Acceleration of electrons through test particle simulation in electric fields generated by 3D reconnection

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Presentation of the problem

Magnetic reconnection is believed to be responsible for the production of energetic particles in solar flares

A current sheet can be spontaneously unstable to tearing instability, which produce reconnection.

The magnetic energy released during reconnection can be converted to thermal and kinetic energy of protons and electrons.

RHESSI measurements

Lin et al. (2003)

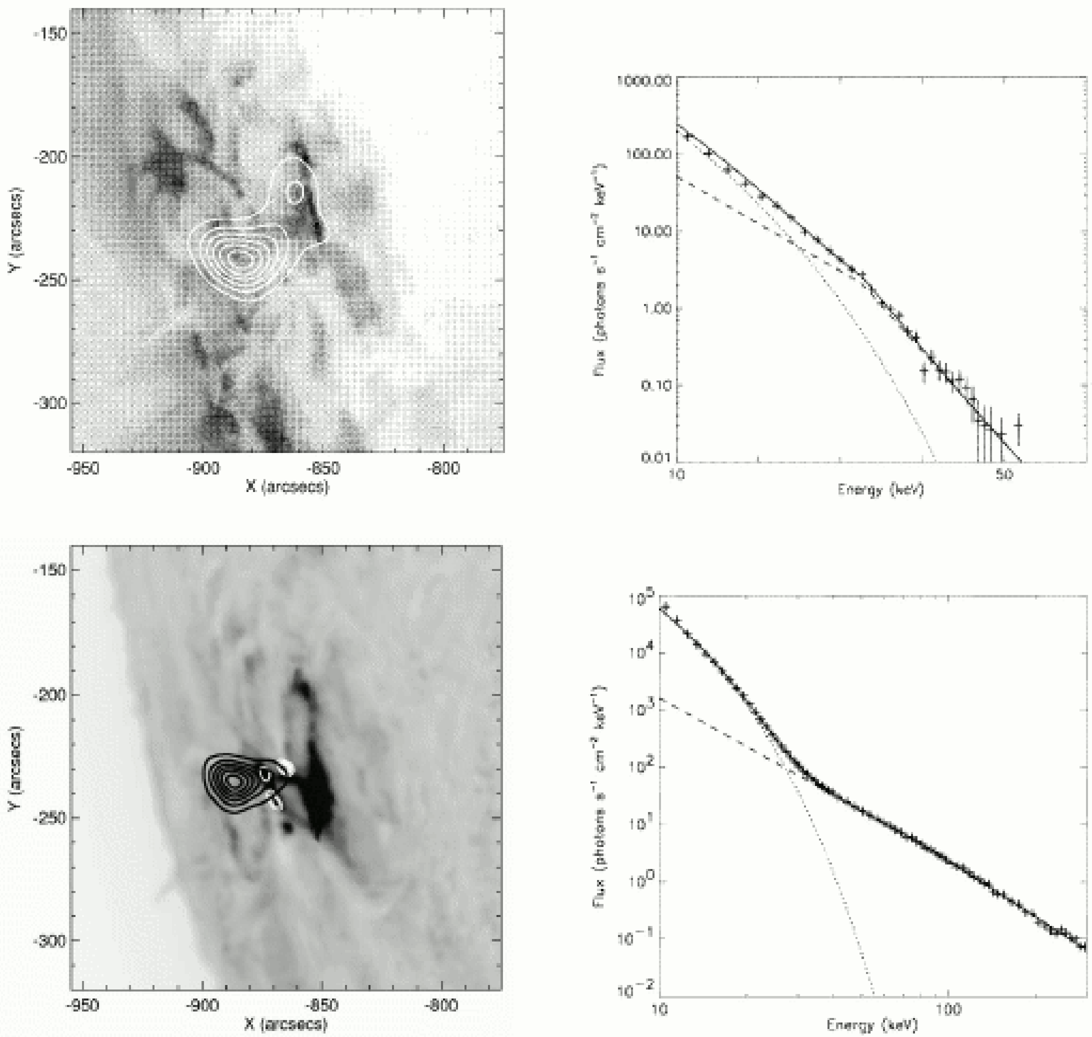
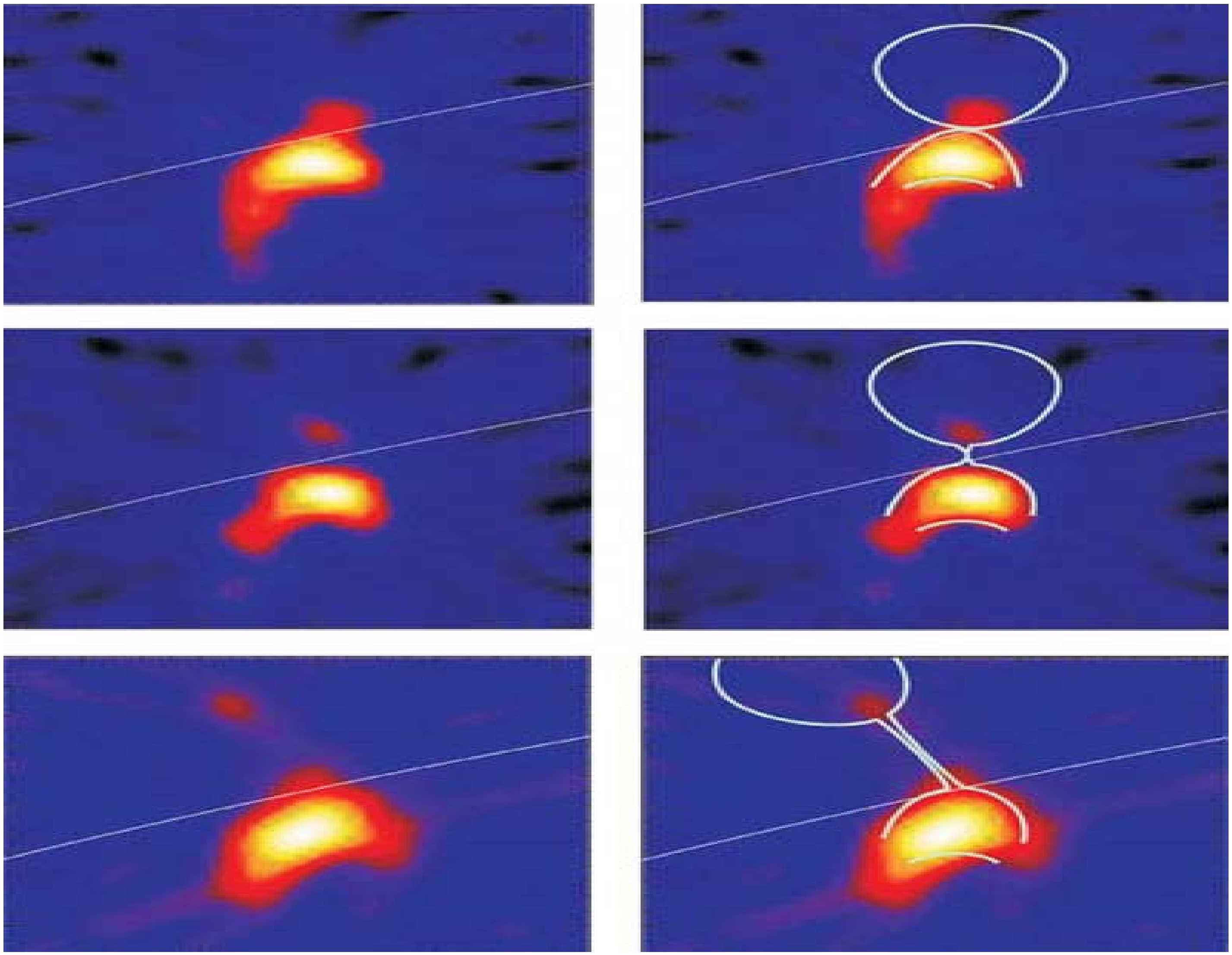
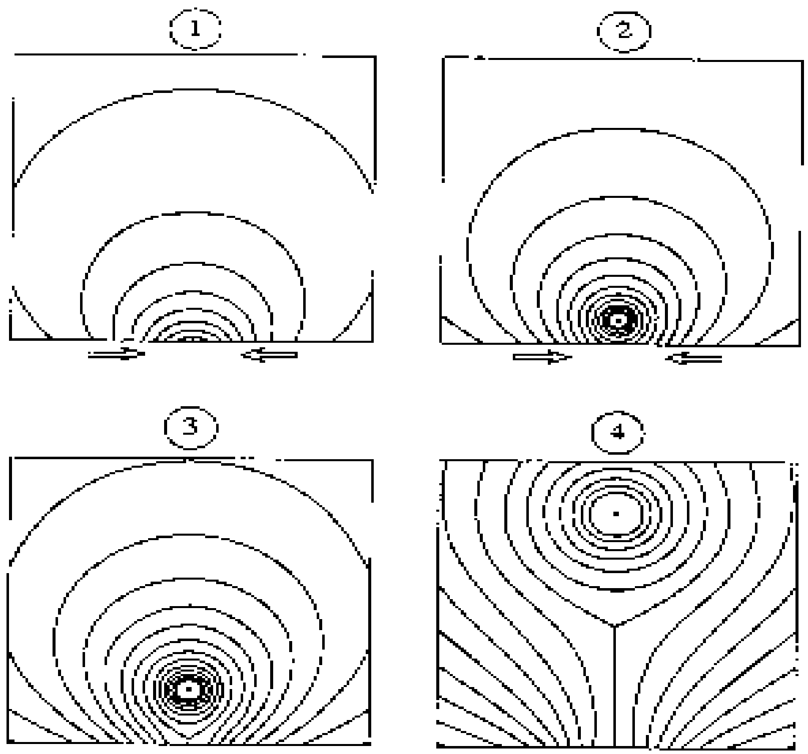


FIG. 2.—*Top left*: *RHESSI* 12–30 keV image (contour levels 15%, 30%, 45%, 60%, 75%, and 90%) during the rise phase (0021:42 UT) superposed on the *TRACE* 195 Å image. *Top right*: *RHESSI* X-ray spectrum for 0021:42 UT, with fit to isothermal (*dotted line*) and double-power-law (*dashed line*) spectra and the sum (*solid line*). *Bottom left*: *RHESSI* image (*black contours*: 12–18 keV, levels 15%, 30%, 45%, 60%, 75%, and 90%; *white contours*: 30–80 keV, levels 30%, 60%, 70%, and 90%) at 0028:15 UT during the impulsive phase, superposed on an Hα image from Big Bear Solar Observatory. *Bottom right*: *RHESSI* X-ray spectrum for 0028:15 UT, with fits as in the top right panel.

