Final Technical Report for the

Center for Momentum Transport and Flow Organization:

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Executive Summary

The Center for Momentum Transport and Flow Organization (CMTFO) is a DOE Plasma Science Center formed in late 2009 to focus on the general principles underlying momentum transport in magnetic fusion and astrophysical systems. It is composed of funded researchers from UCSD, UW Madison, U. Colorado, PPPL. As of 2011, UCSD supported postdocs are collaborating at MIT/Columbia and UC Santa Cruz and beginning in 2012, will also be based at PPPL. In the initial startup period, the Center supported the construction of two basic experiments at PPPL and UW Madison to focus on accretion disk hydrodynamic instabilities and solar physics issues. We now have computational efforts underway focused on understanding recent experimental tests of dynamos, solar tachocline physics, intrinsic rotation in tokamak plasmas and L-H transition physics in tokamak devices. In addition, we have the basic experiments discussed above complemented by work on a basic linear plasma device at UCSD and a collaboration at the LAPD located at UCLA. We are also performing experiments on intrinsic rotation and L-H transition physics in the DIII-D, NSTX, C-Mod, HBT EP, HL-2A, and EAST tokamaks in the US and China, and expect to begin collaborations on K-STAR in the coming year. Center funds provide support to over 10 postdocs and graduate students each year, who work with 8 senior faculty and researchers at their respective institutions. The Center has sponsored a mini-conference at the APS DPP 2010 meeting, and co-sponsored the recent Festival de Theorie (2011) with the CEA in Cadarache, and will co-sponsor a Winter School in January 2012 in collaboration with the CMSO-UW Madison. Center researchers have published over 50 papers in the peer reviewed literature, and given over 10 talks at major international meetings. In addition, the Center co-PI, Professor Patrick Diamond, shared the 2011 Alfven Prize at the EPS meeting.

Key scientific results from this startup period include initial simulations of the effects of boundary conditions on turbulent dynamo experiments; simulations of intrinsic rotation showing the strong link between toroidal rotation and temperature gradients and elucidation of the turbulence symmetry breaking mechanisms that lead to this macroscopic behavior; first experiments in a large tokamak testing the roll of turbulent momentum transport in driving intrinsic rotation; experiments in tokamaks showing strong evidence that zonal flows, together with the more widely recognized mean sheared ExB flow, act to trigger the L-H transition in tokamak devices and the first experimental measurement of collisional viscosity in an unmagnetized plasma. In the coming three year period, we will continue these efforts by a combination of basic hydrodynamic, liquid metal and plasma experiments combined with experiments on numerous tokamak devices around the world. In addition, we will use MHD, gyrofluid and gyrokinetic codes combined with theory to address the problems of interest to the Center.

Background

Scientific Significance: Momentum transport and flow self-organization dynamics are ubiquitous and critically important processes in plasmas and magnetofluids. Historically the importance of magnetic self-organization has been widely recognized in plasma physics but the discovery of transport barriers, zonal flows and intrinsic rotation have now forced the community to regard flow self-organization as equally important as magnetic self-organization. Examples of momentum transport physics issues include, but are not limited to, the origins and dynamics of intrinsic rotation in tokamaks and especially in the burning plasma of the International Thermonuclear Experimental Reactor (ITER); flow-shear induced formation of transport barriers and associated transition of confinement regimes; momentum transport in shallow, stratified magnetofluids and its implication for the formation of the solar tachocline and stellar differential rotation; mechanisms for mean-field turbulent viscosity and angular momentum transport in accretion disks (*n.b.* the precise implications of the interplay of angular momentum transport, magnetic dissipation, and magnetorotational instability (MRI) for accretion in these objects is of particular interest); and the dynamics of flow shear formation associated with magnetic dynamos, with emphasis on possible shear quenching processes. Many other possibilities exist; however it already is clear that the broad importance and pervasiveness of the momentum transport and flow self-organization theme are unquestionable and central to both magnetic fusion and astrophysical plasmas. Elucidating the general principles underlying the momentum transport and flow self-organization is a challenge in basic plasma physics with important implications in Astrophysics, Geophysics and Magnetic Fusion.

The **Center for Momentum Transport and Flow Organization** in Plasmas and Magnetofluids (CMTFO) was formed in September 2009 to bring together astrophysical and magnetic fusion theorists, experimentalists and computationalists from multiple institutions. Working across a range of experiments extending from liquid metal magnetohydrodynamics (MHD) and small laboratory plasmas to large magnetic confinement devices, Center researchers will directly examine the link between turbulent momentum transport and large scale flow self-organization using newly developed diagnostic and data analysis techniques to investigate and critically test emerging theoretical and computational models. The computational tools range from nonlinear turbulent MHD codes to collisionless gyrokinetic plasma simulations. Center activities are focused on a set of cross-cutting scientific themes relevant to systems as diverse as magnetic fusion plasmas, the solar tachocline and ionized accretion disks, and will seek to identify the underlying principles that govern self-organization of plasma flows. Utilizing small and large experimental facilities and supercomputers at national laboratories and universities and leveraging off of no-cost international collaborations, the Center supports the activities of nearly 60 person-years of post-doctoral and student research with a bare minimum of funds for faculty and professional research staff, thereby providing strong support for the training of a new generation of researchers for the plasma physics community. The Center hosts an annual School for graduate students,postdoctoral researchers and scientists interested in this research topic; the lectures will be collected into a series of research monographs. Web-based seminars and presentations will be provided and archived for future reference.

Problems of Interest

Momentum transport and flow self-organization dynamics are ubiquitous, critically important processes in turbulent plasmas and magnetofluids found in the laboratory and in nature. Examples of turbulent momentum transport physics issues include, but are not limited to:

- the origins and dynamics of intrinsic rotation in tokamaks in general, and ITER in particular [Rice:2007, Yoshida:2008] which is of critical importance for resistive wall mode control in ITER;
- flow-shear induced confinement regime transitions such as the L-H transition, ITB formation [Burrell:1997];
- momentum transport in shallow, stratified magnetofluids and its implication for the formation of the solar tachocline [Hughes:2007];
- momentum transport in the turbulent interiors of rotating stars [Mestel:2003, Rudiger:1989];
- mechanisms for mean-field viscosity [Shakura] and transport in accretion disks, ranging from partially ionized proto-stellar disks to collisionless AGNs. The precise implications of the interplay of momentum transport, turbulent resistivity, and magnetorotational instability (MRI) for accretion in these objects is of particular interest [Shu:2007]; and
- the effects of flow shear formation on magnetic dynamos [Moffatt:1978], with emphasis on possible shear effects on quenching processes [Gruzinov:1994, Vishniac:2001] and shear-driven helicity flux [Vishniac:2001].

Many other possibilities exist; however it already is clear that the broad importance and pervasiveness of the momentum transport and flow self-organization theme are unquestionable. While the list of interesting problems in the turbulent transport of plasma momentum is indeed long, **we have elected to focus, at least initially, on three specific topical areas in the CMTFO**. These are:

- MFE Flow Organization (with specific foci on Intrinsic Rotation, the L-H Transition and the formation of the QSH regime in the RFP),
- Momentum Transport in Accretion Disks, and
- Momentum Transport in the Solar Tachocline

Below, we briefly discuss the significance of each, and the outstanding problems in each topical area.

Intrinsic rotation refers to the apparently spontaneous toroidal rotation observed in the absence of obvious momentum input on tokamaks. The scope of this generic label has now expanded to encompass the questions of:

a. How does turbulence control the self-organization of the toroidal velocity profile $\langle V_\phi \rangle$? For the low collisionality plasmas typical of ITER, turbulent processes are expected to control $\langle V_\phi \rangle$ as well as the poloidal rotation $\langle V_\theta \rangle$.
b. How do intrinsic toroidal and poloidal rotation then interact to determine electric field shear flow $\langle V_E \rangle'$, which in turn impacts confinement, and what is the physics and role of boundary effects?
c. How does $\langle V_E \rangle'$ then feedback on rotation? What types of stationary states are possible? How does intrinsic rotation couple to ITB formation?
d. Is intrinsic rotation significant enough to mitigate resistive wall modes (RWMs) [Jensen:1983, Betti:1998, Garofolo:1999] in high β ITER discharges?

Several outstanding problems in intrinsic rotation are enumerated in Table 1. Some particularly interesting issues include: Does the non-diffusive momentum flux include both a velocity or momentum "pinch" [Hahm:2007]]and a wave-driven residual stress [Gurcan:2007, Diamond:2008]] ? What is the origin of the requisite symmetry breaking for the latter? What sets $\langle V_\theta \rangle$ at very low collisionality? How do Alfven eigenmodes (AEs) in burning plasmas affect intrinsic rotation?

<u>Transport Barrier Formation:</u> The H-mode is universally recognized to be of great importance, both as a regime of improved confinement – and thus a route to ignition in ITER, - and as a fundamental constituent of tokamak transport and confinement phenomenology. While extensive progress has been made on clarifying and resolving the basic issues of the physics and evolution of L→H transition dynamics, it is nevertheless fair to say that after nearly 30 years, a quantitative, predictive understanding of the L→H transition remains elusive. In particular, the links between "micro-dynamics", such as shearing, zonal flows etc. and "macroscopics", such as power thresholds, grad B drift asymmetries, etc. have not yet been established. CTMFO research in this topical area consists of studies of i) pre-transition turbulence and secondary flows, ii) intermediate (I) phase and transition dynamics, iii) post-transition evolution, and iv) back transition (H→L) evolution. We also discuss certain special issues related to i) – iv) above. We are using a mixture of basic laboratory plasma and tokamak experiments, theory and numerical simulation to make progress.

<u>Solar tachocline</u>: This topic is concerned with momentum transport in β-plane MHD (i.e. a rotating 2D MHD fluid with a gradient in the Coriolis force), which is, in turn, critical to the formation of the solar tachocline – a thin, stably stratified layer at the base of the solar convection zone thought to play an important role in the solar dynamo. The tachocline is thought to be formed by the competition between meridional circulation driven "burrowing" and either turbulent viscosity or ambient (fossil) magnetic fields [Gough:1998]. Hence, understanding the solar tachocline absolutely requires an understanding of wave and turbulence driven momentum transport in MHD systems. Since the ambient flow shears of the tachocline can amplify magnetic fields by differential stretching, the result of tachocline flow formation can also play in important role in the solar dynamo, thus linking momentum

transport and flow self-organization to the issue of magnetic self-organization. More generally, in recent years difficulties with the theoretical foundation of the α effect [Vainshtein:1992, Gruzinov:1996, Cattanneo:1996], central to dynamo theory, has prompted increased interest in the velocity shear-driven flux of magnetic helicity [Vishniac:2001]. However, this, in turn, begs the question of what regulates the shear? In particular, quenching of shear amplification by Alfvenization of turbulence is a key concern here. This again leads us back to the problem of momentum transport [Rhines:1982, Batchelor:1956] in β-plane MHD – a central topic of this proposal. Several outstanding problems are listed in Table 1. One is particularly particularly interesting is the fate of potential vorticity (PV) (a generalized form of vorticity in an inhomogeneous plasma or MHD fluid) homogenization in β-plane MHD. Here the issue is to what extent Lorentz forces can maintain a finite PV gradient against viscous mixing. This is a very important and fundamental theoretical question, since PV homogenization is often invoked to explain macroscopic flow self-organization in geophysical fluids[Rhines:1986].

Accretion Disks: The third topic focuses on the origins of turbulent momentum transport in disks, which is thought to lead to rapid accretion as observed. The important issues of this problem are discussed in Table 1. It is well known that accretion requires "turbulent" viscous transport of angular momentum. Two viable mechanisms for this turbulence (and thus for accretion) are either the magnetorotational instability (MRI) [Balbus:1991,Balbus:1998] or a nonlinear hydrodynamic instability triggered by finite amplitude velocity perturbations. Important aspects of these mechanisms are: Is there any evidence for a nonlinear hydrodynamic instability in non-Keplerian flows thought to occur in disks? What is the turbulent viscosity expected from the nonlinear evolution of the MRI? For the MRI-driven accretion process to function, accreting matter must "slip" relative to the magnetic field. This, in turn, requires a turbulent resistivity [Lubow:1994], and begs the question of what turbulent magnetic Prandlt number, P_M, is required for stationary accretion [Shu:2007]. Thus, the mean-field MHD theory of turbulent resistivity is identified as a critical issue in the physics of MRI-driven momentum transport. Of particular interest are the possible consequences for planet formation resulting from departures from Keplerian rotation induced by magnetic fields [Goldreich:2004].

We are then naturally motivated to ask what the *common* physics approaches and foci of inquiry are, and to outline how they link the seemingly disparate themes above. Possible common elements are:

a. modeling momentum transport – usually the development of a mean field theory of momentum transport for turbulent plasmas and magnetofluids – construction, validation and application;
b. identifying and validating unifying principles which govern flow self-organization,;
c. tracking feedback loop dynamics and self-regulation [Diamond:2005].

These common elements are tabulated vs. physical systems in Table 2. Below we now discuss these issues and identify questions that need to be answered in more detail.

Momentum transport in plasmas and magnetofluids: The problem of turbulent momentum transport requires determining the turbulent stress tensor

$$\vec{\Pi} = \langle n \rangle \langle \tilde{\mathbf{v}}\tilde{\mathbf{v}} \rangle + \langle \tilde{n}\tilde{\mathbf{v}} \rangle \langle \mathbf{V} \rangle + \langle \tilde{n}\tilde{\mathbf{v}}\tilde{\mathbf{v}} \rangle$$

(where <> denotes the usual ensemble average and the tilde denotes a fluctuating quantity). Here the first term is the turbulent Reynolds stress, the second is the convective flux, related to particle transport, and the third is the fully nonlinear triplet or "spreading" term. Magnetic or "Maxwell" stresses, $\sim \langle \tilde{B}\tilde{B} \rangle / 4\pi$, can also be important as well, though not always significant. Thus we see immediately that calculation of momentum transport is, in part, a problem in mean field theory. Nearly all problems in turbulent flow self-organization require some calculation of mean field Reynolds and Maxwell stresses for a variety of regimes, from fluid-like to collisionless. This is the flow momentum counterpart of the mean field electrodynamics problem. As with quasilinear theory [Vedinov:1962, Frisch:1989], the aim of the mean field methodology is to reduce a mean flux (i.e. $\langle \tilde{v}\tilde{v} \rangle - \frac{\langle \tilde{B}\tilde{B} \rangle}{4\pi\rho}$ in the case of momentum transport) or EMF (i.e. $\langle \tilde{v} \times \tilde{B} \rangle$ in the case of electrodynamics) to a well behaved functional of the local fluctuation intensity field and some number of cross phase factors [Diamond:2005, Diamond:2010]. The latter, of course, are the most crucial and most sensitive physics elements of the problem.

Specific questions include: How does one calculate the differential stress, $\langle \tilde{v}\tilde{v} \rangle - \frac{\langle \tilde{B}\tilde{B} \rangle}{4\pi\rho}$, for MHD? Is it quenched, i.e. drastically reduced, say in proportion to Reynolds or magnetic Reynolds numbers Re, or R_M due to near Alfvenization, as for the EMF in near-ideal high R_M mean field electrodynamics? How do symmetry breaking and dissipation enter? What controls the net stress in a nearly Alfvenized state (i.e. $E_{\parallel} \neq 0$ but still small)? Even for electrostatic turbulence, is it possible to represent the momentum flux as the sum of turbulent viscous diffusion, a convective term – possibly including a pinch velocity, V_R, and a residual stress, S_R, determined by anisotropic wave dynamics in the system so that $\bar{\bar{\pi}} = -\bar{\bar{\chi}} \cdot \nabla \vec{V} + \vec{V}_R \vec{V} + \bar{\bar{S}}_R$ [Diamond:2009] as shown in Table 2. Note that the residual stress is required to confront phenomena such as intrinsic rotation in tokamaks, in which a plasma is accelerated from rest by the interaction of the stress at the boundary. The residual stress is driven by grad P and grad-n via symmetry breaking, but is not explicitly proportional to toroidal rotation V_ϕ or shearing rate $\frac{dV_\phi}{dr}$. How does one construct a mean field theory of momentum transport in collisionless, kinetic regimes characteristic of a burning plasma, such as in ITER [McDevitt:2009] ? What determines the necessary irreversibility? Such plasmas can be expected to support electromagnetic microturbulence, as well as Alfven eigenmodes (AEs) driven by energetic particles. In such plasmas, the field momentum density may be a substantial fraction of the momentum density, and so decidedly non-negligible.

Identifying and validating potential unifying principles: There is no doubt of the enormous impact that Taylor's theory of relaxation has had on our conception of magnetic self-organization [Taylor:1986]. It is easy to underestimate the impact of this classic paradigm, which often helps guide our thinking in otherwise hideously complex circumstances, by providing an intuitively plausible and successful theory. Thus, we are motivated to ask if there are similarly powerful counterparts for flow self-organization. Two candidates are the theory of potential vorticity (PV) homogenization [Rhines:1982], developed as an outgrowth of the Prandtl-Batchelor theorem [Batchelor:1956], and the minimum enstrophy hypothesis, which is a selective decay model first proposed by Bretherton and Haidvogel [Bretherton:1976, Mattor:1991].

PV is a generalized vorticity which is conserved along fluid element trajectories [Diamond:2009]. In the Hasegawa-Mima model [Hasegawa:1978] of drift turbulence, for example, $PV = (1-\nabla_\perp^2\rho_S^2)\frac{e\tilde{\phi}}{kT_e} + \frac{n(r)}{n_0}$. Similar definitions arise in GFD applications. The local, conservative nature of the PV evolution underlies its importance in describing multi-field dynamics. The theory of PV homogenization, addressed in the fourth column of Table 2, predicts that potential vorticity will asymptote to a constant value within regions of quasi-geostrophic flows contained within a closed bounding streamline. It will then make a jump across zonal flow layers in the system. Many questions arise immediately. For example, under what conditions is PV homogenized in MHD, where Lorentz forces break local PV conservation for inviscid dynamics? Gyrokinetic simulations show that multi-zonal flow "staircase" states arise as a consequence of competing processes of PV homogenization within neighboring zonal bands in drift wave turbulence [Dif-Pradalier:2010]; simulations also show similar effects for quasi-geostrophic turbulence [Dritschel:2007]. Do similar results occur in experiment? What is the analogue of PV for collisionless, kinetic systems? Finding an answer to this seemingly philosophical but very important question is more likely than it appears, since the Vlasov/gyrokinetic equation is locally conserving with an incompressible phase space as is the quasi-geostrophic equation for PV evolution.

The minimum enstrophy hypothesis rests on the notion of a dual cascade of energy to large scale accompanied by enstrophy transfer to small scale dissipation, thus justifying selective decay. In this sense, it resembles the Taylor hypothesis for magnetic self-organization which posits that the system naturally relaxes to a desired state determined by a principle of minimum energy subject to certain magnetic helicity conservation requirements. Is this type of approach at all viable for flow self-organization? How might we apply this idea to multi-field systems? The list of questions is long. Note that while unifying principles may be difficult to elucidate, the search is worthwhile, since it forces us to confront the essential core of the physics in otherwise highly complicated systems.

Feedback dynamics and self-regulation: This topic is addressed in the third column of Table 2. Momentum transport and flow self-organization do not exist in a vacuum. These dynamics feedback on the relaxation which drives them and so are naturally self-regulating. Multiple feedback loops imply multiple energy transfer channels. Various types of transport (momentum, heat, magnetic field…) are linked sometimes tightly. Examples of these types of issues include the impact of self-generated flows and intrinsic rotation on confinement and upon the thermal transport which drives them, the value of the self-consistent turbulent magnetic Prandtl number associated with MRI-driven accretion, and the branching ratio of energy deposition into zonal field [Gruzinov:2002] and zonal flow structures [Diamond:2005]. All of these questions, and many others like them, are critical to understanding the dynamics of the underlying physical systems. Moreover, the theme should be approached by a combination of both dynamical and statistical methods. Thus, one can address the feedback between heat transport, on the one hand, and zonal flows and momentum transport on the other by both reduced dynamical models, which treat the self-consistent interaction of heat and momentum transport, as well as by studies of the statistics of heat avalanches [Diamond:1995, Carreras:1996, Idomura:2008], its relation to turbulence driven flow statistics, and in turn their dependence on flow control parameters.

Some specific issues in feedback loop dynamics are: How do we understand the interplay of zonal, mean and GAM shear flows on the L-H transition? How does intrinsic rotation feedback on confinement? How does the driving heat flux divide its energy between sheared mean rotation and turbulent transport? What is the spatio-temporal breakdown of this division? Do PV or ExB staircases, in which the steps are interspersed between zones of avalanches, form spontaneously in drift turbulence? Under what circumstances do intrinsic rotation states connect to or evolve into internal transport barriers? What is the relation between intrinsic toroidal and poloidal rotation? How do zonal flow control parameters, such as ion collisionality, impact heat avalanche statistics? What are the statistics of turbulent momentum transport and Reynolds stresses? How does GAM propagation impact turbulence spreading? What is the branching ratio of zonal flow and zonal field energy in β-plane MHD turbulence? How does collisional resistivity affect momentum transport in β-plane MHD? How does the magnetic Prandtl number P_M affect PV homogenization in β-plane MHD? How does the *turbulent* P_M regulate and control disk accretion? Can we parameterize the net departure from Keplerian profiles for a magnetized accretion disk, and if so, then how?

Physical System	Significance of Turbulent Momentum Transport	Outstanding Problems
Magnetically Confined Plasmas (Tokamaks and Alternate Concepts)	1. $\langle V_\theta \rangle, \langle V_\phi \rangle$ profiles 2. $\langle V_E \rangle'$ and transport/transition regulation and control 3. RWM stability	1. What determines rotation profiles: non-diffusive fluxes, electromagnetic effects, stiffness? 2. Is intrinsic rotation (toroidal) sufficient to mitigate RWMs in ITER? 3. What determines $\langle V_\theta \rangle, \langle V_\theta \rangle'$ at low collisionality? 4. What determines momentum dynamics/profiles in high β, burning plasmas?
Solar tachocline and high R_M dynamo	1. Limitation of tachocline penetration (i.e. turbulent viscosity vs. burrowing) 2. Tachocline shears amplify field pumped into tachocline 3. Shear driven dynamo process enabled by momentum transport	1. What limits flow shear in the tachocline? 2. Does flow shear generation "self-quench" at high R_M? 3. Is potential vorticity homogenized in β-plane MHD turbulence?
Magnetized accretion disks	1. Turbulent viscosity from MRI 2. Interplay of turbulent resistivity and viscosity in controlling accretion? 3. Rotation profiles?	1. What is parametrization of effective turbulent viscosity for magnetized accretion? 2. Does turbulent resistivity or turbulent viscosity control high and low states of accretion? 3. How does the rotation profile depart from Keplerian?

Table 1: Impact of turbulent momentum transport upon outstanding problems in physical systems to be investigated within the proposed CMTFO.

