DAY1: 26 Jun 2023

<Session 1: Laboratory Plasma 1> Chair: Masahiro Hoshino

[Inv]	10:00	10:20	Hiroshi Tanabe	High field particle acceleration/heating experiment in keV regime
[Inv]	10:20	10:40	Jongsoo Yoo	Anomalous resistivity and electron heating by lower hybrid drift waves during magnetic reconnection with a guide field
[Inv]	10:40	11:00	Michiaki Inomoto	Active Control of Parallel Electric Field to Enhance Particle Acceleration in Guide Field Reconnection
[Inv]	11:00	11:20	JongYoon Park	Experimental evidence of voltage-driven merging for flux ropes in 3D helical field configuration
[Inv]	11:20	11:40	Y.S. Hwang	Internal Reconnection Events in Versatile Experiment Spherical Torus
[Inv]	11:40	12:00	P. Gradney	Investigating the Collisionless Kinetic Regime with the New TREX Drive Cylinder
[Con]	12:00	12:15	Cameron Kuchta	Towards Measurement of Electron Pressure Anisotropy in Collisionless Laboratory Reconnection
[Con]	12:15	12:30	Y. Ono	Scaling Study of Reconnection Heating in Tokamak Merging Experiments and Simulations
	12:30	14:00	Lunch Break & Poster	

<Session 2: Theory> Chair: Li-Jen Chen

[Key]	14:00	14:30	Masahiro Hoshino	Energy Partition of Thermal and Nonthermal Plasmas in Magnetic Reconnection
[Key]	14:30	15:00	William Daughton	Current Status and Future Prospects for Understanding the Multiscale Physics of Magnetic Reconnection
[Inv]	15:00	15:20	Seiji Zenitani	Hyper Boris solvers for kinetic plasma simulations
[Inv]	15:20	15:40	Riddhi Bandyopadhyay	Energy Dissipation in Electron-only Reconnection
	15:40	16:10	Break & Poster	
[Inv]	16:10	16:30	Tomohisa Kawashima	Particle-In-Cell Simulations of Mushroom-instability-driven Magnetic Reconnections in Collisionless Relativistic Jets
[Con]	16:30	16:45	Michael Hesse	What do we Know About the Reconnection Electric Field?
[Con]	16:45	17:00	Samuel Totorica	Exact Calculation of Nonideal Electric Fields Demonstrates their Dominance of Injection in Relativistic Magnetic Reconnection
[Con]	17:00	17:15	Young Dae Yoon	Ion phase-space distributions and nonthermal energization mechanisms during magnetic reconnection
[Con]	17:15	17:30	Masaaki Yamada	Analytical model of magnetic energy conversion to plasma in a proto-typical two-fluid magnetic reconnection layer
[Con]	17:30	17:45	James A. Klimchuk	The Thickness of Current Sheets
[Con]	17:45	18:00	Chuanfei Dong	Reconnection-Driven Energy Cascade Revealed by the World's Largest Magnetohydrodynamic Turbulence Simulation

Dinner

High field particle acceleration/heating experiment in keV regime

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Here we report the highlights of our reconnection heating experiments in a series of high power merging experiments such as in ST40, MAST and TS-6. The major difference in the high temperature experiment is the time scale of ion-electron collision time τ^{E}_{ei}. In many experiments, "collisionless" condition is invisibly claimed but it is not necessarily satisfied when electron temperature is low. For example, electron-ion collision time of low temperature plasma has somehow comparable time scale with reconnection heating and the established heating structure does not explain FLARE-like high energy impulsive event. Our MR reconnection community somehow solves the feature of semi-stable reconnection events but violent/impulsive acceleration/heating such as in flare has not yet been well understood.

To resolve ion and electron heating structure from different energy conversion mechanism clearly, satisfying collisionless experimental condition is an important criterion. In TS-6, the time scale of the impulsive reconnection is compressed to ~ 10μs to enable the access by probes, while MAST and ST40 enables the extension of the collisional time scale to millisecond with the full non-invasive/high-energy experimental condition. In both approaches, ion heating in the downstream region clearly documented double-peak structure whose temperature is much higher than that of inflow region (~10eV). The initial ~10eV temperature is amplified to 10 ~ 250eV in U-Tokyo experiments, 0.1 ~ 1.2keV in MAST and 2.3keV at maximum in ST40. The strong deposition forms steep ion temperature gradient and it drives heat transfer on the downstream field lines and flare loop-top like clear structure is formed. Under the influence of guide field, the field aligned structure becomes clearer, while tilted ion temperature profile is also formed under the influence of parallel electric field profile which is formed by reconnecting electric field and quadrupole potential structure.

In the high temperature experiments, electron heating also shows interesting features. In comparison with low T_e experiments with electron collision time τ_{ee} in nanosecond time scale, high T_e experiment leads to microsecond time scale of τ_{ee} and electrons could be easily accelerated by parallel electric field. For example, when electrons are accelerated for 1μs without collision, even 1V/m electric field could accelerate electrons up to hundreds of eV. In MAST, this acceleration leads to the production of 1keV peaked electron temperature profile. The peak structure depends on the amplitude of guide field ratio and the increment of acceleration path length leads to clearer peaked structure formation. In ST40 experiment, keV regime high T_e plasma are routinely forms and leads to the initiation of hard X-ray burst for the first time in laboratory experiment. Although diagnostics has not yet been fully optimized to investigate full parameters in ST40, several new features in the collision-less regime are explored by the keV regime reconnection experiments.

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Anomalous resistivity and electron heating by lower hybrid drift waves during magnetic reconnection with a guide field

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Anomalous resistivity and electron heating by lower hybrid drift waves (LHDW) are studied inside the electron diffusion region of magnetic reconnection in the Magnetic Reconnection Experiment (MRX). Quasi-electrostatic LHDW propagating along the direction nearly perpendicular to the local magnetic field becomes unstable with a finite guide field. We observe large density fluctuations (about 25 % of the mean density) that are correlated with fluctuations in the out-of-plane electric field (about twice larger than the mean reconnection electric field). The phase difference between two fluctuations is about 30 degrees. The direct estimate of the anomalous resistivity is twice larger than the classical resistivity and accounts for 20 % of the mean reconnection electric field. The linear relation between two fluctuations from a local linear theory with collisional effects [1] agrees with measured data. With quasilinear analysis, anomalous electron heating by LHDW is estimated to be about 2.6 ± 0.3 MW/m^3, which exceeds the classical Ohmic heating of about 2.0 ± 0.2 MW/m^3. A statistical analysis also supports electron heating by LHDW and the electron temperature increase is larger at a high guide field.

We also present data from the Magnetospheric Multiscale (MMS) mission [2], which shows similar wave activities with anomalous resistivity. Fundamental physics of LHDW related to anomalous resistivity will be also discussed.

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Active Control of Parallel Electric Field to Enhance Particle Acceleration in Guide Field Reconnection

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Axial merging of two torus plasmas is utilized as an effective formation scheme of a high-beta torus plasma in fusion plasma experiments. The dominant heating source in plasma merging is considered to be the ion outflow in the reconnection downstream region, however, the plasma motion is drastically modified by the parallel electric field which intrinsically involved in the guide field reconnection.

Magnetic reconnection under a strong guide field takes place in a spherical tokamak merging experiment and the inductive reconnection electric field is almost parallel to the magnetic field particularly in the inboard-side down stream region. Large static in-plane electric field is required to sustain the plasma outflow in the downstream region. In other words, if the in-plane electric field does not balance the reconnection electric field, plasma motion in the downstream region is transformed from the outflow perpendicular to the magnetic field lines to the acceleration parallel to the magnetic field lines.

Experimental results from the soft X-ray (SXR) imaging diagnostic in the UTST device revealed that the intense SXR emission was observed in the inboard-side downstream region in the early phase of the plasma merging, and then the emission was localized near the current layer [1], suggesting that the electrons are transiently accelerated by the residual parallel electric field in the downstream region. Another finding was that the conductor plates inserted in the inboard-side downstream region made a large enhancement in the SXR emission because they prevented the charge separation along the magnetic field lines. In order to investigate the detailed mechanism of particle acceleration in the downstream region, a control system of the in-plane electric field by using multiple electrode pairs and fast switching devices was installed on the UTST experiment.

It is demonstrated that the developed method significantly reduces the static in-plane electric field in the downstream region within a sufficiently shorter time period than the reconnection time scale [2], and enhances the parallel electric field which provides direct acceleration of the charged particles. On the other hand, the reduction of the in-plane electric field decelerates the reconnection outflow velocity.

These experimental results suggest that the balanced condition in the reconnection downstream region could be easily broken and the transformation of energy conversion process should be considered in the high-guide-field reconnection.

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Experimental evidence of voltage-driven merging for flux ropes in 3D helical field configuration

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The onset of magnetic reconnection has been a significant challenge in understanding its underlying physics and associated natural phenomena, such as solar eruptions involving flux ropes [1]. Laboratory data indicate that both attractive forces and kink instability are the primary causes of the abrupt, impulsive onset of merging through magnetic reconnection [2-4]. However, these results are only applicable within a limited distance between the flux ropes. In this study, we present experimental evidence of voltage-driven merging between flux ropes in a three-dimensional helical field structure [5]. Our findings demonstrate that increasing the bias voltage triggers the merging of flux ropes, resulting in localized ion heating, a decrease in impedance (corresponding to the length of the flux rope), and localized magnetic field amplification due to changes in magnetic topology. We also observe an increase in broadband magnetic fluctuation activity in response to bias voltage. The beam-driven instability, initiated by bias voltage, may play a crucial role in the onset, generating circularly polarized fluctuations that can drive local current[6-7]. These findings provide valuable insights into the onset problem of magnetic reconnection.

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Internal Reconnection Events in Versatile Experiment Spherical Torus

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Internal Reconnection Event (IRE), similar to disruption in conventional tokamaks while not terminating with resilience, is considered as an interesting magnetic reconnection phenomenon in Spherical tokamak (ST). Overall mechanisms and characteristics of the IRE has been studied experimentally in Versatile Experiment Spherical Torus (VEST) [1]. Although IREs are known to be the nonlinear growth of internal magnetohydrodynamic (MHD) modes, edge filamentary currents such as blobs are found to play a significant role in the reconnection process as reported in VEST recently.[2] Edge filaments are observed to be co-rotating with similar speed to the internal MHD mode, and trigger the onset of IREs by providing external seed current in phase with the internal mode. The onset can be changed by inserting graphite limiter into the plasmas, indicating the possibility of controlling the blob and eventually IRE externally. Electron density and temperature profiles are measured with Thomson scattering systems to see the characteristics of the IRE.[3] With the reconnection event, electron density profile gets flattened as expected. Significant electron heating is also observed, but only at high field side. Ion heating is also measured with ion Doppler spectroscopy for impurity carbon line. Interestingly ion rotation follows ion heating sequentially and its torque changes the direction with different wall conditionings, suggesting a neoclassical toroidal viscosity torque rather than mechanisms such as the reconnection outflow and toroidal electric field induced by the current profile change.[4] Overall processes related to magnetic reconnection will be discussed from mechanisms to effects with wide range of experimental data.

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Investigating the Collisionless Kinetic Regime with the New TREX Drive Cylinder

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The Terrestrial Reconnection EXperiment (TREX) at the Wisconsin Plasma Physics Laboratory (WiPPL) [1] can reliably reach the collisionless kinetic regime by driving an induced magnetic field through a cylindrical coil geometry against a background magnetic field. The enhanced drive reduces the effects of collisionality in the experiment, such that electron pressure anisotropy is expected to develop unimpeded by Coulomb collisions. Comparing the upgraded Drive Cylinder to the previous 4-coil TREX configuration [2], the reconnection current layer extends 2m, which is a factor of two longer. The absolute system size is L/di = 15, and the reconnection rate has increased from Erec ~ 100V/m to 900V/m. These improved parameters allow the Drive Cylinder to reach a Lundquist number of S ~ 10^5, the highest value achieved by dedicated reconnection experiments. In this regime, the Drive Cylinder can explore plasma dynamics that are more applicable to the collisionless settings in planetary magnetospheres and other space physics phenomenon.

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Towards Measurement of Electron Pressure Anisotropy in Collisionless Laboratory Reconnection

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The purpose of the MR workshop is to review and discuss the recent progress in magnetic reconnection research in theories / simulations, laboratory experiments and solar, magnetosphere and astrophysical observations[1]. For more than a decade, the MR workshops have been a major international meeting series of magnetic reconnection. There will be both oral sessions (consisting of tutorial and invited talks) and short talk/or poster sessions.

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The Terrestrial Reconnection EXperiment (TREX) operates as a nominally cylindrically symmetric experiment, where an initial uniform axial background field is generated and plasma is injected creating a theta-pinch equilibrium. To begin reconnection, a large current is driven through coils creating a reversed field. As the current increases in time, the magnetic pressure near the coils is rapidly reduced allowing plasma to expand radially outward. Since the background field is frozen into the plasma we can measure the resulting magnetosonic wave using our magnetic probes, and through the characterization of the wave speed the initial plasma density profile is inferred. Ringing in the drive circuit creates additional pressure waves which are applied to measure density evolution. In the latter phase of the experiment the reversed field becomes sufficiently large that the total field is reversed and a reconnection current layer is generated. Given recent upgrades to TREX, we identify electron jets in the reconnection outflow, which collisionless reconnection theory predicts to be driven by electron pressure anisotropy. We've developed a pressure anisotropy probe that uses 12 directional Langmuir probes to measure this anisotropy.

Scaling Study of Reconnection Heating in Tokamak Merging Experiments and Simulations

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The merging operations of tokamak plasmas have been developed using TS-3[1], START, TS-4, UTST, MAST[2] and ST-40 experiments and MHD/ PIC simulations[3] for (1) high-power reconnection heating and (2) magnetic helicity injection. The former realizes the high ion temperature plasma production useful for a direct access to high-beta burning plasmas and the latter is often used for startup and helicity injection (current drive) of tokamak plasmas. Then, an important question arises as to what conditions are required for the merging operations to optimize the ion heating and helicity injection, respectively.

We found that (i) the compression of current sheet thickness δ to ion gyroadius ρ_i is required for fast reconnection as well as high-power ion heating with heating power increasing with the square of reconnecting magnetic field B_{rec} which is the poloidal magnetic field B_p, and (ii) δ larger than ρ_i produces slow reconnection with small magnetic-energy loss for the magnetic helicity injection. The former reconnection converts about 40% of reconnecting magnetic energy into ion thermal energy, while the latter does less than 10%.

Under the high current-sheet compression, we made two-fluid scaling study of ion heating by measuring the axial (poloidal) electric field E_z produced by the quadrupole potential wells and hills. We found that the maximum E_z in the downstream increases almost linearly with B_{rec} as shown in Fig. (b) and with the guide toroidal field B_t as shown in Fig. (c). Since E_z in the R-Z plane is proportional to $B_{rec}B_t$, the reconnection outflow speed V_{out} under high $B_t >> B_p$ is obtained from $V_{\mathbf{out}} = |\mathbf{E}\times\mathbf{B}|/B^2 \sim E_z/B_t \sim CB_{rec}$[4]. Since the ion heating energy is proportional to V_{out}^2, the ion energy/temperature increment ΔT_i increases with B_{rec}^2 under constant density as shown in Fig. (a). Recently, 2D PIC simulation under high guide field ($B_t/B_{rec}\sim 4$) confirmed that the ion kinetic energy increment ΔK_i increases with B_{rec}^2, as shown in Fig. (a'). Based on this promising B_{rec}^2-scaling, the recent ST-40 tokamak merging experiment at Tokamak Energy Inc. realized the maximum ion temperature T_i~3keV just using tokamak merging and finally reached 9.6keV in combination with NBI heating. It is noted that this B_{rec}^2-scaling depends on B_{rec}, not on device size or confinement time. All of ST-40, MAST, TS-4 and TS-3 have their data on the same scaling line, as shown in Fig. (a). The bifurcated tokamak merging operations for high-power ion heating and for helicity injection also depend uniquely on the current sheet compression to $\delta \sim \rho_i$ and to $\delta >> \rho_i$, respectively. The former operation is useful not only for the high-power reconnection heating but also for formation of interesting high-beta tokamaks with reversed-shear and absolute minimum-B profile.

