Computational study of ultra-high intensity laser pulse interacting with near-critical density plasmas

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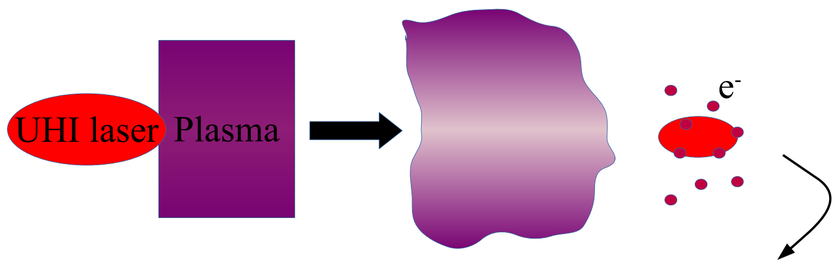
At the interaction between an ultra-high intensity laser pulse ($I \geq 10^{18} W/cm^2$) with a plasma, the plasma constituents will absorb a significant part of the laser energy and will be accelerated up to relativistic velocities for electrons. The laser energy absorption depends on the interaction regime which is determined by the laser and the target parameters. Studies like [1:5] present different interaction regimes which lead to different absorption efficiency.

We investigated the laser energy absorption in the case of an ultra-short high intensity laser pulse interacting with a near critical density target. We want to model the energy transfer from laser to plasma constituents, in the transition from the transparent to less transparent regime, and to optimize the ion acceleration. We tested our model through 2D PIC simulations performed with SMILEI [6]. The ion acceleration results are in good agreement with [7, 8].

Theoretical model of laser energy absorption in plasmas

Laser energy ⇒ absorbed energy in hot electrons



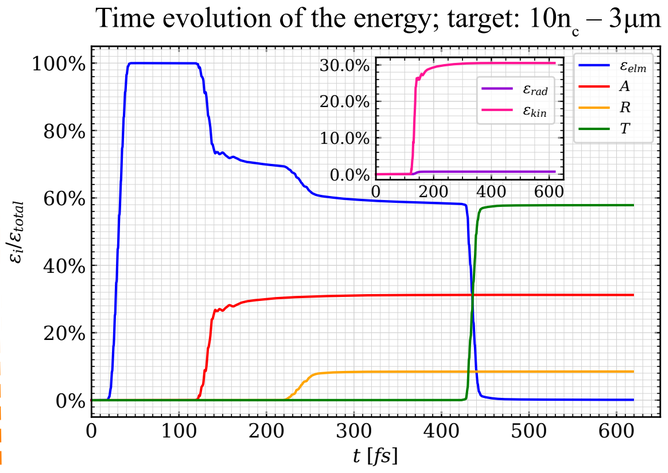
Optimum target thickness for maximum absorption

$$\frac{L_0}{\lambda} = 0.195 \cdot \eta \cdot a_0^2 \cdot \frac{\tau_L}{t_0} \cdot \frac{m_e c^2}{\varepsilon_{el,avg}} \cdot \frac{n_c}{n_{e0}} \cdot \frac{1}{\lambda_{\mu m}^3}$$

2D PIC Simulation results on laser energy absorption

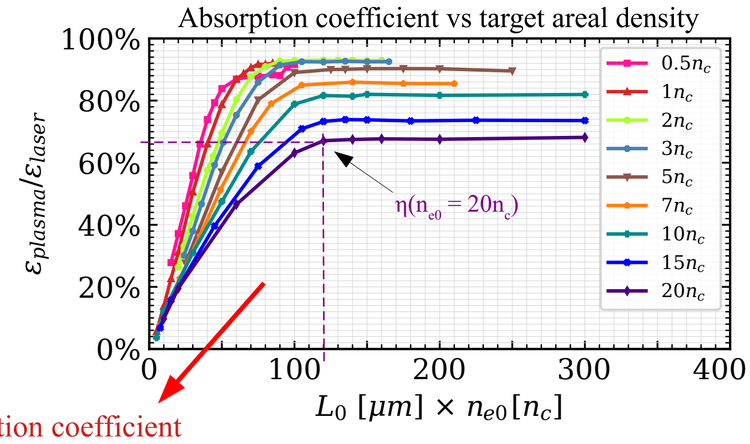
$a_0 = 85$

Time evolution of the energy; target: $10 n_c$ – 3µm



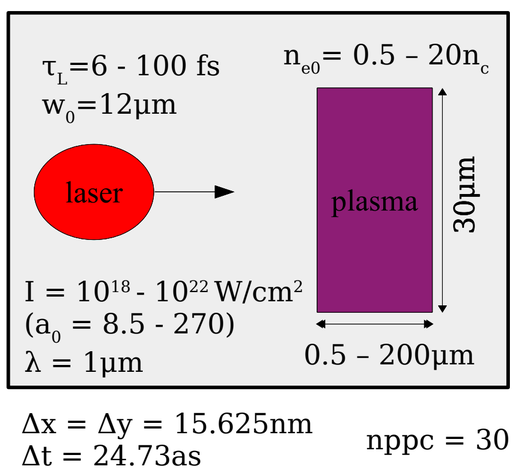
A – absorption;
R – reflection;
T – transmission

