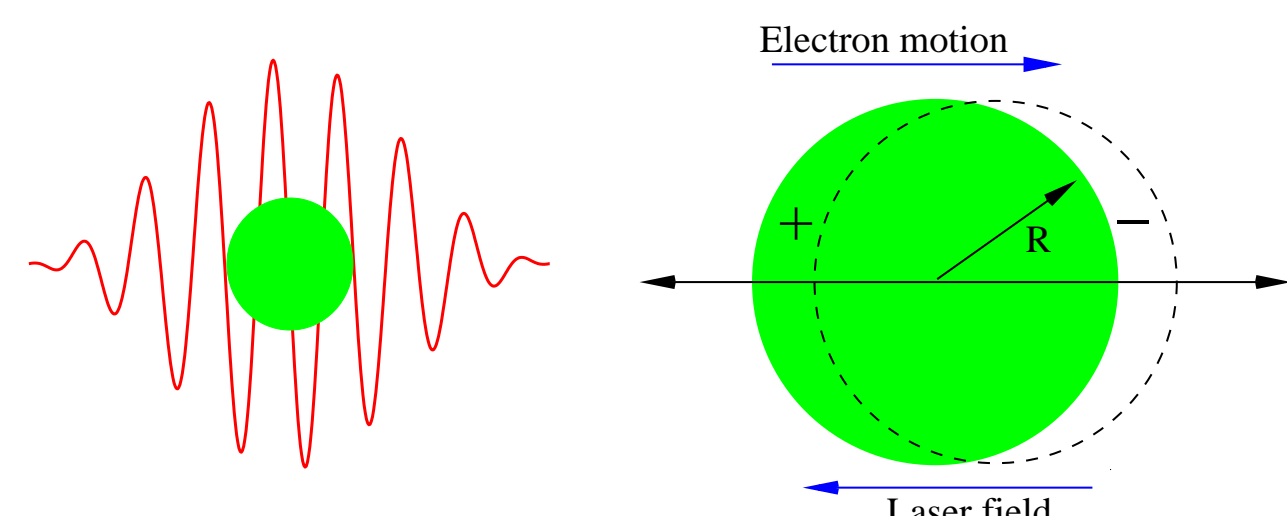


Figure 1: Schematic of laser cluster interaction

- Table-top source of highly charged MeV ions and keV electrons
- Soft and hard x-rays, laser-harmonic generation
- Nuclear fusion with Deuterium cluster

2 Laser-cluster interaction scenario

A simple man's view

- Initially laser field E_{laser} removes electrons from cluster atoms (Inner ionization) and Mie-plasma frequency $\omega_M = \sqrt{4\pi\rho(t)}/3$ soon crosses the laser frequency ω .
- Some of these electrons are also removed from cluster (Outer ionization) and leads to space charge field E_{sc} .
- E_{sc} often exceeds E_{laser} and the total field $|E_{sc} + E_{laser}|$ may create even higher charge states Z of ions (Ionization ignition).
- The bare ionic background Coulomb explodes and potential energy of charged cluster is converted to ion kinetic energies.

How laser energy is coupled to electrons?

- For high Z one should remove as many electrons as possible.
- How electrons absorb energy from the laser field (mechanism?)

3 Prevailing concept of energy absorption

Most common idea: Linear resonance (LR)