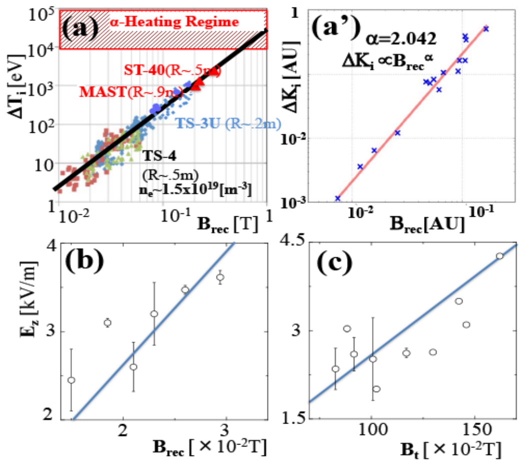

Fig. Dependences of ion temperature increment ΔT_i on B_{rec} in (a) tokamak merging experiments (TS-3, TS4, MAST and ST-40 under $n_e \sim 1.5\times10^{19} m^{-3}$) and (a') in 2D PIC simulation. Dependence of axial electric field E_z in the downstream on (b) B_{rec} and (c) guide (toroidal) magnetic field B_t in TS-3.

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Energy Partition of Thermal and Nonthermal Plasmas in Magnetic Reconnection

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In our space and astrophysical collisionless plasmas, nonthermal particles whose energies are much higher than the thermal temperature are often observed, yet our understanding of the energy partition between thermal and nonthermal particles remains to be elucidated. In this presentation. we discuss the energy partition during magnetic reconnection by using PIC simulations. We have investigated the energy partition for hot plasmas in plasma sheet as a function of guide magnetic field and plasma sheet temperature from nonrelativistic to relativistic reconnections. For simplicity, we have assumed a pair plasma, and analyzed the hot plasmas heated by reconnection by fitting a model function composing of Maxwellian and kappa distributions. In relativistic reconnection with an antiparallel magnetic field or a weak guide magnetic field, it was found that the nonthermal energy density can occupy more than 90% of the total kinetic plasma energy density, but strengthening the guide magnetic field suppresses the efficiency of the nonthermal particle acceleration. In nonrelativistic reconnection for an antiparallel magnetic field, most dissipated magnetic field energy is converted into thermal plasma heating. For a weak guide magnetic field with a moderate value, however, the nonthermal particle acceleration efficiency was enhanced, but strengthening the guide field beyond the moderate value suppresses the efficiency.

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Current Status and Future Prospects for Understanding the Multiscale Physics of Magnetic Reconnection

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Magnetic reconnection is inherently a multiscale process due to the large separation between the macroscope scale L, where magnetic fields become stressed and the dissipation scale δ, where the topological constraints are relaxed either through collisional or kinetic mechanisms. Tremendous progress has been made towards understanding applications where these scales are not too disparate ($L/\delta \lesssim 10^2$) including the Earth's magnetosphere and small-scale laboratory experiments, both of which are amenable to direct simulations that resolve kinetic scales. For these intermediate scale applications, important questions remain regarding the influence of 3D instabilities and the cross-scale coupling between the reconnection layer and the larger scale dynamics.

Looking outward to the broader Universe, our understanding of magnetic reconnection remains largely untested. For solar and astrophysical applications, the scale separation is so vast ($L/\delta \gtrsim 10^8$), that resolving the full range of scales is far beyond any foreseeable computing technology. Nevertheless, there are promising ideas that may explain how reconnection works in these large systems, along with exciting opportunities for new progress. In particular, large-scale current sheets may trigger the MHD plasmoid instability, leading to a hierarchy of flux ropes and new current sheets that extend down to dissipation scales. This hypothesis is supported by a growing body of fluid and kinetic simulations and upcoming laboratory experiments [1] are poised to critically examine this physics. However, even with laboratory validation, there will remain some outstanding questions regarding the general applicability in astrophysics. Can we extrapolate the plasmoid mediated reconnection scenario to the enormous scale separation ($L/\delta \gtrsim 10^8$) in the solar corona? Do new regimes emerge in which the turbulence regulates the geometry of the diffusion region? How might this impact heating and non-thermal particle acceleration?

This talk will give an overview of these challenges, with an emphasis on recent progress and future research prospects enabled by exascale computing, space observations and multiscale laboratory experiments [1].

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Hyper Boris solvers for kinetic plasma simulations

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Theory and modeling of magnetic reconnection highly rely on particle-in-cell (PIC) simulations. Inside PIC simulation, the Boris solver (or the Buneman-Boris solver) is widely used to solve the particle motion. Owing to its simplicity and good accuracy, it has been used over a half century.

In this contribution, we propose three improvements to the Boris solver. First, we repeat the 4-step procedure N times with a 1/N timestep. To speed up the calculation, an expression for arbitrary N is provided, based on Chebyshev polynomials [1]. Second, extending the so-called "gyrophase correction," we internally modify the electromagnetic fields to achieve M-th (M=2,4,6,...) order accuracy. Third, combining the two methods, we construct a family of particle solvers. The (M,N) solver provides N^M times smaller error than the standard Boris solver at affordable computational cost. The new solvers will be useful for better modeling of magnetic reconnection and other kinetic processes in space plasmas.

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Energy Dissipation in Electron-only Reconnection

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Magnetic reconnection is one of the fundamental plasma processes involved in converting energy stored in the magnetic fields into the kinetic energy of the constituent particles. A question of interest is how the partition of dissipated energy varies with parameters such as guide field strength and system size. In the standard model of reconnection, both ions and electrons participate in the reconnection process. However, recently, some events were observed using NASA's Magnetospheric MultiScale (MMS) mission where the electrons participate, but the ions do not, which was termed "electron-only reconnection" [1]. In this study, we employ several particle-in-cell (PIC) simulations and MMS observations to investigate how the partition of the dissipated energy over electrons versus ions varies as the reconnection regime changes from ion-coupled to electron-only.

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Particle-In-Cell Simulations of Mushroom-instability-driven Magnetic Reconnections in Collisionless Relativistic Jets

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Relativistic jets launched from supermassive black holes [1] indicates the acceleration of the charged particles [2] and also imply the enigmatic substructure inside them, e.g., fast jet-spine and slow jet-sheath parts [3-5]. In order to understand the physics and the observed features of relativistic jets, a number of general relativistic MHD simulations have been performed [6]. However, the mechanism of the electron accelerations and the origin of the appearance of the substructure of the jet (in particular, jet-spine region) are still uncertain up to today.

Because the relativistic jets are collisionless plasma, the kinetic studies will give us a new insight to address the above problems. Up to today, a limited number of particle-in-cell (PIC) simulations of relativistic jets has been carried out to explore the kinetic plasma processes of jets [7-9].

An important electron-scale shear instability called mushroom instability (MI [10]) was found in the plasma with relativistic bulk shear flow. Importantly, the MI dominates the electron-scale Kelvin–Helmholtz instability when relative bulk speed is greater than roughly 30% of the speed of light [11]. Attributed to MI, the magnetic fields are generated and amplified in the transverse plane of the plasma shear flows.

It is expected that the kinetic plasma phenomena associated with MI would play an important role in the high energy phenomena in relativistic jets. We, therefore, study the kinetic plasma dynamics in collisionless relativistic jets with velocity shear, by carrying out 2D-3V PIC simulations in the transverse plane of a jet [12]. We use a two-dimensional relativistic PIC simulation code PASTEL[13]. It is discovered that intermittent magnetic reconnections (MRs) are driven by MI. We refer to this sequence of kinetic plasma phenomena as "MI-driven MR." The MI-driven MRs intermittently occur with moving the location of the reconnection points from the vicinity of the initial velocity-shear surface toward the jet center. Subsequently, the number density of high-energy electrons that are accelerated by MI-driven MRs increases with time in the region inside the initial velocity-shear surface with the accompanying generation and subsequent amplification of magnetic fields by MI. The maximum Lorentz factor of electrons increases with initial bulk Lorentz factor of the jet. The MI-driven MRs may be related to the origin of the bright synchrotron emission in the jet spine of an active galactic nucleus jet.

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What do we Know About the Reconnection Electric Field?

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The reconnection electric field is at the core of the reconnection process. Its magnitude is directly related to the effectiveness of the magnetic flux, energy, and mass transport in general and across magnetic boundaries. The reconnection electric field has hence been the focus of intense research, fueled by the Magnetospheric Multiscale mission (MMS) and concurrent theory and modeling. In this presentation, we review the present state of knowledge pertaining to the reconnection electric fields and its plasma physical underpinnings. We will take a close look at reconnection in symmetric and asymmetric systems, and how they are related. The presentation will further relate relevant theory and modeling results to the ground truth provided by MMS observations, and how observations have driven theory and vice-versa. After summing up the current state of knowledge, we will identify a set of open questions, which call for future scientific investigations.

Exact Calculation of Nonideal Electric Fields Demonstrates their Dominance of Injection in Relativistic Magnetic Reconnection

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Magnetic reconnection is an important source of energetic particles in systems ranging from astrophysical compact objects to laboratory fusion devices. The large separation of spatiotemporal scales involved in reconnection makes it critical to determine the minimum physical model containing the necessary physics for modeling particle acceleration. By resolving the energy gain from ideal and nonideal magnetohydrodynamic electric fields self-consistently in kinetic particle-in-cell simulations of reconnection, the dominant role of the nonideal field for the early stage of energization known as injection is shown. Parameters scans show that the importance of the nonideal field increases with magnetization, guide field, and in three-dimensions, indicating its general importance for reconnection in natural astrophysical systems. The statistical properties of the injection process are obtained from the simulations, paving the way for the development of extended fluid models capable of accurately modeling particle acceleration in large-scale systems. This novel analysis method can be applied more broadly to give new insight into a wide range of processes in plasma physics.

Ion phase-space distributions and nonthermal energization mechanisms during magnetic reconnection

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Although magnetic reconnection in essence is a conversion process from magnetic to particle kinetic energy, ion acceleration during reconnection is a longstanding problem. In situations like collisionless reconnection where sub-kinetic scales are important and so distribution functions are translationally variant, phase-space distributions are more informing than velocity-space distributions. Here we examine ion phase-space distributions in kinetic simulations of 2D antiparallel reconnection to identify nonthermal ion acceleration mechanisms. The ions can be classified into different motional stages, and the phase-space distributions can be well described by the relative proportion of said stages. Ion temperature tensor components are also well understood by the phase-space distributions. It is shown that the reconnection electric field does zero net work on the ions, and only the in-plane electric fields contribute to net acceleration. Bulk ion heating is due to rapid phase-mixing by stochastic heating, which is confirmed by a direct calculation of Lyapunov exponents.

Analytical model of magnetic energy conversion to plasma in a proto-typical two-fluid magnetic reconnection layer

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In a prototypical two-dimensional antiparallel reconnection layer, An analytical model of the energy inventory is developed for the ion diffusion layer. In the two-fluid reconnection layer, as electrons and ions move into the reconnection layer with different paths, the magnetized electrons penetrate deep into the reconnection layer generating a strong potential well in the diffusion region. Magnetic field energy is converted to electric field potential energy through the motion of magnetized electrons in the background of non-magnetized ions. While some of the magnetic energy is deposited to the electrons in the electron-diffusion layer, ions gain their energy through electrostatic acceleration across the potential well in the broader ion diffusion region. In this work we have developed an analytical model based on our generalized Harris equilibrium (1) to evaluate quantitatively the energy partition of the reconnection layer. An important feature of the present model is that energy flow partitioning can be calculated without knowing the exact microscopic mechanisms of energy dissipation to ions and electron (2).

In the present study, the effects of density asymmetry and guide field are also discussed. Our analytical model concludes that one half of magnetic energy is efficiently converted to particles, primarily to ions in a prototypical two-fluid reconnection layer. Our analytical results are compared well with the recent MRX data, namely 50% of magnetic energy flux being converted to the particle energy dominated by the ion enthalpy flux, with smaller contributions from both the electron enthalpy and heat flux. These results from laboratory and space plasmas are remarkably consistent with our quantitative estimate made based on our physical picture of two-fluid mechanisms.

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(2) J. Yoo and M. Yamada; To be published, (2023)
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The Thickness of Current Sheets

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The thickness of electric current sheets is extremely important, especially as it relates to the onset of fast magnetic reconnection. It controls the slow buildup and explosive release of magnetic energy and plays a major role in the heating of the solar corona. Significant effort has been devoted to the question of whether current sheets have finite or zero thickness. Using a simple force balance analysis, we show why current sheets without a guide field (2D) and with a guide field that is invariant in the guide field direction (2.5D) cannot be in equilibrium if they have both finite thickness and finite width. We then estimate the conditions under which the tension of a curved line-tied guide field can produce a 3D equilibrium sheet that is finite in all dimensions. Finally, we speculate that some quasi-statically evolving current sheets undergoing slow stressing may reach a critical point at which equilibrium is no longer possible, and they suddenly thin to arbitrarily small scale.

Reconnection-Driven Energy Cascade Revealed by the World's Largest Magnetohydrodynamic Turbulence Simulation

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Magnetohydrodynamic turbulence regulates the transfer of energy from large to small scales in many astrophysical systems, including the solar atmosphere. We performed three-dimensional magnetohydrodynamic simulations with unprecedentedly large magnetic Reynolds number (at a cost of ~200 million CPU hours) to reveal how rapid reconnection of magnetic field lines changes the classical paradigm of the turbulent energy cascade. By breaking elongated current sheets into chains of small magnetic flux ropes (or plasmoids), magnetic reconnection leads to a new range of energy cascade, where the rate of energy transfer is controlled by the growth rate of the plasmoids [1,2]. As a consequence, the turbulent energy spectra steepen and attain a spectral index of -2.2 [1,2] that is accompanied by changes in the anisotropy of turbulence eddies [2]. The omnipresence of plasmoids and their consequences on, e.g., solar coronal heating, can be further explored with current and future satellites/telescopes.)

