Frontiers in Intense Laser Matter Interaction Theory

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

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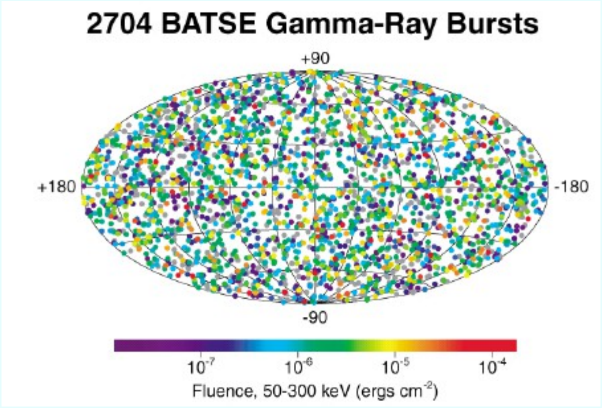
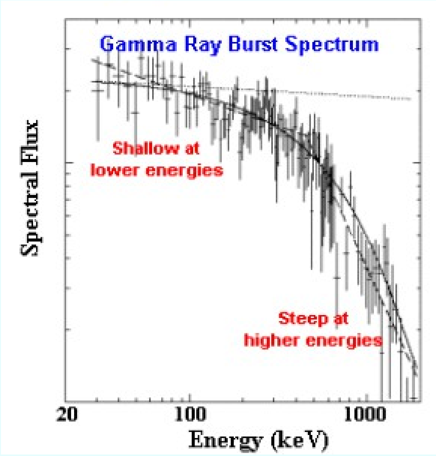
Outline

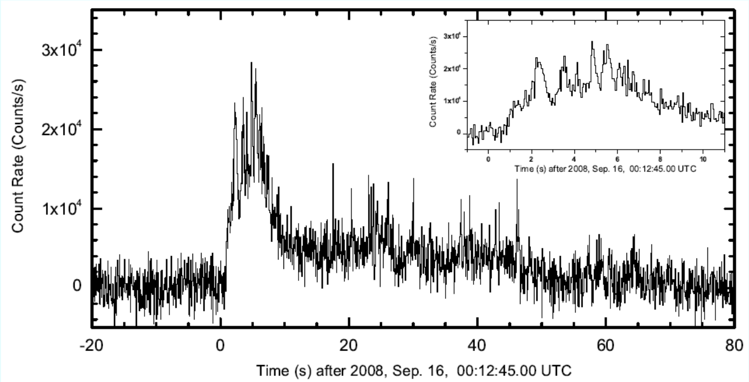
- Colliding plasmas in the Universe and in laboratory
- Instability analysis
- Long term behavior and shock formation
- Electron heating in the colliding plasmas
- Single filament evolution

Gamma Ray Burst phenomenology



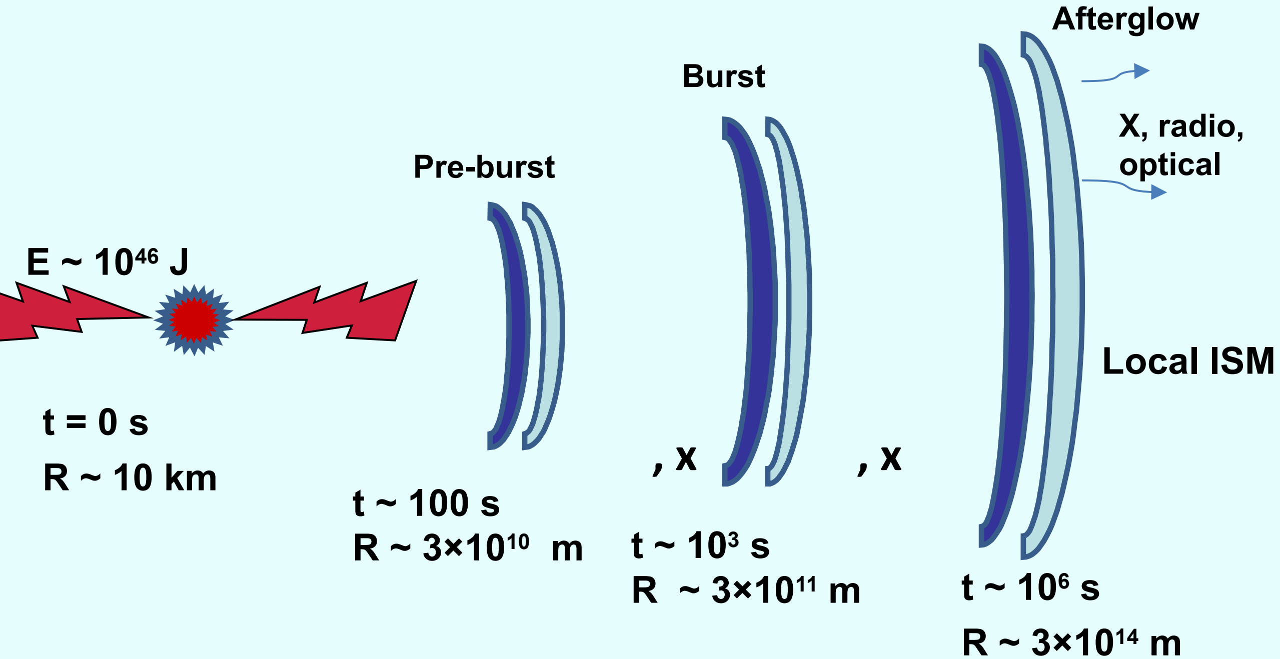
- Evenly distributed across the sky
- Cosmological distances, up to Z ~ 8 (~ **10^{23} km**)
- Electromagnetic emission in domain 10 keV – 1 MeV
- Fluence up to **10^{-11} J/cm^2** in the range 50 – 300 keV
- Electromagnetic energy release **10^{45} J/sr**
- Short pulse duration 10 – 100 s
- Millisecond time scale variability (0.1 – 10 ms)
- Long afterglow – several days





How such an enormous energy ~10^{45} J/sr can be released in 10 s ?

Fireball Model of a GRB



Major hypothesis

- Efficient transformation of the directed jet energy into « thermal energy »
- Energy equipartition
- Large scale slowly varying magnetic field
- Power law electron energy distribution
- Collisionless processes dominate

- Ejecta from the central explosion slows down at the distance ~ 10^{11} km in the interaction with the ISM in the time scale of 10^{6} s
- Relativistic factor of the jet ~ 100 explains a short pulse duration recorded by observer
- Directed energy of the jet is transformed in the « thermal » energy of plasma and in the energy of magnetic field in the internal collisions and in the external collisions with the ISM
- Compton and synchrotron emissions provide a radiation cooling of plasma – a significant part of the ejecta energy is radiated

Sequence of instabilities

$\vec{u} \quad e$ $\qquad -\vec{u} \quad e$

First stage of interaction – electron-electron instability

Two-stream & Weibel e-e instabilities
isotropization (mutualization)
and heating of electrons

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

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

$\vec{u} \quad i$ $\qquad$ e $\qquad -\vec{u} \quad i$

Second stage of interaction – ion-electron instability

Filamentation ion-electron instability
filamentation of ion streams
in a hot electron plasma, electron heating

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

This slower instability allows extracting energy from the ions
the competing ion-acoustic instability appears only for slow flows u < c_s

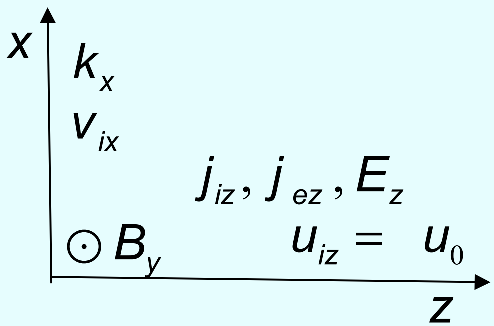
Ion filamentation instability as an energy transformer

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

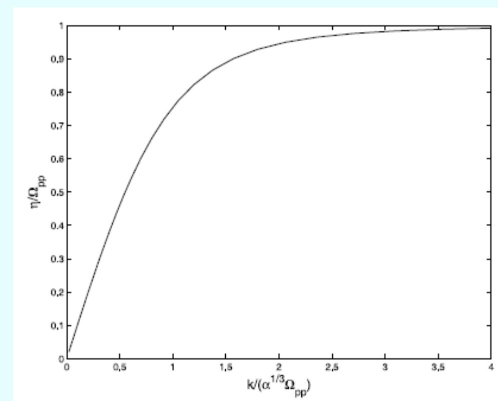
Growth rate is in the ion time scale, wavelength is on the electron spatial scale

Ion stopping length ~ $(m_p c^2/T_e)^{3/2}$ $c/\ _{pi}$ – depends on the electron temperature



$u_{iz}B_y$ v_{ix} δn_i j_{iz}

B_y E_z j_{ez}



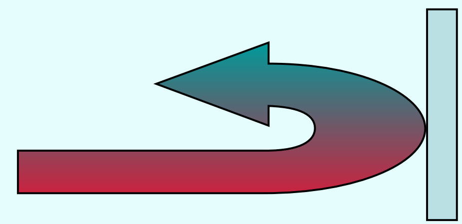
Instability is driven by phase difference between the electron and ion currents
Electron heating is essential

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

$$\frac{B_y^2}{n_0 T_e} \sim \frac{u_0^2}{c^2}$$

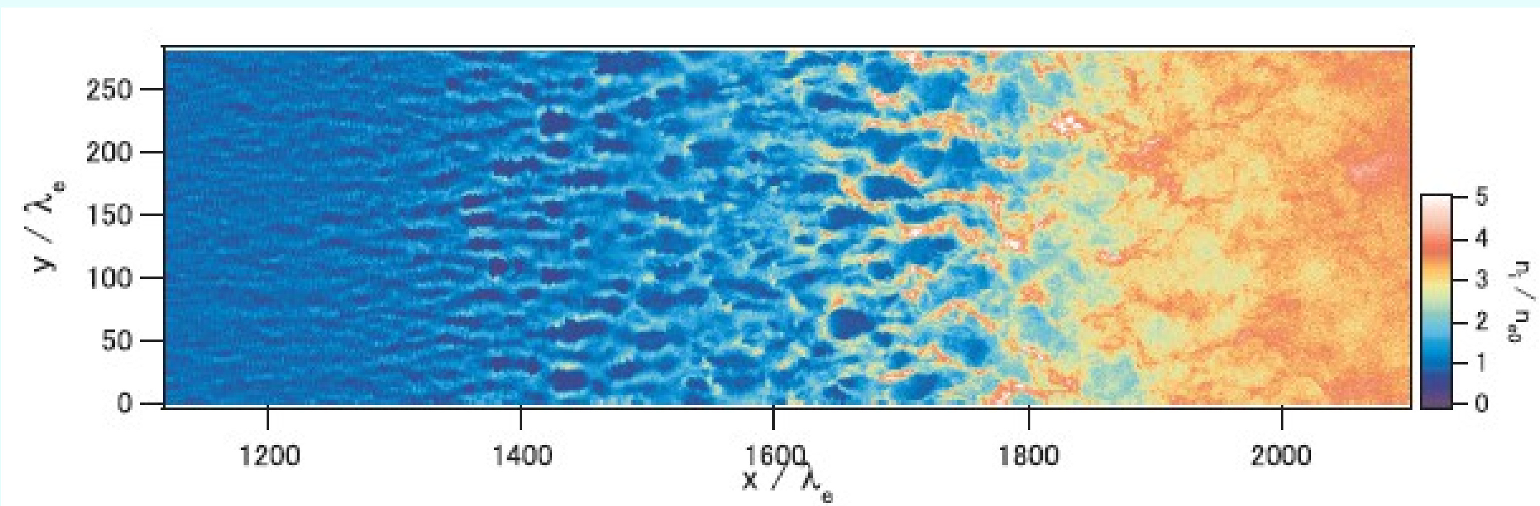
Numerical simulations of ion filamentation instability

- 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%



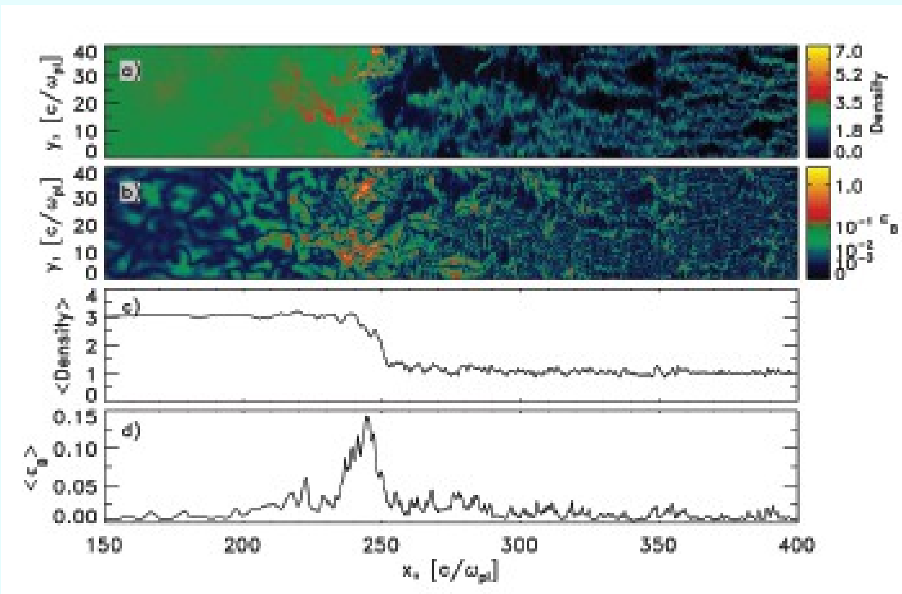
Plasma collision with the solid wall

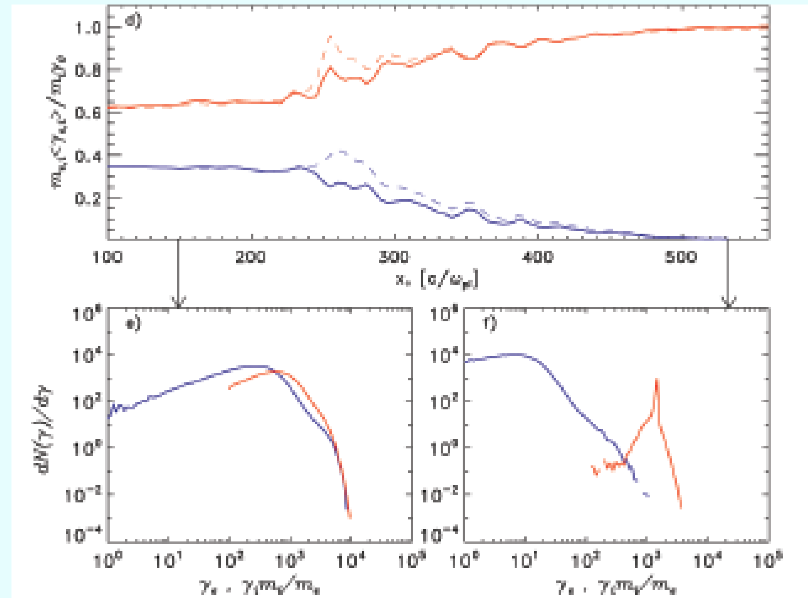
Kato & Takabe, ApJ 2008



Relativistic collisionless shock

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





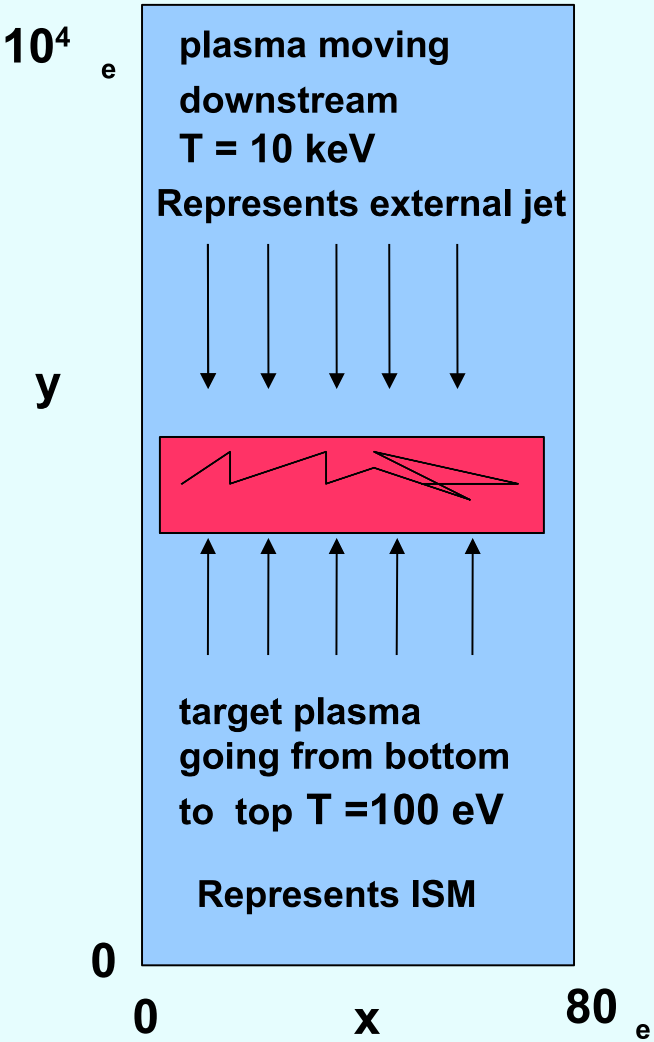
Energy budget:

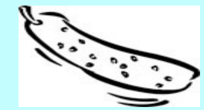
ions are losing 40% of their initial energy, $T_e \sim T_i$, shock speed ~ c/2

electrons are gaining 35%, ~ Maxwellian energy distribution

magnetic field energy raising to 15% at the shock front ~20 c/ $_{pi}$

Simulation of collision of two sub-relativistic plasmas



= u_p /c = 0.2 $_p$ ≈ 20 MeV 

for $n_0 = 10^{18}$ cm^{-3}

size 0.5×60 mm^2

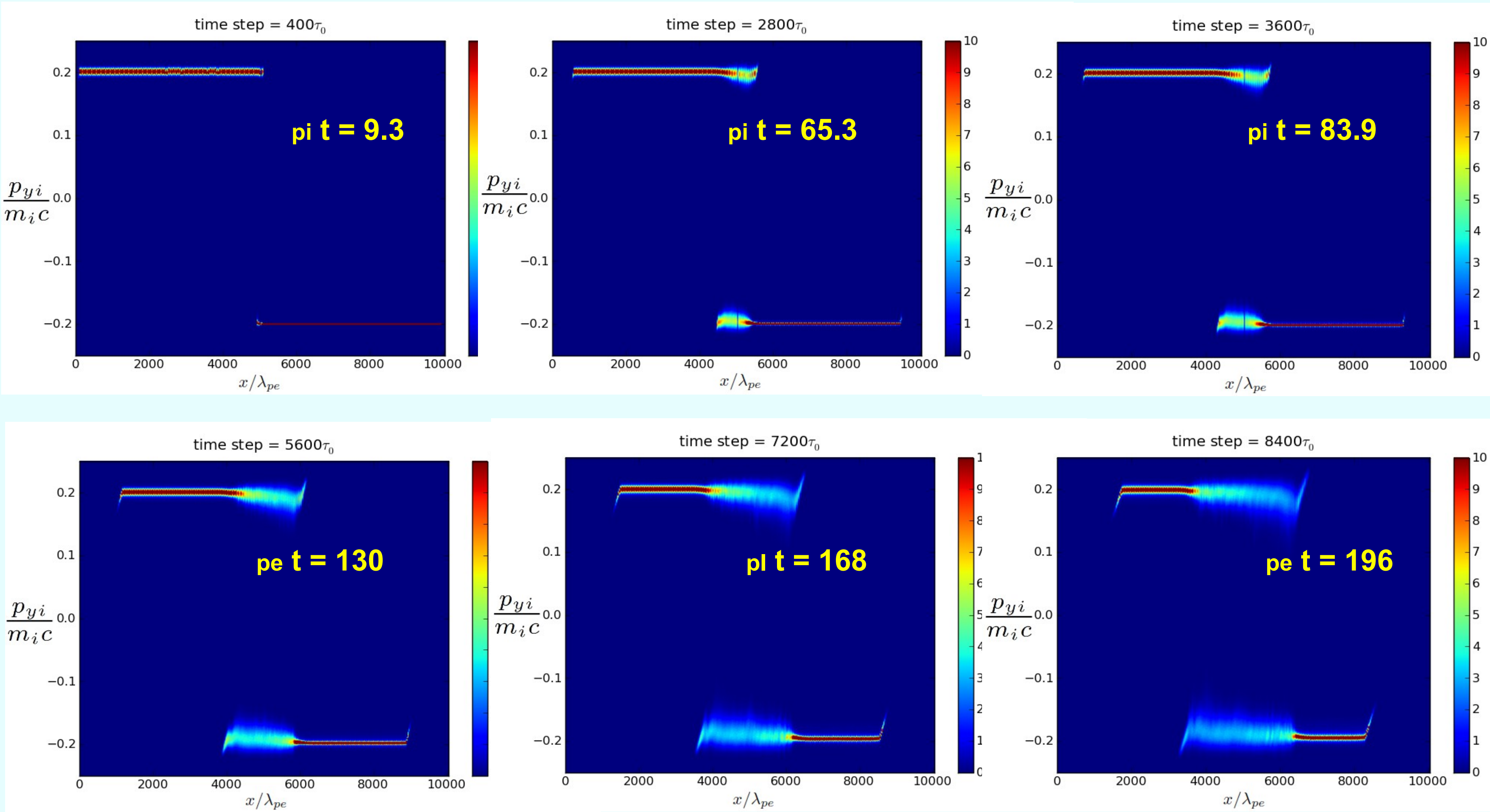
time $_{pi}^{-1}$ = 1 ps = c/ $_{pi}$ = 220 m

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

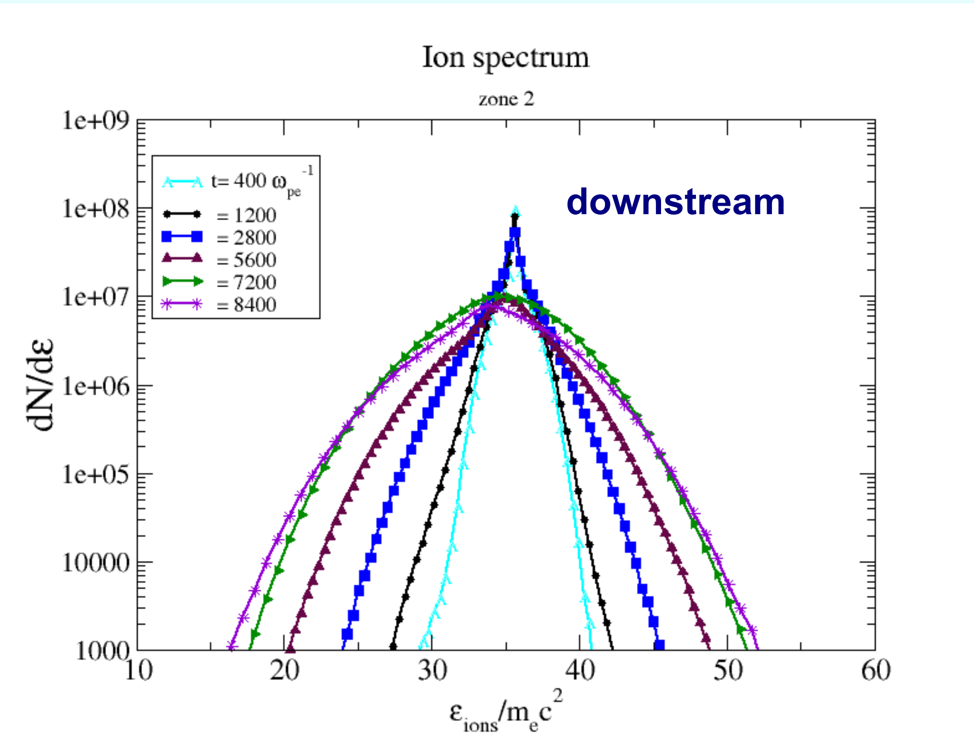
Ion phase space – time evolution

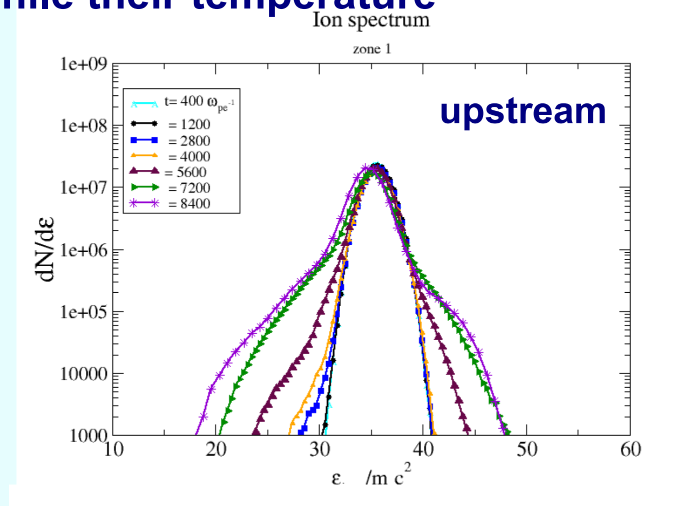


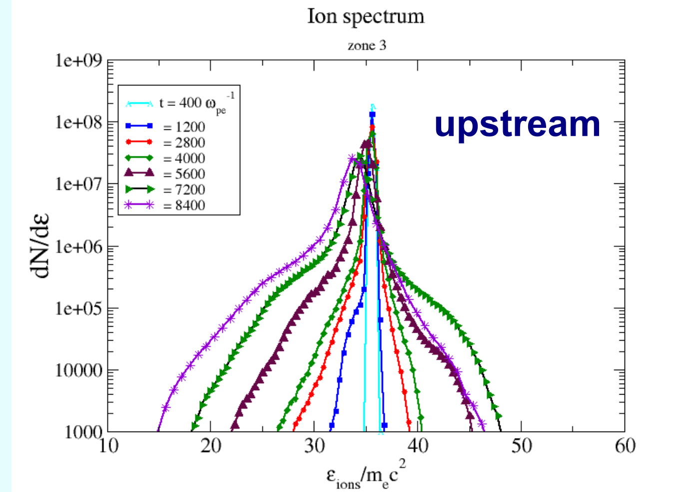
shock front formation takes a long time after a significant ion heating

Ion heating and slowing down

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

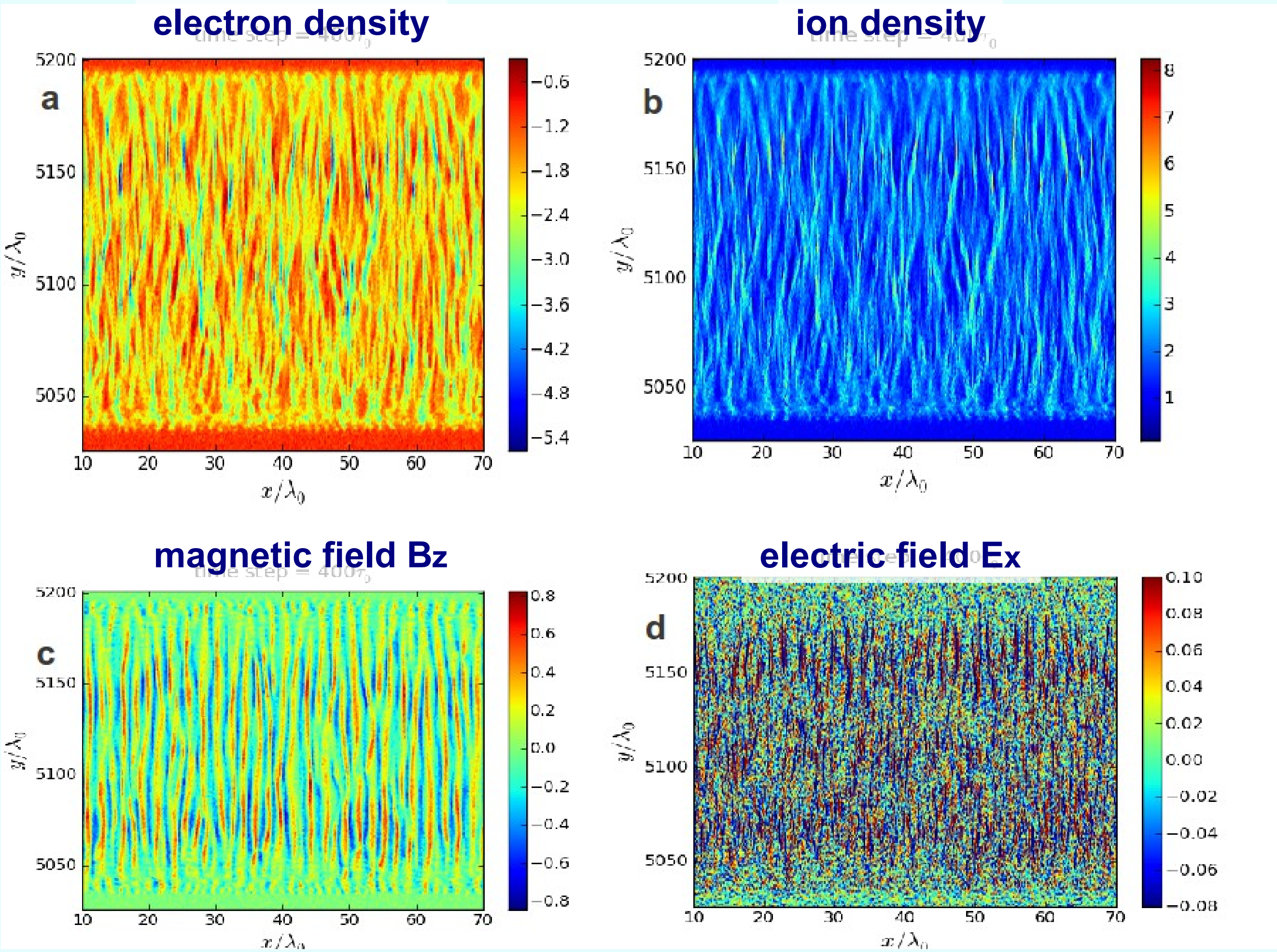






Global properties: filaments and fields

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



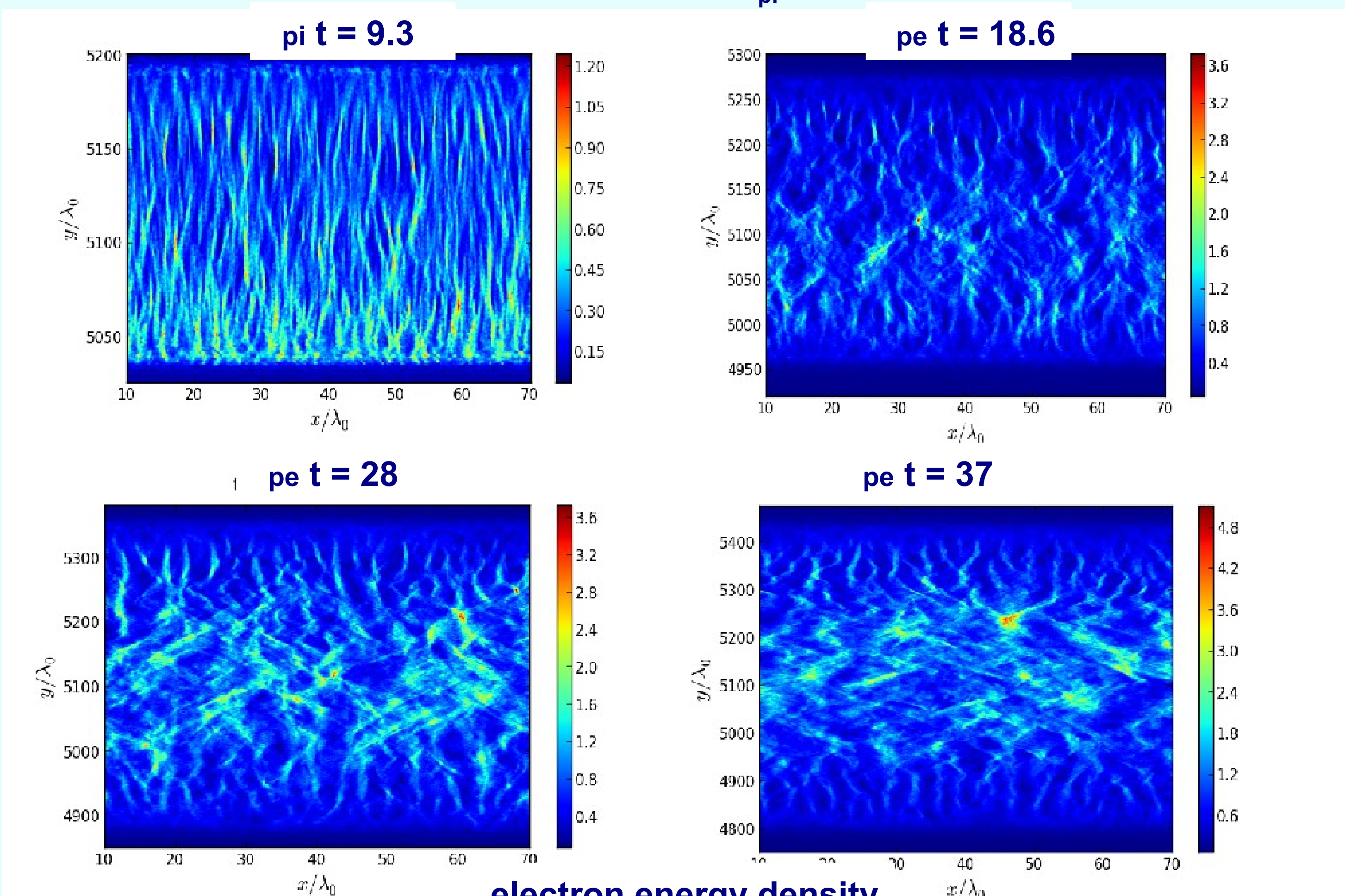
$_{pi}$ t = 10

current filaments are associated with strong small scale magnetic fields

large amplitude charge density modulations producing strong electrostatic fields

Electron heating in the filaments

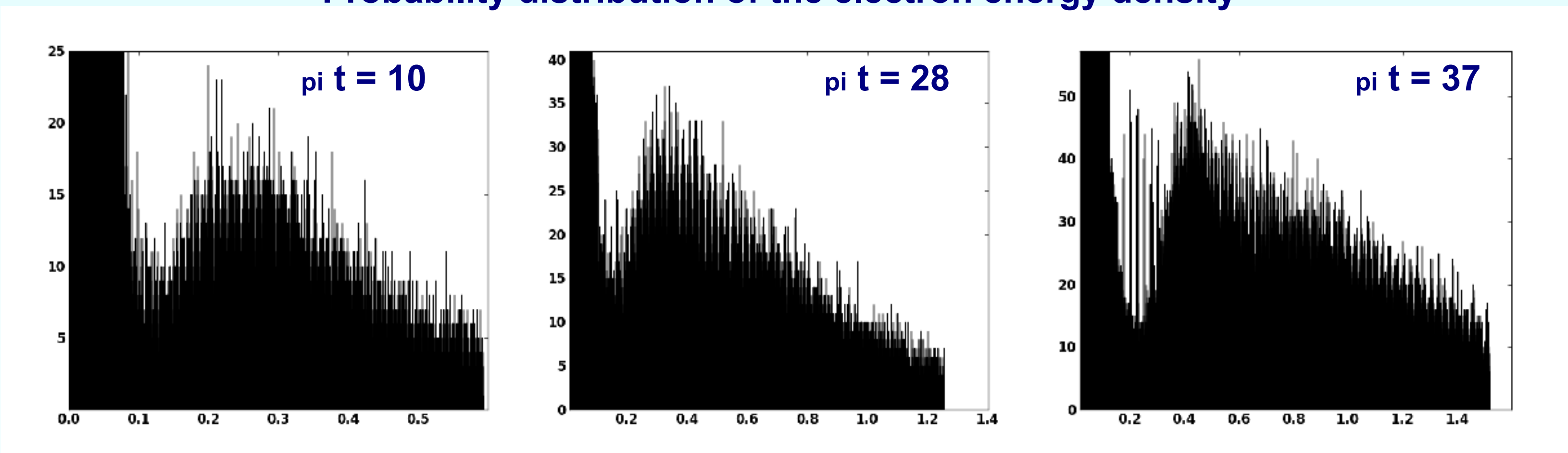
Nonlinear evolution of filaments is associated with strong electron heating – by factor of 100 in the time scale of 10 – 20 $_{pi}^{-1}$

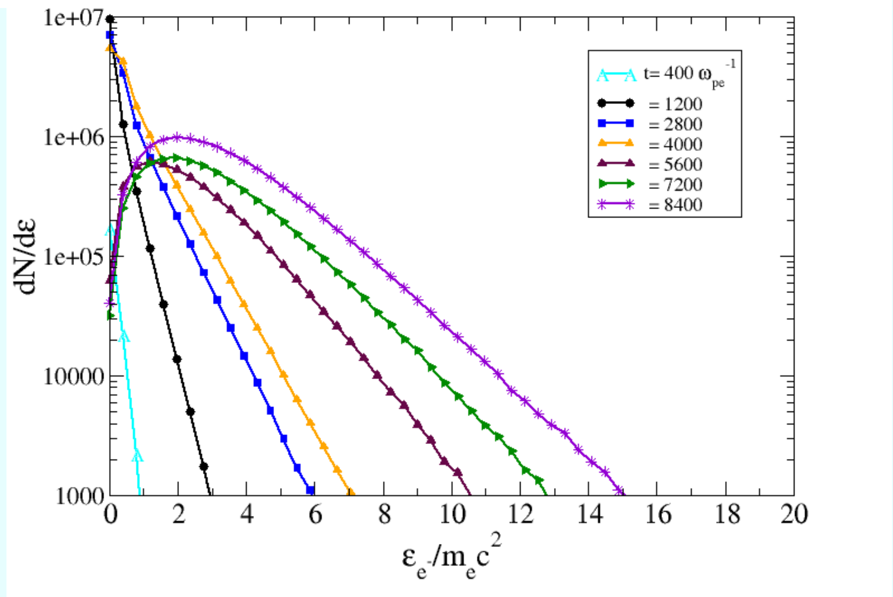


electron energy density

Temporal evolution of electron energy

Probability distribution of the electron energy density



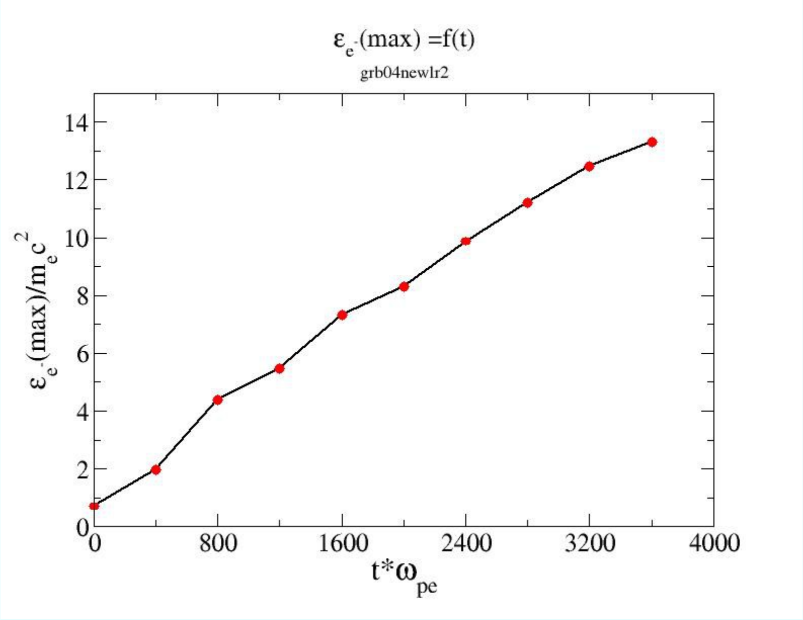


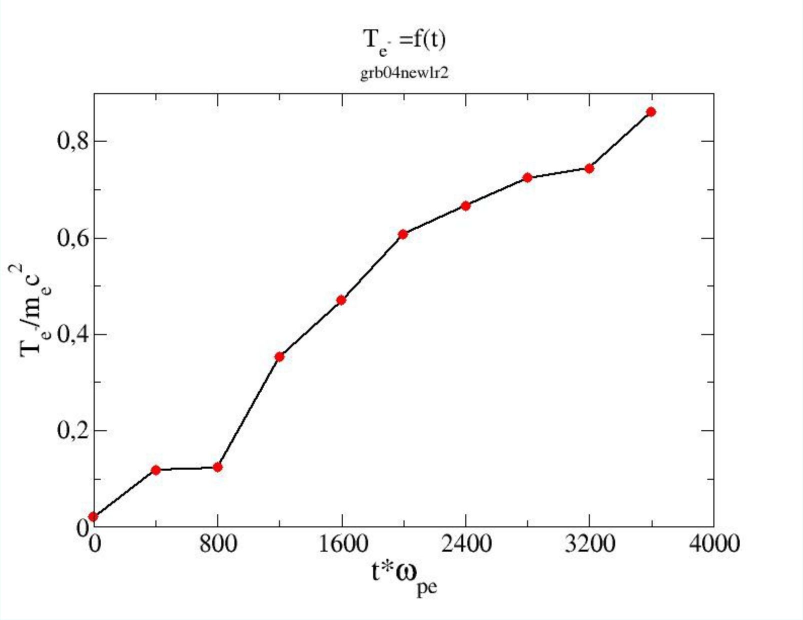
Electron energy density saturates at the average level of 0.4 with a sharp cut-off at 1.5$n_0 m_e c^2$

Electron temperature increases with time from 0.02 $m_e c^2$ to 0.9$m_e c^2$ in the time scale of 200 $_{pi}^{-}$ 1

Continuous electron heating in filaments

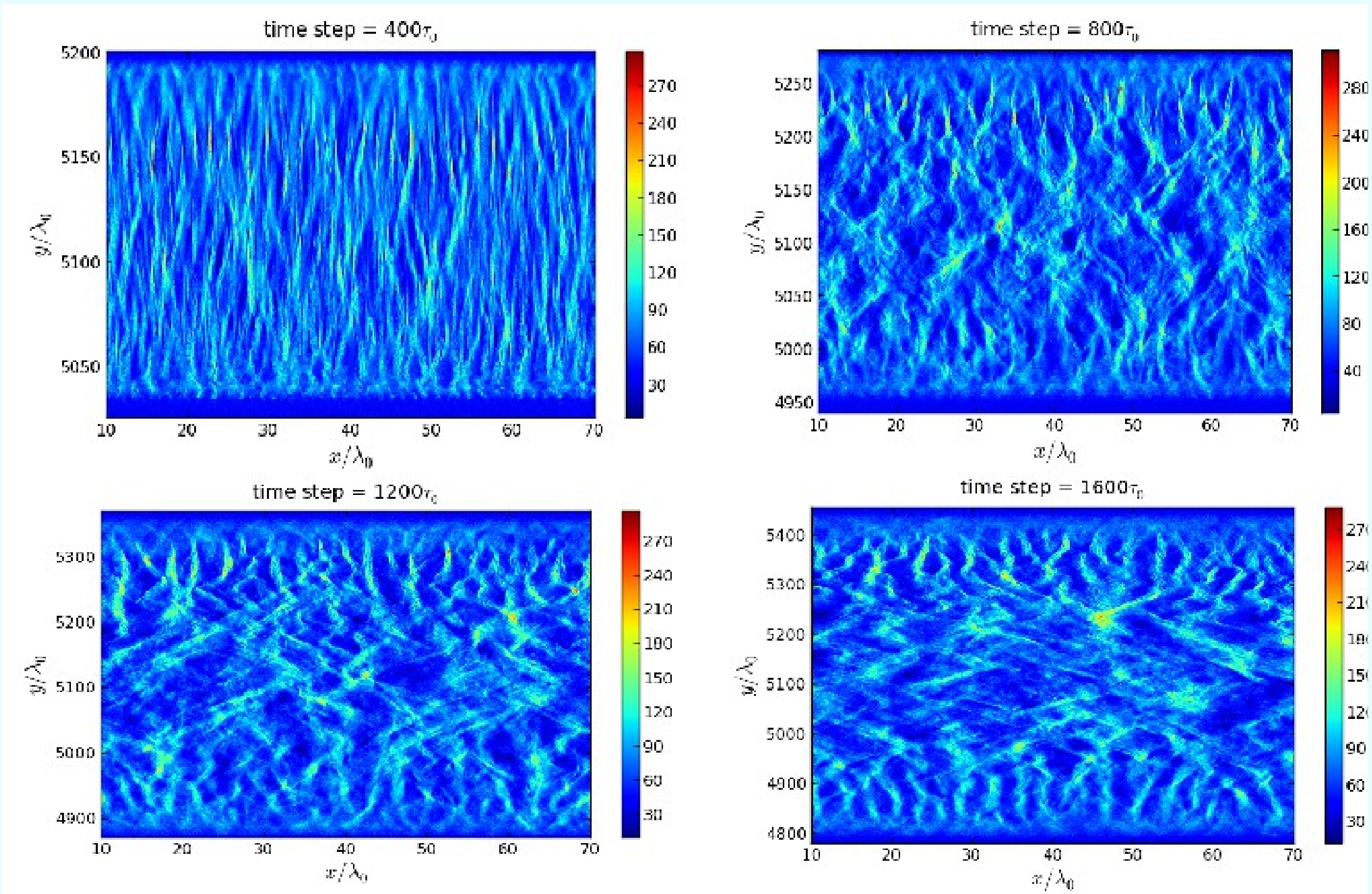
Hot electron temperature and their cut-off energy increase lineraly in time
Stochastic heating process



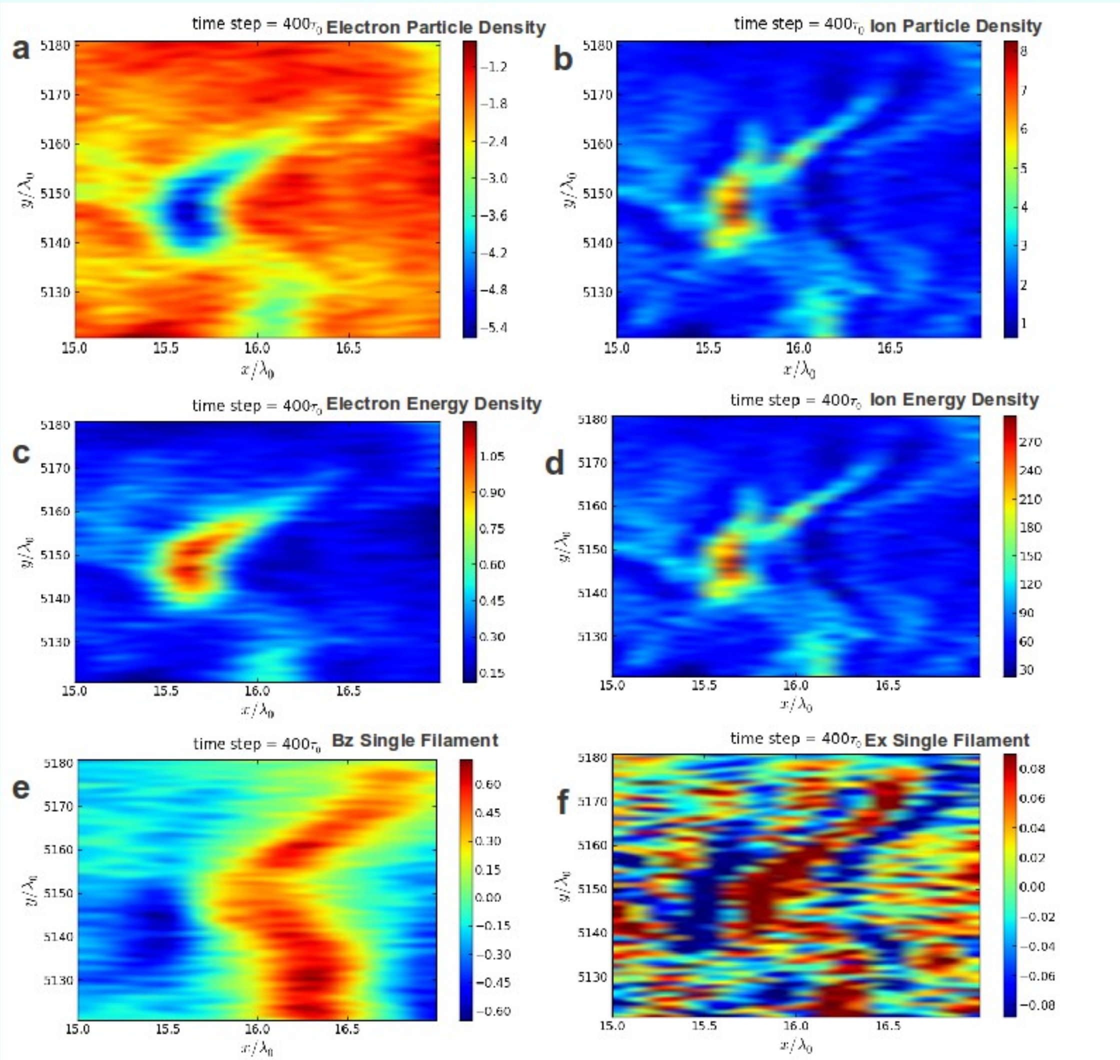


Evolution of the ion energy density

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



Single filament characterization



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

- **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 $_{pi}^{-1}$**

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 in magnetic fields in limited to the near front zone, the downstream magnetic field is relatively small
- 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

Estimates of the GRB energetics

Physical parameters of the Fireball model

Total number of protons in the jet

dN [redacted] $d\text{o}$ $\simeq$ 1 [redacted] $\gamma_i m_i c$ dE [redacted] $d\text{o}$ $\simeq$ $10^{45}\, J/sr$ [redacted] $10\, J$ $\simeq 10^{53}\, p/sr$

Proton density at the distance 10^{12} km

$n_p \simeq$ 1 [redacted] $R\,\Delta R$ dN [redacted] $d\text{o}$ $\simeq$ $10^{53}\, p/sr$ [redacted] $10\, m$ $\simeq 10^{3}\, cm^{-3}$

Proton collisional stopping power

$n_p \ell \simeq$ 1 [redacted] σ_{ie} $\simeq$ m [redacted] $\sigma_T m_e \ln \Lambda$ $\simeq 10^{30}\, m^{-2}$

- **How long is the stage of free flight ? 10^6 s**
- **Where the collisions cease to dominate ? 10^{12} m**
- **How one can transfer energy from streaming ions to electrons ? → strong electric fields**
- **What would be a mechanism of the collisionless interaction ? → plasma streaming instabilities: two-stream and Weibel – electrons and ions**
- **How the stored energy can be radiated? → electron synchrotron and/or jitter radiation**
- **How the particles can be accelerated in a shock front ?**

Evolution of the magnetic and electric fields

The magentic field is saturated quickly and is localized near the fronts. The electric field are growing in time. The parallel electric field is created due to the filmant rotation at the late stage of evolution