Density Oscillation – Applying GISAXS for ultra high intensities

A simulation study of high-intensity laser irradiation of multilayer targets

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Structure

(1) GISAXS – What motivated this study?

(2) Target and Laser – What does the Setup look like?

(3) Target Dynamics – What plasma dynamics do we see?

(4) Density Oscillation – What is Density Oscillation? How can we determine T_e?

(5) Summary and Outlook – What did we learn?

Motivation

- XFEL-Experiments → $I_{Laser} < 10^{16}\ \mathrm{W/cm^{-2}}$ → Promising results!
- Modern laser facilities → $I_{Laser} < 10^{22}\ W/cm^{-2}$ → Can we go there?

Is GISAXS feasible for ultra-high intensities ($> 10^{17}\ W/cm^{-2}$)?

- What we want: Observe relativistic plasma dynamics with GISAXS
- What we need: Dynamics within **time Resolution (~500fs), intact layer structure**
- What we do: Simulation study to predict feasibility

Is GISAXS feasible for ultra-high intensities?

- **What should the target look like?**

  Material? How many layers? Thickness?

- **What dynamics appear? Which are recognizable with GISAXS?**

  Ablation? Compression? Density Oscillation? Particle Acceleration?

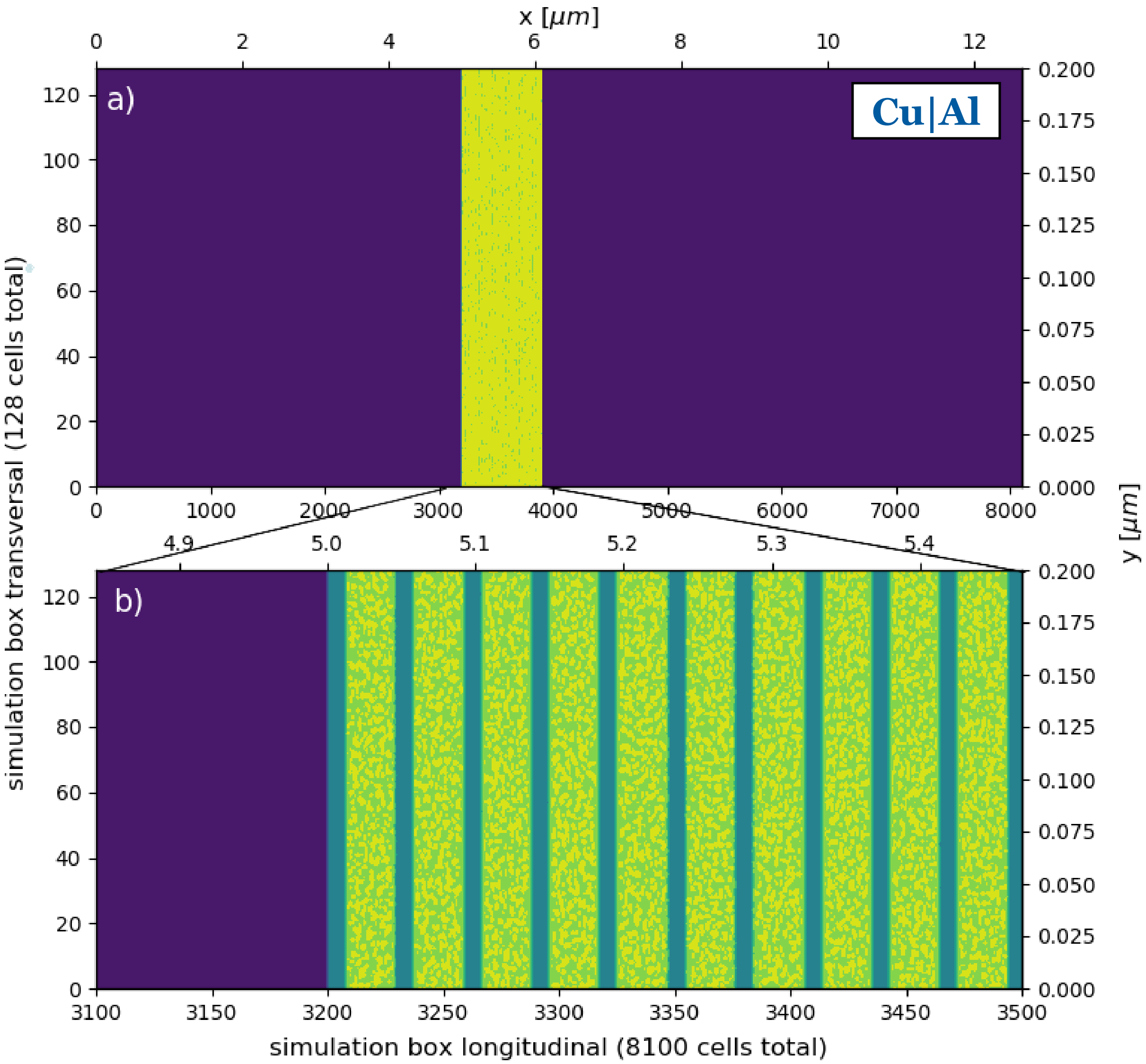
- **What parameters can extract?**

  Can we learn about the ablation velocity v_{abl} or about electron temperature T_e?

- **What time resolution do we need?**

  Are the relativistic dynamics too fast for *in situ* observation?

Target Setup and Laser



Laser: $I = 10^{17} - 10^{21}$ W/cm^{-2}

$\tau = 40$ fs

Target: **Copper, Aluminum Tantalum, Copper Nitrite**

Geometry:

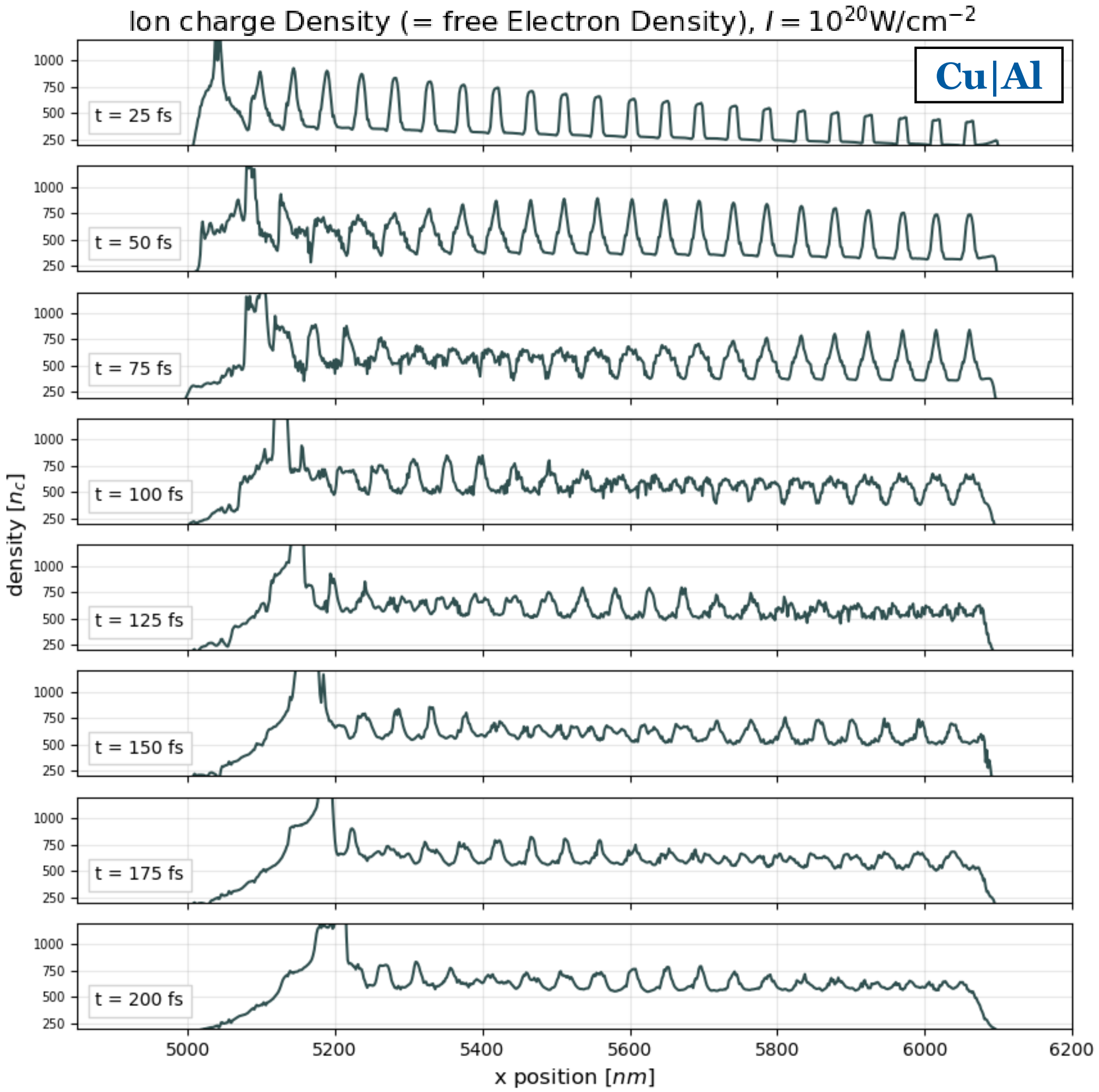
$n_{Layer} = 24$

$d_{Cu/Ta} = 12.55$ nm

$d_{Al/Cu3N} = 33.33$ nm

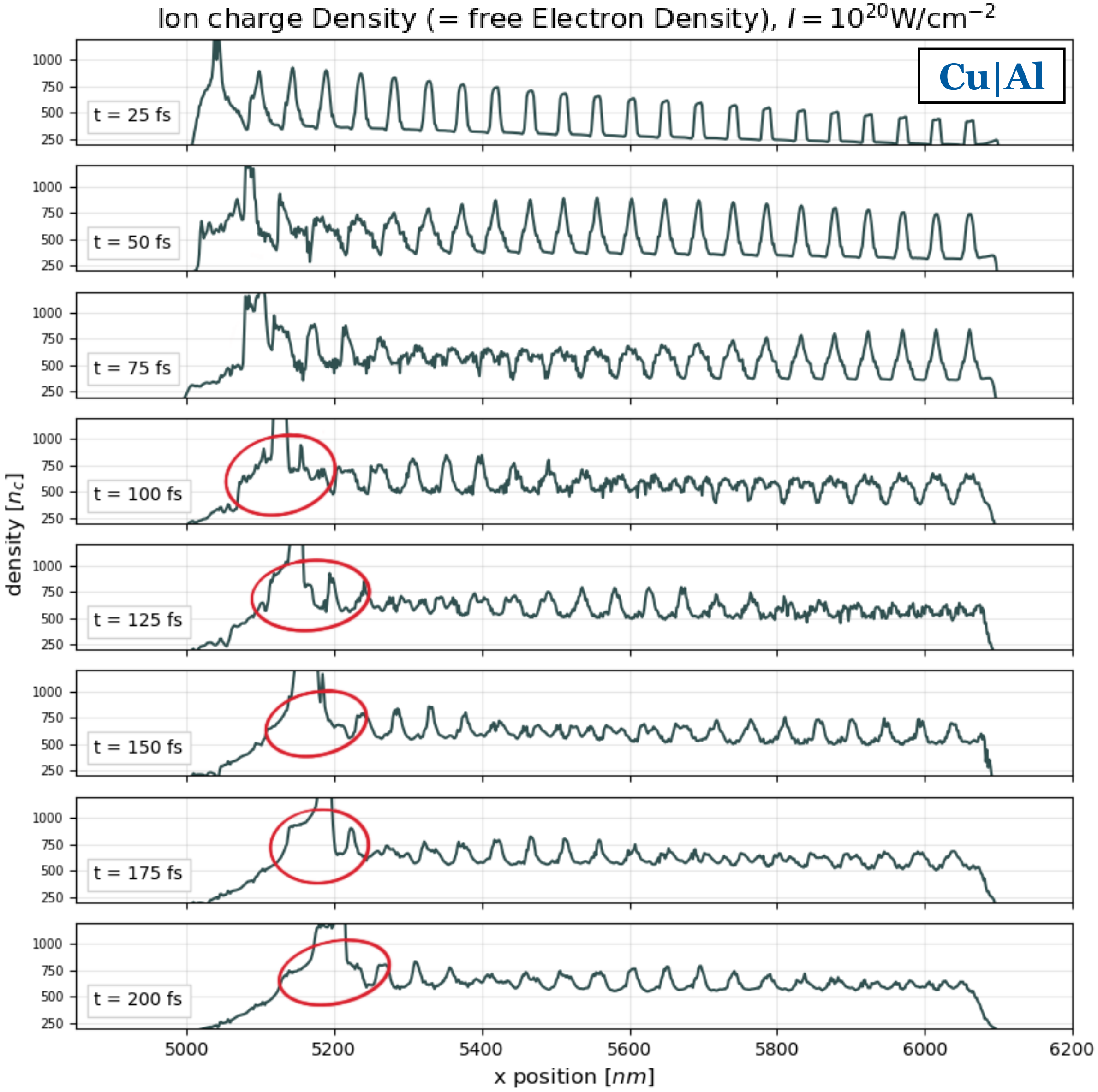
$d_{total} = 1100$ nm

What dynamics appear?



