Workshop

on

PLASMA EXPERIMENTS IN THE LABORATORY AND IN SPACE

- ABSTRACTS -

Session 1

OPENING

DIAGNOSTICS AND REPRESENTATION

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The current status of plasma experimental science is reviewed by presenting sets of laboratory configurations and measurement techniques which, when combined together, afford reasonably complete control and description of the plasma state. Examples include linear and toroidal plasma research devices; modern diagnostics, with emphasis on high resolution techniques adapted from atomic, laser and detector physics; and a selected number of new plasma processes which have been uncovered through their use.

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Session 2

WAVES AND INSTABILITIES

BEAM-PLASMA INSTABILITIES

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Beam Driven Instabilities in the Auroral Acceleration Region

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The auroral acceleration region is characterized by an electrostatic acceleration parallel to the magnetic field. This results in the upward acceleration of ionospheric ions and downward flow of magnetosperic electrons. The relative drifts of these species excite electrostatic hydrogen cyclotron (EHC) waves and broadband electrostatic noise. The former instability may be related to relative electron-ion or ion-ion streaming; the latter is associated with the relative drift of different mass ion beams. The waves lead to ion heating. The linear stability of the system is well understood. The spatial and temporal development of the heating and the nonlinear development of the wave spectra are not. This presentation will provide a brief overview of acceleration region parameters, the evidence for electrostatic acceleration, and a discussion of the conditions necessary for the linear excitation of EHC and broadband waves. The nonlinear development of the ion distributions and wave spectra depend on the spatial scale lengths of the plasma and whether the wave fields remain quasilinear or form nonlinear structures such as weak double layers. The conditions for quasilinear *vs.* nonlinear wave development under acceleration region conditions need investigation, as does the ion heating that can be realized in each case.

ION CYCLOTRON OSCILLATIONS INDUCED BY AN EMMISSIVE ELECTRODE FLOATING IN A PLASMA

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Ion cyclotron oscillations are observed to be induced by a small emmissive electrode floating in a magnetized collisionless plasma. The oscillations cannot be induced when the electrode is cold. Main features of the oscillations are almost the same as those of the well-known ion cyclotron oscillations induced by applying a positive potential to a small cold electrode in a magnetized plasma. A generation mechanism is presented of the ion cyclotron oscillations observed. Details of the phenomenon are also described.

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Wave Particle Interaction at the Inner Edge of the Ring Current/Plasmasphere Overlap Region

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The inner edge of the ring current presents an example of interaction between plasmas of different nature. The AMPTE IRM satellite revealed in the region of overlap between plasmaspheric and ring current plasmas a gradual decrease of cold plasma density along with a sharp rise in the hot plasma component. These measurements were accompanied by a sudden increase in ion drift velocity and electrostatic waves around and above the lower hybrid frequency. The excitation, saturation and thermal fluctuation levels of these waves are analyzed with the help of a model which includes cold plasmaspheric ions, hot dilute inhomogeneous ring current ions and cold neutralizing electrons. The coupling of the lower hybrid drift with the drift cyclotron harmonic mode destabilizes the plasma around the lower hybrid frequency while thermal fluctuations of the hot ions enhance the higher cyclotron harmonics. The importance of the thermal fluctuations in the presence of hot plasma component and small linear growth rates is discussed and applied to other physical configurations.

Electromagnetic Plasma Wave Emissions

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Many types of electromagnetic plasma wave emissions have been observed in space plasmas, too many in fact to be reviewed in one short presentation. In this review the focus is on two types of electromagnetic instabilities; whistler-mode emissions and cyclotron maser radiation. Whistler-mode emissions and cyclotron maser radiation are among the most intense waves observed in planetary magnetospheres. Although these two instabilities occur in quite different frequency ranges ($f < f_c$ for whistler-mode waves, and $f > f_c/2 + [(f_c/2)^2 + f_p^2]^{1/2}$ for cyclotron maser radiation), they are in fact very similar. Both are right-hand polarized, involve cyclotron resonance interactions with energetic electrons, and are driven by a loss-cone anisotropy. Whistler-mode emissions primarily occur in planetary radiation belts and are widely believed to play an important role in the scattering and loss of energetic electrons from radiation belts. Cyclotron maser radiation is generated along the auroral field lines, and is closely associated with the precipitation of electrons responsible for the aurora. The role of cyclotron maser radiation in the precipitation of auroral electrons remains an open issue. Both types of emissions also have very complicated frequency-time structures that are almost certainly caused by nonlinear saturation effects. The origin of this fine structure remains largely unexplained. Possible experiments that could resolve some of these questions are discussed.

VLF waves and Auroral Kilometric Radiation in the Auroral Magnetospere: Highlights from the Viking wave experiment.

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The high-time resolution of the wave experiment on board the Swedish auroral satellite Viking has revealed the extreme time variability of the wave phenomena associated with particles acceleration in the key regions of the high latitudes magnetosphere such as the dayside Cleft and Cusp, and the nightside auroral oval.

As derived from the wave activity, the Cusp is characterized by weak plasma acceleration and by large magnetosheath-like plasma density. In contrast, at adjacent magnetic local times, the Cleft is generally associated with low plasma density and with strong plasma turbulence illustrated by sporadic and intense broadband electrostatic noise emissions (BEN). The duration of such bursts is typically a few hundreds of milliseconds, and the electric field amplitude of the BEN emissions can reach a few tens mV/m in the 1kHz range. These bursts are closely associated with 0.1-1 keV parallel electron beams and ion conics, and with large DC electric field fluctuations. These emissions are greatly influenced by non-linear effects and occur simulteanously with the observation of particles distributions favouring the destabilization of electron acoustic waves. It will be shown that electron acoustic solitons passing by the satellite would generate spectra that can explain the high-frequency part of BEN, above the plasma frequency.

In the nigthside auroral magnetosphere BEN is usually less impulsive and more intense than in the Cleft; it is also associated with more energetic electron beams and ion conics (1-10 keV). Its characteristic variation time is a few seconds, and its electric field strength can reach a few hundreds mV/m around the lower hybrid frequency. Sporadic Auroral Kilometric Radiation (AKR) bursts are associated with this strong bursty electrostatic turbulence. These observations suggest that formation of lower hybrid solitons plays a crucial role in the complex plasma processes leading to AKR generation. A theoretical model based on the nonlinear interaction between lower hybrid solitons and upper hybrid waves will be proposed. The solitons act as sporadic, localized antennas allowing for efficient conversion of the electrostatic energy contained in the upper hybrid waves into radiation energy at frequencies above the X mode cutoff. The sporadicity of the radiation derives from the lower hybrid soliton collapses which occur on ~ 1s time scale.

