

Large-scale dynamos driven by shear-flow-induced jets

<https://doi.org/10.1038/s41586-025-09912-0>

Received: 18 December 2024

Accepted: 13 November 2025

Published online: 21 January 2026

 Check for updates

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At every scale they occupy, magnetic fields affect various phenomena, including star formation, cosmic-ray transport, charged-particle acceleration, space weather, transport in planetary atmospheres and laboratory plasmas. These fields are often generated and sustained by turbulent flows in a process called the dynamo. In 1955, E. N. Parker parameterized the effects of small-scale turbulence to propose a mean-field dynamo theory¹. The widely used theory reproduces observed large-scale fields but suffers from difficulty in tuning parameters as they are not justified from first principles: studies of turbulent flows show tangled magnetic fields, which are folded and fragmented into small-scale structures owing to shear-flow straining^{2,3}. Here, considering a shear flow that is unstable and driven, we develop analytic theory and perform three-dimensional, advanced computer simulations of turbulence with up to $4,096 \times 4,096 \times 8,192$ grid points, showing ab initio generation of quasi-periodic, large-scale magnetic fields. The generation occurs via the mean-vorticity effect—an additional mean-field dynamo process postulated⁴ in 1990. Crucial to this dynamo is the prior generation of large-scale three-dimensional jets, robustly produced as topologically protected and exact nonlinear solutions of the magnetohydrodynamic equations. The jet-driven dynamo applies to shear-driven laboratory and astrophysical systems. These include binary neutron star mergers^{5,6}, where the reported dynamo probably operates on microsecond timescales to produce in milliseconds some of the strongest magnetic fields in the Universe⁷, providing signals for multi-messenger astronomy⁸.

+general intro/reminder
about the purpose of
JC

Miljenko Čemeljić

CAMK Journal Club,
October 12, 2026, Warsaw

General intro about JC

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-Astronomical knowledge advances very fast thanks to use of the state-of-the-art facilities: telescopes, cameras, detectors and computers (remember to mention this when people ask you “why do we pay you to count stars?”: our demands are moving the industry on and, typically after a decade, part of the invented technics trickles to general consumers who pay for it dearly and make the producers very rich).

Discoveries are fast rewriting physics and astronomy textbooks. As always in the forefront of research, there is an increasing demand for digesting new information.

-One of the many ways of keeping updated of the latest knowledge is through journal clubs. A journal club is defined as an education forum of a group of individuals with the agenda of discussing articles to stay up-to-date with literature.

-Such forum started in medicine in the 19th ct., but probably even earlier. New works in academias of sciences were often presented in a form similar to JC today.

- some suggest that astrophysicists have replaced journal reading with regular visits to the Astrophysics subject (astro-ph) at arXiv www.arxiv.org.
- a **preprint** is an unpublished manuscript meant to be published in journals and/or serials. Preprints can be reviewed/accepted manuscripts, submitted manuscripts that are yet to be reviewed, and circulated manuscripts for peer-review before formally submitting them to a journal
- preprint servers are repositories of preprints. Most used in astrophysics is arXiv, from 1991. Advantage: **free for all**.
- by reading papers that are not yet peer-reviewed, participants may provide the authors of the papers direct criticisms before publication.
- It can help students develop critical evaluation skills in understanding manuscripts that are not yet peer-reviewed.
- addition 2026: became too many in a week to even skim through the list of titles.

Published articles studying journal club implementation have found certain points about journal clubs:

- goal of most JC is to do “critical appraisal”. This refers to “the process of carefully and systematically examining research to judge its trustworthiness, and its value and relevance in a particular context”.
- Without this, journal clubs just become a way to practice and improve presentation skills.-Not a bad thing, in my opinion, it is a needed skill.
- Didactic-like journal clubs (i.e. such which do not promote discussion) may cause participants to become passive learners.
- Senior organizers of journal clubs are more likely to dominate the discussion, by providing more experienced points of view. This may unintentionally cause pressure to other attendees who have less experience.-I think this is a good reason to have students involved in organizing the JC.

- Other factors which play a role in journal club success: maintaining attendance and engagement, having good and trustworthy resources for articles (e.g. websites, books, past presentations of other people, etc.), and **choosing an organizer who can facilitate the discussion.**
- Effective JC include: mandatory attendance, regular meetings with suitable schedules for everyone, clear short- and long-term purposes, circulating papers to be discussed before sessions, having an organizer that can lead the discussion.
- Having a **safe space where participants can ask “low-level questions”**, everyone can share perspectives without stress or fear of being embarrassed, the balance between the needs of those who are still learning and those who are experts.

Conclusions about JC in general

There are 4 important factors for a successful JC:

- commitment (dedication of organizer/s and participants in maintaining JC),
- environment (the overall organization of the JC as a forum for learning),
- content (topics and platforms for discussion),
- objective (goals of the JC)

Recommendations:

- Specify what you would like to achieve in attending and implementing JC (**objective**)
- Have a core of people and an organizer, who are dedicated to attend JC every session and participate regularly (**commitment**)
- Achieve balance in having an in-depth discussion of the papers presented and casual communication among participants, avoiding pressure and stress (**environment**)
- For each paper discussed, introduce the basic concepts and show other visual aids (videos, pictures from the internet, etc.) if necessary (**content**).

