Relativistic magnetic reconnection driven by a laser interacting with a micro-scale plasma slab

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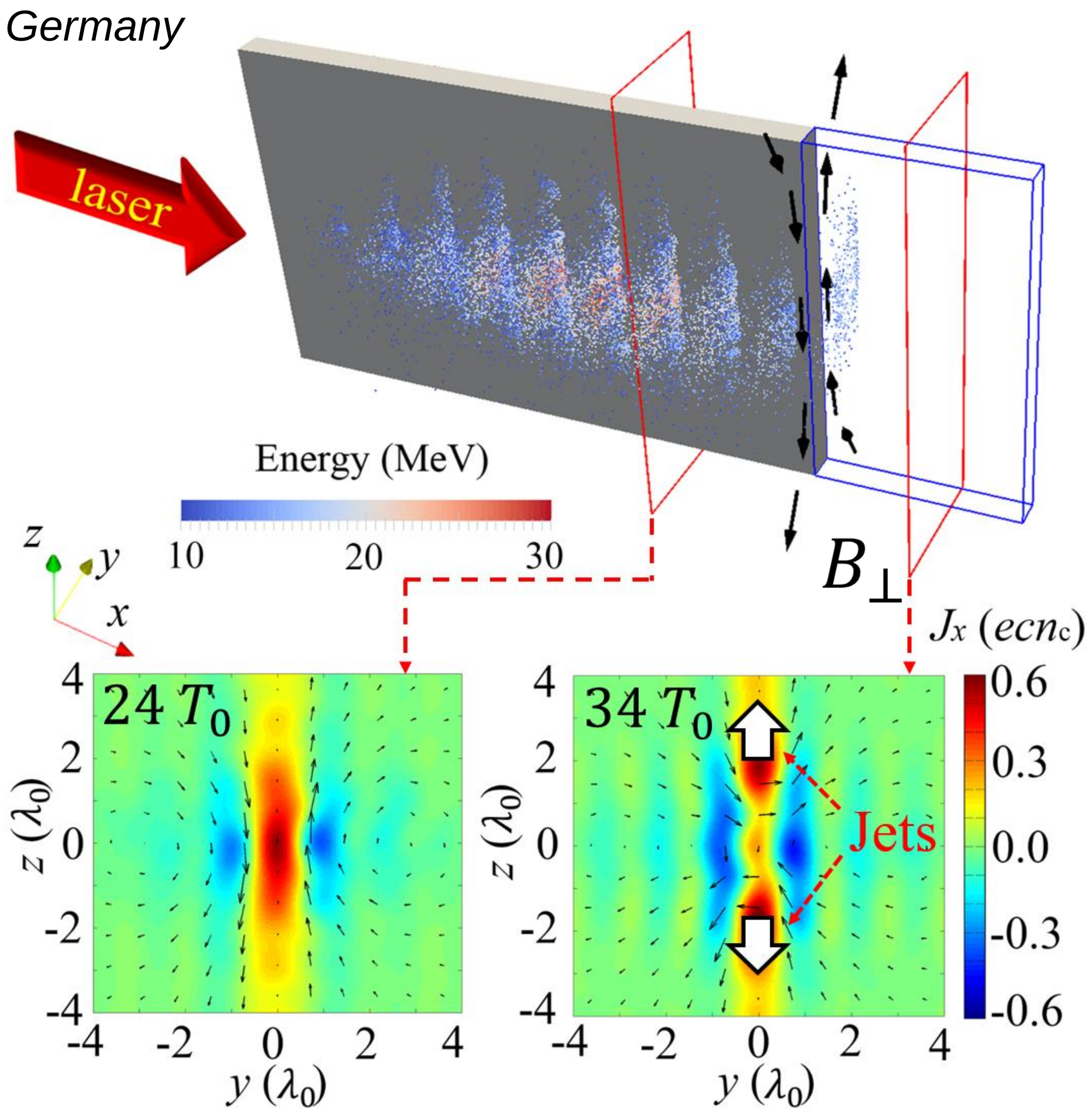
Abstract