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DAY2: 27 Jun 2023

<Session 3: Solar Plasma 1> Chair: Yasushi Ono

[Key]	8:30	9:00	Kanya Kusano	What triggers the onset of solar flares
[Inv]	9:00	9:20	Joel T. Dahlin	Decoding Three-Dimensional Reconnection in Solar Flare Observations
[Inv]	9:20	9:40	Xin Cheng	Observations and Simulations of Turbulent Reconnection within CME-flare Current Sheet
[Con]	9:40	9:55	Yulei Wang	Three-dimensional Turbulent Reconnection within Solar Flaring Current Sheet
[Con]	9:55	10:10	Nian Liu	Observation and Modeling of the X5.4 Flare on March 7, 2012
	10:10	11:05	Break & Flash talk 1-4	
[Inv]	11:05	11:25	Mitsuo Oka	Electron Acceleration and Energy Partition during Solar Flares and Terrestrial Substorms
[Inv]	11:25	11:45	Daiki Yamasaki	Magnetohydrodynamic Modeling of Magnetic Field Structure of Solar Flares
[Con]	11:45	12:00	Toshifumi Shimizu	Two findings from the first solar microflare captured by coordinated Hinode, IRIS, and ALMA observation
[Con]	12:00	12:15	Quanming Lu	Electron-only Reconnection as a Transition from Current Sheet to Standard Reconnection
	12:30	14:00	Lunch Break & Poster	

<Session 4: Astrophysical Plasma> Chair: Michael Hesse

[Key]	14:00	14:30	Fan Guo	The Origin of Nonthermal Particle Acceleration in Relativistic Magnetic Reconnection
[Inv]	14:30	14:50	Benjamin Crinquand	Magnetic Reconnection in Black-Hole Magnetospheres
[Inv]	14:50	15:10	Shigeo S. Kimura	Magnetic Reconnection at Black-hole Magnetosphere
	15:10	16:05	Break & Flash talk 5-8	
[Inv]	16:05	16:25	J. Mehlhaff	QED Magnetic Reconnection in Gamma-Ray Blazars
[Con]	16:25	16:40	Giovani H. Vicentin	2D and 3D magnetohydrodynamical simulations of current sheets and magnetic reconnection: the effects of turbulence versus plasmoid instabilities
[Inv]	16:40	17:00	K. M. Schoeffler	Limits on the compression of magnetic islands, a source of synchrotron radiation bursts in PIC simulations of strong-field 3D relativistic magnetic
[Con]	17:00	17:15	Taiki Jikei	Condition for Magnetic Reconnection in Collisionless Shock Transition Regions
[Con]	17:15	17:30	Yi-Hsin Liu	First-Principles Theory of the Relativistic Magnetic Reconnection Rate in Astrophysical Pair Plasmas

Dinner

What triggers the onset of solar flares

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The Predictive research of solar flares is essential for a better understanding of solar activities and for developing space weather forecasts. However, although various models have been developed so far, the onset mechanism and prediction of solar flares still need to be clarified and advanced, respectively. We have recently developed a new prediction scheme for large flares, i.e., the kappa scheme, based on the MHD instability theory (Kusano et al. 2020). The kappa scheme can accurately predict large flares' onset and is capable of pinning down the precise location of flares. The successful prediction suggests that the distribution of the twist flux density on the polarity inversion line determines when and where a flare occurs and that a small-scale reconnection may trigger a large solar flare. However, the kappa scheme is imperfect and fails to predict specific flares in a few active regions. In this talk, I investigate the possible reason for the failure of the kappa-scheme predictions. Through the analyses, we argue what needs to advance our understanding and predictive capability of solar flares.

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Decoding Three-Dimensional Reconnection in Solar Flare Observations

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Solar flares are spectacular manifestations of explosive energy release powered by magnetic reconnection. The three-dimensional structure and dynamics of flares are thought to be critical to understanding the nature of this energy release, especially regarding the acceleration mechanism of nonthermal particles. Direct measurement of the magnetic fields in the corona where the reconnection occurs is, however, highly challenging. By contrast, 'indirect' high-resolution observations of flare loops and ribbons are plentiful and contain critical information regarding the three-dimensional structure. Flare ribbons are chromospheric patches illuminated by particle beams, tracing the footpoints of newly reconnected field lines. Hot and dense plasma evaporated by these beams form 'flare loops' that reveal the morphology of the reconnected magnetic field. We present recent high-resolution three-dimensional MHD modeling of flare reconnection and discuss our efforts to decode the information contained in these observations. We show that flare ribbons contain fine structure associated with current sheet plasmoids, whereas the tilt of the flare loops reveals the spatiotemporal evolution of the reconnection guide field. We discuss the implications for understanding energy release and particle acceleration via reconnection in solar flares and throughout the universe.

Observations and Simulations of Turbulent Reconnection within CME-flare Current Sheet

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Magnetic reconnection is a fundamental physical process in various astrophysical, space, and laboratory environments. In solar physics, it is even believed to be a key mechanism to heat/accelerate plasmas and drive the eruption of large-scale magnetic configurations. High-cadence and high-resolution observations recently show that magnetic reconnection always presents an intermittency characterized of the generation of magnetic islands of different scales, which can be well understood in the framework of turbulent reconnection theory. In this talk, I will present observational evidence for turbulent reconnection within the current sheet connecting flare loops to coronal mass ejections. We also implemented a 3D high-resolution MHD simulation of magnetic reconnection in a realistic flare configuration in order to explore the origin and property of turbulent reconnection, as well as its physical links to large-scale flare dynamics.

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Three-dimensional Turbulent Reconnection within Solar Flaring Current Sheet

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Solar flares can release coronal magnetic energy explosively and may impact the safety of near-earth space environments. Their structures and properties on macroscale have been interpreted successfully by the generally-accepted two-dimension standard model invoking magnetic reconnection theory as the key energy conversion mechanism. Nevertheless, some momentous dynamical features as discovered by recent high-resolution observations remain elusive.

Here, we achieve a cutting-edge high-resolution 3D MHD simulation of turbulent magnetic reconnection within a flare current sheet, self-consistently realizing the whole causal chain of 3D turbulent reconnection in a realistic flare configuration, including the growth of instabilities, the spontaneous formation of flux ropes (plasmoids in 2D), the development of turbulence in the CS, the outflow-induced turbulence at the flare loop top, and the sub-structures at the flare ribbon fronts.

It is found that fragmented current patches of different scales are spontaneously generated with a well-developed turbulence spectrum at the current sheet, as well as at flare loop-top region. The close coupling of tearing-mode and Kelvin-Helmholtz instabilities plays a critical role in developing turbulent reconnection and in forming dynamical structures with synthetic observables in a good agreement with realistic observations. The observational characteristics of flare CSs in different spatial scales are also investigated, which helps understand both high-resolution remote-sensing and future *in-situ* observations.

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Observation and Modeling of the X5.4 Flare on March 7, 2012

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The magnetic reconnection has been considered as an important process in solar eruptions, but its role in triggering mechanisms of solar eruptions and magnetic field evolutions during the solar flares has not been well understood.

In this talk, we present a study of the X5.4 flare on March 7, 2012[1], focusing on its initiation mechanism and back-reaction[2,3] effects. Our analysis shows that: 1) this flare is most likely triggered by the tether-cutting reconnection[4] and the subsequent double-arc instability[5], 2) the spacial preference of the observed back-reaction effect in terms of increase of horizontal magnetic field and downward Lorentz force show the back-reaction is likely a consequence of magnetic reconnection.

We also include magnetohydrodynamic (MHD) simulations of this flare to investigate the importance of the magnetic reconnection location in flare eruptions. The MHD simulation result reproduce the X5.4 flare and the following X1.3 flare with clear development of two highly twisted magnetic flux ropes. Further more, the results show that the magnetic flux rope corresponding to the larger flare (X5.4) is more sensitive to magnetic reconnections compared with the smaller flare.

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Electron Acceleration and Energy Partition during Solar Flares and Terrestrial Substorms

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Particles are accelerated to very high, non-thermal energies during explosive energy-release phenomena in space, solar, and astrophysical plasma environments. While it has been established that magnetic reconnection plays an important role in solar flares and terrestrial substorms, it remains unclear how magnetic reconnection can further explain particle acceleration to non-thermal energies. Here we review recent progress in our understanding of particle acceleration by magnetic reconnection in Earth's magnetotail and compare with particle acceleration during solar flares. With improved resolutions, recent in-situ measurements have enabled detailed studies of particle acceleration at various structures such as the diffusion region, separatrix, jets, magnetic islands (flux ropes), and dipolarization front. However, in order to fully understand the particle acceleration mechanism and further compare with particle acceleration in solar plasma environments, there is a need for further investigation of, for example, energy partition, the precise role of turbulence, and the effect of pre-existing non-thermal particles.

Magnetohydrodynamic Modeling of Magnetic Field Structure of Solar Flares

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Solar flares are rapid energy-release phenomena via magnetic reconnection in the solar corona. It is widely accepted that the eruption of dark filaments, the cool and dense plasma cloud in the hot solar corona, drives magnetic reconnection during solar flares. Plasma materials of dark filaments are supported by a bundle of helical magnetic field lines: magnetic flux ropes (MFRs). Due to observational limitations, it is hard to obtain the magnetic field structures of the MFRs directly, and the formation process and the eruption mechanism of the MFRs have not yet been cleared. To understand the evolution of the three-dimensional (3D) coronal magnetic field including MFRs, we performed a nonlinear force-free field extrapolation and a data-constrained magnetohydrodynamic simulation using a series of photospheric vector magnetic field data obtained from the Helioseismic and Magnetic Imager onboard the Solar Dynamics Observatory. In our study, we focused on two large-scale solar flares which have GOES flare class larger than X1: an X9 flare observed in an active region (AR) NOAA 12673 of 2017 September and an X1 flare observed in an AR NOAA 12887 of 2021 October. Both flares were accompanied by dark filament eruptions. According to the investigation of the AR NOAA 12673, we found that a large MFR concerning the X9 flare formed 2 days before the onset of the flare. We suggested that the magnetic field reconfiguration via magnetic reconnection of several M flares took place two days before the onset of the X9 flare suppressed the MFR [1]. From the results of the study on the AR NOAA 12887, we found that both the torus instability and the formation of the magnetic arcade below the MFR during the eruption contributed to the acceleration of the erupting MFR of the X1 flare [2]. In this talk, we will also briefly introduce the recent studies of solar flares focused on the temporal evolution of the 3D coronal magnetic field by using extrapolation techniques.

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Two findings from the first solar microflare captured by coordinated Hinode, IRIS, and ALMA observation

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Solar microflares are amongst the major energy input sources that form the active nature of the solar corona. They are also an important target in understanding energy release mechanisms in the corona. We coordinated Hinode and IRIS satellite observations with ALMA's millimeter wave observation and succeeded to capture the behavior at the foot of a microflare for the first time. One of the interesting and surprising findings is that the magnitude of non-thermal energy impinging on the microflare foot was approximately 100 times smaller than the thermal energy produced in the corona. Another interesting finding is that the exact locations of the foot, which is detected as several brightening kernels, are in weak and void magnetic areas formed within a patchy distribution of strong magnetic flux at the solar surface. This provides a conceptual image that the transient energy release occurs in the corona on the sheaths of magnetic flux bundles connecting from the strong flux islands at the solar surface. These results are providing important suggestions in the understanding of physical mechanisms for transient energy release in the solar atmosphere.

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Calcium Bright Knots and the Formation of Chromospheric Anemone Jets

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Recent space solar observations have revealed that the solar atmosphere is filled with small-scale jets, associated with small- scale explosions. There is increasing indirect evidence that these jets may be produced by a physical mechanism similar to that of large scale flares, i.e., the release of magnetic energy stored in the solar atmosphere through magnetic reconnection, and also that these jets may be related to the heating of corona and chromosphere as well as acceleration of solar wind. Among small scale jets, the so called **chromospheric anemone jets** [1] in active regions remain puzzling, because they are at such small scales that their footpoints (bright knots) have not been well resolved. We propose a new model for chromospheric jets using the three-dimensional magnetohydrodynamic (MHD) simulations, which show that the continuous, upward rising of small-scale twisted magnetic flux ropes in a magnetized solar chromosphere drive small-scale magnetic reconnection and the launching of several small-scale jets during the evolution of the **chromospheric anemone jets**. Our new, self-consistent, three-dimensional computer modeling [2] of small-scale, but ever-changing flux rope emergence in the magnetized solar atmosphere is fully consistent with observations and provides a universal mechanism for nanoflare and jet formation.

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Electron-only Reconnection as a Transition from Current Sheet to Standard Reconnection

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Standard magnetic reconnection couples with both electron- and ion dynamics. Recently, a new type of magnetic reconnection, electron-only reconnection without the coupling of ion dynamics, has been observed in space. With two-dimensional particle-in-cell simulations and satellite observations, we show that in the externally-driven magnetotail, electron-only reconnection is a transition from quiet current sheet to standard reconnection. We find that (a) energy conversion $\mathbf{j} \cdot \mathbf{E}'$ is around zero in quiet current sheet but nonzero in electron-only reconnection, and (b) ion temperature does not change across electron-only reconnection but peaks at the center of standard reconnection. These two differences can be used as criteria to distinguish magnetotail electron-only reconnection from quiet current sheet and standard reconnection, respectively. Based on the two criteria, we justify that the MMS 17 June 2017 event is a magnetotail electron-only reconnection event, which is subsequently evolved into standard magnetic reconnection.

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The Origin of Nonthermal Particle Acceleration in Relativistic Magnetic Reconnection

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Magnetic reconnection occurs ubiquitously in the universe and is often invoked to explain fast energy release and particle acceleration in high-energy astrophysics. Relativistic magnetic reconnection in the magnetically dominated regime has surged over the past two decades, revealing the physics of fast magnetic reconnection and nonthermal particle acceleration. Much of the recent debate is the physics of particle acceleration and the origin of the nonthermal power-law spectra. We discuss the recent progress including the low-energy injection and further acceleration that generates a power-law energy spectrum. We evaluate the contribution of several different mechanisms and regions such as reconnection X-points. The Fermi and pickup processes, related to the electric field perpendicular to the magnetic field, govern the injection for weak guide fields and larger domains. Meanwhile, parallel electric fields are important for injection in the strong guide-field regime. In the post-injection stage, we find that perpendicular electric fields dominate particle acceleration in the weak guide-field regime, whereas parallel electric fields control acceleration for strong guide fields. These findings will help explain the nonthermal acceleration and emission in high-energy astrophysics.

Magnetic Reconnection in Black-Hole Magnetospheres

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A variety of astrophysical phenomena can only be explained as being powered by black holes. A particular instance is accreting supermassive black holes, which are responsible for producing intense, rapid flares of non-thermal gamma-ray emission, whose origin is still unknown. Besides, black-hole X-ray binaries emit hard non-thermal X-rays, which are often thought to origin from Comptonization of soft X-rays by a ``coronal'' hot, optically thin and magnetically dominated plasma. In both cases, this non-thermal emission carries a significant fraction of the total energy output of the black-hole system. Magnetic reconnection is believed to provide a crucial link between theory and observations, by quickly and efficiently converting the magnetic energy stored in these systems into radiation. In this talk, I will present recent efforts to model black-hole magnetospheres and coronae from first principles. To do so, I will show the results of global general-relativistic kinetic simulations which can capture both the kinetic plasma physics of reconnection, and the knowledge of where and under which physical conditions it does occur. I will highlight how magnetic reconnection can successfully account for high-energy emission by shaping the large-scale structure of the magnetic field around black holes, and I will also address how to connect the microphysics of reconnection with observables.

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Magnetic Reconnection at Black-hole Magnetosphere

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Relativistic jets are observed in radio-loud active galactic nuclei. However, the mass-loading process onto radio jets has been a long-lasting problem. In this talk, I will propose a promising scenario for mass loading onto radio jets. The accretion flows onto supermassive black holes in radio galaxies are likely to be the magnetically arrested disk (MAD) regime, where large-scale magnetic fields affect their dynamics. Recent general magnetohydrodynamic simulations revealed that magnetic reconnection quasi-periodically occurs at the vicinity of black holes [1]. Magnetic reconnection is expected to accelerate non-thermal electrons very efficiently, based on particle-in-cell simulations [2]. These accelerated electrons emit copious gamma rays at the vicinity of black holes. These gamma rays interact each other, producing a copious electron-positron pairs. These pairs become radio blobs after they travel away from the black hole. We analytically estimate the mass-loading rate onto radio jets and find that this scenario can achieve the mass loading rate required by radio observations. We also find that future X-ray observations of nearby radio galaxies are crucial to test our scenario.