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At every scale they occupy, magnetic fields affect various phenomena, including star formation, cosmic-ray transport, charged-particle acceleration, space weather, transport in planetary atmospheres and laboratory plasmas. These fields are often generated and sustained by turbulent flows in a process called the dynamo. In 1955, E. N. Parker parameterized the effects of small-scale turbulence to propose a mean-field dynamo theory¹. The widely used theory reproduces observed large-scale fields but suffers from difficulty in tuning parameters as they are not justified from first principles: studies of turbulent flows show tangled magnetic fields, which are folded and fragmented into small-scale structures owing to shear-flow straining^{2,3}. Here, considering a shear flow that is unstable and driven, we develop analytic theory and perform three-dimensional, advanced computer simulations of turbulence with up to $4,096 \times 4,096 \times 8,192$ grid points, showing *ab initio* generation of quasi-periodic, large-scale magnetic fields. The generation occurs via the mean-vorticity effect—an additional mean-field dynamo process postulated⁴ in 1990. Crucial to this dynamo is the prior generation of large-scale three-dimensional jets, robustly produced as topologically protected and exact nonlinear solutions of the magnetohydrodynamic equations. The jet-driven dynamo applies to shear-driven laboratory and astrophysical systems. These include binary neutron star mergers^{5,6}, where the reported dynamo probably operates on microsecond timescales to produce in milliseconds some of the strongest magnetic fields in the Universe⁷, providing signals for multi-messenger astronomy⁸.

Helicity:

$$H_f = \int_V \vec{f} \cdot (\nabla \times \vec{f}) dV$$

Magnetic helicity:

$$H_m = \int_V \vec{A} \cdot \vec{B} dV, \quad \vec{B} = \nabla \times \vec{A}$$

Current helicity:

$$H_J = \int_V \vec{B} \cdot \vec{J} dV, \quad \vec{J} = \nabla \times \vec{B}$$

Kinetic helicity:

$$H_k = \int_V \vec{v} \cdot \vec{\omega} dV \neq 0, \quad \text{vorticity } \vec{\omega} = \nabla \times \vec{v}$$

Helicity because of helical path of fluid particles with velocity $\mathbf{V}$ and vorticity $\mathbf{w}=\nabla \times \mathbf{V}$ in parts of volume where the kinetic helicity is nonzero. With $H_k > 0$ the helix is right-handed, with $H_k < 0$ it is left-handed.

Flows with gradients, very common in nature, are often unstable, drive turbulence and appear with magnetic fields. Shear flows also rather support small structures, because of turbulences fragmentating the flows.

Q: How then the large-scale, smooth magnetic fields in magnetized planets, the solar cycle, stars, galaxies and cosmic voids can arise in the presence of destructive turbulent motions?

Because of Alfvénization—a fundamental magneto-hydrodynamic (MHD) process through which velocity and magnetic fluctuations become equipartitioned=smoothed and aligned, the traditional dynamos are almost completely suppressed.

Authors investigate a fundamentally different dynamo mechanism, in which Alfvénization **enables** the generation of large-scale magnetic fields.

In Yoshizawa, A., *Self-consistent turbulent dynamo modeling of reversed field pinches and planetary magnetic fields*, Phys. Fluids B 2, 1589–1600 (1990), a dynamo was presented which is linked to large-scale vortical structures. It is still a hypothetical mechanism, but authors verify it with simulations presented in this paper. They find that **such dynamo develops from the self-organization of large-scale jets and can arise naturally in astrophysical environment.**

Model and computational considerations

Using 90 million central processing unit hours, we performed more than 90 KH-dynamo simulations. We analysed 0.25 petabytes of turbulence data generated by evolving velocity $\mathbf{u}$ and magnetic field $\mathbf{b}$ according to the 3D incompressible MHD equations

$$\partial_t \mathbf{u} - \nu \nabla^2 \mathbf{u} + \nabla P = -\mathbf{u} \cdot \nabla \mathbf{u} + \frac{(\nabla \times \mathbf{b}) \times \mathbf{b}}{\mu_0 \rho} + \mathbf{f}, \quad (\text{S1a})$$

$$\partial_t \mathbf{A} - \eta \nabla^2 \mathbf{A} + \nabla \psi = \mathbf{u} \times \mathbf{b}, \quad (\text{S1b})$$

$$\mathbf{b} = \nabla \times \mathbf{A}, \quad (\text{S1c})$$

$$\nabla \cdot \mathbf{u} = 0, \quad (\text{S1d})$$

$$\nabla \cdot \mathbf{A} = 0, \quad (\text{S1e})$$

where $\mathbf{A}$ is the magnetic vector potential; ν is the kinematic viscosity; η is the electric resistivity; μ_0 is the vacuum magnetic permeability; P is the fluid pressure; ψ is a scalar function; and $\mathbf{f}$ represents external acceleration applied on a fluid of density ρ (here, $\mu_0 \rho = 1$). Equation (S1c) ensures $\nabla \cdot \mathbf{b} = 0$. We consider non-periodic and periodic domains. We simulate turbulence with and without an external mean magnetic field.

External mean-flow forcing

We externally force only the mean flow $u_x(k_x = 0, k_y = 0)$. The magnetic fields evolve freely. This allows us to focus on KH instability, which excites fluctuations at various scales via its nonlinear coupling. The forcing $\mathbf{f} = f_x(z) \hat{\mathbf{e}}_x$ in equation (S1a) is^{30,57–61}

$$f_x(z) = \frac{\langle u_x(t=0) \rangle_{x,y} - \langle u_x(t) \rangle_{x,y}}{\tau_f} + F_0, \quad (\text{S4})$$

where τ_f is the forcing timescale; F_0 is added to merely remove the viscous relaxation of the mean shear flow at $t = 0$, ensuring that the initial mean flow is a true MHD equilibrium, $F_0 + \nu \nabla^2 \langle u_x(t=0) \rangle_{x,y} = 0$.

