The formation of a relativistic planar plasma shock

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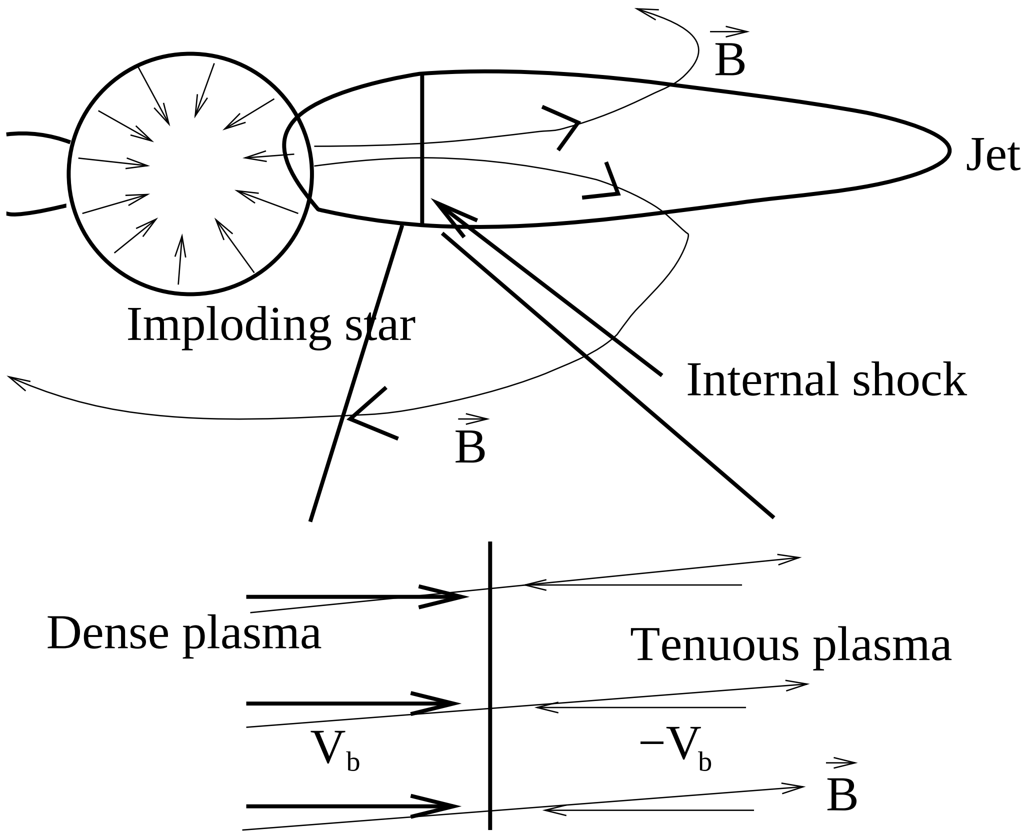
Motivation

- *Aim:* Modelling a shock that could be representative for an internal gamma-ray burst shock
- *Method:* Particle-in-cell simulation
- *Constraints:* Realistic ion-to-electron mass ratio
- *Trick:* Reducing the simulation geometry to 1D by making use of suitable plasma parameters. 2D simulations are used for verification.
- *Conclusions:* Interpretation of simulation results w.r.t the prompt gamma-ray emissions

GRB Fireball model

- Imploding star yields compact object
- Magnetic field and angular momentum constrain flow → Collimated jets
- Jet Lorentz factor: > 100
- **Prompt emissions**: Plasma collisions in the jet
- **Afterglow**: Collision between jet plasma and the ambient plasma.



Simulation setup

- Two plasma clouds collide at $x=x_0$ at the speed 0.9 c or $\Gamma=2.3$
- Direction of motion is the x-direction. 1D simulation resolves x
- Both clouds consist of electrons and ions with mass ratio 400
- Dense cloud 10 times denser than the tenuous one
- Magnetic field with $\omega_p = \omega_{ce}$ in dense cloud
- Almost flow-aligned magnetic field with $B_x = 10\ B_z$
- Plasma temperature 100 keV

- Suppression of filamentation by (1) guiding magnetic field, (2) high cloud density ratio, (3) high temperature (4) low collision speed

