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Optical Probing of Ultrafast Laser-induced Transitions from Solid to Overdense Plasma

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Outline

- Motivation
  - Laser-driven ion acceleration
- Methods
  - ***Experiment***: Single-Shot Space & Time – Resolved Probe Transmission
  - ***Modeling:*** *SMILEI PIC & Solid state interaction*
- Results
  - Interplay of Ionization processes
  - Overdense Plasma dynamics
- Outlook

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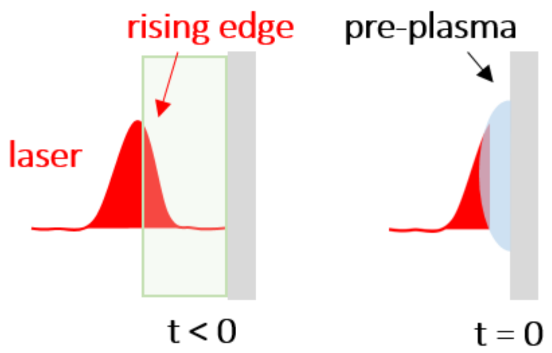
Motivation

Laser-driven ion acceleration

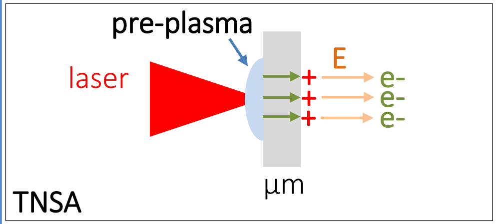
- Optimize **accelerated** ion beams in relativistic laser- ultrathin foil interaction



- *How?*
  - Predict & control target behavior
  - Insight into Pre-Plasma Evolution

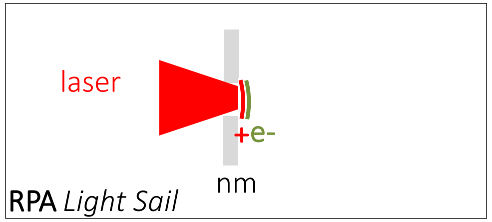
- *Why?*

Surface Interaction



Target Normal Sheath Acceleration

Optimize pre-plasma conditions



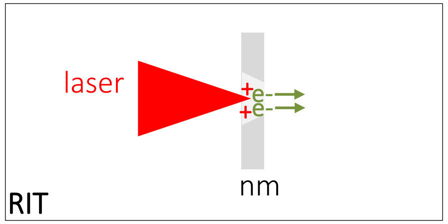
Radiation Pressure Acceleration

Minimize pre-plasma expansion

Mora, PRL 90, 185002 (2003)
Keppler *et al.*, PRR 4, 013065 (2022)

Esirkepov *et al.*, PRL 92, 175003 (2004)

Volumetric Interaction



Relativistic-Induced Transparency

$m_e \rightarrow \gamma m_e$
➢ $\omega_p < \omega_L$
$n_e \sim \gamma n_c$

Transparency of an **overdense plasma** at peak arrival

Palaniyappan *et al.*, Nature Physics 8, 763 (2012)

