# 1st European conference on magnetic reconnection in Plasmas

May 23- 26, 2023, Marseille

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## Topics

Turbulent magnetic reconnection

Large magnetic islands

Interaction of magnetic reconnection and accelerated particles

Magnetic island control

Magnetic chaos

Microtearing turbulence

Institut Sciences de la Fusion et de l'Instrumentation en Environnements Nucléaires
Aix Marseille Université

European Conference on Magnetic Reconnection in Plasmas

May 23 - 26, 2023, Marseille

| | Tuesday | Wednesday | Thursday | Friday |
|---|---|---|---|---|
| | | **Session chairs:** A. V. Dudkovskaia & D. Borgogno | **Session chairs:** C. Parnell & N. Dubuit | **Session chairs:** C. Norgren & M.J. Pueschel |
| **9h30 - 10h15** | | **C. F. Parnell** 3D Magnetic Reconnection with a particle focus on Separator Reconnection | **M.J. Choi** How the evolution of a magnetic island can be complicated in tokamak plasmas: turbulence, secondary instabilities, and fast ions | **D.I. Pontin** Magnetic reconnection in 3D: MHD theory and modelling |
| **10h15 - 10h45** | | **V. Igochine** Magnetic reconnection during sawtooth crashes | **M. Faganello** Three-dimensional aspect of magnetic reconnection in Kelvin-Helmholtz vortice | **L. Singh** Runaway Electron driven Magnetic reconnection |
| **10h45 - 11h05** | | Coffee breack | Coffee breack | Coffee breack |
| **11h05 - 11h35** | | **S. Musset** Energetic electrons in solar flares: observational diagnostics of the acceleration processes linked to magnetic reconnection | **A. V. Dudkovskaia** Drift kinetic theory of neoclassical tearing modes near the threshold in shaped tokamak geometry | **J. Stawarz** Turbulence-Driven Magnetic Reconnection: Insights from NASA's Magnetospheric Multiscale Mission in Earth's Magnetosheath |
| **11h35 - 12h05** | | **C. Marchetto** Interplay between magnetic island and heavy impurity transport in tokamaks | **G. Cozzani** Interplay between magnetic reconnection and current sheet instabilities | **D. Villa** Turbulence driven magnetic islands in low and high β plasmas: generation and non-linear dynamics |
| **12h05 - 12h30** | | Discussions | Discussions | **D. F. Escande** Summary of the conference and discussion |
| **12h30 - 13h00** | | 5 min posters presentations | 5 min posters presentations | |
| **13h00 - 14h00** | **Conference opening at 13h30**<br>**Session chairs:** D. Grasso & E. Poli | Lunch time | Lunch time | |
| **14h00 - 15h00** | **H. Ji** Magnetic reconnection: past, present, and future | **Poster Session I** - E. Balkovic, L. Bonalumi, B. Momo, E. Tassi, S.W. Tsao, B. Zhu, | **Poster Session II** - D. Borgogno, A. Dudkovskaia, D.F. Escande, A. Grondin-Exbrayat, E. Poli, A. Poyé | |
| **15h00 - 15h30** | **C. Norgen** Reconnection cessation and onset in the magnetotail | | | |
| **15h30 - 16h** | Coffee breack | Coffee breack | Coffee breack | |
| **16h - 16h30** | **M. Hamed** Towards a reduced transport model for microtearing modes | Poster Session I + Discussions | Poster Session II + Discussions | |
| **16h30 - 17h00** | **F. Widmer** Self-consistent gyrokinetic simulations of collisionless tearing mode in tokamaks | | | |
| **17h00 - 17h30** | **C. Granier** Gyrofluid and gyrokinetic approaches for non-collisional plasmoid instability with finite βe | | | |
| **17h30 - 18HH** | **D. Del Sarto** About the role of microscopic scales in linear tearing modes and some of their implications for secondary and turbulent reconnection | | | |
| **19h30 - 23h** | | **Gala dinner - UNM Restaurant - 34 Bd Charles Livon, Marseille** | | |

# Magnetic reconnection: past, present, and future

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Magnetic reconnection has been regarded as one of most fundamental physical processes in space and astrophysics responsible for explosive release of magnetic energy to particles. It plays a pivotal role in electron and ion heating, particle acceleration to high energies, energy transport, and self-organization. The relevant phenomena range from solar flares, coronal heating, solar wind interactions with planets' magnetospheres including Earth's, star formation in molecular clouds, to explosions on magnetars and pulsars including Crab Nebula, as well as to disruptive phenomena in laboratory fusion plasmas. This talk concisely reviews the history of magnetic reconnection research starting from solar flares since 1950s, summarizes the status of our current understanding, and provides an outlook into the future to solve the reconnection problem.

# Reconnection cessation and onset in the magnetotail

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Magnetic reconnection is an often intermittent process strongly characterised by temporal effects related to upstream, downstream, or internal conditions. In this work, we investigate a reconnection event with intermittent signatures in the terrestrial magnetotail. First, magnetic reconnection is active, inferred from a field-aligned off-equatorial plasma jet. Over 40 seconds, this jet is replaced by a quiet time interval with dusk-ward ion flow carried by a hot population that persists for about two minutes. During this interval, we observe signs of current sheet thickening followed by thinning. The change in the dawn-dusk current associated with the inferred thickening is provided by changes in the electron flux, and we argue this is a result of momentum conservation. Thereafter, we observe an equatorial jet of hot plasma that gradually builds up before the spacecraft encounter a dipolarization front about 20 seconds later. This first dipolarization front is associated with a transition from a hot pre-existing plasma sheet, to colder plasma of lobe origin. Shortly thereafter, another dipolarization front is observed. With the aid of numerical particle-in-cell simulations, we interpret kinetic signatures in the early stage of the re-onset as the merging of a magnetic island - possibly produced by the tearing of the reformed quiet current - with the with the pre-existing sheet. We also discuss how the inertia (the duskward ion flow) that remains in the system during the off-time should enable a more efficient reconnection re-onset and how this can lead to a temporally intermittent reconnection process.