We vary τ_f from 0 (frozen mean flow) to infinity (decaying mean flow). We reproduce essentially the same results except when τ_f is very large. In the latter case, the gradient of the mean shear flow quickly flattens because its energy is extracted by the KH instability at a rate faster than the rate of energy injection to the mean flow by the external forcing.

Background profiles and non-dimensionalization

In non-periodic domains, we consider a single shear layer¹⁰ $\mathbf{u}_0 = u_0(z) \hat{\mathbf{e}}_x$ where

$$u_0(z) = U_0 \tanh\left(\frac{z}{a}\right), \quad (\text{S2})$$

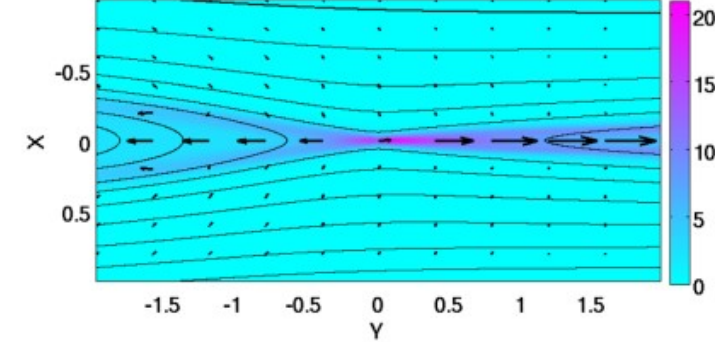
in a volume $[0, L) \times [0, L) \times [-L/2, L/2]$. In periodic domains, we consider a double shear layer³⁵ $\mathbf{u}_0 = u_0(z) \hat{\mathbf{e}}_x$ where

$$u_0(z) = U_0 \left[\tanh\left(\frac{z - z_1}{a}\right) - \tanh\left(\frac{z - z_2}{a}\right) - 1 \right], \quad (\text{S3})$$

in a volume $[0, L) \times [0, L) \times [0, 2L)$. Here $z_1 = L/4$ and $z_2 = 3L/4$, with $L = 10\pi$. Speed and length scales are measured using U_0 and a throughout this work. Fluid and magnetic Reynolds numbers are $\text{Re} = U_0 a / \nu$ and $\text{Rm} = U_0 a / \eta$, respectively. See Extended Data Table 1 for a list of symbols and meanings.

When a weak, uniform, external mean magnetic field $\mathbf{b}_0$ is initially imposed, $\mathbf{b}_0 = (\hat{\mathbf{e}}_x \cos\theta + \hat{\mathbf{e}}_y \sin\theta) / M_A$, where M_A is the Alfvénic Mach number, and θ is the angle between the initial mean field $\mathbf{b}_0$ and the mean flow $\mathbf{u}_0$. Dynamo saturation properties remain largely unimpacted by variations in M_A until M_A approaches the KH-instability threshold. Variations in θ are found to not affect dynamo saturation.

We seed instability by adding broadband, phase-randomized, divergence-free perturbations⁵⁰ to $\mathbf{u}$ and $\mathbf{A}$. The jet-driven dynamo emerges from general random perturbations. We solve equa-



Benchmarks and major code optimizations

Dedalus simulations. Using Dedalus⁵¹ (an open-source, general code written primarily in Python), we parallelize computations along the periodic directions x and y using the message passing interface (MPI). We use the pseudospectral τ -method^{35,51}, RK443 and SBDF2 mixed implicit–explicit time-steppers^{52,53}, and the 3/2 dealiasing for nonlinearities⁵¹. For non-periodic domains, we use Fourier–Fourier–Chebyshev bases, whose harmonics range from $128^2 \times 512$ to $1,024^3$.

GHOST simulations. Using GHOST^{54,55} (an open-source code written primarily in Fortran 90/95 to efficiently solve triply periodic systems), we parallelize computations along z using MPI and along y using OpenMP. For efficient computations, we place OpenMP threads next to each other within a NUMA node and bind OpenMP threads to an MPI task. The nonlinear terms are solved using the second-order explicit Runge–Kutta scheme. We have benchmarked GHOST against Dedalus, using identical initial conditions⁵⁶. We find that the dynamo-enabling jets appear in all test and production simulations, whose resolutions we vary from $32^2 \times 512$ to $4,096^2 \times 8,192$. The high z -resolution captures the mean shear flow.

The public GHOST code solves the visco-resistive terms using an explicit method, which is not ideal to capture small-scale fluctuations. These fluctuations, if not resolved, can lead to numerical instability. We have implemented a new time-integrator, that is, an exact integrating factor technique, which produces exact solutions corresponding to the visco-resistive terms. We have also implemented a forcing function, which maintains the mean flow.

