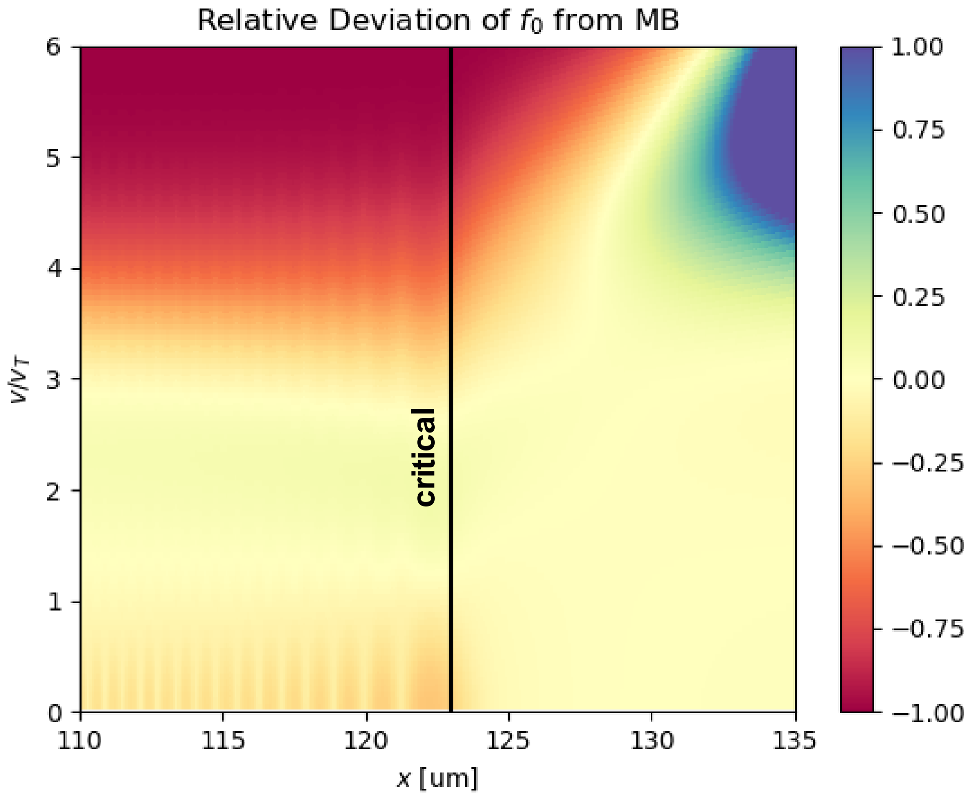
Vlasov–Fokker–Planck Modeling of Heat Flow Modifications due to Laser Absorption and Pondermotive Transport Effects



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CHANGING WHAT'S POSSIBLE

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Summary

Vlasov-Fokker-Planck simulations have been conducted to assess how laser fields influence electron conduction near the critical density

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- **Strong intensity gradients near the critical density can affect heat transport through non-uniform absorption of laser light as well as the ponderomotive force**
- **A new capability has been implemented in the Vlasov-Fokker-Planck (VFP) code *K2** to directly simulate laser fields without resolving laser oscillations**
- **VFP simulations show strong ponderomotive heat flux inhibition in the local transport limit, affirming theoretical predictions**
- **Heat flow simulations in sharp intensity gradients demonstrate that the laser modifies transport primarily through the Langdon effect, rather than the ponderomotive force itself**

* M. Sherlock et al., *Phys. Plasmas* 24, 082706 (2017).

Collaborators

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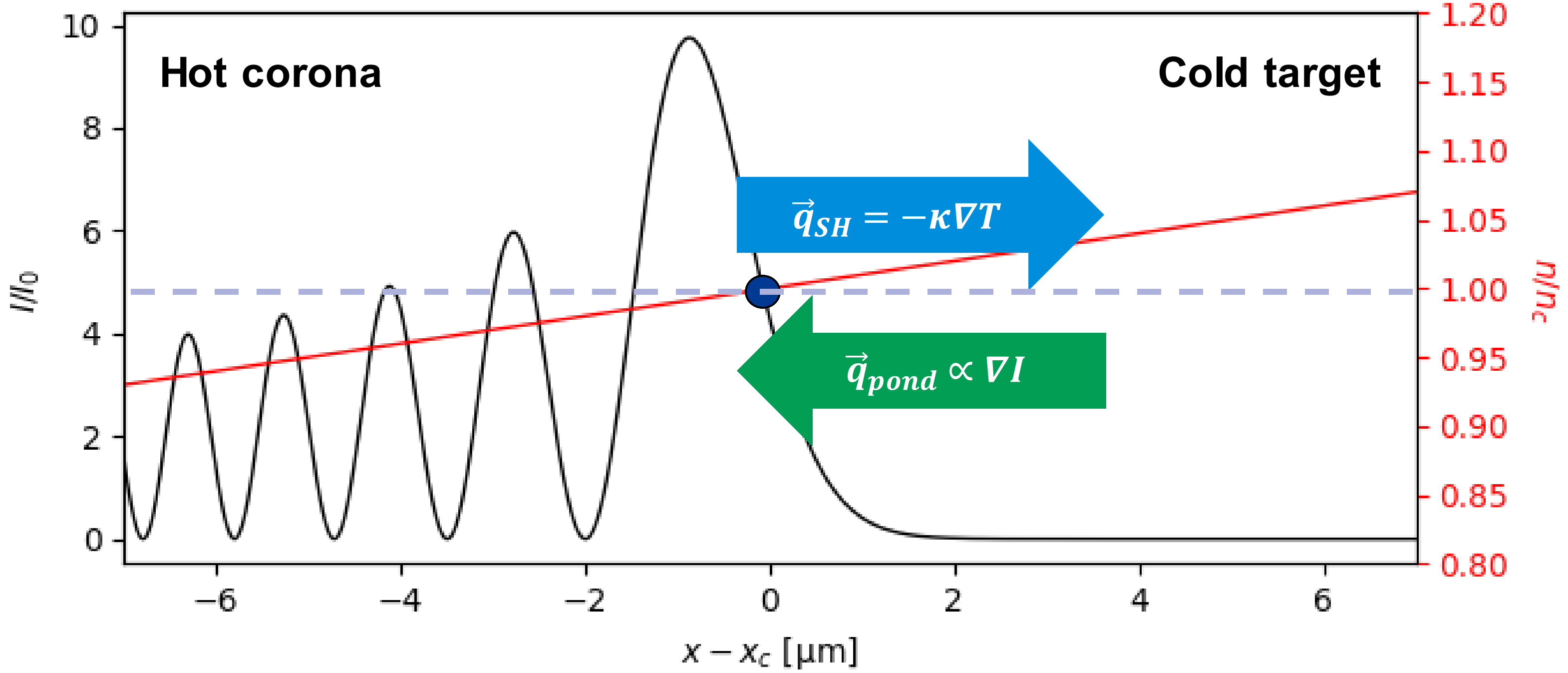
Mark Sherlock (LLNL)

Intensity gradients are as important as temperature gradients for heat transport near the critical density



Typical direct-drive scales

$L_n = 100\ \mu\text{m}$ $\quad L_T = 10 - 100\ \mu\text{m}$

Laser field scale at critical

$$L_E \approx 0.4\lambda_0^{\frac{2}{3}} L_n^{\frac{1}{3}} \sim 1\ \mu\text{m}$$

Ponderomotive force strength

$$L_{pond} = \frac{4L_E}{(v_E/v_T)^2} \sim 10 - 100\ \mu\text{m}$$

Accounting for intensity gradients reduces inward heat flow

* A. V. Maksimov et al., *Sov. J. Plasma Phys.* 16, 331 (1990).
** V. N. Goncharov and G. Li, *Phys. Plasmas* 11, 5680 (2004).