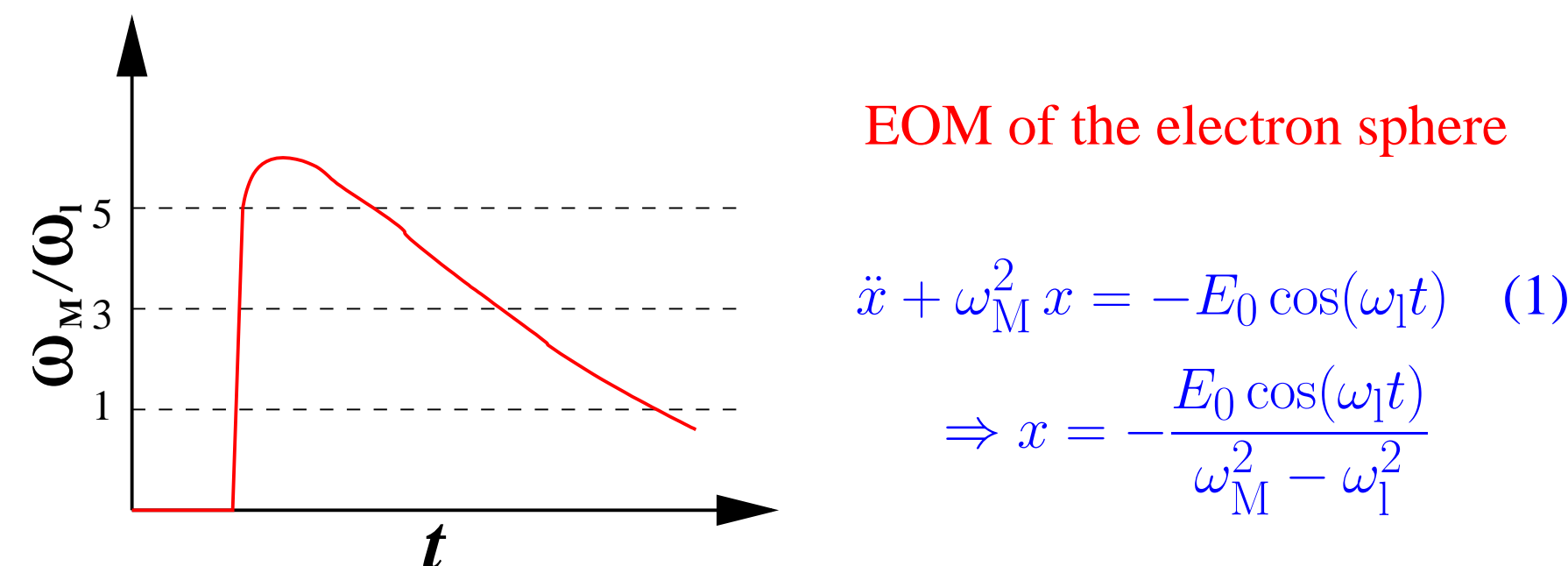


Figure 2: Schematic of LR

- LR $\omega_M(t) = \omega_1$ occurs **only** after cluster expansion.
- This conventional LR requires long pulses.
- However, electrons must absorb energy and leave the cluster, otherwise cluster can't expand, the conventional LR can't work.
- What is the absorption process before LR?

Not so common idea: Non-linear resonance (NLR)

- $\omega_M(t) \neq \omega_1$ for short pulses (or early duration of a long pulse).
- We still see significant energy absorption.
- Is NLR responsible?