➡ Need to capture the target behavior before peak arrival

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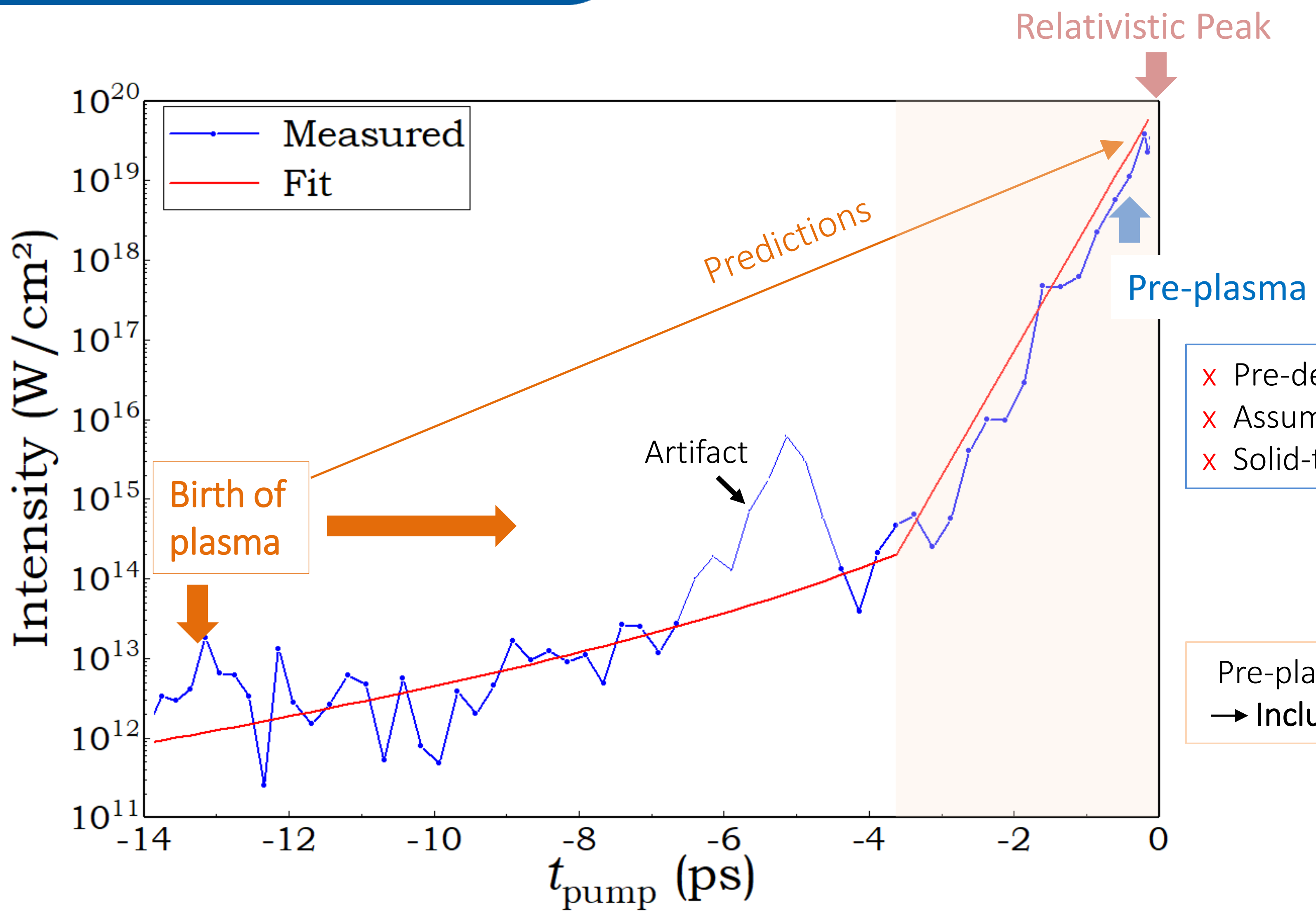
Motivation

Laser-driven ion acceleration



- x Pre-defined
- x Assumptions/ Approximations
- x Solid-to-plasma transition ***not described***

Pre-plasma properties at peak arrival closer to reality
→ Include Solid-to-plasma transition

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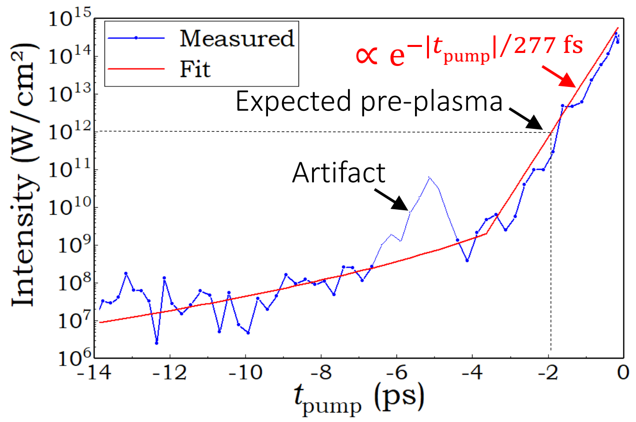
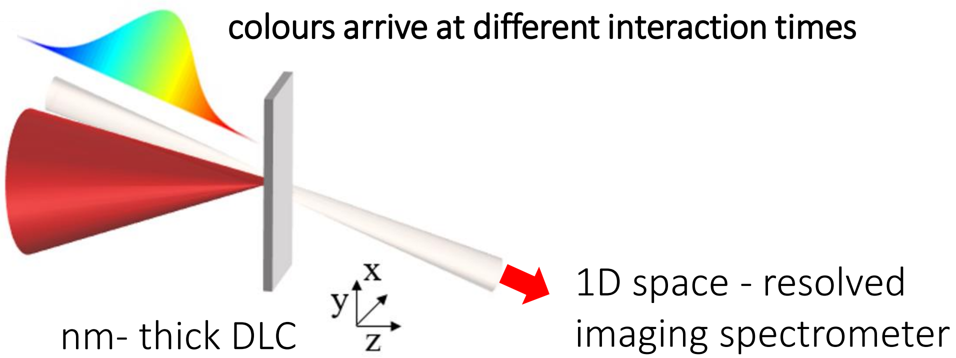
Experiment: Laser - NanoFoil DLC Interaction