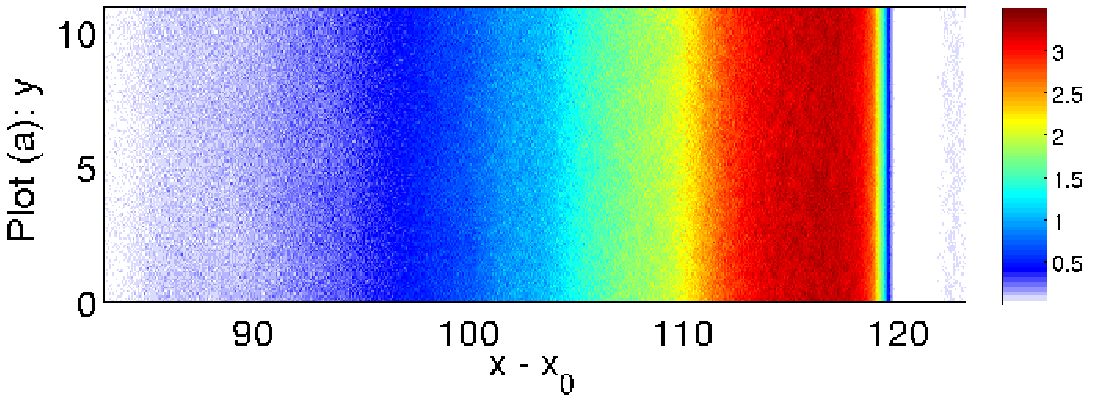
2D test result

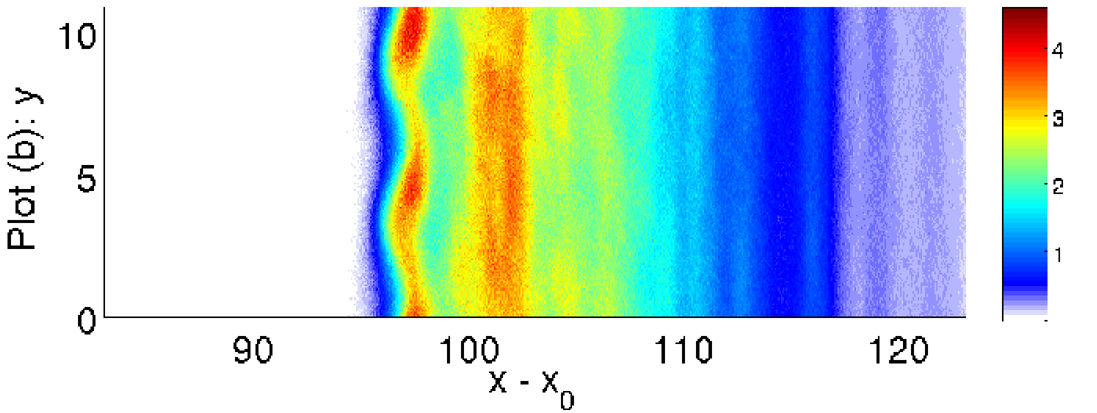
- **Shown**: Magnetic field component out of box at simulation's end and the dense cloud's front
- *Upper plot*: Almost flow aligned magnetic field