False-color images of solar X-rays detected by RHESSI and possible interpretation



Observational constraints from RHESSI:



Possible 2D model of a solar flare
(Priest and Forbes, 1990)

- ***The energy distributions have power law tails with slopes around* 1 *to* 5**
- ***The electrons reach a maximum energy of* 1 *MeV and the ions hundreds of MeV***
- ***The high energy particles absorb more than 50% of the energy released in a flare***

Three-dimensional effects are important in determining the spatial structure of the current sheet and the reconnection rate (Dahlburg et al., 2002; Onofri et al.,2004)

In the study of particle acceleration 2D treatments, with simplified electric fields are not enogh to understand the phenomenon (Nodes et al., 2003)

We study particle acceleration in a 3D turbulent configuration

Our model

An MHD numerical code is used to produce a turbulent electric field form magnetic reconnection in a 3D current sheet

Particles are injected in the fields obtained from the MHD simulation at different times

The fields are frozen during the motion of the particles

MHD simulation

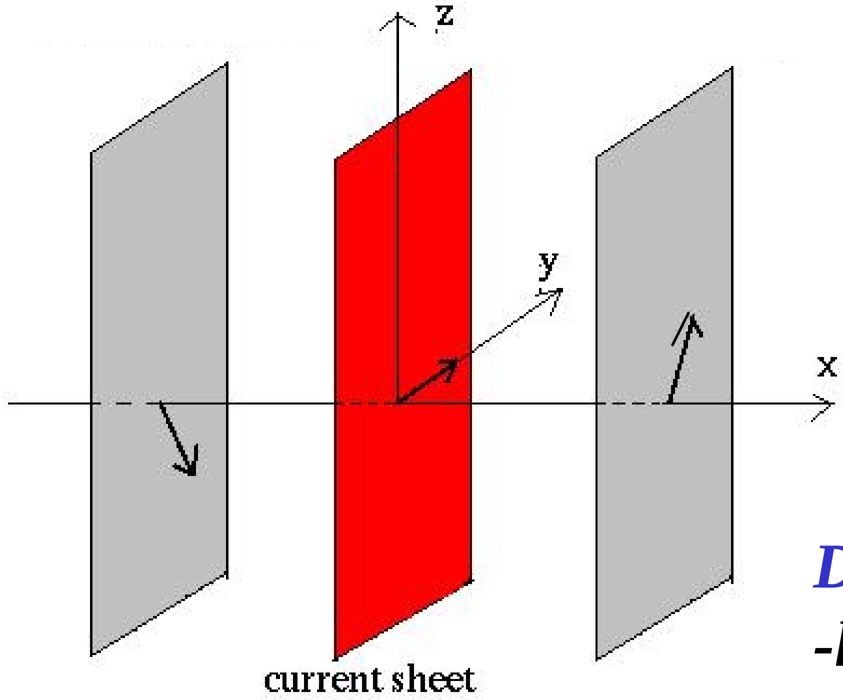
We study the magnetic reconnection in an incompressible plasma in three-dimensional slab geometry.

Different resonant surfaces are simultaneously present in different positions of the simulation domain and nonlinear interactions are possible not only on a single resonant surface, but also between different resonant surfaces.

The nonlinear evolution of the system is different from what has been observed in configurations with an antiparallel magnetic field.

Geometry

The MHD incompressible equations are solved to study magnetic reconnection in a current layer in slab geometry:



Periodic boundary conditions along y and z directions

Dimensions of the domain:

$-l_x < x < l_x, \; 0 < y < 2\pi l_y, \; 0 < z < 2\pi l_z$

Description of the simulations

Incompressible, viscous, dimensionless MHD equations:

$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V}\cdot\nabla)\mathbf{V} - \nabla P + (\nabla\times\mathbf{B})\times\mathbf{B} + \frac{1}{R_v}\nabla^2\mathbf{V}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{V}\times\mathbf{B}) + \frac{1}{R_M}\nabla^2\mathbf{B}$$

$$\nabla\cdot\mathbf{B} = 0$$

$$\nabla\cdot\mathbf{V} = 0$$

B ***is the magnetic field,*** **V** ***the plasma velocity and*** **P** ***the kinetic pressure***

R_M ***and*** R_v ***Are the kinetic and magnetic Reynolds numbers.***

Description of the simulations

Boundary conditions:

- *periodic boundaries along* **y** *and* **z** *directions*
- *in the* **x** *direction:*

$$B_x = 0 \quad \mathbf{V} = 0 \quad \frac{dP}{dx} = 0$$

$$\frac{\partial B_y}{\partial x} = 0 \qquad \frac{\partial B_z}{\partial x} = 0$$

Numerical method:

- **FFT** *algorithms for the periodic directions (***y** *and* **z***)*
- *fourth-order* **compact difference** *scheme in the inhomogeneous direction (***x***)*
- *third order* **Runge-Kutta** *time scheme*
- *code parallelized using* **MPI** *directives*

Description of the simulations: the initial conditions

Equilibrium field: plane current sheet

$$V_x = 0 \qquad B_x = 0$$

$$V_y = 0 \qquad B_y = B_{y0}$$

$$V_z = 0 \qquad B_z = \tanh\frac{x}{a} - \frac{x/a}{\cosh^2(1/a)}$$

Incompressible perturbations superposed:

$$\delta v_x = \delta b_x = \sum_{k_{y\min}}^{k_{y\max}} \sum_{k_{z\min}}^{k_{z\max}} \varepsilon \cos(\tfrac{\pi}{2}x)^2 k^{-2}(k_y + k_z)\sin(k_z z + k_y y)$$

$$\delta v_y = \delta b_y = \sum_{k_{y\min}}^{k_{y\max}} \sum_{k_{z\min}}^{k_{z\max}} \varepsilon\pi \cos(\tfrac{\pi}{2}x)\sin(\tfrac{\pi}{2}x)k^{-2}\cos(k_z z + k_y y)$$

$$\delta v_z = \delta b_z = \sum_{k_{y\min}}^{k_{y\max}} \sum_{k_{z\min}}^{k_{z\max}} \varepsilon\pi \cos(\tfrac{\pi}{2}x)\sin(\tfrac{\pi}{2}x)k^{-2}\cos(k_z z + k_y y)$$

Numerical results: characteristics of the runs

Magnetic reconnection takes place on resonant surfaces defined by the condition:

$$\mathbf{k} \cdot \mathbf{B}_0 = 0$$

where $\mathbf{k}$ ***is the wave vector of the perturbation.***

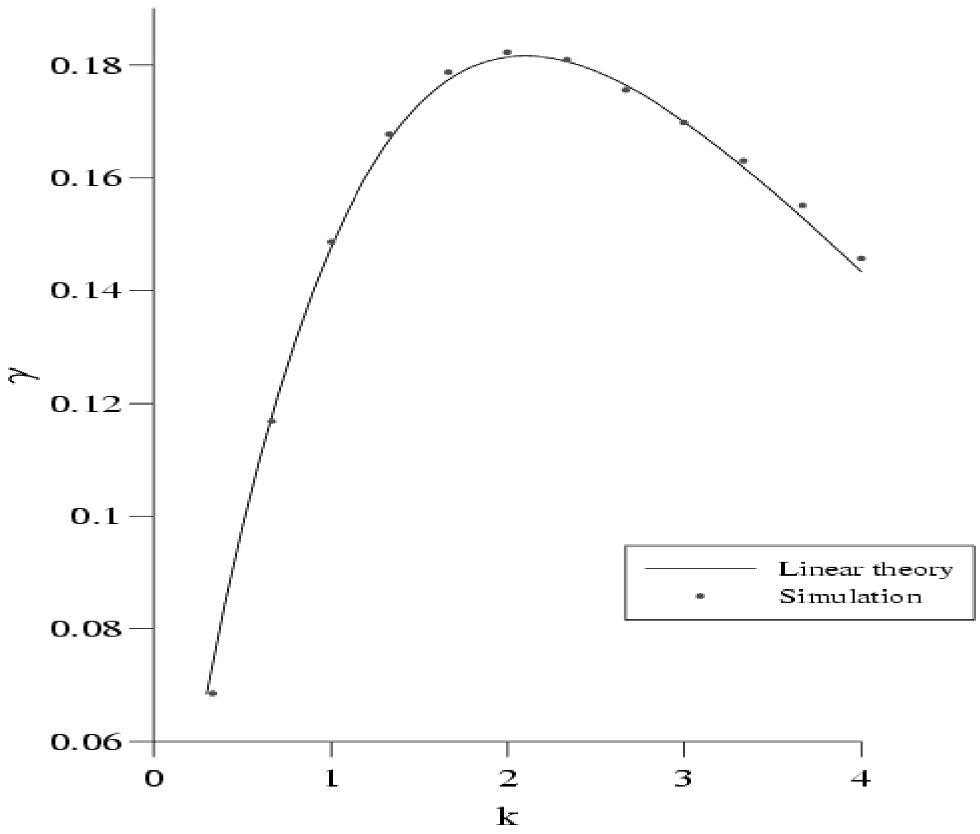
The periodicity in y and z directions imposes the following conditions:

$$k_y = \frac{m}{l_y} \qquad\qquad k_z = \frac{n}{l_z}$$

$$\mathbf{k} \cdot \mathbf{B}_0 = 0 \quad \Rightarrow \quad \frac{B_z l_y}{B_y l_z} = -\frac{m}{n}$$