# Towards a reduced transport model for microtearing modes

**M. Hamed**
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Small-scale instabilities localized near the rational surfaces, such as MT mode, have a significant effect on confinement in tokamak breaking the nested magnetic topology leading to the forma- tion of magnetic islands. Understanding the electron heat transport due to MT turbulence is a crucial issue for magnetic fusion device. The magnetic drift and the electric potential play an important role in microtearing destabilization by increasing the growth rate of this instabil- ity in the presence of collisions, while in electrostatic plasma micro-turbulence, zonal electric potentials can have a strong impact on turbulent saturation. Nonlinear gyrokinetic flux-tube simulations are performed in order to compute the characteristics of microtearing turbulence and the associated heat fluxes in tokamak plasmas and to assess how zonal flows and zonal fields affect saturation.

# Self-consistent gyrokinetic simulations of collisionless tearing mode in tokamaks

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The non-linear evolution of the tearing mode (TM) in collisionless limit is investigated using the gyrokinetic code ORB5. An m/n=2/1 TM is destabilized by an unstable current profile in toroidal geometry with large aspect ratio and low mass ratio. We investigate the self-consistent time evolution of the 2/1 TM varying the plasma-beta, ratio of the kinetic to magnetic pressure, in presence or not of turbulence. We validate linearly that a 2/1 TM is growing, confronting simulation results and theory.

We found non-linearly and for flat temperature profiles that turbulence develops at the island separatrix. At low plasma-beta, strong turbulence is produced, the island width is strongly reduced at saturation and strong zonal current is generated. At large beta, the growth of the tearing is reduced, the saturated island size is smaller compared to lower plasma beta case and less turbulence develops.

Finally, allowing for turbulence by means of temperature gradients, we obtain that the mutual interaction between micro-instabilities and tearing mode strongly depends on the initial type of micro-instability. An initial unstable tearing mode can be enhanced by micro-instability during exponential phase, while a magnetic island is found at saturation growing out of turbulence for an initial stable tearing mode only with micro-instability driven by the electron temperature gradient.

# Gyrofluid and gyrokinetic approaches for non-collisional plasmoid instability with finite βe

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Non-collisional current sheets that form during the nonlinear development of spontaneous mag- netic reconnection are characterized by a small thickness, of the order of the electron skin depth. They can become unstable to the formation of plasmoids, which allows the magnetic reconnec- tion process to reach high reconnection rates. In this work we carry out a detailed study of the impact of a finite βe, the latter being a parameter corresponding to the ratio between equilib- rium electron kinetic pressure and magnetic pressure, on the collisionless plasmoid instability, in the case of a strong guide field. We consider inertial reconnection, and finite electron FLR effects arise from the combination of the presence of electron inertia with a finite βe parameter. This study is conducted through a comparison of gyrofluid and gyrokinetic simulations. We analyze the geometry that characterizes the reconnecting current sheet, and what promotes its elongation. Once the reconnecting current sheet is formed, we identify the regimes for which it is plasmoid unstable. Our study shows that plasmoids can be obtained, in this context, from current sheets with an aspect ratio much smaller than in the collisional regime, and that the plasma flow channel of the marginally stable current layers maintains an inverse aspect ratio of 0.1.

# About the role of microscopic scales in linear tearing modes and some of their implications for secondary and turbulent reconnection

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The large scale separation between microscopic and equilibrium MHD scale lengths justifies the asymptotic analysis on which the tearing mode theory is grounded. Keeping into account non-ideal effects of different physical nature introduces, already in the linear problem, several microscopic scale lengths, which display non-trivial power-law scalings with respect to the microscopic parameters.

We first provide a characterization of these scale lengths -some of which have been only recently identified [1,2]- and we discuss the role of different non-ideal parameters in determining them and in affecting the scalings of the growth rate of tearing modes in different reconnection regimes [1-3]. Then, we address the implications of the results of the linear analysis for the onset of secondary instabilities to primary tearing-type modes (see, e.g., Refs.[4-5]). Some elements related to the the relevance and to the limitations of these results for the modelling of magnetic reconnection in turbulence will be finally discussed, with an emphasis on some nonlinear numerical results shown in a few recent works about collisionless/kinetic turbulent regimes.

[1] “Microscopic scales of linear tearing modes: a tutorial on boundary layer theory for magnetic reconnection”, H. Betar, D. Del Sarto, M. Ottaviani, A. Ghizzo, J. Plasma Phys. 88, 925880601 (2022).
[2] “Asymptotic scalings of fluid, incompressible "electron-only" reconnection instabilities: electron-magnetohydrodynamics tearing modes”, H. Betar, D. Del Sarto, submitted (2023) to PoP.
[3] “Multiparametric study of tearing modes in thin current sheets”, H. Betar, D. Del Sarto, M. Ottaviani, A. Ghizzo, Phys. Plasmas 27, 102106 (2020).
[4] “Ideal tearing and the transition to fast reconnection in the weakly collisional MHD and EMHD regimes”, D. Del Sarto, F. Pucci, A. Tenerani, M. Velli, J. Geophys. Res. 121, 1857 (2016).
[5] “Secondary fast reconnecting instability in the sawtooth crash”, D. Del Sarto, M. Ottaviani, Phys. Plasmas 24, 012102 (2017).

