Filamentation instability of counterstreaming pair plasmas: particle acceleration and radiation friction effects

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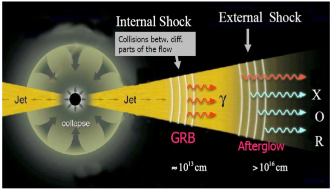
Pair Plasmas in the Laboratory

Laser-plasma experiments:

- $\sim 10^{10}$ positrons at ~ 20 MeV, estimated density $n_p \sim 10^{16}$ cm^{-3} into target
  F. Chen et al PRL **105** (2010) 015003
- > 100 MeV positron beams at high density ($n_p \sim 10^{15}$ cm^{-3})
  G. Sarri et al, PRL **110** (2013) 255002
- generation of a neutral pair plasma $n_e \simeq n_p \simeq 10^{15}$ cm^{-3} with ~ 7 MeV energy
  G. Sarri et al, arXiv:1312.0211

Pair Plasmas in Space



T.Piran, Rev. Mod. Phys. **76** (2005) 1143

Astrophysical settings:

- Gamma-ray Bursts (GRB)
- plasma outflows in Pulsar Wind Nebulae (PWN)
- relativistic jets from Active Galactic Nuclei (AGN)
- *Thunderstorms*! Beams of antimatter and gamma-ray flashes launched by thunderstorms (TGF) have been detected by FERMI space telescope

The Crab Flares Problem

Gamma-Ray flares from Crab nebula (detected by FERMI and AGILE) challenge current models for particle acceleration in pair plasmas:
- MHD validity violated
- radiative effects dominant

$\rightarrow$ kinetic simulations with radiation friction included are necessary

See e.g. Cerutti et al ApJ **770** (2013) 147; Jaroschek and Hoshino, Phys. Rev. Lett. **103** (2009) 075002; and refs. therein

Motivations for this work

- revisit the filamentation instability (FI aka "Weibel") in pair plasmas

  only electrons case: see e.g. Califano et al PRE **58** (2008) 7837

- (Notice: only the *transverse* case in 2D ($\mathbf{k} \cdot \mathbf{p}_{\text{beam}} = 0$) is considered here)

- extend to this context our approach to radiation friction in PIC simulations of ultrarelativistic laser-plasma interactions

  Tamburini et al, New J. Phys. **12** (2010) 123005

  Some previous work on FI in pair plasmas: Kazimura et al, ApJ **498** (1998) L183; Silva et al, ApJ **596** (2003) L121

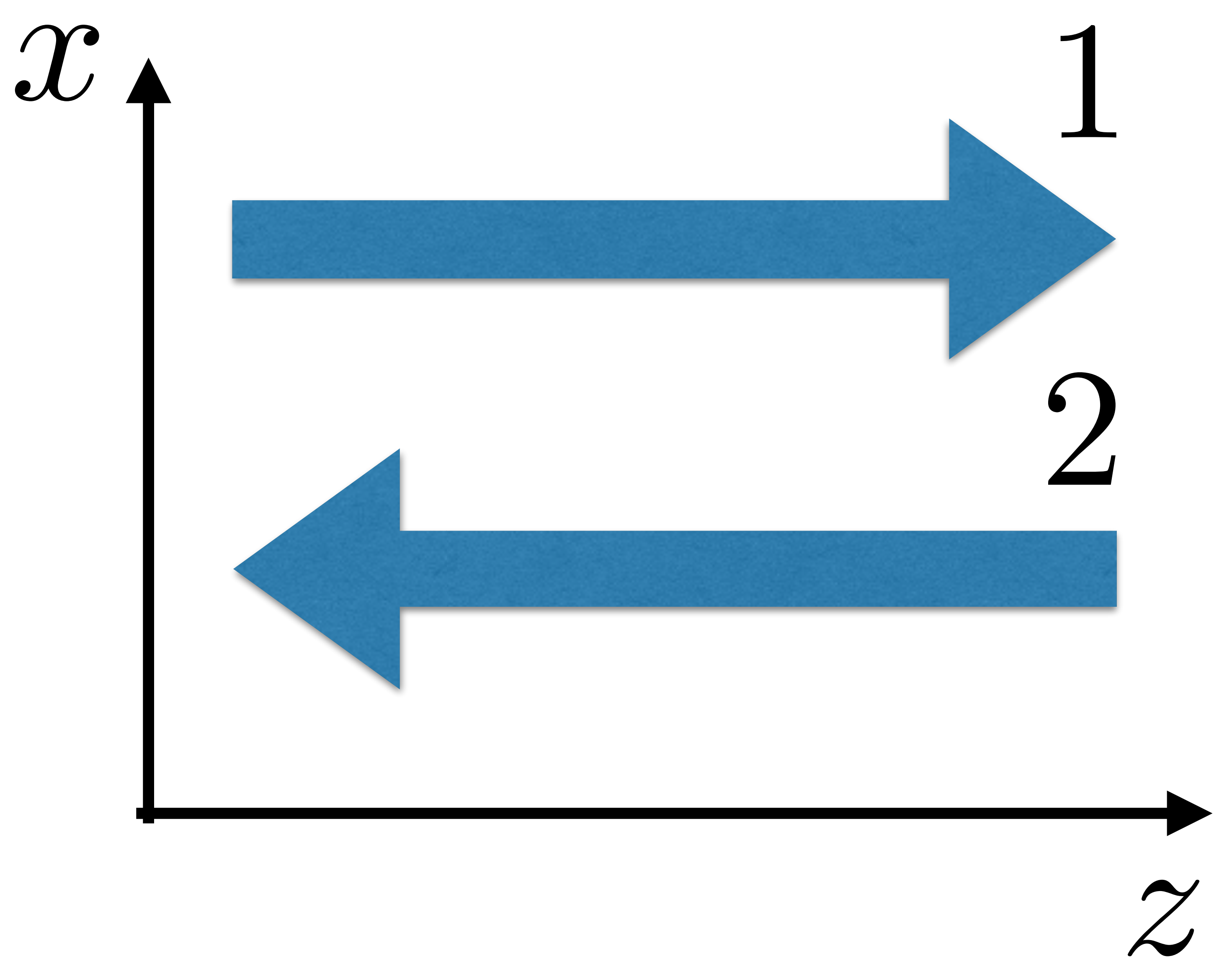
About PIC simulations

2D simulations performed on FERMI BlueGene/Q^{TM} supercomputer with the Open Source Particle-In-Cell code PICcante developed and maintained by L.Fedeli, A.Sgattoni, S.Sinigardi, A.Marocchino
github.com/ALaDyn/piccante

Access to FERMI at CINECA (Italy) sponsored by PRACE project “LSAIL”

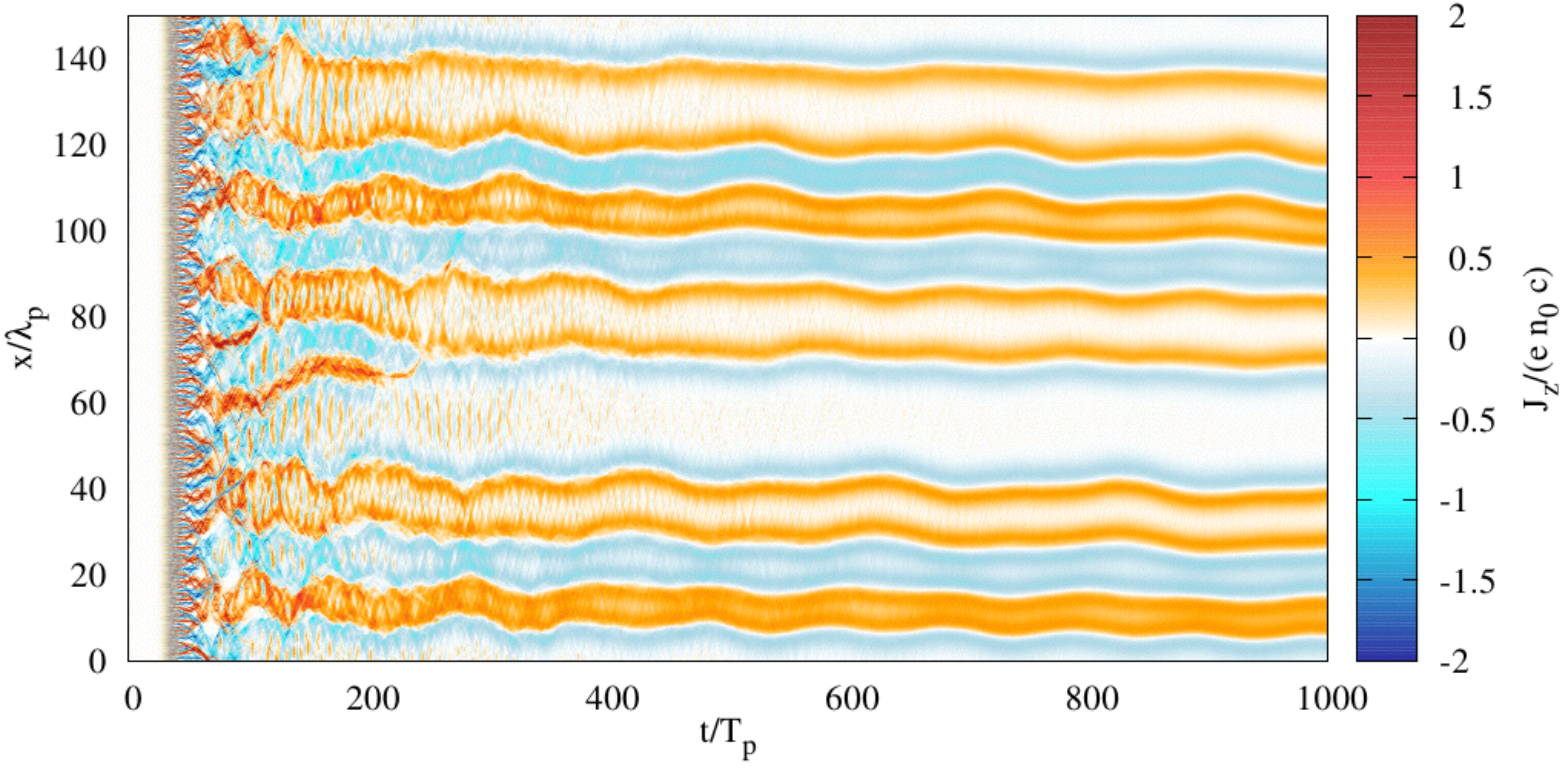
1D3P simulation: parameters

- $n_{e_1^-} = n_{e_1^+} = n_{e_2^-} = n_{e_2^+} = n_0/4$
- $p_{e_1^-} = p_{e_1^+} = p_0 \qquad p_{e_2^-} = p_{e_2^+} = -p_0$
- $L_g = 150\, l_p \quad \text{where} \quad l_p = c/\omega_p$
- $T_f = 10^3\, T_p \quad \text{where} \quad T_p = 2\pi/\omega_p$
- $N_{cp} = 3 \times 10^6 \quad \text{per specie}$

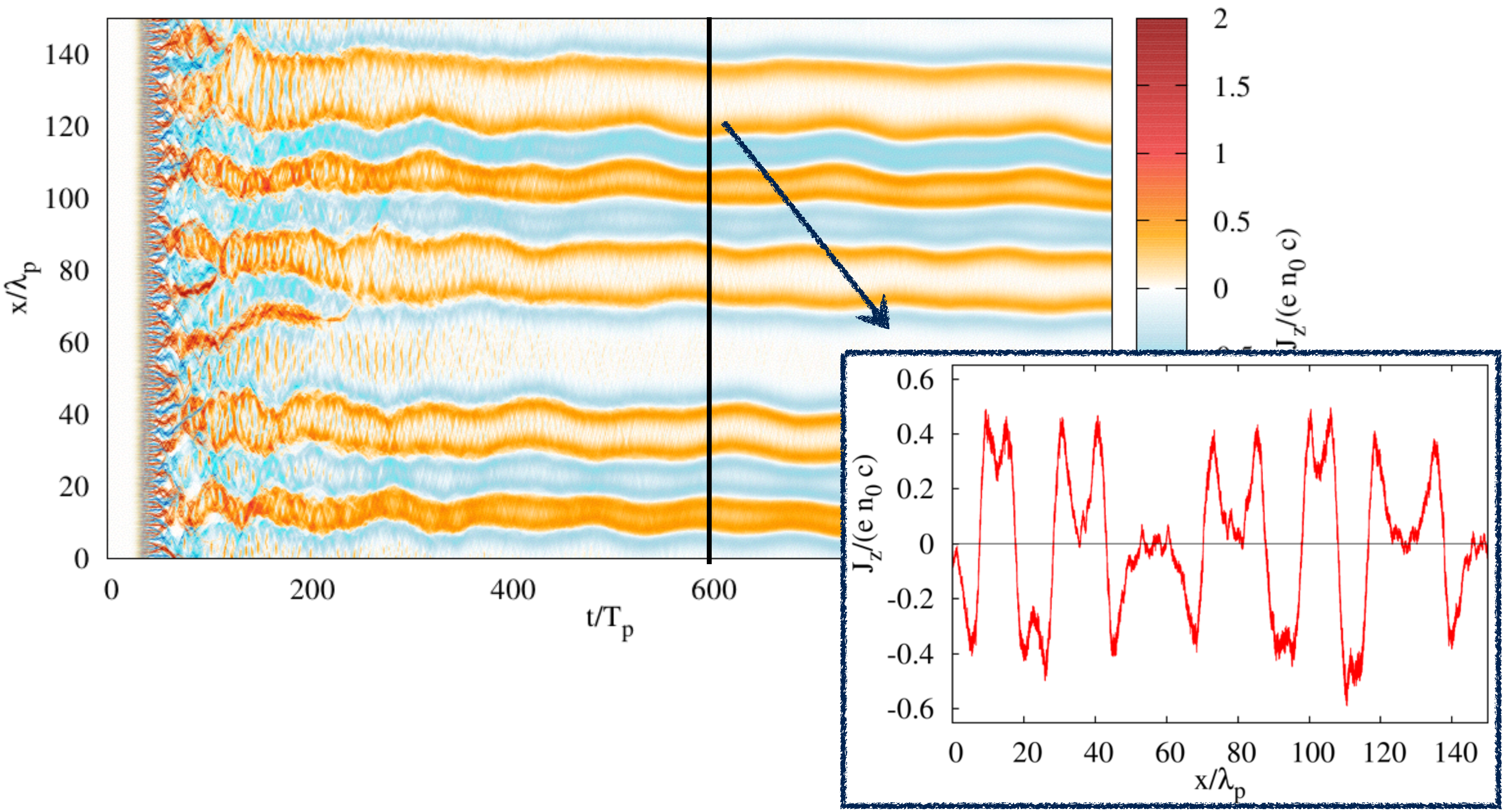


We performed simulations with $p_0 \in [1, 10^3]$. Here I will show the most representative case $p_0 = 200$.

