Turbulent plasma flow, its energies, and structures: Velocity vortices, magnetic field cocoons, and plasmoids

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Motivation

Turbulence is a ubiquitous process not only in astrophysics but also in other areas of plasma physics and fluid dynamics. Turbulent flow gains energy from the mean plasma flow and transports it from the largest scales to the smallest ones, where it is dissipated as heat.

- **Turbulence and magnetic reconnection** are fundamental processes in astrophysical plasmas.
- In the **solar corona**, turbulence is expected during solar flares and CMEs when large amounts of energy are released.
- **Energy cascade**: large-scale plasma motions transfer energy to smaller scales, where it is dissipated as heat → possible source of **coronal heating**.
- **Reconnection outflows** are often turbulent, producing secondary reconnection sites and complex plasma structures.
- **Velocity vortices, magnetic cocoons, and plasmoids** act as channels of energy dissipation and plasma heating.
- Studying turbulence in reconnection-driven flows helps explain **energy conversion in solar and space plasmas**.

Numerical model

In the numerical model, we describe the plasma dynamics with the set of 3D, time-dependent resistive and compressible MHD equations in the Cartesian coordinate system

$$\frac{\partial \varrho}{\partial t} + \nabla \cdot (\varrho \boldsymbol{v}) = 0,$$

$$\varrho \left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \nabla \right) \boldsymbol{v} = -\nabla p + \frac{1}{\mu_0} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B},$$

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \nabla \right) p = -\gamma p \nabla \cdot \boldsymbol{v} + (\gamma - 1) \frac{\eta}{\mu_0^2} (\nabla \times \boldsymbol{B})^2$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \frac{1}{\mu_0} \nabla \times (\eta \nabla \times \boldsymbol{B}),$$

$$\nabla \cdot \boldsymbol{B} = 0.$$

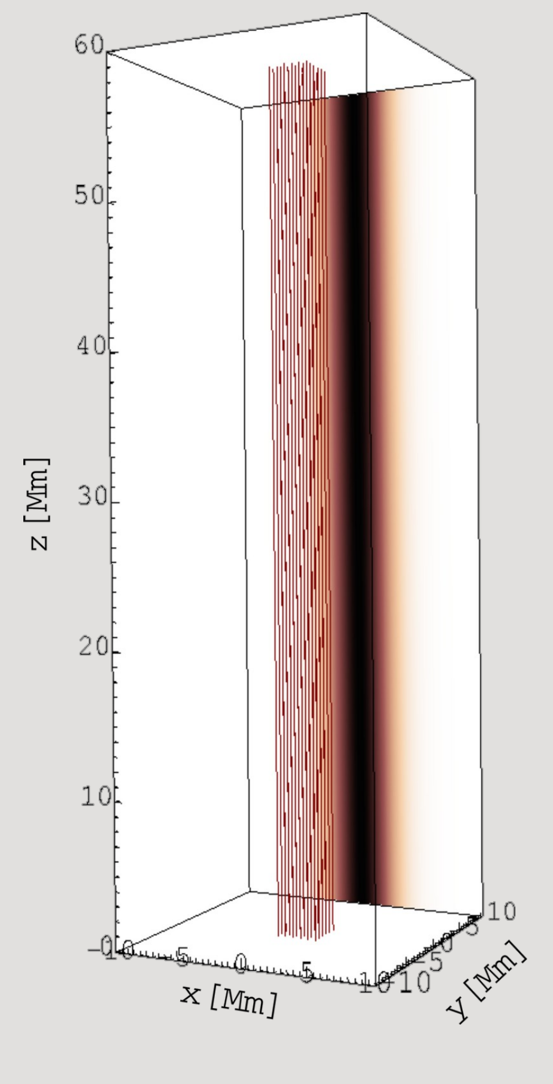

Fig. 1. Initial state of the model: magnetic field lines (solid red lines) starting at the bottom plane of the numerical box at the same positions as those in Fig. 2. The mass density is shown as a slice in the x–z plane at the box boundary.

