Particle acceleration by dispersive Alfven waves in 2.5D and 3D solar flare plasmas

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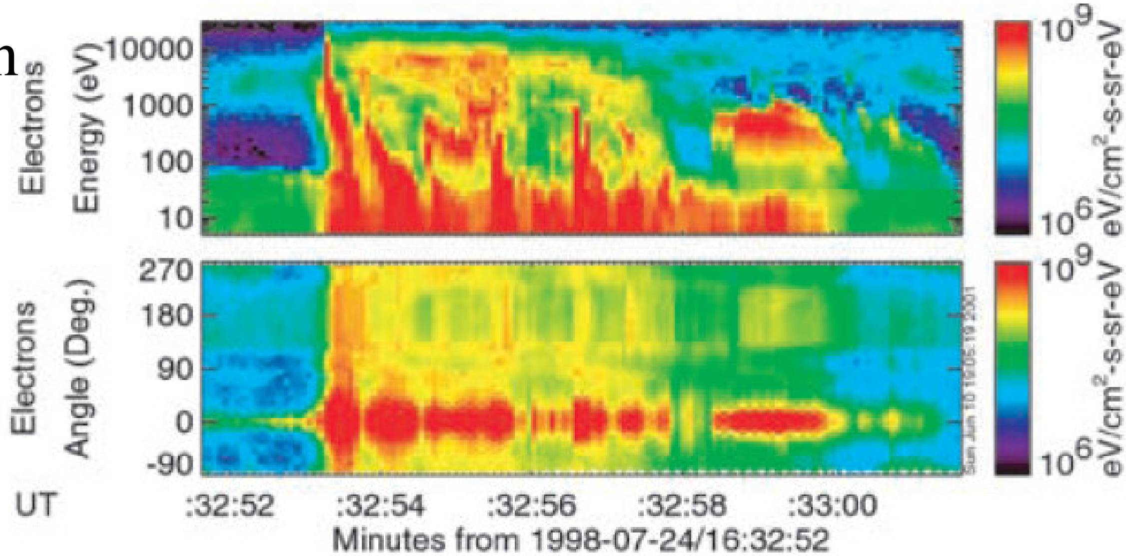
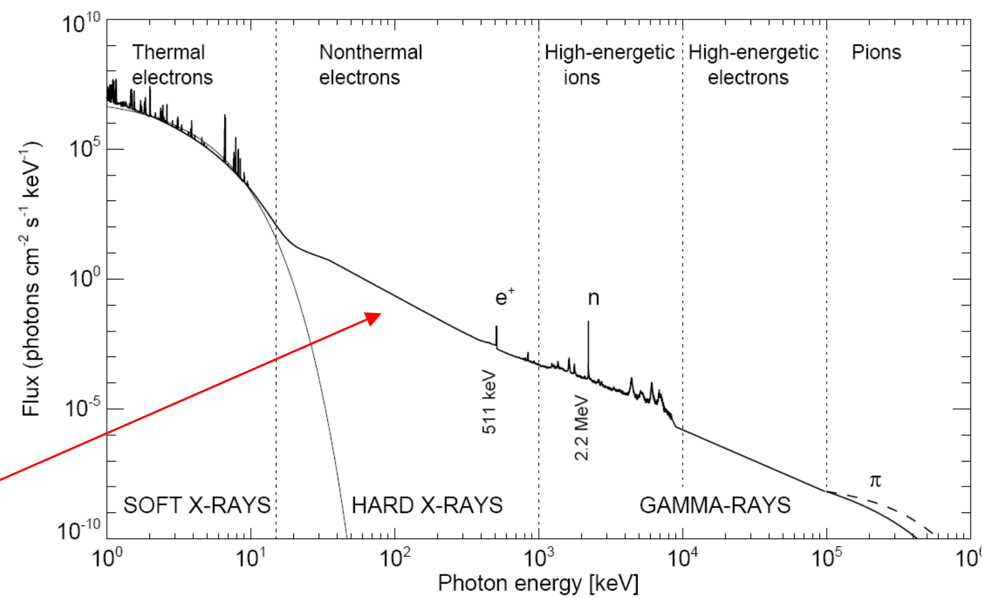
1) FAST satellite, has shown accelerated auroral *e*'s exhibit distributions that are narrow in pitch angle and broad in energy, consistent with acceleration in a time-varying $E_{\|}$ (DAW) [e.g., Chaston et al., 2002, JGR, 107, A11, 1413]



2) In solar corona, upto 50% of the energy released during solar flares is converted into the energy of accelerated particles [Emslie, et al JGR. 109, A10104, (2004)].



Super-thermal electrons in the solar corona, Aschwanden book, page 608

It is clear why one needs to study particle acceleration by DAWs in the AZ, but why do we need to invoke DAWs for particle acceleration in flares in the solar corona?

The answer is in so called "number problem" --

too high total number (10^{34}–10^{37} per second) of accelerated *e*'s are required to produce the observed hard x-ray emission compared to that available in the corona, if the particle acceleration takes place at the *loop apex*.

This would mean that, if the solar flare particle acceleration volume is in the range of 1–10 Mm^3 with the number density of $n=10^{16}$ m^{-3}, to match the observational 10^{34}–10^{37} accelerated electrons per second, full 100% of electrons need to be accelerated!

(no mechanism is known that operates with the 100% efficiency)

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Kinetic (PIC) simulations of DAWs

Tsiklauri D., et al., A&A, 435, 1105, (2005) ← mechanism proposed

Tsiklauri D., New J. Phys. 9, 262 (2007)

Tsiklauri D., T. Haruki, Phys. of Plasmas, 15, 112902 (2008)

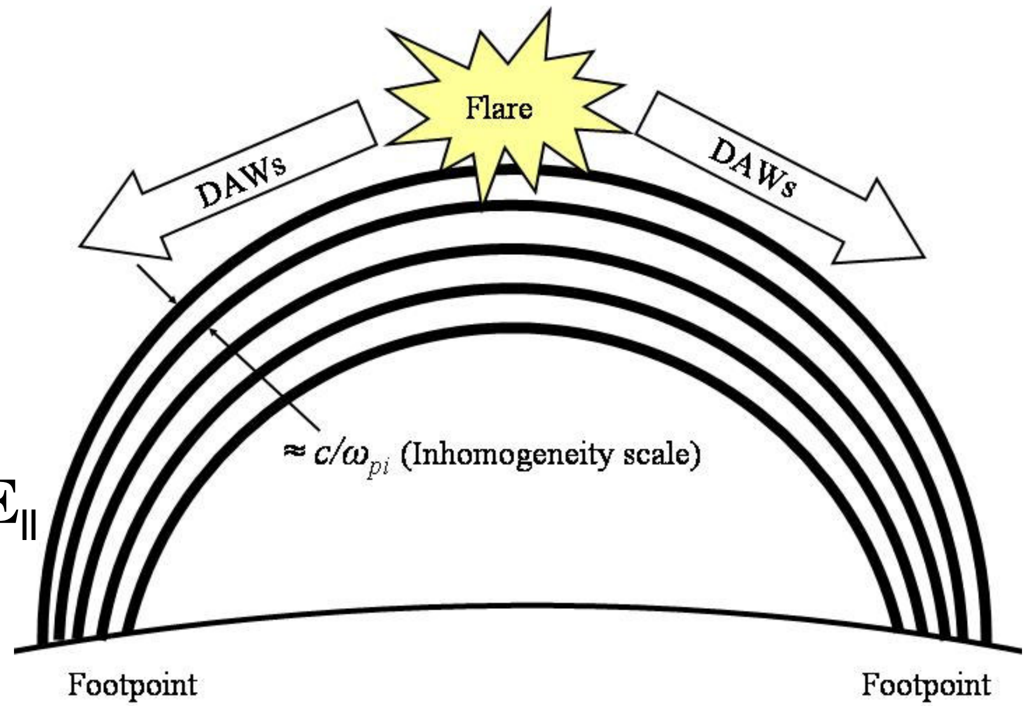
Tsiklauri D., Phys. Plasmas 18, 092903 (2011)