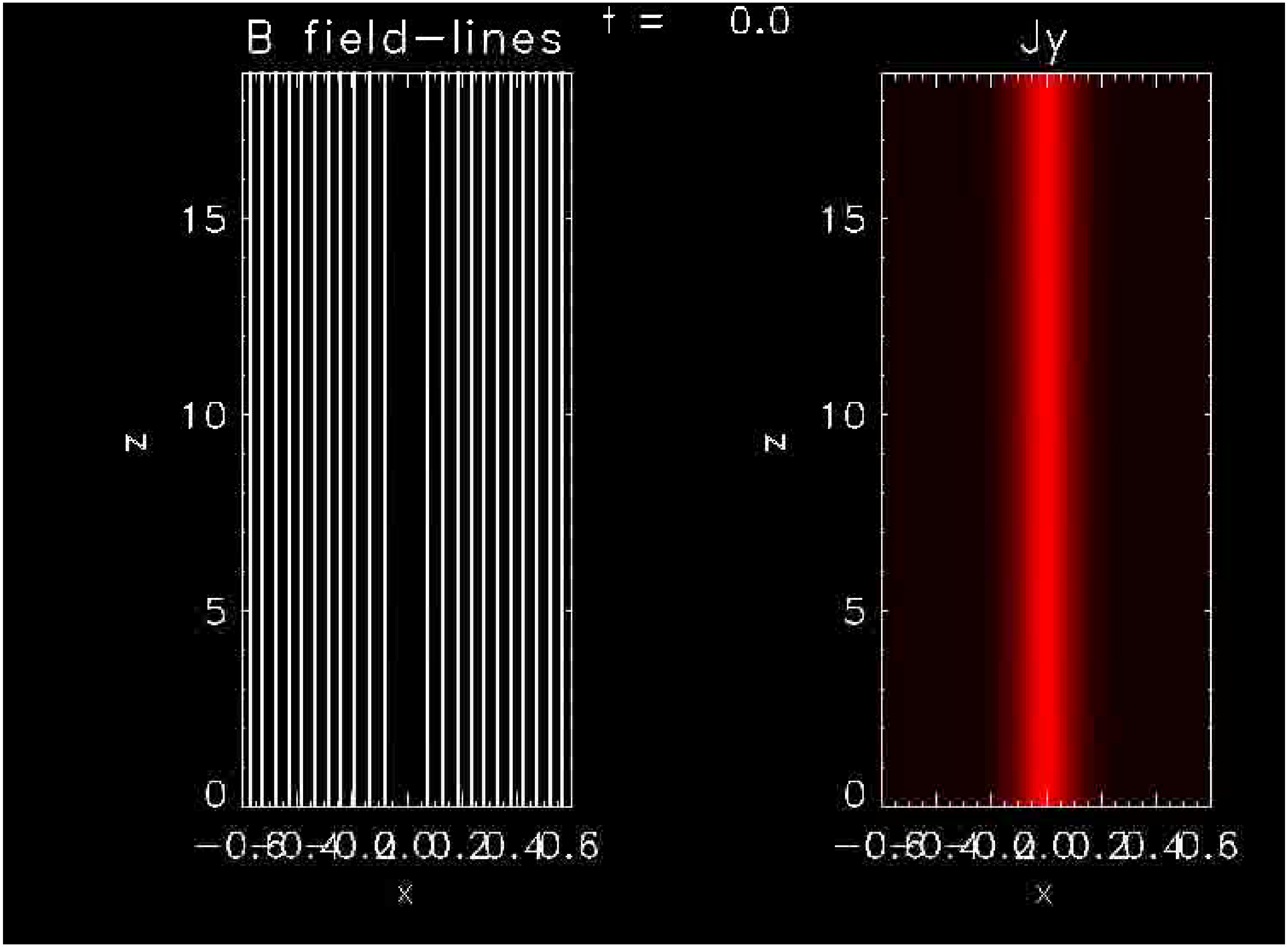
Testing the code: growth rates

The numerical code has been tested by comparing the growth rates calculated in the linear stage of the simulation with the growth rates predicted by the linear theory.

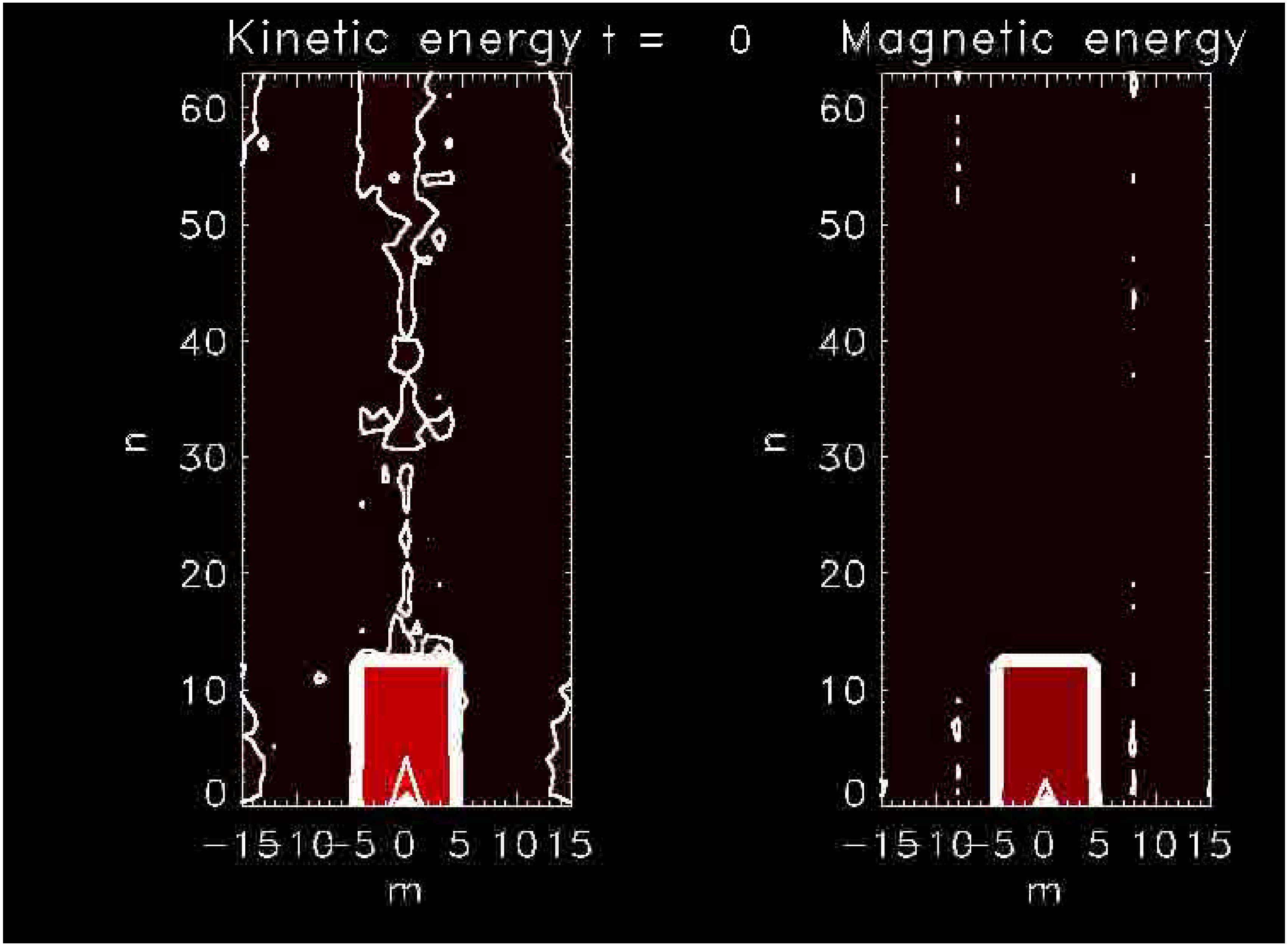


Two-dimensional modes

Numerical results: reconnection of magnetic field lines



Numerical results: time evolution of the spectra



Spectrum anisotropy

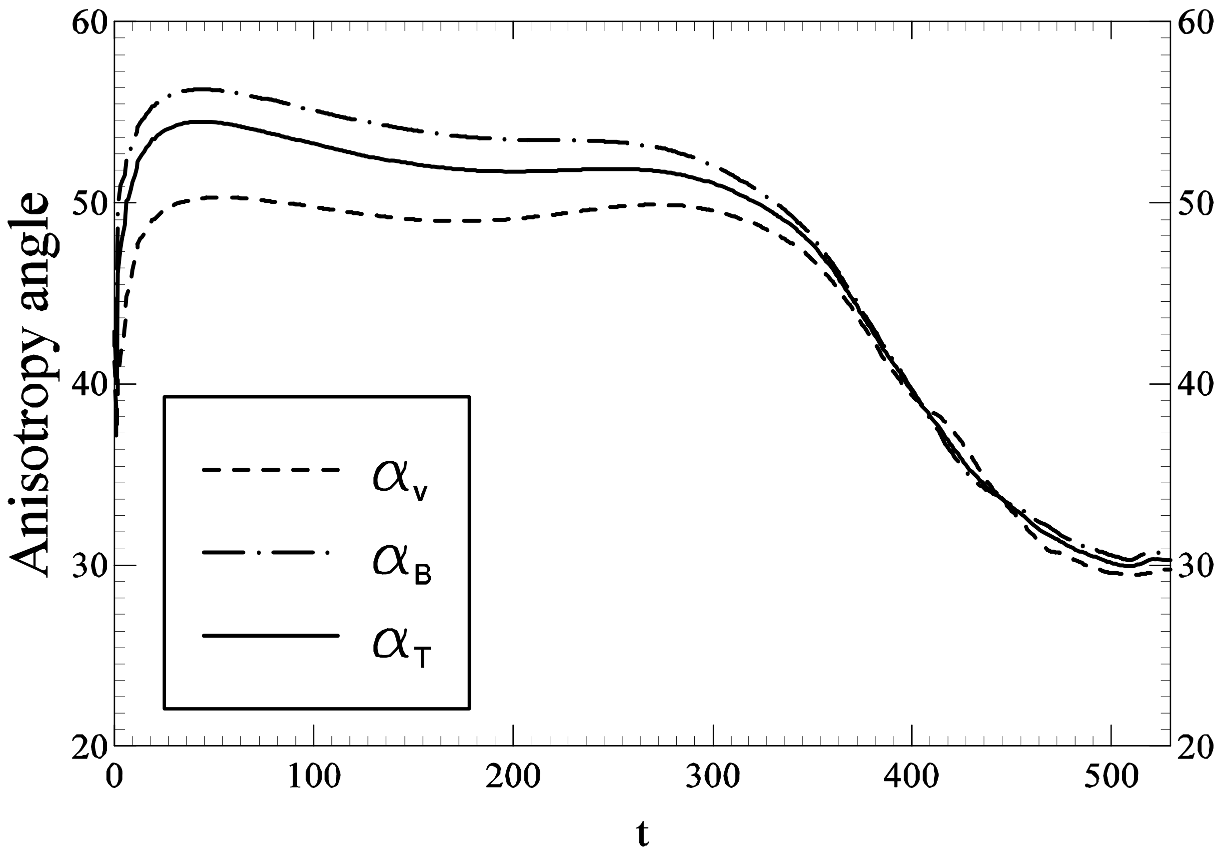
The energy spectrum is anisotropic, developping mainly in one specific direction in the plane, identified by a particular value of the ratio, which increases with time. This can be expressed by introducing an anisotropy angle:

$$\alpha = \tan^{-1}\sqrt{\frac{\langle k_z^2 \rangle}{\langle k_y^2 \rangle}}$$ ***where*** $\langle k_z^2 \rangle$ ***and*** $\langle k_y^2 \rangle$

are the r.m.s. of the wave vectors weighted by the specrtal energy:

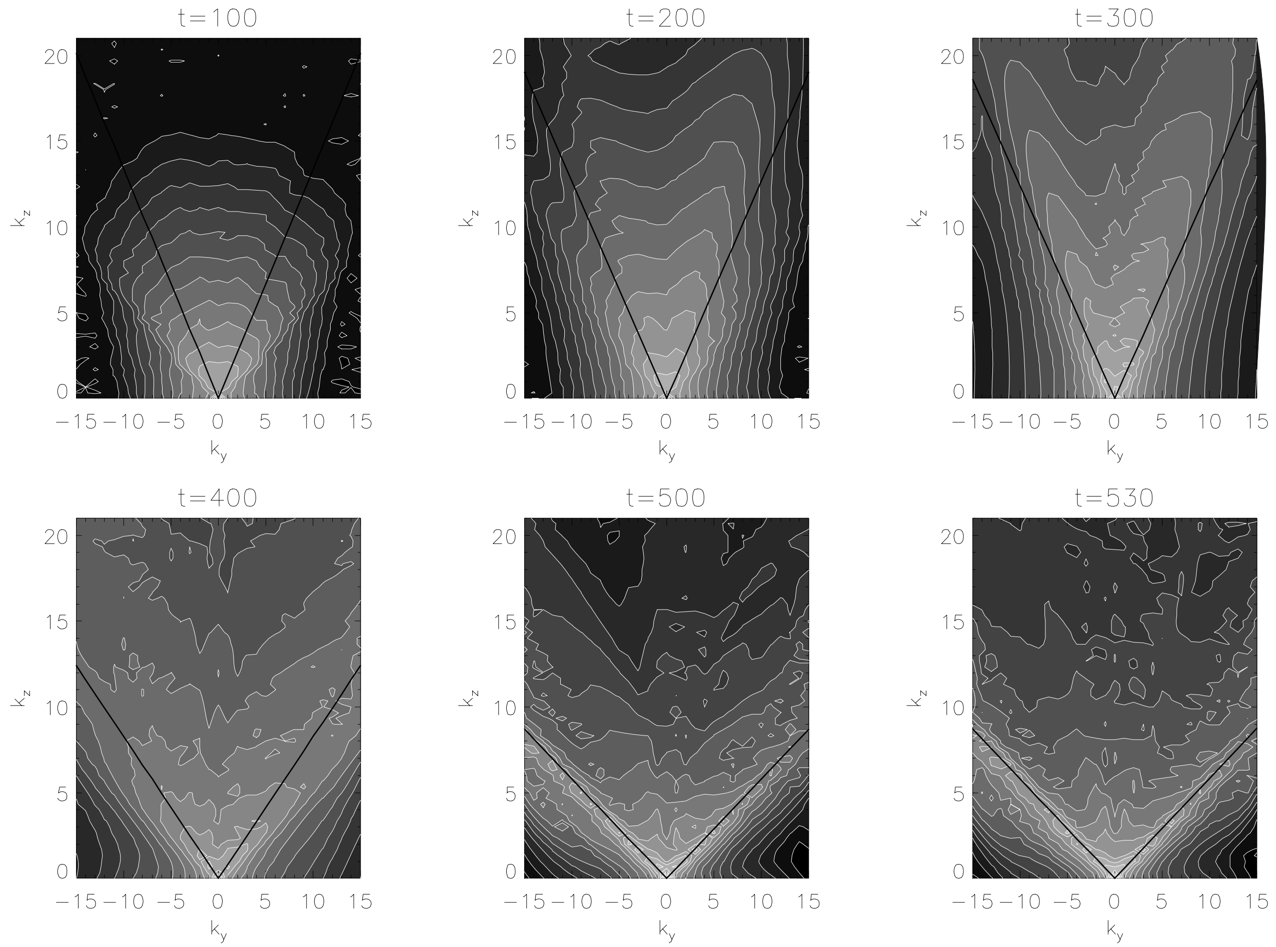
$$\langle k_z^2 \rangle = \frac{\sum_{m,n} (n / L_z)^2 E_{m,n}}{\sum_{m,n} E_{m,n}} \qquad \langle k_y^2 \rangle = \frac{\sum_{m,n} (m / L_y)^2 E_{m,n}}{\sum_{m,n} E_{m,n}}$$

Spectrum anisotropy



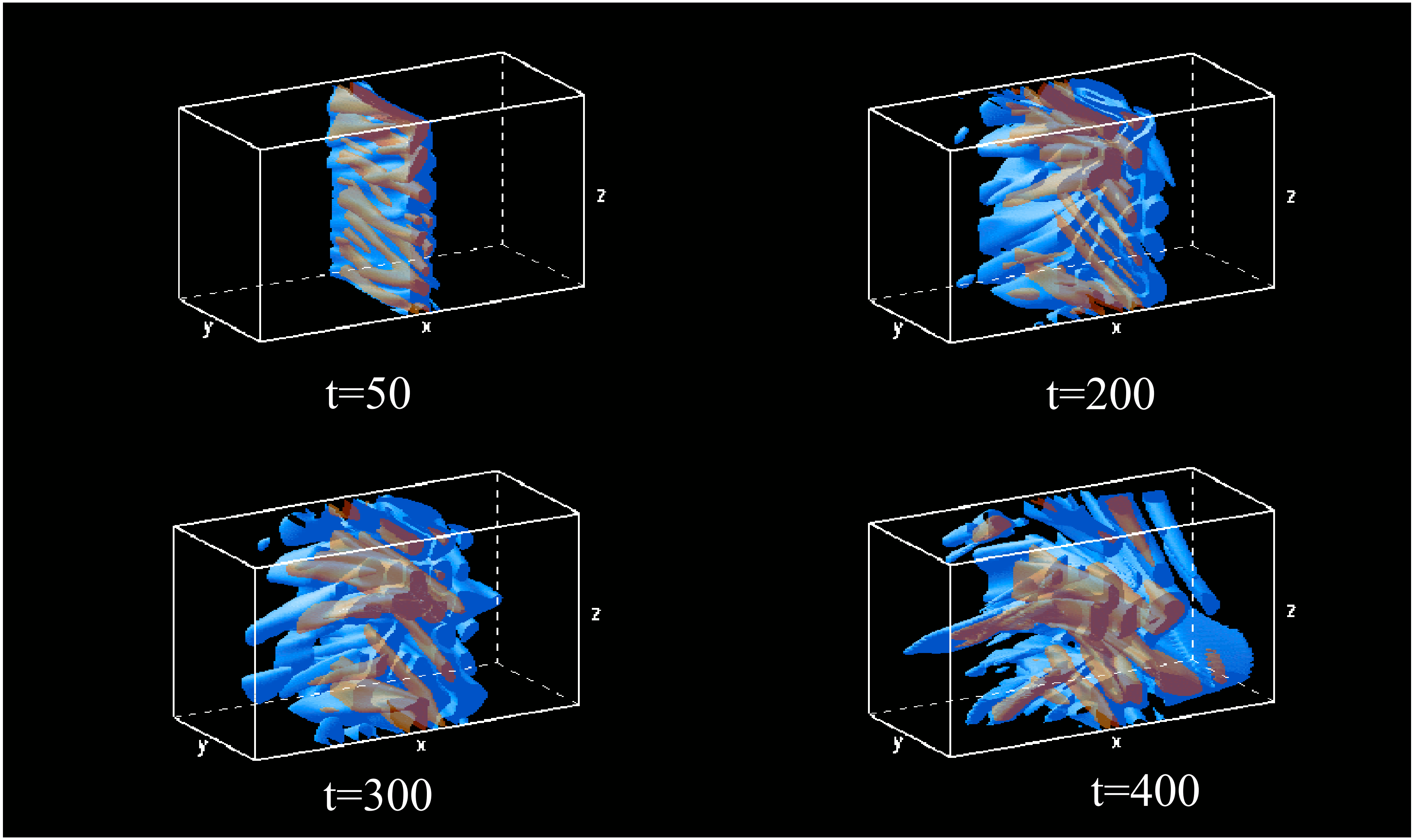
Spectrum anisotrpy

Contour plots of the total energy spectrum at different times. The straight lines have a slope corresponding to the anisotropy angle.



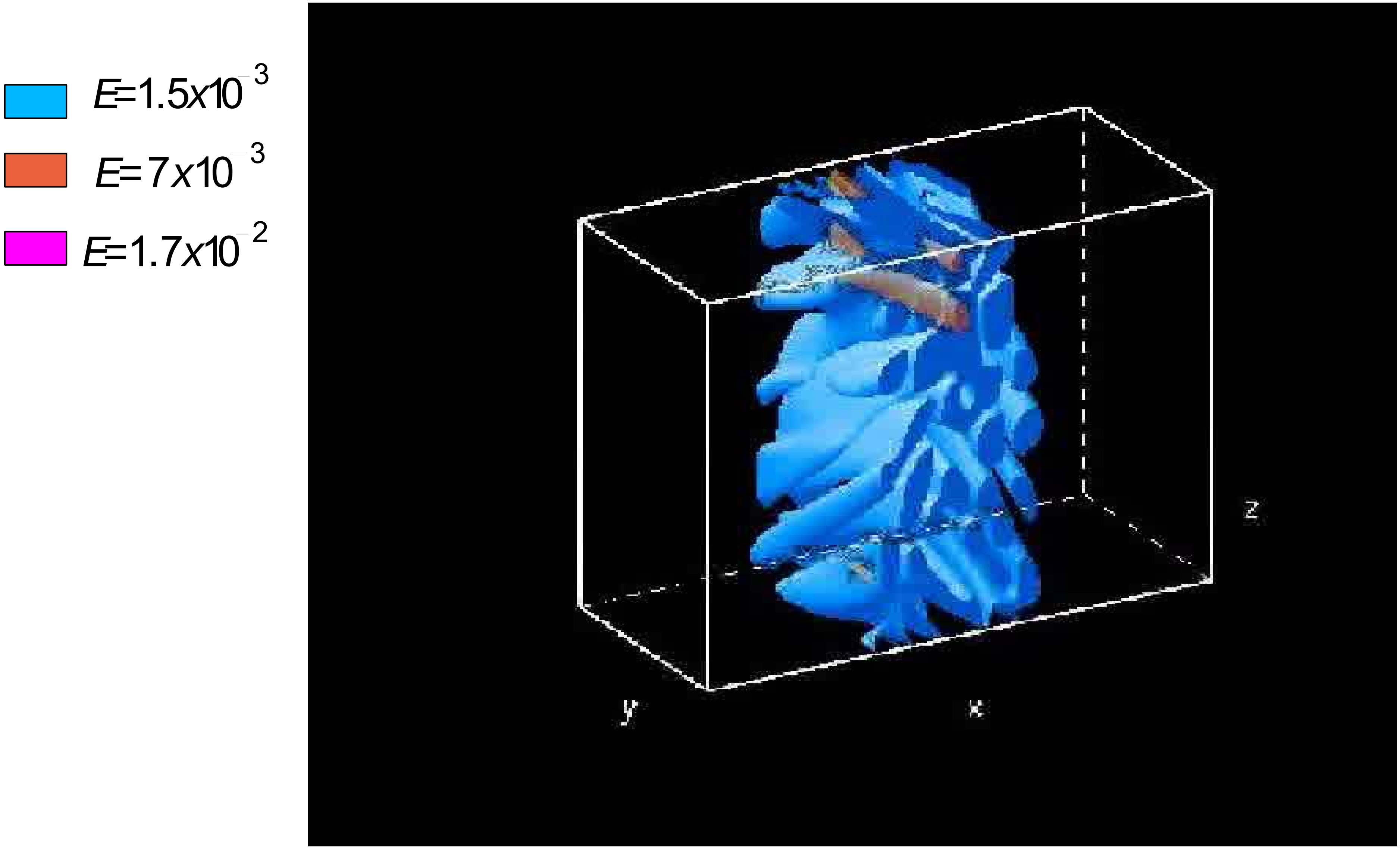
Three-dimensional structure of the electric field