# 3D Magnetic Reconnection with a particle focus on Separator Reconnection

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In 2D, the electric field is directed out of the plane and thus is always orthogonal to the mag- netic field. In 3D, the electric field may have components both perpendicular and parallel to the magnetic field. The parallel component of electric field is key to 3D reconnection, deter- mining both the location and rate of reconnection. In this talk, I shall briefly discuss the key similarities and differences between 2D and 3D reconnection and also the locations at which 3D reconnection can occur. Separator reconnection is one type of 3D reconnection. Through a series of examples relating to both solar and magnetospheric physics I shall focus on separator reconnection, explaining how it occurs and what its observational signatures could be.

# Magnetic reconnection during sawtooth crashes

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Sawteeth oscillations are periodic relaxations of the core plasma density and temperature in tokamaks. The rise of the temperature due to external heating is terminated by the crash phase, which involves magnetic reconnection. This is the case of fast magnetic reconnection in collisionless plasmas (Lundquist number S≥1e8) with a strong guide field. (The toroidal magnetic field in a tokamak is a few orders larger compared to the reconnected helical field.) Experimental measurements show strongly non-linear evolutions before and during the crash phase. Simplified single-fluid models are not able to explain the reconnection dynamics during the crash and two-fluid effects have to be considered. In this case, numerical simulations give good agreement with the observations for the crashduration. At the same time, the present simulations are not able to explain all experimentally observed phenomena, for example, the existence of instability after the crash phase, the evolution of the crash agrees only partially.

# Energetic electrons in solar flares: observational diagnostics of the acceleration processes linked to magnetic reconnection

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Solar flares are some of the most energetic events in the solar system. They are powered by magnetic energy released via magnetic reconnection, and a large fraction of this energy is accelerating particles in the solar corona. However, the link between the magnetic topology of the flare site and the physical processes involved in particle acceleration is still unclear. In this talk, I will review recent results linking solar accelerated particles, via their X-ray and radio emissions, to the localisation of electric current sheets, magnetic reconnection sites, and termination shocks in the corona, derived from white light and EUV observations.

# Interplay between magnetic island and heavy impurity transport in tokamaks

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One of the ways in which magnetic reconnection appears in tokamak plasmas is by forming magnetic islands which can cover a large portion of the small radius. There is the risk and some experimental evidence that the island carries heavy impurities from the edge to the core, where they worsen the particle and energy confinement and can terminate the discharge by forcing a thermal collapse. The problem is important given that, in operating and under design tokamaks, the inner vessel is coated partially or totally with Tungsten (Atomic Mass 183.85) as this element presents both a good thermic resistance and a poor Tritium retention. This issue couples the fields of MHD and transport in plasmas and requires theoretical and modelling insight and experimental diagnostic interpretation. In this work we will try to involve the audience into some key aspects of the interplay between magnetic islands and heavy impurity transport in tokamaks, using experimental data from JET and AUG and modelling tools like ASTRA and JETTO and the suite of codes to which they are interfaced.

**Session Poster I**

# Prediction of nonlinear saturation of classical and neoclassical tearing modes with SPEC

**E. Balkovic[1], J. Loizu[1], J. Graves[1], Y.-M. Huang[2], A. Baillod[1]**

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We show that an MHD equilibrium solver can be applied to efficiently predict the non-linearly saturated state of tearing modes. This approach has already been demonstrated for the classical tearing modes in slab geometry [1], where it was shown that the predicted island width and shape matches with one obtained through explicit time-integration of the resistive MHD equations, as implemented in the HMHD code [2]. To construct MHD equilibria that do not globally constrain the magnetic topology and thus allow finding states which have undergone reconnection, we use SPEC (Stepped Pressure Equilibrium Code) [3]. SPEC is based on a variational principle known as multi-region relaxed MHD (MRxMHD) and finds stepped-pressure equilibrium solutions in a set of subvolumes that are described by Beltrami fields and separated by magnetic surfaces supporting pressure gradients. The work on classical tearing modes is extended by considering the effects of asymmetry of the inital equilibria on the saturated island. Furthermore, we present the application of our approach to the neoclassical tearing modes (NTM), driven by bootstrap current which is included through a simple ad-hoc model $J_{BS} \propto \frac{\partial p}{\partial r}$ [4]. We employ HMHD to reproduce well-known features of NTMs related to the increased island size and existence of a threshold for development of neoclassical effects. We use SPEC to directly obtain these saturated NTM states, with a bootstrap current profile that is described by a set of sheet currents at the subvolume interfaces supporting pressure gradients [5, 6]. Based on the results from the two codes, we discuss how saturated states of NTMs differ from their classical equivalents, and to what extent can saturation of NTMs be directly inferred without evolution of MHD.