Physics Themes => Systems	Basic Processes	Modeling of Momentum Transport	Feedback Dynamics and Self-Regulation	Unifying Principles For Relaxation and Transport	Macroscopic Implications
Magnetically Confined Plasmas (Tokamaks and Alternates)	Drift-ITG-Alfven turbulence; AE's Diffusive off-diagonal fluxes Neoclassical-turbulence interplay	Intrinsic rotation & validity of $\pi_{r\phi} = -\chi \langle V_\phi \rangle' + V_r \langle V_\phi \rangle + S_{r\phi}^{res}$ flux decomposition, Physics of V_r, S_{res} Origins of symmetry breaking, resonant vs. wave transport processes, EM Coupling, high β effects	Interplay of SOL flows and intrinsic rotation, Multi-predator/prey feedback (ZF/GAM/mean flow), Role of potential enstrophy budget in flow evolution, Boundary flux and GAM propagation effects.	analogue of Hides' Thm for toroidal rotation? How to describe PV homogenization in GK? Is ZF formation described by PV homogenization?	Will intrinsic rotation in ITER avoid RWMs? Interplay of momentum and particle pinch leads density, rotation profile coupling? Transport barrier initiation?
Solar Tachocline and High R_M Dynamo	Rossby-Alfvenic waves and turbulence, Magneto-inertial waves, Zonal Flow formation	AKA and mean field theory for $\langle \tilde{v}\tilde{v} \rangle - \langle \tilde{b}\tilde{b} \rangle$ in β-plane MHD Effective viscosity and its quenching with R_M Rhines mechanism for β-plane MHD	R_M as control parameter for momentum transport? Zonal field vs. zonal flow branching ratio? Symbiosis or competition between momentum transport and dynamo?	Is PV homogenized in 2D MHD? Scaling of Re, Ha, Pr dependence? Does system access minimum enstrophy state?	Implication of momentum transport for tachocline thickness? Viability of shearing-driven models of dynamo? Does V' beat α quenching?
Accretion Disks	MRI, Rossby modes in disk Critical P_M for stationary magnetized accretion	Modelling turbulent viscosity, resistivity from MRI Does microdynamics allow macrodynamic stationary accretion?	Intrinsic turbulent P_M for steady state accretion? MRI-driven dynamo?	Is there an underlying, unifying principle for MRI-driven accretion?	Stationary vs. episodic accretion? R_M dependent high vs. slow accretion transitions? Systematic deviation from Keplerian profiles?

Table 2: Issues and questions organized by Scientific Themes and Physical System.

Progress: Research Tool Development, Science Results and Synergistic Activities

The CMTFO was officially launched in September 2009, and an initial kickoff meeting was held at UCSD in January 2010 to discuss initial plans for recruiting and research activities. Collaborators from UCSD, UCI, PPPL, MIT, UCSC, Colorado, and UW Madison were in attendance and discussed their ideas and plans for their initial focus. As discussed in the original proposal, UCSD worked with Professor N. Brummell at UCSC to support a postdoctoral researcher at UCSC to work on tachocline studies using MHD simulations. PPPL, UC Irvine, UW-Madison and Colorado had existing students and postdocs who immediately began working on Center related tasks. UCSD had to recruit new postdocs; that recruiting process began shortly thereafter, and continued through February 2011 when the final UCSD postdoc position was filled. We held our annual face-to-face meeting in January 2011 at which we heard from each collaborating group about their initial progress, status and plans for 2011. Thus the year 2010 was really a startup year in which projects were launched staff were recruited, and our first serious scientific discussions occurred. Progress on a number of scientific fronts began to occur later in 2010 and then in earnest in 2011.

Research Tools

During this startup period, the CMTFO sponsored the fabrication and/or completion of two new basic experiments – one at PPPL and one at UW Madison – which focus on Center-related research. In addition, using funding from the Center as well as other funding sources, a linear plasma device at UCSD was upgraded to permit direct fast framing camera visualization studies of turbulent momentum transport. In addition, we established a number of new experimental collaborations to pursue the science goals of the Center. Patrick Diamond, co-PI of the CMTFO, also established the World Class Institute (WCI) for Center for Fusion Theory at the NFRI in the Republic of Korea, giving CMTFO access to a major new computational activity in Korea. A number of researchers from the WCI will visit UCSD in the Winter and Spring 2012 as part of this collaboration. Finally, CMTFO affiliated researchers at UCSC began using nonlinear MHD simulations to study relevant problems. We briefly summarize these research tools in the succeeding subsections, and then turn our attention to the initial scientific accomplishments and synergistic activities of the Center in this initial startup period.

Experiments

The CMTFO provides direct support for several small-scaled experiments. These include the Controlled Shear Decorrelation experiment (CSDX) located at UCSD, the Hydrodynamic Turbulence Experiment (HTX) located at PPPL, and the Plasma Couette Experiment (PCX) locatd at UW-Madison. These three facilities respectively allow detailed study of drift turbulence-zonal flow coupling, accretion disk stability, and plasma viscosity, magneto-rotational and Parker instability studies relevant to both disk physics and solar tachocline physics. We provide a brief summary of their capabilities below. In addition we make extensive use of collaborations on a number of fusion confinement experiments which are also summarized as well.

Controlled Shear Decorrelation eXperiment (CSDX)

The CSDX device, located at UCSD, is being used to study drift wave turbulence-zonal flow (DWT-ZF) interactions and intrinsic rotation in a simple magnetized cylindrical plasma configuration. This is a linear plasma device is operated with a 13.56 MHz 1500W RF helicon wave source that uses an antenna surrounding a 10 cm diameter glass belljar. A matching circuit is adjusted so that reflected power is negiligible. The device has an overall length of 2.8m and a diameter of 0.2m. Both source and vacuum chamber are surrounded by a set of disk-shaped electromagnet coils, providing a solenoidal magnetic field that can be varied from 0 up to 1kG. The typical working gas pressure is P = 3 mTorr and a 1000l/s turbopump is located downstream from the source. The typical peak plasma density is ~10^{19} m^{-3}, electron temperature is ~3 eV, the ion temperature is ~0.5-0.7eV, and the netural gas temperature is ≤0.4eV. All of the magnetic field lines exiting the two ends of the device terminate on insulating surfaces to eliminate the possibility of currents flowing through the end plates of the device. Thus any axial currents due to drift waves must be balanced by cross-field currents carried by ion polarization drifts (which are equivalent to the turbulent Reynolds stress [Diamond:2001]). A more detailed description of the machine can be found in the literature [Tynan:1997, Burin:2005].

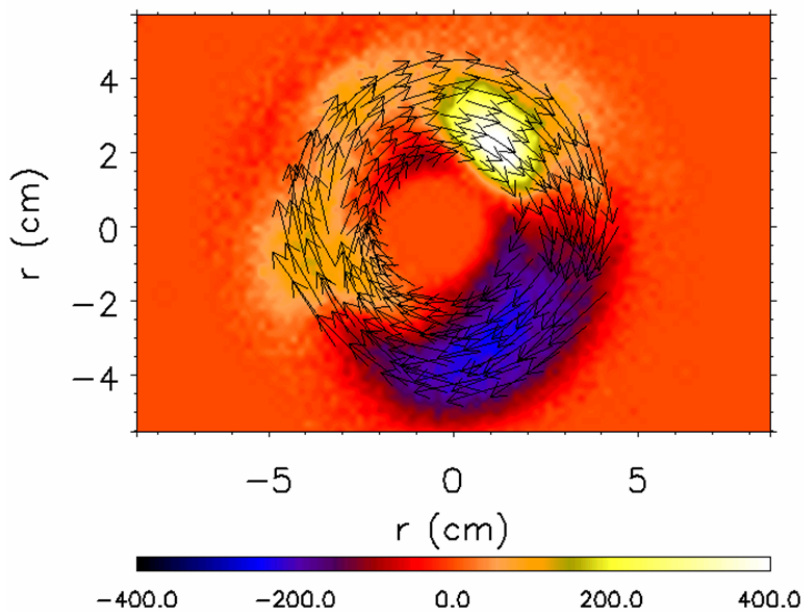


Figure 1: Radially sheared azimuthal flow field (vector field) inferred by tracking the motion of plasma density fluctuations (shown as false color image). The radially sheared flow has been shown to be consistent with the turbulent Reynolds stress created by the drift turbulence. View is looking parallel to axis at r=0.

Measurements of mean plasma profiles, the fluctuating density, potential, and electric fields along with the resulting turbulent Reynolds stress are made by using multi-tipped probe arrays. Published results from the period 2005-2010 have shown that the turbulent Reynolds stress appears to be consistent with the shear flow that is spontaneously generated by the turbulence, that the Maxwell stress associated with finite beta effects is small, and have revealed spatiotemporal dynamics of turbulence and zonal flow dynamics. Recently these measurements have been supplemented by fast-imaging studies of the fluctuations and zonal flow.

This fast framing technique has recently allowed for the first direct visualization of the zonal flow field, as shown in **Figure 1** above. Previous probe based measurements have shown the existence of such a sheared flow and have related it to the turbulent momentum transport associated with the turbulent Reynolds stress. As we discuss later in this report, the visualization approach allows a much deeper insight into the physics of turbulent generation of shear flows.

Plasma Couette flow eXperiment (PCX)
The Center supports work with the group of Prof. C. Forest on the Plasma Couette Experiment (PCX) located at UW-Madison, primarily through support of a postdoctoral fellow, and a graduate student. In the PCX device (see Figure 2 below), most of the plasma is unmagnetized, with strong multipole confining fields located at the periphery of the device. An external Helmholtz coil pair will permit magnetized plasma studies in the future. The essence of the experiment is to study plasmas in which the kinetic energy in the flowing plasma is much larger than the magnetic energy, as is usually the case in astrophysical plasmas, and is distinctly different from fusion plasmas in this respect. Two main activities are being pursued and are discussed next.

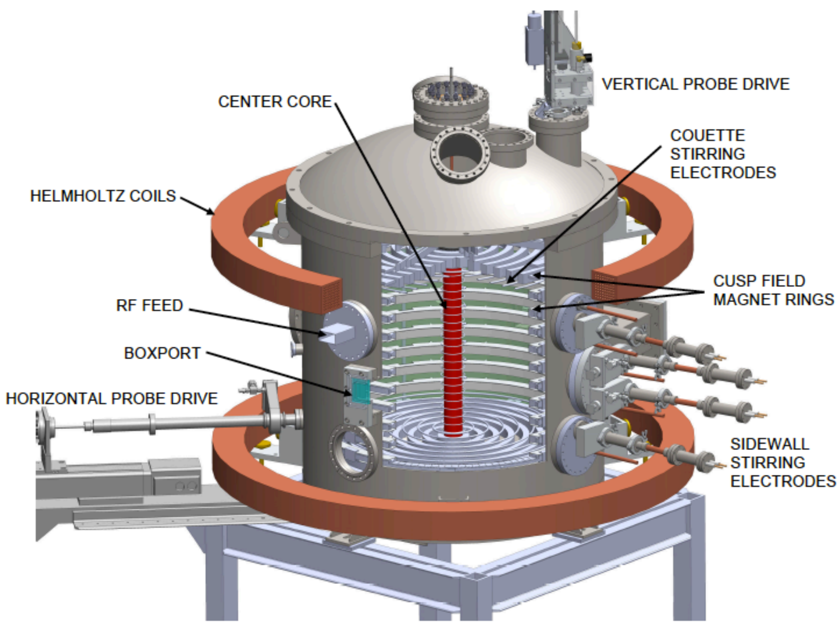


Figure 2: Three-dimensional rendering of the Plasma Couette Flow experiment (PCX) located at UW-Madison.

The experiment is a prototype device designed to study momentum transport in weakly magnetized flowing plasmas; a variety of different velocity fields can, in principle, be generated by controlling the spatial profile of plasma rotation (via JxB forces driven by currents from a hot filament array located at the plasma boundary combined with a multipole magnetic field localized to the region near the vessel wall, see Figure 3); collisional viscosity should then transfer momentum into the unmagnetized central plasma. The boundary condition is analogous to the rotating wall boundary condition used in the hydrodynamic experiments at PPPL (described below), but is more flexible in the sense that every electrode magnet set is an independently controllable ring. Use of a center post in the apparatus results in "plasma Couette flow" where the center rotates at a different speed than the outside. The collisional plasma viscosity can be manipulated by changing the ion species and density. Initial experiments have demonstrated our ability to drive A variety of different profiles can be generated that will have bearing upon the center activities, all of which involve studying self-consistent flow equilibria to find the effective viscosity in either quiescent or turbulent plasmas. The center will support exploratory measurements of flow equilibria in both laminar and turbulent plasmas that in themselves will constitute a measurement of plasma viscosity.

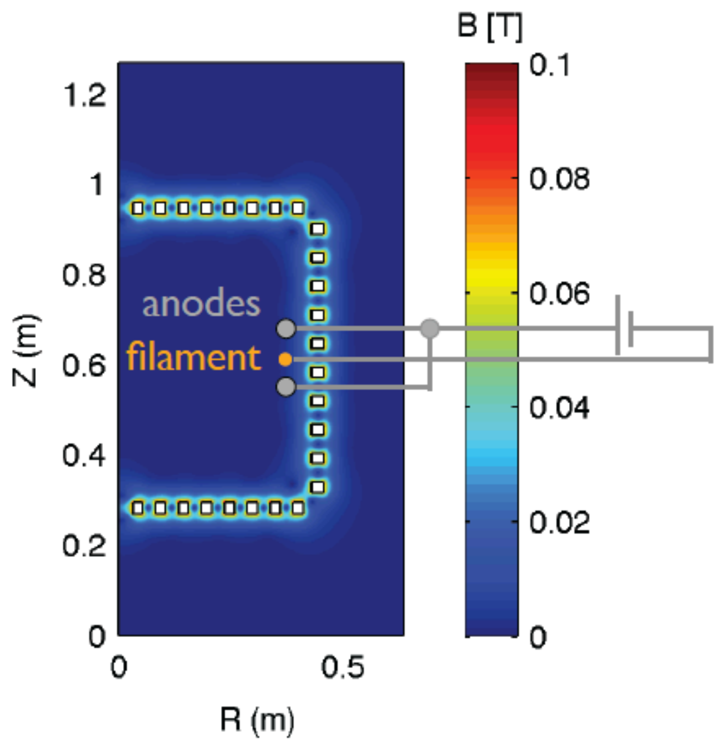


Figure 3: Cross-section of multipole magnetic field and hot-cathode/anode arrangement used to drive rotation via JxB Lorentz forces at the plasma boundary.

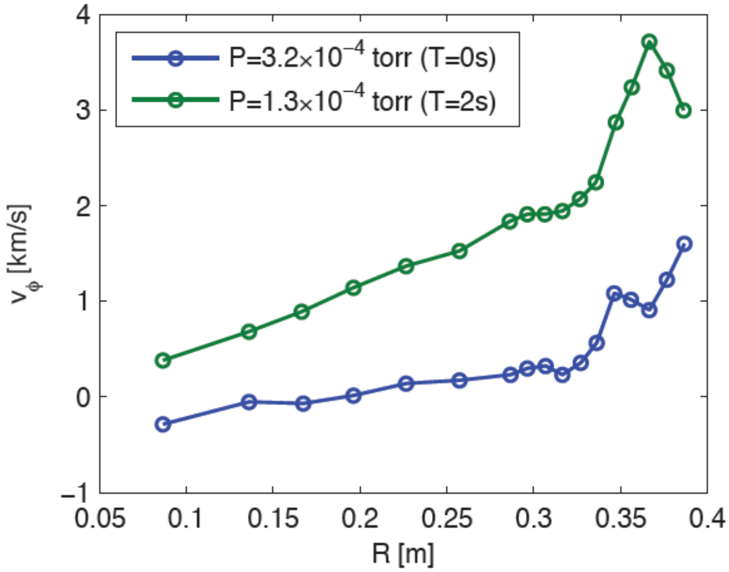


Figure 4: Toroidal rotation velocity radial profile in PCX device. Results obtained for neutral He gas pressure of 0.1mTorr (green) and 0.3mTorr (blue).

Hydrodynamic Turbulence Experiment (HTX) - PPPL

The accretion rate in astrophysical disks, as inferred from measurements of the disk luminosity, must be accompanied by radially outward transport of angular momentum at rates that greatly exceed that predicted by classical processes based on binary collisions. In this sense, the problem bears a strong similarity to the problem of observed anomalous transport in toroidal fusion plasmas. The essential problem in both cases is to find the mechanism(s) that generate the required turbulence to support this enhanced transport. Since Keplerian disks are linearly stable hydro-dynamically to the best of our knowledge, there exists only two possible solutions: one relies on the effects due to a magnetic field on accretion of a conducting fluid or plasma, while the other relies nonlinear hydrodynamic effects such as a subcritical instability to drive turbulence and associated momentum transport. In order to determine if a nonlinearly unstable (a.k.a. a subcritical instability) purely hydrodynamic pathway to turbulence in disk-like flows exists, the PPPL Hydrodynamic Turbulence Experiment (HTX) has been constructed [Edlund et al., 2010]). This modifed Taylor-Couette device is very similar to the Princeton MRI Experiment [Schartman et al., 2009] in size and draws on technology developed for implementation of differential boundary components that mitigate the secondary Eckman flows which are present in most other such devices.

The HTX is a new device at PPPL, designed, constructed and tested over the last two years with support from the CMTFO in order to determine if a subcritical hydrodynamic instability exists in the non-Keplerian sheared flows found in accretion disks and, if such an instability is found, study how it develops nonlinearly. Like the Princeton MRI Experiment, HTX is a modified Taylor-Couette device using an independently rotating ring at each of the top and bottom boundaries (see Figure 5). The rings are driven by a common transmission to a single motor so that they rotate in unison. Experience gained during operation of the MRI Experiment allowed for significant simplification of the four ring system to the two ring system in HTX with the addition of extensions from the inner and outer cylinder. Secondary circulation can be controlled through appropriate selection of the ring speed, allowing ideal Couette profiles to be closely matched except within a few millimeters of the inner and outer cylinder, as illustrated in Figure 6. The interior top and bottom surfaces of HTX are completely modular, which allows for an eventual upgrade to a configuration where the interior surfaces are curved for the study of Rossby waves, as discussed in the section on future plans.

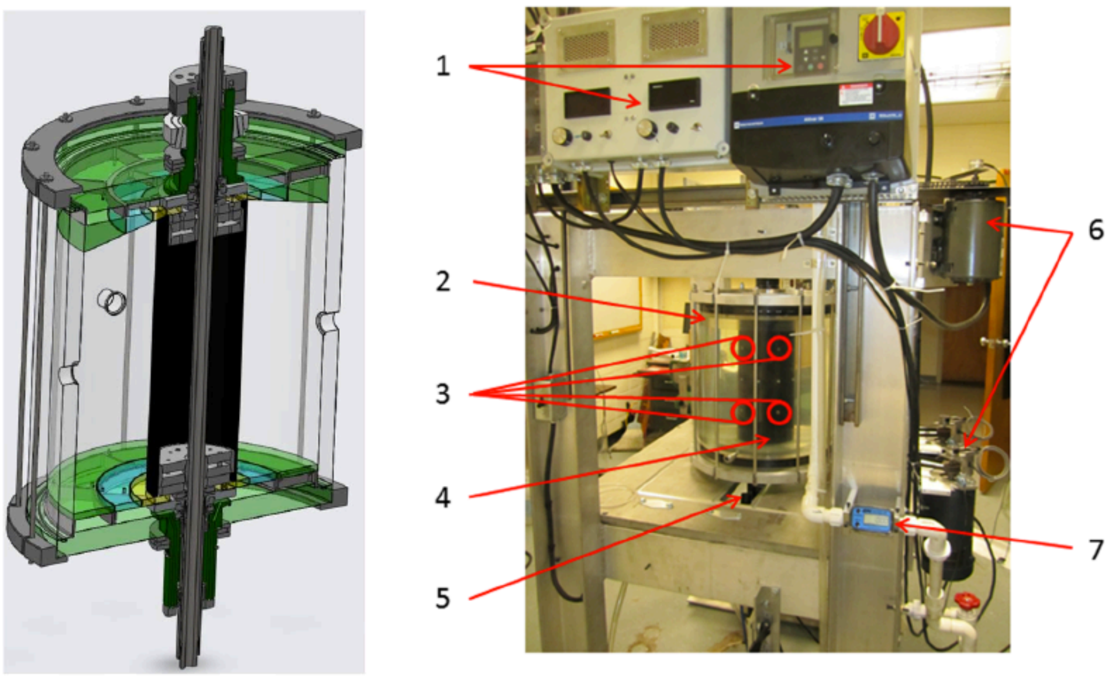


Figure 5: The left panel shows a cutaway mechanical drawing of the experimental device. The inner and outer cylinder extensions are shown in yellow and green, respectively, and the independent rings are shown in blue. Note that the sloped surfaces shown at top are not yet implemented. The right panel shows a photo of the experimental apparatus identifying (1) motor drives, (2) outer cylinder, (3) active perturbation nozzles, (4) inner cylinder, (5) LDV heads, (6) motors and (7) flow-meter and circulation system for the active perturbations.

The main diagnostic employed in HTX is a two-component laser Doppler velocimetry (LDV) system similar to that used in former experiments on the Princeton MRI Experiment [Ji et al., 2006]. Simultaneous measurement of both the radial and azimuthal components of velocity, at the same location, allows the local angular momentum transport to be measured. When fully implemented, this technique will allow for quantitative analysis of the fluctuation level and its relation to angular momentum transport for different flow regimes. Two diagnostic upgrades will allow for direct measurement of vorticity and torque. An imaging system using a camera with a frame rate on the order of 100-1000 frames per second can be used in conjunction with a line laser to illuminate a thin layer of tracer particles in the r–θ plane. With the use of a slip-ring to provide power and a wireless transmitting device, a camera may be mounted on the outer cylinder so that the evolution of Rossby waves and zonal flows can be recorded in the rotating frame. The addition of a torque sensor to the HTX inner cylinder will allow for direct comparison between experiments in HTX and those in other devices which employ a torque sensor as the main diagnostic (as in Paoletti and Lathrop [2010]). With the addition of these additional diagnostics, HTX will become a world leader in disk-like hydrodynamic turbulence and angular momentum transport studies.

Two means exist for introducing perturbations to the flow – a critically important procedural step for studies of both the non-linear stability of sheared flows and the development of the Rossby wave-Zonal Flow system. One technique involves a brief spin-up or spin-down of the inner cylinder. Control of the motors is governed by a computer feedback system, maintaining speed control to within 1 rpm. This technique was successfully applied by Borrero-Echeverry and Schatz [2010] in studies of turbulent lifetimes in cyclonic systems. The computer feedback control system installed on HTX can control the motors in a similar fashion to produce transient turbulent states. An alternate method for inducing steady-state perturbations to the system uses is already installed on HTX and uses an external pump to to circulate fluid through a hollow inner cylinder axle to a set of nozzles fixed to the inner cylinder itself. This method has the advantage over the former that it does not modify the azimuthal boundary conditions at any of the surfaces. The circulating fluid exhausts out of a set of four radial jets on the inner cylinder, returning by an additional four also located on the inner cylinder. In its present configuration the perturbations are arranged in an m = 2 configuration, with two sets of symmetric nozzles located at 1=4 and 3=4 of the inner cylinder height. Exhaust speeds upward of 1 m/sec are present at the nozzle outlet. An upgrade to a total of 16 nozzles is in progress and will allow for a significant increase in the total flow volume (effectively, the amplitude of the perturbations), and provide for the ability to configure the perturbations in symmetric m = 1 and m = 0 configurations. Preliminary results from the active perturbation system are described in the next section.