Tsiklauri D. Phys. Plasmas (2012) in preparation

(last two: discussed here)

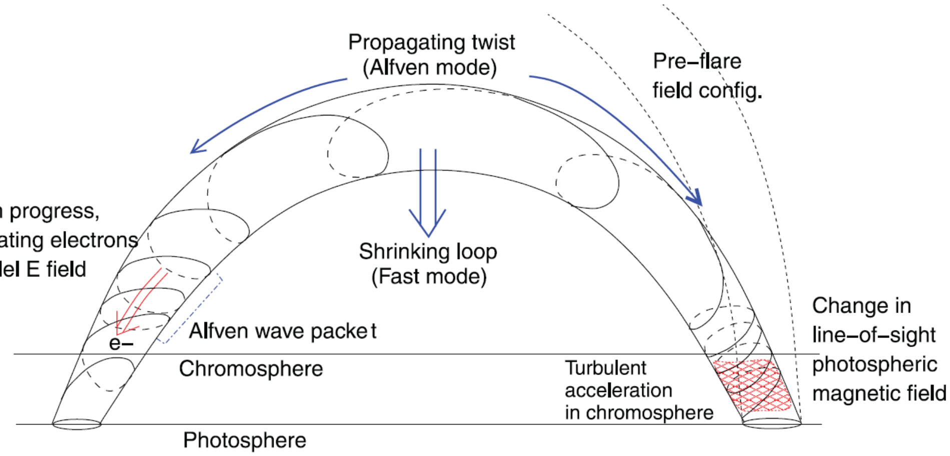
• 2.5D and 3D fully relativistic, electromagnetic, PIC code used **also** two-fluid code developed.

• **New mechanism for electron acceleration via generation of $E_{||}$ found.**

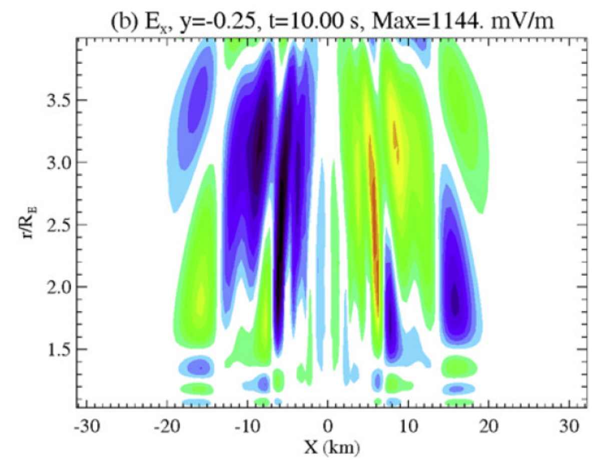


Flare wave based models

1. Alfven waves, in the presence, of strong spatial gradients, generate $E_{||}$ that can accelerate e's to $E >$ 10 keV. Fletcher & Hudson, 2008, ApJ, 675, 1645



2. Phase mixing at the boundaries of the density cavity leads to small-scale Alfven waves, which can develop $E_{||}$ needed to accelerate the Alfvenic aurora.
Lysak & Song, 2008, GRL, 35, L20101
Lysak & Song 2011, GJR, 116, A00K14



3. McClements, & Fletcher (2009); Generation of $E_{||}$ by postulating non-zero $k_{\perp} \approx c/\omega_{pi}$ (1D -- no phase mixing)

4. Bian and Kontar, Astron. Astrophys. 527, A130 (2011)

5. Threlfall et al. Astron. Astrophys. 525, A155 (2011)

In MHD approximation AW has $E_\perp \neq 0$ and $E_\parallel = 0$. In terms of k's: $k_\perp = 0$ and $k_\parallel \neq 0$.

In full kinetic approach, if $\lambda_\perp = 2\pi/k_\perp$ of AW approaches the small kinetic scales such as $r_{L,i} = v_{th,i}/\omega_{pi}$ or $\rho_s = \sqrt{kT_e / m_i} / \omega_{ci}$ or c/ω_{pe}, $E_\parallel \neq 0$. This can have serious consequence for particle acceleration. Such waves are called *dispersive Alfven waves* (DAW).

Properties of DAWs can be quantified using collisionless (i.e. without dissipation) two-fluid theory α = e,i:

$$\frac{\partial \vec{v}_\alpha}{\partial t} + (\vec{v}_\alpha \cdot \nabla)\vec{v}_\alpha = \frac{q_\alpha}{m_\alpha}(\vec{E} + \vec{v}_\alpha \times \vec{B}) - \frac{1}{m_\alpha n_\alpha} \nabla \cdot \overleftrightarrow{P}_e$$

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \vec{v}_\alpha) = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}; \qquad \nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

which are equations of motion of species alpha, continuity equations, and relevant Maxwell equations.

Inertial Alfven Waves (IAWs)

DAWs are subdivided into IAWs or Kinetic Alfven Waves (KAWs) depending on the relation $\beta < m_e/m_i$, i.e. $v_A > v_{th,i}, v_{th,e}$

when $\beta < m_e/m_i$ dominant mechanism for sustaining $E_{\|}$ is parallel electron inertia (that is why such waves are called *inertial* AW).

Thus in Eq. motion for electrons we ignore pressure term $O(v_{th,e}^2)$ compared to the inertia term:

$$\frac{\partial v_{e\|}}{\partial t} = \frac{q_e}{m_e} E_{\|}$$

Then one obtains a *wave equation* for IAW:

$$\left(1 - \lambda_e^2 \nabla_\perp^2\right) \frac{\partial^2 A_z}{\partial t^2} = v_A^2 \frac{\partial^2 A_z}{\partial z^2} \qquad \text{where} \quad \lambda_e = \frac{c}{\omega_{pe}}$$

Fourier transform of which gives the dispersion relation for IAW

$$\omega^2 = \frac{k_{\|}^2 v_A^2}{\left(1 + \lambda_e^2 k_\perp^2\right)}$$

<u>Kinetic Alfven Waves (KAWs)</u>

When $\beta > m_e/m_i$, i.e. $v_A < v_{th,i}, v_{th,e}$ then clearly thermal effects become important. Thus dominant mechanism for sustaining $E_{\|}$ is parallel electron pressure gradient (that is why such waves are called *kinetic* AW – kinetic motion of electrons is source of the pressure). Thus in Eq. motion for electrons we balance parallel electric field with the pressure gradient term:

$$E_{\|} = -\frac{kT_e}{en_0}\frac{\partial n_e}{\partial z} = -e\mu_0\rho_s^2 v_A^2 \frac{\partial n_e}{\partial z} \qquad (\rho_s = \sqrt{kT_e/m_i}/\omega_{ci})$$

the dispersion relation for KAWs

$$\boxed{\omega^2 = k_{\|}^2 v_A^2 \left(1 + \rho_s^2 k_{\perp}^2\right)}$$

Note that both DAWs, i.e. IAWs and KAWs in the MHD limit, i.e. when $k_{\perp} \to 0$ recover normal low frequency Alfven waves with usual dispersion relation $\omega^2 = k_{\|}^2 v_A^2$. Good source of <u>further reading</u> is **Stasiewicz et al. Sp. Sci. Rev. 92, 423 (2000).**