Magnetic field (Harris current-sheet)

$$\boldsymbol{B} = B_{\mathrm{out}} \tanh \left(\frac{x}{w_{\mathrm{cs}}} \right) \hat{\boldsymbol{e}}_z$$

The **mass density distribution** was calculated from the equilibrium condition, $p_{\mathrm{kin}} + p_{\mathrm{mag}} = \mathrm{const.}$

$$\varrho(x) = \varrho(0) - \frac{B(x)^2}{2\mu_0} \frac{\mu_m}{k_{\mathrm{B}} T}$$

The **initial velocity** of the outflowing plasma is oriented in a positive z-direction and has the **Gaussian profile**

$$v_z(x, y) = v_{\mathrm{i}} \exp \left[-\frac{(x^2 + y^2)}{\lambda^2} \right]$$

Results

Using a 3D MHD model, in which we solved a full set of the 3D time-dependent resistive and compressible MHD equations, we studied a generation of the turbulent plasma flow, its energies, and structures, such as velocity vortices, magnetic field cocoons, and plasmoids, in the system with the current sheet. This model can mimic processes in the turbulent plasma-reconnection outflow. Analysing a turbulent flow evolution, we found that the most of the kinetic energy of the initial plasma flow is transformed into plasma heating (about 95%) and only a small part into magnetic energy (about 5%).