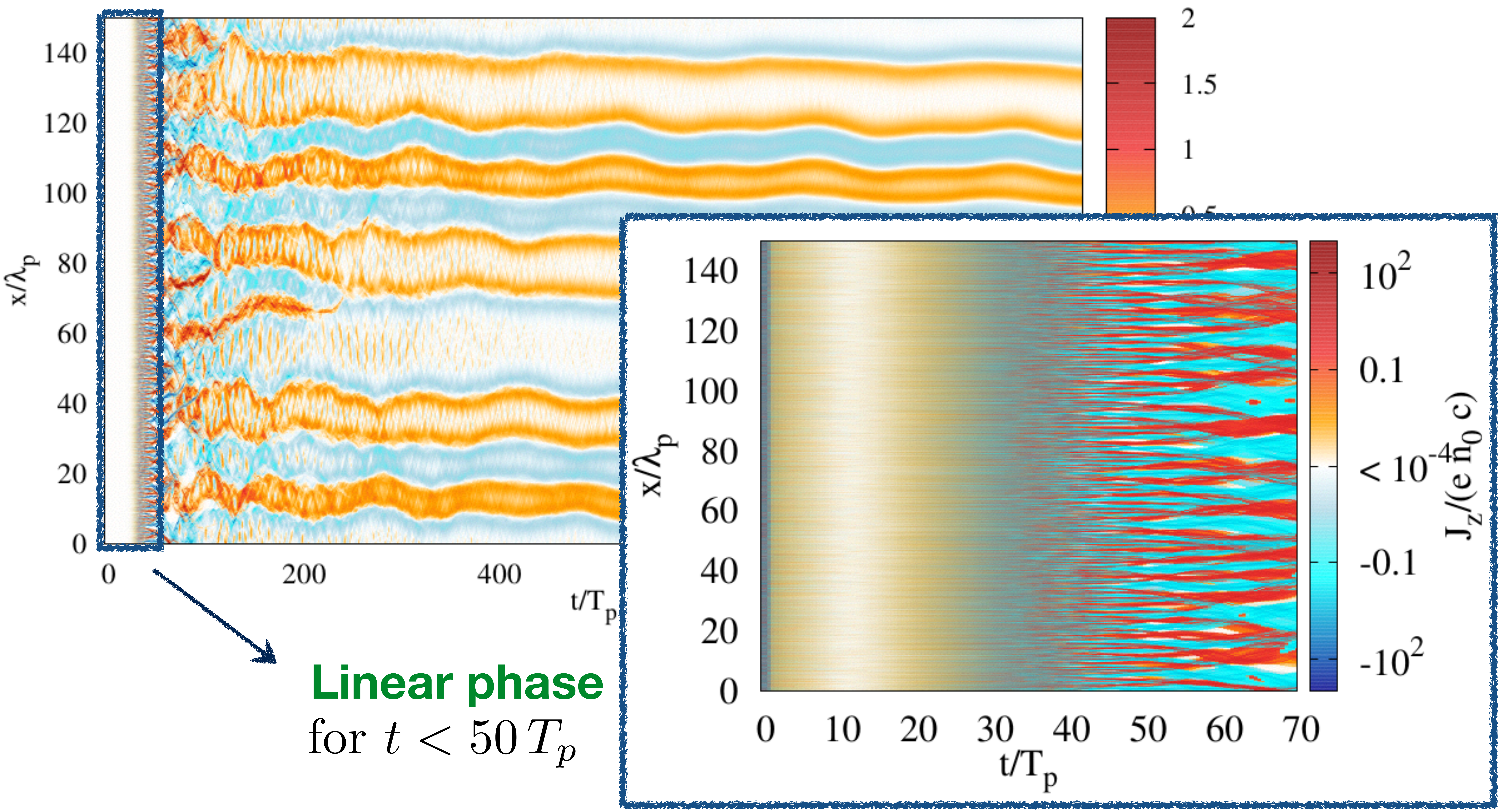
Current filaments



Current filaments

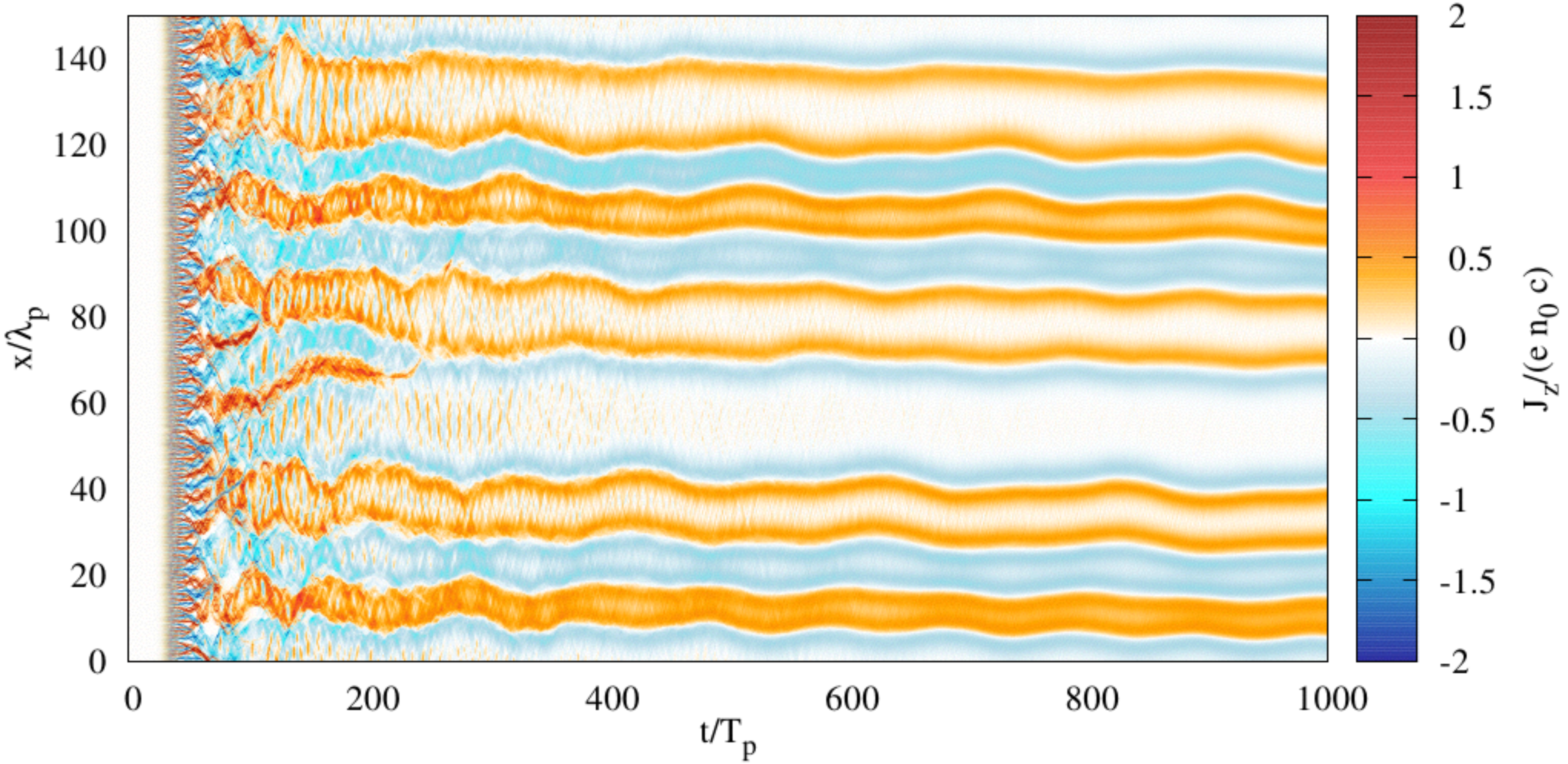


Current filaments



Linear phase
for $t < 50\,T_p$

Current filaments

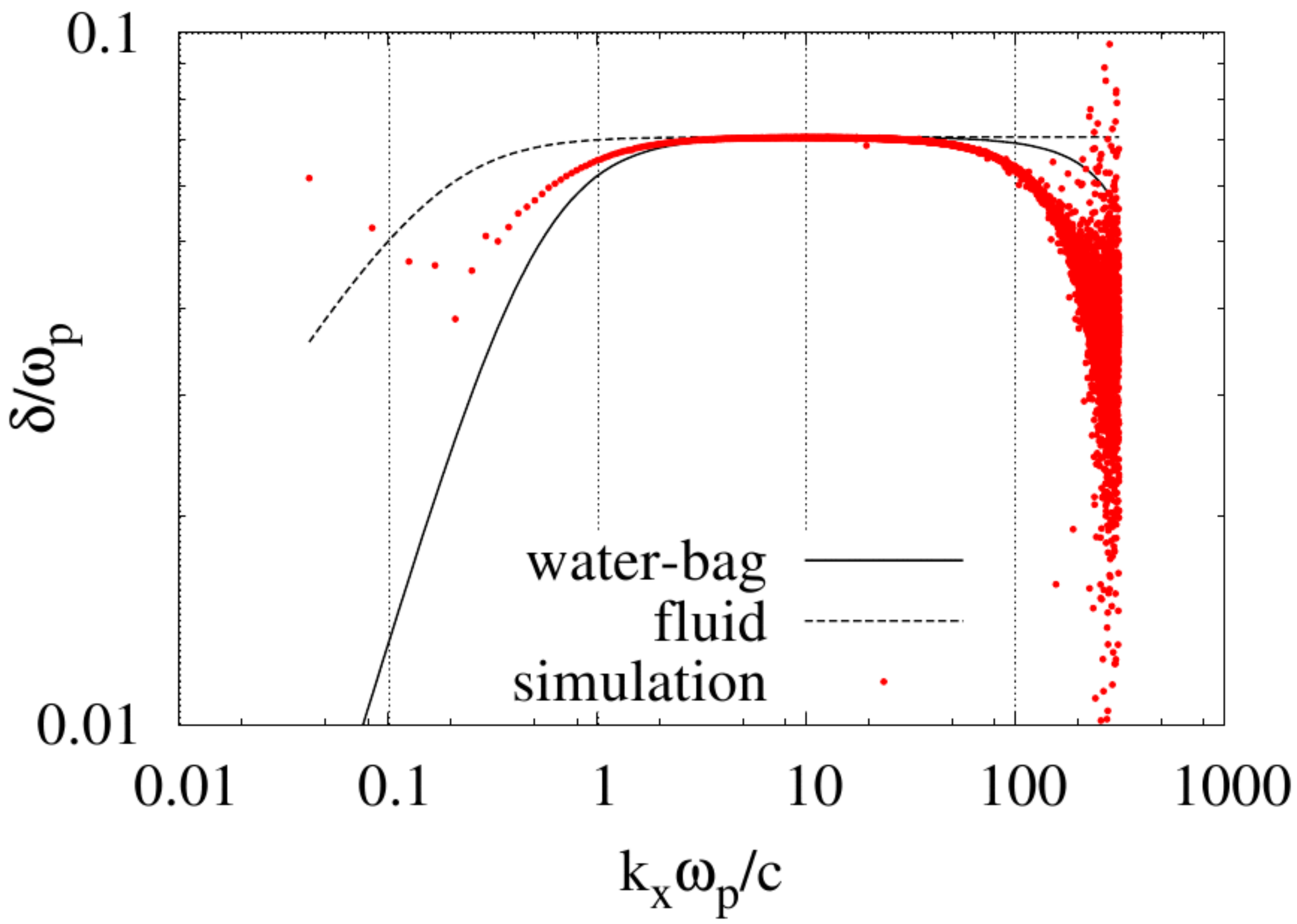


Linear phase
for $t < 50\,T_p$

Merging phase
for $50\,T_p < t < 200\,T_p$

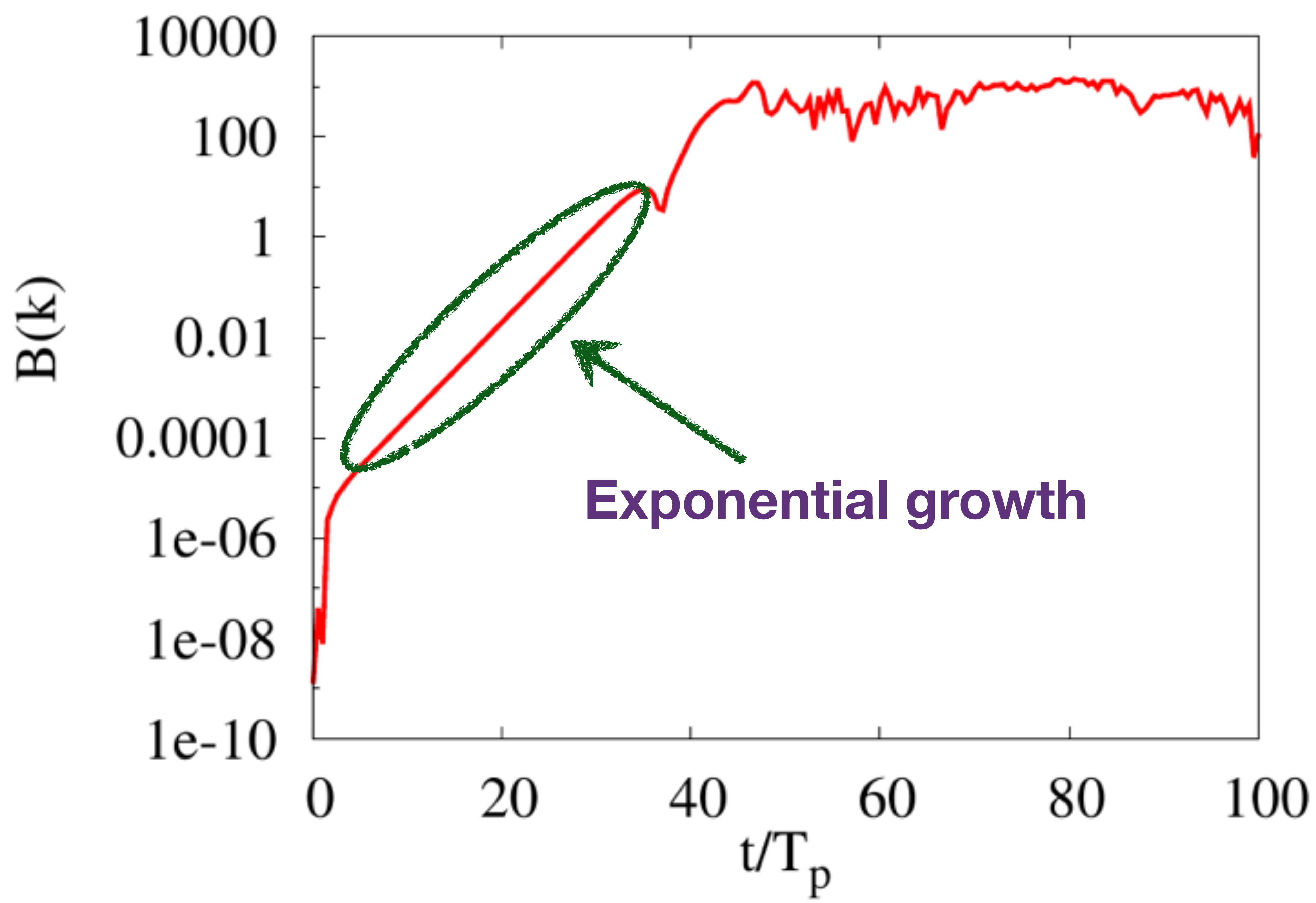
Quasi-saturated phase
for $t > 200\,T_p$