The first goal of experiments in HTX since the beginning of operations on August 25, 2011 was to establish a baseline for the effectiveness of the differentially rotating ring to produce profiles close to the ideal Couette profile. This state is considered ideal because when the steady-state azimuthal rotation profile takes the form of the ideal Couette profile, and the system can be considered to have vertical uniformity, then it follows that the radial velocity must vanish and all angular momentum is transferred via the viscous force. We have mapped out the radial profiles for a family of configurations in which the
inner cylinder and outer cylinder speeds are held constant the inner ring speed is varied. The results of one such scan is presented in Figure 6, which shows the ability to control the radial profile of azimuthal velocity in the device.

Additional tests will be performed to test more carefully the vertical uniformity of these states, as well as the sensitivity of the flows to the width of the rings. The active pumping system has been used to explore the stability of various flows to induced perturbations. The spread in measured velocities under solid body rotation, due to imperfect optical properties of the acrylic walls, defines a systematic fluctuation level against which other fluctuation levels should be compared. In all solid body cases observed, the fluctuation level normalized to the mean local velocity decreases from about 0.5% near the inner cylinder to about 0.3% near the outer cylinder. These levels are a significant improvement over the previous systematic limit in similar experiments reported in [Ji et al.2006].

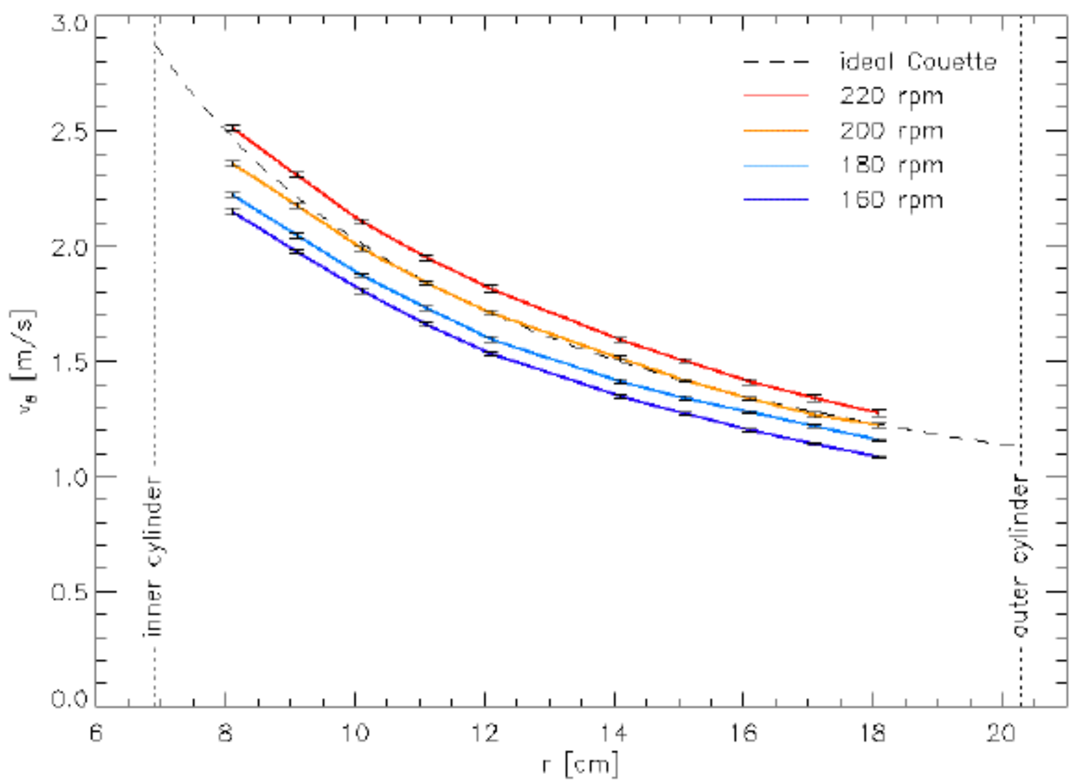


Figure 6: Azimuthal velocity pro_le measurements made with the LDV system as a function of ring speed for fixed inner cylinder (400 rpm) and outer cylinder (50 rpm) speeds. In this configuration or inner and outer cylinder speeds, a ring speed of 200 rpm produces the optimal profile

Experimental Collaborations

In addition to the dedicated experimental devices discussed above, the CMTFO takes maximum advantage of collaborations to advance our science program. Since the establishment of the Center, we have launched over 10 new collaborations with either experimental or theory groups; several of the new experimental collaborations have already resulted in work that is in review for publication. These are briefly described below. Letters of support from most of these devices are provided in the Appendix.

SWIP/HL-2A: The HL-2A device is a tokamak (the former ASDEX device) located at the Southwestern Institute of Physics in Chengdu, China. CMTFO researchers from UCSD are involved in experimental studies of zonal flow dynamics and evolution leading up to the L-H transition in this device, along with studies of intrinsic rotation and the H-L back transition. These efforts are complemented by a strong link to theory both at the SWIP, at the NFRI/WCI in Korea and at UCSD. Initial results have focused on experimental study of the evolution of nonlinear turbulence-zonal flows energy transfer as the L-H transition power threshold is approached, and have been submitted for publication [Xu:2011].

ASIPP/EAST: The EAST tokamak, located at the Chinese Academy of Sciences Institute for Plasma Physics (ASIPP) in Hefei, China. CMTFO researchers from UCSD are involved in experimental studies of the L-H transition in this device, along with studies of intrinsic rotation and the H-L back transition. These efforts are also complemented by a strong link to theory both at the SWIP, at the NFRI/WCI in Korea and at UCSD. This has resulted in one major paper in print [GSXu:2011] and a second paper in preparation [Tynan&Manz:2011].

DIII-D: CMTFO affiliated researchers from Colorado and UCSD are collaborating on the DIIID device. Research foci include the origins of intrinsic rotation, the physics of the L-H transition, and imaging diagnostic development and data analysis. Center-sponsored research has motivated three (3) run-days of experiments, and has resulting in an invited APS-DPP talk and publications [Mueller:2011]; we anticipate a major additional paper on the physics of the trigger for the L-H transition will be submitted in the coming months.

PPPL/NSTX: CMTFO affiliated researchers from Colorado are collaborating on the NSTX device, and are focused on the analysis of edge turbulence imaging data, with a focus on the L-H transition, the back transition into L-mode. They are using both traditional (e.g. integral transform) analysis techniques as well as exploring use of new approaches taken from the image processing and data compression communities. This work has been the subject of a recent publication [Sechrest:2010].

MIT/ALCATOR C-MOD*:* CMTFO researchers from UCSD and from the WCI at the Korean NFRI are collaborating with John Rice at ALCATOR C-Mod on theoretical and computations studies of intrinsic rotation physics, with a particular focus on the recently discovered phenomena of rotation reversal. This work was the subject of a talk at the IAEA 2010 meeting [Rice:2010] and two very recent publications by Rice, Diamond and others [RicE:2010b, Rice:2011]. These efforts are now being strengthened with the addition of UCSD-supported experimental postdoc, and a in 2012 will be further bolstered with the additional of a UCSD-supported postdoc to work at PPPL with Dr. Weixing Wang on gyrokinetic simulations of these experiments.

Columbia/HBT-EP*:* A CMTFO-supported postdoc from UCSD has recently (August 2011) been based at Columbia University, and is now working on an experiment to study intrinsic rotation in the small HBT-EP tokamak device located at Columbia University in a collaboration with Professors Mike Mauel and Gerry Navratil. A small biased electrode is being used to introduce a torque on the plasma, and the response of the plasma rotation and the associated turbulent stresses at the plasma edge to this external torque are being looked at. In addition, this postdoc is working on intrinsic rotation studies on C-Mod (described above) in collaboration with Dr. John Rice.

UCLA/LAPD**:** CMTFO researchers from Colorado are working at the LAPD device at UCLA to study the evolution of turbulent stress and large scale shear flows as the plasma beta is increased from the electrostatic regime to the electromagnetic regime. Particular interest is focused on the possible competition between Reynolds and Maxwell stresses and the resulting effect on large scale shear flow generation.

Computation

A number of state-of-art numerical simulations of plasma turbulence and momentum transport are available and will be used in the CMTFO research program. These include:

GTS: (Collaboration with PPPL) The Gyrokinetic Tokamak Simulation (GTS) code is a full geometry, delta-f particle-in-cell code [1, 2]. It is based on a generalized gyrokinetic simulation model and the use of realistic magnetic configurations. The GTS code targets at simulating plasma turbulence and transport in practical fusion experiments. It is highly robust at treating globally consistent, shaped cross-section tokamaks by directly importing plasma profiles of temperature, density and rotation from experimental databases, along with the related numerical MHD equilibria reconstructed by MHD codes. The GTS includes fully-kinetic electron physics so as to simulate electron turbulence and ion turbulence with non-adiabatic electron physics.

GYSELA (collaboration with CEA-Cadarache and the WCI-NFRI): A full f, flux driven gyrokinetic code for studies of turbulence driven flows and rotation profiles and transport non-locality

XGC1 and **XGC1P** (collaboration with PPPL and WCI-NFRI): a full f, flux driven PIC gyrokinetic code including separatrix geometry, for studies of flows, rotation and transition dynamics

GKPSP (collaboration with WCI): a global delta-f PIC gyrokinetic code with electron dynamics for studies of intrinsic torque and q(r) profile effects on rotation

TRB (collaboration with WCI-NFRI and CEA-Cadarache): a global gyrofluid code with a trapped electron module, for studies of intrinsic rotation and ITB dynamics in reversed shear plasmas. WCI has significantly upgraded the legacy TRB code.

BOUT++ (collaboration with LLNL and WCI): a global multi-fluid code in full geometry, for studies of L-H transition and related flow phenomena. BOUT++ is currently being upgraded to incorporate a multi-gyro-fluid foundation. A cylindrical version of the code, suitable for studies of open field line laboratory plasma devices, is also available.

MHD Codes (UCSC): Turbulent dynamo experiments are being studied using a self-consistent three-dimensional MHD model. The numerical code is a modified version of the PARODY code, which solves the magnetic induction equation and the momentum equation for an incompressible fluid in a spherical shell geometry using spherical harmonic expansion and finite differences in the radial direction (Dormy et al. 1998 EPSL). The code operates with a finite thickness solid wall where the induction equation is still solved, matched to a potential field exterior. The permeability and conductivity of the wall (relative to the fluid) can be varied individually. In addition, UCSC investigators are using the HPS code (see e.g. Brummell, Clune & Toomre, 2002, ApJ, 570, 825). to perform local Cartesian simulations designed to mimic the important properties of the tachocline.

Scientific Results

Although the Center has only been fully functional for about 1 ½ years, we have already made a number of significant contributions to the understanding of momentum transport. Highlights of these results include:

- Results on NSTX by the Colorado group showing evidence that zonal flows play a key role in the L-H transition on that device [Sechrest:2010], results from the UCSD group working on the HL-2A experiment in China showing that the edge turbulence begins to drive zonal flows as the L-H power threshold is approached [Xu:2011], results from the UCSD group working on the EAST tokamak showing the role of zonal flows in the L-H transition [GSXu:2011] and that the L-H transition appears to be triggered by a transient peaking in the rate of energy transfer from the edge turbulence into the edge zonal flow [Tynan&Manz:2011];
- Laboratory plasma experiments providing i) evidence for a non-diffusive turbulent stress at the plasma boundary [Yan:2010], ii) the first study ever of the onset of plasma turbulent energy transfer during a transition to turbulence [Manz:2011], iii) direct imaging of drift wave packet emission, propagation and absorption that leads to shear flow amplification [Xu:2011] and iv) evidence of a hydrodynamic instability leading to zonal flow collapse and blob emission [Manz:2011];
- Initial comparison of turbulent stress inferred from probe and fast imaging diagnostics which may permit quantitative physics studies using imaging diagnostics from both the edge and core regions of MFE devices [Light:2011].
- The first measurements of turbulent stress in a large tokamak (DIII-D) during H-mode, testing the hypothesis that turbulence can drive intrinsic rotation [Mueller:2011]; initial results did not seem to be consistent with theoretical expectations, however repeated experiments under wider variety of conditions show plasma shaping plays an important role and needs to be taken into account;
- Initial (i.e. as yet unpublished) results from the PCX and HDX experiments at Wisconsin and Princeton, providing experimental tests of collisional plasma viscosity in PCX [Katz:2011] and initial searches for subcritical hydrodynamic instability in non-Keplerian flows in the HDX device [Edlund:2011];
- Development of a model that may explain why magnetic flux surface shaping and X-point location impacts edge plasma flow shear and the L-H transition power threshold [Fedorczak:2011]
- Nonlinear MHD simulations of recent dynamo experiments showing the significance of magnetic field boundary conditions for the formation of the dynamo from MHD turbulence [Guervilly:2011]
- Development of a spatio-temporal multi-predator/prey model of the L-H transition [Miki&Diamond:2011];
- Discovery via numerical experiment of the formation of zonal flow staircase-like profiles, providing a mechanism to introduce meso-scale dynamics to core plasma transport [Dif Pradelier:2010] and showing that PV homogenization may play a crucial role in core plasma transport;

- Experiments on ALCATOR C-Mod which indicate that intrinsic rotation seems to scale with edge temperature gradient [Rice:2010b] and that core plasma toroidal rotation undergoes a spontaneous reversal as the density exceeds a critical value [Rice:2011]. These reversals show hysteresis, and the critical density for reversal coincides with the density for saturation of linear Ohmic energy confinement.
- Proof of a Momentum Theorem in fluid systems and extension to collisionless systems for the role of potential vorticity homogenization as the key unifying mechanism behind flow organization in magnetic fusion and geophysical/astrophysical fluid systems [Diamond:2011];
- Global flux-driven gyro-kinetic numerical experiments showing clear evidence for the role of turbulent residual stresses in driving intrinsic toroidal rotation in tokamaks [Ku:2010] and elucidation of residual stress' relation to grad-T and the role of residual stress in flow reversals in Ohmically heated discharges;
- Gyro-fluid studies of the role of intrinsic rotation in reversed shear ITB formation, and identification of the ratio of heat flux to external torque Q/τ_{ext} as the critical parameter in the transition [Kim:2011];
- Development of a heat engine model of intrinsic rotation [Kusuga:2011].

We provide a summary of some of these results in the discussion below, and then use these initial results to sketch out our research plan for the 2012-2015 period. For convenience, the results are organized into Experimental, Theoretical and Computation approaches.

Experimental Results

Role of Zonal Flows in the L-H Transition: (NSTX) Recently Yancey Sechrest, a CMTFO sponsored student from Colorado, recently made a series of Gas Puff Imaging (GPI) observations on NSTX that revealed a quasi-periodic oscillation in the plasma edge preceding the L-H transition in a limited set of neutral beam heated plasmas. These ~3 kHz flow oscillations exhibit both long wavelength and long correlation lengths, suggesting they are zonal-flow-like (see ***Figure*** *7*). The flow oscillations are strongly correlated with modulations of the level of edge turbulence, thus the system appears to undergo a predator-prey type limit-cycle preceding the L-H transition. However, a clear trigger for the L-H transition was not observed. Reynolds stress profiles were obtained directly from image velocimetry for L-mode periods preceding the L-H transitions.

Imaging data from the GPI diagnostic also recently captured several L-H and H-L transitions in RF heated plasmas near the L-H input power threshold on NSTX. These observations exhibit a distinct ~25 kHz ($k_{poloidal} \sim 0.1\text{-}0.2\ cm^{-1}$) feature present during H-mode that appears to precede large ELM-like ejections of plasma into the scrape-off-layer, triggering an H-L back-transition in many cases. The analysis of this behavior is still ongoing and may provide insights into the origins of ELM events and /or the H-L back transition.

Role of Zonal Flows in the L-H Transition: (HL-2A): We have established a collaboration with the HL-2A group located at the Southwestern Institute of Physics (SWIP) in Chengdu, China, and performed the first set of collaborative experiments on that device in spring 2011. In this experiment, a multi-tip probe array diagnostic, developed first at UCSD on the CSDX device [Xu:2009, Xu:2010] was used to directly measure the rate of transfer of kinetic energy from the high frequency, small scaled turbulent fluctuations to the low frequency large scale zonal flows and geodesic acoustic modes (GAMs) which coexist in the plasma boundary region.. By careful choice of experimental conditions, measurements were taken just inside of the LCFS of the

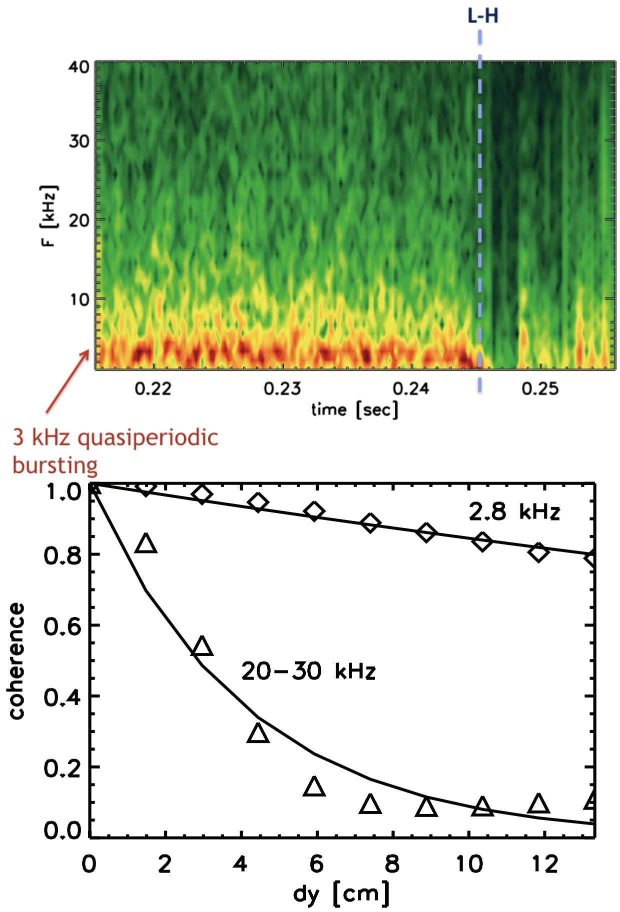


Figure 7: *(a) Spectrogram of GPI scrape-off layer light, indicating quasi-periodic bursts at ~3 kHz. (b) Coherence of poloidal velocity vs. y separation for 3 kHz mode and background turbulence between 20-30 kHz. Correlation lengths are 56 cm for the 3 kHz mode and 4 cm for the background turbulence. Results published in [Sechrest:2011]*

tokamak as the plasma went from a weakly heated Ohmic discharge up to a strongly heated (700kW) ECH L-mode discharge. The results show that in weakly heated L-mode discharges the energy transfer goes predominantly into the geodesic acoustic mode. However, as the ECH heating power was increased towards the L-H power threshold, the GAM amplitude and nonlinear coupling fade away, while the zonal flow amplitude and nonlinear coupling become much more pronounced, suggesting a competition between GAMs and ZFs in which the ZFs dominate as the L-H transition is approached. These results, while obtained in L-mode, provide strong evidence that the turbulence-zonal flow coupling likely play an important role in the L-H transition – a result that is bolstered by very new work which we have done collaboratively on the EAST tokamak and which is discussed below.

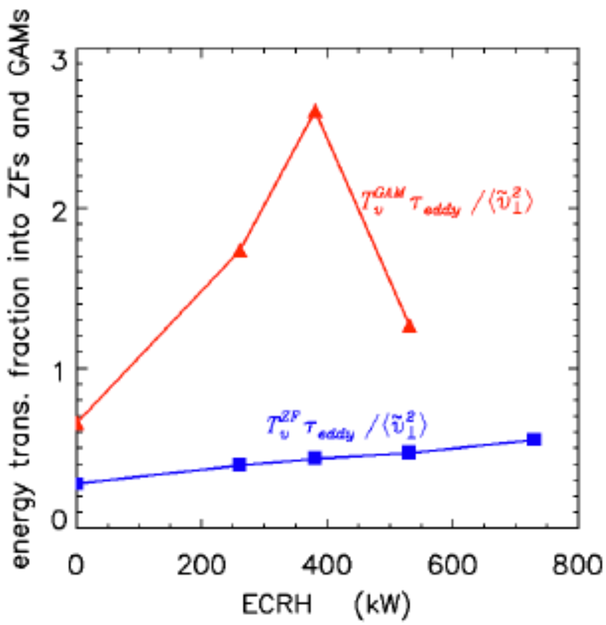


Figure 8: *Evolution of the rate of nonlinear energy transfer from turbulence into the GAM and ZF frequency bands v. ECH auxiliary heating power in the HL-2A device. Data obtained ~1cm insight the LCFS in a limiter discharge. Coupling to the GAM first increases rapidly for low values of ECH heating. As heating power is increased further, couping into the GAM begins to decrease, while ZF coupling begins to increase, suggesting a competition between GAM and ZF coupling, and an eventual dominant role fot he ZF as the L-H power thresholds is approached. [M. Xu:2011, submitted]*

Role of Zonal Flows in the L-H Transition: (EAST) We have also established a collaboration with the EAST device located at the ASIPP in Hefei, China. Our initial focus has been on the L-H transition in the EAST device. Recently published results (G. Xu et al, Phys. Rev. Lett. 2011] show that as the L-H transition was approached, a limit cycle behavior ensued for the plasma turbulence and zonal flows found at the boundary of the plasma, in a manner reminiscent of results from ASDEX UG (G. Conway:2010] and earlier work in TJ-II [T. Estrada:2009]. Motivated by these results, CMTFO researchers have used probe array data from EAST to make the first direct measuremenst of the nonlinear energy eschange between turbulence and zonal flows during an L-H transition.

In 2003, theoretical work by Kim & Diamond predicted that the L−H transition can be explained by an intermediate, oscillatory transient stage, where turbulence, zonal flow, mean shear flow and the pressure gradient are coupled [Kim:2003a, Kim:2003b]. As the input power increases also the pressure gradient increase resulting in stronger instabilities and fluctuation levels. The turbulence level grows until it triggers a finite zonal flow, which then begins to extract kinetic energy from the turbulence and thereby acts to damp the turbulence amplitude. Zonal flows can lower the critical input power and trigger the transition by regulating the turbulence level until the mean shear flow is high enough to quench turbulence and zonal flow. The self-regulation between turbulence and zonal flows occur as an oscillatory behavior, characteristic for predator-prey systems. Recently these predator-prey oscillations have been observed in various devices [15–18]. Up to now all investigation of energetic interaction between zonal flows and the ambient turbulence studied the temporal relationship between turbulence amplitudes, zonal flow amplitudes, and the evolution of the sheared background mean radial electric field; the results of these studies have been qualitatively consistent with the predator-prey model. The essential physics - namely the nonlinear exchange of energy between the turbulence (the prey) and the zonal flow (the predator) in the presence of a background mean sheared ExB flow has to date never been studied during the L − H transition. This CMTFO-ASIPP/EAST collaboration has allowed the first such study by inserting a suitably arranged Langmuir probe array inside the separatrix region of a discharge which undergoes an L−H transition, and thereby provide the first quantitative measurement of the energetics of turbulence-zonal flow coupling during the L−H transition. The results (***Figure 9***) show that the H-mode transition is triggered by a transient increase in the rate of energy transfer from the turbulence into the zonal flow that is large enough to quench turbulent transport. The resulting increase in edge pressure gradient then sustains a mean sheared ExB flow which then locks in the H-mode state as the zonal flow then dies away.

