**11th International Workshop on the Interrelationship between Plasma Experiments in the Laboratory and in Space (IPELS)**

# Book of Abstracts

July 10-15, 2011
Whistler, Canada

# CONTENTS

As a 20-year old tradition, we aim to bring together active members of the laboratory, space and astrophysics plasma physics communities from around the world and we also aim to foster intellectual interaction and scientific collaboration addressing the processes responsible for various common plasma phenomena.

**Sponsors**

This meeting is supported by U.S. DoE , NSF and NASA, and also in part by the JSPS Core-to-Core Program on CMSO.

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# IPELS-2011 ORAL PROGRAM

| *July 10 Sunday* | *July 11 Monday* | *July 12 Tuesday* | *July 13 Wednesday* | *July 14 Thursday* | *July 15 Friday* |
|---|---|---|---|---|---|
| | 8:00 Registration | 8:00 Registration | | | |
| | 8:25 announcement | 8:25 announcement | 8:25 announcement | 8:25 announcement | 8:25 announcement |
| | **Shocks (Sydora)** | **Alfven waves (Dendy)** | **20 years (Koepke)** | **Dynamo/jet (Zweibel)** | **Reconnection (Egedal)** |
| | 8:30 Raymond | 8:30 Morales | 8:30 Yamada | 8:30 Pudritz | 8:30 Drake, J. |
| | 9:15 Kucharek | 9:15 Gurnett | 8:55 Bhattacharjee | 9:15 Kronberg | 9:15 Mozer |
| | 9:40 Hoshino | 9:40 Bingham | 9:20 Stone | 9:30 Li | 9:40 Dorfman |
| | 10:05 break | 10:05 break | 10:05 break | 9:55 break | 10:05 break |
| | **Shocks (Hoshino)** | **Alfven waves (Gekelman)** | **20 years (Yamada)** | **Dynamo/jet (Li)** | **Reconnection (Drake, J.)** |
| | 10:30 Kirk | 10:30 Speirs | 10:30 Koepke | 10:20 Zweibel | 10:25 Ono |
| | 10:55 Gargate | 10:55 Gillespie | 10:55 Forest | 11:05 Pinton | 10:50 Daughton |
| | 11:20 Niemann | 11:10 McConville | 11:20 Kletzing | 11:30 Rahbarnia | 11:15 Oieroset |
| | 11:35 Fruchtman | 11:25 Drake, D. | 11:45 Panel discussion | 11:45 Colgate | 11:40 Inomoto |
| | 11:50 Gunell | 11:40 Nordblad | | | 11:55 Opher |
| | | | 12:05 lunch-on your own | 12:00 lunch-provided | |
| | 12:05 lunch-provided | 11:55 lunch-on your own | | | 12:10 lunch-provided |
| | | | **excursion** | **Dusty/sheath (Lynch)** | |
| | **Turbulence (Stenzel)** | **Alfven waves (Horiuchi)** | | 1:30 Robertson | **Reconnection (Daughton)** |
| | 1:30 Goldstein | 1:30 Dendy | | 2:15 Marchand | 1:30 Shimizu |
| | 2:15 Thuecks | 1:55 Skiff | | 2:40 Thomas | 1:55 Egedal |
| | 2:30 Grulke | 2:20 Pilipenko | | 3:05 Stenzel | 2:20 Horiuchi |
| 3:00 Registration | 2:55 Carter | 2:35 Vincena | | | 2:45 Sydora |
| | | | | 3:30 break | |
| | 3:20 break | 2:50 break | | | 3:10 break |
| | | | | 3:50 **Poster session** | |
| | **Turbulence (Brown)** | **Kintner (Kletzing)** | | | **Reconnection (Phan)** |
| | 3:35 Gray | 3:20 Lynch | | | 3:30 Lukin |
| | 4:00 Spence | 3:45 Schuck | | | 3:45 Magee |
| | 4:15 Intrator | 4:10 Chen | | | 4:00 Fox |
| | | 4:35 Gekelman | | | 4:15 Vrublevkis |
| **Townhall (Ji)** | 4:30 **Poster session** | 5:00 Discussion | | | 4:30 Moser |
| 5:00 cash bar | | 5:20 end | | | 4:45 end |
| 5:30 food served | 5:30 end | | | 5:30 end | |
| 6:00 Koepke | | | | | |
| 6:20 Drake, J. | | | | **Working Dinner (Ji)** | |
| 6:40 Ono | | | | 6:30 cash bar | |
| 7:00 Bingham | | | | 7:00 food served | |
| 7:20 Discussion | | | | 7:30 presentations | |
| 8:00 end | | | | 8:10 Discussion | |
| | | | | 9:00 end | |

# IPELS-2011 POSTERS

| *Topic* | *Author* | *Title* |
|---|---|---|
| Shocks | Constantin, Carmen | Opportunities for collisionless laboratory astrophysics in magnetized plasma with a high-energy laser |
| Shocks | Grosskopf, M | Hydrodynamic simulation of laboratory astrophysics experiments generating collisionless shocks with intense lasers |
| Turbulence | Gunell, Herbert | Impulsive penetration observed at the magnetopause |
| Turbulence | DuBois, Ami | First observations of electromagnetic instabilities in the ALEXIS plasma column |
| Turbulence | Eadon, Ashley | Laboratory study of shear flow driven ion cyclotron electrostatic instabilities |
| Turbulence | Kuranz, Carolyn | Blast-wave-driven instability experiments relevant to supernova hydrodynamics |
| Turbulence | Roach, Austin | Observation of large-scale velocity fluctuations in the princeton MRI experiment |
| Turbulence | Cianciosa, Mark | Measurements and simulations of electric field modified flows in the compact torodial  hybrid stellarator |
| Alfven waves | Mansfeld, Dmitry | Pulsed Regimes of electron cycltron instabilities in a mirror confined plasma produced by ECR discharge |
| Alfven waves | Wang, Yuhou | Scattering of magnetic mirror-trapped fasst electrons by an alfven wave |
| Dynamo/jet | Kaplan, Elliot | Reducing global turbulent resistivity by eliminating large eddies in a spherical liquid-sodium experiment |
| Dynamo/jet | Weisberg, David | Plasma dynamo experiments |
| Dusty/sheath | Cho, Soon-Gook | Development of transport and removal experiment of dust (TReD) device for the large magnetic fusion devices |
| Dusty/sheath | Cianciosa, Mark | Development and performance tuning of the dusty plasma simulation code DEMON |
| Dusty/sheath | Collette, Andrew | Plasma physics at the colorado center for lunar dust and atmospheric studies (CCLDAS) |
| Dusty/sheath | Gayetsky, Lisa | Complex sheath structure within realistic low energy plasmas |
| Dusty/sheath | Siddiqui, Mohammed | A laboratory experiment to mimic the effect of auroral beams on spacecraft charging in the ionshpere |
| Dusty/sheath | Wang, Xu | Electric potential distributions in craters on airless bodies |
| Reconnection | Brookhart, Matthew | Stability of a line-tied screw pinch with standard and coaxial current injection |
| Reconnection | Craig, Darren | The Wheaton impulsive reconnection experiment |
| Reconnection | Lawrence, Eric | Hall reconnection in partially ionized plasmas in the magnetic reconnection experiment |
| Reconnection | Le, Ari | Electron Outflow Jets in Reconnection with a Guide Field |
| Reconnection | Montag, Peter | A design study of a new facility, MITPX, for experimental investigations of kinetic reconnection |
| Reconnection | Myers, Clayton | Laboratory Study of Equilibrium Force Balance and External Kink Stability in Solar-Relevant Magnetic Flux Ropes |
| Reconnection | Ng, Jonathan | Kinetic structure of electron diffusion region in antiparallel reconnection |
| Reconnection | Ohia, Obioma | First results from a two-fluid code, implementing the electron pressure tensor with new aniostropic equations of state |
| Reconnection | Bering, Edgar | ISS space plasma laboratory (ISPL): A boundry free laboratory to investigate reconnection phenomena in 3D |
| Other | Kempes, Philipp | Experimental Investigation of Arch-Shaped Magnetic Flux |
| Other | Moritaka, Toseo | Electromegnatic interaction between the solar wind and a kinetic scale artifical magnetosphere |
| Other | Nornberg, Mark | Momentum transport experiments in the Madison Symmetric Torus |
| Other | Tripathi, Deepak | Nonstationary ponderomotive self-focusing of a Gaussian laser pulse in a plasma |

**SUNDAY, JULY 10, 2011**

3:00pm Registration

**Townhall Meeting (H. Ji, PPPL)**

5:00pm Cash bar
5:30pm Food served
6:00pm **M. Koepke** (U.S. DoE): Prospectives from U.S. DOE
6:20pm **J. Drake** (U. Maryland): Updates on Heliophysics Decal Survey
6:40pm **Y. Ono** (U. Tokyo): Updates from Japan
7:00pm **R. Bingham** (RAL, U. Strathclyde): Updates from Europe
7:20pm Open discussion
8:00pm End

## MONDAY, JULY 11, 2011

| | |
|---|---|
| 8:00am | Registration |
| 8:25am | Announcements |

**Collisionless Shocks (R. Sydora, U. Alberta)**

| | |
|---|---|
| 8:30am | **J. Raymond** (Harvard): A tutorial on collisionless shock waves |
| 9:15am | **H. Kucharek** (U. New Hampshire): The physics of collisionless shocks: cluster observations and numerical simulations |
| 9:40am | **M. Hoshino** (U. Tokyo): Particle Acceleration in Turbulent Magnetic Reconnection and in Accretion Disks |
| 10:05am | Break |

**Collisionless Shocks (M. Hoshino, U. Tokyo)**

| | |
|---|---|
| 10:30am | **J. Kirk** (MPI for Nuclear Physics, Heidelberg): Relativistic shocks and particle acceleration |
| 10:55am | **L. Gargate** (Princeton): PIC simulations of laser-induced collisionless shocks in the laboratory |
| 11:20am | **C. Niemann** (UCLA): Laboratory simulations of collisionless shocks with high-power lasers |
| 11:35am | **A. Fruchtman** (Holon Inst. of Tech. - Israel): Double layers in space and laboratory plasmas |
| 11:50am | **H. Gunell** (Belgium Inst. for Space Aeronomy): Parallel electric fields in the laboratory, in space, and in Vlasov simulations |
| 12:05pm | Lunch - provided |

**Shear Flow and Turbulence (R. Stenzel, UCLA)**

| | |
|---|---|
| 1:30pm | **M. Goldstein** (NASA Goddard): The Solar Wind as a Laboratory for the Study of Magnetofluid Turbulence |
| 2:15pm | **D. Thuecks** (U. Wisconsin): The nature of broadband electrostatic and magnetic turbulence in the MST reversed-field pinch |
| 2:30pm | **O. Grulke** (MPI for Plasma Physics, Greifswald): Experimental investigation of turbulent structure propagation and related shear flow generation |
| 2:55pm | **T. Carter** (UCLA): Studies of flows and turbulence in the Large Plasma Device |
| 3:20pm | Break |

**Shear Flow and Turbulence (M. Brown, Swarthmore)**

| | |
|---|---|
| 3:35pm | **T. Gray** (Swarthmore): Turbulence and selective decay in a long cylindrical geometry in SSX |
| 4:00pm | **E. Spence** (PPPL): Recent results from the Princeton MRI experiment |
| 4:15pm | **T. Intrator** (LANL): Unsteady wandering magnetic field lines, turbulence and laboratory flux ropes |
| 4:30pm | **Poster session** |
| 5:30pm | Adjourn |

# A Tutorial on Collisionless Shock Waves

John C. Raymond
Harvard-Smithsonian Center for Astrophysics

Collisional shock waves are relatively straightforward, in that the collisions that mediate the shock bring the participating particles into thermal equilibrium. A simple set of jump conditions relates the pre- and post-shock values of the three fluid parameters and the magnetic field. In contrast, when the shock jump occurs over a thickness many orders of magnitude smaller than the collisional length scale, thermal equilibrium does not hold. A large fraction of the energy dissipated can go into a small number of energetic particles. Different particle species can be heated by very different amounts. Strong magnetic fields can be generated. We discuss the physics of collisionless shocks and the macroscopic plasma parameters in the shocked plasma.

# The Physics of Collissionless Shocks: Cluster Observations and Numerical Simulations

*Harald Kucharek*
Space Science Center and Department of Physics
University of New Hampshire
Durham, NH

The physics of collisionless shocks is an overarching scientific topic that connects magnetopsheric physics, heliospheric physics, and astrophysics. Collisionless shocks are considered prime candidates for accelerating ions in the entire plasma universe. Understanding physical processes occurring at these structures in detail is therefore of fundamental importance. While these same processes are occurring throughout the universe, the Earth's bow shock provides the only opportunity to study collisionless shock processes at a shock that is accessible, permanent, and relatively steady. Past and current magnetospheric missions such as ISEE, AMPTE, Cluster and Themis as well as future missions such as MMS have the Earth's bow shock as a primary science target. Cluster, the first four-spacecraft magnetospheric mission highlighted that a better understanding of the conspiracy between the ion, electron scales, and the ion composition are needed to solve many outstanding problems in collisionless shock physics. Among them are: ion reflection and the local shock structure, ion heating and thermalization, and ion acceleration.
However, in situ observations provide information of the plasma conditions which may be a result of one or many physical processes working together. Numerical simulations have been very successful in identifying some of these processes and allowed detailed insights to be gained. With increased computational power these simulations nowadays include several ion species, electron scales. The scope of the scientific topics Cluster addressed is wide ranging and so are the results of numerical simulations. Needless to mention that the results provided by both observations and simulations are of extreme importance to interpret data from heliospheric missions such as Voyager and IBEX. To keep this talk on a manageable level we will concentrate on processes which accelerate ions and the impact of the local shock structure on the acceleration efficiency.

## Particle Acceleration in Turbulent Magnetic Reconnection and in Accretion Disks

Masahiro Hoshino
University of Tokyo, JAPAN

It is now widely appreciated that magnetic reconnection is one of important particle acceleration processes. Recently the magnetic island coalescence and contraction during magnetic reconnection has been investigated in application to the termination shock in Heliosphere, the pulsar-wind nebula and accretion disks in astrophysical environments. We extend these reconnection studies to the regime having many magnetic reconnection sites randomly in space, and combine the magnetic reconnection with the original Fermi acceleration mechanism proposed by Fermi in 1949 as a stochastic means by which charged particles colliding with "magnetic clouds or mirrors". Namely, we study the original Fermi acceleration with magnetic reconnection instead of the magnetic clouds or mirrors. We discuss that the average increase in energy becomes the first-order of Va/c, where Va and c are the Alfven velocity and the speed of light, respectively. We also show that this turbulent acceleration of magnetic reconnection can happen during the magneto-rotational instabilities (MRI) in accretion disks by using two- and three-dimensional particle-in-cell simulations.

# Relativistic shocks and particle acceleration

J. G. Kirk

*Max-Planck-Institut für Kernphysik, Heidelberg, Germany*

A overview will be given of the theoretical and experimental (via PIC simulation) status of particle acceleration by the first-order Fermi mechanism at relativistic shocks. Because these objects are difficult to resolve observationally, their possible radiation signatures are particularly important. Recent work constraining these will be presented, and the possibility of extracting such signatures from PIC simulations will be discussed.

## PIC simulations of laser-induced collisionless shocks in the laboratory

L. Gargaté[1], A. Spitkovsky[1], H.-S. Park[2], N. L. Kugland[2], J. S. Ross[2], B. A. Remington[2], S. M. Pollaine[2], D. D. Ryutov[2], G. Gregori[3], Y. Sakawa[4], Y. Kuramitsu[4], H. Takabe[4], D. H. Froula[5], G. Fiksel[5], F. Miniati[6], M. Koenig[7], A. Ravasio[7], N. Woolsey[8], M. Grosskopf[9]

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[2] *Lawrence Livermore National Lab, 7000 East Ave, Livermore CA 94550*
[3] *University of Oxford, Oxford, UK;* [4] *Osaka University, Osaka, Japan*
[5] *Laboratory for Laser Energetics, Rochester, NY*
[6] *ETH Science and Technology University, Zurich, Switzerland*
[7] *Ecole Polytechnique, Paris, France*
[8] *University of York, Heslington, York, UK;* [9] *University of Michigan, Ann Arbor, MI*

Collisions of supersonic flows occur frequently in astrophysics, and the resulting shock waves are responsible for the properties of many astrophysical objects, such as supernova remnants and Gamma Ray Bursts. Understanding how these collisionless shocks behave and determining the relevant mechanisms responsible for magnetic field generation and particle acceleration is the ultimate goal of ongoing laboratory experiments at high energy density laser facilities. Here we present the results of Particle-In-Cell (PIC) simulations of laboratory collisionless shock experiments with the aim of predicting and explaining the signatures of shock formation in the diagnostics.

We perform PIC simulations of counter-streaming quasi-neutral supersonic plasma beams. We consider both an unmagnetized configuration, and a setup with a perpendicular externally-generated magnetic field. In the unmagnetized case, the plasma flows are unstable to the electromagnetic filamentation (Weibel) instability that generates magnetic fields that deflect and thermalize particles, forming a collisionless shock. When an externally generated magnetic field is used, the the Weibel instability is suppressed, and the shock is formed due to particle reection from the compressed magnetic field.

We apply these simulations to the shock experiment at the Omega Laser, in which two solid target foils are ablated, producing counter-propagating plasma flows with densities of $10^{18}\,\mathrm{cm}^{-3}$, $1000\,\mathrm{km/s}$ velocities, and typical sonic Mach numbers of $M_{ac} \sim 10$. Using the PIC code TRISTAN-MP we simulated this experimental setup and modeled its diagnostics. We found that, for an unmagnetized configuration, collisionless shocks form over a typical distance of $\sim 300\,\mathrm{c}/\omega_{\mathrm{pi}}$ (ion skin depths). In the magnetized setup with external field of $B_{ext} = 20\,\mathrm{kG}$, shock formation happens over a much smaller distance of $\sim 20\,\mathrm{c}/\omega_{\mathrm{pi}}$. The maximum self-generated magnetic field amplitudes observed are in the $\sim 100\,\mathrm{kG}$ range, and depend on the specific plasma parameters used.

These simulation results are used to interpret the current experimental data from Omega, and to design a class of next-generation collisionless shock experiments using short-pulse lasers.

## Laboratory simulations of collisionless shocks with high-power lasers

C. Niemann, C. Constantin, E. Everson, D. Schaeffer, A. Bondarenko, L. Morton, W. Gekelman
*University of California Los Angeles, Department of Physics and Astronomy, Los Angeles, CA 90095*

D. Winske, D. Montgomery, K. Flippo, S. Gaillard, R. Johnson, T. Shimada, A. Letzing
*Los Alamos National Laboratory*

We will present an overview of an ongoing experimental program on laser-driven collisionless shocks in large preformed magnetized plasmas. Experiments were performed with a new high-energy laser at UCLA's Large Plasma Device, as well as in a large Helmholtz coil (50 cm, kG) at the LANL Trident laser facility. In these experiments an exploding plasma drives a diamagnetic cavity at super-Alfvénic speed ($M_A$=1-8) over several collisionless skin depths across the external magnetic field. The evolution of the magnetic field across the bubble was measured with magnetic pickup coils and proton deflectometry, while plasma parameters were measured with Thomson scattering.

This work was supported by the DOE/NSF partnership in basic plasma science, UCLA's BaPSF, and the LANL Trident laser facility.

# Double layers in space and laboratory plasmas

A. Fruchtman

*H.I.T. - Holon Institute of Technology, 52 Golomb St., Holon 58102, Israel*

Double layers are excited in space and laboratory plasmas. I will discuss two kinds of double layers: double layers located at a plasma bulk that generate particle beams and double layers formed at the boundary between plasma and electron-emitting surface.

Energetic particle beams in space have been often proposed to result from double layers. Double layers, discovered several years ago in helicon sources, also generate energetic ion beams [1]. This mechanism has been recently proposed to be used for space propulsion [2]. I pointed out, however, that the double layer itself does not impart net momentum to the plasma [3, 4]. Nevertheless, the combination of the acceleration by the double layer with an imposed magnetic field pressure could result in imparting net momentum and in thrust generation. The effect of such a combination in space plasma configurations as well its implication for plasmas thrusters will be discussed.

Double layers are also formed at the boundary between plasma and electron-emitting surface at the space-charge limit. The electric field at the surface vanishes due to the space charge of the emitted electrons. Secondary electrons are often emitted from dust grains in space [5]. This electron emission significantly affects the evolution of the dust grains. We have recently developed a theory for a cylindrical emissive probe [6]. We will present an equivalent theory for spherical dust grains at the limit of space-charge saturation. The double layer at the boundary will be analyzed; the calculated particle fluxes and the potential difference between the plasma and the dust surface will be presented. Analytical results for a small Debye length and numerical results for a Debye length comparable to the grain radius will be given.

1. C. Charles and R. Boswell, Appl. Phys. Lett. **82**, 1356 (2003).
2. K. Takahashi *et al*., Appl. Phys. Lett. **98**, 141503 (2011).
3. A. Fruchtman, Phys. Rev. Lett. **96**, 065002 (2006).
4. A. Fruchtman, IPELS 2007 Abstract booklet, p. 19.
5. M. M. Abbas *et al*., The Astrophysical Journal **718**, 795 (2010).
6. A. Fruchtman, D. Zoler, and G. Makrinich, submitted for publication.

# Parallel electric fields in the laboratory, in space, and in Vlasov simulations

Herbert Gunell, Johan De Keyser, and Emmanuel Gamby

*Belgian Institute for Space Aeronomy*

*Avenue Circulaire 3, B-1180 Brussels, Belgium*

Electrostatic fields that are parallel to the earth's magnetic field are known to exist in the auroral zone and contribute to the acceleration of auroral electrons. Transverse electric fields at high altitude result in parallel electric fields as a consequence of the closure of the field-aligned currents through the conducting ionosphere (*L. R. Lyons*, JGR, vol. 85, 17–24, 1980). These parallel electric fields can be supported by the magnetic mirror field (*Alfvén and Fälthammar*, Cosmical Electrodynamics, 2nd ed., 1963).

Stationary kinetic models have been used to study the current–voltage characteristics of the auroral current circuit (*Knight*, Planet. and Space Sci., vol. 21, 741–750, 1973). Fluid and hybrid simulations have been used to model parallel electric fields and Alfvén waves, and to study the relationship between them (*e.g., Vedin and Rönnmark*, JGR, vol. 111, 12201, 2006). *Ergun, et al.* (GRL, vol. 27, 4053–4056, 2000) found stationary Vlasov solutions over regions extending several Earth radii, and *Main, et al.* (PRL, vol. 97, 185001, 2006) performed Vlasov simulations of the auroral acceleration region. Observations have shown that field-aligned potential drops often are concentrated in electric double layers (*e.g. Ergun, et al.*, Phys. Plasmas, vol. 9, 3685–3694, 2002).