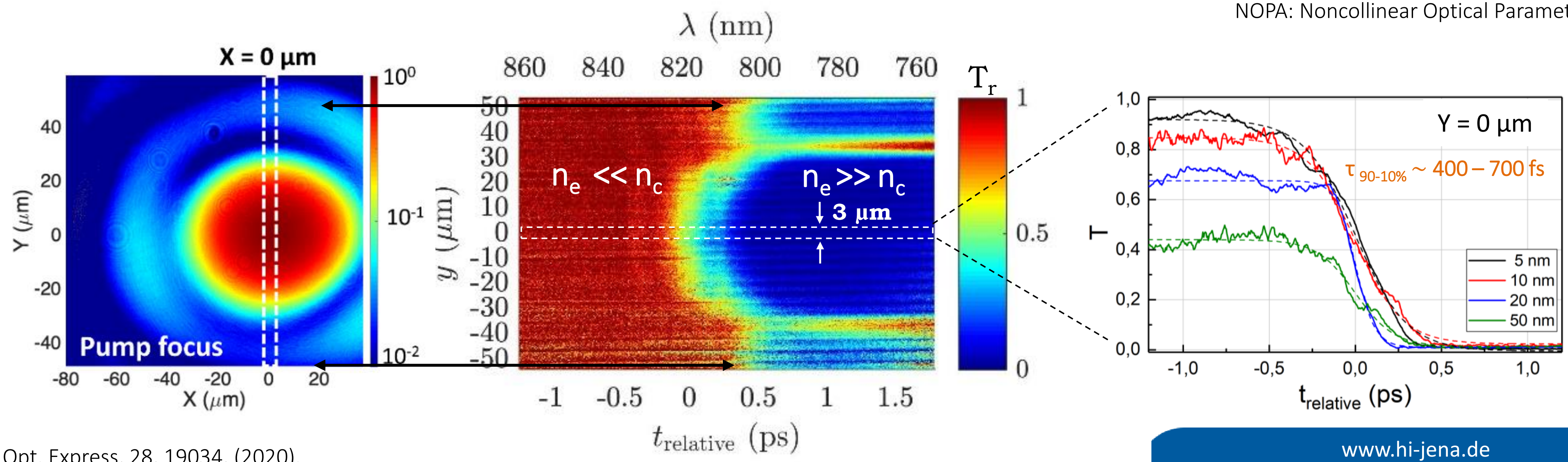
probe pulse
NIR Chirped NOPA*
$\Delta\lambda \sim 150$ nm, $\lambda_c \approx 840$ nm

pump pulse
Polaris, low- energy/
defined focus
$\lambda_c \approx 1030$ nm



DLC: Diamond-like carbon
NIR: Near-infrared
NOPA: Noncollinear Optical Parametric Amplification