1D simulation **possible**

- *Lower plot*: No initial B_x

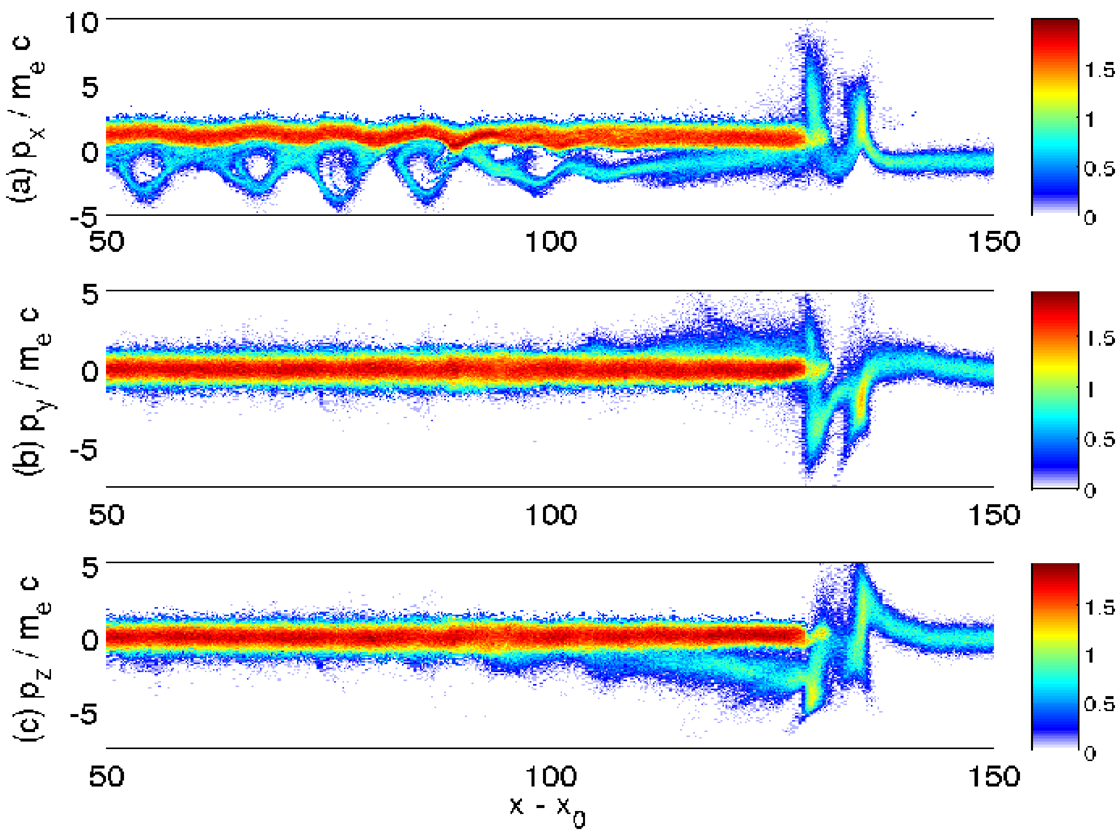
1D simulation **impossible**





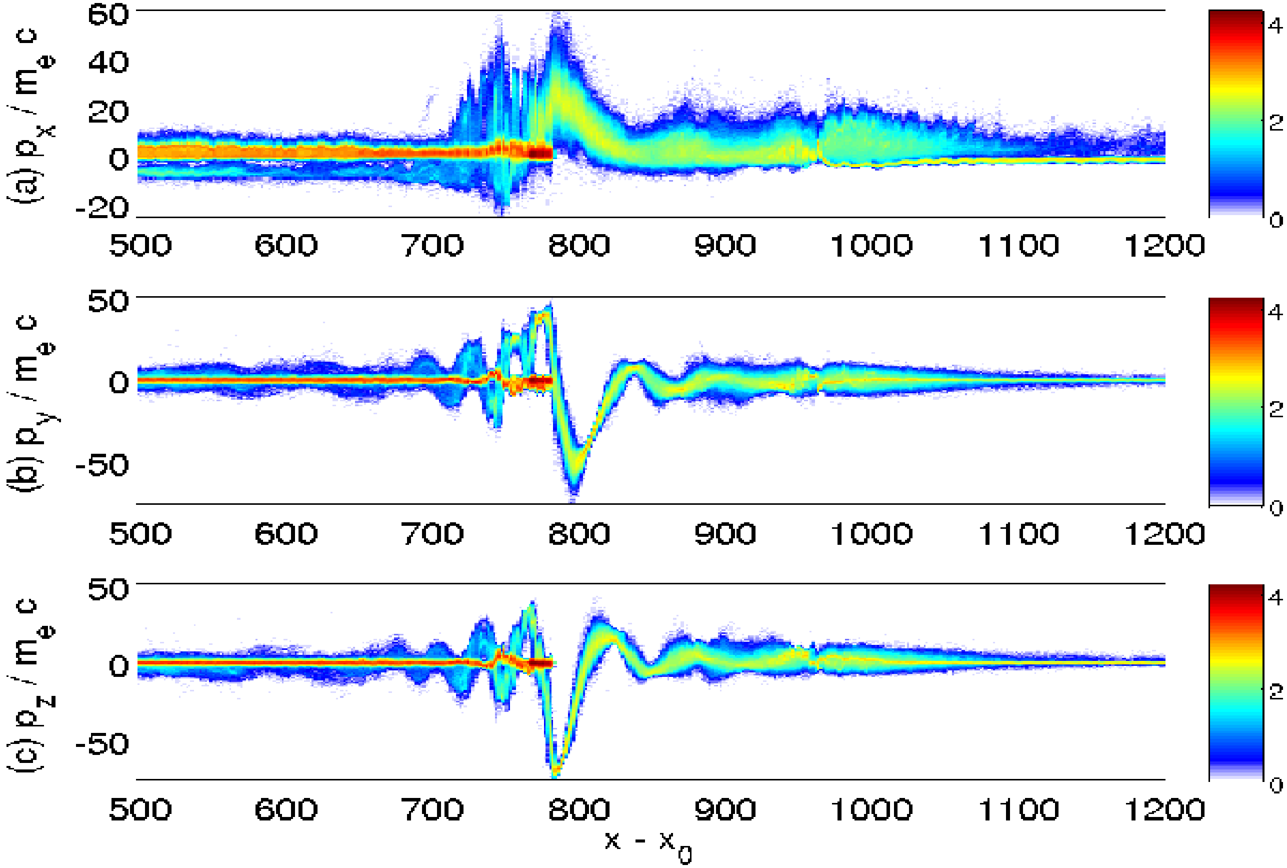
1D simulation (1)