A new computational approach bridges the timescale gap between laser oscillations and collisional transport

- Accurately resolving laser oscillations in time (~fs) over collisional timescales (~10ps) is unfeasible
- Remove oscillations by expressing fields and distribution function in terms of slowly varying amplitudes

$$\vec{E}(\vec{x},t) = \vec{E}_0(\vec{x},t) + \Re\left[\vec{E}_L(\vec{x},t)\, e^{-i\omega_L t}\right] \qquad f(\vec{x},\vec{v},t) \rightarrow f(\vec{x},\vec{v},t) + \Re\left[f_L(\vec{x},\vec{v},t) e^{-i\omega_L t}\right]$$

Quasiharmonic ("AC") applied laser field

Quasistatic ("DC") field generated by plasma flows

- Laser-plasma effects emerge via coupled AC and DC kinetic equations

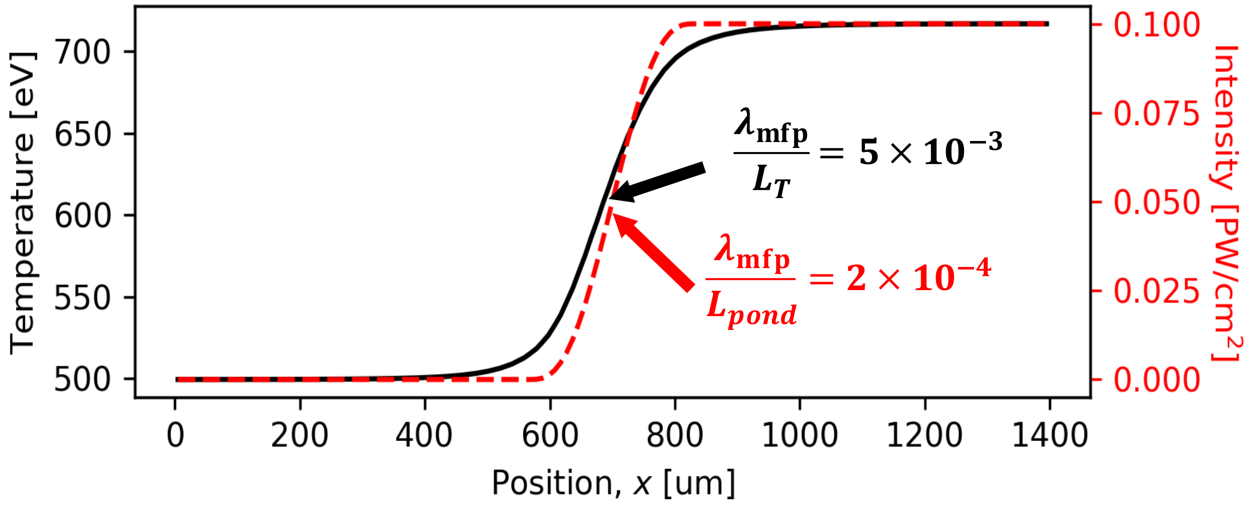
$$L_0[f] - \frac{e}{2}\Re\left\{\left(\vec{E}_L + \vec{v}\times\vec{B}_L\right)\cdot\frac{\partial f_L^*}{\partial\vec{p}}\right\} = C_{ei}[f] + C_{ee}[f,f] + \frac{1}{2}\Re\{C_{ee}[f_L, f_L^*]\}$$

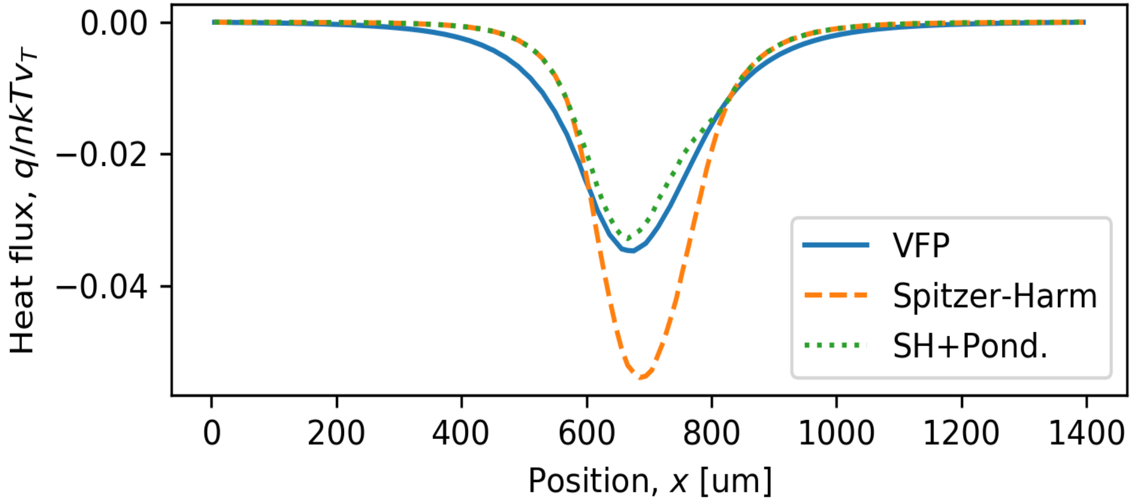
$$L_0[f_L] - e\left(\vec{E}_L + \vec{v}\times\vec{B}_L\right)\cdot\frac{\partial f}{\partial\vec{p}} = i\omega_L f_L + C_{ei}[f_L] + C_{ee}[f,f_L] + C_{ee}[f_L,f]$$

The coupled solution for f and f_L is a computationally viable way to study laser-coupling effects on heat transport

Local heat flow tests validate theoretical predictions of ponderomotive heat flux inhibition

- Create a weak temperature gradient ($L_T < 0.01\lambda_{\mathrm{mfp}}$) by heating a uniform plasma in an soft intensity gradient
- Analytic theories predict the ponderomotive effects reduce the heat flux in this configuration[*,**]
- Simulations affirm a strong ponderomotive heat flux inhibition relative to Spitzer-Harm (SH)