- Single Shot 1D Space & Time - Resolved Probe Transmission

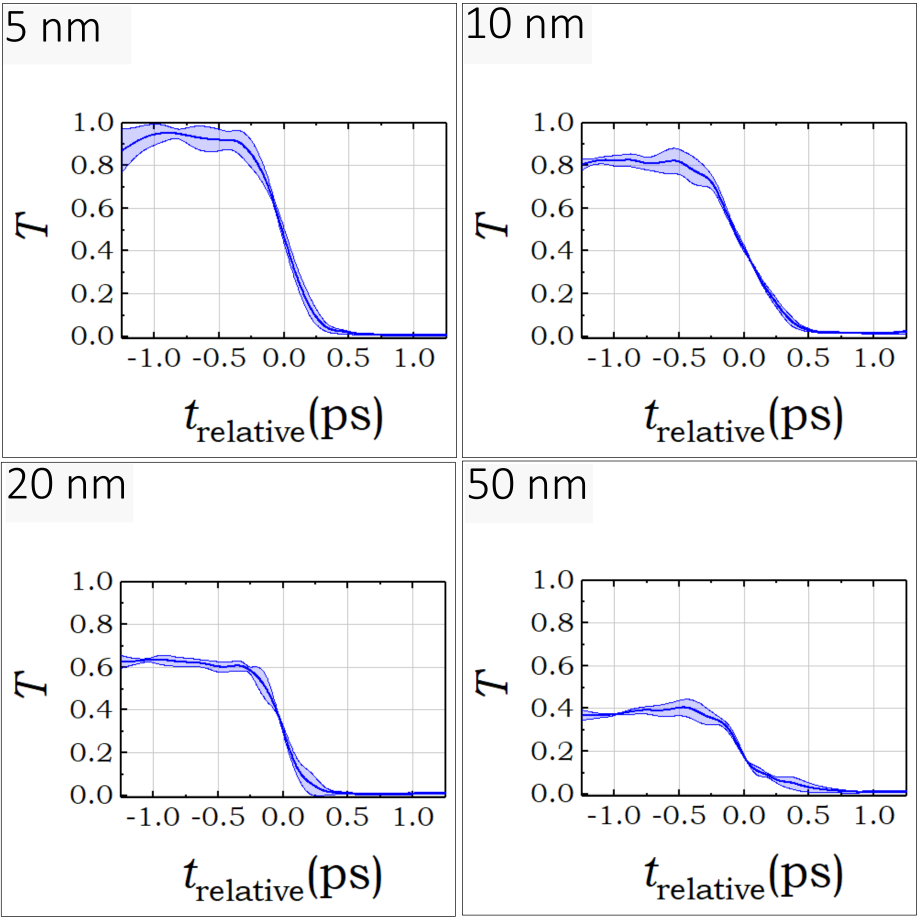


*Tamer *et al.*, Opt. Express, 28, 19034, (2020).

Methods

Experiment: Laser - NanoFoil DLC Interaction

Measured, I ~ $10^{15} - 10^{16}$ W/cm²



1. T profile insensitive to intensity variation

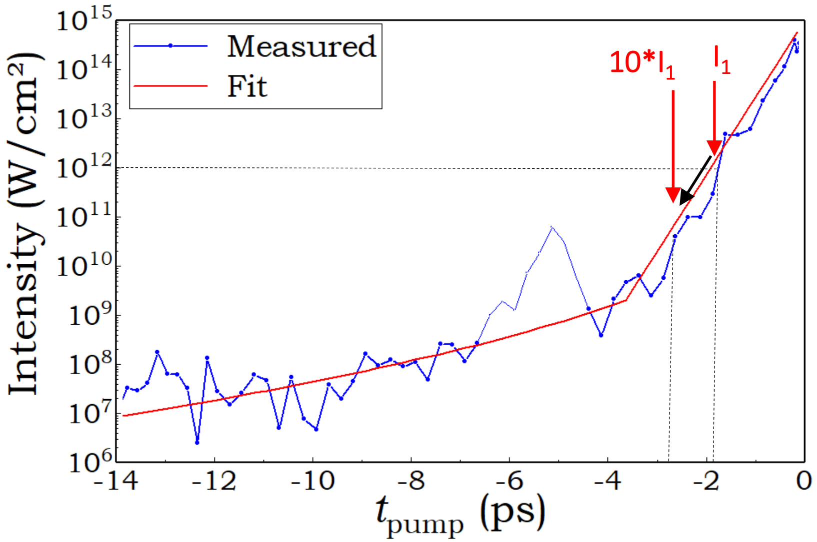
- Plasma always forms during laser rising edge, shifted in time by ~ 1 ps.

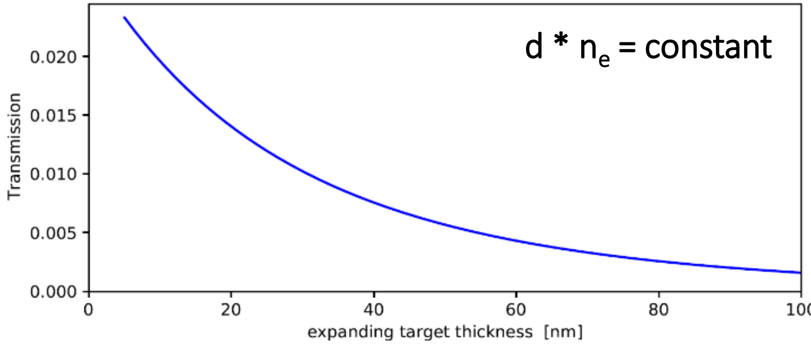
2. T_{exp} < 1 % for 10 & 5 nm

➢ Optical tunneling model through overdense plasma (thickness d):

- d =10 nm, $n_e = 50n_c$ ⟶ **T ≈ 26 % >> T_{exp}**
- d = 5 nm, $n_e^{max} = 371n_c$ ⟶ **T ≈ 2.5 % > T_{exp}**