Plasma dynamics:

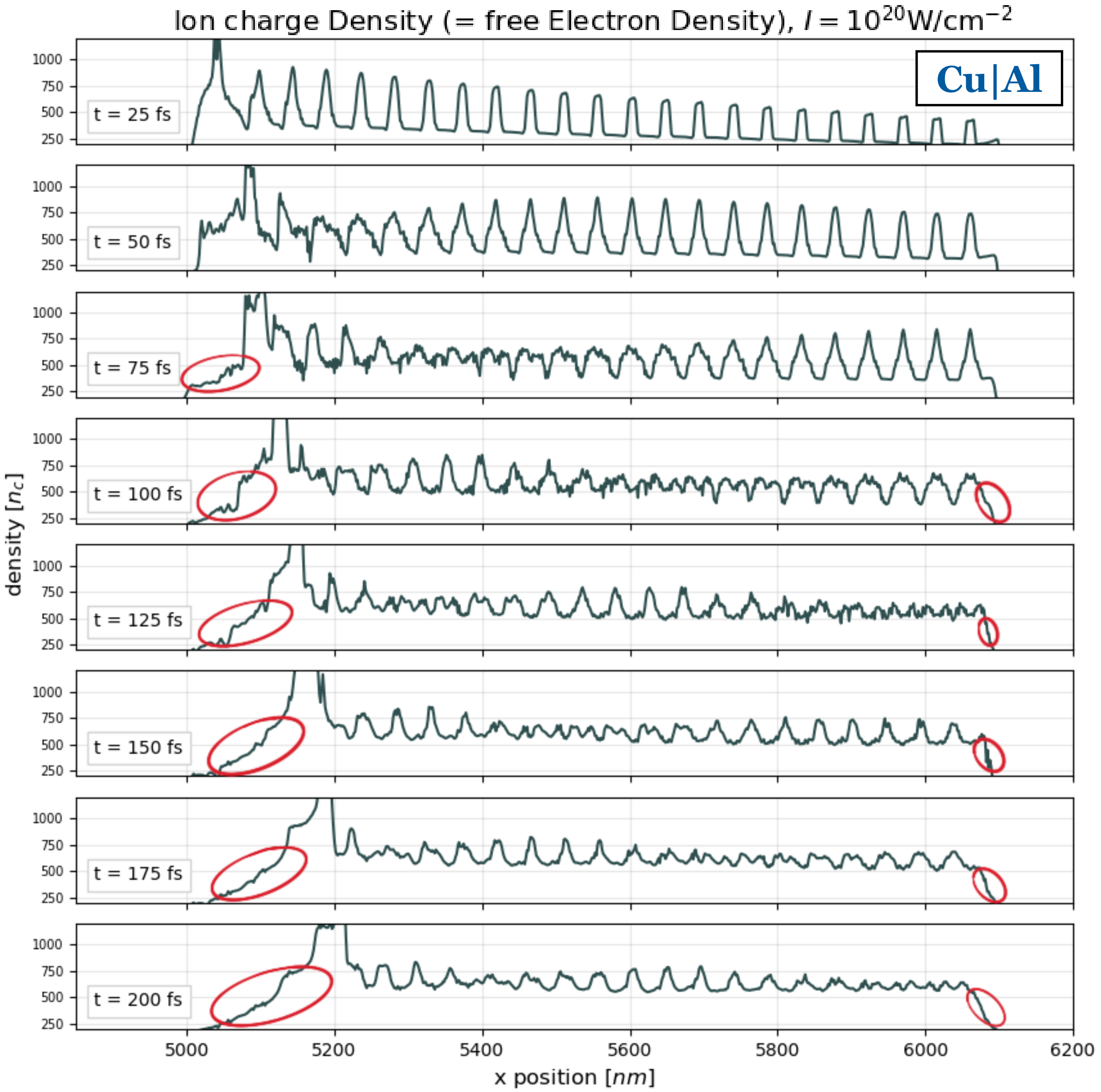
What dynamics appear?



Plasma dynamics:

- **Compression**

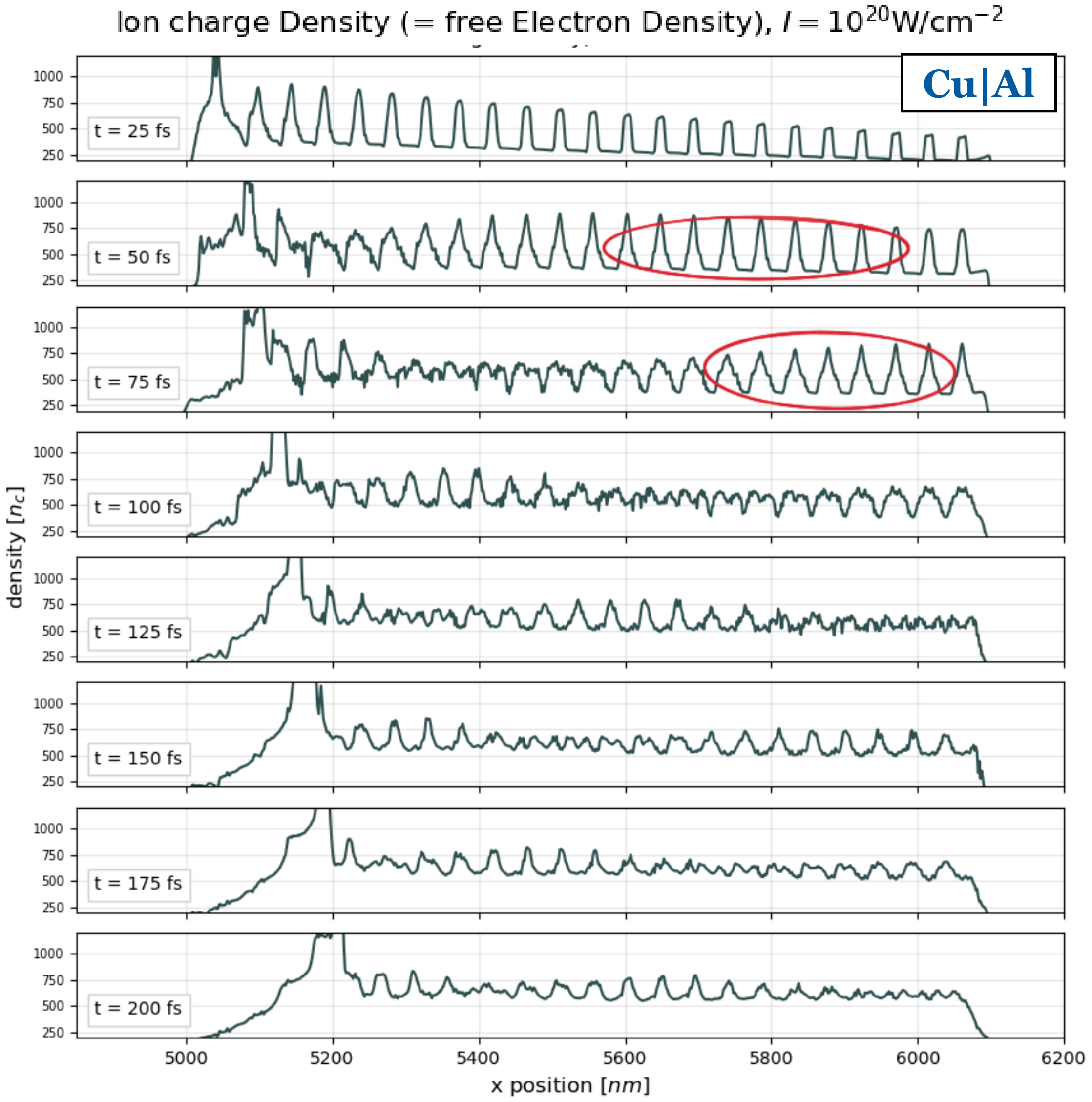
What dynamics appear?



Plasma dynamics:

- Compression
- **Expansion/ Ablation**

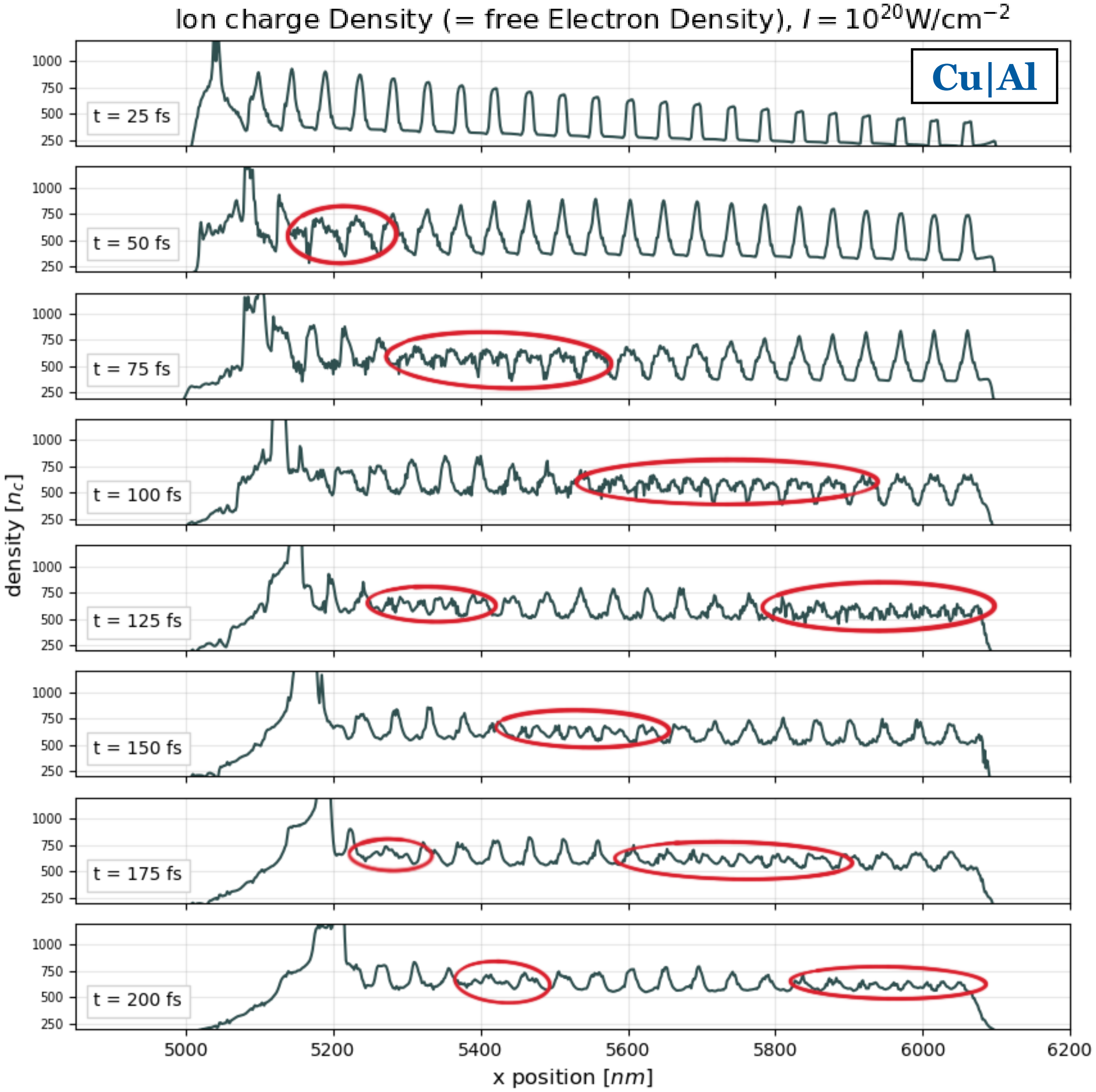
What dynamics appear?