Growth rate

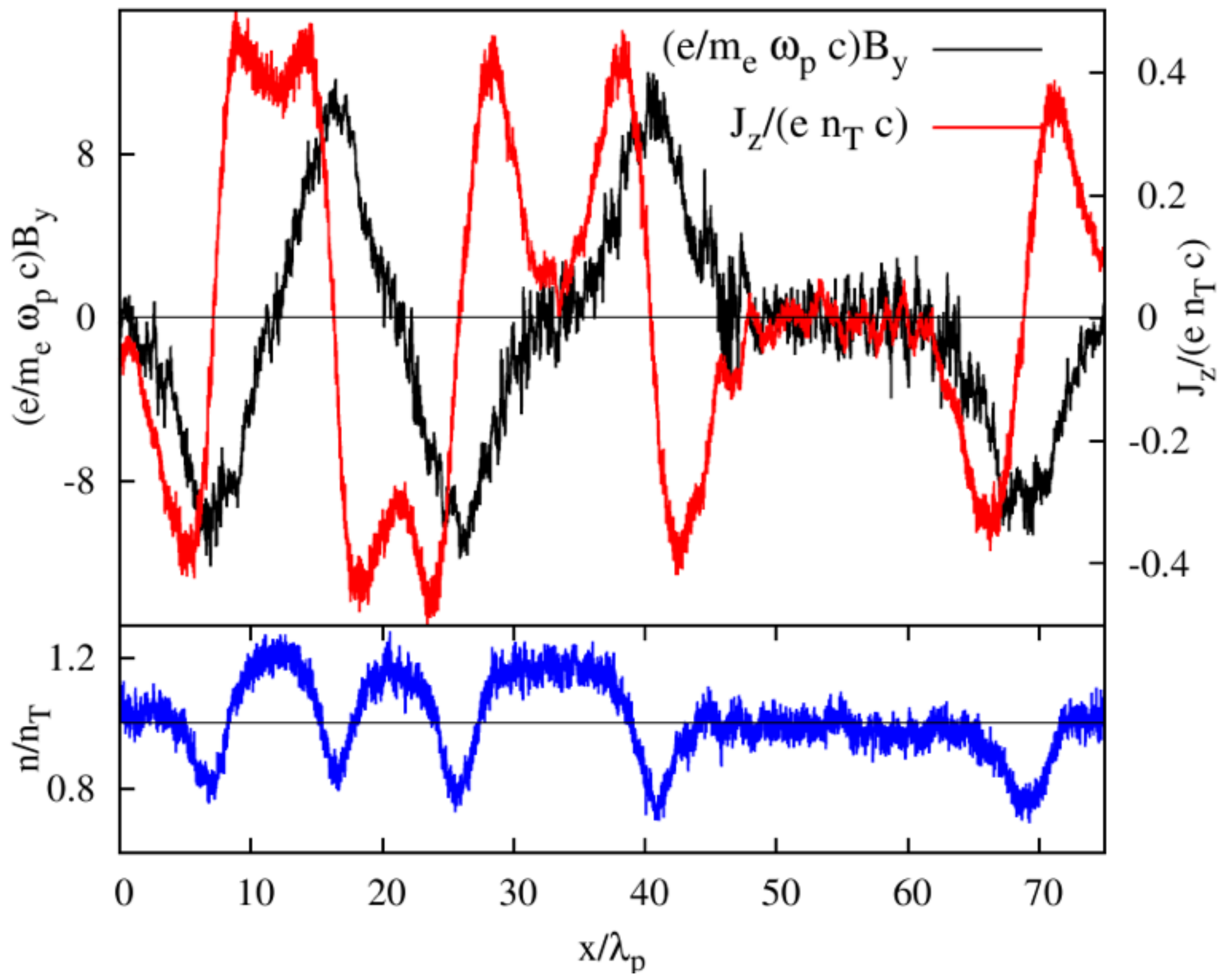


$$\delta_{max}/\omega_p = 1/\sqrt{\gamma_0} = 0.07$$

Mode with $k_x c/\omega_p = 1.5$



Non-linear phase



Current filament with + polarity is characterized by two consecutive maxima

Current filament with - polarity is characterized by two consecutive minima

Non-linear phase

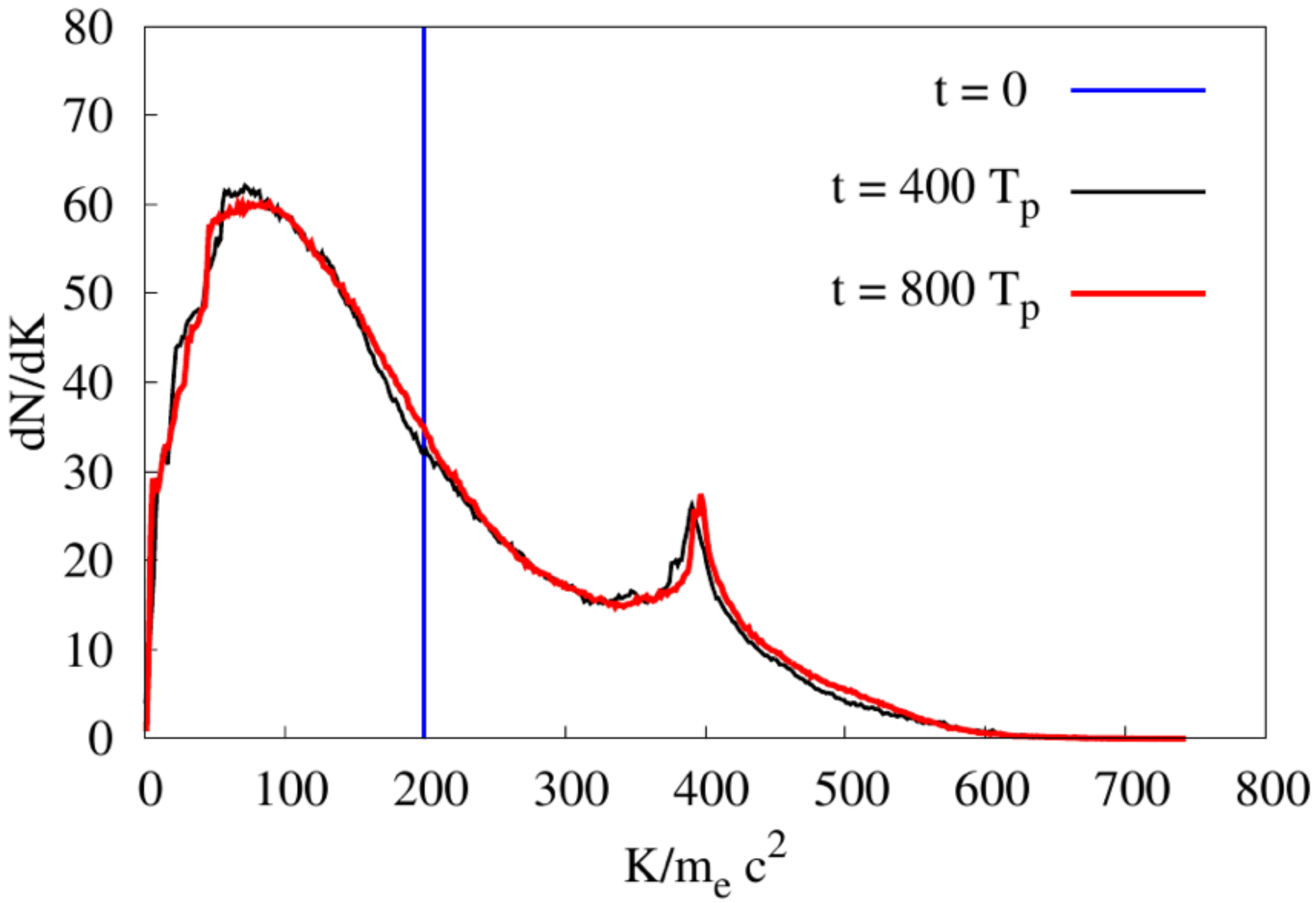
- Size of a filament $d \sim k_{max}^{-1} = \sqrt{\gamma_0} l_p$
- Saturation $\rightarrow$ magnetic confinement

$$\begin{cases} k_{max}^{-1} \sim \gamma_0 m_e c^2 / eB \\ \dfrac{e}{m_e c \omega_p} B_{sat} \sim \sqrt{\gamma_0} \end{cases}$$

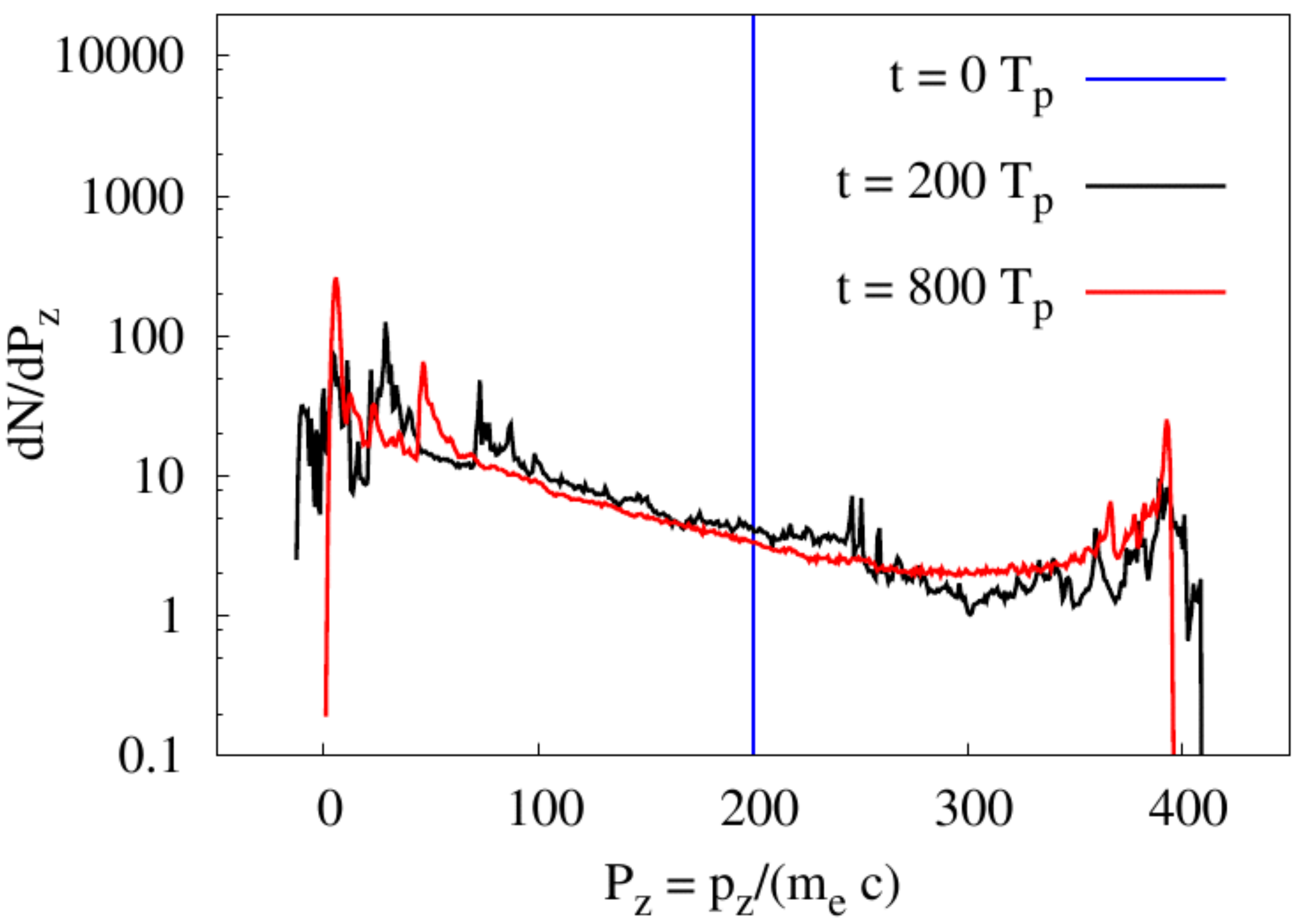
$$B_{sat}(\text{Gauss}) \approx 3.21 \times 10^{-3} \sqrt{\gamma_0} [n_0(\text{cm}^{-3})]^{-1/2}$$

Particle spectra

Energy spectrum

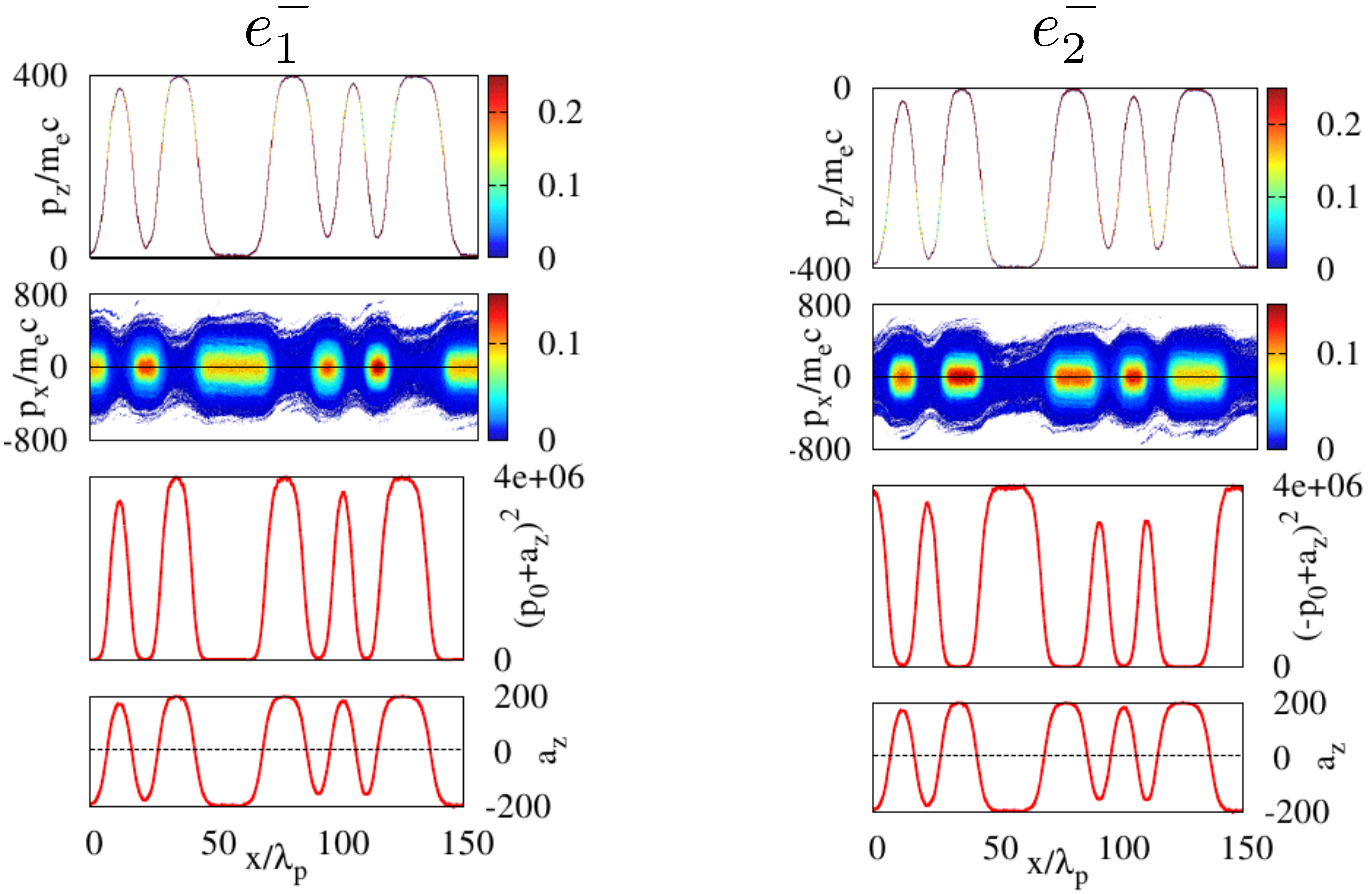


Momentum spectrum



The distribution function changes: the majority of particles loses its kinetic energy.

Confined and accelerated particles



Non-linear phase

Most of particles is confined within current filaments

Single particle dynamics:

Conservation of the canonical momentum $\mathbf{\Pi} = \mathbf{p} \pm \mathbf{a} = \pm p_0 \mathbf{z}$

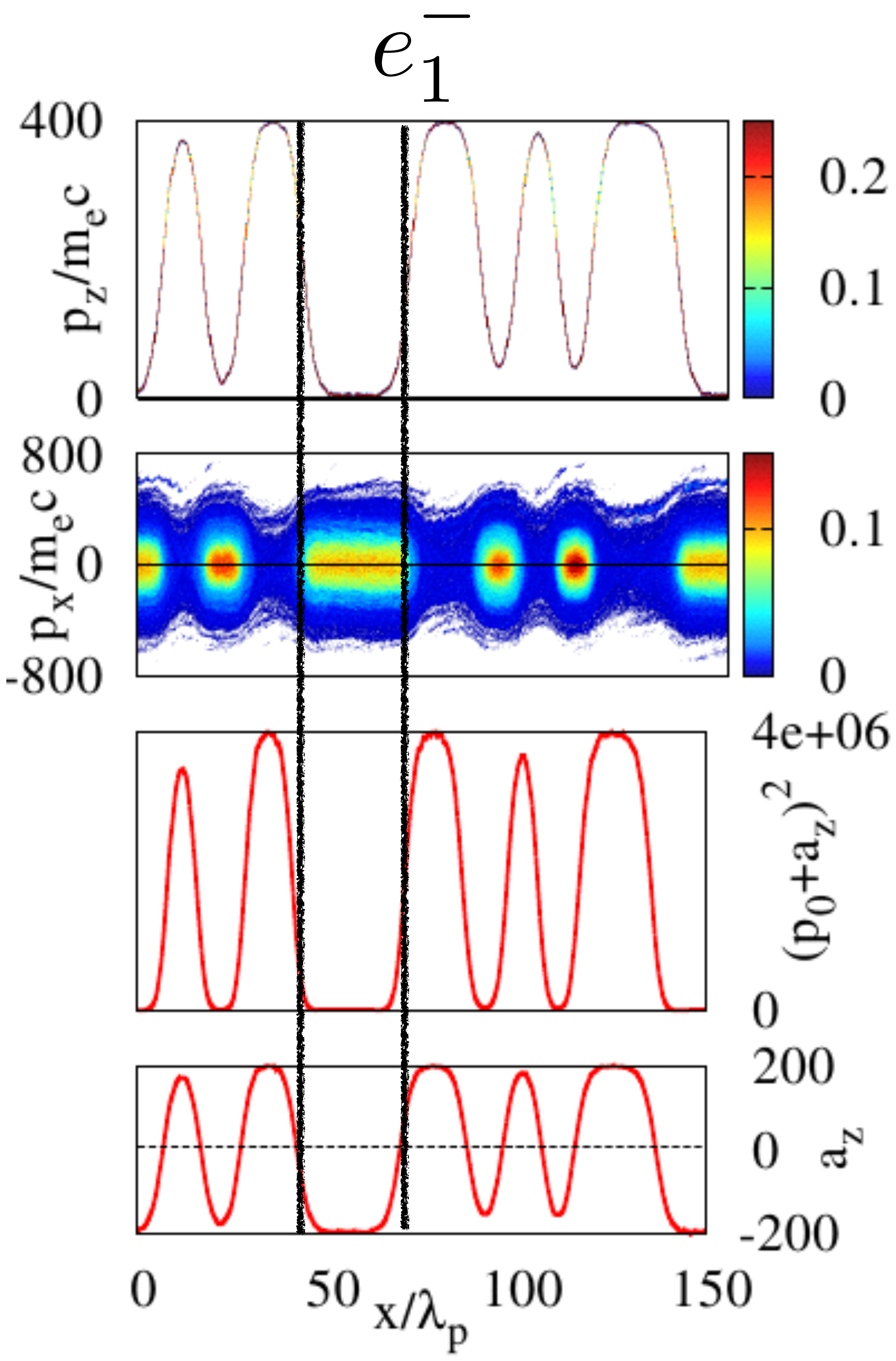
$$e_1^- \rightarrow \left(\frac{E_1}{m_e c^2}\right)^2 = 1 + p_{x1}^2 + \underbrace{[p_0 + a_z(x)]^2}$$