[1] J. Loizu et al (2020) Physics of Plasmas 27, 070701
[2] Y.-M. Huang and A. Bhattacharjee (2016) Astrophysics J. 818, 20
[3] S. R. Hudson et al (2012) Physics of Plasmas 19, 112502
[4] M. Muraglia et al (2021) Plasma Phys. Control. Fusion 63 084005
[5] A. Baillod et al (2021) Journal of Plas. Phys. 87(4) 905870403
[6] A. Baillod et al (2022) arXiv:2211.12948

**Session Poster I**

# Analysis of the role of the ion polarization current on the onset of the neoclassical tearing mode in disrupting plasmas

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In the linear theory, the stability of the mode is completely defined by the stability index $\Delta'$ connected to the change of the magnetic energy of the plasma due to the reconnection. However, after the magnetic reconnection, non-linear mechanisms start to play an important role so that the magnetic island grows if the destabilizing (linear and non-linear) drives overcome the stabilizing effects.
The contribution of the phenomena which affects the island growth are described in the Generalized Rutherford Equation (GRE). According with the GRE theory, the curvature of the magnetic field lines in a toroidal configuration has a stabilizing effect, while the reduction of the bootstrap current due to the flattening of the pressure profile inside the island producesthe neoclassical destabilization of the magnetic tearing perturbation.
In an inhomogeneous two-fluid plasma, difference in the drift motion of electrons and ions drives a parallel return current, called "polarization current", which depends on the island width w and can be either stabilizing or destabilizing depending on the ratio $\omega/\omega_i$ where $\omega$ and $\omega_i$ are the island frequency and the ion diamagnetic frequency.
The ion polarization current is thought to play an important role at the onset of the mode because of its scaling a $1/w^3$ that makes it a dominant term in the GRE when the island width is small. The curvature and the bootstrap terms depend on the equilibrium profiles (safety factor, pressure) and the poloidal $\beta$, so that they change following a slower equilibrium timescale. On the other hand, the magnitude of the ion polarization current contribution also depends on equilibrium quantities, but its sign directly depends on the island frequency shift from the diamagnetic frequency, which may respond to faster temperature changes at the rational surface.
This suggests that in an essentially stable discharge, a rapid change of the local temperature due to different phenomena (e.g., impurities radiation, other MHD activities...), could lead to a sudden offset of the balance of the competing bootstrap and curvature effects, leading to the onset of the mode, and eventually to disruption. The effect of the ion polarization current is evaluated with a time resolution of the available diagnostic used to estimate the ion temperature (~10ms). Firstly the analysis is performed on four JET pulses, that develop a neoclassical tearing mode in the termination phase of the plasma shot, after a strong reduction of the temperature at the edge due to the presence of impurities (Edge Cooling). The behavior of the ion polarization current contribution is then compared to stable pulses, which exhibit an edge cooling without developing a mode. The analysis on the unstable pulses shows that

the temperature fluctuation due to the edge cooling increases the destabilizing contribution of the ion polarization current. When this happens, it is easier for a resonant helical perturbation of the rational surface to overcome the stabilizing contributions leading to an unstable mode. This is confirmed by the analysis on the stable pulses showing that the destabilizing contribution of the ion polarization current does not increase after the edge cooling. The reason why the ion polarization current contribution seems not to be affected by the edge cooling is because the reduction due to the temperature fluctuation does not reach the rational surface. This finding has been tested on a more general database of selected pulses with edge cooling. The flattening width is evaluated and compared to the position of the rational surface of every pulse in the database, showing that the mode is triggered whenever the flattening is close enough to the rational surface, producing a result which is consistent with the physical interpretation.

**Poster Session I**

# Phenomenology of magnetic reconnection in the RFX-mod reversed-field pinch

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Magnetic reconnection is usually observed in fusion plasmas, being related to the presence of resonating tearing modes and to impulsive events deeply involved in plasma self-organization. Rapid rearrangements of magnetic fluxes particularly characterize the plasma d ynamics of thereversed-field pinch (RFP) magnetic configuration, which involve large plasma currents and therefore a large amount of available magnetic energy. RFPs also contain multiple reconnection sites associated to a variety of resonant tearing modes that eventually give rise to a stochasticmagnetic field background. Energy conversion and topological change are highly linked in the definition of reconnection properties.

In this contribution, the phenomenology of the impulsive and periodic reconnections, associated to relaxations in high-current (~1.5 MA) plasmas of the RFX–mod device, is analyzed in detail, through an ensemble average of the data from many reconnecti on events. Spatial andtemporal scales are invoked as fundamental observables.

Each relaxation event is described as a series of stages, where the locking in phase of many resonant modes initiates the reconnection process that changes the global magnetic topology [1]. We discuss other fingerprints of magnetic reconnection in RFX-mod, such as the ion heating [2] and the excitation of Alfvèn waves [3,4], as well as analogous aspects found in nonlinear visco-resistive MHD modelling [5].

[1] B. Momo et al 2020 Nucl. Fusion 60 056023, “The phenomenology of reconnection events in the reversed field pinch”

[2] M. Gobbin et al 2022 Nucl. Fusion 62 026030, “Ion heating and energy balance during magnetic reconnection events in the RFX-mod experiment”

[3] S. Spagnolo et al 2011 Nucl. Fusion 51 083038, “Alfvén eigenmodes in the RFX-mod reversed-field pinch plasma”

[4] A. Kryzhanovskyy et al 2022 Nucl. Fusion 62 086019, “Alfvén waves in reversed-field pinch and tokamak ohmic plasmas: nonlinear 3D MHD modeling and comparison with RFX-mod”

[5] S. Cappello, this conference, poster session

# Finite ion temperature effects on secondary instabilities and turbulence induced by collisionless reconnection

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Numerical simulations, performed in particular in the cold-ion regime, have provided evidence that collisionless magnetic reconnection can trigger fluid-like secondary instabilities (see, e.g. Refs. [1-5]). In this contribution we present a preliminary analysis, in the two-dimensional limit, of the turbulent regimes following such secondary instabilities. We complement previous studies by analyzing the role of the parameter tau, corresponding to the ratio between ion and electron equilibrium temperatures. The analysis is carried out by means of a reduced Hamiltonian gyrofluid model [6] accounting for ion finite Larmor radius effects. The model makes it possible to study the transition from the cold to the hot-ion regime. The latter case, corresponding to tau>>1, can be relevant in particular for sub-ion reconnection occurring in the Earth's magnetosheath. From a qualitative observation, in the hot-ion regime a Kelvin-Helmholtz-like secondary instability generates turbulence which develops outside the magnetic island, and also leads to the formation of vortex structures. In the turbulent state reached in the hot-ion regime, the spectral index of the perpendicular magnetic energy, at scales below the electron skin depth, appears to be close to -11/3, as predicted by estimates based on strong-turbulence phenomenology [6]. We complement the analysis of the nonlinear turbulent regime by providing scalings of the linear growth rate of tearing modes in asymptotic limits.