NONLINEAR INTERACTIONS BETWEEN AN ELECTRON BEAM AND RF WAVES

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Two laboratory experiments have been initiated to study nonlinear electron-wave interactions. In the first experiment, the interaction between a guided rf wave and an electron beam is investigated using a large crossed field amplifier. The electron beam is injected through externally imposed crossed electric and magnetic fields. The large amplitude rf wave is guided by a serpentine slow wave structure and travels at a phase velocity approximately equal to the average velocity of the electron beam. Under certain electron beam injection conditions, the electron beam trajectories can be highly cycloidal. The so-called "ripple beam" exchanges its energy with the rf wave and this energy exchange can be correlated to the changes in the electron beam trajectories. At high rf power, the beam electrons were captured by the rf waves and significant diffusion of the electron beam cycloidal orbits were observed. A numerical simulation of the same experiment has also been performed and the details of the electron-rf interactions can be followed within a rf period. In the second experiment, an electron stream slowly drifts across a low density background plasma is followed in time. Our latest measurements on the evolution of fluctuating electric fields will be given. These resutls may be useful in the study of wave-electron interactions in regions of space plasmas where localized electric fields are present.

The Determination of Wave Fields from Perturbed Particle Orbits. Frederick N. Skiff, LPR, University of Maryland. — Propagation of wave fields in plasma is influenced by the particle motions through charge densities and currents. Likewise, the dynamics of particle motion is influenced by the wave fields. A family of techniques for determining wave fields given time-resolved measurements of the particle distribution function will be presented. Essential aspects of the theory behind these techniques will be outlined. Because the plasma dielectric response is nonlocal in space and time, a measurement of the particle velocity distribution which is resolved in space and time may indicate the wavelength as well as phase and amplitude of a wave. Data from laboratory experiments will be presented, and the possible application of this method to satellite data will be considered.

DIAGNOSTICS OF IONOSPHERIC PLASMA BY THE RESONANCE CONE TECHNIQUE

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Wave propagation techniques represent a complementary approach to measure T_e and n_e in magnetized plasmas. A resonance cone is excited by a small antenna that is driven at typically half electron-cyclotron frequency. The cone half-angle is sensitive to n_e, and the cone possesses an internal interference pattern, that is related to T_e. We describe the application of the resonance cone technique to the ionosphere in the COREX-I experiment, we compare n_e and T_e profiles with other instruments, and show that non-reciprocities of the resonance cone are related to electron drift motion.

Session 3

CRITICAL IONIZATION VELOCITY AND DUSTY PLASMAS

Recent Space Experiments on the Critical Velocity

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A survey of recent chemical release experiments in the Ionosphere that were designed to study Alfven's Critical Ionization Velocity (CIV) Effect in space plasmas will be presented.

The data from several such sounding rockets experiments suggest that the wave and particle effects of plasma instabilities thought to be associated with this effect, are commonly observed. Thus, The total ion yield, which appears to vary widely between several experiments, may be a poor indicator of the presence of the CIV effect. The in-situ data shows clearly that ionization occurs and is consistent with at least some of the theoretical work on the subject. Comparisons of several of these parameters with predictions will be presented. In particular, I will examine the effects of a much better estimation of the charge-exchange cross-section for Ba and the background ionospheric O+ on the total yield and on the evolution of the electron distribution. I will also show the effects of the precursor atomic oxygen beam that results from barium that forward scatters the ambient neutral oxygen at resulting speeds that exceed the critical velocity for oxygen. This may account for the commonly observed heating of electrons at times before the presence of the main barium beam.

A COMPARISON BETWEEN LABORATORY AND SPACE EXPERIMENTS ON ALFVÉN'S CIV EFFECT

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Laboratory experiments on Alfvén's Critical Ionization Velocity (CIV) effect have been made during 30 years, and space experiments in the form of ionospheric shaped-charge releases for the last 10 years. These two types of experiments to a large extent complement each other. The laboratory experiments have definitely established the reality of the CIV effect, and have also determined the parameter limits within which the effect can be expected in the laboratory for different combinations of plasma and neutral gas species: velocity, magnetic field strength, and neutral gas and plasma density. However in the laboratory experiments there are always walls and electrodes present, and the available parameter regime is such that the details inside the CIV process are difficult to study.

The ionospheric release experiments have several advantages. The parameter range is much closer to the proposed space applications of the CIV effect, where the magnetic field is typically a factor 10^5, and the density a factor 10^8, below the values in the laboratory. Waves and particle spectra can be directly measured inside the interaction region in a way that would be impossible in the laboratory. Finally, most of the proposed space applications refer to situations where a limited neutral gas cloud interacts with a larger surrounding plasma. This problem can not be adequately studied in the laboratory because of the limitation in size, but it is a natural part of the ionospheric injection experiments.

The major drawback with the injection experiments is the short time duration. A scaling comparison show that they, due to the rapid expansion of the injected neutral gas clouds, typically correspond to initial transients in laboratory CIV experiments. On a corresponding time scale in the laboratory, the steady state CIV effect has usually not developed. The obvious question to ask is this: provided that the CIV effect has the same efficiency in space as in the laboratory, where would we expect it to operate? The answer is: it should turn on 0.5 - 2 km from the explosion and switch off somewhere inside 5-10 km, for a typical barium release at 400 km altitude. There are several independent reasons for the CIV effect to be absent outside this distance: (1) the electron heating time problem, (2) the oxygen damping limit, (3) the Townsend condition, and (4) the problem to heat a large volume of electrons to ionizing energies, the volume heating problem. Seen in the light of this expectation, the ionospheric CIV releases live up beautifully to the results from the laboratory experiments and given unique material concerning both the waves and particle scattering inside the interaction region, and also concerning the coupling mechanism between the CIV region and the surrounding plasma.

