An efficient kinetic modeling in plasmas by using the AWBS transport equation

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Abstract

The AWBS Boltzmann transport equation for electrons equipped with a simplified e-e collision operator [**?**] provides an efficient, yet physically relevant, kinetic extension compared the classical Spitzer-Harm heat flux (SH) based on local approximation and flux-limiting. This classical approach is widely used in plasma kinetics models coupled to hydrodynamics. Even though SH reflects the electron-electron collision effect, the essential physical properties of the electron transport cannot be modeled with an explicitly local model. A simple form of the AWBS model opens a way to couple kinetics to hydrodynamic codes while describing the important physics correctly. Since the electron-electron collision effect becomes especially important in the case of low ion potential, we focus on presenting results related to low Z plasmas.

Keywords: kinetics; hydrodynamics; nonlocal electron transport; laser-heated plasmas.

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$$\frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\nabla_{\boldsymbol{x}}f + \tilde{\boldsymbol{E}}\cdot\nabla_{\boldsymbol{v}}f = v\frac{\nu_e}{2}\frac{\partial}{\partial v}\left(f - f_M\right) + \frac{\nu_{ei} + \frac{\nu_e}{2}}{2}\frac{\partial^2 f}{\partial \boldsymbol{n}^2}, \qquad (1)$$

20 [1]

21 **3. BGK, AWBS, and Fokker-Planck models in diffusive regime**

22 We can try to find an approximate solution while using the first term of
23 expansion in λ_e and muas

$$\tilde{f}(z,v,\mu) = f^0(z,v) + f^1(z,v)\lambda_{ei}\mu. \qquad (2)$$

24 *3.1. The BGK diffusive electron transport*

$$\boldsymbol{n}\cdot\nabla f + \frac{1}{v}\left[\tilde{\boldsymbol{E}}\cdot\boldsymbol{n}\frac{\partial f}{\partial v} + \frac{\tilde{\boldsymbol{E}}\cdot\boldsymbol{e}_\phi - v\tilde{\boldsymbol{B}}\cdot\boldsymbol{e}_\theta}{v}\frac{\partial f}{\partial\phi} + \frac{\tilde{\boldsymbol{E}}\cdot\boldsymbol{e}_\theta + v\tilde{\boldsymbol{B}}\cdot\boldsymbol{e}_\phi}{v\sin(\phi)}\frac{\partial f}{\partial\theta}\right] =$$
$$\frac{(f_M - f)}{\lambda^e} + \frac{1}{2\lambda^{ei}}\left(\frac{\partial}{\partial\mu}\left((1-\mu^2)\frac{\partial f}{\partial\mu}\right) + \frac{1}{\sin^2(\phi)}\frac{\partial^2 f}{\partial\theta^2}\right), \quad (3)$$

25 where $\mu = \cos(\phi)$, λ_e is the electron-electron mean free path, and λ_{ei} is
26 the electron-ion mean free path. We also approximate $\lambda_e = \bar{Z}\lambda_{ei}$.

Clearly, $\frac{\partial\tilde{f}}{\partial\theta} = 0$, and if $\tilde{\boldsymbol{B}} = \tilde{B}_z\boldsymbol{e}_z$, there is no effect of magnetic field. We also assume, that $\nabla f = \frac{\partial f}{\partial z}\boldsymbol{e}_z$ and appropriately $\tilde{\boldsymbol{E}} = \tilde{E}_z\boldsymbol{e}_z$. From the orientation of the Cartesian basis vectors and spherical basis vectors, one can find $\tilde{\boldsymbol{E}}\cdot\boldsymbol{n} = \tilde{E}_z\cos(\phi) = \mu$ and $\tilde{\boldsymbol{E}}\cdot\boldsymbol{e}_\phi = -\tilde{E}_z\sin(\phi)$. As a result, the analyzed BGK equation reads

$$\mu\frac{\partial}{\partial z}\left(f^0 + f^1\lambda_{ei}\mu\right) + \frac{1}{v}\left[\tilde{E}_z\mu\frac{\partial}{\partial v}\left(f^0 + f^1\lambda_{ei}\mu\right) - \frac{\tilde{E}_z\sin(\phi)}{v}\frac{\partial}{\partial\phi}\left(f^0 + f^1\lambda_{ei}\mu\right)\right] =$$
$$\frac{(f_M - (f^0 + f^1\lambda_{ei}\mu))}{\lambda_e} + \frac{1}{2\lambda_{ei}}\frac{\partial}{\partial\mu}\left((1-\mu^2)\frac{\partial}{\partial\mu}\left(f^0 + f^1\lambda_{ei}\mu\right)\right), \quad (4)$$

3

$$\mu\frac{\partial f^0}{\partial z} + \mu^2\frac{\partial}{\partial z}\left(f^1\lambda_{ei}\right) + \frac{\tilde{E}_z}{v}\left[\mu\frac{\partial f^0}{\partial v} + \mu^2\frac{\partial}{\partial v}\left(f^1\lambda_{ei}\right) + \frac{1-\mu^2}{v}f^1\lambda_{ei}\right] =$$
$$\frac{f_M - f^0}{\bar{Z}\lambda_{ei}} - \mu\frac{1}{\bar{Z}}f^1 - \mu f^1, \quad (5)$$

consequently, we have the following anisotropy expansion $\mu^0, \mu^1, \mu^2, ...$ equations

$$\frac{f_M - f^0}{\bar{Z}\lambda_{ei}} = \frac{\tilde{E}_z}{v^2}f^1\lambda_{ei},$$

$$\frac{\partial f^0}{\partial z} + \frac{\tilde{E}_z}{v}\frac{\partial f^0}{\partial v} = -\frac{1}{\bar{Z}}f^1 - f^1,$$

$$\frac{\partial}{\partial z}\left(f^1\lambda_{ei}\right) + \frac{\tilde{E}_z}{v}\left[\frac{\partial}{\partial v}\left(f^1\lambda_{ei}\right) - \frac{1}{v}f^1\lambda_{ei}\right] = 0,$$