[1] D. Del Sarto, F. Califano, F. Pegoraro, Phys. Rev. Lett., 91, 235001 (2003).
[2] D. Del Sarto, F. Califano, F. Pegoraro, Mod. Phys. Lett. B, 20, 931 (2006).
[3] D. Grasso, D. Borgogno, F. Pegoraro, Phys. Plasmas, 14, 055703 (2007).
[4] D. Grasso, D. Borgogno, E. Tassi, Comm. Nonlin. Sci. and Numer. Simulat., 17, 2085 (2012).
[5] D. Grasso, D. Borgogno, E. Tassi, A. Perona, Phys. Plasmas, 27, 012302 (2020).
[6] T. Passot, P.L. Sulem, E.Tassi, Phys. Plasmas, 25, 042107 (2018).

# Kinetic 3D reconnection heating in the solar corona at hydrogen mass ratio

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Reconnection turbulence, which is driven by tearing modes arising from current sheets, is a promising candidate mechanism to explain the coronal heating problem. The plasma temperature in the solar atmosphere is two orders of magnitude higher than that of the surface of the sun, requiring a strong heating process. In order to capture the kinetic properties of reconnection turbulence, which is computationally expensive, the gyrokinetic framework is employed to allow for an arbitrarily strong magnetic guide field. 2D simulations with artificially high normalized plasma β and reduced mass ratio have shown that the heating rate extrapolates to the observed solar corona heating rate [Pueschel et al., ApJS 213, 30 (2014)]. Here, we use hydrogen mass ratio and realistic β to verify these extrapolations with nonlinear Gene simulations.
To study how parallel dynamics impact reconnection rates and heating, we design a half-torus geometry with frozen-in flux conditions at the parallel boundary, thus modeling the shape of a coronal loop. With realistic β and hydrogen mass ratio, linear studies show a mismatch of reconnection rates between the 3D half-torus and the 2D slab. The curvature and ∇B drifts are scaled in the 3D half-torus simulations showing that they cause the observed stabilization in the 3D system. The reconnection rates in these geometries are γ3D,circular < γ2D < γ3D,slab. Thus, while curvature stabilizes reconnection, parallel streaming can enhance it. Linear analysis of the effect of the field-line twist q, magnetic trapping, and the relaxation of the frozen-in flux conditions are presented. Preliminary results of a nonlinear simulation of the full system are discussed.

**Poster Session I**

# Fine-structure investigation of 3D LTSTMR induced extreme space weather SEPs with RHPIC-LBM on heterogeneous GPU

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Solar flare, as a typical large temporal-spatial turbulent magnetic reconnection (LTSTMR, the ratio of observed current sheets thickness to characteristic electron length, electron Larmor radius for low-β and electron inertial length for high-β, is on the order of 10E10–10E11; the ratio of observed evolution time to electron gyroperiod is on the order of 10E7–10E9) explosion in the solar atmosphere activities, involving sudden bursts of particle acceleration that from the sudden release of magnetic energy in a few minutes to a few tens of minutes.

The extreme space weather GeV-level solar energetic particles (SEPs), produced by the notable solar flare and coronal mass ejections (CMEs) interplanetary propagation through the solar winds, are the most critical factor leading to space weather disasters and seriously affect the safety of on-orbit aircraft in deep space exploration.

Observation spectral analysis shows that SEPs' composition, abundance, particle type, origin, and acceleration mechanism are challenging and complicated. In recent years, Parker Solar Probe (PSP, 2018) and Solar Orbiter (SOLO, 2020) provided unprecedented fine-structure solar energy Flare-CME observation data to investigate the source and origin of SEPs.

The hard x-rays and gamma rays are believed to result from the interactions of the high energy electrons energized and nuclear interaction of the high energy protons and other heavier ions, respectively; Understanding self-generated turbulence by plasmas and magnetic field collective interaction in LTSTMR is essential for correctly describing the fine-structure evolution of turbulence acceleration (turbulence-induced charged particle energization-acceleration); While many particle acceleration models consider turbulence acceleration as an effective way of generating energetic electrons, the precise turbulence roles during acceleration and heating of electrons remain unclear.

Some researchers believe that turbulence acceleration depends on the Fermi acceleration mechanism, while others believe that turbulence acceleration is an independent acceleration mechanism.

In this work, based on the heterogeneous GPU cluster of the DF-series (CAS) with 3D relativistic hybrid particle-in-cell and lattice Boltzmann method (RHPIC-LBM), we reconsider the acceleration model by introducing a fully kinetic-dynamic continuous instead of the micro-kinetic & macro-dynamic scale, investigate the interaction of proton and electron with the turbulent electric field and magnetic field by applying the statistical treatment of the plasma physics, combing with the filter theory of turbulence, the actual ratio of the proton mass to the electron mass, and the mass-to-charge ratios.