These initial results are being prepared for publication, and plans are underway to repeat these experiments in EAST under a wider variety of conditions; we have also recently performed similar experiments on the DIII-D tokamak using both probe and fast imaging diagnostics. Preliminary analysis of those data provide a similar physics picture. ***Thus CMTFO led research on NSTX, HL-2A, EAST and DIII-D provides tests of a theory-based model of the trigger for the L-H transition in tokamaks – a CRITICAL physics issue for ITER and an problem that has been outstanding since the discovery of H-mode in 1982, and which, if resolved, could allow a physics-based model of the L-H threshold to be developed.***

Drift-Interchange Turbulence-Zonal Flow Interactions in Basic Experiment

Direct Imaging Studies: Collisional electron drift wave turbulence has been shown [M. Xu:2011] to nonlinearly generate drift wave packet structures with density and vorticity fluctuations in the central plasma pressure gradient region of the CSDX device. A 28 cm diameter f/10 telescope coupled to a digital fast-framing (100,000 frames/sec) camera located ~8m away from the object focal plane located at z=75 cm provides a view with sightlines aligned within +/-0.7 deg of the magnetic field lines. The camera detects visible light intensity fluctuations $\tilde{I}_{vis}$ (due primarily to neutral argon emission) as shown in Figure 10 below. These $\tilde{I}_{vis}$ fluctuations have been shown to be correlated with I_{sat} Langmuir probe fluctuations [Antar:2007] caused primarily by plasma density fluctuations. The initially isotropic m~3 structures with frequency $f \geq 6kHz$ are born between the plasma center and the maximum density gradient at r~3cm, and propagate primarily in the electron diamagnetic drift direction.

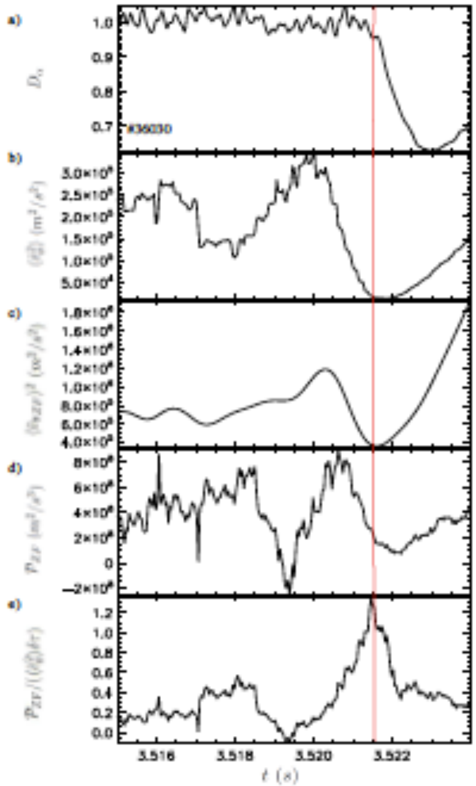


Figure 9: *Time evolution of Dalpha, edge turbulence and zonal flows during an L-H transition in EAST. (a) Dalpha light, (b) turbulence kinetic energy, (c) zonal flow and mean flow kinetic energy, (d) nonlinear power transfer between turbulence and zonal flow, (e) dimensionless power transfer rate between turbulence and zonal flow. The turbulence energy peaks before the L-H transition, leading to a peak in zonal flow kinetic energy. The combination of these two then leads to a peak in the nonlinear energy coupling into the zonal flow and collapse of the turbulent kinetic energy. An L-H transition then ensues due to the elimination of the turbulent transport. To be submitted to Phys. Rev. Lett., 2011.*

Tracking these packets reveals that they follow an outward directed spiral shaped trajectory in the (r,θ) plane, are azimuthally stretched and develop anisotropy, and finally are absorbed, as they approach an axisymmetric, radially sheared azimuthal flow located at the plasma boundary. The absorption of these structures leads to the amplification of sheared flows at the boundary. The time-averaged momentum carried by these structures yields the turbulent Reynolds stress profiles that have been previously published by our group and shown to be associated with the amplification of the shear flow. Thus these imaging studies provide a direct visualization of shear flow amplification by turbulent momentum transport

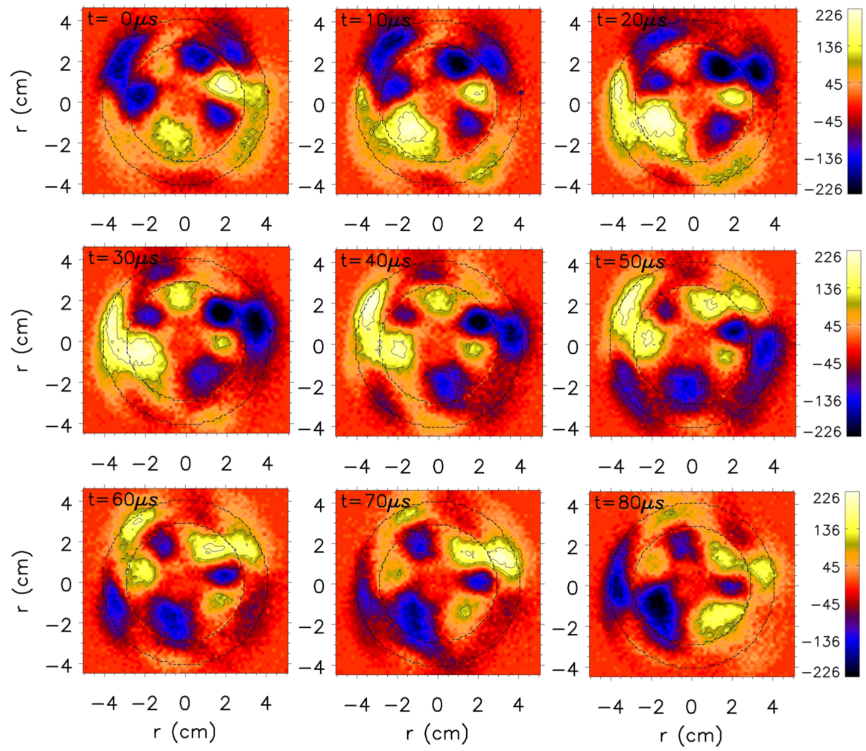


Figure 10: Sequential visible light emissions images showing the birth, evolution, and death of vortex-like structures. Radii of r = 3.0 cm and r = 4.0 cm are denoted by the two dashed circles. A strong shear layer exists at r~3.5cm. Figure taken from [Xu:2011]

Nonlinear Energy Transfer During Transition to Drift-Interchange Turbulence: We have also made the first studies of the evolution of turbulent nonlinear energy transfer in a plasma that undergoes a controlled transition to a state of weak drift-interchange turbulence. In this work, the background gradient containing the free energy drives density fluctuations by the linear drift-wave instability, and a controlled transition to turbulence is induced by gradually increasing the magnetic field. Due to parallel electron motion, the density and potential fluctuations are coupled and thus fluctuations in the potential can be excited. The kinetic energy of the potential is observed to be transferred to larger scales as seen in *Figure 11*. In the presence of flows the density fluctuations are advected resulting in a transfer of free energy by a cross-field coupling of potential and density fluctuations. The free energy transfer shows that large scale potential fluctuations generated by the inverse kinetic energy transfer effectively modulate density fluctuations at all scales and not just at the linear driving scale. Large scale flows are then phase locked with the density fluctuations and the two fields together appear as a quasi-coherent mode. Since the density fluctuations gain energy from large scale potential fluctuations as well as from the density gradient and losses energy to smaller scales. Therefore density fluctuations at a given scale can be significant even if the energy input at the same scale from the density gradient is much smaller than expected from the linear growth rate. The results were recently published

[Manz:2011] and details can be found there. Manz, P. et al, Plasma Phys. Controlled Fusion 53 (2011) 095001

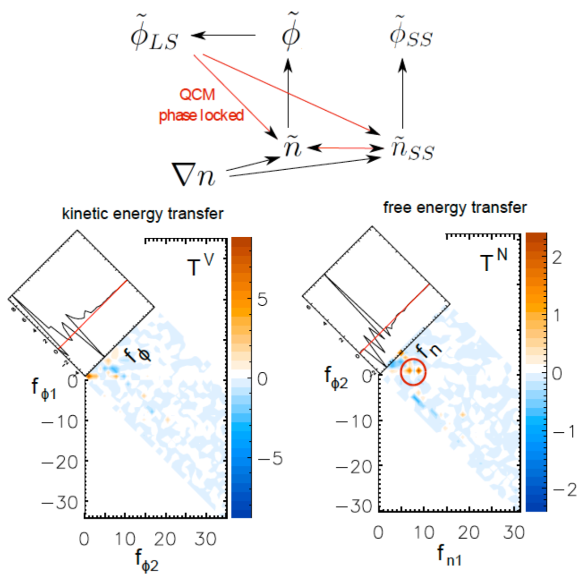


Figure 11: *Left panel: Nonlinear kinetic energy transfer between frequency f1 and frequency f2 (color plot). Inset: Net kinetic energy transfer into/out of frequency f = f1+f2. Right panel: Nonlinear free energy transfer between frequency f1 and frequency f2 (color plot). Inset: Net free energy transfer into/out of frequency f = f1+f2. Figure taken from Manz, P. et al, Plasma Phys. Controlled Fusion 53 (2011) 095001*

Zonal Flow Stability in Basic Experiment: Recent work on the CSDX device has focused on the collapse phase of the sheared azimuthal m=0 or zonal flow, which has been previously found to be associated with the formation and ejection of a large "blob" of plasma from the central region, and which results in loss of plasma density and azimuthal momentum from the central region. The results suggest that Zonal flows do not just absorb energy from the small scale turbulence, they can also excite instabilities that lead to transport. As the turbulence is suppressed by the zonal flow, the zonal is losing its energetic drive and starts to decay, which leaves the plasma in a regime of rather strong large-scale modes as m = 1 in the case of CSDX. Such an m = 1 mode forms a counter rotating vortex pair. As the straining fields of the vortices start to interact they get elliptical deformed, which is reflected by m = 1 internal waves within the vorticies. A characteristic oscillation of the vortex centers is observed and can be interpreted as a secondary instability of the basic drift-wave turbulence. All these have been observed in CSDX as shown in Fig. 2. The internal positive density (vorticity) perturbation of the right hand side vortex is equivalent to a plasma blob. These findings reveal a new generation mechanism of plasma blobs in magnetized plasmas. The results have recently (October 2011) been accepted for publication in Physical Review Letters.

Intrinsic Rotation Experiment (DIII-D): Based upon theoretical models of intrinsic rotation generation [Gurcan:2007,Diamond:2008] along with macroscopic studies of rotation cancellation [Solomon:2007], an experiment was planned and carried out on the DIII-D device in 2010 to test the expectation that turbulent momentum transport provided a source of non-diffusive stress, a.k.a. a residual stress, at the plasma boundary. An existing midplane scanning probe, designed and operated by the UCSD group, was used to measure the turbulent Reynolds stress in Ohmic and H-mode plasmas. ECH heating, along with co-current and counter current beams were used to vary the external torque input into the plasma. Measurements of the mean toroidal rotation profile and the turbulent stress where then used to address the hypothesis that turbulent momentum transport is responsible for generating the observed intrinsic rotation.

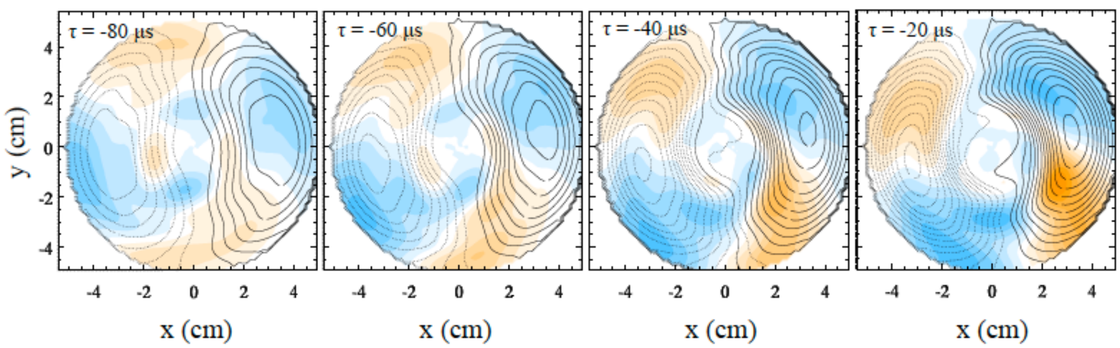


Figure 12: *Internal wave structure (color scale) of a counter-rotating vortex pair (black contours) during the initial phase of shear layer collapse, blob formation and ejection. Accepted, Phys. Rev. Letters.*

The results (see below) showed that, at least for the mid-plane measurements in the plasma condition studied, the local turbulent stress was not consistent with the required momentum flux inferred from a time-dependent global angular momentum balance analysis, thus calling into question the underlying hypothesis. However, we note that recently (September 2011) these experiments were repeated for a variety of plasma conditions and shapes; preliminary analysis of those results suggests that the interpretation is more complex, and in particular indicates that the midplane turbulent stress is quite sensitive to plasma shaping, X-point location and so forth, suggesting that the analysis needs to take such effects into account. In the theory and modeling section below, we summarize recent efforts that may provide insight into these observations, and help reconcile the hypothesis with the experiment. Work is continuing on this topic.

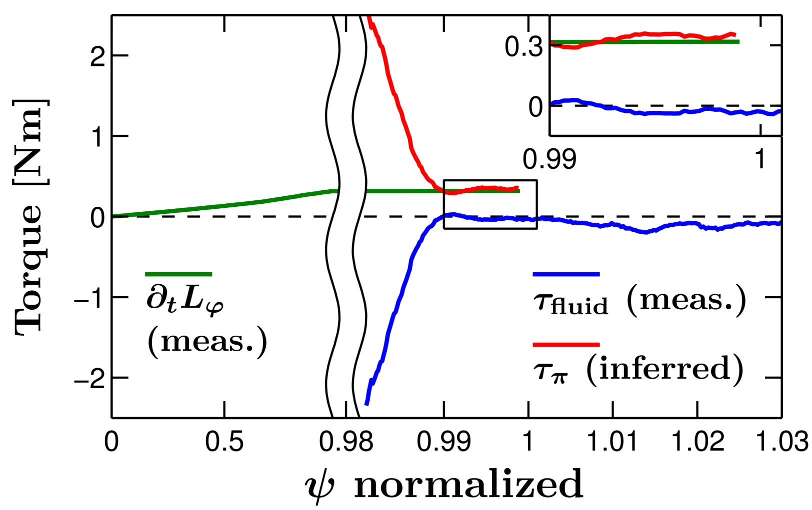


Figure 13: *Radial profile of torque required to match globally observed toroidal angular momentum (green), from the measured turbulent stress (blue) and inferred missing torque taken as the difference between these two torques (red). Results obtained in DIII-D. Figure taken from S.H. Mueller et al, Phys. Rev. Lett. 2011*

Measurement of Classical Viscosity in PCX: As was discussed earlier, the PCX device has demonstrated the ability to spin up a cylindrical unmagnetized plasma by applying a JxB torque to the boundary of a plasma that is contained within a multi-pole magnetic bucket, as shown above. Using the biased hot cathode/cold anode arrangement, strong (~5-10 km/sec) edge plasma rotation has been measured. This velocity then diffuses inwards into the unmagnetized region via collisoinal processes. The measured velocity profile, therefore, is a direct measurement of the plasma viscosity, assuming the the role of neutral drag can be properly accounted for. In the central region, the JxB is negligible and if we further assume the the system is uniform in the vertical direction and that the plasmas are stationary, then velocity field satisfies a 1-D diffusion equation with a boundary source. A comparison of the measured plasma rotation profile and a best-fit to this diffusion equation is shown in Figure 14 below. The agreement is excellent, in spite of the poor assumption of vertical symmetry, and provide the first-ever direct measurement of collisional plasma viscosity in an unmagnetized plasma.. The experiments are now being repeated with a 4 biased filaments on the outer wall which will provide much better vertical symmetry and thus permit a robust measurement of collisional viscosity in an unmagnetized plasma – a fundamental measurement which has not been reported before. This will be followed with the inner wall stirring in the near future using a similar hot cathode/cold anode geometry, which will then allow full plasma Couette flow experiments to occur. Application of an external vertical field from the existing Helmholtz coil pair on the device will then permit study of momentum transport in a magnetized plasma by both collisional and collective (i.e. wave and/or turbulent) mechanisms.

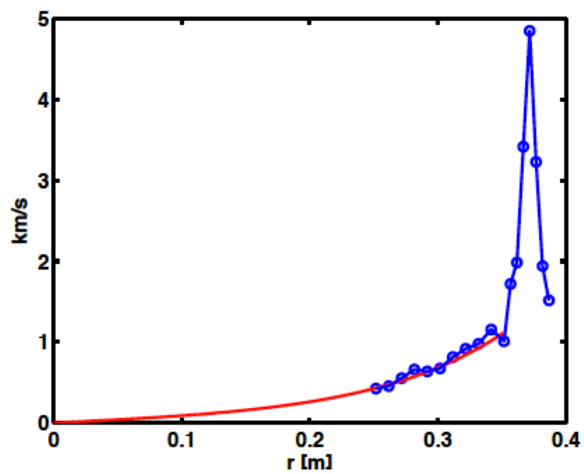


Figure 14: *Toroidal velocity profile for PCX driven by a single filament at the edge. Velocity is measured by Mach probe at opposite toroidal location from the filament. Velocity with unbiased filament has been subtracted off. The fit is the Bessel function model incorporating unmagnetized Braginskii viscosity and neutral drag (primarily due to charge exchange) as calculated for measured plasma parameters and neutral pressure ($n_e = 4 \times 10^{10}$ cm^{-3}, $T_i = 0.3eV$, and $n_0 = 3 \times 10^{13}$ cm^{-3}).*

Initial Tests of a Subcritical Hydrodynamic Instability in the HTX device as a Test of Accretion Disk Physics: Experiments on HTX have begun to explore the hydrodynamic stability of non-Keplerian sheared flows. The results are preliminary, but they provide a glimse at how these experiments will permit us to test the existence (or lack thereof) of nonlinear hydrodynamic instabilities (a.k.a. subcritical instabilities) in these configurations. Figure 15 presents two plots of the measured fluctuation level in the azimuthal component, normalized to the background level as a function of Reynolds number which is here defined as $Re = [(r_1 + r_2)/2](r_2 - r_1)(\Omega_2 - \Omega_1)/\nu = 2x10^6$ where $r_1\, and\, r_2$ denote the inner and outer cylinder radii, $\Omega_1\, and\, \Omega_2$ denote cylinder rotation frequency, and ν denotes the kinematic viscosity for water. Figure 3(a) compares the fluctuation level in solid body, stable quasi-Keplerian and Rayleigh unstable cases. It should be noted that, in agreement with expectations, the fluctuation level in the Rayleigh unstable configuration is an order of magnitude larger than that observed in the optimized quasi-Keplerian regime, and that the stable quasi-Keplerian fluctuation level is very close to the systematic fluctuation level set by the solid body limit. Figure 3(b) presents data illustrating the ratio of the fluctuation level with and without the active perturbation system for these same configurations, as a function of Reynolds number. These studies were performed with the nozzles configured so as to produce a dominant m = 2 perturbation. The solid body cases, which by definition possess no shear, show a large response to the perturbation, with over an order of magnitude enhancement of the fluctuation level at smaller Re. The decrease in the solid body response as Reynolds number is increased is expected since the magnitude of the perturbation is constant and hence the fluctuation level must tend to zero as the rotation speed (Reynolds number) is increased. In contrast, the quasi-Keplerian and Rayleigh unstable profiles show almost no change in the fluctuation level, suggesting that the shear in both cases effectively disrupts the perturbations. Future studies will explore the stability of these configurations to m = 1 and m = 0 perturbations. In particular we will look at the effect of perturbation amplitude and spatial mode number on stability in a variety of rotation profiles. Steady-state and step function (on/off) perturbations will be used to search for dynamics consistent with subcritical instability in these quasi-Keplerian flows.

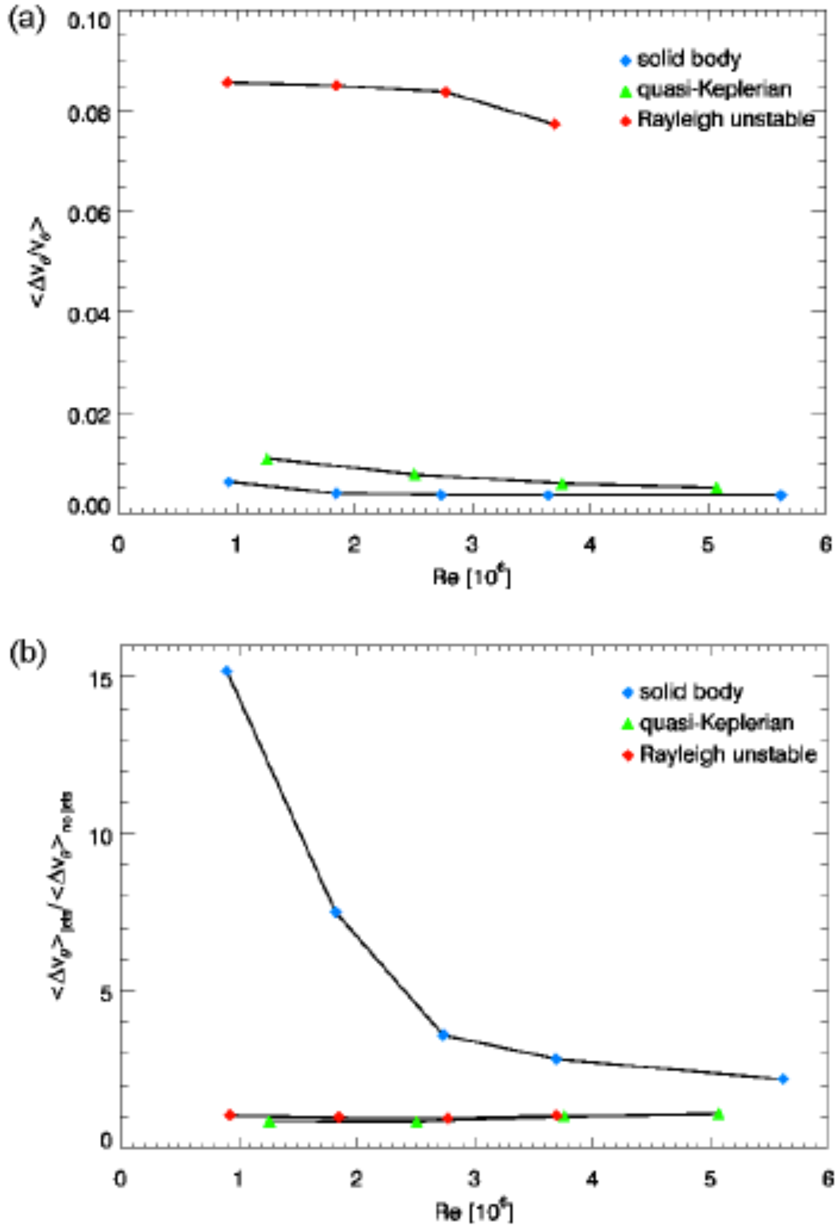


Figure 15: Comparison of azimuthal velocity fluctuation levels (a) normalized to the mean azimuthal velocity and averaged over radius under normal operation and (b) with active perturbations normalized to the fluctuation level without active perturbations. In all cases there is negligible modification of the mean azimuthal velocity profile when the perturbation system is active.