We present results from Vlasov simulations using a model that is one-dimensional in configuration space and two-dimensional in velocity space. The model is verified by comparison with a double layer experiment in the laboratory (*Gunell, et al.*, J. Phys. D: Appl. Phys., vol. 29, 643–654, 1996), and it is applied to the auroral field lines.

We model a flux tube from the equator to the ionosphere. By introducing a relative dielectric constant $\epsilon_r$ such that $\epsilon = \epsilon_0 \epsilon_r$ we can run the simulation on a coarser spatial grid and with a longer time step, because $\lambda_D \sim \sqrt{\epsilon_r}$ and $\omega_p \sim 1/\sqrt{\epsilon_r}$ (*Rönnmark and Hamrin*, JGR, vol. 105, 25333–25344, 2000) We start with a large $\epsilon_r$-value, filling the simulation region with plasma from the ends. We then conduct a series of simulation runs, successively decreasing $\epsilon_r$ toward realistic values.

About half of the potential drop is found in a thin double layer and the remaining part in an extended region above it. While the double layer itself remains stationary, there are oscillations in the longer low-field region. The altitude of the double layer decreases with increasing field-aligned potential drop. The current-voltage characteristic agrees approximately with the Knight relation.

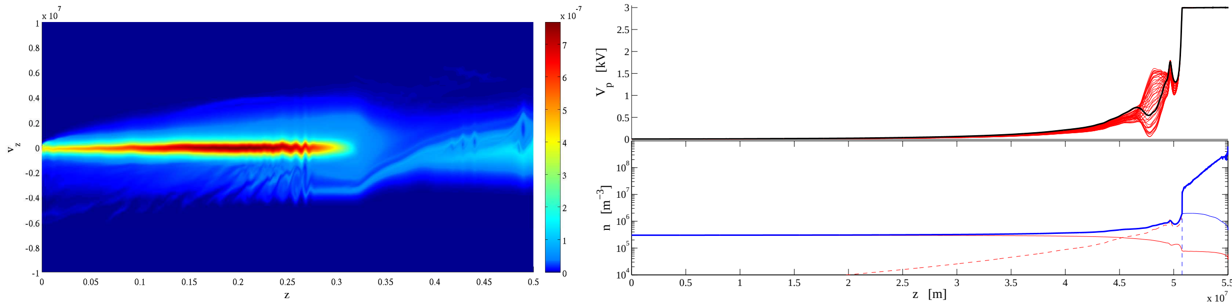


Figure 1: Left: Electron velocity distribution function in a simulation of a double layer experiment. Right: Plasma potential and densities in a simulation of an auroral fluxtube.

# The Solar Wind as a Laboratory for the Study of Magnetofluid Turbulence

Melvyn Goldstein
*NASA Goddard Space Flight Center*

The solar wind is the Sun's exosphere. As the solar atmosphere expands into interplanetary space, it is accelerated and heated. Data from spacecraft located throughout the heliosphere have revealed that this exosphere has velocities of several hundred kilometers/sec, densities at Earth orbit of about 5 particles/$cm^3$, and an entrained magnetic field that at Earth orbit that is about 5 $10^{-5}$ Gauss. A fascinating feature of this magnetized plasma, which is a gas containing both charged particles and magnetic field, is that the magnetic field fluctuates in a way that is highly reminiscent of "Alfvén waves", first defined by Hannes Alfvén in 1942. Such waves have the defining property that the fluctuating magnetic fields are aligned with fluctuations in the velocity of the plasma and that, when properly normalized, the fluctuations have equal magnitudes. The observed alignment is not perfect and the resulting mismatch leads to a variety of complex interactions. In many respects, the flow patterns appear to be an example of fully developed magnetofluid turbulence. Recently, the dissipation range of this turbulence has been revealed by Search Coil magnetometer data from the four Cluster spacecraft. This tutorial will describe some of the properties of the large-scale and small-scale turbulence.

**The nature of broadband electrostatic and magnetic turbulence in the MST reversed-field pinch**

D.J. Thuecks[1,3], A.F. Almagri[1,3], Y. Ren[2,3], J.S. Sarff[1,3], P.W. Terry[1,3]
[1]University of Wisconsin-Madison
[2]Princeton Plasma Physics Laboratory
[3]Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas

Turbulence plays an important role in the dynamics of reversed-field pinch plasmas. In the Madison Symmetric Torus (MST), low-frequency fluctuations (10-30 kHz) that are associated with tearing modes are large ($\tilde{B} \sim .02B_0$) and dominate the fluctuation power spectrum. High-frequency turbulence is also present and may play a significant role in particle and energy transport. Additionally, turbulence in MST is thought to contribute to non-collisional ion heating through the interplay between a fluctuating radial electric field and a stochastic magnetic field or by cyclotron resonant absorption of fluctuation power.

Recent magnetic fluctuation measurements suggest the broadband magnetic turbulence arises via a nonlinear cascade from tearing mode scales to smaller scales. These studies have shown that magnetic turbulence is highly anisotropic in MST, with power being spread broadly in the direction perpendicular to the background magnetic field. Additionally, scaling studies have shown evidence of both an inertial range (characterized by a power-law scaling of the power spectrum) and a dissipation range (characterized by a power spectrum scaling of the form $P(k) \sim k^{-\alpha}\exp(-b(k/k_\eta)^\beta))$. These two ranges represent a constant energy transfer rate from large to small scales and energy dissipation by some external process at small scales, respectively. Dissipation range scaling results imply that dissipation is stronger than predicted assuming the Spitzer resistivity. This stronger level of dissipation may be connected to kinetic effects or non-collisional ion heating.

The present work shows results from high-frequency electrostatic fluctuation measurements made with an insertable multi-tip probe in the edge plasma region. This probe is able to measure density, electron temperature, and plasma potential/electric field at multiple locations simultaneously. This allows the wavenumber spectra and turbulence anisotropy to be measured for these quantities. Wavenumber spectra for electrostatic fluctuations have clear inertial range behavior, but evidence of a dissipation range has not yet been found. These fluctuations also do not appear to show the same level of anisotropy as is present for magnetic fluctuations.

Despite the previous work conducted on MST, the nature of the constituent fluctuations is poorly understood. Correlation and phase measurements between electrostatic fluctuations, as well as between electrostatic and magnetic fluctuations, may provide clues to the nature of the turbulence present in this experiment. Measurements of electric and magnetic field fluctuations can also be used to examine the partitioning of kinetic and magnetic energy in the turbulence. Preliminary work has shown that magnetic energy is dominant at large scales, but that the kinetic energy in the flow due to $\tilde{\mathbf{E}} \times \mathbf{B}_0$ fluctuations may overtake magnetic energy somewhat at small scales. This work is ongoing, and updated results will be discussed.

This work is supported by NSF and DOE.

# Experimental investigation of turbulent structure propagation and related shear flow generation

O. Grulke, T. Windisch and T. Klinger

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The most important property of turbulent plasmas is the associated transport of particles and heat, which contributes to the distribution of matter in astrophysical systems eventually supporting star formation and represents the major challenge in the context of magnetic plasma confinement. The paradigm of turbulent transport is the advection in plasma potential eddies. However, especially the meso- and large scale turbulent eddies have been observed to propagate coherently across the magnetic field. Experimental investigations using turbulence imaging diagnostics reveal that in curved magnetic field geometry turbulent plasma density structures form in the strong poloidal velocity shear region, e.g. at the last closed magnetic flux surface in tokamaks, and propagate due to the self-consistent dipolar potential and the associated $E \times B$ drift. Numerical simulations indicate that the dipolar potential is mainly a result of the curvature and $\nabla B$ drift. Experimental investigations in homogeneous magnetic field geometry, in which this charge separation mechanism is absent, show, however, very similar results. In the linear cylindrical helicon device VINETA turbulent structures are observed to peel off the linear instability region and propagate into the plasma edge due to the self-consistent turbulent electric field. Normalized radial velocities are on the order of 10% of the local ion sound speed, which is similar to the tokamak case. The experimental results of turbulent structure propagation is supported by fully nonlinear global fluid simulations, which agree qualitatively very well with the experimental results. The peel-off is associated with a turbulent driven shear flow in experiment and simulations, which is quantified by the azimuthally averaged Reynolds stress. The detailed processes leading to the self-consistent structure's electric field are still under debate. The role of parallel currents and azimuthal structure propagation in the generation of phase-shifted potential eddies is discussed.

**Studies of flows and turbulence in the Large Plasma Device**

T.A. Carter[1], D. Schaffner[1], B. Friedman[1], S. Vincena[1], G. Rossi[2], D. Guice[1], M.V. Umansky[3], and J.E. Maggs[1]

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The Large Plasma Device (LAPD) at UCLA is a 17m long, 0.6m diameter linear magnetized plasma. Broadband, low-frequency ($\omega \ll \Omega_{c,i}$) turbulence is observed in the edge of the LAPD plasma. Free energy sources in the LAPD edge plasma include pressure gradients and azimuthal flow and flow shear. The charactersitics of the measured edge turbulence are consistent with instabilities associated with these energy sources: drift (and drift-Alfvén) waves and the rotational interchange and Kelvin-Helmholtz instabilities[1]. Azimuthal flows in the LAPD edge arise spontaneously and also can be driven through biasing either the vacuum chamber wall or limiter plates (driving radial currents that apply torque to the plasma)[2]. Turbulent cross-field particle transport can be suppressed ("H-mode" in LAPD) with bias-driven cross-field flows in LAPD[3]. Recent studies using new biasable limiters have allowed for a continuous variation in the edge flow and flow shear. Experiments using this new capability have revealed a threshold in driven flow/flow shear for the confinement transition. Additionally, evidence for spontaneous confinement transitions at low magnetic field have been found. Modeling of LAPD turbulence has been performed using the 3D Braginskii fluid turbulence code BOUT (and BOUT++), which has been modified for and verified in cylindrical geometry for application to LAPD[4]. Nonlinear simulations yield good qualitative and semi-quantitative agreement with LAPD data[5].

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[3]T. A. Carter and J. E. Maggs, Phys. Plasmas 16, 012304 (2009)
[4]P. Popovich, M. V. Umansky, T. A. Carter, and B. Friedman Phys. Plasmas 17, 102107 (2010)
[5]P. Popovich, M. V. Umansky, T. A. Carter, and B. Friedman, Phys. Plasmas 17, 122312 (2010)

**Turbulence and selective decay in a long cylindrical geometry in SSX*** T. Gray, M. Brown, and D. Dandurand *Swarthmore College* - A helical, minimum-energy relaxed plasma state has been observed in a long cylindrical volume. The cylinder has dimensions $L = 1$ m and $R = 0.08$ m ($R/L = 13$). The cylinder is long enough so that the predicted minimum energy state is a close approximation to the infinite cylinder solution. The plasma is injected at $v \geq 50$ km/s by a coaxial magnetized plasma gun located at one end of the cylindrical volume. Typical plasma parameters are $T_i = 25$ eV, $n_e \leq 10^{21}$ m$^{-3}$, and $B = 0.25$ T. The relaxed state is rapidly attained in 1–2 axial Alfvén times after initiation of the plasma. Magnetic data is favorably compared with an analytical model. Magnetic data exhibits broadband fluctuations of the measured axial modes during the formation period. The broadband activity rapidly decays as the energy condenses into the lowest energy mode, which is in agreement to the minimum energy eigenstate of $\nabla \times \vec{B} = \lambda \vec{B}$. Fluctuation results from a new high speed, high resolution magnetic radial probe will also be presented. The new probe has a higher spatial resolution (4.5 mm $\leq \rho_i$) and higher temporal resolution ($f = 65$ MHz $\gg f_{ci}$) than previous probes used in prior SSX studies. The data acquisition digitizes at 14 bits, providing for a dynamic range of 4 decades. Merging studies with plasma plumes injected from both ends of the cylinder are planned.

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# Recent results from the Princeton MRI experiment

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The Princeton MRI experiment is used to study the magnetorotational instability (MRI), which is believed to be responsible for turbulent transport of angular momentum in accretion disks. The MRI can be generated when an electrically conducting fluid has a radially-decreasing azimuthal velocity profile and is exposed to a vertical magnetic field. For this experiment, such a velocity field is generated in a flow of the gallium eutectic GaInSn using a Taylor-Couette apparatus with independently-rotating split endcaps. When an axial magnetic field is applied to the flowing gallium, the hydrodynamic azimuthal velocity profile, as measured using an ultrasonic velocimetry system, is modified, but the ideal Couette profile can be recovered by modifying the endcap speeds. Results from a global-mode MRI instability analysis, and 3D numerical simulations, are presented, indicating our operational proximity to instability. The latest results from the search for the MRI will be presented.

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# Unsteady wandering magnetic field lines, turbulence and laboratory flux ropes

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A. Lazarian, University of Wisconsin - Madison, Dept Astronomy

Abstract

We describe earth bound laboratory experiment investigations of patchy, unsteady, bursty, patchy magnetic field structures that are unifying features of magnetic reconnection and turbulence in helio, space and astro physics. The ideal zero radius magnetic field line does not exist. However macroscopic field lines occupy cross sectional areas, and fill up three dimensional (3D) volumes as flux tubes, which are physically meaningful objects with their own dynamics. This universal object in the plasma universe contains mass and obeys Newtonian mechanics, magneto-hydro-dynamic (MHD) equations of motion, and can experience Kepler like orbits with a central attraction force. Flux rope geometry can be ubiquitous in laminar reconnection sheet geometries that are themselves unstable to formation of secondary "islands" that in 3D are really flux ropes. Flux ropes are ubiquitous structures on the sun and the rest of the heliosphere.

Understanding the dynamics of flux ropes and their mutual interactions offers the key to many important astrophysical phenomena, including magnetic reconnection and turbulence. We describe laboratory investigations on RSX, where 3D interaction of flux ropes can be studied in great detail. A graceful transition from 2D dynamics with a strong guide magnetic field is possible as the guide field is successively reduced to allow increasingly 3D topologies. We use experimental probes inside the the flux ropes to measure the magnetic and electric fields, current density, density, temperatures, pressure, and electrostatic and vector plasma potentials. Macroscopic magnetic field lines, unsteady wandering characteristics, and dynamic objects with structure down to the dissipation scale length can be traced from data sets in a 3D volume. Computational approaches are finally able to tackle simple 3D systems and we sketch some intriguing simulation results that are consistent with 3D extensions of typical 2D cartoons for magnetic reconnection and turbulence.
*Supported by NASA grant NNH10A0441 & Center for Magnetic Self Organization NSF-OFES

## TUESDAY, JULY 12, 2011

8:00am Registration
8:25am Announcements

**Alfven Resonance and Wave-Particle Interaction (R. Dendy, Culham)**

8:30am **G. Morales**(UCLA): Properties of Wave-Particle Interactions Worth Knowing
9:15am **D. Gurnett** (U. Iowa): Standing Alfven Waves, Electron Beams, Aurora, and Whistler Mode Emissions Excited by Saturn's Moon Enceladus
9:40am **R. Bingham** (RAL, U. Strathclyde): Micro-physics of Space and Astrophysical Processes Investigated in Laboratory Experiments

10:05am Break

**Alfven Resonance and Wave-Particle Interaction (W. Gekelman, UCLA)**

10:30am **D. Speirs** (U. Strathclyde): Numerical and laboratory simulation of astrophysical cyclotron emission processes
10:55am **K. Gillespie** (U. Strathclyde): Experimental and numerical simulation of auroral radio emission processes
11:10am **S. McConville** (U. Strathclyde): Impact of a background plasma on cyclotron instabilities relevant to the auroral magnetosphere
11:25am **D. Drake** (U. Iowa): Design and use of an Elsasser probe for analysis of Alfven wave fields according to wave direction
11:40am **E. Nordblad** (Swedish Inst. of Space Physics): Geometrical optics results for spin and orbital Hall effects of a nonparaxial beam in a grad-index medium

11:55am Lunch – on your own

**Alfven Resonance and Wave-Particle Interaction (R. Horiuchi, NIFS, Japan)**

1:30pm **R. Dendy** (Culham): Lower hybrid drift instability and collective coupling of energy from ions to electrons
1:55pm **F. Skiff** (U. Iowa): Using the whistler mode to observe electron dynamics in a laboratory plasma
2:20pm **V. Pilipenko** (Space Res. Inst., Moscow): MHD Wave Propagation and Conversion: Lessons from the Terestrial Magnetosphere
2:35pm **S. Vincena** (UCLA): Laboratory realization of an ion-ion hybrid Alfven wave resonator

2:50pm Break

**Paul Kintner Retrospectives (C. Kletzing, U. Iowa)**

3:20pm **K. Lynch** (Dartmouth): Paul M Kintner Jr: Plasma Experiments in the Laboratory of the Ionosphere
3:45pm **P. Schuck** (NASA Goddard): Lower Hybrid Solitary Structures
4:10pm **L.-J. Chen** (U. New Hampshire): Electrostatic solitary waves in space and laboratory
4:35pm **W. Gekelman** (UCLA): The Interaction of Whistler and Lower Hybrid Waves with density striations
5:00pm Discussion
5:20pm Adjourn

# Properties of Wave-Particle Interactions Worth Knowing

**G. J. Morales**
Physics and Astronomy Department, University of California
Los Angeles, Los Angeles, CA 90095

A central feature in the behavior of collisionless plasmas is the interaction between waves and particles. In general, the nature of this interaction can be catalogued into an adiabatic, inertial, and resonant response, depending on the ratio of the effective phase velocity of the wave to the particle speed. For a distribution of particle velocities, the collective wave-particle response, for small signals, is succinctly contained in the plasma dispersion function and its generalizations. From this linear description it is found that the contribution from those particles in resonance with a wave can result in the damping or growth of the wave, i.e., Landau damping/amplification that reflects the conservation of momentum in the system. These processes are of great importance in laboratory studies as they can lead to efficient sources of coherent radiation (e.g., TWTs, magnetrons, gyrotrons) with numerous practical applications, and to methods (e.g., current-drive, plasma heating) that are necessary to achieve fusion conditions. In the natural plasmas encountered in near-earth and astrophysical environments, the strong interplay between wave generation and damping via wave-particle interactions, in fact, determines what these complex, non-equilibrium systems really are (e.g., auroral ionosphere, solar corona). Currently, much attention is devoted to wave –particle interactions that could manipulate the population of energetic electrons and ions that are mirror trapped in the geomagnetic field. In non-equilibrium problems of current interest to laboratory and space researchers, the simple picture of wave-particle interactions, captured by the plasma dispersion function, is enriched by considerations of nonlinearity (e.g., particle trapping, stochasticity), strong amplitude gradients (e.g., transit-time acceleration, phase-independent acceleration), and broadband spectra (e.g., quasilinear theory, sidebands), among other factors. This talk presents an overview of established concepts related to these topics, and is complemented by an exposure to some important aspects that are not widely appreciated.

**Standing Alfvén Waves, Electron Beams, Aurora, and Whistler Mode Emissions Excited by Saturn's Moon Enceladus**

D. A. Gurnett
*Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242*

Recent observations from the Cassini spacecraft, which is in orbit around Saturn, have shown that the interaction of Saturn's rapidly rotating magnetosphere with its small moon Enceladus excites a standing Alfvén wave (also called an Alfvén wing). The Alfvén wave propagates downward along the magnetic field line to Saturn's atmosphere where it produces a spot of auroral light. During two passes directly through the Alfvén wave, observations have been made of low-energy magnetic field-aligned electron beams, apparently accelerated by parallel electric fields associated with the Alfvén wave. It is these electron beams that are the likely cause of the auroral light. The electron beams also generate whistler-mode emissions similar to a type of radio emission called auroral hiss that is commonly observed in Earth's auroral zones. Of all of Saturn's moons, Enceladus is unique in that it is emitting a geyser-like plume of water vapor from vents in the southern polar region of the moon. The presence of water vapor around the moon appears to be the crucial factor responsible for Enceladus' strong electrodynamic interaction with the magnetospheric plasma. No other moon at Saturn has a comparable interaction. As such it provides a unique laboratory for studying the interaction of a rapidly streaming plasma with a gaseous astrophysical object.

# Micro-physics of Space and Astrophysical Processes Investigated in Laboratory Experiments

*Robert Bingham*
*STFC Rutherford Appleton Laboratory*

This talk will concentrate on several topics that have been actively investigated to reveal the micro-physical processes involved in space and astrophysical phenomena. For example cyclotron maser emission is well known as an efficient coherent radiation mechanism in the aurora and young stellar atmospheres with strong magnetic fields. Laboratory experiments (see Speirs et al this meeting) have revealed that the radiation can be generated by electron horseshoe distributions in velocity space. The conditions under which this particular distribution can generate maser radiation will be outlined. Mini-magnetosphere experiments demonstrate the role finite Larmor radius effects have in controlling the dynamics of magnetised plasma flows interacting with magnetic field structures or plasma bubbles. Here the interaction is mainly through electric fields produced by space charge created by magnetic field gradients. Other experiments presented involve high power lasers interacting with solid targets to study colliding plasmas and magnetic field generation in expanding plasmas.

# Numerical and laboratory simulation of astrophysical cyclotron emission processes

D. C. Speirs[1], S. L. McConville[1], K. Ronald[1], K. M. Gillespie[1], A. D. R. Phelps[1], A. W. Cross[1], R. Bingham[1,2], B. J. Kellett[2], R. A. Cairns[3] and I. Vorgul[3]

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There are a variety of astrophysical radio emissions in association with non-uniform magnetic fields that have been the subject of particular interest and debate over the last thirty years [1]. Numerous such sources, including planetary and stellar auroral radio emission are spectrally well defined with a high degree of extraordinary (X-mode) polarisation. In particular, for the terrestrial auroral case it is now widely accepted that such emissions are generated by an electron cyclotron-maser instability driven by a horseshoe shaped electron velocity distribution [2,3]. Such distributions are formed when particles are accelerated into the increasing magnetic field of planetary / stellar auroral magnetospheres. Conservation of magnetic moment results in the conversion of axial momentum into rotational momentum forming an electron velocity distribution having a large spread in pitch factor. Theory has shown that such distributions are unstable to cyclotron emission in the X-mode [4].

Experiments have been conducted at the University of Strathclyde investigating the electrodynamics of an electron beam subject to significant magnetic compression within a bounding waveguide structure [5]. More recently, a background plasma of variable density has been introduced to the interaction region of the laboratory experiment through use of a Penning discharge geometry [6]. Corroboratory simulations have been conducted using the PiC code VORPAL to investigate the cyclotron emission process in the presence of a background plasma of variable density. The dynamics of the emission mechanism will be discussed for both bounded and unbounded interaction scenarios as a function of $\omega_{ce} / \omega_{pe}$ in line with recent laboratory experiments [6] and earlier numerical simulations of unconstrained electron-cyclotron emission [7].

