



HAL
open science

Numerical simulations of energy transfer in counter-streaming plasmas

M Hadj-Bachir, R Capdessus, Vladimir Tikhonchuk, Emmanuel d'Humières

► **To cite this version:**

M Hadj-Bachir, R Capdessus, Vladimir Tikhonchuk, Emmanuel d'Humières. Numerical simulations of energy transfer in counter-streaming plasmas. Summer school in the frame of ERASMUS IP “An Introduction to high power light-matter interactions (HIPOLIN 2013)”, Jul 2013, Crete Greece. hal-01332843

HAL Id: hal-01332843

<https://hal.science/hal-01332843v1>

Submitted on 16 Jun 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Numerical simulations of energy transfer in counter-streaming plasmas

M. HADJ-BACHIR

Supervisors: R. CAPDESSUS, E. d'HUMMIERES, V. T. TIKHONCHUK

Univ. Bordeaux, CEA, CNRS, CELIA, 33405 Talence France.

Email: hadjbachir@celia.u-bordeaux1.fr



Introduction

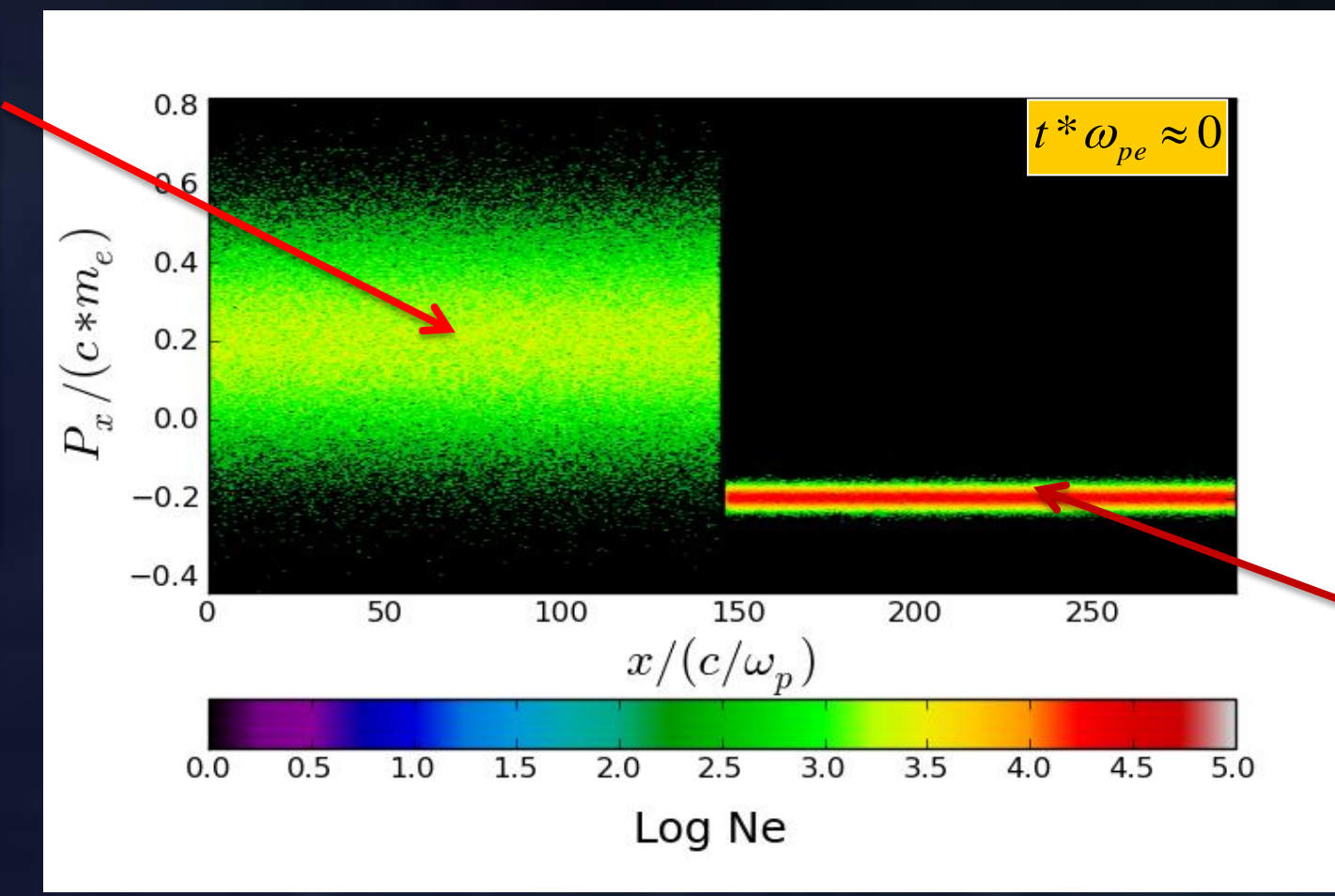
Collisionless shocks are frequent events in the universe. They transform energy of star explosion into hot plasma, high energy particles and radiation. It has been shown that the Weibel instability is a very good candidate to explain GRBs [7]. We demonstrate with particule-in-cell simulations that a part of directed kinetic energy of proton beams is converted into energy of electron, ions, electric and magnetic fields [1]. We study the shock structure and energetics of flow and we demonstrate that electron heating is an important catalyst to shock formation via filamentation instability [3], [4].