In recent studies of scaling of torque measured at the inner cylinder as a function of global Rossby number (Ro) Paoletti and Lathrop [2010] reported an anomalously large torque in the quasi-Keplerian regime. A set of experiments conducted in HTX sought to explore these claims that flows in the the quasi-Keplerian regime can exist in a turbulent state with an enhanced angular momentum transport. These studies find no such enhanced turbulent state in the quasi-Keplerian regime, even when running under conditions where the ring speed is not optimized to produce an ideal Couette profile. Furthermore, Paoletti and Lathrop [2010] claimed that an apparent discontinuity in torque measurements as the system is brought to Ro = 0 (solid body rotation) separately from the negative Ro side (cylconic) and positive Ro side (anti-cyclonic) may be the result of hysterisis. We have investigated both this claim by performing experiments in HTX covering a similar range in Ro. A scan of increasing Ro, from Ro = 0 to large positive values of Ro through the Rayleigh stability limit, where the system becomes highly turbulent (as in _gure 3a) and back to Ro = 0 showed no signs of hysterisis. Our experiments were performed in a configuration similar to that used in Paoletti and Lathrop [2010] where the ring is rotated with the outer cylinder so that the majority of the top and bottom boundaries rotate as a solid body. Future studies in HTX will continue to explore the stability of quasi-Keplerian flow profiles with controlled boundary conditions and address outstanding issues in the community regarding the stability of these configurations.

Modeling, Theory and Computational Results

Plasma Shaping Effects on flux-surface averaged stress: As discussed above, recent intrinsic rotation experiments suggest that the turbulent stress can depend upon the detailed magnetic flux surface shape; it is also well-known that the L-H power threshold has a strong dependence on the location of the X-point relative to the grad-BxB drift direction.

Taking these observations into account, CMTFO researchers developed a model which may explain why the L-H power threshold depends upon the magnetic geometry. The key results can be explained by referring to *Figure **16*** below. Using an existing 2D tokamak edge turbulence fluid code (the TOKAM2D code from the French CEA group) we studied how a background ExB shear layer (*Figure **16***(a)) acts to stretch and tilt turbulent eddies as seen in the region 125<x<225 in *Figure **16***(b). Experiments also show that magnetic shear acts to tilt turbulent eddies as well. Taking these observations into account, we hypothesize that in a tokamak the eddies are generated near the midplane region by a mix of pressure gradient and magnetic field curvature. Following the eddies along a magnetic field line, the eddies are then tilted and stretched by a mix of magnetix and ExB shear as shown in *Figure **16***(c) as they propagate toroidally along a magnetic flux tube. This anisotropy leads to a poloidally varying turbulent stress as shown in *Figure **16***(c) schematically. When the flux-surface averaged stress is computed, a non-diffusive stress component arises; when used in a 1-d flux-surface averaged radially varying poloidal momentum balance analysis, these stresses can then act to drive poloidal plasma rotation.

This provides insight into an important aspect of edge transport which is well documented, namely how does the topology of the magnetic flux surfaces modify the sheared flow. This effect has been recognized for decades, some configurations being called favorable or unfavorable for the achievement of an L-mode to H-mode confinement transition. These topology dependent mechanisms are not understood and are strongly linked to the macroscopic conditions needed for the L-H transition. The mechanism works as follows. As discussed above, the ballooning mode-like turbulent eddy cross-section depends on magnetic and flow shear effects, both of which can introduce a tilted, stretched eddy from an originally isotropic eddy. Now, if the flux surface is up-down asymmetric then the localization of the mode at the outboard midplane helps to create a radial transport of transverse momentum (linked to the orientation of the velocity field) which is also asymmetric poloidally. When this is averaged over a flux surface, the resulting net shear stress can act to modify the plasma rotation profile. When used in a 1-d radial, flux-surface averaged momentum balance, we can then predict what the radial profile of poloidal plasma rotation should be, along with the associated radial electric field and ExB profiles. The results are shown in Figure 17 where we see that these physics effects naturally lead to stronger ExB shear in a LSN configuration. Thus this model – if validated- could help defining what is the optimized tokamak geometry to create the strongest shear layer at the edge and hence optimize the route to high confinement in tokamak devices. We are seeking out opportunities for validation experiments using GPI to image turbulent structure anisotropy and profile measurements, most likely at the EAST, HL-2A or C-Mod tokamaks.

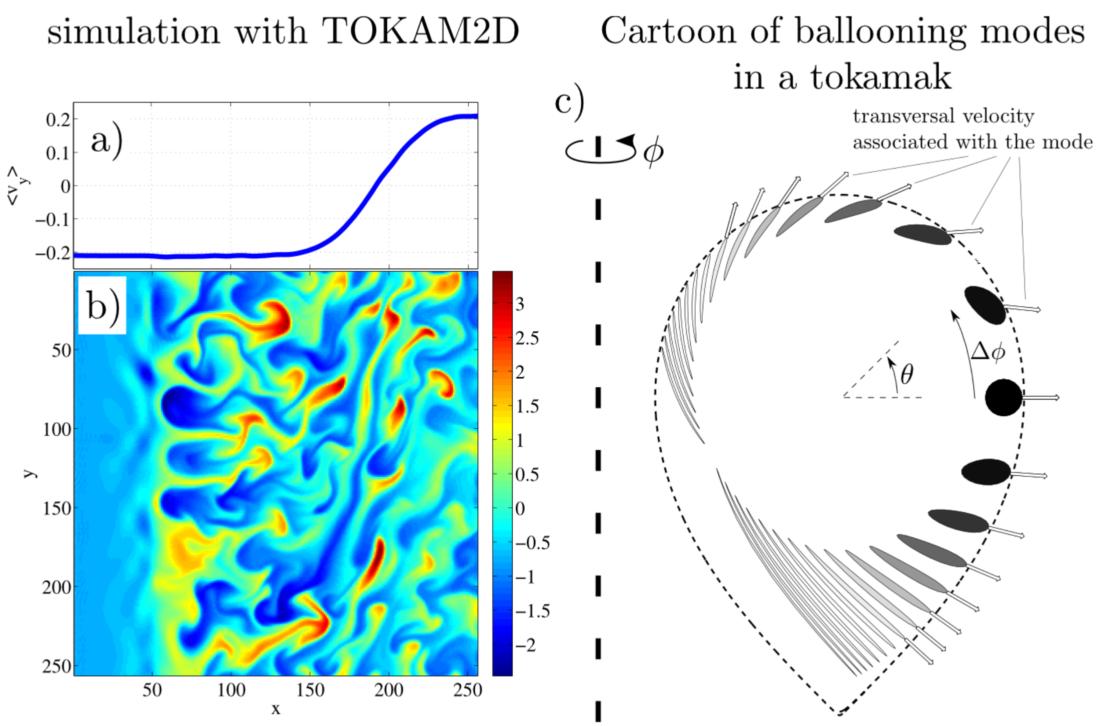


Figure 16: Left : simulation results with TOKAM2D. a) : azimuthal (along y) velocity profile. The shear is located at x~200. b): snapshot of density map (normalized). Structures propagate from left to right and tilt in the shear region. Right (c) : poloidal cross section of a tokamak plasma with x-point. The dashed curve is the separatrix. The cross section of a ballooning mode is shown at different positions along its flux tube, starting with a circular section at the outboard midplane. The grey fading of the mode illustrates the ballooning envelope centered at the outboard midplane. The transversal velocity along the flux tube is indicated by the white arrows.

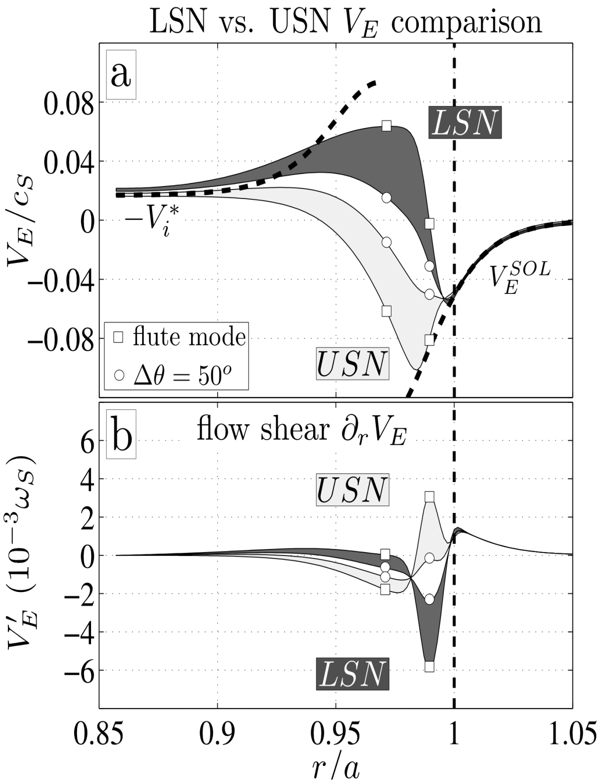


Figure 17: Upper: Radial profiles of ExB velocity (upper panel) and ExB shear (lower panel) for USN and LSN configurations. Identical pressure gradients are assumed; differences in profiles occur due to difference in flux-surface averaged Reynolds stress from the combined self-consistent effects of magnetic shear and ExB shear.

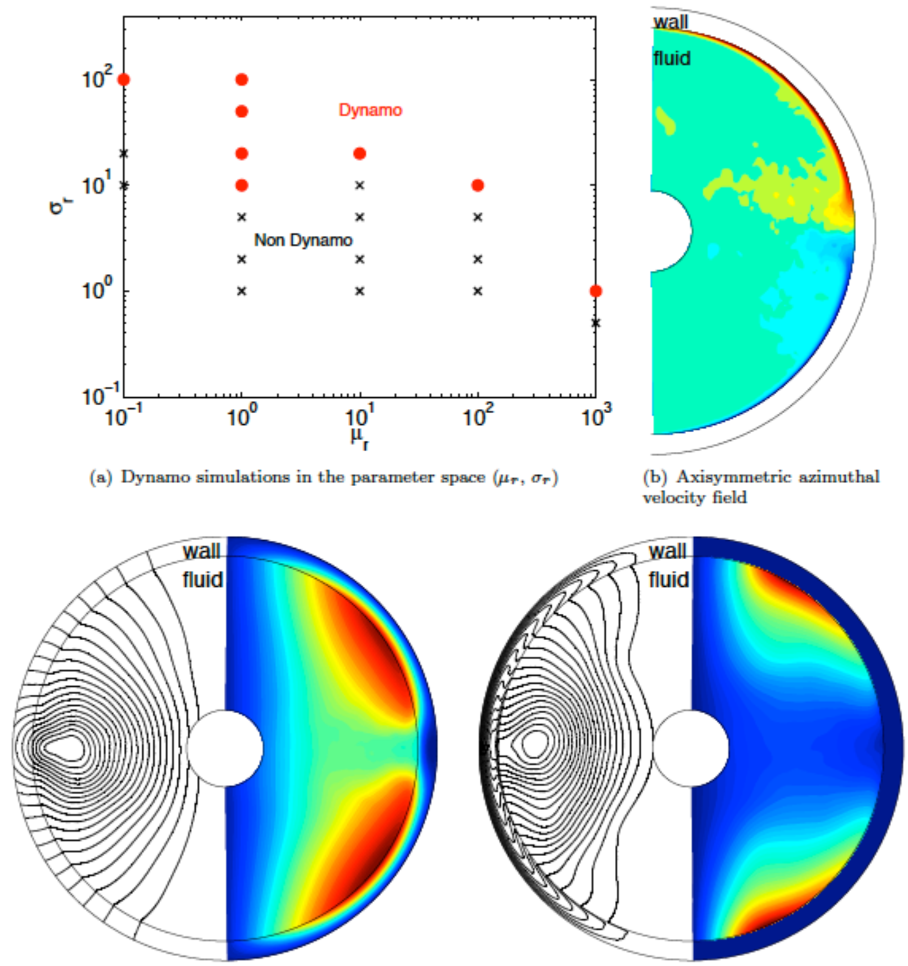
Effects of Boundary Conditions on Dynamo Formation in Experiment: In 2007, the Von Karman Sodium (VKS) dynamo experiment in Cadarache, France, produced a large scale self-sustained magnetic field from a highly turbulent flow of liquid sodium driven by the mechanical forcing exerted by two counter-rotating impellers (Monchaux: 2007 PRL, Aumaıtre:2008). However, this achievement is overshadowed by the fact that, even for the strongest mechanical forcing achievable in the experiment, dynamo action only occurs when the impellers are made of soft iron – a material with high magnetic permeability, which allows a discontinuity in the magnetic field between the fluid and the impellers. Elucidating the effects of magnetic boundary conditions on the dynamo is critical to understanding how the dynamo mechanism operates in shear driven systems, such as the VKS dynamo experiment, the plasma Couette experiment in Madison, Wisconsin (Spence:2009), and the spherical Couette experiment in College Park, Maryland (Kelley:2007).

CMTFO-supported researchers at UCSC have numerically investigated this problem by using a self-consistent three-dimensional MHD model. The numerical code is a modified version of the PARODY code, which solves the magnetic induction equation and the momentum equation for an incompressible fluid in a spherical shell geometry using spherical harmonic expansion and finite differences in the radial direction (Dormy:1998). The code operates with a finite thickness solid wall where the induction equation is still solved, matched to a potential field exterior. The permeability and conductivity of the wall (relative to the fluid) can be varied individually. An azimuthal viscous boundary forcing exerted by the symmetric counter-rotation of the two hemispheric walls drives the mean flow. For sufficiently large forcing, the mean flow is unstable to non-axisymmetric shear instabilities, which generate time-dependent small scale motions. Mean large scale and fluctuating small scale motions can act as a dynamo mechanism, amplifying an initial weak magnetic field and ultimately sustaining a strong magnetic field. Such a process requires a coherent organization of the flow and magnetic field on various spatial scales, despite the turbulent nature of the flow.

For fixed forcing and magnetic properties of the fluid, we have varied the properties of the wall-impellers: magnetic permeability μ, electrical conductivity σ, and thickness h. For a homogenous system (same μ and σ in the wall and fluid), the flow is unable to maintain a magnetic field. Increasing either μ or σ in the wall promotes dynamo action and a magnetic field at the largest scale of the system is generated (Figure 18 (a)). Large electrical conductivity and large magnetic permeability in the wall act differently on the dynamo mechanism: the reduction of the magnetic diffusivity of the wall $\eta=1/\sigma\mu$, which allows for slower decay rate of magnetic field within the wall, is therefore not the key ingredient. A strong axisymmetric toroidal (i.e. azimuthal) magnetic field is produced in the azimuthal shear layer located in the fluid region close to the wall (Figure 18(b)) by shearing of poloidal (latitudinally and radially directed) magnetic field lines – the so-called ω effect. The ω effect is amplified by a large conductivity of the wall: the circulation of strong latitudinal electric currents in the walls supports the generation of a strong toroidal field in the shear layer (Figure 18(c)). Large magnetic permeability tends to align the poloidal magnetic field lines perpendicular to the wall, and so amplify the ω effect by forcing strong radial magnetic field in the shear layer (Figure 18(d)). In both cases, a thicker wall, which allows for enhanced circulation of electric currents in the wall, promotes dynamo action.

A dipolar poloidal (large scale) magnetic field is generated by correlations of small scale velocity and magnetic structures in the equatorial region of the fluid. Only structures whose azimuthal symmetry is larger than m = 5 produce a mean time-consistent electromotive force as the source of the large scale poloidal structures. The small scale magnetic field is mainly produced by distortion of axisymmetric toroidal field lines by the small scale motions. The production of the mean electromotive force is controlled by the scale-dependent organization between the structure of the small scale velocity and azimuthal shear.

We have further examined a different approach to the same problem using Prof. Gary Glatzmaier's code that solves the same problem but whereby the outer wall is replaced by a simple boundary condition that integrates the effect of the finite shell wall into an infinitely thin approximation (Roberts, Glatzmaier & Clune, 2000, GAFD). We are comparing the results between the two codes for the finite and infinitely-thin wall conditions. Initially, we find that, for fixed other conditions, a thicker finite wall appears to aid dynamo action. Furthermore, Katelyn is investigating the situation where the two hemispheres are not driven symmetrically. Experimentally, this was found to encourage dynamo action. We are investigating a range of asymmetrical differential rotation forcing geometries to examine this idea. So far we have found that extreme asymmetry can extinguish an existing symmetrically-forced dynamo, and possibly that symmetric non-dynamos can indeed become dynamos for a certain degree of asymmetric forcing.



(a) Dynamo simulations in the parameter space (μ_r, σ_r)

(b) Axisymmetric azimuthal velocity field

(c) Axisymmetric magnetic field ($\sigma_r = 10$, $\mu_r = 1$). left: poloidal field lines; right: azimuthal field.

(d) Axisymmetric magnetic field ($\sigma_r = 1$, $\mu_r = 1000$). The colorscale is saturated in the wall.

Figure 18: *Dynamo simulations with a thick wall, fixed forcing and fixed properties of the fluid. The relative electrical conductivity σ_r is the ratio of the wall conductivity over the fluid conductivity. The relative magnetic permeability μ_r is the ratio of the wall permeability over the fluid permeability.*

Convective Overshoot into the Tachocline & Effect on Shear Flows: It is increasingly apparent that any global model of the solar interior and the solar dynamo must take into account the processes acting within the tachocline, the thin shear layer at the base of the convection zone. Within this layer, transport of angular momentum, entropy and magnetic flux by convective overshoot and meridional flows profoundly influences the Sun's internal rotation profile and magnetic activity cycle. Each of these processes has been well studied in isolation. For example, it is well-known that convective turbulence can transport (or "pump") a horizontal magnetic field into a convectively stable region (Tobias:2001) and it has been postulated that the "burrowing" of slow radiatively-driven meridional flows (Spiegel:1992,) could be balanced by a weak fossil interior field (Gough:1998,; Woods:2010). However, incorporating all of these individual effects faithfully into a three-dimensional global solar model has so far proved impossible. As a result, no such model (e.g. the ASH simulations of the Toomre group) has ever reproduced the full solar internal rotation profile (including the tachocline and below) inferred from helioseismology. Part of the problem is our incomplete knowledge of the parameter regimes in which each of the essential ingredients operates efficiently, and the difficulty of achieving extreme parameter values in global simulations.

The overarching problem is really a question of the interaction of various transport mechanisms – turbulent pumping, Spiegel & Zahn burrowing, Taylor-Proudman enforcement of transport under the influence of rotation, Ferraro's Law dictating of transport under the influence of magnetic fields – and whether anything like a Gough & MacIntyre balance can be achieved. As such, this generic interaction of transport mechanisms and the possibility of field confinement leads to interesting applications in many other fields including plasma devices. We have therefore begun to incorporate each of the necessary elements into local Cartesian simulations designed to mimic the important properties of the tachocline, using the HPS code (see e.g. Brummell:2002). We create a penetrative compressible convection simulation domain where the upper portion of the box is convectively unstable and the lower portion is stable. Convection can penetrate from the convective to the stable region, and it is this compressible action that leads to turbulent pumping. We also force a latitudinal differential rotation that tapers off from the upper boundary throughout the convective region. In the absence of convection, this generates a meridional circulation by gyroscopic pumping that then burrows into the stable region by the Spiegel & Zahn mechanism. We explore the interaction of these two mechanisms by having both convective forcing and the differential rotation forcing acting at the same time, and then further examine the effect on an imposed interior (i.e. in the stable region) magnetic field.

We have performed several exploratory runs on the mesoscale cluster Pleiades at UCSC, and now we have used the NSF Teragrid Cray XT5 Kraken to run larger, longer simulations. We have confirmed that the Speigel & Zahn predicted burrowing does indeed exist in a full hydrodynamic simulation, including the case when convective turbulence is present. Indeed, turbulence actually seems to enhance the spread of (azimuthal) momentum. We have also performed two long simula tions, in slightly different geometries, incorporating magnetic field. One is quasi-two dimensional, in that the boundary conditions are invariant in one direction (Figure 2a). This simulation is intended to model conditions surrounding the tachocline at high latitudes, but far from the pole. The other simulation is intended to model conditions in a neighbourhood of the pole. In order to approximate the polar geometry in a Cartesian domain, we actually simulate four poles, which together make up the doubly periodic structure necessary for the code (Figure 2b).

The results of the quasi-two dimensional simulation confirm the efficiency of overshooting convection in transporting and storing mean magnetic flux. The mean flux is pumped out of the convective layer on the timescale of the turbulent convection, and achieves a statistically-steady equilibrium on the timescale of magnetic diffusion across the computational domain. The magnetic field suppresses shear within the stable layer, enforcing solid body rotation below the overshoot layer. Mean meridional flows modify the distribution of the mean field, but do not contribute to the field's confinement. In the polar simulation, on the other hand, where the magnetic field is not all (initially) horizontal, meridional flows are thought to be essential to the confinement of the field. Very preliminary results seem to confirm this hypothesis, but further study is required. Clearly, the Cartesian simulations, although nicely simple, are not ideal. We are therefore also using the PARODY code (mentioned in the previous section) to construct a global, hydrodynamic model of this problem related to the solar interior. The model is designed to reproduce the parameter (timescale) ordering appropriate to the tachocline, but not the detailed dynamics of the convection zone. The aim of these global simulations is to allow the differential rotation to be generated self-consistently by the action of (this time, Boussinesq) convection, and, of course, to avoid the issue of artificially representing the geometry. We are in the process of creating hydrodynamic simulations that produce a representative differential rotation. After that, we will repeat the same sort of experiments as are currently being performed in the Cartesian case, to verify the results found there.

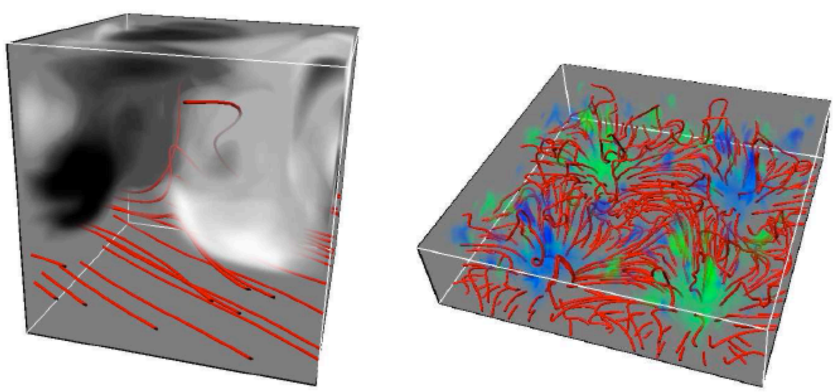


Figure 19: The left panel shows the quasi-two dimensional simulation. Within the convectively unstable upper half of the box we drive a shear flow, indicated by black and white coloring. The shear extends into the overshoot layer, but the stable lower layers are held in uniform rotation by the magnetic field, shown in red. The right panel shows the "four poles" simulation. The blue and green shading indicates the sense of the vertical field.

Modeling Quasi-Single Helicity in the RFP: Rotation is a long observed feature of reversed field pinch (RFP) plasmas. Extensive experimental observations with multiple diagnostics and MHD modeling have established a connection between the dominant global tearing mode activity that characterizes RFP operation and global rotation [Kuritsyn:2009]. The tearing mode activity is organized into discrete cyclical sawtooth events, making the RFP a magnetically relaxing plasma. RFP studies of flow organization and momentum transport naturally compliment other center activities related to tokamaks by providing a system with strong magnetic self organization. A key question is how this interacts with flow organization processes that are both independent of tearing mode activity or intimately connected with it.