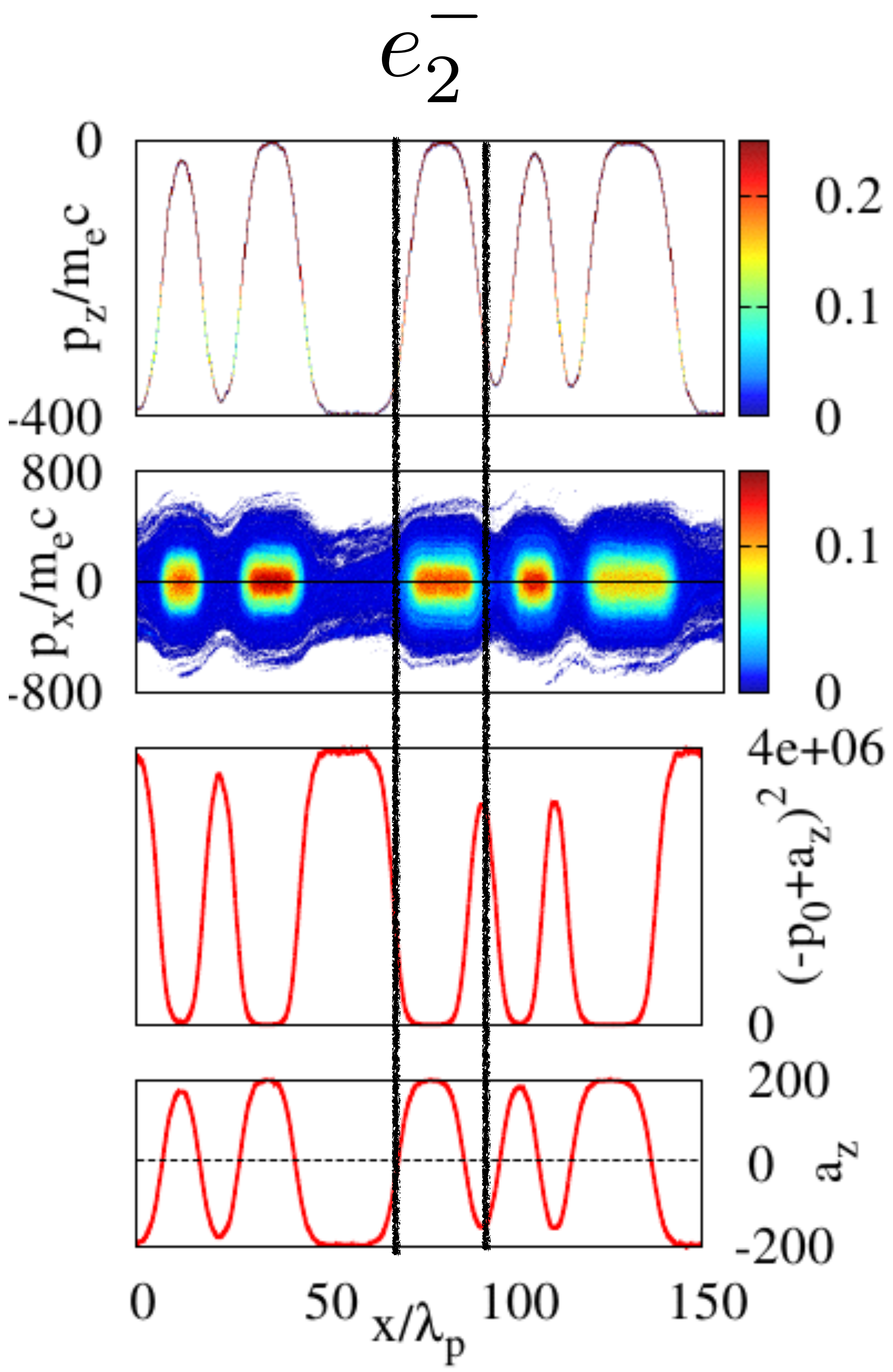
Effective potential

$$e_2^- \rightarrow \left(\frac{E_2}{m_e c^2}\right)^2 = 1 + p_{x2}^2 + \underbrace{[-p_0 + a_z(x)]^2}$$

Effective potential

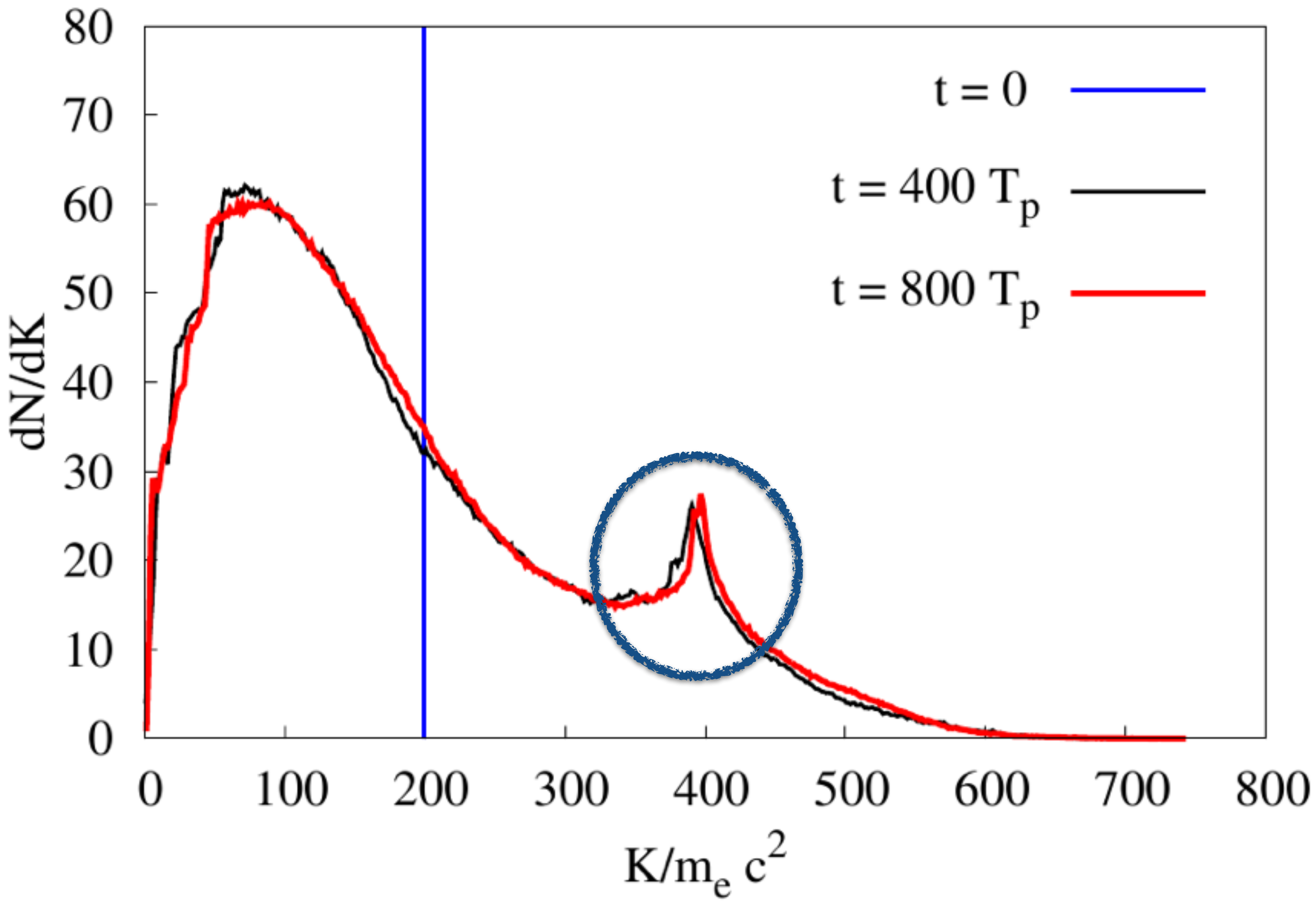
Confined and accelerated particles



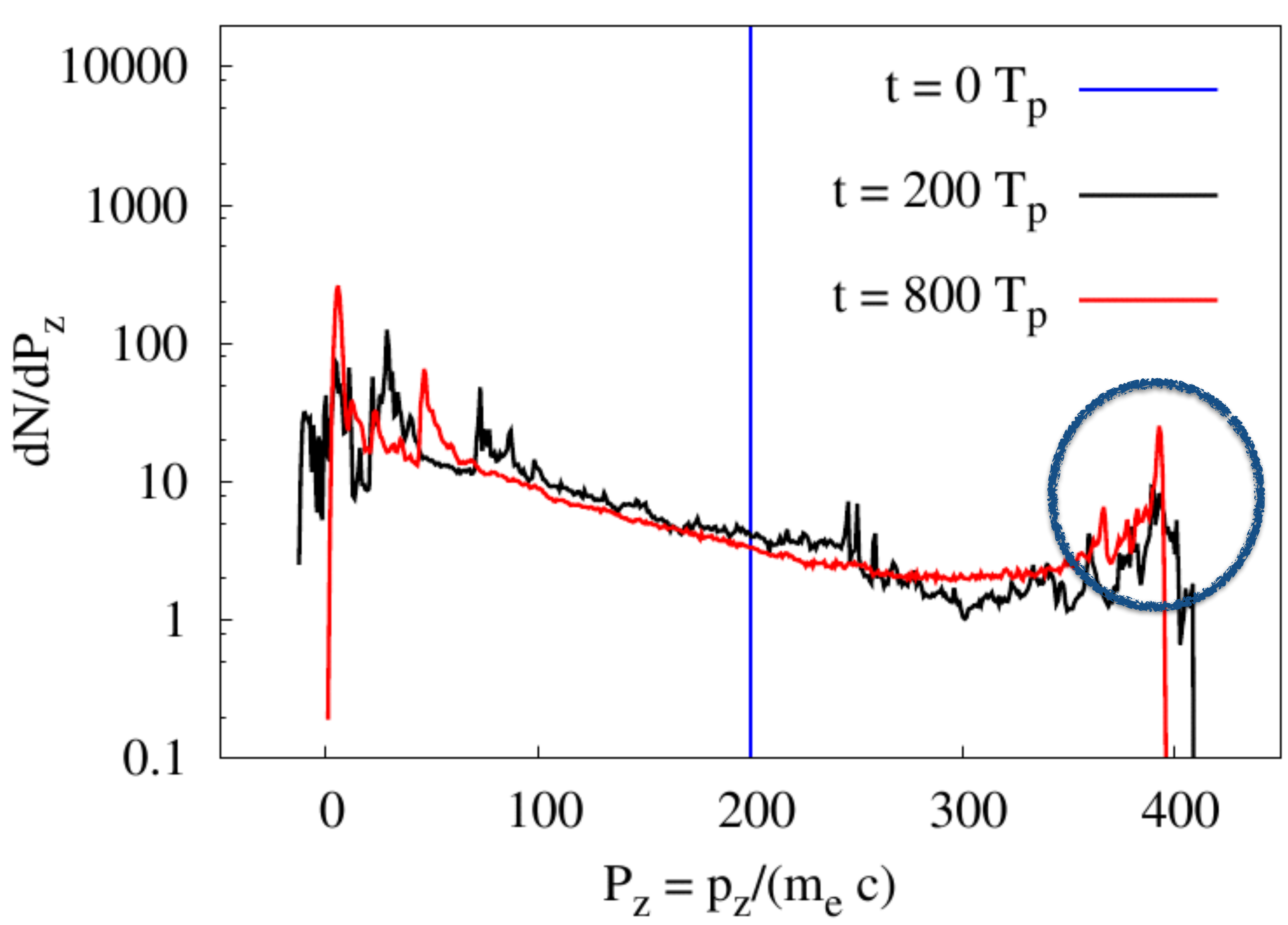


Peak in the spectra

Energy spectrum



Mometum spectrum



The energy spectrum presents a peak at $2\gamma_0$ and the momentum spectrum presents a peak at $2p_0$

Why this peak?

1. Why does a maximum energy value exist?

Spatial separation of the species

Locally $\mathbf{E} = -\partial_t \mathbf{A}$ subtracts p_0 to e_1^- and adds p_0 to e_2^-

2. Why does a cusp form in the energy spectrum?

$$\frac{dA}{dx}(x_0) = 0$$

In the dx interval, centered around x_0, particles acquire the same momentum at first order

Radiative losses

Problem of the effects of e.m. radiation emitted by a charged particle on the motion of the particle itself: radiation friction

(L.Landau and E. Lifshitz *The Classical Theory of Fields*. Number v.2 in Course of theoretical physics. Butterworth-Heinemann, 1975)

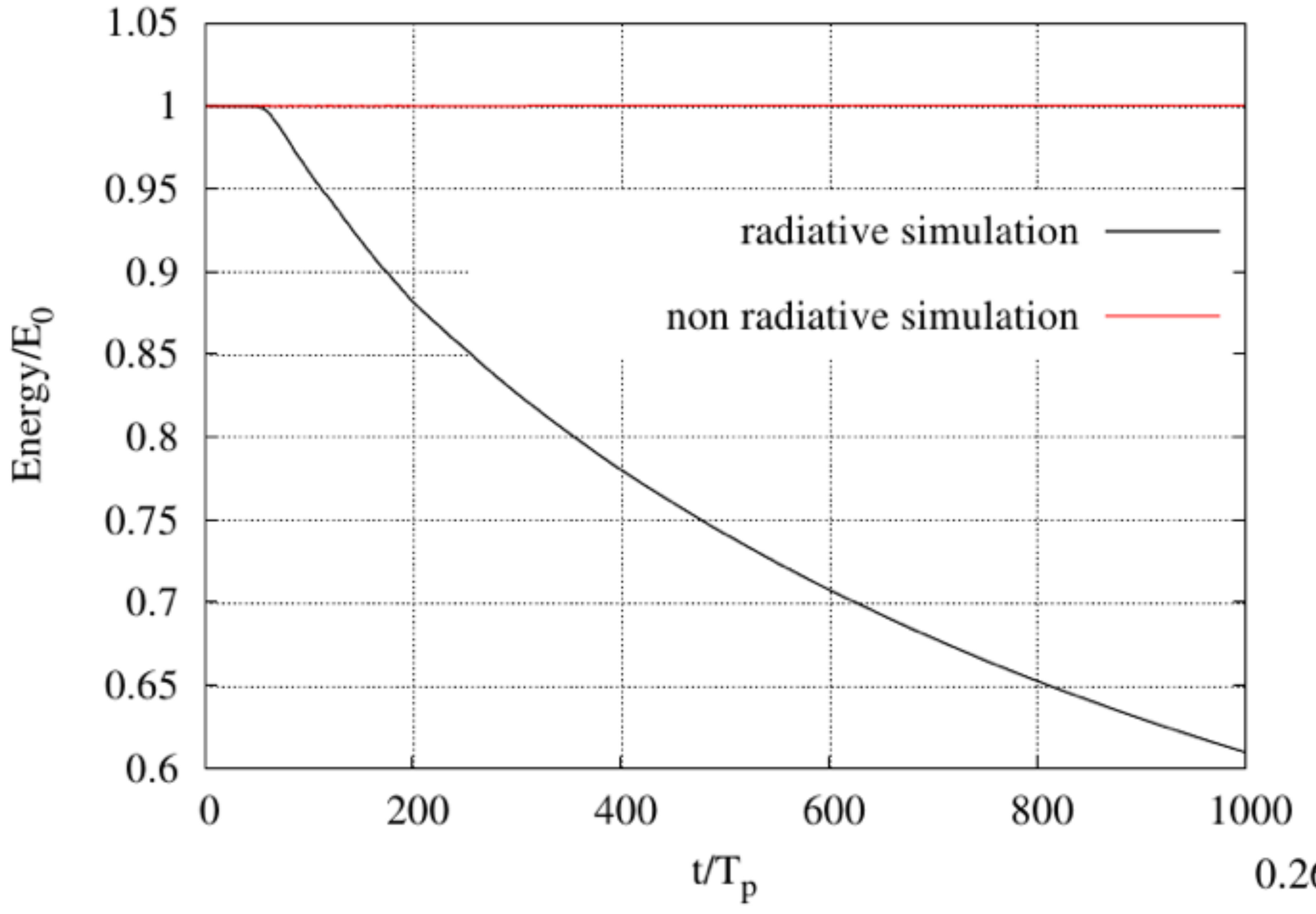
Code implementation:

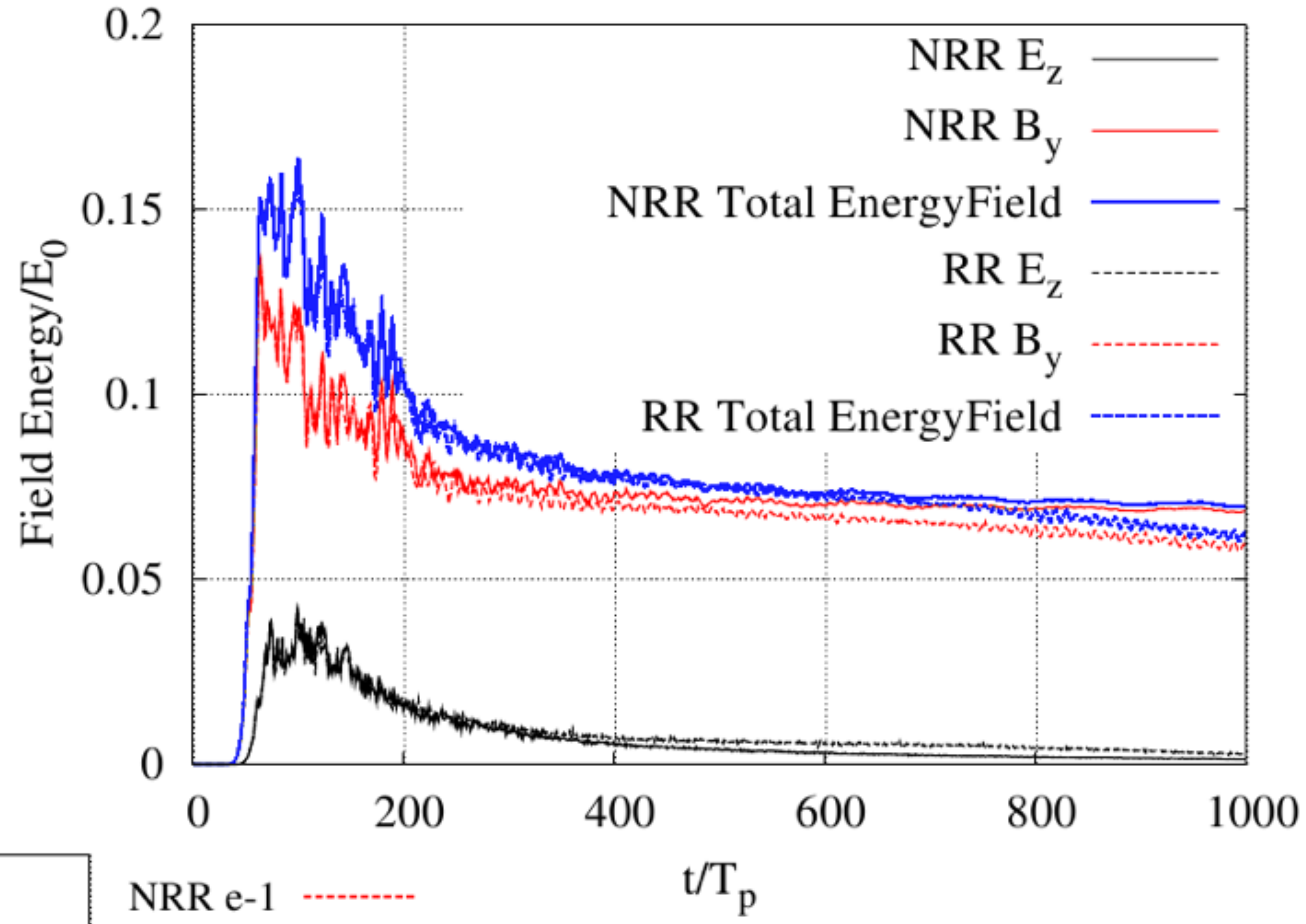
$$\frac{d\mathbf{p}}{dt} = \mathbf{F}_L - d\mathbf{v} \qquad \text{where } d \equiv (4\pi r_e/3l_p)\gamma^2[\mathbf{F}_L^2 - (\mathbf{v}\cdot\mathbf{F}_L)^2]$$

