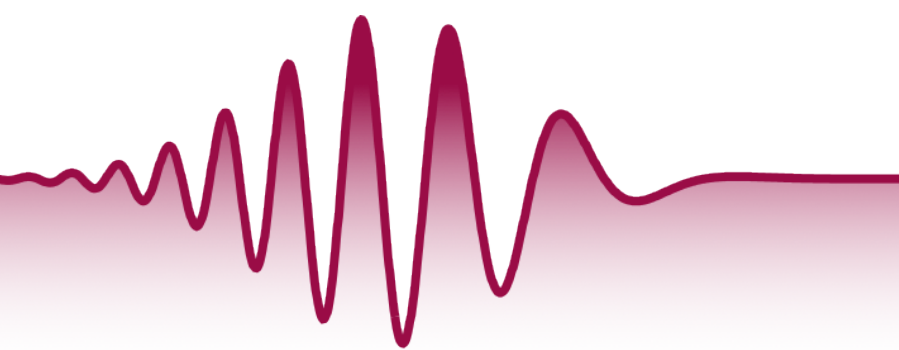




# Modification of fused silica with temporally shaped femtosecond laser pulses

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**Abstract:** Temporal Airy pulses enable enhanced control of ultrashort-pulse laser modifications in transparent materials by redistributing the laser-induced plasma along the propagation direction. In fused silica, they produce ultranarrow craters extending several micrometres into the material, with significantly enhanced aspect ratios compared with Gaussian pulses. The modifications were characterized by FIB cross-sectioning and SEM and modelled in COMSOL Multiphysics®. A system of differential equations was solved using the Mathematics interfaces to describe the plasma-mediated energy deposition, while the Heat Transfer Module was used to calculate the subsequent thermal response. A temperature threshold was implemented to modify the computational mesh and estimate the ablated volume. The simulations reproduce the experimentally observed elongated crater morphology, supporting subsurface plasma formation as the mechanism responsible for the enhanced modification depth.

## 1. Motivation

Femtosecond laser processing of transparent dielectrics is governed by nonlinear absorption processes that generate free electrons, transfer energy to the lattice, and ultimately determine material modification and ablation. In bandwidth-limited (BWL) pulses, the high peak intensity leads to rapid free-electron generation near the surface, resulting in strong plasma shielding that restricts energy penetration into the material. To overcome this limitation, temporal pulse shaping can be employed to modify the interaction dynamics. In this work, the influence of bandwidth-limited, group-delay-dispersed (GDD), and temporally shaped Airy/TOD pulses on fused silica is investigated using a coupled numerical model in COMSOL Multiphysics®. The simulations implement the Mathematics interfaces for the solving of the differential equations and the Heat Transfer Module for the determination of the ablation region. We demonstrate that temporal pulse shaping significantly affects electron density, electron temperature, lattice heating, and energy deposition depth. While BWL pulses produce the strongest surface plasma, GDD and TOD pulses distribute the energy over a longer time scale, reducing plasma shielding and enabling deeper energy deposition.