Plasma dynamics:

- Compression
- Expansion/ Ablation
- **Bulk effects e.g. heating**

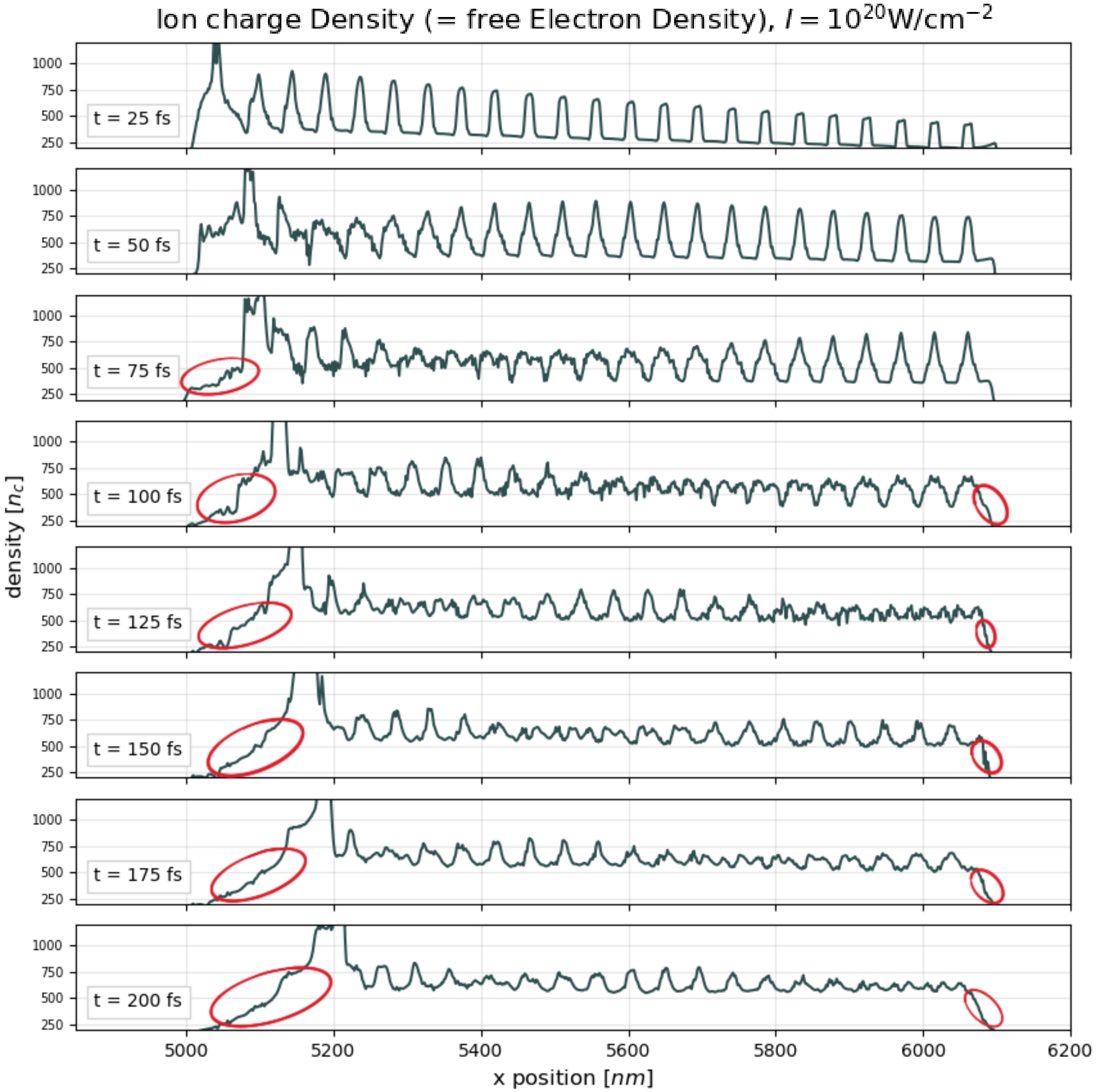
What dynamics appear?



Plasma dynamics:

- Compression
- Expansion/ Ablation
- Bulk effects e.g. layer melting
- **Density oscillation**

What dynamics appear?

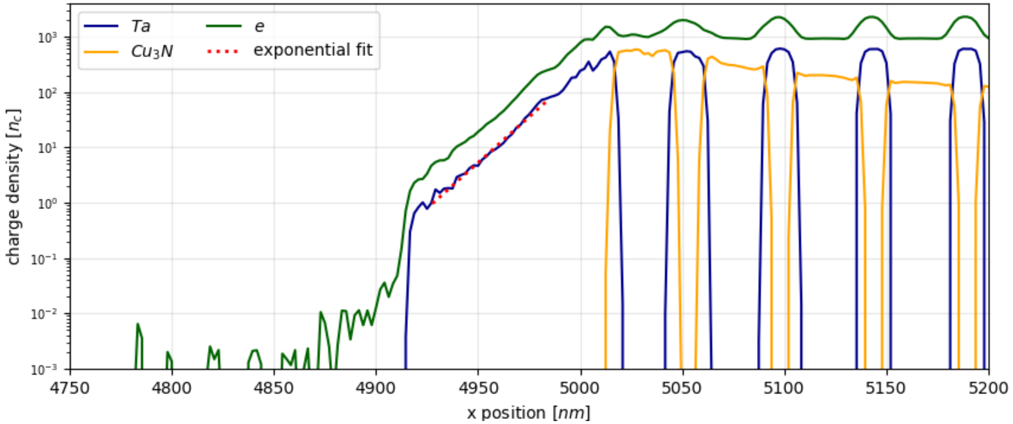


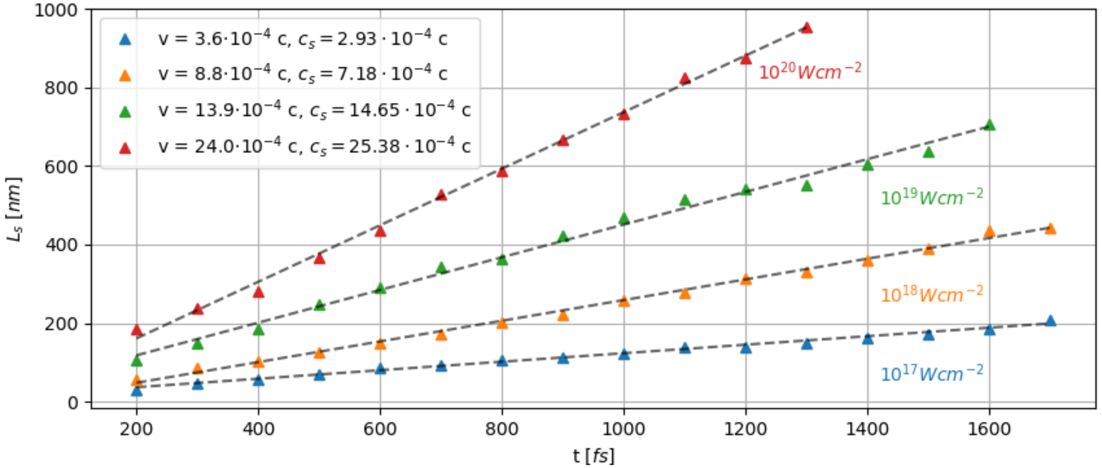
Plasma dynamics:

- **Compression**
- **Expansion/ Ablation**
- Bulk effects e.g. layer melting
- Density oscillation