During a sawtooth crash the parallel rotation profile is observed to flatten. This involves a redistribution of momentum with the core slowing down and the edge speeding up. The sawtooth crash corresponds to a significant increase in tearing mode fluctuation levels, both at low frequencies associated with the linearly unstable modes of the tearing mode drive and at the higher frequencies believed to result from a cascade. These observations indicate that tearing modes drive outward momentum transport. MHD modeling efforts, which have been ongoing in MST for many years [Ebrahimi:2008, King:2011], are broadly consistent with experiment and constantly being refined. The Center can address questions that require going beyond MHD. These include seeking the source of momentum profile peaking that occurs in between sawtooth events and examining the effect on momentum transport of microturbulence, specifically from ITG turbulence at low beta, and from temperature-gradient-driven microtearing turbulence at high beta.

An intriguing laboratory for flow organization and its effects in a magnetically relaxing system is the quasi-single helicity state [Lorenzini:2009, Bergerson:2010]. In this state a tearing fluctuation of a single helicity becomes strongly dominant over other helicities to the extent that the fluctuation structure assumes characteristics of a new helical equilibrium. This state becomes more robust at higher current [Lorenzini:2009]. Moreover, there is a spatial correlation between the helical structure and transport barrier-like regions of steep gradients in temperature and density. These observations raise several questions related to flow organization. Can one helicity of an unstable tearing mode actively suppress other unstable helicities, and if so, what conditions are required for this effect? Do the flow and current profiles of the suppressing helicity then become quasi stationary, sufficient to make instability plus suppression a self-organization mechanism? What are the relative effects in this process of flow shear and magnetic shear?

An emerging area in microturbulence and transport is the effect of subdominant fluctuations [Hatch:2011a]. For example, in tokamak ITG turbulence it has been shown that stable modes in the wavenumber range of the instability saturate the turbulence and produce stochastic magnetic fields and electron transport [Hatch:2011b]. A component of the stable modes has tearing parity. In the RFP, it is now understood that ITG modes are stable at the RFP beta values of order 10% and microscale fluctuations are driven by tearing-parity microtearing modes [Carmody:2011]. Is there a reciprocal effect in the RFP wherein unstable tearing parity modes drive stable ITG-like modes? What effect do the subdominant modes have on momentum transport and flow organization?

Since formation of the center an effort to understand and describe suppression in the quasi-single helicity state has been undertaken. This work has developed an analytical framework for characterizing the flow and magnetic shear profiles in an unstable RFP tearing mode fluctuation and for calculating their effect on neighboring fluctuations of different helicity. This work combines into a single model the results of two separate earlier threads. One showed that an intense vortex fluctuation in Navier-Stokes turbulence suppresses neighboring fluctuations and turbulent mixing [Terry:1992], and the other showed that an intense current filament in kinetic Alfvén turbulence suppresses magnetic fluctuations and current diffusion [Terry:2007]. These physical processes combine in MHD. It has been found that both magnetic shear and flow shear can suppress neighboring helicities, and that, under certain circumstances the effects of each type of shear can offset one another. Conditions for one helicity to disrupt the nonlinear interaction with other helicities have been found, and it has been shown that these make the dominant helicity quasi stationary. A paper describing this work is presently under preparation.

To examine flow and momentum transport in RFP microturbulence, gyrokinetic computational tools and expertise are being developed. Initial work to develop computational capabilities and to characterize the nature of small-scale fluctuations in MST has been carried out primarily on another grant. However, this work lays the foundation for studies that will be carried out under CMTFO. It has been shown that ITG turbulence is unstable in MST at low beta, but through coupling to Alfvénic fluctuations becomes stable at higher beta. At beta values of 5% the fluctuations change character from ballooning parity to tearing parity. The tearing parity fluctuations have a growth rate that peaks near $k_\theta\rho_s$ =1 and scales with the temperature gradient. Theoretical work shows that these fluctuations are microtearing modes that are destabilized by negative magnetic shear even in weak collisionality regimes.

1-D Predator-Prey Model of the L-H Transition:

Motivated by recent experiments on AUG [Conway:2010], DIII-D [Schmitz:2011] and EAST {Xu:2011], theory researchers at the CMTFO and the WCI-NFRI have extended the 0-D multi-predator/prey model of the L-H transition [Kim:2003] to now include spatiotemporal dynamics of the turbulence, zonal flow and mean shear flow thought to be key players in the transition to the H-mode improved confinement state. In this work, the particle and heat source profiles are modeled to be similar to experiment, with particle source localized to the external boundary region and the heat source localized to the inner region of the 1-D spatial domain. Neoclassical and turbulent diffusion for both fields are assumed, as is an inward pinch for particles. Turbulent diffusivities are taken to be proportional to turbulence intensity as observed in experiment. The 0-D predator-prey model is then modified by assuming a critical gradient form for the linear drive of the turbulence and by including the effect of turbulence spreading in space. The zonal flow and mean shear flow damping effects are transferred over from the earlier 0-D model. The zonal flow energy balance equation is carried over from the 0-D model but includes a term for zonal flow/mean shear flow competition and a zonal flow collisional damping term. Mean flow shear is taken from radial force balance including pressure gradient and curvature terms along with poloidal plasma flow effects. The inclusion of poloidal flow then requires the inclusion of a conservation equation for poloidal momentum, which then includes turbulent stress effects and neoclassical flow damping.

The resulting model evolves the density, pressure, poloidal rotation, turbulence intensity and zonal flow energy simultaneously in time over a 1-D spatial domain; key results from the model are summarized in

Figure 20 below. The heat flux input into the model is then used as to induce a transition from L-mode to Intermediate (I-mode) confinement characterized by turbulence/zonal flow limit cycle oscillations, and then finally an I-mode to H_mode confinement transition in which the turbulence and zonal flows die away and a state of strong mean shear flow ensues and an edge density and pressure pedestal then grow. This modeling work, combined with the recent experimental work being undertaken by CMTFO researchers working on the tokamak devices discussed earlier can be expected to provide breakthrough insights into the physics of the transition to H-mode in the near future.

Intrinsic Rotation and Turbulent Transport of Mean Toroidal Momentum:

In a collaboration between the CMTFO, PPPL and the WCI-NFRI, numerical experiments were performed to study the physics origins of intrinsic toroidal rotation in tokamak devices [Ku:2011]. The PIC-based XGC1p and semi-Lagrangian GYSELA full-f gyrokinetic codes were used to perform global heat-flux driven simulations. A momentum-conserving heat source was imposed in the central plasma region, and in the the XGC1p simulations a sink for that heat was assumed to exist in the outer boundary region, while in the GYSELA simulations a diffusive term near the outer boundary acts as a heat sink. A no-slip flow boundary condition is imposed in the outer region, coming presumably from plasma-neutral interactions which damp plasma rotation in the outer region due to rapid momentum transport to the walls via the neutral particles. This implementation of the no-slip boundary condition does not damp the turbulent fluctuations near the boundary and so allows the transmission of stress into the boundary layer by turbulent transport. This interaction between the plasma and the boundary through turbulence is crucial to achieving global spontaneous spin-up of tokamak plasma without external torque input.

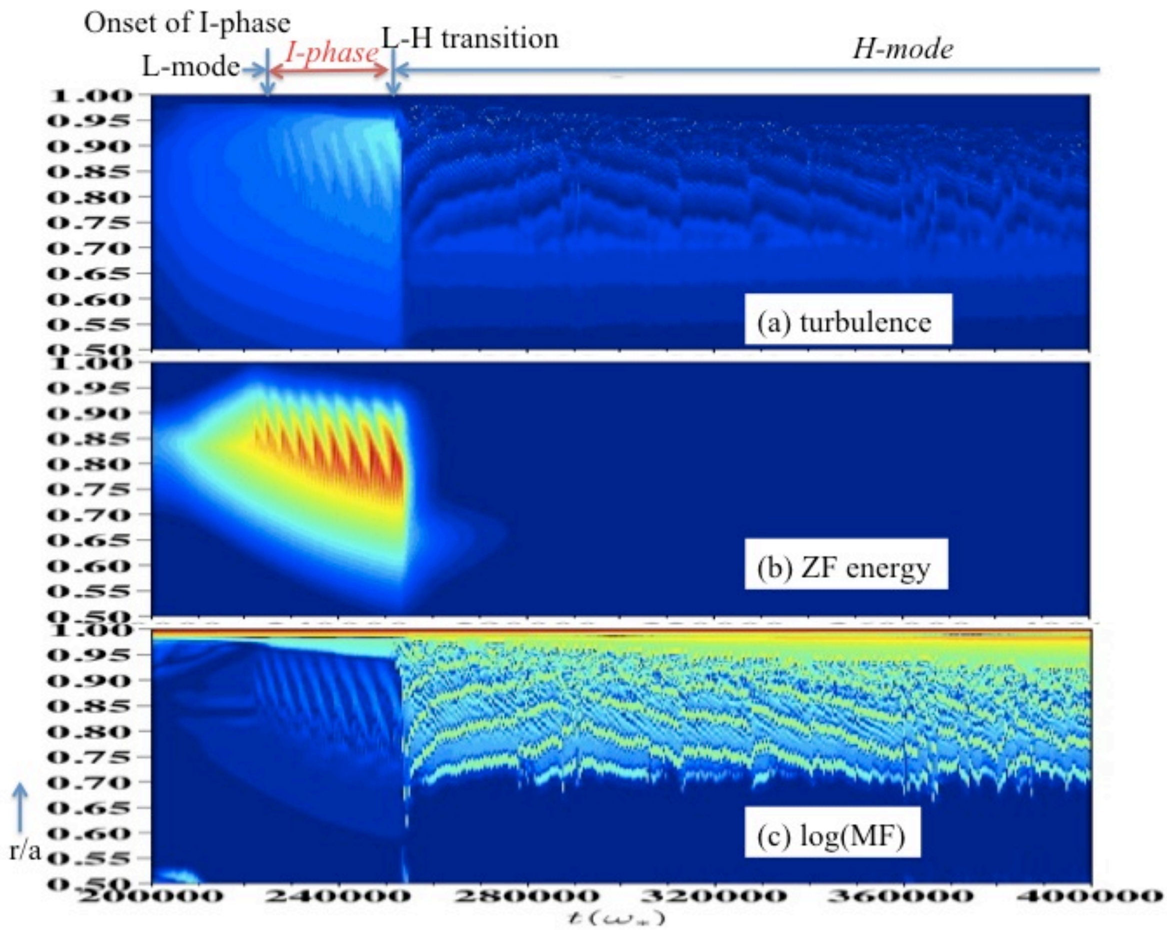


Figure 20: Time evolution (horizontal axis) of radial profiles of (a) turbulence intensity, (b) ZF kinetic energy, and (mean ExB flow) from a new spatio-temporal model of the L-mode – I-mode – H-mode transition in tokamaks that accounts for evolution of turbulence, zonal flows, mean shear flows and both density and pressure profiles. The transition is triggered by a heat flux that is proportional to time. As heat flux is increased, limit cycle oscillations in the turbulence intensity and zonal flow amplitude set it, and result in a inward propagation of a zonal flow from the boundary region in towards the central region (inset). Further increases in heat flux then trigger a transition to H-mode characterized by decaying turbulence and zonal flow, and an increased mean shear flow. Pressure and density gradients then steepen at the plasma boundary, and form the H-mode pedestal. [Miki & Diamond, private communication, to be published, 2011].

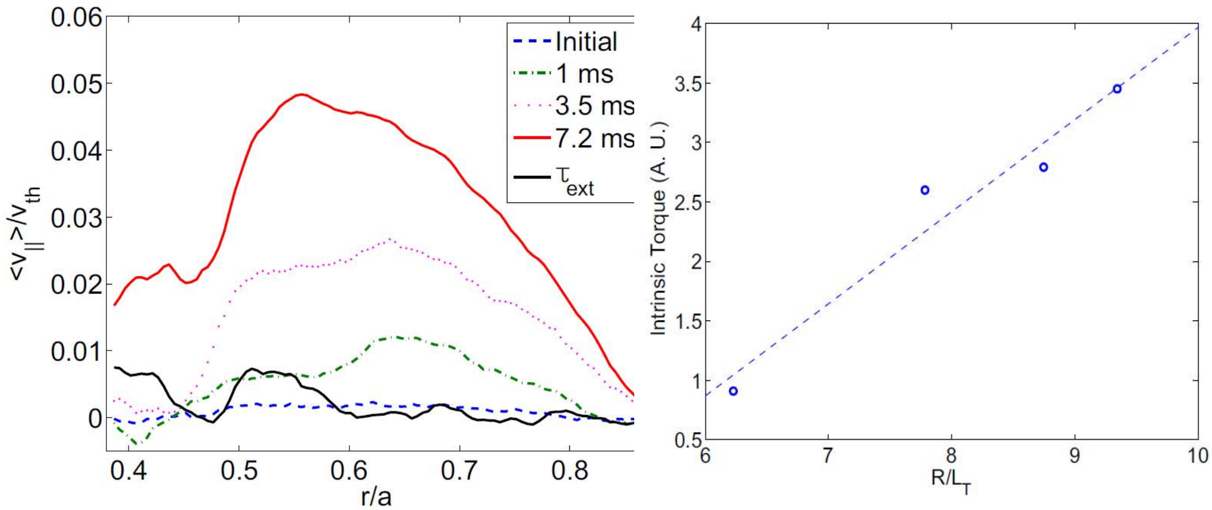


Figure 21: Left: *Development of net co-current toroidal rotation from a zero-flow initial condition in flux-driven ITG simulations. Once flow develops, application of an external torque, t_{ext}, is then capable of cancelling out the rotation. Results are shown from the XGC1p simulations; similar results were obtained from GYSELA. Right: Intrinsic torque density is proportional to the temperature gradient at the edge. Figure taken from [Ku:2011]*

The results from both simulations demonstrated the formation of macroscopic mean toroidal flows with a maximum thermal Mach number of ~0.05 from an initial plasma which has no rotation (see Figure 21 above). Both numerical codes shows that flux-driven ITG turbulence result in co-current unidirectional intrinsic rotation. Application of an external torque to the fully developed rotation case can then null out the rotation; the torque needed to to cancel the rotation is inversely proportional to the ion temperature gradient. These results are similar to recent work on ALCATOR C-Mod which has been published [Rice:2010b]. Analysis of the turbulence in the simulations show that correlations between the radial velocity and toroidal velocity yield a turbulent Reynolds stress whose gradient results in the intrinsic torque. Two equally significant symmetry breaking mechanisms – radially sheared ExB drifts and radially varying turbulent intensity – were identified (see below). Correlations between the turbulent stress and these two quantities show that both are operative. Outgoing heat flux avalanches are found to be correlated with inward going avalanches of parallel momentum, showing that both fluxes are carried by mesoscale avalanches, and demonstrating the key role that the boundary region plays for the origin of intrinsic rotation. These results have been submitted to Nuclear Fusion for publication [Ku:2011].

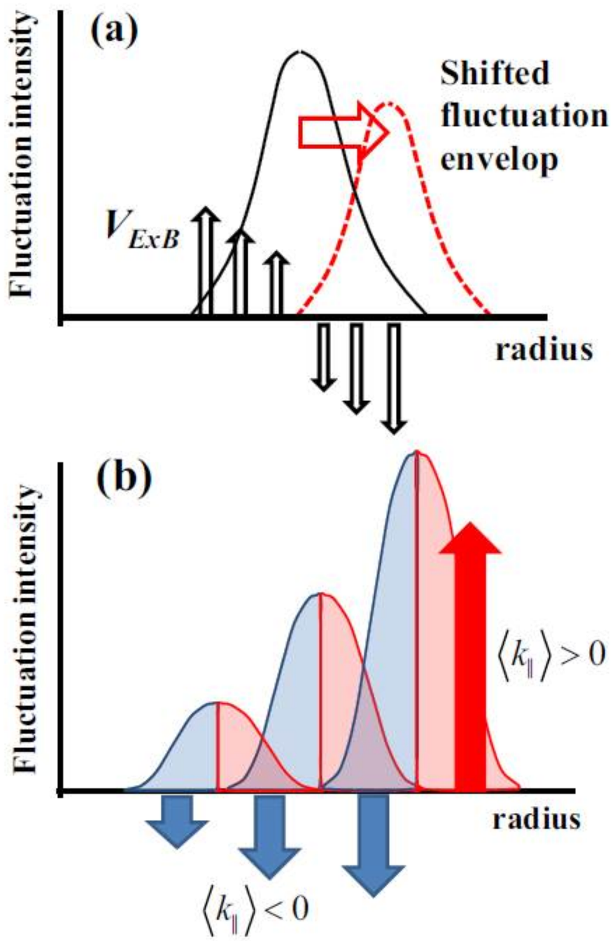


Figure 22: *The mechanism for intrinsic rotation generation via turbulent stress involves k|| spectrum symmetry breaking that can be induced either by (a) Radially sheared ExB drifts or (b) by radially varying turbulence intensity. Both radial profile effects occur in simulation; radial variations in ExB and fluctuation intensity are also observed in experiments.Figure taken from [Ku:2011]*

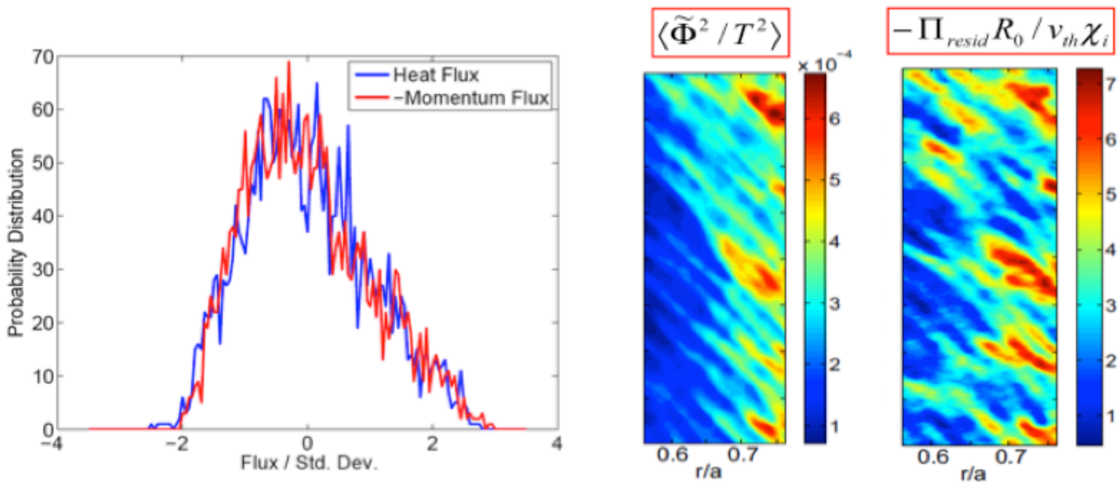


Figure 23: *Left: PDF of heat flux and toroidal momentum flux. Both fluxes show similar statistical shape indicating their relationship. Center: Radial and time variation of electrostatic potential fluctuations and (Right) radial-toroidal stress component, both showing avalanche like events propagating inward from the boundary, thus demonstrating the key of boundary effects for the origin of intrinsic rotation. Figure from [Ku:2011] and {Diamond, private communication]*

Other Areas of Significant Theory Progress:
There were a number of other areas in which significant theoretical progress was made during the initial period of the Center. A brief summary of these topics includes:

Evolution and Structure of the H-mode Pedestal and Internal Transport Barrier Formation: This topic was another major focus of the two years. Specific progress includes: The first simulation demonstrating crucial role of intrinsic rotation in ITB formation, i.e. intrinsic rotation dominates $E \times B$ shear, the first study of hysteresis in ITB, linking it to Nusselt Number, a detailed phenomenology of L $\longrightarrow$H transition based on Kim-Diamond [Kim:2003] model in collaboration with EAST, Hl-2A, Tynan group and presented earlier in this report. Results support the idea that the ZF is required to trigger transition. Detailed theory of GAM-ZF mode competition approaching transition, complementing recent CMTFO experiments on HL-2A discussed earlier in this report. Initial work on 1D model of multi-predator L-H dynamics. The model recovers nonlinear shearing-intensity waves, now observed in experiment.

Shearing, Zonal Flows and Zonal Momentum Theorems: Research progress on this topic included basic theory and phenomenology of tilt-stretch-absorb mechanism, in collaboration with the Tynan group, described in more detailed earlier in this report. Basic theory of GAM-ZF mode competition, with emphasis on dominance criterion.An updated review of zonal flow and shearing physics, in collaboration with Hasegawa and Mima. Ongoing work on exploring flow evolution dynamics in the Kim-Diamond model. We developed a novel model for mean field theory of momentum transport in 2D, incorporating negative viscosity and positive hyper-viscosity.

Non-local Dynamics of Transport and Turbulence: Recent progress here includes improved theory of electron and ion heat pinch, demonstrating link to density profile peaking. Novel theory of turbulent heating and turbulence-mediated inter-species heat transfer. Comprehensive theory of turbulent front propagation as mechanism of non-locality phenomena. This analysis recovers the fast propagation time required to explain cold pulse experiments. New results on "non-locality phenomenology", in collaboration with HL-2A. Sustainment for 10 energy confinement times was demonstrated, supporting the notion of the existence of a meta-stable state accessed by edge cooling.

RMP Effects on Turbulence and Zonal Flows: A novel theory of RMP effects on zonal flows was completed. The crux of this model is that RMP-induced radial currents partially cancel the ion polarization current which drives the zonal flow. As a consequence, zonal flows are damped by coupling to (turbulent) diffusive damping of zonal flows, and turbulence consequently is enhanced.

Phase Space Turbulence Dynamics: Significant progress on phase space density granulation in drift wave turbulence and in the Berk-Breizman model was made. Both a single structure (hole/blob) and statistical theory were developed. A kinetic Charney-Drazin type momentum theorem was proved. Sub-critical structure growth has been confirmed in the 1D B and B model.

Astrophysical Fluid Dynamics: Significant progress was made on the topic of turbulent momentum transport and zonal jet formation in 2D MHD on a beta plane. This work is motivated by earlier studies of beta plane MHD, but presents more complete studies of varying orientations of the jets and the magnetic field, and an analysis of the meaning and role of the Rhines scale. Theoretical work aims at a mean field theory of momentum transport, which includes the effect of a mean shear, which is externally forced or fixed. Parallels have been drawn with the two predator-one prey model of the $L \rightarrow H$ transition, familiar from tokamak physics. Ongoing work is concerned with refining the multi-shear model, calculating an effective momentum flux for the tachocline and exploring its implication for the Spiegel-Zahn model, and developing a two layer model with (in layer) magnetic fields.

Invited Talks, Honors and Awards

IAEA 2010: CMTFO related work was discussed in several keynote talks at the IAEA-2010 meeting held in Korea. As was discussed above, XGC1P and GYSELA simulations by S.Ku et al used full-device flux-driven gyrokinetic simulations to study the origins of intrinsic rotation in tokamak devices. The results showed how a non-diffusive turbulent stress localized to the boundary region was responsible for the observed plasma spinup. In a separate talk by J. Rice, experiments from ALCATOR C-MOD along with theory and a basic laboratory plasma device were discussed and provided a detailed examination of the origins of the residual stress and its effect on tokamak rotation in experiment.