CONTROL OF CRITICAL VELOCITY IONIZATION
BY MOMENTUM COUPLING TO THE ENVIRONMENT

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The CIV effect is thought to operate by energy transfer from the ions, freshly generated out of a neutral gas jet, to the electrons. For this to occur, excess momentum must be transferred to the plasma background. If the interaction volume of neutral beam and plasma is spatially limited, the momentum can be efficiently absorbed by the outside plasma or, in the laboratory, by the current closing external conductors. In a space experiment, Alfvén waves are instrumental in transporting the momentum. Alfvén speed and ambient plasma density limit the rate at which this can occur. It is not only the initial momentum of the ions that has to be removed, at least in part, but also the momentum gained subsequently by the Lorentz force has to be balanced by a reactive force on the background plasma. Both contributions combine to determine the local electric field, or the plasma rest frame inside the interaction volume. A general formulation of this problem is presented and compared with observations. The reasons for the observed large slippage between plasma and neutral beam are discussed and attributed to a self-limitation of the momentum coupling efficiency through the development of barriers (plasma density holes) on either side (along $\underline{B}$) of the interaction volume.

DUSTY PLASMAS IN THE SOLAR SYSTEM

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The processes that lead to charging of dust grains in a plasma are briefly reviewed. Whereas for single grains the results have been long known, the reduction of the average charge on a grain by "Debye screening" has only recently been discovered. This reduction can be important in the Jovian ring and in the rings of Uranus. The emerging field of gravitoelectrodynamics which deals with the motion of charged grains in a planetary magnetosphere is then reviewed. Important mechanisms for distributing grains in radial distance are due to stochastic fluctuations of the grain charge and a systematic variation due to motion through plasma gradients. The electrostatic levitation model for the formation of spokes is discussed, and it is shown that the radial transport of dust contained in the spokes may be responsible for the rich radial structure in Saturn's rings. Finally, collective effects in dusty plasmas are discussed which affect various waves, such as density waves in planetary rings and low-frequency plasma waves. The possibility of charged grains forming a Coulomb lattice is briefly described.

Session 4

PLASMA - PLASMA INTERACTIONS

Experiments on the Merging of Currents in a Laboratory MagnetoPlasma†

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The interaction of current channels has long been a topic of interest for those working in solar physics (magnetic flux rope interactions), magnetic field line reconnection (tearing of current sheets and coalescence of current fibers) and fusion physics (the behavior of currents in Tokomaks and Pinches). A series of experiments on the merging and twisting of two current channels has been performed in a new laboratory device at UCLA. The **LArge Plasma Device (LAPD)** has a ten meter long, quiescent plasma column which is 0.5 m in diameter. The ambient magnetic field is $B_z \leq 3$ kG and plasma density $n \leq 5.0X10^{12}$ /cm^3 in Ar. The two current channels are formed by coating the cathode source nonuniformly and then biasing it with respect to an anode ten meters away. Volume data of the plasma parameters n_e, V_p, T_e and **B** are taken at about 5355 locations within the plasma volume, and at 10,000 time steps, using a unique three dimensional probe drive and data acquisition system. The current channels are observe to twist about each other and merge when their self generated magnetic fields are of order of the background magnetic field. Forces on the the plasma such as $j \times \mathbf{B}$, and ∇P are shown in three dimensions to illustrate the processes at play in this interaction. As the currents twist magnetic helicity is generated and serves to keep the currents flowing after the external current drive is shut off. The dynamics of the current system and the time and space dependence of the return currents will be shown in detail. The relaxation of the system to a minimum energy state will be examined and compared to theory. The time history and three dimensional nature of this interaction will be illustrated with computer generated videos of the data.

Investigation of 3-Dimensional Magnetic Reconnection in a Laboratory Plasma and Initial results

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Abstract

A comprehensive laboratory experiment has been proposed to investigate the fundamental 3-D physics of magnetic reconnection regions and their associated hydromagnetic flows. Two toroidal plasma rings, with equal or opposite magnetic helicity, are formed and then brought together, contacting along a toroidally symmetric line. This research addresses three important questions: (1) How does magnetic helicity affect reconnection? (2) Will three-dimensional processes arise spontaneously and modify the usual Sweet-Parker or Petschek picture of two-dimensional reconnection where the global configuration is that of an axisymmetric x-point line? (3) How does the reconnection rate respond to global forcing? In a preliminary experiment carried out at the University of Tokyo [Phys. Rev. Letts. 65, 721 (1990)], the direction of the toroidal field plays an important role in the merging process. Three important physical characteristics have been extracted from this experiment. (i) The three-dimensional reconnection features of merging field lines are found to be quite different depending on whether the toroids have co-helicity or counter-helicity configurations, even if their two-dimensional picture is identical; (ii) counter-helicity merging induces magnetic reconnection more efficiently than co-helicity merging and sometimes is accompanied by non-axisymmetric MHD fluctuations; and (iii) reconnection rate is determined by the external forcing i.e. the initial approaching velocity of two plasmas. The details of this preliminary experiment will be reported together with future plans of the MRX experiment.

Transport of Time-Varying Plasma Currents by Whistler Wave Packets.*

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In a large magnetized laboratory plasma the properties of time-varying current systems are studied experimentally. Currents are generated either by collection/emission of charged particles at conducting boundaries or by induction with time-varying/moving magnetic fields. Similar situations arise in space plasmas naturally (reconnection, flux ropes, auroral arcs) and in active experiments (beam injections, electrodynamic tethers, magnetic antennas). In the laboratory the complete three-dimensional, time-varying vector field of the total current density $\vec{J}(\vec{r},t) = \nabla\times\vec{B}/\mu_0$ is obtained from magnetic probe measurements.[1] Pulsed currents are observed to propagate at the speed of whistler wave packets. Their field structure forms flux rope-like configurations which are electromagnetically force-free ($\vec{J}\times\vec{B}+\rho\vec{E} = 0$).[2] Current closure and neutralization of field-aligned transient currents occurs via induced return currents. Cross-field current closure between tethered electrodes occurs via displacement currents of whistlers excited by an insulated tether.[3] Moving dc currents/magnetic fields induce "eddy" currents in a magnetoplasma which couple to propagating eigenmodes and form Cherenkov-like whistler "wings" or "wedges". The radiation patterns of moving magnetic antennas and electrodynamic tethers have been demonstrated. A new, Gendrin-like mode of wave propagation has been observed for bounded whistler wave packets launched by magnetic antennas in a uniform unbounded magnetoplasma.

Nonlinear effects of strong current systems arise from density modifications and electron heating. For example, current collection by positively charged electrodes depletes the density in the flux tube of the electrode causing repetitive current disruptions. For Coulomb collision-dominated plasmas electron heating creates a field-aligned channel of high conductivity which allows an anomalous penetration of waves/currents.

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3. J.M. Urrutia and R.L. Stenzel, Geophys. Res. Lett. 17, 1589 (1991).