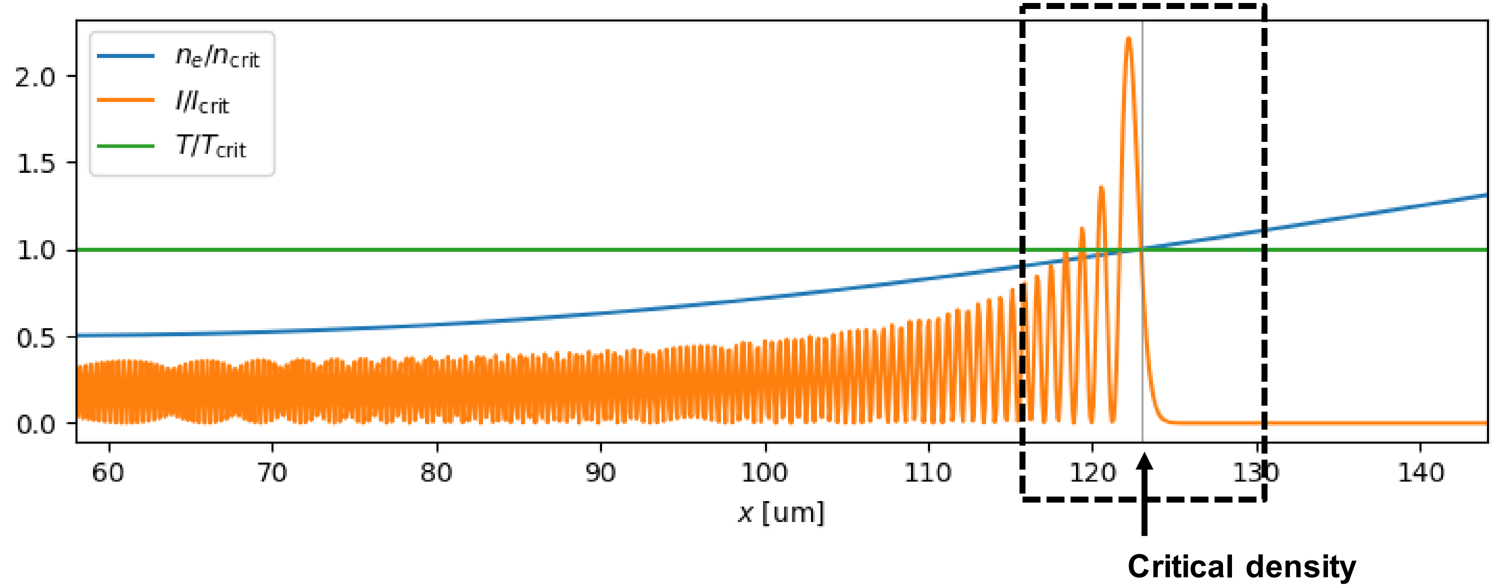
$Z = 10, T_0 = 500$ eV,
$n_e = 0.3 n_c, Z\left({}^{v_E}/_{v_T}\right)^2 = 0.04$

Ponderomotive effects in the local transport limit have been validated to agree with theory

* A. V. Maximov et al., *Sov. J. Plasma Phys.* 16, 331 (1990).
** V. N. Goncharov and G. Li, *Phys. Plasmas* 11, 5680 (2004).

Assessing ponderomotive effects in direct-drive scenarios requires realistic plasma and laser profiles

Initial profiles for ICF-relevant heat flow problems

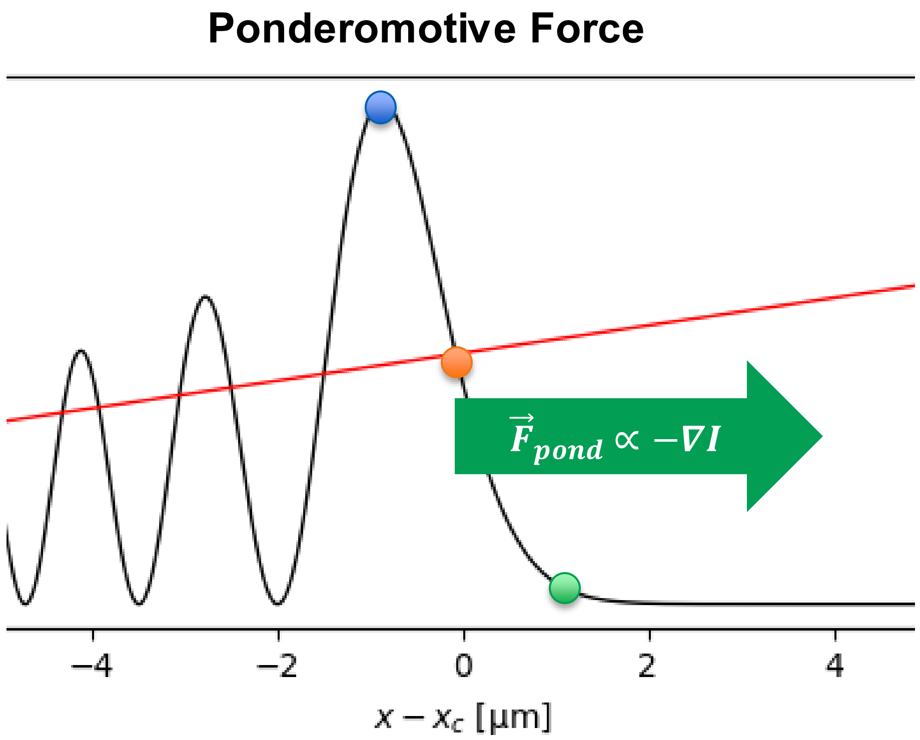


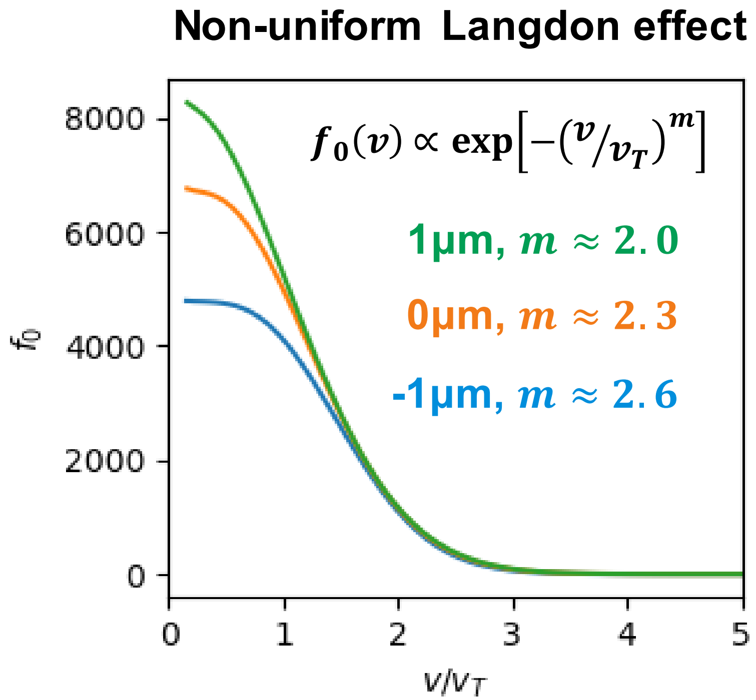
Isothermal initial $T_e(x)$

Fixed $n_e(x)$ (no hydro motion)

$E_L(x)$, $B_L(x)$ determined from wave equation

Heat flow simulations with sharp gradients inform the relative importance of ponderomotive force versus indirect intensity-gradient effects