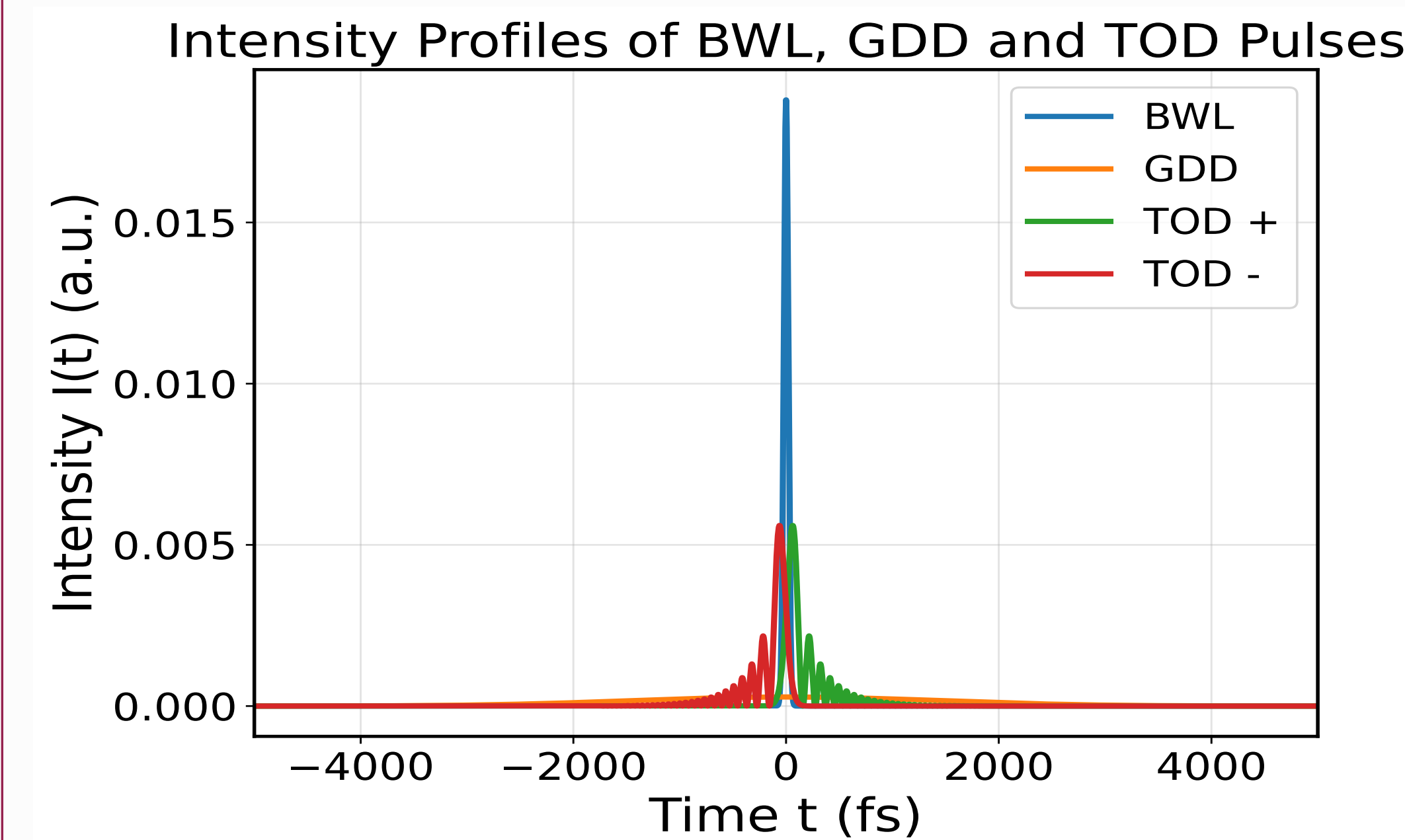
## 2. Model

The simulation is based on a coupled description of laser energy absorption, electron dynamics, carrier generation and lattice heating.

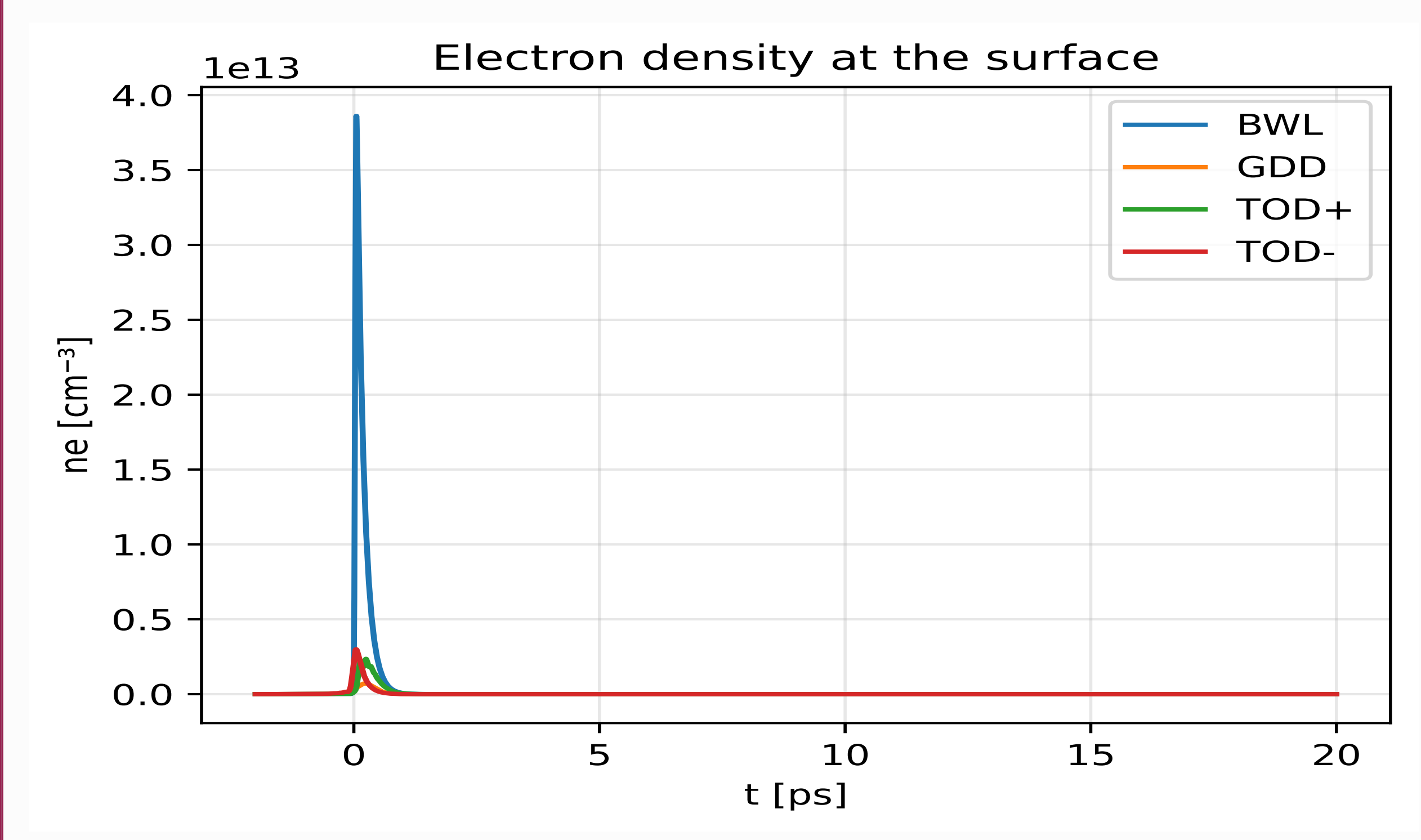
$$\frac{\partial \mathcal{E}}{\partial z} = i \Delta_{\perp} \mathcal{E} - i \frac{k''}{2} \frac{\partial^2 \mathcal{E}}{\partial t^2}$$
$$C_e \frac{\partial T_e}{\partial t} = \nabla(k_e \nabla T_e) - g(T_e - T_l) + Q$$
$$C_l \frac{\partial T_l}{\partial t} = \nabla(k_l \nabla T_l) + g(T_e - T_l)$$
$$\frac{\partial N}{\partial t} = W_{\text{MPI}} + W_{\text{ava}} - \frac{N}{\tau_r}$$