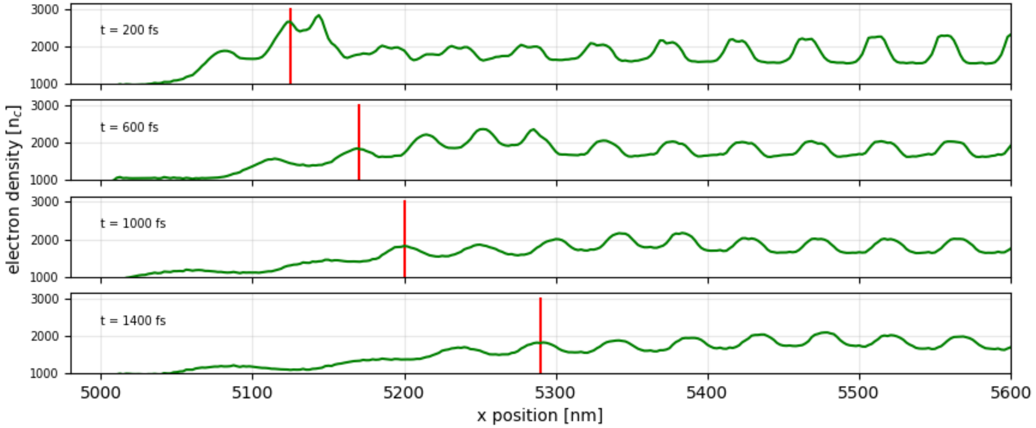
Ablation and Compression

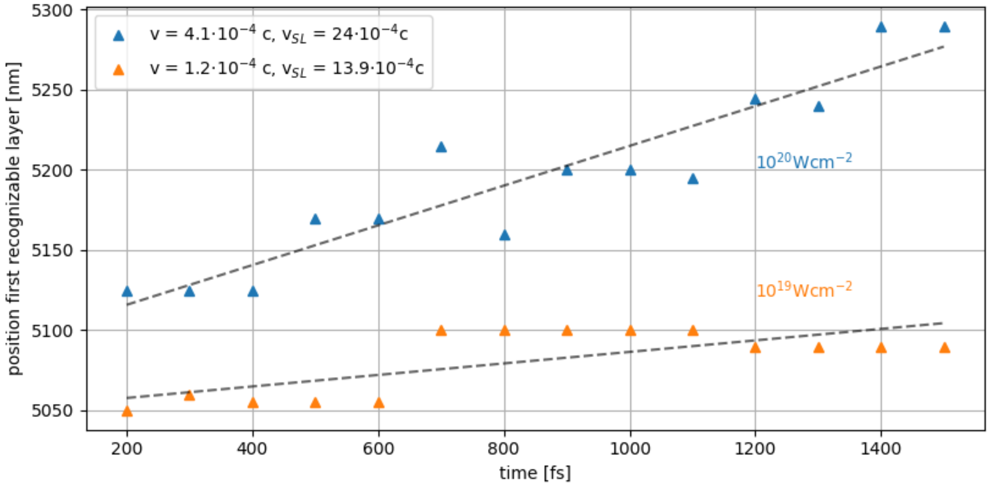
Velocity of scale length L_S





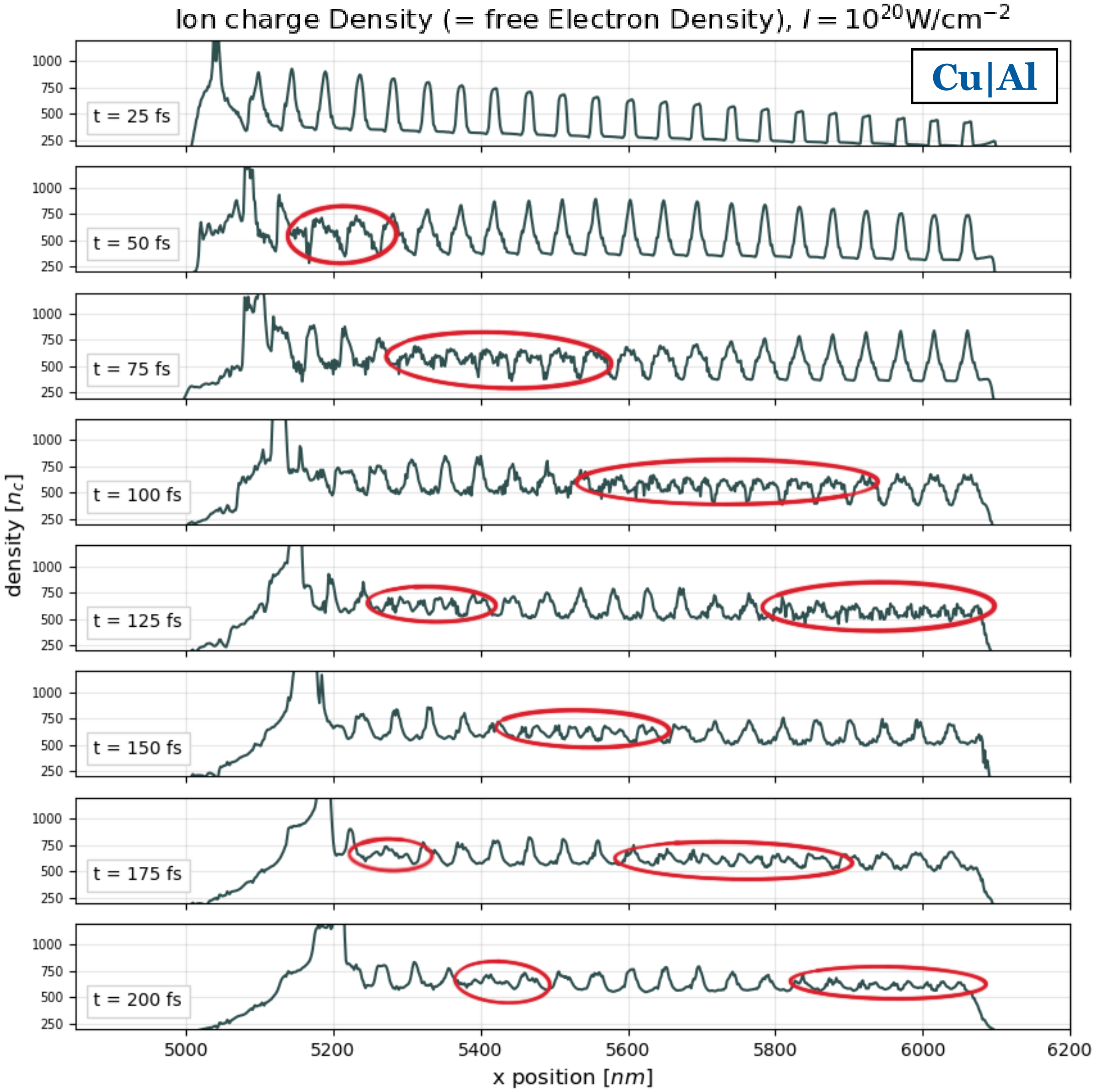
Velocity of first recognizable layer





→ in the UHI regime the **first recognizable layer** does **not correlate with ablation velocity** but it **correlates with compression velocity**

What dynamics appear?

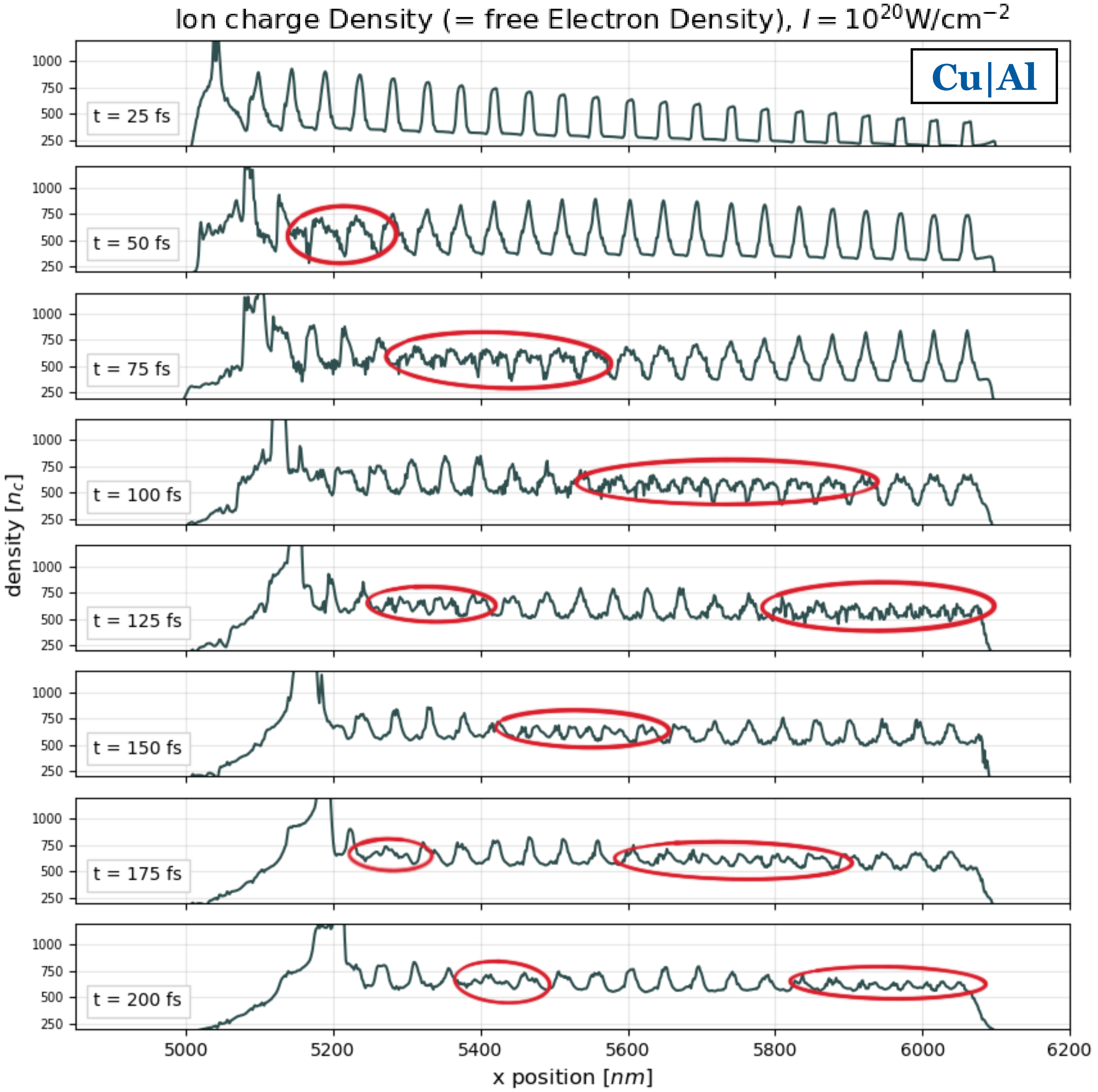


Plasma dynamics:

- Compression
- Expansion/ Ablation
- Bulk effects e.g. layer melting
- **Density oscillation**

HIBEF DRESDEN concept HZDR

Density Oscillation



What does Density Oscillation look like?

→ **Density alteration** moving through the target

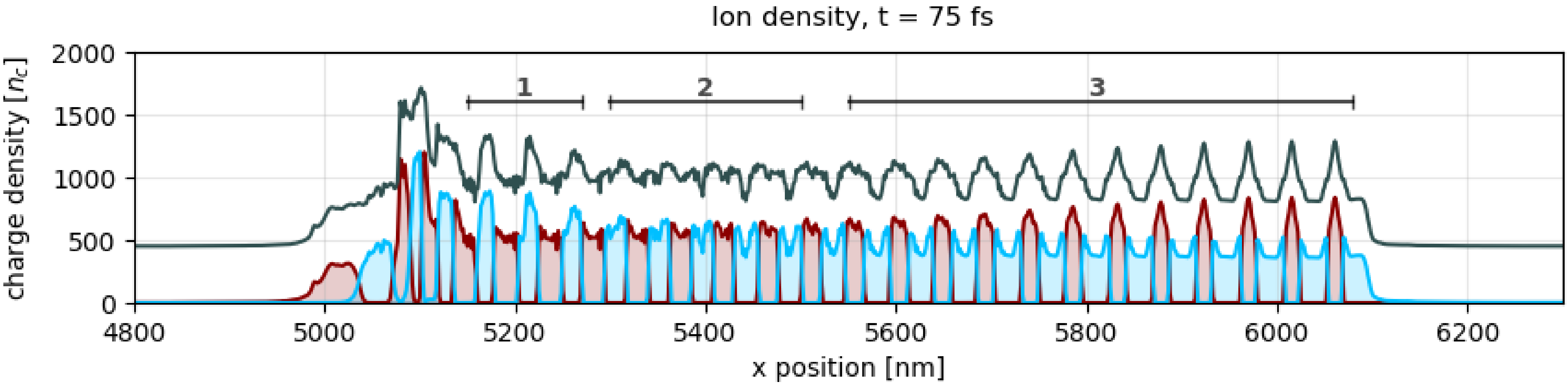
→ no melting, multilayer structure recovers

→ wave-like movement through target

Density Oscillation - Basics

What is oscillating?