Turbulent flow and magnetic field lines

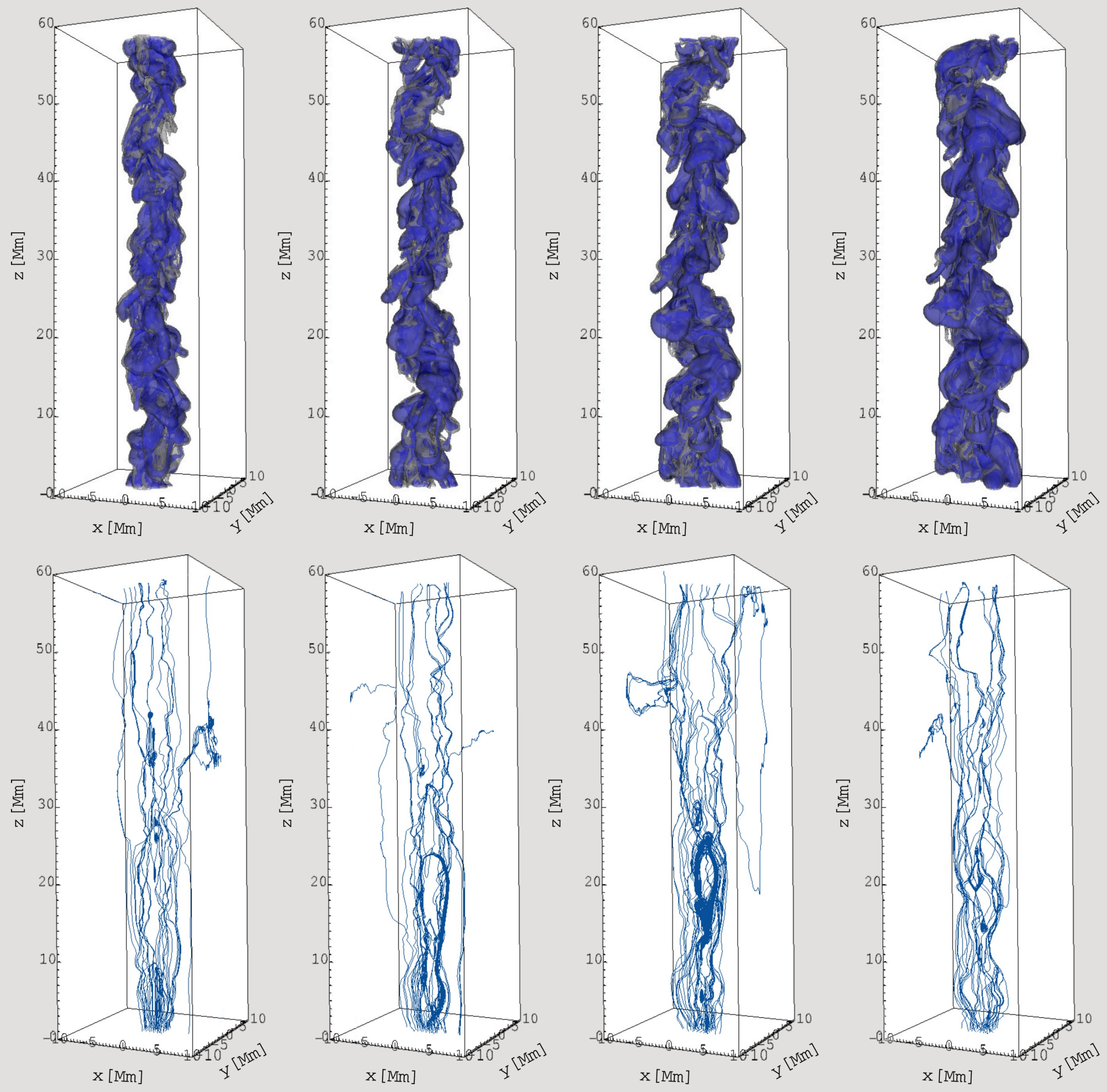

Fig. 2. Turbulent flow and magnetic field lines at four times: t = 493, 538, 583, and 627 s. The blue and grey colours represent two different values of mass density. Magnetic field lines starting at the bottom plane of the numerical box at the same positions as those in Fig. 1.

Time evolution of normalised energies

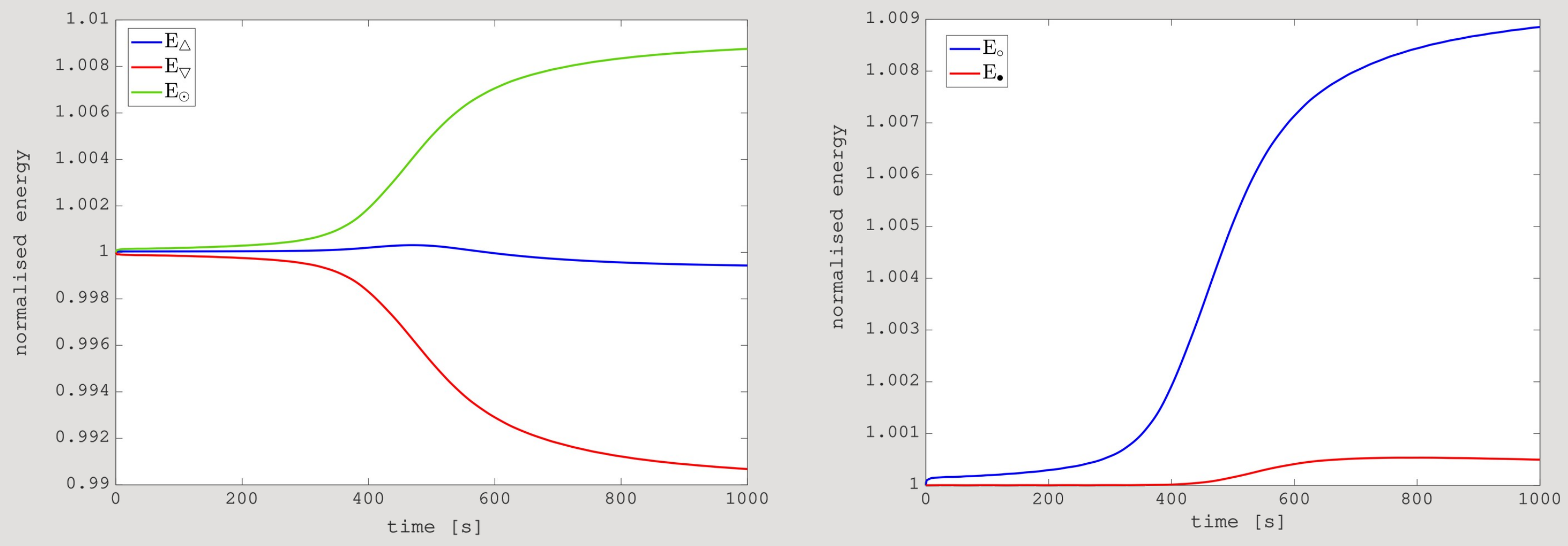

Fig. 3. Time evolution of normalised energies. **Left:** The total energy, kinetic energy, and magnetic energy, together with the internal one, are shown with blue, red, and green lines, respectively. **Right:** The blue line shows the magnetic and internal energy, and the red one represents the magnetic energy.