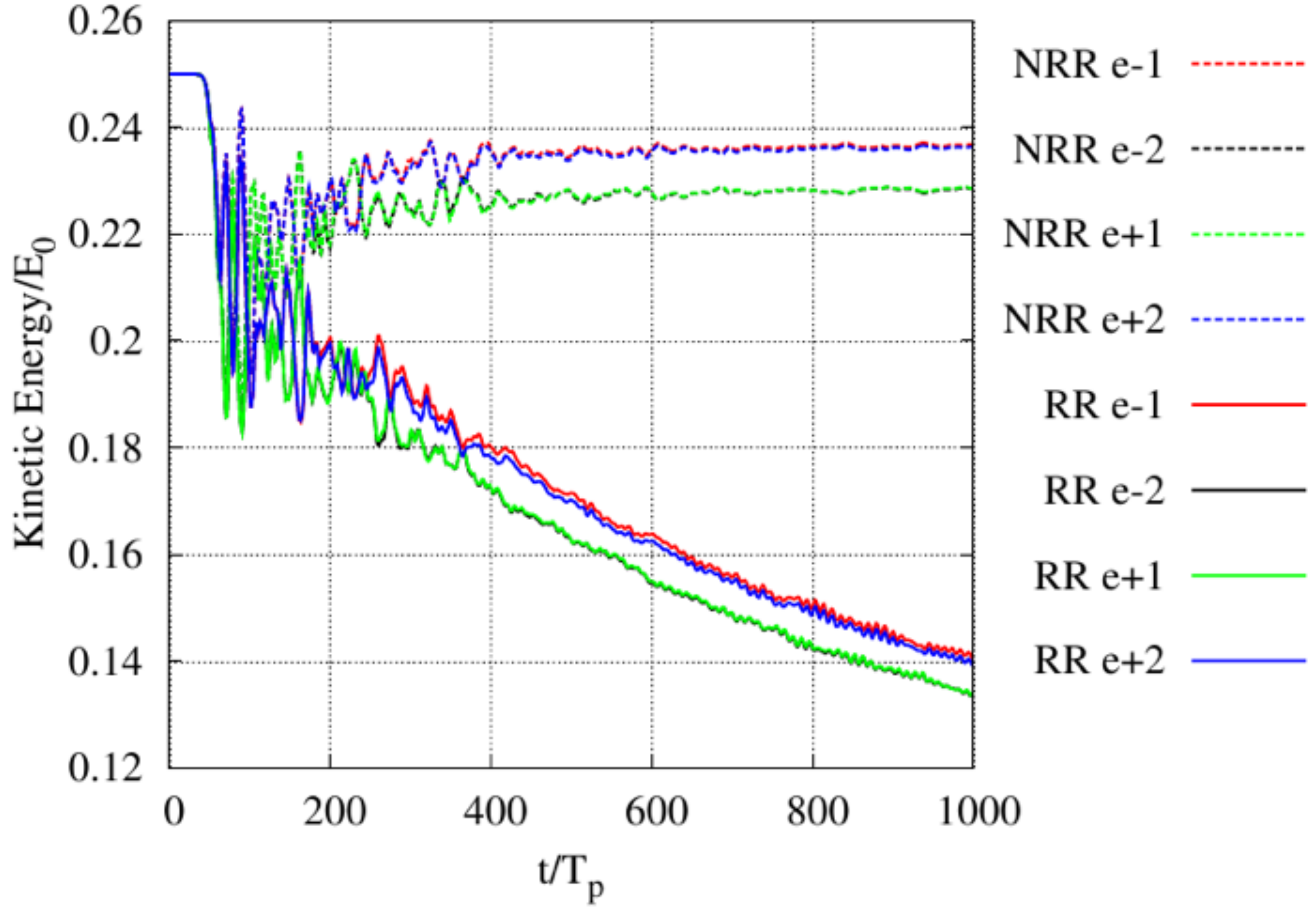
Dissipative term

M.Tamburini et al. *New Journal of physics*, 12(12):123005, 2010

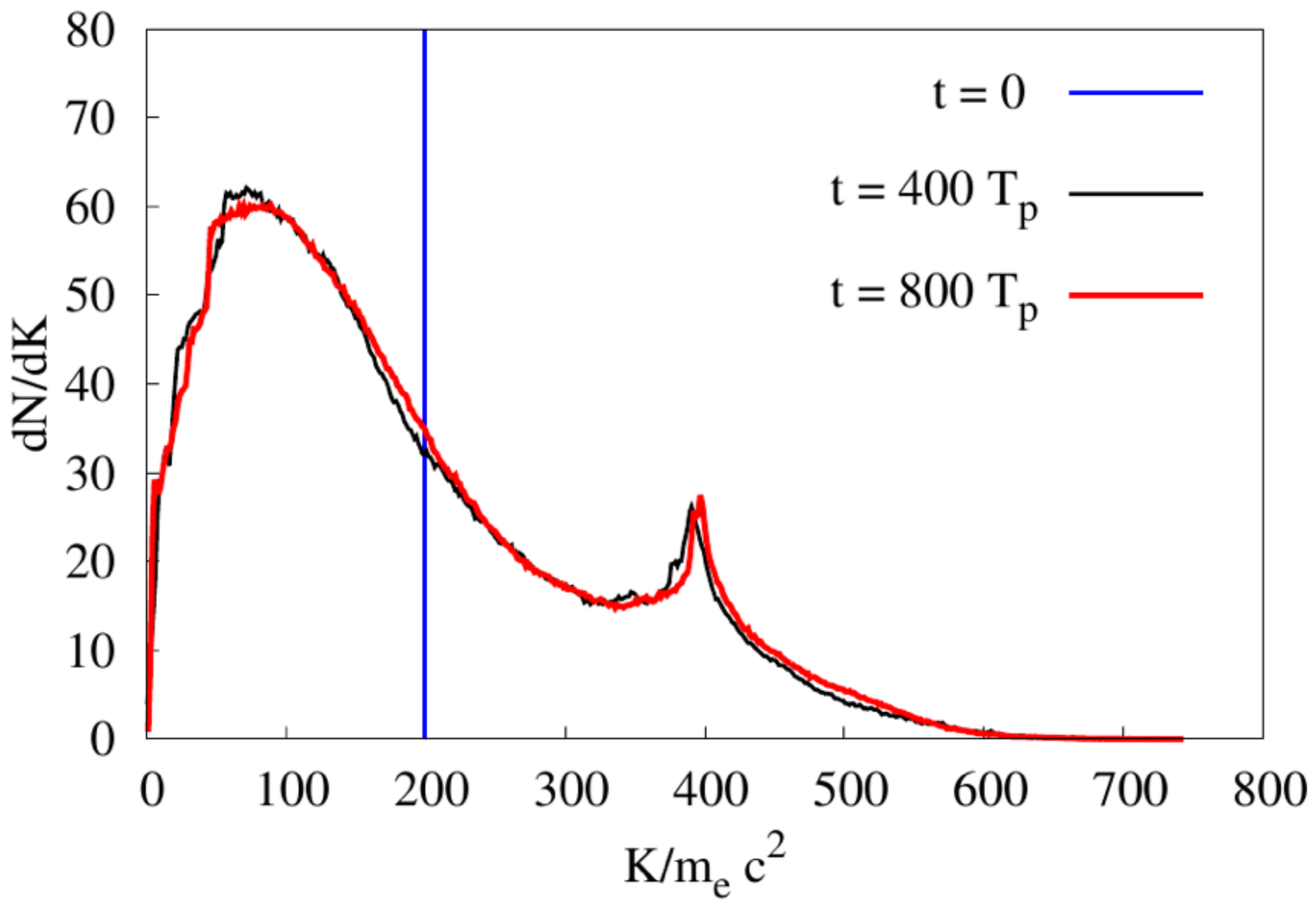
Effects due to RF: energies



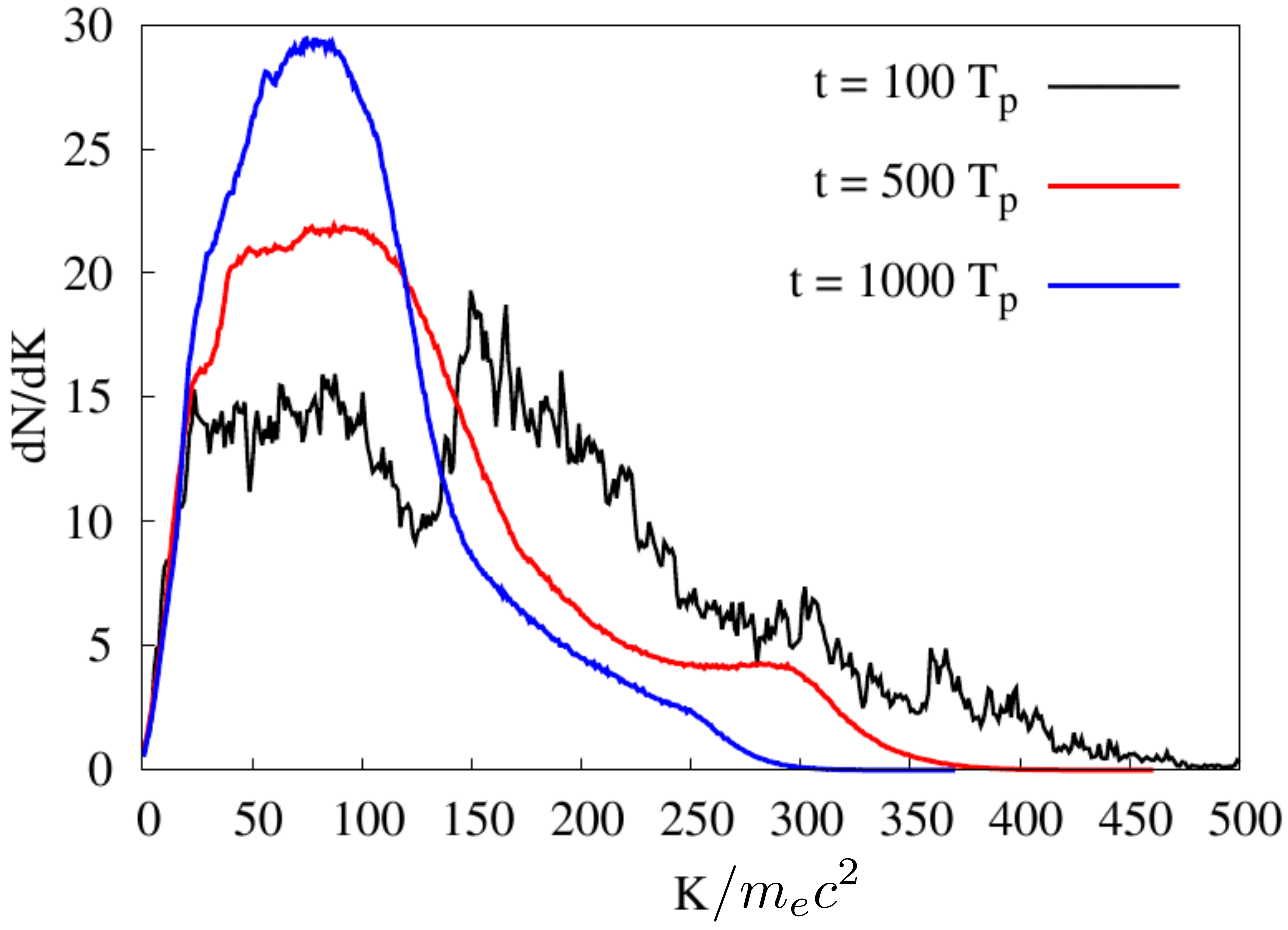




Effects due to RF: energy spectrum

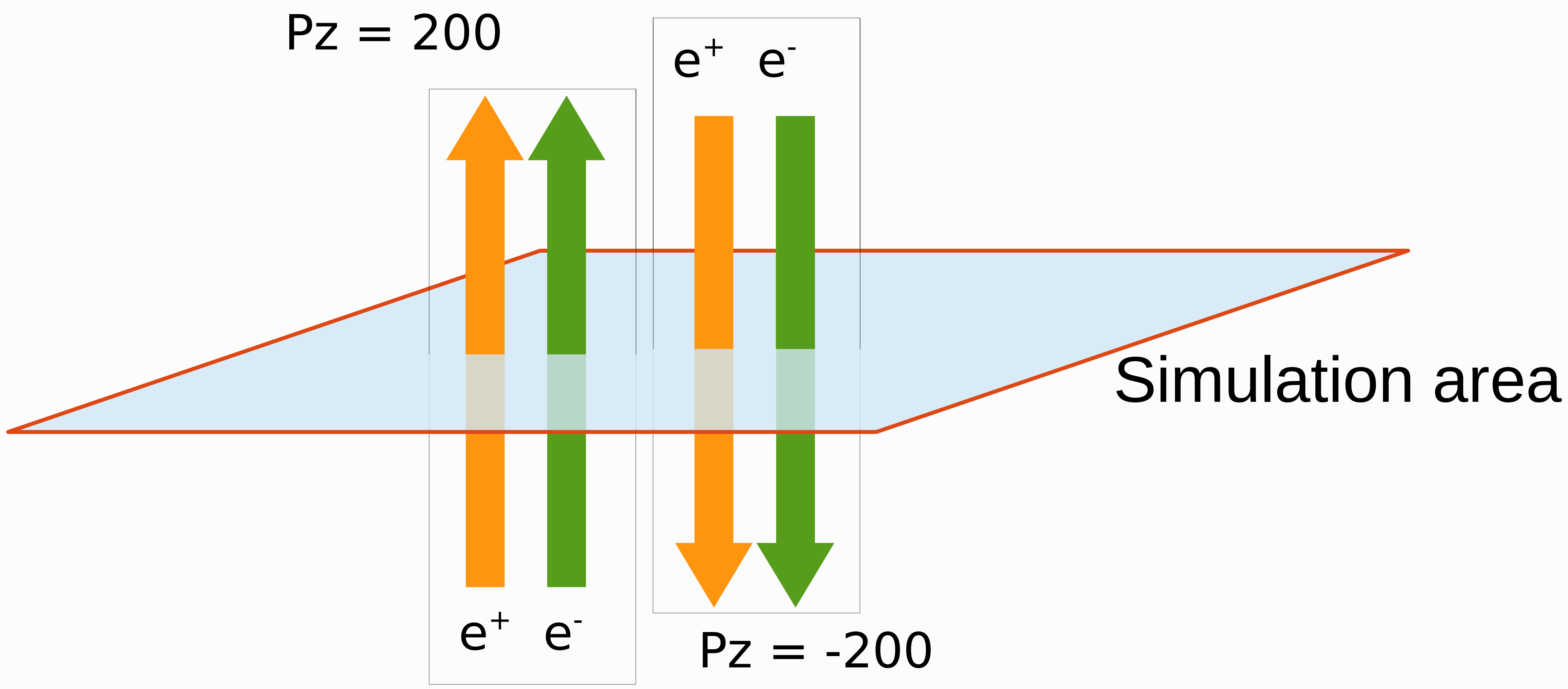


Simulation without radiative losses



Simulation with radiative losses

2D3P simulations



Simulation grid

Lx = 100.0 Lp (1000 cells)
Ly = 100.0 Lp (1000 cells)
Δx = 0.1 Lp
Δy = 0.1 Lp
Δt = 0.05 Tp