Session 5

PARTICLE ACCELERATIONS

The Cross-Field Propagation of Low-β Plasma Streams: Physics Issues

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Collisionless, magnetized plasmas in motion couple to one another by means of the currents that they induce in each other. The cross-field motion of one plasma will drive magnetic-field-aligned currents that can close across the magnetic field in the other plasma. In the current system the transfer of bulk momentum is manifested in the $\vec{j} \times \vec{B}$ force. At the fluid-plasma level of understanding, this coupling comes under the names "MHD generator", "Alfven wing", or "unipolar inductor".

For space physics, the breakdown of this fluid picture is of interest because it results in the production of strong electric fields, which can lead to the acceleration of charged particles and to energy dissipation via $\vec{J} \cdot \vec{E}$. Examples of this breakdown for low-β motion may be found in the driving of auroral arcs by velocity shears and the coupling of Io to the Jovian ionosphere. To treat this breakdown, a kinetic description of the coupling is needed. Many kinetic aspects of this coupling can be studied in detail by examining the simple problem of the propagation of a stream of plasma across a magnetic field. Towards the goal of an electromagnetic and kinetic description of the plasma-coupling problem, work has been ongoing on the electrostatic description of how plasmas moving across magnetic fields drive currents and how those currents flow along magnetic field lines. An overview of the electromagnetic problem will be given, the progress of the electrostatic investigation will be reviewed, and outstanding physics issues will be discussed.

QUESTIONS ABOUT THE ELECTRIC FIELDS IN THE AURORAL ACCELERATION REGION

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TRANSVERSE ION ACCELERATION MEASURED AT ROCKET ALTITUDES

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Transverse ion acceleration has been observed at rocket altitudes between 500 and 1000 km due to: 1) the injection of 100-200 eV Argon plasma; 2) auroral electron precipitation; and, 3) the injection of electromagnetic waves. Field-aligned currents necessary to neutralize the plasma injection payloads and naturally occurring in the aurora are apparently responsible for the ions observed in 1) and 2) above. Associated with the aurora, both bulk heating and tail heating is observed, sometimes simultaneously. In this case, either different masses are accelerated and/or different mechanisms are responsible. The bulk heating is closely correlated with the aurora structure while tail heating is not so well correlated. The tail heating is generally more energetic at rocket altitudes. Electrostatic oxygen cyclotron waves (EOCW) are closely correlated with the transverse bulk heating and the bulk flow or streaming of ambient ions towards the atmosphere. Such downstreaming may be driven by field-aligned electric fields that drive part of the auroral return current which in turn might produce the EOCW. Structured auroral hiss (SAH) just above the lower hybrid frequency is loosely correlated with the aurora and the tail heating events. Finally, wave injections of electromagnetic waves near the lower hybrid frequency does result in the transverse acceleration of ambient ions.

Transverse Acceleration of H+ by Lower Hybrid/H+ Bernstein Waves in the High Altitude Ionosphere--Experimental Results

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Sounding rocket observations of the auroral ionosphere above 500 km altitude during periods of auroral activity consistently indicate transverse H+ tail heating and auroral hiss with absorption features at multiples of the H+ gyrofrequency. The H+ tail heating produces two populations characterized by temperatures of 10eV and 100eV. The auroral hiss is characterized by short wavelengths ($k\rho_i \simeq 1$) and we interpret its gyroharmonic features as being produced by the connection structure between the lower hybrid mode and the H+ Bernstein modes. The auroral hiss could be produced directly at short wavelengths although production at longer wavelengths followed by propagation/refraction to shorter wavelengths appears to be more likely. Supporting evidence for our interpretation of transverse H+ heating is also found in the Injun V wave data.

The acceleration of electrons and ions by electromagnetic ion cyclotron waves.

M. Temerin and I. Roth

Electromagnetic ion cyclotron waves provide a second important mechanism, in addition to parallel electric fields, for accelerating electrons in the aurora. Such waves are responsible for flickering aurora and for the intense field-aligned electron component of the aurora. Electrons are accelerated by the small parallel electric field component of the wave at the Landau resonance. In an inhomogeneous magnetic field the phase velocity of the wave can increase and electrons that are nearly trapped can be accelerated to large energies. These waves can also accelerate ions transverse to the magnetic field to produce ion conics through the cyclotron resonance or its harmonics. Such waves are also likely to exist in solar flares where they can accelerate ^3He. ^3He is observed to be enhanced relative to ^4He by four orders of magnitude in some small impulsive solar flares. Test-particle calculations of the interaction of electrons and ions with electromagnetic ion cyclotron waves are in good agreement with observed electron fluxes in the aurora and show that ^3He can be accelerated to the required energies in solar flares.

Session 6

DOUBLE LAYERS

OBSERVATIONS OF WEAK DOUBLE LAYERS ON AURORAL FIELD LINES

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The wave instrument on the Swedish Viking satellite performed high temporal resolution (1 ms) measurements of plasma density fluctuations ($\Delta n/n$) at two points in space separated 80 m, and of potential differences ($\Phi_i - \Phi_j$) between points 80 m apart and in two orthogonal directions. The measurements proved ideal for characterizing small-scale solitary structures and weak double layers. These structures, of a scale of about 100 m along the geomagnetic field, constitute localized plasma holes, where the density is reduced by up to 50 %, which have a negative potential of up to 5 V relative to the surrounding plasma. The structures often have a net potential drop of up to about 2 V, predominantly in the upward direction, and then constitute weak double layers, WDL ($e\Phi \lesssim kT$). The strucutres move upwards with velocities of 5 to 50 km/s. They occur above the auroral regions of the earth, in the auroral acceleration region of the magnetosphere, at altitudes of 1-2 earthradii. Their occurrence is correlated with that of beams of upward flowing ions (~ 1 keV) and downward accelerated electrons, as well as with that of electrostatic ion-cyclotron waves (EIC). In these regions WDLs are so ubiquitous that it is likely that series of such WDLs along each magnetic field line together builds up a large scale U-shaped equipotential pattern, with a kilovolt potential drop along the field lines accounting for the acceleration of auroral particles. Support for this view is found from the simultaneous observation of energies of the accelerated ions and electrons, and from the measurement of the large-scale potential variations along the satellite orbit, which shows a potential minimum of about 1 kV. The structures with upward potential drops occur where there are upward field-aligned currents of moderate intensity, assumed to be the driving agent. Evidently $E \cdot j > 0$, and the structures convert electric energy of the magnetospheric current generator to kinetic energy of the auroral particles. The EIC waves show a bursty nature, suggesting that they might be excited by the solitary structures, or the instability generating these.