which lead to the definitions

$$f^0 = f_M + \frac{1}{v}f^1\bar{Z}\lambda_{ei}^2, \quad (6)$$

$$f^1 = -\frac{\bar{Z}}{\bar{Z}+1}\left[\frac{\partial f^0}{\partial z} + \frac{\tilde{E}_z}{v}\frac{\partial f^0}{\partial v}\right]$$

$$= -\frac{\bar{Z}}{\bar{Z}+1}\left[\frac{1}{\rho}\frac{\partial\rho}{\partial z} + \left(\frac{v^2}{2v_{th}^2} - \frac{3}{2}\right)\frac{1}{T}\frac{\partial T}{\partial z} - \frac{\tilde{E}_z}{v_{th}^2}\right]f_M \quad (7)$$

In order to ensure the plasma to be quasi-neutral, the zero-current condition

$$\boldsymbol{j} = \int_0^\infty \int_{4\pi} q_e v \boldsymbol{n} f \, \mathrm{d}\boldsymbol{n} \, v^2 \, \mathrm{d}v = \boldsymbol{0}, \quad (8)$$

can be achieved by providing a consistent electric field in (15), i.e.

$$\tilde{\boldsymbol{E}} = \frac{v_{th}^2 \, \int_{4\pi}\boldsymbol{n}\otimes\boldsymbol{n}\cdot\int_0^\infty v f_M\frac{\lambda}{\alpha}\left(\frac{\nabla\rho}{\rho} + \left(\frac{v^2}{2v_{th}^2} - \frac{3}{2}\right)\frac{\nabla T}{T}\right)v^2\,\mathrm{d}v\,\mathrm{d}\boldsymbol{n}}{\int_{4\pi}\boldsymbol{n}\otimes\boldsymbol{n}\cdot\int_0^\infty v f_M\frac{\lambda}{\alpha}v^2\,\mathrm{d}v\,\mathrm{d}\boldsymbol{n}}, \quad (9)$$

which may be further simplified as

$$\tilde{\boldsymbol{E}} = \frac{\int_0^\infty f_M\frac{1}{2}\frac{\nabla T}{T}v^9\,\mathrm{d}v}{\int_0^\infty f_M v^7\,\mathrm{d}v} + v_{th}^2\left(\frac{\nabla\rho}{\rho} - \frac{3}{2}\frac{\nabla T}{T}\right) = v_{th}^2\left(\frac{\nabla\rho}{\rho} + \frac{5}{2}\frac{\nabla T}{T}\right), \quad (10)$$

where it is worth mentioning, that the part $f_M + \frac{v\lambda}{\alpha}\frac{\partial f_1}{\partial v}$ of the distribution does not contribute to the current since it is isotropic. One can write the quasi-neutral distribution function explicitly distinguishing between original part (blue color) and E field correction (red color) as

$$f \approx f_M \left(1 - \frac{\lambda}{\alpha}\boldsymbol{n} \cdot \left(\frac{v^2}{2v_{th}^2} - \frac{3}{2} - \frac{5}{2} \right) \frac{\nabla T}{T} \right) + \frac{v\lambda}{\alpha}\frac{\partial f_1}{\partial v}. \tag{11}$$

which leads to the resulting heat flux

$$\boldsymbol{q}_H = \int_{4\pi}\int_0^\infty \frac{m_e v^2}{2}v\boldsymbol{n}fv^2 \, \mathrm{d}v \, \mathrm{d}\boldsymbol{n} = \frac{4\pi}{3}\frac{m_e}{2}\frac{1}{\alpha\sigma\rho}\int_0^\infty \left(\frac{v^2}{2v_{th}^2} - \frac{3}{2} - \frac{5}{2} \right) v^9 f_M \, \mathrm{d}v \frac{\nabla T}{T}.$$

Based on the Gauss integral formula

$$\int v^{2s+1}\exp\left(-\frac{v^2}{2v_{th}^2} \right) \mathrm{d}v = \frac{s! \, (2v_{th}^2)^{s+1}}{2}$$

and Maxwell-Boltzmann distribution (**??**) the heat flux can be written as

$$\boldsymbol{q}_H = \frac{4\pi}{3}\frac{m_e}{2}\frac{1}{\alpha\sigma\rho}\frac{\rho}{v_{th}^3 \, (2\pi)^{3/2}}\frac{4! \, 2^4 v_{th}^{10}}{T}\left(5 - \frac{3}{2} - \frac{5}{2} \right)\nabla T = \frac{m_e}{\alpha\sigma}\frac{128}{\sqrt{2\pi}}\left(\frac{k_B}{m_e} \right)^{\frac{7}{2}}T^{\frac{5}{2}}\nabla T. \tag{12}$$

In conclusion, equation (12) provides nothing else than the well known Lorentz approximation heat flux and its nonlinearity 2.5 in temperature. What is worth mentioning is the effect of E field (quasi-neutrality), which reduces the flux of about 71.4% (also assuming constant density).