[1] A. P. Zarka, Advances in Space Research **12**, 99 (1992).
[2] R. E. Ergun, C. W. Carlson, C. W. McFadden et al., Astrophys. J. **538**, 456 (2000).
[3] I. Vorgul, R. A. Cairns and R. Bingham, Phys. Plasmas **12**, 122903 (2005).
[4] R. A. Cairns, I. Vorgul, R. Bingham et al., Phys. Plasmas **18**, 022902 (2011).
[5] K. Ronald, D. C. Speirs, S. L. McConville, et al., Phys. Plasmas, **15**, 056503 (2008).
[6] K. Ronald, D.C. Speirs, S.L. McConville et al., Plasma Phys. Control. Fusion (In Press).
[7] D. C. Speirs, K. Ronald, S.L. McConville, Phys. Plasmas **17**, 056501 (2010).

# Experimental and numerical simulation of auroral radio emission processes

K.M. Gillespie[1], S.L. M$^{c}$Conville[1], D.C. Speirs[1], K. Ronald[1], A.D.R. Phelps[1], A.W. Cross[1], C.W. Robertson[1], C.G. Whyte[1], R. Bingham[1,2], I. Vorgul[3], R.A. Cairns[3], W. He[1] and B.J Kellett[2]

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The particle in cell (PiC) code KARAT has been used to investigate electron cyclotron radio emissions that are known to originate in the X-mode from regions of locally depleted plasma in the terrestrial polar magnetosphere. These emissions are commonly known as Auroral Kilometric Radiation (AKR). A laboratory experiment was constructed to study the emission mechanism of AKR scaled to microwave frequencies [1]. Initial investigations were conducted numerically in the form of 2D PiC code simulations [2], with subsequent 3D PiC simulations conducted to study resonant energy transfer with non-azimuthally symmetric modes of the bounding interaction structure [3].

These 3D simulations show a backward-wave instability to be more resilient to Doppler broadening of the beam-wave resonance than forward-wave coupling. This resilience has important implications when there is a cold, tenuous plasma in the resonant region. It would suggest that the auroral process may emit with backward-wave coupling giving a spectral downshift and thus avoiding the upper hybrid stop-band [4].

Simulations show how various factors such as electron beam current and cyclotron-wave detuning influence mode excitation within the interaction region and the saturated rf output power. The results also demonstrate that cyclotron-wave coupling becomes weaker as the resonant wave moves away from near transverse propagation ($|k_z| > 0$) and provide for a detailed analysis of the output radiation mode content and impact of injecting an RF seed signal into the apparatus for convective growth.

Comparisons will be presented with the latest experimental studies testing the numerical predictions. Recent experimental results have shown a clear backward wave interaction verifying simulations.

[1] K. Ronald et al, Plasma Sources Sci. Technol, **17**, 035011 (2008)

[2] D.C. Speirs et al, Plasma Phys. Control. Fusion, **50**, 074011 (2008)

[3] K. M. Gillespie et al, Plasma Phys. Control. Fusion, **50**, 124038 (2008)

[4] A.V. Savilov et al, Phys. Plasmas, **14**, 113104 (2007)

# Impact of a background plasma on cyclotron instabilities relevant to the auroral magnetosphere

S.L.McConville[1], K.Ronald[1], D.C.Speirs[1], K.M.Gillespie[1], A.D.R.Phelps[1], A.W.Cross[1], C.G.Whyte[1], C.W.Robertson[1], W.He[1], R.Bingham[1,3], I.Vorgul[2], R.A.Cairns[2] and B.J.Kellett[3]

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Numerical simulations and scaled laboratory experiments[1,2] at the University of Strathclyde have investigated the phenomenon of Auroral Kilometric Radiation (AKR), which is generated naturally in the polar regions of the Earth's magnetosphere as electrons descend through regions of plasma depletion, the auroral density cavity, and experience magnetic compression[3]. Through adiabatic conservation of the magnetic moment these electrons must sacrifice axial velocity in exchange for perpendicular velocity, thus exhibiting a horseshoe/crescent shaped distribution in velocity space. Radiation is emitted as the distribution of electrons spreads out in velocity space. Satellites have measured $f_{pe}$~9kHz, $n_e$~$10^6$m$^{-3}$ and $f_{ce}$~300kHz (ratio of $f_{ce}/f_{pe}$~30) within the auroral density cavity, and have seen that emitted radiation is polarised in the X-mode with peak powers ~$10^9$W. This power corresponds to an estimated radiation efficiency ~1% of the precipitated electron kinetic energy[4].

A scaled laboratory experiment was constructed to replicate the magnetospheric dynamics. A set of solenoids provided the increasing magnetic field region through which electrons would pass upon injection from an explosive emission cathode. Measurements of the beam transport showed evidence of mirroring (evidence for this was the progressive decline in beam current measured with increasing mirror ratio) and therefore of the formation of the horseshoe velocity distribution. Radiation emissions were observed with a cyclotron frequency of $f_{ce}$~4.42GHz close to cut-off for the $TE_{01}$ mode. Experiments measured the power of the microwave emission as ~15-35kW. The efficiency of emission of radiation was determined to be ~1%, comparable to numerical and astrophysical results.

To improve comparison between the laboratory and the auroral situation, experiments have been conducted to create a low temperature, low density discharge as the initial AKR simulation experiments did not reproduce the magnetospheric background plasma[5,6]. To achieve this, a Penning trap was designed and installed into the interaction region of the experimental apparatus allowing a discharge to be formed in helium at 5x$10^{-4}$mBar. A plasma probe was used to characterize the discharge, estimating $f_{pe}$~150-300MHz and $n_e$~$10^{14}$-$10^{15}$m$^{-3}$, whilst the cyclotron frequency of the electrons within the Penning trap was 5.87GHz giving the ratio $f_{ce}/f_{pe}$~19-40, comparable to the magnetospheric case.

1. D.C. Speirs et al., Phys. Plas., **17**, 056501 (2010)
2. K.M. Gillespie et al., Plasma Phys. Control. Fusion, **50**, 124038 (2008)
3. R.E. Ergun et al., Ap. J. **538**, 456 (2000)
4. D.A. Gurnett, Journal of Geophysical Research, **79**, pp4227-4238 (1974)
5. K. Ronald et al., Plasma Sources Sci. Technol., **17**, 035011 (2008)

# Design and use of an Elsässer probe for analysis of Alfvén wave fields according to wave direction

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## Abstract

The theoretical characterization of turbulent cascades in plasmas invokes wave-wave coupling as a key mechanism for the cascade to proceed. However, verification of this tenet of plasma turbulence requires detailed laboratory observations of wave-wave interactions. Understanding these wave-wave interactions necessitates detailed measurements of the directions and polarization of the electric and magnetic components of counter-propagating waves. We have designed an electric and magnetic field probe which can simultaneously measures both quantities in the directions perpendicular to the applied magnetic field for application to Alfvén wave experiments in the Large Plasma Device (LaPD) at UCLA. This new probe allows for the projection of measured wave fields onto modified Elsässer variables,

$$\boldsymbol{z}^{\pm} = \frac{E_{\perp} \times B_0}{B_0^2} \pm \frac{B_{\perp}}{\sqrt{\mu_0 \rho}} \quad .$$

Here $E_{\perp}$ and $B_{\perp}$ are the Alfvén wave electric and magnetic fields, respectively, $B_0$ is the ambient magnetic field, and $\rho$ is the plasma mass density. Experiments were conducted in singly ionized He plasma at 1850 G in which propagation of Alfvén waves was observed using this new probe. We show the Poynting flux that was calculated for the wave and demonstrate that a clear separation of transmitted and reflected signals can be achieved, thus laying the groundwork for the future experiments on turbulent cascades.

**Geometrical optics results for spin and orbital Hall effects of a nonparaxial beam in a gradient-index medium**

E. Nordblad and T. B. Leyser
Swedish Institute of Space Physics, Uppsala, Sweden

By applying geometrical optics to each plane wave component of a non-paraxial Bessel beam carrying orbital angular momentum (OAM), we study the effects of refraction on the beam during propagation perpendicular to a weak refractive index gradient in an isotropic, inhomogeneous medium. The results show a transverse shift on the scale of the wavelength. In the paraxial limit, the calculated shift agrees with the existing theory of spin and orbital Hall effects. Generalisations to the anisotropic case - e.g., radio waves propagating in a magnetised plasma - are discussed.

# Lower hybrid drift instability and collective coupling of energy from ions to electrons

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The lower hybrid drift instability (LHDI) has been extensively researched for space plasma applications (see *e.g.* P H Yoon and A T Y Lui, *Phys Plasmas* **10**, 4260 (2003)) and is highly topical in magnetic confinement fusion. For space plasmas, the ion flows whose free energy underlies the instability are typically central to the self-consistent local equilibrium, for example drifts arising from spatial gradients. In contrast, for the fusion application, the ion flows are typically those of energetic minority populations, and need not sustain the local equilibrium. Here the LHDI is interesting as the highest frequency – hence potentially most rapid – collective instability to which energetic ions are subject. It may arise spontaneously among fusion-born alpha-particles during the early stages of reactivity growth in magnetically confined deuterium-tritium plasmas. This would be beneficial if the electromagnetic waves excited by the LHDI can be used constructively: in particular, if they can undergo Landau damping on the electrons in a way that creates asymmetry in their distribution of parallel velocities, and hence a current. This example of an “alpha channelling” (N J Fisch and J-M Rax, *Phys Rev Lett* **69** 612 (1992)) scenario has recently been investigated by means of self-consistent electromagnetic relativistic particle-in-cell simulations that capture the full kinetics of electrons and ions (J W S Cook *et al*, *Phys Rev Lett* **105** 255003 (2010); *Plasma Phys Control Fusion* **53** 065006 (2011)). These simulations demonstrate the pervasiveness of the LHDI for fusion-born ions, here modelled using a distribution inferred from observations of ion cyclotron emission driven by centrally born fusion products passing through the outer mid-plane in JET and TFTR, see *e.g.* R O Dendy *et al*, *Nucl Fusion* **35** 1733 (1995).

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# Using the whistler mode to observe electron dynamics

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Abstrtact

We report experiments on the BAPSF user facility where whistler mode absorption is used to observe electron dynamics in a magnetized plasma column. Even in an overdense plasma ($\omega_p$>$\Omega_c$) where traditional electron-cyclotron emission measurements are not possible whistler mode absorption can be used to observe the dynamics of (especially suprathermal) electrons which travel along magnetic field lines. Observation of whistler modes and analysis of their excitation has a long history of providing information on electron dynamics in planetary magnetospheres. We explore the strength and limitations of this technique for detecting the effects of Alfven waves on electrons in a laboratory plasma. Two small dipole antennas are inserted in the plasma with a known separation along the background magnetic field. A rapidly swept microwave source (3-7 GHz) is used to launch and homodyne detect whistler mode waves in the range $\omega/\Omega_c$=0.6-.99 with an intermediate frequency in the tens of MHz - depending on plasma dispersion and the sweep rate. The signal time-of-flight determines the plasma density (integrated along the magnetic field) and the amplitude indicates the absorption due to cyclotron damping at the Doppler-shifted fundamental cyclotron resonance ($\omega = \Omega_c - kv$). Because whistler modes have a resonance ($k \to \infty$) at the cyclotron frequency, wave-particle resonance can be achieved over a wide range of particle velocities.

# MHD WAVE PROPAGATION and CONVERSION: LESSONS FROM THE TERRESTRIAL MAGNETOSPHERE

V.A. Pilipenko
*Space Research Institute, Moscow*

The study of MHD waves in the terrestrial magnetosphere has revealed the effects that may be invoked for the MHD wave processes in the laboratory plasma as well.

(a) The basics of the Alfven wave interaction with the auroral acceleration region with a field-aligned potential drop and turbulent layers with an anomalous resistivity is essential for the processes of the energy transfer in space. Though these phenomena are kinetic in essence, for their analytical description a hybrid approach has been elaborated when kinetic effects are included in the MHD theory via their "proxies": current-voltage relationship and modified conductivity tensor. The analysis of the Alfven waves interaction with a layer with field-aligned potential drop or turbulent layer reveals that the wave transmission/absorption through these layers is very scale dependent. The characteristic scale of such process is found to be the Alfven resistive scale $\lambda_A$.

(b) In a region with extended field lines, the resonant mode conversion, resulting in the formation of band-limited signals, can occur even without a resonator with conductive boundaries. The conversion of propagating fast waves into Alfven waves becomes possible in a longitudinally inhomogeneous plasma owing to the finite frequency effect.

(c) The study of the poloidal Alfven wave propagation in a plasma immersed in a curvilinear magnetic field has shown that an Alfvenic mode is partly reflected from regions where the magnetic field lines sharply converge, when its wavelength becomes comparable to the magnetic field inhomogeneity scale. On the other hand, for poloidal Alfven waves propagating along curved magnetic field lines in a finite-beta plasma a non-propagating (opaque) region may be formed. Both these effects may result in the formation of Alfvenic resonators in systems without reflecting boundaries.

**Laboratory realization of an ion-ion hybrid Alfvén wave resonator**

S. T. Vincena, W. A. Farmer, J. E. Maggs and G. J. Morales

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Abstract

In a magnetized plasma with two ion species, shear Alfvén waves (or guided electromagnetic ion cyclotron waves) have zero parallel group velocity and experience a cut-off near the ion-ion hybrid frequency $\omega_{ii}$. Since the ion-ion hybrid frequency is proportional to the magnetic field, it is possible, in principle, for a magnetic well configuration to behave as an Alfvén wave resonator in a two-ion plasma [1]. The important role played by the wave cut-off at $\omega = \omega_{ii}$ in determining the structure of low frequency wave spectra has long been recognized in space plasma studies. For instance, Temerin and Lysak [2] identified that the narrow-banded ELF waves seen in the S3-3 satellite were generated by the auroral electron beam in a limited spatial region determined by the local value of $\omega_{ii}$ for a mix of $H^+$-$He^+$ ions.

The present study demonstrates such a resonator in a controlled laboratory experiment (in the Large Plasma Device at UCLA) using a $H^+$-$He^+$ mixture. The resonator response is investigated by launching monochromatic waves and sharp tone-bursts from a magnetic loop antenna. The topic is also investigated theoretically, and the observed frequency spectra are found to agree with predictions of a theoretical model of trapped eigenmodes. Results of the experiment and theory will also be discussed in their relation to the ion-ion resonator feature proposed for planetary magnetospheres [3-5.]

This study was sponsored by ONR under the MURI grant #N000140710789. The experiments were performed at the Basic Plasma Science Facility (BaPSF), which is jointly supported by DOE and NSF.

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# PAUL M KINTNER JR: PLASMA EXPERIMENTS IN THE LABORATORY OF THE IONOSPHERE

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Cornell University Professor Paul Kintner was one of the original driving forces behind the IPELS community. He spent many years flying innovative instrumentation to explore the plasma physics of the ionosphere, and then mining the plasma physics community for understanding of the resulting observations. The experiments covered current-driven instabilities, ion cyclotron waves, interferometry techniques, Alfvenic activity, and recent work with GPS observations of ionospheric scintillations. Within the IPELS community and beyond it, Paul made deliberate efforts to connect this work to the larger field of plasma physics. His 21 sounding rockets explored a variety of plasma processes in the laboratory of our ionosphere. In this talk we take a tour of these experiments and consider the remaining open questions he has left for us to address.

# Lower Hybrid Solitary Structures

Peter W. Schuck (peter.schuck@nasa.gov),[1]

Lower hybrid solitary structures (LHSS) have been observed by sounding rockets in the auroral ionosphere for over a decade and a half. LHSS are spatial structures embedded in space plasmas containing ambient whistler mode hiss. They are characterized by a density depletion of a few percent to several tens of percent in which electric fields near, both above and below, the lower hybrid resonance are more intense than the background fields by a factor of three to five. LHSS have dimensions across the magnetic field of a few to many thermal ion gyroradii, usually 10-100 meters and a density profile that is Gaussian and consistent with cylindrical symmetry. Along the magnetic field the dimensions are estimated to be several kilometers to several hundred kilometers. Electric field interferometry reveals that the phase fronts of LHSS electric fields rotate azimuthally within the density depletions; right-hand above the lower hybrid resonance and left-hand below the lower hybrid resonance [*Pinçon et al.*, 1997; *Schuck et al.*, 1998; *Bonnell et al.*, 1998; *Tjulin et al.*, 2003; *Schuck et al.*, 2003]. The description of this phenomena was driven by the observations the Cornell University sounding rocket program headed by the late Paul Kintner.

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Electrostatic solitary waves in space and laboratory

Li-Jen Chen (1), Walter Gekelman (2), Bertrand Lefebvre (1), Jolene Pickett (3), Patrick Pribyl (2), Stephan Vincena (2)

(1) Space Science Center, University of New Hampshire
(2) Basic Plasma Science Facility, UCLA
(3) Department of Physics and Astronomy, University of Iowa

Electrostatic solitary waves are observed in virtually every dynamical regions in space. In this talk, we  will discuss and compare the characteristics of these waves at shock transition layers, the turbulentdownstream of shocks, auroral current layers, polar cusp, plasma sheet boundary, and reconnection separatrix layers. The ubiquitous presence of these solitary waves in space motivated laboratory studies on their generation and evolution. In IPELS 2003, a plan to try to measure these waves in the LArge Plasma Device at UCLA was conceived. Microprobes with tip size smaller than the Debye length were developed to measure electric fields. Under the injection of a suprathermal electron beam, solitary waves and nonlinear wave packets were measured to move at 1-3 times the background electron thermal speed along the beam travel direction. The solitary waves are interpreted as BGK electron holes based on their width, amplitude, and velocity characteristics. The ensuing turbulence, including the solitary waves and wave packets, exhibits a band dispersion relation with its central line consistent with the electrostatic whistler mode. We will discuss how the laboratory experiments help us understand the space observations.

## The Interaction of Whistler and Lower Hybrid Waves with density striations

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[1]Department of Physics and Astronomy, University of California, Los Angeles
[2] Los Alamos National Laboratory, Los Alamos, New Mexico

In the early 1990's the UCLA group, motivated by a series of rocket experiments in the Earth's auroral region, became interested in carefully scaling laboratory experiments to spacecraft observations. The first series of experiments focused on the direct conversion of whistler to lower hybrid waves on the edge of density striations[1]. Several years later we met Paul Kintner at the 1997 IPELS meeting. He was aware of this work and had interesting spacecraft data on accelerated ions associated with density cavities[2] and subsequently published related electric field data[3]. A second set of experiments at UCLA focused on the trapping of lower hybrid waves in density striations[4]. Although there was never a direct collaboration been Paul and UCLA on these experiments, there were many interesting discussions and scientific exchanges. Recently there has been a resurgence of interest in this problem and a collaborative project between UCLA and LANL has been initiated. A 16 element slow wave antenna has been constructed ($5 \le f_{wave} \le 100 MHz,\ \mathrm{L}_{ant} = 2m, 12.5cm \le \lambda_{\|-wave} \le 4m$) that is capable of launching low amplitude waves for linear studies, as well as, high power waves in which the ponderomotive force is capable of modifying the plasma density and changing the wave's trajectory[5]. The waves will be studied in the LAPD plasma ( $1 \le \frac{\omega_{pe}}{\omega_{ce}} \le 5, n \le 3\times 10^{12} cm^{-3}, He, L = 18m$) and the interaction with field aligned density striations ($\frac{c}{\omega_{pe}} \le dia \le 10\lambda_{\perp}$) will be documented. Electric dipole, and magnetic loop probes will be used to measure the three dimensional wave patterns inside and outside the striation. Extensive simulations using two and three-D, fully electromagnetic PIC codes as well as a fully electromagnetic linear wave solver for predicting wave propagation and antenna loading have been developed at Los Alamos National Laboratory. Preliminary results of the new experimental campaign and computer simulations will be presented.

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## WEDNESDAY, JULY 13, 2011

8:25am Announcements

**20 Year Anniversary (M. Koepke, West Virginia U.)**

8:30am **M. Yamada** (PPPL): Progress in the Research on Magnetic Reconnection through 20 year Collaborations

8:55am **A. Bhattacharjee** (U. New Hampshire): Magnetic Reconnection and Instability of Thin Current Sheets: Bridging Laboratory and Space Plasma Physics

9:20am **J. Stone** (Princeton): Astrophysical Accretion Disks: Simulations and Experiments

10:05am Break

**20 Year Anniversary (M. Yamada, PPPL)**

10:30am **M. Koepke** (West Virginia U.): Highlights of productive interaction between space and lab communities on wave & turbulence related physics research

10:55am **C. Forest** (U. Wisconsin): Experiments on Plasma Dynamos and Other Flow Driven Magnetic Instabilities

11:20am **C. Kletzing** (U. Iowa): Observation of Electron Phase Bunching in Auroral Langmuir Waves

11:45am Panel discussion

12:05pm Lunch – on your own

**Excursion**

# Progress in the Research on Magnetic Reconnection through 20 year Collaborations

Masaaki Yamada
Princeton Plasma Physics Laboratory, Princeton University,
Princeton NJ 08543

## Abstract

The recent advances in laboratory plasma experiments and the surge of space physics data from cluster satellites using advanced diagnostics have made collaborative research very productive for obtaining a universal understanding of key space and astrophysical phenomena. Since the early 1990's, cross fertilization has been significantly increased between laboratory plasma physics and space astrophysics communities through meetings such as this IPELS conference. During this period, several "physics-issue-dedicated" laboratory experiments have been built to help understanding the fundamental physics for magnetic reconnection. The collaboration between space and lab scientists on reconnection research has recently reached a point we can compare measurements of the reconnection layer profile in detail with aids from numerical simulations. In spite of the large difference in physical scales by$10^6$-$10^7$, we find remarkable commonalities in the features of the magnetic reconnection region in laboratory and the magnetospheric plasmas. Here we review major progress in the research on magnetic reconnection together with successful cases of cross-cutting collaborations.

## Magnetic Reconnection and Instability of Thin Current Sheets : Bridging Laboratory and Space Plasma Physics

Amitava Bhattacharjee
*Center for Integrated Computation and Analysis of Reconnection and Turbulence, and Center for Magnetic Self-Organization*
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Developments in experimental and theoretical studies of magnetic reconnection over the last 20 years hold the promise for providing solutions to some outstanding problems in laboratory, space, and astrophysical plasma physics. Examples of such problems are sawtooth oscillations in tokamaks, substorms in the Earth's Magnetosphere, eruptive solar or stellar flares, and more recently, fast reconnection in laser-produced high energy density plasmas. In each of these examples, a long-standing challenge has been to explain why fast reconnection proceeds rapidly from a relatively quiescent state. In this talk, we will demonstrate that these problems and their solutions can be viewed from a common perspective. This perspective also elucidates the role of mechanisms that can quench nonlinearly the onset of fast reconnection. Thus, we can explain not only when reconnection is near-explosive, but also when it cedes, as seen in observations.

The problem takes on additional complexity when it is applied to large systems. Thin current sheets, embedded in reconnection layers in two-dimensional systems, can be unstable to secondary instabilities, such as the ideal ballooning instability or the plasmoid instability. The former can play a critical role in tokamaks and the Earth's magnetotail. The latter is a super-Alfvénic instability that can be a copious source of plasmoids (or magnetic islands). As a result of the latter, the system can be shown to attain reconnection rates in collisional plasmas that are independent of the plasma resistivity. In weakly collisional or collisionless plasmas, the system can be shown to realize multiple strongly time-dependent nonlinear states that act as metastable fixed points with distinct topological properties. The three-dimensional dynamics of such systems presents several open questions that are fertile ground for both experiment and theory.

