Current starvation and relativistic magnetic reconnection

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Main reference

Y.J. GU, F. PEGORARO, P. V. SASOROV, D. GOLOVIN, A. YOGO, G. KORN , S.V. BULANOV, Electromagnetic Burst Generation during Annihilation of Magnetic Field in Relativistic Laser-Plasma Interaction. Sci Rep 9, 19462 (2019).

An old idea of present interest

In an ultra-relativistic plasma regime, magnetic reconnection may take completely different features due to the relativistic limit on the particle velocity.
Conditions can be realized when the spatial variation of the magnetic field cannot be balanced by the electron current in Ampere's law.

In this case the standard MHD description fails and the magnetic field dynamics is dominated by the displacement current and by the corresponding inductive electric field.

These regime corresponds to the so-called *dynamic dissipation* regime of the magnetic field, first proposed by S.I. Syrovatskii nearly 60 years ago in the context of Cosmic physics.

An old idea of present interest

This regime may not be realizable under solar conditions:

see Ulrich Anzer, *Why Syrovatskii's Mechanism of Dynamic Dissipation of Magnetic Fields Does Not Work*, Solar Physics, **30**, 459 (1973)

but it has become recently of interest and has been numerically verified in the context of relativistic laboratory plasmas and in particularly in the context of high energy laboratory astrophysics.

Fast magnetic-field annihilation in the relativistic collisionless regime driven by two ultrashort high-intensity laser pulses, Y. J. Gu, O. Klimo, D. Kumar, Y. Liu, S. K. Singh, T. Zh. Esirkepov, S. V. Bulanov, S. Weber, and G. Korn, Phys. Rev. E, **93**, 013203 (2016).

Syrovaskii

SOVIET ASTRONOMY—AJ VOL. 10, NO. 2 SEPTEMBER-OCTOBER, 1966

A dynamic dissipation mechanism is proposed that can convert magnetic energy directly into particle energy.

DYNAMIC DISSIPATION OF A MAGNETIC FIELD AND PARTICLE ACCELERATION

S. I. Syrovat-skii

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR

Translated from Astronomicheskii Zhurnal, Vol. 43, No. 2, pp. 340-355, March-April, 1966
Original article submitted November 20, 1965

A "dynamic" dissipation mechanism for a magnetic field is proposed that can convert magnetic energy directly into fast-particle energy. Under certain conditions motion of a conducting medium will produce regions with a strong magnetic gradient and high rarefaction. The maximum current the conducting medium can provide there will be inadequate to maintain the magnetic gradient. As a result a strong magnetic field will develop and accelerate charged particles. The reserve of excess magnetic energy will be transformed into the kinetic energy of the fast particles. Application of criteria that are derived indicates that dynamic-dissipation conditions may be realized in solar chromospheric flares, turbulent supernova envelopes, exploding galactic nuclei, radio galaxies, the earth's magnetosphere, and in certain laboratory experiments. In these objects dynamic dissipation may be the chief mechanism for accelerating particles to high energies, and in particular for generating cosmic rays.

Magnetic reconnection or annihilation?

Usually by magnetic reconnection we refer to a “low frequency” phenomenon that is essentially described within the MHD framework (or within an extended MHD framework) and that arises from the local violation of the so called frozen-in condition.

The frozen-in condition requires two steps:

1) given a velocity field **v**, the ideal Ohm must be valid. Together with Faraday’s equation this leads to the standard magnetic equation for the time evolution of **B**. In this case and magnetic field topology plays a central role. For this step Ampere’s equation and the displacement current are irrelevant.

2) the velocity **v** must result from the self-consistent time evolution of the plasma which does indeed involve Ampere’s equation.
In addition, the violating terms generally include the plasma current density, either multiplied by the plasma resistivity or differentiated with respect to time in the case of reconnection driven by electron inertia. In these terms the current density is related to the magnetic field through Ampere’s equation where the displacement current is neglected.