Conclusions

- **3D MHD** simulations show efficient generation of **turbulent plasma flows** in a **current-sheet** system.
- Most of the **kinetic energy** (≈ **95 %**) of the initial plasma flow is converted into **plasma heating**, while only a small fraction (≈ **5 %**) becomes **magnetic energy**.
- Three key structures are identified:
  - **Velocity vortices** – energy dissipated by **viscosity**
  - **Magnetic cocoons** – energy dissipated by **resistivity**
  - **Plasmoids** – formed by **magnetic reconnection**
- Results indicate that **turbulent plasma flows** can contribute significantly to **coronal heating**.
- **Magnetic cocoons** are suggested as a potential new structure in the **turbulent solar wind**.
- Future work: simulations at **lower plasma β** to study in detail the relation between **vortices** and **magnetic cocoons**.

Paper
in A&A

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Magnetic field cocoon

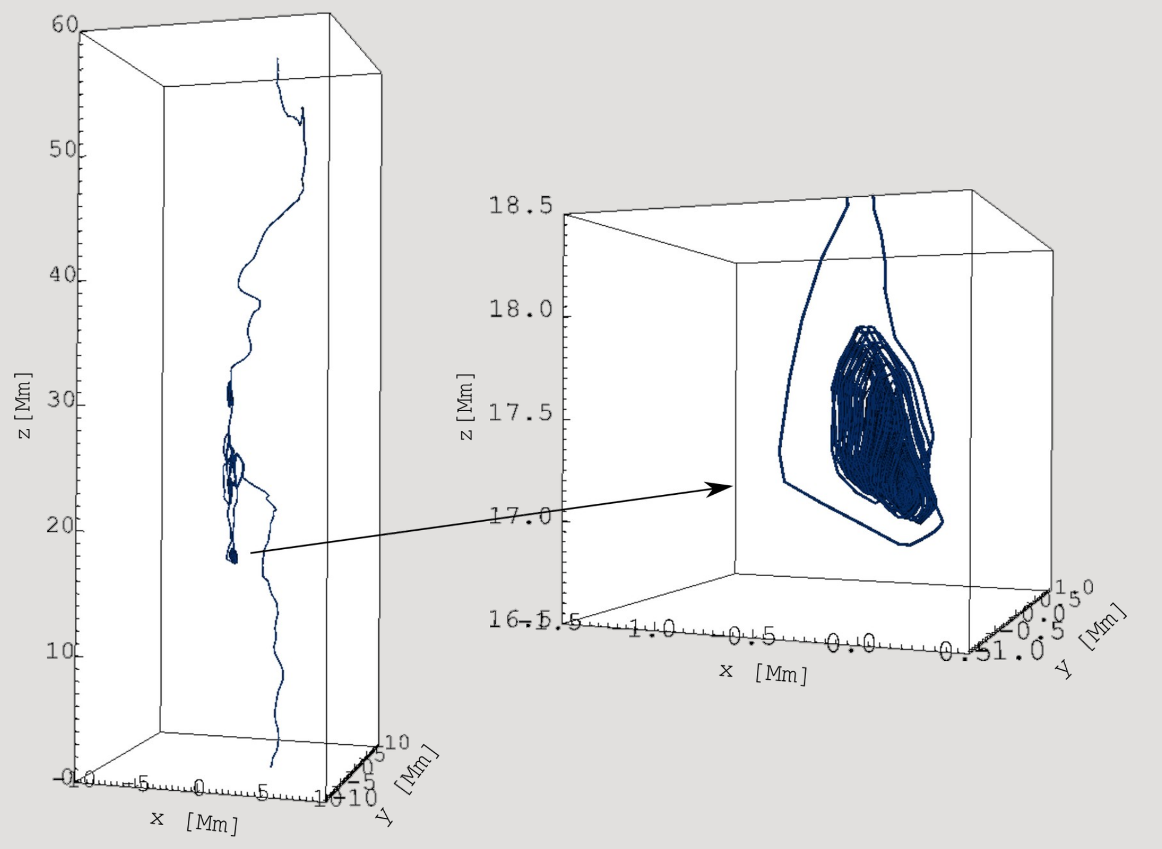

Fig. 4: Example of the **magnetic field cocoon** at time t = 616 s. On the left is shown the selected magnetic line starting at the point (x = 3.175, y = −0.5, z = 0 Mm). On the right is a detailed view of the magnetic cocoon at the same time, expressed by the single magnetic field line.