# Astrophysical Accretion Disks: Simulations and Experiments.

James M. Stone
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In most astrophysical disks, angular momentum transport and accretion is thought to be mediated by magnetohydrodynamical (MHD) turbulence driven by the magnetorotational instability (MRI). Much has been learned about the nonlinear regime of the MRI through direct MHD simulations. Local simulations of a small patch of the disk reveal that the MHD turbulence supports strong correlations in fluctuations of the magnetic field components which transport angular momentum outward. Studies of vertically stratified disks show that this turbulence drives a dynamo which, in combination with buoyancy, results in a strongly magnetized corona above the disk. Recent work has concentrated on global models in which the structure and evolution of the entire disk is computed from first principles, and studies of weakly ionized disks where the ideal MHD limit does not apply. At the same time, there are a number of outstanding questions that remain to be explored, including the role of non-local stresses on angular momentum transport, the important role that the magnetic Prandtl number might play in determining the saturation amplitude of the turbulence, and the details of the energy dissipation mechanisms at microscopic scales.

This talk will review recent progress in understanding the nonlinear saturation of the MRI through both numerical simulations, and laboratory experiments. Experiments can not only provide insight in regimes that are difficult to access through simulations, but they also can be used to verify and validate numerical algorithms. In particular, studies of accretion flows onto compact objects such as neutron stars and black holes not only require algorithms for MHD, but also for radiation hydrodynamics (RHD). Recent progress in algorithmic developments for RHD and validation efforts for both MHD and RHD will also be described.

# Highlights of productive interaction between space and lab communities on wave & turbulence related physics research

Mark Koepke, West Virginia University, Morgantown, WV 26506 USA

This talk highlights space observations and lab experiments on both plasma waves and plasma turbulence that contributed interactively to elucidating fundamental plasma physical processes that operate on a vast range of temporal and spatial scales, such as turbulent cascades, dissipation, particle acceleration and heating, waves and turbulence in inhomogeneous plasmas, interactions of wave and turbulence with mean fields, and coherent structures.

Space observations are interpreted using theoretical models developed to predict the properties and dynamics of space and astrophysical plasmas. Customized lab experiments confirm theory by identifying, isolating, and studying physical phenomena efficiently, quickly, and economically. This talk will highlight the scientific interrelationship that exists between theoretical predictions, *in situ* observations, and laboratory investigations of space-plasma processes. In well designed experiments, the space value and lab value of critical normalized parameters match and, within the laboratory-accessible ranges, a window of flexibility is exploited to controllably, reproducibly, and quantitatively elucidate a space plasma phenomenon. The plasma geometry, source, and boundary conditions associated with a specific lab experiment are characteristic elements that affect the plasma and plasma processes that are being investigated, just as geospace plasma is not exempt from an analogous set of constraining factors that likewise influence the phenomena that occur.

Waves and turbulence influence geospace regions such as the bow shock, magnetopause, ionosphere, plasmasphere, plasma sheet, ring current, radiation belts, and solar wind, as well as dynamics during impulse plasma penetration, magnetospheric compression, and a wide variety of transient geomagnetic and auroral phenomena. Multi-satellite missions have provided unprecedented measurements in some key regions. Theoretical models play the central role in interrelating observation and experiments on the linear and non-linear, fluid and fully kinetic behavior of space plasmas and this role will be discussed.

This work supported by the U.S. National Science Foundation, NASA, and U.S. DOE.

# Experiments on Plasma Dynamos and other Flow Driven Magnetic Instabilities

C. B. Forest[1,*]

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(Dated: May 9, 2011)

Many astrophysical objects, like the Sun, are composed of high magnetic Reynolds number, turbulent, flowing plasma in which the flow energy is much larger than that of magnetic field. Creating such conditions in laboratory plasma experiments is challenging since confinement is usually required to keep the plasma hot (and conducting) which is typically achieved by using strong applied magnetic fields. For this reason, laboratory experiments using liquid metals have been addressing fundamental plasma processes in this unique parameter regime. This talk will begin by reviewing self-generation of a magnetic field of energy comparable to the turbulent flow from which it arises– the dynamo process. Liquid metal experiments have successfully addressed a number of issues in the dynamo process including demonstrating self-excitation of magnetic fields and measurements and characterization of a turbulent electromotive force (mean-field current generation). Liquid metals are, however, not plasmas: dynamos may differ in plasmas where the relative importance of viscosity and resistivity can be interchanged, and new instability mechanisms, outside the scope of incompressible MHD may be critical in plasmas. This suggests that the next generation of experiments in this important astrophysics regime should be based upon plasmas. Recent prototype experiments have been carried out at the UW to demonstrate the feasibility of using a ring-cusp to confine and stir an unmagnetized plasma suitable for dynamo studies. This is also backed up by a number of numerical simulations using NIMROD that can address two-fluid modifications to the dynamo process. The Madison Plasma Dynamo experiment (now under construction) will then be described with an overview of the concept and show how the dynamos might operate in this plasma. Finally, this talk will attempt to make a broader point that a collection of flow-driven experiments (MRI, plasma wind experiments, flow driven reconnection, etc) are ripe for study.

PACS numbers:
Keywords: Dynamo, Turbulence, Mean Field Electrodynamics

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# Observation of Electron Phase Bunching in Auroral Langmuir Waves

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Observations from the Correlation of High-frequencies and Auroral Roar Mission 2 (CHARM-2), launched in 2010 from Poker Flat Alaska, show clear evidence of phase bunching of electrons by Langmuir waves. The measurements were made by a dedicated wave-particle correlator with good phase resolution during a period when the Langmuir waves were very monochromatic and had large amplitudes. The correlated electrons are observed at energies well below the inverted-V peak energy. These electrons are found to be bunched at phase angles with respect to the wave field that indicate both resistive and reactive components of the perturbed distribution function. The resistive component is associated with energy exchange with the waves, while the reactive component is indicative of electron trapping. From the phase-bunched electron energy, we determine the wavelength of the Langmuir waves and also estimate the group velocity of the waves. During a period when time-dispersed electrons are observed below the inverted-V peak, the phase-bunching of the electrons is also observed to be time-dispersed. This interpreted as arising from a positive region of slope in the reduced distribution function created by the dispersed electrons as they decrease decrease in energy over time. We also discuss the observations in terms of wave-packet length and implications for the observed temporal behavior.

**THURSDAY, JULY 14, 2011**

8:25am Announcements

**Dynamo and Jet (E. Zweibel, U. Wisconsin)**

8:30am **R. Pudritz** (McMaster U.): Protostellar Jets and Winds: Laboratories for Astrophysical Jets

9:15am **P. Kronberg** (LANL): Plasma probes of jets, and their energy sink (lobes) on galactic to Mpc scales

9:30am **H. Li** (LANL): Nature and Stability of AGN Jets

9:55am Break

**Dynamo and Jet (H. Li, LANL)**

10:20am **E. Zweibel** (U. Wisconsin): Magnetic Fields in Galaxies

11:05am **J.-F. Pinton** (ENS Lyon): Transition from hydro to magnetohydrodynamics turbulence in a von Karman flow

11:30am **K. Rahbarnia** (U. Wisconsin): The role of system-scale turbulence on MHD activity in the Madison Dynamo Experiment

11:45am **S. Colgate** (LANL, New Mexico Tech.): Dynamo and turbulence

12:00pm Lunch - provided

**Dusty Plasma and Sheath (K. Lynch, Dartmouth)**

1:30pm **S. Robertson** (U. Colorado): Collisionless Sheaths in the Laboratory and in Space

2:15pm **R. Marchand** (U. Alberta): Spacecraft-plasma interaction modeling – physics issues and numerical approach

2:40pm **E. Thomas** (Auburn U.): Laboratory and microgravity studies of density waves in dusty plasmas

3:05pm **R. Stenzel** (UCLA): Instabilities in Electron-rich Sheaths

3:30pm Break

3:50pm **Poster session**

5:30pm End

**Working Dinner (H. Ji, PPPL)**

6:30 Cash bar

7:00 Food served

7:30 Presentations

8:10 Discussion

9:00 Adjourn

# Protostellar Jets and Winds: Laboratories for Astrophysical Jets

R.E. Pudritz (McMaster University), D.F. Duffin (McMaster University), D. Seifried (Hamburg University), R. Banerjee (Hamburg University), J. Staff (Louisiana State University), and R. Ouyed (University of Calgary).

Protostellar jets are observed to be ubiquitous during the formation of stars of all masses, from low mass brown dwarfs to massive stars. Jets are observed to be associated with accretion disks and are an integral part of how individual stars form. Theory and numerical simulations show that magnetized disks, which arise from the gravitational collapse of dense regions within molecular clouds, can generate powerful hydromagnetic winds that self-collimate into high speed jets. Hubble Space Telescope observations show that jets, observed through their shock-induced forbidden-line emission, rotate and carry off the bulk of the angular momentum from extended regions of their associated disks. Finally, powerful accretion-powered stellar winds can be generated by accreting magnetized young stars, and this process may help to resolve the observed problem that such stars rotate far too slowly for the rate at which they accrete disk material. I shall discuss these major stages in the evolution of jets during star formation – from the launch of magnetic “tower flows” in the earliest stages of collapse and disk formation, to the onset of high-speed centrifugally driven winds from disks and accreting stars in the later stages. Many of these physical processes have been studied in state of the art computer simulations, and some even verified in laboratory plasma physics experiments. During this tutorial talk I will also emphasize that the physical processes that are central to the physics of protostellar jets are also directly connected to astrophysical jets in more general contexts such as quasars and micro-quasars.

Plasma probes of jets, and their energy sinks (lobes) on galactic to Mpc scales.

Philipp P. Kronberg

University of Toronto
and
Los Alamos National Laboratory

Capabilities in the imaging of high energy jets and lobes hold great promise for creating passive plasma laboratories on scales well beyond the Solar System and even the Galaxy.

Current state-of-the-art measurements in the radio, X-ray, and γ-ray bands can be combined to define the plasma state of magneto-plasmas in jets and lobes. I discuss and show some observations in some of these wavebands that are mutually complementary in important ways. Presently measureable, or estimatable quantities in these systems are the magnetic and particle energy content, power flow, plasma densities, plasma-$\beta$ estimates and Alfvén speeds, 3-D magnetic structures, and even electric current,.

Recent probes of these quantities illustrate how aspects of instrumental capability, such as angular resolution, can be improved in future -- at modest cost, and with potentially significant gain in insight.

# Nature and Stability of AGN Jets

*H. Li*
*Los Alamos National Laboratory*

We will discuss observations of AGN jets in galaxy clusters. The interaction of jets with the background intra-cluster medium helps us to understand the composition of the jets. We will discuss 3-D MHD simulations of such interactions and compare them with observations in radio and X-rays. We also explore the stability of such jets, especially the role of current driven instability.

## Magnetic Fields in Galaxies

*Ellen Zweibel*
*University of Wisconsin - Madison*

All galaxies with interstellar gas show evidence for magnetic fields. In most cases, the fields are coherent on scales much greater than the characteristic scale of turbulence, and are strong enough to influence the dynamics and energy balance of the gas. I will review the observations as well as theories for the origin, evolution, and maintenance of these fields.

# Transition from hydro to magnetohydrodynamics turbulence in a von Karman flow

*J.-F. Pinton, G. Verhille, S. Miralles, and N. Plihon*

*Laboratoire de Physique, CNRS et Ecole Normale Superieure de Lyon, France*

We report on how how an externally applied magnetic field modifies the turbulence in a von Karman (VK) swirling flows. Measurements concern global variables (such as the flow power consumption) and local induced magnetic field fluctuations. Significant modifications are observed for low interaction parameter (N) values but corresponding to an Alfven speed vA of the order of the fluid velocity fluctuations u_rms. For low ratio, R = vA/u_rms, the flow has the geometry and the dynamic of usual von Karman flow, and the applied magnetic field mainly causes induced currents and additional Joule dissipation. In this regime the flow power consumption scales linearly with N. At high R values, the flow is damped. The configuration is very important and, when the applied field is transverse to the axis of rotation, one observes a strong increase in the fluctuations because the flow alternates chaotically between hydrodynamics and magnetohydrodynamics profiles.

Contribution submission to the conference IPELS2011

**The role of system-scale turbulence on MHD activity in the Madison Dynamo Experiment** — •Kian Rahbarnia[1], Mike M Clark[1], Elliot J Kaplan[1], Mark D Nornberg[1], Alex M Rasmus[1], Eric J Spence[2], Nicholas Z Taylor[1], John P Wallace[1], and Cary B Forest[1] — [1]Department of Physics, University of Wisconsin-Madison, 53706 Madison,WI, USA — [2]Princeton Plasma Physics Laboratory, New Jersey 08544, USA

Self-generation and saturation of magnetic fields due to magnetohydrodynamic (MHD) dynamos remain important fundamental problems in many astrophysical and geophysical systems. The Madison Dynamo Experiment (MDE) studies the onset conditions for magnetic field growth in a turbulent two-vortex flow of liquid sodium and investigates the turbulent electromotive force $\varepsilon = \left\langle \widetilde{v} \times \widetilde{b} \right\rangle$. This work analyzes the influence of a recently installed equatorial baffle to reduce the largest scale turbulent eddies in the flow. A spherical harmonic decomposition of the magnetic field indicates a reduction of the largest scale magnetic fluctuations, consistent with a reduction of the large-scale velocity fluctuations. A decrease of the $\alpha$-effect induced dipole moment together with a reduction of the effective turbulent electrical resistivity ($\beta$-effect) by 57% is observed. A strong flux compression in the sphere center with a gain of about 20 is found. For the first time in the MDE the local $\varepsilon$ is experimentally observed. It shows a significant reduction compared to previous results without equatorial baffle. This work is supported by the CMSO and the NSF/DOE partnership in plasma physics.

Part: 11th IPELS, Whistler, Canada
Type: talk
Topic: Magnetic dynamo and turbulence
Email: rahbarnia@wisc.edu

Dynamo and Turbulence:

Colgate,S., Li,Hui T-2, (Los Alamos Nat. Lab.)
Westpfahl,D., Si,J., and Martinic,J., (New Mexico Tech)

The omega-phase of the liquid sodium alpha-omega dynamo experiment at NMIMT in cooperation with LANL has demonstrated a high toroidal field B_phi that is 8 times B_r where B_r is the radial component of an applied poloidal magnetic field. This enhanced toroidal field is produced by the rotational shear in near-stable Couette flow within liquid sodium at high Re ~ $1.4 \times 10^7$ and magnetic Reynolds number Rm ~ 120. A small turbulence in stable Taylor-Couette flow is caused by Ekman flow at the end walls, which causes an estimated turbulence energy fraction of (delta v/v)^2 ~ $10^{-3}$. This result is compared to three highly turbulent flow measurements with an omega gain of ~1, where without turbulence a much larger omega gain is predicted. This result is interpreted as “turbulence results primarily in the diffusion and dissipation of magnetic flux as compared to the possible creation of magnetic flux by dynamo action”. Large scale low turbulence, coherent flows as opposed to turbulent flows alone are then required to create the magnetic fields of the universe.

**Collisionless Sheaths in the Laboratory and in Space**

S. Robertson, A. Dove, M. Horanyi, A. Poppe, and X. Wang
Colorado Center for Lunar Dust and Atmospheric Studies
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Plasma sheaths occur at walls enclosing laboratory plasmas and at the surfaces of objects inserted into plasmas. For models of the wall sheath, the distance scale of the device is an essential feature and there is an electrostatic presheath on this largest distance scale that gives ions a mean velocity toward the wall. The loss of ions at the wall must be equal to their rate of generation in the plasma volume. Models for the sheath around an inserted object treat the current collected as a small perturbation. Kinetic models for inserted probes use distribution functions specified at an infinite distance and find the sheath potential profile near the surface that is consistent with these distributions and Poisson's equation. Complications include multiple electron distributions that may occur from ionization, photoemission, secondary emission or thermionic emission at surfaces.

Airless natural bodies and manmade objects in space have a photoelectron sheath in sunlight that merges with the solar wind plasma. This photoelectron sheath is likely to have a greater electron density than the solar wind. The zero-current condition for a floating object may require a nonmonotonic sheath profile with a maximum and a minimum that together allow the zero-current condition and the quasineutrality condition at infinity to be satisfied. Non-monotonic sheath potential profiles have been observed in the laboratory and inferred from data taken above the lunar surface.

We will describe laboratory experiments with intense UV sources ~0.5 m above a metal surface that create for the first time photoelectron sheaths with shielding distances of the order of several centimeters. The UV sources are xenon excimer lamps each generating 8 watts in a narrow band centered at 172 nm. The emitting surface is a Zr disk with an illuminated diameter of 28 cm. The disk has a floating potential of about +1 V (relative to nearby surfaces) when illuminated in vacuum and emits about 1 $\mu A/cm^2$. Langmuir probe sweeps above the surface show that the "plasma potential" for the pure electron plasma that is deduced from the maximum in the first derivative is about 1 volt above the potential of the emitting surface for a wide range of surface bias potentials. The photoelectron density is $\leq 10^5$ $cm^{-3}$ and the characteristic electron energy is 1-2 eV. Emissive probe data taken between the emitting surface and a grid placed above the surface data show a depression in the potential due to the space charge of the photoelectrons.

We have applied one-dimensional Vlasov-Poisson models and one-dimensional PIC codes to understanding the photoelectron sheath at surfaces in tenuous solar wind plasma. The models use a variety of electron distribution functions both for the photoelectrons and the solar wind electrons that correspond to different levels of solar activity and to different orbital positions of the Moon. The PIC code modeling shows the existence of non-monotonic potential profiles.

## Spacecraft-plasma interaction modeling - physics issues and numerical approach

**Richard Marchand**
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### Abstract

A difficulty in modeling spacecraft-plasma interaction, comes from the number and complexity of physical processes involved. To name a few, these include charging and possible arcing, sheath and wake formation, the emission of photo- and secondary electrons, material properties and material aging. Another difficulty comes from the geometry and the necessity to account accurately for the shape of objects in order to provide quantitative comparisons with measurements or make reliable predictions for missions being designed. In this talk I describe a model developed to simulate the interaction of spacecraft with surrounding plasma while accounting for important physical processes in realistic geometry. The model accounts for all particle species kinetically using the Particle In Cell (PIC) approach, and it is based on a discretization of space using an unstructured tetrahedral mesh capable of representing physical objects and boundaries of arbitrary shapes. The mesh is also adaptive in that it can be constructed with a higher resolution in regions of space where fine structures are located, or where strong spatial variations occur. Following a brief description of the code, example simulation results are presented for simple objects immersed in a plasma. Results are also presented for actual spacecraft with representative ionospheric plasma conditions. PIC simulation results are also used as input in a particle backtracking code in order to compute particle distribution functions at precise locations with minimal statistical noise. In conclusion, some major open questions in spacecraft-plasma interaction physics are reviewed with a particular emphasis on problems that laboratory experiments could help elucidate.

# Laboratory and microgravity studies of density waves in dusty plasmas

Edward Thomas, Jr., Ross Fisher, Joseph Shaw, Auburn University
Uwe Konopka and Manis Chaudhuri, Max Planck Institute for Extraterrestrial Physics

Dusty plasmas consist of a background of ions, electrons and neutral atoms into which small, charged microparticles, i.e., "dust grains", are present.[1] In both the laboratory and natural plasma environments, the collection of ions and electrons onto the surface of the dust grains is an important charging mechanism.[2,3] However, in regions such as the edges of fusion experiments or star forming regions, ionizing radiation, secondary electron emission, and thermionic emission processes also play important roles determining in the dust grain charge as well as allowing the grains to become a source of ions and electrons to the background plasma.[4,5] Therefore, a dusty plasma is an ensemble system in which there is a strong, mutual interaction between the charged grains and the surrounding plasma. This dust-plasma coupling modifies many plasma instabilities and can give rise to new, dust driven instabilities.

In ground-based laboratory studies, gravity plays a dominating role in determining many of the properties of a dusty plasma. The gravitational force acts to "compress" a dusty plasma to the sheath region where electric fields in the plasma are strong enough to allow the electric force on the grains to balance the gravitational force. Consequently, dusty plasma experiments performed under reduced gravity or microgravity conditions can often provide insights into grain-grain interaction forces that are masked in ground-based laboratory experiments. However, experiments in microgravity are often challenged by limited experimental time; e.g., limited availability of astronaut time or short reduced gravity periods during parabolic flights. Thus, it is highly desirable to perform a combination of laboratory and reduced gravity studies on the same phenomena in order to fully reveal the complexities of dusty plasma phenomena.

The Auburn dusty plasma group in partnership with the complex plasma group at MPE (Garching) has been working to adapt the particle image velocimetry (PIV) technique [6] to the study the transport, instabilities and thermal properties of laboratory and microgravity dusty plasmas. Recent investigations have focused on using sequences of images recorded using high-speed (>50 frames/sec) cameras to study the formation and propagation of dust density waves from the void region of a dusty plasma. This presentation will discuss how the PIV analysis is performed and make comparisons of wave measurements made using laboratory studies of "probe-induced" voids (Auburn) and reduced gravity parabolic studies of naturally occurring voids using the PLASMALAB facility (MPE).

This work is supported by grants from NSF and NASA.

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**Instabilities in Electron-rich Sheaths**

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Positively biased electrodes in plasmas form electron-rich sheaths, which are subject to various instabilities. The electron transit time through a sheath can excite high frequency oscillations near the electron plasma frequency [1]. In a magnetized sheath the $\mathbf{E}\times\mathbf{B}$ drift can excite electron drift waves [2]. In a spherical hollow anode rf oscillations occur whose period corresponds to the electron transit time through the sphere [3]. When electrons are energized above the ionization energy sheath ionization can occur. It changes the sheath potential, which in turn changes the ionization rate, leading to relaxation oscillations. The sheath may also expand into a spherical "fireball" which in turn can be unstable to relaxation instabilities [4]. These phenomena have been studied in laboratory plasmas and are relevant to probe diagnostics, discharge devices, antennas and tethers in space.

Work supported by NSF, DOE and in collaboration with R. Schrittwieser's group at the University of Innsbruck, Austria.