APS DPP 2010: The first direct experimental search for turbulent residual stress was performed on the DIII-D device by CMTFO affiliated researchers in 2010. These initial results showed that turbulent momentum transport did occur, but that the measured stress alone was not consistent with the observed rotation. The results were presented as an invited talk at the APS DPP 2010 meeting, and published [S. Mueller et al, Physical Rev. Letters (2010), S. Mueller et al Phys. Plasmas (2011)]. More recent experiments on DIIID indicate that plasma shaping has a strong influence on the midplane turbulent stress; analysis of those experiments are continuing.

Diamond EPS Alfven Prize Lecture: Finally, the most notable honor for CMTFO affiliated researchers was the award of the Alfven Prize to Professor Patrick Diamond, co-PI of the CMTFO, who shared the 2011 Alfven Prize and gave an invited talk on the physics origin of zonal momentum transport and flow organization at the 2011 EPS meeting in Strassbourg, France.

CMTFO-affiliated Meetings, Schools & Synergistic Activities

The Center has organized and either sponsored or co-sponsored a number of schools, meetings, mini-conferences and workshops since it began in 2010. These include:

January 2010 Kickoff Meeting, UCSD: Shortly after a funding decision was announced by DOE, we made plans to hold our first face-to-face meeting to discuss initial plans and more clearly discuss with each collaborator how they could interact with other Center participants. This first meeting was held at UCSD in January 2010. It was clear from this meeting that a number of groups needed to recruit new staff, acquire the necessary numerical simulation tools and codes, or complete the assembly and commissioning of several new experimental facilities. Two PIs (Tynan & Diamond) attended a workshop in China which focused on US-Chinese collaboration in magnetic fusion research, and used that meeting to establish new collaborations on the HL-2A and EAST tokamaks located at the Soutwestern Institute of Physics in Chengdu, China, and at the Academy of Sciences Institute of Plasma Physics located in Hefei, China.

APS DPP 2010 Miniconference: During the CMTFO sponsored a mini-conference at the APS DPP 2010 meeting on Momentum Transport in Astrophysical and Magnetic Fusion Energy Systems. A listing of the talks and speakers from that mini-conference is given in the Appendices. CMTFO collaborators as well as a number of other talks from others in the larger scientific community were given, focused on accretion disks, intrinsic rotation, and other aspects of momentum transport in plasma phsyics.

January 2011 Face-to-Face Meeting, New Orleans: We held a second face-to-face meeting for CMTFO collaborators in New Orleans in January 2011. At this meeting, we heard updates on the status of the laboratory scale experiments, and brainstormed ideas on how to resolve several technical issues that were making it difficult to make physics progress. We identified science goals for each group for 2011, and also identified how each group was going to make a scientific connection with another CMTFO collaborating group in order to more firmly establish cross-cutting research topics.

Aix en Provence Festival de Theorie, July 2011: As was discussed in our original proposal, we partnered with the French Centre Energie Atomique (CEA) and participated in the 6th Festival de Theorie in July 2011. This workshop provides an opportunity for scientists from the fusion and astrophysical communities to meet for several weeks, hear about common problems from both applications, and develop common research topics and projects. The CMTFO sponsored approximately 20 students and postdocs from the US to participate in this workshop. CMTFO researchers are currently pursuing several of these topics in current work discussed elsewhere in this proposal.

UCSD Winter School 2012: The CMTFO, in partnership with the Center for Magnetic Self-Organization (CMSO, see http://www.cmso.info), will be holding a Winter School at UCSD between 9-12 January 2012. The topic of the School will be Principles of Magnetic and Flow Self-Organization in Plasmas and Magnetofluids, and speakers from the magnetic fusion, astrophysics and geophysical fluid dynamics communities will discuss the current understand and open issues of self-organization in fusion systems, rotating stars and accretion disks. Talks will cover experimental/observational, computation and theoretical studies of flow and magnetic organization in the solar tachocline, accretion disks, astrophysical jets as well as laboratory hydrodynamic, liquid metal and laboratory plasma devices as well as tokamak and reversed field pinch magnetic fusion devices. Participants will be invited to present their work in a mixture of oral and poster sessions.

Webinars: During the academic year the CMTFO holds roughly monthly web-based seminars which are broadcast on the Internet. The audio and slides of the talks are archived and available for anyone to listen to afterwards. A listing of these talks, as well as a schedule for several upcoming talks, is provided in the screen shot of the CMTFO Webinars page seen below. The URL for these talks is http://cmtfo.ucsd.edu/~CMTFO/webinar/index.html

Upcoming Webinars

Date: 2011
Time: Thursday, 1 December 2011, 3pm PST, 6pm PST, 700AM 2 December in Korea, Ms. Pei Chun, UCSD and NFRI
Speaker: "Turbulent Transport of Momentum in the Solar Tachocline"
Title:

Date: 15 December 2011
Time: 5pm EST, 2pm PST, (700am) Korea time on 16 Dec 2011
Speaker: Dr. Eric Edlund
Title: "Search for a sub-critical hydrodynamic transition to turbulence in quasi-Keplerian systems"

Past Webinars

Date	Speaker	Title	Docs	Media
Oct. 28, 2011	Dr. Noam Katz, UW-Madison	"Rotating Unmagnetized Plasma in the Plasma Couette Experiment (PCX)"	PDF	MP3
May 5, 2011	Dr. Weixing Ding, UCLA	"Fluctuation-driven Momentum Transport Studies in the MST Reversed Field Pinch"	PDF	MP3
Apr 28, 2011	Professor Patrick Diamond, UCSD and NFRI	"Potential Vorticity Mixing - Part II: Gyrokinetic and Electromagnetic Effects"	PDF	MP3
Apr 1, 2011	Professor Patrick Diamond UCSD and NFRI	"Potential Vorticity Mixing: Commonalities for CMTFO and Suggestions for Experiments"	PDF	MP3
March 4, 2011	Dr. John Rice MIT	"Spontaneous Rotation Reversals in ALCATOR CMod"	PDF	MP3
Oct 21, 2010	Dr. Min Xu	"Study of nonlinear energy transfer between drift wave turbulence and zonal flow,	PDF	MP3
May 13, 2010	Steve Tobias	Angular Momentum Transport in the Solar Tachocline: Beta Plane MHD	PDF	MP3

Figure 24: **Listing of previous and planned CMTFO-sponsored Webinars. Audio and PDF of slides are available from http://cmtfo.ucsd.edu**

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Publications and Conference Presentations

Center sponsored research has resulted in a large (>50) publications and conference presentations already. A listing, arranged by CMTFO-affiliated group, is provided in Appendix B. These topics include high visibility papers on L-H transition physics, instrinsic rotation, simulations of dynamo experiments, basic theory of momentum theorems, observation of ExB shear flow staircases which lead to mesoscale transport and so forth.

Prospects & Plans for 2012-2015

The Center will support work at UW-Madison, PPPL and Colorado with grants to these institutions. UCSD will also have a grant which will provide financial support to the work at UCSC, MI/Columbia and PPPL by supporting UCSD postdocs who will be based fulltime at these institutions. In addition there will be support for two postdocs at UCSD as well. These Center researchers will focus on the basic problems identified at the beginning of the proposal. Organized by physical systems, these problems are:

MFE Flow Organization: with specific foci on Intrinsic Rotation, the L-H Transition and the formation of the QSH regime in the RFP), CSDX (UCSD) and tokamak experiment (DIII-D, NSTX, C-Mod, EAST, HBT-EP, HL-2A) combined with simulation and theory will be used to study Instrinsic rotation and L-H transition physics; theory and computation will focus on QSH physics, making contact with RFP experiment via the MST group at UW Madison.

Accretion Disk Instabilities Leading to Turbulence: Experiments on the HDX (PPPL) and PCX (UW Madison) devices will test for the existence of subcritical hydrodynamic instability and magneto-rotational instability in fluids or plasmas with quasi-Keplerian rotation profiles.

Solar Tachocline, Dynamo, and Solar Physics: Nonlinear MHD simulation (UCSC) and theory (UCSD/WCI and UCSC) will focus on beta-plane MHD studies of zonal flow forcing caused by convective overshooting from the convectively unstable zone into the tachocline region; experiments will attempt to study the onset of buoyancy driven convection which carries plasma and magnetic flux from the tachocline into the convection zone.

In addition to these three system-oriented problems, we also have identified two cross-cutting themes which will also form foci for the Center. These are:

Tests of PV Homogenization as a Universal Flow Organization Principle: Theory and computation work in the last 1 ½ years of the Center's existence have confirmed the long-standing idea that PV homogenization may be a powerful and universal flow organization principle governing magnetized plasmas, rotating MHD fluids such as stars, and Geophysical Fluid Dynamics (GFD) flows found in planetary atmospheres. We are planning dual experiments in the HDX and CSDX devices to test this hypothesis, originally proposed by Batchelor and Prandtl, in both Rossby wave-ZF (HDX device) and Drift wave-ZF (CSDX) systems. HDX experiments will use laser-based particle velocimetry to directly measure the turbulent flowfield and compute PV from this quantity; CSDX experiments will use a combination of fast framing visible light imaging and multipoint probe measurements to do PV measurements.

Development of Non-Invasive Flow Organization Diagnosis and Analysis Approaches: Key tests of turbulent-driven flow organization usually requires access to complex mult-field correlations such as turbulent stresses and then relating these microscopic quantities to macroscopic system behavior. Small scale experiments can provide direct access to these quantities, but the approaches used in these facilities can not in general be used in large fusion experiments. We will therefore focus attention on comparing non-invasive imaging diagnostics – which can be used in the core of fusion plasmas – against direct but invasive probe diagnostics which do provide direct access to the relevant turbulent microphysics. The hope is that by making such comparisons we can identify markers or signatures of the microphysics in imaging datasets, and then use those diagnostics in large scale fusion experiments to confirm the physics origin of flow organization in these systems.

As illustrated in below, we will have multiple Center groups focused on each of these problems in the 2012-2015 period, and thus provide opportunity for "value-added" Center contributions which take advantage of the strength of having combined experiment, theory and computational efforts focused on the physics of the problem at hand. We emphasize that as a result of combining researchers from the astrophysical and MFE communities, we expect that MFE will obtain significant benefits – i.e. the Center will not only take MFE science into the astrophysical community, but we expect MFE to benefit as well. An example of this is our planned experimental tests of the role of PV homogenization as an organizing principle for flow organization in MFE systems.

Flow Organization in MFE

Research into the MFE Flow Organization problem is organized into three topics: Intrinsic Rotation, the L-H Transition and the formation of the QSH regime in the RFP. In addition, we have one problem – namely the effect of macroscopic plasma shaping and magnetic shear on turbulent stresses – which cuts across these foci which we also plan to work on as well. In the sections below we summarize our planned approach for each of these topics and problems.

Group\System	MFE-Intrinsic Rotation	MFE-Transport Barrier & QSH Physics	Accretion Disks	Solar Tachocline & Dynamo	Basic Physics
UCSD-Tynan	DIII-D, HBT-EP C-Mod, EAST	HL-2A, DIII-D, EAST			CSDX/HDX
UCSD/WCI-Diamond	Theory, Codes DIII-D, HBT-EP, C-Mod, EAST	Theory, Codes DIII-D, HBT-EP, C-Mod, EAST	Theory	Theory	Theory
UCSC-Brummell				PARODY MHD code	
UW-Forest			PCX	PCX	PCX
UW-Terry		Theory, Compuation MST			
Colorado-Munsat		NSTX, DIII-D			HDX/CSDX LAPD
PPPL-Ji			HDX		HDX/CSDX
PPPL-Wang	GTS gyrokinetic code	GTS gyrokinetic code			
MIT-Rice	C-Mod				

Table 3: *Research topics and corresponding approaches or tools to be used by CMTFO-sponsored groups in 2012-2015 period*.

Intrinsic Rotation (CMTFO Groups include: UCSD, MIT, WCI/NFRI (Korea), PPPL):

Intrinsic toroidal rotation will be one major focus of CMTFO research in the next 3 years. We will use a combination of theory, computation and experiments to make progress on this topic; we summarize our planned approaches below.

Numerical Studies of Intrinsic Rotation:

We will use numerical simulation to deepen our understanding of intrinsic rotation and test theoretically motivated physics pictures. A new UCSD-funded postdoctoral researcher will be based at PPPL and work with Dr. Weixing Wang and Professor Patrick Diamond on this task using the Gyrokinetic Tokamak Simulation (GTS) code. GTS is a full geometry, delta-f particle-in-cell code [Wang:2006], Wang:2010] based on a generalized gyrokinetic simulation model and the use of realistic magnetic configurations. The GTS code targets at simulating plasma turbulence and transport in practical fusion experiments. It is highly robust at treating globally consistent, shaped cross-section tokamaks by directly importing plasma profiles of temperature, density and rotation from experimental databases, along with the related numerical MHD equilibria reconstructed by MHD codes. The GTS includes fully-kinetic electron physics so as to simulate electron turbulence and ion turbulence with non-adiabatic electron physics. During the period of the SciDAC GPS-TTBP project, extensive validation studies were carried out by applying the GTS code to NSTX and DIII-D plasmas for heat and momentum transport in the electrostatic regime including electron-gyroradius-scale ETG turbulence to TEM turbulence to ITG turbulence.

Within the research scope of CMTFO, efforts using GTS global gyrokinetic simulations in the next 2-3 years will be carried out in close coupling with experimental and theoretical studies to address some highlighted issues of toroidal momentum transport and intrinsic rotation generation in fusion plasmas. High priority issues are specified as follows.

Core plasma intrinsic rotation reversals Toroidal flow reversals in which rotation switches between the co- and counter-current directions have been robustly observed in Alcator C-Mod Ohmic L-mode plasmas following modest electron density or toroidal magnetic field ramps [Rice:2011]. The rotation reversal phenomenon, which is also observed in other devices, provides an outstanding opportunity to study and understand the physics of intrinsic rotation and plasma confinement. The experimental results in C-Mod show clear changes in density fluctuations during the rotation reversal, suggesting changes in turbulence behavior and possible connections between the two. Nonlinear, global GTS simulations will be applied to these C-Mod plasmas to study distinct roles of various micro-instabilities in rotation generation. Specifically, we will calculate the radial profile of intrinsic torque density associated with turbulent residual stress in various turbulence regimes, characterize the distinct natures of ITG and TEM turbulence driven intrinsic torque, and ultimately, identify and elucidate underlying dynamics for the intrinsic rotation reversals in C-Mod plasma conditions. Further, the characteristic dependence of density threshold, i.e., the plasma density at the reversal, on plasma parameters such as plasma current and magnetic field etc. will be studied using the systematic scan of computational experiments to understand the scaling of the reversal density observed in experiments. At the same time, plasma transport in multiple channels including heat driven by the ITG and CTEM turbulence will also be investigated under C-Mod plasma conditions with focus on gaining insight on what establishes the observed strong correlation between the density thresholds for the rotation reversal and global energy confinement changes from the linear to the saturated regime in C-Mod Ohmic L-mode discharges. As discussed below, we will also link these numerical studies with experiments on C-Mod which will be supported by a UCSD funded experimental postdoc.

In addition to focusing on flow reversal physics, the effects of q(r) profile structure are a very important topic which may have many connections to and implications for intrinsic rotation phenomena observed in experiments. The enhancement of residual stress generation due to the enhanced $k_{//}$ symmetry breaking with increased dq/dr as the current decreases is shown [Wang:2011] to result in the current scaling of intrinsic rotation observed in multiple devices [Rice:2007]. There is indication of a rotation reversal at higher current, possibly related to a q-profile structure induced change in the residual stress. One highlighted issue which is of great interest to ITB physics is the residual stress and intrinsic rotation generation in reversed shear and flat-q region. GTS will contribute to addressing these issues with attention to global effects due to e.g. turbulence spreading.

The effects of impurities and energetic particles on the toroidal momentum transport and flow generation should draw more attention. In fact, impurities and energetic particles could be important players in overall plasma rotation generation. So far, most of toroidal flow measurements in experiments have been made for impurities. Recently, bulk ion (deuteron) toroidal rotation has been directly measured in DIII-D using the D-alpha emission spectrum, which shows strong discrepancy between the deuteron and carbon intrinsic rotation in the core region with strong plasma pressure gradient [6]. Besides the direct impact of impurities via their effect on turbulence fluctuations, important issues to be understood include the momentum exchange and partition between the bulk ions and impurities. The momentum exchange can be made through Coulomb collisions (neoclassical) and turbulence wave-particle interactions. These issues are directly relevant to overall toroidal momentum conservation. We propose to address these issues using GTS gyrokinetic simulations including self-consistent impurity dynamics. Specifically, we will explore whether turbulence can produce different torque for main ions and impurities, which may contribute to the large difference in intrinsic rotation between deuterons and carbons observed in DIII-D experiments. We will explore the effect of turbulence induced momentum exchange between bulk ions and impurities. We will assess how these effects impact overall toroidal momentum balance under experimental conditions.

Electromagnetic effects on toroidal momentum transport and rotation generation remain relatively unexplored. In the later phase of CMTFO funding period, GTS with upgraded capabilities will be applied to electromagnetic turbulence regime. Major tasks include the identification of mechanisms for residual stress generation which are specific to electromagnetic fluctuations [McDevitt:2009], and the quantification of the field momentum and its impact on overall momentum balance and plasma flow generation. Profile effects on residual stress will be a major focus.

Flow shear, on the one hand, can suppress turbulence through the associated ExB shear; on the other hand, the free energy associated with it may drive a negative compressibility mode [Mattor:1988]. The flow shear driven turbulence has been observed in linear machines. However, little attention has been paid to it in tokamak devices because it was presumably considered to be hardly driven unstable due to the magnetic shear effect. Our recent nonlinear gyrokinetic simulations using GTS indicate that strong flow shear may drive the negative compressibility mode unstable in tokamak geometry in some experimentally relevant parameter regimes and associated turbulence can produce significant momentum and energy transport. As a new player for toroidal plasma transport, the flow shear turbulence in tokamaks is largely unexplored. The generic nature of flow shear turbulence will be investigated in detail using realistic plasma parameters of tokamak experiments. Special attention will be paid to flow optimization for minimizing plasma transport in flat q and reversed shear regimes.

A CMTFO funded postdoc from UCSD, based at PPPL, will play an essential role in performing the proposed numerical research in collaboration with Dr. John Rice (MIT) and the UCSD funded experimental postdoc based at Columbia University and MIT.

Experimental Studies of Intrinsic Rotation on the HBT-EP and ALCATOR C-MOD Tokamaks:

A Center funded UCSD postdoc, based at Columbia University, will also play a key role in experimental studies of intrinsic rotation in tokamak devices on both the small HBT-EP tokamak located at Columbia University and on ALCATOR C-Mod and on. Probe measurements will be continued in HBT-EP, a relatively low magnetic field (~0.3 T), low operating density (up to ~10^{19} m^{-3}) tokamak at Columbia University. For this purpose, a multi-tip probe has been constructed to measure the radial-toroidal component, $\langle \tilde{v}_r \tilde{v}_{//} \rangle$ of the bulk ion fluid contribution to the stress tensor. The relatively cold (~10-100 eV) and tenuous plasmas commonly generated in HBT-EP allow the probe to be used up to ~5 cm inside the last closed flux surface, or $\rho \approx 0.67$. These measurements will be combined with measurements of the time-averaged toroidal rotation (which is known to exist in this Ohmically heated device) in a turbulent momentum balance to determine if the turbulence is associated with the observed toroidal rotation. In addition, by making use of an existing biasable electrode which can be inserted into the plasma on HBT-EP, the evolution of momentum profiles will be studied with a direct application of torque. This can be done in two ways: 1) by enforcing a radial electric field via a high voltage bias probe leading to a finite radial current and thus a $\mathbf{J}\times\mathbf{B}$ torque, 2) using resonant magnetic perturbations which can significantly slow down (speed up) and even lock the dominant fluctuation modes leading to a torque on the bulk ions. Both methods will be tested for the experiments on HBT-EP at Columbia University. These studies will allow direct measurement of the turbulent stress and test whether it plays a role in the observed rotation in this small device.

The UCSD supported postdoc will also perform phase contrast imaging (PCI) studies in combination with X-ray Doppler spectroscopy in Alcator C-Mod at MIT, in collaboration with Dr. John Rice at MIT. Recent experiments using this approach revealed a significant change in the density fluctuations of the core region when core rotation inversion occurs. During the co-current rotating phase of these plasmas two counter-propagating features appear in the wavenumber and frequency spectra of PCI signals, which are not present when the rotation is directed counter-current. During the reversal process the fluctuation phase velocities are well correlated to the toroidal rotation velocity or the inferred radial electric field E_r, speeding up to as much as v_{pol} = 3.8 km/s, at which point the fast turbulence features distinctly stand out from the low frequency spectrum. These spectral lobes speed up simultaneously in both propagation directions, suggesting that they are collected from two spatial locations along the PCI chord, from the top and bottom of a flux surface where they suffer the same Doppler shift caused by the local E_r fields which is thought to be uniform poloidally on a flux surfaces inside $r/a \approx 0.85$. These preliminary observations suggest that the turbulence in the region plays a role in the rotation reversal process. Since, however, the fluctuation induced stresses cannot directly be measured in this system due to diagnostic limitations, it is important to learn more about the charactersitics of this turbulence in order to determine its species (ITG, TEM, ETG, etc), which is a crucial piece of information, since a change in sign of the dominant turbulence type's propagation direction can cause the residual stress and consequently the intrinsic torque to change sign.

These experimental studies will be carefully coordinated and compared against the GTS code simulations that will be performed at PPPL We expect this will include coordinated simulations and experiments, development of a synthetic PCI diagnostic for the GTS results, and subsequent comparison with experiment. the key hyothesis that will be tested is that the change in plasma-frame fluctuation propagation is a signature of a transition from ITG to TEM dominated core turbulence, and that this transition is accompanied by a spontaneous toroidal rotation flow reversal. We expect that the combined work will provide key insight into the origin of instrinsic rotation, and will permit physics based models of rotation in new experiments such as ITER to be constructed.

L-H Transition Studies (CMTFO Groups include: Colorado, UCSD, WCI/NFRI, PPPL):

Studies of the physics of the L-H transition [Wagner:1982] will continue, taking into account the rapid developments that are occurring in CMTFO work as well as work by other groups. CTMFO research in this topical area will focus on four aspects of the problem: i) pre-transition turbulence and secondary flows, ii) intermediate (I) phase and transition dynamics, iii) post-transition evolution, and iv) back transition (H→L) evolution. We also discuss certain special issues related to i) – iv) above. We plan on using a mixture of basic laboratory plasma (CSDX), tokamak device (DIII-D, C-Mod, NSTX, EAST, and HL-2A), theory, modeling, and numerical simulation available either via CMTFO funded work or via collaboration (XGC1, GTS) to make progress on these topics and will involve workers from UCSD, Colorado, NFRI/WCI, PPPL and our extensive experimental collaborations on devices located in the US and Asia.