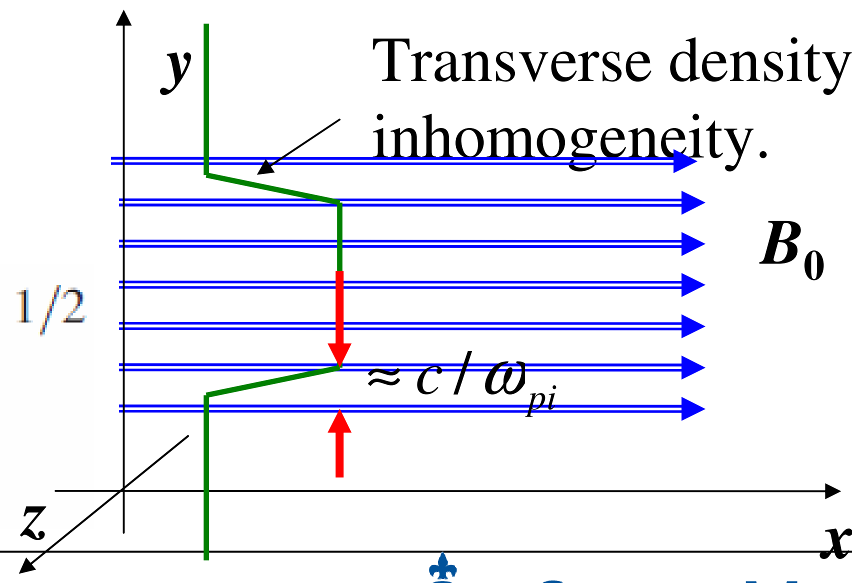
2.5D model 200x10000 grid (upto 72h on 512 processor cores)

We use EPOCH (Extendible Open PIC Collaboration) a fully electromagnetic, relativistic, 2.5D particle-in-cell code.

- Equilibrium is such that the total pressure is constant. $B_0 = const \parallel$ to x;
- density $\rho = \rho(y)$; $T = T(y)$. Such set up mimics solar coronal loop.
- Transverse inhomogeneity scale is $\approx 30\lambda_D \approx 0.75c/\omega_{pi}$ for m_i/m_e=16.
- Initial conditions are: DAW driven at x=1 with $\omega_d = 0.3\omega_{ci}$

$$n_i(y) = n_e(y) = 1 + 3\exp\left[-\left(\frac{y - 100\lambda_D}{50\lambda_D}\right)^6\right] \equiv f(y). \quad (1)$$

$$T_i(y)/T_0 = T_e(y)/T_0 = f(y)^{-1}, \quad (2)$$



The dispersion relation:

$$k = \frac{\omega}{c}\left(1 + \frac{\omega_{pe}^2 + \omega_{pi}^2}{(\omega_{ce} \pm \omega)(\omega_{ci} \mp \omega)}\right)^{1/2}$$

The case of left-polarised DAW:

$$E_y(1,y,t+\Delta t) = E_y(1,y,t) - A_y \sin(\omega_d t)(1-\exp[-(t/t_0)^2]),$$

$$E_z(1,y,t+\Delta t) = E_z(1,y,t) - A_z \cos(\omega_d t)(1-\exp[-(t/t_0)^2]),$$

Left-polarised DAW = Ion-Cyclotron

The case of right-polarised DAW:

$$E_y(1,y,t+\Delta t) = E_y(1,y,t) + A_y \sin(\omega_d t)(1-\exp[-(t/t_0)^2]),$$

$$E_z(1,y,t+\Delta t) = E_z(1,y,t) - A_z \cos(\omega_d t)(1-\exp[-(t/t_0)^2]),$$

Right-polarised DAW = Whistler

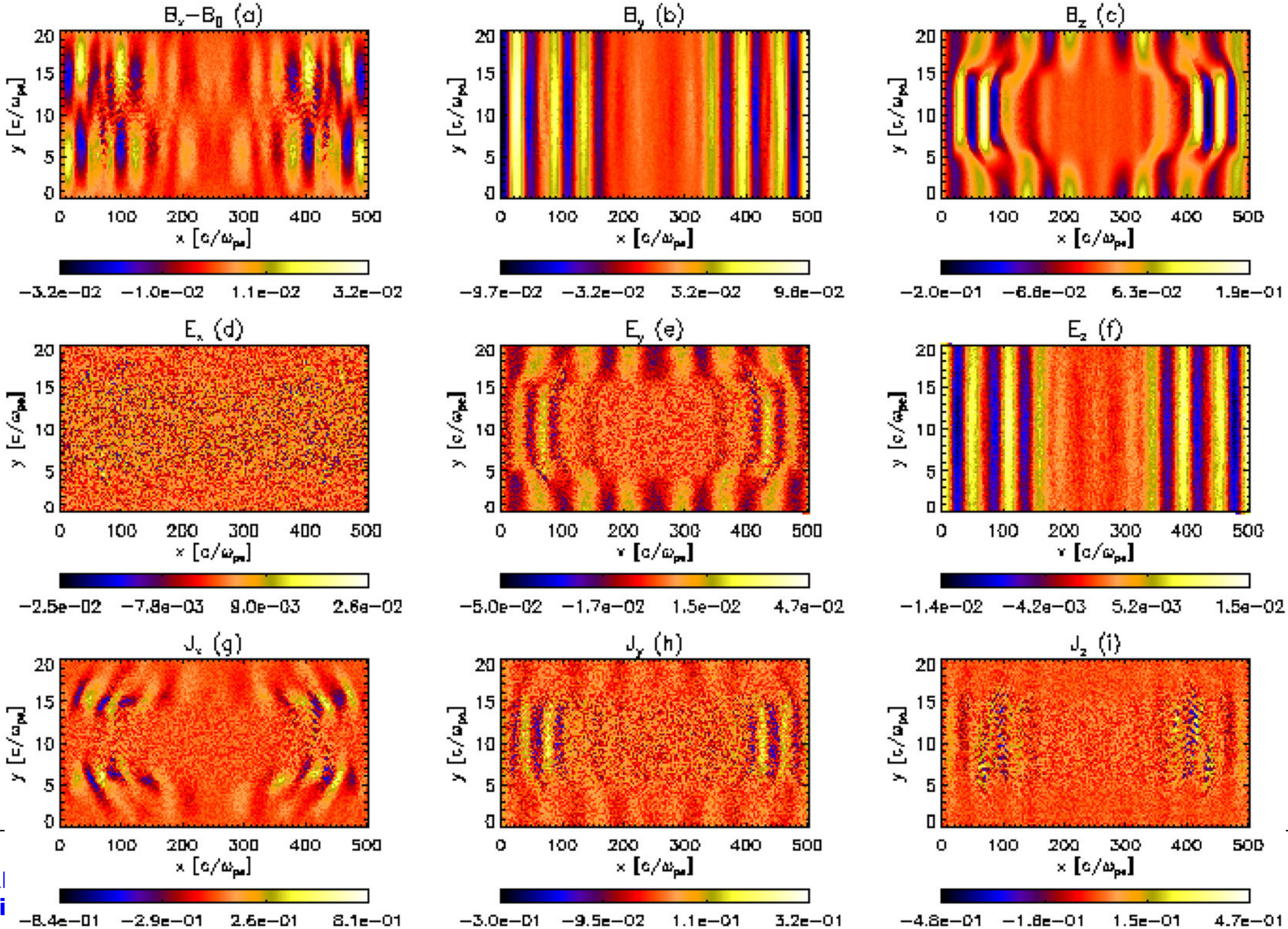
TABLE I. Numerical simulation parameters.