→ the **single** layers oscillate in density

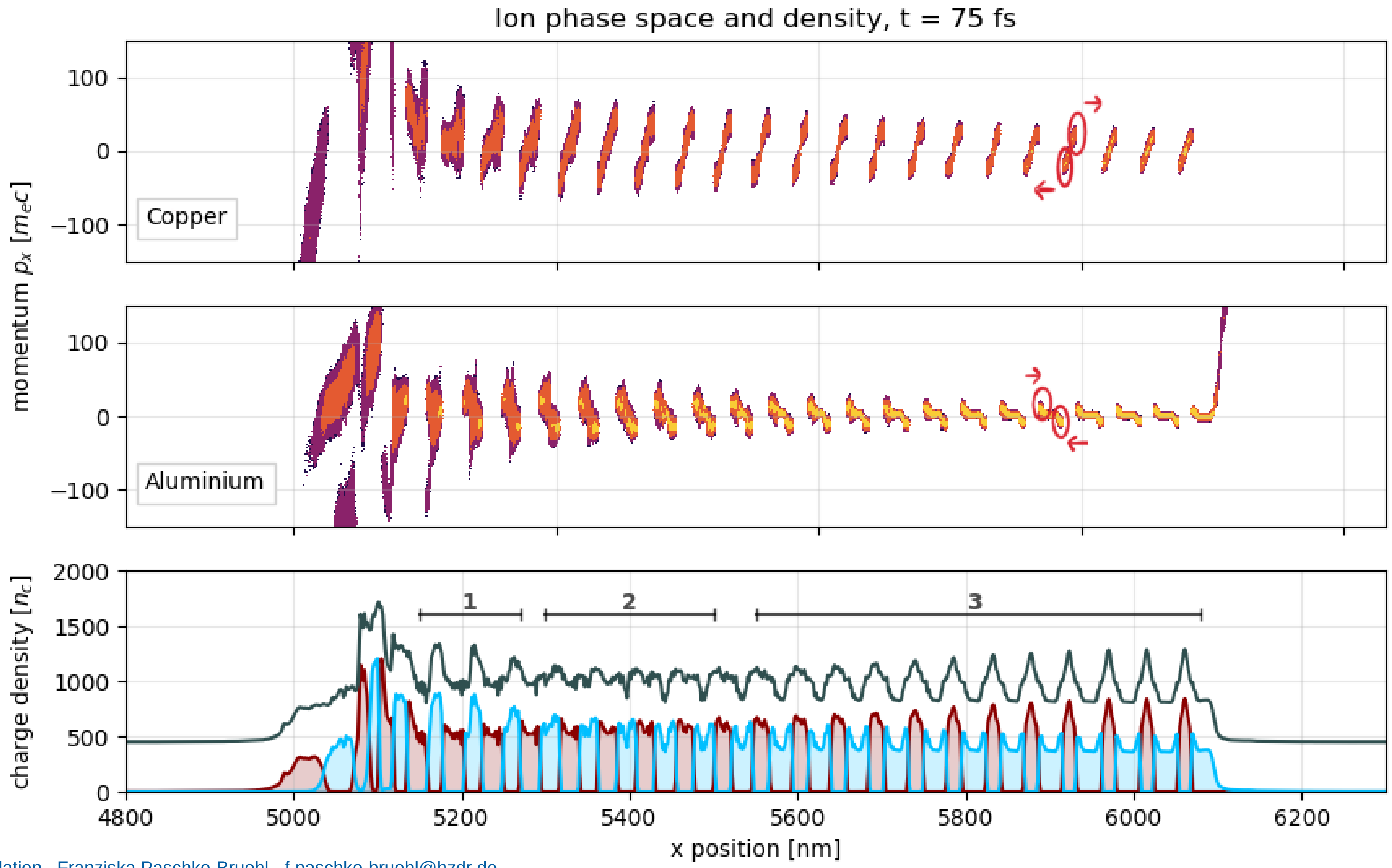


1) **Al** (blue) charge density **exceeds**
2) **charge densities** are fairly **equal (density alteration)**
3) **Cu** (red) charge density **exceeds**

Density Oscillation - Basics

Why are the layers oscillating?

→ the layers repeatedly **compress** each other



HZDR

Density Oscillation - Basics

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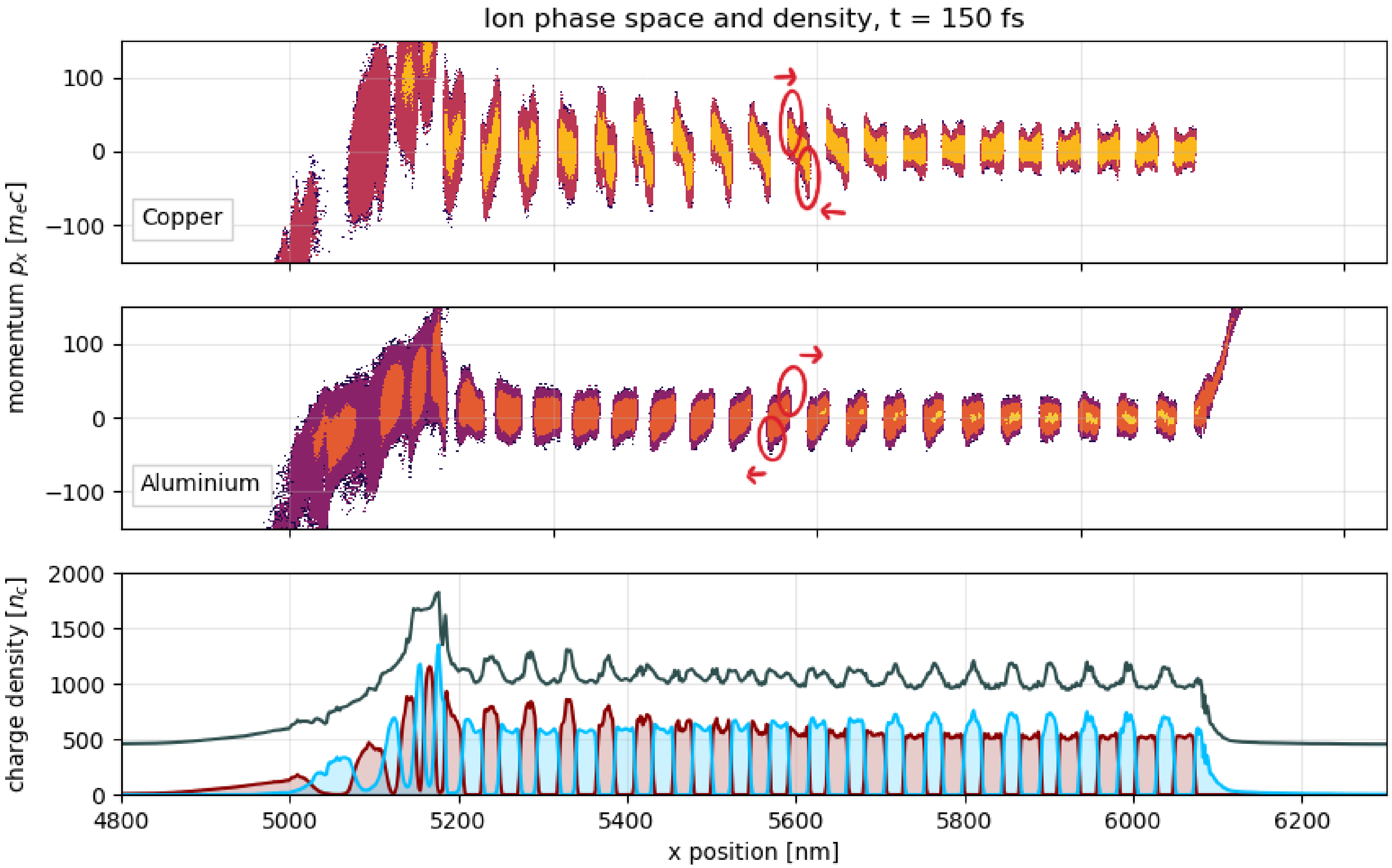

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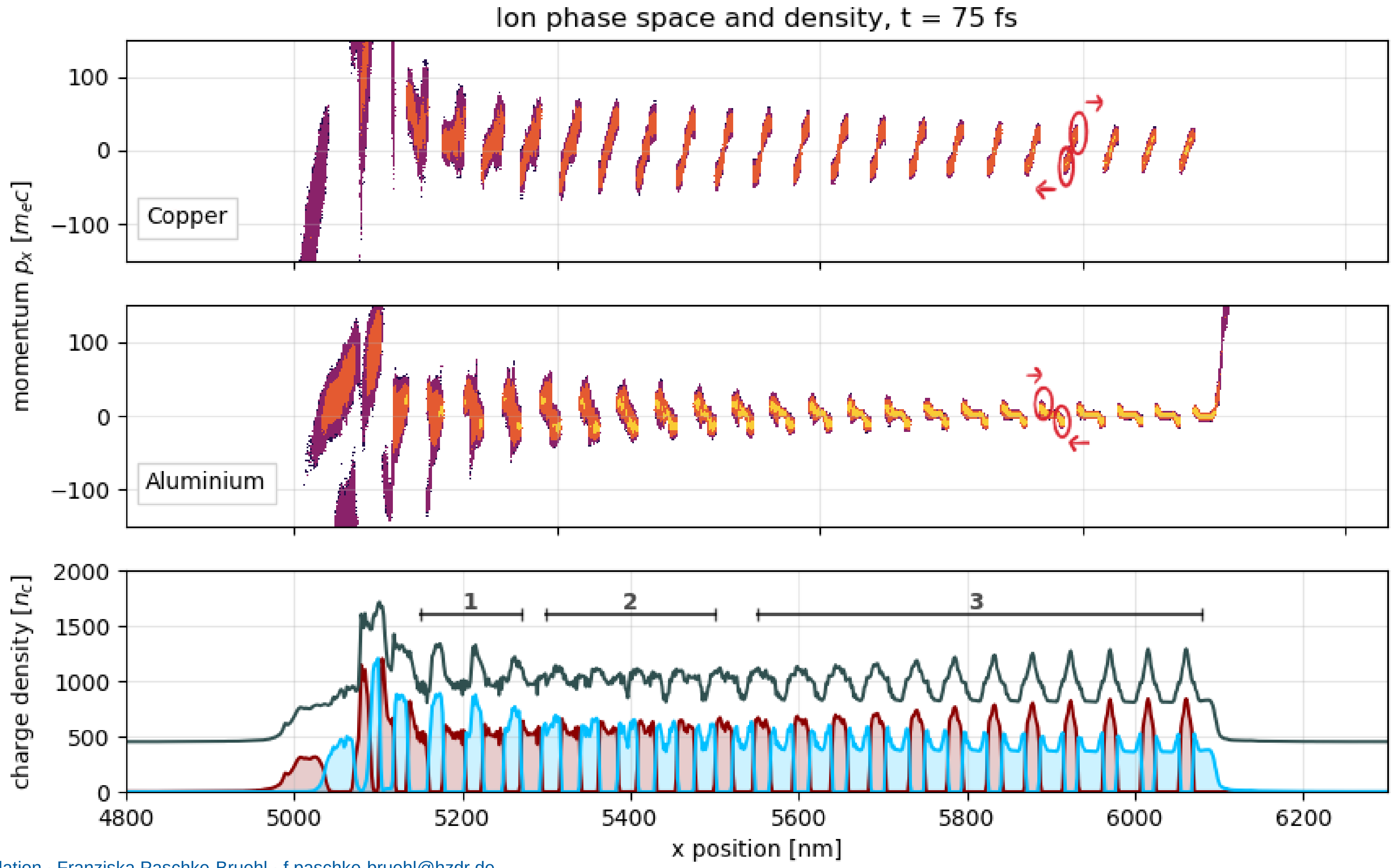
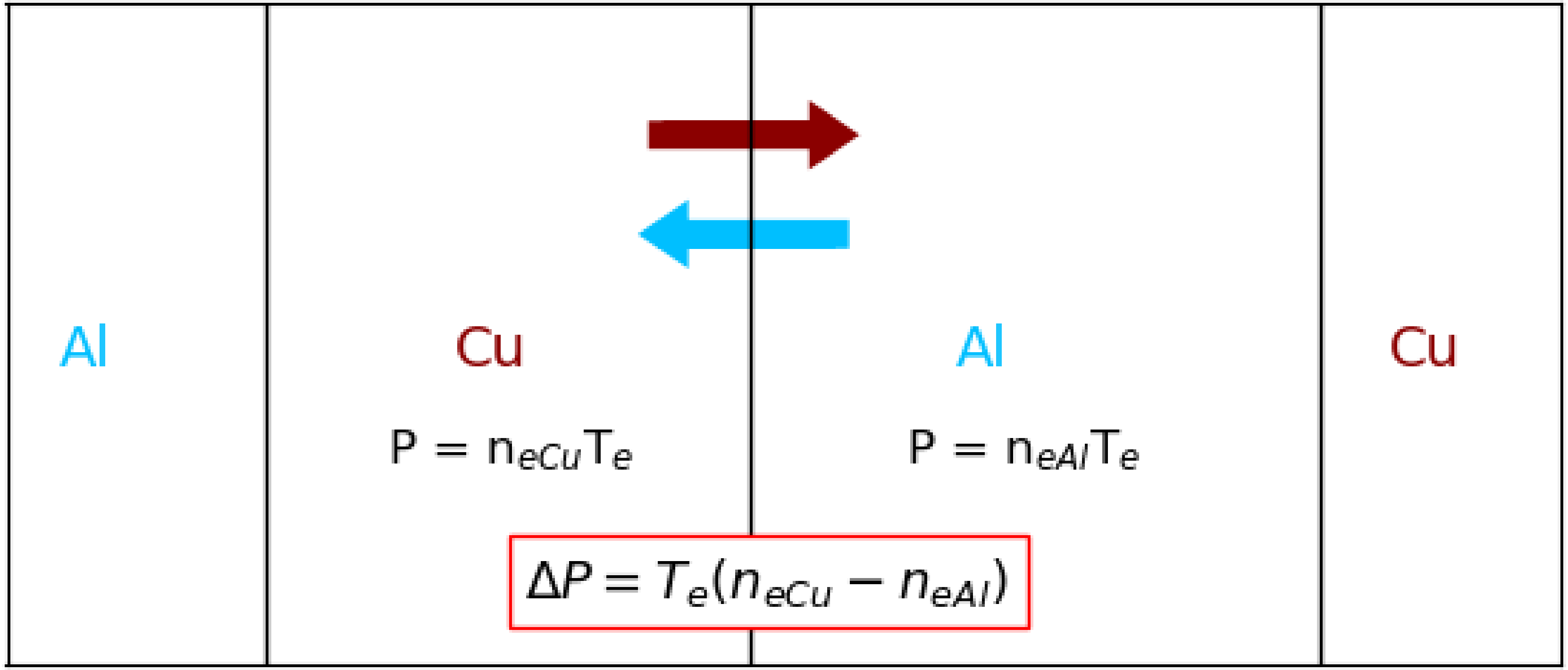


