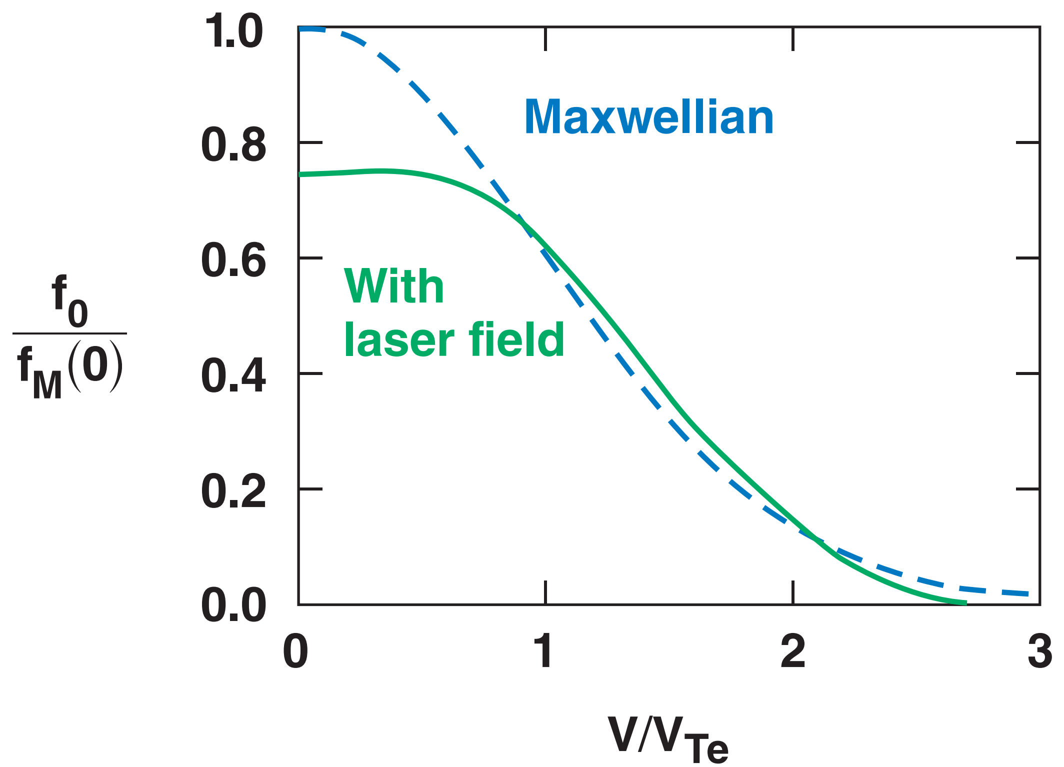
Electron Heat Transport in the Laser Field in Direct-Drive Target Plasmas



$$Z\frac{V_{osc}^2}{V_{Te}^2} = 0.25$$

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Summary

A model for the influence of a moderate laser field on the electron distribution allows calculation of the modification of electron heat flux

- Modeling of laser light propagation near the critical density provides the laser intensity profiles that modify the electron distribution.

- For moderate laser intensities, the heating strongly affects low-velocity electrons, which allows an analytic solution for the electron distribution function.

- The modification of the electron heat flux on hydrodynamic scales is caused by temperature, density, and field intensity gradients.

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Outline

1. Modeling of laser light propagation and absorption near critical density

2. Kinetic equation for electrons in the laser field

3. Distribution function at low velocities and absorption

4. Modification of heat transport

The near-critical density region is important for modeling the propagation and absorption of light

Our model for laser–plasma interaction near critical density can describe the interplay between the following processes:

1. Reflection from the critical-density surface

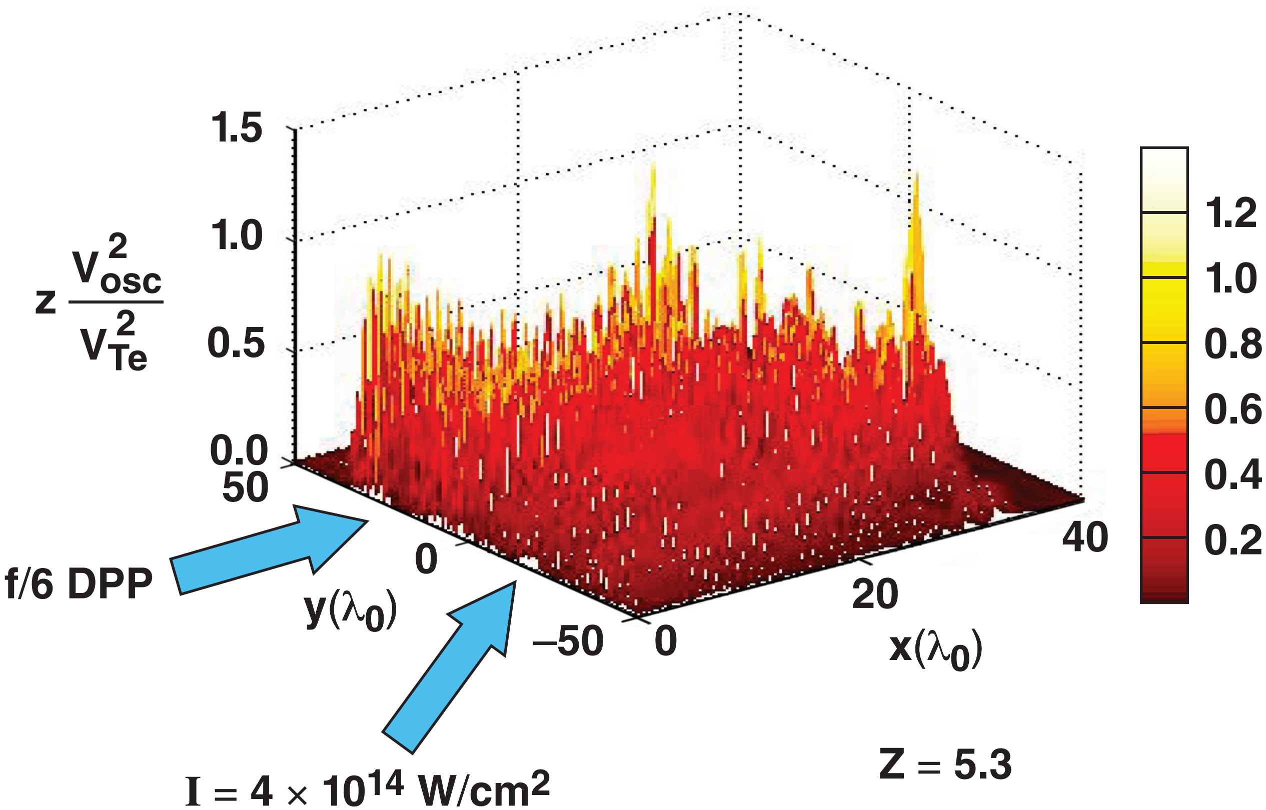
2. Absorption

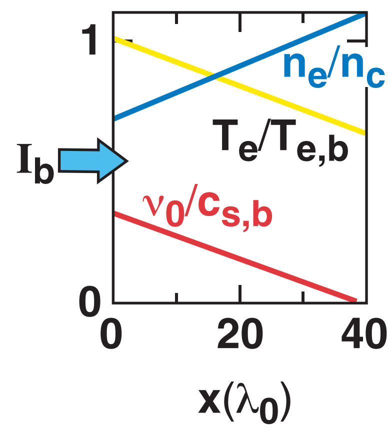
3. Beam self-smoothing due to self-focusing

4. Backward SBS in an inhomogeneous plasma

5. Interaction between crossing beams

Under the crossed-beam irradiation, the laser intensity profiles are strongly inhomogeneous