Regime	Inertial	Kinetic
m_i/m_e	16	73.44
ω_{ce}/ω_{pe}	1.000	1.000
β	0.020	0.020
c/ω_{pe} [m]	0.053	0.053
$\lambda_D = r_{L,e}$ [m]	0.005	0.005
$v_{th,e}/c$	0.101	0.101
$v_{th,i}/c$	0.025	0.012
$V_A/c = \omega_{ci}/\omega_{pi}$	0.25	0.117
$V_{A,ph}/c$	0.243	0.116
V_L/c	0.201	0.097
V_R/c	0.264	0.131
$t_{end} = 75\omega_{ci}^{-1}[\times 10^{-7}$ s]	2.127	9.763
n_y	200	200
n_x	5000	10712

TABLE II. Numerical simulation run identification and physical parameters. I stands for inertial and K for kinetic. Reg. stands for regime.

Run ID	Polarisation	m_i/m_e	Reg.	A_y/A_z	$t_{end}[\omega_{ci}^{-1}]$	Figs.
L16	L–circular	16	I	1	75	1, 2, 3
R16	R–circular	16	I	1	75	4
EL16	L–elliptical	16	I	6	75	5
ER16	R–elliptical	16	I	6	75	6
$EL16_1$	L–elliptical	16	I	1/6	75	7
$ER16_1$	R–elliptical	16	I	1/6	75	8
L73	L–circular	73.44	K	1	75	9
R73	R–circular	73.44	K	1	75	10, 11, 12
EL73	L–elliptical	73.44	K	6	75	13
ER73	R–elliptical	73.44	K	6	75	14
$EL73_1$	L–elliptical	73.44	K	1/6	75	15
$ER73_1$	R–elliptical	73.44	K	1/6	75	16
L16Long	L–circular	16	I	1	300	17, 18

Numerical results for run L16 (Inertial DAW regime).

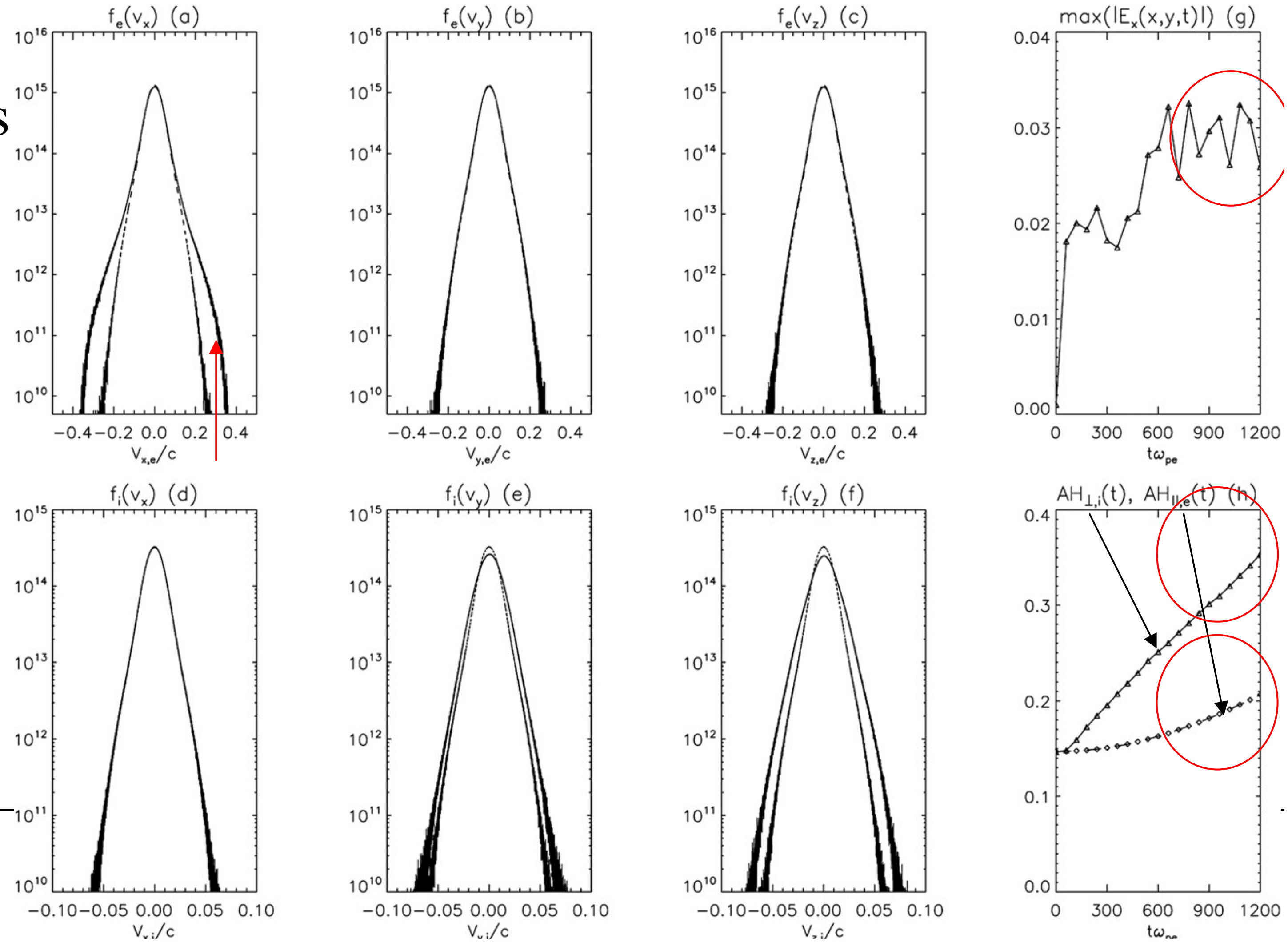


We quantify the particle acceleration and plasma heating by defining the following indexes:

$$AH_{\parallel,e}(t) = \frac{\int_{|v_x|>\langle v_{th,e}\rangle}^{\infty} f_e(v_x,t)dv_x/(2L_{IH,y} \times L_{x,max})}{\int_{-\infty}^{\infty} f_e(v_x,0)dv_x/(L_{y,max} \times L_{x,max})}, \quad (8)$$

$$AH_{\perp,i}(t) = \frac{\int_{|v_\perp|>\langle v_{th,i}\rangle}^{\infty} f_i(v_\perp,t)dv_\perp/(2L_{IH,y} \times L_{x,max})}{\int_{-\infty}^{\infty} f_i(v_\perp,0)dv_\perp/(L_{y,max} \times L_{x,max})}. \quad (9)$$

Numerical results for run L16 (Inertial DAW regime).



(Kinetic DAW regime).