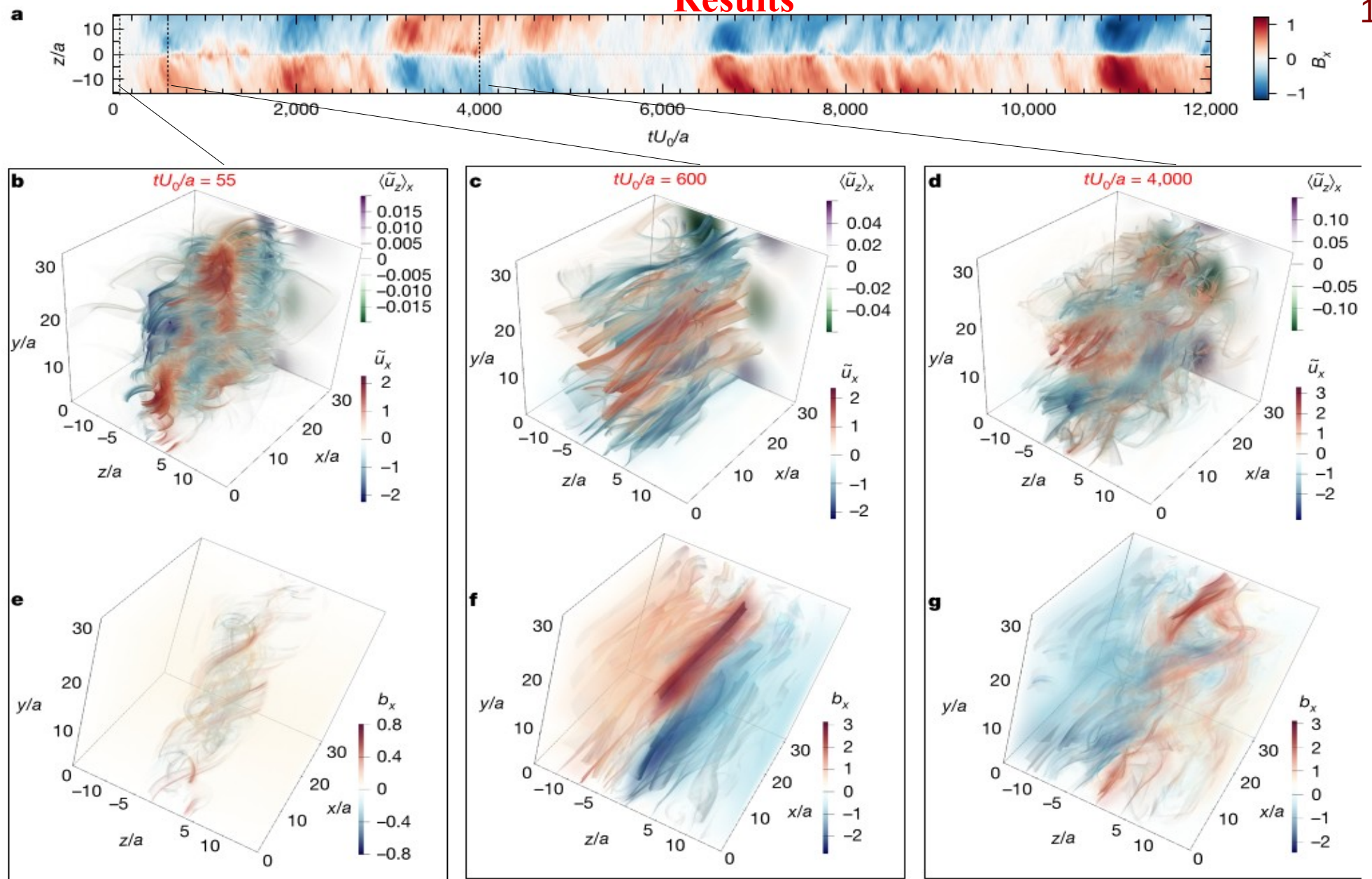


Fig. 1 | Long-time evolution of the MHD-KH dynamo, showing phases of turbulent generation of flows and magnetic fields. **a**, The (x, y) -averaged mean field B_x quasi-cyclically reverses (at time $tU_0/a \approx 3,000$; $5,300$; $6,000$; $6,350$). **b–d**, Three-dimensional streamlines in red–blue show turbulent velocity (the mean flow is not shown). Colours correspond to $\tilde{u}_x$, at times indicated by vertical dashed lines in **a**. The back-plane at $x/a = 10\pi$ shows vertical velocity $\langle \tilde{u}_z \rangle_x$, which is Fourier-filtered to obtain a fluctuation that is invariant in x and fundamental harmonic in y . At $tU_0/a = 55$ in **b**, the two-dimensional KH

eddies appear as cylinders, with almost no variation along y , but they have transformed into x -invariant jets in **c** and **d**. These jets are anchored on the (y, z) -plane at $x/a = 10\pi$, where $\langle \tilde{u}_z \rangle_x$ is large, shown with a purple–green colour bar. **e–g**, Streamlines of magnetic fields are overlaid on top of volume-rendered volume-filling fields. In **e**, the KH instability excites small-scale magnetic fields; in **f** and **g**, the nonlinear jets generate large-scale fields. The polarities of the mean fields flip between **f** and **g**.