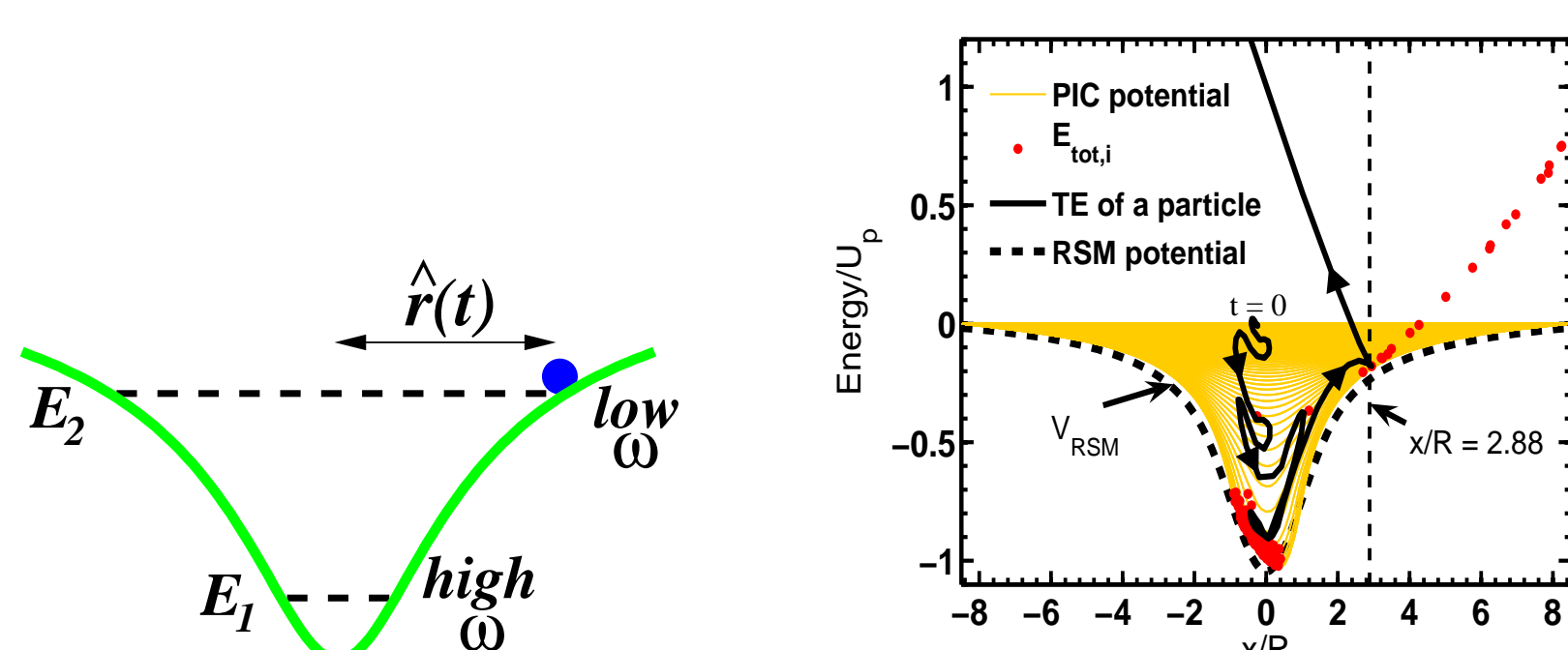


Figure 3: Schematic of NLR

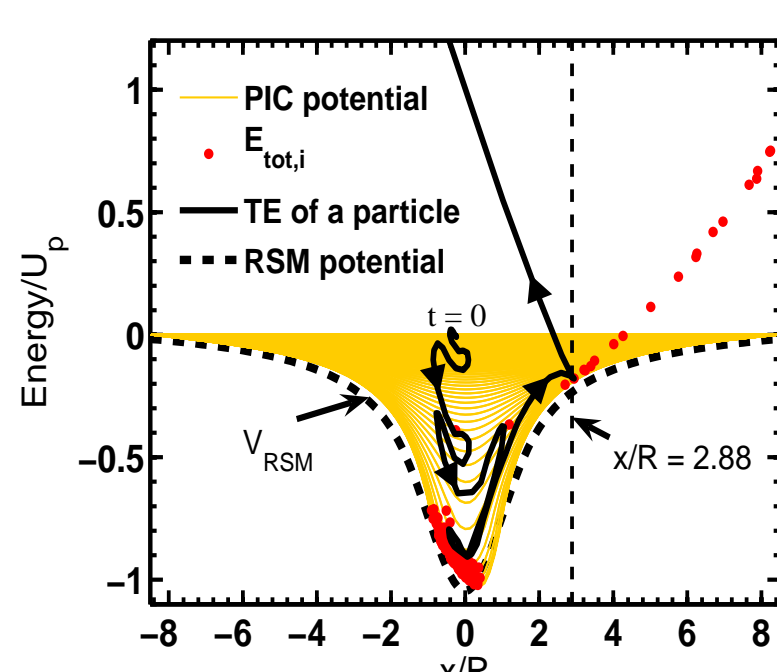


Figure 4: NLR in PIC simulation (Ref.2)

- NLR condition $\omega[r(t)] = \omega_1$ is possible to meet (Refs.1,2).

4 Long pulse vs short pulse interaction

- For long pulse conventional LR, plasma is already dilute after expansion. Some ions are disintegrated and some of may leave the cluster.
- Since charge density is in-homogeneous the conventional long pulse LR can't happen for whole cluster.