- Variables and parameters:**
- $T_e$  Electron temperature [K]
  - $T_l$  Lattice temperature [K]
  - $N$  Free-electron density [ $\text{m}^{-3}$ ]
  - $C_e$  Electron heat capacity
  - $C_l$  Lattice heat capacity
  - $k_e$  Electron thermal conductivity
  - $k_l$  Lattice thermal conductivity
  - $g$  Electron-lattice coupling factor
  - $Q$  Laser source term
  - $W_{\text{MPI}}$  Multiphoton ionization rate
  - $W_{\text{ava}}$  Avalanche ionization rate
  - $\tau_r$  Carrier recombination time

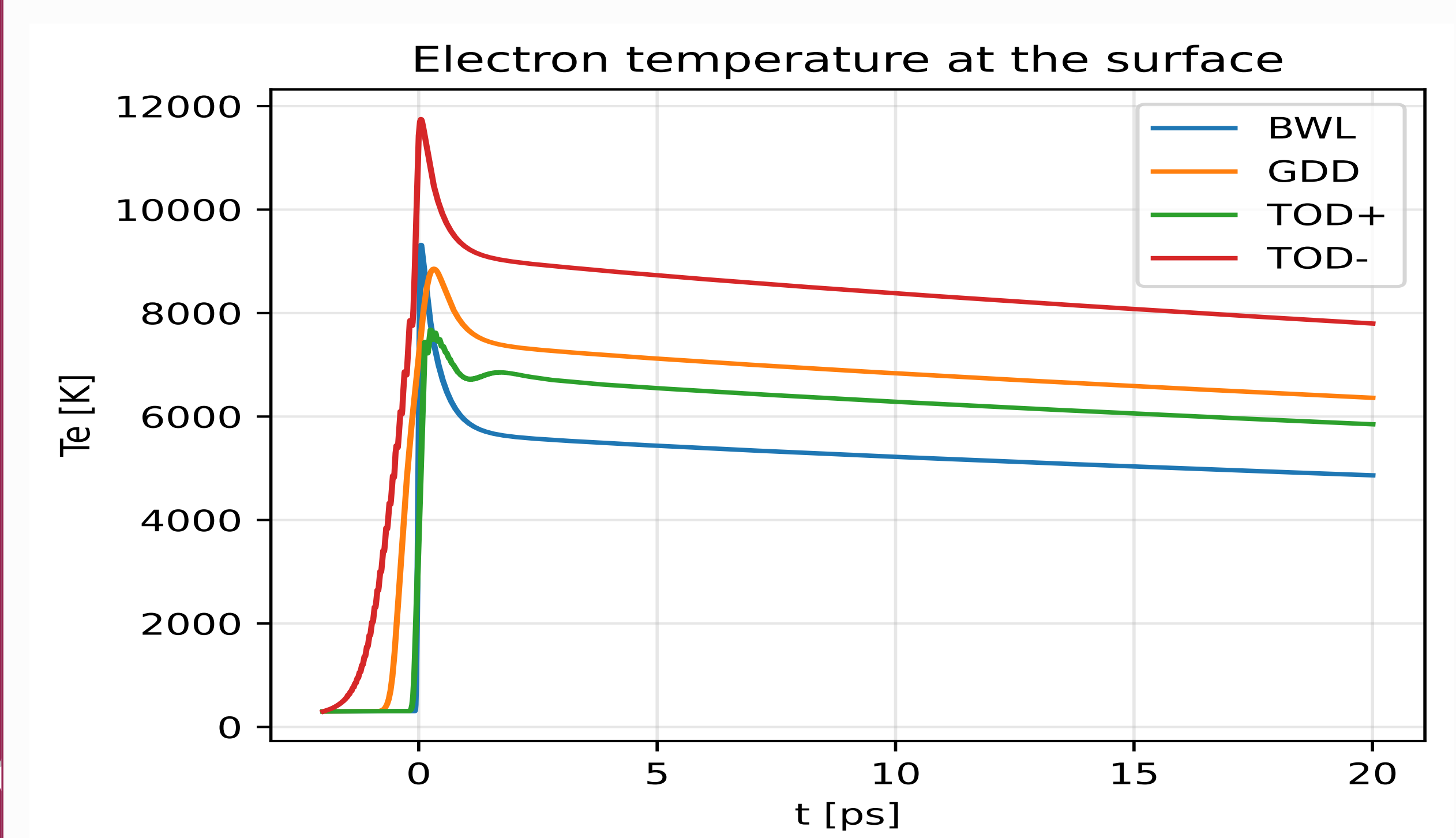