Traditional mean-field dynamo theory expresses the turbulent EMF $\mathcal{E}$ in terms of the mean magnetic field $\mathbf{B}$, by removing a uniform mean flow via Galilean transformation²⁴. In the presence of an inhomogeneous mean flow $\mathbf{U}$, which cannot be removed, traditional mean-field theory needs to be generalized⁴. The essential elements of this generalization are reproduced by our quasilinear EMF model ('Analytic quasilinear EMF model' in Methods). This generalized theory predicts $\mathcal{E} = \alpha\mathbf{B} - \beta\nabla \times \mathbf{B} + \gamma\nabla \times \mathbf{U}$, where α captures kinetic helicity $\langle \tilde{\mathbf{u}} \cdot \nabla \times \tilde{\mathbf{u}} \rangle_{x,y}$ and current helicity $\langle \tilde{\mathbf{b}} \cdot \nabla \times \tilde{\mathbf{b}} \rangle_{x,y}$; here, β measures turbulent energy; and the upsilon γ stands for Yoshizawa's postulated mean-vorticity effect⁴ related to the cross-helicity $\langle \tilde{\mathbf{u}} \cdot \tilde{\mathbf{b}} \rangle_{x,y}$. The γ -effect is robust to variations in Pm (Fig. 2c and 'Analytic quasilinear EMF model' in Methods). A similar trend of γ shown during field-growth is found in the saturated phase. In addition to the multidimensional spatial regression²⁷ used in Fig. 2c, we have used temporal regression³⁴ to recover the dominance of the γ -effect.

We develop a physical understanding of the γ -effect in Fig. 3a. This effect has a strong analogy with the α -effect¹. A visual representation of the α -effect ($\alpha\mathbf{B} \propto \mathbf{B}\langle \tilde{\mathbf{u}} \cdot \nabla \times \tilde{\mathbf{u}} \rangle$) involves three elements: magnetic field ($\mathbf{B}$), velocity ($\tilde{\mathbf{u}}$) and vorticity ($\nabla \times \tilde{\mathbf{u}}$). Following that order, an initial straight mean field $\mathbf{B}$ is bent and rotated¹, thus creating a mean field orthogonal to $\mathbf{B}$. To similarly visualize the γ -effect ($\gamma\nabla \times \mathbf{U} \propto \nabla \times \mathbf{U}\langle \tilde{\mathbf{u}} \cdot \tilde{\mathbf{b}} \rangle$), we reverse the order of the previous three elements: vorticity ($\nabla \times \mathbf{U}$), velocity ($\tilde{\mathbf{u}}$) and magnetic field ($\tilde{\mathbf{b}}$). Following that order, an initial straight mean vortex line is bent, inducing jets (Fig. 3a). The jets are 3D as they vary along the y direction. The jets then operate on $\tilde{\mathbf{b}}$ to produce a mean field.

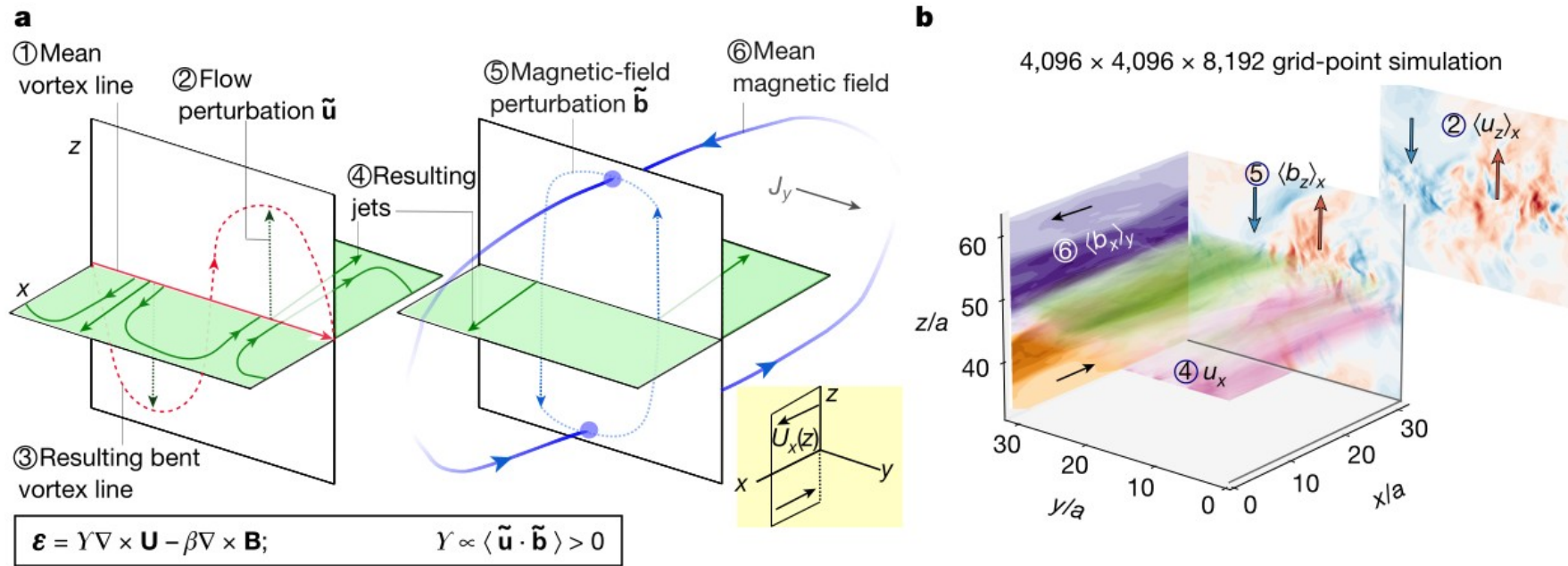


Fig. 3 | Mechanism of the jet-driven γ -dynamo. **a**, Red, green and blue represent vorticity, velocity and magnetic field, respectively. Step 1 shows a y -directed mean vortex line, corresponding to a mean shear flow $U_x(z)$ in the (x, z) plane, shown at the bottom right. In step 2, the KH instability excites a flow perturbation $\tilde{\mathbf{u}}$, with a sinusoidal variation in y , representing a purely 3D process. This flow perturbation bends the mean vortex line in step 3. Where the vortex line points upwards, eddy-like flows are induced around it; these are shown with solid green curves in step 4. This hydrodynamic process generates jets, which have no variation along x but are directed along x . Step 5 is the magnetic counterpart of step 2; the alignment between $\tilde{\mathbf{u}}$ and $\tilde{\mathbf{b}}$ represents here the case of positive γ (an Alfvénic state). The y -varying jets of step 4 stretch the y -varying