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## FRIDAY, JULY 15, 2011

8:25am Announcement

**Magnetic Reconnection (J. Egedal, MIT)**

8:30am **J. Drake** (U. Maryland): The physics of magnetic reconnection and associated particle acceleration

9:15am **F. Mozer** (UC Berkeley): Waves and anomalous drag at the sub-solar magnetopause

9:40am **S. Dorfman** (PPPL): Dynamics of Current Layer Disruptions and Associated Turbulence in the Magnetic Reconnection Experiment (MRX)

10:05am break

**Magnetic Reconnection (J. Drake, U. Maryland)**

10:25am **Y. Ono** (U. Tokyo): High Power Heating of Magnetic Reconnection in Laboratory Merging Experiments

10:50am **W. Daughton** (LANL): Development of Turbulent Magnetic Reconnection through the Formation and Interaction of Flux Ropes

11:15am **M. Oieroset** (UC Berkeley): Direct evidence for a three-dimensional magnetic flux rope flanked by two active magnetic reconnection X-lines at the Earth's magnetopause

11:40am **M. Inomoto** (U. Tokyo): Wave and Plasmoid Mediated Reconnection in Laboratory Experiments

11:55am **M. Opher** (Boston U.): Is the magnetic field in the heliosheath laminar or a turbulent sea of bubbles?

12:10pm Lunch - provided

**Magnetic Reconnection (W. Daughton, LANL)**

1:30pm **T. Shimizu** (JAXA): Hinode observations of dynamics in the solar atmosphere

1:55pm **J. Egedal** (MIT): Parallel electric fields producing Relativistic Electrons at Large Spatial Scales during Magnetic Reconnection

2:20pm **R. Horiuchi** (NIFS, Japan): Anomalous resistivity and multi-scale simulation of collisionless driven reconnection in an open system

2:45pm **R. Sydora** (U. Alberta): Whistler and Alfven-Whistler Mode Emission from Magnetically Reconnecting Current Layers

3:10pm break

**Magnetic Reconnection (T. Phan, UC Berkeley)**

3:30pm **V. Lukin** (Naval Research Lab): Global magnetic reconnection in solar and laboratory environments

3:45pm **R. Magee** (U. Wisconsin): Ion energization during magnetic reconnection in the reversed field pinch

4:00pm **W. Fox** (U. New Hampshire): Fast magnetic reconnection in high-energy-density laser-produced plasmas

4:15pm **A. Vrublevkis** (MIT): Experimental Investigation of the Trigger Problem in Magnetic Reconnection

4:30pm **A. Moser** (Caltech): Experimental observation of instability cascade from MHD to ion skin depth scale resulting in magnetic reconnection

4:45pm Adjourn

# The physics of magnetic reconnection and associated particle acceleration

J. F. Drake, University of Maryland

Solar and stellar flares, substorms in the Earth's magnetosphere, and disruptions in laboratory fusion experiments are driven by the explosive release of magnetic energy through the process of magnetic reconnection. During reconnection oppositely directed magnetic fields break and cross-connect. The resulting magnetic slingshots convert magnetic energy into high velocity flows, thermal energy and energetic particles. A major scientific challenge has been the multi-scale nature of the problem: a narrow boundary layer, "the dissipation region", breaks field lines and controls the release of energy in a macroscale system. Significant progress has been made on fundamental questions such as how magnetic energy is released so quickly and why the release occurs as an explosion. At the small spatial scales of the dissipation region the motion of electrons and ions decouples, the MHD description breaks down and whistler and kinetic Alfven dynamics drives Hall reconnection. However, the role of these non-MHD waves versus self-generated plasmoids continues to be debated. Simulations of the 3-D structure of the dissipation region reveal that self-generated turbulence may dominate laminar dissipation processes in breaking field lines, especially in low beta systems. The physics behind the explosive release of energy during reconnection, which in some cases may arise from the transition from collisional to collisionless Hall reconnection is more complex than previously believed because of the formation of secondary islands in the collisional regime. A large fraction of the magnetic energy released during reconnection appears in the form of energetic electrons and protons -- up to 50% or more during solar flares. The mechanism for energetic particle production during magnetic reconnection has remained a mystery. Models based on reconnection at a single large x-line are incapable of producing the large numbers of energetic electrons seen in observations. Scenarios based on particle acceleration in a multi-x-line environment are more promising. New observational results in the solar wind, outer heliosphere and the broader universe suggest that reconnection plays a much more important role than previously believed.

# Waves and anomalous drag at the sub-solar magnetopause

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Wave turbulence, anomalous drag, and their roles in sustaining the reconnection electric field have been measured at 90 sub-solar magnetopause reconnection sites. In 90% of these crossings, large amplitude waves were confined to the region of the magnetospheric separatrix. Electrostatic lower hybrid drift waves and electrostatic whistler mode waves were found. They contributed less than 10% of the anomalous drag required to support the reconnection electric field in the vicinity of the separatrix and less than 1% of that required in the current layer. An example of a crossing near the X-line is shown.

# Dynamics of Current Layer Disruptions and Associated Turbulence in the Magnetic Reconnection Experiment (MRX)

S. Dorfman, H. Ji, M. Yamada, J. Yoo, C. Myers, T. Tharp, and E. E. Lawrence
*Center for Magnetic Self-Organization, Princeton Plasma Physics Laboratory*

V. Roytershteyn and W. Daughton
*Los Alamos National Laboratory*

(Dated: April 30, 2011)

One of the key open questions in magnetic reconnection is the nature of the mechanism that governs the reconnection rate in real astrophysical and laboratory systems. Comparisons between fully kinetic 2-D simulations of the Magnetic Reconnection Experiment (MRX) and experimental data suggest that three-dimensional dynamics, such as current layer disruptions recently observed in MRX, may play a key role in resolving an important discrepancy in the reconnection rate and layer width [1,2,3]. Space observations have identified a variety of 3-D phenomena, including flux ropes in the reconnection region associated with a large local electric field [4].

During a current layer disruption, the out-of-plane reconnection layer current decreases as current carrying electrons are redirected in the outflow direction. Large fluctuations in the lower hybrid frequency range are often seen along with a peaking of the local reconnection rate. Some discharges also display "O-point" signatures or density striations consistent with the ejection of 3-D flux rope structures.

Fluctuations are observed not only in MRX [5], but also in space [6] and 3-D kinetic simulations. Comparisons between the experiment and simulations show that the fluctuations observed are similar in many aspects (frequency range, phase velocity in appropriately normalized units). However, while the electron drift speed is comparable to the phase velocity at the layer center in the experiment (consistent with previous MRX results [5]), the drift speed in the simulations is considerably larger.

Due to built-in toroidal asymmetries in MRX, density and magnetic field gradients in the out of plane direction are present at the start of the main pull reconnection phase prior to the current layer disruption. A linear two-fluid analysis based on [7] shows that the density gradient may generate magnetic fluctuations at a phase velocity comparable to the drift speed; small fluctuations consistent with this analysis are often observed in the initial state.

Analysis is ongoing to determine if the simulations or linear calculations best describe the experimental observations. This may shed light on the physics responsible for the broader current layers observed in the experiment.

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# High Power Heating of Magnetic Reconnection in Laboratory Merging Experiments

Yasushi Ono

Graduate School of Frontier Sciences, University of Tokyo

A series of tokamak merging experiments: TS-3, TS-4 and UTST revealed high-power ion heating of magnetic reconnection up to 0.3keV. Characteristics of the reconnection heating were measured directly by two dimensional measurements of ion and electron temperatures. While electrons are heated inside the current sheet by the ohmic heating power, ions are heated mainly by fast shock or viscosity damping of the reconnection outflow (<Alfven speed) in the downstream areas. The magnetic reconnection converts energy of reconnecting magnetic field $B_p$ mostly to ion thermal energy, indicating that the reconnection heating energy is proportional to $B_p^2$. The ion heating power was observed to increase with the reconnection speed, indicating that any fast reconnection mechanism enables us to maximize the reconnection heating power. We started the largest-scale tokamak (ST) merging experiment MAST to conclude the reconnection heating physics and documented its strong ion heating up to 1.2keV and electron heating up to 0.8keV during the merging/ reconnection. Fine-scale Thomson scattering measurement measured a strongly peaked electron temperature profile during the reconnection and a caldera type profile after the reconnection. The heating characteristics of reconnection are quite similar in those merging experiments except for their confinement times and magnetic field amplitudes. The merging tokamak plasmas can easily provide MW-order heating power quite useful for efficient formation of high-beta plasma.

# Development of Turbulent Magnetic Reconnection through the Formation and Interaction of Flux Ropes

William Daughton[1], Vadim Roytershteyn[2] and Homa Karimabadi[2]

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Magnetic reconnection is important in a diverse range of applications in space and laboratory plasmas, and mostly commonly occurs in parameter regimes where the influence of collisions is weak or negligible. While significant progress has been made in understanding certain features of collisionless reconnection, most simulation studies have considered pre-existing ion-scale current sheets using 2D models. Understanding the influence of realistic three-dimensional (3D) dynamics remains one of the foremost challenges in reconnection physics. The ongoing exponential increase in computing power is now permitting fully kinetic 3D simulations [1] of sufficient size to explore a range of interesting questions. Here we focus on the most common type of reconnection layer with a finite guide field and highlight some of the profound differences in extending previous 2D results to large 3D systems. With a finite guide field, tearing modes are unstable at resonant surfaces across the initial layer, corresponding to oblique angles relative to the standard 2D geometry. The 2D models artificially suppress these oblique modes and greatly restrict the manner in which magnetic islands can interact. In real 3D systems, magnetic islands correspond to extended *flux ropes*, which can evolve and interact in a variety of complex ways not possible in 2D models, as demonstrated by recent laboratory experiments involving flux ropes [2-3]. The 3D kinetic simulations feature the formation and interaction of flux ropes within the initial current layer, followed by the generation of secondary flux ropes within the elongated electron-scale current sheets extending along the separatrices. New flux ropes spontaneously appear within these layers, leading to a complex turbulent evolution. To better understand the parametric dependencies, a range of guide fields are considered as well as asymmetric current sheets of relevance to the magnetopause. For weaker guide fields, the flux ropes can become kink unstable providing another potential mechanism to drive turbulence.

These results suggest that flux ropes are one of the fundamental building blocks for understanding 3D reconnection, and have motivated new efforts to systematically explore these interactions with kinetic simulations [4]. Preliminary results will be presented and opportunities for comparing with laboratory experiments will be discussed.

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# Direct evidence for a three-dimensional magnetic flux rope flanked by two active magnetic reconnection X-lines at the Earth's magnetopause

Marit Øieroset

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We report the direct detection by three THEMIS spacecraft of a magnetic flux rope flanked by two active X-lines producing colliding bi-directional plasma jets near the center of the flux rope. The observed density depletion and open magnetic field topology inside the flux rope inferred from electron behavior reveal that the flux rope has important three dimensional effects that are significantly different from those of two-dimensional magnetic islands. Furthermore, fluxes of 1 - 4 keVsuper-thermal electrons observed in the flux rope core were higher than those in the converging reconnection jets implying local electron energization within the flux rope. The large flux rope, with its cross section diameter exceeding 200 ion skin depths, also contains ion skin depth scale substructures within its core.

# Wave and Plasmoid Mediated Reconnections in Laboratory Experiments

M. Inomoto, Y. Hayashi, S. Ito, P. Copinger, S. Kamio, H. Tanabe, T. Ii, A. Kuwahata, Q.H. Cao, H. Itagaki, H. Sakamoto, A. Matsuda, S. Inoue, K. Gi, N. Suzuki, G. Watanabe, T. Yamada, Y. Ono

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Large dissipation in magnetic reconnection is usually recognized as a result of current sheet instabilities such as lower hybrid drift instability followed by a low frequency electro-magnetic instability called drift kink instability. In plasma merging experiments, excitation of low frequency wave was observed associated with the magnetic reconnection with a guide field.

Measurement of low frequency magnetic fluctuation in the vicinity of a current sheet was carried out in the TS-3 plasma merging device. The existence of the guide field brings drastic changes in the appearance of the magnetic fluctuation. Large magnitude of fluctuation with ion cyclotron range frequency ($\sim 2\omega_{ci}$) and parallel wavelength in the order of ion gyroradius was observed during the reconnection with guide field, suggesting relevance to the initiation of the fast magnetic reconnection. On the other hand, magnetic reconnection without guide field is accompanied by magnetic fluctuation near the end of and after the reconnection. The observed fluctuation frequency of 200-400kHz is close to that estimated from the motion of the reconnected field lines with m=1 and 2 deformation. This low frequency fluctuation may account for the significant ion heating in the reconnection without guide field observed in detail by a two-dimensional Doppler spectroscopy.

Plasmoid development was also observed in the guide field reconnection, resulting in a non-steady fast magnetic reconnection. Externally driven large inflow provokes tentative imbalance of the inflow and outflow fluxes, resulting in a density pile-up near the X point. The accumulated plasma in the current sheet is then suddenly released to develop transient fast magnetic reconnection, sometimes accompanied by current sheet / plasmoid ejection events.

This work was supported by Grants-in-Aid for Scientific Research, JSPS, Japan (22246119 and 22686085), and the Global COE Program “Secure-Life Electronics", MEXT, Japan.

# Is the magnetic field in the heliosheath laminar or a turbulent sea of bubbles?

*M. Opher, J.Drake, M.Swisdak, K. Shoeffler, J. D.Richardson, R.Decker, and G. Toth*

All the current global models of the heliosphere are based on the assumption that the magnetic field in the heliosheath, in the region close to the heliopause is laminar. We argue that in that region the heliospheric magnetic field is not laminar but instead consists of magnetic bubbles. We refer to it as the bubble-dominated heliosheath region. Recently, we proposed that the annihilation of the “sectored" magnetic field within the heliosheath as it is compressed on its approach to the heliopause produces the anomalous cosmic rays and also energetic electrons. As a product of the annihilation of the sectored magnetic field, densely-packed magnetic islands (that further interacts to form magnetic bubbles) are produced. These magnetic islands/bubbles will be convected with the ambient flows as the sector region is carried to higher latitudes filling the heliosheath. We further argue that the magnetic islands/bubbles will develop upstream within the heliosheath. As a result, the magnetic field in the heliosheath sector region will be disordered well upstream of the heliopause. We present a 3D MHD simulation with very high numerical resolution that captures the northsouth boundaries of the sector region. We show that due to the high pressure of the interstellar magnetic field a north-south asymmetry develops such that the disordered sectored region fills a large portion of the northern part of the heliosphere with a smaller extension in the southern hemisphere. We suggest that this scenario is supported by the following changes that occur around 2008 and from 2009.16 onward: a) the sudden decrease in the intensity of lowenergy electrons (0.02-1.5MeV) detected by Voyager 2; b) a sharp reduction in the intensity of fluctuations of the radial flow; and c) the dramatic differences in intensity trends between galactic cosmic ray electrons (3.8-59 MeV) at Voyager 1 and 2. We argue that these observations are a consequence of Voyager 2 leaving the sector region of disordered field during these periods and crossing into a region of unipolar laminar field.

**Hinode observations of dynamics in the solar atmosphere**

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The outer atmosphere of the Sun consists of the photosphere, chromosphere, transition region, and the corona, which shows us a wide variety of plasma conditions, i.e. weakly ionized to fully ionized plasmas, and collisional to collisionless plasmas. The solar atmosphere is the only astrophysical plasma that can be spatially resolved in order of ~200 km or less with the recent advanced telescopes. *Hinode*, launched on 22 September 2006, has been observing the Sun with high spatial magnetic-field measurements at the photosphere, high spatial Ca II H imaging measurements for the chromosphere, and EUV and soft X-ray imaging and spectroscopic measurements for the corona. *Hinode* observations show a variety of dynamical behaviors of the solar atmosphere, including plasma ejections and heating at the chromosphere and the corona and magneto-convection in the photosphere. One of our surprises is that the chromosphere, weakly ionized and collisional plasma, is much more dynamic than we have imagined. Active regions and emerging flux regions are the regions where more dynamics and intense heating are well observed both in the chromosphere and corona. Understanding the magnetic topology in active regions in association with ejections and heating events is useful for physically understanding magnetic reconnection events, such as solar flares and microflares. After a long minimum period of the solar activity cycle, *Hinode* recently has some successful observations for active regions and emerging flux regions. The observations covering the long-term evolution of active regions show various kinds of physical phenomena, associated with convection, the flux movements, flux emergences, magnetic cancellation and so on. Magnetic reconnection is now widely assumed as the main driver for ejections and heating. With *Hinode* observations, primarily from the Solar Optical Telescope, the presentation will show typical dynamics observed in active regions and will attempt to discuss the current understanding of dynamics and remaining key problems that the solar physicists have. The problems should be explored with the currently available observations from *Hinode*, SDO and other observatories, and in the future with the *Solar-C* mission that can much enhance our diagnostic capabilities.

**Parallel Electric Fields Producing Relativistic Electrons at Large Spatial Scales during Magnetic Reconnection***

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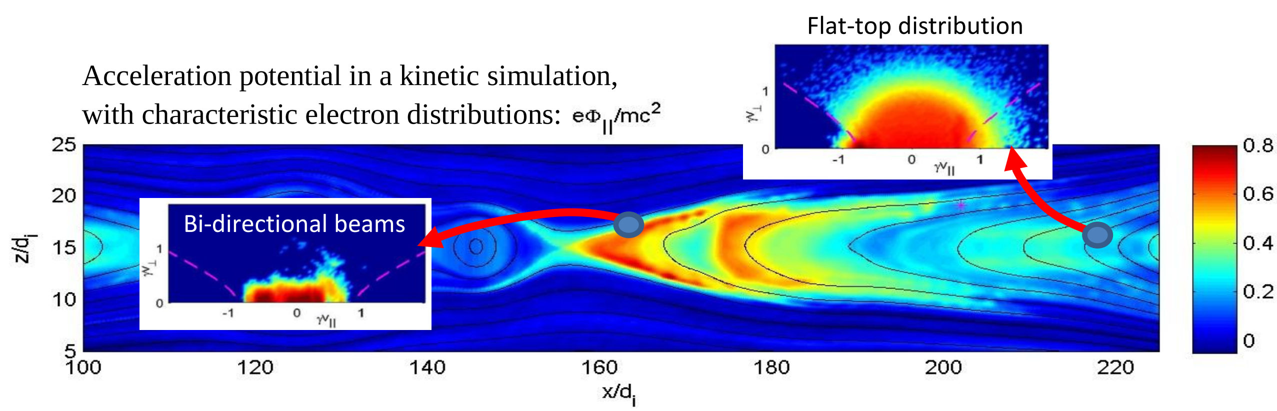
An analysis of superthermal electrons from spacecraft observations in the magnetotail provides evidence that direct acceleration by large scale parallel electric fields is a key mechanism for energizing electrons during magnetic reconnection over length scales reaching far beyond the electron diffusion region [1]. Here we present new kinetic simulation results that corroborate this heating mechanism. The parallel electric fields, $E_{||}$, develop to maintain quasi-neutrality by regulating the electron density, trap a large fraction of thermal electrons, and heat electrons in the parallel direction [2, 3]. Thus, a key parameter for these dynamics is the acceleration potential $\Phi_{||}$, the energy electrons gain from $E_{||}$ as they enter the region along magnetic field lines [4]. With the newly derived equations of state (including the trapped electron dynamics) [5], momentum balance across the electron diffusion region requires that the strength of $\Phi_{||}$ depends strongly on the upstream $\beta_e$ (the electron pressure normalized to the magnetic field pressure) and becomes large at low values of $\beta_e$ [6]. Typically, numerical investigations apply $\beta_e \approx 0.05$ yielding values of $e\Phi_{||}/T_e \approx 2 - 5$. Meanwhile, in our new large scale kinetic simulation, we apply a value of $\beta_e \approx 0.008$ that is likely more representative for magnetotail reconnection [3]. In accordance with our theoretical scaling [6], the simulation reveals strongly elevated values of $e\Phi_{||}/T_e \approx 100$. Furthermore, the area where $\Phi_{||}$ is large fills the exhaust region over tens of ion inertial lengths (note, in the figure $e\Phi_{||}$ is normalized by $m_e c^2$). As additional confirmation of the heating mechanism, the electron distributions in the simulations are in excellent agreement with those observed by spacecraft, reproducing the bi-directional beams in the inflow region, the inward directed beams along the separators and flat-top distributions in the exhaust.

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# Anomalous resistivity and multi-scale simulation of collisionless driven reconnection in an open system

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Magnetic reconnection is a typical cross-hierarchy phenomenon controlled by multi-scale physics from microscopic physics relating to electron and ion dynamics through macroscopic one such as plasma transport in a global scale. In order to investigate full picture of magnetic reconnection, we have developed two kinds of numerical simulation models. One is the electromagnetic particle model for an open system ("PASMO"). The other is multi-scale simulation model for magnetic reconnection ("MARIS").

A series of particle simulations using PASMO code have revealed new features of microscopic physics of collisionless driven reconnection in open systems. The growth of pressure tensor and formation of non-Maxwellian distribution function in the central current layer demonstrate that the meandering orbit effect play a crucial role in triggering collisionless reconnection [1,2].

Anomalous resistivity due to plasma instabilities excited in an ion-scale current sheet is also investigated as another triggering mechanism of collisionless reconnection. Lower hybrid drift instability (LHDI) is excited in the periphery of the current sheet in a relatively early phase. Anisotropic ion distribution is formed through an interaction between electrostatic fluctuation excited by LHDI and meandering ions with large orbit amplitude and causes the growth of a longer kink mode in the central region [3]. The generated anomalous resistivity is large enough to explain magnetic reconnection phenomena observed in the magnetosphere and laboratory experiments.

The multi-scale simulation model consists of three parts, i.e., MHD model to describe global dynamics of reconnection phenomena, PIC model to describe the microscopic processes in the vicinity of reconnection point where PASMO code is used, and interface model to describe the interaction between micro and macro hierarchies [4,5]. The model is applied to a few numerical test programs and collisionless driven reconnection in a simple geometry and is confirmed to work well. We will describe the details of simulation model and obtained new features of collisionless driven reconnection in our presentation.

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# Whistler and Alfven-Whistler Mode Emission from Magnetically Reconnecting Current Layers

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Analysis of whistler mode and Alfven-whistler emissions from magnetically reconnecting current layers can serve as a useful remote-sensing probe of plasma conditions in the vicinity of the electron diffusion region. Whistler waves associated with magnetic reconnection are frequently observed in the Earth's magnetosphere (recent examples: Geotail and Cluster satellites; Wei et al., 2007, Eastwood et al., 2009, Le Contel, et al., 2009, etc.) and in laboratory experiments. From the observations, electron beams and electron thermal anisotropy have been identified as possible free energy sources for the whistler/electron cyclotron emission. In addition, kinetic Alfven waves have also been observed to propagate outwards from the reconnection X-line and that these waves may drive significant transport through the diffusion region (Chaston et al., 2005, 2009). Further analysis by Huang et al., 2010 using the Cluster spacecraft indicates highly oblique propagating modes consistent with the Alfven-whistler branch which seem to interpret the measurements. In light of these observations we make comparisons with kinetic simulations. In our previous work, using 2D electromagnetic particle-in-cell model with adaptive mesh refinement in a Harris-type current sheet (Fujimoto and Sydora, Geo. Res. Lett., vol. 35, L19112 (2008)), we found that whistler modes driven by electron temperature anisotropy transiently formed in the downstream region of the electron outflow where the magnetic field is intensified due to pileup of the field lines. The maximum wave power from the unstable electromagnetic fluctuations ranged from 0.1 to 0.6 of the local electron cyclotron frequency and the quasi-parallel propagating (right-hand polarized) whistler modes were found to contribute weakly to the electron momentum transport. In this presentation we extend our previous results and analyze electron and ion beam-generated whistler fluctuations and Alfven-whistler modes in the vicinity of the outflow regions. A theoretical analysis of the maximally unstable modes and wave polarization properties are presented based on parameters consistent with Cluster spacecraft X-line encounters. We find that whistler mode fluctuations are capable of increasing the phase space density up to 2keV and higher within a second time scale and play a role in beam generation. Implications of these results to future missions, such as MMS, will also be presented along with possible laboratory experiments.

