Particle-In-Cell Simulations of the Rippled Low Mach Number Shock in High Beta Cosmic Plasma

Oleh Kobzar

Department of Gamma-ray Astrophysics

Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland

***Collaborators*:**

Jacek Niemiec – Institute of Nuclear Physics, PAS, Kraków, Poland

Takanobu Amano – University of Tokyo, Japan

Masahiro Hoshino – University of Tokyo, Japan

Shuichi Matsukiyo – Kyushu University, Japan

Yosuke Matsumoto – Chiba University, Japan

Martin Pohl – University of Potsdam and DESY-Zeuthen, Germany

KU KDM'19, Zakopane, March 6 – 8, 2019

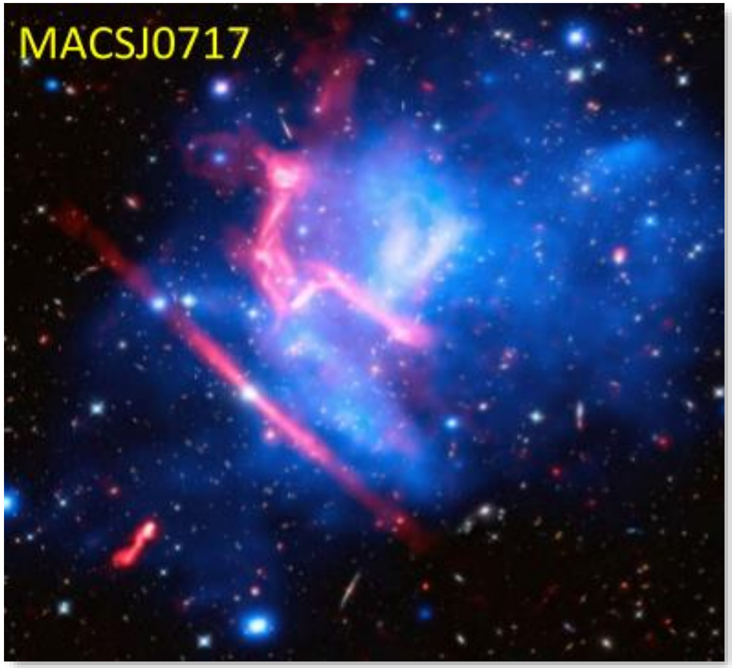
Astrophysical objects

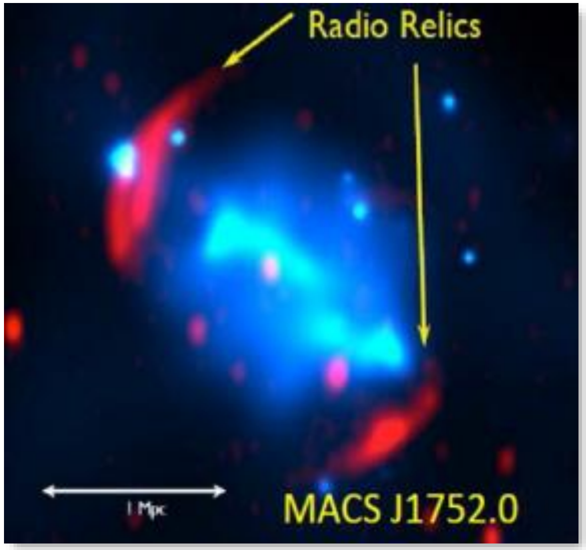
Colisionless shocks in astrophisical objects on the various scales:

- Earth's bow shock.
- Solar wind termination shock.
- Supernova remnant (SNR) shocks.
- Active galactic nuclei (AGN) shocks.
- Large-scale structure formation shocks, mostly in the clusters of galaxies:
  - turbulence shocks,
  - infall shocks,
  - merger shocks.

In the latter case, low-Mach-number (***M*<<10**) shocks are found to propagate in high-beta (**β>1**) plasmas.

X-ray and radio emission show the electron acceleration to non-thermal energies.

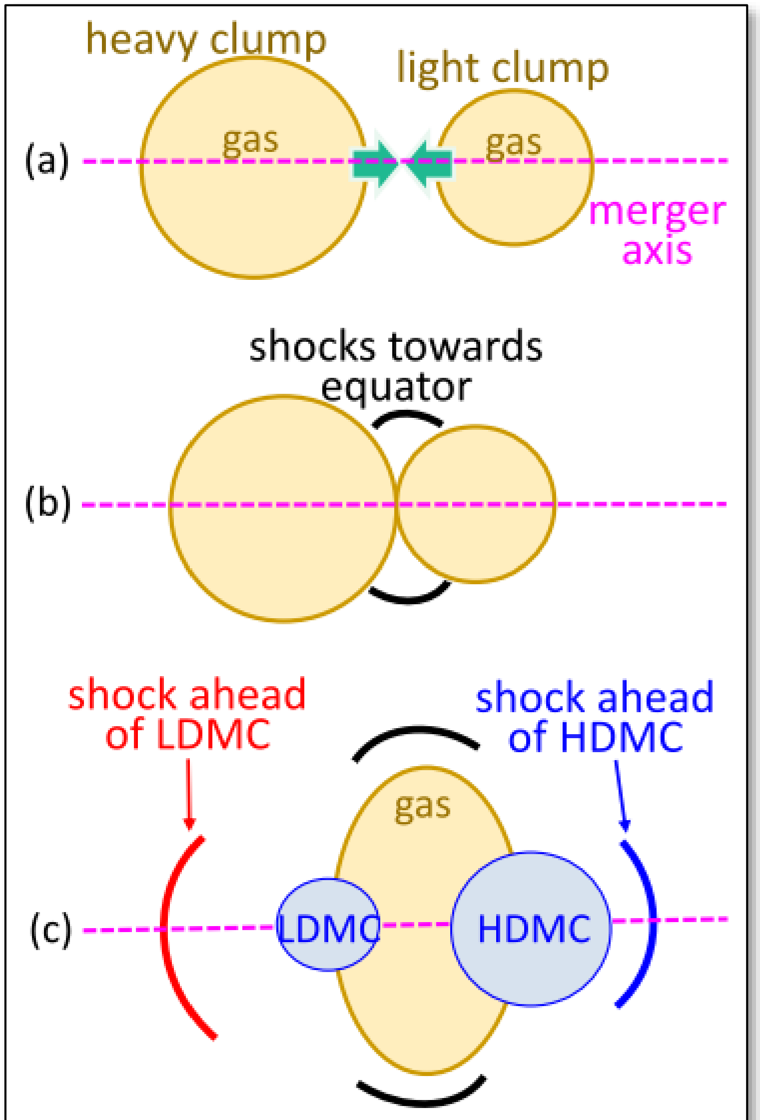




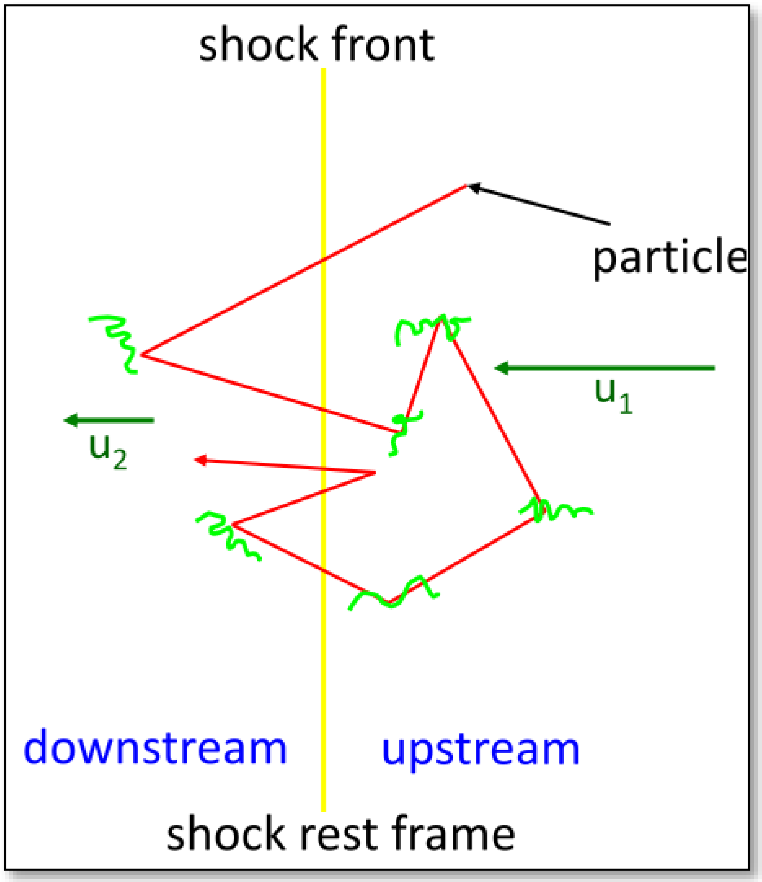
White – optical (Hubble)
Blue – X-ray (Chandra)
Red – radio (VLA)

Shock forming and particles acceleration

Simple binary galaxy merger



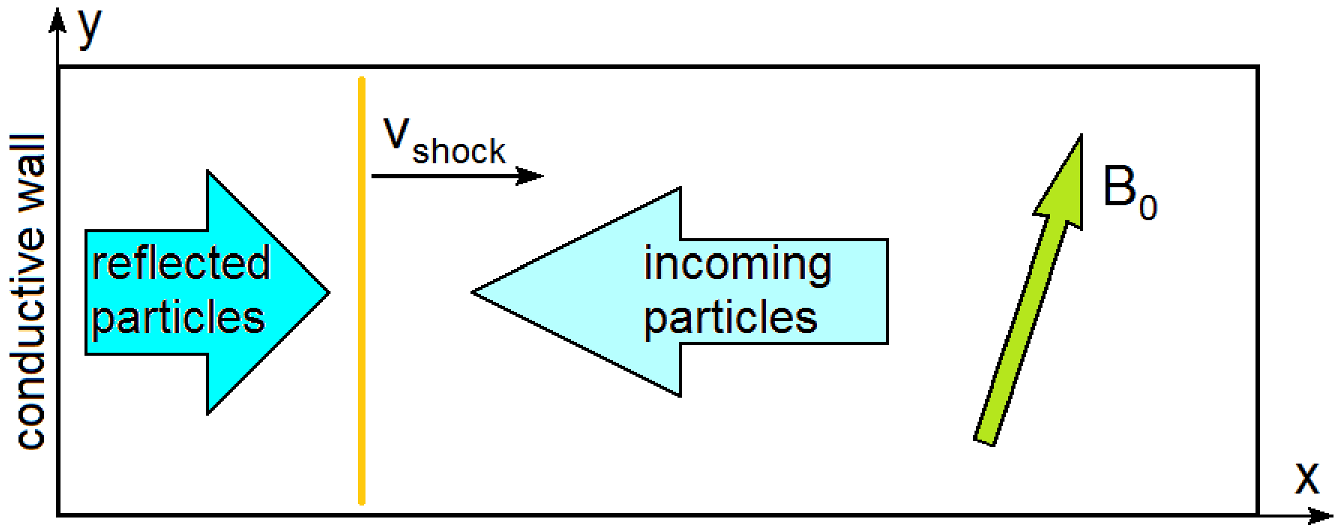
Simple scheme of the DSA



***Injection problem*:**

Particle should be pre-accelerated to be involved in the DSA process

2D-3V Particle-In-Cell simulation



2-component proton-electron plasma.

Shock is formed via interaction between reflected and incoming particles.

$\boldsymbol{L_x} = 65{,}000\ \Delta \approx 433\ \lambda_{si}$ $\boldsymbol{L_y} = 4{,}800\ \Delta \approx 32\ \lambda_{si}$

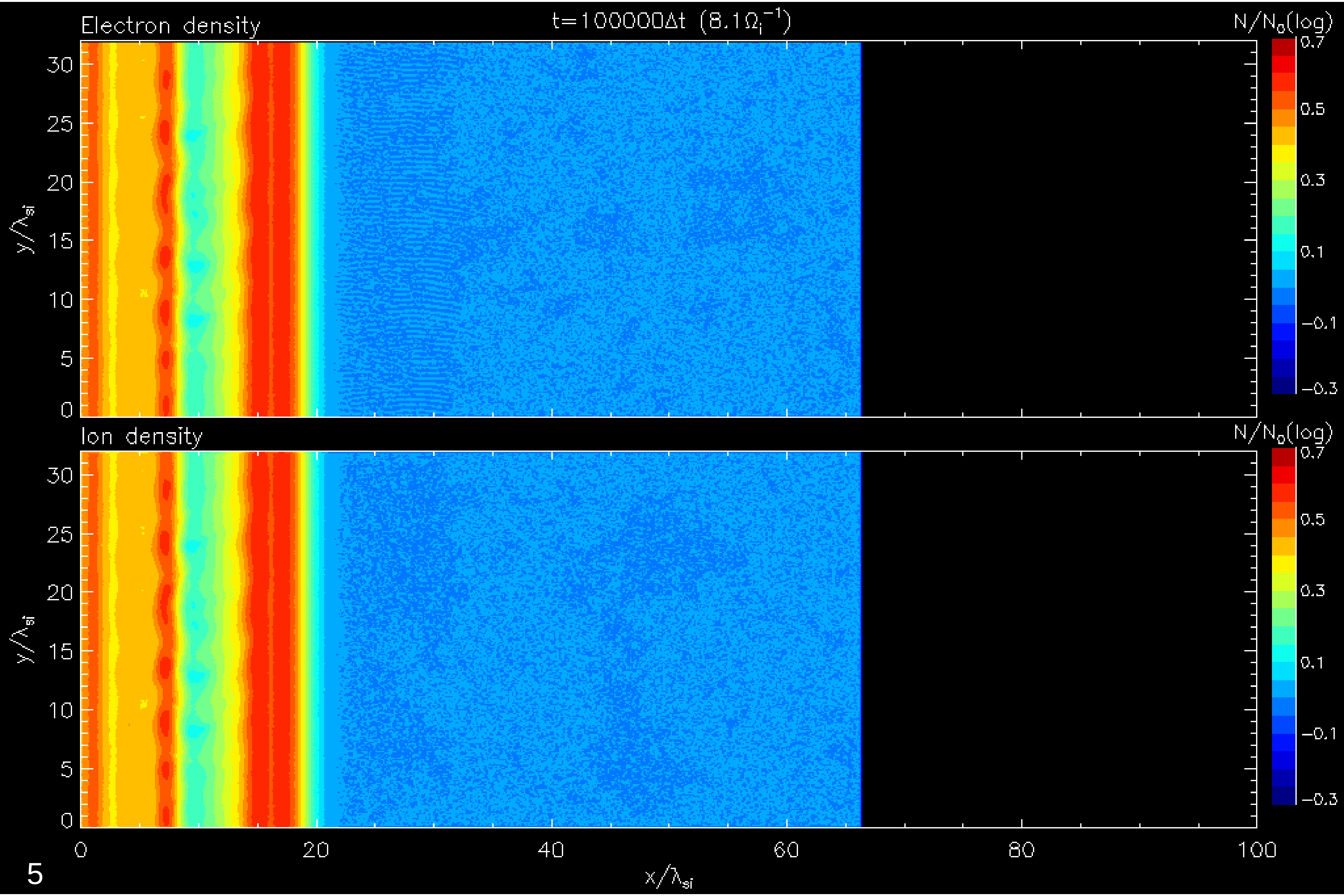
***Physical parameters*:**

- Reduced ion to electron mass ratio $m_i/m_e = 100$
- Upstream plasma velocity $v_0 = 0.1c$
- Electron/ion thermal velocity $v_{e/i\ th} \approx 0.387c\ /\ 0.0387c$ (plasma temperature $k_B T \approx 40$ keV)
- Sonic Mach number of the shock $M_s = 3$
- Alfven Mach number of the shock $M_A \approx 6$
- Plasma beta ($\beta = p_{therm}/p_{mag}$) $\beta = 5$
- Magnetic field orientation $\theta = 75°$

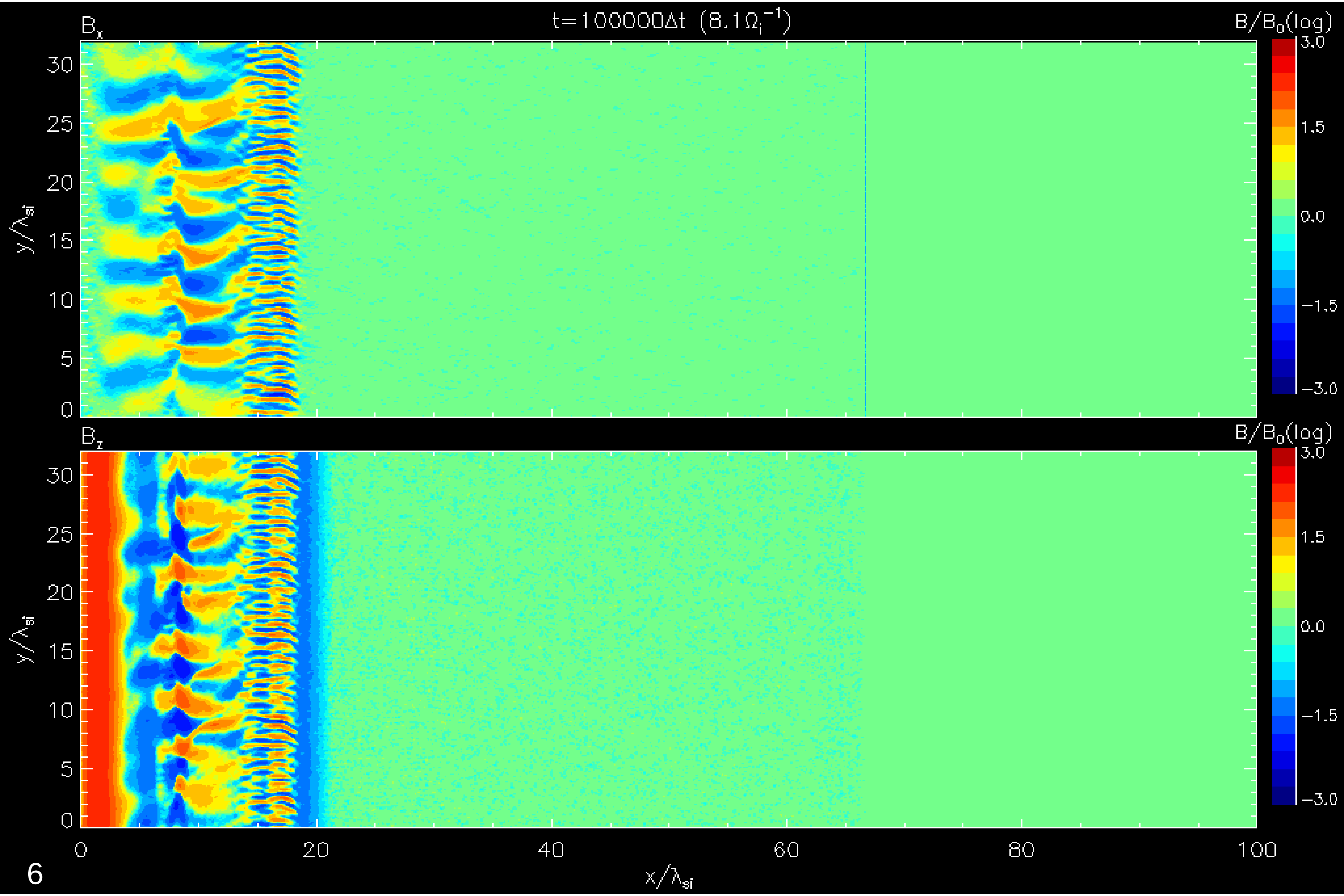
***Computations*:**

- on *PROMETHEUS* cluster
- up to 6240 CPU cores
- ~ 10 mln of CPU-hours
- ~ 60 TB of disk space used for data output

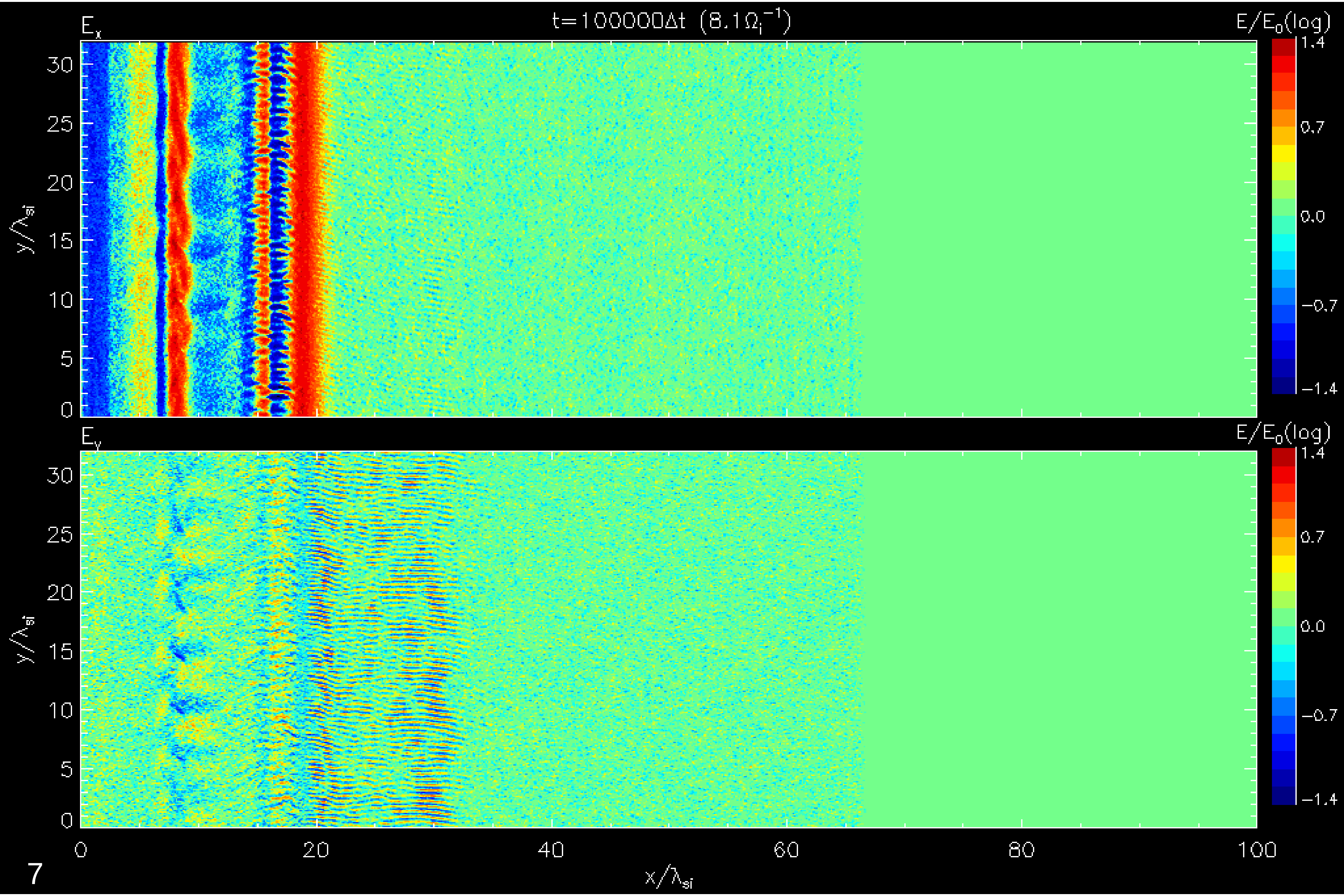
Global system evolution: *Plasma density*



Global system evolution: *Magnetic field*

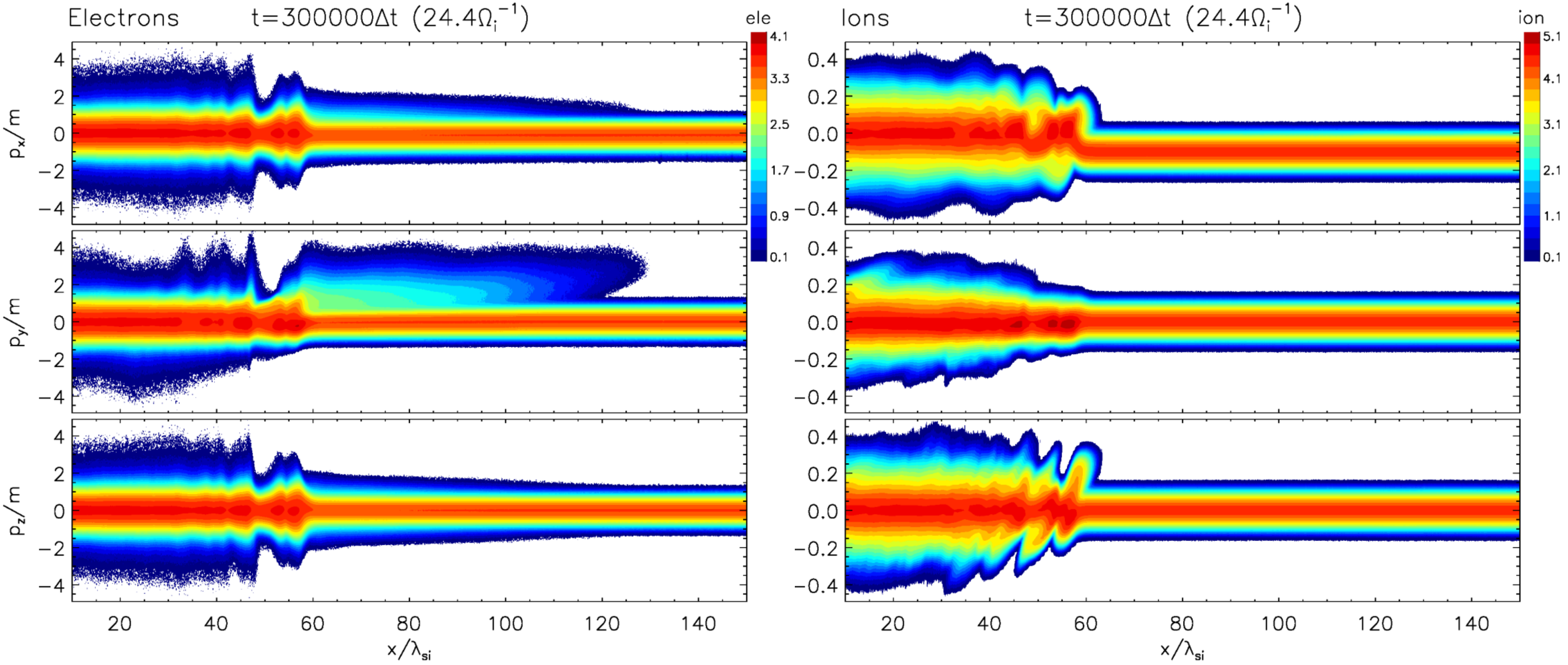


Global system evolution: *Electric field*



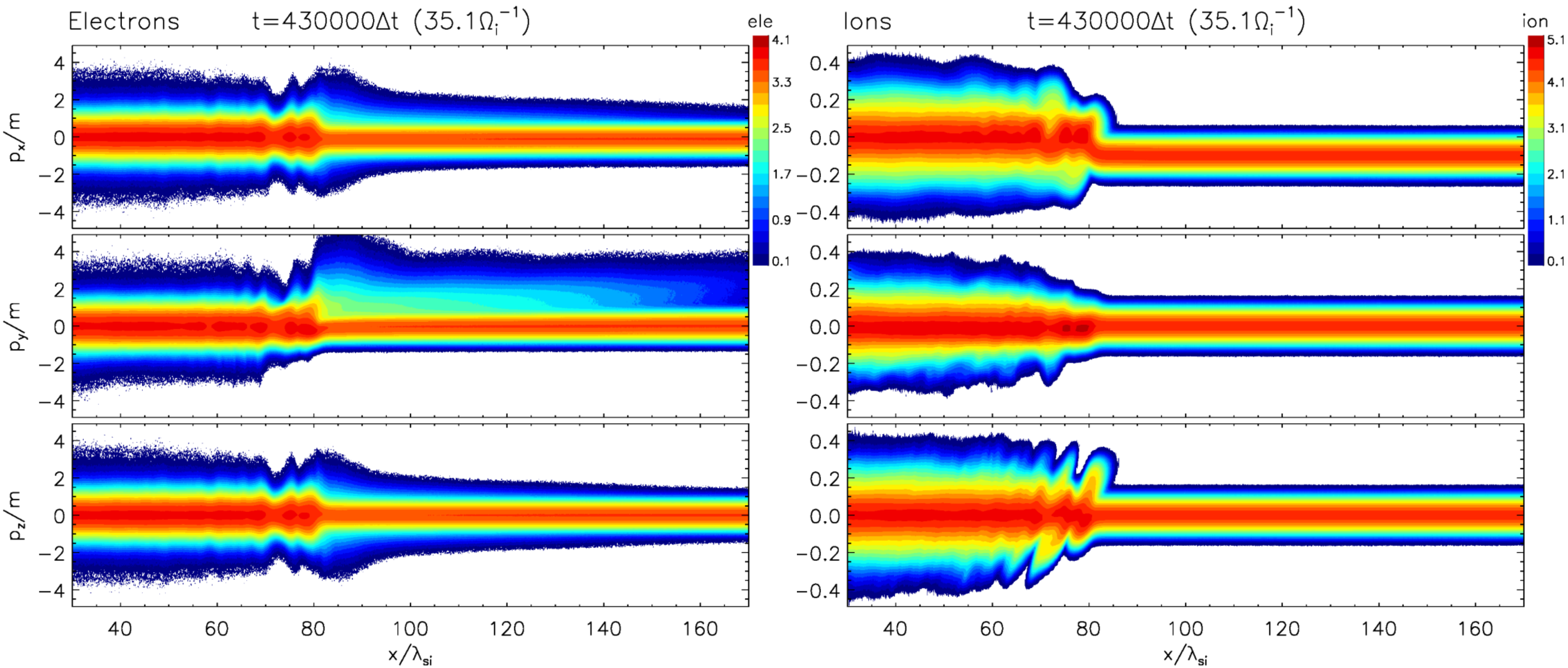
Phase space evolution:

Laminar shock

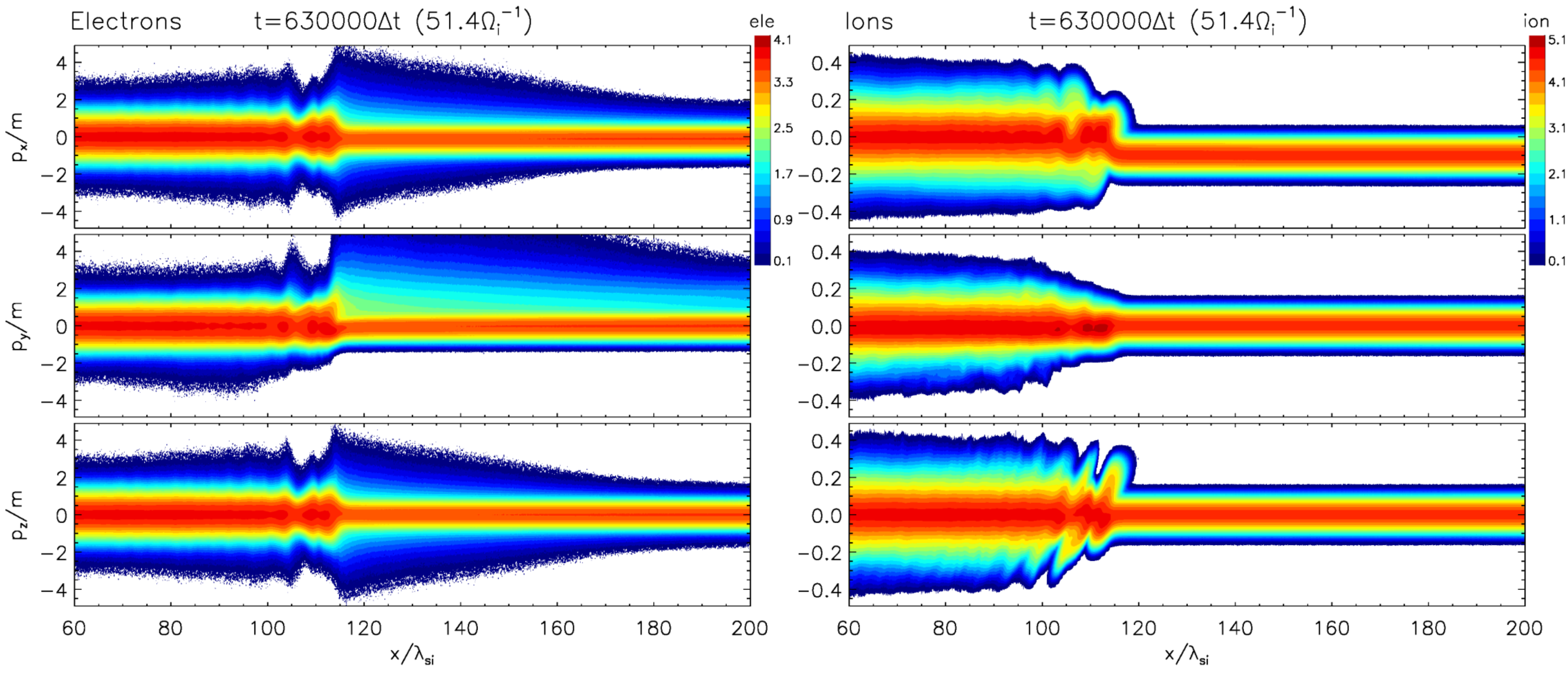


Phase space evolution:

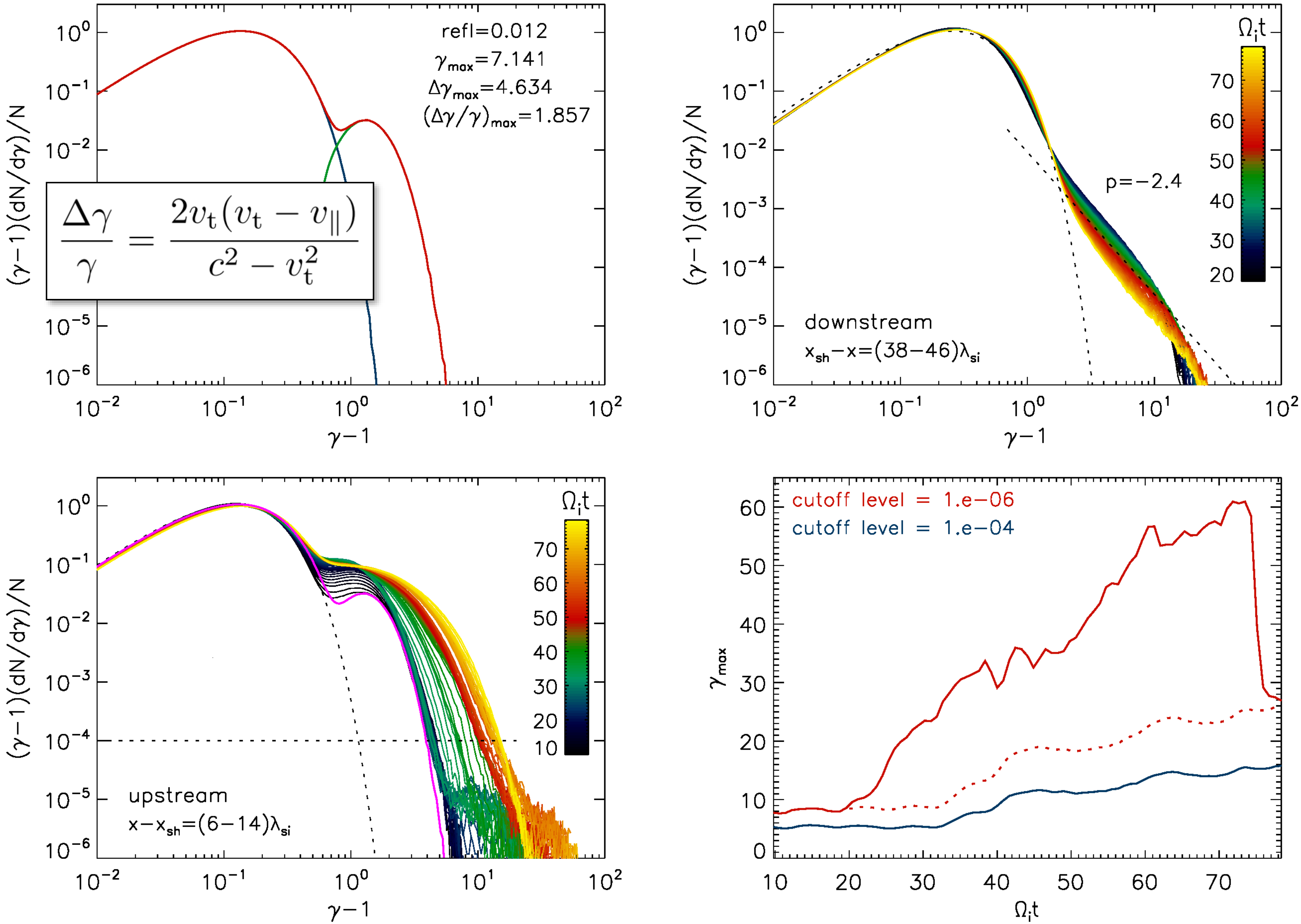
After rippling appearance

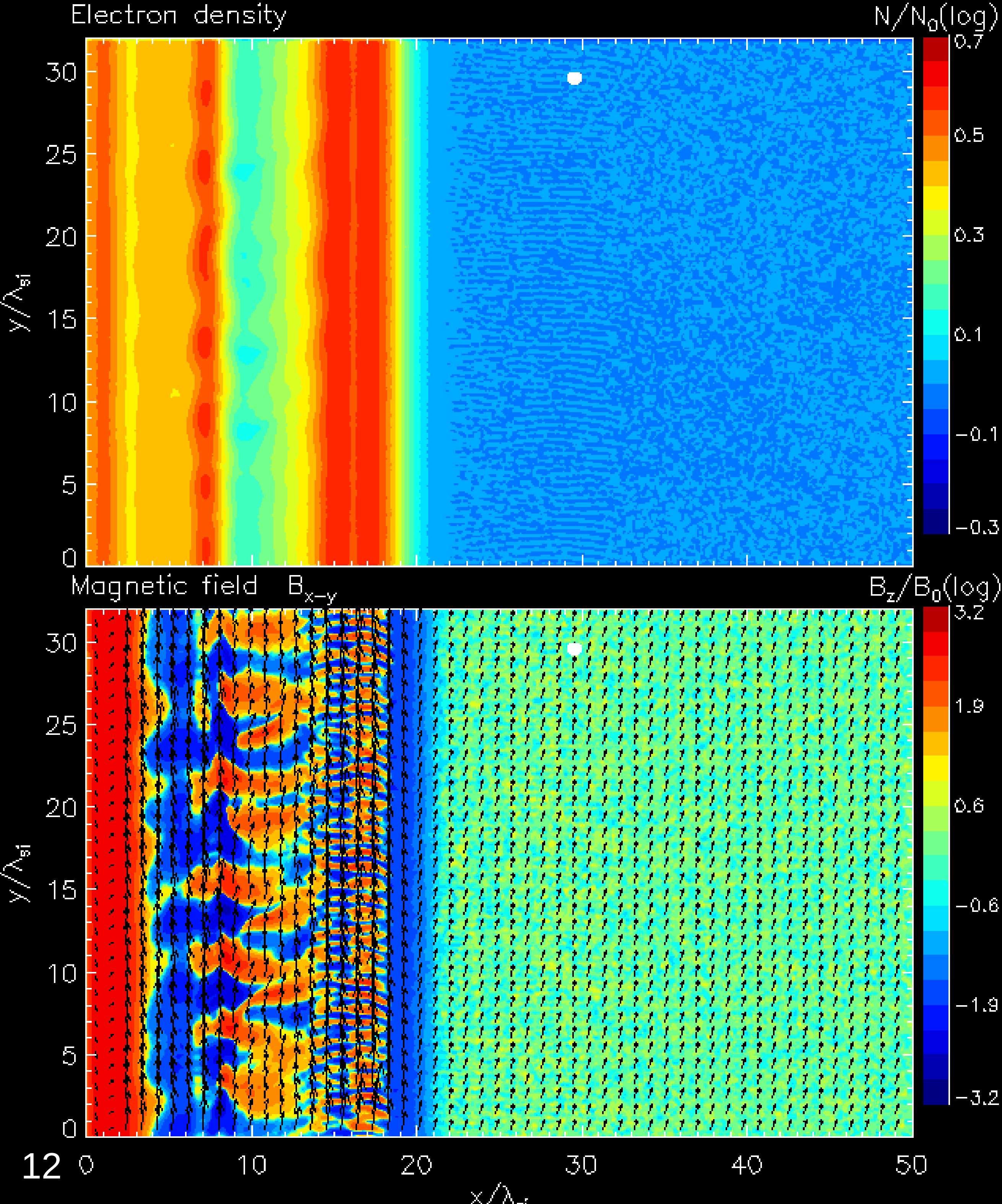


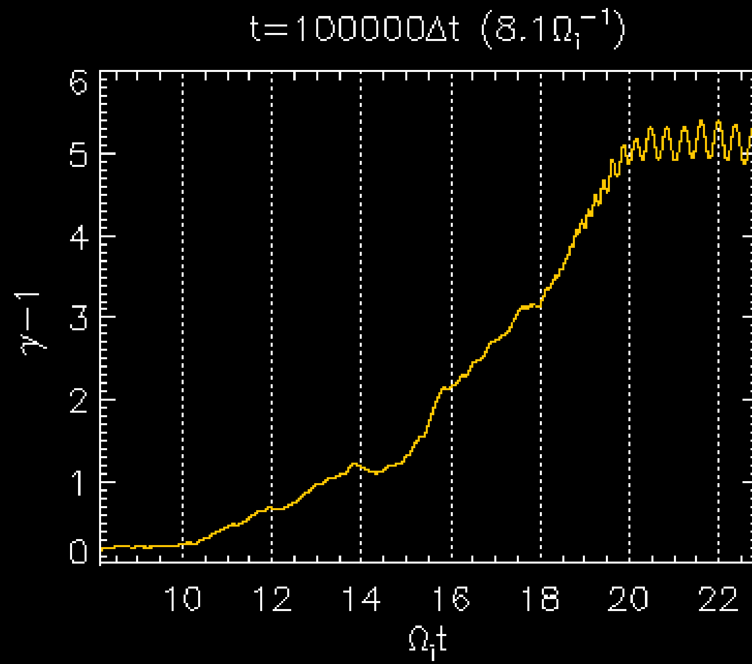
Phase space evolution:
Rippling is well developed



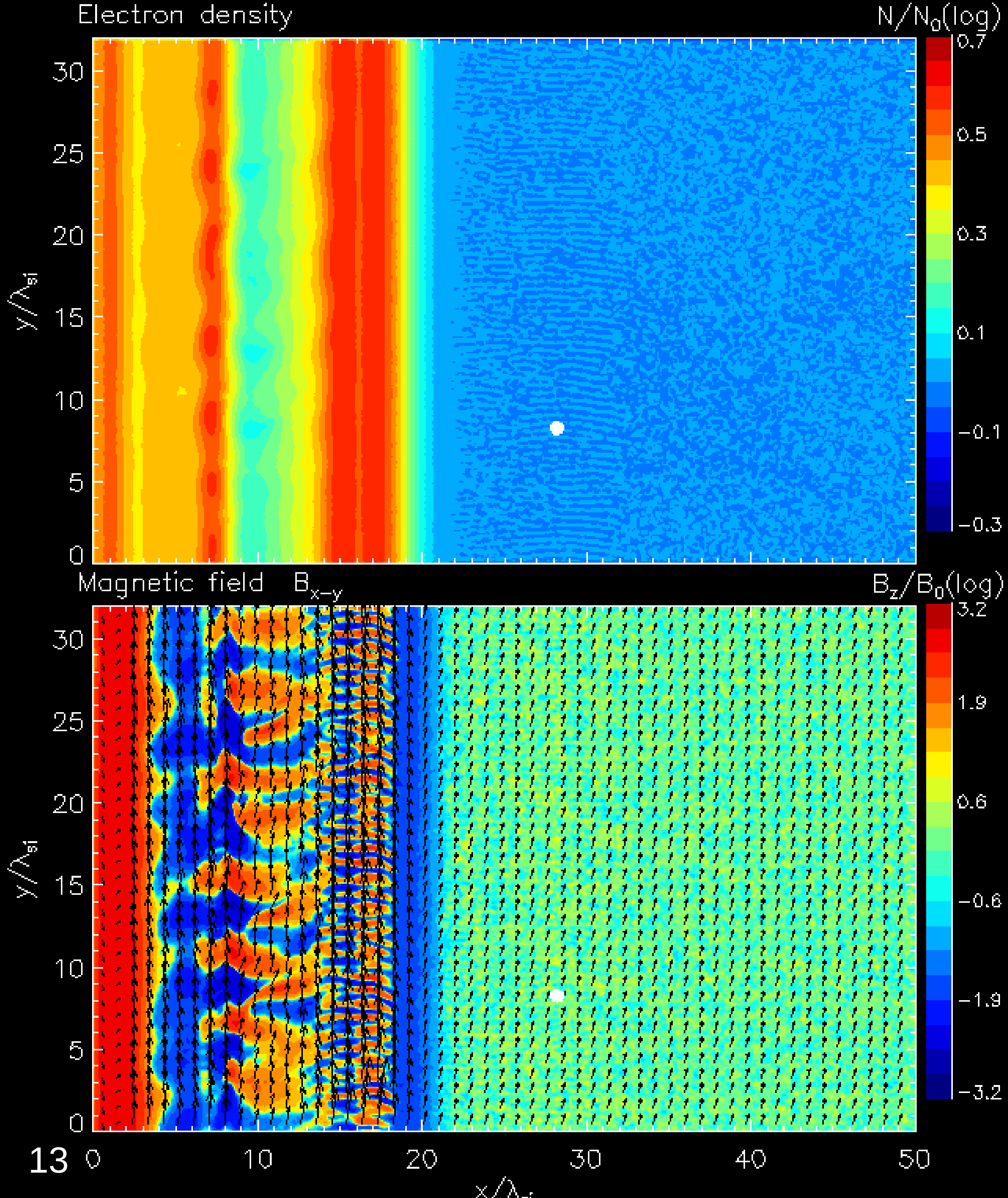
Time evolution of the electron energy spectra

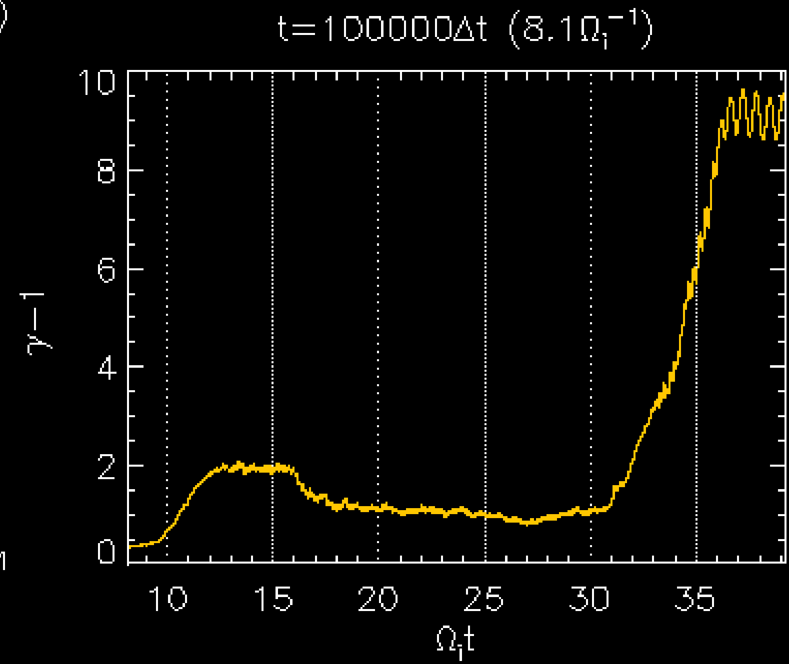




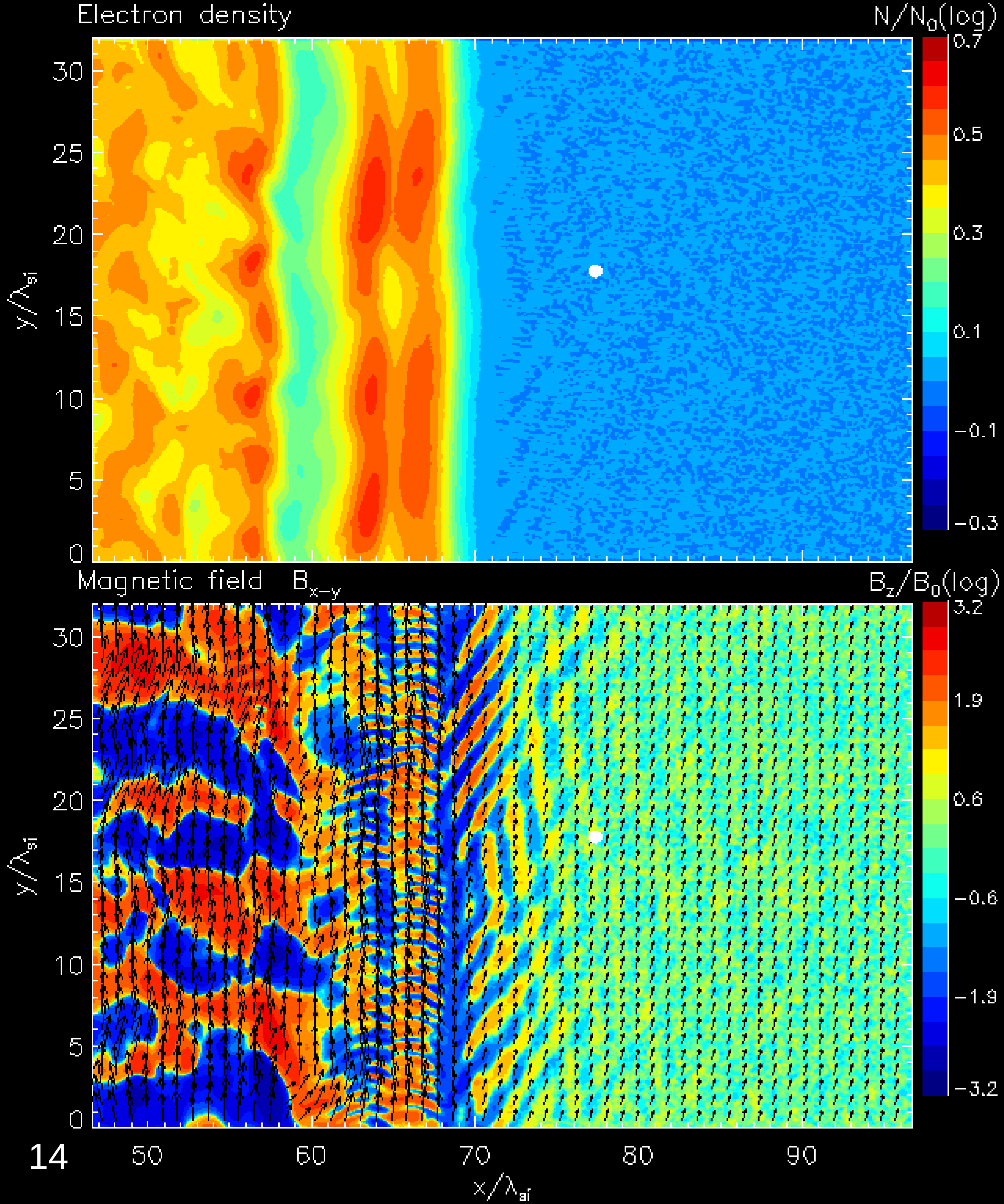


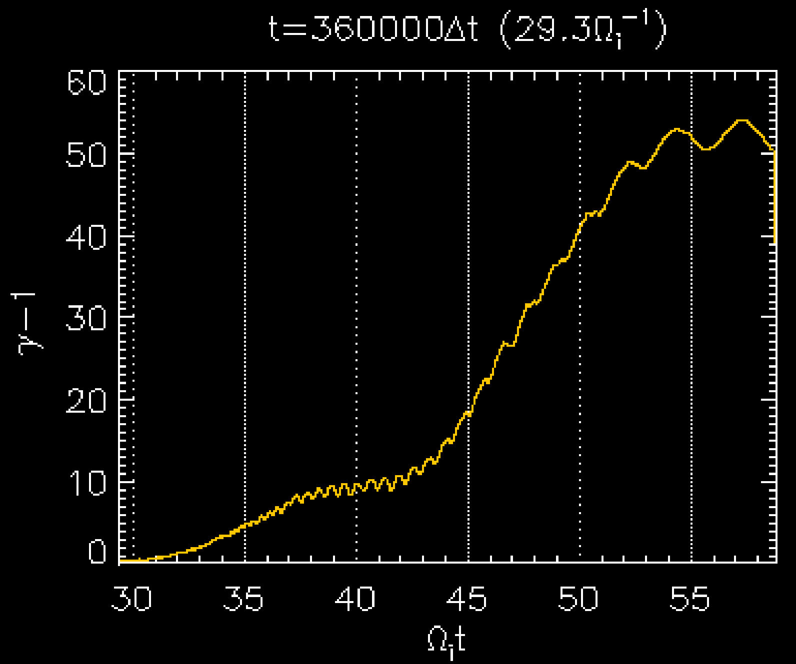
Electron undergoing the **single-cycle** (regular) **SDA** acceleration process at the shock front



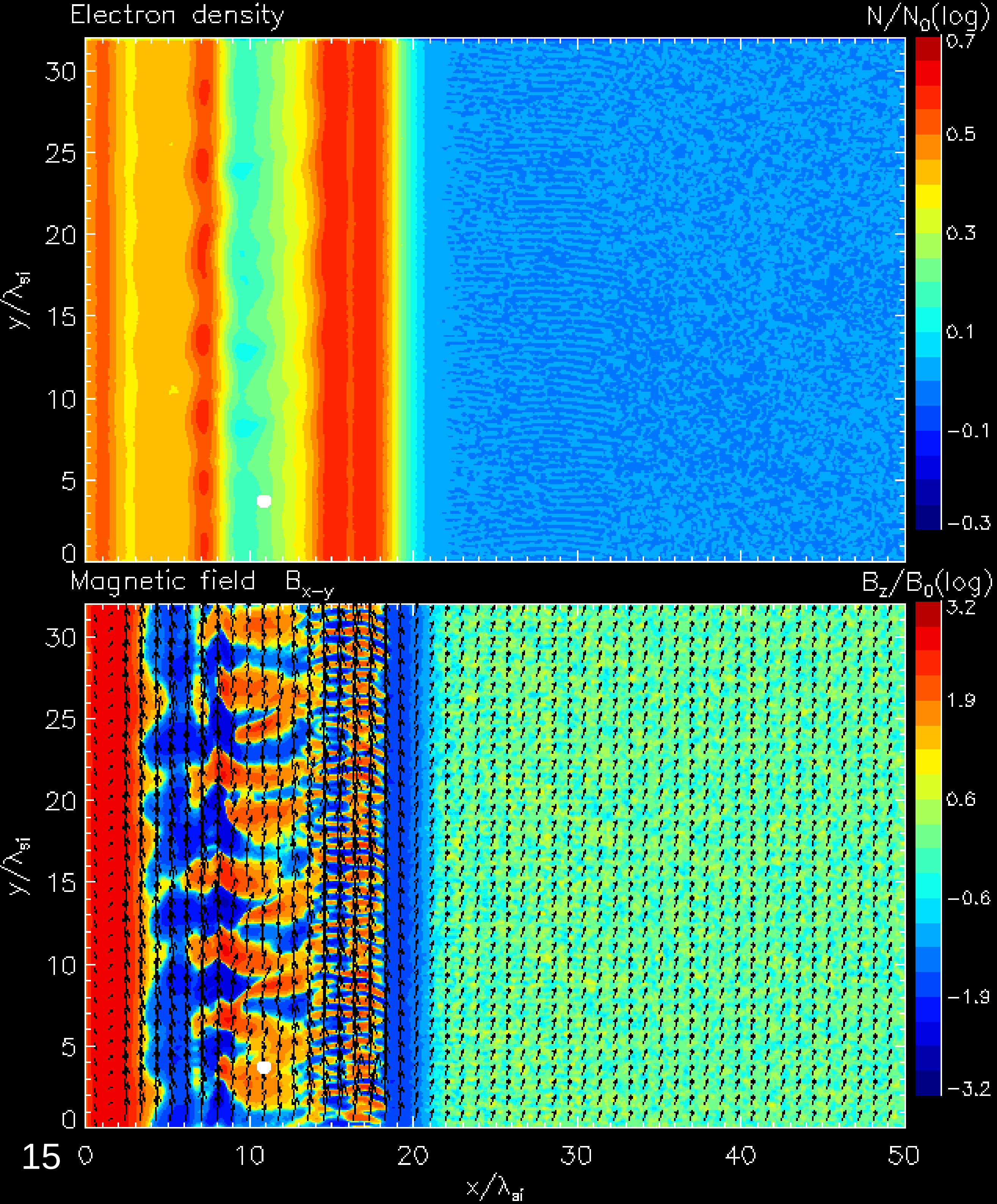


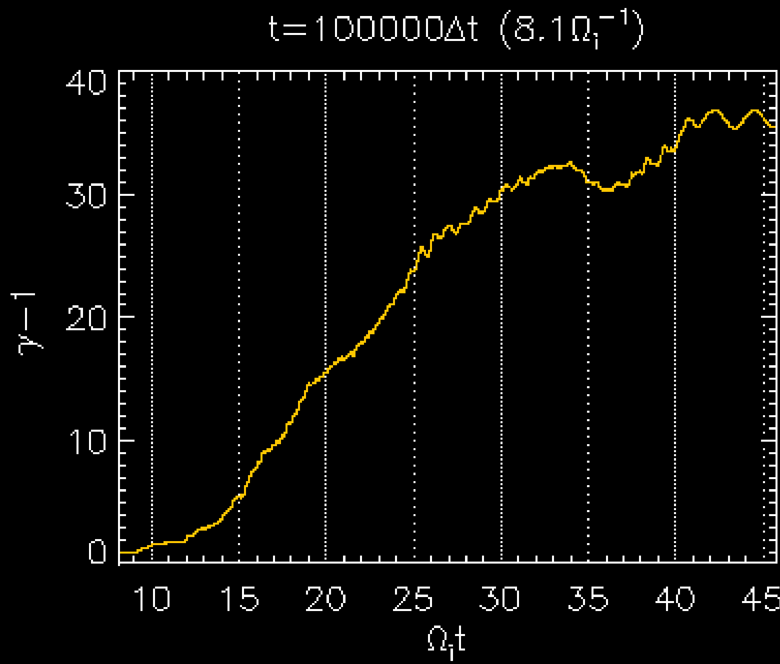
Electron undergoing
the **multi-cycle** (double)
SDA acceleration
process at the shock front





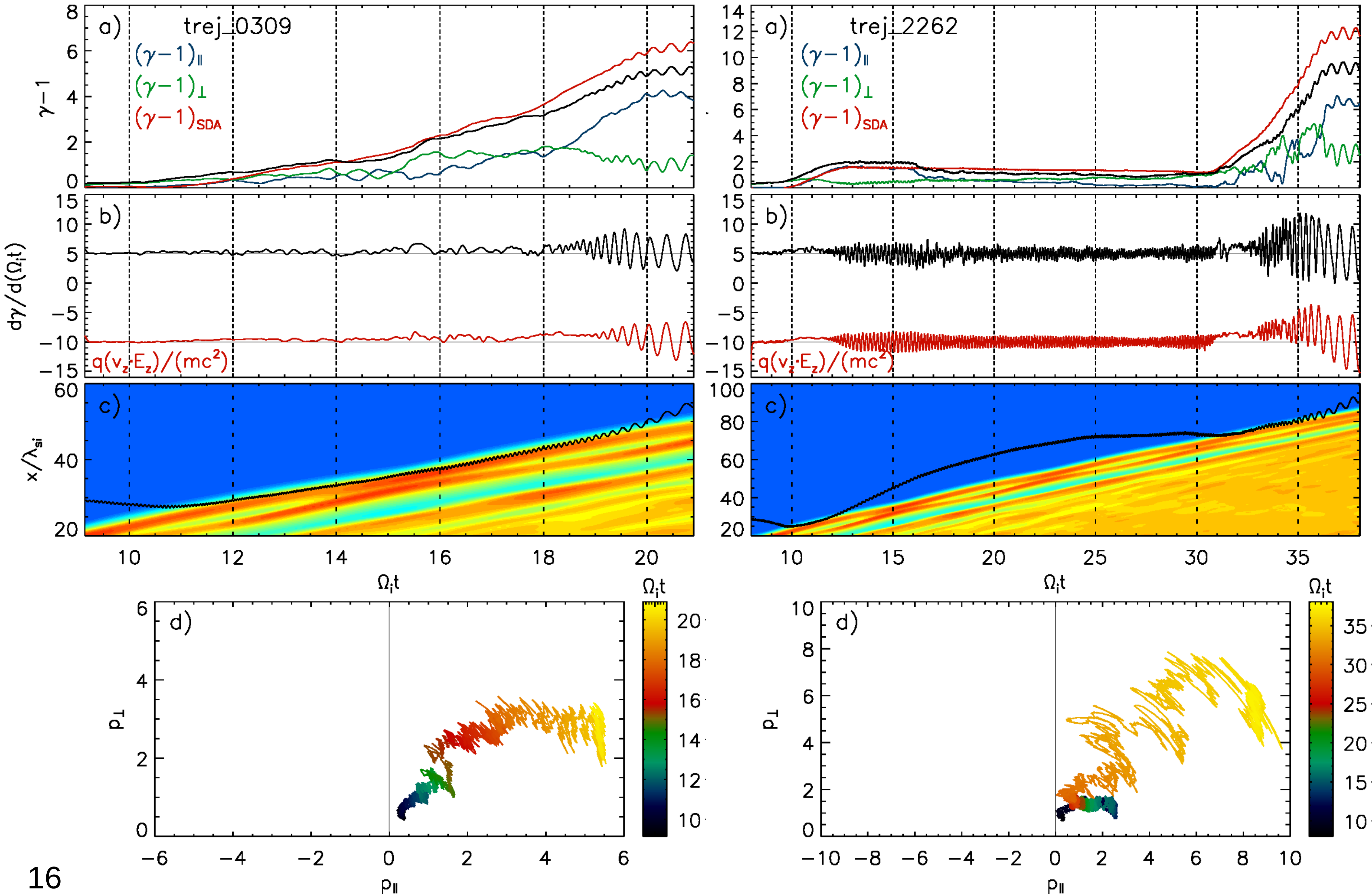
Extra-high energy electron undergoing the **SSDA** acceleration process
at front of the **rippled** shock



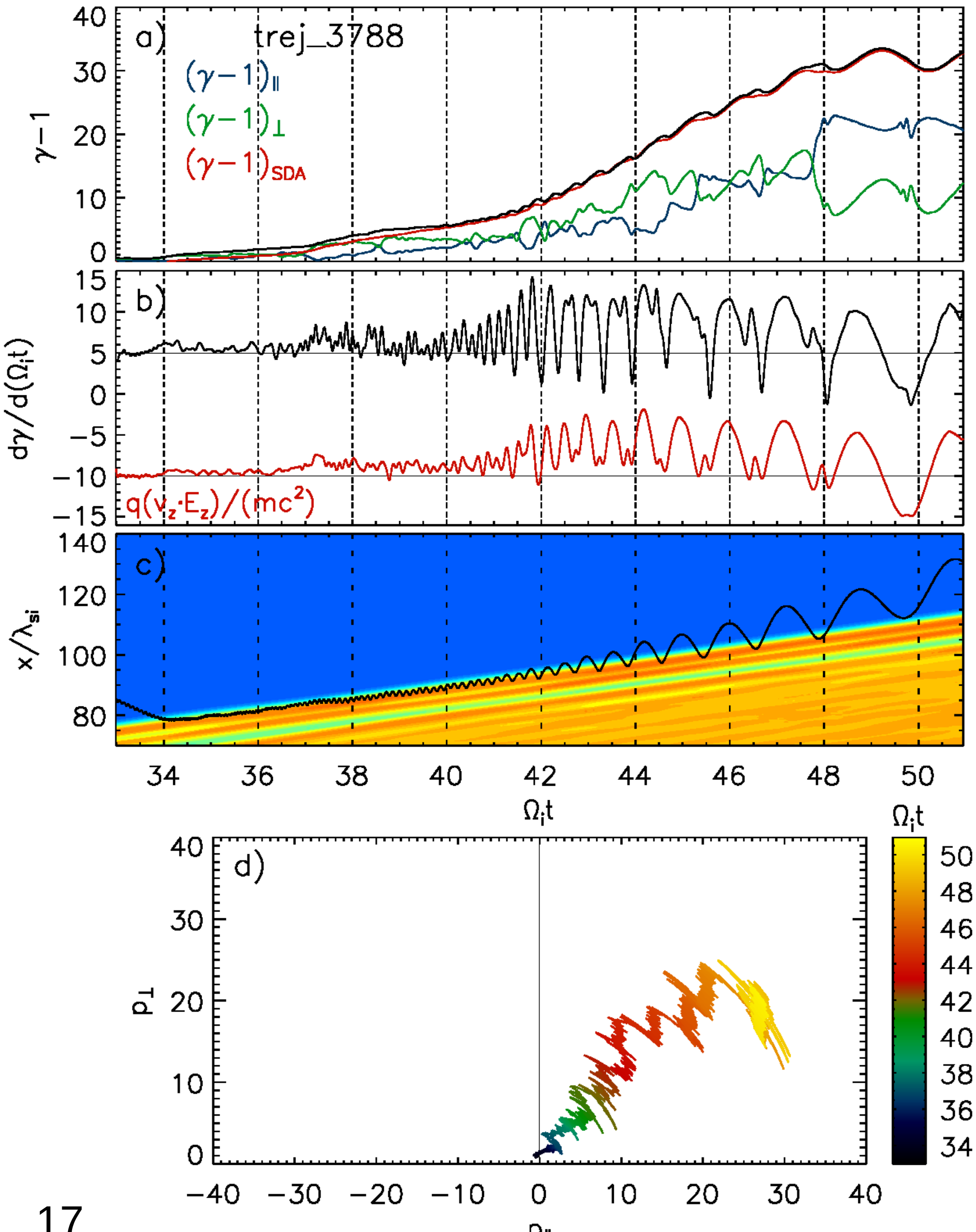


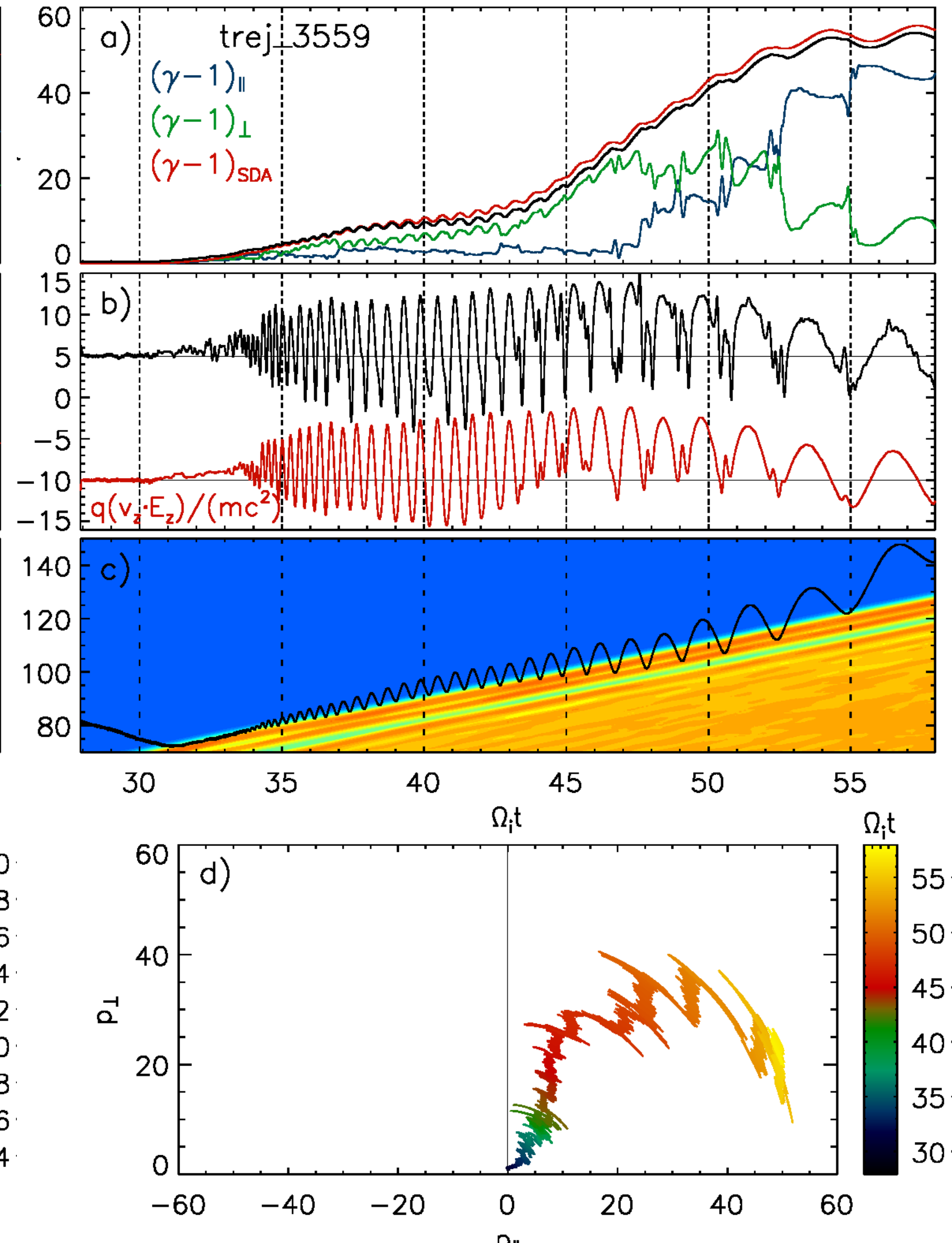
Extra-high energy electron undergoing the **pre-acceleration in the downstream** region before SDA (or SSDA) process at the shock front

Electron acceleration: *SDA*

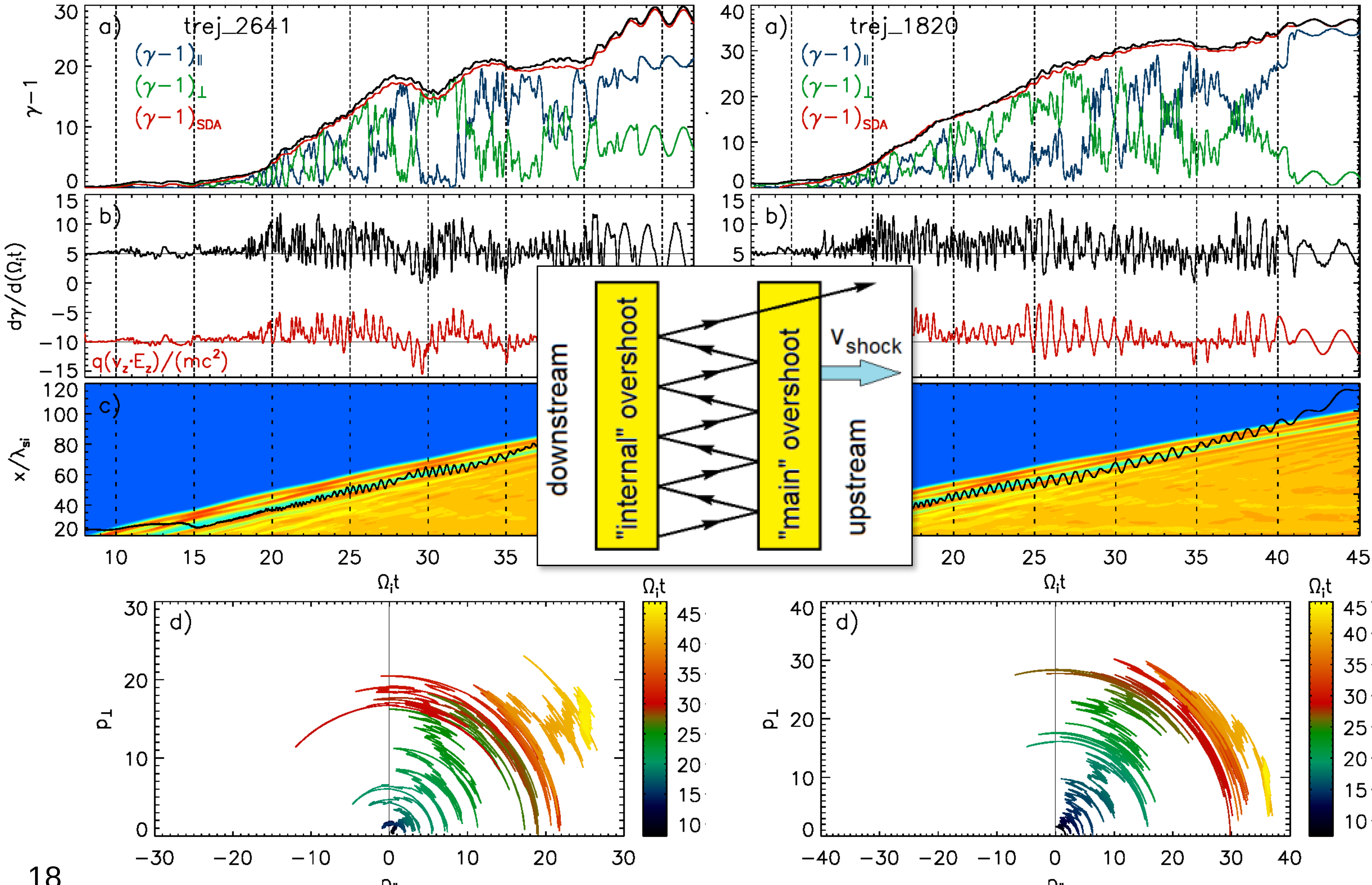


Electron acceleration: *SSDA*





Electron acceleration: *Downstream pre-acceleration*



Summary

- ✓ Performed simulation confirmed all previously described peculiarities of low-Mach-number shocks in high-beta plasma.
- ✓ Acceleration of electrons at laminar shock is found to be in good agreement with SDA theory prediction.
- ✓ Besides of firehose instability, reflected electrons are found to trigger also the bump-on-tail instability, that in turn results in generation of the electrostatic Langmuir waves.
- ✓ Rippling of the shock facilitates the electron acceleration to much higher energies relative to the regular SDA. We interpret this as a result of SSDA process, although rare multi-cycles of SDA are also possible.
- ✓ The population of the most energetic electrons with $\gamma > 50$ are found to be accelerated in the downstream region between two overshoots. We interpret this as a transient effect related with transformation of the shock structure.
- ✓ Downstream electron energy spectra demonstrate non-thermal power-law shape with slope $p = -2.4$, that is consistent with radio-observations.
- ✓ Further work assumes the series of simulations for higher values of plasma beta ($\beta \approx 20$). It requires the usage of several times larger computational resources, up to few tens of thousand CPU-s.