The results show that protons and electrons could be efficiently accelerated simultaneously through the nonlinear resonant wave-particle interaction in the diffusion region, and the interaction of helical magnetic structure leads to efficient energization of electrons, shown as follows:

1. A new nonlinear resonant wave-particle acceleration mechanism in the interaction of helical magnetic structure in large-scale CME/Flare current sheets proposed in solar eruption. The original acceleration model assumed helical magnetic structure evolution in the cross-scaling coupling are separated independent process, which is essential in the helical magnetic structure coalescence and growth process.
2. The multi-component acceleration mechanism and the quantitative relationship between solar flares-CME events and GeV-level SEPs events with the data-driven RHPIC-LBM algorithm and parallel code. We hope this provides a new understanding of SEP sources and origins.
3. We found the Langmuir turbulence acceleration (LTA) through the nonlinear resonant wave-particle interaction by tracking the trajectories and analyzing the energy spectrum of energetic protons and electrons. LTA is an independent acceleration mechanism similar to shock acceleration. Still, it is much more efficient than shock acceleration, indicating that large-scale reconnection is a good candidate for the efficient acceleration of protons and electrons in solar eruption.

In summary, we anticipate identifying the source and origin of SEPs as a critical point for understanding the relationship between SEPs acceleration and explosive energetic electrons observed in the solar flares during MHD Alfven turbulence translates into Kinetic Alfven turbulence progress and provides a tool for extreme space weather SEPs forecasting.

# How the evolution of a magnetic island can be complicated in tokamak plasmas: turbulence, secondary instabilities, and fast ions

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Understanding turbulence and transport around a magnetic island is critical to understand the evolution of the island in tokamak plasmas. Interestingly, it turns out that a magnetic island can be a good test bed for understanding turbulence in tokamak plasmas. For example, the local pressure gradient can be varied (in the outside of the magnetic island) by controlling the size of the magnetic island. As one may expect from the conventional picture of drift-wave turbulence, we found that the fluctuation intensity increases with the local pressure gradient. We were also able to provide evidence on the flow shear saturation of turbulent fluctuation in tokamak plasmas since the strong flow shear naturally develops around the island when it grows over some threshold width. In addition, we could demonstrate the spatially non-local phenomenon (turbulence spreading) of turbulent fluctuation. Magnetic islands may be the best configuration to identify turbulence spreading. For most periods, inside a large magnetic island, the turbulent fluctuation is insignificant since the pressure profile is flat and there is no local drive for turbulence. Occasionally, when a sufficiently large fluctuation intensity jump forms across the island separatrix, i.e. the strong (weak) fluctuation outside (inside) the island, fast transport of fluctuation and heat flux into the island occurs and the initially stable interior becomes turbulent, resulting in partial collapse of the island. Finally, we'll introduce the non- local (in wavenumber) interaction between a magnetic island and ambient turbulence. This may be another example of the disparate scale interaction in tokamak plasmas. The analysis result implies the beneficial effect of the increased (high-k) turbulence for stabilizing the (low-k) neoclassical tearing mode, the most frequent cause of plasma disruption.

Thursday, May 25, 2023

# Three-dimensional aspect of magnetic reconnection in Kelvin-Helmholtz vortice

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Kelvin-Helmholtz vortices naturally develops at the interface between the solar wind and Earth's magnetosphere. They are able to locally pinch the pre-existing current sheet there, as well as to strongly distort magnetic field lines, leading to the creation of new current sheets in disparate regions. As a consequence, magnetic reconnection occurs at different positions, in a strongly three-dimensional geometry. Analysing reconnection events in simulation data reveals the mechanism behind this complex dynamics and allows for an estimation of induced transport at the interface.

# Drift kinetic theory of neoclassical tearing modes near the threshold in shaped tokamak geometry

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A drift kinetic theory to describe the particle response to a small neoclassical tearing mode (NTM) magnetic island in a general tokamak geometry is presented. It extends the original drift island theory of [Plasma Phys. Control. Fusion 63 (2021) 054001], allowing a realistic tokamak geometry characterised by finite beta values and D-shaped plasmas, as well as experimental equilibrium plasma profiles. The effects of plasma shaping are investigated. In particular, it is found that a higher triangularity plasma is more prone to NTMs, which is in agreement with the recent tearing mode onset relative frequency measurements in DIII-D. Second, the NTM threshold dependence on the tokamak inverse aspect ratio is extended to a finite aspect ratio limit. Third, the NTM threshold dependence on poloidal beta is obtained and successfully benchmarked against the EAST threshold island width measurements [Nucl. Fusion 63 (2023) 016020].

Thursday, May 25, 2023

# Interplay between magnetic reconnection and current sheet instabilities

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Magnetic reconnection is a fundamental process in plasma and a major cause of energy con- version and transport by means of magnetic field topology reconfiguration. Reconnection is a key mechanism in the Earth's magnetosphere, where it promotes plasmas mixing and drives geomagnetic storm and substorm activity. Together with reconnection, several other current sheet-related processes, such as tearing instability and a variety of kinking instabilities and waves perturb the magnetotail. We present recent studies investigating the interplay of re- connection and instabilities at different scales, by means of Magnetospheric Multiscale (MMS) observations at the electron scales and Vlasiator global hybrid-Vlasov simulations picturing the entire magnetosphere. MMS observations allow shedding light on the fine electron scales and they reveal that the presence of waves could perturb the establish two-dimensional laminar picture of thin current sheets. Global hybrid-Vlasov magnetospheric simulations are a powerful tool to put MMS observations in the larger magnetospheric context. Recent results from the Vlasiator hybrid-Vlasov simulation suggest that the efficiency of the reconnection process is affected by the development of kinking instability in the magnetotail current sheet.