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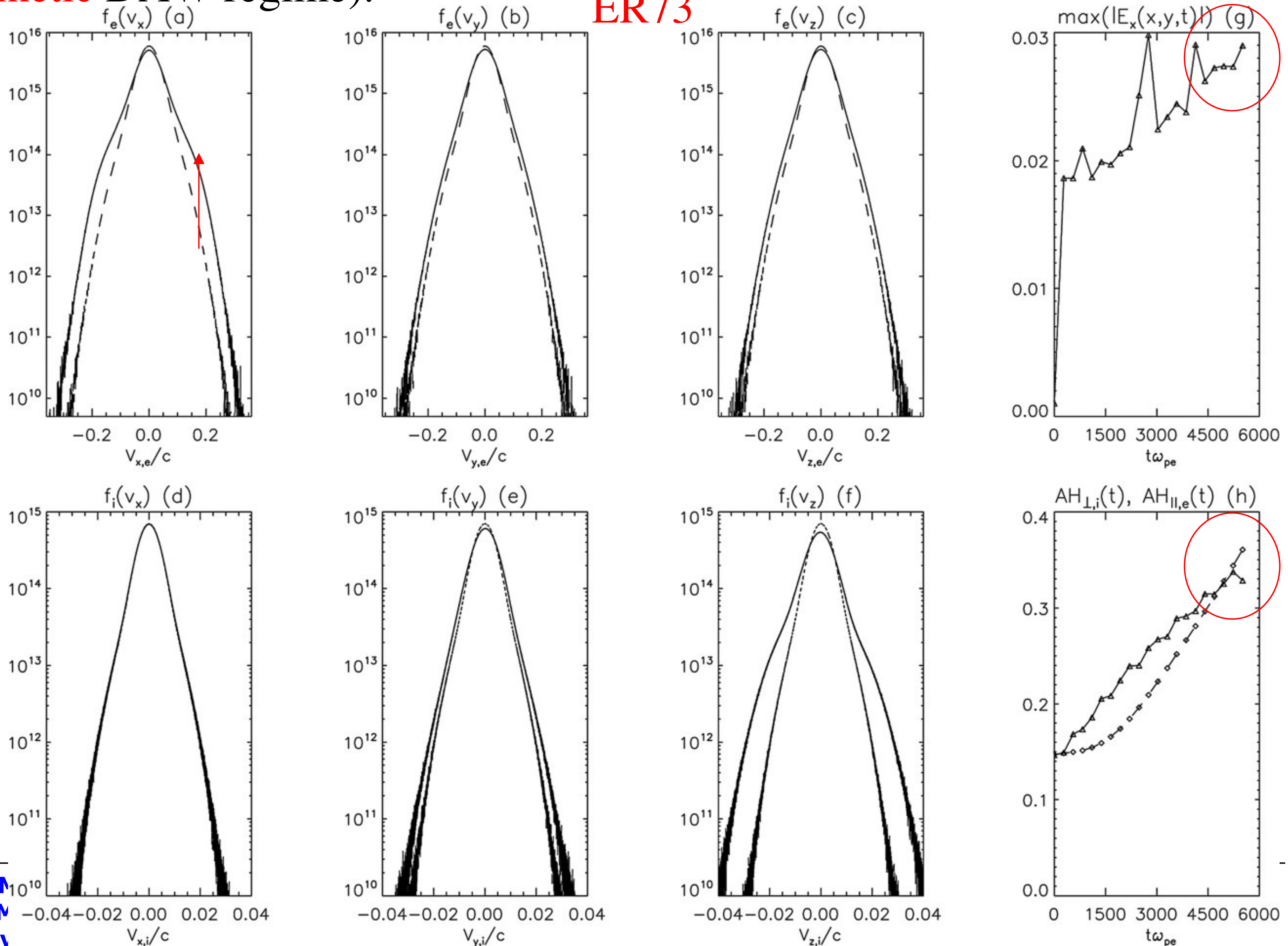