# Global magnetic reconnection in solar and laboratory environments.

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**Abstract**

We present numerical simulations of two magnetically-dominated plasma systems where the global structure and evolution of magnetic fields is shown to be closely tied with the reconnection rate and dynamics of local magnetic reconnection regions. In the solar corona, many of the proposed coronal mass ejection (CME) initiation mechanisms rely on magnetic reconnection as the necessary element in allowing CME flux ropes to elevate from the solar surface and escape through overlying magnetic fields. Here, by way of two-dimensional fluid-based simulations of the breakout CME initiation model, we show that the rate of reconnection both in front and behind the escaping flux rope may be an important factor in determining the acceleration of the CME away from the solar surface. We demonstrate the feedback mechanism between the global and local scales and describe the properties of the two qualitatively different reconnection sites.

In the laboratory environment, we model the dynamics of three-dimensional (3D) magnetic reconnection in a Swarthmore Spheromak Experiment-like system where magnetic fields are observed to evolve from an unstable force-free equilibrium to a minimum energy state by way of global rearrangement of the magnetic topology. The process approximately conserves total magnetic helicity and reconnection through a magnetic null is the dominant magnetic energy loss mechanism. During the period of most intense reconnection, the 3D localized reconnection region is observed to follow the magnetic null moving at a substantial fraction of the Alfvén speed (up to $0.2 v_{Alf}$)[1]. Here, we explore the qualitative effects of a moving 3D reconnection region on the rate of change of magnetic topology and the associated non-ideal electric fields. We also demonstrate the quantitative impact of background plasma beta and ion inertia (the Hall effect) on the measured correlation between the motion of the magnetic null and the reconnection region.

*This research is supported by the Department of Energy and the Office of Naval Research.

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# Ion energization during magnetic reconnection in the reversed field pinch

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(Dated: April 28, 2011)

## Abstract

In the Madison Symmetric Torus reversed field pinch discrete bursts of magnetic reconnection are the result of resonant tearing modes. These events liberate a large amount of energy ($\sim$ 20 kJ) from the equilibrium magnetic field some of which is then converted into ion kinetic energy. A significant fraction appears as ion thermal energy in a time $\lesssim 100$ $\mu$s, much shorter than the collisional e-i relaxation time ($\sim 10$ ms). The efficiency of this energy conversion is found to vary as $m^{1/2}$ from 10% for hydrogen plasmas to 20% for helium. Localized measurements of the impurity $C^{+6}$ ion temperature reveal it to be higher than the majority temperature in deuterium plasmas (although the thermal energy content is lower). Furthermore, the impurity temperature is found to be anisotropic such that the temperature perpendicular to the mean magnetic field is larger than the temperature parallel to the magnetic field near in time to the reconnection. This observation implies a heating mechanism which favors the perpendicular degree of freedom.

In addition to thermal heating, measurements of neutral particle energy spectra and neutron flux show that a high energy tail on the distribution function of the majority ions is generated at the reconnection. The fast ions are well-described by a power law and have energies up to 10x the thermal energy, and possibly higher. It is not yet clear whether these fast ions are a result of the same process responsible for the heating or if they are the result of a distinct physical mechanism. It is clear however that they are energetically important, accounting for up to 10% of the initial magnetic field energy.

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**Fast magnetic reconnection in high-energy-density laser-produced plasmas**

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University of New Hampshire

Recent experiments have observed magnetic reconnection in high-energy-density, laser-produced plasma bubbles [1,2], with reconnection rates observed to be much higher than can be explained by classical theory. This is a novel regime for magnetic reconnection study, characterized by extremely high magnetic fields, high plasma beta and strong, supersonic plasma inflow. Reconnection in this regime is investigated with particle-in-cell simulations. Work to-date with collisionless simulations has identified two key ingredients, simultaneously present for the first time: two-fluid reconnection mediated by collisionless effects (that is, the Hall current and electron pressure tensor), and strong flux-pileup of the inflowing magnetic field [3]. We will present initial studies of more detailed experimental modeling which includes a collision operator, and also present some ideas for future laser-driven reconnection experiments.

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# Experimental Investigation of the Trigger Problem in Magnetic Reconnection*

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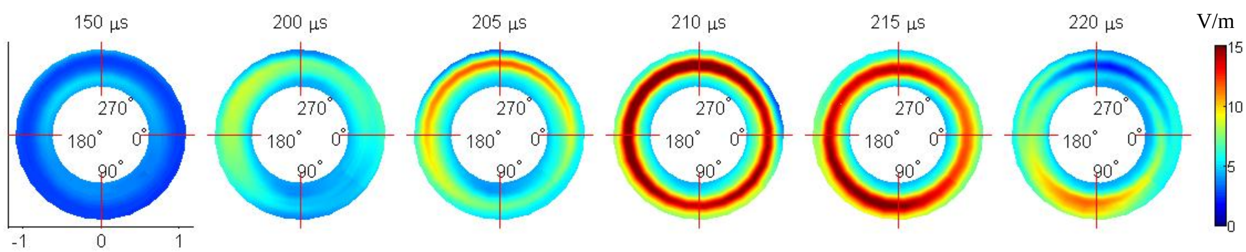
Magnetic reconnection releases magnetic energy not only in steady-state, but also in time-dependent and often explosive events requiring a transition from slow reconnection to fast. The question of what causes this transition is known as the “trigger problem” and is not well understood. We address the trigger problem using the Versatile Toroidal Facility (VTF) at MIT. We observe spontaneous reconnection events [1] with exponentially growing reconnection rates, and we characterize the 3D dynamics of these events using multiple internal probes. The observed reconnection is asymmetric: it begins at one toroidal location and propagates around in both directions (see [2] and Fig. below). The spontaneous onset is facilitated by an interaction between the x-line current channel and a global mode in the electrostatic potential. It is this mode which breaks axisymmetry and enables a localized decrease in x-line current. We model the onset using an empirical Ohm’s law and current continuity, which is maintained by ion polarization currents associated with the mode. The model reproduces the exponential growth of the reconnection electric field, and the model growth rate agrees well with the experimentally measured growth rate. The onset location is likely determined by small asymmetries in the in-vessel coils. To further investigate this conjecture new coils have been installed, which allow for controlled changes in toroidal asymmetry. The observations are suggestive of solar flare dynamics and are relevant to tokamak research [3].

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# Experimental observation of instability cascade from MHD to ion skin depth scale resulting in magnetic reconnection

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Magnetic reconnection necessarily involves processes beyond the scope of ideal MHD. Finite resistivity is known to provide a possible non-ideal MHD process, but is quantitatively inadequate to explain observed reconnection rates in many important situations. Shibata and Tanuma[1] proposed that the observed high magnetic reconnection rates result from a cascade of instabilities through progressively smaller scales until a microscopic scale length is reached at which non-MHD processes enable magnetic reconnection. Our experiment at Caltech produces a magnetically driven plasma jet that undergoes an ideal MHD, current-driven kink instability; the addition of a longer duration power supply revealed that the kink instability amplitude could grow either linearly or exponentially. In the case of exponential growth, a segment of the kinked jet thins to form a bright filament. The laterally outward acceleration of this segment of the kinked jet provides an effective gravity, leading to development of a Rayleigh-Taylor instability on the trailing edge of the thin filament. At the time we observe this distinct, spatially periodic Rayleigh-Taylor instability, the plasma has reached the ion skin depth scale (i.e. non-MHD scale), the current density becomes so large that the electron drift velocity reaches the order of the Alfvén velocity, and the instability initiates observed magnetic reconnection of the jet. The instability cascade from macroscopic kink instability to microscopic Rayleigh-Taylor instability thus transitions the plasma from an ideal MHD scale to an ion skin depth scale where non-MHD processes enable magnetic reconnection.

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**Opportunities for collisionless laboratory astrophysics in magnetized plasmas with a high-energy laser**

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The recent activation of a kilojoule-class laser at UCLA which can be coupled into the existing Large Plasma Device (LAPD) opened up new possibilities for experimental studies of laboratory astrophysics. Impulsive plasma bursts exploding in a surrounding steady, magnetized plasma can be used as a platform for triggering processes relevant to collisionless shocks, highly-nonlinear plasma waves, magnetic reconnection, and others. Here we present the laser facility capability, as well as the new parameter space available.

**Hydrodynamic Simulation of Laboratory Astrophysics Experiments Generating Collisionless Shocks With Intense Lasers**

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[5]Osaka University, Osaka, Japan;
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[8]Ecole Polytechnique, Paris, France;
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[10]University of York, Heslington, York, UK

Collisionless shocks, shocks generated by plasma wave interactions in regions where the collisional mean-free-path for particles is long compared to the length scale for instability growth in counter-propagating flows, are found ubiquitously in astrophysics. Experiments to investigate collisionless shocks in a laboratory-scale system are being carried out in which intense lasers were used to generate counter-streaming flows by laser ablation. Diagnostic techniques such as Thomson scattering and optical interferometry can probe the interaction region to provide measurements of density, temperature, and velocity of the plasma, while proton deflectometry can be used to characterize the magnetic field in the interaction region. Hydrodynamic simulations can be used to model the ablative flow of plasma generated in the experiment in order to assess experimental designs and infer properties of collected data from previous single foil experiments. Additionally, Particle-In-Cell (PIC) (see poster by L. Gargate et al.) codes are used to model the interaction of the two flows in the experiment, as the fluid model breaks down in collisionless regime. This poster will provide some overview of our current efforts to carry out these experiments, and will focus in more detail on hydrodynamic simulations for design and analysis.

# Impulsive penetration observed at the magnetopause

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Plasmoids with higher momentum density than the surrounding plasma can penetrate magnetic field barriers through self-polarisation. As the electrons and ions gyrate in opposite directions, space charge sheaths form on the plasmoid edges, and this causes a polarisation electric field $\vec{E} = -\vec{v} \times \vec{B}$ to be set up inside. Thus, the plasma is able to continue moving with its initial velocity by means of an $\vec{E} \times \vec{B}$-drift, as described theoretically by *Schmidt* (Phys. Fluids, vol. 3, 961, 1960).

This process has been studied rather extensively in laboratory experiments with flowing plasmas (*e.g. Baker and Hammel*, Phys. Fluids, vol. 8, 713, 1965; *Lindberg*, Astrophys. Space Sci., vol. 55, 203, 1978; *Ishizuka and Robertson*, Phys. Fluids, vol. 25, 2353, 1982; *Hurtig*, et al., Phys. Plasmas, vol. 11, L33, 2004). Similar behaviour has been observed for laser produced plasmas in magnetic fields (*Ripin, et al.*, Phys. Rev. Lett., vol. 59, 2299, 1987; *Mostovych, et al.*, Phys. Rev. Lett., vol. 62, 2837, 1989).

Lemaire suggested that inhomogeneities in the solar wind can penetrate the magnetopause as plasma filaments through a process called impulsive penetration (*Lemaire*, Planet. Space Sci., vol. 25, 887, 1977). Satellite based measurements have shown evidence of magnetosheath plasma inside the magnetosphere (*Woch and Lundin*, J. Geophys. Res., vol. 97, 1431, 1992; *Lundin, et al.*, Annales Geophysicae, vol. 21, 457, 2003).

We present Cluster data showing in situ observations of magnetosheath plasma penetrating the dayside magnetopause. Plasmoids of magnetosheath plasma are observed when the spacecraft are located on closed field lines in the dayside magnetosphere. As the spacecraft cross the magnetopause, a transition region is seen in which there is a net flux of plasma from the magnetosheath into the magnetosphere. The plasma flux across the magnetopause was a few per cent of the solar wind flux at the time. We show that impulsive penetration, which is known from the laboratory, also occurs in space.

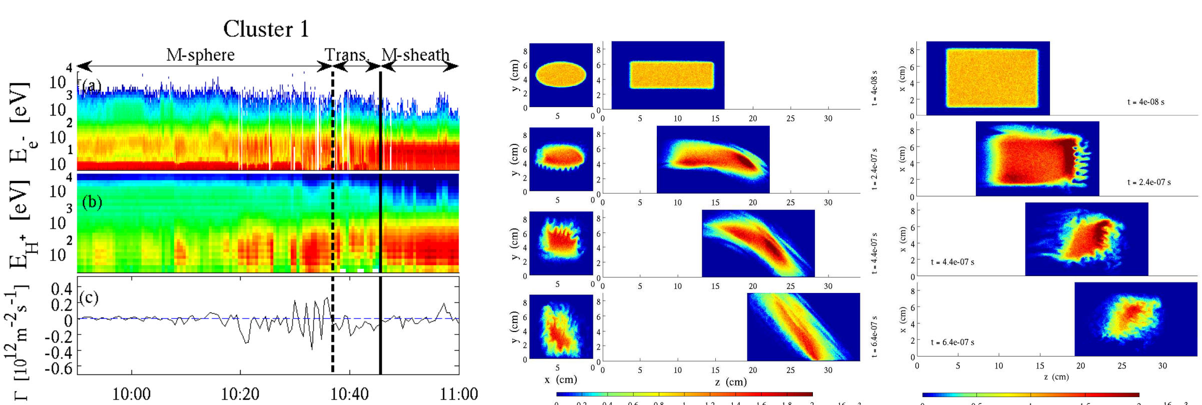


Figure 1: Left column: Cluster data showing the electron spectrum (a), ion spectrum (b), and cross-magnetopause proton flux (c). Negative values correspond to inward flux. The other panels show the plasma density in a simulation of a laboratory experiment where a plasmoid entered a magnetic field at a 45° angle (simulation pictures from *Gunell, et al.*, Phys. Plasmas, vol. 16, 112901, 2009).

**First observations of electromagnetic instabilities in the ALEXIS plasma column**

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Electromagnetic waves, such as the whistler and ion cyclotron modes are commonly observed in the Earth's ionosphere and magnetosphere. In the auroral ionosphere, ion cyclotron waves can affect space weather by heating ions and initiating outflows. In the magnetosphere, whistlers and electromagnetic ion cyclotron (EMIC) waves help to control radiation belt particle fluxes by scattering trapped high-energy electrons.

The goal of this project is to investigate generation of EMIC waves by localized cross-magnEriketic field plasma flows and then to use these waves as a starting point for the investigation of EMIC wave-energetic electron interactions. EMIC waves are driven by inhomogeneous **E** x **B** flows for combinations of plasma density and background magnetic field strength yielding sufficient plasma β. It is possible to characterize the EMIC wave by studying the effects from a localized magnetic field and electron density profiles, as well as to study the properties of the instability in multiple gas species. Once EMIC waves are generated, energetic electron beams will be introduced into the plasma to investigate particle scattering.

This study is performed through a series of coordinated experiments that use the Auburn Linear Experiment for Instability Studies (ALEXIS) and the Naval Research Laboratory Space Physics Simulation Chamber (SPSC). ALEXIS is being used for studies of wave generation. The SPSC is used for both wave generation[1] and wave-particle interaction studies. Previous studies of electrostatic ion cyclotron instabilities have demonstrated that the two experiments can be used to investigate scaled, space-relevant phenomena.[2,3] This presentation discusses the first observations of electromagnetic instabilities in the ALEXIS device. In these studies, a three axis magnetic loop probe that was developed in partnership with the NRL group is used to measure the changing magnetic field associated with electromagnetic instabilities in ALEXIS. The instability is shown to occur near the ion cyclotron frequency and the properties are shown to change as the structure of a localized electric field varies. Measurements of wave amplitude, frequency and wave magnetic field will be presented.

This project is supported with funds from the Defense Threat Reduction Agency (DTRA) and the U.S. Department of Energy (DOE).

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**Laboratory study of shear flow driven ion cyclotron electrostatic instabilities**

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The role of transverse and parallel sheared flows in ionospheric plasmas has been a topic of great importance to the space plasma community. For example, both transverse and parallel flow shears are believed to be important mechanisms for the generation of ion acoustic and ion cyclotron instabilities. Much work has been done, both by laboratory experiments and by satellite observations, to fully understand the conditions that lead to stability or instability in the presence of these flows.

The scale size of space plasmas provides a unique diagnostic challenge. Satellites typically make very localized measurements, making it difficult to completely diagnose the global plasma environment. Additionally, the Earth's plasma environment is in constant flux, further complicating the task of isolating individual mechanisms.

Small scale laboratory experiments are often more flexible and provide easier diagnostic access than other plasma environments. The Auburn Linear EXperiment for Instability Studies (ALEXIS) is a 170 cm long, 10 cm diameter, linear magnetized, rf generated plasma column, which, in addition to existing Langmuir and emissive probes, has recently been outfitted with a Laser Induced Fluorescence system. Recent experiments have focused on modifying the plasma potential and characterizing the plasma response. Initial results indicate that modification of the radial electric field results in modification of both the azimuthal and radial ion flows. Measurements will be presented on the correlation between different low frequency ($\omega \approx \omega_{ci}$) wave features and the electric field, density, and flow structures in the plasma.

This project is supported with funds from the Defense Threat Reduction Agency (DTRA) and the U.S. Department of Energy (DOE).

Blast-wave-driven instability experiments relevant to supernova hydrodynamics

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T. Plewa
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This presentation discusses experiments scaled to the blast wave driven instabilities at the He/H interface during the explosion phase of SN1987A. This core-collapse supernova was detected about 50 kpc from Earth making it the first supernova observed so closely to earth in modern times. The progenitor star was a blue supergiant with a mass of ~18-20 solar masses. A blast wave occurred following the supernova explosion because there was a sudden, finite release of energy. Blast waves consist of a shock front followed by a rarefaction wave. When a blast wave crosses an interface with a decrease in density, hydrodynamic instabilities will develop. These experiments include target materials scaled in density to the He/H layer in SN1987A. About 5 kJ of laser energy from the Omega Laser facility irradiates a 150 $\mu$m plastic layer that is followed by a low-density foam layer. A blast wave structure similar to those in supernovae is created in the plastic layer. The blast wave crosses an interface with a drop in density and a precision-machined interface with multiple modes. The specific modal structure is based on simulation results of the evolution of the progenitor star. This produces unstable growth dominated by the Rayleigh-Taylor (RT) instability. We have detected the interface structure under these conditions, using dual orthogonal radiography, and will show some of the resulting data.

This work is funded by the NNSA-DS and SC-OFES Joint Program in High-Energy-Density Laboratory Plasmas, grant number DE-FG52-09NA29548, and by the National Laser User Facility Program, grant number DE-FG52-09NA29034.

# Observation of large-scale velocity fluctuations in the Princeton MRI experiment

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The Princeton MRI Experiment is a modi ed Taylor-Couette device with a GaInSn working uid used for the study of rotating MHD ows. A recently-installed Ultrasound Doppler Velocimetry (UDV) system allows the measurement of internal uid velocities. Starting from both hydrodynamically stable and hydrodynamically unstable background ow states, large-scale, large-amplitude, coherent, nonaxisymmetric velocity uctuations have been observed when a su ciently strong magnetic eld is applied. The presence and saturated amplitude of these uctuations is dependent on both magnetic eld strength and rotation speed. There is a particular dependence on the shear between the axial endcaps of the experiment, suggesting that the boundary layers play a signi cant role. The uctuations are absent in regimes where the magnetorotational instability is expected to be observed. Theoretical investigations of these uctuations using linear stability analysis and nonlinear 3-D simulations are ongoing. Measurements from the UDV diagnostic and from external magnetic diagnostics will be presented.

**Measurements and Simulations of Electric Field Modified Flows in the Compact Toroidal Hybrid Stellarator**

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Auburn University

Sheared flows arising from spatially inhomogeneous, transverse electric fields are common phenomena found in space, laboratory, and fusion plasmas. These flows are a source of free energy that can drive or suppress instabilities. In space plasmas, numerous observations of electrostatic and electromagnetic instabilities in the ion cyclotron regime[1] have been made. By contrast, in fusion plasmas, edge localized sheared flows provide a barrier against cross field particle transport and the presence of these flows are associated with enhanced confinement regimes (H-mode).[2]

A multi-regime project to explore sheared flows and the instabilities associated with them, is an on going collaboration between the Auburn University (AU) Plasma Sciences Lab (PSL), Compact Toroidal Hybrid (CTH) and the Naval Research Laboratory Space Simulation Chamber (SPSC). The SPSC contribution explores parameter ranges relevant to space conditions. At AU, CTH resides in the fusion regime with the PSL acting as a bridge between the two. This presentation will focus on the CTH contributions to this project.

CTH is five field period continuously wound stellarator ($R_0 = 0.75m$, $a \sim 0.2m$, $B_0 \leq 0.7T$, $\bar{n}_e = 0.2 - 1.5 \times 10^{19} m^{-3}$) run with $100ms$ long plasmas. Primary plasma generation and heating is provided through Electron Cyclotron Resonance Heating (ECRH) with a secondary Ohmic heating system. Flow experiments are performed by modifying the radial electric field by inserting an biasing electrode probe past the last closed flux surface. Plasma parameters are measured using a triple probe. Initial measurements of flows from a newly constructed Gundestrup probe will be presented. This probe is a multi-headed mach probe that allows not only measurements of fluid speed but direction as well.

One unique aspect of CTH is the incorporation of the three dimensional equilibrium reconstruction code V3FIT as a standard diagnostic. A newly developed code based upon reconstructed equilibria, calculates full particle trajectories. Using a Monte-Carlo technique the effects of confinement time and particle fluid flow can be explored for various electric field configurations. This presentation will discuss the development and initial results of this code.

This work is supported by DOE grants:
DE-FG02-00ER54476 and DE-FG02-00ER54610

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# Pulsed regimes of electron cyclotron instabilities in a mirror confined plasma produced by ECR discharge

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Despite more than half a century history, the studies of the interaction between electromagnetic waves and particles in magnetoactive plasma under electron cyclotron resonance (ECR) conditions still remain topical. One of the most interesting ECR manifestations is the generation of bursts of electromagnetic radiation that are related to the explosive growth of cyclotron instabilities of the magnetoactive plasma confined in magnetic traps of various kinds and that are accompanied by particle precipitations from the trap. Such phenomena are observed in a wide range of plasma parameters under various conditions: in the magnetospheres of the Earth and planets, in solar coronal loops, and in laboratory magnetic traps.