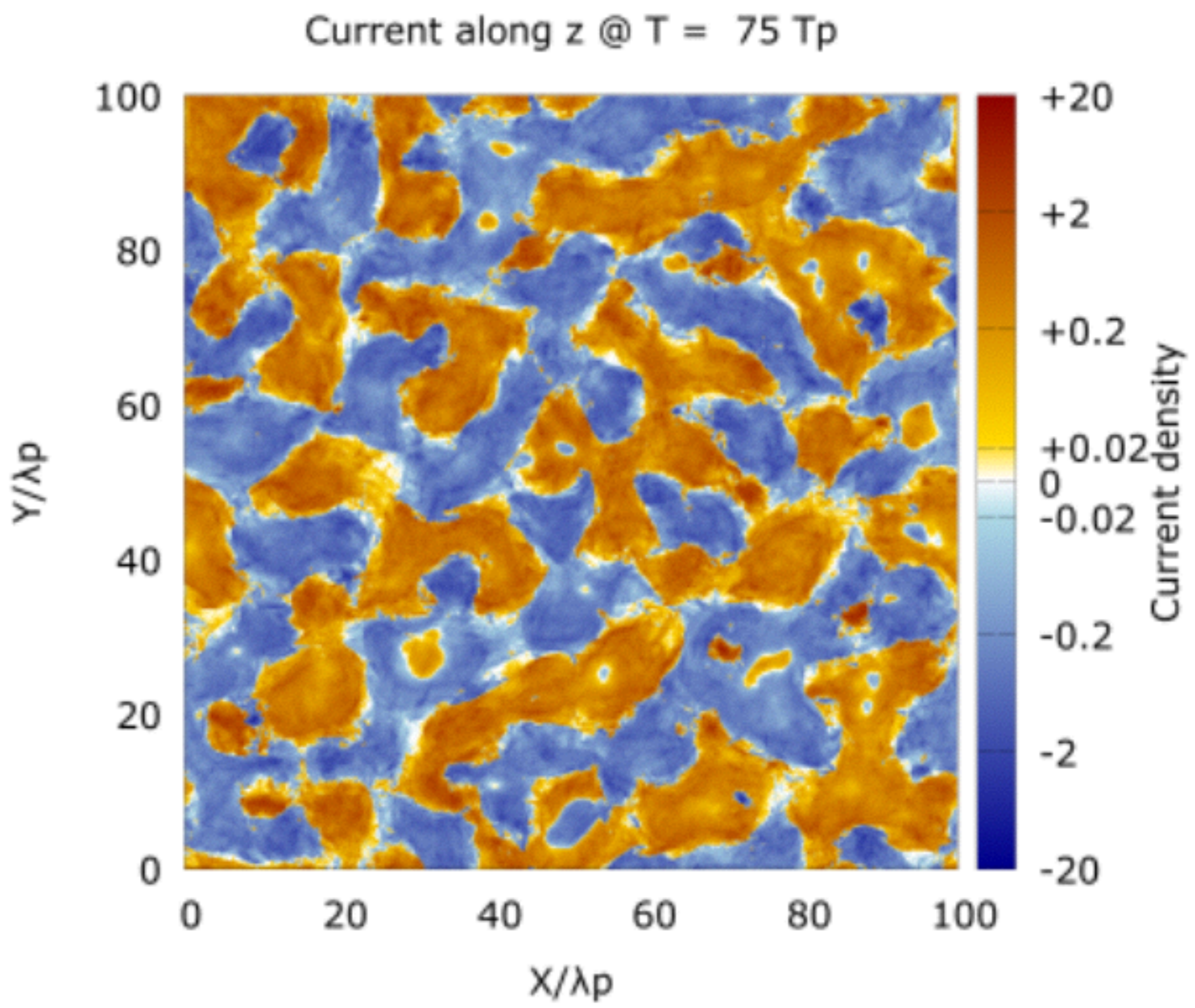
Simulation parameters

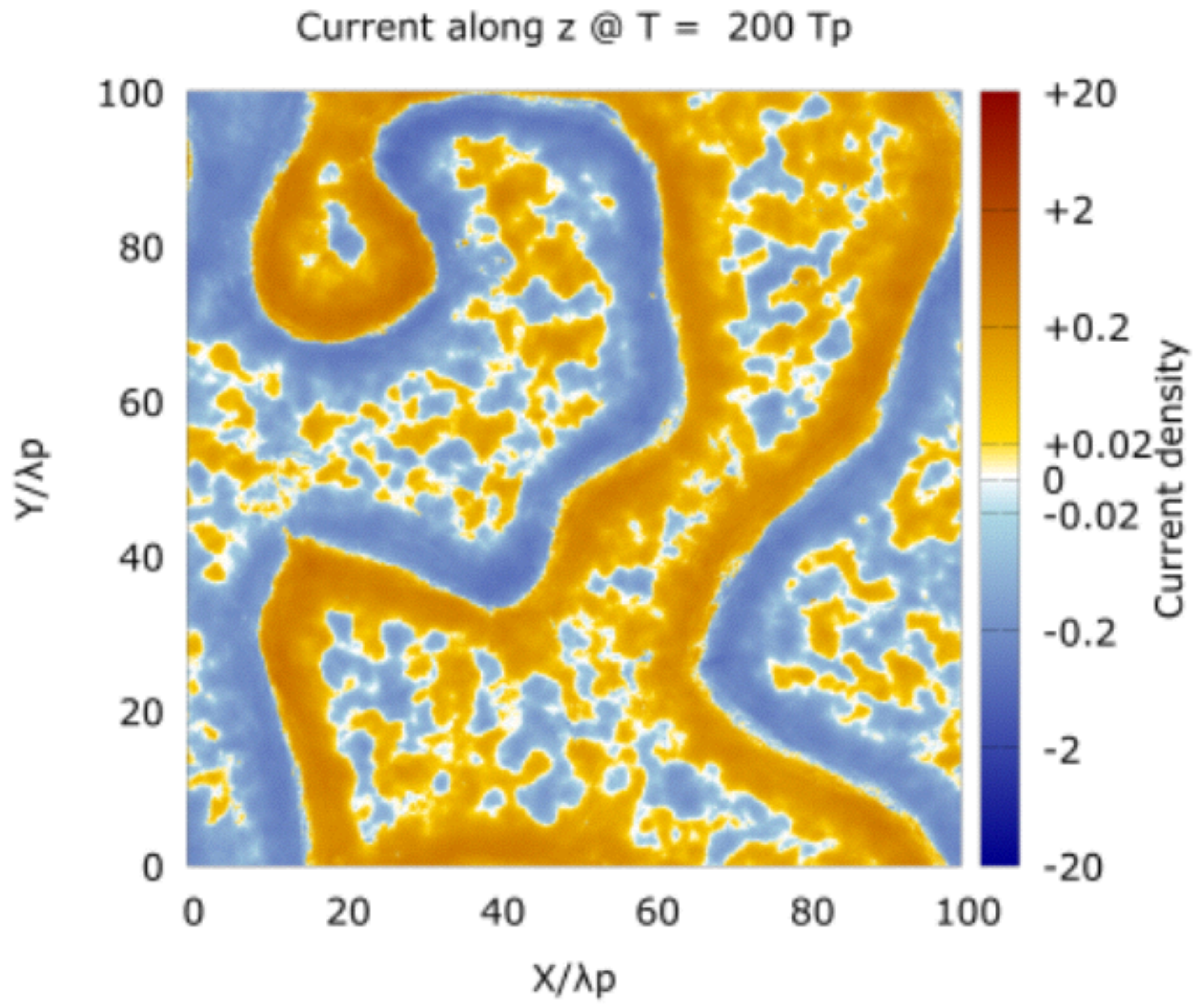
Density: 0.25 per specie

Temperature: 4×10^{-8}

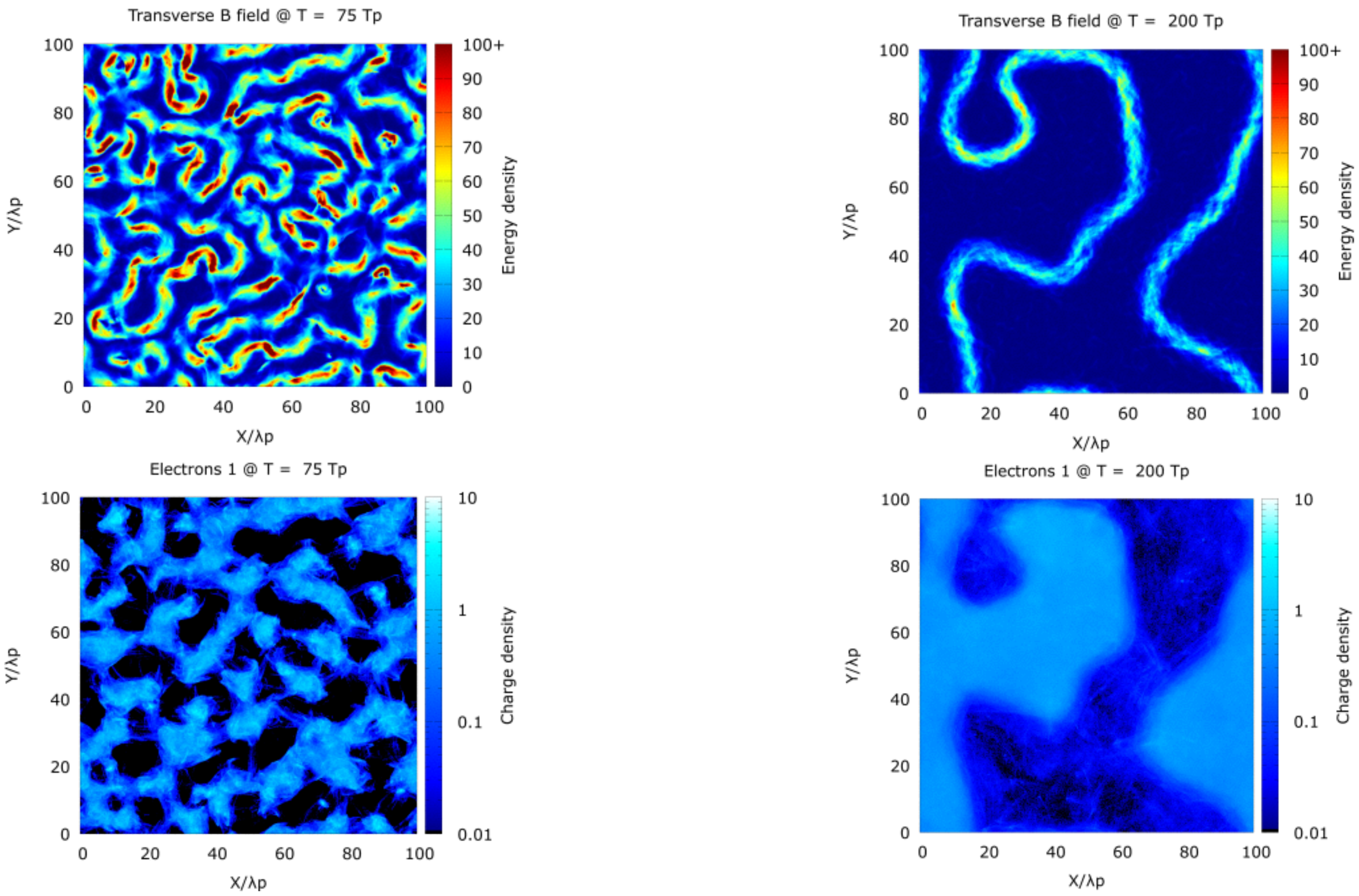
Particles per cell: 7x7 per specie

Current density

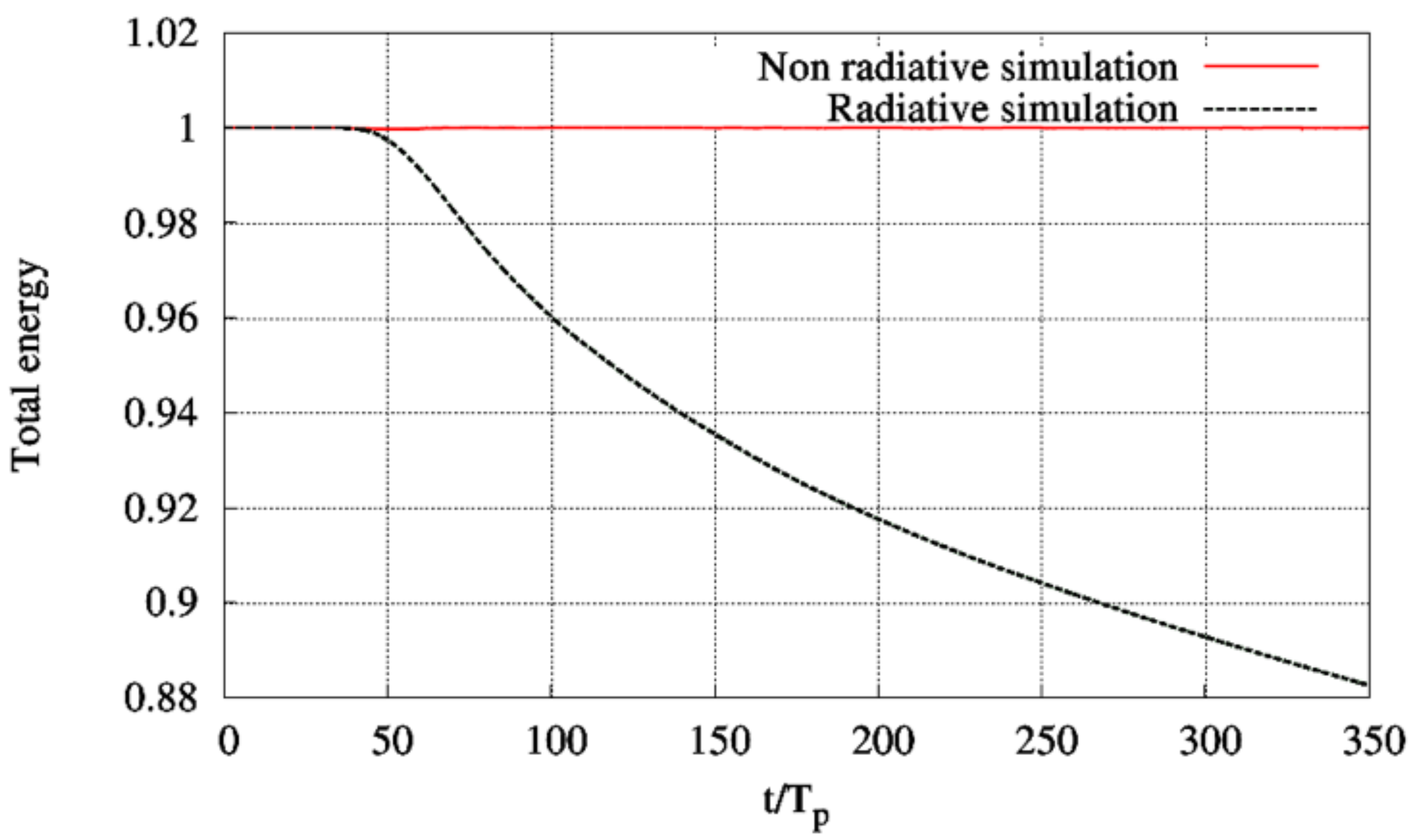


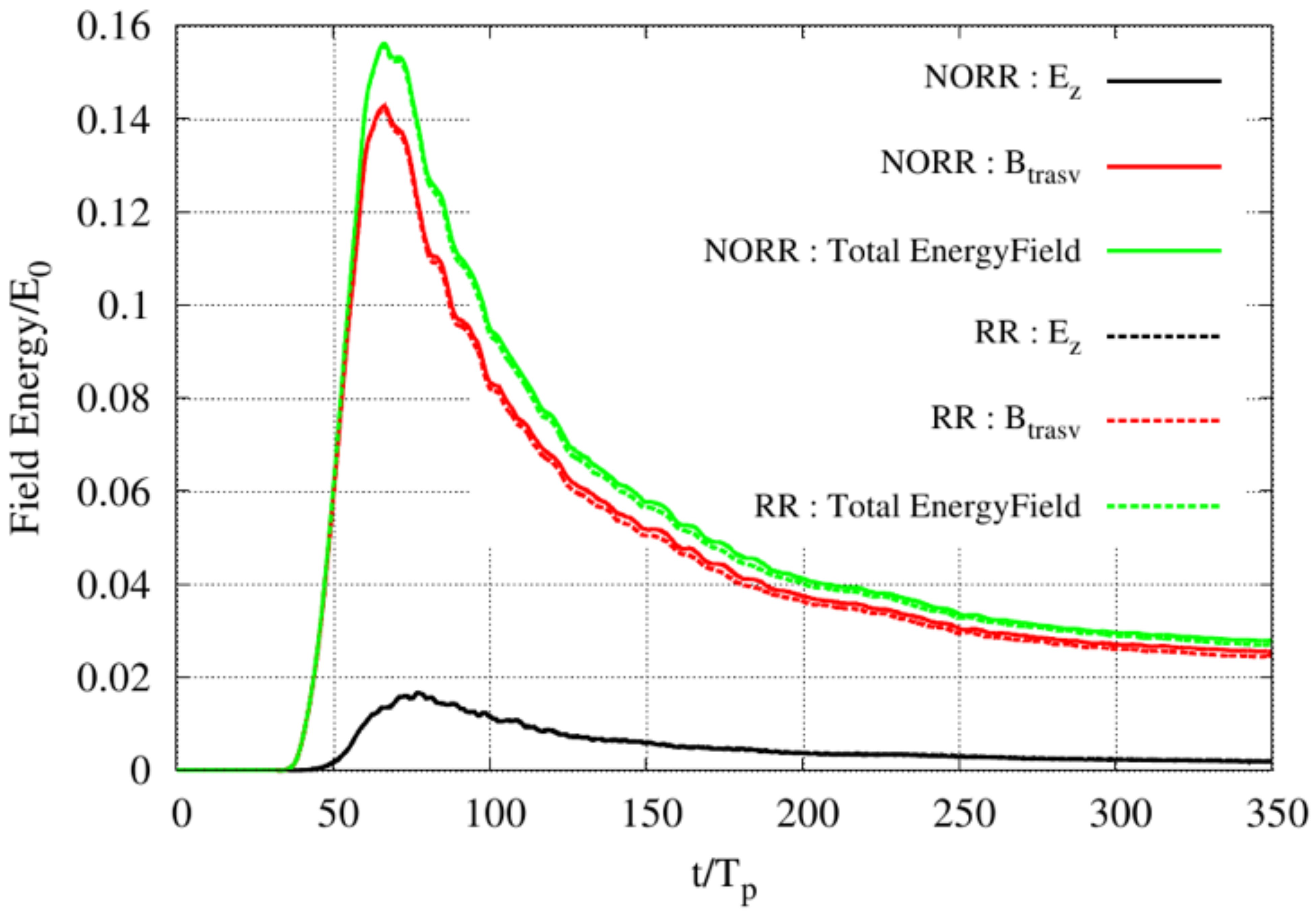


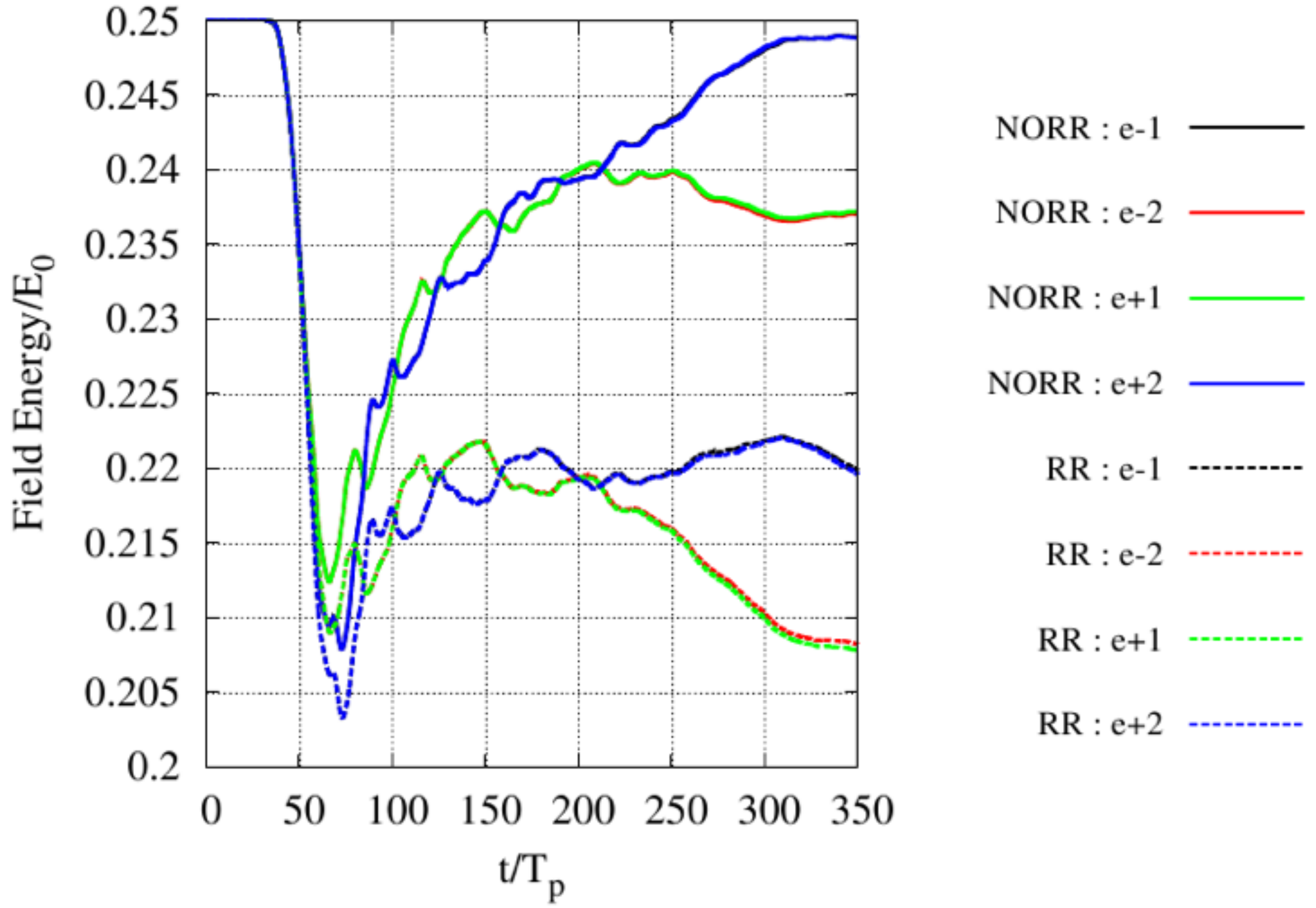
Particle and energy density



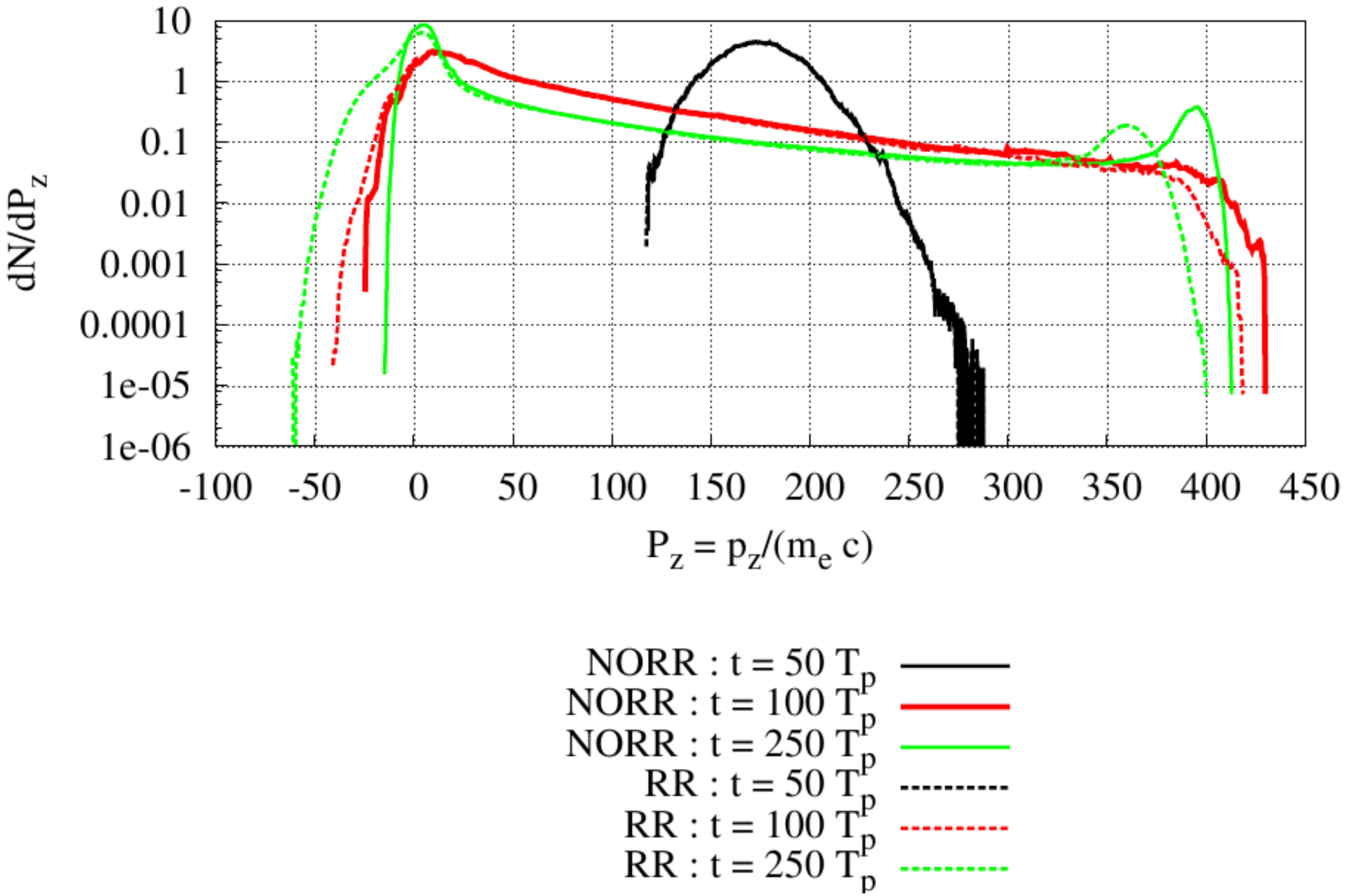