THEORETICAL ASPECTS OF WEAK DOUBLE LAYERS AND THEIR RELATION TO THE ELECTRODYNAMIC COUPLING BETWEEN THE MAGNETOSPHERE AND IONOSPHERE

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ABSTRACT

Ion scale solitary waves and weak double layers on auroral magnetic field lines have been studied experimentally by the U.S. S3-3 and Swedish Viking spacecraft. Considerable theoretical effort has been paid for the study of plasma physics behind these phenomena but with relatively modest success. In this talk the present status of the theoretical understanding is reviewed. It has frequently been suggested that weak double layers may build up a considerable part of the field-aligned potential drop between the auroral ionosphere and magnetosphere. This suggestion is discussed in order to determine the possible role of weak double layers in the global magnetosphere ionosphere coupling. A comprehensive understanding of electric fields on auroral field lines requires the consideration of a variety of physical mechanisms, including field-aligned and perpendicular (small and large scale) potential structures, wave phenomena, field-aligned currents, etc. Weak double layers seem to be one of the ways how auroral plasma can support parallel electric fields under certain boundary conditions imposed by the global coupling process.

The Physics of Electrostatic Double Layers: Weak Double Layer Dynamics

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Abstract

The equilibrium state of electrostatic double layers has been studied in detail for all amplitude ranges. Time independent models imply generalised Bohm criteria as matching conditions to the ambient plasma on both sides. Formation may be related to the nonlinear growth of current driven instabilities. These can lead to a localised density dip, whose pre-existence may also act as a trigger for the formation process. Large amplitude dynamics may be studied in particle simulation of plasmas, showing the creation of double layers. In the case of very weak double layers their evolution may be described using the modified Korteweg-de Vries equation, and in particular intial conditions for formation can be determined. Generalisations to three dimensions show that magnetised weak double layers are stable, whereas without magnetic field instabilities develop. Simulation methods must be used for ion acoustic double layer studies where the amplitude is comparable to the ambient plasma thermal energy. There is evidence for such double layers in satellite observations in the Earth's magnetosphere.

DOUBLE LAYER RELEVANT LABORATORY RESULTS

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Many double layer relevant experiments have been carried out during the last few years at the University of Wisconsin. Much of this work has been performed in triple plasma devices. The operation of these devices, as well as their general strengths and weaknesses, will be discussed. Characteristics of stairstep double layers, which resemble several double layers joined in series, will be presented. We have tried, without success so far, to measure the associated electron distribution functions. Plasma Gradient Induced Errors are a problem with general applicability to double layer data. We have recently begun to investigate this problem and our results, particularly space charge effects on electric field measurements, will be presented. Lastly, a discussion will be given of a new type of inductive source for making uniform magnetized plasmas. Double layer data in the presence of a magnetic field will be presented.

THE ROLE OF SELF-CONSISTENCY IN DOUBLE LAYER CALCULATIONS

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It was suggested[1] that satellite observations of rarefactive auroral DLs[2] could be explained by a model including negative ions. Self-consistent calculations of the Sagdeev potential for ion-acoustic DLs[3], however, contradicted this and arbitrary-amplitude studies[4] have shown that in a two-electron temperature plasma, negative ions destroy IADLs if their density exceeds ~ 1 %.

In contrast to KdV theory, self-consistent arbitrary-amplitude calculations also show that negative ions cannot replace the second electron species needed to support IADLs[4] and that electron-acoustic DLs do not occur in a two electron species plasma. Self-consistent, arbitrary-amplitude calculations of solitons have also been carried out[5].

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The Formation of Anomalous Potential Drops and Electric Double Layers Due to Ion Density Cavities

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Abstract

It has been proposed that a local ion density minimum (an ion density cavity) can lead to the formation of a double layer when a voltage drop is applied to the plasma. Density cavities formed by ion cyclotron waves in the magnetosphere have also been proposed to lead to formation of weak double layers supporting magnetic-field-aligned electric fields above the Aurora. Laboratory investigations demonstrating the importance of density cavities will be presented. When a step voltage is applied to a plasma with an initial cavity, most of the potential drop is distributed over the cavity after about an electron transit time. Then the potential profile steepens slowly to a double layer on the time scale of the ion motion. When the initial plasma is homogeneous, the applied potential drop is instead supported by a cathode sheath which begins to propagate into the plasma as a double layer on the time scale of the ion motion. Numerical simulations and a theoretical model clarifying the experimental results will also be presented. The existence regions for the two different plasma responses in the parameter plane are found in the simulations and shown to agree with the regions predicted theoretically.

EVOLUTION OF PARTICLE CLOUDS AROUND ABLATING PELLETS IN MAGNETICALLY CONFINED HOT PLASMAS

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Abstract

Cryogenic hydrogen isotope pellets are being currently used for introducing fuel particles into the plasma interior in magnetic confinement fusion experiments. The spatial and time evolution of the initially low-temperature high-density particle clouds forming around such pellets is the subject of this presentation. Particular attention is given to such physical processes as heating of the cloud by the energy fluxes carried by incident plasma particles, gasdynamic expansion with $\vec{j} \times \vec{B}$-produced deceleration in the transverse direction, finite-rate ionization and recombination (collisional and radiative) processes, and magnetic field convection and diffusion. While the dynamic processes associated with the ionization and radial confinement processes are characterized by the relatively short Alfvén time scale (μs range), the subsequent phase of axial expansion is associated with a notably larger hydrodynamic time scale defined by the heat input and gasdynamic expansion rates (ms range). The rediffusion of the magnetic field into the cloud seems to occur on the resistive diffusion time scale. A characteristic cloud structure results: a hollow temperature profile coupled to a peaked density profile in the plane normal to the magnetic field direction. The separation distance between the high and low temperature and/or density layers is typically the ionization or confinement radius. Also the flutes that may develop at the cloud surface have, at a certain phase of their development, the same wavelength.
Data stemming from experimental measurements in toroidal confinement machines are compared with results of model calculations. Some similarities with other exprimental scenarios, such as the earlier magnetospheric barium release experiments, are briefly discussed.