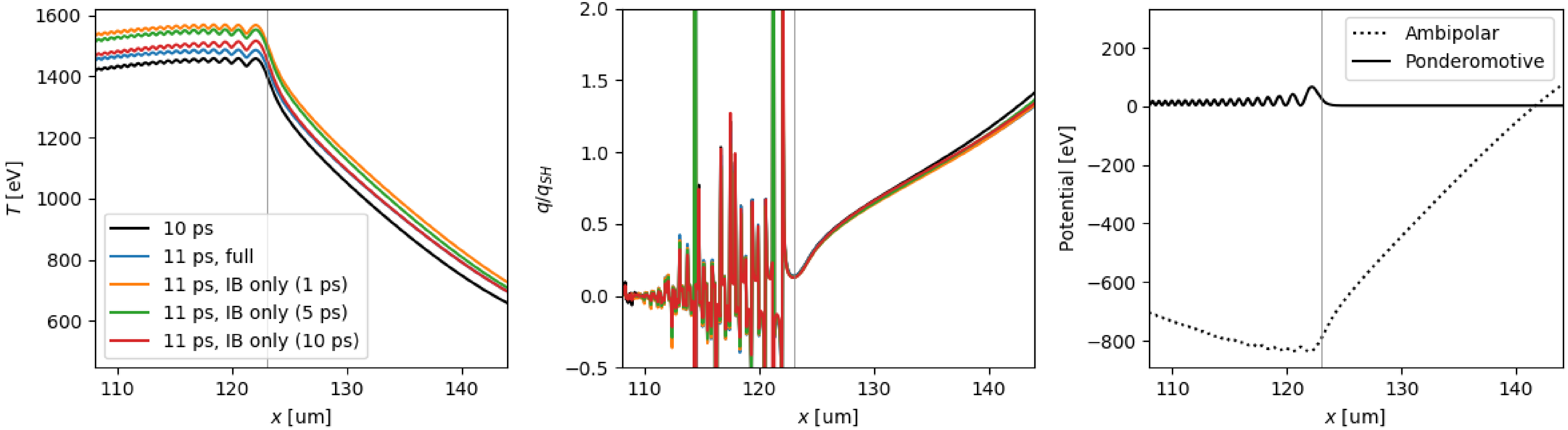




Identifying the main laser-coupling effect is critical to developing practical reduced models

*A. B. Langdon, *Phys. Rev. Lett.* 44, 570 (1980).

The role of the ponderomotive force can be quantified by switching from AC/DC VFP to conventional VFP with Langdon IB

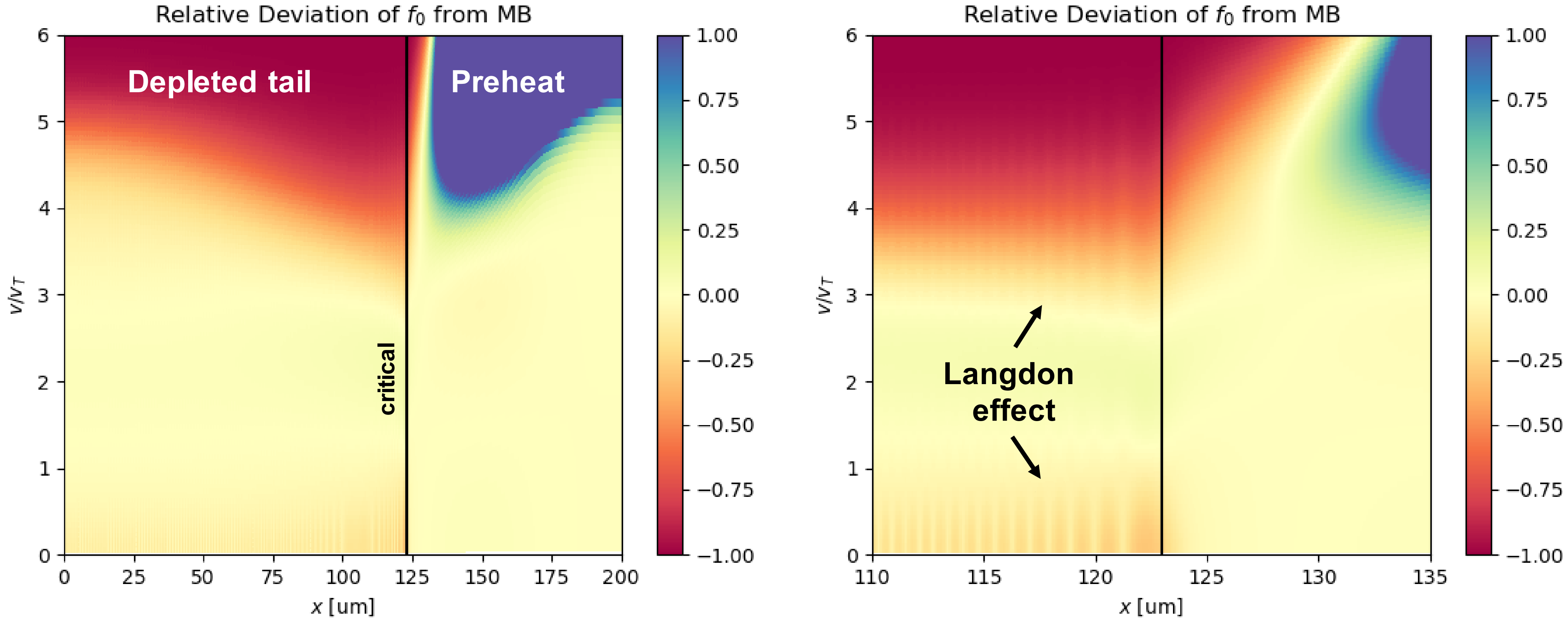


$\lambda_{\mathrm{mfp}}(3v_T) \gg L_E$

Even in sharp intensity gradients, the ponderomotive force does not significantly affect transport

$I_0 = 9 \times 10^{14}$ W/cm^2
Z = 3
T_0 = 500 eV
L_n = 50 um

The main effect of the laser is to reshape the distribution function via the Langdon effect



$I_0 = 9\mathrm{x}10^{14}$ W/cm^2
Z = 3
L_n = 50 um
t = 20 ps

The conduction-relevant tail population is sharply non-Maxwellian due to interplay of Langdon effect and nonlocality

Vlasov-Fokker-Planck simulations have been conducted to assess how laser fields influence electron conduction near the critical density