$n_c \approx 1.7 \times 10^{21}$ cm^{-3} for λ_{probe} = 800 nm





Evidence of

- Sub-picosecond dynamics
- Plasma formation during laser rising
- $n_e >> 10n_c$ plasma
- Plasma expansion

➡ **Modeling**

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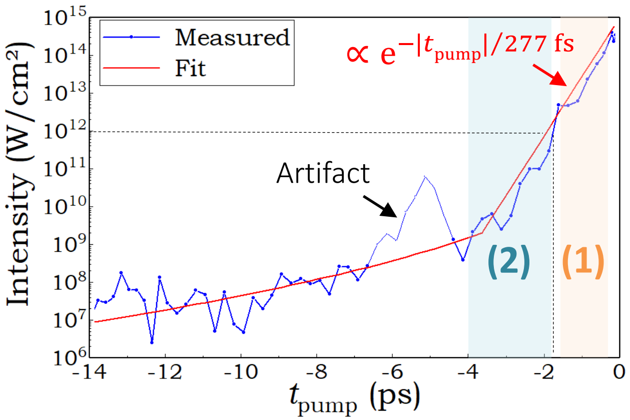
Methods

Modeling: PIC, Solid State interaction model

Interaction Model → $n_e(t)$

Maxwell Solver + Optical Tunneling → T (t)*

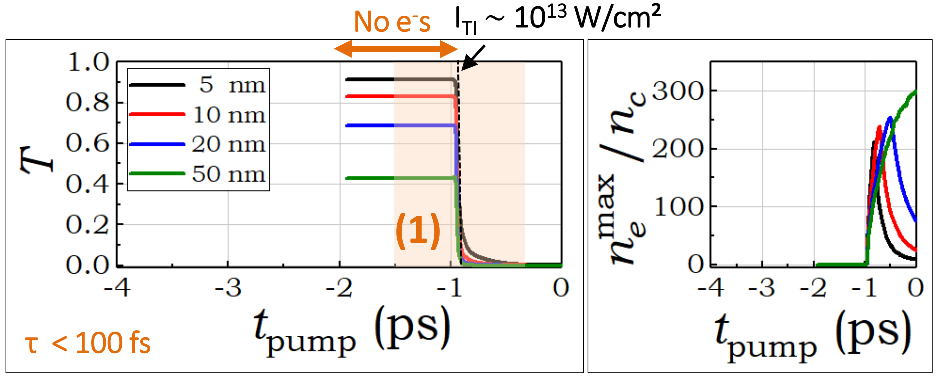


PIC (SMILEI)

n_{solid} cold Carbon nm-slabs

Pump *rising edge*

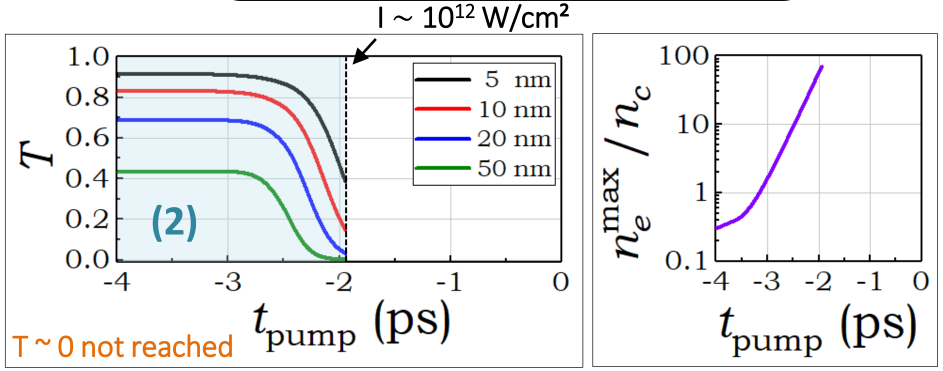
→ *1D Cartesian TI, CI* → n_e, $n_{C\alpha+}$ (z, t), spectra, …



- Free atoms
- Ionization of solid not supported

Solid State Interaction (SSI)

MRE[1], MPI + TI + CI + Avalanche
band gap[2] $E_g \sim 1.1$ eV
Pump temporal profile
Homogeneous plasma slab



- $n_e > 70\ n_c$ not supported
- Inner shells' ionization not supported

➡ **Hybrid model *SSI + PIC* ?**

*λ_{probe} = 800 nm

TI: Tunnel Ionization
CI: Collisional Ionization
MRE: Multiple Rate Equation
MPI: MultiPhoton Ionization

[1]Rethfeld, PRL, 92, 187401, (2004).
[2]Tauc *et al.* Physica Status Solidi, 15, 627, (1966).