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QED Magnetic Reconnection in Gamma-Ray Blazars

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In the highly magnetized plasma environments of neutron stars and black holes, magnetic reconnection provides an efficient mechanism to accelerate radiating relativistic particles and, thus, to power the broadband electromagnetic emission for which these objects are renowned. Constructing realistic reconnection models is complicated, however, because the energized plasma particles often suffer strong radiative losses, even straying into the high-energy, QED regime where they may radiate an order-unity fraction of their energy through discrete gamma-ray quanta. Moreover, once emitted, the gamma-rays are not necessarily free to escape the reconnection region; they may instead be absorbed to produce electron-positron pairs. In such cases, the collective reconnection dynamics become coupled to QED—a coupling that must be self-consistently modeled in order to predict realistic observational signatures. This is necessary, in particular, in the context of reconnection-powered gamma-ray emission from certain types of blazars (powerful relativistic jets launched toward the Earth from accreting supermassive black holes). In this contribution, I present results from a recent study where we couple blazar-relevant QED processes to magnetic reconnection in particle-in-cell simulations. The simulations reveal how QED physics manifests in unique reconnection observables reminiscent of gamma-ray blazar flares, which I illustrate via a few example observations. The simulations also enable diagnosing the reconnection electron-positron pair yield, opening up the possibility that reconnection-powered gamma-ray emission may provide clues into the matter/antimatter composition of luminous high-energy astrophysical plasmas.

2D and 3D magnetohydrodynamical simulations of current sheets and magnetic reconnection: the effects of turbulence versus plasmoid instabilities

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Magnetic reconnection is ubiquitous in astrophysical environments, like the solar corona, Earth's magnetosphere, and the accretion disks and jets of black holes. The classical models of magnetic reconnection, such as Sweet-Parker and Petscheck mechanisms, are not able to reproduce the high reconnection rates observed, for example, in the Sun, of $V_{rec} \sim 0.1 – 0.3\ V_A$, since they predict a reconnection rate dependence on the inverse of the Lundquist number ($S = LV_A/\eta$) that results slow rates, considering the typical astrophysical values, as high as $S = 10^{18\text{-}20}$. The problem of slow reconnection in MHD flows was solved by Lazarian and Vishniac (ref. [1]), who showed that in the presence of turbulence, several reconnection sites can occur simultaneously, providing rates that are fast and independent of S or the ohmic resistivity (η). In this work (ref. [2]), we present results of very high resolution 2D and 3D magneto-hydrodynamical (MHD) simulations of current sheets where forced turbulence is injected initially in the domain, up to $t = 0.1\ t_A$. We have covered an extensive parametric space, including the dependence on the equation of state (EOS), the plasma-β, the Lundquist number and the effective resolution of the simulations and we show that the system remains turbulent longer after the turbulence injection, providing high reconnection rates compatible to those observed in the Sun, and substantially higher and more persistent than the ones obtained from models where reconnection is driven solely by the plasmoid (or tearing mode) instability, which is often claimed to be the only effective process able to produce fast reconnection (e.g., refs. [3] and [4]).

Keywords: Magnetohydrodynamics (MHD), Magnetic Reconnection, Turbulence, Numerical Simulations.

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Limits on the compression of magnetic islands, a source of synchrotron radiation bursts in PIC simulations of strong-field 3D relativistic magnetic reconnection.

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Magnetic reconnection has been suggested to play an important role in the production of gamma-ray flares, which are observed near the magnetospheres around compact objects such as pulsars and magnetars. Reconnection leads to the generation of magnetic islands and acceleration of non-thermal particles. In such scenarios, the field strength can be close to the critical (Schwinger) field, resulting in quantum electrodynamic (QED) effects including discrete gamma-ray emission and pair creation. Therefore, standard plasma models for magnetic reconnection are no longer valid in these scenarios.

A study [3] employing 2D and 3D particle-in-cell simulations taking advantage of the radiative quantum electrodynamic (QED) module [1] of the OSIRIS framework investigates relativistic magnetic reconnection of a pair plasma with strong fields. These conditions are expected in magnetospheres around compact objects such as neutron stars. Our previous 2D study [2] has shown that reconnection produces concentrated regions at the centers of magnetic islands with higher temperatures and compressed density and magnetic fields, leading to enhanced synchrotron emission. For sufficiently strong fields, this emission can reach the gamma-ray range. In the present work, our simulations show this also to be true in 3D, and we provide a theoretical model for the limits of the compression of the magnetic field and plasma density. These limits can be clearly visualized using a novel 2D histogram diagnostic of the density and magnetic fields measured at each point in space of our simulations. The magnetic field compression is theorized to be limited by dissipation manifested as an effective radiative resistivity, and the density compression to be limited by 3D kinking instabilities. This process of compression and enhancement of radiation may help explain the gamma-ray flares observed near pulsar and magnetar magnetospheres, where strong-field reconnection regimes are expected.

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Condition for Magnetic Reconnection in Collisionless Shock Transition Regions

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Cosmic rays are one of the significant energy components in space. Their interactions with the interstellar magnetic field, planets' atmosphere, etc., relate to various phenomena. The most promising candidate that accelerates the high-energy cosmic rays is a process called first-order Fermi acceleration in collisionless shocks. Particles reflected by waves gain energy by repeatedly traveling back and forth between the upstream and the downstream. One of the most significant problems related to this acceleration mechanism is the (electron) injection problem. A sufficient number of particles must be pre-accelerated to high-enough energy to initiate an efficient Fermi acceleration. Electrons with a smaller mass than ions are more relevant to this problem. For this pre-acceleration, it is necessary to investigate the microphysics in the shock transition region. Theory and simulations suggest that the dynamics of non-relativistic, high-Mach number shocks are dominated by Weibel instability, which is an electromagnetic instability driven by the reflected ions. Although this instability is excited regardless of the background magnetic field, previous shock simulations show that the magnetic field structure can drastically change with a weak background magnetic field. Moreover, magnetic reconnection could occur in the transition region with some shock parameters[1,2]. Observations suggest that magnetic reconnection can efficiently produce non-thermal electrons[3,4]. However, the role of the weak background magnetic field in collisionless shocks and the conditions for the onset of the reconnection were unknown. In this study, we show that a finite magnetic field that is strong enough to magnetize the electrons, but not the ions, changes how the electrons respond to the induced electric field. The qualitatively different behavior of the electrons results in different linear and nonlinear evolution between the unmagnetized and magnetized Weibel instability. We have performed 2D particle-in-cell simulations to investigate the nonlinear evolutions of the Weibel instability with magnetized electrons. We found that the magnetic field amplified by an electron MHD dynamo-like process in the early nonlinear stage results in spontaneous magnetic reconnection (Fig. 1). We confirmed that this type of magnetic field is also generated in 3D. The condition for the Weibel-dominated shock with magnetized electrons is $30 \lesssim M_{\mathrm{A}} \lesssim 4000$ with Alfven Mach number of the shock M_{A}. This theory is applicable to typical young supernova remnant shocks, which are common accelerators in our galaxy.

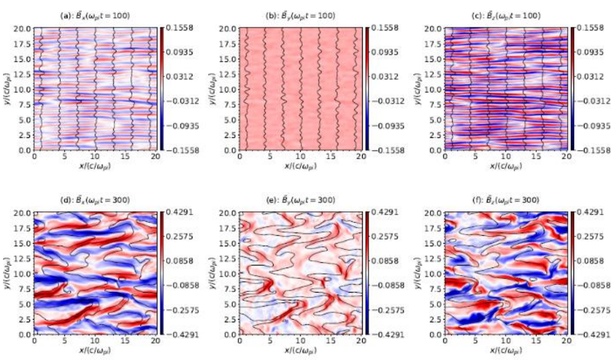

Fig. 1. Snapshots of the magnetic field in the 2D simulation. Black lines show the in-plane field lines.

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First-Principles Theory of the Relativistic Magnetic Reconnection Rate in Astrophysical Pair Plasmas

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A recent theory [2] illustrates why and how the Hall effect leads to fast magnetic reconnection in non-relativistic electron-proton plasmas. In this talk, we will present a new theoretical model of the relativistic magnetic reconnection rate [1] in strongly magnetized electron-positron plasmas, that do not have the Hall effect. By considering the energy budget and required current density near the x-line, we analytically show that in the magnetically-dominated relativistic regime, the x-line thermal pressure is significantly lower than the upstream magnetic pressure due to the energy needed to sustain the extreme current density. This depleted x-line pressure causes the upstream magnetic field lines to collapse in, producing the open outflow geometry, which enables fast reconnection.

The extension of this low-pressure region into the outflow exhausts further explains why the relativistic antiparallel reconnection is very bursty in Particle-in-Cell (PIC) simulations [3]; because a once-opened outflow exhaust also collapses, triggering secondary tearing islands to temporarily restore the force-balance. However, those islands will be push out by the primary outflows from the dominant x-line. Thus, the generation of magnetic islands inside the relativistic reconnection layer appears to be bursty and repetitive. This island-producing mechanism is different from the plasmoid instability shown in the high Lunguist number resistive MHD simulations.

Regardless of unsteady fluctuations introduced by these tearing islands, the predicted scaling of relativistic reconnection rate as a function of the magnetization parameter, based on the overall force balance, is consistent with PIC simulations. This result is important for understanding a wide range of extreme astrophysical environments where fast magnetic reconnection has been evoked to explain observations, such as transient flares and nonthermal particle signatures

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DAY3: 28 Jun 2023

<Session 5: Solar Plasma 2> Chair: Ryoji Matsumoto

[Inv] 8:30 8:50 S. D. Bale Interchange reconnection as the source of the fast solar wind within coronal holes

[Inv] 8:50 9:10 Tai Phan Parker Solar Probe Observations of the Prevalence of Magnetic Reconnection in the near- Sun Heliospheric Current Sheet

[Inv] 9:10 9:30 Lei Ni RMHD studies of magnetic reconnection in the partially ionized low solar atmosphere

[Con] 9:30 9:45 Q. M. Wargnier 2D and 3D Magnetic Reconnection in the upper solar atmosphere with Helium-Hydrogen-Carbon mixture

[Con] 9:45 10:00 James Leake The Onset of Magnetic Reconnection in Dynamically Evolving Current Sheets in the Solar Corona

10:00 10:30 Break & Poster

[Con] 10:30 10:45 L. K. S. Daldorff Implication of line tied magnetic field on magnetic reconnection in the closed corona

[Con] 10:45 11:00 Yusuke Kawabata Multi-line Spectropolarimetric Observations of Solar Magnetic Reconnection Events

[Con] 11:00 11:15 Satoshi Masuda Recent Solar Flare Researches with Nobeyama Radioheliograph

[Con] 11:15 11:30 Shinsuke Imada Magnetic Reconnection in the Solar Corona and SOLAR-C Mission

11:45 Excursion

18:30 Banquet

Interchange reconnection as the source of the fast solar wind within coronal holes

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The fast solar wind that fills the heliosphere originates from deep within regions of open magnetic field on the Sun called 'coronal holes'. The energy source responsible for accelerating the plasma is widely debated; however, there is evidence that it is ultimately magnetic in nature, with candidate mechanisms including wave heating[1,2] and interchange reconnection[3–5]. The coronal magnetic field near the solar surface is structured on scales associated with 'supergranulation' convection cells, whereby descending flows create intense fields. The energy density in these 'network' magnetic field bundles is a candidate energy source for the wind. Here we report measurements of fast solar wind streams from the Parker Solar Probe (PSP) spacecraft[6] that provide strong evidence for the interchange reconnection mechanism. We show that the supergranulation structure at the coronal base remains imprinted in the near-Sun solar wind, resulting in asymmetric patches of magnetic 'switchbacks'[7,8] and bursty wind streams with power-law-like energetic ion spectra to beyond 100 keV. Computer simulations of interchange reconnection support key features of the observations, including the ion spectra. Important characteristics of interchange reconnection in the low corona are inferred from the data, including that the reconnection is collisionless and that the energy release rate is sufficient to power the fast wind. In this scenario, magnetic reconnection is continuous and the wind is driven by both the resulting plasma pressure and the radial Alfvénic flow bursts.

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Parker Solar Probe Observations of the Prevalence of Magnetic Reconnection in the near-Sun Heliospheric Current Sheet

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The heliospheric current sheet (HCS), which originates from the Sun and extends throughout the heliosphere, is the largest current sheet in the solar system. One of the surprises of the Parker Solar Probe mission is the finding that magnetic reconnection is almost always active in the near-Sun HCS, despite its enormous scales. In this talk, I will discuss some key findings on the properties of such large scale reconnection. One of the findings is that reconnection in the near-Sun HCS accelerates protons to high energies (to tens of kilo-electronvolts), because the available magnetic energy per particle is high close to the Sun. The energized protons leak out of the reconnection exhaust along separatrix field lines, and become a source of energetic proton beams observed in the solar wind.

RMHD studies of magnetic reconnection in the partially ionized low solar atmosphere

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The low solar atmosphere is highly gravity stratified and the total hydrogen density decreases by 7 orders of magnitude within a thin layer of several Mm. The temperature in this region is generally only several thousand K and the plasmas are partially ionized. Thanks to the high resolution telescopes, plenty of small scale reconnection events at different altitudes in this region have been observed. The interactions between ions and neutrals may strongly affect the reconnection process and make the reconnection mechanisms to be very different from those in fully ionized plasmas. What's more, the radiative transfer and cooling process make the studies of magnetic reconnection in this region to be more difficult. In this talk, we will present our recent progresses on numerical studies of magnetic reconnection in the low solar atmosphere, and discuss the mechanisms which lead to plasma heating in different reconnection events, such as EBs and UV bursts. Based on the RMHD simulation results about magnetic reconnection between the emerging magnetic flux and back ground magnetic fields in the partially ionized and highly stratificated low solar atmosphere, we proposed a model for explaning the co-spatial and co-temporal EBs and UV bursts.

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2D and 3D Magnetic Reconnection in the upper solar atmosphere with Helium-Hydrogen-Carbon mixture

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The Sun's corona is a puzzle as the mechanism responsible for heating it remains unclear. Magnetic reconnection and wave dissipation are two suggested processes, but their relative contributions to coronal heating are unknown. We use numerical simulations to investigate the role of magnetic reconnection in transition region conditions and the effects of multi-fluid/multi-species on this process. Our simulations consider a Helium-Hydrogen-Carbon mixture with six species. We compare 3D scenarios with 2D scenarios to examine how three-dimensional effects influence the reconnection process. For this, we developed an efficient numerical strategy that employs a partitioned implicit-explicit orthogonal Runge-Kutta method for integrating the MFMS model in the Ebysus code. Our findings show that MFMS effects and particle decoupling lead to efficient heating mechanisms. The decoupling between the hydrogen, helium, and carbon species could also result in chemical fractionation and enrichment of helium. Our results have significant implications for recent observations of helium enrichment in switchbacks or coronal mass ejections.

The Onset of Magnetic Reconnection in Dynamically Evolving Current Sheets in the Solar Corona

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The problem of the onset of reconnection in the solar corona is a nuanced one. Release of magnetic energy via reconnection cannot be ubiquitous and efficient, or not enough energy would build up to drive the observed heating and explosive events in the corona. However, deriving criteria for rapid onset is not trivial. Here we focus on two parameters of coronal current sheets thought to be responsible for nano-flare heating of the corona: thickness and the strength of the reconnecting component (sometimes called 'shear'). We present results of simulations of the onset of magnetic reconnection in dynamically thinning current sheets applicable to coronal current sheets. We find that onset occurs when tearing instability growth timescales are smaller than the system dynamical timescale (thinning time), and that the onset of reconnection follows a similar storyline as in previous studies of static sheets, which allows for predictions of onset criteria to be developed.