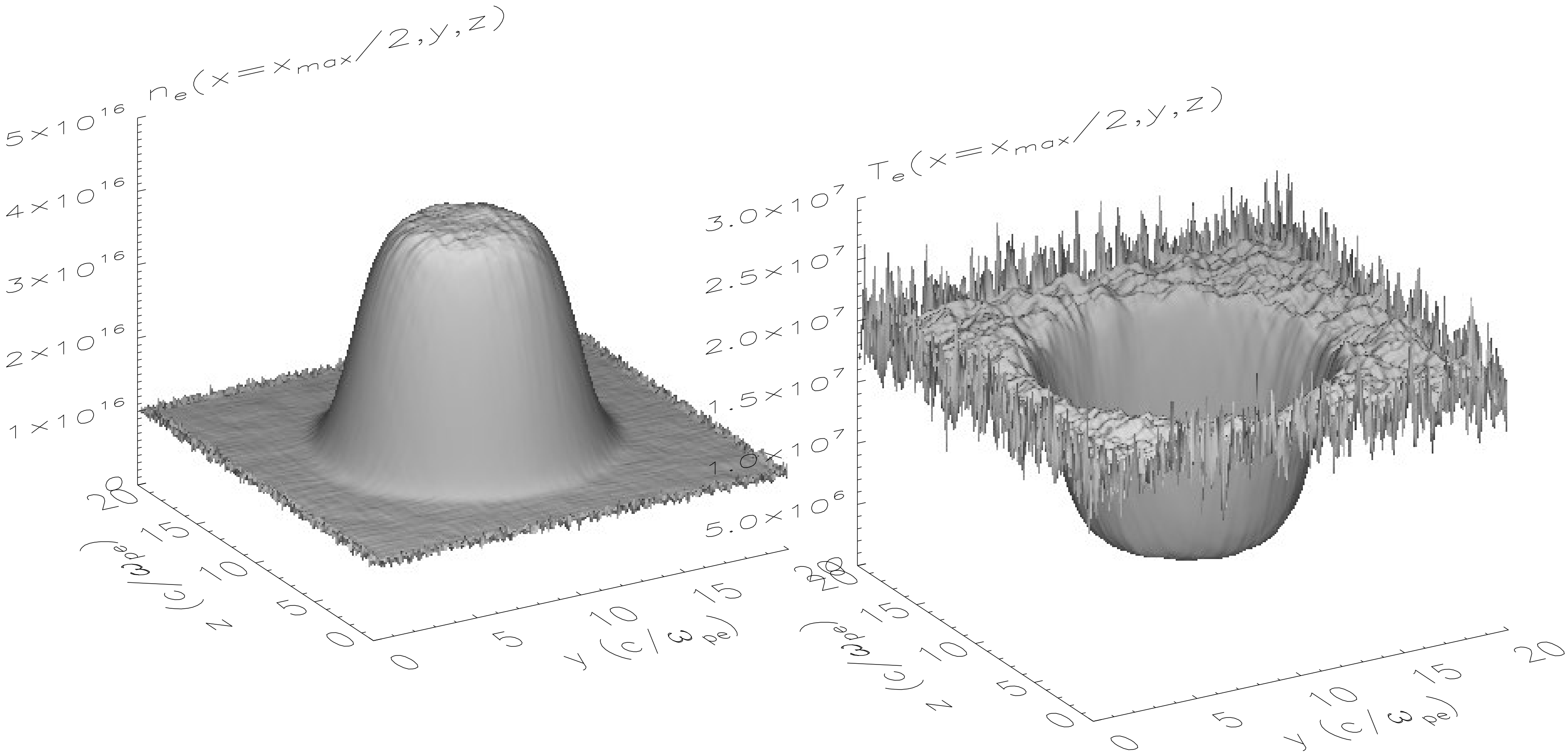
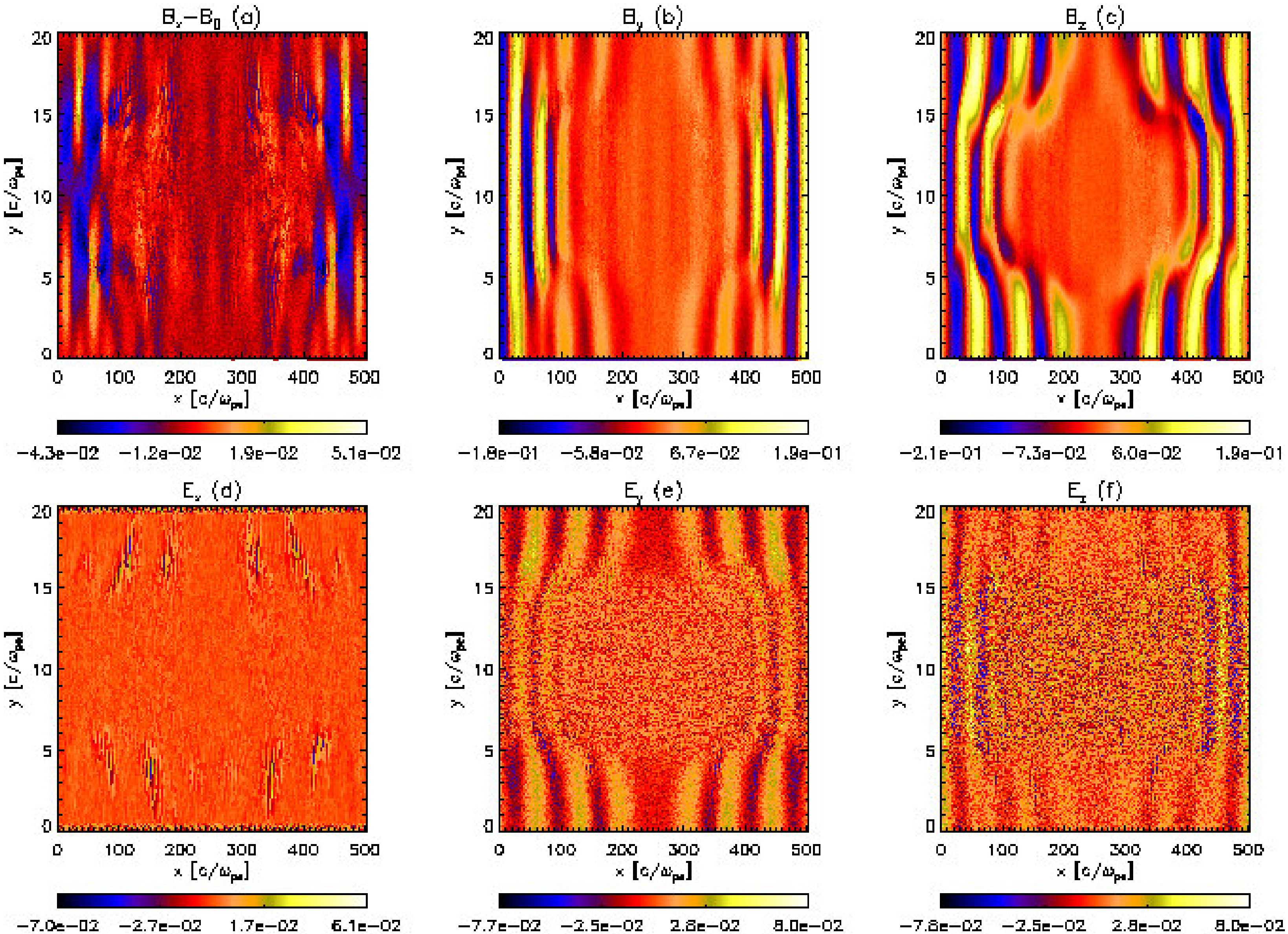