Finally, one can find the approximate solution

$$\tilde{f} = f_M - \lambda_{ei}\frac{\bar{Z}}{\bar{Z}+1}\left(\frac{v^2}{2v_{th}^2} - \frac{3}{2} - \alpha \right)\frac{\boldsymbol{n}\cdot\nabla T}{T}f_M. \tag{13}$$

3.2. The AWBS diffusive electron transport

The AWBS electron transport equation in 6D reads

$$\boldsymbol{n}\cdot\nabla f + \frac{1}{v}\left[\tilde{\boldsymbol{E}}\cdot\boldsymbol{n}\frac{\partial f}{\partial v} + \frac{\tilde{\boldsymbol{E}}\cdot\boldsymbol{e}_\phi - v\tilde{\boldsymbol{B}}\cdot\boldsymbol{e}_\theta}{v}\frac{\partial f}{\partial \phi} + \frac{\tilde{\boldsymbol{E}}\cdot\boldsymbol{e}_\theta + v\tilde{\boldsymbol{B}}\cdot\boldsymbol{e}_\phi}{v\sin(\phi)}\frac{\partial f}{\partial \theta} \right] =$$

$$\frac{v}{\lambda^e}\frac{\partial}{\partial v}\left(f - f_M \right) + \left(\frac{1}{\lambda_{ei}} + \frac{1}{\lambda_e} \right)\frac{1}{2}\left(\frac{\partial}{\partial \mu}\left((1-\mu^2)\frac{\partial f}{\partial \mu} \right) + \frac{1}{\sin^2(\phi)}\frac{\partial^2 f}{\partial \theta^2} \right), \tag{14}$$

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where $\mu = \cos(\phi)$, λ_e is the electron-electron mean free path, and λ_{ei} is the electron-ion mean free path, and $\lambda_e = \bar{Z}\lambda_{ei}$.

We can try to find an approximate solution while using the first term of expansion in λ_e and μ as

$$\tilde{f}(z, v, \mu) = f^0(z, v) + f^1(z, v)\lambda_{ei}\mu. \tag{15}$$

Clearly, $\frac{\partial \tilde{f}}{\partial \theta} = 0$, and if $\tilde{\boldsymbol{B}} = \tilde{B}_z \boldsymbol{e}_z$, there is no effect of magnetic field. We also assume, that $\nabla f = \frac{\partial f}{\partial z}\boldsymbol{e}_z$ and appropriately $\tilde{\boldsymbol{E}} = \tilde{E}_z \boldsymbol{e}_z$. From the orientation of the Cartesian basis vectors and spherical basis vectors, one can find $\tilde{\boldsymbol{E}}\cdot\boldsymbol{n} = \tilde{E}_z \cos(\phi) = \mu$ and $\tilde{\boldsymbol{E}} \cdot \boldsymbol{e}_\phi = -\tilde{E}_z \sin(\phi)$. As a result, the analyzed AWBS equation reads

$$\mu\frac{\partial}{\partial z}\left(f^0 + f^1\lambda_{ei}\mu\right) + \frac{1}{v}\left[\tilde{E}_z\mu\frac{\partial}{\partial v}\left(f^0 + f^1\lambda_{ei}\mu\right) - \frac{\tilde{E}_z\sin(\phi)}{v}\frac{\partial}{\partial \phi}\left(f^0 + f^1\lambda_{ei}\mu\right)\right] = \\ \frac{v}{\lambda_e}\frac{\partial}{\partial v}\left((f^0 + f^1\lambda_{ei}\mu) - f_M\right) + \frac{\bar{Z}+1}{2\lambda_{ei}\bar{Z}}\frac{\partial}{\partial \mu}\left((1-\mu^2)\frac{\partial}{\partial \mu}\left(f^0 + f^1\lambda_{ei}\mu\right)\right), \tag{16}$$

$$\mu\frac{\partial f^0}{\partial z} + \mu^2\frac{\partial}{\partial z}\left(f^1\lambda_{ei}\right) + \frac{\tilde{E}_z}{v}\left[\mu\frac{\partial f^0}{\partial v} + \mu^2\frac{\partial}{\partial v}\left(f^1\lambda_{ei}\right) + \frac{1-\mu^2}{v}f^1\lambda_{ei}\right] = \\ \frac{v}{\bar{Z}\lambda_{ei}}\frac{\partial}{\partial v}\left(f^0 - f_M\right) + \mu\frac{v}{\bar{Z}\lambda_{ei}}\frac{\partial(f^1\lambda_{ei})}{\partial v} - \mu\frac{\bar{Z}+1}{\bar{Z}}f^1, \tag{17}$$

consequently, we have the following anisotropy expansion $\mu^0, \mu^1, \mu^2, ...$ equations

$$\frac{v}{\bar{Z}\lambda_{ei}}\frac{\partial}{\partial v}\left(f^0 - f_M\right) = \frac{\tilde{E}_z}{v^2}f^1\lambda_{ei},$$

$$\frac{\partial f^0}{\partial z} + \frac{\tilde{E}_z}{v}\frac{\partial f^0}{\partial v} = \frac{v}{\bar{Z}\lambda_{ei}}\frac{\partial(f^1\lambda_{ei})}{\partial v} - \frac{\bar{Z}+1}{\bar{Z}}f^1,$$

$$\frac{\partial}{\partial z}\left(f^1\lambda_{ei}\right) + \frac{\tilde{E}_z}{v}\left[\frac{\partial}{\partial v}\left(f^1\lambda_{ei}\right) - \frac{1}{v}f^1\lambda_{ei}\right] = 0,$$

6

which lead to the definitions

$$\frac{\partial}{\partial v}\left(f^0 - f_M\right) = \frac{1}{v^2}f^1\bar{Z}\lambda_{ei}^2, \tag{18}$$

$$\frac{v}{\bar{Z}\lambda_{ei}}\frac{\partial(f^1\lambda_{ei})}{\partial v} - \frac{\bar{Z}+1}{\bar{Z}}f^1 = \frac{\partial f^0}{\partial z} + \frac{\tilde{E}_z}{v}\frac{\partial f^0}{\partial v}$$

$$\frac{v}{\bar{Z}}\frac{\partial f^1}{\partial v} + \frac{4}{\bar{Z}}f^1 - \frac{\bar{Z}+1}{\bar{Z}}f^1 = \frac{\partial f^0}{\partial z} + \frac{\tilde{E}_z}{v}\frac{\partial f^0}{\partial v}$$

$$\frac{\partial f^1}{\partial v} + \frac{1}{v}(3-\bar{Z})f^1 = \frac{\bar{Z}}{v}\left(\frac{1}{\rho}\frac{\partial\rho}{\partial z} + \left(\frac{v^2}{2v_{th}^2} - \frac{3}{2}\right)\frac{1}{T}\frac{\partial T}{\partial z} - \frac{\tilde{E}_z}{v_{th}^2}\right)f_M \tag{19}$$