Implication of line tied magnetic field on magnetic reconnection in the closed corona

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Magnetic reconnection plays an important role in the rapid release of stored magnetic energy in the solar corona. This includes small events like nanoflares that heat the corona to multi-million Kelvin temperatures and large events like flares and CMEs. In the magnetically closed corona, both footpoints of the field lines are essentially fixed in the dense photospheric plasma at the base. Thus, studies of reconnection must take line-tying into account. In the case of nanoflares, it is the guide field component that is line-tied. Magnetic reconnection in the corona begins in the fluid regime and is initiated by the tearing instability. Line-tying has been shown to play a stabilizing role. We present results of high-fidelity 3D visco-resistive MHD simulations with both periodic and line-tied guide-field boundary conditions. We focus on the linear and non-linear growth of the tearing instability and the development of islands (flux ropes in 3D). We show that tension forces associated with line-tying restrict the interaction and coalescence of islands, which would otherwise happen freely. We present examples where there is a modest interference with the normal tearing evolution and other examples where the tearing is shut down entirely. We discuss the implications for coronal heating.

Multi-line Spectropolarimetric Observations of Solar Magnetic Reconnection Events

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There are many kinds of explosive phenomena caused by magnetic reconnections in the solar atmosphere. Ellerman bombs (EBs) are magnetic reconnection events occurring in weakly ionized and moderate plasma β (~1) environments in the solar photosphere and chromosphere. Owing to the observability of the physical quantities around the reconnection site, EBs are one of interesting observation targets for studying magnetic reconnections. While measuring the magnetic field in the solar corona is still difficult, inferring magnetic field in the chromosphere with high spatial resolution and reasonable temporal cadence will be achieved soon.

One such opportunity is SUNRISE III, which is an international balloon-borne solar observatory employing a 1 m diameter telescope. SUNRISE III will achieve five days of stable observations in a seeing-less environment at altitudes around 37 km. We are developing the Sunrise Chromospheric Infrared spectroPolarimeter (SCIP)[1] as a focal plane instrument for SUNRISE III. SCIP will perform multi-line spectropolarimetric observations, enabling us to seamlessly diagnose the physical quantities (magnetic field, velocity field, and temperature) from the photosphere to the chromosphere.

In this talk, we would like to introduce the capability of SCIP for performing observations of magnetic reconnection events. In addition, we will present our recent study, where we used a realistic magnetohydrodynamic (MHD) simulation of EB to study how SCIP will have access to the physical phenomena. We synthesized the polarimetric signals by solving radiative transfer equation based on the physical quantities in the MHD simulation, and compared the polarimetric signals with the physical quantities in the MHD results. We found that the multi-line observations of SCIP can detect the bidirectional flow associated with the EBs and suggest the height of the reconnection site.

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Recent Solar Flare Researches with Nobeyama Radioheliograph

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After National Astronomical Observatory of Japan retreated the operation of Nobeyama Radioheliograph (NoRH) at the end of March in 2015, NoRH had been operated by the International Consortium for the Continued Operation of Nobeyama Radioheliograph (ICCON[1]). After the five-year extension of the operation by ICCON, finally, it was shut down at the end of March 2020.

During this operating period (~28 years), about 900 major flares were observed with NoRH. These flares were recorded with a high time resolution of 0.1 second (event mode), instead of 1 second (normal mode). This high time-resolution is one of unique and important characteristics of NoRH, especially for solar flare research. This provides us the capability to investigate propagation motion of accelerated electrons along a magnetic loop. This kind of study can not be realized by other instruments.

Another strong point of NoRH is its high sensitivity. It can detect a very weak (< 1 solar flux unit) flare such as a B-class event and can realize imaging observations with a time resolution of 1 second. It is very useful to understand the particle acceleration process in small solar flares.

Recently, a new Chinese solar radio telescope, 'Mingantu Spectral Radioheliograph (MUSER)' was developed and started observations during this extension period. While NoRH observes the sun at two frequencies (17 and 34 GHz), MUSER observes at relatively lower, but much wider frequency range (0.4 – 15 GHz). The observation using these two instruments provides us the information of the accelerated electrons with different energies and at different altitudes in the solar atmosphere. This is a great advantage to reveal the electron acceleration process in the standard solar model based on magnetic reconnection.

In this presentation, we briefly review some results of our recent researches on solar flares using the large observational database of NoRH.

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Magnetic Reconnection in the Solar Corona and SOLAR-C Mission

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Magnetic reconnection has been recognized as one of the key mechanisms for heating and bulk acceleration of space plasmas. This energy conversion mechanism is not limited to the solar atmosphere but was also observed in the Earth's magnetosphere and in the laboratory, as well as in other space plasmas. The solar atmosphere is an excellent space laboratory for magnetic reconnection study, as it allows large-scale observation of magnetic reconnection. To date, many observations have been made on the solar corona to confirm the presence of high-temperature and high-speed plasma flows produced by magnetic reconnection above flare arcades. In this talk, we will introduce the study on plasma heating considers the time-dependent ionization process during a large solar flare on 2017 September 10, observed by Hinode/EUV Imaging Spectrometer (EIS) [1]. The observed Fe XXIV/Fe XXIII ratios increase downstream of the reconnection outflow, and they are consistent with the time-dependent ionization effect at a constant electron temperature T_e = 25 MK. Moreover, this study also shows that the nonthermal velocity, which can be related to the turbulent velocity, reduces significantly along the downstream of the reconnection outflow, even when considering the time-dependent ionization process. The number of high-temperature lines observed by Hinode/EIS is limited, so it is difficult to make a sufficient diagnosis of the reconnection region. Recently, the next generation solar observation satellite SOLAR-C has been discussed intensively. An ultraviolet imaging spectrometer with dramatically improved spatial and temporal resolution is planned for this satellite. In the SOLAR-C era, thermal nonequilibrium plasma will be extensively discussed. We expect that SOLAR-C will reveal the reconnection region in detail.

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DAY4: 29 Jun 2023

<Session 6: Magnetospheric Plasma> Chair: Hantao Ji

[Key]	8:30	9:00	Kevin Genestreti	Physics of collisionless electron diffusion regions: the reconnection rate, energy conversion, and reconnection onset
[Inv]	9:00	9:20	Naoki Bessho	Electron Acceleration by magnetic reconnection in the Earth's bow shock
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[Inv]	9:40	10:00	C. Norgren	Investigating the particle dynamics associated with off-diagonal pressure components around the electron diffusion region
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[Inv]	10:40	11:00	R. E. Ergun	Near Runaway Ion Acceleration Associated with Magnetic Reconnection-Driven Turbulence
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[Inv]	11:40	12:00	Mao Aohua	Numerical simulations on 3D asymmetric reconnection in SPERF
[Con]	12:00	12:15	K. A. Blasl	Reconnection signatures within the Kelvin-Helmholtz vortex-induced Lower- Hybrid waves at Earth's magnetopause
[Con]	12:15	12:30	B. Michotte de Welle	Global Environmental Constraints on Magnetic Reconnection at the Magnetopause from In-Situ Measurements
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[Inv]	14:00	14:20	Lan Gao	Particle Acceleration and Ion Acoustic Waves during Magnetically Driven Reconnection using Laser-Powered Capacitor Coils
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[Inv]	14:40	15:00	Yongli Ping	Turbulent magnetic reconnection generated by intense lasers
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[Con]	15:15	15:30	Tara Ahmadi	The role of guide field on electrostatic potential and ion temperature profiles
[Con]	15:30	15:45	R Datta	Experiments and simulations of radiative collapse in pulsed-power-driven magnetic reconnection
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[Con]	16:00	16:15	Peng E	Status of the Space Plasma Environment Simulation Facility
[Con]	16:15	16:30	Cary Forest	A Laboratory Analog of the Parker Spiral in the Big Red Ball
[Con]	16:30	16:45	H. Ji	Multiscale Magnetic Reconnection and the FLARE Project
	16:45		Closing	

Physics of collisionless electron diffusion regions: the reconnection rate, energy conversion, and reconnection onset

Kevin Genestreti

Magnetic reconnection is a process in thin plasma current sheets that exchanges electromagnetic energy for particle energy and changes the magnetic topology. It is enabled by non-ideal-MHD electric fields in electron diffusion regions (EDRs), which mediate the reconnection rate and energy conversion. MMS has observed EDRs in a broad variety plasma conditions, which enables comparative studies for how the conditions upstream of thin reconnecting current sheets impact EDR processes. The vast majority of these observations are assumed to be made after reconnection has developed, though some fortuitous observations have been made during the onset of reconnection. This talk reviews work the reconnection and energy conversion rates in EDRs, including their relationships to one another and the background plasma conditions. Briefly, observations of reconnection onset are discussed, as well as persistent mysteries related to onset.

Electron Acceleration by magnetic reconnection in the Earth's bow shock

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Active magnetic reconnection is often observed by space satellites, such as NASA's Magnetospheric Multiscale (MMS), in current sheets in shock-driven turbulence in the Earth's bow shock [1-7]. It is important to elucidate the role of reconnecting current sheets in the shock to produce energetic particles, and determine the contribution to the total shock heating. To reveal the properties of reconnection in the shock-driven turbulence, and understand electron acceleration and heating mechanisms, we perform 2 and 1/2 dimensional particle-in-cell (PIC) simulations of quasi-parallel shocks based on the parameters in the Earth's bow shock.

The electron temperature rapidly rises from the upstream to the downstream of the shock. In the shock transition region, the electron temperature in magnetic islands becomes a few times larger than that in the surrounding regions. The energy distribution function of electrons in the shock transition region shows a power-law spectrum, and the maximum energy of the electrons becomes largest when a large number of ion-scale magnetic islands are produced. After those ion-scale islands dissipate the magnetic energy and disappear, small-scale (electron-scale) reconnection regions where electron-only reconnection can occur dominate the shock transition region, and the electron temperature keeps increasing.

We investigate the electron energization mechanisms by tracing individual particles in the PIC simulation. We discuss major electron acceleration mechanisms working in reconnecting current sheets and magnetic islands in the shock. Fermi acceleration can energize particles when they interact with multiple reconnection sites [8, 9]. Electrons trapped in a contracting island can be accelerated, and they are ejected from one region to another and can be further accelerated. We also found other new electron acceleration mechanisms that can occur in islands [10, 11]. In ion-scale magnetic islands, there are strong Hall electric fields pointing toward the center of each island. As these islands move, electrons trapped in the islands can gain energies larger than the electric potential due to the Hall electric fields, because the travel distances for the trapped electrons can be larger than the radius of each moving island. Also, the trapped electrons can gain energies from the reconnection electric fields in the islands, which is similar to the island surfing mechanism [12]. In addition, when the core magnetic fields in the islands evolve, electric fields with non-zero curl E are generated, and electrons moving around those islands can gain energies. This is a new type of betatron acceleration that can occur in magnetic islands [11].

We estimate that the electron energy gain due to reconnection in the shock transition region is up to around 1 keV. The energy increase due to these acceleration mechanisms in reconnecting current sheets and magnetic islands is much larger than the acceleration due to the parallel electric field in the transition region and the shock drift acceleration.

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Interplay of Magnetic Reconnection and Current Sheet Instabilities in the Earth's magnetotail

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Magnetic reconnection is a fundamental process in plasma and a major cause of energy conversion 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 perturb the magnetotail, such as a variety of kinking instabilities [1, 2] and waves [3]. We present results of a 3D global magnetospheric hybrid-Vlasov Vlasiator [4] simulation where we analyze the interaction of magnetic reconnection and a kinking instability – propagating in the dawn-dusk direction – that develops in the magnetotail current sheet. We follow the evolution of reconnection (in terms of reconnection rate) in the different phases of the instability development, from before the onset to the decaying phase. Our results suggest that the efficiency of the reconnection process is affected by the development of the kinking instability. In particular, the reconnection rate decreases locally, and reconnection appears to be suppressed in the region where the current sheet is perturbated the most and at the time of maximum amplitude of the current sheet fluctuations. At those locations, the expected inflow pattern is altered and high vorticity is observed. Our results indicate that there is a complex interplay between reconnection and kinking instabilities in the magnetotail.

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Investigating the particle dynamics associated with off-diagonal pressure components around the electron diffusion region

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Magnetic reconnection has far-ranging consequences but is enabled by the magnetic diffusion inside the small electron diffusion region. Inside the electron diffusion region, the reconnection electric field is balanced by the off-diagonal components of the electron pressure gradients[1,2,3]

$$E_y = -\frac{1}{ne}\left(\frac{\partial P_{xy}}{\partial x} + \frac{\partial P_{yz}}{\partial z}\right).$$

In this study, we employ numerical particle-in-cell simulations and spacecraft observations by the Magnetospheric MultiScale (MMS) mission to elucidate what components of the electron distribution, and associated electron dynamics, conspire to produce these off-diagonal pressure components.

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Suprathermal electrons in the terrestrial magnetotail

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Measurements from NASA's Magnetospheric Multiscale (MMS) mission in the terrestrial magnetotail indicate that suprathermal electrons are observed most probably in closed-field regions earthward of the reconnection X line. Statistically, the region that hosts the most suprathermal electron flux enhancements features elevated magnetic fluxes and weak plasma flows behind the earthward-propagating reconnection front. Case studies of MMS electron diffusion region (EDR) crossings exhibit suprathermal electron flux enhancements only earthward of the EDR.

The MMS statistical results further show that coherent magnetic islands and high magnetic fluctuations surrounding a reconnection X line, although effective in electron energization, are not the dominant agents for energizing electrons to suprathermal energies in the magnetotail. We discuss potential implications of these observations to electron energization in solar flares.

Near Runaway Ion Acceleration Associated with Magnetic Reconnection-Driven Turbulence

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Magnetic reconnection in the Earth's magnetotail has been observed to drive strong turbulence resulting in energetic particle acceleration. We focus on three properties that are emerging from observations. (1) Despite substantial electric and magnetic field fluctuations of turbulence, the electron diffusion region of the on-going magnetic reconnection has many similar properties to laminar, 2D magnetic reconnection including Hall electric fields, Hall magnetic fields, a thin electron current sheet, and ion and electron jets. These observations provide direct confirmation that magnetic reconnection can not only be responsible for but also can continue in regions of large-scale turbulence. (2) We observe that three types of ion energization that are active during turbulent magnetic reconnection. Ion jets from magnetic reconnection produce a nonthermal population up to a few times the initial ion energy. Speiser-like energization in the current sheet imparts a roughly equal amount of energy. These processes act on a majority of the ions but, by themselves, do not appear to produce a strong, energetic (>100 keV) tail in the proton distribution. We find that the most energetic ions that are accelerated to significantly higher energies (>100 keV) by the turbulent fields. (3) Turbulent magnetic reconnection appears to enable near run-away ion acceleration. The ion jets of magnetic reconnection result in a density depletion in the plasma sheet due to the low-beta inflow from the lobes. Not only does the magnetic reconnection sustain, magnetic field annihilation rate appears to increase. With fewer particles to absorb the magnetic annihilation energy, ions are energized to many times their initial thermal energy.

Turbulent Magnetic Reconnection and suprathermal electron acceleration

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Magnetic reconnection is a fundamental plasma process by which magnetic field lines on two sides of the current sheet flow inward to yield an X-line topology. It is responsible for producing energetic electrons in explosive phenomena in space, astrophysical, and laboratorial plasmas. The X-line region is supposed to be the important place for generating energetic electrons. However, how these energetic electrons are generated in such a limited region is still poorly understood. Here, using Magnetospheric multiscale mission data acquired in Earth's magnetotail, we present direct evidence of super-thermal electrons up to 300 keV inside an X-line region, and the electrons display a power-law spectrum with an index of about 8.0. Concurrently, three-dimensional network of dynamic filamentary currents in electron scale is observed and leads to electromagnetic turbulence therein. The observations indicate that the electrons are effectively accelerated while the X-line region evolves into turbulence with a complex filamentary current network.