**Poster Session II**

# Current and vorticity layer dynamics in collisionless turbulent plasmas

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In ideal magnetized plasma, sheet-like field discontinuities, where current and vorticity peak, naturally form. According to the linear theory, these layers undergo fluid and magnetic instabilities whose strength depends on the amplitude the local magnetic field and flow. In non-ideal plasmas, in presence of magnetic reconnection, the combined action of the sheared flow and the sheared magnetic field broadens the spectrum of the linearly unstable tearing modes and increases their growth rate compared to the static current layer case, both in collisional [1] and collisionless plasmas [2,3].
Here we present the results from high resolution numerical simulations addressing the nonlinear dynamics of current and vorticity layers in a turbulent setup. We find a complex situation in which, due to the presence of strong velocity shears, the typical plasmoid formation, observed to influence the energy cascade in the magnetohydrodynamic context, has to coexist with the Kelvin–Helmholtz instability. The competition among these instabilities affects not olny the evolution of the current sheets, that may generate plasmoid chains or KH-driven vortices, but also the energy cascade, that is different for the magnetic and kinetic spectra [2].

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**Poster Session II**

# Generalised electromagnetic gyrokinetic theory for steep gradient regions in tokamak plasmas

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A nonlinear electromagnetic global gyrokinetic theory is derived in [1] to ensure that effects associated with steep pressure gradients and consequential high bootstrap and Pfirsch-Schluter currents are fully incorporated in the nonlinear electromagnetic gyrokinetic plasma description. In particular, it is demon- strated that to allow for $B_\theta \sim B_0$, where $B_0$ is the total equilibrium magnetic field and $B_\theta$ is its poloidal component, some additional nonlinear terms must be retained in addition to the conventional $E \times B$ non- linearity of [2]. The latter has previously been addressed, for example, in [3] for electrostatic fluctuations and for straight field lines.
A reduced version of this theory ($B_\theta \ll B_0$) has been implemented in the local turbulence code GS2 to provide initial assessment of the impact of these new terms in sharp pressure gradient regions where the bootstrap current becomes large (such as the pedestal plasma and a spherical tokamak core plasma) [4]. Based on the test cases considered, the dominant impact is found to be on kinetic-ballooning modes (KBMs). In particular, it is found that the KBM growth rate is significantly suppressed by inclusion of neo- classical equilibrium effects at large density gradients, representative of the tokamak pedestal values. Under certain conditions [4], electrostatic modes are also found to be impacted.

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# Description of magnetic field lines without arcane

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The action principles for magnetic field lines and for Hamiltonian mechanics are analogous. The first one is rigorously proved from first principles without calculations. Not only the action principles are analogous, but also a change of canonical coordinates is equivalent to a change of gauge. Furthermore, using the vector potential makes obvious the freedom in the choice of ``time" for describing Hamiltonian dynamics. This may be used for a new pedagogical and intuitive introduction to Hamiltonian mechanics. In the context of confined magnetic fields, the action principle for magnetic field lines makes practical calculations simpler and safer, with an intuitive background. In particular, it yields the first expression of a magnetic island width avoiding abstract Fourier components: this width is proportional to the square root of the magnetic flux through a ribbon whose edges are the field lines related to the O and X point of the island. Moreover, a single formula provides explicitly the Boozer and Hamada magnetic coordinates from action-angle coordinates.

**Poster Session II**

# Numerical and analytical analysis of internal kink mode in cylindrical geometry

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Understanding the transport and losses of energetic particles in Tokamaks is crucial for operating future fusion reactors. Trapped energetic particles can resonate with the low-frequency kink mode, leading to a growing Fishbone instability (Idouakass et al., 2016). Via this instability, they can be expelled before being able to deposit their energy in the Tokamak core. These energetic particles can be generated by heating systems in D-D experiments or correspond to the population of $\alpha$ particles with a velocity mainly perpendicular to the ambient magnetic field in D-T experiments.

In this work, we will present simulations of a kink mode with a reduced MagnetoHydroDynamic code, AMON, developed by members of the team Plasma, Theory and Modeling of the PIIM laboratory, and benchmark it with the analytical model of internal kink mode presented in White et al. (1986). The work was done using a reduced MagnetoHydroDynamics (MHD) description, in cylindrical geometry, for which the pressure of the thermal plasma has been neglected. We ran linear and nonlinear simulations with small resistivity and studied the development of internal kink mode, checking for the correct growth rate of the mode, for the eigenfunction profiles, and for the thickness of the resistive layer.

This work represents a first step toward a numerical description of the Fishbone instability. In the near future, an existing kinetic code (Idouakass et al., 2016), describing the dynamics of trapped energetic particles, will be coupled to the MHD code. A brief presentation of the full model (MHD + kinetic) will be given.

# Particle-In-Cell gyrokinetic simulations of the collisionless Tearing Mode in tokamak geometry

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The dynamics of collisionless tearing modes (TMs) in tokamaks is investigated through gyrokinetic simulations performed with the global particle-in-cell code ORB5 [1]. This contribution focuses on "isolated" TMs, while the interaction between TMs and turbulence is presented elsewhere [2]. For linear TMs, detailed scans around a reference setup with an unstable (m,n)=(2,1) mode, aspect ratio R/a=10, ion-to-electron mass ratio $m_i/m_e=200$ and $L_x=2a/\rho_s=200$, have been performed (where m and n are the poloidal and toroidal mode numbers and $(\rho_s)^2=T_e/m_i$). The expected [3,4] scaling of the growth rate with respect to the plasma β, mass ratio and temperature are recovered. In the presence of background density and temperature gradients, the TM rotates in the electron diamagnetic direction, unless the only gradient is in the ion temperature, in which case the mode rotates slowly in the ion direction. The growth rate is less affected by the electron temperature gradient than by the ion temperature gradient. Benchmarks of the linear dynamics with the global version of the Eulerian gyrokinetic code GENE [5] are presented. The TM is stabilized by increasing β and above a threshold is replaced by an "ideal" (non-tearing) pressure-driven instability exhibiting a coupling of neighbouring poloidal harmonic, typically m=2 and m=3. In the nonlinear phase of the island growth (excluding linearly unstable micro-instabilities) we characterize the shape of the plasma profiles and show that density perturbations produced by the TM can become unstable and alter the island evolution.