- Electron phase space distribution equivalent to the end of the 2D simulation: Front end of dense cloud
- At x=130 we have corkscrew orbits
- At x<100 we have ’phase space holes’.



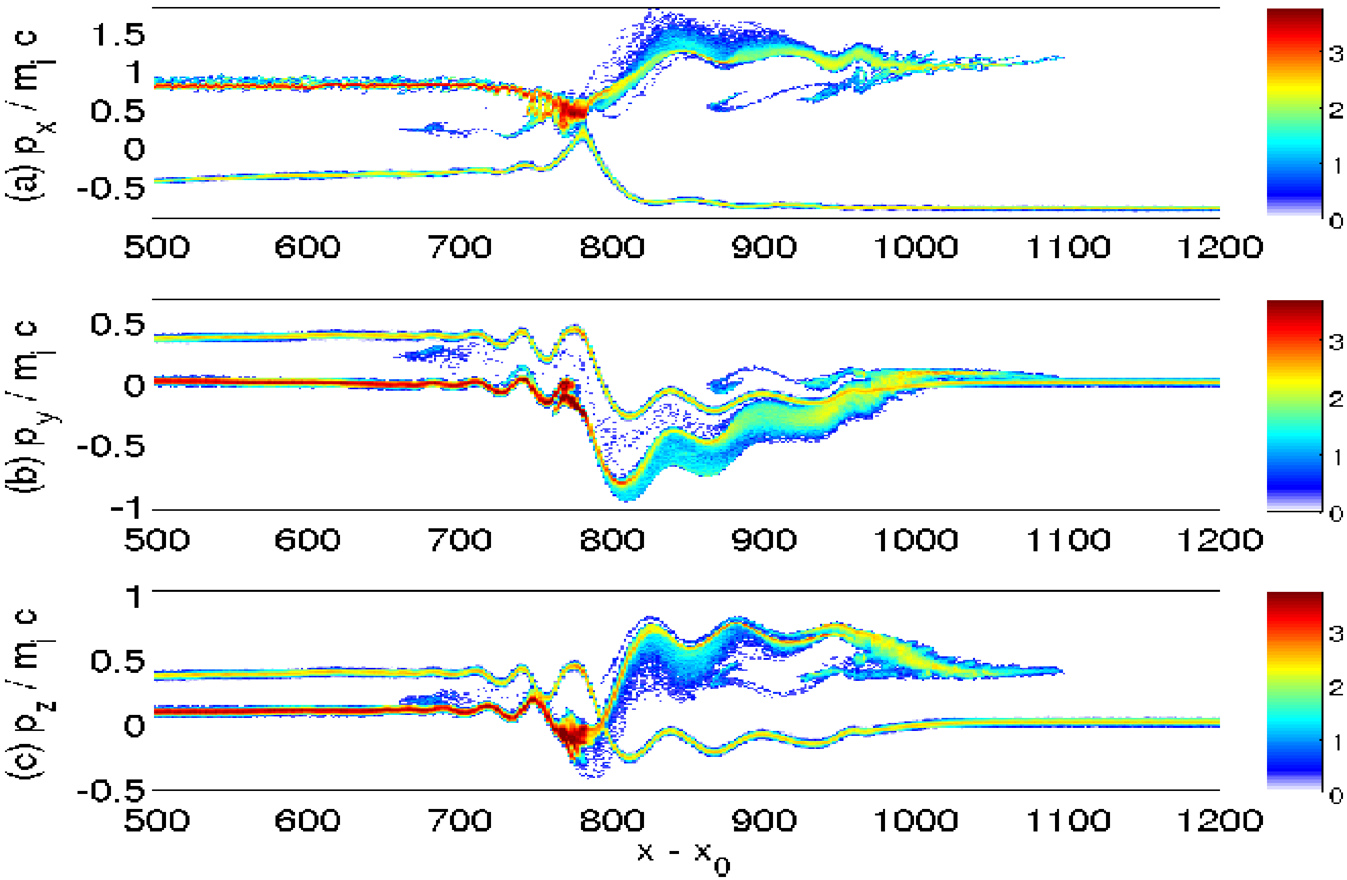
1D simulation (2)