Invited talk

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Transient Processes in Magnetic Reconnection in the Earth's Magnetosphere: Magnetic Field Annihilation and Flux Rope Generation

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We report transient processes in magnetic reconnection revealed by multi-spacecraft analysis of high-resolution electromagnetic field and plasma data acquired by the Magnetospheric Multiscale (MMS) mission in Earth's magnetosphere. The transient processes presented are collisionless magnetic field annihilation in an elongated electron diffusion region (EDR) [1], which can proceed at a rate much higher than that expected from the resistive MHD theory, and the generation of ion-scale magnetic flux ropes from an electron-scale reconnecting current sheet (ERCS) [2].

Evidence for the former (annihilation) was found from MMS observations of approximately antiparallel reconnection in the magnetotail, and both theoretical analysis and fully kinetic simulation [3] show that the annihilation can be significant only when the EDR is elongated in the outflow jet direction. Thus annihilation is a transient process. The latter transient process (flux rope formation) was investigated by utilizing MMS observations of a magnetopause current sheet in which asymmetric, guide-field reconnection was ongoing. Our analysis, based on the reconstruction of two-dimensional [4] and three-dimensional [5] magnetic fields in the current sheet, is consistent with kinetic simulations [6], which show that ion-scale flux ropes can be spontaneously and repeatedly generated from an elongated ERCS through secondary magnetic reconnection or the electron tearing instability. We suggest that fast collisionless magnetic field annihilation may play a key role in the dissipation of magnetic energy in plasma turbulence where reconnecting current sheets are common [7], and that secondary reconnection in ERCSs may be responsible for a class of flux transfer events and plasmoid events that is observed during quasi-continuous reconnection at the magnetopause [8,9] and in the magnetotail, respectively.

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Numerical simulations on 3D asymmetric reconnection in SPERF

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The Space Plasma Environment Research Facility (SPERF) has constructed at the Harbin Institute of Technology in China. One of its experimental components, the Asymmetric Reconnection EXperiment (AREX), aims to study the asymmetric reconnection dynamics relevant to the magnetic reconnection process at the magnetopause. The numerical simulations of the 3D reconnection process in AREX in a 3D magnetohydrodynamics (3D MHD) model are carried out for planned experiments. Different reconnection regimes and 3D topologies relevant to the magnetopause reconnection with different interplanetary magnetic field (IMF) conditions and the dipole field configurations are investigated by adjusting plasma parameters and coil setups as well as coil current waveforms. The simulation results reveals that the plasma distribution of the asymmetric reconnection in SPERF is analogous to the magnetopause. Three types of the 3D reconnection topology, including the X-line structure, the B-A-B null pair structure, and the A-B null pair structure, are discussed in detail.

Reconnection signatures within the Kelvin-Helmholtz vortex-induced Lower-Hybrid waves at Earth's magnetopause

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The Kelvin-Helmholtz (KH) instability excited at the Earth's magnetopause has been considered responsible for causing efficient mass and energy transfer across the magnetopause. Theoretical, numerical and observational studies have revealed that the evolution of the KHI and the resulting non-linear vortex flow involve secondary processes. As a unique case of such multi-scale and inter-process couplings, we recently reported observations of the MHD-scale KH waves and embedded smaller-scale phenomena in data from NASA's Magnetospheric Multiscale (MMS) mission at the dusk- flank magnetopause during southward interplanetary magnetic field (IMF) conditions. Given quantitative consistencies with corresponding fully-kinetic particle-in-cell simulations designed for this event, the MMS observations demonstrate the onset of the Lower-Hybrid Drift Instability (LHDI) during the nonlinear phase of the KHI and the subsequent mixing of plasmas near the boundary layer.

In this study, we further explored this KHI event during southward IMF and found signatures of magnetic reconnection in an electron-scale current sheet observed in the KH vortex-driven LHDI turbulence. This reconnection event was observed under high guide field conditions and features a super-Alfvénic electron outflow, a Hall perturbation of the magnetic field and enhanced energy conversion. Results from a high-resolution PIC simulation designed for this reconnecting current sheet suggest a highly dynamical current sheet evolution, which is quantitatively consistent with the observations made by MMS.

In addition, we performed a statistical study utilizing data from several KH wave/vortex edge crossings from this southward IMF period. Several of these KH events show the formation of electron-scale current sheets due to the interplay between the KHI and LHDI accompanied by reconnection signatures. This result suggests that these reconnecting electron-scale current sheets would be a ubiquitous phenomenon at least under the observed conditions of this magnetopause event and thus an important factor in the study of cross-scale energy transfer of the KHI.

Global Environmental Constraints on Magnetic Reconnection at the Magnetopause from In-Situ Measurements

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The location of magnetic reconnection at the Earth's magnetopause is a long-standing question in magnetospheric physics. Several models have been proposed to predict the position of the X-line at the magnetopause with respect to the IMF and solar wind conditions. These models often rely on quantities whose global spatial distributions at the magnetopause are typically obtained by analytical or numerical modeling. In this work, we attempt to reconstruct these global distributions using only in-situ measurements. We used statistical learning to automatically select in-situ data from four missions (Cluster, Doublestar, THEMIS, MMS). This allowed a 3D reconstruction of the magnetic field draping [1] in the dayside magnetosheath, which shows significant differences with the model of Kobel et Fluckiger 1994 for a certain range of IMF orientations. Since this magnetostatic model is often used to predict magnetic shear at the magnetopause, we will examine the implications of these differences for the X-lines that maximize this quantity [2]. We will also extend this discussion to other relevant quantities, such as current density and the Cassak-Shay reconnection rate, which are also available from in-situ measurements.

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Formation of thin current sheets and reconnection in collisionless turbulent plasmas

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We describe the formation of thin current sheets and reconnection through them in the collisionless turbulent plasmas of the solar wind and the Earth's magnetosheath by means of 2D and 3D fully kinetic and hybrid plasma simulations and compare them with MMS observations. In particular we dwell on role of ultrathin current sheets maintained by the anisotropic particle distributions.

Particle Acceleration and Ion Acoustic Waves during Magnetically Driven Reconnection using Laser-Powered Capacitor Coils

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Over the past decade, our team has been dedicated to developing a robust new experimental platform to study magnetically driven reconnection using strong coil currents powered by high power lasers [1]. KJ-class lasers were used to drive parallel currents to reconnect MegaGauss-level magnetic fields in a quasi-axisymmetric geometry. In this presentation, we report an overview of our unique platform and most recent results on direct measurement of particle acceleration and observation of ion acoustic waves during magnetic reconnection. The angular dependence of the measured electron energy spectrum and the resulting accelerated energies, supported by particle-in-cell simulations, indicate that the mechanism of direct electric field acceleration by the out-of-plane reconnection electric field is at work [2]. Furthermore, we observe a sudden onset of ion acoustic bursts measured by collective Thomson scattering in the exhaust of anti-parallel magnetically driven reconnection, which are followed by electron acoustic bursts with electron heating and bulk acceleration [3]. Our results therefore validate one of the proposed particle acceleration mechanisms by reconnection and demonstrate the importance of ion and electron acoustic dynamics during reconnection when ion Landau damping is ineffective, a condition applicable to a range of astrophysical plasmas.

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Magnetic Reconnections in Laser-Produced Plasmas

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We have been investigating laboratory astrophysics, where space and astrophysical phenomena are experimentally simulated using high-power and intense lasers [1]. In space plasmas, direct local measurements provide microscopic information although global information is hard to obtain. Contrary, in astrophysical plasmas, global imaging provides macroscopic information on the phenomena although they are inaccessible by direct measurements. One of the unique features of laboratory astrophysics is the simultaneous observations of local and global information by controlling manners.

By controlling an external magnetic field, we address magnetic reconnection driven by electron dynamics in laser-produced plasmas, where only electrons are directly coupled with the magnetic field. We observe the cusp and plasmoid using optical imaging [2], and pure electron outflows using local measurement with collective Thomson scattering [3]. We also observe magnetic field inversion relevant to plasmoid, and whistler waves by local measurements with magnetic induction probes [3]. We review our recent progress of experimental investigations of the electron scale magnetic reconnections using high-power lasers [4] and report the latest experimental results on magnetic field imaging using ion radiography.

We further discuss experimental models on spontaneous magnetic reconnections associated with the Weibel instability in sub-relativistic counterstreaming plasmas using intense laser pulses in the presence of an external magnetic field [5].

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Turbulent magnetic reconnection generated by intense lasers

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Magnetic reconnection is a process of the annihilation of an opposing magnetic field lines with significant and fast magnetic energy release in plasmas, and thus considered as one of a major trigger of the eruptive onset of solar flares. A fundamental open issue is how the magnetic energy stored in the plasma to be transferred from large to small scales where its actual dissipation occurs. The concept of turbulent magnetic reconnection has been then proposed to answer the question. Such reconnection processes are observed that solar flares are in the large scale picture while signatures of the energy release with flare accelerated particles are fragmented/chaotic. It is nevertheless still lack of direct observational evidence for turbulent magnetic reconnection in solar studies. The particular physical processes and properties of turbulent reconnection thus remain unclear. Here, we report the turbulent magnetic reconnection process in the laser-driven solid targets experiment with formation of a fragmented current sheet in this paper. Characteristics of turbulence power spectra are analyzed to establish a bridge between astronomical and laboratory observations. Moreover, it is shown that the parallel electric field dominates electron acceleration in the turbulent magnetic reconnection processes while the betatron mechanism plays a cooling role.

Relativistic electron injection acceleration in laser-driven magnetic reconnection plasmas

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The standard gamma-ray burst (GRB) prompt emission model is the internal shock (IS) model. However, this model suffers from insufficient aspects, such as the energy dissipation mechanism, efficiency problem, and spectral index problem. The internal collision-induced magnetic reconnection and turbulence (ICMART) model is acceptable to overcome these criticisms in theoretical and physical scenarios. Here, we partially and experimentally investigate the feasibility of this model by using intense laser facilities. We use long pulse lasers to drive low- and high- (the ratio of thermal pressure to magnetic pressure) magnetic reconnection (MR) plasmas with coils and planar targets. A short pulse intense laser is used to irradiate a gold target to produce original relativistic electrons, which are injected into the MR configurations for further acceleration. We find that MR with different plasma beta values plays a different role in further accelerating relativistic electrons. Low-beta MR can flatten the energy spectra even with a striking electron bump. In contrast, high- beta MR softens the energy spectra, which benefits a deeper understanding of GRB emissions.

The role of guide field on electrostatic potential and ion temperature profiles

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In high guide field magnetic reconnection, the inductive electric field is aligned with magnetic field causing plasma polarization along the magnetic field, leading to the formation of a quadruple potential structure in the downstream area, which increases the in-plane electric field and suppresses $E_{\parallel}$. It is expected that this strong in-plane electrostatic electric field is responsible for ion acceleration downstream. In this study, the role of the guide field on the electrostatic potential and ion temperature profiles has been studied using the Particle-in-Cell and experimental setups.

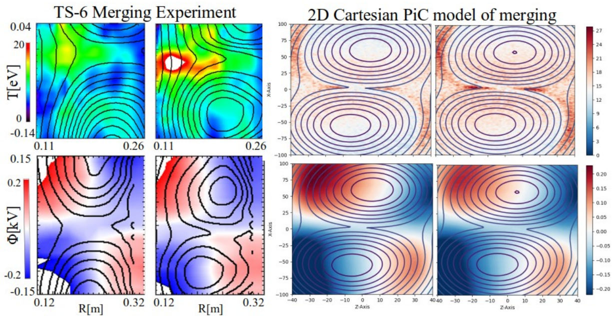

Figure 1: The 2D ion temperature and electrostatic potential measured in TS-6 experiment and calculated by 2D PiC simulation.

Initially, two plasma rings are formed inductively around the PF coils on both sides of the vacuum vessel. As soon as the PF coil's current damps fully, the plasma toroids separate from the coils and move toward the mid-plane due to the mutual attraction of the parallel plasma currents. At the end of the magnetic reconnection process, a single hot core plasma is observed in the mid-plane. A 2D magnetic probe array system installed at the poloidal cross-section measures all the components of magnetic field.
The local ion temperature is measured by a 2D high-resolution ion Doppler tomography system consisting of 288 viewing cords (fig1 left/top). Electrostatic potential Φ measurement is done with the Langmuir probe on the R-Z plane (fig1 left/bottom). From the other side, a 2D Cartesian PiC simulation of plasmoids coalescence with high mass-ratio (mi/me~500) confirms the experimental results of quadruple structure of in-plane potential (fig1 right). Despite the geometry difference, the two sets of profiles show a good correlation both in ion temperature and electrostatic potential. Figure 2 shows the dependency of potential gap and ion temperature over magnetic fields ratio, confirming the experimental measurements in TS-3/TS-4 devices [1]. It is clear that there is no guide field dependency for high-guide field regimes. If we assume that the guide field is mostly attributable in making the diffusion region thinner, then the decrease in the ion temperature due to increase in the guide field value is reasonable as energy conversion mechanisms occur at this region. The situation is different for the potential gap. In this case, thinning the diffusion region continues until Bg/Brec~5. For ultra-high guide field values, the changes of the diffusion region decreases, resulting in the no-guide field dependency in the energy conversion related parameters such as potential drop, electric field and temperature.

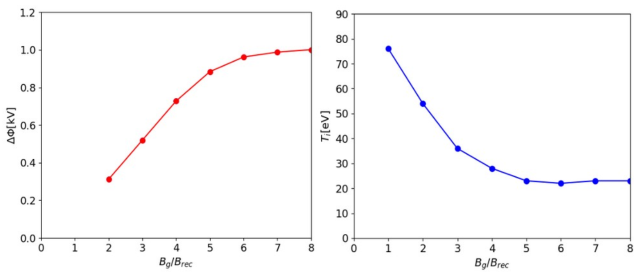

Figure 2: The dependency of potential gap and ion temperature on Bg/Brec ratio from PiC simulation

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Experiments and simulations of radiative collapse in pulsed-power-driven magnetic reconnection

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In many high-energy-density astrophysical systems, magnetic reconnection occurs in a strongly radiatively-cooled environment. Radiative cooling can lead to radiative collapse of the reconnection layer, generating a cold and strongly-compressed current sheet. In this talk, we present results from the first experimental investigation of pulsed-power-driven magnetic reconnection in a strongly-radiatively cooled regime. The experiment is designed to provide cooling rates much faster than the hydrodynamic transit rate $\tau_H/\tau_{cool} \approx 240$), which is required to observe the radiative collapse of the reconnection layer. A dual inverse wire array load driven by the Z machine (20 MA, 300 ns rise time) generates oppositely-directed highly-collisional, super-Alfvénic ($M_A > 2$) plasma flows with anti-parallel magnetic fields. The flows interact in the mid-plane to generate an elongated current sheet of Lundquist no. ≈ 400, that exhibits strong XUV and X-Ray emission. Inductive probes measure peak magnetic fields of 25-30 T in the inflow to the current sheet, which is roughly 10x larger than in previous pulsed-power-driven reconnection experiments. Visible spectroscopy, which exhibits well-defined Al-II and Al-III emission lines, is used to characterize the inflows to the reconnection layer ($T_e \approx 2 - 3\ eV, n_e \approx 1 \times 10^{18} cm^{-3}$).

A filtered X-ray diode, which collects >1 keV photons from the reconnection layer, exhibits a sharp peak in intensity (50 ns FWHM), indicating radiative collapse of the layer. X-ray spectroscopy of the reconnection layer shows well-defined He-like and Li-like k-shell emission lines, consistent with temperatures > 150 eV. Radiation transport calculations further indicate that the X-ray spectrum corresponds to localized hotspots of enhanced temperature embedded within a relatively colder and less dense layer. Time-resolved X-ray images confirm this picture, and show an elongated current sheet with brightly-emitting fast-moving hotspots (up to 30% of the magnetosonic velocity near the center of the reconnection layer). Resistive MHD simulations in 2D and 3D indicate that hotspots are consistent with plasmoids, which appear as localized regions of enhanced emission.