2D simulations with RF







Spectrum in pz



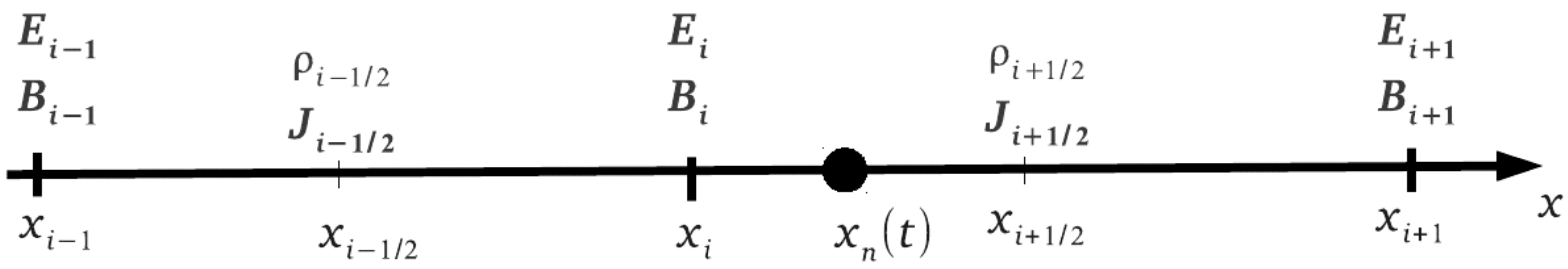
Conclusions

- Filamentation instability is characterized by a linear phase and by a non-linear quasi-saturated phase
- Current and magnetic field organize themselves into filamentary structures on length scale of the order of l_p
- Energy spectrum presents a peak at twice the initial kinetic energy
- Implementation of radiative losses