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Methods

Modeling: Hybrid

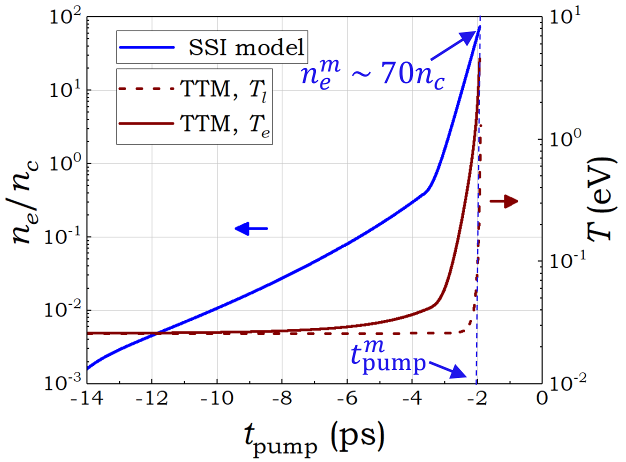
Bridge the codes?

Melting ➡ Non-thermal, starts $n_e \sim 10 n_c$[1]

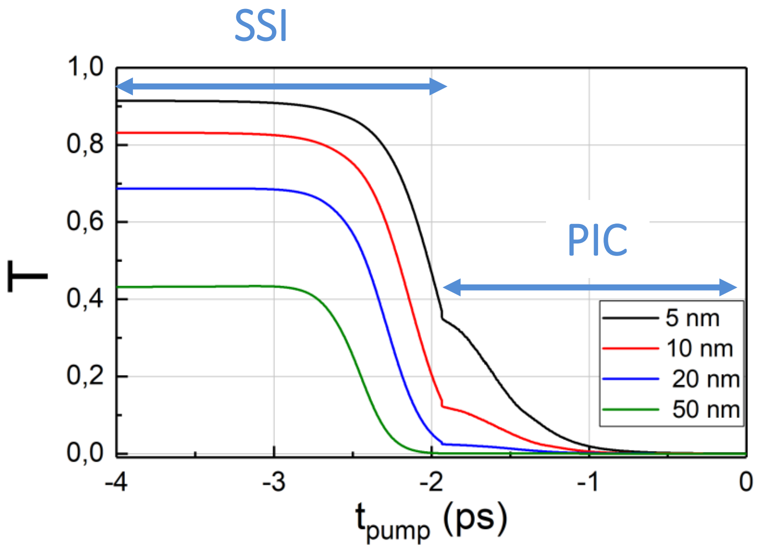
(*DLC semiconductor under continuous, strong and rapidly increasing laser intensity*)

Atomic description ➡ Ions free after ~ 100s fs[1], $n_e^m \sim 70 n_c$

Two-Step Interaction model (TSI)

<table>
<tr><th>1st: SSI</th><th>2nd: PIC (SMILEI)</th></tr>
<tr><td>

TTM: Two-temperature model</td>
<td>
1D cartesian
Homogeneous plasma slab (5 - 50 nm)
$I^m \sim 10^{12}$ W/cm², $I = I^m e^{t/277}$, $0 \le t \le T_{sim}$.
Species: Maxwell-Boltzmann distribution $T_e^m \sim 4.6$ eV, $T_l^m \sim 0.34$ eV
Ion mixture : $n_{C^{1+}} = 54 n_c$, $n_{C^{2+}} = 8 n_c$
L_{sim} = 1 µm, Δz = 0.16 nm, Δt = 5 × 10^{-4} fs, Δt = 0.95 (Δz/c) (CFL) , T_{sim} = 2 ps
</td></tr>
</table>