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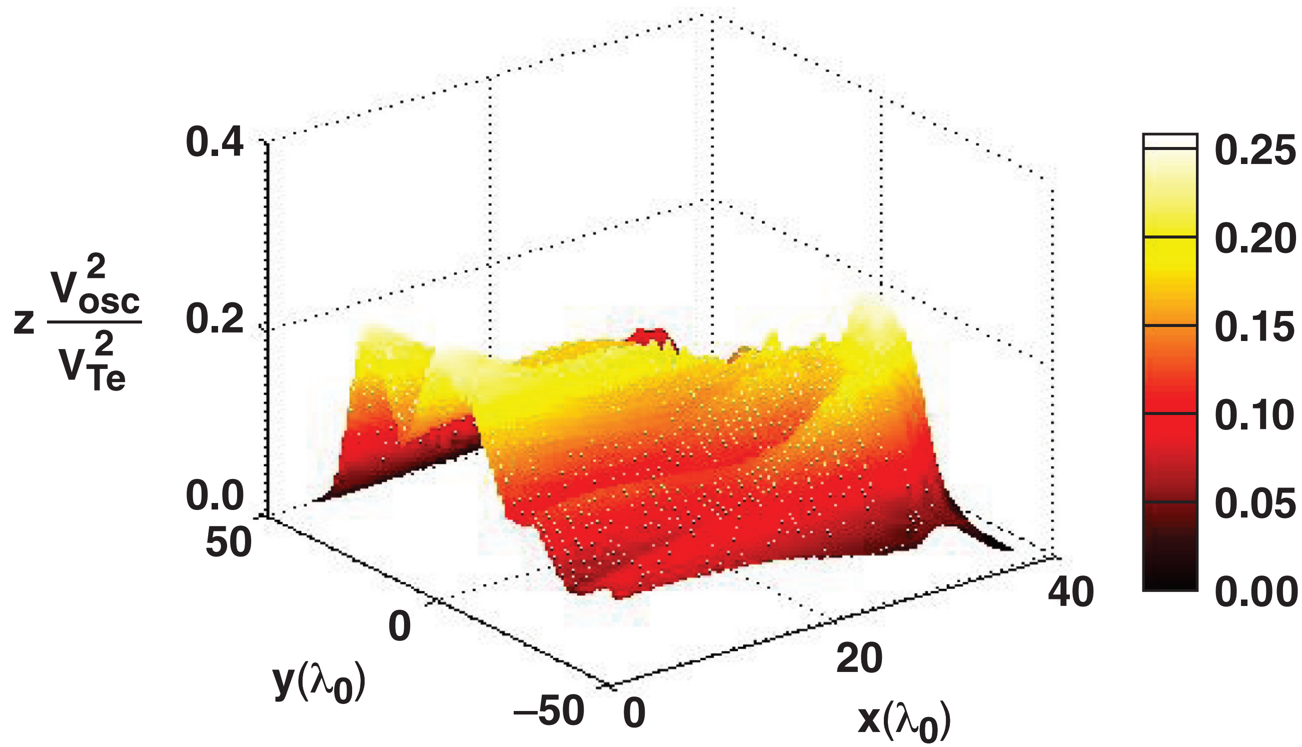
For large-scale modeling, the laser intensity is averaged over spatial scales much larger than the laser wavelength

Large-scale modeling resolves hydrodynamic scales for density and temperature.



After averaging over the electron mean-free path $\sqrt{\lambda_{ei}\lambda_{ee}} \sim \lambda_{ei}\sqrt{Z}$.

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To calculate the electron distribution function in the laser field, the kinetic equation is solved

- After averaging the kinetic equation* over scales larger than the electron mean free path

$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{r}} + e\vec{E}_0\frac{\partial f}{\partial \vec{p}} - J_{ei}(f) - J_{ee}(f,f)$$

$$= \frac{e^2}{4\omega_0^2}\left(E_i E_j^* + E_j E_i^*\right)\left[\frac{\partial}{\partial p_i} J_{ei}\left(\frac{\partial f}{\partial p_j}\right) + J_{ee}\left(\frac{\partial f}{\partial p_i}, \frac{\partial f}{\partial p_j}\right)\right]$$

} Heating in the laser field

$\mathrm{Re}\left[\vec{E}\exp\left(-i\omega_0 t\right)\right]$

$$J_{ei} \sim \nu(v) \sim \nu_{ei}\frac{v_{Te}^3}{v^3} \qquad J_{ee} \sim \nu_{ee}(v) \sim \frac{\nu_{ei}}{Z}\left(\frac{v_{Te}}{v}\right)^2 \qquad z = \frac{\langle z^2\rangle}{\langle z\rangle}.$$

- The self-consistent field $\vec{E}_0$ is determined from $\vec{j} = 0$

*A. V. Maximov *et al.*, JETP 86, 710 (1998).