## 3. Pulse Shapes



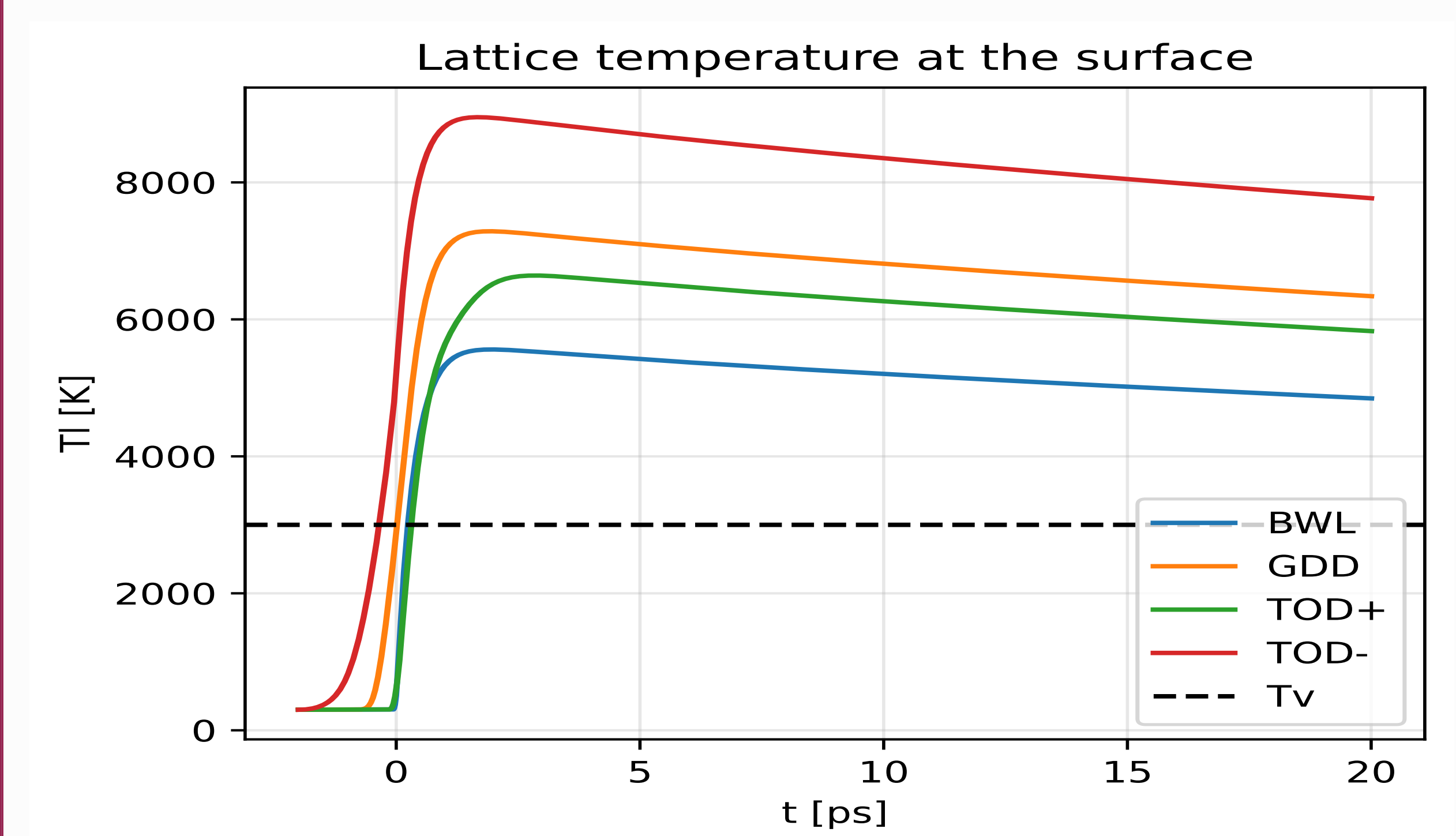
## 4. Electron Density



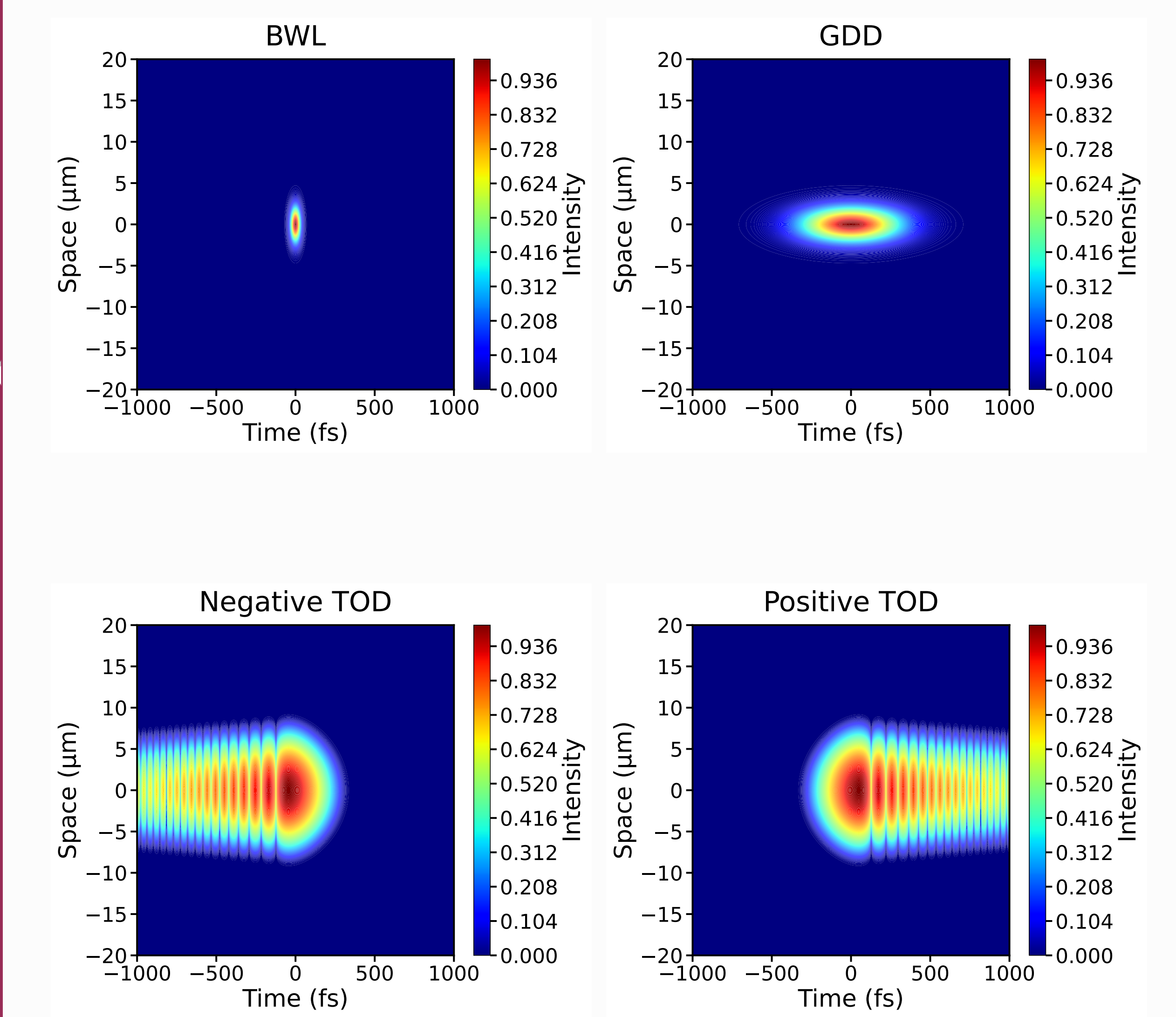
## 5. Electron Temperature



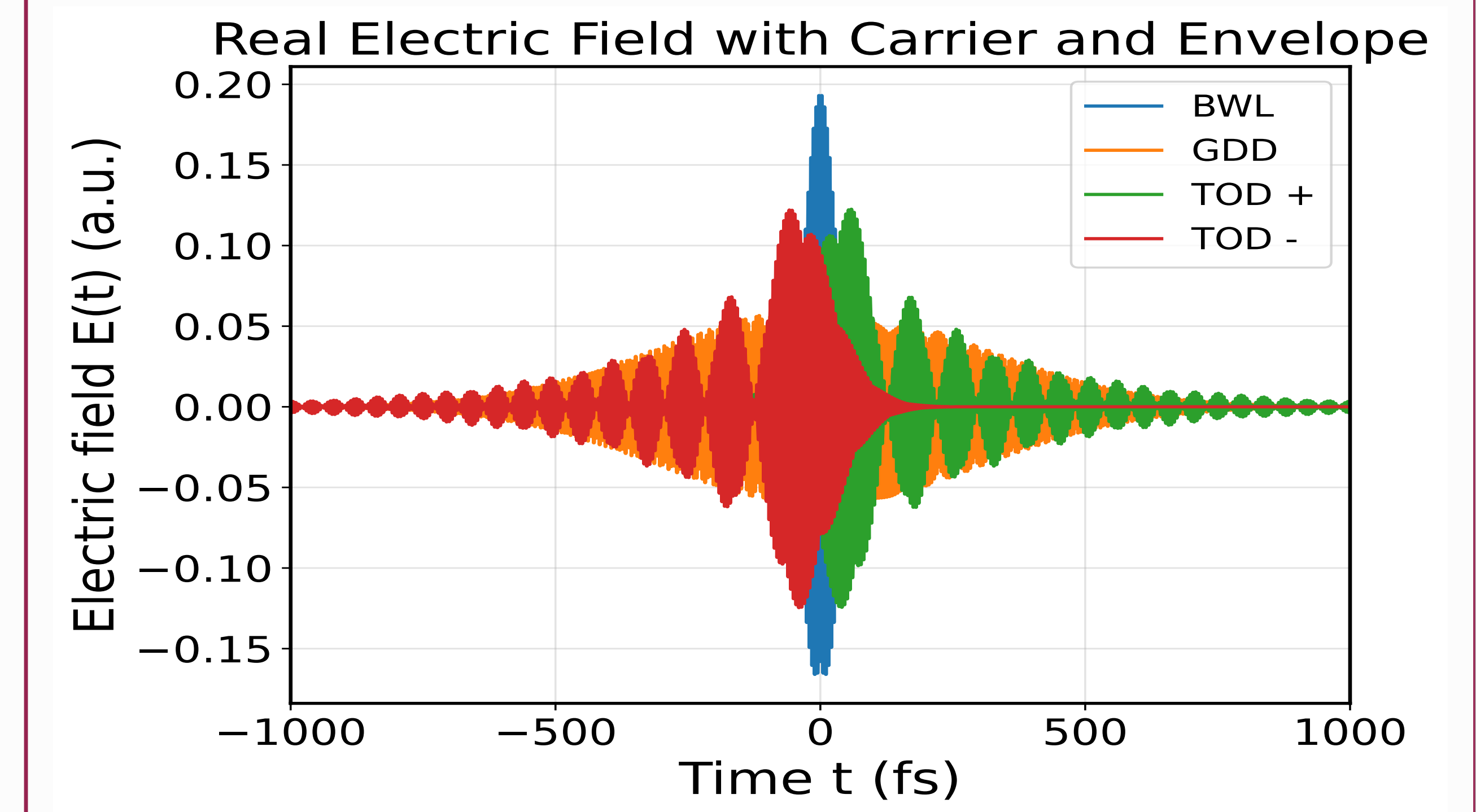
## 6. Lattice Temperature



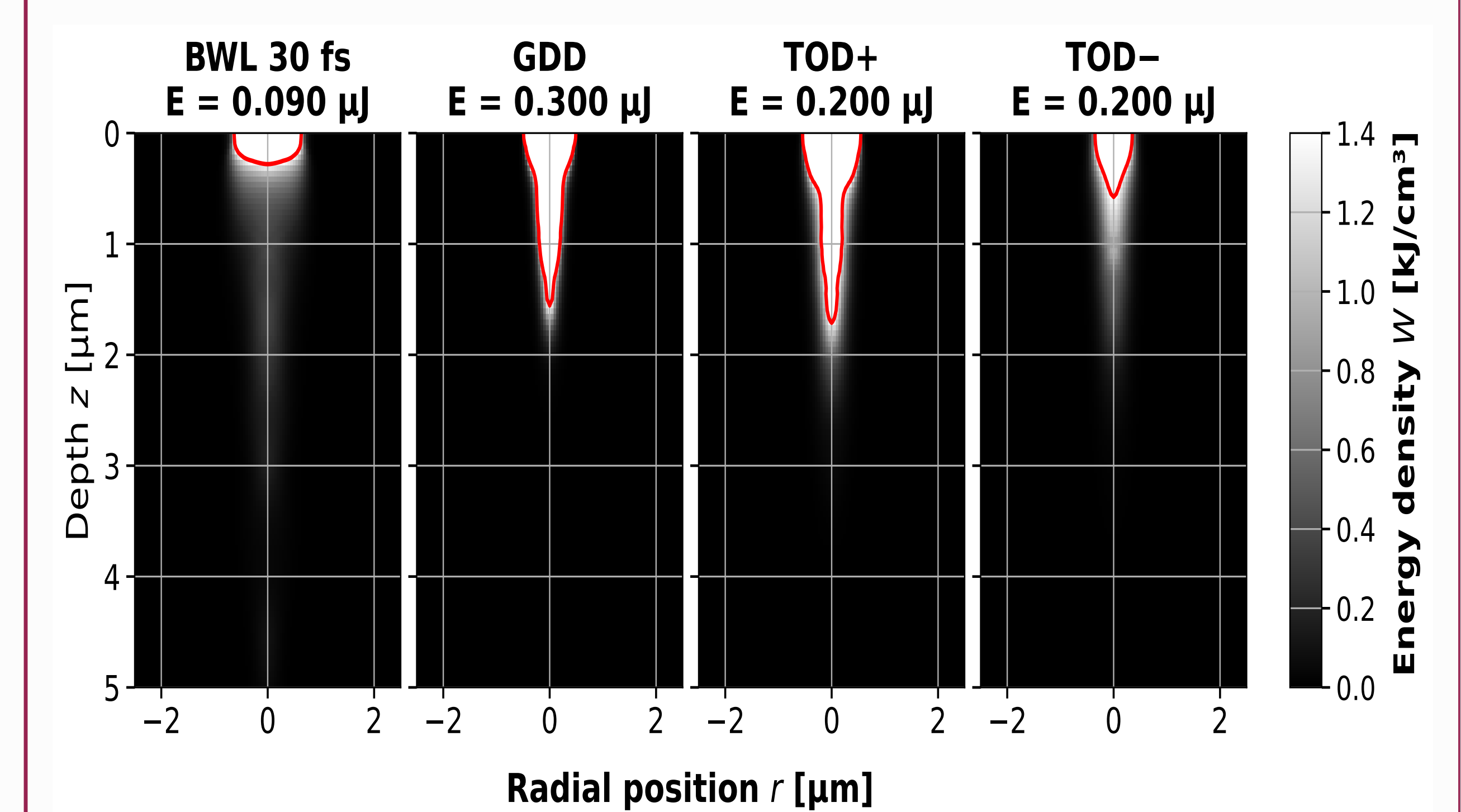