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- **A new capability has been implemented in the Vlasov-Fokker-Planck (VFP) code *K2** to directly simulate laser fields without resolving laser oscillations**
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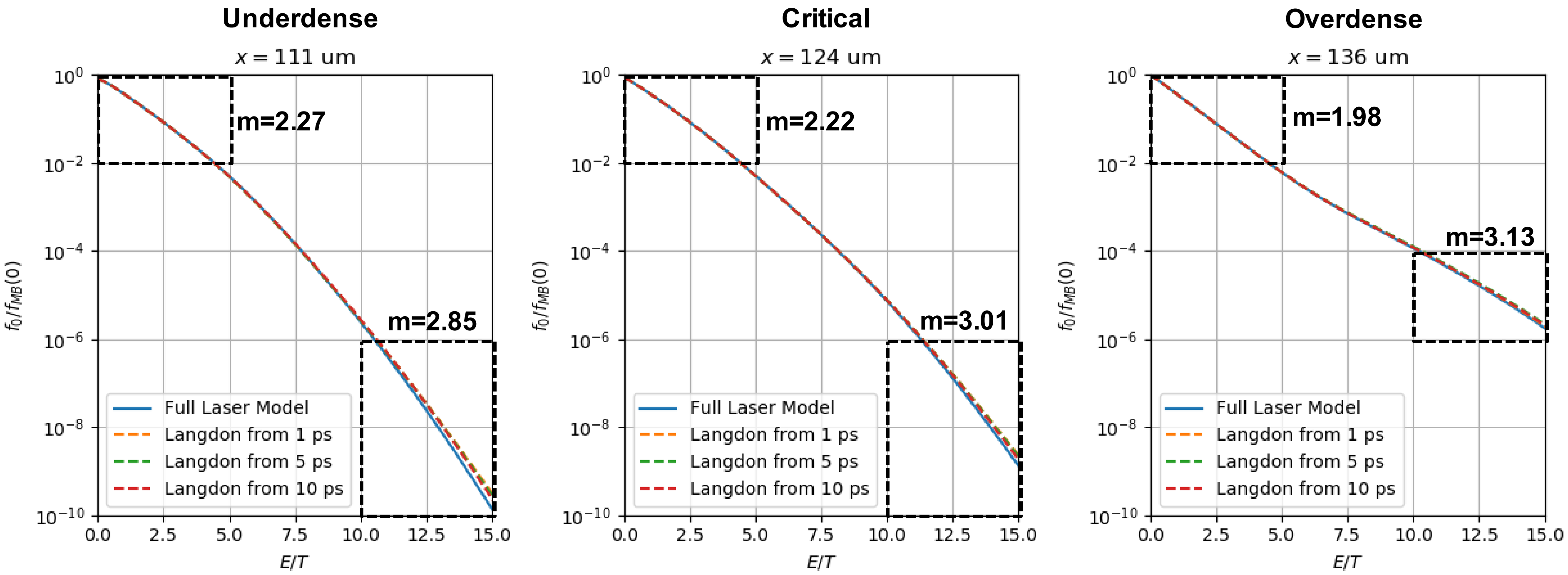
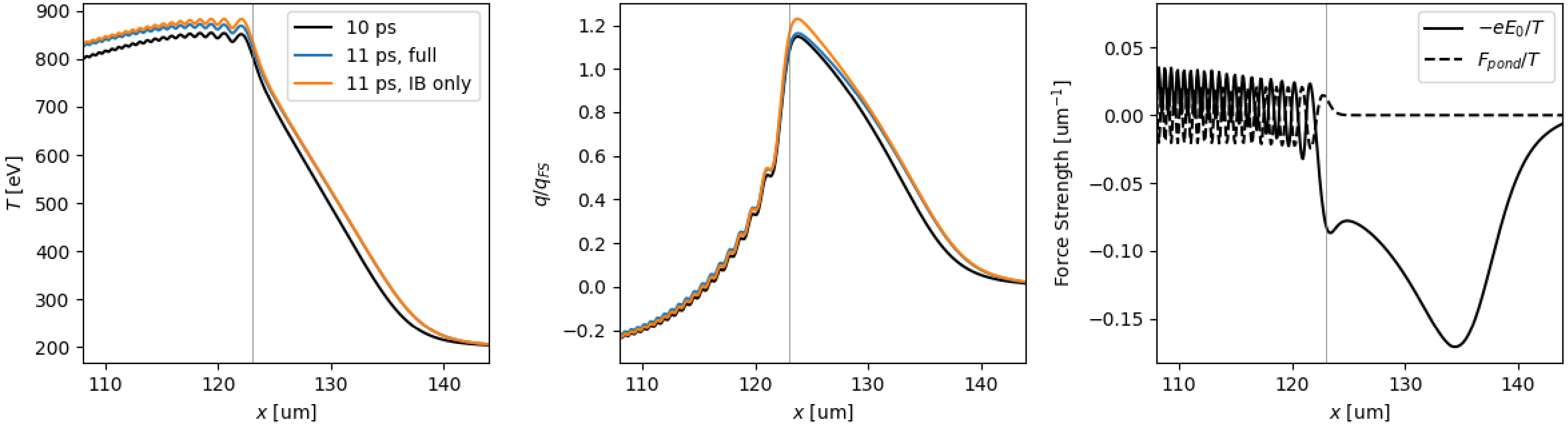


The conduction-relevant tail population is sharply non-Maxwellian due to interplay of Langdon effect and nonlocality

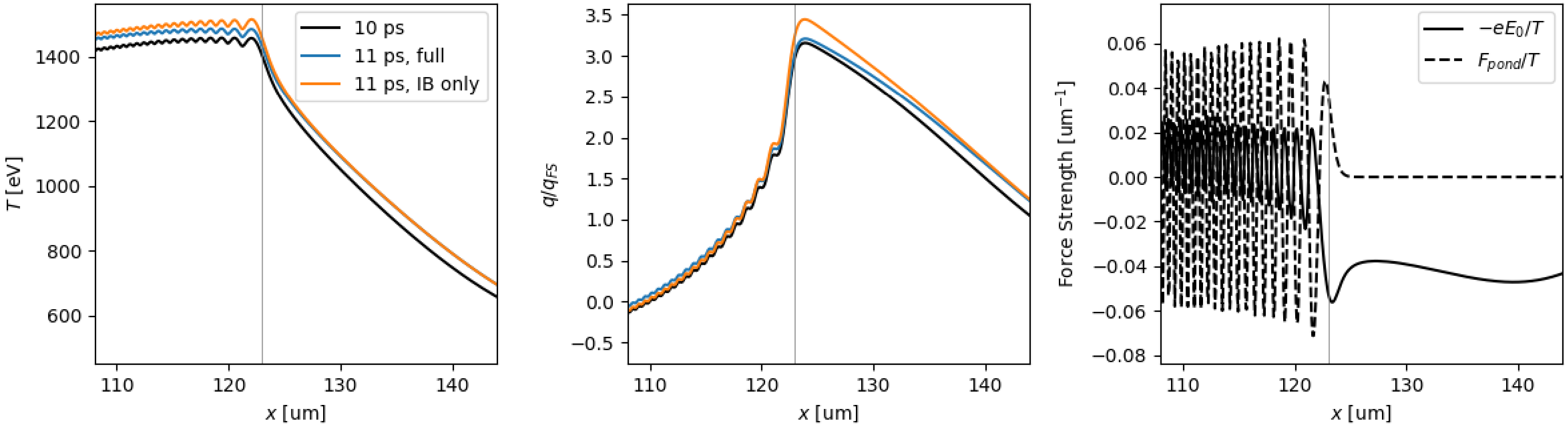
I_0 = 9x10^{14} W/cm^2
Z = 3
T_0 = 500 eV
L_n = 50 um
t = 11 ps