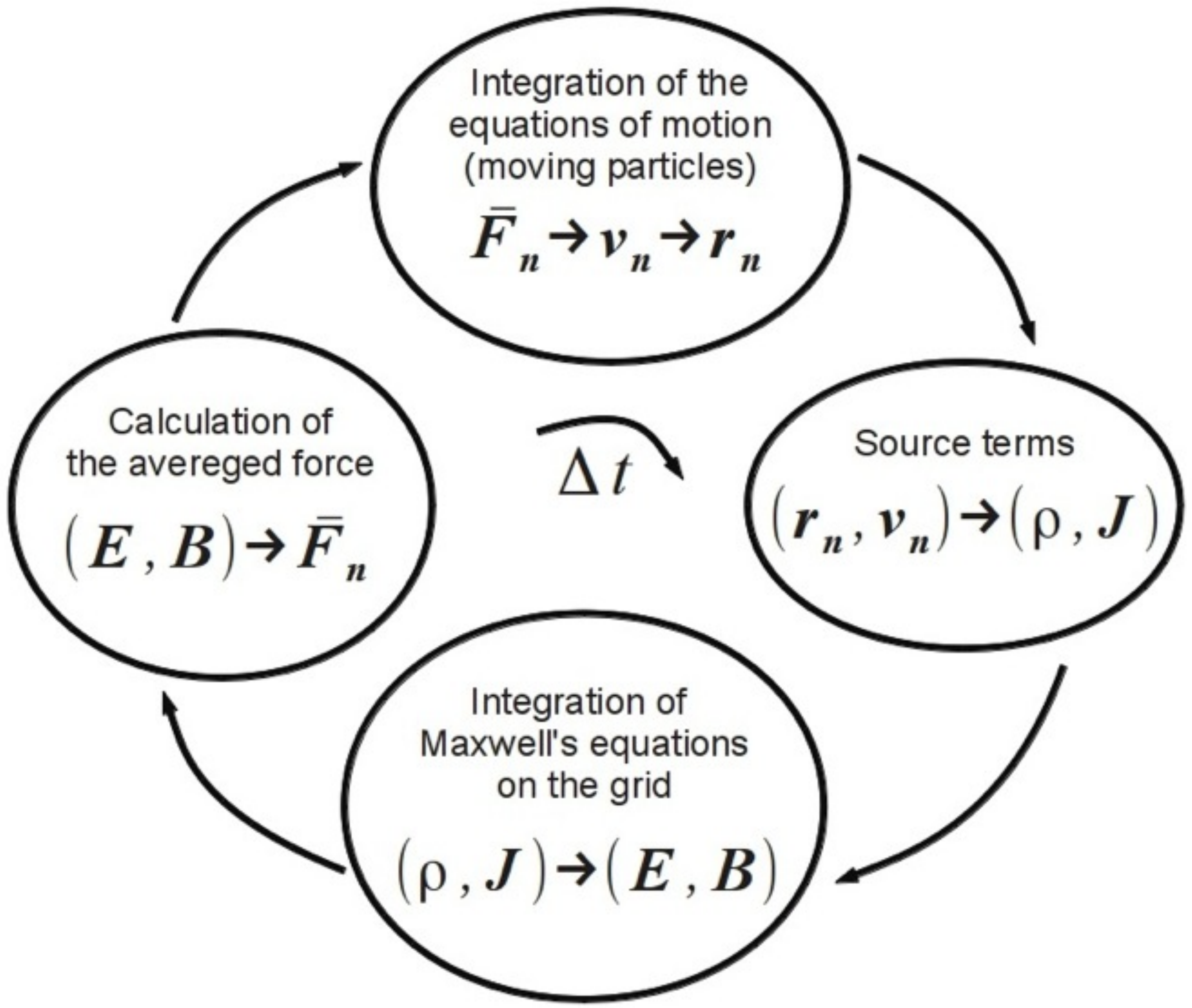
Backup

PIC algorithm

Numerical integration

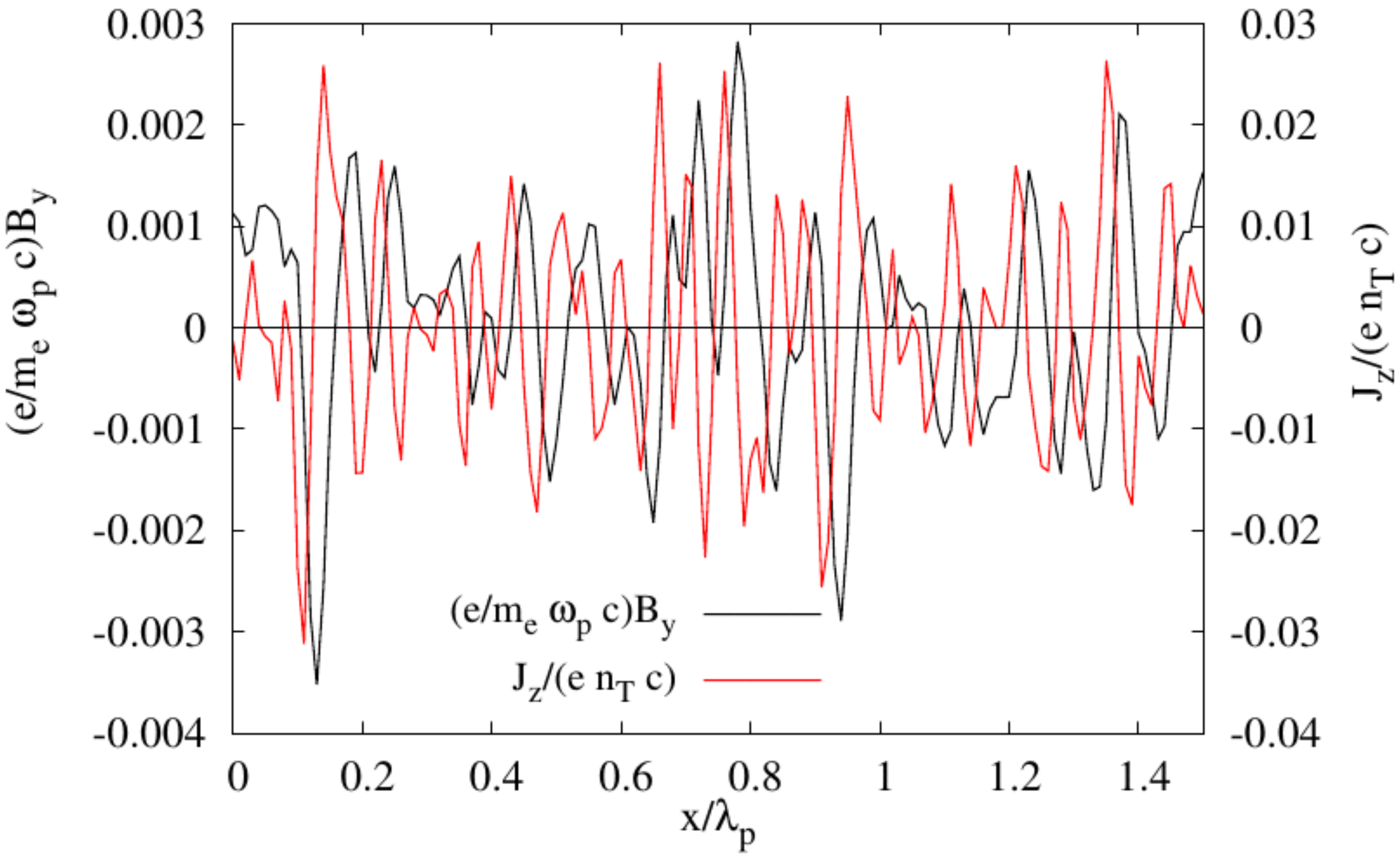


Temporal loop



Linear phase

Case: $p_0 = 10 \quad t = 5\,T_p$



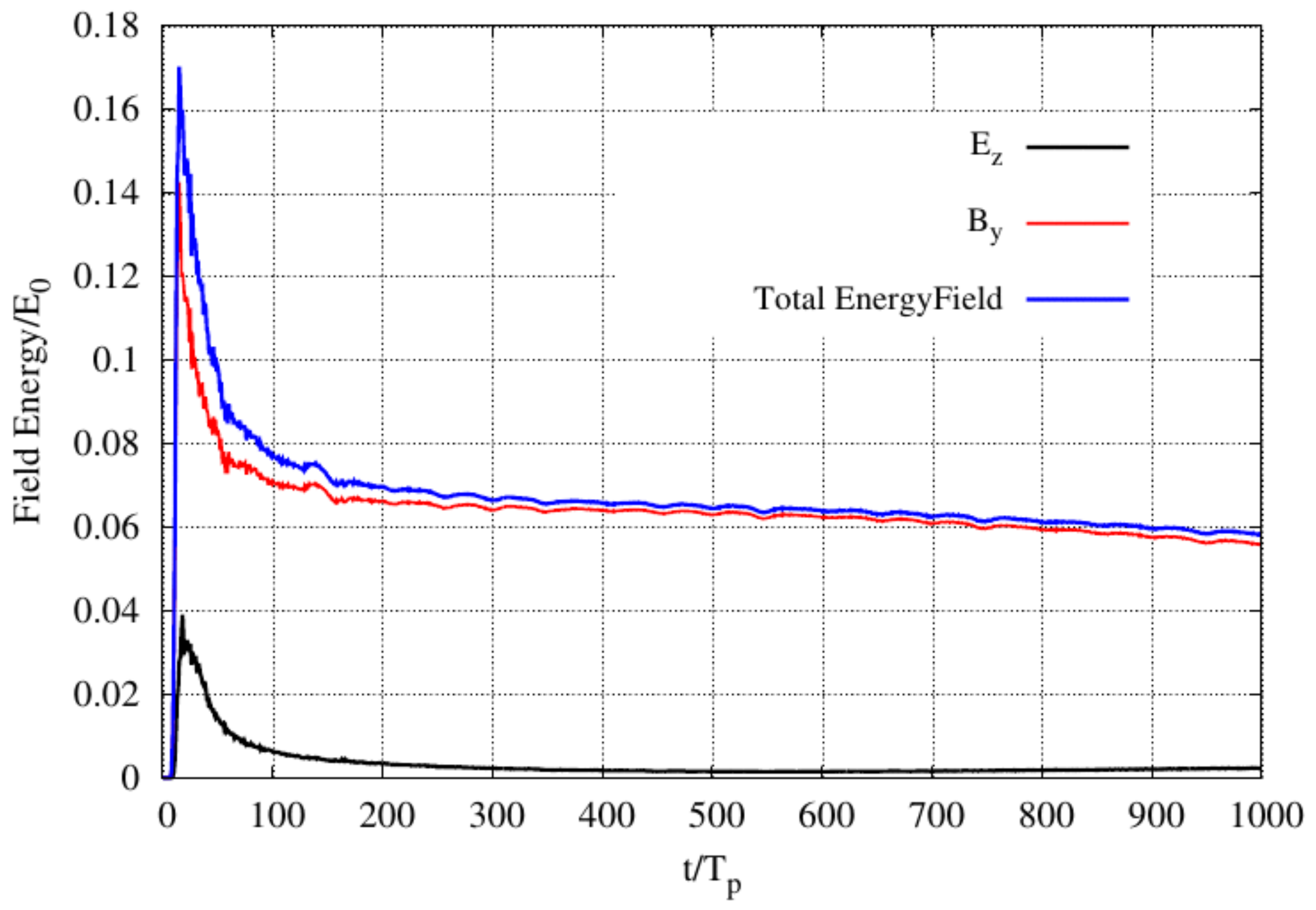
Local fluctuations on current → Local fluctuations on magnetic field → Growth of the instability

Magnetic efficiency

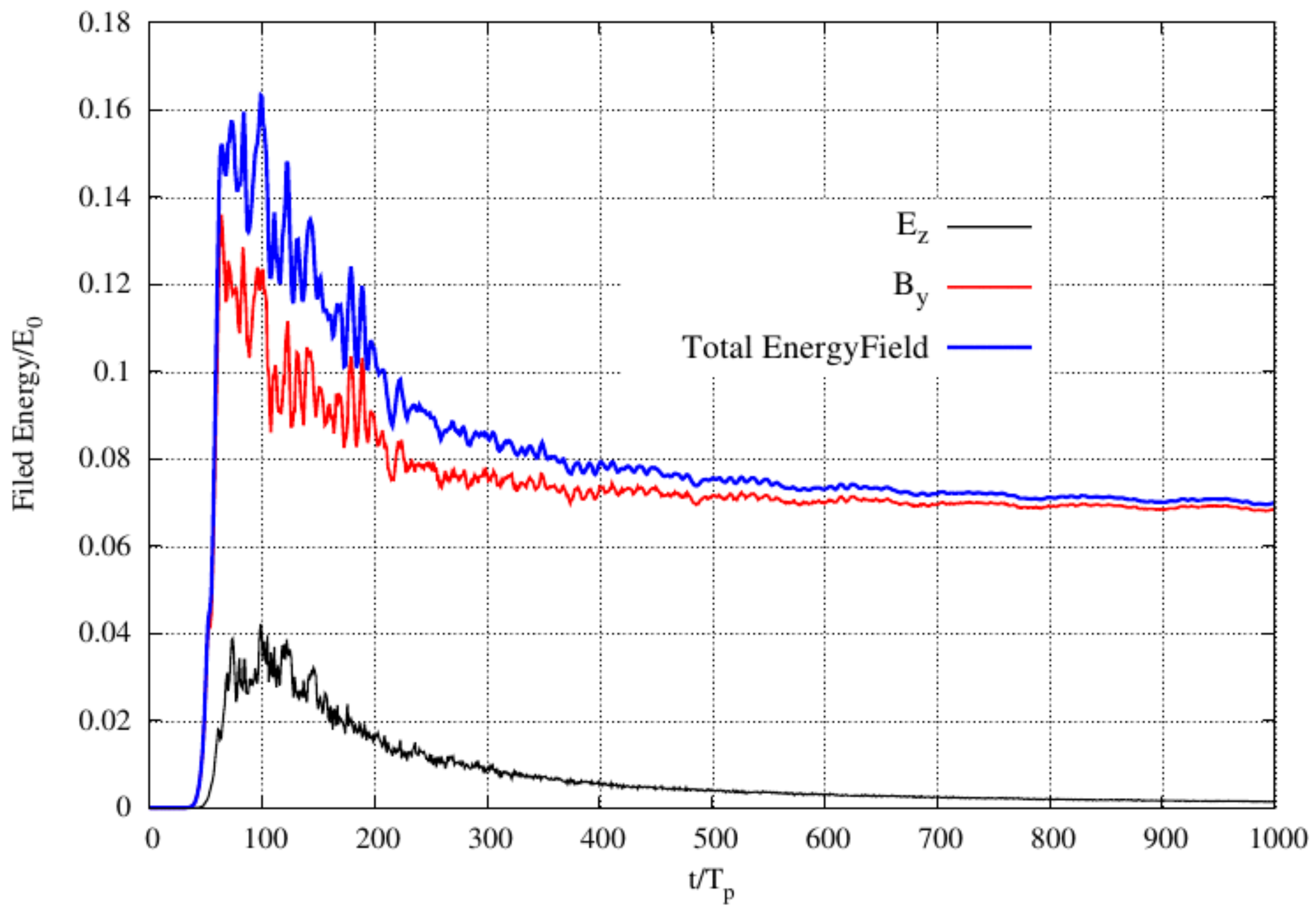
Efficiency: capability to transform initial kinetic energy (K_0) into magnetic energy

$$\eta \equiv \frac{B^2/8\pi}{K_0}$$

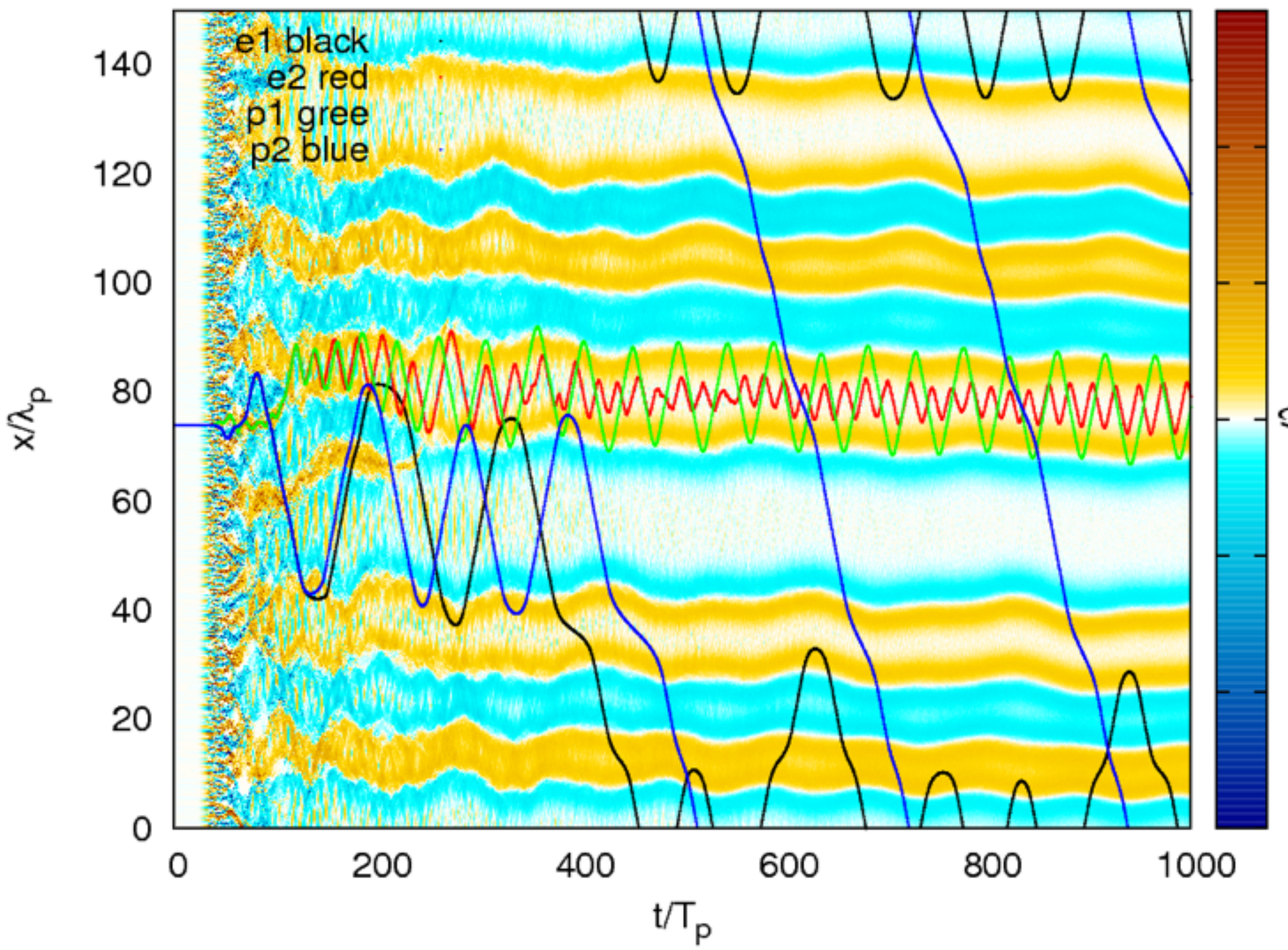
$p_0 = 10 \qquad \eta_f = 0.06$

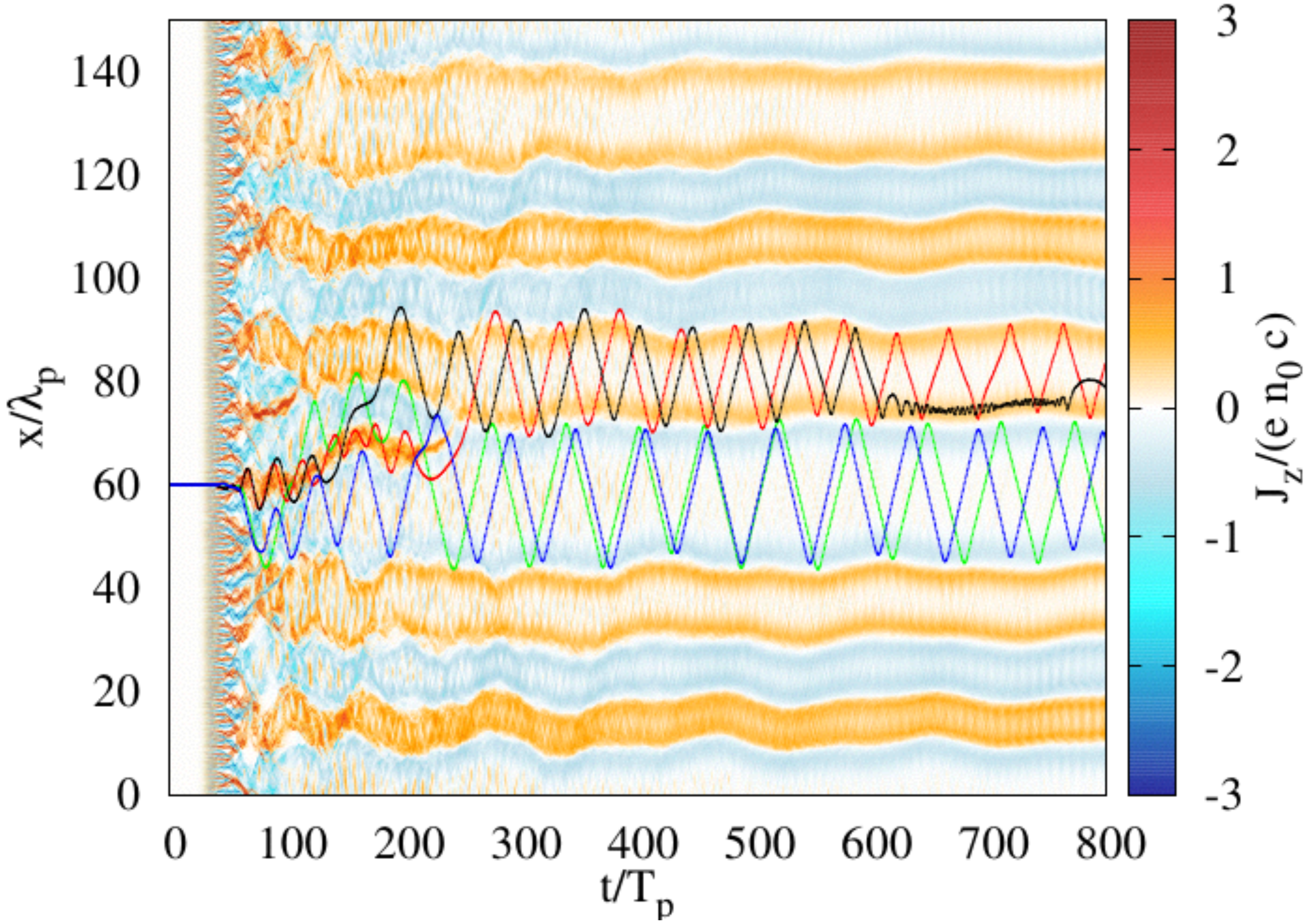


$p_0 = 200 \qquad \eta_f = 0.07$



Effects due to RF





Non radiative simulation

Radiative simulation

Non radiative simulation		Radiative simulation	
e_1^-	black	e_1^-	blue
e_1^+	green	e_1^+	red
e_2^-	red	e_2^-	green
e_2^+	blue	e_2^+	black

Field energy