# Magnetic reconnection in space and fusion plasmas

**Guest editorial for the special issue "European conference on magnetic reconnection in plasmas"**

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## I. COMPLEMENTARITY BETWEEN SPACE AND FUSION PLASMAS

Magnetic reconnection (MR) processes, which result from local modifications of the connectivity of magnetic field lines and can thus connect plasmas of different origins (such as solar plasma and the terrestrial magnetosphere), are by nature multi-scale. This change of connectivity is accompanied by a fast release of magnetic energy as heat and accelerated particles which are at the origin of many observed phenomena in nature and plasma experiments [1, 2]. Taking into account different geometries, common features characterizing MR in both space and fusion plasmas become apparent.

While the presence of a strong magnetic guide field in one direction may suggest a 2D approach, under many circumstances, a 3D description is unavoidable when attempting to capture key dynamics. When the 2D picture is possible and thus a (quasi-)periodic direction is present or a nearly-invariant direction can be identified, the change of topology of the magnetic field occurring during a MR event leads to the formation of magnetic islands. They are routinely detected in fusion devices and are believed to play a major role in space plasmas, for instance in the dynamics of strongly heated coronal loops [3].

Even though MR is ubiquitous in nature and in strongly magnetized experimental plasmas, interactions between the space plasma and fusion communities remain rare. However, it is worth noting that these areas are often complementary not only in terms of dimensionless parameters, underlying physics, and processes seeding reconnection [36] but also in terms of the data that experiments and observations can provide to test theories and validate heuristic models or numerical results. Indeed, on the fusion side, no direct in situ measurements of the magnetic fluctuations and currents inside an experimental device can be done [4–7], while space missions such as CLUSTER and its successo MMS (Magnetospheric Multiscale Mission) collect data in-situ on spatio-temporally fast-varying scales compared to the resulting large-scale magnetohydrodynamic (MHD) phenomena involving MR [8]. Both space missions use four identically instrumented spacecrafts to study magnetosphere. On the space-plasma side, spacecrafts provide only quasi-pointwise measurements along their trajectories. Conversely, in magnetized plasma devices such as tokamaks and reversed-field pinches, diagnostics targeting magnetic fluctuations allow one to follow the global island dynamics which result from various reconnection processes [7]. Such diagnostics are indirect or remote measurements and include edge probes (Mirnov coils) or electron cyclotron emission imaging diagnostics. In other words, even if satellites from different missions are spread over several regions of the magnetosphere, a volumetric mesh of measurements is not accessible in space plasmas, and this makes the study of the dynamics of large-scale magnetic structures developing in the magnetosphere and comparisons with simulation data fairly complex. As a consequence, in each community, but for opposite reasons, there is almost no experimental access to multi-scale aspects of MR physics. However, over the last decade, research, often owing to theoretical and numerical advances, is increasingly focusing on the multi-scale aspects of magnetic reconnection. In the future, corresponding experimental and observation data may become available. A deeper understanding of this fascinating and dynamically essential physics, however, necessarily requires fostering interactions between the two communities.

Moreover, even though physics of fusion and space plasmas can operate in very different regimes, including collisionality and dimensionless parameters such as $\beta$ (the ratio between the thermal and magnetic pressure), the fundamental mechanisms which drive MR are in principle universal. In particular, in the framework of fluid descriptions, it has been shown that for reconnection to occur, the non-inductive part of the electric field parallel to the magnetic field must be finite and that, generally, reconnection occurs in so-called diffusive regions where four different magnetic-flux transport regions are encountered. In 2D geometry, reconnection relies on magnetic null points. In particular, X-type nulls are hyperbolic points from which magnetic field lines called separatrices diverge (positive null) or to which they converge (negative null). They separate the four distinct flux regions. Note, however, that the associated existence of a quadrupolar flow crossing these flux regions [9] is still a matter of open debate, relating to the saturation mechanisms of MR—flow being enclosed in flux regions has

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been observed in fluid and kinetic simulations [10, 11]. Owing to laboratory studies of MR [12] and advances in high-performance computing, there also is growing interest in multi-scale aspects of MR using kinetic models; such an approach would allow us to verify or go beyond fluid models, which have been used to analyze salient features of the processes at play, including interactions between turbulent phenomena and MR [8, 13, 14, 16, 17]. To achieve a deeper understanding of multi-scale MR physics, cross-comparisons between experiments, observations and numerical simulations can make an essential contribution. By pooling work involving specialists from both communities, we can provide a stepping stone to obtain a global picture of magnetic reconnection.