## 7. Spatio-Temporal Intensity



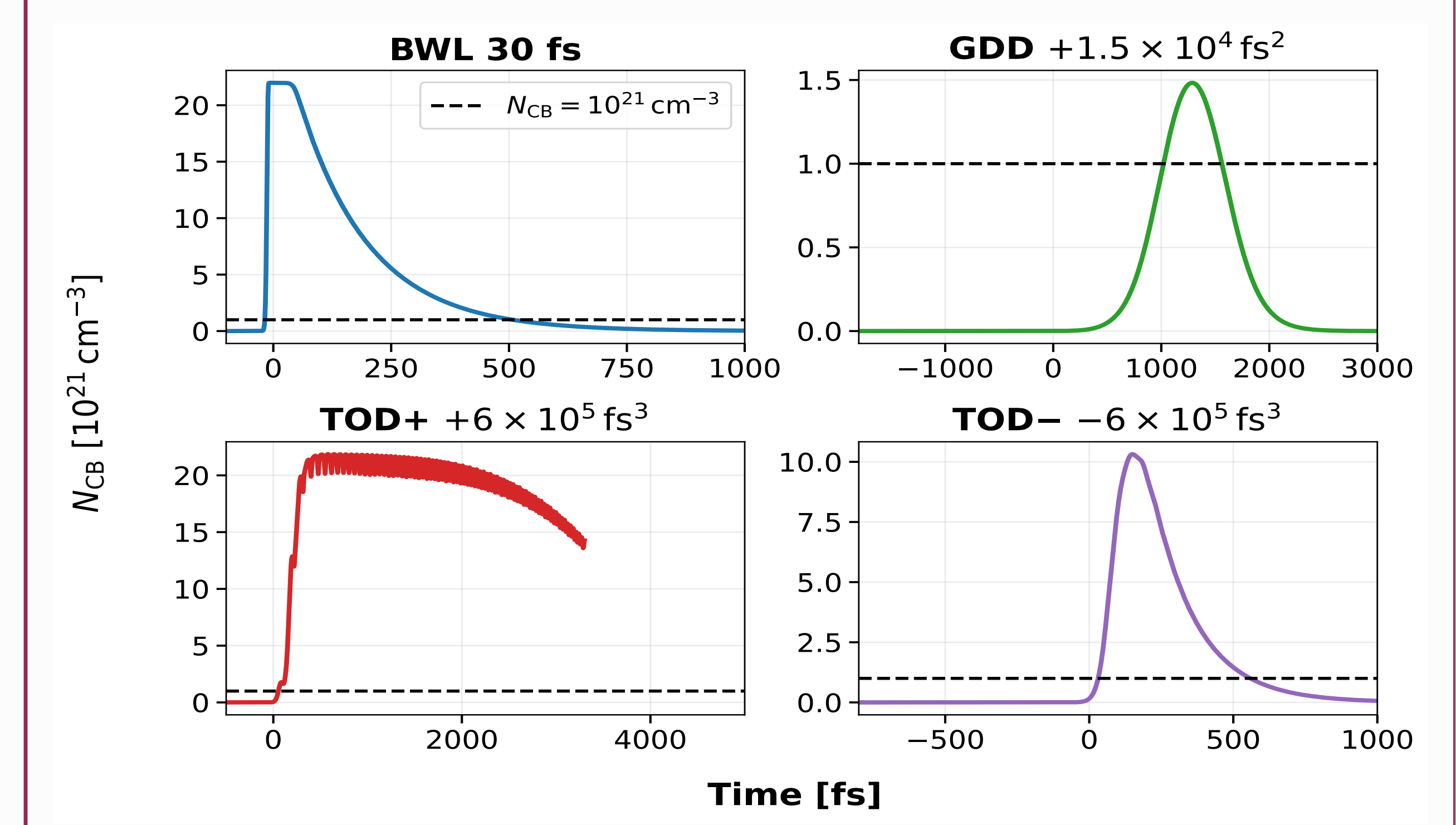
## 8. Electric field



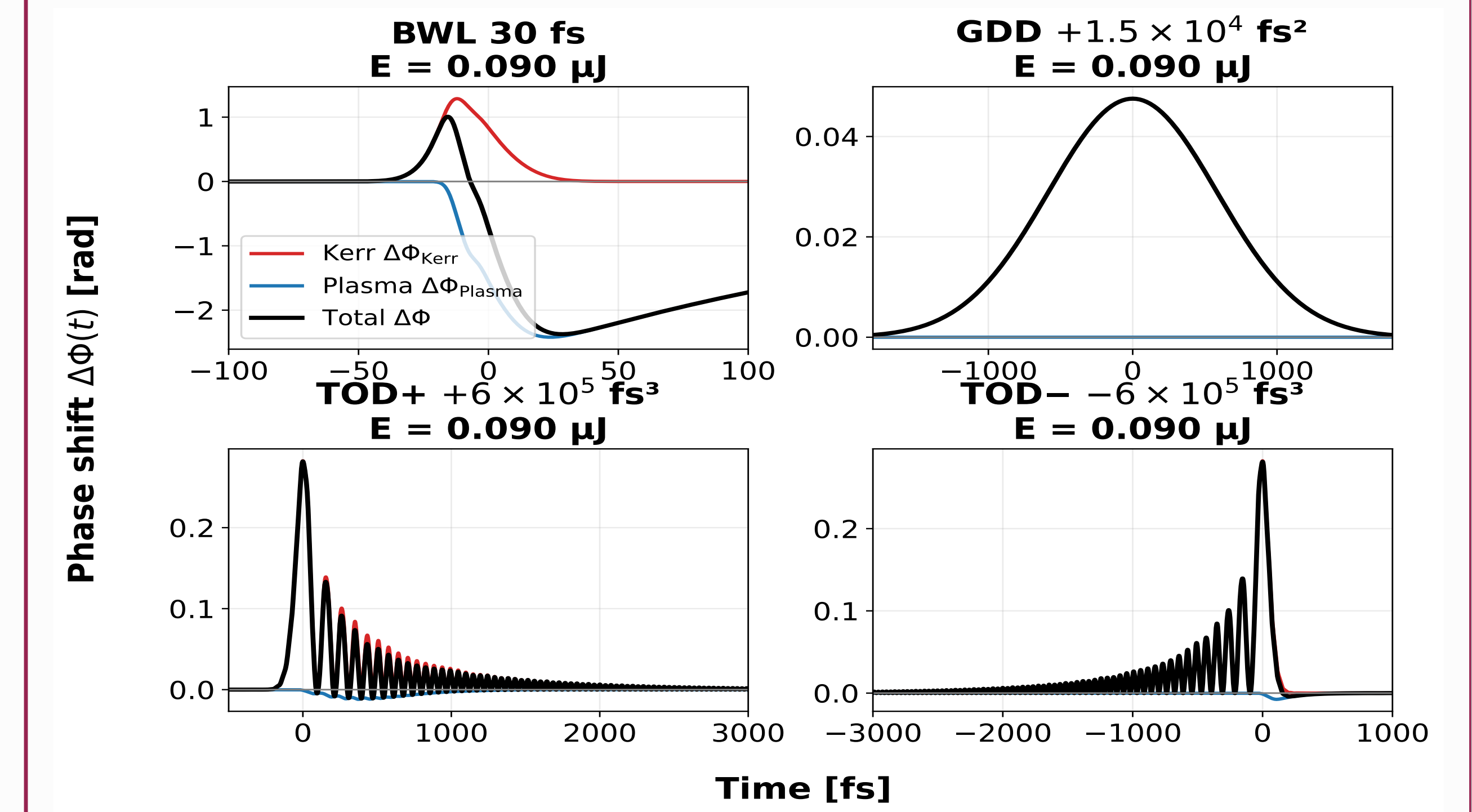
## 9. Ablation Geometry



## 10. $N_{CB}$ Electron density



## 12. Phase Modulation



## Conclusions

The simulated results reproduce with high fidelity the crater-like formation typical from temporal Gaussian ultrashort pulses, and the filamentation induced by the other temporal pulse shapes. It should be noted that the current calculations do not include non-linear transient optical effects, however, they represent a good approximation to forecast the resulting topography for the irradiation of fused silica and potentially other high band-gap materials.

## References

- [1] N. Götte, et al. Optica 3, 389-395 (2016) [2] L. Englert, et al. Opt. Express 15, 17855-17862 (2007)