3.3. The Fokker-Planck diffusive electron transport

$$v_{2th} = \sqrt{\frac{2k_BT}{m_e}} = 1/j,$$

$$A = -\frac{m_e^2 v_{2th}^2\tilde{\boldsymbol{E}}}{2\pi e^4 n_e\ln\Lambda} = -\frac{mE}{2\pi j^2 e^3 n_e\ln\Lambda},$$

$$B = \frac{m_e^2 v_{2th}^4|\nabla T|}{2\pi e^4 n_e\ln\Lambda T} = \frac{2k_B^2 T|\nabla T|}{\pi e^4 n_e\ln\Lambda},$$

$$\frac{A}{B} = -\frac{|\tilde{\boldsymbol{E}}|T}{v_{2th}^2|\nabla T|},$$

$$\tilde{\boldsymbol{E}} = -\frac{3}{2}\frac{v_{2th}^2}{2}\frac{\gamma_T}{\gamma_E}\frac{\nabla T}{T},$$

From Eq. (24) CSR, we can write the form of f_1 including both ∇T and $\tilde{\boldsymbol{E}}$ effects as

$$f_1(v,\theta) = \cos(\theta)\frac{B}{\bar{Z}}\left(d_T(v/v_{2th}) + \frac{A}{B}d_E(v/v_{2th})\right)f_M(v),$$

where in the case of vanishing current one gets

$$\frac{A}{B} = \frac{3}{2}\frac{\gamma_T}{2\gamma_E},$$

7

61 i.e.

$$f_1(v, \theta) = \cos(\theta) \frac{m_e^2}{4\pi e^4 \ln\Lambda} \frac{v_{2th}^4}{\bar{Z}} \left(2d_T(v/v_{2th}) + \frac{3}{2} \frac{\gamma_T}{\gamma_E} d_E(v/v_{2th}) \right) \frac{f_M(v)}{n_e} \frac{\nabla T}{T},$$

(20)

62 where $d_T(x) = \bar{Z} D_T(x)/B$ and $d_E(x) = \bar{Z} D_E(x)/A$ are represented by nu-
63 merical values in TABLE I and TABLE II in [5], respectively. In the case of
64 high $\bar{Z}$ limit, $\gamma_T \to 1$, $\gamma_E \to 1$, $d_E(x) = x^4$, and $d_T(x) = x^4(2.5 - x^2)/2$ [5],
65 which leads to the standard Lorentz gas model

$$f_1(v, \theta) = \cos(\theta) \frac{m_e^2}{4\pi e^4 \ln\Lambda} \frac{v^4}{\bar{Z}} \left(4 - \frac{v^2}{v_{2th}^2} \right) \frac{f_M(v)}{n_e} \frac{\nabla T}{T},$$

(21)

66   [2], [3], [4]

67 *3.4. Summary of BGK, AWBS, and Fokker-Planck diffusion*
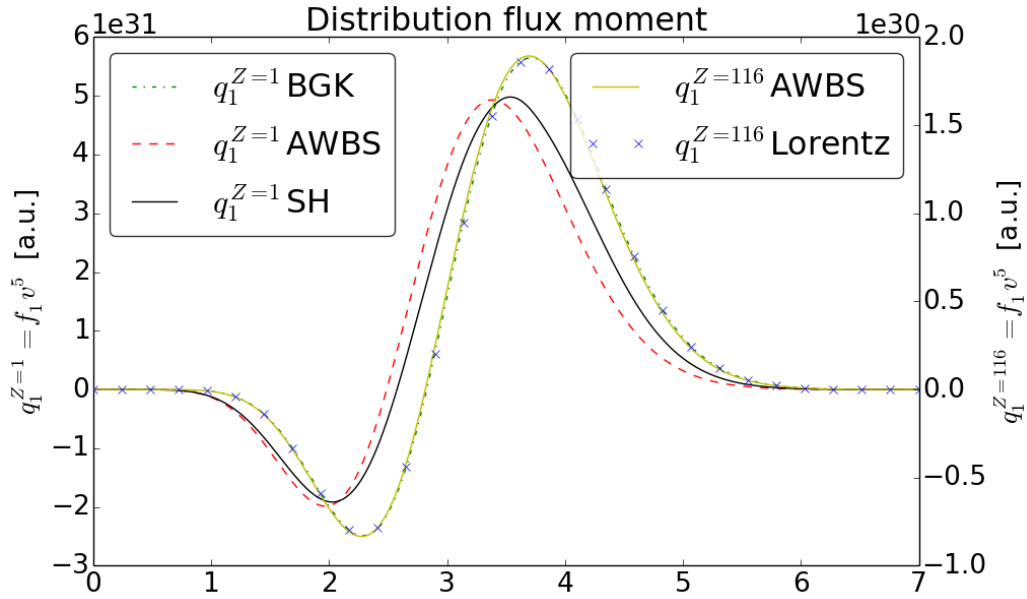
Figure 1: The flux velocity moment of the anisotropic part of the electron distribution function in low $Z = 1$ and high $Z = 116$ plasmas in diffusive regime.

	$\bar{Z}=1$	$\bar{Z}=2$	$\bar{Z}=4$	$\bar{Z}=16$	$\bar{Z}=116$
$error(\boldsymbol{q}_{AWBS})$	0.057	0.004	0.038	0.049	0.004

Table 1: Relative $error(\boldsymbol{q}_{AWBS}) = |\boldsymbol{q}_{AWBS} - \boldsymbol{q}_{SH}|/\boldsymbol{q}_{SH}$ of the AWBS kinetic model equation (1) showing the discrepancy (maximum around 5%) with respect to the original solution of the heat flux given by Spitzer and Harm [5].