Isosurfaces of the electric field at different times



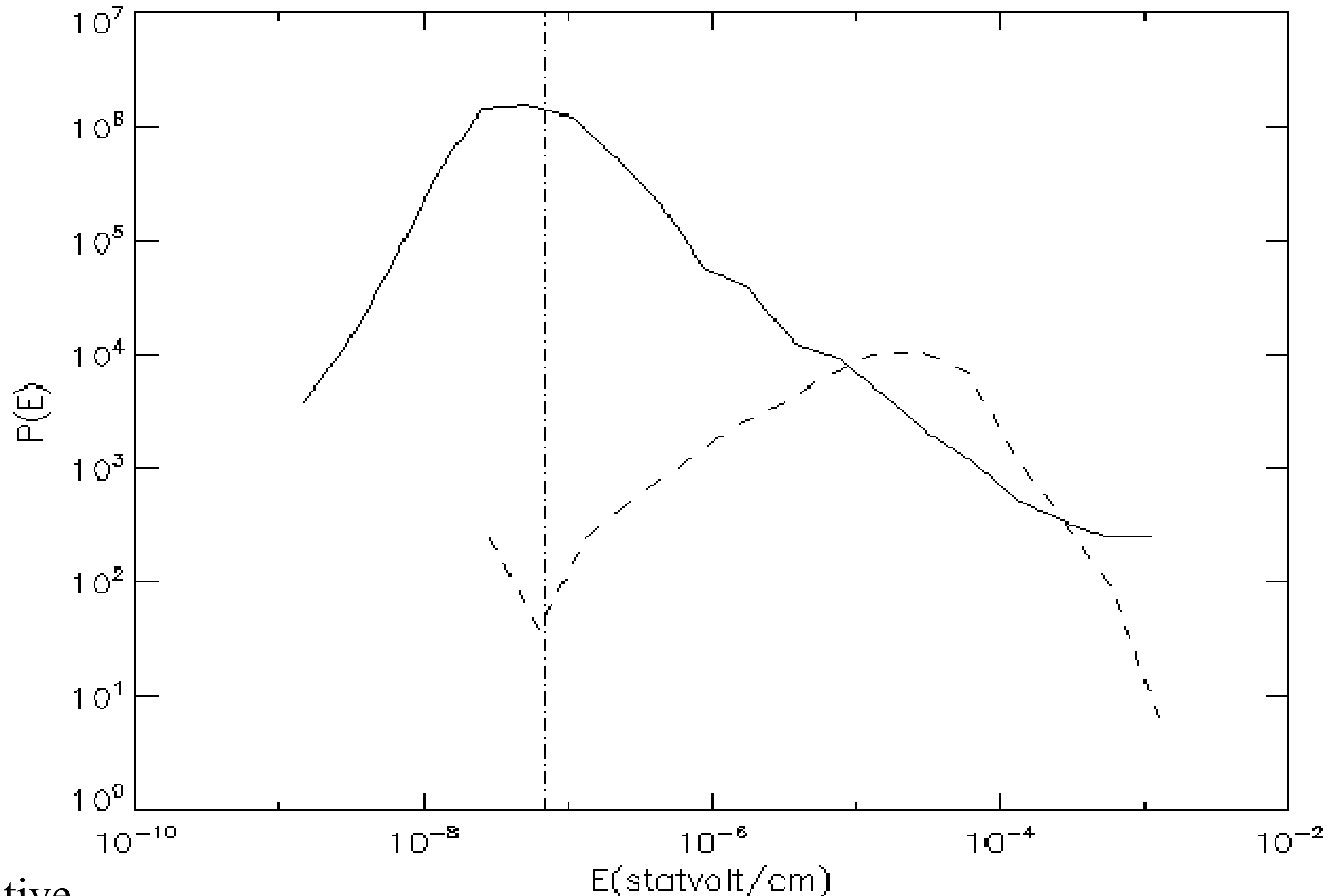
Time evolution of the electric field

Isosurfaces of the electric field from **t=200** *to* **t=400**



Distribution function of the electric field at t=50

P(E)



resistive

convective

E

Particle acceleration

Relativistic equations of motions:

$$\frac{d\mathbf{r}}{dt} = \mathbf{v} \qquad \frac{d\,\mathbf{p}}{d\,t} = e\,\mathbf{E} + \frac{e}{c}\,\mathbf{v} \times \mathbf{B}$$

$$\mathbf{p} = \gamma m\,\mathbf{v} \qquad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

The equations are solved with a fourth-order Runge Kutta adaptive step-size scheme.

The electric and magnetic field are interpolated with local 3D interpolation to provide the field values where they are needed

Parameters of the run:

Number of particles: **10000**

Maximum time: $8 \times 10^{-5} s$

Magnetic field: **100 G**

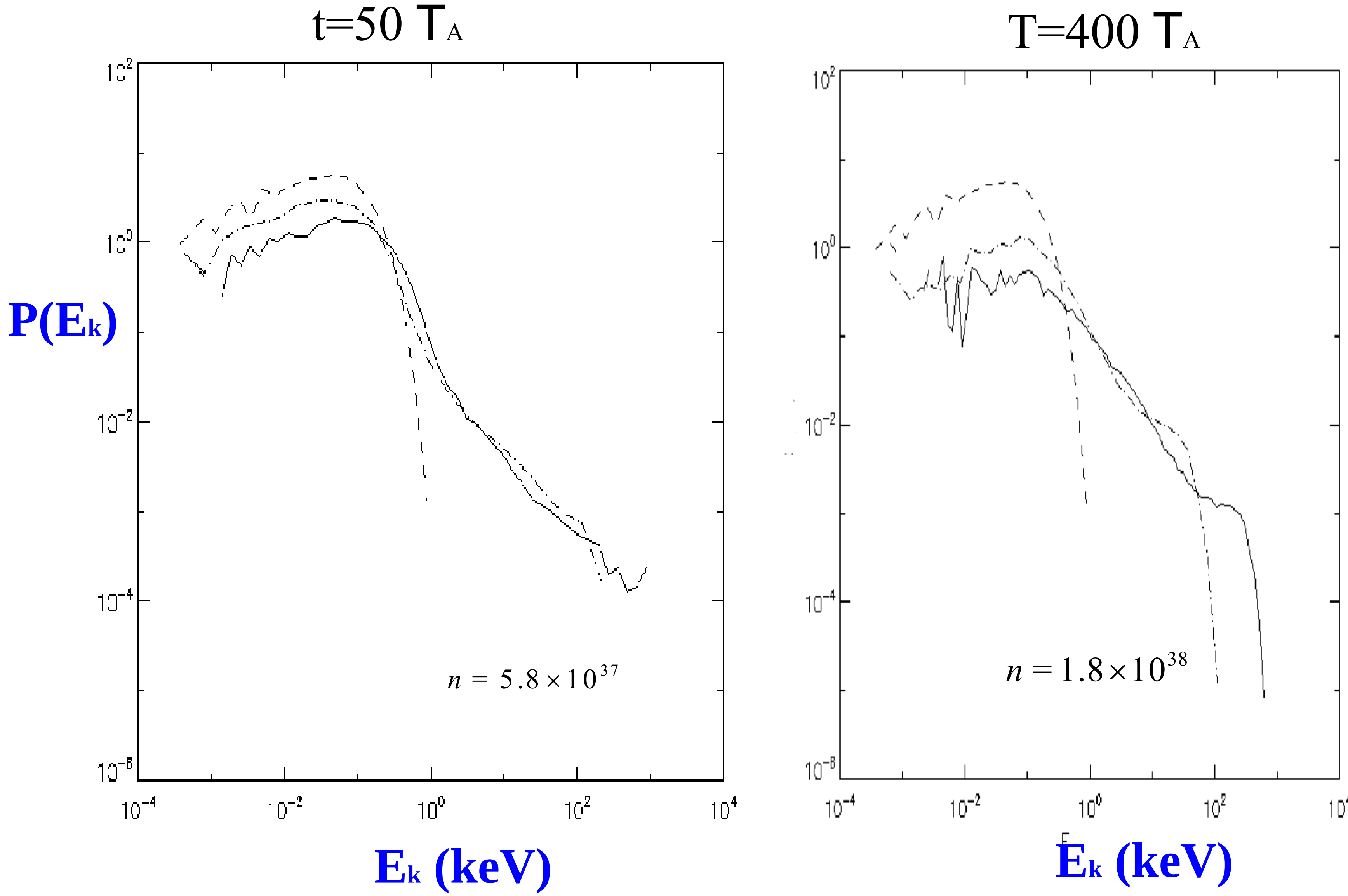
Particle density: $10^{9} cm^{-3}$

Size of the box: $l_x = 10^{9} cm$

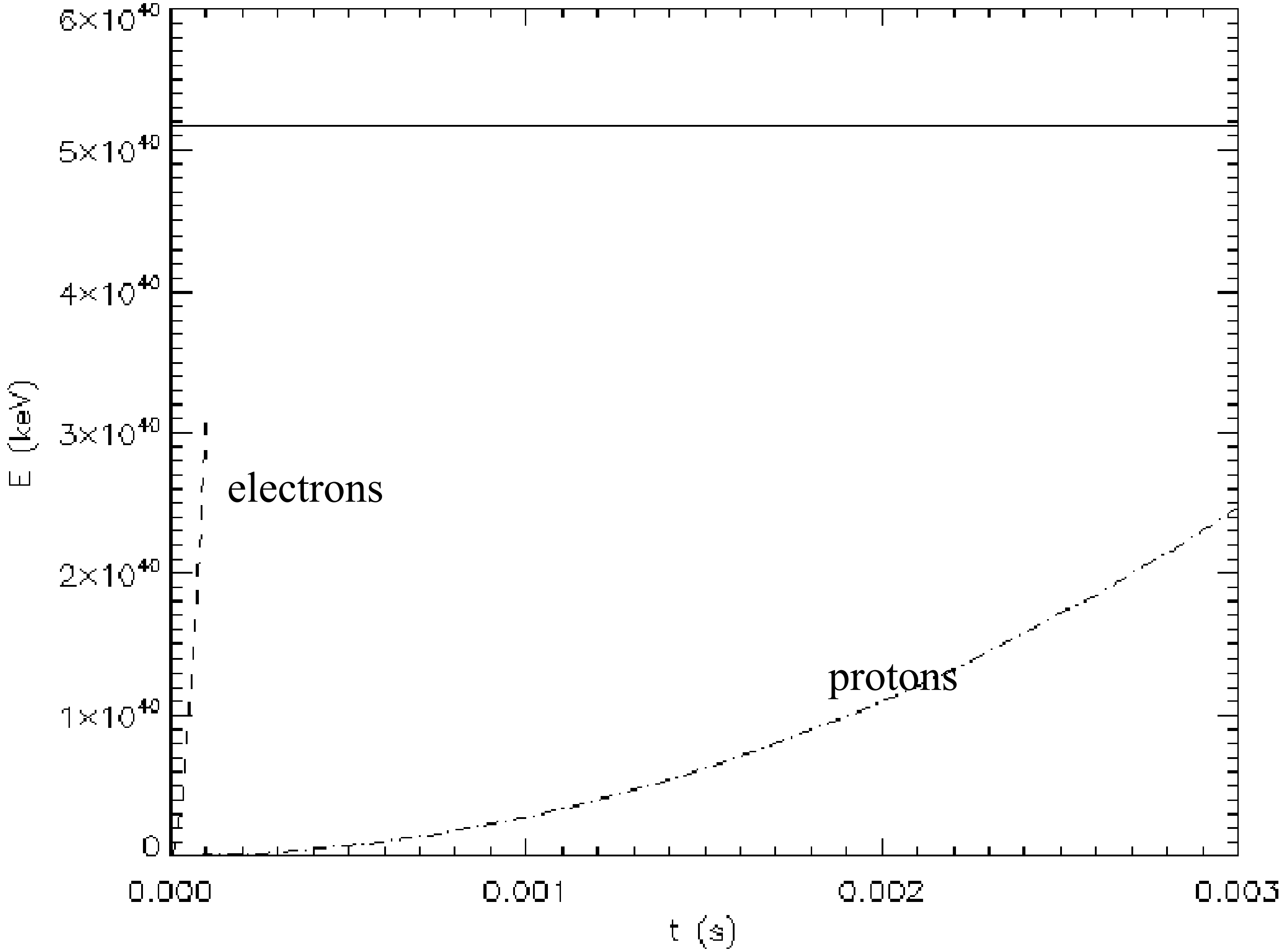
Particle temperature: $1.5 \times 10^{6} K$

The particles are injected with a maxwellian distribution and with random positions

Kinetic energy distribution function of electrons

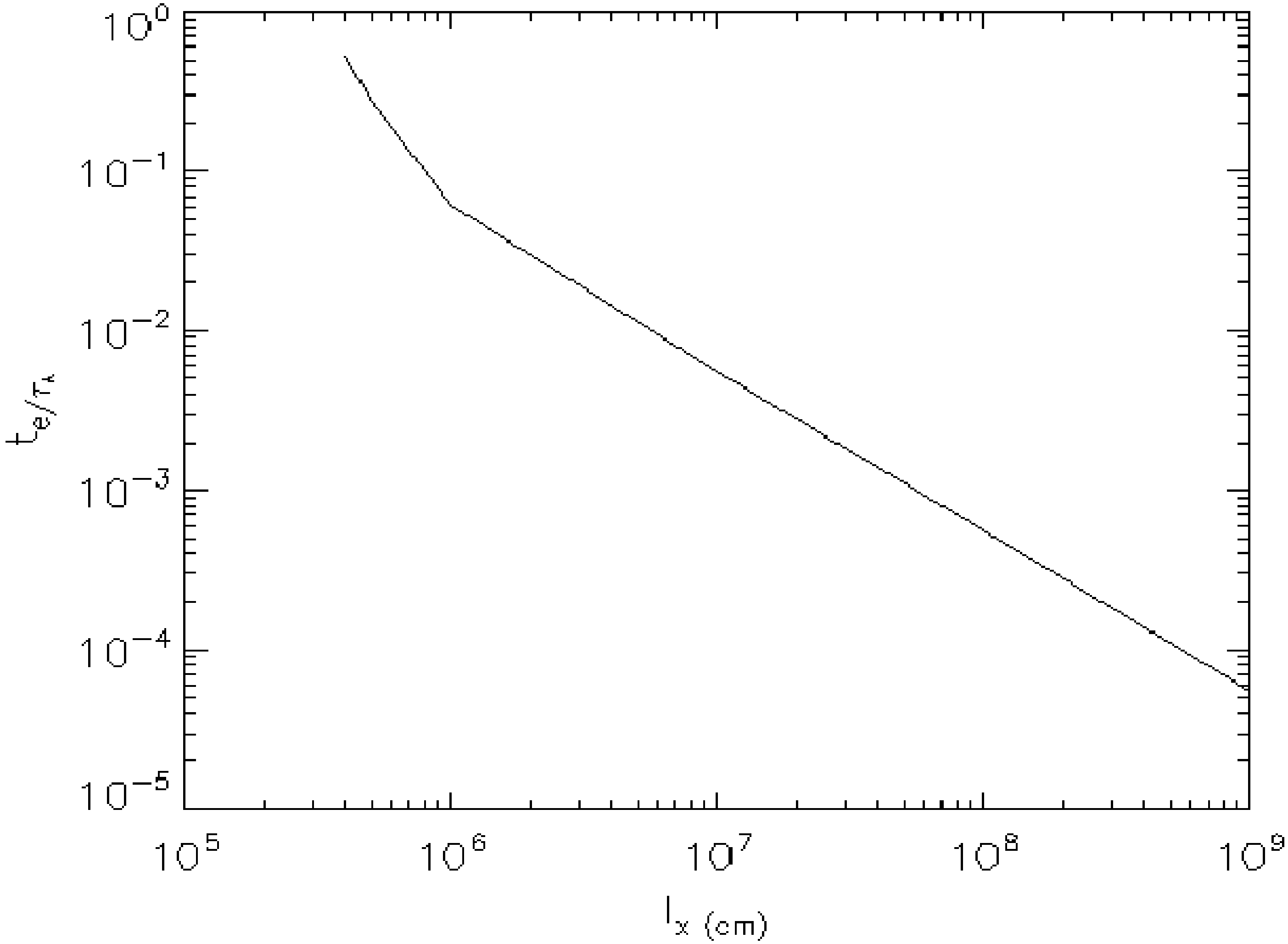


Energetics

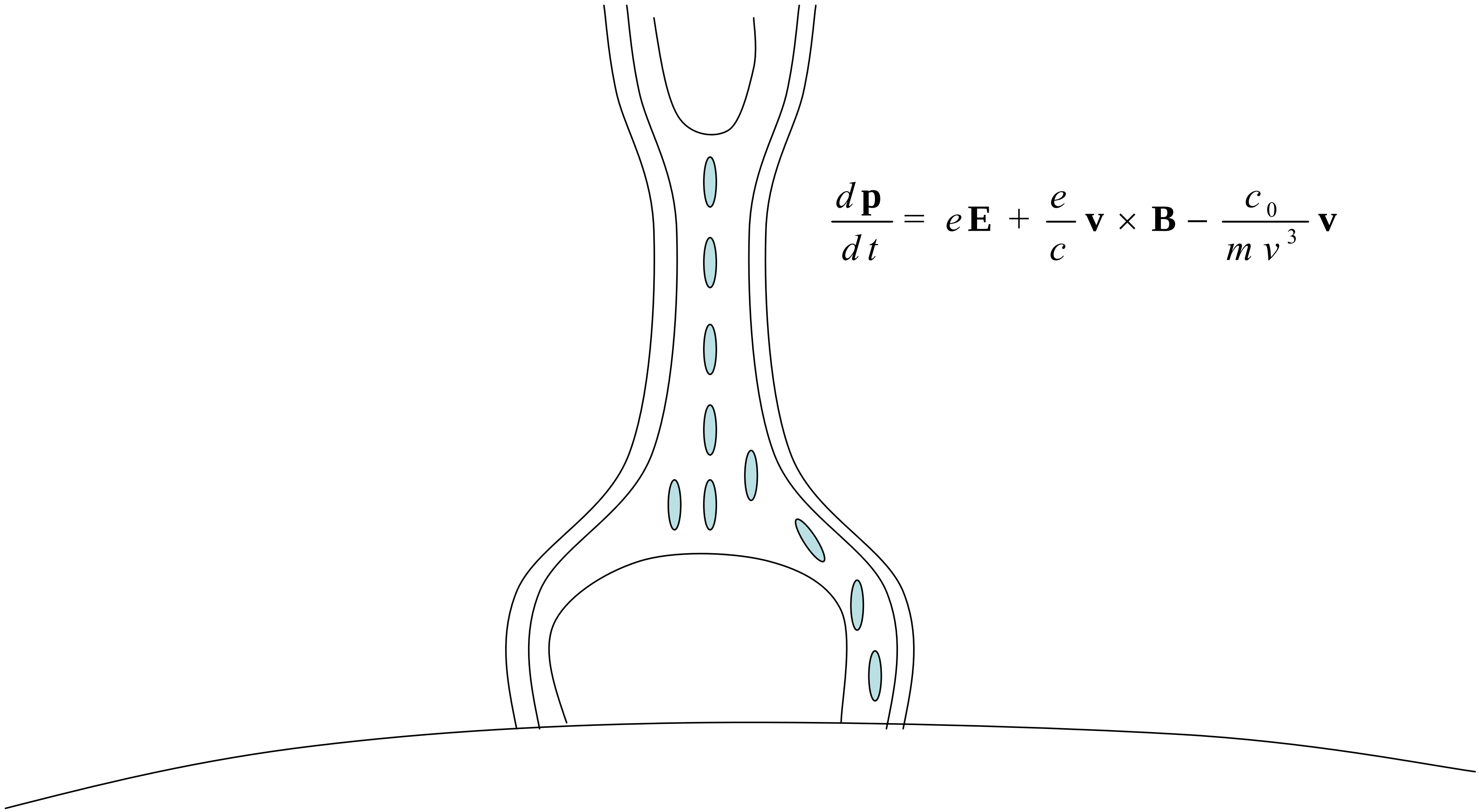


6×10^40
5×10^40
4×10^40
3×10^40
2×10^40
1×10^40
0
E (keV)
electrons
protons
0.000
0.001
0.002
0.003
t (s)