The symmetric part of the electron distribution function is modified by heating

- For moderate laser intensities $Z\frac{V_{osc}^2}{V_{Te}^2} \ll 1$ in the collisional limit

$$\frac{\partial f_0}{\partial t} - J_{ee}(f_0, f_0) = \frac{v_{osc}^2}{3}\frac{1}{v^2}\frac{\partial}{\partial v}\left[v^2 \nu(v)\frac{\partial f_0}{\partial v}\right].$$

For small velocities $V \ll V_{Te}$, the term $\sim v_{osc}^2 \cdot J_{ee}$ can be neglected.

- The heating time $t_{hc} \sim \frac{v^2}{v_{osc}^2}\frac{1}{\nu(v)} \sim v^5$ is much smaller for cold electrons compared to the heating time for the bulk of electron distribution

$$t_h \sim \frac{v_{Te}^2}{v_{osc}^2}\frac{1}{\nu_{ei}}.$$

Heating strongly affects the low-velocity part of the distribution function

- The solution for $V \ll V_{Te}$

$$f_{0,S}(v) = f_0(0)\exp\left(-\frac{1}{v_{Te}^2}\int_0^v \frac{u^4\,du}{u^3+v_L^3}\right) \qquad v_L = v_{Te}\left(\sqrt{\frac{\pi}{8}}\,\frac{Zv_{osc}^2}{v_{Te}^2}\right)^{1/3}$$

describes the transition from $\ln f_0 \sim -v^5$ to $\ln f_0 \sim -v^2$; different from the super-Gaussian distributions*

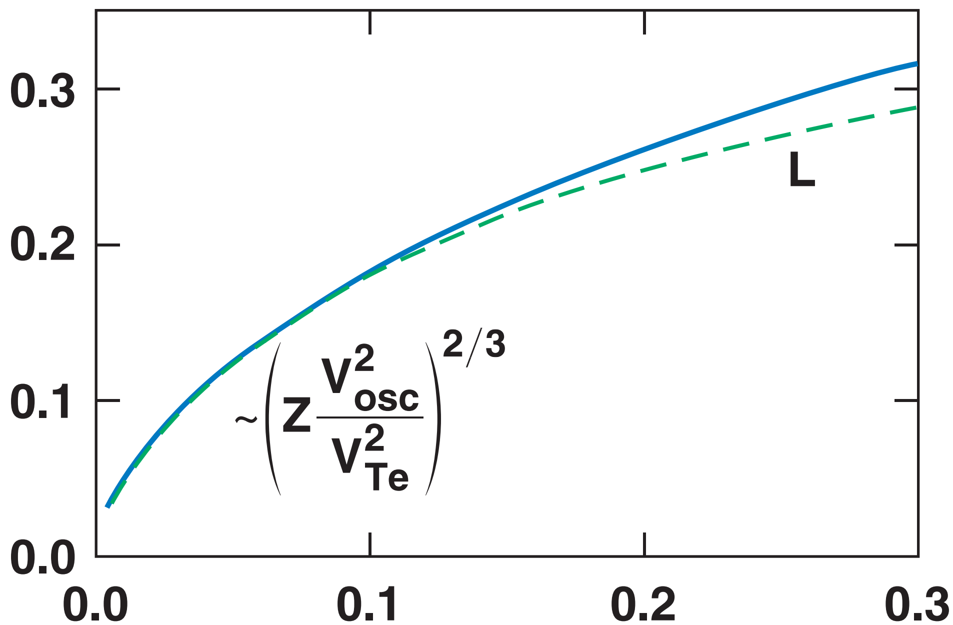
$$f_0(v) \sim \exp\left[-\left(\frac{v}{v_m}\right)^m\right] \qquad m = 2 \div 5.$$

*J. P. Matte *et al.*, Plasma Phys. Contr. Fusion 30, 1665 (1988).

The laser absorption fraction is calculated from the electron distribution at low velocities

$1 - \frac{f_0(0)}{f_M(0)}$

Reduction factor in absorption



$$Z \frac{v_{osc}^2}{v_{Te}^2} = 0.046 \cdot Z \cdot \frac{I\left(10^{15}\,\mathrm{W/cm^2}\right)}{T_e(\mathrm{keV})}$$

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[L] A. B. Langdon, PRL 44, 575 (1980).