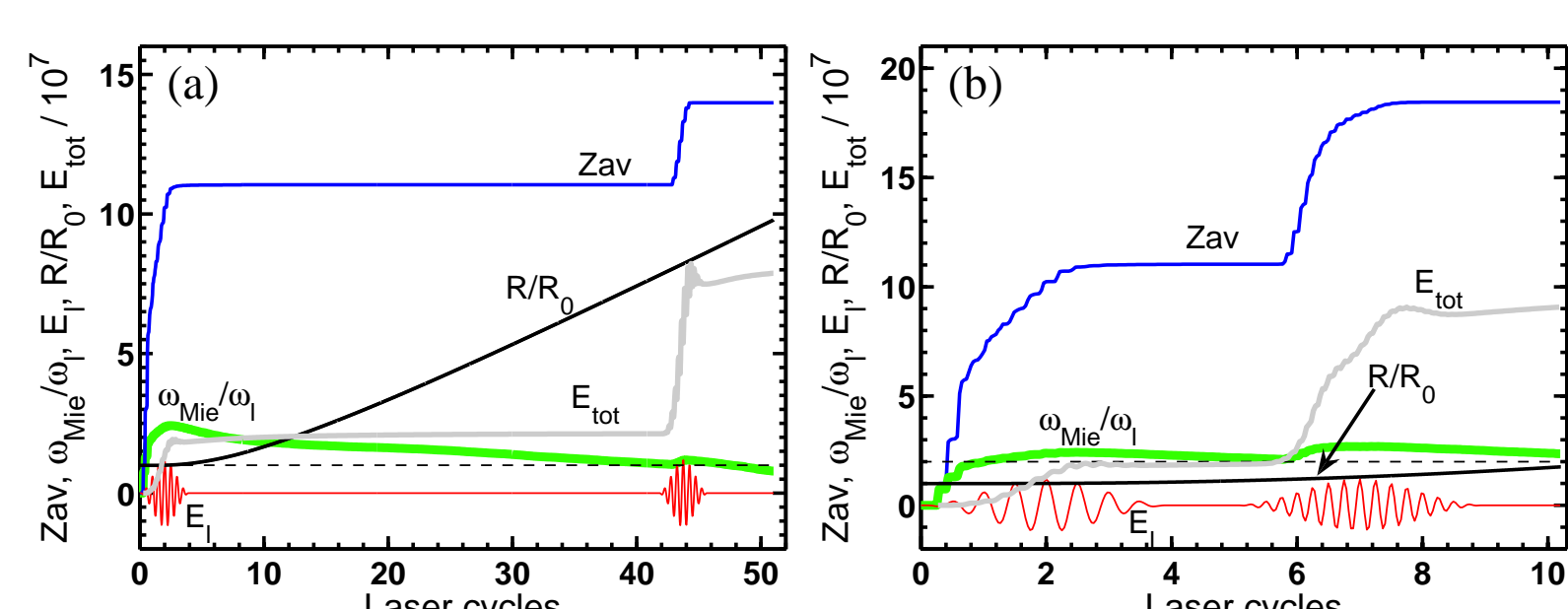


Figure 5: Pump-probe PIC simulation. (a) LR with a 400 nm pump and 400 nm probe. (b) LR with a 400 nm pump and 200 nm probe (Ref.3).

- Long pulse LR is not expected to be as efficient as short pulse LR of shorter λ_1 .

5 Objective and New idea

- LR occurs at a specific time when $\omega_M(t) = \omega_1$, however NLR may occur almost all the time during the laser pulse.
- **How to combine LR and NLR so that energy absorption is maximum.**
- **Use sub-cycle broadband pulses (having many frequencies).**
- Due to inhomogeneous charge density ω_M has a broader spectrum which may match with the broader spectrum of the sub-cycle pulse leading to efficient LR and NLR.

Model of a sub-cycle pulse

$$E(t) = (E_0/\omega) \begin{cases} \sum_{i=1}^3 d_i \omega_i \sin(\omega_i t) & 0 < t < nT \\ 0 & t > nT \end{cases} \quad (2)$$

where $d_1 = 1/2, d_2 = d_3 = -1/4, \omega_1 = \omega, \omega_2 = (1 + 1/n)\omega, \omega_3 = (1 - 1/n)\omega$.

- The integral $\int_0^{nT} E(t) dt = 0$ irrespective of the pulse duration $\tau = nT$, otherwise a free charge will gain energy (artificially) from the pulse.

6 Laser absorption in Deuterium cluster

- Cluster radius $R_0 = 2.2$ nm (number of atoms $N = 2176$), charge density $\rho = 27.86\rho_c(\omega)$ and $\omega_M \approx 3\omega$.

Anharmonic oscillator model (RSM)

EOM of the electron sphere, in a linearly polarized (along x) field $E(t)$

$$\ddot{x} + g(r)x/r = -\hat{x}E(t), \quad (3)$$

where $r = |x|$ is the displacement of the electron sphere and $g(r)$ is the electrostatic restoring force given by

$$g(r) = \omega_M^2 \begin{cases} r + \alpha r^2 + \beta r^4 & 0 \leq r \leq 2R_0 \\ \gamma/r^2 & r \geq 2R_0 \end{cases} \quad (4)$$

with $\alpha = -9/16R_0, \beta = 1/32R_0^3$, and $\gamma = 1$.

- Absorbed energy $E_a = E_a(\tau) = m_s \dot{x}^2/2 + q_s \int g(r) dr$.