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Profile relaxation by merging of two spherical-tokamak-type plasmoids

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A merging process of two spherical-tokamak-type (ST) plasmoids, which are confined inside a rectangular conducting vessel, has been examined by means of two-dimensional PIC simulation [1]. Magnetic reconnection takes place at a contact point of two STs and a part of poloidal magnetic energy is transferred to the ion and electron thermal energies mainly in the central confinement region. Two STs are relaxed into one large ST while changing an equilibrium profile. A series of simulation runs with different guide fields clarify that there appears a strong dependence of the energy partition on the guide field. This result is consistent with the TS3 experiment for a strong guide-field [2]. The merging process leads to the increase in the total thermal pressure and the decrease in the total magnetic pressure in the central confinement region. Thus, the plasma in the central region expands towards the edge region by changing the total confinement profile. Finally, a trapezoid-shaped pressure profile with a flat top and a hollow magnetic pressure profile are formed in the central confinement region. This result is also consistent with the TS3 merging experiment [3].

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Status of the Space Plasma Environment Simulation Facility

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The SPERF (Space Plasma Environment Simulation Facility) is a user facility dedicated to studying the basic space plasma physics, ranging from the three-dimensional magnetic reconnection at the Earth's magnetopause to the wave-particle interaction in the Earth's radiation belts, through creating the magnetic field and plasma to simulate the large-scale terrestrial magnetosphere in the laboratory and deploying a group of advanced plasma diagnostic tools. Most of the subsystems of the SPERF, including vacuum, magnets, pulsed power supplies, plasma sources, and diagnostic tools, have been constructed and integrated into the facility, and now they are being under test. Here, the subsystems of the SPERF are introduced with emphasis on their present statuses. Meanwhile, possible issues of space plasma physics that can be investigated based on the facility will be sketched.

A Laboratory Analog of the Parker Spiral in the Big Red Ball

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Many rotating stars have magnetic fields that interact with the winds they produce. The Sun is no exception. The interaction between the Sun's magnetic field and the solar wind gives rise to the heliospheric magnetic field -- a spiraling magnetic structure, known as the Parker Spiral, which pervades the solar system. In this talk, I will report the creation of a laboratory model of the Parker spiral system based on a rapidly-rotating plasma magnetosphere and the measurement of its global structure and dynamic behavior including reconnection. This laboratory system exhibits regions where the plasma flows evolve similarly to many magnetized stellar winds. We observe the advection of magnetic field into an Archimedean spiral and the ejection of quasi-periodic plasma blobs into the stellar outflow, which mimics the observed plasmoids that fuel the slow solar wind. The Parker spiral system mimicked in the laboratory can be used for studying solar wind dynamics in complementary fashion to conventional space missions such as NASA's Parker Solar Probe mission.

The main takeaways from this talk will be:
1. We observe axisymmetric plasmoids in a Parker Spiral experimental geometry for the first time.
2. These plasmoids are not the result of a linear instability, but are a result of a lack of equilibrium caused by transport - namely particle and energy sources.
3. The region of closed field lines between the hydrostatic inner streamer and hydrodynamic solar wind outside the streamer are never in equilibrium and dynamically produce these plasmoids as a result of non-equilibrium.
4. The pressure gradient in this region is responsible for driving plasma flow outward irrespective of the magnetic field because beta is so large.
5. The toy model of this is simple: there is a critical current sheet lengthening rate necessary for reconnection to occur Ldot/L ~ ¥gamma where ¥gamma is the tearing mode growth rate. The pressure gradient determines this lengthening rate simply by driving radial flow from the stationary boundary at the edge of the hydrostatic equilibrium out into the current sheet. The steeper the pressure gradient, the shorter the timescale for the current sheet to reach the critical lengthening rate.
6. When the drive is very strong plasmoids of many scales appear and the current sheet becomes turbulent.

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Multiscale Magnetic Reconnection and the FLARE Project

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Magnetic reconnection is widely recognized as a fundamental plasma process underlying many explosive and energetic phenomena observed throughout the Universe. These plasmas are characterized by their high Lundquist numbers, S, and large normalized system sizes by ion kinetic scale, λ. Globally, these plasmas are well described by fluid descriptions, while in locally reconnecting current sheets, kinetic physics dominates. Different multiscale coupling mechanisms between global fluid scales and local kinetic scales can occur, and they are organized in a reconnection phase diagram in terms of S and λ[1]. Reconnection research is entering a new stage to explore these different couplings. Statistical properties of reconnecting current sheets in these multiscale phases are crucial in determining the energetic consequences of magnetic reconnection, such as the non-thermal acceleration of electrons. This presentation highlights our recent effort in quantifying statistical properties by analyzing data during turbulent magnetotail reconnection[2] and theoretically predicting the effect of a guide field on plasmoid size distributions[3]. More recently, we expanded our effort to study particle energization during multiscale reconnection, including enhanced particle acceleration by MHD plasmoids[4], electron heating and acceleration by Lower-Hybrid Drift Waves (LHDW)[6], and turbulent magnetotail reconnection. New progress has been made using laser plasmas to study electron acceleration, and ion and electron acoustic waves during low-β anti-parallel reconnection[7]. The upgraded multiscale experiment FLARE (Facility for Laboratory Reconnection Experiments) is close to its commissioning phase, and project status and plans will be discussed.

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Posters

P-1 Yuka Doke Externally Driven Inflow Effect on Current Sheet Dynamics in TS-6 Tokamak Merging Experiment

P-2 Ryo Someya Profile Study of Reconnection Outflow in Tokamak Merging Experiment

P-3 Shinjiro Takeda Soft X-ray Imaging of High Energy Electrons in High-Guide Field Reconnection of TS-6 Merging Tokamak Experiment

P-4 Yunhan Cai Experimental observation of relaxation to Taylor state through ejection of an FRC

P-5 Zitao Hu Magnetohydrodynamic-guiding-center-particle-in-cell Method for Multiscale Plasma Kinetic Simulations

P-6 Yi-Min Huang Do chaotic field lines cause fast reconnection in coronal loops?

P-7 Jack Schroeder 2D Reconstruction of Magnetotail Electron Diffusion Region Measured by MMS

P-8 F. Widmer Mutual Interaction Between Turbulence and Magnetic Island in Toroidal Geometry

P-9 Kentaro Sakai Electron outflow and whistler waves associated with magnetic reconnection in laser-produced plasmas

P-10 King Fai Farley Law Mutual Interaction Between Turbulence and Magnetic Island in Toroidal Geometry

P-11 Shun Kamiya Development of 2D Thomson Scattering Measurement for Electron Heating Characteristics of Guide-field Reconnection in TS-6 Tokamak Merging Experiments

MR2023 Workshop on Magnetic Reconnection, 26-29 Jun, 2023, Ise-Shima, Mie, Japan

Externally Driven Inflow Effect on Current Sheet Dynamics in TS-6 Tokamak Merging Experiment

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We have found the current sheet structure, especially its blob structure, depends on the flow condition of externally driven plasma. As shown in Fig. 1, we used a pair of poloidal field (PF) coils to form two tokamak plasmas and to compress them together in TS-6, the tokamak plasma merging device. Setting three positions of PF coils, we varied the inflow speed/sheet compression to study its effect on the current sheet structure. We measured the detailed 2D structure of the current sheet: contours of poloidal flux, the current sheet density, and effective resistivity at X point using the newly developed printed-circuit board (PCB) type magnetic probe array whose spatial resolution is as high as 5 mm. Our 2D magnetic probe measurements reveal the current sheet structure is determined by the following three effects:
(a) anomalous resistivity when the current sheet is compressed to the order of ion gyro radius ρ_i,[1], [2]
(b) plasmoid generation and diffusion area expansion, [2]
(c) plasma blobs ejection. [3]

Under the low external inflow condition with coil separation length L=700mm, the sheet transforms into a large single plasmoid, and the reconnection speed increases, probably due to the expansion of the diffusion area. Under the medium inflow condition with L=600mm, the reconnection speed/electric field increases right after the current sheet splits into several blobs. And then the number of blobs decreases when the effective resistivity rises as the current sheet is compressed to ρ_i as shown in Fig. 2. Under the high inflow condition with L=427mm, the effective resistivity becomes larger in the early stage of the reconnection by compressing the sheet to ρ_i, increasing reconnection speed without forming a plasma blob. We also found the further increase in external inflow causes the current sheet to split and eject, accelerating the reconnection due to the effective mass ejection from the X-point area.

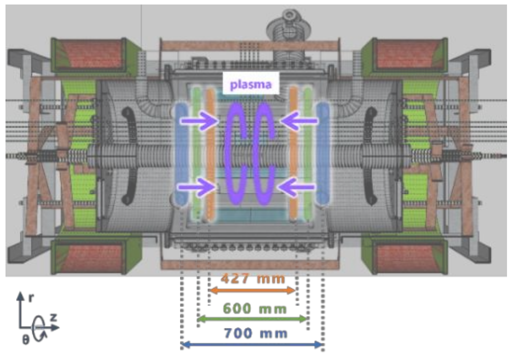

Fig.1 Vertical cross-section of TS-6 tokamak plasma merging device with three PF coil positions

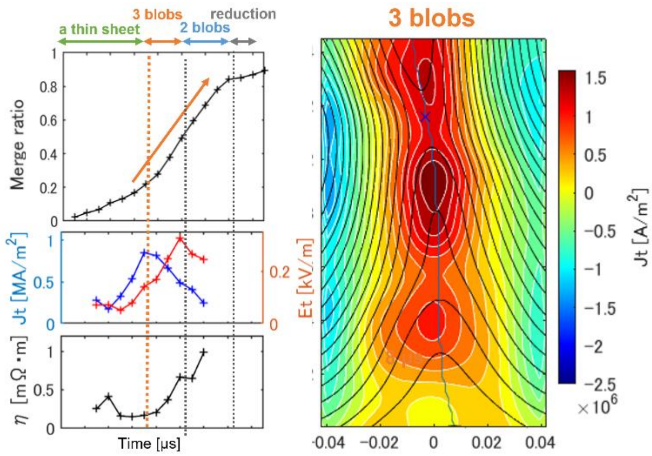

Fig.2 The time evolution of the merging ratio of two tokamak plasmas (upper left), toroidal current density (middle left), effective resistivity (lower left) at the X point, and 2D profiles of the poloidal flux (black line) and current density (color contour) (right) under medium inflow

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Profile Study of Reconnection Outflow in Tokamak Merging Experiment

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We had developed Doppler probe arrays[1] which can measure radial profile of ion velocity using two glass tubes and 2D high-resolution magnetic probe arrays[2] which can measure local 2D magnetic field in laboratory reconnection experiments. Using these diagnostics, we observed a bi-directional ion outflow on the midplane when we merge two tokamak plasmas in TS-6 tokamak merging experiment[3]. The maximum outflow speed is about 70% of Alfven velocity defined by the upstream poloidal field. The outflow velocity profile measurement indicates that rapid increase in magnetic field pressure at two downstream regions are related with the outflow velocity profile and also with the density profile.

Fig. 1(a) shows time evolution of radial profiles of ion velocity measured by the Doppler probe arrays and poloidal flux contours measured by magnetic probe arrays in the reconnection region of two merging tokamak plasmas. As time elapses, magnetic field lines approach the mid-plane and reconnect with a bi-directional ion outflow which is about 70% of Alfven velocity defined by the upstream poloidal field. Fig. 1(b) shows radial profiles of magnetic pressure at t=479 and 483μs. A significant increase in the magnetic field at two downstream regions is observed, suggesting formation of fast shock. From these results, the rapid increase in the magnetic field at two downstream regions corresponds to the ion outflow velocity profile as well as density profile, in agreement with the Rankine–Hugoniot relationship.

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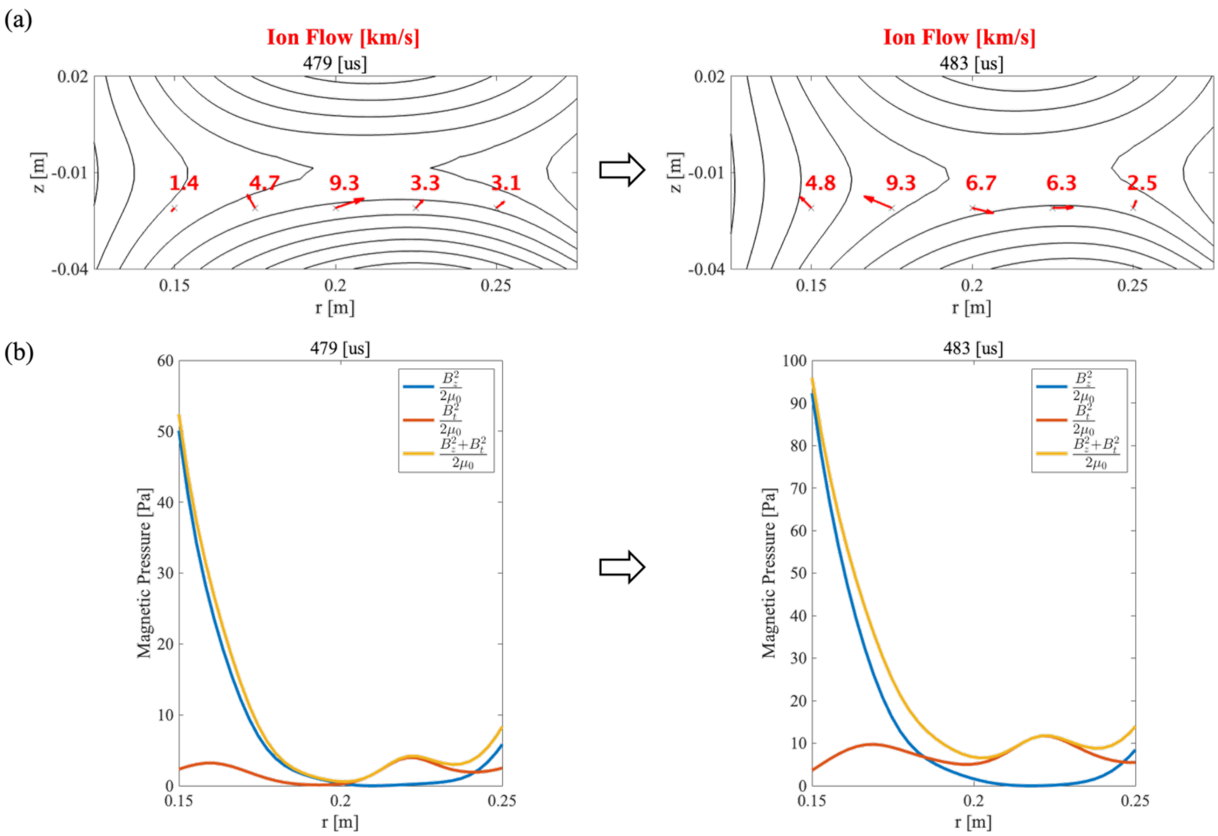

Figure 1 (a) Radial profiles of ion velocity (red allows) at t=479 and 483μs, which are measured by Doppler probe arrays and the poloidal flux contours by magnetic probe arrays, (b) the corresponding radial profiles of magnetic pressure measured by magnetic probe arrays.