Toggle plots with absolute heat flux

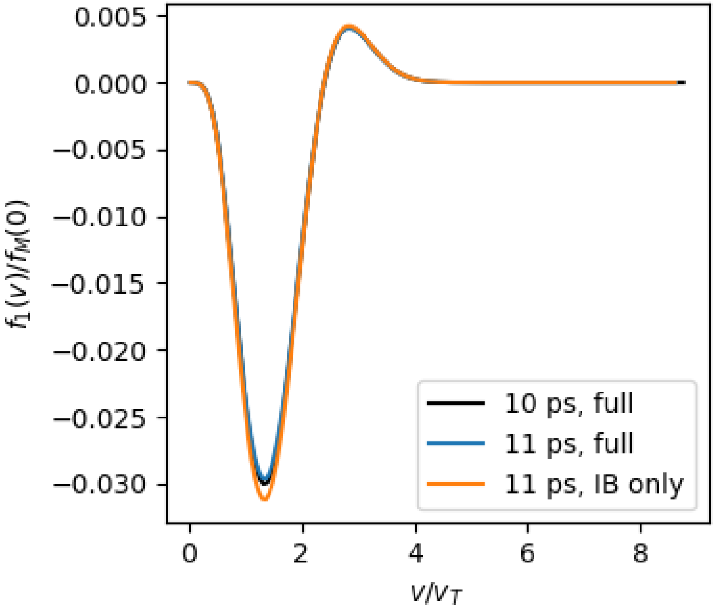
I_{14}=1.8



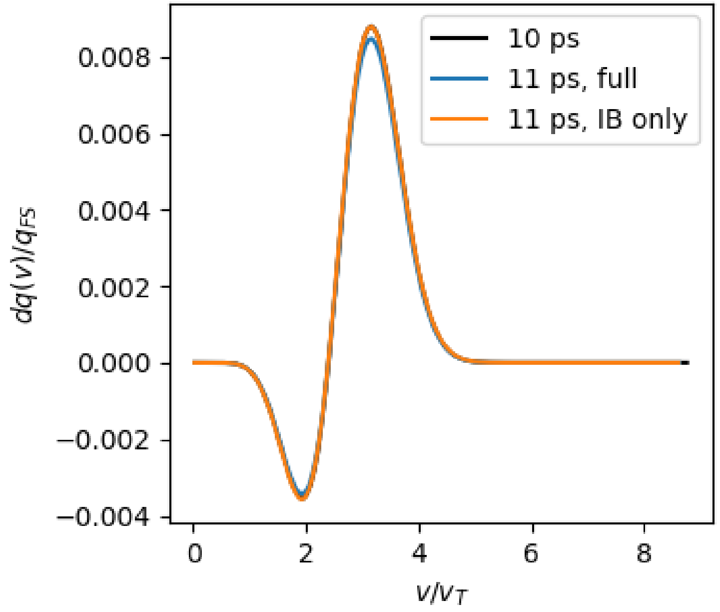
I_{14}=9.0



Velocity-space analysis shows removing ponderomotive force mainly affects cold (return-current) electrons, which do not significantly contribute to the heat flux



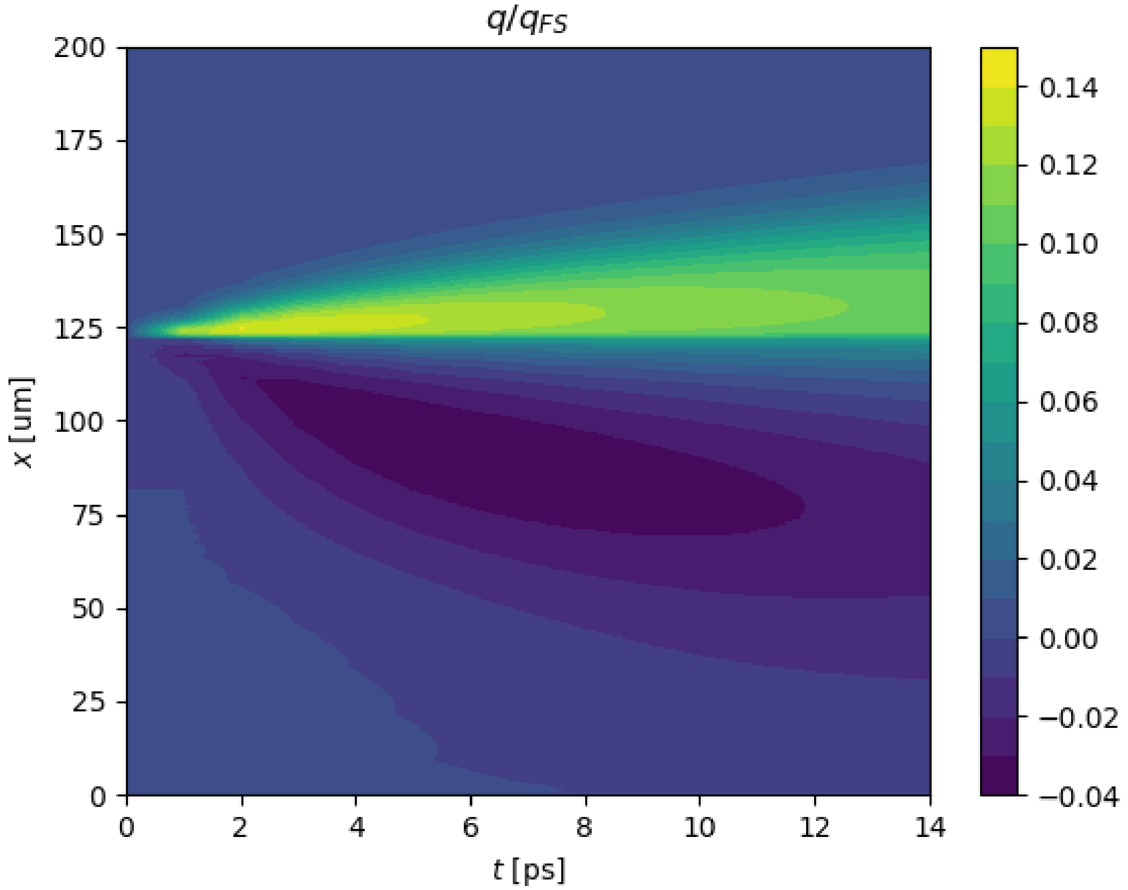
F_{pond} accelerates conduction electrons and slows down return-current electrons. The cold return-current electrons are more sensitive to F_{pond}, thus the larger change in negative f_1 when F_{pond} is off.



The conduction electrons are not sensitive to F_{pond}, but removing it does allow some cold electrons to speed up. This leads to a small increase in forward heat flux.