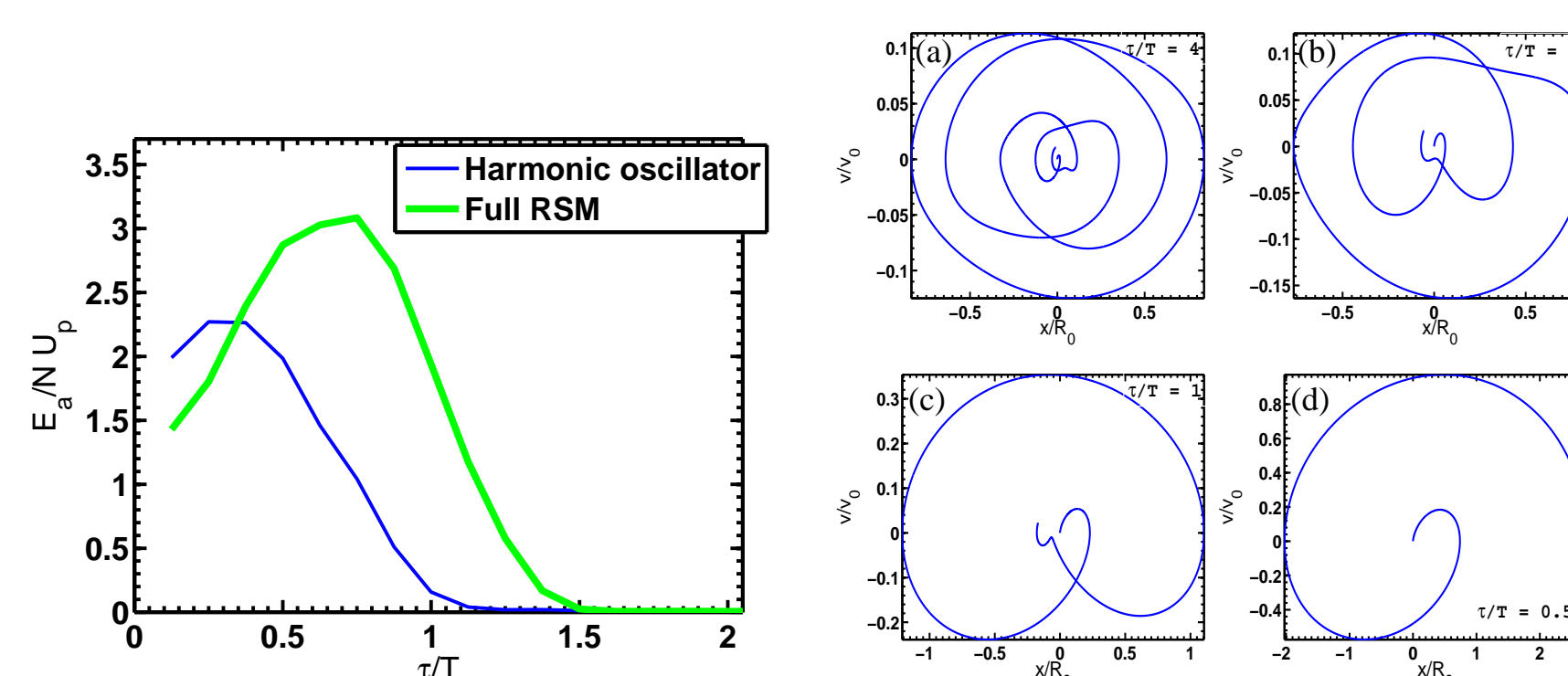


Figure 6: (Left figure) Absorbed energy E_a/NU_p vs τ/T for RSM (thick solid, green) and harmonic oscillator (thin-solid, blue, with $\alpha = \beta = \gamma = 0$ in Eq.(4)) using $E(t)$ of Eq.(2). (Right figure) Phase space (x,v) diagram for the harmonic oscillator at various pulse length $\tau/T = 4, 2, 1, 0.5$. The Deuterium cluster is irradiated by laser pulses of central wavelength $\lambda_0 = 800$ nm and peak intensity $5 \times 10^{15} \text{Wcm}^{-2}$.

- E_a/NU_p increases in spite of decreasing pulse length $nT < 2T$, reaches a peak and then drops. In presence of an-anharmonicity peak is shifted.
- Contrary to the known long pulse scenario (where HO can't gain energy at all) an HO driven by ultra-broadband pulses may gain energy by retaining phase different from its initial value.