Absorption coefficient vs target areal density

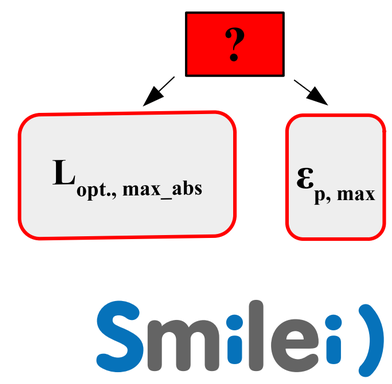


the absorption coefficient reaches a plateau

2D PIC Simulation setup



Δx = Δy = 15.625nm
Δt = 24.73as
nppc = 30



Smilei

$$\varepsilon_{el,avg} = \sqrt{1 + \frac{a_0^2}{2}} m_e c^2 \left(1 + \frac{n_c}{n_{e0}}\right)$$

average hot electron energy, semi-empirical formula

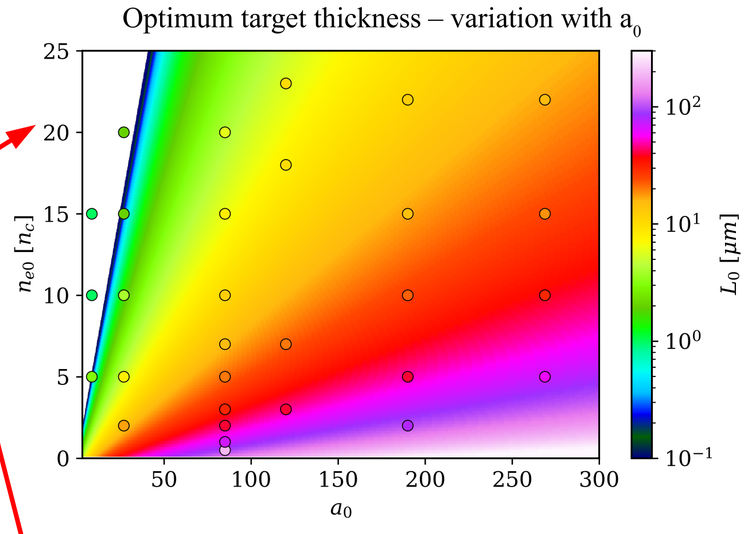
$$\eta = 1 - \frac{4}{a_0} \cdot \frac{n_{e0}}{n_c} \cdot \sqrt{\frac{t_0}{\tau_L}}$$

absorption coefficient, semi-empirical formula

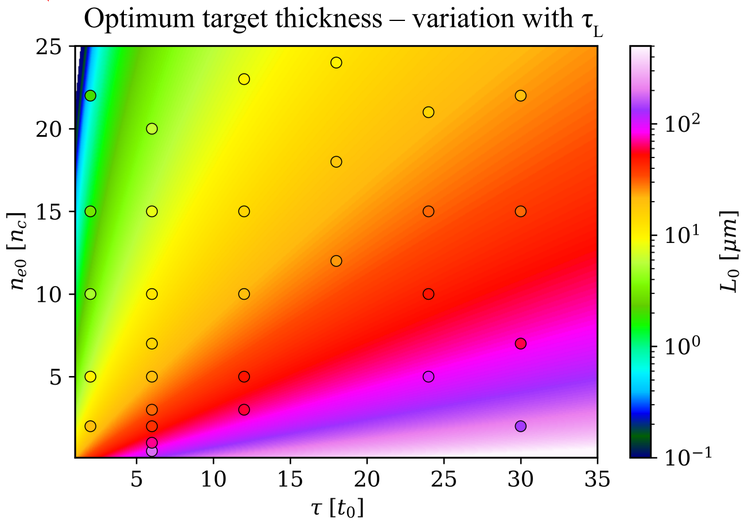
no variation with τ_L was observed

very good agreement between the theoretical model and the simulation results for a wide range of parameters