4. Benchmarking the AWBS nonlocal transport model

4.1. Review of simulation codes

4.2. C7

Since in the laser heated plasmas the Knudsen number Kn= $\frac{v_{th}}{\nu_t(v_{th})L} \in$ $(0,1)$, i.e. the collisionality in the kinetics of electrons plays always an important effect for thermal-like particles, the electron distribution function can be treated as out-of-equilibrium approximation

$$f = f_M + \delta f, \tag{22}$$

where the consequent AWBS model reads

$$v\boldsymbol{n} \cdot \nabla(f_M + \delta f) + \tilde{\boldsymbol{E}} \cdot \boldsymbol{n}\left(\frac{\partial f_M}{\partial v} + \frac{\partial \delta f}{\partial v}\right) + \frac{\tilde{\boldsymbol{E}} \cdot \boldsymbol{e}_\theta}{v}\frac{\partial \delta f}{\partial \theta} = $$
$$v\frac{\nu_e}{2}\frac{\partial \delta f}{\partial v} + \left(\nu_{ei} + \frac{\nu_e}{2}\right)(f_0 - (f_M + \delta f)), \quad (23)$$

or its 1D version

$$v\mu\frac{\partial}{\partial z}(f_M + \delta f) + \tilde{E}_z\mu\left(\frac{\partial f_M}{\partial v} + \frac{\partial \delta f}{\partial v}\right) + \frac{\tilde{E}_z(1-\mu^2)}{v}\frac{\partial \delta f}{\partial \mu} = $$
$$v\frac{\nu_e}{2}\frac{\partial \delta f}{\partial v} + \left(\nu_{ei} + \frac{\nu_e}{2}\right)(f_0 - (f_M + \delta f)), \quad (24)$$

9

Kn	10^{-3}	5×10^{-3}	10^{-2}	5×10^{-2}	10^{-1}
$v_{lim}^{Z=2}$	27.5	12.7	9.3	5.3	4.9
$v_{lim}^{Z=10}$	12.5	6.3	4.9	3.0	2.4

Table 2: .

where $\tilde{\boldsymbol{E}} \cdot \boldsymbol{e}_\theta = \tilde{E}_z \sin(\theta)$ and $\frac{\partial}{\partial \theta} = \sin(\theta)\frac{\partial}{\partial \mu}$, $\mu = \cos(\theta)$.

$$\left(v\frac{\nu_e}{2} - \tilde{E}_z\mu\right)\frac{\partial \delta f}{\partial v} = v\mu\frac{\partial \delta f}{\partial z} + v\mu\frac{\partial f_M}{\partial z} + \tilde{E}_z\mu\frac{\partial f_M}{\partial v}$$
$$+ \frac{\tilde{E}_z(1-\mu^2)}{v}\frac{\partial \delta f}{\partial \mu} - \left(\nu_{ei} + \frac{\nu_e}{2}\right)(f_0 - (f_M + \delta f)),$$

we adopt $\delta f(v,\mu) = \delta f_0(v) + \mu \delta f_1(v)$, which leads to

$$\left(v\frac{\nu_e}{2} - \tilde{E}_z\mu\right)\frac{\partial}{\partial v}(\delta f_0 + \mu\delta f_1) = v\mu\frac{\partial}{\partial z}(\delta f_0 + \mu\delta f_1) + v\mu\frac{\partial f_M}{\partial z} + \tilde{E}_z\mu\frac{\partial f_M}{\partial v}$$
$$+ \frac{\tilde{E}_z(1-\mu^2)}{v}\delta f_1 + \left(\nu_{ei} + \frac{\nu_e}{2}\right)\mu\delta f_1,$$

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$$v\frac{\nu_e}{2}\frac{\partial \delta f_0}{\partial v} - \tilde{E}_z\mu^2\frac{\partial \delta f_1}{\partial v} = v\mu^2\frac{\partial \delta f_1}{\partial z} + \frac{\tilde{E}_z(1-\mu^2)}{v}\delta f_1,$$
$$\mu v\frac{\nu_e}{2}\frac{\partial \delta f_1}{\partial v} - \tilde{E}_z\mu\frac{\partial \delta f_0}{\partial v} = v\mu\frac{\partial \delta f_0}{\partial z} + v\mu\frac{\partial f_M}{\partial z} + \tilde{E}_z\mu\frac{\partial f_M}{\partial v} + \left(\nu_{ei} + \frac{\nu_e}{2}\right)\mu\delta f_1,$$

76 *4.2.1. Nonlocal electric field treatment*

$$|\boldsymbol{E}_{red}| = v\nu_e + \alpha^E v\nu_e, \tag{25}$$

$$|\boldsymbol{E}_{red}| = |\boldsymbol{E}_d| + |\boldsymbol{E}_{iso}|,$$
$$v\nu_e + |\boldsymbol{E}_{iso}| = |\boldsymbol{E}_d|,$$

10

where we define the isotropic effect of E field as $|\boldsymbol{E}_{iso}| = v\nu_e^E$ by introducing the effective collisional frequency ν_e^E.

Since the effect of the original E field $\tilde{\boldsymbol{E}}$ has been reduced in (25), an additional collision term

$$v\nu_t^E = |\tilde{\boldsymbol{E}}| - |\bar{\boldsymbol{E}}|,$$

is added to scattering on ions. The improved collision AWBS operator then takes the following form

$$C_{AWBS} = v\left(\frac{1}{2} + \alpha^E\right)\nu_e\frac{\partial}{\partial v}\left(f - f_M\right) + \left(\nu_{ei} + \nu_t^E + \frac{\nu_e}{2}\right)(f_0 - f),$$