✓ T ~ 0 reached

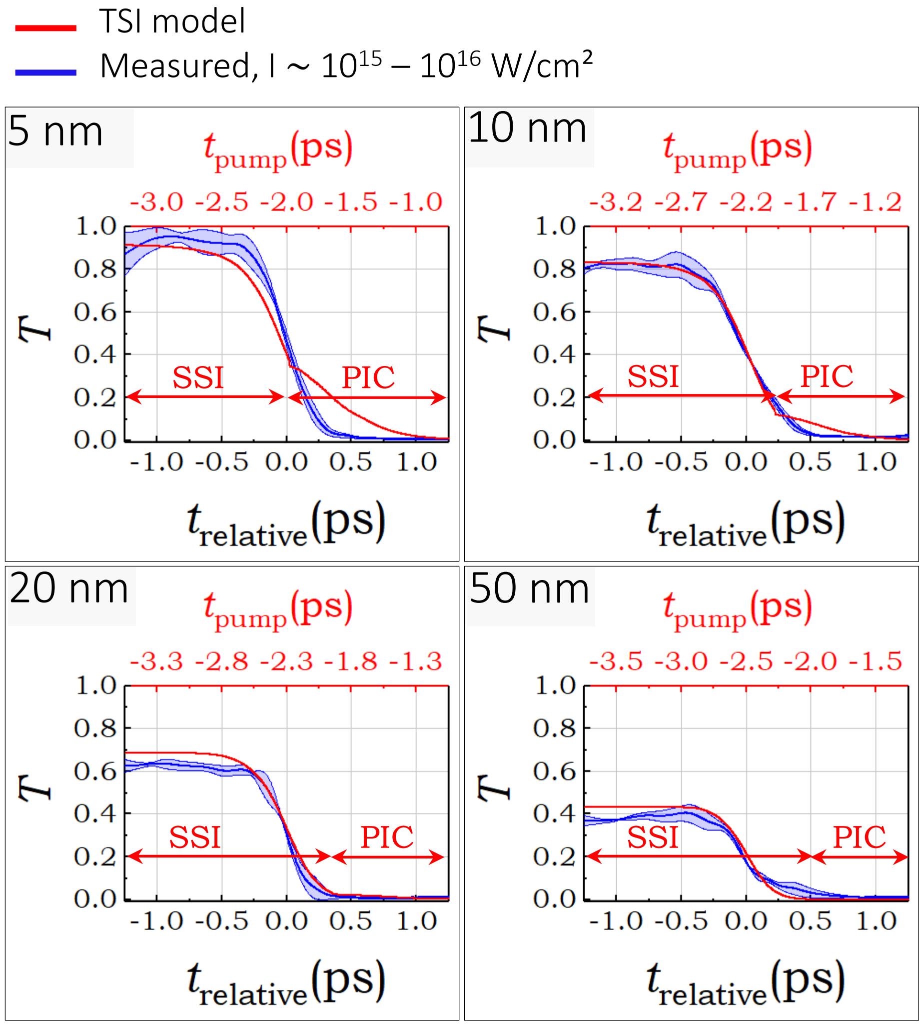
✓ τ_{sim} ~ 100s fs, closer to measurements

$n_{solid} = 62 n_c$

[1]Rousse *et al. Nature,* 410, 65, (2001)

Results

Ionization processes



- ✓ Good agreement : simulation Vs experiment
- ✓ TSI model **required** for targets ≤ 10 nm
  - **Initial phase**: Ionization of Solid
  - **Final phase**: Plasma Expansion (T ~ 0)
- ✓ **Insight into Ionization Processes**

Step 1: SSI	Step 2: PIC (SMILEI)
MPI dominates Free e-s by MPI CI ~ 1%	**CI dominates** Free e-s at I < 10^{13} W/cm² (≈ I_{TI})
TI does not play a role	