$Z = 3$
$I_{15} = 0.9$
$T_0 = 500$ eV
x=126 um

Onset of self-similar thermal wave behavior



Practical and accurate simulations of laser effects on heat flow must avoid resolving oscillations without resorting to unnecessary approximations

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Naive approach

- Include laser as external fields in standard VFP

$$\partial_t f + \vec{v} \cdot \partial_{\vec{x}} f - e\vec{E}_0 \cdot \partial_{\vec{p}} f$$
$$- e\left[\left(\vec{E}_L + \vec{v} \times \vec{B}_L\right)\cos(\omega_L t)\right] \cdot \partial_{\vec{p}} f$$
$$= C_{ei}[f] + C_{ee}[f, f]$$

- Difficult to accurately resolve oscillations over long run time scales
  - Small time step
  - High-order time integration

Standard approach

- Treat laser-plasma coupling *ad hoc* with approximate operators
  - Langdon collisional absorption operator*
  - External ponderomotive force
- Tends to predict excess absorption**
- Validity in the presence of strong (wavelength-scale) inhomogeneities is unclear†

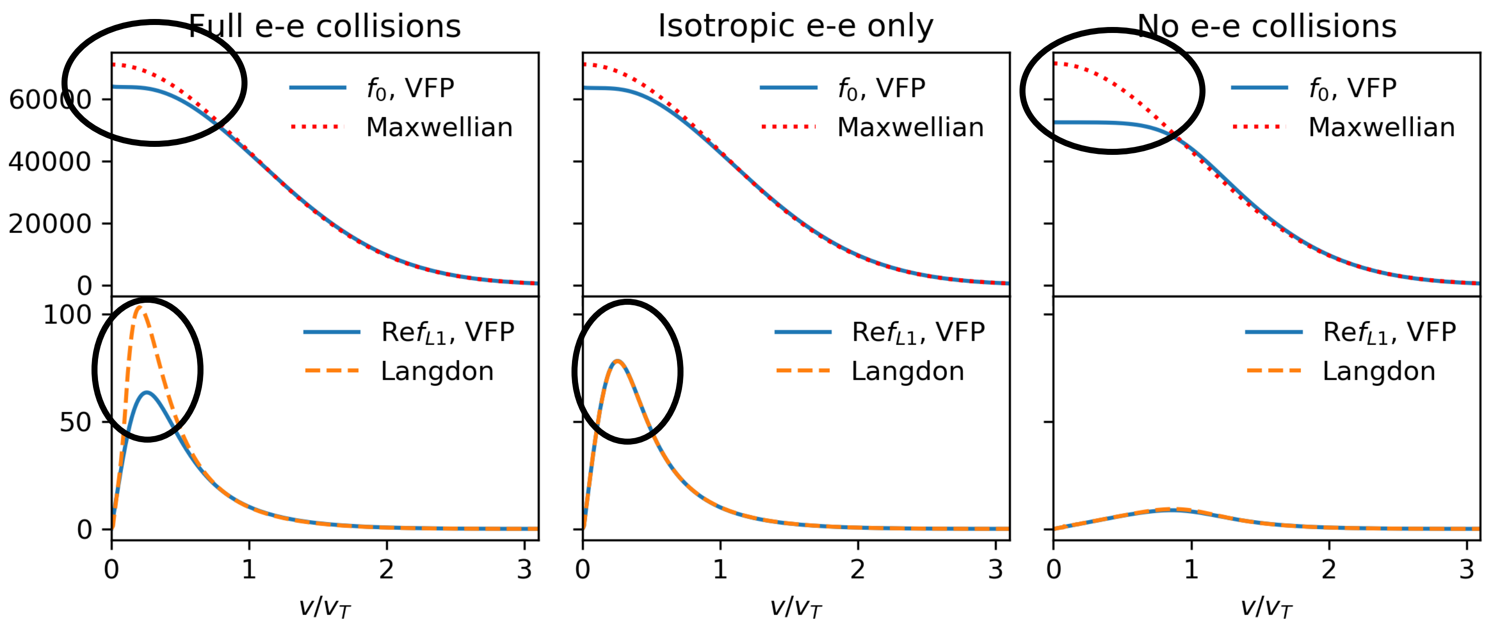
Laser-coupling effects at the critical density require a new computational approach

* A. B. Langdon, *Phys. Rev. Lett.* 44, 570 (1980).
** S.-M. Weng et al., *Phys. Rev. E* 80, 056406 (2009).
† J. Limpouch et al., *Laser and Particle Beams* 12, 101 (1994).

A detailed treatment of IB absorption allows full account of the Langdon effect and the role of e-e collisions

- **In low-Z plasma, e-e collisions affect IB absorption in two ways**
  - **Reduces the Langdon effect to give a more Maxwellian distribution (greatly increases absorption)**
  - **Reduces the population of electrons participating in collisional resonance (slightly decreases absorption)**

$$Z = 1, Z(v_E/v_T)^2 = 0.02$$



Our approach ensures that IB is treated accurately, even in low-Z plasmas where e-e collisions are important

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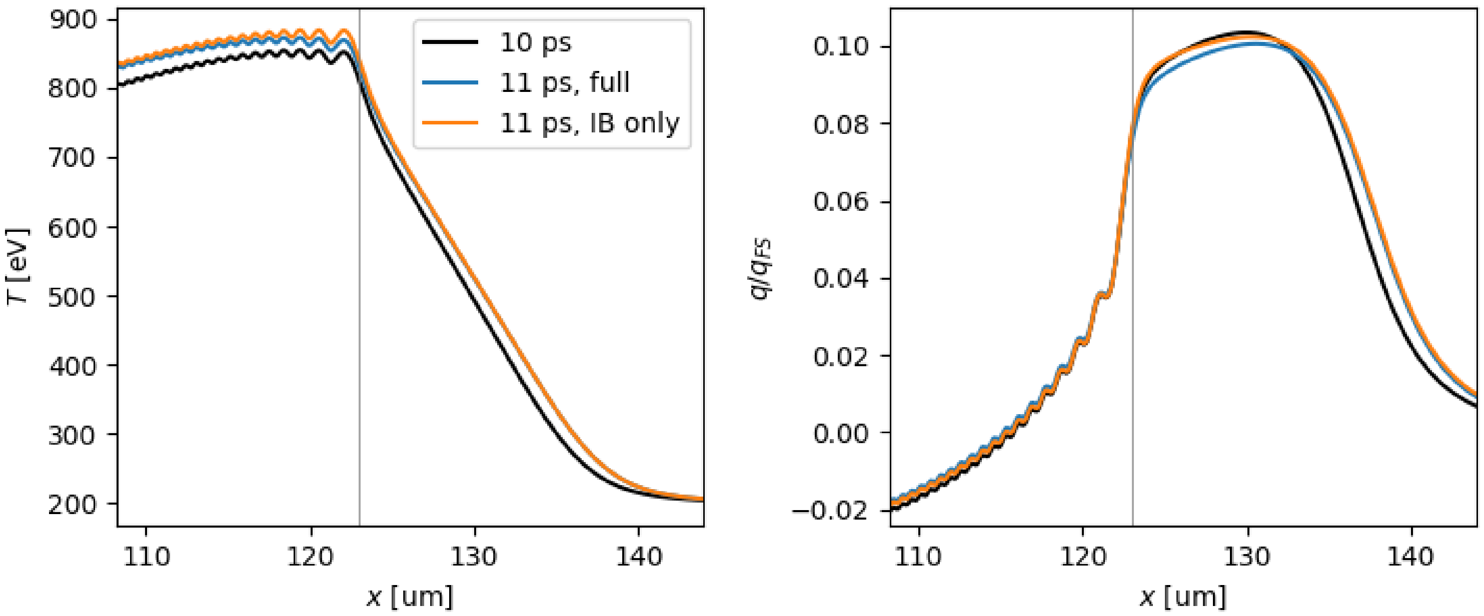
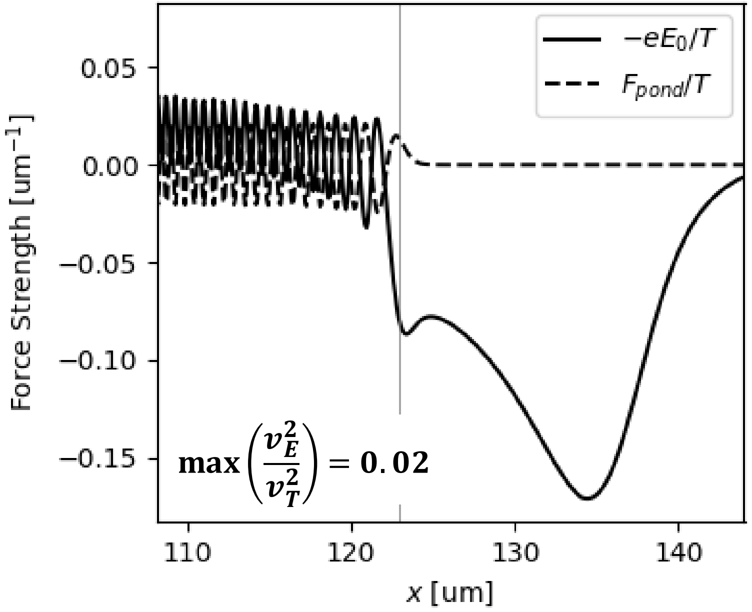
The role of the ponderomotive force can be quantified by switching from AC/DC VFP to conventional VFP with Langdon IB