In many high-energy astrophysical events, magnetic reconnection (MR) operating in the relativistic regime, i.e. with magnetic energy per particle exceeds the rest mass energy ($\sigma \equiv B^2/4\pi nmc^2 > 1$), is usually invoked to explain the non-thermal signatures. In this work [1], we propose a novel scenario where the relativistic MR is accessed via the interaction of a readily available (TW-mJ-class) laser with micro-scale plasma slab. By means of 3D particle-in-cell simulations, we show that when the electron beams excited on both sides of the slab approaches the end of the plasma structure, ultra-fast relativistic MR occurs in a magnetically-dominated (low-β) plasma. As the field topology changes, the explosive release of magnetic energy results in the emission of relativistic electron jets with cut-off energy ~ 12 MeV. In the meantime, various signatures of MR are observed, including a hard power-law electron energy distribution (with index p ~ 1.8), out-of-plane quadrupole field pattern, and quantified agyrotropy peaks in the reconnection site. The significant field dissipation process (0.1-TW-class) makes it a promising platform to study the non-thermal signatures and energy conversion in the relativistic regime of MR.



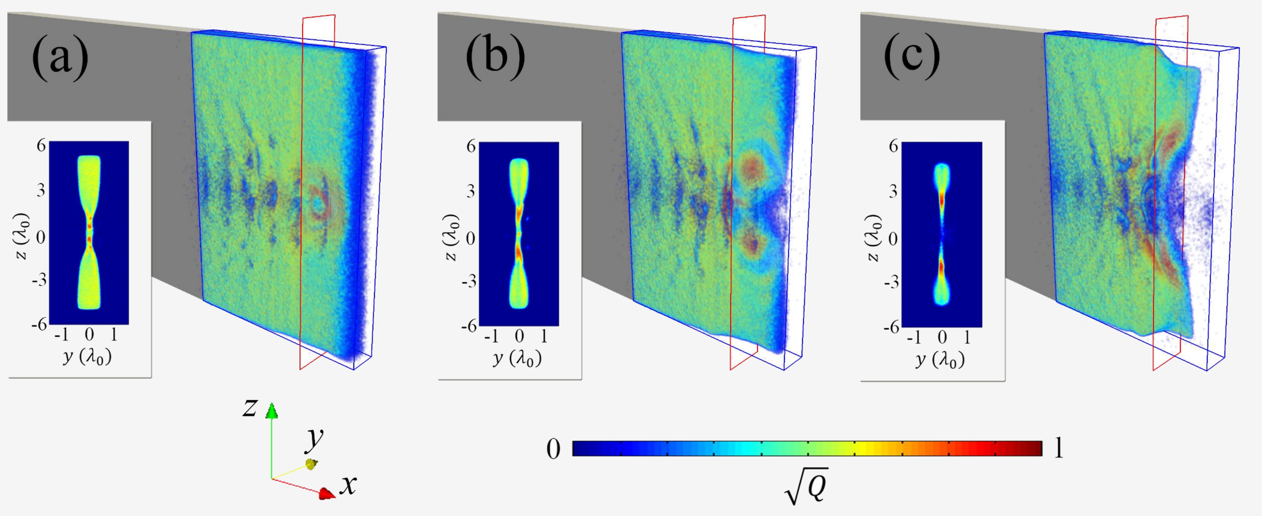
Sketch: a laser pulse irradiates the narrow side of a slab, the overdense plasma splits it in half and the light sweeps along the sharp boundary of the slab. The electrons in the skin layer are extracted from the plasma, forming relativistic bunches with inherited overdense densities, which is capable of producing **> 100 Mega-Gauss anti-parallel magnetic fields** in the mid-plane. The reconnection occurs when the electron bunches reach the coronal region, where, due to the decreasing in the electron number, the return currents inside the slab are not sufficient to separate the magnetic fields.