Examples of studied magnetic structures

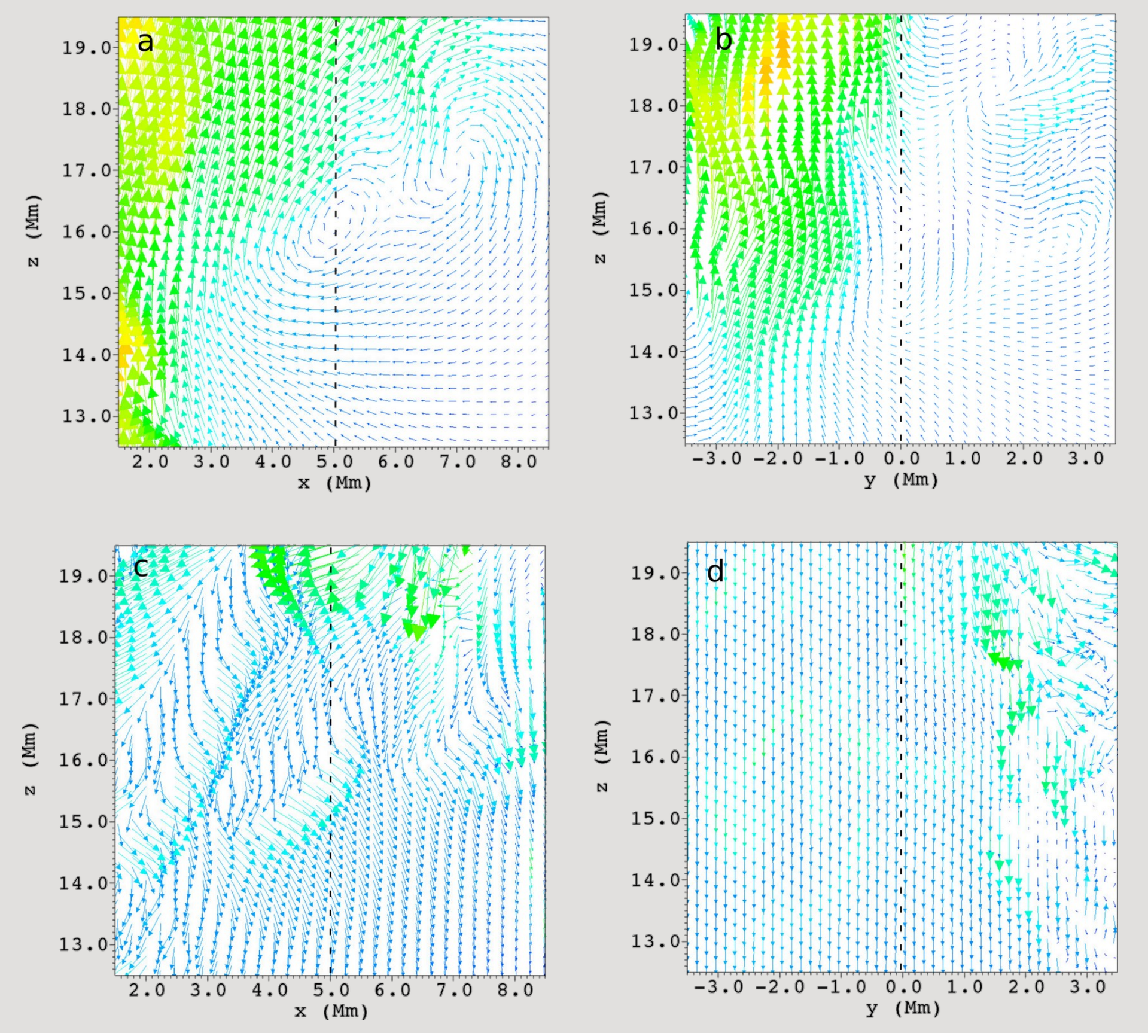

Fig. 5. Example of the **plasma velocity vortex** detected at the time 627 s. Its velocity and magnetic vector fields in the x−z and y−z planes are shown in the a, b panels and c, d panels, respectively. Vertical dashed lines in the a and c panels mean the crossing of the x−z plane by the y−z plane. On the other hand, vertical dashed lines in the b, d panels mean the crossing of the y−z plane by the x−z plane.