Laser “Reconnection”

nature physics

Article https://doi.org/10.1038/s41567-022-01855-x

Turbulent magnetic reconnection generated by intense lasers

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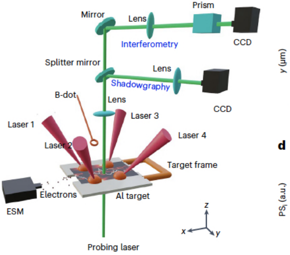
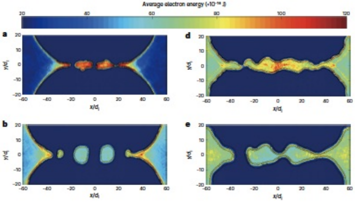




Magnetic reconnection or annihilation?

In Syrovatskii's approach the variation of the magnetic field is related to the displacement current in a context where the whole MHD framework stops to hold locally, not just Ohm's law.

The magnetic dynamics becomes locally wave-like and the topological constraints less relevant.

Such conditions can be realized when the spatial gradients of the magnetic field becomes too steep to be balanced by the plasma current that may be limited either because of a plasma density rarefaction or by relativistic effects, i.e. by the electron velocity approaching the speed of light.

The large electric fields that arise under these conditions can accelerate electrons directly and give rise, in Syrovatskii's words, to "dynamical dissipation" of the magnetic energy.

This process of magnetic energy realise would be better described as magnetic field annihilation, but the two terms are often mixed.

A clarification is due

Relativistic current limitation. The current of a single particle is not relativistically limited as can be seen immediately from the expression $j^\mu = qu^\mu$ so that $\vec{j} = q\gamma\vec{v}$ where γ is the particle Lorentz factor that can be arbitrarily large. Similarly the current density in a plasma is not limited and, for each species α, it is given by

$$\vec{J}_\alpha = n_{0\,\alpha}\, q_\alpha \gamma_\alpha \vec{v}_\alpha = q_\alpha\, n_\alpha \vec{v}_\alpha$$

with $n_{0\,\alpha}$ the proper density (the density in the fluid rest frame, i.e. essentially the number or electrons) and $qn_\alpha = qn_{0\,\alpha}\gamma_\alpha$ the charge density (the time component of the 4-current vector) which enters the Poisson equation.

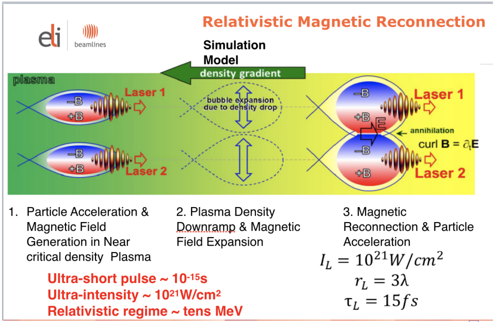
The relativistic electron current limitation occurs when $n_e = n_{0\,ea}\,\gamma_e$ cannot become arbitrarily large, as is the case e.g. when ions are slow to move and, on the time scales of interest the quasi-neutrality condition $n_e \sim n_i \rightarrow J_{\alpha\,\mu} U^\mu \sim 0$ applies. Here U^μ is the fluid plasma velocity 4-vector.

A related example of relativistic current limitation: relativistic transparency when the plasma current is not sufficient to cancel the displacement current of a large amplitude e.m. wave which can thus propagate even if $\omega < \omega_{pe}$.

Numerical simulations. Configuration

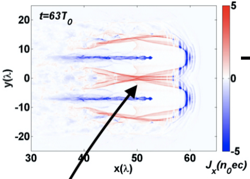
Here I recall the results of kinetic simulations on the collisionless relativistic magnetic reconnection regime in the 3D configurations (from Gu et al 2019 and 62nd Annual Meeting of the APS Division of Plasma Physics, 2020).

A configuration was used in which two sub-petawatt short laser pulses interact with a plasma target consisting of two density steps. The magnetic fields with opposite polarities generated by the laser driven electron current annihilate in the low density region due to the transverse expansion of the magnetic field. The fast annihilation creates a strong electric field that accelerates electrons.