magnetic-field perturbation of step 5, thereby creating a mean magnetic field (invariant in x and y) in step 6. The mean field aligns with the mean flow. **b**, All quantities are plotted using red (pink) for positive and blue (green) for negative, where the colour map spans $[-M, M]$, with M representing the absolute maximum of each quantity. A half of the symmetric double shear layer³⁵ is shown. As flow and fields in steps 2 and 5 (in **a**) do not vary along x , they are x -averaged and displayed on the (y, z) plane at arbitrary x coordinates for visual clarity. Multiple (x, y) slices of jets u_x are plotted near a shear layer interface where jets are the strongest. The x -directed magnetic field is averaged in y , and $\langle b_x \rangle_y$, shown on the (x, z) plane. The mean flow is shown with the black arrows.

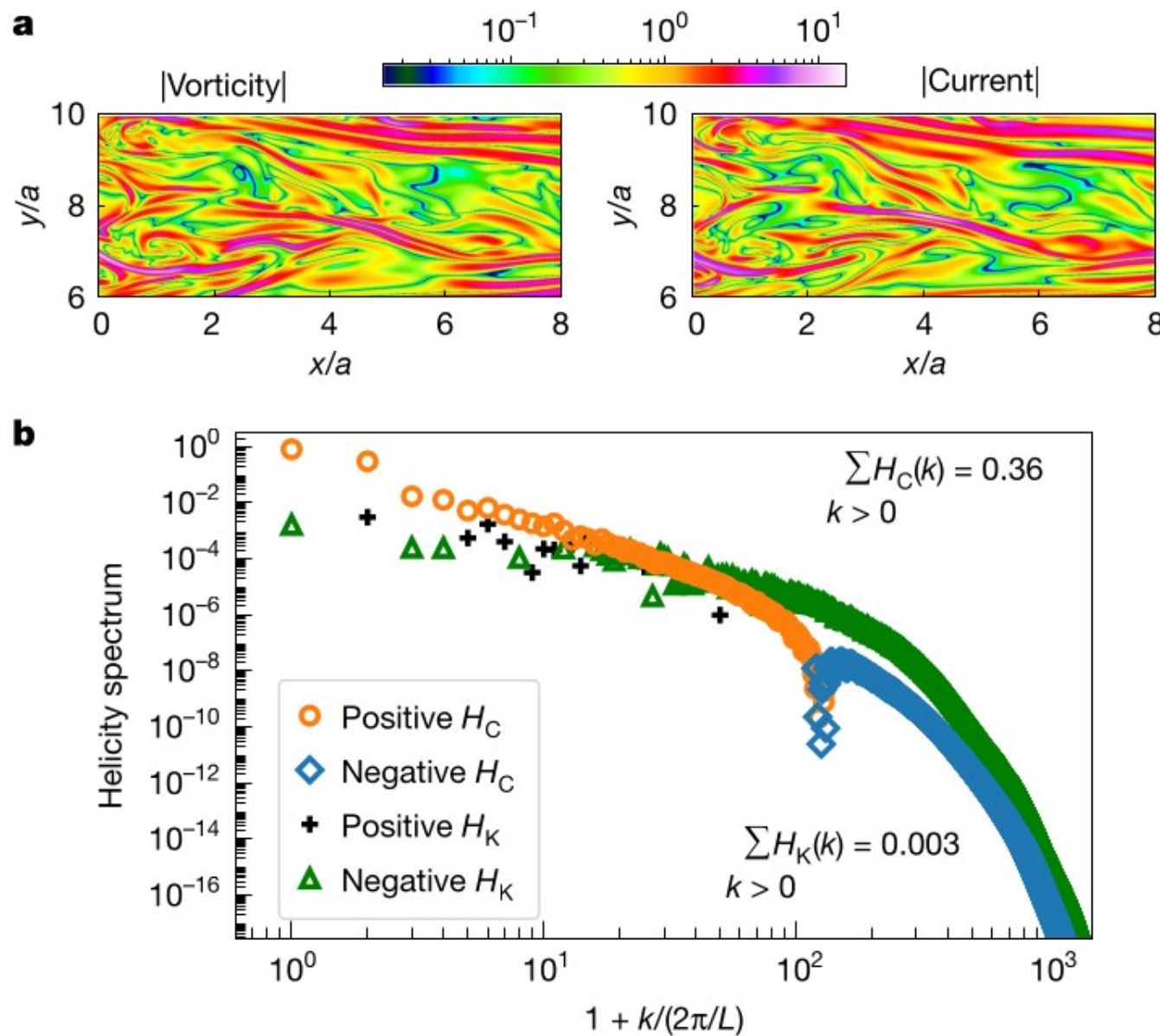


Fig. 4 | Dominance of cross-helicity. **a**, Vorticity $|\omega_z|/\omega_z^{\text{rms}}$ and electric current density $|j_z|/j_z^{\text{rms}}$ are similar; rms stands for root mean square. A typical slice is shown at a shear-layer interface ($z = 3L_z/4$); the full simulation domain is $[0, 10\pi) \times [0, 10\pi) \times [0, 20\pi)$. **b**, The total turbulent cross-helicity $H_C (\equiv \tilde{\mathbf{u}} \cdot \tilde{\mathbf{b}})$ is two orders of magnitude larger than the total turbulent kinetic helicity $H_K (\equiv \tilde{\mathbf{u}} \cdot \nabla \times \tilde{\mathbf{u}})$. Cross-helicity dominates at larger scales.