Simulation Parameters

- **Laser pulse**
  - $a_0 = 5$
  - Spot size $= 5\lambda_0$
  - $\lambda_0 = 1\ \mu m$
  - Duration $= 15T_0$
  - Peak Power ≈ 12 TW
  - Total energy ≈ 200 mJ
  - Polarization: LP(y)
- **Plasma slab**
  - $n_0 = 20n_c$
  - Dimention $(x \times y \times z) = 20\lambda_0 \times 1\lambda_0 \times 10\lambda_0$
  - Coronal region ($7\lambda_0$ in x): represented by the blue box frame (see sketch map on the top right), where plasma density decreases exponentially as x increases [$n = n_0 \exp(-(x - x_{\text{end}})^2/2l^2)$, scale length: $l = 2\lambda_0$]

Reconnection signatures

- **Pressure tensor agyrotropy** [2]

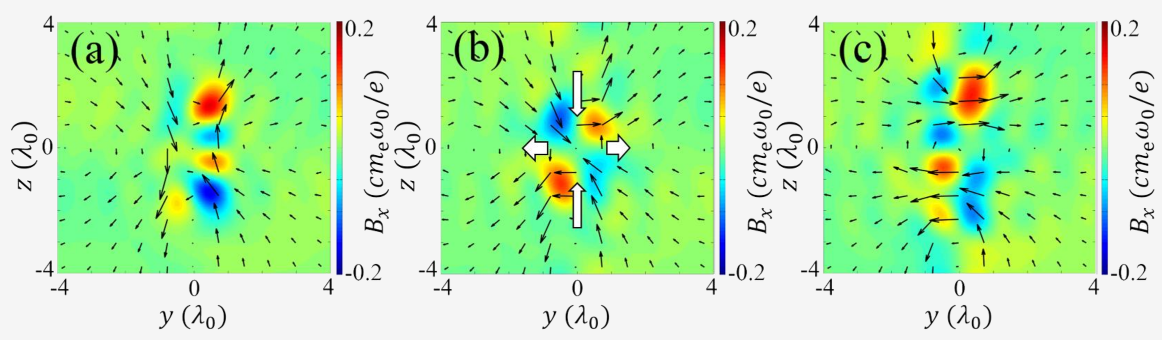


$$Q = \frac{\mathcal{P}_{12}^2 + \mathcal{P}_{13}^2 + \mathcal{P}_{23}^2}{\mathcal{P}_\perp^2 + 2\mathcal{P}_\perp \mathcal{P}_\parallel}$$

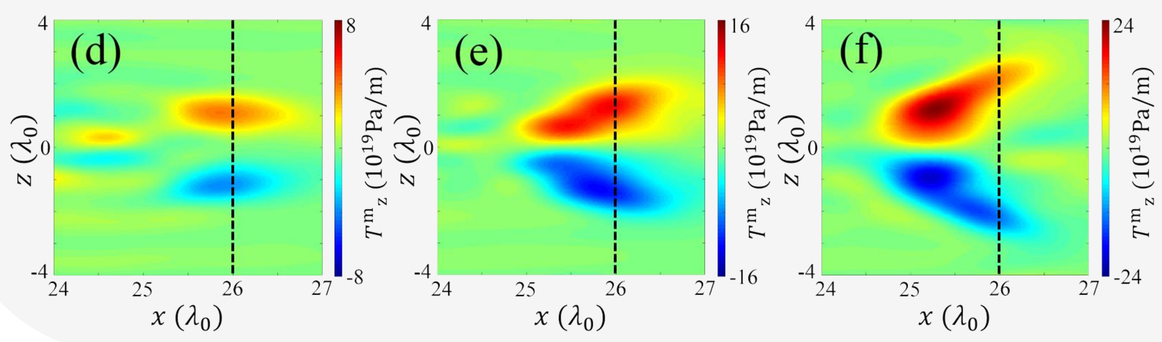
Here $\begin{pmatrix} \mathcal{P}_\parallel & \mathcal{P}_{12} & \mathcal{P}_{13} \\ \mathcal{P}_{12} & \mathcal{P}_\perp & \mathcal{P}_{23} \\ \mathcal{P}_{13} & \mathcal{P}_{23} & \mathcal{P}_\perp \end{pmatrix}$ is the electron pressure tensor

$$\mathbb{P} = m\int (\mathbf{v} - \bar{\mathbf{v}})(\mathbf{v} - \bar{\mathbf{v}}) f d^3\mathbf{v}$$