PIC results

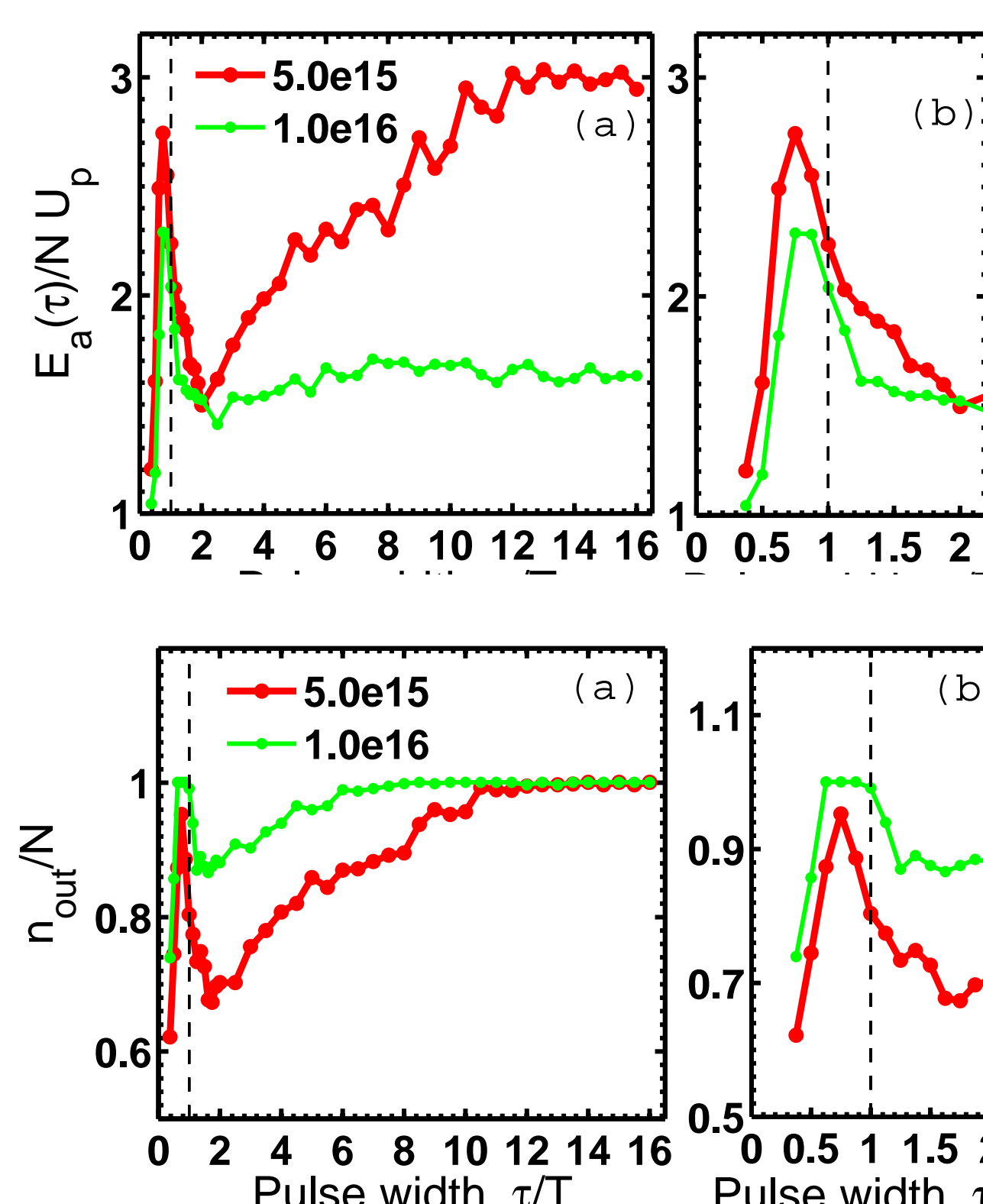


Figure 7: (Top) PIC results for energy absorbed E_a/NU_p per cluster ion N in units of U_p vs pulse width τ/T for $5.0 \times 10^{15} \text{Wcm}^{-2}$ (red) and 10^{16}Wcm^{-2} . (b) is the expanded view of (a) for $\tau/T < 2$. (Bottom) Corresponding outer ionization n_{out}/N vs τ/T .

- Above $\tau/T = 2$, absorbed energy increases with increasing τ/T , may reach a saturation for higher $\tau/T > 12$ due to saturation of inner and outer ionization.
- From $\tau/T = 2$, E_a/NU_p turns, increases with decreasing τ/T , and reaches a peak about $\tau/T \approx 0.8$ (as shown by anharmonic oscillator).
- Outer ionization (n_{out}/N) also shows same nature as E_a/NU_p with τ/T . In spite of decreasing pulse energy, n_{out}/N and E_a/NU_p increases for $\tau/T < 2$.