PIC simulations of sub-relativistic plasmas

We present here an analysis of a very large PIC simulations of two inter-penetrating plasmas at sub-relativistic velocities. At the initial time moment in the center-of-mass reference frame two homogenous plasmas of the density $n_0 = 10^{23} \text{ cm}^{-3}$ are facing each other in the simulation plane (x,y). All lengths are measured in terms of electron inertia length, c/ω_{pe} , the time is in inverse electron plasma frequencies, ω_{pe}^{-1} , the energy is measured in units of electron rest energy, $m_e c^2$, the electric and magnetic fields are in relativistic plasma units, $\vec{E} = cE/m_e \omega_{pe} c$ and $\vec{B} = cB/m_e \omega_{pe} c$, respectively.

Hot plasma jet 10keV representing the particles of the core engine.

$$u_p = 0.2c$$

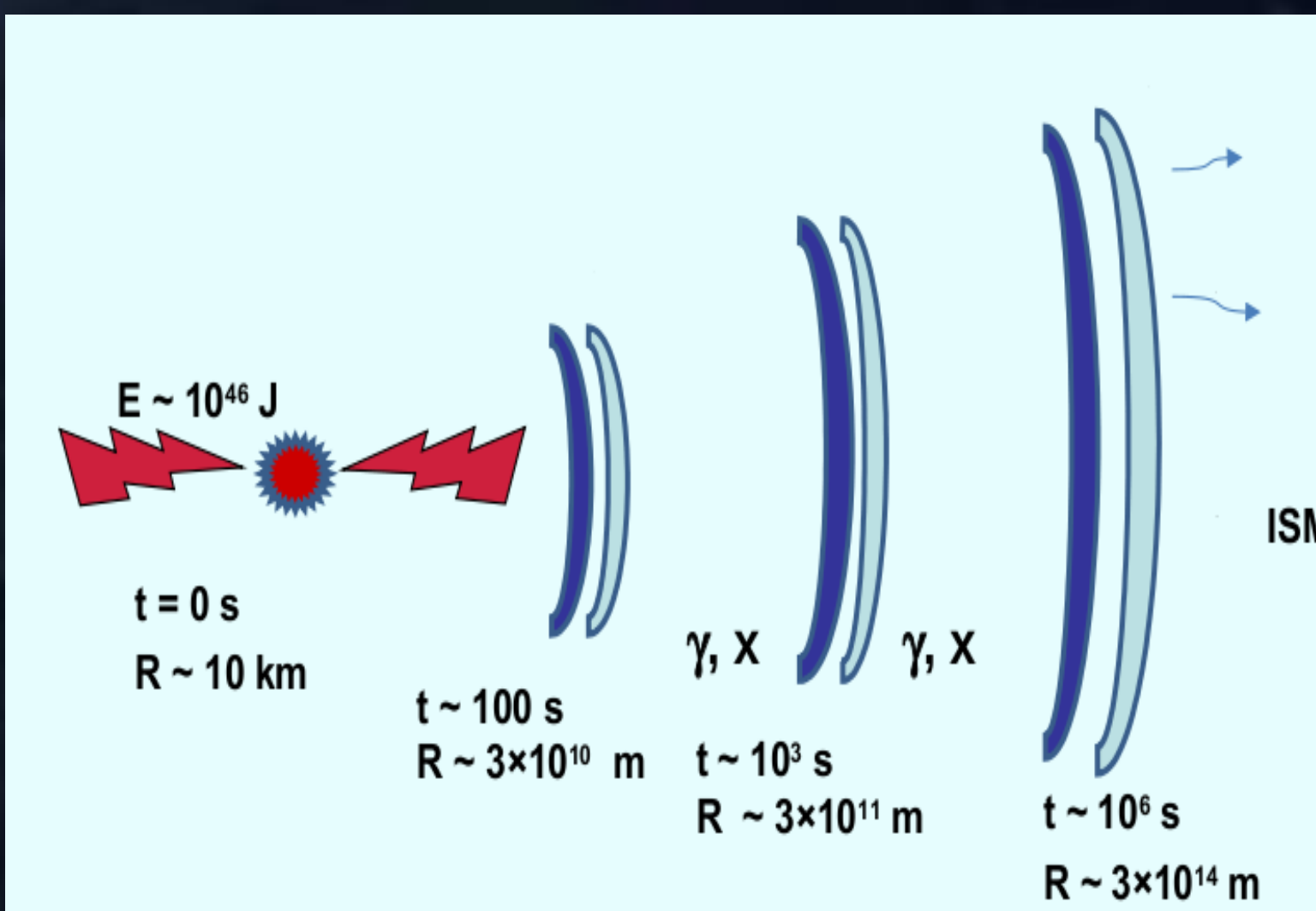


Cold plasma 100 eV representing the ISM $u_p = -0.2c$

We use the 2D version of PICLS. For these kind of numerical simulation we use at least : 160 cores, 14500 * 1000 cells of plasma, 33 of macro-particles per cell, the time step is $\Delta t = 0.1/\omega_{pe}$. Time computation is typically 2 weeks.

Temporal development of inter-penetrating plasmas

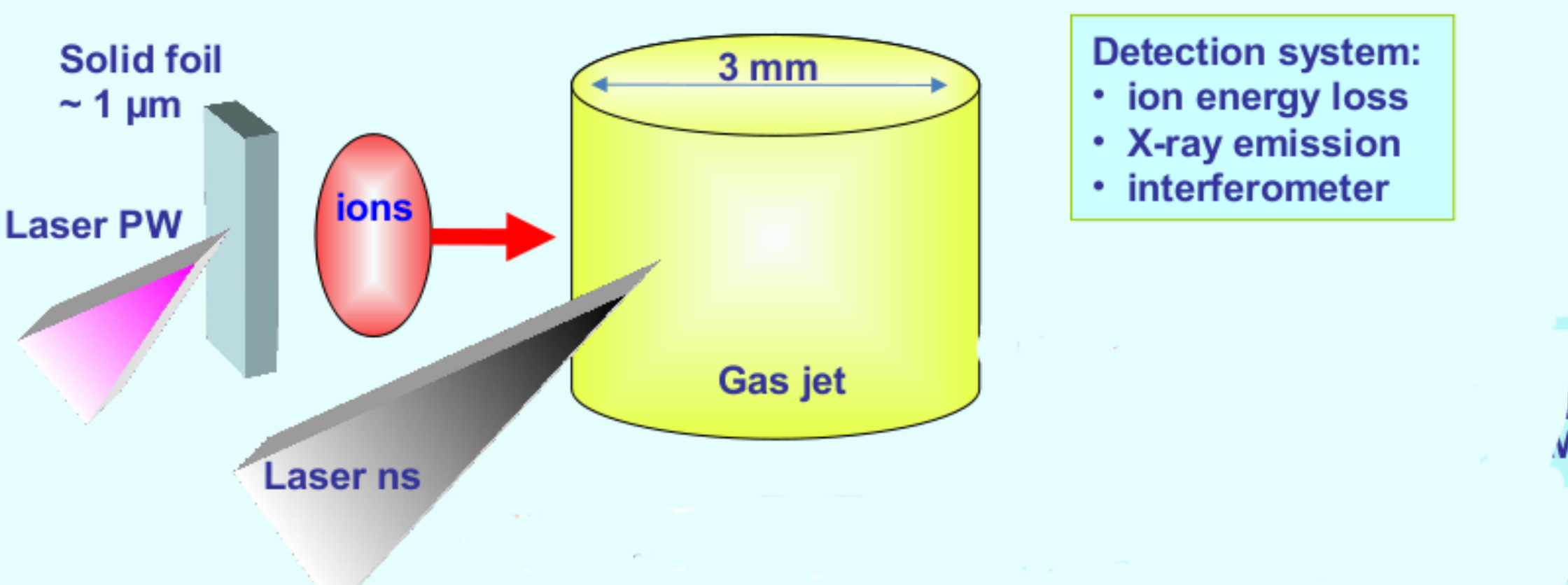
Colliding plasmas in universe.



Major hypothesis
- Transformation of the directed energy into thermal energy.
- Compton and synchrotron emission provides a radiation cooling of plasma [2].

Ejecta from the central explosion : hot plasma. Interaction with the ISM cold plasma. Relativistic factor of the jet $\gamma = 100$ explains the short pulse duration recorded by observers [2],[4].

Modeling shocks in astrophysical laboratories



Detection system:
• ion energy loss
• X-ray emission
• interferometer

First stage of interaction electron instability [2],[3]

$$u > v_{Te}, \gamma = \theta_{pe} (m_e/m_i)^{1/2} \hat{k} \parallel \vec{u} \parallel \vec{E}$$

$$u < v_{Te}, \gamma = \theta_{pe} u/c, \hat{k} \perp \vec{u} \parallel \vec{E}$$

Second stage of interaction ion-electron instability [2],[3]

$$u < v_{Te}, \gamma = \theta_{pe} u/c, \hat{k} \perp \vec{u} \parallel \vec{E}$$

The electron vortex is attached to the edge of the hot plasma and increases in size.

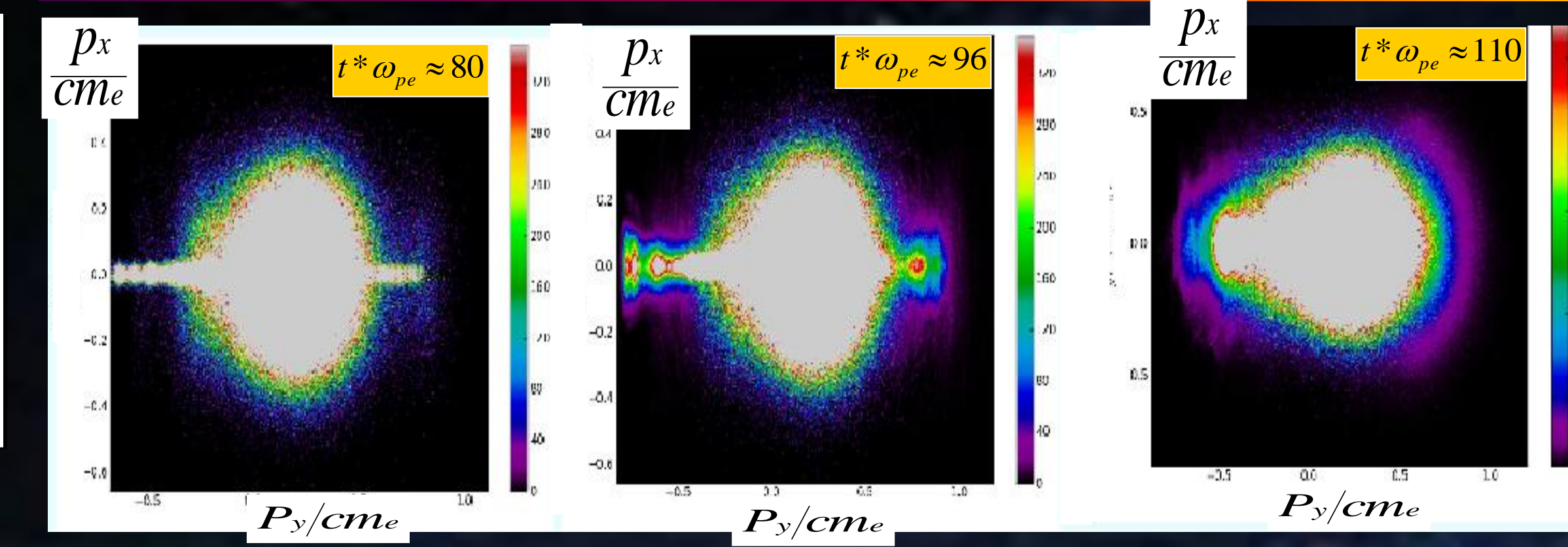
Electron mixing and heating in parallel direction stabilizes the two-stream instability but excites the Weibel instability in the transverse direction.

The characteristic field is defined by the relative electron-ion motion [2],[3]

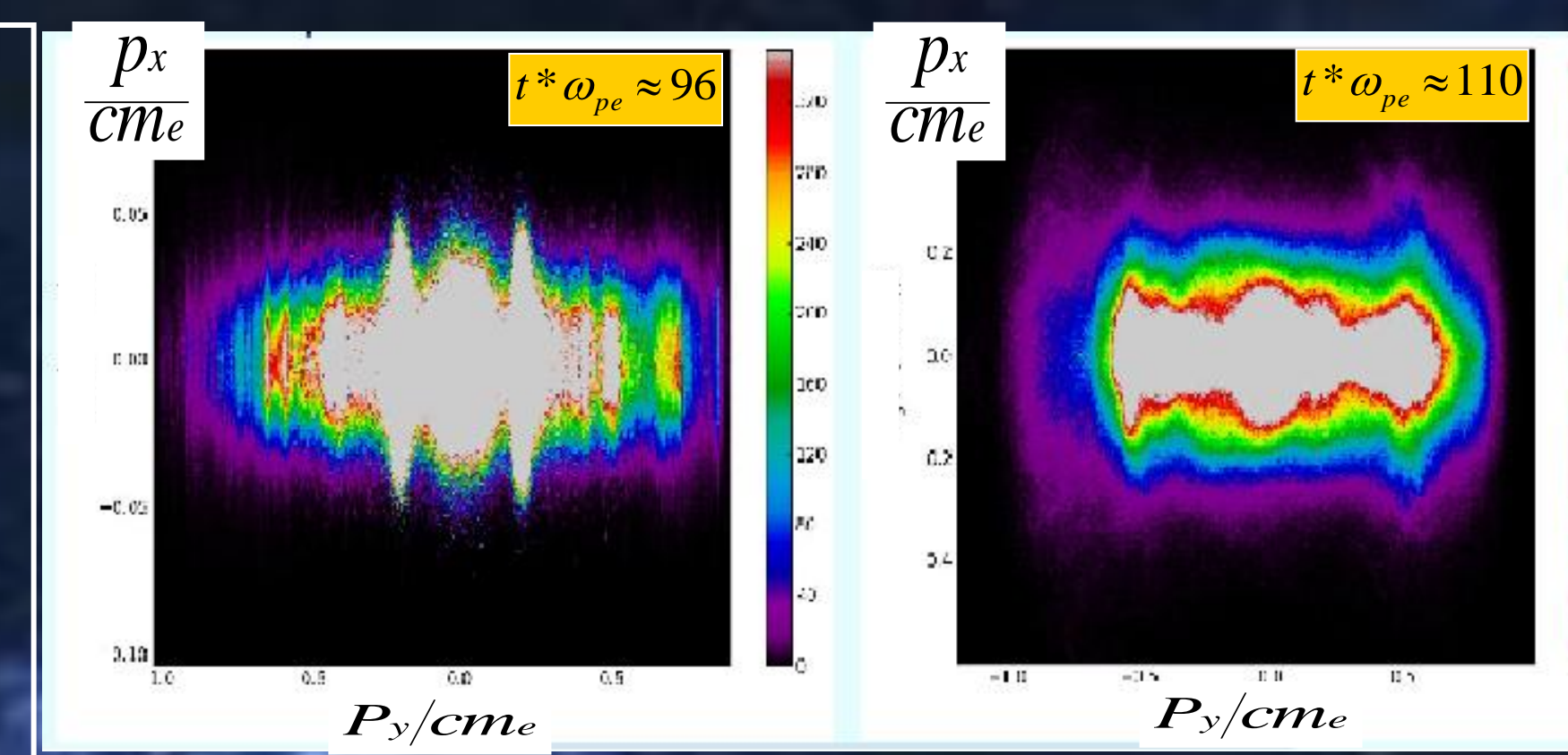
$$\gamma \approx \omega_{pe} \left(\frac{m_e}{m_i} \right)^{1/2} k_x \approx \frac{\omega_{pe}}{u}$$

$$\frac{eE_x}{m_e \omega_{pe} c} \approx 0.6 \frac{u}{c}$$

Distribution functions of the electrons. Asymmetric case 10 keV / 100 eV

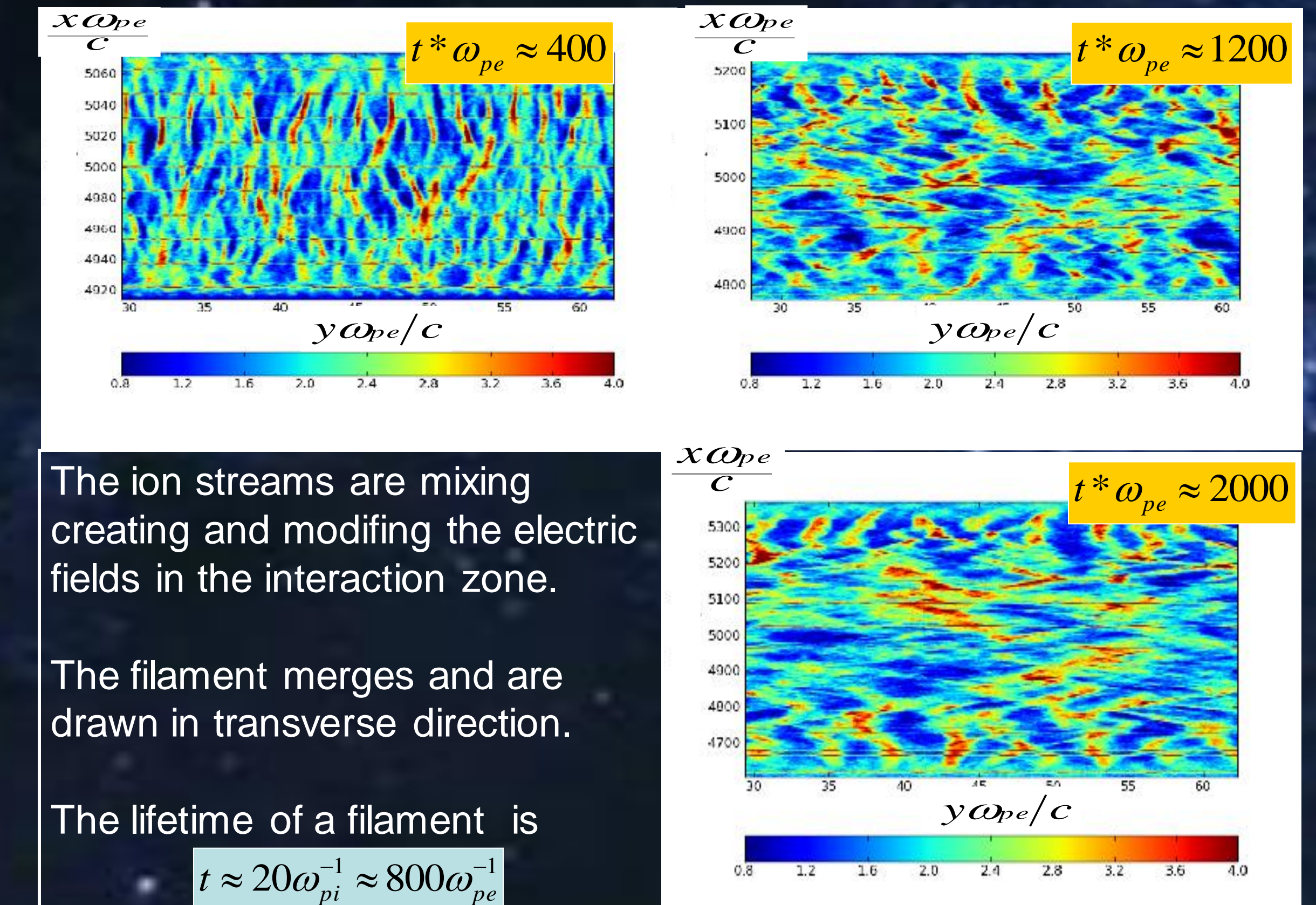


Distribution functions of the electrons. Symetric case: two cold plasmas 100 eV.



Energy transfer in the transverse direction and heating of electron.
Weibel instability leads to electron heating in the transverse direction.

Evolution of filaments



The ion streams are mixing creating and modifying the electric fields in the interaction zone.
The filament merges and are drawn in transverse direction.
The lifetime of a filament is $t \approx 20\omega_{pe}^{-1} \approx 800\omega_{pe}^{-1}$

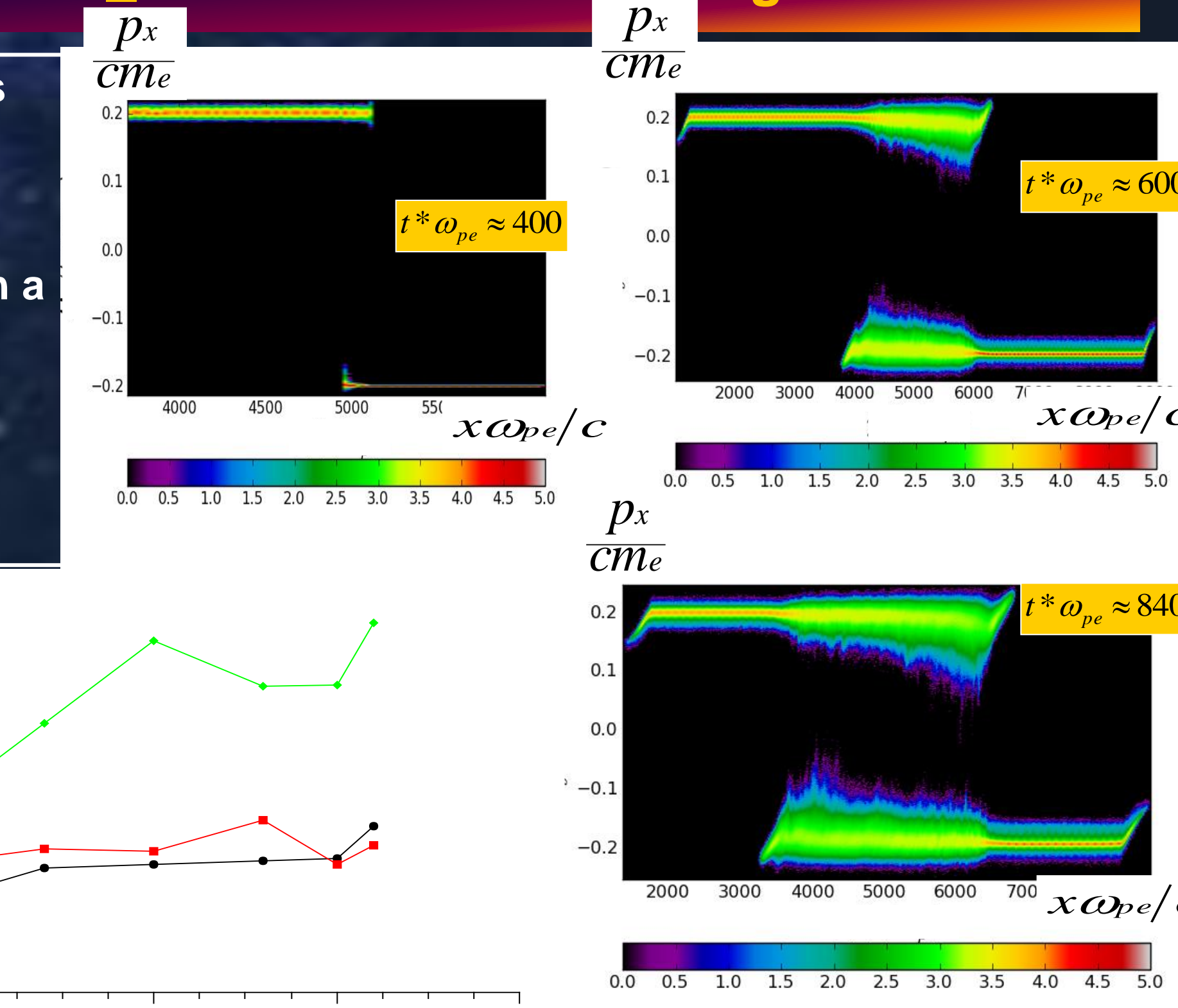
Very high energy of electrons in the filament.
Strong electrostatic field due to the charge separation.

Ions phase space time evolution over longer time scale

Mass ratio of electrons

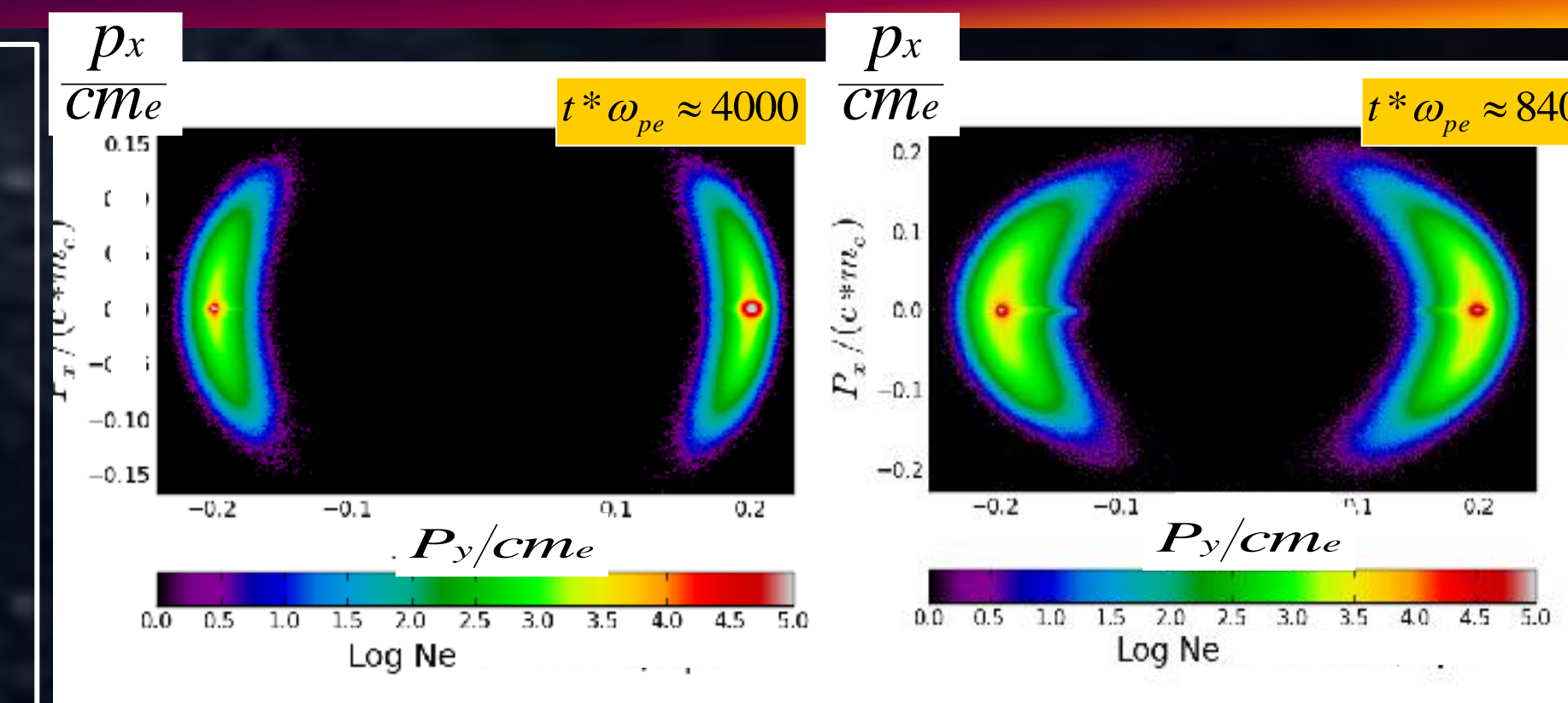
$$\frac{\omega_{pe}}{\omega_{pi}} \approx \sqrt{\frac{m_i}{m_e}} \approx 42.84$$

The ion motion starts on a longer time scale, and they lose 10% of their energy at $200\omega_{pi}$



Ions distribution functions

The electric field amplitude decreases.
magnetic field becomes dominant with the time.
Ions are stopped on higher scale of time.



Conclusion

An experiment for studying the collisionless mechanism of fast ion energy in laboratory plasma is proposed. We have performed two dimensional PIC simulations of electron-ion sub-relativistic counter-streaming plasma beams propagating without an external magnetic field. Electron heating is an important stage of shock formation. This is probably due to stochastic processes that occurs due to the strong charge separation. Radiation emission losses is due to electron synchrotron emission [7]. Simulations of similar physical processes at the GRB scale are ongoing.

References

[1] Davis S., Tikhonchuk V., E d'Humieres E., and Weber S., "Proton beam Weibel instability simulations of energy transfer in gamma-ray bursts," Journ. Physics: Conf. Series 244, 04206 (2010).
[2] V. Tikhonchuk, R. Capdessus, E. d'Humieres, S. Jequier, and S.P. Davis., "Energy transfer in counter-propagating plasmas at sub-relativistic velocities," Proceeding Prague (2013).
[3] Davis S. P., Capdessus R., d'Humieres E., Jequier S., Andriyash I., and Tikhonchuk V., "Numerical simulations of energy transfer in counter-streaming plasmas," High Energy Density Phys. 9, 213 (2012).
[4] Spitkovsky A., "On the structure of relativistic collisionless shocks in electron-ion plasmas," Astrophys. Journ. 673, L39 (2008).
[5] Martins S. F., Fonseca R. A., Silva L. O., and Mori W. B., "Ion dynamics and acceleration in relativistic shocks," Astrophys. Journ. 695, L189 (2009).
[6] Sentoku Y. and Kemp A. J., "Numerical methods for particle simulations at extreme densities and temperatures: Weighted particles, relativistic collisions and reduced currents," Journ. Comput. Phys. 227, 6846 (2008).
[7] V. Medvedev Radiation of in Weibel-generated fields: a general case, arXiv:0906.1090v1 [astro-ph.HE] 5 jun 2009.