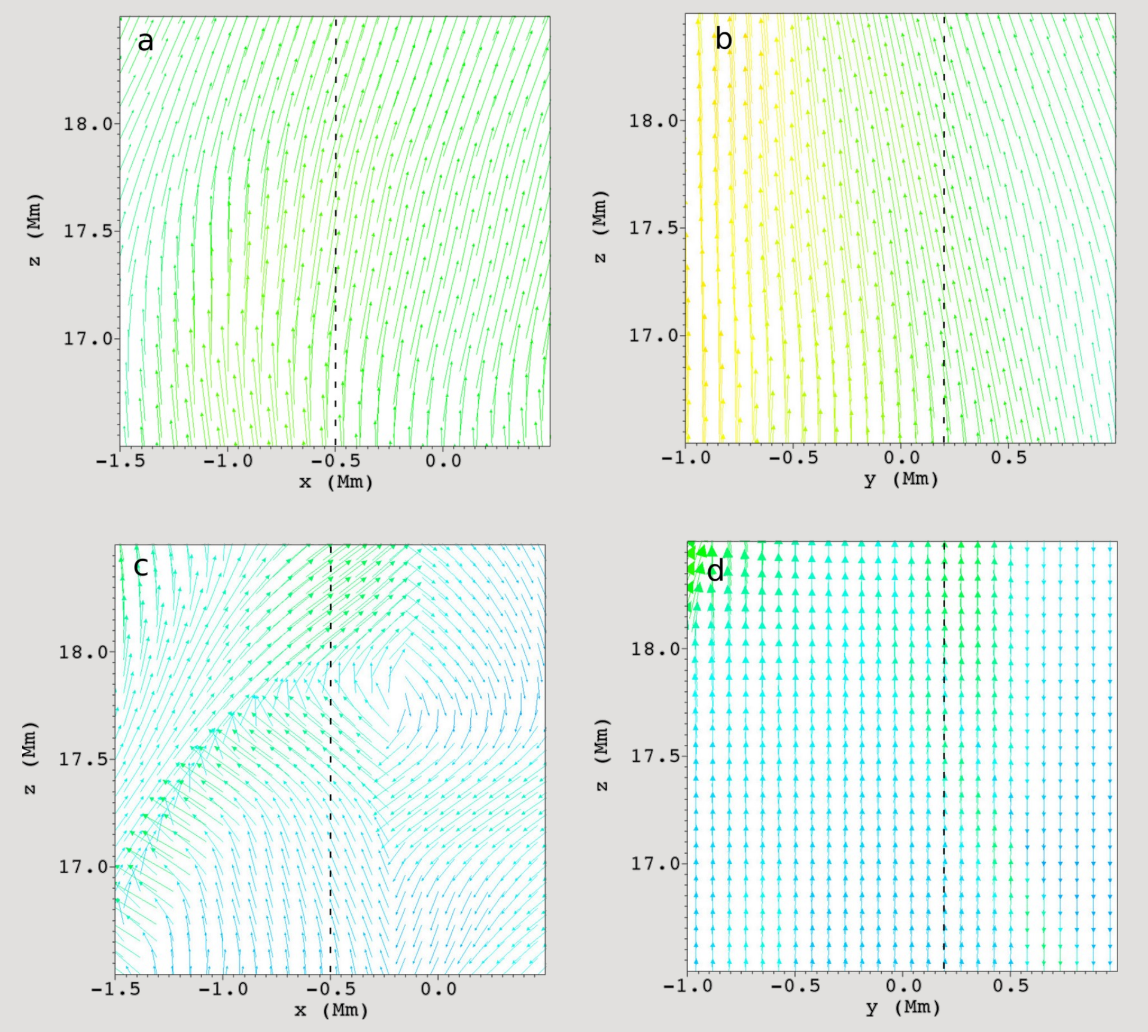

Fig. 6. **Magnetic cocoon** - its velocity and magnetic vector fields in the x−z and y−z planes at time 616 s are shown in the a, b panels and cd panels, respectively. Vertical dashed lines in the a and c panels mean the crossing of the x−z plane by the y−z plane. On the other hand, vertical dashed lines in the b, d panels mean the crossing of the y−z plane by the x−z plane.