The modification of the electron distribution function in the laser field at large velocities is calculated using the Chapman–Enskog method

- The laser field also modifies the electron distribution in the range of velocities contributing to the heat flux* $V > V_{Te}$.

$$f_{0,1}(V) = f_M(V)\left(1 + \Phi_E(V) \cdot \frac{ZV_{osc}^2}{V_{Te}^2}\right)$$

$\Phi_E(V)$ does not directly change the density and temperature

- The solution for low velocities is close to Maxwellian

$f_{0,s}(V) \sim f_M(V)$, when V approaches V_{Te};

allowing solutions to match at low and large velocities.

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

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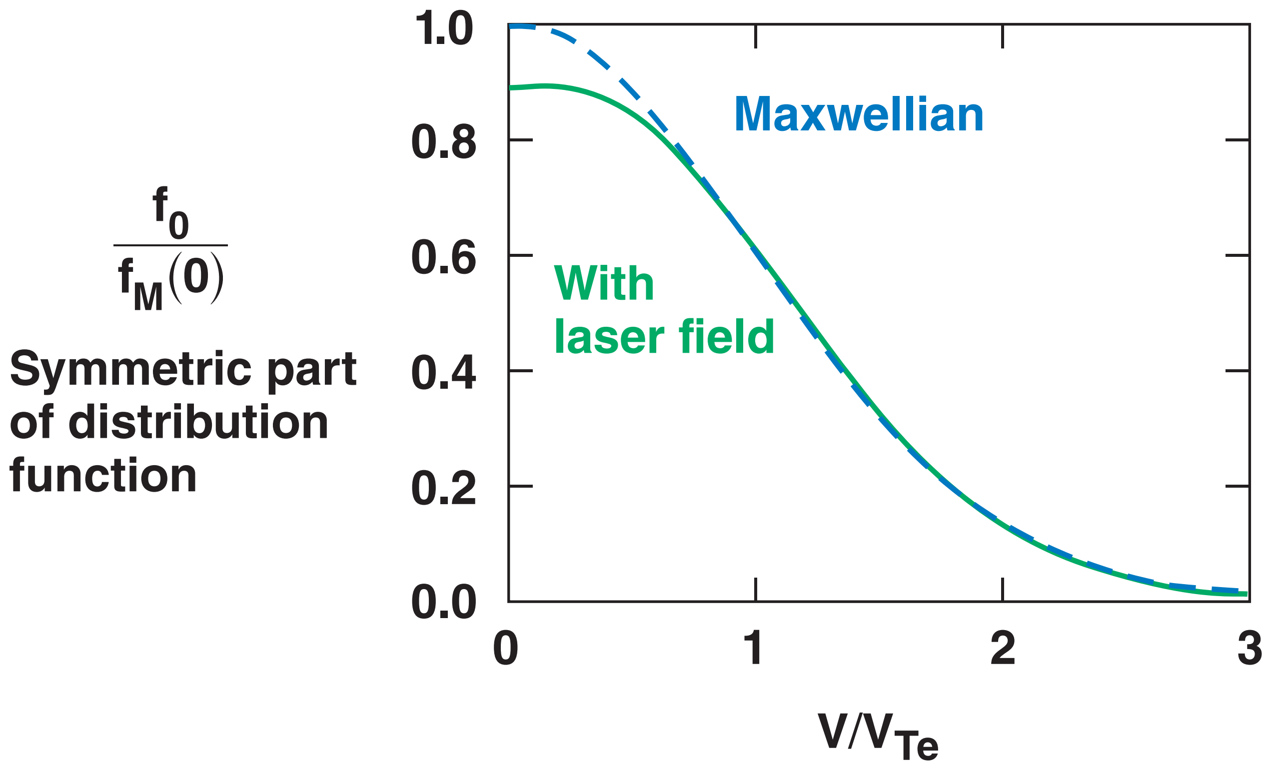
The symmetric part of the electron distribution function in the laser field deviates from the Maxwellian distribution at low velocities



$$Z\frac{V_{osc}^2}{V_{Te}^2} = 0.05$$

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At the higher intensities of the laser field, the symmetric part of the electron distribution function also deviates from the Maxwellian distribution at larger velocities