## II. CONNECTING FUSION AND SPACE-PLASMA RESEARCH

In Igochine (2023) [20], an overview of the reconnection physics in the specific context of sawtooth crashes is given. Such crashes are routinely observed in tokamaks and lead to a redistribution of core temperature on a fast timescale. It is pointed out that numerical results from simulations based on the so-called Kadomtsev model [21] – an adaptation of the Sweet–Parker model which describes time-independent magnetic reconnection in the resistive MHD for tokamak configurations – present contradictions with experiments to a significant extent. It is also highlighted that two-fluid effects and partial magnetic stochasticity of the field lines could be a key player and resolve disagreements.

Stochasticity of magnetic field lines is a natural 3D MR effect in fusion plasmas. However, such plasmas are characterized by strong guide fields and thus, locally, magnetic structure is symmetric and MR occurs on specific resonant equilibrium magnetic surfaces that can be identified experimentally [22]. MR results in a transfer of magnetic flux driven by a combination of inward and outward plasma flows. In a 2D context, the different flux regions brush against each other in the vicinity of the X-points. In a space physics context, the identification of sites where reconnection occurs is a matter of ongoing efforts [13, 15, 19] and, moreover, involves 3D features. In Parnell (2023) [23], using an analytical model for the magnetic field, the importance is stressed of magnetic field lines linking positive and negative nulls, called separators, and the bifurcation processes leading to their creation. 3D separators are topologically equivalent to 2D null points in that they form the boundaries between the four flux domains. A key point is that MR can occur on a significant fraction of the separators but not in the vicinity of null points. Solar separators can reach many solar radii in length. It is concluded that intercluster separators that connect two distinct and distant weak field regions could provide a significant amount of MR.

Local MR can also connect magnetically two distant and different regions of space such as the Sun and the Earth, giving rise to, e.g., the Aurora Borealis, which results from a flux of particle from the Sun to the Earth through the generation of a magnetic islands at the magnetotail of the Earth. The generation and the dynamics of magnetic islands is also a major issue in tokamak plasmas because they can radially expand and generate a significant flow of hot particles from the core to the edge of the machine, reducing reactor efficiency and possibly even damaging the reactor wall. Despite the implementation of active control of island dynamics – for instance by injecting current at resonant surfaces where an island grows – preventing these disruptive processes cannot be guaranteed, in particular for the next tokamak generation.

The birth of a magnetic island in a tokamak can have various causes, such as a current driven instability [24] or microturbulent forcing [17, 18]. In [25], analyzing discharges of the Joint European Torus (JET) tokamak, it is observed that sawteeth tend to reduce the rate of island generation. Islands are shifted radially outward compared to where sawteeth arise, with little to no overlap. In tokamaks, the global magnetic equilibrium configuration is such that, if the island reaches a critical radial extension, it can be strongly amplified in size and produce a so-called neoclassical tearing mode (NTM) [26]. The community has made strides to predict the island width evolution, relying in particular on generalized Rutherford models [27, 28], even though their predictive ability is limited in terms of parameter space [29]. The main focus of [25] lies on the role of the ion polarization current (IOPC) in the triggering of NTMs, which is investigated using tokamak JET disruptive discharges. This current is perpendicular to the magnetic island and is induced by particle drifts. According to Rutherford models, the IOPC strongly impacts the island width dynamics, but this impact is itself very sensitive to the rotation frequency of the island with respect to the plasma. Analyzing JET discharges, it is found that IOPC is always destabilizing and, to a large extent, is a dominant mechanism for the onset of the island. This result is in agreement with theoretical work based on drift kinetic models [30]. Furthermore, the IOPC is shown to substantially decrease the critical radial width beyond which the island results in an NTM. An interesting conclusion is that, IOPC being sensitive to (external) magnetic perturbations, it introduces randomness in the onset of the NTM.