Lifetime of a current sheet



A big current sheet is fragmented in small current sheets in different locations, with different conditions of temperature and density



$$\frac{d\mathbf{p}}{dt} = e\mathbf{E} + \frac{e}{c}\mathbf{v}\times\mathbf{B} - \frac{c_0}{mv^3}\mathbf{v}$$

Parameters of the run:

Number of particles: **10000**

Maximum time: $3\times 10^{-4} s$

Magnetic field: **100 G**

Particle density: $10^{9} cm^{-3}$

Size of the box: $l_x = 4\times 10^{5} cm^{-3}$

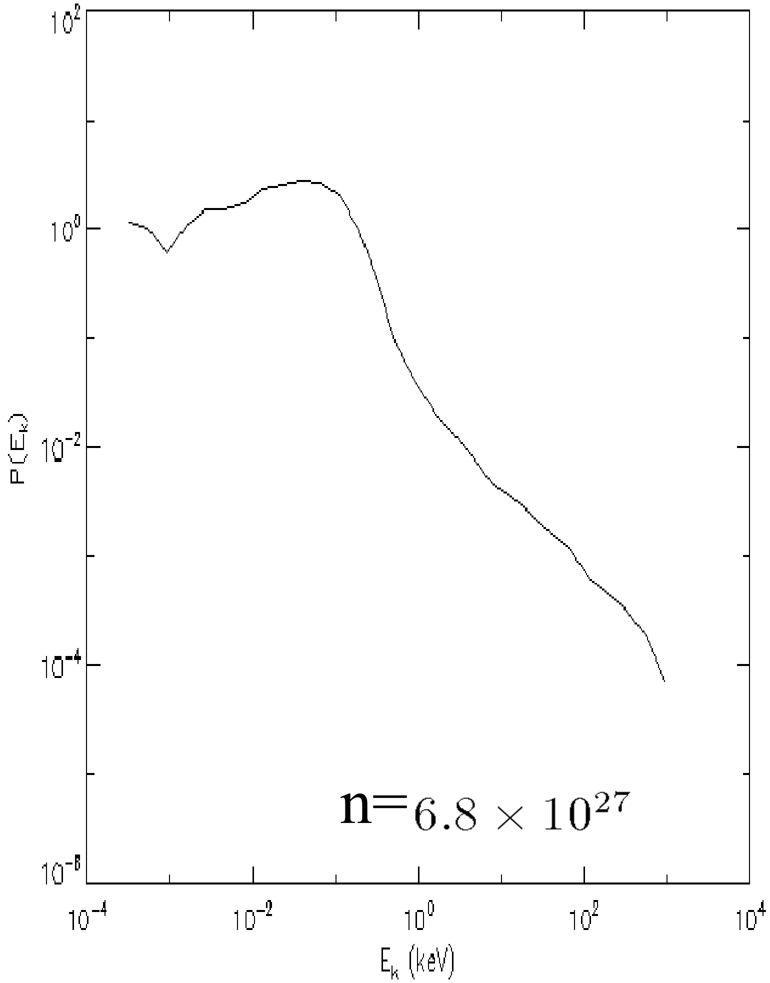
Particle temperature: $1.5\times 10^{6} K$

Kinetic energy distribution functions of electrons

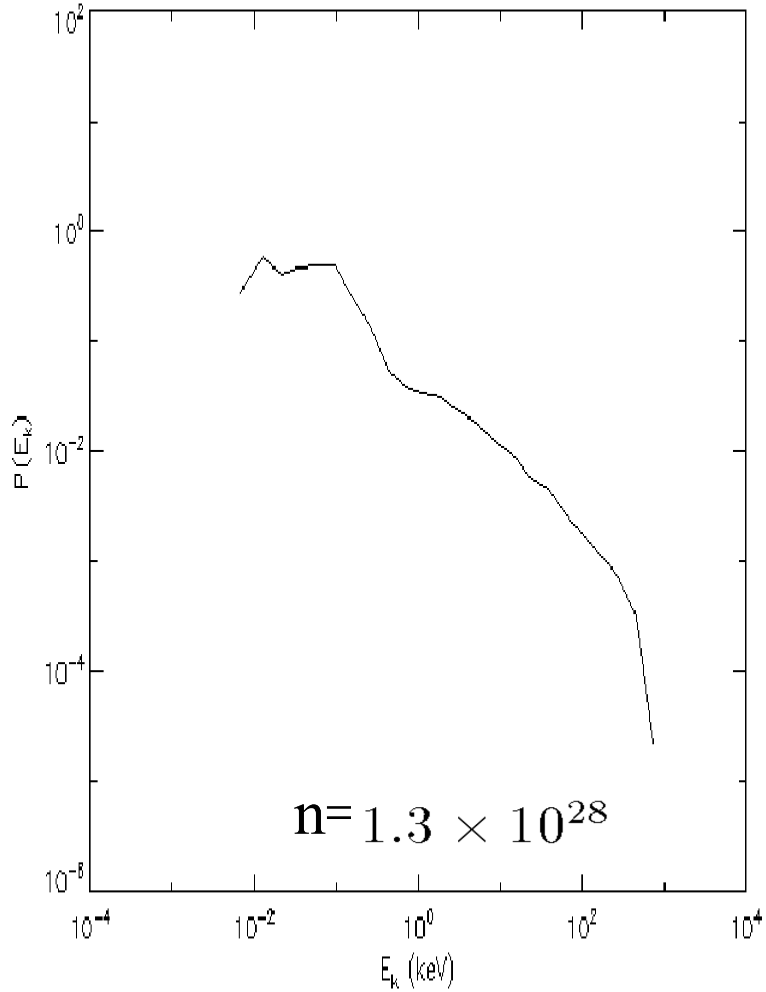
t=50 T_A

t=400 T_A

P(E_k)

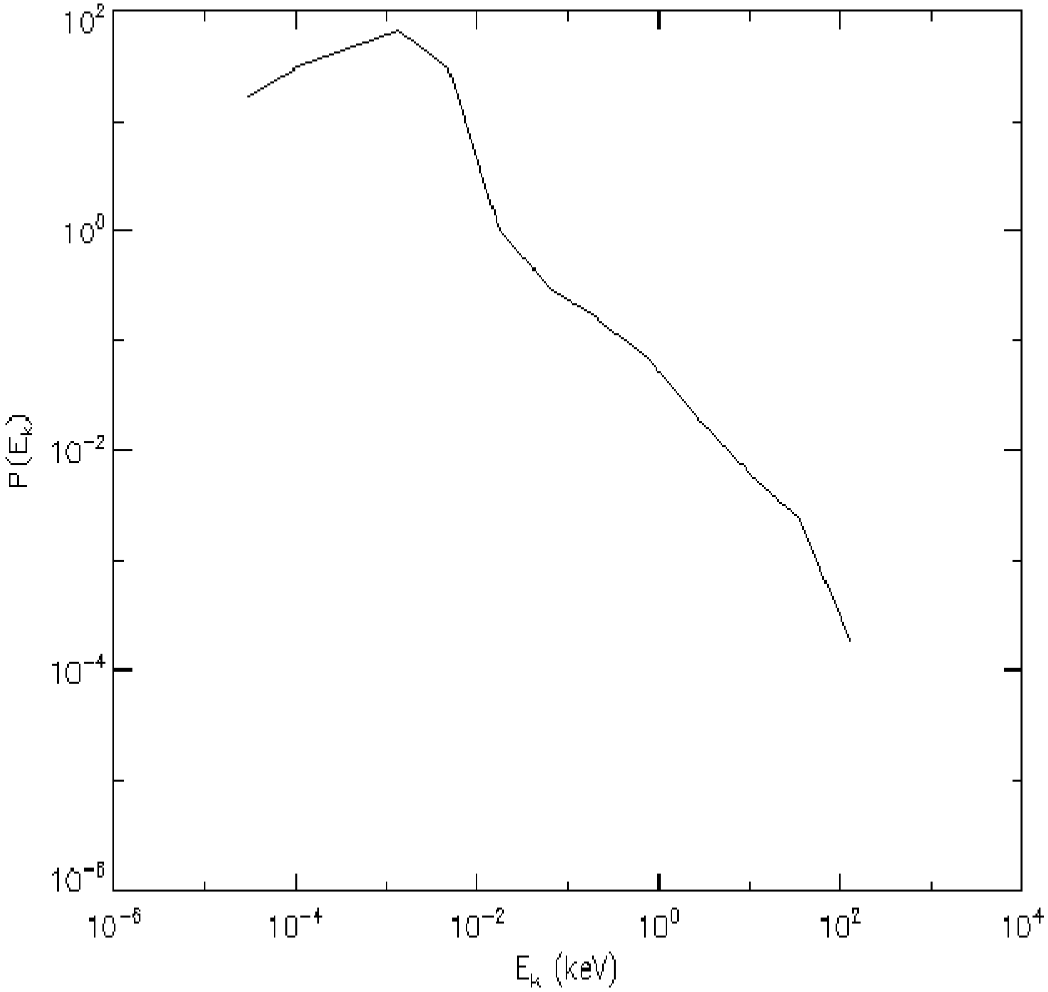


E_k (keV)



E_k (keV)