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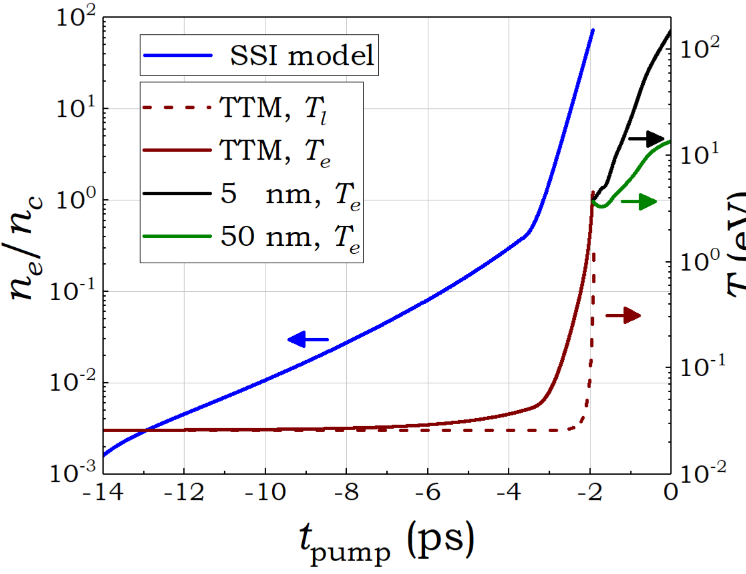
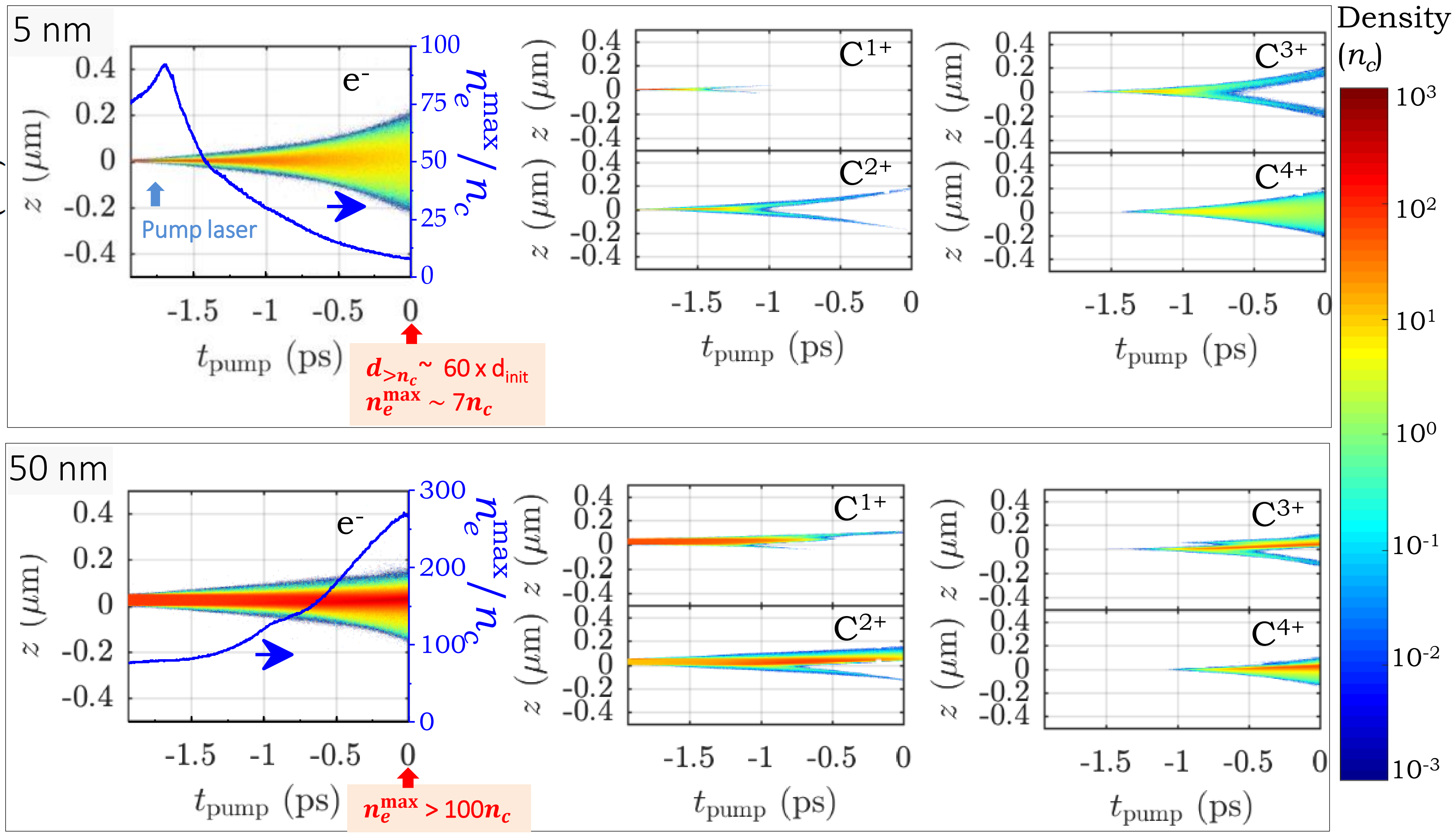
Results

Overdense plasma dynamics





- ✓ Overdense plasma spatio-temporal dynamics
- ✓ Plasma properties before peak arrival described

Outlook

✓ Solid-to-Overdense Plasma Transition described with **a simple approach**:

Experiment

- **Laser – DLC nano-foil Interaction**

Single-Shot Space-Time Resolved NIR Probe Transmission

➢ Evidence of >> 10n_c plasma, sub-ps dynamics & expansion

Modeling

- **Original Two-Step Model**

Solid state interaction + PIC (SMILEI)

➢ Onset / Evolution: Kinetics

✓ Interplay of ionization processes

✓ Overdense plasma dynamics

➢ Towards detailed pre-plasma conditions for relativistic laser-solid interaction

Azamoum *et al.*, under review, arXiv:2309.00303 (2023)

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Acknowledgments

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