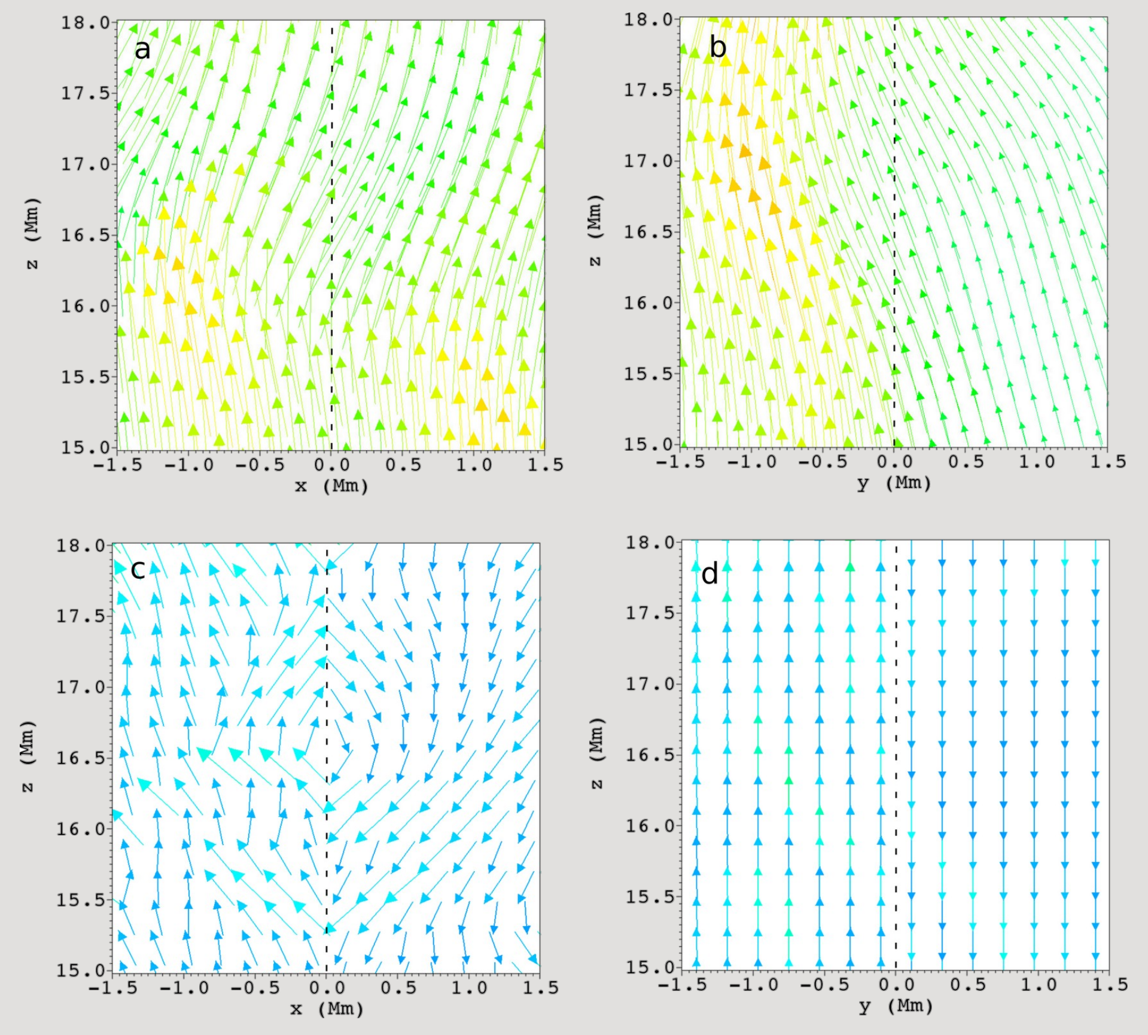

Fig. 7. Example of the **plasmoid** detected at time 627 s. Its velocity and magnetic vector fields in the x−z and y−z planes are shown in the a, b panels and c, d panels, respectively. Vertical dashed lines in the a, c panels mean the crossing of the x−z plane by the y − z plane. On the other hand, vertical dashed lines in the b, d panels mean the crossing of the y−z plane by the x−z plane.