In the article are outlined the main features of the jet-driven γ (upsilon)-dynamo arising in turbulence generated by shear flows, with potential applications in laboratory dynamo experiments, the Sun, main-sequence stars, planets, accretion flows around compact objects and binary NS mergers.

The robust nonlinear jets are shown to be the physical mechanism behind the previously postulated γ (upsilon)-effect, which is confirmed in this work.

Article

Additional context info

Kinetic turbulence drives MHD equilibrium change via 3D reconnection

<https://doi.org/10.1038/s41586-025-09345-9>

Received: 23 September 2024

Accepted: 27 June 2025

Published online: 6 August 2025

Open access

 Check for updates

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Cross-scale coupling from magnetohydrodynamics (MHD) to non-MHD scales is important in interpreting observations of explosive events in nature, such as solar flares and geomagnetic storms^{1,2}. Experiments and observations also link it to the emergence of energetic particles and X-rays³. However, how this multi-scale physics affects the abrupt onset of reconnection remains unknown. Here we report observations from laboratory experiments involving two flux ropes with electron beams that induce magnetic turbulence and then abruptly merge into a single structure, altering the magnetic topology in the MHD regime. Two separate electron beams are launched along magnetic field lines and form individual flux ropes with a drift velocity higher than the ambient Alfvén velocity, effectively driving magnetic turbulence through beam-driven instabilities, as inferred from the increased level of the turbulent power spectrum. Experimental observations, including the appearance of energetic particles, increased ion temperature and changes in the characteristics of the flux ropes, suggest that beam-driven turbulence drives three-dimensional (3D) reconnection. 3D particle-in-cell simulations are performed, which successfully reproduce the key aspects of the experiment. These results directly explain how non-MHD kinetic processes progress through multiple scales to induce global MHD changes.

Magnetic flux ropes, which are current-carrying structures of plasma embedded in a magnetic field, play important parts in astrophysical^{4,5} and laboratory^{6,7} plasmas. As laboratory experiments are scalable to actual natural phenomena, flux rope experiments emulate solar flux ropes^{2,3,6,8–11} to study magnetic reconnection—a rapid energy-release process during merging^{12,13} that alters magnetic topologies—making investigation of its rather haphazard trigger mechanism essential. Previous research identified magnetohydrodynamics (MHD) mechanisms (such as attraction force and kink instability^{9–11,14}) and external forces^{15,16} that bring ropes into close proximity to initiate reconnection.

Reconnection fundamentally spans sub-ion to MHD scales: spacecraft^{1,17} and laboratory^{1–3} data confirm this multi-scale nature^{1,18} and suggest triggers in the MHD regime may be insufficient, necessitating simultaneous kinetic-scale onset and global MHD observations.

Magnetic turbulence is also closely related to magnetic reconnection¹⁹: pre-existing Alfvénic turbulence broadens the reconnection layer^{19–22} and reconnection-induced turbulence further accelerates the process itself^{23–25}. Parker Solar Probe data and simulations show Kolmogorov-like spectra^{26–30}, which match the predictions^{31–35}. However, the lack of reliable experimental methods to induce turbulence at specific locations within the plasma has impeded progress in the experimental domain.

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MHD equilibrium changes by merging

The experiment presented in this paper originates from a non-inductive current drive technique known as electrostatic (d.c.) helicity injection³⁶,

which is a key component of spherical torus fusion reactors³⁷. In this paper, we focus on the early phase of the technique using arc plasma guns, during which we demonstrate MHD equilibrium changes driven by turbulent flux rope merging. The experiment is conducted using two flux ropes in a three-dimensional (3D) helical magnetic field configuration in the Versatile Experiment Spherical Torus (VEST)³⁸. A schematic of the experiment in 3D view is shown in Extended Data Fig. 1. Before the merging, the two flux ropes discharged along the vacuum magnetic field form an open-field 3D helical configuration. Figure 1a shows the fast camera image at this phase (301.2 ms) with the 3D paths calculated from the field-following method (see Methods) for each flux rope. At the X-point shown in Extended Data Fig. 1b as a red cross, if the flux ropes merge by magnetic reconnection, a toroidally symmetric closed flux surface (CFS) forms¹⁴. The camera image after the merging at 301.6 ms is shown in Fig. 1b, in which a clear formation of CFS can be seen, coincident with marked changes in the structure of the magnetic field in the system and the whole MHD equilibrium.