Soft X-ray Imaging of High Energy Electrons in High-Guide Field Reconnection of TS-6 Merging Tokamak Experiment

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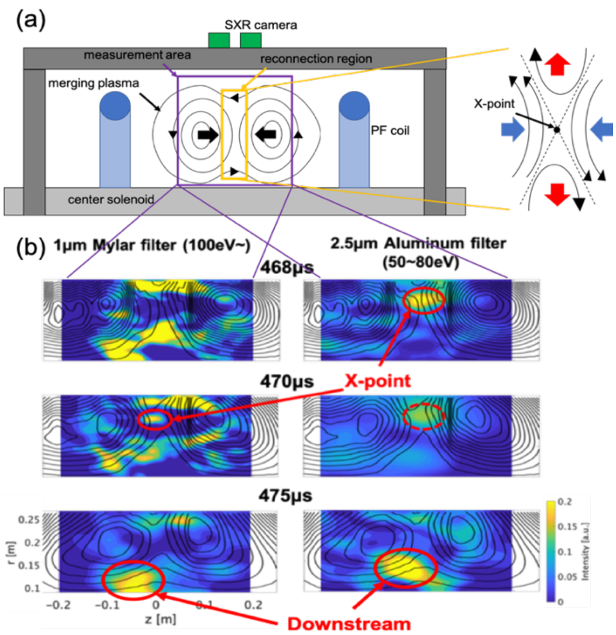
Under a high guide field, the reconnection electric field is observed to accelerate electrons downstream, forming quadra-pole type electrostatic potential profiles for the following ion acceleration and heating. In this key process, the production of energetic electrons has been detected both in PIC simulations [1], and in laboratory plasmas [2,3]. The spatial profile of energetic electrons is often measured by observing Bremsstrahlung emitted from them. In this study, we measured the high-guide field reconnection generated in two merging tokamaks using a stereo-view soft X-ray camera [4], which can simultaneously measure two 2D images of Bremsstrahlung emission through two different filters.

As shown in Figure (a), a small vacuum vessel (soft X-ray camera) with a built-in microchannel plate and filtered pinholes was installed on the TS-6 spherical merging tokamak device. Two types of filters were used in this experiment: 1 µm mylar film for high energy electrons and 2.5 µm aluminum film for low energy. Tikhonov-Philips regularization and the minimum GCV criterion [5] were used to reconstruct the 2D soft X-ray emission profile from the measured stereo images.

The time evolutions of the soft X-ray emission profiles were measured as shown in Figure (b). The left column shows the high-energy electron image observed through the Mylar filter, and the right column shows the low-energy image through the aluminum filter. The emission peak is localized near the X point at t = 470 µs in the high-energy image and at 468 µs in the low-energy image. The intensity of the high-energy emission peak increases with the guide magnetic field, while that of the low-energy one decreases. This fact suggests that the electron acceleration near the X-point increases with the length of the magnetic field lines around the X-point region without a poloidal magnetic field. Emission peaks in the downstream region were observed in both the high- and low-energy images, and their intensity increased with the reconnecting magnetic field strength. This emission possibly detected the electrons accelerated in the downstream region with negative electrostatic potential by an electric field parallel to the magnetic field. They may also include high-energy electrons by Fermi acceleration [6]. To specify the electron acceleration mechanism, we are increasing the number of X-ray images through different filters from two to six in an attempt to obtain the 2D Bremsstrahlung spectrum information.



(a)Schematic diagram of the measurement system and (b)R-Z contours of 2D soft X-ray emission (color) with poloidal flux surfaces (black lines) for 1-µm-thick Mylar and 2.5-µm-thick Aluminum

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Experimental observation of relaxation to Taylor state through ejection of an FRC

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We have observed that by introducing time delay in poloidal field (PF) reversal between the two flux-core coils, an initially formed spheromak-like plasma linked with a flux-core coil will split into a spheromak and an oblate field-reversed configuration (FRC). The result suggests a spheromak relaxation process that minimizes magnetic energy by ejecting plasmoid with null helicity.

Past studies showed that spheromak is well described as a Taylor state[1]. The idea originated from the Taylor relaxation theory, which proposes that during relaxation the plasmas conserve total helicity while minimize energy, leading to a force-free state: $\nabla \times \vec{B} = \lambda\vec{B}$, where λ is a constant. This naturally leads to a toroidal magnetic field profile peaked near the magnetic axis and zero at the edge. The Taylor relaxation theory successfully predicted the end state of the plasma, but there are still controversies regarding the process by which the plasma evolves during relaxation[2].

On the other hand, an FRC has a distinct equilibria with only poloidal magnetic field. Experimental observations showed that FRCs have robust global stability equivalent to the Taylor state[3].

In this experiment, by forming a spheromak-like plasma on one side of the TS-6 device using flux-core and delaying the poloidal field reversal of the PF coil on the opposite side, we observe a new relaxation process in which the spheromak-like plasma split into a spheromak and a null helicity plasmoid, or an FRC. One example is shown in Figure 1. The magnetic field profile is measured with a 2D array of B-dot probes on a poloidal cross section. By scanning different parameters, including injected toroidal field flux, timing of PF coil current reversal, equilibrium field strength, and type of gas, we attempt to identify the condition of such plasma splitting phenomenon. The result may suggest an alternative process to the Taylor relaxation.

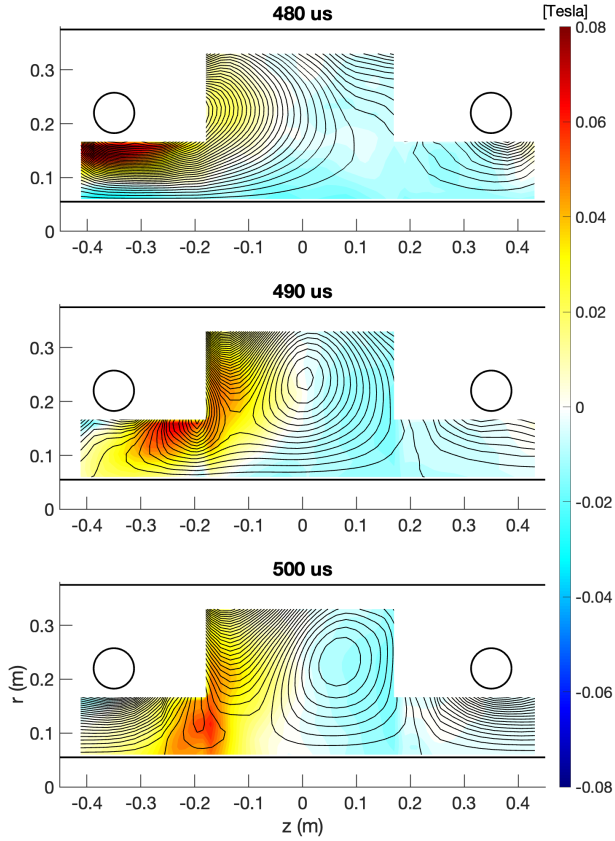

Figure 1: Poloidal flux (contour=0.2mWb) and toroidal magnetic field (color) profile of plasma relaxation to Taylor state through ejection of an FRC in the TS-6 device. Locations of two flux-core coils and vacuum chamber walls are shown.

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Magnetohydrodynamic-guiding-center-particle-in-cell Method for Multiscale Plasma Kinetic Simulations

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Magnetic reconnection has been recognized as a significant source for non-thermal particles, e.g., as indicated by the observations of solar flares. Particle-in-cell (PIC) simulations have revealed that the Fermi mechanism is likely the dominant process for particle acceleration, which generally does not involve gyro-resonance. The particle acceleration process is intrinsically multi-scale in nature, which is expected to continue from microscopic all the way into global scales. However, PIC simulations, which requires resolving the microscopic plasma scales and accommodating the speed of light, are severely limited in their ability to simulate the acceleration process towards global scale, especially in the non-relativistic regime.

We aim to develop numerical methods that enable the study of non-thermal particle acceleration process on the MHD scale, while capturing the essential physics. Here, we present the formulation, algorithm and numerical tests of the magnetohydrodynamic-particle-in-cell (MHD-PIC) method with particles treated under the guiding center approximation, which we term the MHD-gPIC method, and it is implemented in the Athena++ MHD code. The new MHD-gPIC model consists of thermal (cold) fluid and non-thermal electrons whose dynamics are integrated through guiding center equations including drift motion, with carefully evaluated source terms as particle backreaction. The code is validated with a series of tests, and it is expected to be primarily applicable to study particle acceleration in systems where gyro-resonance is considered insignificant. We also present preliminary studies of particle acceleration during non-relativistic magnetic reconnection.

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Do chaotic field lines cause fast reconnection in coronal loops?

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The footpoints of coronal loops are constantly shuffled by convection on the solar surface, entangling the magnetic field lines. In Parker's coronal heating model, the field line entanglement causes the formation of intense current sheets, which reconnect magnetic field lines and convert magnetic energy to plasma energy. We perform a series of reduced magnetohydrodynamic simulations to examine how coronal loops with entangled field lines evolve from a quasi-static state to a dynamic state of activity. The simulations show that current sheets intensify as the Lundquist number increases; the current sheets become unstable to the tearing instability when the Lundquist number is sufficiently high, despite the stabilizing effects of line-tying. Using a suite of diagnostics, including parallel voltage, squashing factors of the field line mapping, and field line velocity, we address whether the chaotic separation of neighboring field lines causes fast reconnection, as has been suggested in some recent studies. We find that chaotic field line separation dramatically enhances the field line velocity to extremely high values for field lines of high squashing factors. However, the field line velocity appears to be an unreliable measure of the reconnection rate. In comparison, the parallel voltage, which is directly related to the current density, is a better metric. We also discuss possible observational signatures of reconnection onset.[1]

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2D Reconstruction of Magnetotail Electron Diffusion Region Measured by MMS

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Models for collisionless magnetic reconnection in near-Earth space are distinctly characterized as 2D or 3D. In 2D kinetic models, the frozen-in law for the electron fluid is usually broken by laminar dynamics involving structures set by the electron orbit size, while in 3D models the width of the electron diffusion region is broadened by turbulent effects. We present an analysis of in situ spacecraft observations from the Earth's magnetotail of a fortuitous encounter with an active reconnection region, mapping the observations onto a 2D spatial domain. While the event likely was perturbed by low-frequency 3D dynamics, the structure of the electron diffusion region remains consistent with results from a 2D kinetic simulation. As such, the event represents a unique validation of 2D kinetic, and laminar reconnection models.

Mutual Interaction Between Turbulence and Magnetic Island in Toroidal Geometry

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The non-linear evolution of the tearing mode (TM) in collisionless limit is investigated using the gyrokinetic code ORB5 [1]. 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 kinetic theory [2]. 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, as micro-instabilities develops during the exponential phase due to finite temperature and density gradient, we show that the mutual interaction with the TM strongly depends on the initial type of micro-instability. An initial unstable tearing mode can be enhanced by micro-instability during exponential phase while an initial stable TM cannot be destabilized by micro-instabilities.

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Electron outflow and whistler waves associated with magnetic reconnection in laser-produced plasmas

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Magnetic reconnection converts magnetic energy into kinetic and thermal energies of plasma through a topological rearrangement of magnetic field lines. The space observations reveal that the onset of magnetic reconnection is triggered by electron-scale dynamics [1]. The connection between tiny electron-scale structures and magnetohydrodynamic (MHD) ones is an unsolved question. We have been experimentally investigating magnetic reconnection to understand its multiscale nature.

We performed experiments with Gekko XII HIPER laser facility at Institute of Laser Engineering, Osaka University. We observed global plasma structures with optical imaging [2] and local physical quantities with collective Thomson scattering (CTS) and a B-dot probe [3]. We directly measured the individual velocities of electrons and ions at the reconnection region with CTS [3]. While the ion velocity is constant in space, the electron velocity diverges which is consistent with outflow. Since the estimated electron and ion gyroradii are smaller and larger than the spatial scale of the outflow, respectively, only the electrons are magnetized in the magnetic reconnection. The electron outflow velocity close to the electron Alfvén speed is evidence of magnetic reconnection occurring at the electron scale. We observed the magnetic fields with a three-axis B-dot probe [3]. Using the wavelet analysis of the magnetic fields, we find the magnetic fluctuations in the frequency range between the electron and ion gyrofrequencies. Because the phase difference of two magnetic components perpendicular to the background magnetic field is ~90 degrees, the fluctuations can be whistler waves. Considering a simple propagation model of whistler waves, we find that the observed whistler waves originate from the reconnection region.

So far, we have observed electron-scale structures in laser-produced plasmas. To observe the connection between electron-scale and MHD structures, we are planning experiments in magnetically confined plasmas coupled with high-power lasers.

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Development of 2D Thomson Scattering Measurement for Electron Heating Characteristics of Guide-field Reconnection in TS-6 Tokamak Merging Experiments

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1. Introduction

We are developing a cost-effective two-dimensional (2D) Thomson scattering measurement system using multiple reflections and the time-of-flight effect of a single Nd:YAG laser pulse[1, 2] for 2D elucidation of electron heating/acceleration of magnetic reconnection. Its key ideas are to cover the 2D measurement area by multiple reflections of laser light and to save the number of polychromators using the time of flight of laser light.

2. The Experimental Setup

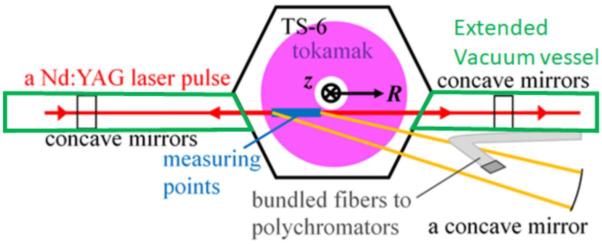
Figure 1 shows our experimental setup. Nd:YAG laser light reciprocates between ϕ25 concave mirrors and its backscattered light collected by a concave mirror is guided to polychromators through optical fibers. Scattered pulses from 2D (20 x 7) measurement points are detected by 1D (20) polychromators.

3. Progress

Figure 2 shows Raman scattering signals of laser light reciprocating between plane mirrors under 3kPa air for our test of time-of-flight measurement. We detected scattering signals from two laser paths as time evolved.

To increase the intensity of scattered signals, we are now developing an automatic alignment system where laser light is focused on measuring range by concave mirrors as shown in Fig. 1. Although time generates optical misalignment, misalignment of the first few round trips of laser light is relatively small. We plan to present measured electron temperatures and densities on the first or the first few return trips. As seven polychromators are converted for the 2D measurement, the presented measurement points will be 7 x 1-3.

(a)



(b)

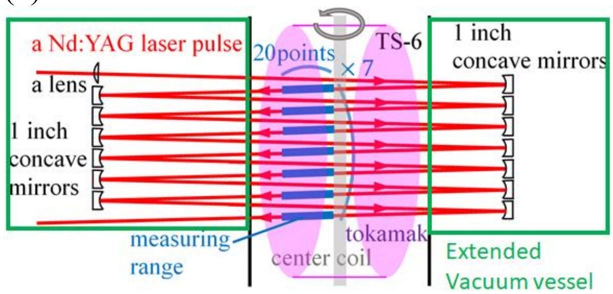


Fig. 1 (a) The vertical and (b) the horizontal cross section of the experimental setup.

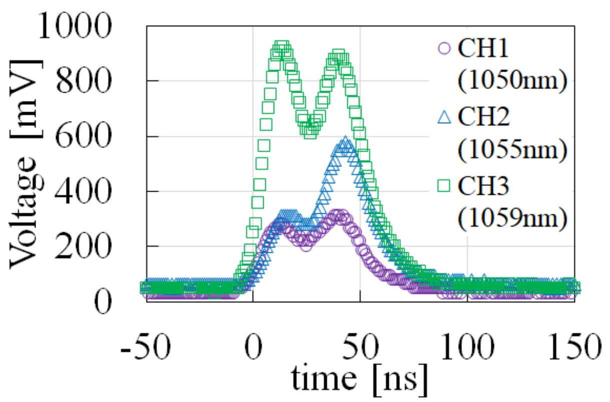


Fig. 2 Time-of-flight measurement of Raman scattering signals.

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