Fully 3D model 200x200x5000 grid (10d on 720 processor cores)



3D equilibrium is in pressure balance $T(y,z) \sim 1/n(y,z)$



B_x-B_0 (a)
B_y (b)
B_z (c)
E_x (d)
E_y (e)
E_z (f)
y [c/ω_{pe}]
x [c/ω_{pe}]
0 100 200 300 400 500
0 5 10 15 20
-4.3e-02 -1.2e-02 1.9e-02 5.1e-02
-1.8e-01 -5.8e-02 6.7e-02 1.9e-01
-2.1e-01 -7.3e-02 6.0e-02 1.9e-01
-7.0e-02 -2.7e-02 1.7e-02 6.1e-02
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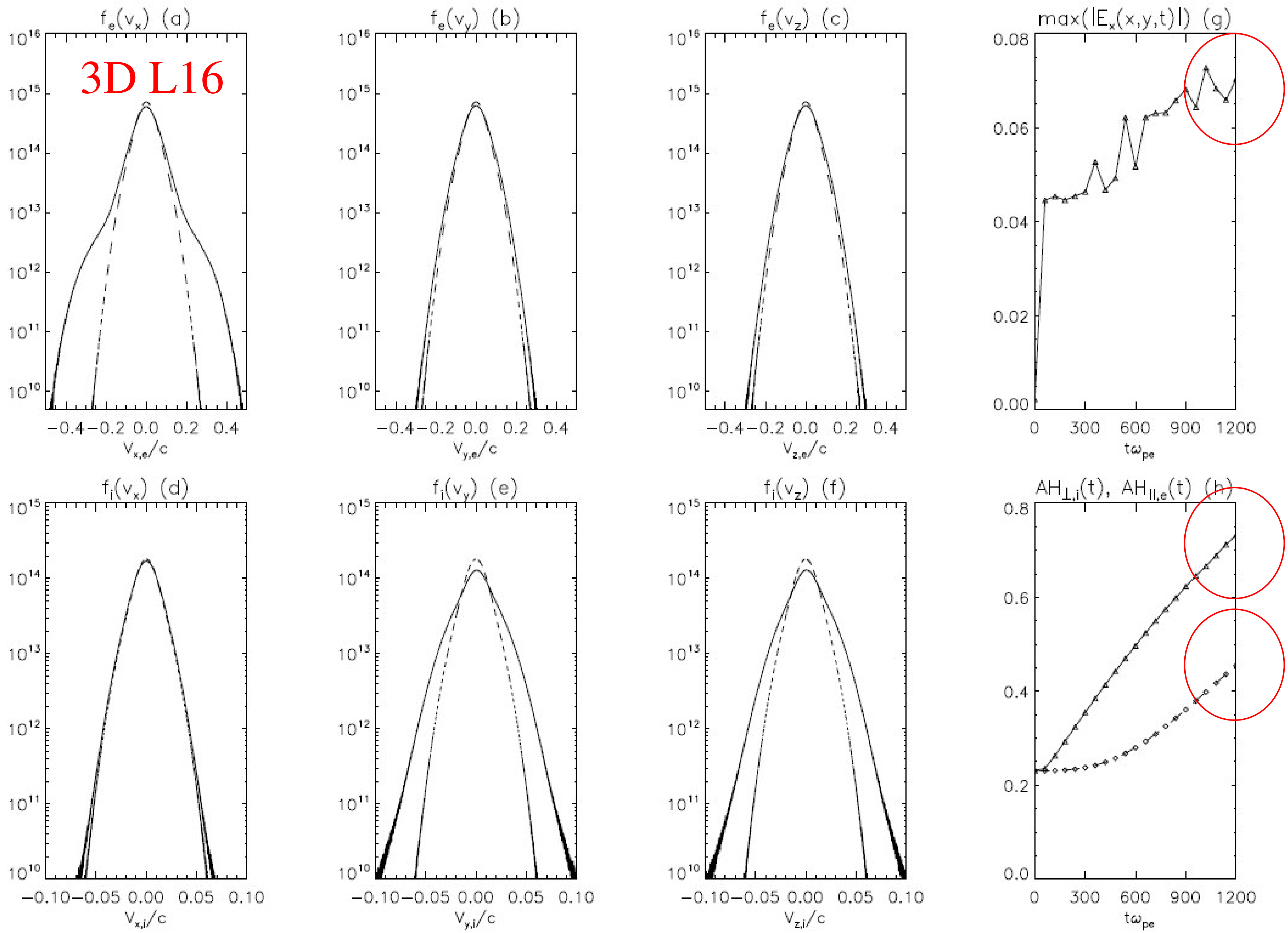
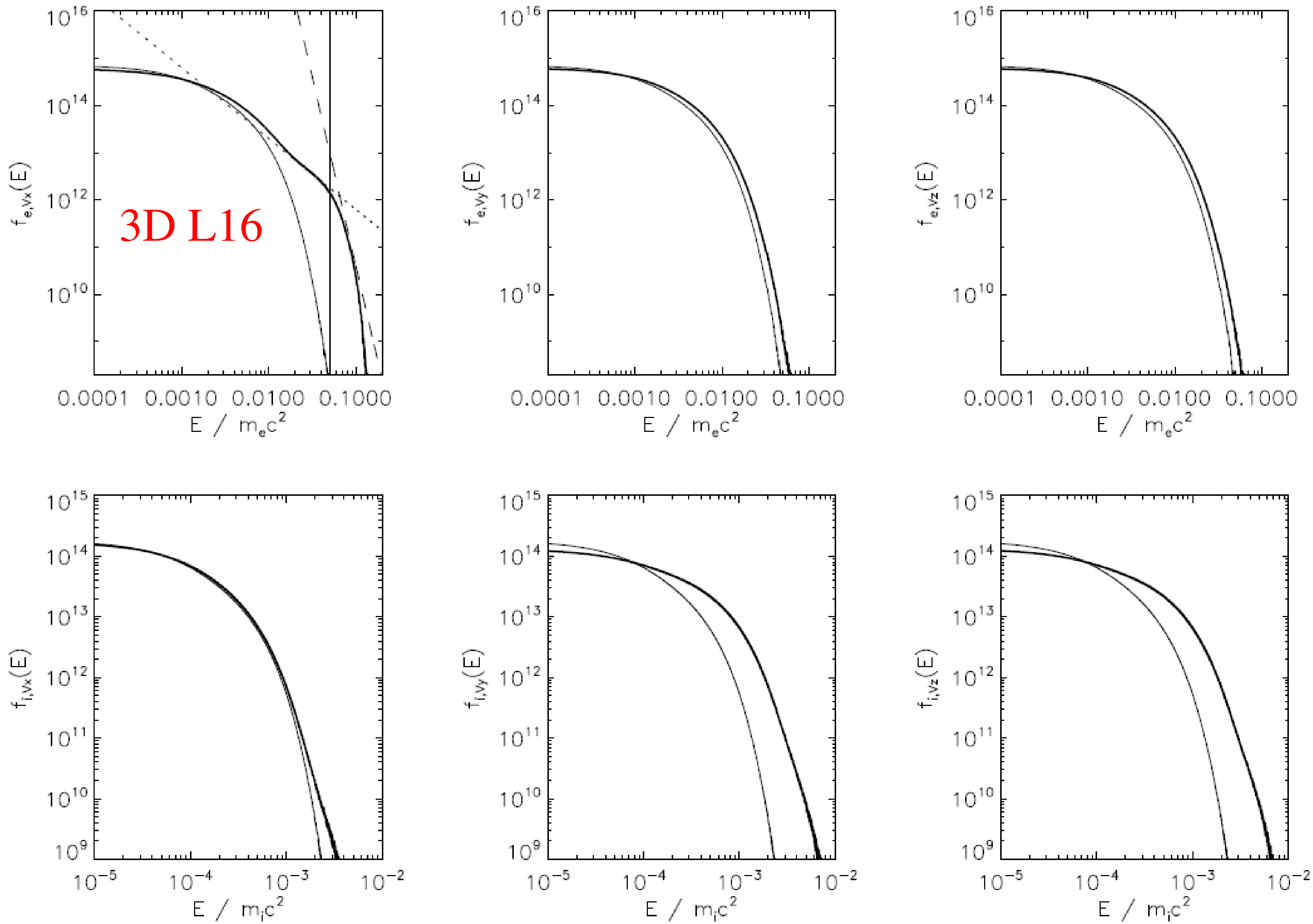
-7.8e-02 -2.5e-02 2.8e-02 8.0e-02


3D L16
fe(vx) (a)
fe(vy) (b)
fe(vz) (c)
max(|Ex(x,y,t)|) (g)
fi(vx) (d)
fi(vy) (e)
fi(vz) (f)
AH⊥,i(t), AH||,e(t) (h)
Vx,e/c
Vy,e/c
Vz,e/c
Vx,i/c
Vy,i/c
Vz,i/c
tωpe