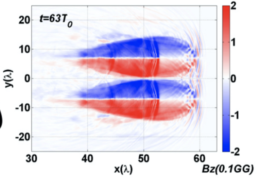
Simulation results

Magnetic quadrupole generation, expansion and annihilation

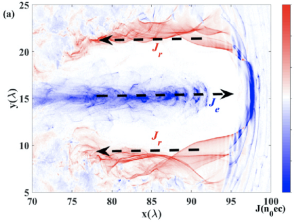


$$c\nabla \times B = 4\pi J + \frac{\partial E}{\partial t}$$

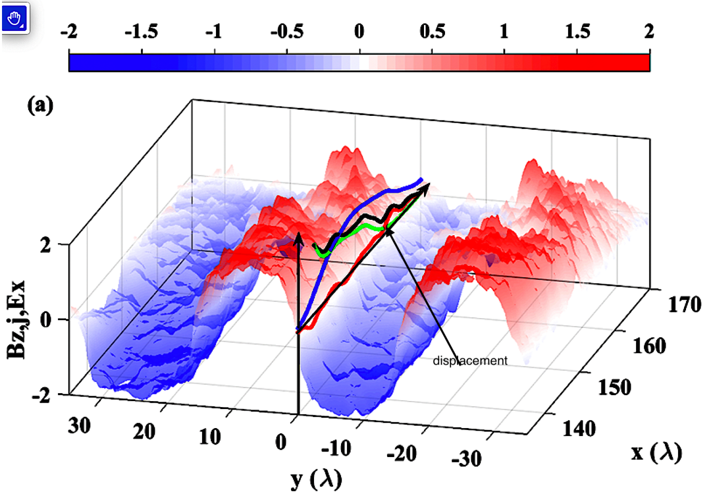
$$B_z = \frac{4\pi n_0 ec\sqrt{\gamma}}{\omega_p} \approx 0.2GG$$



X-point



Simulation results: displacement current



Energy peak

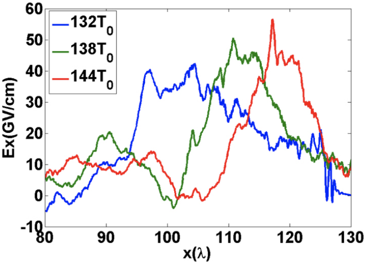
From Gu *et al*, 2019.

The strength of the inductive electric field reaches about $E_0 \approx 30\ GVcm^{-1}$. The inductive electric field region moves in the forward direction with the propagation of the opposite magnetic polarities. In this case, the backward accelerated electrons only experience a short range in the acceleration phase and then are ejected away from the field. The relative small region and the strong field strength decide that the electrons experience almost the same interaction time. Therefore the energy of the ejected electrons can be estimated as $\mathcal{E}_{ke} \sim eE_0\delta l$, here δl is the distance in which the electron experiences the field and can be approximately equal to the size of the X-line region as 10λ. Then the characteristic energy is about $\mathcal{E}_{ke} \sim eE_0\delta l \approx 30\ MeV$. Here the energy spectrum of the electrons which are initially localized in the current sheet is provided in Fig. 4(c). An energy peak appears at around $30\ MeV$ which is expected by our estimation. The mono-energetic radiation in the astrophysics is one of the difficulties in explaining by other acceleration mechanisms. Here we found by the MR induced particle acceleration, it is natural to obtain the mono-energetic beam.

Simulation results

eli beamlines

Inductive Field Growing & Propagating



Since the inductive electric field moves in the forward direction with respect to the propagating of the laser field, the electrons, which are accelerated in the backward direction, experience only an instantaneous kick.

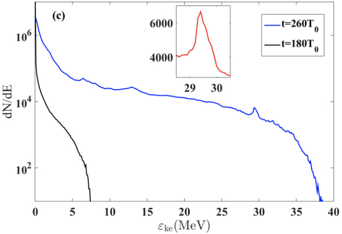
Therefore the corresponding electron bunch has a relative small energy spread.