- 6 times later: Electron oscillation is self-amplifying!
- Relativistic electron mass comparable to ion mass 400



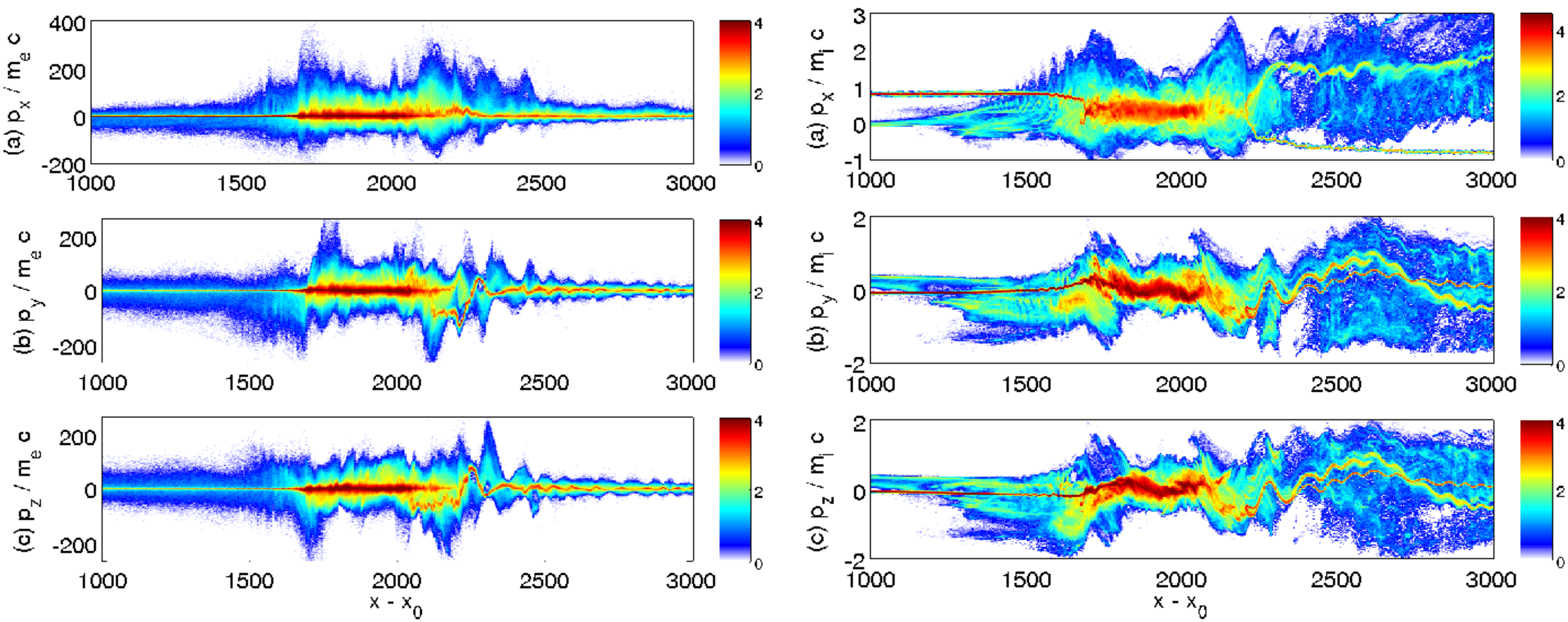
1D simulation (3)

- The electromagnetic fields that accelerate the electrons start to twist the ions
- At x=780 the upper plot shows beam merging -> shock