Optimum target thickness – variation with a_0



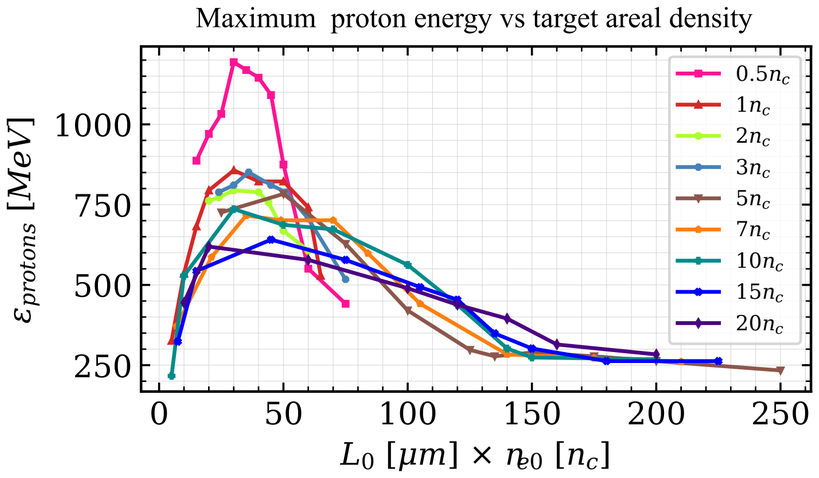
Optimum target thickness – variation with τ_L



2D PIC Simulation results on proton acceleration

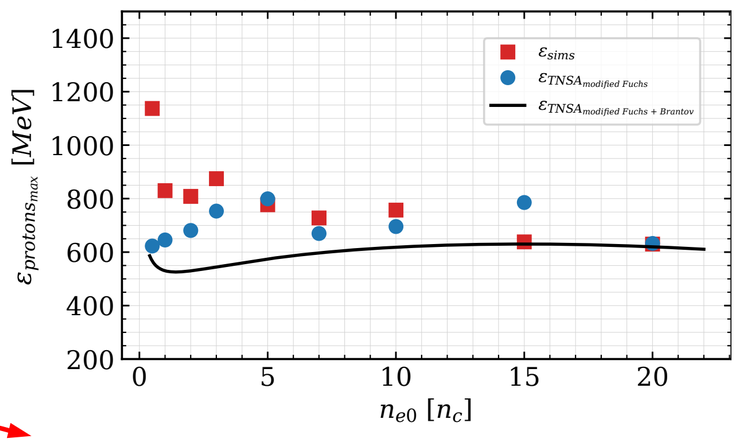
a_0=85; τ_L =20fs

Maximum proton energy vs target areal density

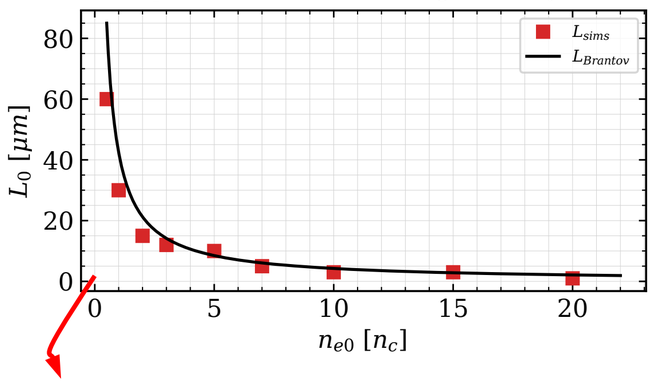


optimum areal density for proton acceleration is reached before the absorption is maximized

Maximum proton energy in the optimum case vs target density



Optimum thickness vs target density



very good agreement with:

$$L_{ion,th[7]} = 0.5 \cdot a_0 \cdot \lambda_0 \cdot \frac{n_c}{n_{e0}}$$

in good agreement with:

$$\varepsilon_{max,TNSA[8]} = 2 T_{hot} \cdot \ln\left(t_p + \sqrt{(t_p^2 + 1)}\right)^2$$

References

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Conclusions

- We proposed the first model for laser-plasma energy transfer including all laser and target parameters in the ultra short high laser intensity regime for near-critical density targets.
- We found a semi-empirical model for the average hot electron energy, based on the ponderomotive scaling and the simulation results, and on the absorption coefficient, based on the reflection coefficients.
- The absorption model could be used to guide maximum absorption in plasma for studying the generation of hot electrons and the generation of high energy radiation.
- The scaling of [7] at ultra-high intensities could be used for applications requiring high energy protons and for preparations of experiments at the Apollon and ELI laser facilities.
- The most predominant mechanism of proton acceleration is TNSA in the range of parameters studied.

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