where both α^E and ν_t^E apply only if $|\tilde{\boldsymbol{E}}| > v\nu_e$ and are set to zero otherwise.
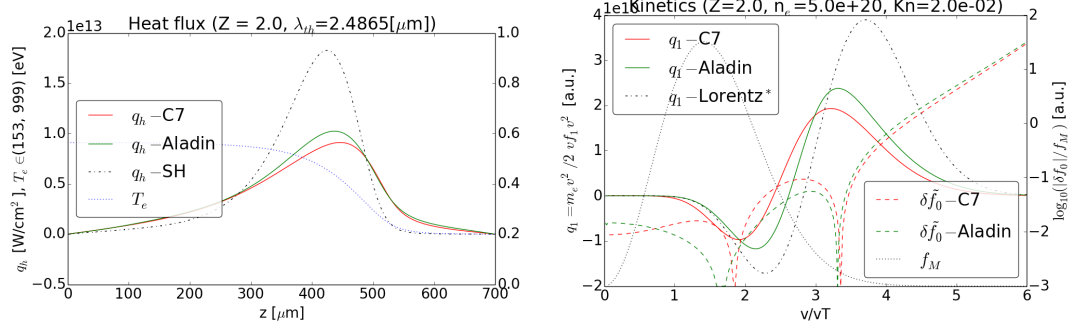
4.3. Aladin

Figure 2: Snapshot 12 ps. Left: correct steady solution. Right: correct comparison to kinetic profiles at point 442 μm by Aladin.
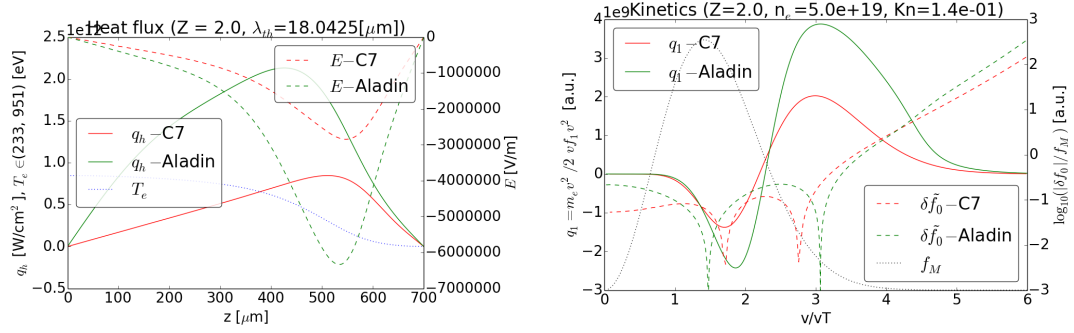
Figure 3: Snapshot 12 ps. Left: correct steady solution. Right: correct comparison to kinetic profiles at point 480 μm by Aladin.
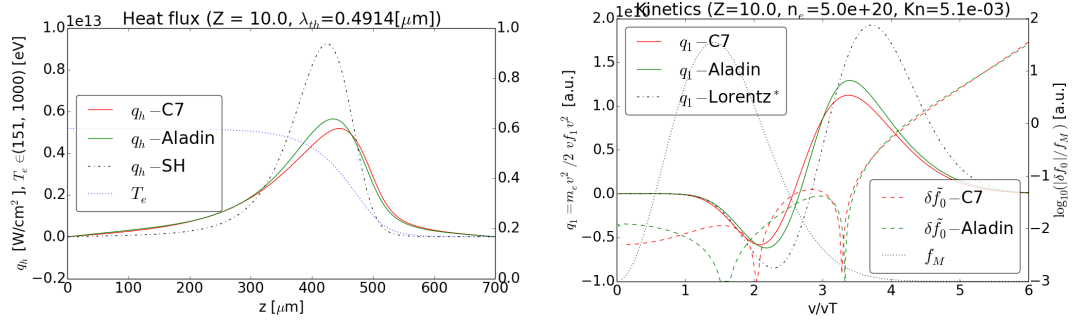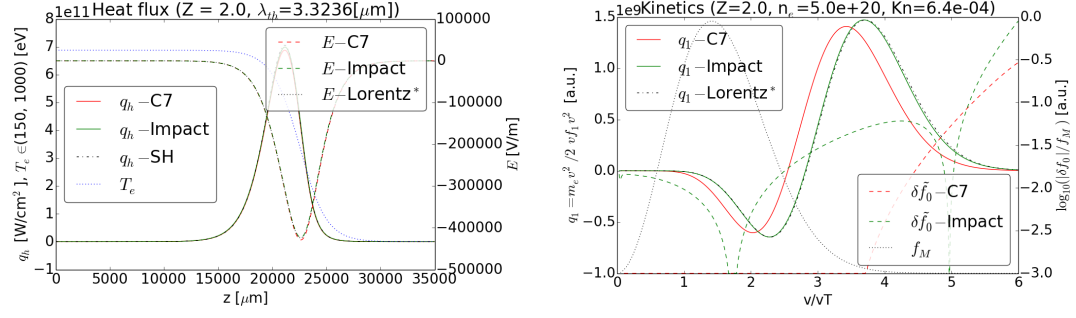