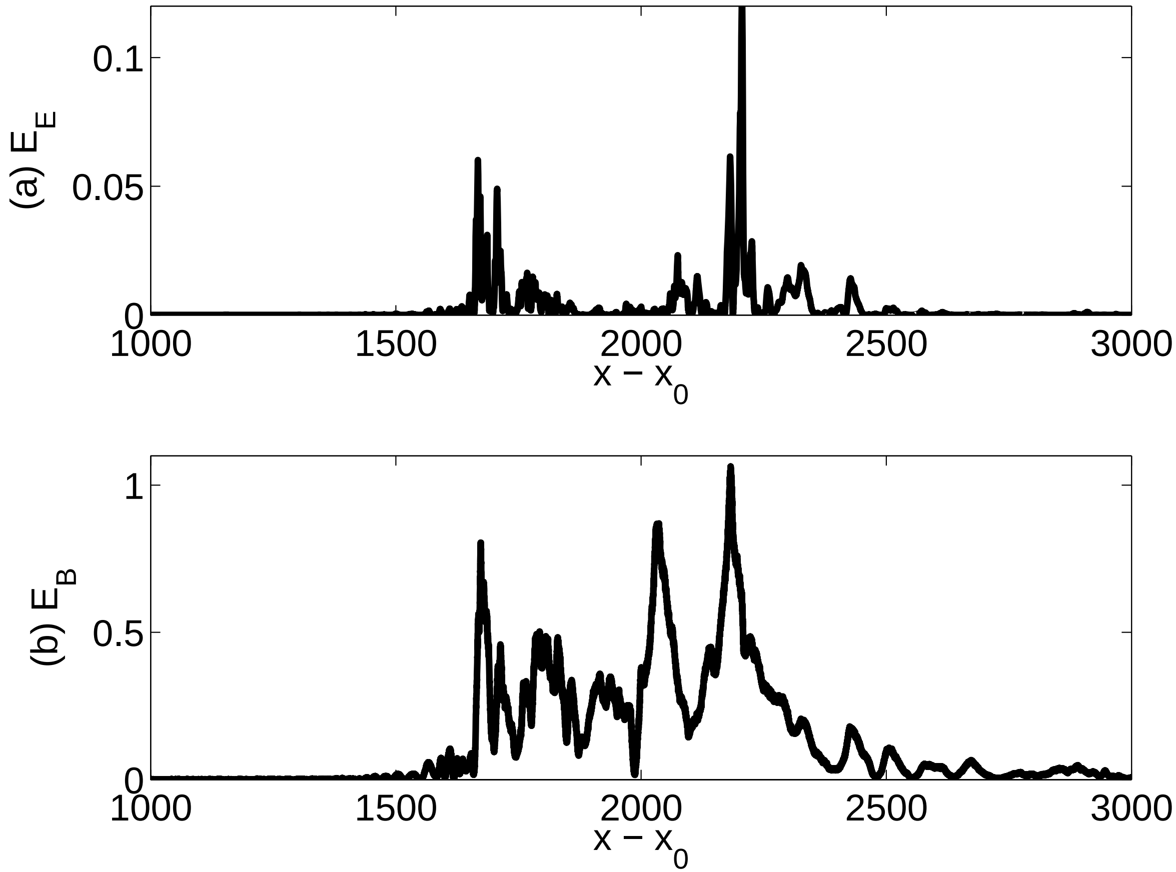
1D simulation (4)

- Simulation's end shows extreme heating of electrons (left) and ions (right) in 1700<x<2200
- A downstream region has formed that separates forward and reverse shocks: Energy equipartition!



1D simulation (5)

- Electric energy density (upper plot) and magnetic energy density (lower plot).
- Electric field strong at the shocks
- Magnetic field strong in the downstream.
- Magnetic field: One third of total energy



Discussion

- Suitable initial magnetic field strength / direction, plasma temperature and cloud density ratio ’allows’ 1D simulation
- For realistic plasma flow speeds, a shock develops in a few milliseconds in the jet frame.
- The underlying instability grows fast despite comparable electron thermal speeds and plasma flow speeds.
- Time dilation: Shock formation on sub-seconds in Earth frame: Prompt GRB emissions are on second-to-minute time scales
- Energy equi-partition between ions, electrons and magnetic field that ’is stable’: *Perfect scenario*
- Particles reach TeV energies in the Earth frame

- *Details in:* Dieckmann, Shukla, Drury, ApJ 2008