Density Oscillation - Process

What causes the compression?

→ the **pressure difference** between the layers ΔP causes a force

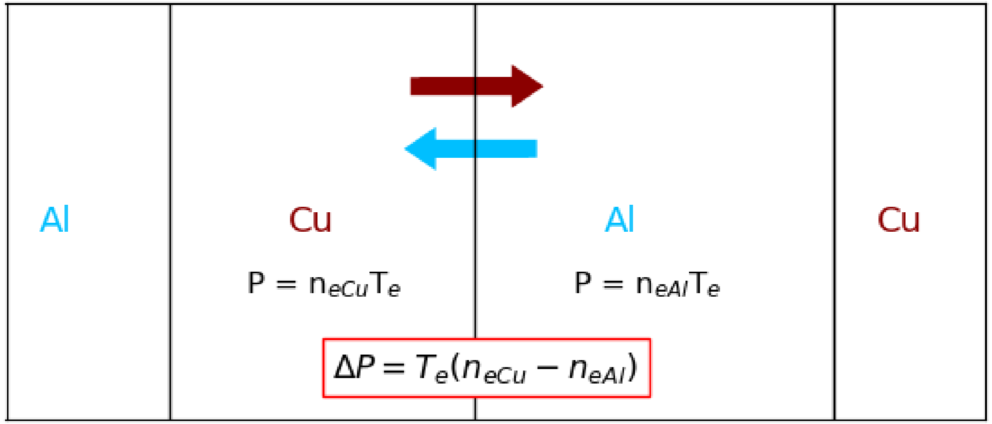


Assumptions: $T_i \ll T_e$

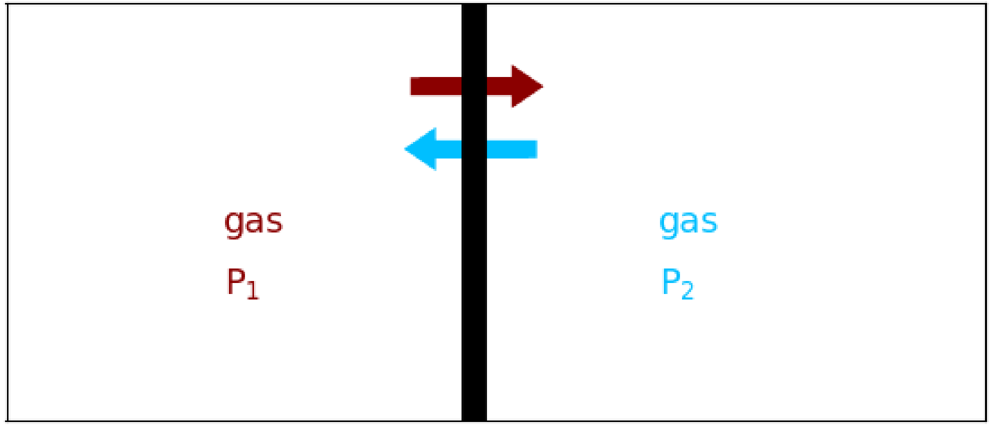
$T_{e,layer1} = T_{e,layer2} = T_e$

Density Oscillation - Process

How can we model the process?



layers in target

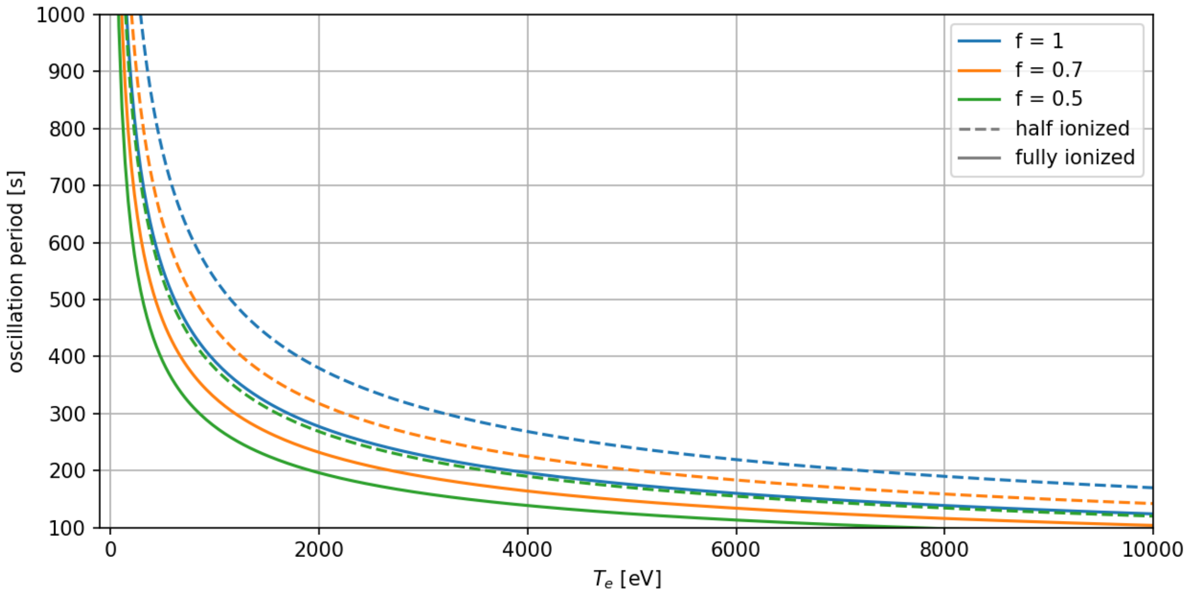


gases in cylinder separated by heavy pistof after E.Gislason in "A close examination of the motion of an adiabatic piston"

→ gases with pressure P = energetic electrons with pressure P
→ heavy piston = heavy, considerable cold ions

Density Oscillation - Modeling

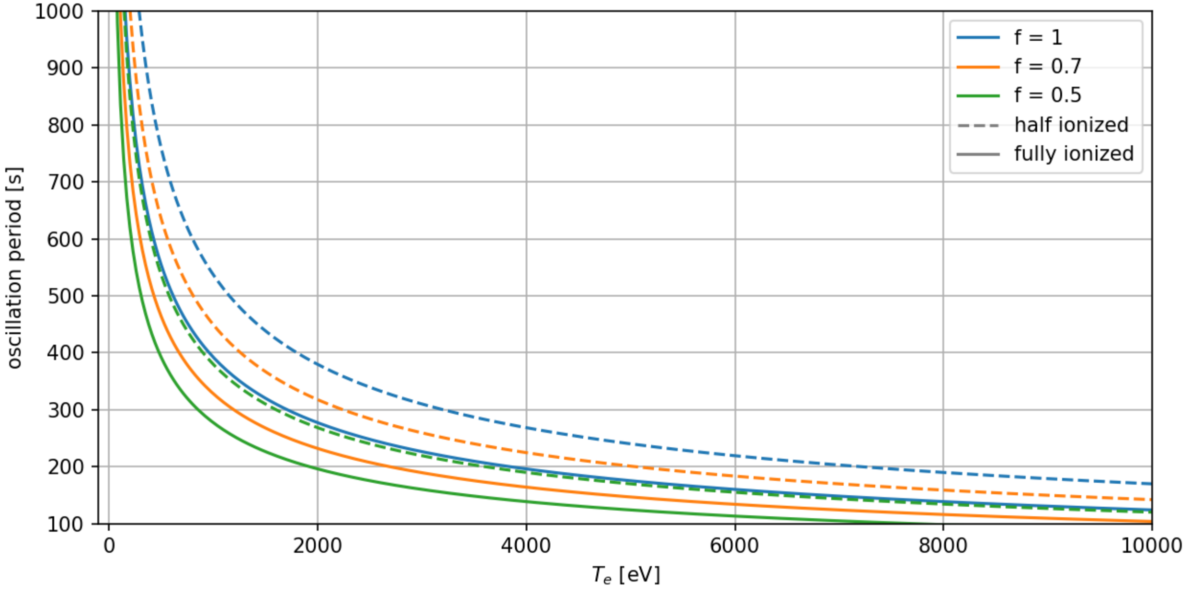
$$\omega_{osc}^2 = \frac{T_e}{f\tilde{m}}\left[n_{1e}^0 \frac{x_0}{x_\infty^2} + n_{2e}^0 \frac{(L-x_0)}{(L-x_\infty^2)}\right]$$



$n_{i,e}^0$ - initial electron density of layer i
x_0, L - layer thickness parameters
$x_\infty(n_{i,e}^0, x_0, L)$ - final position layer boundary (final position piston)
$\tilde{m}(m_{i,ions})$ - mass factor heavy ions