With this kind of change in MHD equilibrium, changes in fundamental characteristics of the flux ropes must arise. As the impedance of flux rope, $Z_{fr} = V_{bias}/I_{fr,total}$, is a function of multiple variables such as length, area and density, it should be a good measure of these changes. The experimentally measured time evolution of Z_{fr} is consistent with this intuition, as shown in Fig. 1c. For the $V_{bias,high}$ condition (black line), a sudden and significant drop in Z_{fr} at 301.4 ms is observed and remains at a lower value, whereas for the $V_{bias,low}$ condition (green dotted line) Z_{fr} is relatively steady at a low value. The length of the flux rope L_{fr} calculated based on the magnetic configuration with formed CFS is also

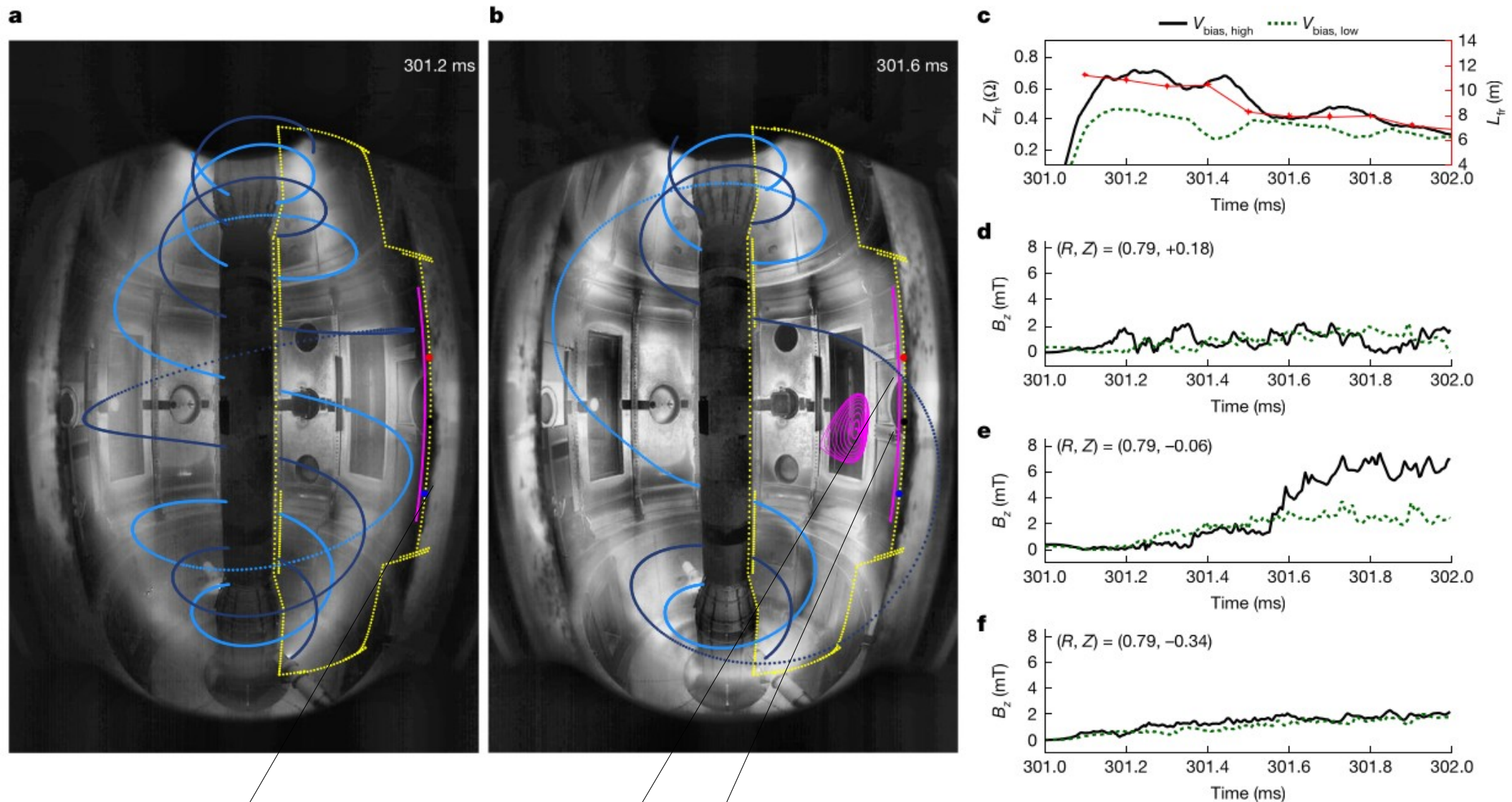


Fig. 1 | Changes in MHD equilibrium before and after flux rope merging.
a, A fast camera image taken with a fish-eye lens before the merging of two flux ropes. The integration time for a frame is 301.0–301.4 ms. The 3D field-following calculation result is also depicted (see Methods and Extended Data Fig. 1). The yellow dotted line indicates the inner wall boundary, the magenta line at the outer region indicates the limiter. The three coloured (red for top, black for middle and blue for bottom) dots are the locations of the selected magnetic pickup coils. **b**, A fast camera image after the merging of two flux ropes. The integration time for a frame is 301.4–301.8 ms. The magenta contours indicate

the CFS formed by merging activity. The CFS is calculated by FEM using magnetic pickup coil array measurement (see Methods). Note that after merging activity and in the formation of the CFS, the whole magnetic field configuration changes, resulting in short flux rope lengths. **c**, Time evolution of impedance of flux ropes (Z_{fr}). For the case of $V_{bias, high}$ (black line), a huge impedance drop after 301.4 ms is observed. The red starred line shows the trend of the flux rope length, L_{fr} , calculated using the vacuum field and FEM method. By contrast, in the case of $V_{bias, low}$ (green dotted line), only fluctuations can be seen. **d–f**, Magnetic field measurement results at the outer region.

Finite Element Method code

**Thank you.
Stay safe.
Stay sane. Run? Therapy?
Do Science!**