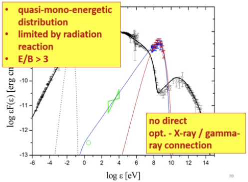
Simulation results

Energy spectrum

Monoenergetic peak

An energy peak appears at around 30 MeV. The appearance of mono-energetic radiation in astrophysics is difficult to explain by other acceleration mechanisms.
Here it is shown that it is natural to obtain a mono-energetic particle beam accelerated by magnetic reconnection





Energy spectrum

Tavani, *et al.*, *Science*, **331**, 736 2011

Conclusion

I have reported the investigation of a process of
fast magnetic annihilation induced by PW laser pulses in an underdense plasma in a highly relativistic regime,

based on
Y.J. Gu, F. Pegoraro, P. V. Sasorov, D. Golovin, A. Yogo, G. Korn, S.V. Bulanov, Electromagnetic Burst Generation during Annihilation of Magnetic Field in Relativistic Laser-Plasma Interaction. Sci Rep 9, 19462 (2019).
not a highly quoted article. See also
Y. J. Gu, O. Klimo, D. Kumar, Y. Liu, S.K. Singh, T. Zh. Esirkepov, S.V. Bulanov, S. Weber, G. Korn, Fast magnetic-field annihilation in the relativistic collisionless regime driven by two ultrashort high-intensity laser pulses Phys.Rev. E, 93, 013203 (2016).

These results confirm that the plasma dynamics in a suitable plasma configuration can reach a regime where the contribution of the displacement current is significant in the region of magnetic field annihilation and of growth of the inductive electric field.

The accelerated electrons present a peak in the distribution function. *The narrow energy spectrum provides a potential explanation for the observed radiation spectrum.*

The current sheet breaks into separated pieces and forms magnetic islands as in standard reconnection.

Simulation parameters

These kinetic simulations are based on the relativistic electromagnetic PIC code EPOCH in a 3-dimensional configuration.

The simulation box has the size of $L_x = 240\lambda$ and $L_y = L_z = 90\lambda$. Here $\lambda = 1\mu$ is the laser wavelength.
The mesh size in the simulations is $dx = dy = dz = \lambda/20$. All the quasiparticles (8 per cell) are initially at rest with a total number of 7x10^7. The real mass ratio of electron and proton ($m_p/m_e = 1836$) is used in the simulations. Open boundary conditions are applied for both fields and particles.

Two linearly polarized Gaussian pulses with the peak intensity of $10^{21} W/cm^2$ propagating in parallel along the x-axis are focused on the plane $x = 15\lambda$. The optical axes of the two pulses are transversely separated by 30λ, being located at $y = 15\lambda$.
The normalized amplitude is $a_0 = eE_0/(m_e\omega c) \sim 27$, where E_0 and ω are the laser electric field strength and frequency.
The pulse duration is $= 30fs$ and the spot size (FWHM) is 5λ,

Simulation parameters

The near critical density hydrogen plasma target has a thickness of 220λ along x and is uniform in the transverse direction in the region $(y2+z2)^{1/2} < 35\lambda$.

The density increases linearly from 0 to $n_1 = 0.2n_c$ in the region $10\lambda < x < 15\lambda$ and then remains constant for 40λ. Here $n_c = m_e\omega^2 = 4\pi e^2$ is the plasma critical density, which is approximately $10^{21}cm^{-3}$ for 1μ wavelength laser radiation.

From $x = 55\lambda$ to 165λ, the density decreases to $n_2 = 2x10^{-3}n_c$. This second density plateau region extends over the length of 60λ from $x = 165\lambda$ to 225λ. By employing a density down-ramp region, the magnetic field is forced to expand in the lateral direction quickly.

The second density plateau suppresses the strength of the longitudinal electric field arising due to the electric charge separation effect so that the inductive electric field effect can be clearly distinguished.