We demonstrate the use of a laboratory setup based on a magnetic mirror trap with plasma sustained by a gyrotron radiation under ECR conditions for investigation of the cyclotron instabilities similar to the ones which take place in space plasmas. Two regimes of the cyclotron instability are studied. In the first place, quasi-periodic pulsed precipitation of energetic electrons from the trap, accompanied by microwave bursts at frequencies below the electron gyrofrequency in the center of the trap, is detected. The study of the microwave plasma emission and the energetic electrons precipitated from the trap shows that the precipitation is related to the excitation of whistlers propagating nearly parallel to the trap axis. The observed instability has much in common with phenomena in space magnetic traps, such as radiation belts of magnetized planets and solar coronal loops. Such regimes have much in common with the quasi-periodic VLF radiation in the Earth's inner magnetosphere (with periods of T ~ 100 s) and can also be met in solar flaring loops and at other space objects.

In the second place, we have detected and investigated quasi-periodic series of pulsed energetic electron precipitations in the decaying plasma of a pulsed ECR discharge in a mirror axisymmetric magnetic trap. The observed particle ejections from the trap are interpreted as the result of resonant interaction between energetic electrons and a slow extraordinary wave propagating in the rarefied plasma across the external magnetic field. We have been able to explain the generation mechanism of the sequences of pulsed precipitations at the nonlinear instability growth phase in terms of a cyclotron maser model in which the instability threshold is exceeded through a reduction in electromagnetic energy losses characteristic of the plasma decay. The conditions in the decaying plasma resemble those in auroral plasma cavities and similar systems, and in this case electromagnetic waves with quasi-perpendicular propagation direction are excited.

Our experimental results and their comparison to theory allow us to expect that future experiments will provide a more detailed study of such phenomena that play an important role in the dynamics of laboratory, geospace, planetary, and solar plasmas.

Scattering of Magnetic Mirror-trapped fast Electrons by an Alfven Wave

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Highly energetic electrons produced naturally or artificially can be trapped in the earth's radiation belts for months, posing a danger to satellites. A technique for artificially de-trapping these electrons with Alfven waves is under investigation at the Large Plasma Device (LaPD) at UCLA. The experiment is performed in a quiescent afterglow plasma ($n_e \approx 0.1 \text{ to } 1\times10^{18}$/m$^3$, $T_e \approx 0.5$ eV, $B_0$ = 400 to 1200 G, $L$ = 18 m, and diameter = 0.6 m). The magnetic field is programmed to include a magnetic mirror section approximately 3 m long, with $1.1 \le R_m \le 4$. A trapped fast electron population is generated in the mirror section using second harmonic ECRH. The heating source utilizes a 25 kW magnetron, operating at 2.45 GHz, with the microwave power injected for 10 - 50 ms. Longer injection periods ($\tau$>30ms) resulted in a population of runaway electrons as evidenced by X-ray production when the electron orbits hit a probe or the waveguide. The fastest electrons are generated in an annular region in front of the waveguide, with a radial extent of several cm and axial extent L≈ 1 m. Alfven waves are launched with $\delta B/B_{min}$ less than 0.5%, at frequencies ranging from 115 to 230 kHz (0.19 to 0.75 of $f_{ci}$ in the straight field). Using the X-ray production, $V_\perp$ probes and Langmuir probes as diagnostics, the Alfven waves are observed to dramatically affect the fast electron orbits. Within as little as 10 Alfven wave periods, the X-ray signal as well as signals from probe measurements of mirror trapped fast electrons disappear. Runaway electrons are observed even after the microwaves are terminated. The Alfven wave can modify the runaway orbits sufficiently to produce X-rays for up to 7 ms after the microwaves are terminated, as they scattered out of the plasma.

This work is supported by The Office of Naval Research and performed at the Basic Plasma Science Facility under ONR MURI 00014-07-1-0789. The BaPSF is funded by the Department of Energy and the National Science Foundation.

Contribution submission to the conference IPELS2011

**Reducing global turbulent resistivity by eliminating large eddies in a spherical liquid-sodium experiment** — •Elliot J Kaplan[1], Mike M Clark[1], Mark D Nornberg[1], Kian Rahbarnia[1], Alex M Rasmus[1], Eric J Spence[2], Nicholas Z Taylor[1], John P Wallace[1], and Cary B Forest[1] — [1]Department of Physics, University of Wisconsin-Madison, 53706 Madison,WI, USA — [2]Princeton Plasma Physics Laboratory, New Jersey 08544, USA

The magnetic induction equation is often simplified by applying mean field magnetohydrodynamics to approximate the effects of small-scale fluctuations upon the evolution of the large scale magnetic field. It is not always valid to assume scale separation between the field and the flow in physical systems, but the $\alpha$ and $\beta$ effects of mean field theory can be recovered for the largest scale eddies in a spherical geometry. This geometry allows the magnetic evolution to be evaluated as the product of a set of three-wave-couplings between the large-scale field and the turbulent flow. The Madison Dynamo Experiment (MDE) is a liquid-sodium sphere (1 m in diameter) studying onset conditions of the Dynamo instability. A baffle was recently added to the MDE to inhibit the turbulent eddies that cross the boundary. Measurements of the induced field reveal that the baffle has diminished the effects of turbulent eddies upon the magnetic evolution. This has resulted in a $\sim$ 2.4 fold increase in field line stretching by the toroidal flow (decreased $\beta$ effect) and a $\sim$ 90% reduction in the induced axisymmetric dipole field ($\alpha$ effect). This work is supported by the CMSO and the NSF/DOE partnership in plasma physics.

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| Part: | 11th IPELS, Whistler, Canada |
| Type: | poster |
| Topic: | Magnetic dynamo and turbulence |
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# Plasma Dynamo Experiments

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April 29, 2011

**Abstract**

The Madison Plasma Dynamo Experiment (MPDX) is under construction to explore the self-excitation processes of a range of astrophysical dynamos. Numerical simulations of von Kármán flow have shown that a two-vortex flow can produce a dynamo when the magnetic Reynolds number is sufficiently high, which, for a plasma, requires a large, hot, flowing AND unmagnetized plasma. This poster discusses experimental plans for von Kármán flow in MPDX as well as prototype experiments on the Plasma Couette Experiment (PCX). The PCX is a cylindrical plasma experiment currently being used to optimize a multi-cusp magnetic confinement scheme for experiments on the magnetorotational instability. It also provides a platform for prototyping two types of plasma sources (electron cyclotron heating and LaB6 cathode), and ExB stirring mechanism, diagnostics, and future MPDX dynamo scenarios. This poster will review recent findings from PCX involving two different azimuthal flow driving mechanisms: measured ExB driven flows of up to 10 km/s using a heated electrode, as well as the fabrication of a new LaB6 electron source and its use in driving Dean flow. While currently attainable densities ($n_e \approx 10^{17}$ m$^{-3}$, using electron cyclotron heating ) require Hall MHD in calculating the plasma response to various flow profiles, the new LaB6 electron source may allow high enough densities to place the plasma in a purely MHD regime. Work supported by NSF.

# Development of Transport and Removal experiment of Dust (TReD) Device for the large magnetic Fusion Devices

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Hazardous dust particles in fusion machines have to be controlled due to significant issues such as radioactivity, fuel retention, and safety in future fusion devices like ITER since they are radio-active toxic or explosive Although the dust removal experiments for fusion reactor had been tried in 1990s [1], it cannot applied to future machines since the experimental scale was too small (12 cm) compared to the size of a tokamak. To study the dust particle transport and removal from the vacuum chamber, we have developed a dedicated plasma device TReD (Transport and Removal experiments of Dust) by applying "electric potential curtain". In order to get the relevant effect in real size tokamaks, the device is designed to transport dusts up to 100 cm. The dust transport experiment has been carried out by varying amplitude and frequency of voltage applied to bottom electrode, and the dust transportation is to be observed by CCD cameras (from a side and from the top). We present the preliminary results of the TReD experiment along with the comparison of a semi-analytical solution to the experimental condition for the translation of dust particles to the two-dimensional directions.

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**Development and Performance Tuning of the Dusty Plasma Simulation Code DEMON**

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Dusty (complex) plasmas are found in a broad range of environments ranging from the largest nebula to the manufacturing of the smallest microchips. In these systems, charged micro particles are suspended in a background plasma. The mutual interaction between the microparticles and the plasmas, in particular, the exchange of charge and energy, leads to the emergence of new plasma behaviors. Numerical tools that complement experimental investigations can provide new insights into the complex behaviors of dusty plasmas. The newly developed `DEMON`[1] (Dynamic Exploration of Microparticle clouds Optimized Numerically) code is a tool to simulate dusty plasmas using experimentally relevant parameters.

`DEMON` is an adaptive time step 2D N-body simulation of a dusty plasma using the $4^{th}$ order Runge-Kutta method to solve the equations of motion. A main feature of `DEMON` is use of a modular force model made possible though the use of Object-Oriented programming techniques. The architecture of `DEMON` allows the flexibility of a wide range of plasma dynamics to be simulated. New types of forces can be add with out altering the underlying solver. `DEMON` self consistently computes the dust motion using the user supplied force model assuming a uniform plasma background.

By using carefully defined constraints and choosing realistic plasma parameters, a broad range of dusty plasma phenomena can be recreated. Numerical experiments performed on `DEMON` have demonstrated the generation of phenomena such as: plasma crystals, waves, temperature effects and mach cones. All of these different systems were created by varying the forces acting on the particles.

In recent years single processor performance has plateaued. To compensate for this the number of processors in typical computer system has been steadily increasing. In order to achieve good statistics, a large number of particles must be used which increases computation time. To achieve reasonable computational times, all computing resources must be utilized. This presentation will discuss the adaptation of Single Instruction Multiple Data (SIMD) and parallel programing technologies to the `DEMON` codebase and the various types of forces acting on the dust grains.

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# Plasma Physics at the Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS)

A. Collette, M. Horanyi, Z. Sternovsky, T. Munsat, The CCLDAS Team

The Colorado Center for Lunar Dust and Atmospheric Studies (CCLDAS) is a member of the NASA Lunar Science Institute, focused on experimental and theoretical investigations of the lunar surface, including dusty plasma and impact processes, the origins of the lunar atmosphere, and the development of new instrument concepts.

CCLDAS supports a diverse experimental program, performed in conjunction with theory and simulation, to investigate the near-surface lunar plasma environment, dust charging and mobilization, and the effects of micrometeoroids. The flagship device at CCLDAS is a dust accelerator, completed and undergoing commissioning, which will allow simulation of micrometeoroid impacts at speeds relevant to the lunar environment. The accelerator will be available for direct science investigation as well as instrument calibration; in addition to our own research program, the experimental facilities are open to the lunar and space physics community.

The new Lunar Environment and Impact Laboratory (LEIL) at CCLDAS provides a vacuum chamber 1.2 m in diameter and 1.5 m long to house a simulated lunar surface with various regolith simulants. The chamber will be outfitted with UV sources to create a photoelectron layer and an ion source to simulate the solar wind. Particle and field probes will be tested in the simulated environment and adhesion of the lunar simulants to various materials will be examined. LEIL can be directly attached to the dust accelerator for impact studies. An additional UHV vacuum chamber enables investigation of impact physics, including sputtering and impact-generated plasmas.

CCLDAS is also working on simulating the near-surface lunar plasma environment via 1- and 3-dimensional particle-in-cell codes. The 3-dimensional code, VORPAL, is being used to investigate the role of surface topography on surface charge, potentials and electric fields, with emphasis on the resulting effects on dust transport or lofting processes.

# Complex sheath structure within realistic, low energy plasmas

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The measurement of low energy particles (T < =1eV), such as in ionospheric plasma, is inherently difficult for a variety of reasons. The inescapable ram velocity of in-situ rocket and satellite studies and the presence of a plasma sheath will prevent simplistic measurements of low energy plasmas. While simplified models of sheaths in stationary, Maxwellian plasmas are well understood, real sheaths can differ significantly when the plasma is more complicated.

Additional complications to the sheath structure are caused by high energy beams, non-Maxwellian populations, screen potentials, and plasma flow velocities. Other factors include the effects of a real boundary, such as secondary electron emission and non-uniform surface potential. The latter encompasses both unintentional non-uniformities, such as dirty or oxidized surfaces, and intentionally biased surfaces, such as Langmuir probes and electron detectors. These complications must be included in the data analysis due to their significant impact on current collection, and in extreme cases can form non-monotonic potential structures. In order to measure low energy plasmas accurately, sheaths must be rigorously studied.

Our research group seeks to study these non-ideal sheath structures for the accurate measurement of low energy ionospheric plasma using only low-resource detectors such that a multi-point array of such devices is cost effective. Additionally this research allows us to study the fundamental physics of static sheaths in complex environments, which has applications in all areas of plasma physics where thin sheath approximations are inappropriate.

We intend to both model complex sheaths through particle-in-cell codes and measure sheaths experimentally within the ELEPHANT plasma facility at Dartmouth College. This plasma facility generates argon plasma within a microwave resonance cavity, after which the plasma passes into the main experimental chamber with an ion flow velocity of 8 km/sec. The main experimental chamber is 1.5m long with a diameter of 1.2m. This large size allows many Debye lengths to be contained, since a typical Debye length for our plasma is a few centimeters.

We will present preliminary results of this extensive and ongoing sheath analysis and outline future goals and methods. Our first experiment within this study examines the perturbation to the sheath's structure caused by a sweep screen "hidden" behind a ground screen. This is common for retarding potential analyzers used in both laboratory and space based experiments. The prevailing assumption is that if the sweep screen is placed behind a grounded screen, the plasma will be unaffected by the modulating potential of the sweep. This however neglects the space charge due to the particles which are alternately being rejected, and thus reflected back into the sheath region, or accepted over the course of the sweep. We will examine the possible impact of this additional reflected population on the sheath structure.

**A LABORATORY EXPERIMENT TO MIMIC THE EFFECT OF AURORAL BEAMS ON SPACECRAFT CHARGING IN THE IONOSPHERE**

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A 2.54 cm diameter conducting, electrically isolated Copper sphere is suspended in a low density (~$10^{-4}$ $cm^{-3}$), low temperature ($T_e$ ~ 0.5 eV) Argon plasma, which mimics a spacecraft in an ionospheric plasma[1,2]. A collimated electron beam with current density of approximately $10^{-10}$ $A/cm^2$, which simulates an auroral electron beam[3], is fired at the sphere while varying beam energy from 0 – 2 keV. The plasma potential in the sheath around the sphere is measured using an emissive probe for various beam energies. The bulk plasma density and temperature is measured with a Langmuir probe. To observe the effects of the electron beam, the experimental sheath potential profiles are compared to a model of the plasma potential around a spherically symmetric charge distribution in the absence of electron beams. Comparison between the experimental data and the model shows that the sphere charges less negative than predicted by the model for beam energies that correspond with high secondary electron emission from the sphere's surface. This explains why spacecraft in the ionosphere do not charge up as negative as predicted by simple theory that does not take into account secondary emission, when flying through auroral electron beams.

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## Electric potential distributions in craters on airless bodies

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Craters on planetary surfaces have a variety of sizes relative to ambient plasma shielding distances. Our laboratory measurements show that the electric potential distributions in these craters vary significantly. An insulating plastic disc 11.5 cm in diameter with a hemispherical crater 2 cm in diameter in the center was immersed in plasma. The plasma shielding distance was adjusted with the plasma density. When the plasma shielding distance is smaller than the radius of the crater, the plasma expands into the crater and a potential barrier forms along the crater surface. When the shielding distance is larger than the radius of the crater, the potential distribution in the crater becomes more homogenous because the particle fluxes are balanced out at the entrance of the crater, indicating the plasma shield-out. This results in largely decreased electric fields in the crater, especially at the bottom. When charged dust particles are transported into these craters, they are unlikely to be transported out and will accumulate in the bottom. This mechanism could contribute to the formation of the dust ponds such as those observed on asteroid Eros and potentially present on other airless planetary bodies.

# Stability of a Line-tied Screw Pinch with Standard and Coaxial Current Injection

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April 29, 2011

**Abstract**

The internal kink instability in the Rotating Wall Machine (RWM) has an ideal character, but also exhibits reconnection events that periodically flatten the current profile and change the magnetic topology. The line-tied boundary conditions present an ideal analogue to coronal loop and solar flare physics. Internal measurements of $B$, $J$, and $V_z$ have been extensively gathered in the screw-pinch geometry. Through shot-to-shot averaging 2D equilibrium profiles and steady-state merger of current filaments are measured. The line-tying conditions in the RWM are examined through the structure of the measured magnetic field. Additionally, multiple-shot correlation analysis allows the reconstruction of mode eigenfunctions. Theories of coronal loop formation and stability indicate that current in coronal loops may be created by twisting vortices in the photosphere at the line-tied footprints of loops. Such convection necessarily creates a coaxial current structure where current on axis flows oppositely to current at larger radii. To study the equilibria and MHD stability of these 'Zero Net Current' structures, the modular current injection scheme on the RWM has been modified to allow coaxial current injection. Construction and preliminary results from these studies are presented.

# The Wheaton Impulsive Reconnection Experiment

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A new experiment for the study of impulsive magnetic reconnection in three dimensions is underway at Wheaton College. The Wheaton Impulsive Reconnection Experiment (WIRX) is composed of two parallel electrodes, linked by a magnetic arcade that is generated by a coil surrounding the electrodes. Plasma current I has been varied from 0.5 kA to 11 kA and the startup magnetic field B has been independently varied from 0 to 400 Gauss. A large ratio of I/B is expected to result in instability and potentially reconnection. Under some driving conditions, bursty events appear which are similar in some ways to reconnection events in other plasmas. Work is ongoing to determine if these events involve reconnection. ICCD camera images suggest a bursty emission of plasma from the arcade in these situations. Photodiode cameras and magnetic probes are being used to better characterize the evolution of the arcade in time and space and to look for signatures of reconnection.

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# Hall Reconnection in Partially Ionized Plasmas in the Magnetic Reconnection Experiment

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In many space and astrophysical plasmas, such as the solar chromosphere and protoplanetary disks, the degree of ionization can be quite low: often 1% or less. The effects of the presence of neutral atoms on magnetic reconnection in these systems has been the subject of recent theoretical work [1]. We describe a experimental campaign to study reconnection in partially and weakly ionized plasmas in the Magnetic Reconnection Experiment (MRX).

Ion-neutral collisions are most likely to produce interesting physics. Depending on the level of collisionality, it has been predicted that ion-neutral coupling would effectively increase the ion mass [1]. This, in turn, would increase the length scales on which fast Hall reconnection is expected to occur. We will present detailed magnetic measurements of Hall reconnection in a mostly ionized and weakly ionized plasmas, and make comparisons between the two. In each case the plasma parameters are similar except for the degree of ionization. Scalings of certain parameters with ionization fraction will also be presented.

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**Electron Outflow Jets in Reconnection with a Guide Field***

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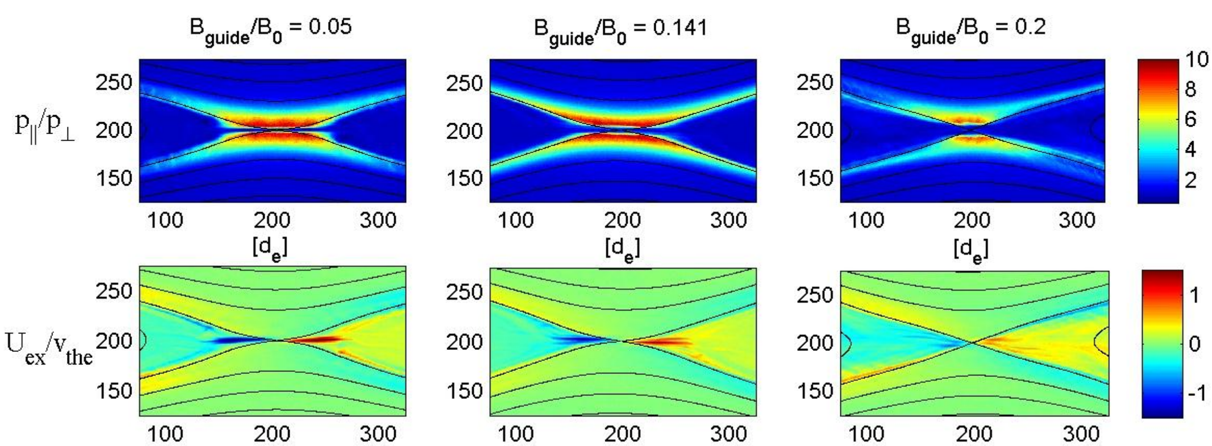
Phan *et al.* report on a super-Alfvenic electron outflow jet measured by the Cluster spacecraft near a magnetospheric reconnection site [1]. Similar electron current layers also form in kinetic simulations of anti-parallel reconnection. A model for the electron layer, using new equations of state for the electron pressure [2], shows that the current is driven by gradients in the electron pressure tensor and that the magnitude of the current depends on the upstream electron beta [3,4]. This model was originally based on PIC simulations of reconnection beginning with exactly anti-parallel magnetic fields, a configuration unlikely to be realized in space plasmas. To study the electron layer in the presence of a guide magnetic field, kinetic simulation runs have been carried out with a range of guide fields relevant to magnetotail reconnection. With initial guide fields up to 15% of the upstream reconnecting field, the Hall magnetic field structure modifies in response to the guide field. The Hall currents become asymmetric and virtually expel the guide field from the region around the electron layer. As in the model, collimated electron outflow jets are driven in the central region by the electron pressure anisotropy (see figure below). For guide fields larger than 15% of the upstream reconnecting field, the strength of the Hall currents is insufficient to expel the guide field and the outflow jets do not form.

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**A Design Study of a New Facility, MITPX, for Experimental Investigations of Kinetic Reconnection***

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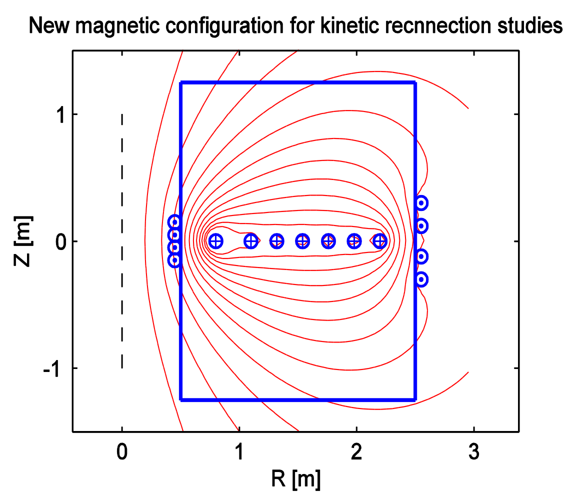
A new model for effective heating of electrons during reconnection is now gaining support from spacecraft observations, theoretical considerations and kinetic simulations [1]. The key ingredient in the model is the physics of trapped electrons whose dynamics causes the electron pressure tensor to be strongly anisotropic. As a result the electrons acquire equations of state that resemble the familiar CGL scaling with $p_{||} \propto n^3/B^2$ and $p_{\perp} \propto nB$ [2]. The model is applicable to collisionless reconnection where gradients in $p_{||}$ can sustain large scale electric fields. The heating mechanism becomes highly efficient for geometries with low upstream electron pressure ($\beta_{e\infty} < 5\%$); conditions relevant to the magnetotail. The experimental exploration of this dynamics requires a carefully designed dedicated reconnection experiment. The plasma must be fully collisionless such that the pressure anisotropy can develop, but its temperature must be sufficiently small to ensure that $\beta_{e\infty} < 5\%$. Furthermore, a high plasma density is desirable to obtain a plasma that is large compared to the ion skindepth, $d_i$. These constraints are all satisfied at a parameter regime around $B \sim 15$mT, $n \sim 10^{18}$ m$^{-3}$ and $T_e \sim 30$eV, conditions which are readily achieved in a toroidal plasma device [3]. To accommodate a current sheet with a normalized size of about $L/d_i \sim 10$ the size of the experiment must have a spatial scale on the order of 2.5 m. In addition, a condition of symmetry across the reconnection layer can be achieved by forming the reconnecting current sheet along the midplane of the device.




