Workshop “Processus d'accélération en astrophysique

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Electron heating and acceleration in two plasmas colliding with sub-relativistic velocities

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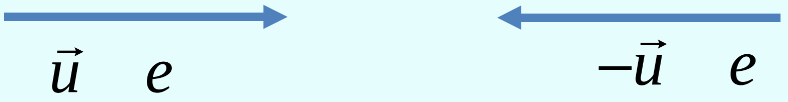
Outline

- Instability analysis
- Long term behavior and shock formation
- Electron heating in the colliding plasmas
- Single filament evolution

Colliding plasmas: sequence of instabilities



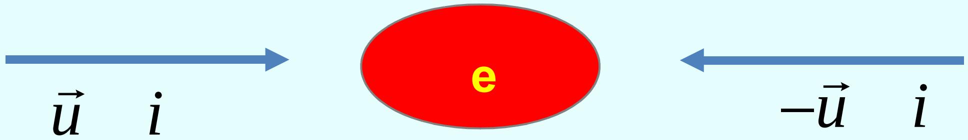
First stage of interaction – electron-electron instability

Two-stream & Weibel e-e instabilities

isotropization (mutualization)
and heating of electrons

$$u > v_{Te} \quad \gamma \simeq 0.5\omega_{pe} \quad \vec{k} \parallel \vec{u} \parallel \vec{E}$$

$$u < v_{Te} \quad \gamma \simeq \omega_{pe} u / c \quad \vec{k} \perp \vec{u} \parallel \vec{E}$$



Second stage of interaction – ion-electron instability

Filamentation ion-electron instability

filamentation of ion streams
in a hot electron plasma, electron heating

$$u < v_{Te}, \quad \gamma \simeq \omega_{pi} u / c, \quad \vec{k} \perp \vec{u} \parallel \vec{E}$$

Ion acoustic instability – electrostatic turbulence

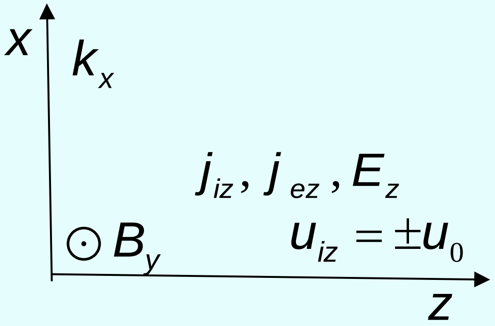
$$u < c_s, \quad \gamma \simeq ku \le \omega_{pi}, \quad \vec{k} \parallel \vec{u} \parallel \vec{E}$$

Ion filamentation instability

Ion Weibel instability has attracted attention recently in relation with the GRB physics: Medvedev, Loeb, ApJ 1999, Lubarsky, Eichler, ApJ 2006

It is also of interest for ICF – RPA ions

Growth rate is in the ion time scale, wavelength is on the electron spatial scale



Dispersion equation

$$\varepsilon_{zz} - \frac{\varepsilon_{xz}^2}{\varepsilon_{xx}} = \frac{k_x^2 c^2}{\omega^2}$$

$$1 + i\sqrt{\frac{\pi}{2}}\,\frac{\omega_{pe}^2}{k_x v_{Te}\,\omega} - \frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pi}^2}{\omega^2}\,\frac{k_x^2 u_0^2}{\omega^2} = \frac{k_x^2 c^2}{\omega^2}$$

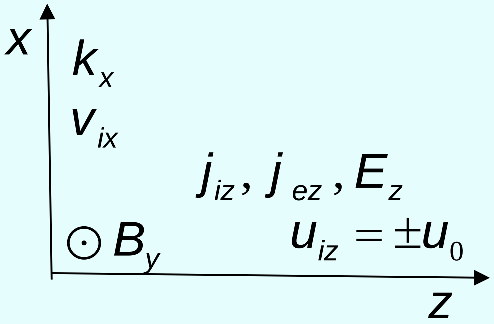
In the limit $\omega \ll kc$

$$i\sqrt{\frac{\pi}{2}}\,\frac{\omega_{pe}^2}{k_x v_{Te}} = \omega_{pi}^2\,\frac{k_x^2 u_0^2}{\omega^3} + \frac{k_x^2 c^2}{\omega}$$

$$\gamma_{ifi} \simeq \omega_{pi}\frac{u_0}{c} \qquad k_x \simeq \frac{\omega_{pe}}{c}\left(\frac{\omega_{pi}}{\omega_{pe}}\,\frac{u_0}{v_{Te}}\right)^{1/3}$$

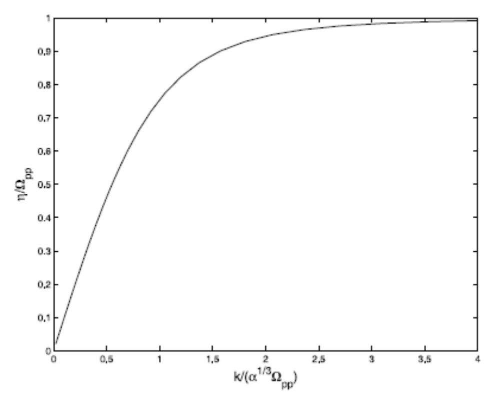
Ion filamentation instability as an energy transformer

Ion filamentation induces the charge separation



$$u_{iz} B_y \to v_{ix} \to \delta n_i \to j_{iz}$$

$$B_y \to E_z \to j_{ez}$$



Instability is driven by phase difference between the electron and ion currents
Saturation is due to the ion trapping → electron heating is important

$$\omega_{tr} \simeq \sqrt{\omega_{ci} k_x u_0} \simeq \gamma_{ifi}$$

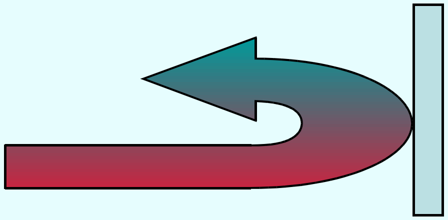
$$\gamma_{ifi} \simeq \omega_{pi} \frac{u_0}{c} \qquad k_x \simeq \frac{\omega_{pe}}{c} \left(\frac{\omega_{pi}}{\omega_{pe}} \frac{u_0}{v_{Te}} \right)^{1/3}$$

$$\frac{v_{ix}}{u_0} \simeq \frac{\omega_{tr}}{k_x u_0} \simeq \left(\frac{m_e}{m_i} \frac{v_{Te}}{u_0} \right)^{1/3}$$

$$\frac{B_y^2}{\mu_0 n_0 m_i u_0^2} \sim \left(\frac{m_e}{m_i} \frac{T_e}{m_i u_0^2} \right)^{1/3}$$