The linear properties of magnetic islands substantially impact the associated nonlinear regimes and saturation mechanisms, and thus the reconnection properties of the medium. In space plasmas, the evolution of current sheets is commonly set by the maximum growth rate of a broad range of unstable modes [31], while in fusion plasmas, the periodicity of current sheets typically reduces the problem to the evaluation of a single, well-identified unstable mode. However, it is worthwhile to mention that both in fusion device experiments and in space plasma observations, the linear regimes of island growth are not generally observed. Moreover, the linear properties depend on various effects and parameters, and a unified view of linear reconnection is still lacking. In Betar *et al.* 2020 and 2023 [31, 32], using heuristic methods, a systematic multi-parametric study of the linear properties of islands is carried out, determining scaling laws of the tearing mode and validating them by numerical simulations. In particular, in Betar *et al.* 2023 [32], the focus lies on electron-magnetohydrodynamics (EMHD), extracting analytically scalings for different regimes, from the collisionless, electron-inertia driven regime to various collisional regimes. Scalings are numerically verified using an arbitrary-precision eigensolver. EMHD relies on magnetized electrons and unmagnetized ion flows and has been used to analyze spacecraft reconnection data [33], but it has also been deployed in fusion contexts [34, 35]. This work is extended in Betar *et al.* 2024 [36] to cases of interest for laboratory experiments and solar-wind turbulence by considering coupling of conjugate ideal-MHD effects. Fixing the electron skin depth, the growth rate is computed for cases of interest either for tokamaks or solar plasmas. Specifically, cases are considered where either anisotropic resistive parameters and parallel viscosity are on the same order, or where resistivity and viscosity are isotropic.

To describe reconnection in collisionless plasmas, different fluid-like models exist, ranging from cold-ion to hot-ion regimes, including or excluding finite-Larmor-radius or skin-depth effects, among others. A key point is that effects from finite ion temperature can not generally be neglected. Indeed, the ratio of ion to electron temperature, $\tau$, typically ranges from 1 in the solar wind to more than 10 in the Earth's magnetoshere. In Granier *et al.* 2024 [37], the influence of $\tau$ on the tearing instability is analyzed in the limit of low electron $\beta$. This study uses a gyrofluid model [38] which bridges the gap between different models including MHD, EMHD, and inertial kinetic Alfvén waves (IKAW), and thus is not limited to cold ions. 2D numerical simulations show that when a magnetic island is generated by a current-driven instability, a secondary Kelvin-Helmholtz instability (KHI) develops in the vicinity of the separatrices for any $\tau$ and, thus, for any Larmor radius, whether it is small or large compared to the equilibrium current sheet. The KHI in turn drives turbulence characterized by $\tau$-dependent spectral slopes. Moreover, for large but finite $\tau$, magnetic vortices develop and flow outside the island. On the other hand it is also well known that, when the KHI is the primary instability, magnetic islands can emerge through a secondary instability in the nonlinear phase of nearly 2D KHI structures,in particular along vortex arms where magnetic field lines have been rolled-up, i.e. in a very simplified dynamics of the low-latitude magnetopause [39].

A more complex process occurs in intrinsic 3D situations once latitudinal variation of the magnetopause is taken into account. In [40], based on resistive-Hall-MHD simulations, magnetic reconnection events induced by KHI dynamics at Earth's magnetospheric flanks are analyzed. They focus on the role of the equilibrium magnetic shear (initial shear at the magnetopause) on the KHI and reconnection dynamics. The magnetopause shear defines the transition between the Earth's magnetosphere and the magnetosheath where solar-wind flows around the former. Even if in the early evolution the KHI features are localized around the equators, numerical simulations show that the later evolution is characterized by an asymmetric migration of vortices toward the southern hemisphere and thus toward what initially corresponds to the magnetosphere. Such migration is enabled by a weakning of the magnetic shear induced by the differential advection of the magnetic field lines, which in turn increases KHI drive. The converse occurs in the northern hemisphere, where, first, KHI drive decreases, second, magnetic shear increases and seeds current sheets. This differential advection is due to the combination of KHI vortex motion and field line tying on the Earth. As a consequence, the initial current sheet is enforced in the northern hemisphere, and reconnection starts to occur there. In the southern hemisphere, the magnetic mid-latitude reconnection (MLR) is observed. A striking observation is that MLR does not occur in a symmetric way as it is the case in the absence of magnetic shear as observed in previous works [39]. The resulting structure of the magnetic field lines is quantified in terms of latitudinal distribution of magnetic field line connection changes. The main current sheets drifting northward also produce vortex-induced reconnection and, combined with MLR phenomena, enhance the number of connection changes at mid-latitude; thus, a barrage reconnection events ensues. One of the key outcomes of this study is that it provides a path to obtaining an adequate magnetic equilibrium.