The figure illustrates a possible design for a new Magnetic Interaction Toroidal Plasma Experiment (MITPX) that will be optimized for the study of kinetic reconnection including the dynamics of trapped electrons and pressure anisotropy. After a plasma is established the currents in some or all of the central coils will be turned off rapidly, driving magnetic reconnection. All internal coils will be movable such that a large variety of magnetic configurations can be established and tailored for continuation of our ongoing study of spontaneous 3D reconnection [4]. In addition, the flexible design allows for configurations suitable for the study of merging magnetic islands, which may also be a source of super thermal electrons in naturally occurring plasmas.

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# Laboratory Study of Equilibrium Force Balance and External Kink Stability in Solar-Relevant Magnetic Flux Ropes

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## Abstract

Arched magnetic structures in the solar corona are often modeled as partial-toroidal magnetic flux ropes. Because these coronal structures are thought to play a vital role in dynamic solar events such as coronal mass ejections (CMEs), understanding their behavior is of great heliophysical interest. In the laboratory experiments presented here, solar-relevant partial-toroidal magnetic flux ropes are studied in the MRX device [M. Yamada et al., *Phys. Plasmas*, **4**, 1936 (1997)]. The MRX flux ropes, which are magnetized arc discharges formed between two toroidally-separated electrodes, are diagnosed with an array of internal magnetic probes and with a fast framing camera. They are found to exhibit a variety of interesting equilibrium and stability phenomena. Their equilibrium evolution, which occurs on timescales much longer than the Alfvén time ($t_A \simeq 1\ \mu s$), is found to be governed primarily by radially-directed $\mathbf{J} \times \mathbf{B}$ forces. In particular, the flux rope is driven outward by the "hoop" force from the partial toroidal geometry of the plasma current channel, while interactions between the flux rope and externally applied magnetic field components counter this expansion. Contributions arise both from tension in the applied toroidal "guide" field $B_T$ and from interaction between the plasma current and an applied $z$-directed "equilibrium" field $B_E$. With regard to stability, the plasmas studied here are susceptible to to an external kink instability that develops when the edge safety factor $q_a$ drops below a critical value. This critical value, which for periodic (full-toroidal) systems is the $q_a = 1$ Kruskal-Shafranov limit, depends here on the boundary conditions at the two electrodes. Flux ropes with both ends fixed to the electrodes are found to exhibit $q_a = 1$ stability behavior, while others with one end fixed and the other free to move are instead found to exhibit $q_a = 2$ behavior. These results, which are congruent with recent theories and experimental results, underscore the importance of boundary conditions in determining the stability properties of non-periodic magnetic flux ropes.

# Kinetic Structure of Electron Diffusion Region in Antiparallel Reconnection*

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Observations in the Earth's magnetotail and kinetic simulations of magnetic reconnection have shown high electron pressure and temperature anisotropy in the inflow of the electron diffusion region. This anisotropy is accurately accounted for in a new fluid closure for collisionless reconnection [1], and we find that the anisotropy drives the electron current in the diffusion region, which is insensitive to the reconnection electric field. By tracing electron orbits in the fields taken from particle-in-cell simulations [2], we reconstruct the electron distribution function in the diffusion region at enhanced resolutions, revealing its highly structured nature, with striations corresponding to the number of times an electron has been reflected within the region (Fig. 1). The analysis reveals how the upstream electron anisotropy drives the current in the layer independent of the reconnection electric field. In turn, the analysis also exposes the origin of gradients in the electron pressure tensor important for momentum balance in the region and the mechanism by which the anisotropy sets the structure of the region [3].

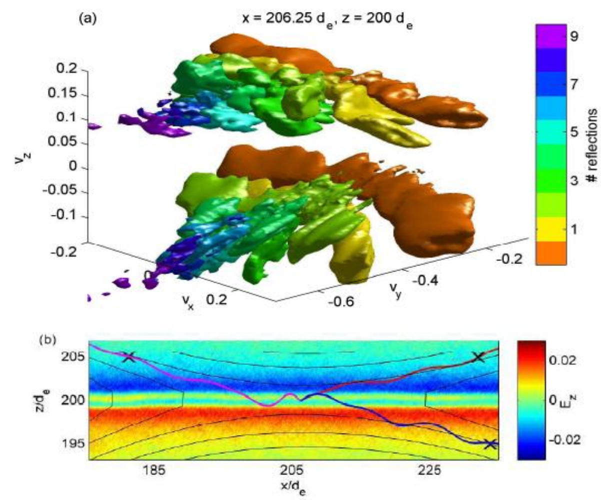


FIG. 1. (colour) (a) Isosurface of the reconstructed electron distribution at the x line in a PIC simulation. The different colours correspond to the number of times electrons have been reflected in the diffusion region. (b) Electron orbits from x line with 0, 1 and 2 reflections. Colour plot is in-plane electric field $E_z$, with contours of in-plane projection of magnetic field lines.

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[2] Daughton W, Scudder J, and Karimabadi H, *Phys. Plasmas* **13**, 072101 (2006).

[3] Ng J, Egedal J , Le A, Daughton W, and Chen L-J, *Phys. Rev. Lett*. **106**, 065002 (2011).

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**First Results from a Two-Fluid Code, Implementing the Electron Pressure Tensor with new Anisotropic Equations of State***

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Collisionless magnetic reconnection plays an important role in space and laboratory plasmas. When comparing two-fluid and fully kinetic particle simulations of the process, it is found that the structure surrounding the electron diffusion region and the electron current layer differ vastly [1]. For example, in kinetic simulations of guide field reconnection, the diffusion region often includes elongated and asymmetric electron current layers. This is in contrast to the shorter and more symmetric current channels observed in traditional fluid simulations. The differences between kinetic codes and two-fluid codes are likely due to the simplifying assumption of isotropic pressure; a closure employed widely in fluid models. Recently, a new fluid closure has been obtained for electrons that relate parallel and perpendicular pressures to the density and magnetic field [2]. The closure has been confirmed in fully kinetic simulations and is obtained using an adiabatic solution of the Vlasov equation, which includes the dynamics of electrons trapped in parallel electric fields [3]. Using an implicit, high-order spectral-element framework (HiFi [4]), a two-fluid code is developed that implements the new approximation for the electron pressure tensor. The code is applied to guide-field reconnection using double Harris sheet configuration with periodic boundary conditions. Our first results include an asymmetric out of plane current channel driven in part by the large pressure anisotropy that develops in the run. The results of the fluid simulation will be compared to a fully kinetic particle simulation with a similar setup.

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[3] Egedal J, Fox W, Katz N, Porkolab M , Øieroset M, Lin RP, Daughton W, and Drake JF, *J. Geophys. Res*. **113** (2008)

[4] Lukin VS, Glasser AH, Lowrie W, and Meier ET, *J. Comput. Phys.* Submitted (2010)

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# ISS Space Plasma Laboratory (ISPL): A boundary free laboratory to investigate reconnection phenomena in 3D magnetized plasmas

Edgar A. Bering, III, Spiro K. Antiochos, Mark Carter, Leonard Cassady, Franklin R. Chang Díaz, C. Richard DeVore, Benjamin W. Longmier, James McFadden, John V. Shebalin, David M. Smith, Jared Squire, and Barbara J. Thompson

We describe a proposed laboratory-experiment research program that will answer the fundamental question:

- What is the role of reconnection in opening and closing the solar magnetic field?

While attacking this question, we will also address the most important, long-standing questions on magnetic reconnection, in all contexts:

- What determines the rate of reconnection, and whether or not it is bursty?
- How is the released energy partitioned between thermal, kinetic, and particle?

Of course, it seems completely contradictory to use a laboratory experiment to study an open system, because so far all laboratory plasmas have very solid walls. The pioneering feature of our program is that the experiments will be performed on the International Space Station (ISS). Only by going into space can we obtain the open domain that is absolutely essential for studying the observed solar/heliospheric phenomena. We describe a research program that will provide the instrumentation infrastructure, modeling and solar data expertise and initial scientific understanding required to develop the privately funded Aurora electric propulsion package with its VASIMR® VF-200 high powered plasma source into a wall-less, orbiting ISS Space Plasma Laboratory (ISPL) national facility.

The VAriable Specific Impulse Magnetoplasma Rocket (VASIMR®) is a high power electric spacecraft propulsion system, capable of $I_{sp}$/thrust modulation at constant power [E. A. Bering, III, *et al.*, "Observations of single-pass ion cyclotron heating in a transsonic flowing plasma," *Phys. Plasmas, 17,* 043509, doi: 10.1063/1.3389205, (2010).]. The VASIMR® uses a helicon source to generate plasma. The plasma is leaked though a strong magnetic mirror to a second stage. In the second stage, the plasma is energized by a process that uses left hand polarized slow mode waves launched from the high field side of the ion cyclotron resonance. The single pass ion cyclotron heating (ICH) produces a substantial increase in ion velocity. The ionization cost of argon propellant was determined to be 87 eV for optimized values of RF power and propellant flow rate. Recent results at 200 kW coupled RF power have shown a thruster efficiency of 72% at a specific impulse of 5000 s and a thrust of 5.7 N. Ad Astra Rocket Company (AARC) is planning to fly a plasma rocket experiment as a major element of the company's "Aurora" electric power and propulsion test platform on the ISS in 2014. The Aurora platform will support a dual-jet magnetic quadrupole 200 kW version of the VASIMR® plasma rocket (the VF-200). It will consist of two 100 kW parallel plasma engines with opposite magnetic dipoles, resulting in a near zero-torque magnetic system. The system will be available for basic plasma physics research in parallel with the testing of the VF-200 engine performance as a high power electric propulsion system. The Aurora package would thus become a National Plasma Physics Laboratory (the ISPL) suitable for plasma physics studies in an open, wall free near-Earth orbital laboratory environment. An ISS arm deployed instrument package similar to the Plasma Diagnostics Package used on STS-3 in conjunction with the OSS-1 experiment and STS-51F in conjunction with Spacelab 2 has been proposed to NASA. The Aurora Plasma Diagnostics Package (APDP) will carry Langmuir probes, an RPA, dc magnetometer, plasma wave detectors, Faraday cups, electrostatic analyzers, solid state energetic particle telescope and Ar II and broadband imagers. The studies that will be performed on this revolutionary facility will not only provide ground-truth experimental answers to the questions above, but undoubtedly discover new and unexpected plasma behavior in the unique environment of the ISPL, leading to new understanding of the Sun, the Earth's magnetosphere, and the Heliosphere. Furthermore, all ISPL operations will pose important ionospheric physics questions: What happens to 150mg/s of argon that is injected into the magnetosphere at an altitude of 250km? How fast does it precipitate out of the atmosphere? Is it detectable by ground stations or in the aurora? Opportunities for collaborative plasma physics experiments at the AARC facility and using the ISPL facilities will be discussed.

# Experimental Investigation of Arch-Shaped Magnetic Flux Tubes

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The FlareLab experiment is designed to investigate the evolution of arch-shaped magnetic flux tubes. The original configuration of the experiment closely followed the work of P. Bellan *et.al.* [1]. A set of permanent magnets was used to generate an arch-shaped magnetic guide field along which a plasma was formed by discharging a ~1 kJ capacitor bank.

Recently, the experimental setup has been modified following the model considerations proposed by Titov and Démoulin [2] in order to reproduce a certain class of solar phenomena.

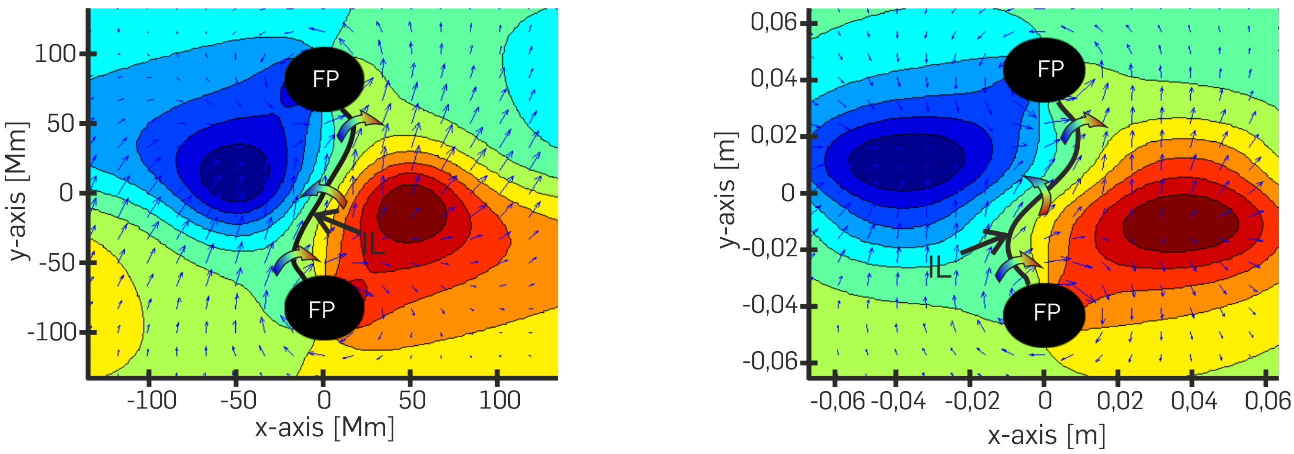


*Fig. 1 Left: Magnetic field topology in the photospheric plane, numerical calculation based on the model values, given in [2]. Right: numerical calculation based on the configuration of the experiment (in the electrode plane of the plasma source). Small arrows: in-plane magnetic field component, color coding: vertical magnetic field component, FP: footpoints of the plasma arch, IL: inversion line of the vertical field component. The colored arrows indicate the crossing direction of the in-plane field component over the inversion line.*

To this end, the permanent magnets generating the guide field have been replaced by a strong line current. Additional permanent magnets are used to generate an arcade-shaped strapping field. Figure 1 shows that the principal magnetic field topology, proposed in [2] can be achieved in the experiment, especially the change in the crossing direction of the in-plane magnetic field component over the inversion line.

First results obtained with the improved plasma source are presented in this contribution: differences of the magnetic topology as compared to a previous plasma source design are shown; the corresponding influence on the discharge evolution is investigated. The phenomenon of pronounced striations perpendicular to the current channel is presented, which appears to be damped by an axial magnetic field.

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[2] V.S. Titov and P. Demoulin, Astron. Astrophys. **351** (1999), 707

# Electromagnetic interaction between the solar wind and a kinetic scale artificial magnetosphere

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(1) Kobe University, (2) Japan Aerospace Exploration Agency (JAXA)

Solar wind interaction with a small-scale artificial magnetosphere is investigated by means of a full particle-in-cell simulation. The resultant momentum transfer of solar wind plasmas may provide the propulsion for a magnetic sail[1] or mini-magnetosphere plasma propulsion(M2P2)[2], which is a potential next-generation interplanetary flight system. The spatial scale of the magnetosphere is expected to be quite small, at large on the order of a few hundred meters for a realistic size hoop coil having a radius of a few meters. Plasma kinetic effects would considerably affect the momentum transfer process in such a small magnetosphere, and the quantitative estimation of the trust is still an open question.

In addition to the whistler wake expected from the hybrid simulations[3], two electron-scale structures are observed in the present simulation. One is the thin current layer at the front of the magnetosphere and the other is the magnetic reconnection region. The electrostatic deceleration of the solar wind ions in the current layer plays a dominant role in the momentum transfer process. The electron inflow to the magnetosphere through the reconnection region enhances the electrostatic interaction under the influence of the whistler wake. Thrust characteristics of magnetic sail including these dynamics will be discussed.

A demonstration mission for M2P2 has been planned in JAXA[4]. In the proposed mission, the thrust is estimated by the orbit determination result, and the plasma wind monitor is installed to investigate the relationship between the solar wind and the thrust. Such mission is expected to give a lot of insights into collision-less plasma physics as well as space aeronautics.

This study was supported by Japan Science and Technology Agency (CREST).

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[3] N.Omidi *et al*, Advances in space research. **33** 1996 (2004)
[4] H.Yamakawa *et al*, Acta Astronautica **59** 777 (2006)

Contribution submission to the conference IPELS 2011

**Momentum transport experiments in the Reversed Field Pinch** — •M.D. Nornberg[1], J.S. Sarff[1], W.X. Ding[2], G. Fiksel[3], J. Anderson[1], D. Liu[1], J. Waksman[1], and J. King[1] — [1]University of Wisconsin-Madison, Madison, WI, USA — [2]University of California, Los Angeles, CA, USA — [3]University of Rochester, Rochester, NY, USA

Resistive tearing modes in a Reversed Field Pinch plasma cause a relaxation of the plasma current profile through magnetic reconnection. This rapid reorganization of the magnetic topology reduces the free energy available to the tearing modes while roughly conserving magnetic helicity. In addition to the magnetic field self-organization, these tearing modes also give rise to rapid transport of plasma momentum. Measurements of the core parallel plasma flow show a reduction in the core and rise in the edge. A two-fluid model of the plasma would suggest a relaxation model dependent on the helicities of both the ion and electron fluids. This presentation will summarize recent measurements and simulations of momentum transport in the Madison Symmetric Torus. Core measurements of the magnetic field and density fluctuations reveal a strong momentum flux due to correlated density and radial magnetic field fluctuations while probe measurements in the edge show a strong turbulent Reynolds stress in balance with the Maxwell stress. Neutral Beam Injection is used to drive plasma flow in the core as a means of studying the turbulent transport and momentum confinement.

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# Nonstationary ponderomotive self-focusing of a Gaussian laser pulse in a plasma

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## ABSTRACT

A model of relaxing ponderomotive nonlinearity is developed to study the nonstationary self-focusing of a Gaussian laser pulse in a plasma. The ponderomotive force acts on the electrons instantaneously but the plasma density redistribution via the process of ambipolar diffusion is taken to evolve on the time scale $\tau_R \cong r_0 / c_s$ where $r_0$ is the laser spot size and $c_s$ is the sound speed. The paraxial ray approximation is used to solve the wave equation. The focusing is stronger at the rear of the pulse than at the front, causing considerable distortion of the pulse when pulse duration is comparable to nonlinearity relaxation time. The saturation effect of nonlinearity leads to focusing of any portion of the pulse to a minimum spot size $r_0 f_{\min}$ at an optimum distance $z_{op}$ and then the spot size increases. $f_{\min}$ and $z_{op}$ depend on the intensity of the portion of the pulse.

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# IPELS-2011 ORAL PROGRAM

| *July 10 Sunday* | *July 11 Monday* | *July 12 Tuesday* | *July 13 Wednesday* | *July 14 Thursday* | *July 15 Friday* |
|---|---|---|---|---|---|
| | 8:00 Registration<br>8:25 announcement | 8:00 Registration<br>8:25 announcement | 8:25 announcement | 8:25 announcement | 8:25 announcement |
| | **Shocks (Sydora)**<br>8:30 Raymond<br>9:15 Kucharek<br>9:40 Hoshino | **Alfven waves (Dendy)**<br>8:30 Morales<br>9:15 Gurnett<br>9:40 Bingham | **20 years (Koepke)**<br>8:30 Yamada<br>8:55 Bhattacharjee<br>9:20 Stone | **Dynamo/jet (Zweibel)**<br>8:30 Pudritz<br>9:15 Kronberg<br>9:30 Li | **Reconnection (Egedal)**<br>8:30 Drake, J.<br>9:15 Mozer<br>9:40 Dorfman |
| | 10:05 break | 10:05 break | 10:05 break | 9:55 break | 10:05 break |
| | **Shocks (Hoshino)**<br>10:30 Kirk<br>10:55 Gargate<br>11:20 Niemann<br>11:35 Fruchtman<br>11:50 Gunell | **Alfven waves (Gekelman)**<br>10:30 Speirs<br>10:55 Gillespie<br>11:10 McConville<br>11:25 Drake, D.<br>11:40 Nordblad | **20 years (Yamada)**<br>10:30 Koepke<br>10:55 Forest<br>11:20 Kletzing<br>11:45 Panel discussion | **Dynamo/jet (Li)**<br>10:20 Zweibel<br>11:05 Pinton<br>11:30 Rahbarnia<br>11:45 Colgate | **Reconnection (Drake, J.)**<br>10:25 Ono<br>10:50 Daughton<br>11:15 Oieroset<br>11:40 Inomoto<br>11:55 Opher |
| | 12:05 lunch-provided | 11:55 lunch-on your own | 12:05 lunch-on your own | 12:00 lunch-provided | 12:10 lunch-provided |
| 3:00 Registration | **Turbulence (Stenzel)**<br>1:30 Goldstein<br>2:15 Thuecks<br>2:30 Grulke<br>2:55 Carter | **Alfven waves (Horiuchi)**<br>1:30 Dendy<br>1:55 Skiff<br>2:20 Pilipenko<br>2:35 Vincena | **excursion** | **Dusty/sheath (Lynch)**<br>1:30 Robertson<br>2:15 Marchand<br>2:40 Thomas<br>3:05 Stenzel | **Reconnection (Daughton)**<br>1:30 Shimizu<br>1:55 Egedal<br>2:20 Horiuchi<br>2:45 Sydora |
| | 3:20 break | 2:50 break | | 3:30 break | 3:10 break |
| | **Turbulence (Brown)**<br>3:35 Gray<br>4:00 Spence<br>4:15 Intrator | **Kintner (Kletzing)**<br>3:20 Lynch<br>3:45 Schuck<br>4:10 Chen<br>4:35 Gekelman<br>5:00 Discussion<br>5:20 end | | 3:50 **Poster session**<br>5:30 end | **Reconnection (Phan)**<br>3:30 Lukin<br>3:45 Magee<br>4:00 Fox<br>4:15 Vrublevkis<br>4:30 Moser<br>4:45 end |
| **Townhall (Ji)**<br>5:00 cash bar<br>5:30 food served<br>6:00 Koepke<br>6:20 Drake, J.<br>6:40 Ono<br>7:00 Bingham<br>7:20 Discussion<br>8:00 end | 4:30 **Poster session**<br>5:30 end | | | **Working Dinner (Ji)**<br>6:30 cash bar<br>7:00 food served<br>7:30 presentations<br>8:10 Discussion<br>9:00 end | |