Efficiency of laser energy absorption

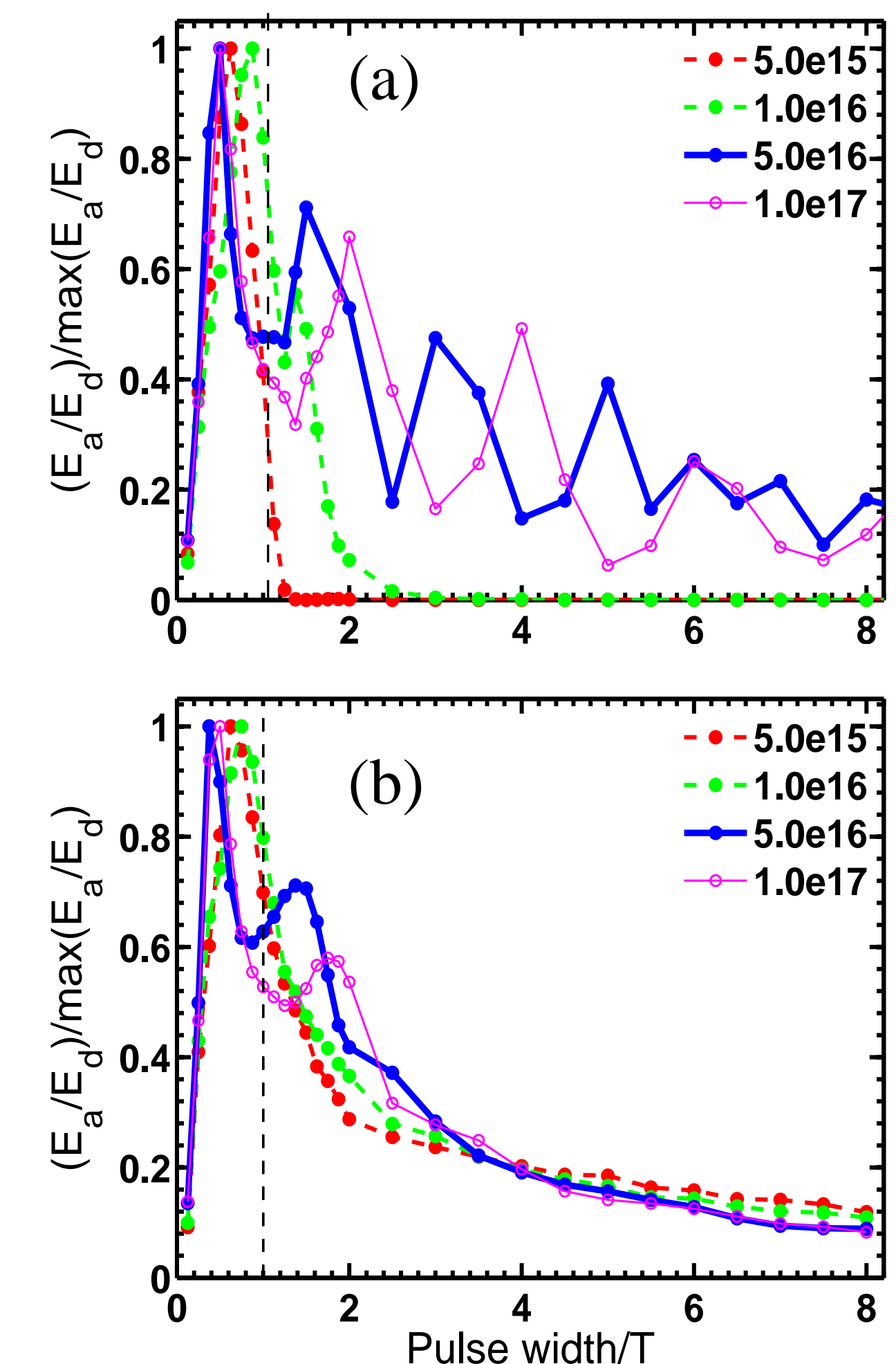


Figure 8: Energy absorption efficiency $\eta = (E_a/E_d) / \max(E_a/E_d)$ vs pulse length τ/T at various peak intensities $5.0 \times 10^{15}, 10^{16}, 5.0 \times 10^{16}, 10^{17} \text{Wcm}^{-2}$ with (a) RSM, and (b) PIC using $E(t)$ of Eq.(2). The same Deuterium cluster is considered.

- Absorption efficiency $\eta = (E_a/E_d) / \max(E_a/E_d)$ increases in spite of decreasing pulse length (decreasing pulse energy $E_d = \int_0^{nT} E(t) dt$).
- η is maximum close to $\tau = 0.8T$ in (a) and (b).

7 Deuterium cluster at fixed energy laser pulse

- Keep laser power $I_0 \times n_0 T$ fixed and decrease $\tau = nT$ which will effectively increase the peak intensity $I_{peak} = I_0 \times n_0 / n$.
- One passes through $I_{peak} = 10^{15}, 10^{16}, 10^{17} \text{Wcm}^{-2}$ with respective $n = \tau/T = 10, 1, 0.1$ after fixing $n_0 = 1, I_0 = 10^{16} \text{Wcm}^{-2}$.