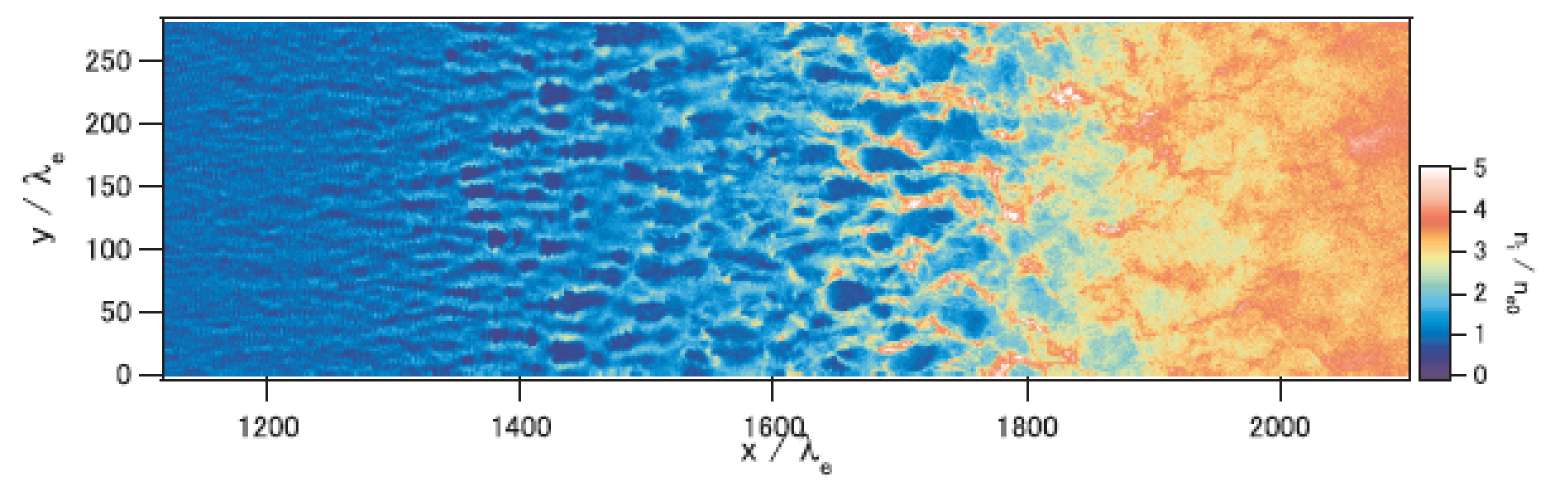
Numerical simulations of ion filamentation instability

- Numerical simulations are very challenging, but the results are contradictory:
- Spitkovsky, ApJ 2008, 2009 – very efficient energy transfer > 40%
- Dieckmann et al., PPCF 2008 ?
- Kato, Takabe, ApJ 2008 – very weak transfer 2%
- Martins et al, ApJ 2009, Fiuza et al PRL 2012 – efficiency of energy transfer ~10%



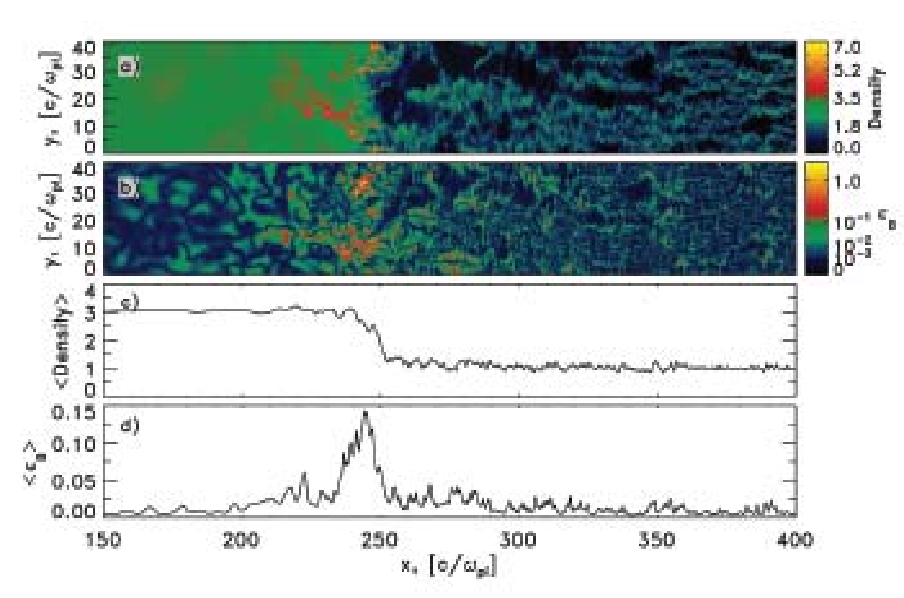
Plasma collision with the solid wall

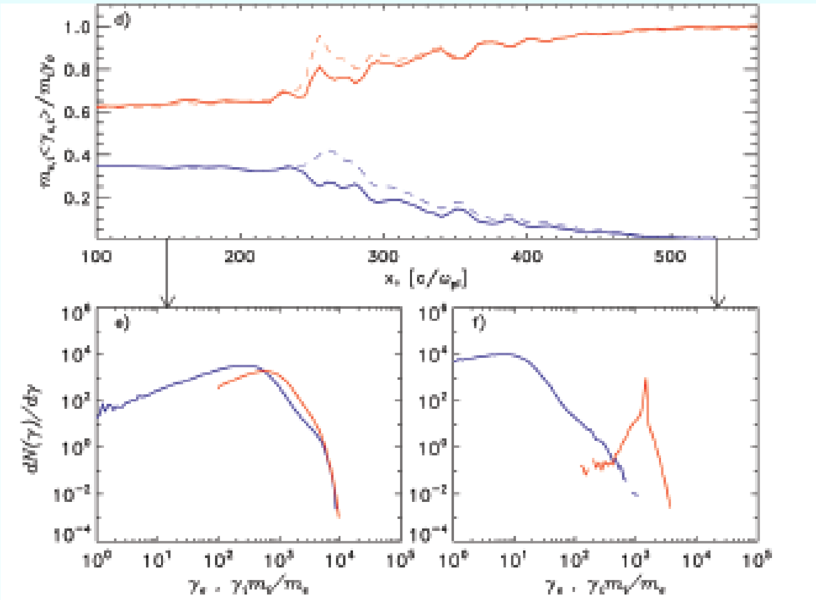
Kato & Takabe, ApJ 2008



Relativistic collisionless shock

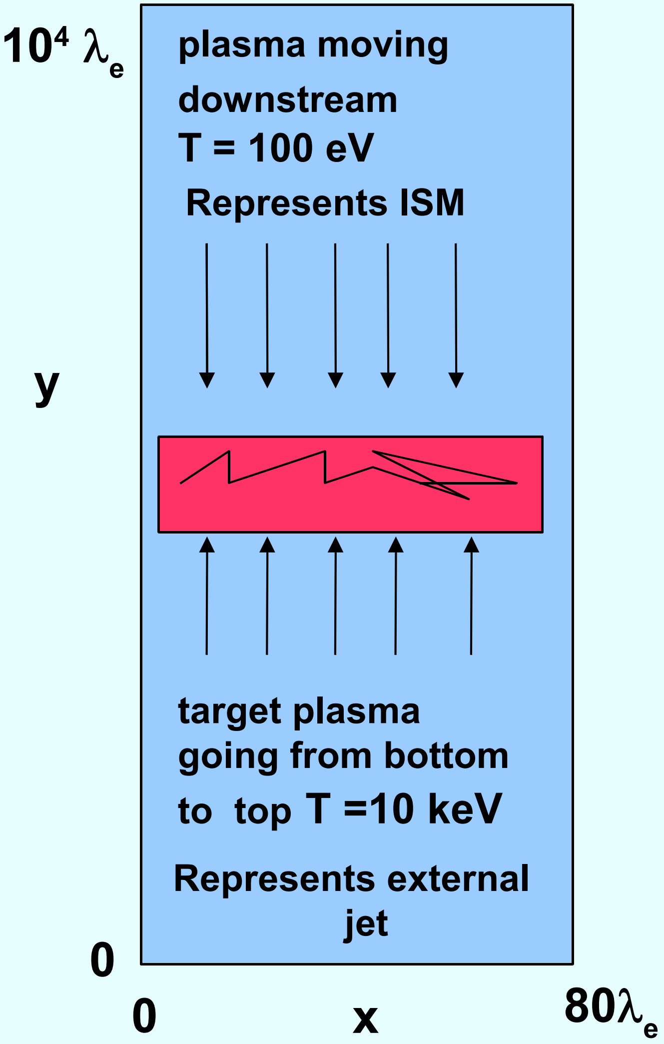
Spitkovsky, ApJ 2008: collision of two identical relativistic plasmas with γ = 15: efficient energy exchange – electron heating and magnetic field generation, but the mass ratio is small m_i/m_e ~ 16 – 100





Energy budget:
ions are losing 40% of their initial energy, T_e ~ T_i, shock speed ~ c/2
electrons are gaining 35%, ~ Maxwellian energy distribution
magnetic field energy raising to 15% at the shock front ~20 c/ω_{pi}

Simulation of collision of two sub-relativistic plasmas



plasma moving downstream
T = 100 eV
Represents ISM

target plasma going from bottom to top T =10 keV
Represents external jet

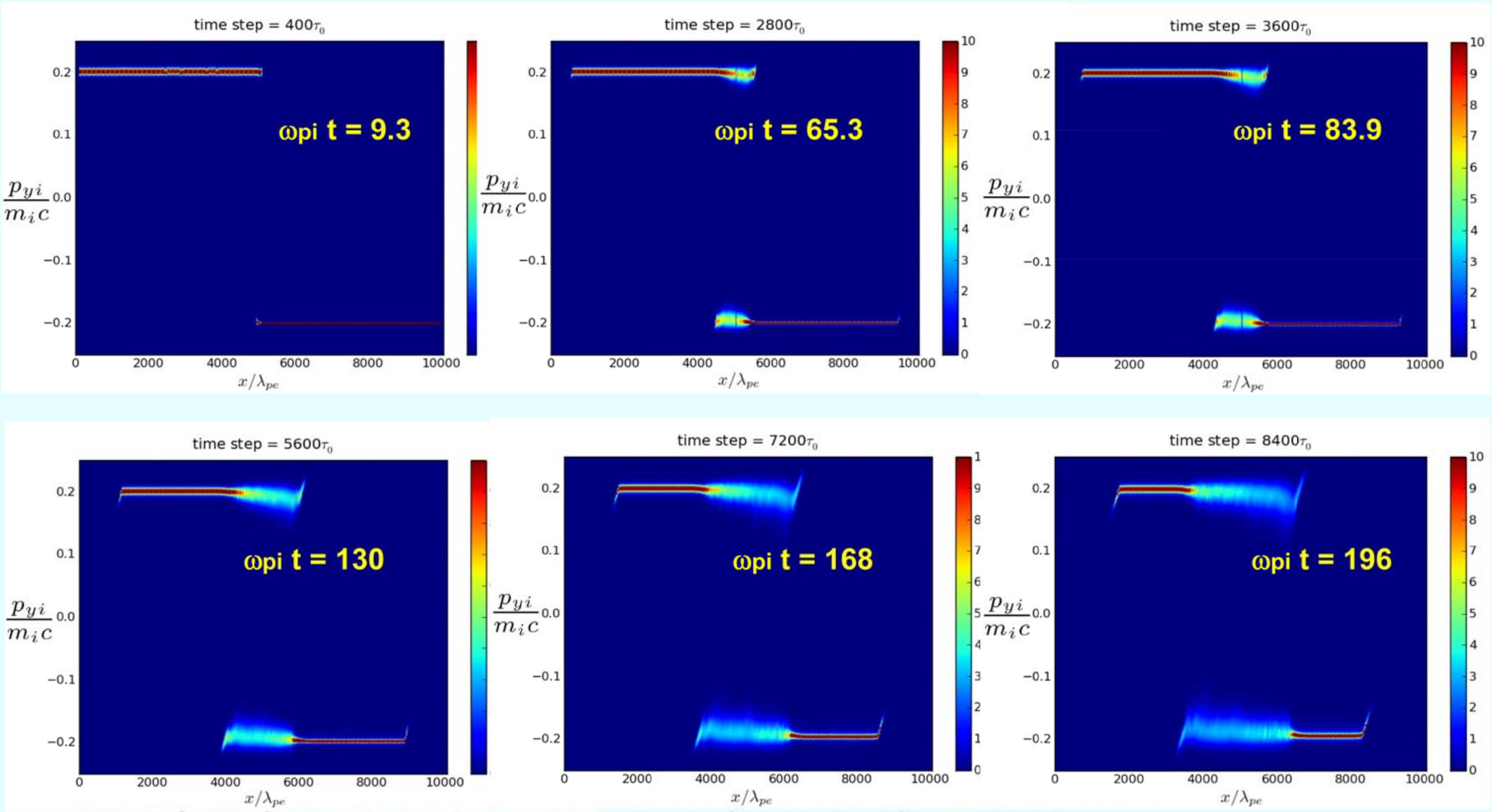
$\beta = u_p/c = 0.2$ $\varepsilon_p \approx 20$ MeV
for $n_0 = 10^{18}\ \mathrm{cm}^{-3}$
size $0.5\times60\ \mathrm{mm}^2$
time $\omega_{pi}^{-1} = 1$ ps $\lambda_\iota = c/\omega_{pi} = 220\ \mu$m

Simulation of the plasma interaction in the center of mass reference frame in the ion filamentation-dominated regime

$$u_p \gg c_s \simeq c\sqrt{m_e/m_i}$$

- electron heating
- ion slowing down
- magnetic field generation
- energy repartition in the upstream flow
- shock front formation

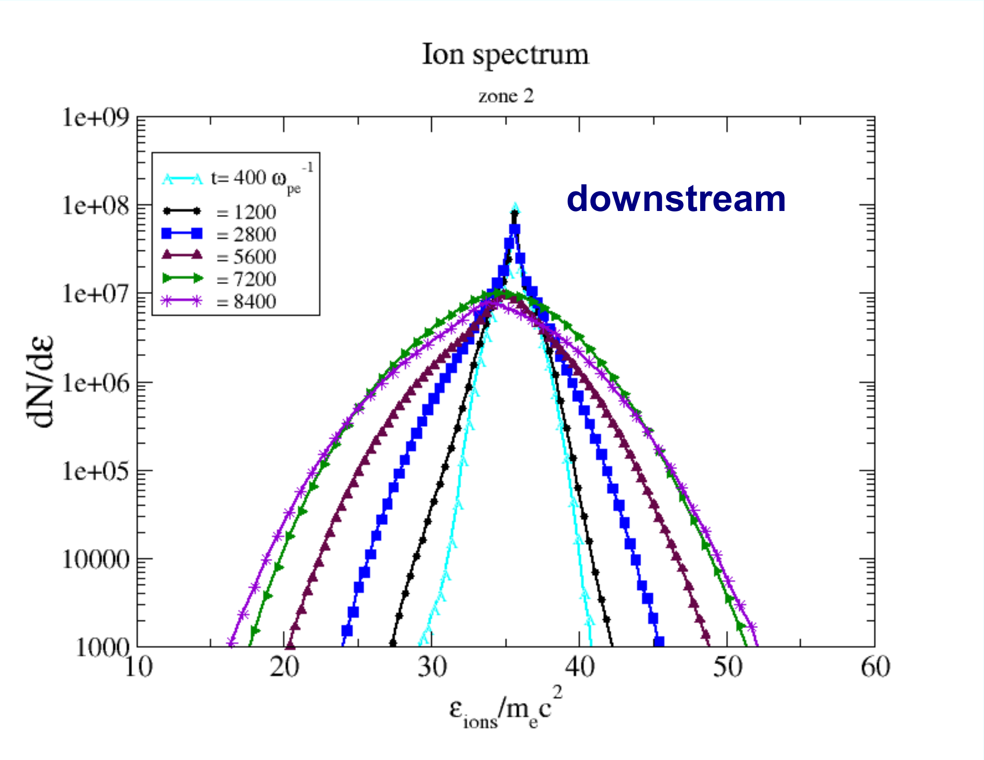
Ion phase space – time evolution

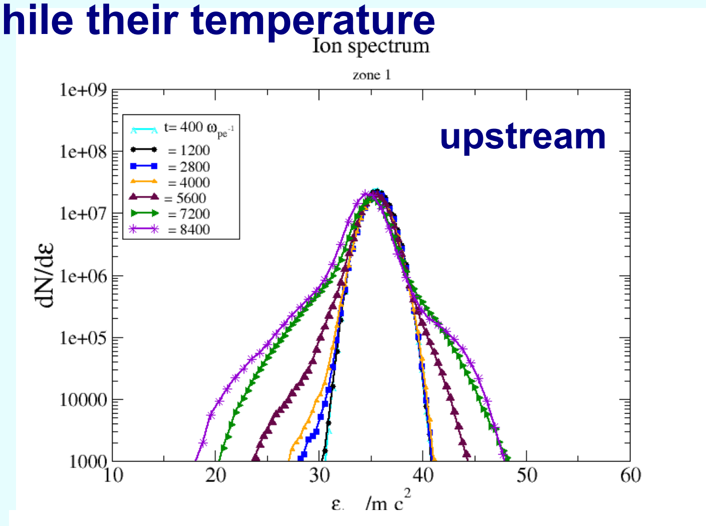


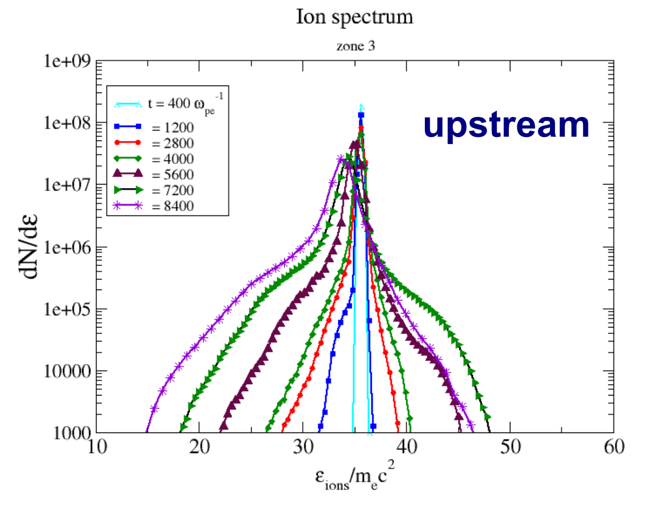
shock front formation takes a long time after a significant ion heating

Ion heating and slowing down

Ion heating proceeds faster than slowing down – in the time scale of 200 ω_{pi}^{-1} they are loosing less than 10% of their energy, while their temperature increases dramatically

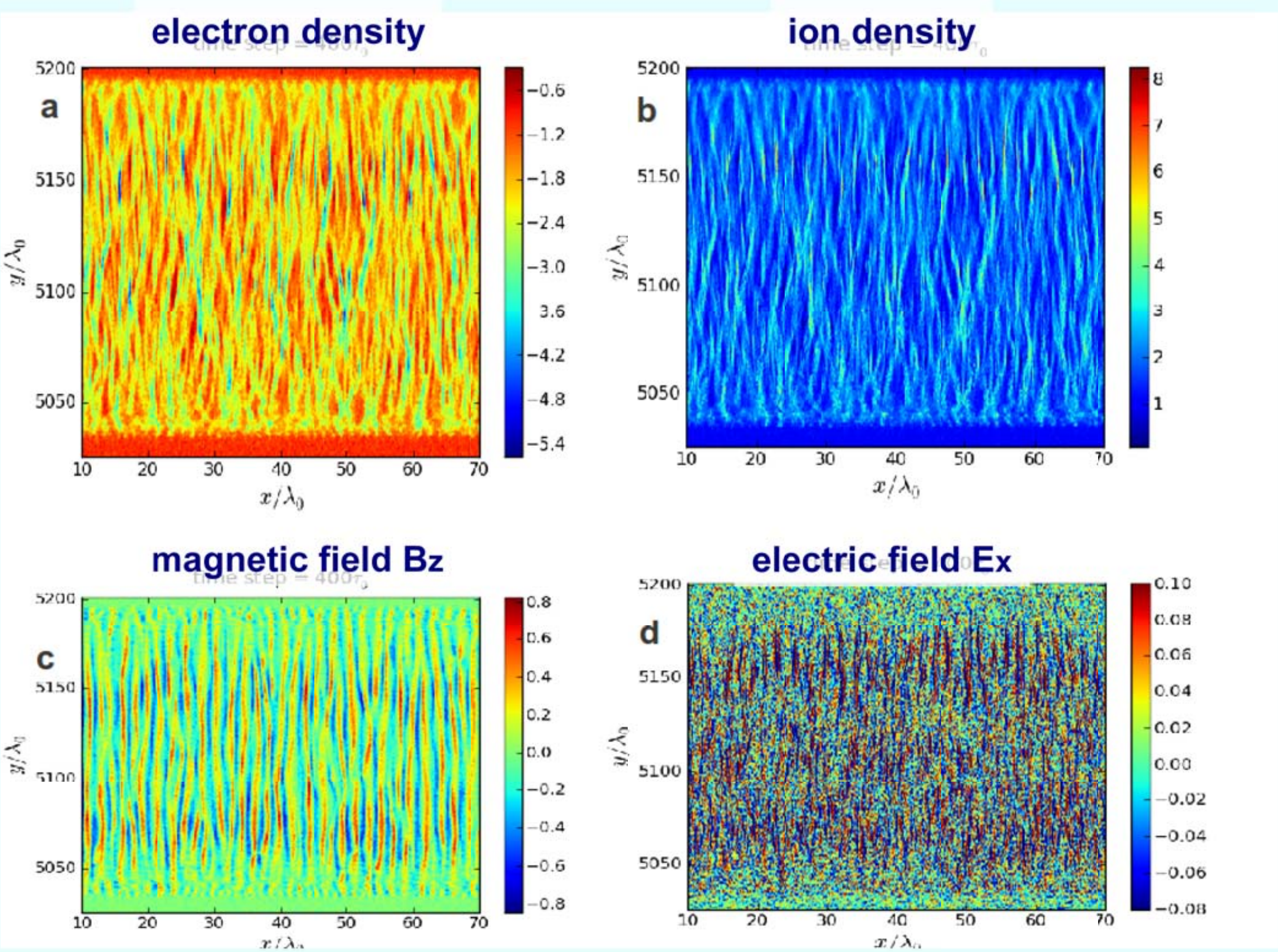






Global properties: filaments and fields

Plasma filamentation in the electron spatial scale c/ω_{pe} develops in the ion time scale $1/\omega_{pi}$



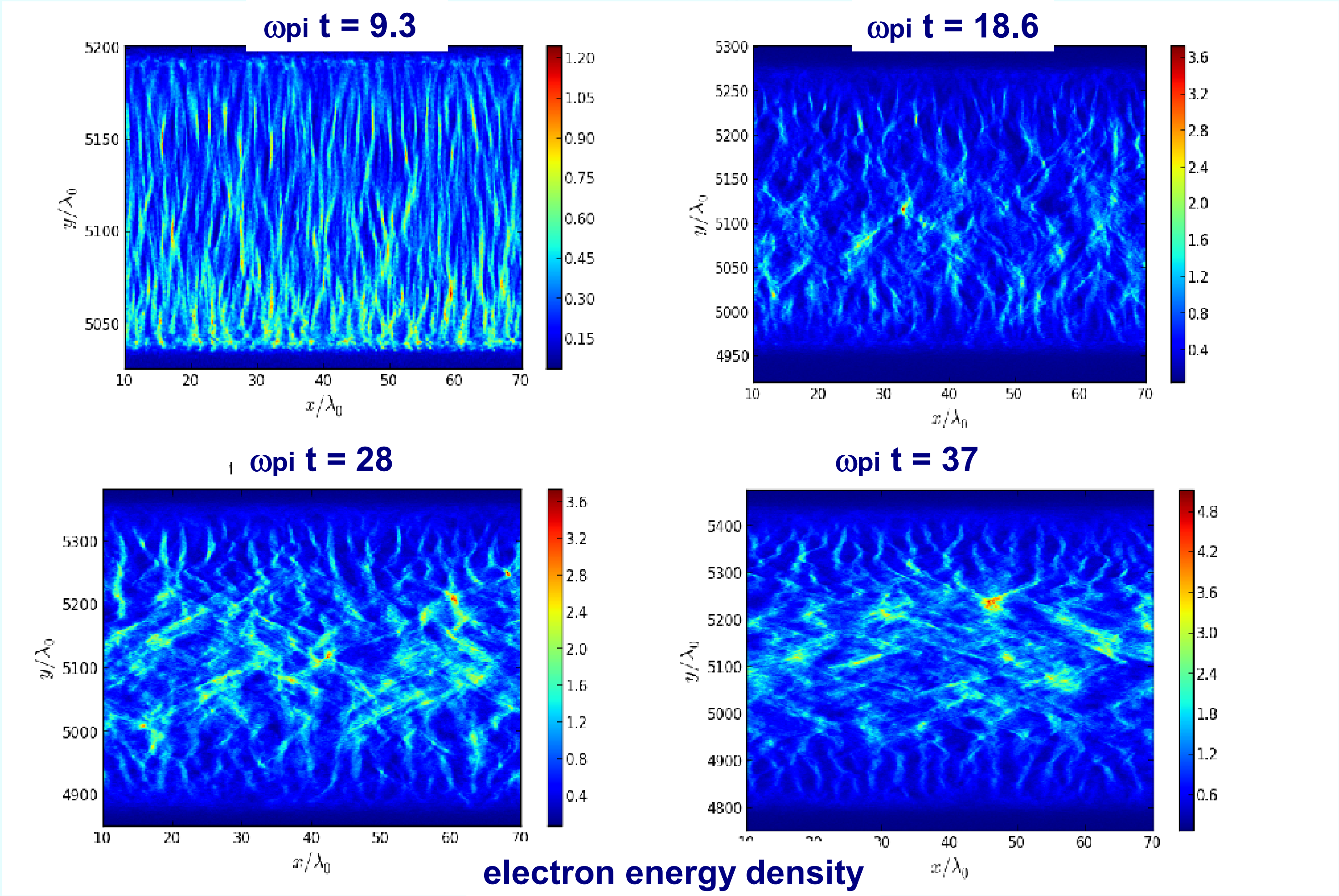
ω_{pi} t = 10

current filaments are associated with strong small scale magnetic fields

large amplitude charge density modulations producing strong electrostatic fields

Electron heating in the filaments

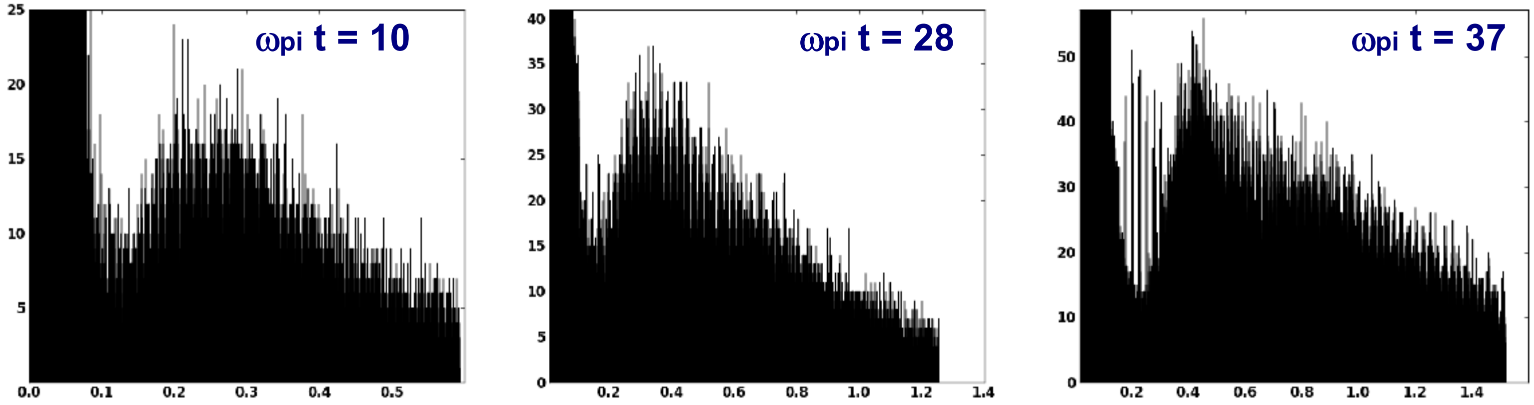
Nonlinear evolution of filaments is associated with strong electron heating – by factor of 100 in the time scale of 10 – 20 ω_{pi}^{-1}



electron energy density

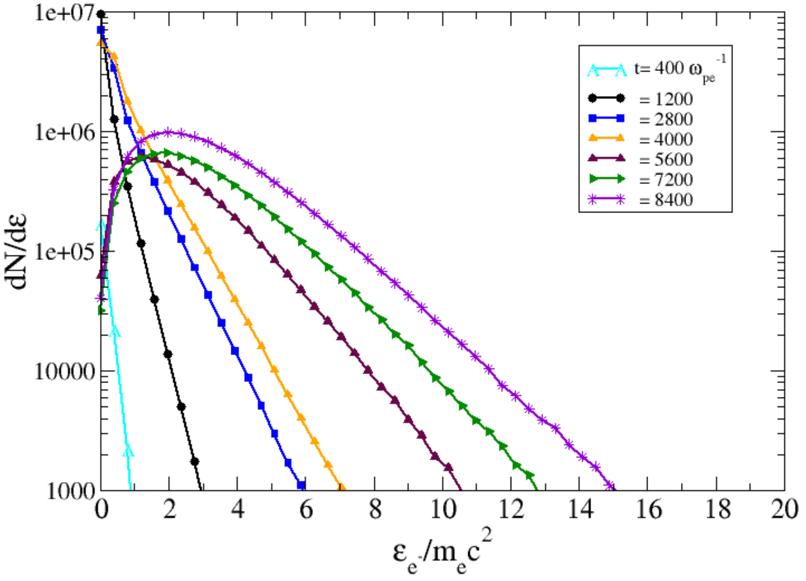
Temporal evolution of electron energy

Probability distribution of the electron energy density



Electron energy density saturates at the average level of 0.4 with a sharp cut-off at $1.5 n_0 m_e c^2$

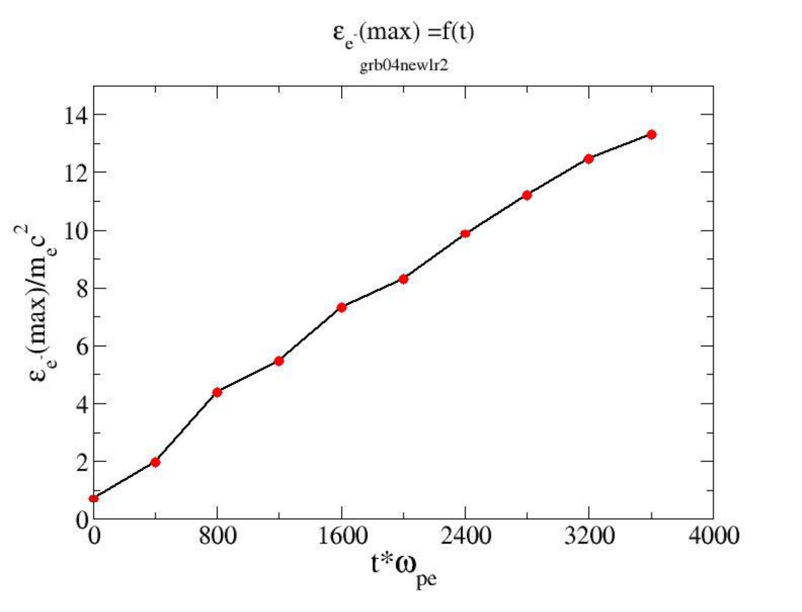
Electron temperature increases with time from 0.02 $m_e c^2$ to $1.5 m_e c^2$ in the time scale of 200 ω_{pi}^{-1}

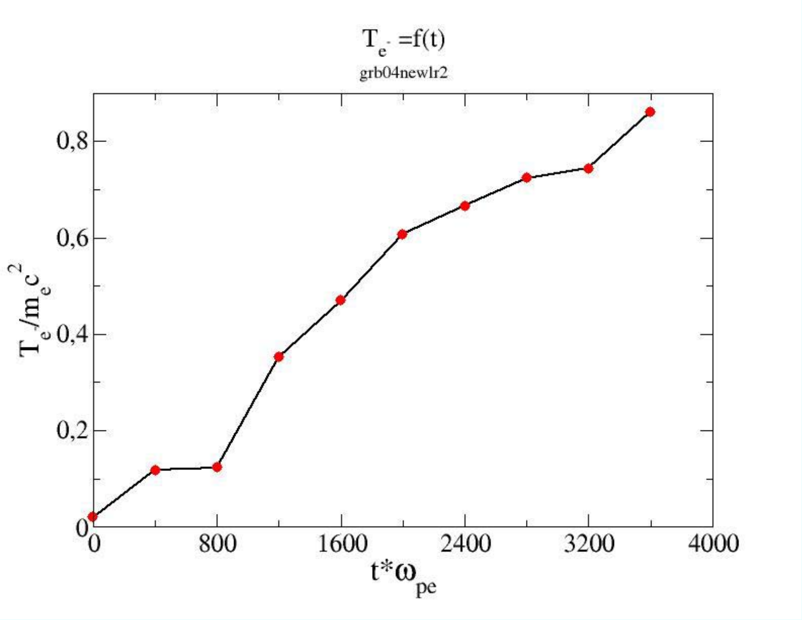


Continuous electron heating in filaments

Hot electron temperature and their cut-off energy increase lineraly in time

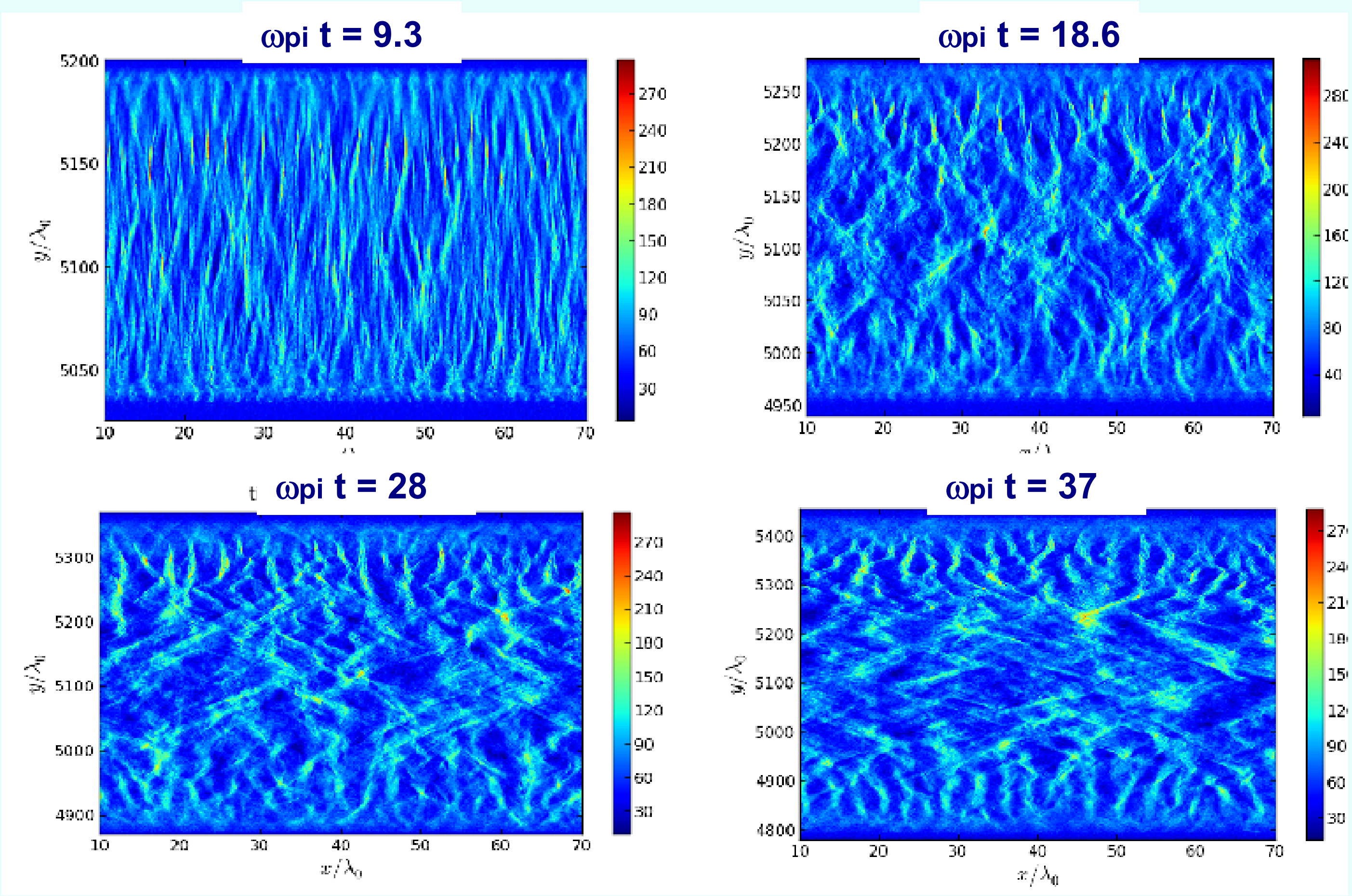
Stochastic heating process





Evolution of the ion energy density

Ion energy evolution is much slower – in the time scale of 200 ω_{pi}^{-1} they are losing less than 10% of their energy. Filament rotation generates the parallel electric field that slows down the ions


ωpi t = 9.3

ωpi t = 18.6

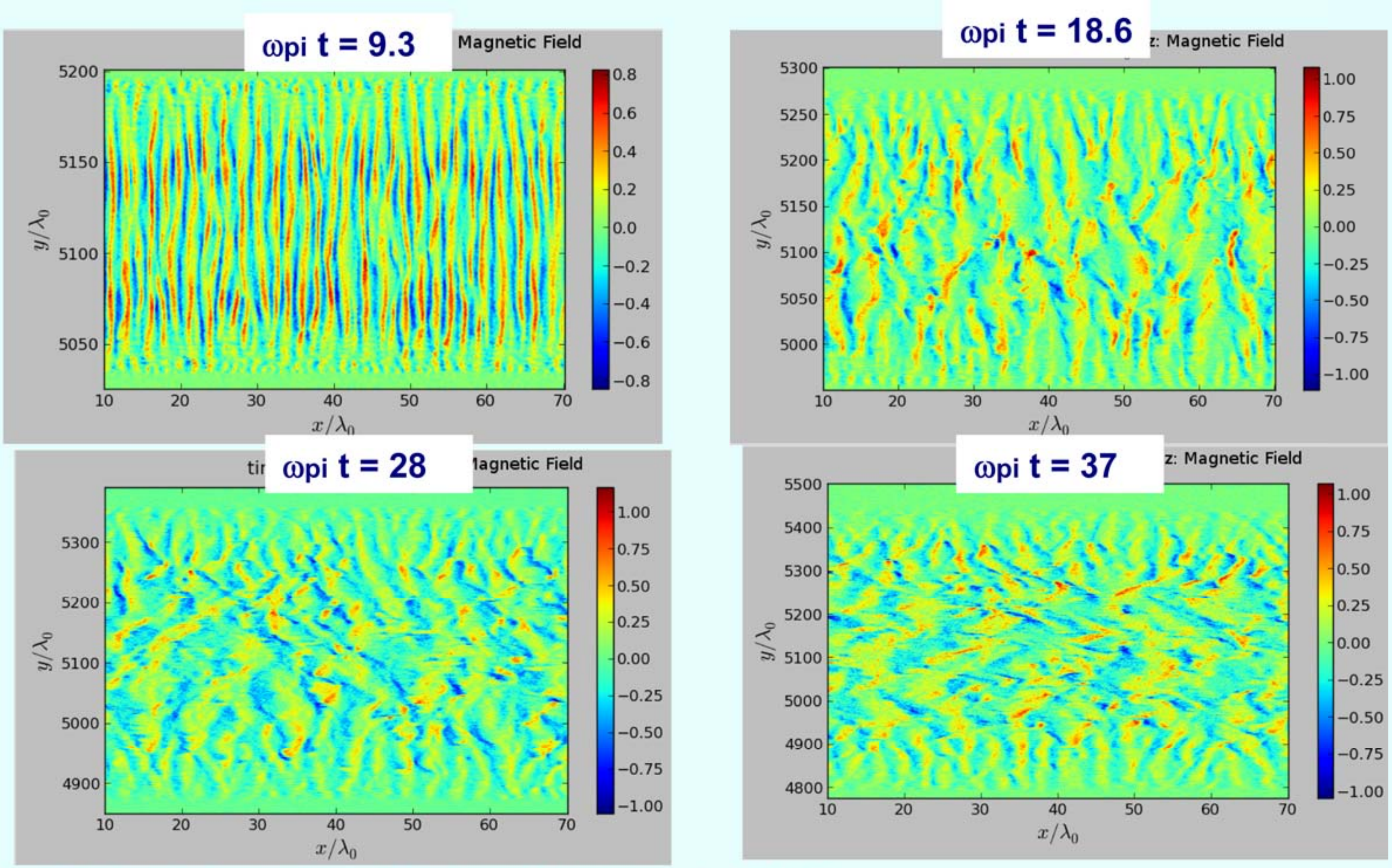
ωpi t = 28

ωpi t = 37

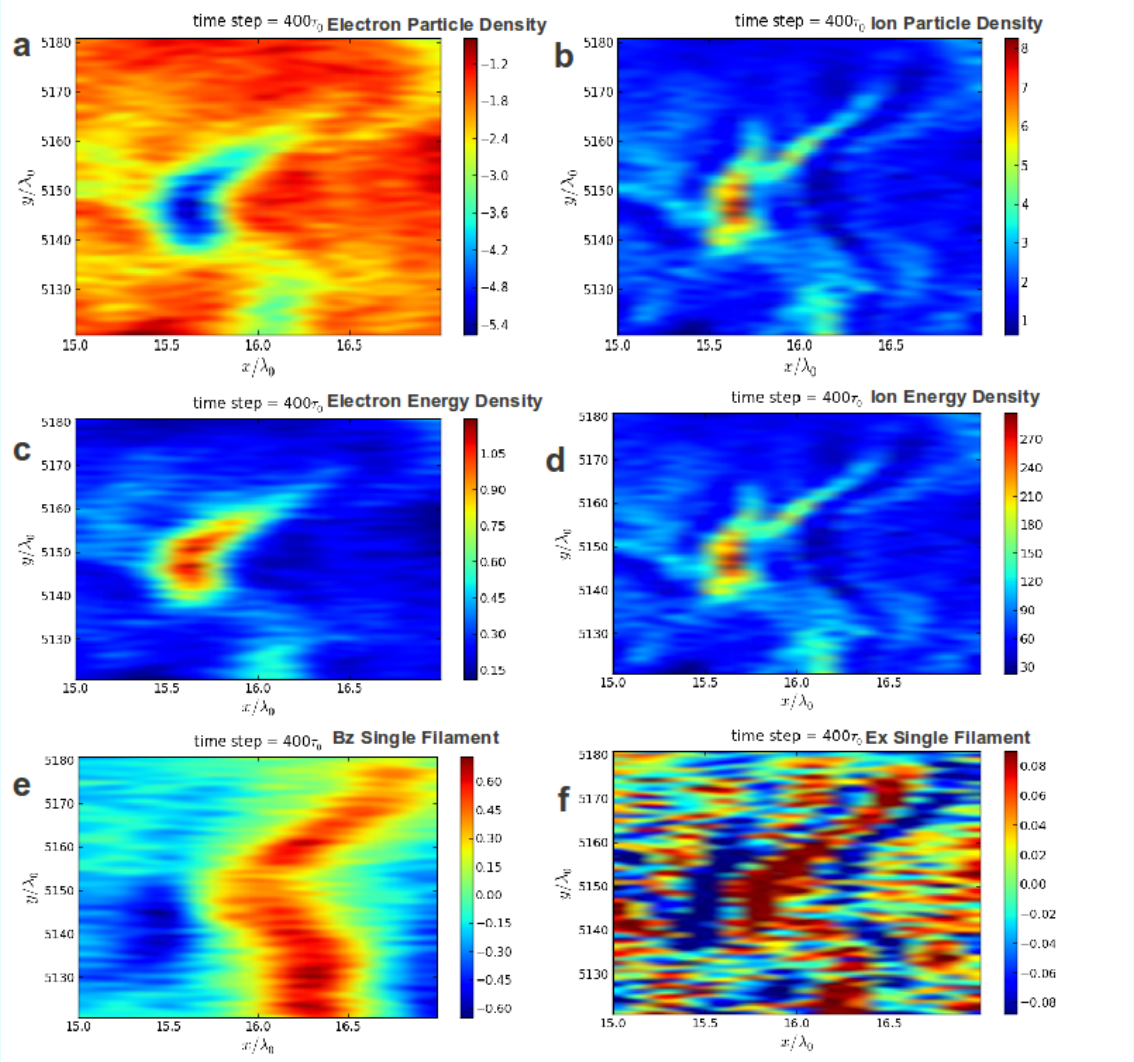
Evolution of the magnetic fields

Magnetic fields follow essentially the filament evolution – their spatial scale and the volume increase with time. The amplitude agrees with the saturation level.

$$\frac{\omega_{ce}}{\omega_{pe}} \sim \frac{u_0 / c}{\left(\omega_{pi} u_0 / \omega_{pe} v_{Te}\right)^{1/3}}$$



Single filament characterization



Zoom of a single filament at the time of 400 ω_{pe}^{-1}

- **very large compression by a factor of 6**
- **ion density maximum is higher than the electron one**
- **very high energy of electrons in the filament**
- **strong magnetic field around the filament – high electric current**
- **strong electrostatic field due to the charge separation**
- **filament life time about 10 – 20 ω_{pi}^{-1}**

Conclusions

- Similarity in the physics of laser plasma interaction and some phenomena in the GRBs – modeling of the collisionless sub-relativistic shocks in laser plasma interactions requires very big volumes, long times and high laser energies
- Electron heating is an important stage of the shock formation. This is a stochastic process that occurs due to the strong charge separation in filaments
- Energy transfer to magnetic fields in limited by the ion trapping in the filaments
- Parallel electric field is generated later in time in the downstream zone due to the filament rotation
- Radiation losses due to the electron synchrotron emission. Next step: photon – electron kinetics