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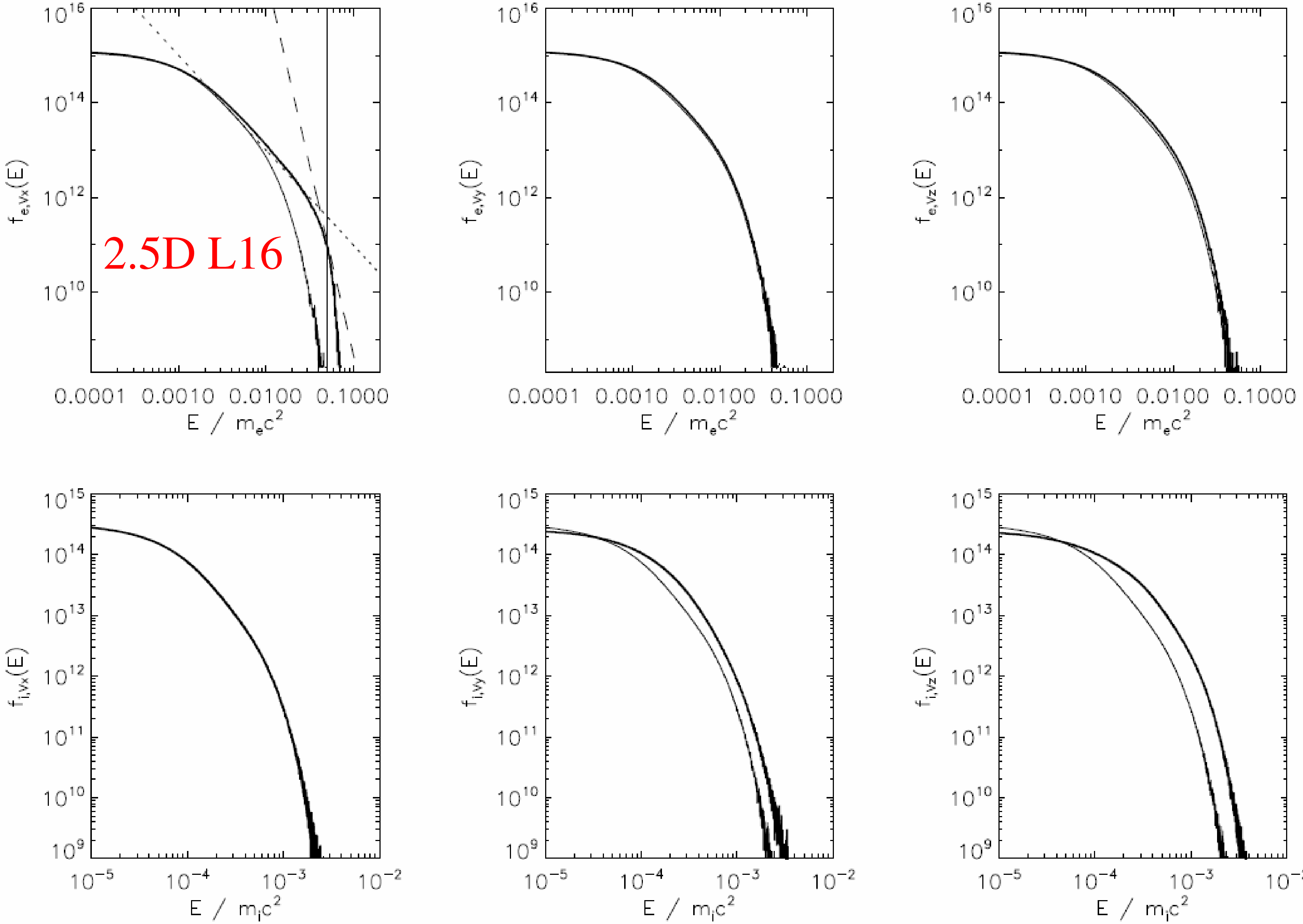
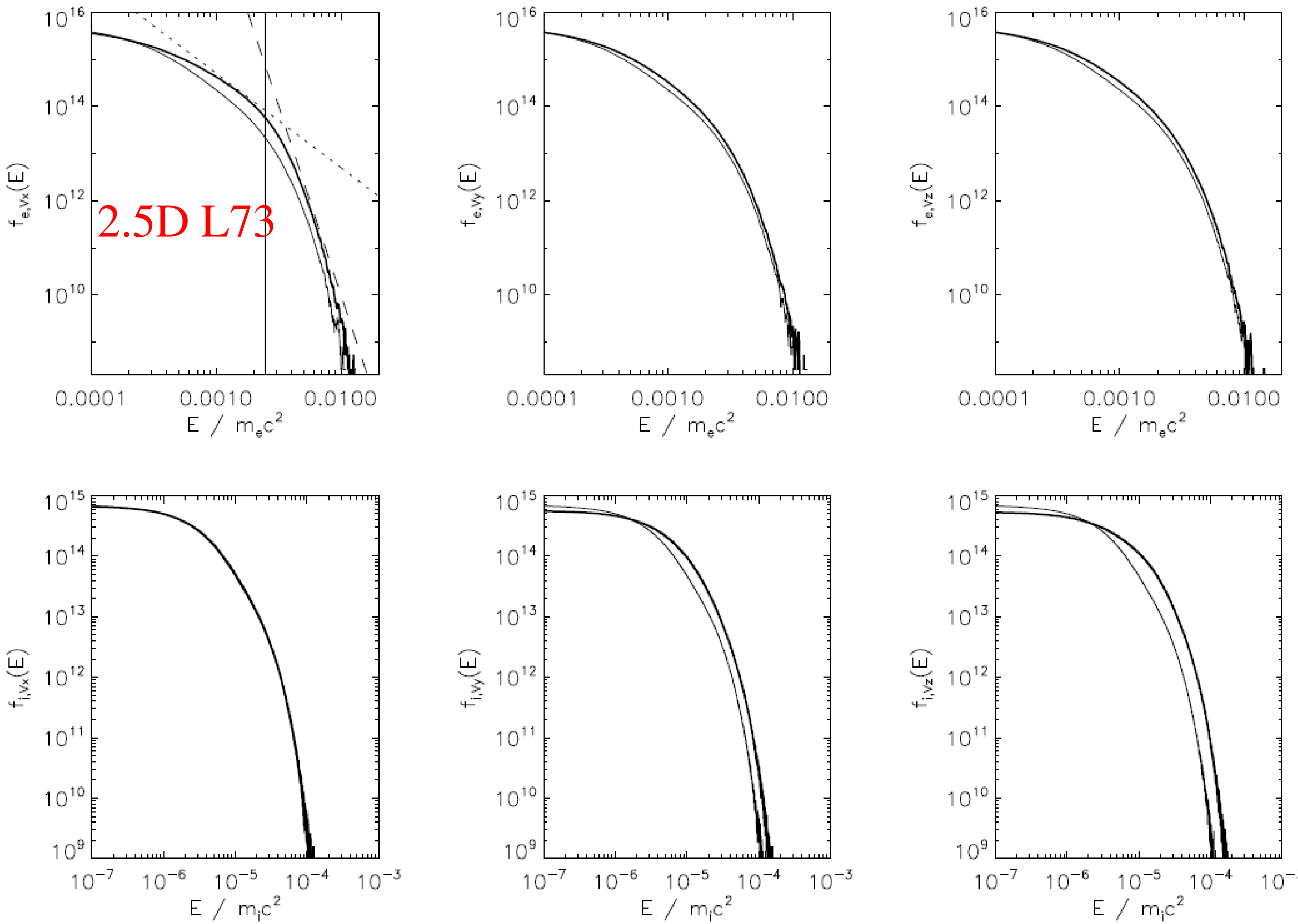


2.5D L16
$f_{e,Vx}(E)$
$f_{e,Vy}(E)$
$f_{e,Vz}(E)$
$E / m_e c^2$
0.0001 0.0010 0.0100 0.1000
10^{16} 10^{14} 10^{12} 10^{10}
$f_{i,Vx}(E)$
$f_{i,Vy}(E)$
$f_{i,Vz}(E)$
$E / m_i c^2$
10^{-5} 10^{-4} 10^{-3} 10^{-2}
10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9}



2.5D L73
f_e,Vx(E)
f_e,Vy(E)
f_e,Vz(E)
E / m_ec^2
0.0001
0.0010
0.0100
f_i,Vx(E)
f_i,Vy(E)
f_i,Vz(E)
E / m_ic^2

Conclusions

(i) The fraction of accelerated electrons (along the magnetic field), in the density gradient regions is 20%-35% in 2.5D and 45% in 3D. 75% ions get heated in 3D (in the transverse to B directions)!

(ii) While keeping the power of injected DAWs the same in all considered numerical simulation runs, in the case of right circular, left and right elliptical polarisation DAWs with $Ey/Ez=6$ produce more pronounced parallel electron beams.

(iii) The parallel electric field for solar flaring plasma parameters exceeds Dreicer electric field by eight orders of magnitude.

(iv) Electron beam velocity has the phase velocity of the DAW. This can be understood by Landau damping of DAWs. The mechanism can readily provide electrons with few tens of keV.

(v) In 2.5D case, as we increased the mass ratio from m_i/m_e=16 to 73.44 the fraction of accelerated electrons has increased from 20% to 30-35% (depending on DAW polarisation).

This is because the velocity of the beam has shifted to lower velocity. Since there are always more electrons with a smaller velocity than higher velocity in the Maxwellian distribution, for the mass ratio m_i/m_e=1836 the fraction of accelerated electrons would be even higher than 35%.

cf. Tsiklauri D., Phys. Plasmas 18, 092903 (2011)
Tsiklauri D. Phys. Plasmas (2012) in preparation