T_e - electron Temperature
f - geometry factor ions $(0 < f \leq 1)$

Density Oscillation - Modeling



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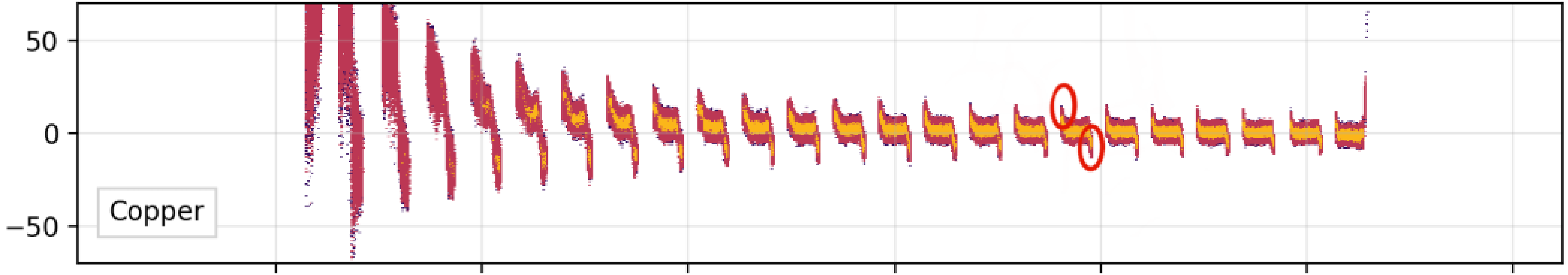
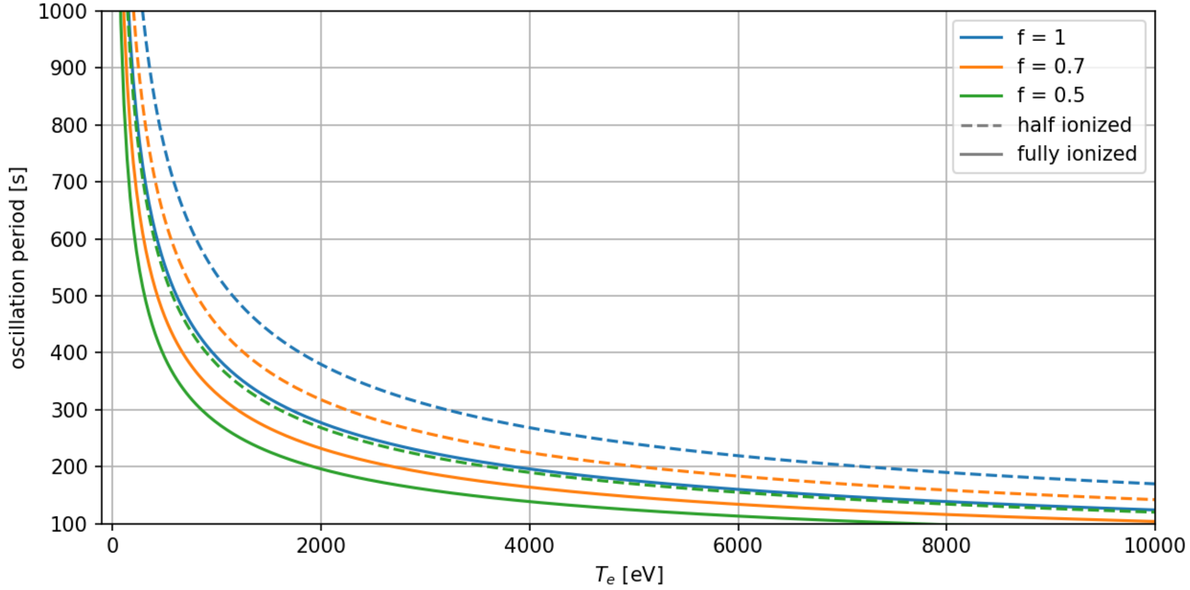


Density Oscillation - Modeling



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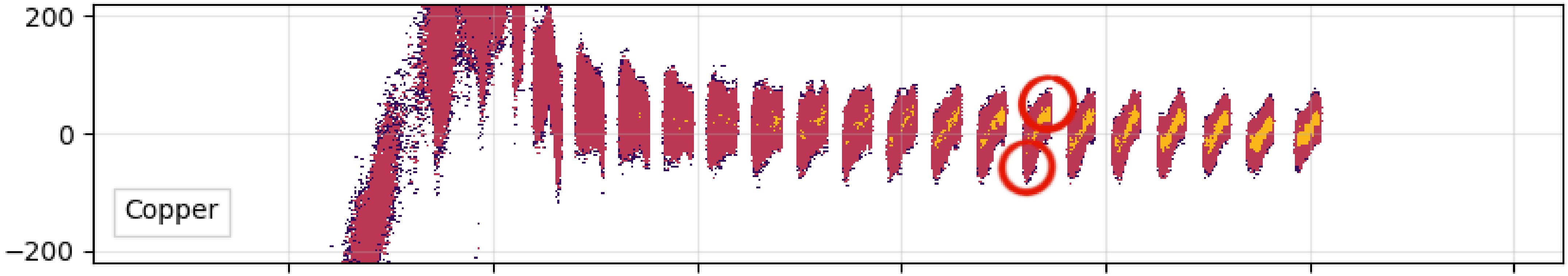
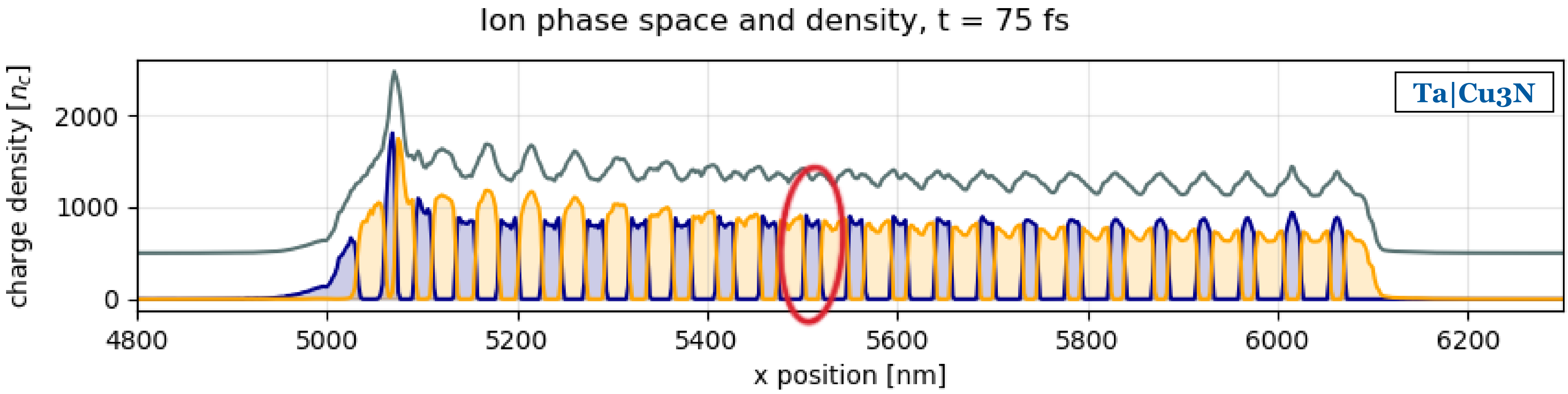
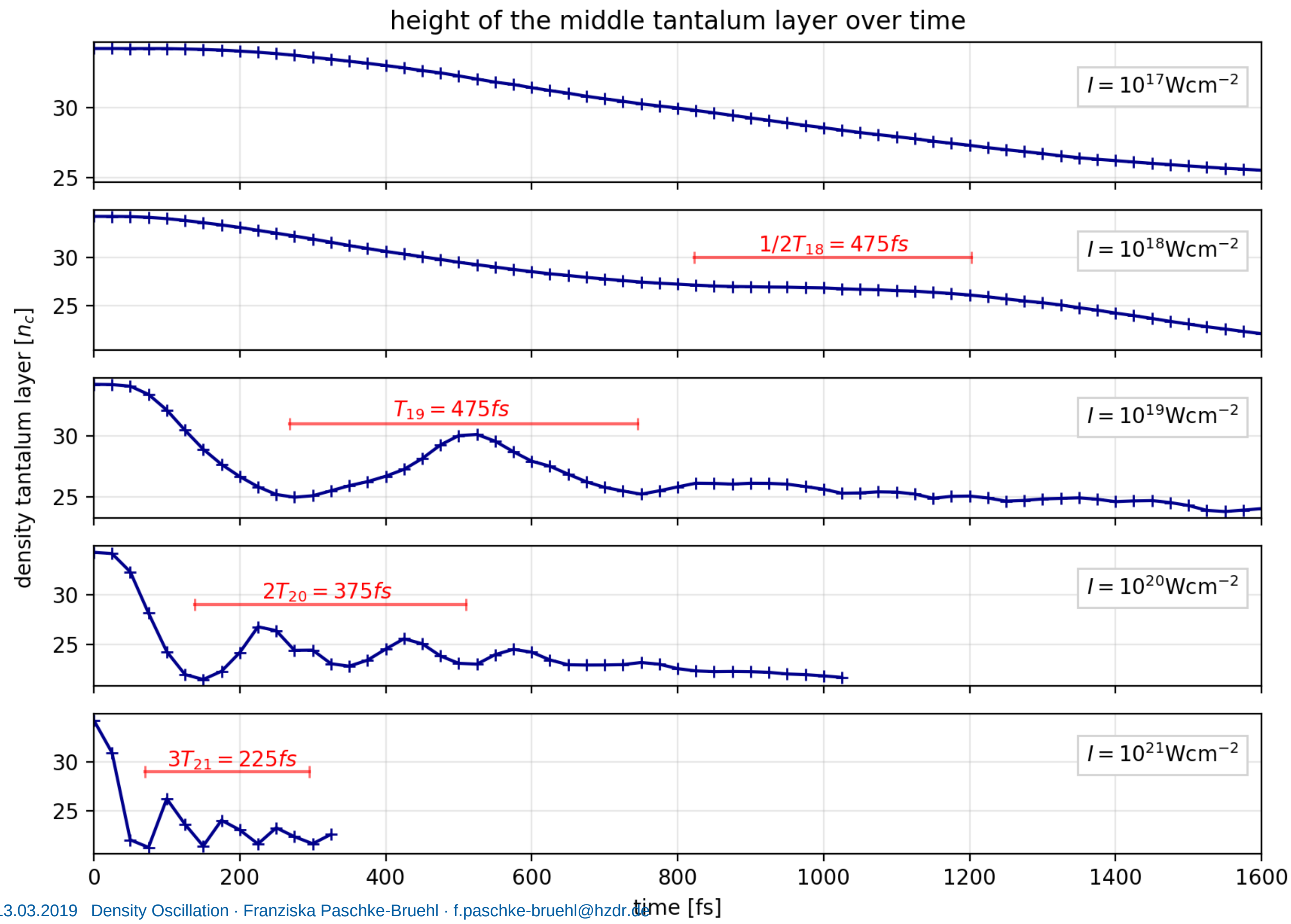


Density Oscillation – T_{osc} Measurement



Density Oscillation – T_{osc} Measurement



→ we can measure the oscillation period

Oscillation period for Layer no.12:

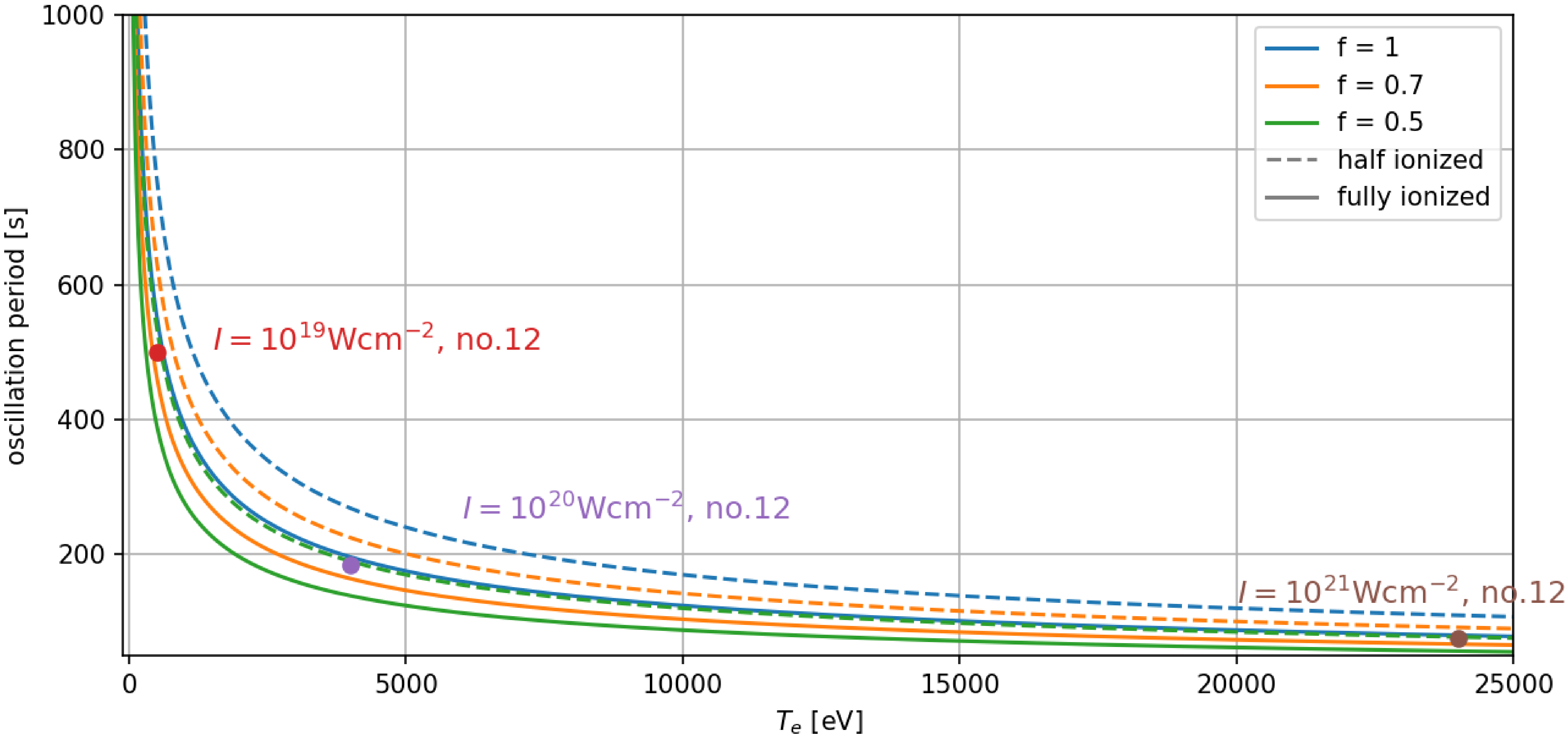
$T_{18} = 950$ fs

$T_{19} = 475$ fs

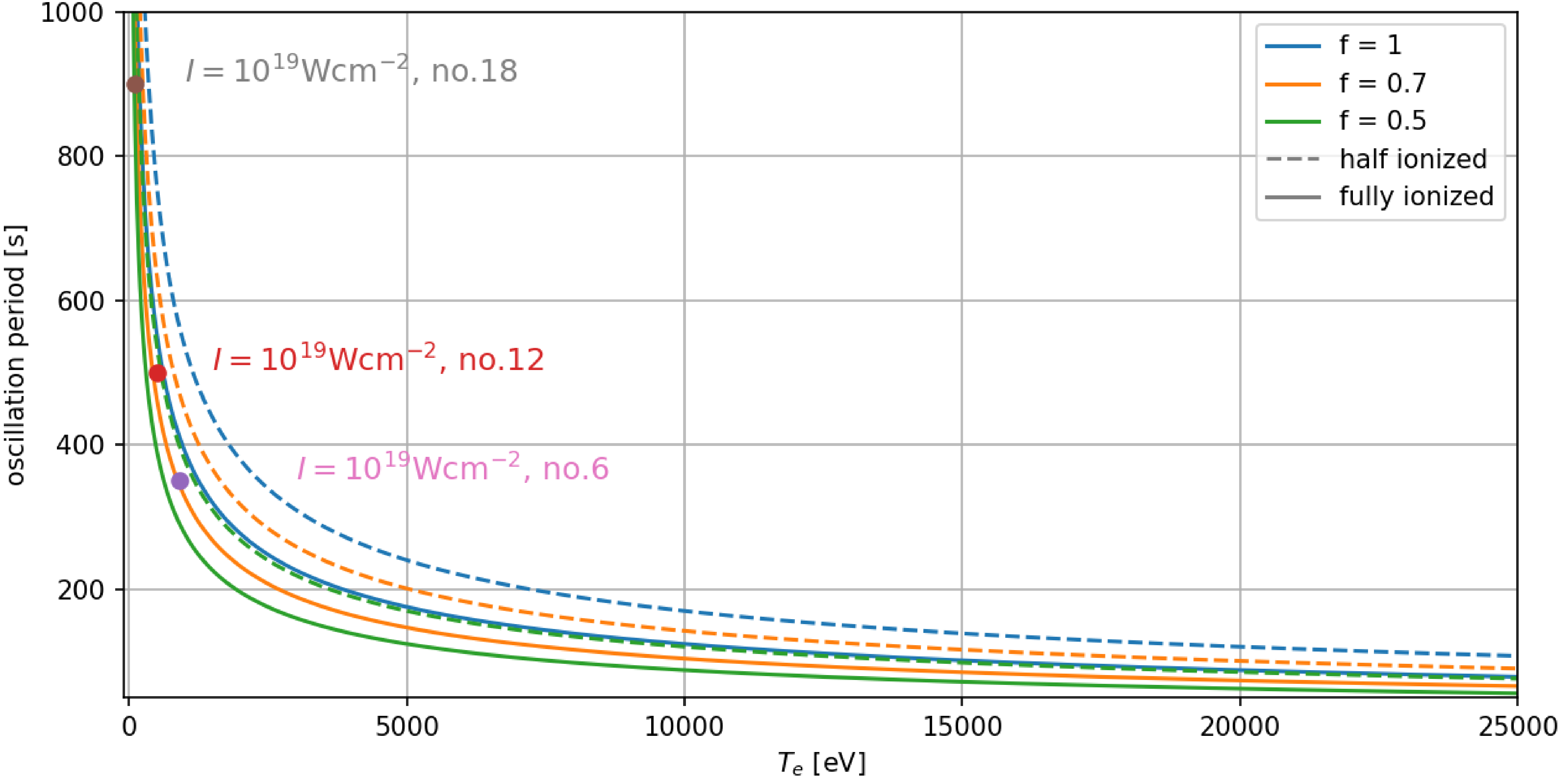
$T_{20} = 187$ fs

$T_{21} = 75$ fs

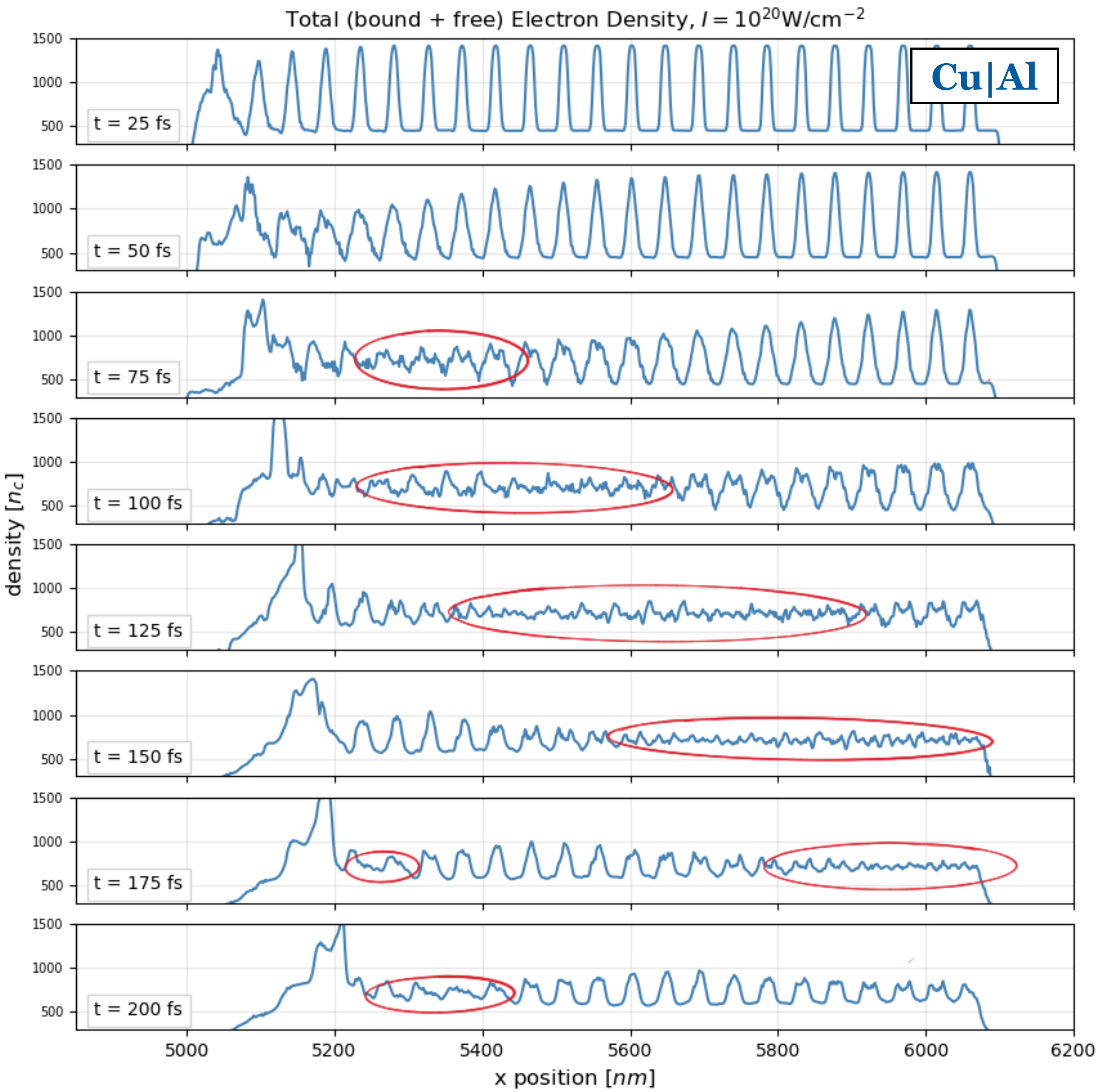
Comparison Model and Simulation



Comparison Model and Simulation



Density Osciallation - GISAXS Feasibility



- Electron density dominated by copper/tantalum -> shows oscillation period of copper/tantalum

We can not follow single layer oscillations!

We can follow the density alteration over time!

GISAXS: Is the layer structure in tact or not?

BUT: Time Resolution: $\Delta t = 50 - 100$ fs
Density Sensitivity: $\Delta n = 100 - 400\ n_c$

Is GISAXS feasible for ultra-high intensities?

- **What should the target look like?**

  similar to the simulation setup, more layers for higher intensities

- **What dynamics appear? Which are recognizable with GISAXS?**

  ~~Ablation~~, Compression, Density Oscillation, ~~Particle Acceleration~~ Backside Expansion

- **What parameters can extract?**

  ~~ablation velocity~~ v_{abl}, compression velocity v_{comp}, electron temperature T_e

- **What time resolution do we need?**

  time resolution of 50 – 100 fs

Outlook

UHI GISAXS experiments:

- Create scattering pattern with **BornAgain** to confirm **density sensitivity**
- Find Target setup that allows high **time resolution** ✓

  → mass-limited targets, nano-focus

- **perform experiments**

Model:

- damping and diffusion to erase free parameter f