Figure 4: Snapshot 12 ps. Left: correct steady solution. Right: correct comparison to kinetic profiles at point 442 μm by Aladin.
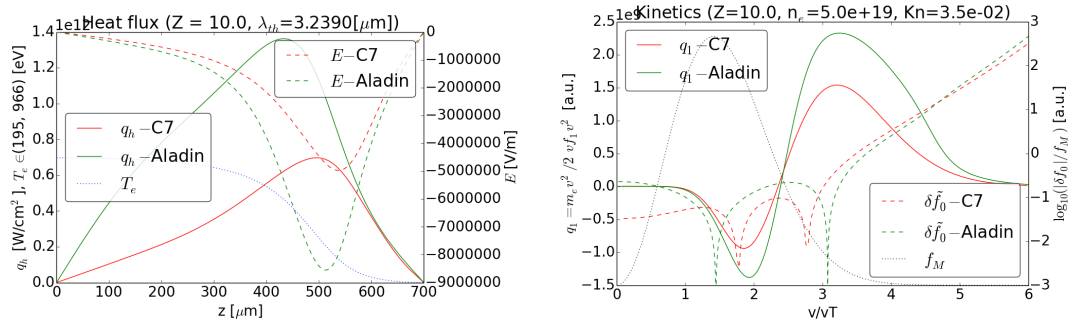
Figure 5: Snapshot 12 ps. Left: correct steady solution. Right: correct comparison to kinetic profiles at point 480 μm by Aladin.
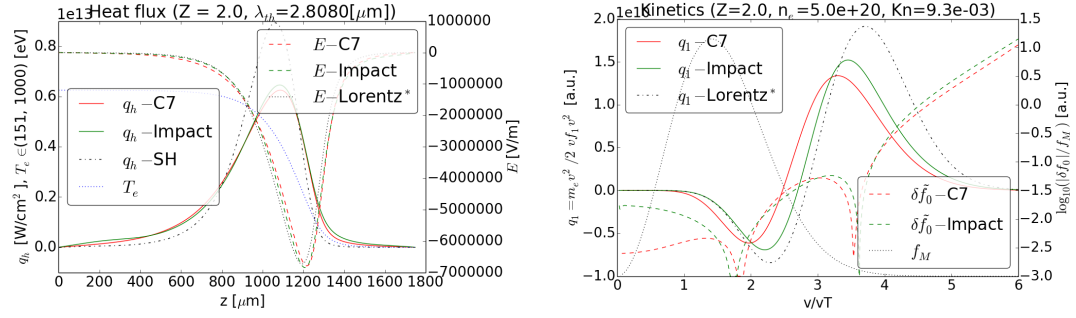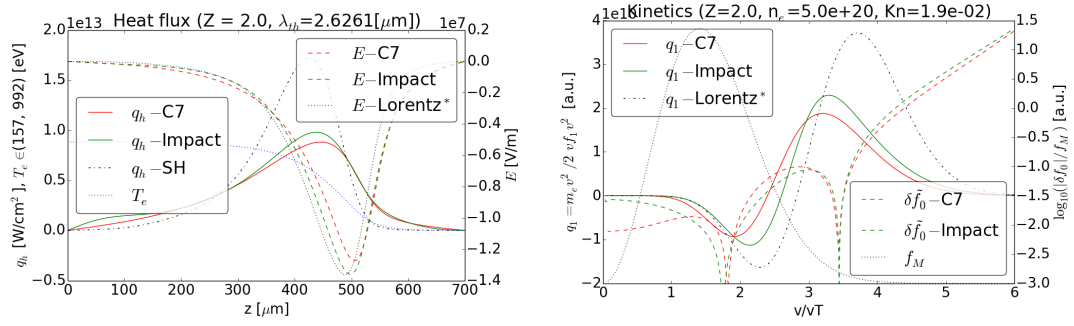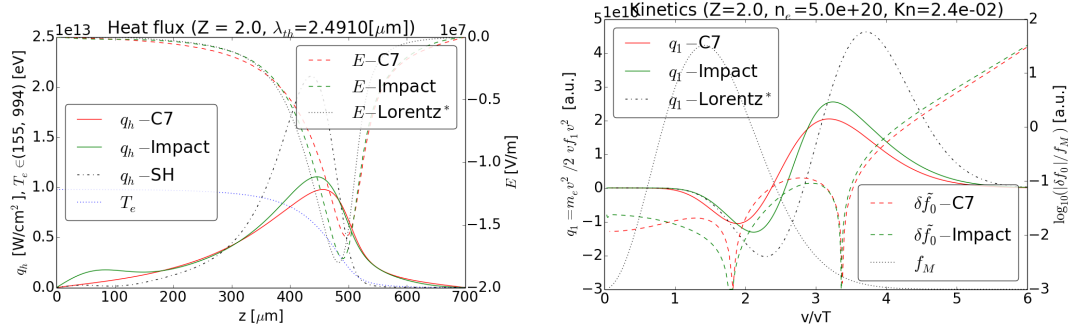
Figure 6:   Impact diffusive case 1.

Figure 7:   Impact case 2.

Figure 8: Snapshot 12 ps. Left: correct steady solution. Right: correct comparison to kinetic profiles at point 437 μm by Impact.
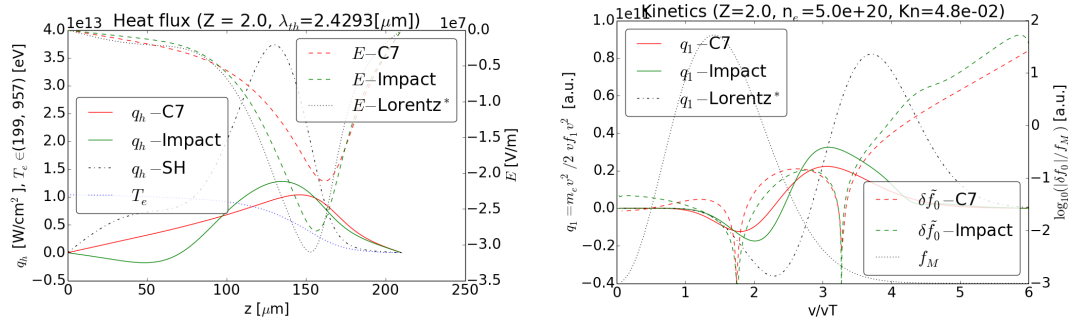

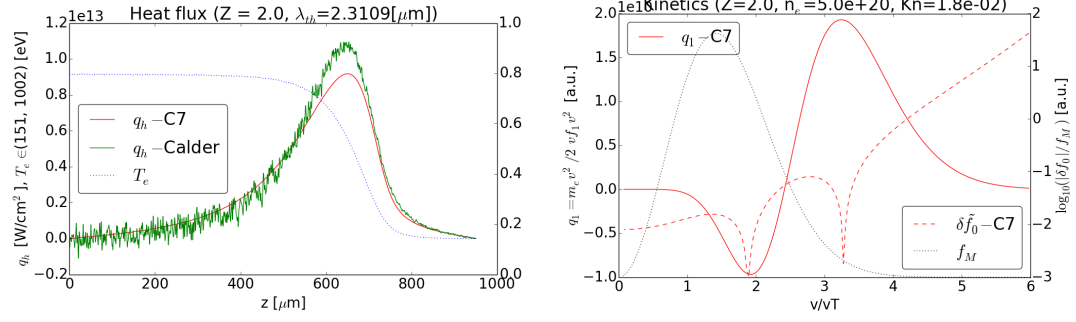Figure 9: Impact case 4.