EXPERIMENTAL OBSERVATIONS OF TURBULENCE DRIVEN PARTICLE TRANSPORT AND DIFFUSION IN A DOUBLE PLASMA DEVICE

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Electron transport properties have been investigated in a Double Plasma (DP) device using two independent diagnostics- a multiple probe array and a test particle beam. In the DP device an Argon ion beam of energy 30 eV is injected into a weakly magnetized background plasma. This configuration gives rise to the Cross-Field Ion Acoustic Instability. The turbulence level $\tilde{n}/n$ can be varied between 1 % and 30 % by launching broadband noise (between 50 kHz and 300 kHz) onto the ion beam. Our first diagnostic employs an array of Langmuir probes measuring correlated fluctuations of plasma density $\tilde{n}$ and plasma potential $\tilde{\phi}$. The transport spectrum $\Gamma(\omega)$ is derived from these measurements. Measurements of electron transport parallel and perpendicular to the ion beam at different values of $\tilde{n}/n$ are presented. Our second diagnostic, employed under the same plasma conditions, utilizes test particles injected into the DP device by a Pierce type electron gun. These low-energy electrons were detected using a Langmuir probe and lockin techniques. From these measurements the perpendicular diffusion coefficient, $D_\perp$ was calculated and related to transport via, $\Gamma = < nv > = -D_\perp \nabla n_e$. Data obtained with these two diagnostics at different fluctuation levels indicate the presence of non-isotropic turbulence driven transport in the $\mathbf{k} \times \mathbf{B}$ direction.

The Transport of Test Ions in Laboratory Plasmas*

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Ion diffusion across and along magnetic fields has been measured in quiet and turbulent plasmas. In the same spirit as particle injection experiments in the magnetosphere, test ions were created[1] and their phase space trajectories followed temporally. Both real and velocity space diffusion coefficients have been measured. In quiet plasmas the diffusion[2] agrees with classical predictions. In turbulent plasmas studied thus far, the spatial cross field diffusion was given[3] by $D_\perp \approx 4(cT_e/eB)(\delta n_i/n_{io})_{rms}$. The laboratory experiments study controlled wave spectra and thus examine individual processes which may contribute to magnetospheric transport.

*In collaboration with J. Bowles, N. Rynn, N.S. Wolf, and M. Zintl.

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Session 7

PLASMA AND MAGNETIC FIELD TRANSPORT

THE ROLE OF PLASMA INSTABILITIES IN THE PLASMA EROSION SWITCH

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The plasma erosion switch is a device to carry a large current through a plasma, and then to interrupt this current in a very short time. It plays an important role in pulse power research. A striking observation in erosion switches is that the during the conduction phase the large magnetic field produced by these currents is observed to penetrate into the plasma in a time very short compared to that expected from normal Spitzer resistivity. This rapid penetration is believed to be due to an anomalously large resistivity in the plasma. This resistivity could possibly be produced by a particular ion-acoustic instability driven by large electron drift velocity of the cross field current. I will give a brief survey of erosion switches and the role they play in pulse power research Then I will describe the instability. the resistivity it generates, and its nonlinear evolution and saturation. The saturation amplitude seems to be large enough to generate the required anomalous resistivity. A similar rapid penetration of magnetic field into plasma occurs in space, and is observed in the barium cloud experiments, in which conditions somewhat similar to the erosion switch occur. I will discuss this possibility.

MAGNETIC FIELD PENETRATION AND EROSION

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A class of plasma-plasma interactions in space is constituted by comets and unmagnetized planetary bodies exposed to the magnetized solar wind. The interaction, collision-free or collision-dominated, requires penetration of the magnetic field into the unmagnetized ionized gas. The penetration process has been studied in artificial comet experiments involving barium releases in near-Earth space. It was found that the process can be described by a snow-plough model. The magnetization does not proceed by resistive diffusion of the magnetic field, but by a combination of inertial penetration of the ions and convective transport of the electrons, practically "noiseless". The process requires formation of small-scale structures with transverse scales of the order of the ion inertial length. - Once magnetized plasma can be eroded. This occurs in an asymmetric fashion, whereby the side on which the electric field vector (related to the ambient plasma flow) points away from the cometary plasma, is subject to the ion extraction. This creates interesting recoil effects, which are also manifested in the Venusian ionosphere.

Diffusion Processes at the Magnetopause

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Plasma entry from the solar wind/magnetosheath across the magnetopause into the magnetosphere is known to proceed on time scales of some ten minutes under magnetospherically quiet conditions and possibly faster during violent disturbances of the magnetosphere. The main evidence for this continuous entry is the existence of a layer of mixed magnetosheath/magnetospheric plasma in the outer magnetosphere, called the low latitude boundary layer. While in the disturbed case plasma may directly penetrate into this layer through the magnetopause via reconnected field lines, the processes responsible for maintaining the boundary layer during quiet times are still under debate. It is however expected that diffusion caused either by micro or macroinstabilities plays the dominant role in providing the required cross boundary flux. Candidates of microinstabilities are ion cyclotron waves and lower hybrid waves. We estimate the diffusion coefficients caused by the latter and find that lower hybrid waves excited by the density gradients at the magnetopause are strong enough to yield the diffusion required for plasma entry. Hence, lower hybrid turbulence seems to be rather important. The mechanism is probably also of interest for other magnetised astrophysical objects as the interfaces between accretion disks and neutron star magnetospheres.

Session 8

CHAOS AND TURBULENCE

Low-Dimensional Behavior and Symmetry Breaking of Nonlinear Stochastic Systems - Can these effects be observed in the laboratory and in space?

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It is demonstrated, using the techniques of path integrals and renormalization-group, that nonlinear stochastic systems at "criticality" generally exhibit low-dimensional behavior. The symmetry which characterizes a particular criticality may be broken by the appearance of new relevant scaling fields. The possibility of observing such effects in space (such as the onset of substorms), in the laboratory (such as stochastic particle heating in a "noisy" magnetic field), and through numerical simulations will be described. The associated crossover phenomena will also be discussed.

Turbulent Relaxation in Space and Laboratory Plasma

David Tetreault (MIT Center for Space Research, Cambridge, MA 02139)

Relaxation of highly collisionless plasma typically relies on collisionless instabilities and therefore is a turbulent phenomenon. While the plasma is constrained globally by dynamical invariants (*e.g.*, by the conservation of energy, momentum, magnetic helicity, *etc.*), the relaxation frequently involves the generation of localized, large amplitude fluctuations (double layers, magnetic islands, *etc.*). A theoretical model for such intermitent relaxation is reviewed and then applied to several space and laboratory experiments including: (1) double layers aligned along the Earth's geomagnetic field lines in the auroral acceleration region, (2) magnetic reconnection and associated flux transfer events (FTE) in the Earth's dayside magnetopause, and (3) turbulent relaxation in tokamak and reversed field pinch (RFP) fusion devices. The physical and conceptual similarities of these various phenomena will be stressed as well as the implications for future space experiments.