Z = 3
I_{15} = 0.18
T_0 = 200 eV

At low intensities, nonlocal conduction is not significantly affected by the ponderomotive force

At low intensities, the ponderomotive force is swamped by the larger ambipolar electric force



Ambipolar force: $\frac{-eE_0}{T} \sim \alpha \frac{\nabla T_e}{T}$

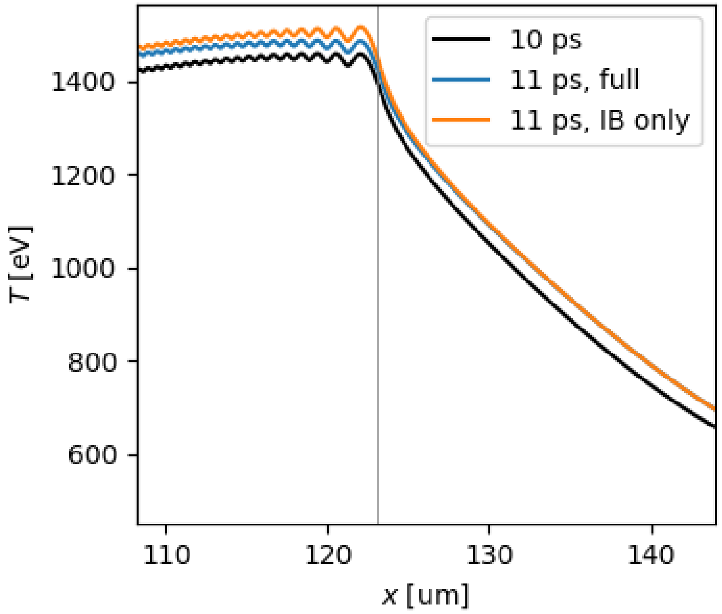
Ponderomotive force: $\frac{F_P}{T} = -\frac{\nabla v_E^2}{4 v_T^2}$

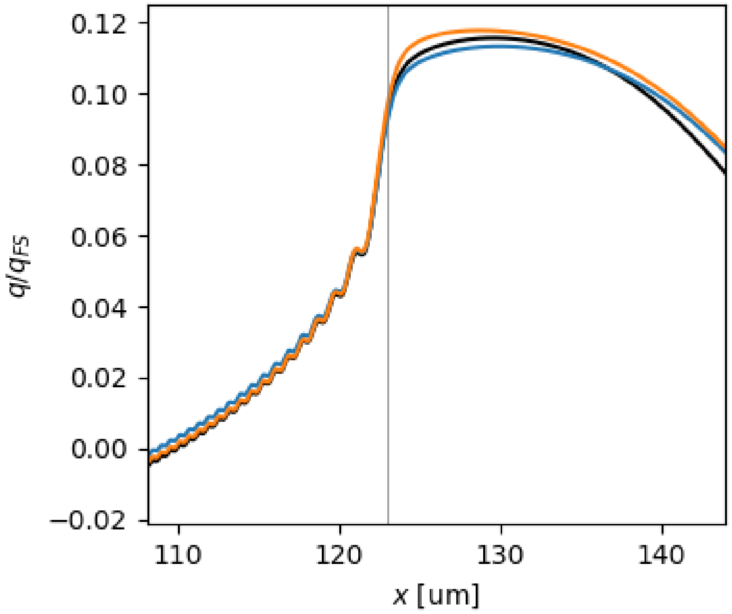
$$\left|\frac{F_P}{eE_0}\right| \sim \frac{1}{4\alpha} \frac{v_E^2}{v_T^2} \frac{L_T}{L_E} \sim \frac{v_E^2}{v_T^2}$$

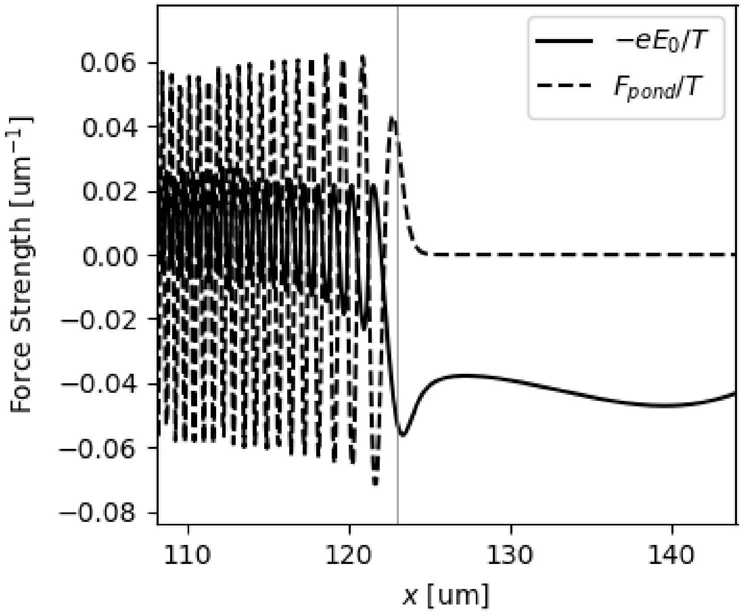
The ponderomotive force can affect nonlocal conduction only at high intensity

Z = 3
I_{15} = 0.18
T_0 = 200 eV

Even at high intensity, Higher intensity heat flow calculations demonstrate a larger but still mild effect of the ponderomotive force on the heat flux







$\lambda_{mfp} \sim 2\ \mu\text{m}$

The laser field primarily modifies heat flow through the non-uniform Langdon effect rather than the ponderomotive force itself

Z = 3
I_{15} = 0.9
T_0 = 500 eV