- **Field-line rearrangement**



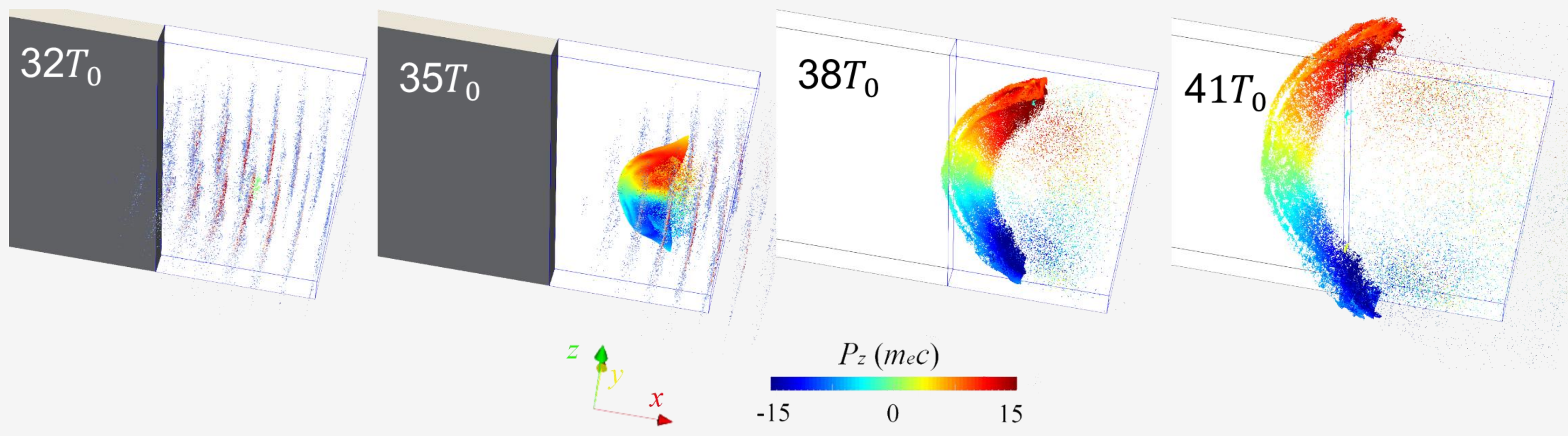
- Out-of-plane *quadrupole* magnetic field pattern



- Significant magnetic tension force $(\boldsymbol{B} \cdot \nabla)\boldsymbol{B}/4\pi$ arises due to *newly-connected, strongly-bent* magnetic field lines

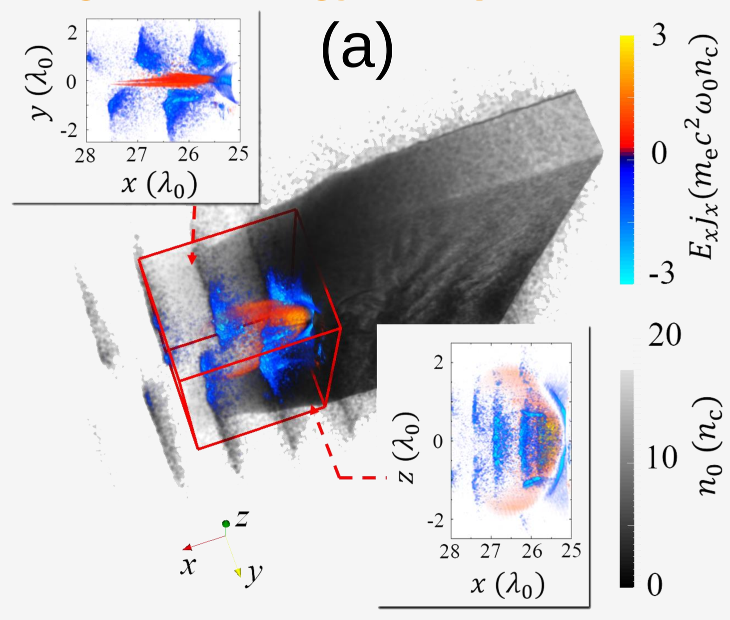
Particle acceleration & Field dissipation