Session 9

CONCLUSION OF WORKSHOP

PLASMA PHYSICS IN SPACE AND LABORATORY*

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ABSTRACT

Space plasmas span a broad range of physical parameters, extend over large dimensions, and exhibit a multitude of fascinating and unexplained phenomena. They frequently involve several non-equilibrium components which interact with each other and the ambient magnetic field to drive a rich collection of plasma instabilities and phenomena. Great progress has been made in finding and many of these processes through *in-situ* rocket and satellite experiments coupled with plasma theory advances. However, actual space experiments are expensive and infrequent and they offer limited capability to perform interactive experiments required to understand the basic science involved. Laboratory experiments, on the other hand, can accommodate detailed studies which bring deep physical understanding and are relatively inexpensive. But, they often have physical parameters far from those in space and run the risk of being irrelevant to space phenomena. The most efficient approach, therefore, is an integrated effort involving space experiments, laboratory experiments, and theory. Laboratory experiments then help interpret space observations, verify theory, and can provide direction for future space experiments.

Laboratory space related investigations NRL utilize two facilities: the Pharos Laser-Target facility, and a large volume space chamber. Laser-produced plasmas are particularly well suited for laboratory investigations of many space phenomena. Laser-produced plasmas can be formed with parameters either very close, or scalable, to many space and astrophysical plasmas and active space experiments.[1] We describe several such space-plasma experimental investigations using the NRL Pharos Laser Facility and their relationship to *in-situ* experiments and theory. In other space plasma regimes, the large volume space chamber experimental facilityas being built up now at NRL is preferable. We will outline experiments being planned for this facility and any preliminary results that may be available at the time of the Conference.

* Collaborators in this work are: P. Bernhardt, R. Burris, J. Chen, J. Crawford, R. Elton, G. Ganguli, J. Grun, J. Huba, C. Manka, E. McLean, T. Peyser, J. Resnick, J. Stamper, and D. Walker of NRL.

Work is sponsored by the ONR.

Posters

Direct Excitation and Nonlinear Behaviour of Shear Alfven Waves

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Shear Alfven waves (poloidal mode number $m = 0$) were excited directly (not from the mode conversion) by the small current element parallel to the magnetic field. Their polarizations in the cross section of the plasma column are first found to be elliptically polarized from the circle when the enhanced amplitude of the waves becomes larger.

ONE– AND TWO–HARMONIC APPROXIMATIONS TO WEAKLY NONLINEAR OSCILLATIONS IN THE PIERCE DIODE

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Any laboratory plasma is part of a "bounded plasma system (BPS)", characterized by the self–consistent interaction of the plasma itself, its boundaries, and the external circuit(s). However, BPS models have also been proposed for *space* plasmas.[1,2] Being *dissipative*, BPSs are usually encountered in some attractor state, so that studying these – preferably by analytic means – is a key task of theoretical plasma physics. The most fundamental BPS model is the 1d "classical Pierce diode", with a collisionless cold electron beam propagating against a uniform, immobile ion background between two electrodes shorted externally.[3-5] An extended Pierce–diode model with nontrivial external–circuit elements[2,5] has been applied, e.g., to double–layer formation in space plasmas.[2] *This* work is concerned with an *analytic* approach to *small-amplitude steady–state oscillations* in the Pierce diode, a particularly simple attractor state first found numerically by Godfrey for the short–circuit case.[4] Expanding all perturbations in Fourier series, collecting terms for each harmonic order n, and linearizing the integrodifferential "order–n equations" thus obtained, Hörhager and Kuhn[5] had to include terms up to $n = 3$ ("3–harmonic approximation") to obtain a well–determined nonlinear oscillation. Here, by retaining more of the nonlinearity, such an oscillation follows already in the 1–harmonic approximation, and a 2–harmonic approximation yields the first subharmonic bifurcation. Implications to both laboratory and space plasmas will be discussed.

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Electrostatic ion-cyclotron wave experiments in the WVU Q Machine*

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The influence of transverse, localized, d.c. electric fields (TLE) on the current-driven electrostatic ion-cyclotron instability is being investigated in a Q machine. A small (diameter ~10 ρ_i) segmented disk electrode is being used to excite the mode in a narrow electron-current channel along which exists a radial electric field between regions that magnetically map to the different circular segments (separated by a radial gap ~3 ρ_i). The results of preliminary experiments aimed at demonstrating a TLE-dependence in the threshold current for mode excitation will be presented. The development of the segmented disk electrode and the diagnostic techniques to measure threshold electron drift velocity and threshold electric field will be discussed.

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The Effect of a Magnetic Field Gradient on Anode Double Layers.*

R. L. MERLINO, BIN SONG, and N. D'ANGELO, Dept. of Physics and Astronomy, U. of Iowa, Iowa City, IA 52242. -- In experiments on double layer formation in non-uniform magnetic fields it has been noted[1,2] that the magnetic field inhomogeneity stabilizes the double layer position. These experiments were performed in devices where the magnetic field geometry was fixed. We have further investigated this effect in a device in which the magnetic field gradient could be varied. Our experiments were performed in a single-ended Q machine (IQ-2) operating with a potassium plasma produced by surface ionization on a 6 cm diameter tantalum hot plate. Anode double layers were produced by applying a positive bias to the endplate under conditions where the background (argon) pressure was $\sim 10^{-4} - 10^{-3}$T. The double layers were maintained by ionization of the neutral gas by the electrons which are accelerated through the potential step. We found that: (a) double layers could only be formed with potential gradients in the direction opposite to the magnetic field gradient, and (b) the axial position of the double layers can be controlled by varying the magnetic field gradient. The location and stability of these double layers are considered on the basis of a model which takes into account ionization, ion losses across the magnetic field and reflection of ions due to the $\mu \cdot \nabla B$ force.