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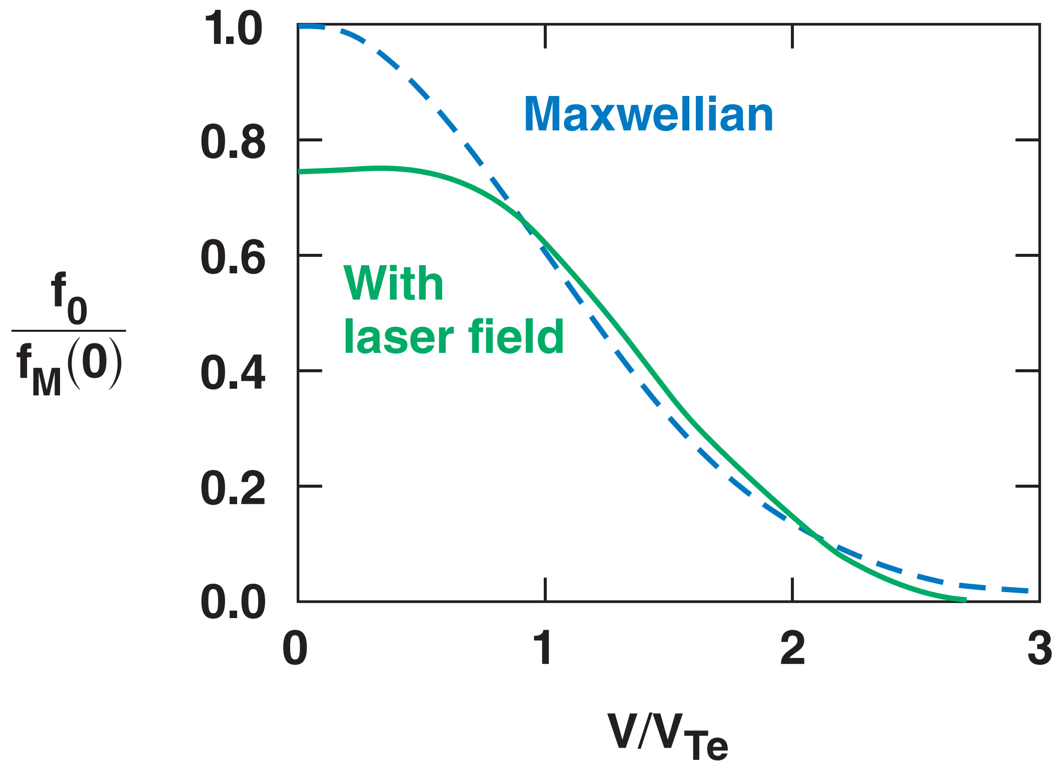

$$Z\frac{V_{osc}^2}{V_{Te}^2} = 0.25$$

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The modification of the symmetric part of the distribution function leads to changes in the electron heat flux

- The electron heat flux after using the condition $\vec{j} = 0$

$$\vec{q} = -\frac{m_e}{\nu_{ei} V_{Te}^3}\left[\alpha_{SH} \cdot n_e V_{Te}^5 \frac{\partial V_{Te}^2}{\partial \vec{r}} - \alpha_1 \cdot \frac{\partial}{\partial \vec{r}}\left(n_e V_{Te}^3 Z V_{osc}^2\right) + \alpha_2 \cdot V_{Te}^2 \frac{\partial}{\partial \vec{r}}\left(n_e V_{Te}^3 Z V_{osc}^2\right) - \alpha_p \cdot n_e V_{Te}^5 \frac{\partial}{\partial \vec{r}}\left(V_{osc}^2\right)\right]$$

coefficients

$\alpha_{SH} = 13.6$, $\alpha_1 = 31.2$, $\alpha_2 = 13.9$, $\alpha_p = 2.3$ $\quad Z \gg 1$

$\alpha_{SH} = 3.2$, $\alpha_1 = 15.2$, $\alpha_2 = 11.1$, $\alpha_p = 2.7$ $\quad Z = 1$

- New terms in the heat flux depend on $\frac{\partial n_e}{\partial \vec{r}}$.

Summary/Conclusions

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