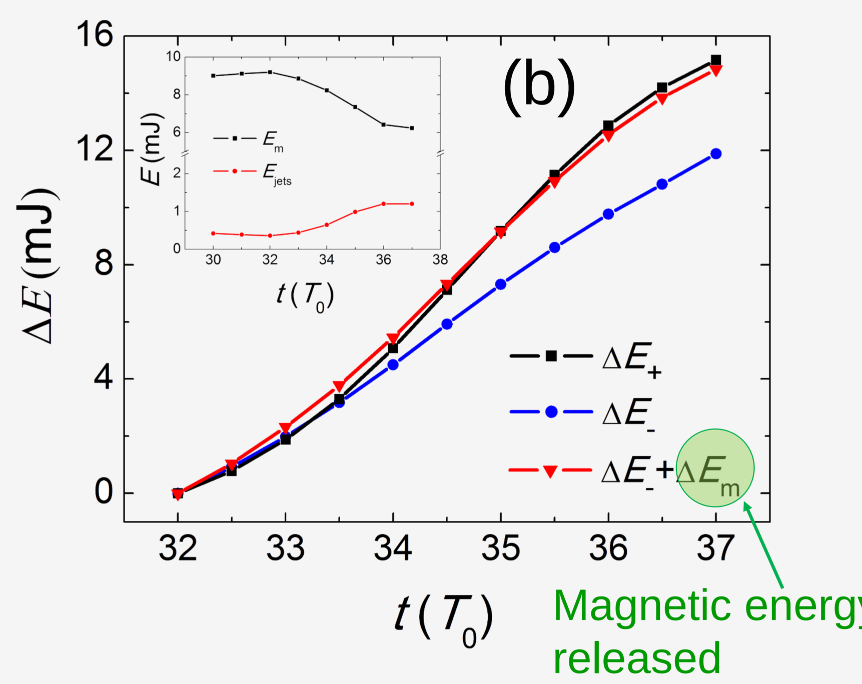
- **Emission of relativistic jets**

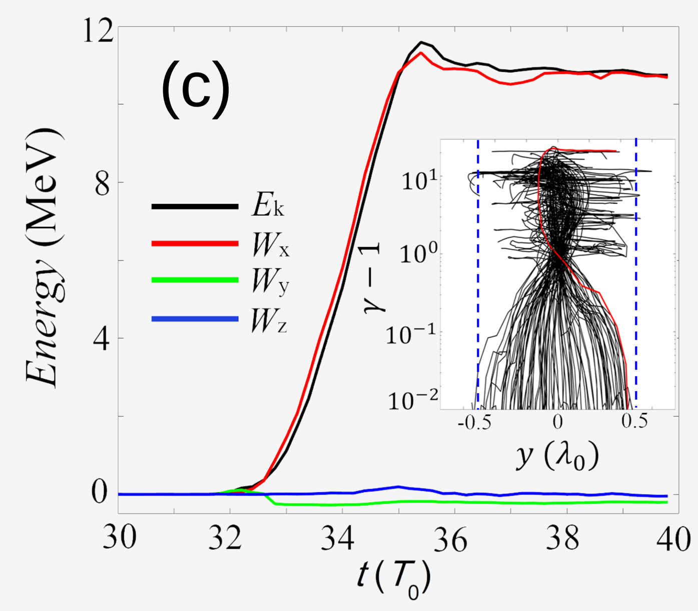


- Energy (cut-off) ~ 12 MeV
- Divergence (in y) ~ 0.1
- Total charge ~ 0.2 n_c

- **Magnetic energy dissipation**







- Electrons in the reconnection site **collectively** extract energy from (reconnection associated) electric field [see (a)]
- The reconnection event has a significant effect on the whole system, which accounts for ~ **20%** of total energy transition [see (b), the inset shows energy evolution of static magnetic energy and kinetic energy of jets]
- Dominating acceleration mechanism in this setup is **direct acceleration** by the reconnection field near the X-point [3] [see (c), the inset shows the accelerated electron trajectories]

Summary

- Relativistic MR can be triggered by irradiating a micro-plasma-slab with a readily available ($2.5 \times 10^{19}\ \text{W/cm}^2$ / 12 TW / 200 mJ) laser pulse, various of signatures of MR are observed in 3D PIC simulations
- Micro-scale target allows for depositing laser energy in a small volume, hence significantly reducing the laser energy required to achieve relativistic MR
- Comparing with most of previous laser-driven MR studies, since the magnetic field lines are not pushed together by thermal flow, here the magnetically dominated regime ($\beta \backsim 0.02$) can be accessed.

References

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