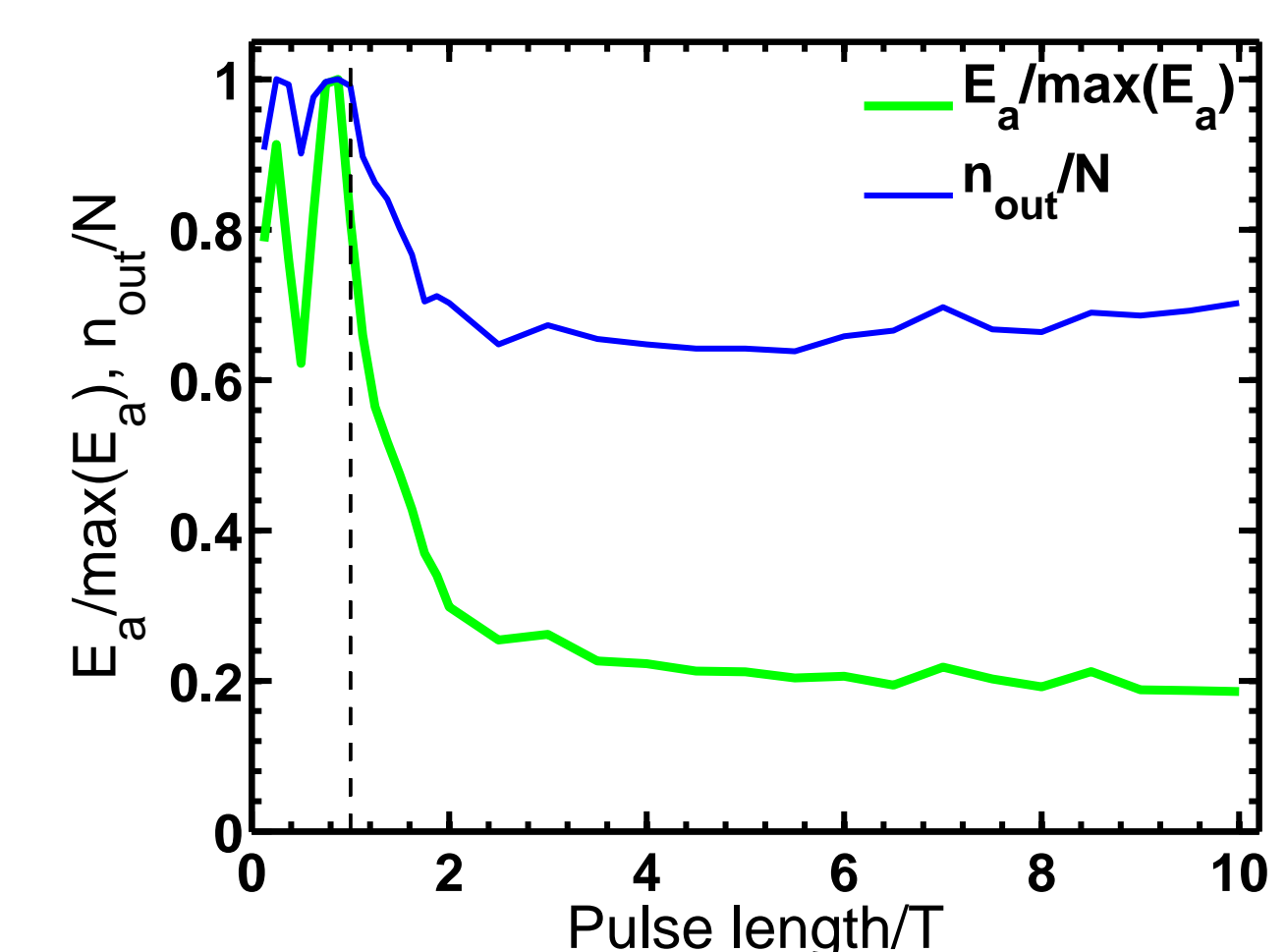


Figure 9: PIC results of normalized energy absorption $E_a/\max(E_a)$, outer ionization n_{out}/N vs τ/T for the same Deuterium cluster with pulse model of Eq.(2). We keep pulse energy fixed at a certain value and decrease the pulse length τ .

- Absorbed energy and outer ionization almost constant for $\tau/T > 2$.
- But $E_a/\max(E_a), n_{out}/N$ increases with decreasing pulse length for $\tau/T < 2$ and reaches a maximum value close to $\tau = 0.8T$ as before.

8 Discussion

- A new regime of laser cluster interaction is initiated through this work. It is shown that for pulse length below two laser cycles (≈ 5 fs) laser-cluster coupling is significantly higher than the long pulse case.
- Note that for Deuterium $\omega_M \approx 3\omega_1$. LR can not occur unless $\tau/T < 1$.
- For $\tau/T = 2 - 16$, $\omega_M > \omega_i$ (plasma remains overdense), and the absorption process is solely due to NLR for all corresponding ω_i 's.
- For $\tau/T = 1$, one finds $\omega_i = \omega, 2\omega, 0$; plasma is marginally overdense w.r.t. $\omega_2 = 2\omega$, NLR becomes more efficient due to the decrease of the relative density $\rho/\rho_c(\omega_2)$ w.r.t. $\omega_2 = 2\omega$.
- In passing from $\tau/T = 2$ to $\tau/T = 1$ increased absorption and outer ionization occurs because of the gradual decrease of the ratio $\rho/\rho_c(\omega_2)$ w.r.t. ω_2 that drives NLR more efficiently (note that the NLR at the central frequency ω always occurs in PIC).
- For $\tau/T = 0.5$, the frequencies are $\omega_i = \omega, 3\omega, \omega$; the laser pulse becomes $E(t) = E_0[\sin(\omega t)/4 - 3\sin(3\omega t)/4]$. In this case LR (for 3ω component) and NLR (for ω component) works together, but the opposite sign of the two components seems to reduce each others contribution resulting absorption and outer ionization below the respective peak values.

References

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3. M. Kundu, D. Bauer, Phys. Plasmas 15, 033303 (2008).