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Experiments on Double Layers in a Convergent Magnetic Field –
R. Schrittwieser[1], S. Torvén and I. Axnäs, *The Alfvén–Laboratory, Royal Institute of Technology, S–10044 Stockholm, Sweden:*
It is well known that space charge double layers (DL) form in the magnetosphere along the convergent magnetic field lines above the magnetic poles. We present an experimental investigation in an argon low pressure discharge plasma confined by a convergent magnetic field. At a certain position in front of the anode a DL forms with a height between 10 and 20 V depending on the magnetic field strength. There is a marked difference between the plasma density profile on the low potential side and on the high potential side of the DL: the latter shows a plateau around the axis whereas the former has a conventional round shape. At the same time we detect strong high frequency (HF–) oscillations of about $f \simeq 560$ MHz on the high potential side. Two questions arise: (i) where do the HF–oscillations come from? (ii) Why is there a plateau of the plasma density on the high potential side of the DL? Concerning (i): The HF– oscillations are obviously produced by fast electrons which are accelerated by the electric field of the DL. Concerning (ii): We believe that the flattening of the plasma density profiles is due to the ponderomotive effect of the HF–oscillations.

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Dust Shedding by Material Bodies in a Plasma

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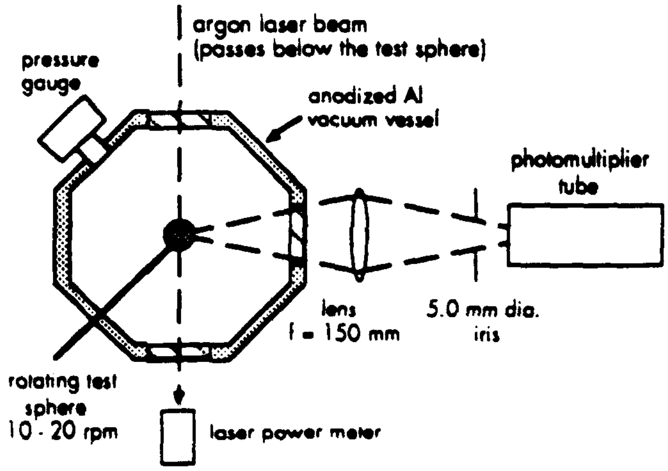
Experiments have been conducted to investigate the release of dust particulates from material bodies during exposure to a plasma. Four spherical test bodies were made of untreated Al, anodized Al, mylar taped Al, and a composite material. These spheres were covered with tabular alumina particulates between 1 to 10 μm in size using an electrostatic process, and then inserted into a vacuum vessel. We observed the shedding of particulates by laser light scattering.

During depressurization, there was no significant shedding except for the mylar-covered sphere. Mechanical tapping of the sphere's holder always produced more shedding than did depressurization.

Turning on a nitrogen plasma caused a very significant dust particle release. The plasma was produced upstream from the test body by a filament multidipole source.



The Tokamak as an Earth-Based Laboratory for Space Physics Related Experiments

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Fusion related plasma experiments in tokamak devices require strong magnetic fields in both the toroidal and poloidal directions to contain the hot, dense plasmas. The PBX-M tokamak is equipped with numerous independent field coil systems, and these allow for a great deal of flexibility and creativity in forming vacuum magnetic topologies in the poloidal plane with no toroidal field component. These topologies can simulate magnetospheric field topologies in the noon-midnight meridional plane. In particular, minimum-B X-line and stretched-out dipolar field topologies can be created that simulate the field topologies of the nose and tail X-line regions and the tail-like field away from the null field, respectively. A toroidal electric field, which can simulate the cross-magnetospheric electric field, is also easily produced in the tokamak. Low energy plasmas can be created by ionizing neutral gas using RF systems. Possible experiments that could be conducted include the study of plasma motion and beam formation in static and time-dependent X-line topologies, the study of the collisionless Ohm's law, and the mapping out of particle trajectory boundaries in tail-like field topologies using electron beam injection. The poster will present details of the plasma and field topologies as well as a discussion of the possible experiments and diagnostic techniques.

Velocity Space Diffusion in Q-machine Plasmas*

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University of California, Irvine

We report measurements of test particle diffusion in velocity space. Test particles are created and examined by the method of optical tagging, an extension of laser induced fluorescence. In quiet plasma conditions ($\frac{\delta n}{n} \leq .01\%$) results show diffusion to be linear with density in agreement with classical theory. Measurements taken in the presence of drift waves($\frac{\delta n}{n} \simeq 6\%$) and in the presence of broadband electro-static ion cyclotron waves ($\frac{\delta n}{n} \leq 5\%$) have been made. Measurements made in the presence of drift waves show resonant particle interactions. Applications to magnetospheric phenomena will be discussed.

*Work supported by National Science Foundation PHY-9024667

Test-ion diffusion in a magnetized plasma

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Abstract

The radial diffusion of Barium test ions has been studied on the LMP Q-machine plasma.
The technique of optical tagging has been used to produce the test particles: a sub-set of the ion population can be chosen according to both radial location and velocity by positioning and tuning a first laser beam. The tagged particles, created along a vertical chord of the cylindrical, axially magnetized plasma, spread out radially as they propagate along the field lines, due to the cross-field diffusive motion.
The comparison between the measured radial profiles at different axial positions and a simple theoretical model based on the transfer function formalism yields a quantitative evaluation of the ion diffusion.
The injection of different buffer noble gases, at different pressures, allows one to change plasma parameters and obtain different collisional regimes. The consequent diffusion mechanisms can then be investigated.

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REGULAR AND STOCHASTIC SOLUTIONS OF DRIVEN BURGERS EQUATION

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The onset of turbulence in the Burgers model, corresponding to the pumping of the energy into a few unstable harmonics at the small viscosity, is investigated by both analytical and numerical approaches. It is shown, that for the case of two unstable harmonics having the growth rates γ_1 and γ_2, respectively, the steady structures occur if $\gamma_2 < C(\mu) \cdot \gamma_1$. Those structures have the form of the travelling shock waves with one shock per the period of the problem and can be described analytically. But in the case $\gamma_2/\gamma_1 > C(\mu)$ the oscillatory solution is formed. If the bifurcation parameter γ_2/γ_1 is high enough the solution corresponds to the consequent transitions from one-shock to the two-shocks structures. Further increasing of the bifurcation parameter leads to establishing of two-shocks steady structure. Only regular dynamics of producing of the shock-trains occurs at the case of two unstable harmonics. The introduction of the next unstable harmonics gives rise to the onset of stochasticity in the system.

ARNOLD DIFFUSION IN A PERTURBED MAGNETIC DIPOLE

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The Collisionless Terrela Experiment, currently under construction at Columbia University, will attempt to simulate the effects of Arnold diffusion on collisionless particle transport in planetary magnetospheres. In support of this effort, we have begun a numerical study of single particle motion in a magnetic dipole with additional azimuthally dependent electrostatic fields. Here we report the dependence of the arnold diffusion rate on particle energy and perturbation strength and compare them with theoretical estimates.