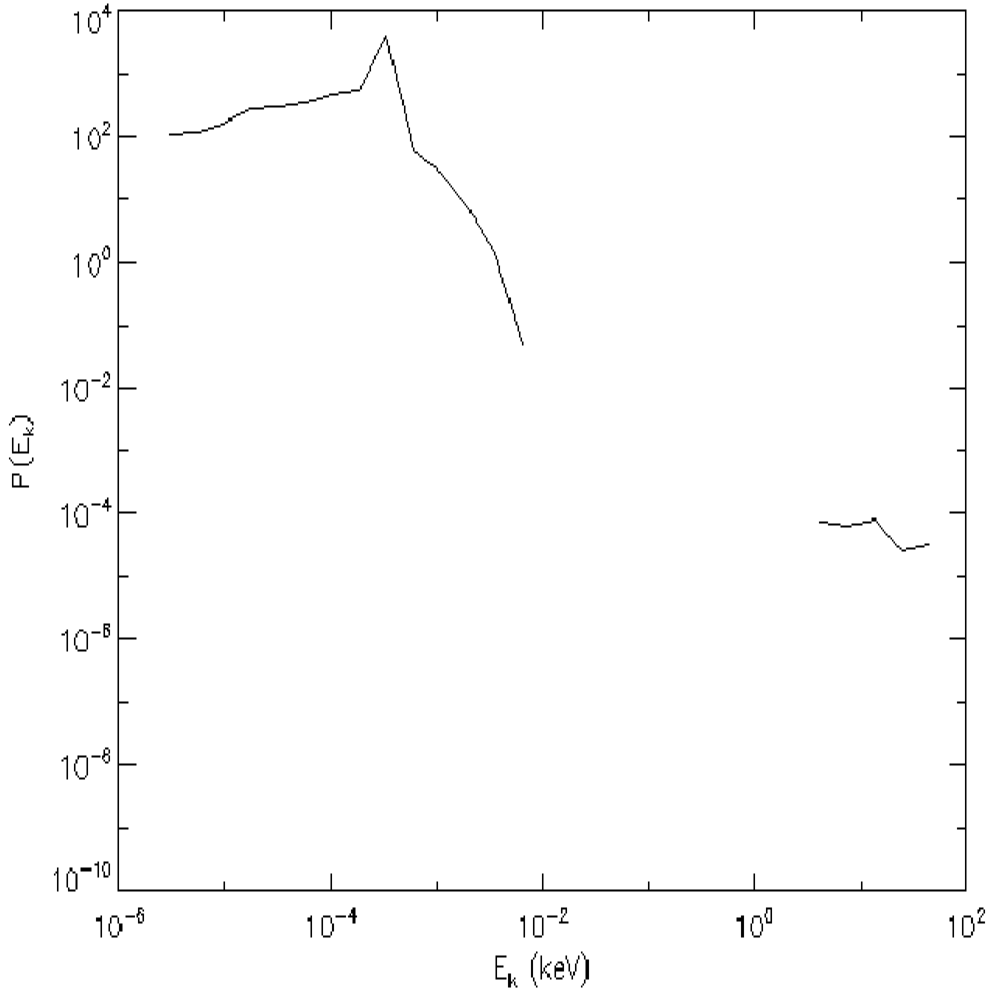
Particle acceleration in the lower corona



Density: $10^{10}\,cm^{-3}$

Temperature: $2.3\times10^5 K$

Maximum time: $10^{-4}\,s$

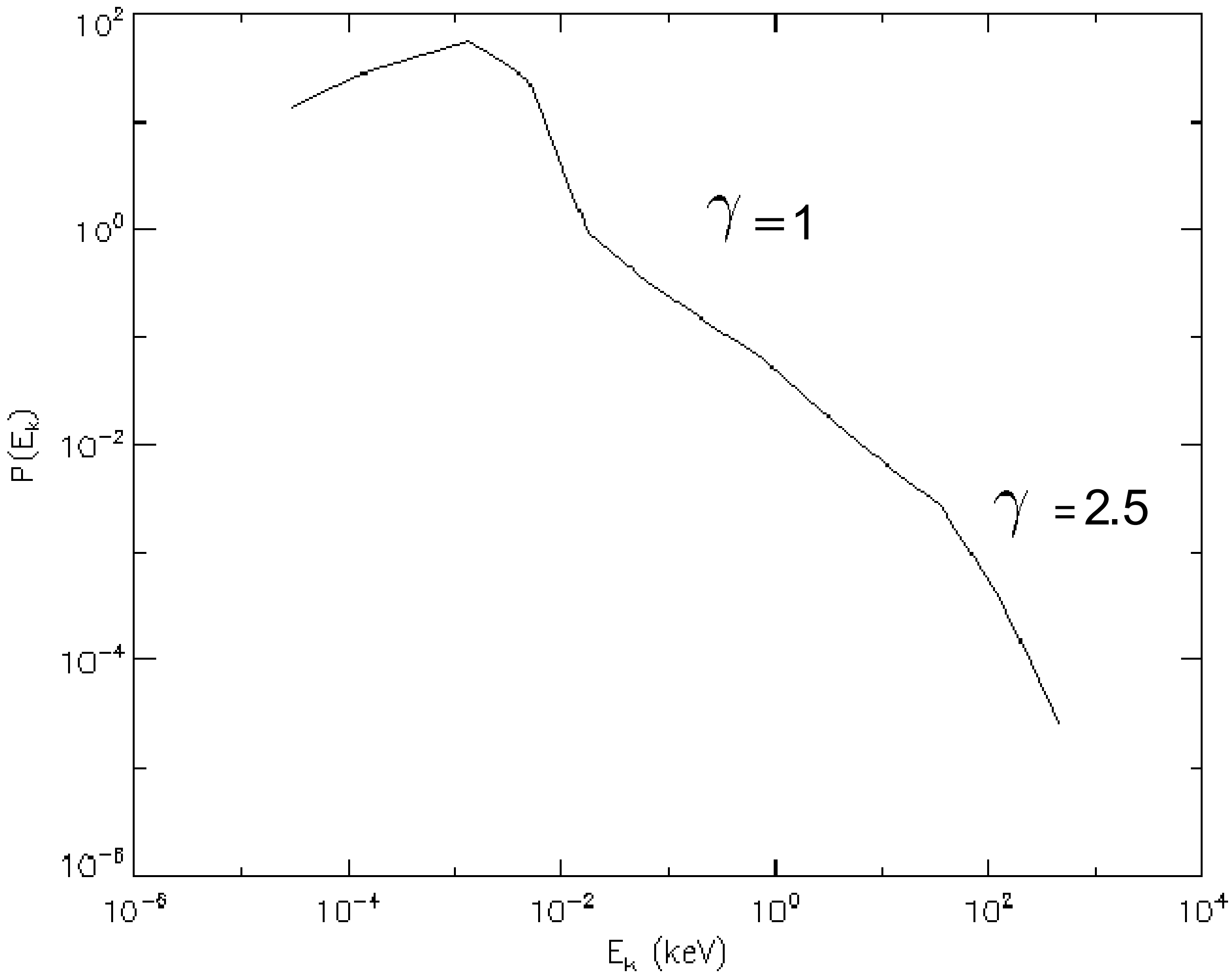


Density: $10^{11} cm^{-3}$

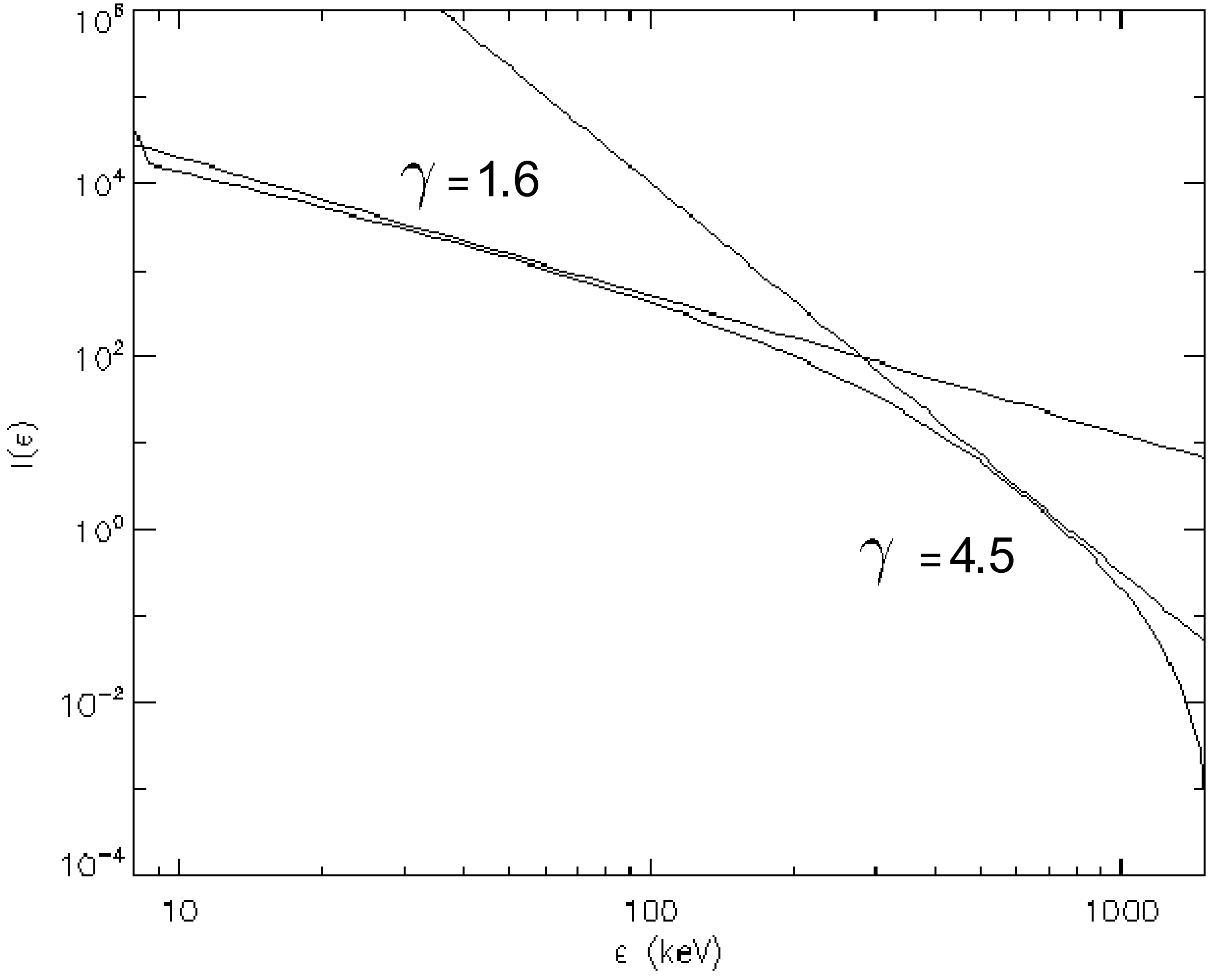
Temperature: $10^{4} K$

Maximum time: $10^{-3} s$

Distribution of electrons accelerated in different regions of the solar corona



HXR bremsstralung spectrum



Discussion and conclusions

- ***A decayed and fragmented current sheet can be a very efficient accelerator***

- ***The electrons absorb* 50% *of the energy of the magnetic field in* $10^{-4} s$ *and reach an energy of* 1 MeV**

- ***Protons cannot be accelerated to the observed energy by a single current sheet***

- ***After the formation of a current sheet the acceleration of electrons becomes important and kinetic effects start to dominate***

- ***The lifetime of a current sheet in the solar corona is comparable with the aceleration time only for current sheets smaller than*** $10^6 cm$

- ***The number of accelerated particles increases with the fragmentation of the current sheet***

- ***Electrons must be accelerated in different regions of the corona to explain the observations***

- ***The HXR spectrum has a double power law tail with slopes* 1.6 *and* 4.5**