The problem of finding a good representation of the equilibrium magnetic field is not specific to space plasmas. In tokamak plasmas, gyrokinetics models [41–44] allowing deviation from Maxwellian distributions typically rely on many assumptions, such as low $\beta$ and collisionality. They also do not include the impact of neoclassical physics on the equilibrium, which is particularly important in magnetic-island and reconnection contexts. In Dudkovskaia (2024) [45], a formalism is laid out that avoids restrictive assumptions on the normalized plasma pressure and, crucially, does not assume the poloidal background magnetic field to be small. As a result, this new equilibrium approach is expected to provide more realistic equilibria in spherical tokamaks (STs). In particular, when coupled with gyrokinetics [46], it allows one to investigate the impact of neoclassical physics on plasma turbulent transport, and vice versa, in steep-gradient regions of STs. Moreover, a special case of interest for MR is considered, addressing the physics of small magnetic islands and enabling improved treatment of the plasma response to propagating magnetic islands.

The dynamics of current driven reconnection in tokamaks using the gyrokinetic framework and in particular the coupling between meso-scale magnetic islands and micro-scale turbulence has remained an active research area since key efforts were started more than a decade ago [11, 47]. In Widmer *et al.* (2024) [48], in the collisionless limit, where the frozen-in constraint is broken by electron inertia, it is shown that a strongly driven large island can flatten the safety factor profile, shifting the resonant surface towards the core. Furthermore, such islands destabilize KHI at their separatrix due to strong shear flows. The Kelvin-Helmholtz induced turbulence modifies the flows and the island size is dramatically reduced as demonstrated in simulations using equilibria with flat pressure profiles or finite gradients below any microinstability threshold. An analysis of the conditions for reversal of the island drift direction is also presented. This work constitutes a first application of the new shifted-Maxwellian equilibrium distribution capability of the gyrokinetic ORB5 code [49], allowing it to capture the physics of tearing modes [50].

In tokamaks, magnetic islands can induce disruptions that may lead to an abrupt stop of the discharge, substantial currents reaching the wall, as well as a fast thermal energy release to the plasma-facing components. During disruptions, the inductive electric field can strongly accelerate electrons up to a sizable fraction of the speed of light. These so-called runaway electrons can potentially cause severe damage to the device, which must be avoided in complex new devices such as ITER. Accelerated particles and in particular energetic electrons are ubiquitous in nature [51]. It follows that the post-disruption runaway problem, although specific to fusion plasmas, can also be seen as a means to gain understanding of the physics of accelerated particles embedded in strong magnetic fields. In Singh *et al.* (2023) [52], assuming the equilibrium current is carried by runaway electrons, an analysis of the stability of such a post-disruption discharge shows that runaways do not alter the growth rate of the island, the resistive layer controlling the transition time to the nonlinear phase. Moreover, a micro-layer, with an extent much narrower than the resistive layer and depending on the velocity of the runaways, characterizes the distribution of runaway electrons. This microlayer can be on the order of the electron skin depth in tokamaks and can generate a secondary instability at small scales in realistic regimes where fast electrons approach the speed of light. This instability could be characterized by quickly-growing oscillations in the electron distribution. These current-sheet oscillations should strongly modify the nature of magnetic reconnection inside such islands, in particular along the separatrix where such oscillations take place. Interestingly, once both runaway and thermal electrons exhibit predominantly nonlinear dynamics, the runaway adopts a spiral structure around the O-point, which ceases to exist when the island approaches the saturation stage.

## III. CONCLUSIONS

As evidenced by the papers published in this Special Issue, substantial overlap and opportunity for exchange and collaboration exists between the space and fusion plasma communities. Relevant findings in this context include theoretical developments on multi-scale aspects of MR. Enabling and reinforcing such collaboration is the raison d'être of the *European Conference on Magnetic Reconnection in Plasmas*. Going forward, we are confident that sustained efforts at maintaining and expanding such joint efforts will bring about a deeper understanding of the fundamental physics as well as provide a cornerstone of future technological development.

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References marked with * correspond to articles that are part of this Special Issue. The authors are indebted to M. Faganello for fruitful discussions. This work has been carried out as part of the ENR *Magnetic reconnection in tokamaks: from theoretical foundations to solutions for fusion energy* within the framework of the EUROfusion Consortium, partially funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200 – EUROfusion). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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