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**Poster Session II**

# Magnetic island width: Theorie and simulations


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We present a short review of the results we obtained on the dynamics of magnetic islands using a minimal 2D slab models [A. Poyé et al. POP 2013]. We emphasize that Rutherford type models have a narrow validity range in parameter space. We demonstrate that the dynamics induced by current far from the resonance cannot be cast into a single ($\Delta' > 0$) or a few parameters in Rutherford ltype equations. Thus this kind of models can be used only for very moderate values of $\Delta' > 0$ such as mainly tearing modes grow in the vicinity of the resonant surface where current is localized. We also investigate the role of the current at the resonance and compare theory to numerical results, expliciting the role of the profile dynamics . Finally, we show that turbulence driven magnetic islands ($\Delta' < 0$) are amplified by neoclassical effects and observe the dynamics is not compatible with Rutherford type models [M. Muraglia et al., PPCF 2021].

# Magnetic reconnection in 3D: MHD theory and modelling

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Magnetic reconnection is a fundamental process in a plasma that allows a change of the magnetic field topology, often associated with a rapid release of magnetic energy. Here we review the current understanding of reconnection, particularly in the framework of MHD and in 3D geometries. One focus will be the importance of magnetic complexity in 3D for both the formation of current sheets and the reconnection dynamics in those current sheets. We will highlight the role of reconnection in heating the Sun's corona to its observed multi-million degree temperature, and for releasing plasma to form the solar wind.

# Runaway Electron driven Magnetic reconnection

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Runaway electrons (RE) generated during disruption represent a serious threat to the future Tokamaks. In fact, RE can cause unrecoverable damages to the plasma-facing components once they reach the plasma edge. In order to mitigate the RE, it is vital to understand their interactions with the core plasma where the characteristics of RE current are defined. The goal of this work is to study the mutual interaction of the RE with the magnetic reconnection instability in a weakly collisional plasma where the current is completely carried by runaway electrons. Here we present the numerical results reproducing recent analytical studies in the linear regime [1] along with the new results obtained in the nonlinear regime. In addition, preliminary results concerning the contribution of non-collisional effects on the evolution of the
magnetic reconnection driven by a RE current are shown.

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# Turbulence-Driven Magnetic Reconnection: Insights from NASA's Magnetospheric Multiscale Mission in Earth's Magnetosheath

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Turbulence and magnetic reconnection are both fundamental phenomena, occurring across a wide variety of plasmas from the laboratory to space and astrophysical systems. The non- linear dynamics within a turbulent system are well known to generate intense current sheet, which have long been thought to be locations where magnetic reconnection can occur. However, the complex dynamics and magnetic field topologies in a turbulent system make it challenging to both identify magnetic reconnection events and assess their influence on the turbulent system. In this talk, I will discuss the new advances that have been made in understanding this turbulence-driven magnetic reconnection that have been enabled by the high-resolution, multipoint measurements from NASA's Magnetosphereic Multiscale (MMS) mission in the re- gion of turbulent plasma downstream of Earth's bow shock, known as the magnetosheath. I will highlight, in particular, how the properties of the turbulent environment can influence how magnetic reconnection proceeds – leading to so-called electron-only reconnection – and how turbulence-driven reconnection may fit into the energy budget of the turbulence.

# Turbulence driven magnetic islands in low and high β plasmas: generation and non-linear dynamics

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The dynamics of magnetic islands and the role they play in fusion plasmas are usually approached and predicted using extensions of the original theory by Rutherford [1, 2], on which estimates for their impact on the operation of present and future magnetic confinement devices are based. Likewise, diagnostics to detect their presence [3] and techniques to limit their im- pact are operated on the assumption that the fundamental physics of the phenomenon have been clarified. Still, there are experimentally reported examples of magnetic islands showing up in systems that are predicted to be stable against the formation of such structures [4], which indicates otherwise. The work presented here shows how turbulence is capable of generating magnetic islands at any regime of β (of particular interest in this study was the region where the transition between ITG and interchange occurs), and how the dynamics of such magnetic islands depend on β itself. This dependence is particularly noticeable through the limit cycles that appear from the energetic diagrams in the two regimes. Furthermore, computing the phase relationships between the small-scale modes and the magnetic island highlights differences in the coupling mechanisms depending on β. Non-linear simulations performed using a 6-field reduced electromagnetic fluid model "AMON" [5] show the generation of magnetic islands by interchange-like turbulence [6, 7] across a wide range of plasma β and magnetic shears. The non-linear phase of the system sees the interplay of turbulence driven magnetic islands (TD- MIs), zonal flows, zonal currents and turbulence. It is found that zonal flows and TDMIs can coexist in a stable manner, with the zonal flow being localized on the resonance, inside the separatrix, where it can maintain the pressure profile relatively stable. From an experimental point of view, this hides the presence of the magnetic island until it has reached a width as much as 3 times the critical width identified by Fitzpatrick [8]. An analytical approach to the problem will also allow us to highlight certain fundamental features of the interplay among the large scale structures and turbulence.

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