Figure 10: Impact case 5.

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Figure 11:   Snapshot 11 ps. Left: correct steady solution. Right: Kinetic profiles at point of maximum flux by C7. Kinetics profiles by CALDER to be added.
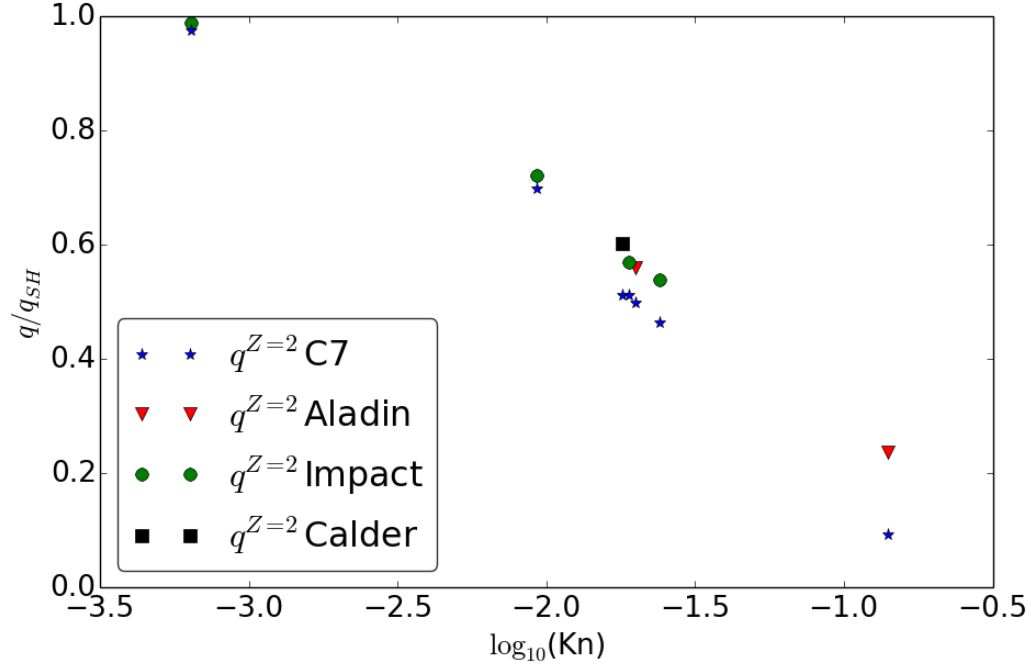
Figure 12:   .

5. Conclusions

88

89 [1] Nathaniel J. Fisch. Theory of current drive in plasmas. Rev. Mod. Phys.,
90   59(1):175234, Jan 1987.

91 [2] Marshall N. Rosenbluth, William M. MacDonald, and David L.
92   Judd. Fokker-planck equation for an inverse-square force. Phys. Rev.,
93   107(1):16, Jul 1957.

94 [3] Longmire, Conrad L. : Elementary Plasma Physics. Intersci. Pub., 1963.

95 [4] I.P. Shkarofsky, T.W. Johnston, T.W. Bachynski, The Particle Kinetics
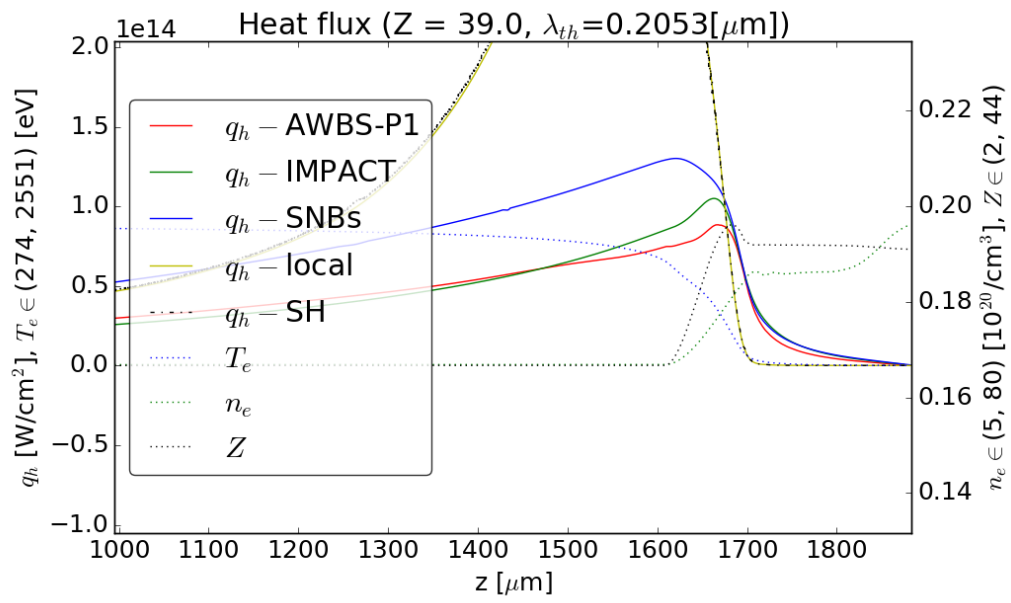96   of Plasmas, Addison-Wesley, Reading, MA, 1966.

97 [5] SH 1953.

Figure 13: