Particle-In-Cell Simulations of Low Mach Number High Beta Collisionless Shocks

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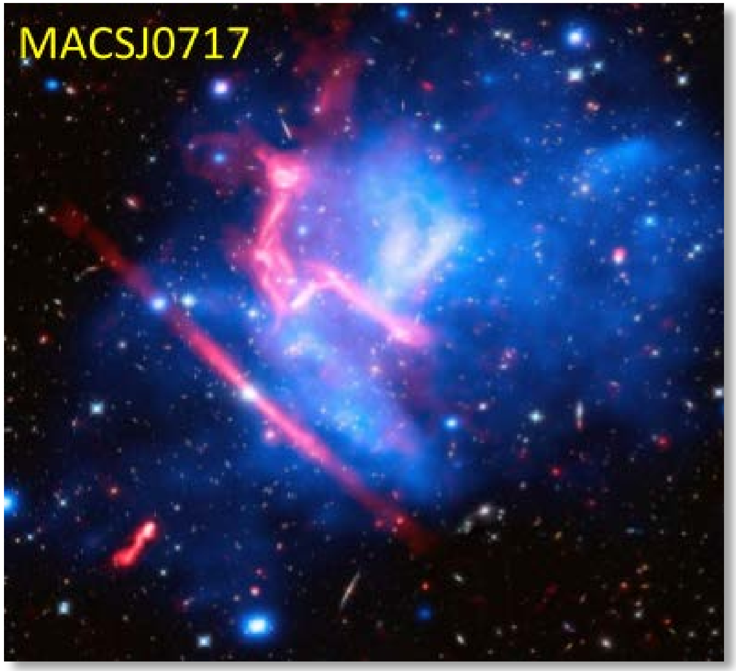
Astrophysical objects

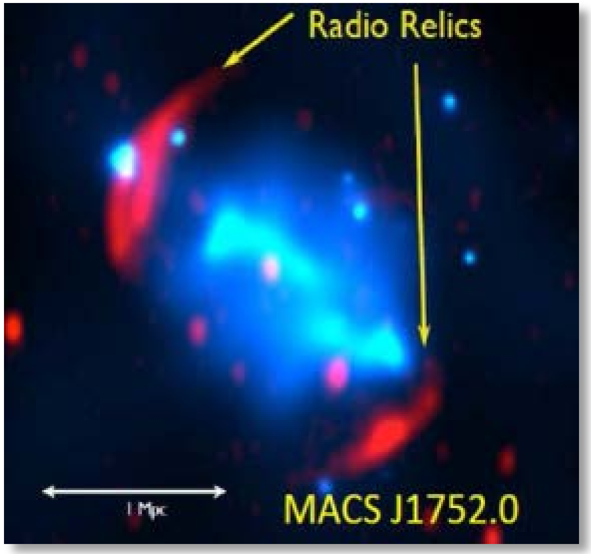
Colisionless shocks in astrophisical objects on the various scales:

- 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 propagating in high beta (**β>1**) plasmas.

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

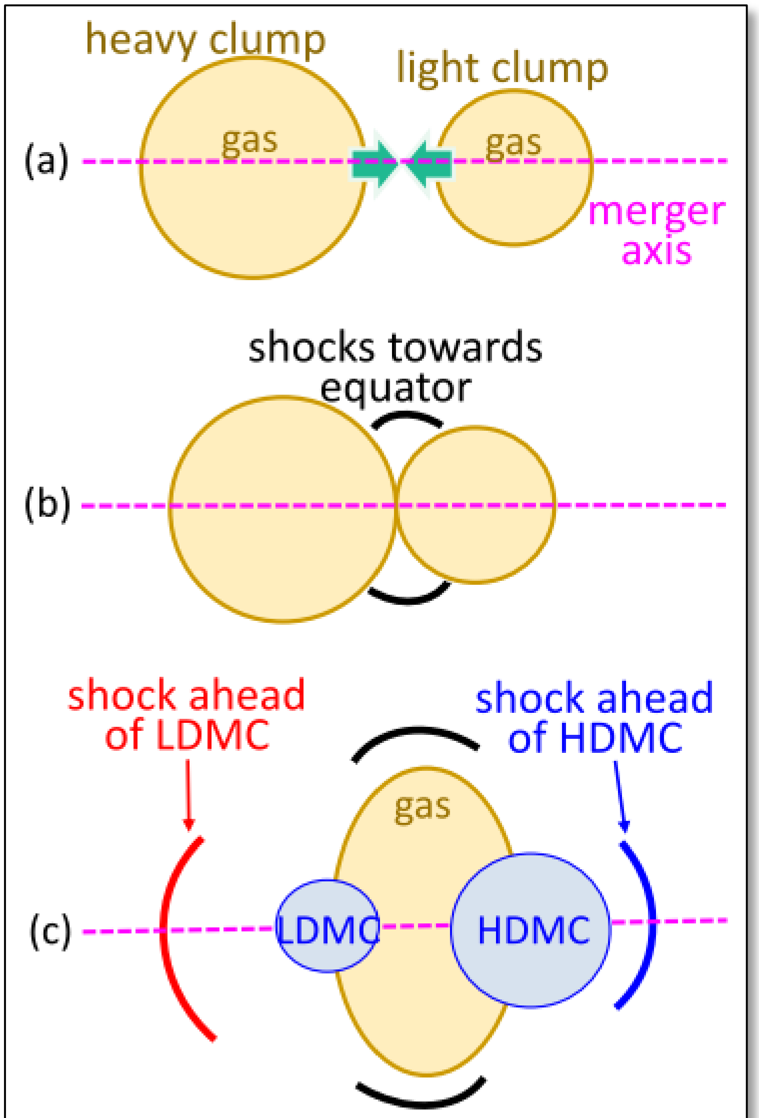




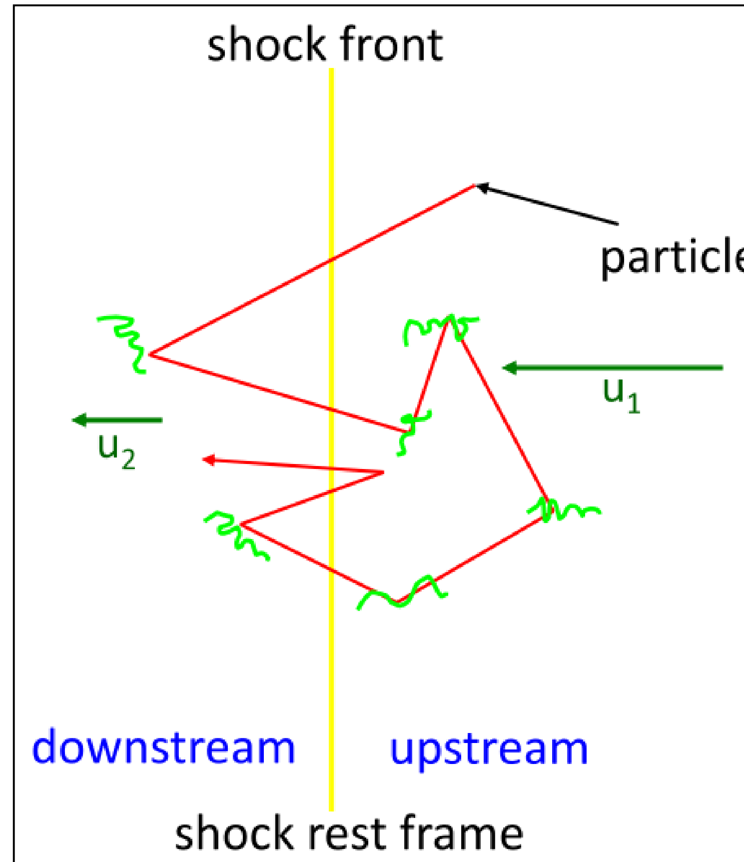
White – optical (Hubble)
Blue – X-ray (Chandra)
Red – radio (VLA)

Shock forming and particles acceleration

Simple binary galaxy merger



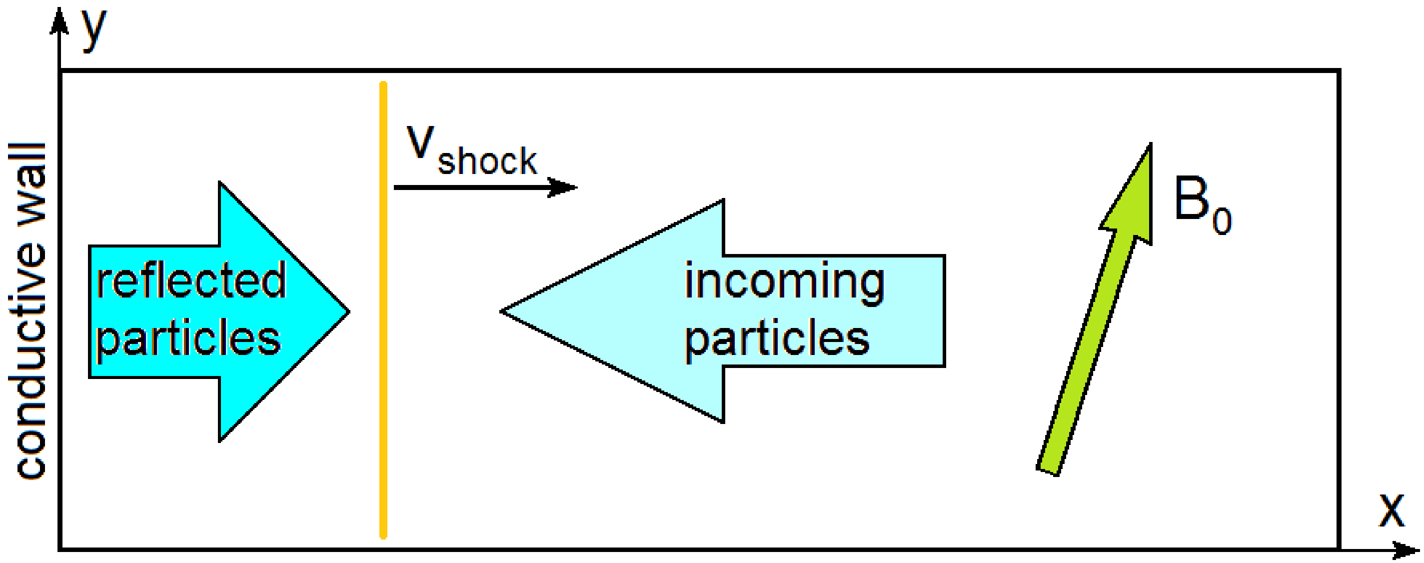
Simple scheme of the DSA



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.

$\boldsymbol{L_x} = 60{,}000\ \Delta \approx 400\ \lambda_{si}$ $\boldsymbol{L_y} = 4{,}800\ \Delta \approx 32\ \lambda_{si}$

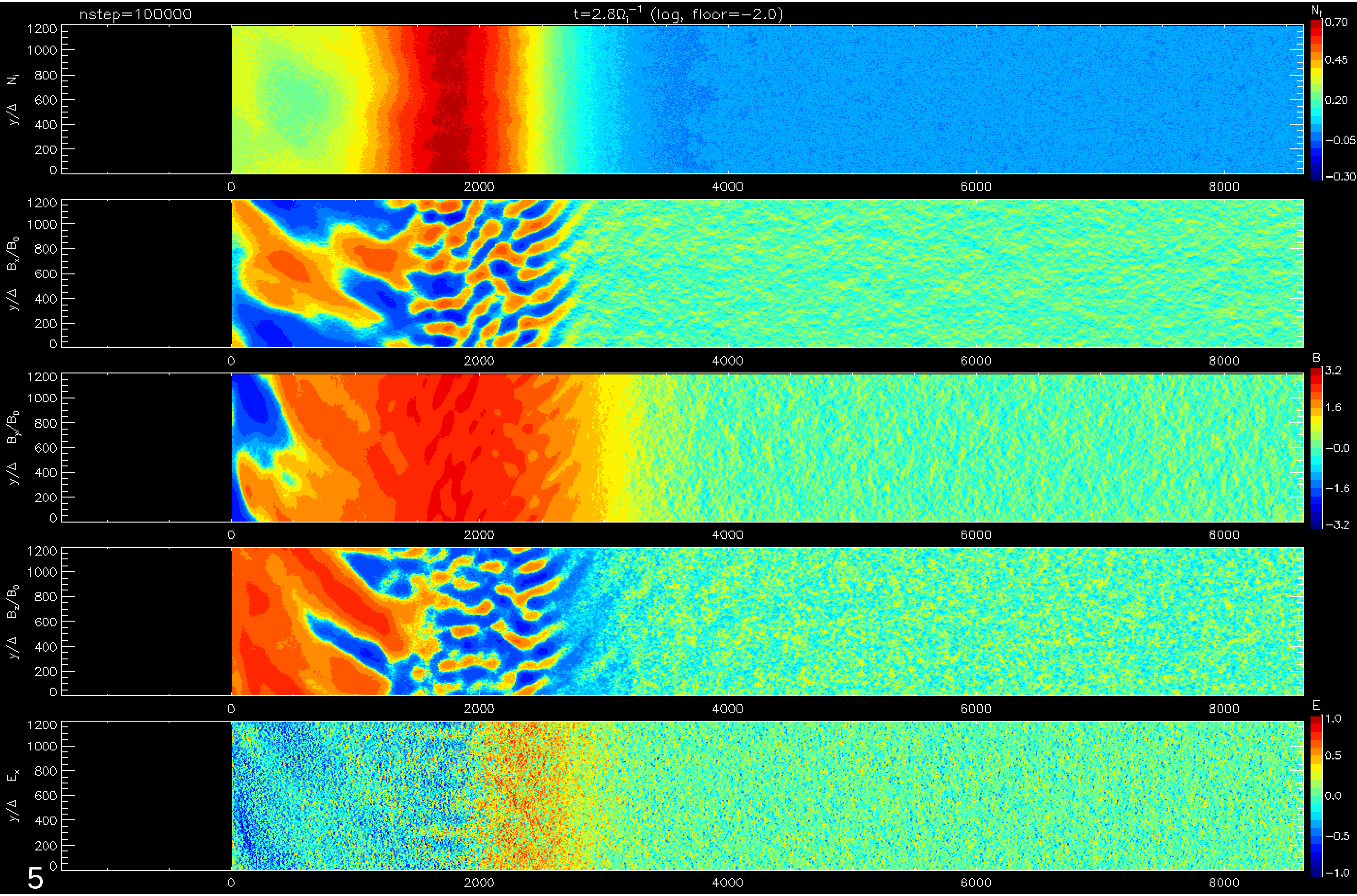
Physical parameters:

- 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 $M_A = (6 – 12)$
- Plasma beta ($\beta = p_{therm}/p_{mag}$) $\beta = (5 – 20)$

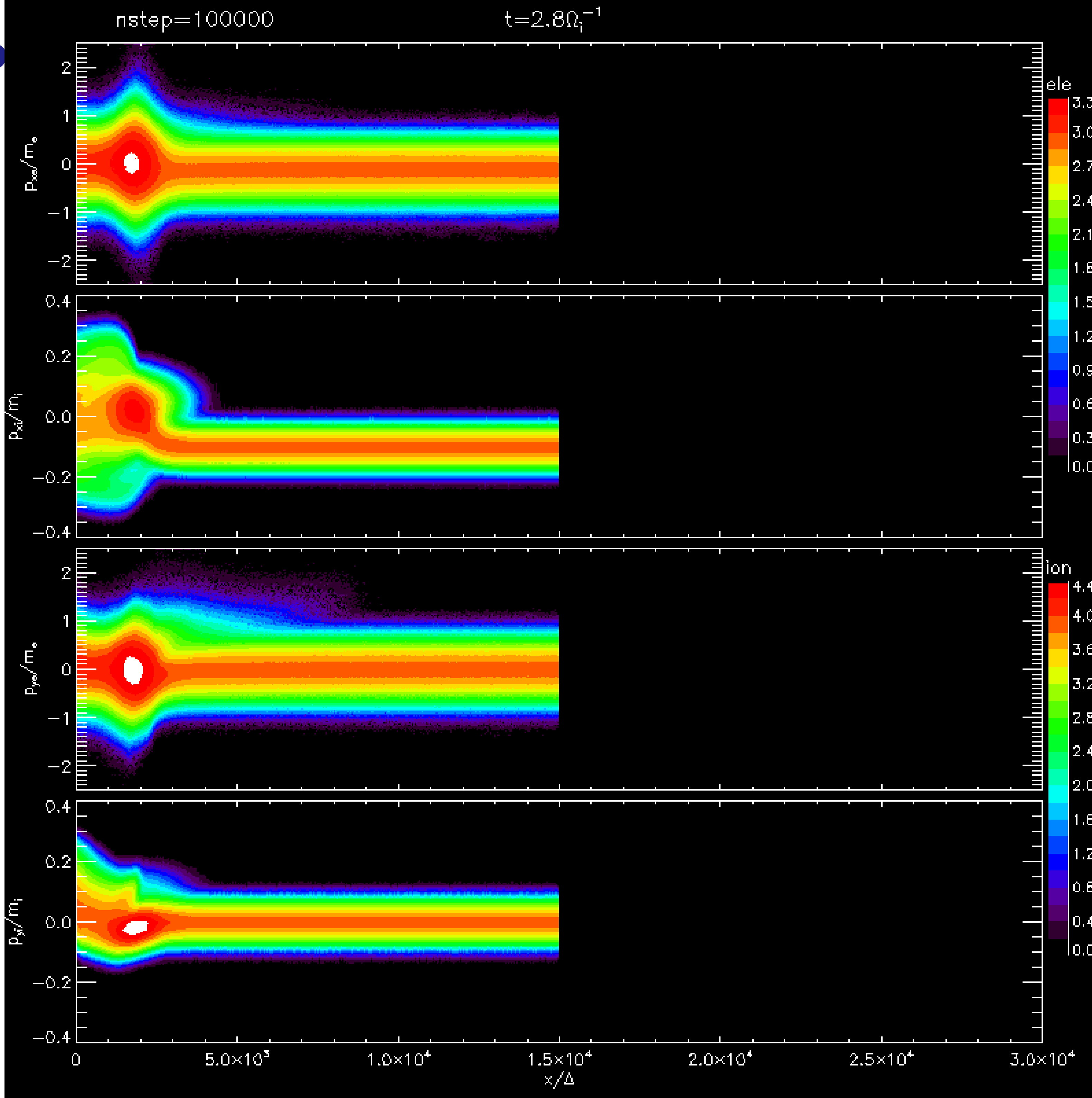
Computations:

- on *PROMETHEUS* cluster
- up to 1920 CPU cores
- ~ 1 mln of CPU-hours
- ~ 20 TB of disk space used for data output

Global system evolution (shock with β = 20)

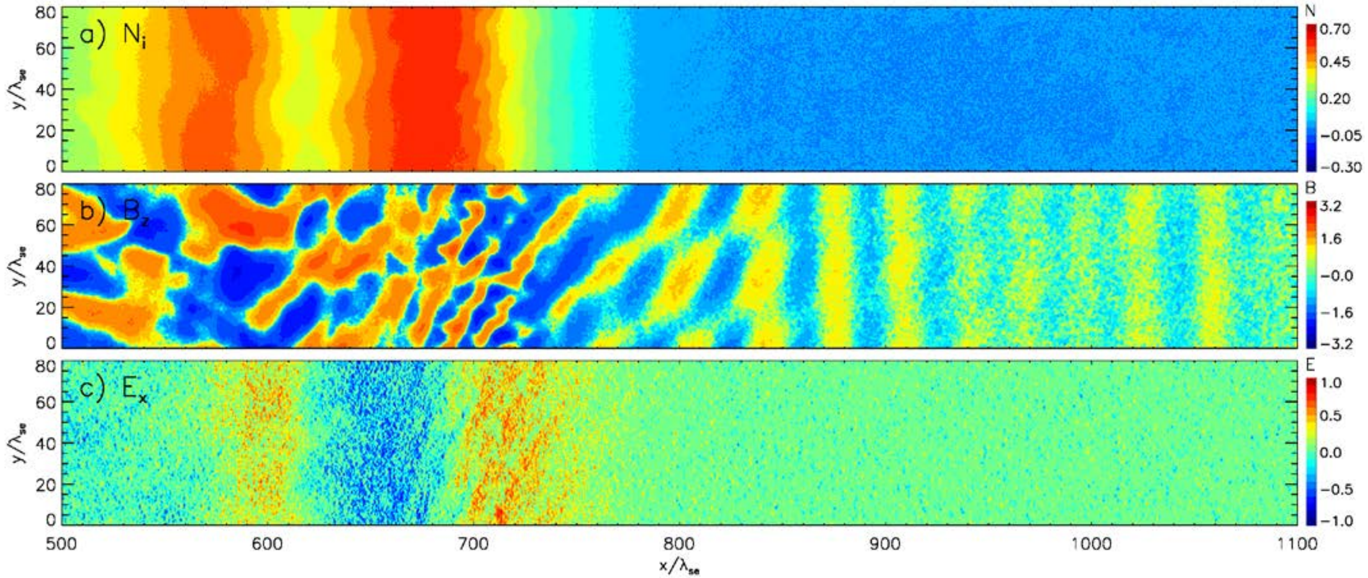


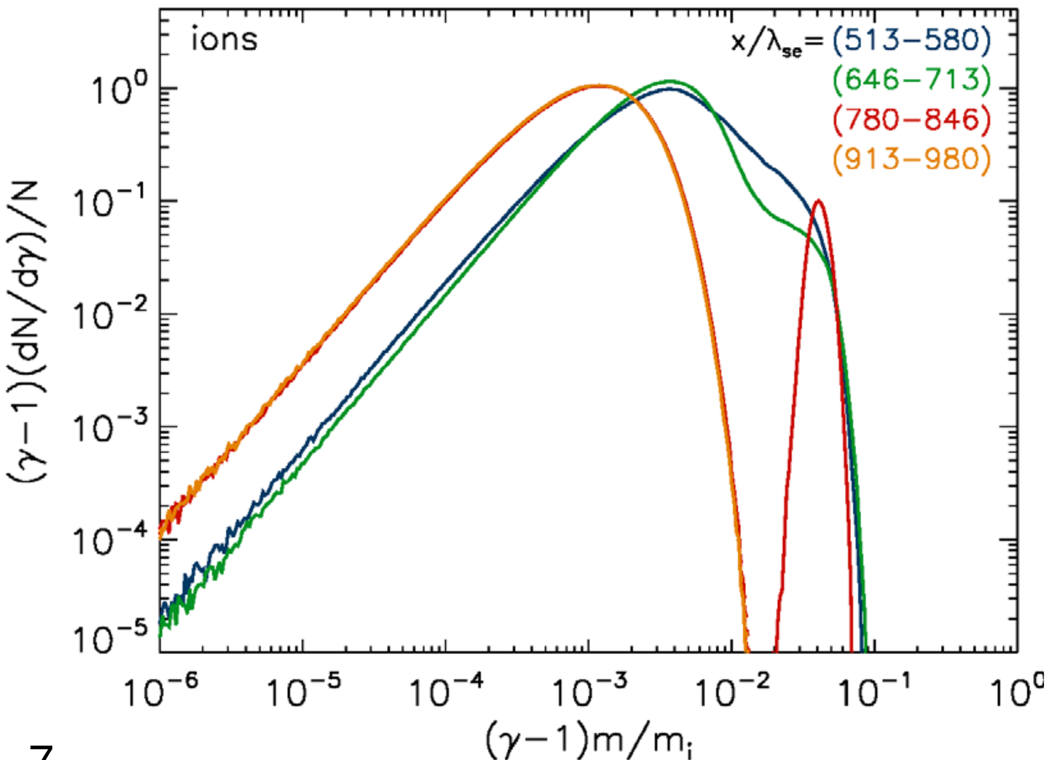
P 0)

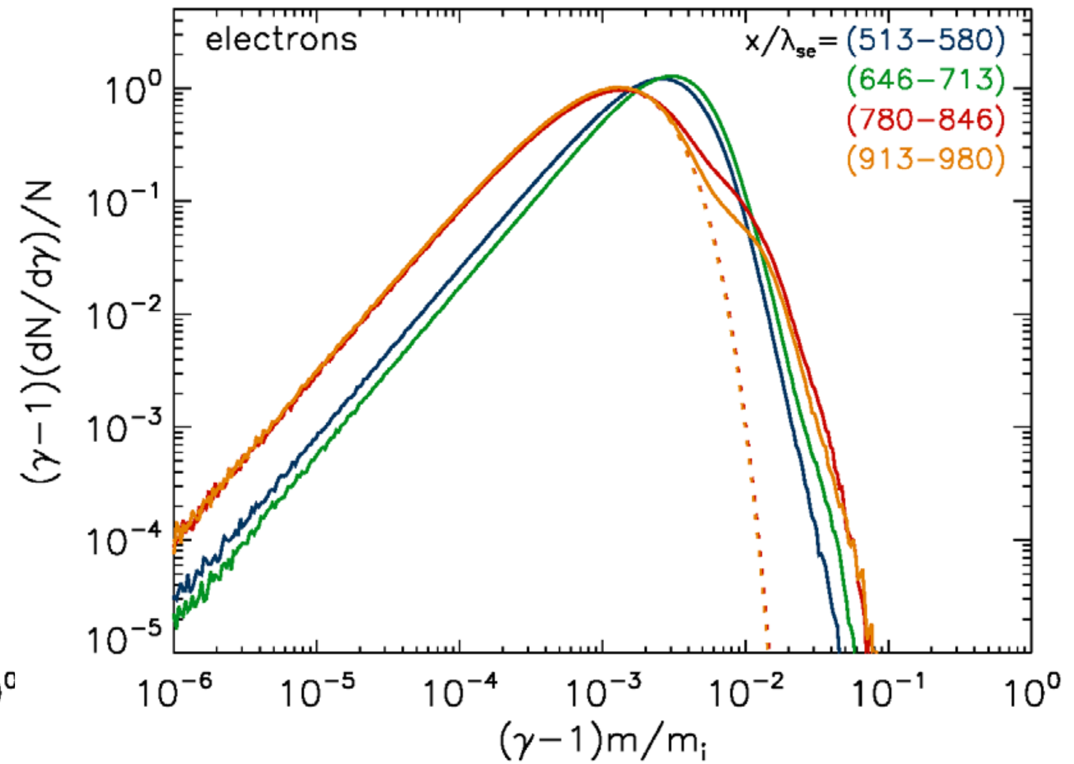


nstep=100000
$t=2.8\Omega_i^{-1}$
p_{xe}/m_e
p_{xi}/m_i
p_{ye}/m_e
p_{yi}/m_i
ele
ion
x/Δ
0
5.0×10^3
1.0×10^4
1.5×10^4
2.0×10^4
2.5×10^4
3.0×10^4
3.3
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0

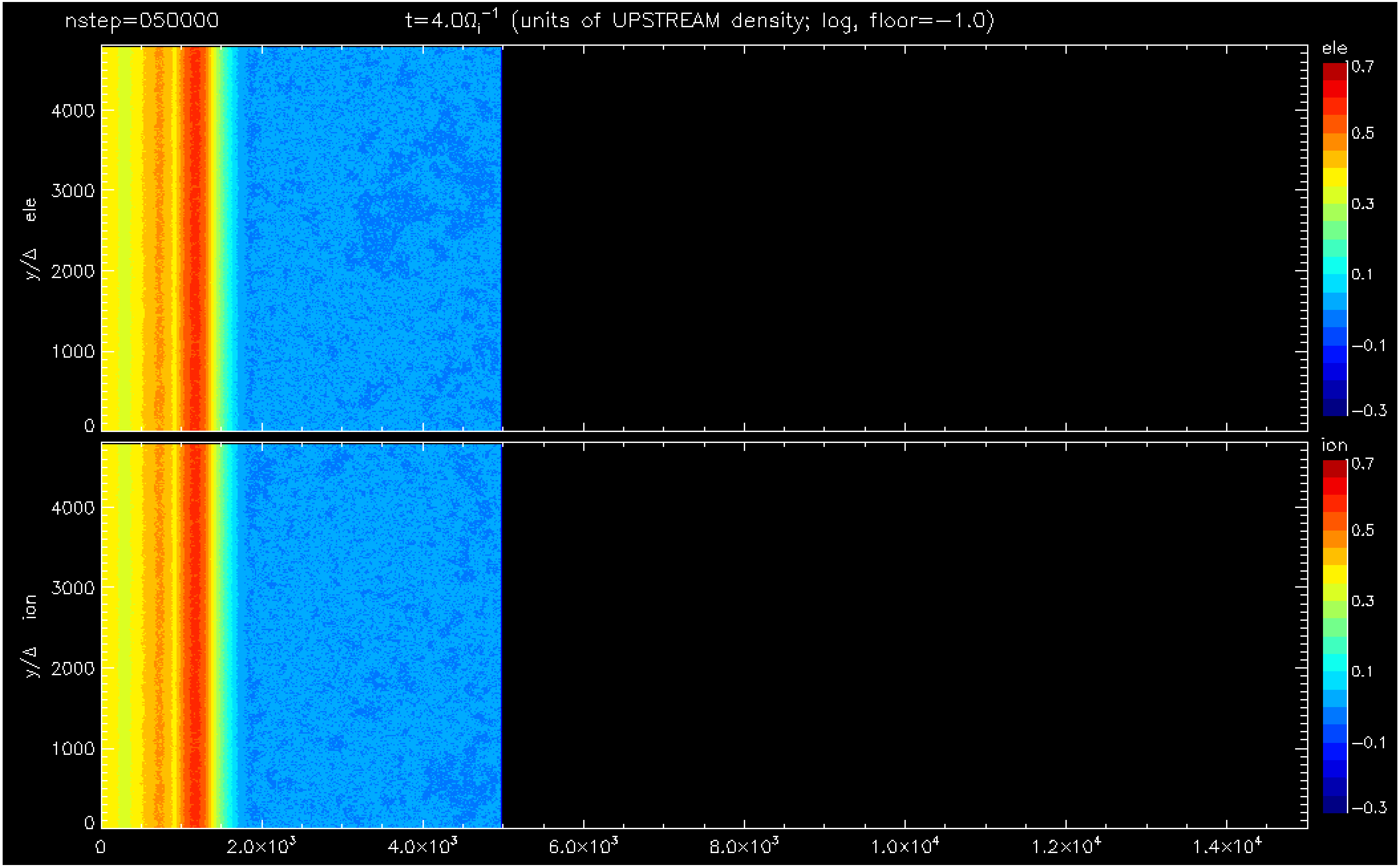
Particle energy spectra (shock with β = 20)

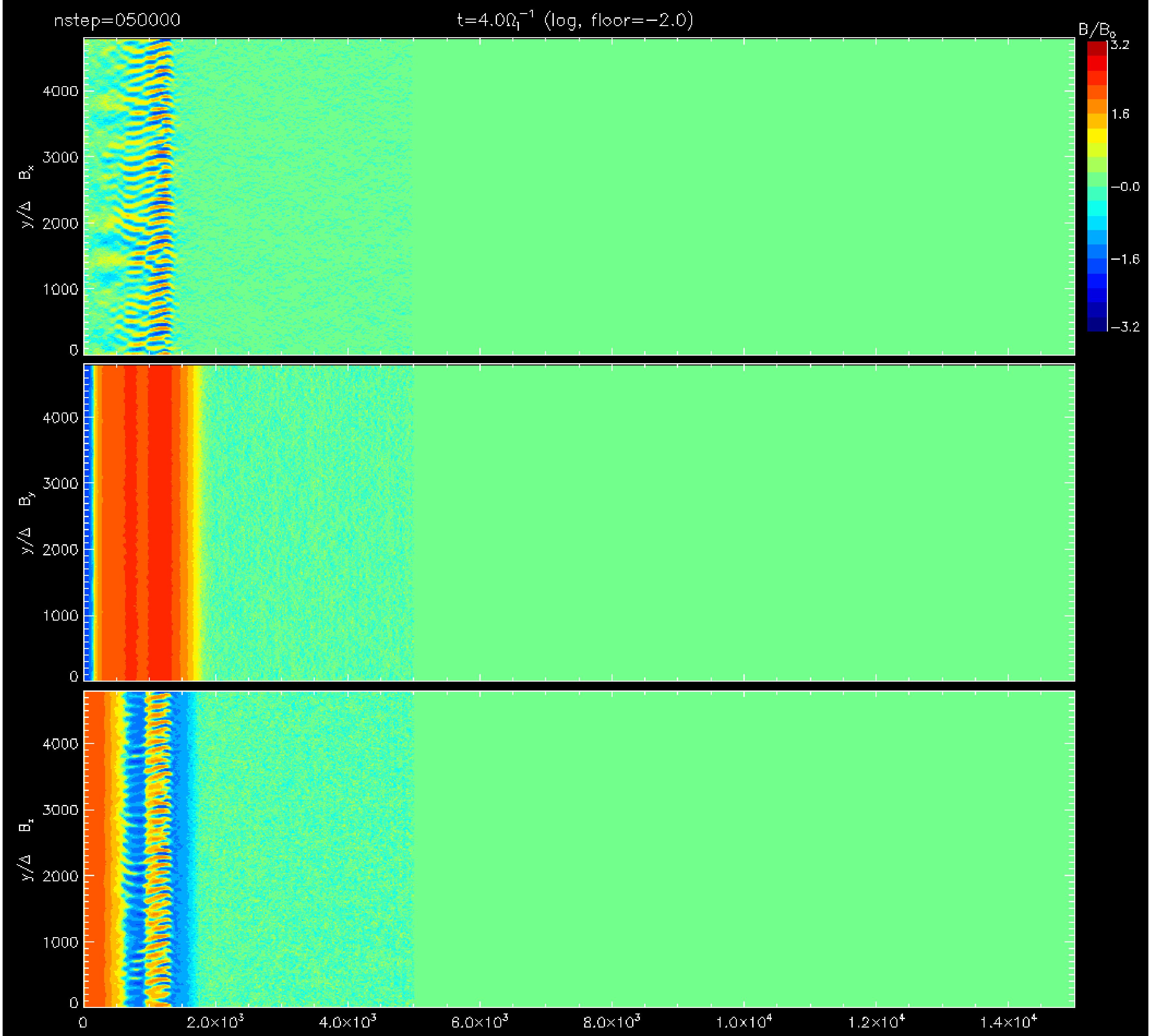


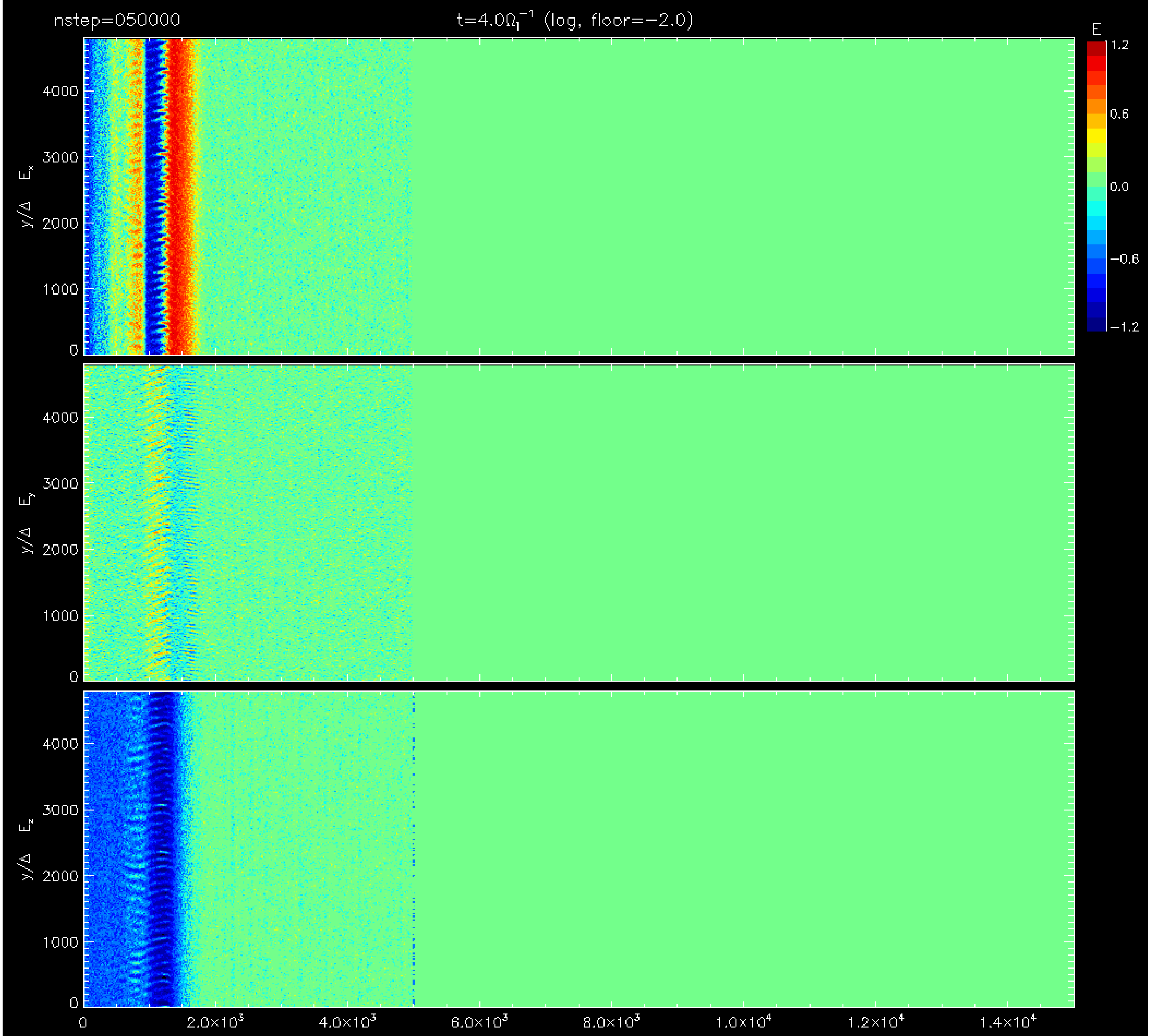


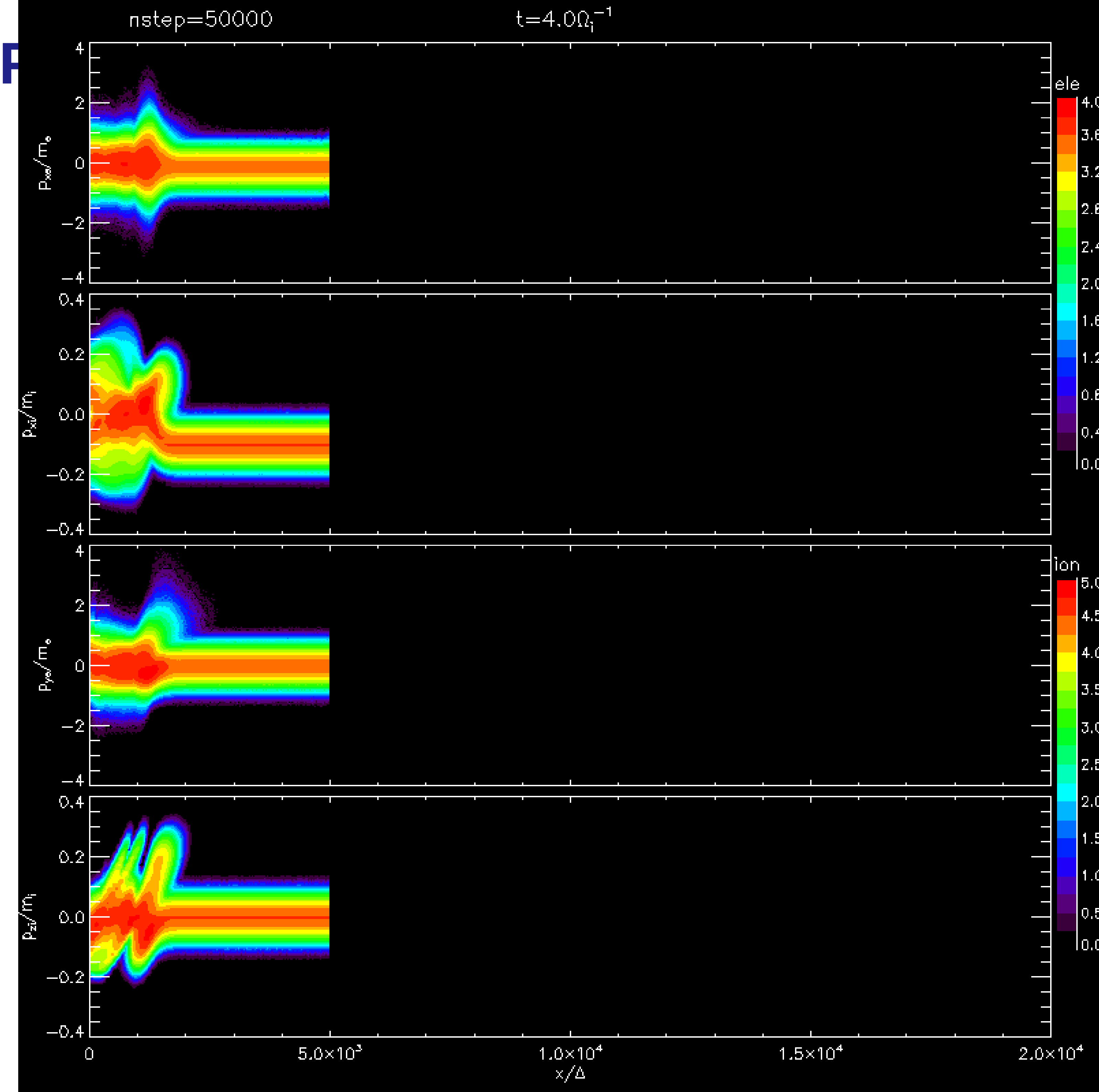


Global system evolution (shock with β = 5)




nstep=050000
t=4.0Ω$_i^{-1}$ (log, floor=−2.0)
B/B$_0$
3.2
1.6
−0.0
−1.6
−3.2
y/Δ B$_x$
y/Δ B$_y$
y/Δ B$_z$
0
1000
2000
3000
4000
2.0×10^3
4.0×10^3
6.0×10^3
8.0×10^3
1.0×10^4
1.2×10^4
1.4×10^4


nstep=050000
t=4.0Ω_i^-1 (log, floor=−2.0)
E
1.2
0.6
0.0
−0.6
−1.2
y/Δ E_x
y/Δ E_y
y/Δ E_z
0
1000
2000
3000
4000
0
2.0×10^3
4.0×10^3
6.0×10^3
8.0×10^3
1.0×10^4
1.2×10^4
1.4×10^4


nstep=50000
t=4.0Ω_i^-1
p_xe/m_e
p_xi/m_i
p_ye/m_e
p_zi/m_i
x/Δ
0
5.0×10^3
1.0×10^4
1.5×10^4
2.0×10^4
ele
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
ion
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

Summary and future work

- Small-size test simulations confirm earlier findings:
  - electrons continuously gain energy via Shock-Drift-Acceleration process,
  - upstream magnetic waves are generated by the reflected electrons via two-stream instability.
- Large-size test simulations also show that:
  - reflected electrons generate small-scale *electrostatic waves* in the upstream region,
  - electron acceleration is *modulated* by the *shock rippling* periodically appearing in the overshoot region.
- Electron acceleration strongly depends on the local physical conditions, such as plasma β, magnetic field angle or shock rippling.
- Further work foresees a *higher-resolution* and *larger-scale* simulation. Numerical parameters will be derived from the analysis of the dispersion relation of the Alfven ion cyclotron instability, responsible for the rippling.

Thank you!