Pre-Transition Turbulence and Secondary Flows: A quantitative understanding of L→H transition dynamics demands a quantitative understanding of pre-transition (L-mode) edge turbulence and secondary flows. L-mode edge turbulence studies must address kinetic effects [Chang:2004], electromagnetic coupling [Scott:2010], shaping and separatrix geometry [Xu:2003], neoclassical flow and electric field effects [Chang:2004] and SOL flow influence. While various elements of the list above have been studied in isolation, no comprehensive simulation has yet been realized. We note that given the complexity, it is unlikely that any one instability or mode explains all cases! We will proceed by performing experiments on DIII-D, EAST, and HL-2A to study the evolution of zonal flows, GAMs, and edge turbulence and the coupling between these spatiotemporal scales as the L-H threshold is approached from the L-mode regime. These facilities have excellent diagnostics including Langmuir probe arrays [Zhao:2006] (density and potential fluctuations – including zonal modes, particle fluxes), Doppler reflectometry [Conway:2011, Schmitz:2011] (spatio-temporal flow structure, density fluctuations) and Beam Emission Spectroscopy (BES) [McKee:2009] (for fluctuations and flow imaging). Particular emphasis will be given to understanding the spatial scales and profiles of secondary, non-linearly driven flow structures – i.e. GAMs and Zonal flows. Recent HL-2A results, discussed earlier in this report, and DIII-D results have indicated a transition from GAM-dominated to zonal flow-dominated edge flow states with increasing heating power, suggestive of a evolving two predator (GAM, ZF) one prey (turbulence) dynamic system [Miki:2010]. This issue is of fundamental importance as a validation benchmark, a challenge to our understanding of non-linear coupling drive of crucial secondary modes, and as a building block for further study of the transition.

Intermediate Phase and L→H Transition Dynamics: An emerging body of experimental results from DIII-D [Schmitz:2011], NSTX[Zweben:2010], TJ-II[Estrada:2010], EAST[Xu:2011], and ASDEX-UG [Conway:2008] all suggest that for $P \leq P\_thresh$, the edge plasma enters an 'intermediate phase', characterized by strong, cyclic oscillations of the zonal flow and turbulence intensity. During this I-phase, the cycle-averaged zonal flow amplitude slowly increases, the spatial extent of the region of strong zonal shear grows inward from the separatrix [Schmitz:2011] and the mean ExB shear flow steadily increases [Conway:2011, Schmitz:2011]. The actual transition, as measured by the drop in D-alpha emission, appears to occur when transfer of fluctuation energy to the zonal flow is sufficiently large so as to allow the mean shear (driven by profile evolution) to grow and then 'lock-in' the state of suppressed transport [Tynan:2011]. At that point, thee turbulence and secondary mode amplitudes drop precipitously and the H-mode state begins to develop. Note that this I-phase evolution is consistent with a two predator (zonal flows and mean shear flows) – one prey (turbulence) model proposed in 2003 [Kim:2003]. In this picture, the interplay and competition between zonal and mean flow shears is crucial to the transition dynamics. There are many outstanding questions which bear on the scenario described above. First, what is the condition for entry to the I-phase? Any putative answer must be consistent with the existence of secondary zonal modes in L-phase. The spatio-temporal scales of the zonal flow layer are of interest (as the 'initializer' of the transition), as is the rate of nonlinear transfer of energy from turbulence to zonal modes. The latter is directly amenable to validation by comparison to the results of bispectral analysis, and may indeed be the transition trigger mechanism. Mean flow evolution must also be addressed. The question of poloidal flow possible contribution to mean ExB flow shear is especially critical, since poloidal spin-up has been associated with the transition from I-phase to H-mode in Alcator C-MOD [Hubbard:2011] and JT60-U [Kamiya:2010]. The goal of this sequence of challenging transition studies is to identify the transition 'trigger', i.e. the physical event which initializes the drop in the turbulent particle flux, the rise in the mean profile gradients and mean ExB shear, and the drop in fluctuation intensity, which, taken together, constitute the L→H transition.

The strategy for pinpointing the trigger will involve a 'differential diagnosis' implemented in numerical experiments by parameter scans and by selective switching off of various physical effects with exploration of the consequences. We caution the reader that there need not even be a unique L→H transition trigger, and that several routes thru the transition point may be possible, depending on parameter regime. Our research will elucidate this question. There are several additional related issues which merit spatial discussion here. First, the space-time evolution of the I-phase layer width is of interest as the 'seed' for pedestal formation. Excellent Doppler reflectometry data on layer structure exists for use in validation studies [Schmitz:2011]. Second, the influence of avalanche and heat micro-pulse statistics on the transition is of great interest, since recent EAST studies [Xu:2011] have shown that sawtooth heat pulses directly modulate the edge zonal flows during the I-phase. Indeed, the L→H transition is probably best described in a statistical framework [Itoh:2004]. We speculate then, that for $P \sim P_{thresh}$, a local heat flux surge as induced by a sufficiently large avalanche, can induce a transition in an otherwise stationary state. Third, consideration of the all-important micro-macro connection suggests that if zonal flow shears are indeed "the trigger", then the zonal flow damping should contribute directly to the power threshold. To test this hypothesis, we will explore high and low density regimes, in order to investigate both branches of the P_thresh(n) curve. We speculate that collisional zonal flow damping [Hinton:1999] control the high-n branch, while GAM Landau damping [Hallatschek:2001] may control the low-n branch. In a related vein, we will also study the effects of neutrals on zonal shears via charge exchange damping. We conjecture that neutral density is a "hidden variable" in the L→H transition, and that the beneficial effect of Lithium on the transition threshold [Xu:2011b] is due to a reduction of recycling and thus of neutral density and its associated charge exchange damping. Fourth, the role of mean poloidal rotation is of interest in the evolution from I-phase to H-phase. A key question here pertains to the long standing issue of whether a poloidal 'spin-up' triggers the L→H transition. A related question is connected to the effect of SOL flows and grad B asymmetry on the transition. It is well known that favorable and unfavorable grad B drift directions result in different SOL flow directions [LaBombard:2004]. We conjecture that these in turn tend to enhance or to reduce, respectively, the edge (i.e. separatrix) ExB shear and so either reduce or raise the power threshold. Indeed, the grad-B drift asymmetry of the threshold power is one of the great unresolved problems in L→H transition dynamics. The question of grad B drift direction also enters the distinction between the Alcator C-Mod I-Mode (Improved Mode) and the H-mode. The I-mode is characterized by an improvement in thermal confinement, - but not particle confinement – when the plasma is operated with P < P_thresh for unfavorable grad B direction. Any fundamental understanding of the physics of the L→H transition must encompass *both* the I-mode *and* the H-mode, as well as the transition from one to the other. The reason for preferential improvement of the thermal, but not particle, transport channel in I-mode remains elusive, and will be examined as part of our research program.

Post-Transition Dynamics: While pedestal physics, especially Type I ELM phenomena, is conceptually distinct from transition physics, certain aspects of the transition dynamics do influence the early stages of pedestal formation, and so post-transition dynamics merit attention here. Of paramount importance is the role of inward convection – a density pinch – in pedestal formation. This not only can build the steep H-mode density profile, but also yields another strong turbulence suppression feedback loop via thermoelectric (i.e. ∇T-driven pinch) increase of grand n which in turn steepens electric field shear and so enhances suppression. A pinch seems necessary in order to confront the phenomenology, since density pedestal widths are observed to be related to, but exceed, the fueling depth set by neutral penetration [Groebner:2009]. A second key post-transition phenomenon is the history of inward expansion of the transport barrier, as the pedestal develops. DIII-D results [Groebner:2010] suggest a 'two stage' process, namely an initial 'jump' at the transition, followed by an approximately linear (in time) inward barrier expansion. Simple S-curve models [Lebedev:1997] have predicted the basic form and scalings of the temporal evolution of the pedestal formation front. We suggest that the scale of the initial 'jump' is set by the width of the zonal flow in I-phase, which then nucleates the inward pedestal growth. We will study pedestal formation fronts using the capabilities of XGC1 to treat fueling in a flux driven state. A third question concerns post-transition bursty and ELM phenomena not explicitly related to ideal stability limits (i.e. as for the familiar peeling ballooning modes). These ELMs are likely a continuation of the cyclic, I-phase behavior *into* the H-mode. Certain classes of Type III ELMs and the recently discovered 'Mossy ELMs' on EAST [Wang:2011] fall into this category. We also note that reduced simple models [Diamond:1994] predict that such cyclic bursts will occur after the transition, during the initial build-up of the H-mode. Thus, we will study these phenomena, with the aim of understanding bursty and cyclic phenomena observed during the early stages of pedestal formation.

Back Transition and Hysteresis: The L→H transition has received far more attention than the H→L transition. This is at least partly due to the difficulty of separating the back transition physics from the phenomenology of the ELM crash. However, the hysteresis of the H-mode is a crucial issue for ITER, and so a serious simulation study of hysteresis and the H→L transition is of great importance, and long overdue. We will study H→L transitions by slow power ramp-down simulations initialized by data obtained from slightly supercritical forward transition studies. The aim of this work is to quantify the strength of hysteresis, and trace the evolution of density, temperature and flow profiles at the back transition. Particular questions of interest include: does any hysteresis exist, at all? How does it compare to the predictions of simple S-curve bistable transition models [Hinton:1991, Malkov:2008]? How do profiles evolve when passing toward and through the back transition? Does the pedestal simply collapse or does the L-mode turbulence 'spread' into the pedestal? Does the system pass thru I-phase or go directly to L-mode from H-mode [Malkov:2009]. We have data from Doppler back scattering (DBS) on DIII-D [Schmitz:2011] that the system does indeed re-visit the I-phase briefly during the back transition into L-mode.

QSH formation in the RFP (CMTFO Group: UW Madison):

Turbulence suppression in the quasi-single helicity state of the RFP is tied directly to magnetic and flow shear profiles. For a dominant helicity corresponding to the resonant tearing mode with lowest *n* number this can be related to the Ohmic drive and plasma current through the energy budget developed to describe ion heating from the tearing mode fluctuation spectrum [Tangri:2008]. A relationship will be derived showing the scaling of turbulence suppression with the Ohmic current and this will be compared with the threshold results from RFX. Analytical results have been obtained with the use of closure theory. The closure equations yield a high order differential equation for the turbulence envelope in the presence of magnetic and flow shears. Approximate analytical solutions from asymptotic analysis will be compared with numerical solutions of the closure equations. Envelope structure and its variation with shears of magnetic field and flow will be checked. A reduced MHD model will also be employed to check the closure results. Noting that rotation and magnetic shear have recently been examined experimentally in JET in the context of profile stiffness [Mantica:2011], further work will be done to understand initial results showing that magnetic shear and flow shear can compete in some cases.

While gyrokinetic codes have been used to model the RFP, equilibrium flow has generally not been included. MST-like flow will be included in gyrokinetic simulation of microturbulence for the zero beta and finite beta cases that have been studied without flow. For zero beta, ITG turbulence is unstable in MST. Momentum transport will be calculated. It will be determined if there is a momentum pinch and its properties will be tracked across the minor radius as the equilibrium field changes from toroidal (core) to poloidal (edge). The rate of momentum transport from an imposed edge source will be determined and compared with flow peaking between sawtooth crashes in MST. At MST beta values, ITG turbulence is stabilized and microtearing fluctuations dominate the fluctuation spectrum. Equilibrium flow will be included for this regime and its effect will be determined, both on the instability and on momentum transport. The quasilinear parallel momentum flux will be computed from the correlation of the linear fluctuations of the $v_{||}$ moment of the gyrokinetic distribution and the potential. Recent work has yielded the first nonlinear gyrokinetic calculations of microtearing turbulence at high beta for the spherical tokamak [Guttenfelder:2011]. Nonlinear runs for the RFP will also be attempted. (High beta simulation with gyrokinetics has not generally been possible for the conventional tokamak, and it is not known if it will be possible for the RFP.) If nonlinear runs are possible it will be determined how the quasilinear flux compares to the true flux. In particular the types of damped modes excited in saturation will be characterized and their effect on momentum transport will be assessed.

Diagnostic development is underway on MST to measure microscale turbulent fluctuations using both the heavy ion beam probe and Thomson scattering. Gyrokinetic simulation will help guide the development, implementation, and interpretation of these measurements. As these diagnostics become routinely available, comparisons between simulation and experiment will be used to validate the models and confirm their predictions.

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Macroscopic Shaping Effects on Stress & Rotation (CMTFO Groups include: UCSD, PPPL, WCI/NFRI):

As was discussed in the Progress section, in the past year CMTFO workers have developed a model which appears to show how macroscopic plasma shaping and symmetry-breaking effects such as an X-point can impact the flux-surface averaged turbulent stress, and thus provide a mechanism to create a non-diffusive turbulent stress (a.k.a. residual stress) which can affect the radial profiles of poloidal and (with an extension of the model) toroidal rotation. Using a combination of numerical experiment, as well as experiment on real confinement devices, we would like to test this model to determine if in fact it provides a plausible explanation for key observations such as the dependence of the L-H power threshold on the grad-BxB drift direction with respect to X-point location. With an extension the model, we could also test how shaping might influence intrinsic toroidal rotation. Numerical experiments provide direct access to the key physics quantities needed to test the model. Actual tokamak experiments, which would provide measurements of pressure gradient, ExB profiles, and turbulent structure orientation at the midplane and near the X-point would provide an ability to also test the model in real world application.

Tachocline, Dynamo and Solar Physics:

Overshooting Convection, Meridional Flows and Magnetic Fields (CMTFO Groups include: UCSC, UCSD/WCI):

Any global model of the solar interior and the solar dynamo must take into account the processes acting within the tachocline, the thin shear layer at the base of the convection zone. Within this layer, transport of angular momentum, entropy and magnetic flux by convective overshoot caused by downward plasma convection from the overlying convection zone, as well as the meridional flows which carry plasma between the equatorial and polar regions profoundly influences the Sun's internal rotation profile and magnetic activity cycle. Incorporating all of these individual effects faithfully into a three-dimensional global solar model has so far proved impossible. As a result, no such model (e.g. the ASH simulations of the Toomre group) has ever reproduced the full solar internal rotation profile (including the tachocline and below) inferred from helioseismology. Part of the problem is our incomplete knowledge of the parameter regimes in which each of the essential ingredients operates efficiently, and the difficulty of achieving extreme parameter values in global simulations.

The overarching problem is really a question of the interaction of various transport mechanisms – turbulent pumping, Spiegel & Zahn burrowing, Taylor-Proudman enforcement of transport under the influence of rotation, Ferraro's Law dictating of transport under the influence of magnetic fields – and whether anything like a Gough & MacIntyre balance can be achieved. In our initial work in the Center we began to incorporate each of the necessary elements into the local Cartesian simulations designed to mimic the important properties of the tachocline, using the HPS code (see e.g. Brummell, Clune & Toomre, 2002, ApJ, 570, 825). As was discussed earlier, the results of the quasi-two dimensional simulation confirm the efficiency of overshooting convection in transporting and storing mean magnetic flux. The mean flux is pumped out of the convective layer on the timescale of the turbulent convection, and achieves a statistically-steady equilibrium on the timescale of magnetic diffusion across the computational domain. The magnetic field suppresses shear within the stable layer, enforcing solid body rotation below the overshoot layer. Mean meridional flows modify the distribution of the mean field, but do not contribute to the field's confinement.

In the polar simulation, on the other hand, where the magnetic field is not all (initially) horizontal, meridional flows are thought to be essential to the confinement of the field. Very preliminary results seem to confirm this hypothesis, but further study is required. Clearly, the Cartesian simulations, although nicely simple, need to be supplemented by more realistic geometries and conditions. In order to do this, in the next three year period we will modify the PARODY code (summarized earlier in this report) to construct a global, hydrodynamic model of this problem related to the solar interior. The model is designed to reproduce the timescale ordering appropriate to the tachocline, but not the detailed dynamics of the convection zone. The aim of these global simulations is to allow the differential rotation to be generated self-consistently by the action of Boussinesq convection, and avoid the issue of artificially representing the geometry. We are in the process of creating hydrodynamic simulations that produce a representative differential rotation. After that, we will repeat the same sort of experiments as are currently being performed in the Cartesian case, to verify the results found there.

In the coming three year period, we will also use both approaches in the study of the tachocline. We anticipate this occuring in two ways. Firstly, we will test the sensitivity of our Cartesian results to the particular choice of parameters and physical conditions. It is clear that the correct ordering of timescales is essential, but it is not yet obvious what the range of dynamics is as the separation of these scales is increased. Furthermore, we need to examine the how the phasing between the magnetic field and meridional flow geometries affects the results to ascertain the role of the meridional flows. Before we can switch to the PARODY incompressible model, we also need to test the sensitivity to the degree of compressibility, and to other parameters, such as the initial field strength and degree of forcing. Secondly, once we have a greater understanding of the regime in which our results hold, we hope to test their robustness using the global incompressible, spherical pseudo-spectral PARODY model. Currently, we are only running hydrodynamic simulations with PARODY in order to find the regime where solar-like differential rotation is spontaneously generated from spherical shell convection. Once this is established, we can insert an interior fossil (non-dynamo) field and see if the balances obtained in the Cartesian simulations can be achieved. All these problems are very computationally intensive.

Feasibility Studies for Studying the Parker Instability (CMTFO Groups include: PCX/UW Madison, UCSC): The numerical work discussed above is focused on the effect of convection on the tachocline shear layer. However, the tachocline shear flow also is thought to contribute to magnetic field formation via the dynamo effect. A crucial aspect of this problem is the formation of magnetically buoyant regions at the interface between the tachocline and convection zones. A CMTFO-supported postdoc fellow at UW Madison will explore possible experimental scenarios to study convection in a rotating, stratified plasma and to study how the resulting convection can in turn contribute to magnetic field generation (the dynamo). The experiment will substitute centrifugal acceleration for gravity: the geometry will be Couette but without the central column and the JxB forces in the are required to simply rotate the unmagnetized plasma resulting in an effective gravity that is directed radially outward. Density stratification should then occur, since in equilibrium a pressure gradient will be required to balance the centripetal acceleration; the density gradient will therefore point outward in this plasma centrifuge. The geometry is analogous to the convection zone in the Sun where the density decreases with radius and but with gravity pointing outward.

Several different techniques will be investigated in PCX for driving convection: thermal convection, compositional buoyancy, and magnetic buoyancy (the Parker instability). Thermal convection will be possible if a sufficient temperature gradient can be maintained from the edge to the center. The edge heating will come from resistive heating driven by the electrode driven currents at the edge and also from electron cyclotron heating which has a 2.45 GHz resonance near the magnetized plasma boundary. If the temperature gradient can be made large enough $\left(\frac{d\,ln T}{dr} > 0.4 \frac{d\,ln n}{dr} \right)$ the plasma will then be unstable to convection. This criteria is identical to the criteria that defines the solar tachocline, the point where the energy transport switches from radiative to convective. A second approach to driving convection will be to use compositional buoyancy (the process thought to be important in the earth's core). Experimentally, this might be accomplished by first forming a heavy ion plasma such as argon and then puffing small amounts of He into the plasma. The final technique for driving convection is through magnetic buoyancy (the Parker instability). The "tachocline" of the experiment is the outer boundary where the poloidal field of the permanent magnets can mimic the turbulent poloidal fields at the base of the solar convection zone. These poloidal fields can be stretched into the toroidal direction and greatly amplified by the strong sheared toroidal plasma rotation. As the plasma dynamically expands due to the increased magnetic pressure, it becomes less dense than the surrounding plasma and would thus "rise" towards the center of the device. As a result, a low density magnetic bubble will exchange position relative to dense plasma. This transport will occur across the background toroidal flow, and thus result in turbulent momentum transport.

Accretion Disk Physics

Work in this topic will focus on experimental studies on the PCX and HDX devices at UW Madison and PPPL respectively. We briefly describe goals for these two experiments, focusing particular attention to their contributions to the study of the two potential instabilities that can lead to turbulence in disks. We would like to complement this work with suitable computational approaches; current funding does not permit this, however we would like to propose to DOE that supplemental funding be made available to permit such work to be added to the Center (we have identified several groups that, if they were involved, would permit this to occur).

Tests of Hall Effects on MRI (CMTFO Groups include: PCX/UW-Madison):

The demonstration of plasma flow in the unmagnetized core region of the PCX device, discussed earlier in this report, allows us to consider possible future flow-driven MHD experiments to model astrophysical plasmas. While not a complete demonstration of Plasma Couette flow suitable to study the MRI, we are now poised to implement the full Couette geometry with the much simplified electrodes developed over the past year. These are now being installed, as is the center post for driving the flow at the inside of the chamber. The recognition that plasma conditions are optimized at low density (where viscosity is largest) and a low neutral pressure (where neutral drag is minimized) is a major advance. These conditions are also conditions under which plasma effects (beyond MHD) thought to be important for proto-planetary disks will play out. This has led us, through collaboration, to estimate the role that Hall effects play on the MRI onset. Nonlinear MHD NIMROD simulations indicate that the conditions for MRI onset should be accessible in PCX; furthermore they indicate that instability onset has a pronounced asymmetry with respect to the direction of external magnetic field and fluid rotation vector orientation when Hall terms are included in the MHD model. This provides a clear test of theory.

Sub-critical hydrodynamic instability in non-Keplerian Flows (CMTFO Groups include: HDX/PPPL):

Here, we propose to experimentally investigate flow stability as a function of Reynolds number, rotation profile, and relevant boundary conditions in a well-controlled and diagnosed laboratory experiment. Questions to be answered via experiment in the coming funding period include:

- Does the nonlinear instability (or the so-called subcritical instability) exist, and if so, how do the critical Reynolds number and critical Rossby number scale with perturbation amplitude?
- If a nonlinear instability does not exist, can the lifetime of transient turbulent states be described in terms of a statistical distribution?
- Does the system's response to perturbations depend strongly on the azimuthal structure of the imposed perturbation (m = 0; 1; 2)?
- Do quasi-Keplerian systems exhibit hysterisis? If so, does the hysterisis have a lifetime or does it represent a stable bifurcation?

In the first year, the overarching objective is to search for evidence of the existence of a sub-critical instability in non-Keplerian flows and investigate measurements of Reynolds stress in HTX. Using the two-component LDV system, we will quantify the Reynolds stress in various flow regimes in HTX, specifically looking for signs of enhanced angular momentum in the quasi-Keplerian regime particularly important to accretion disks. The active perturbation system will be used to look for a subcritical transition to turbulence across a range of Reynolds numbers and amplitudes of the driving perturbation. Sloped boundaries will be manufactured for subsequent studies on Rossby waves and zonal flow interactions. If resources can be secured for upgrades to the diagnostic systems on HTX, we will begin development of an inner-cylinder mounted torque sensor and an optical particle imaging velocimetry (PIV) system using a laser sheet and camera in collaboration with Colorado and UCSD.

These sloped boundaries then enable the study of an important problem which links geophysical fluid dynamics to confined plasmas – a topic we describe below.

Cross-cutting Research Themes (CMTFO Groups Include: (PPPL, UCSD, UCSD/WCI-NFRI, Colorado)

In addition to these three system-oriented problems, we also have identified two cross-cutting themes which will also form foci for the Center. These are:

Tests of PV Homogenization as a Universal Flow Organization Principle (UCSD, WCI/NFRI, PPPL): Theory and computation work in the last 1 ½ years of the Center's existence have suggested that PV homogenization may be a powerful and universal flow organization principle affecting magnetized plasmas, rotating MHD fluids such as stars, and Geophysical Fluid Dynamics (GFD) flows found in plenary atmosphere. In order to test this important theoretical idea, we are planning dual experiments in the HDX and CSDX devices to test this hypothesis.

Development of Non-Invasive Flow Organization Diagnosis and Analysis Approaches (Colorado, UCSD)*:* Key tests of turbulent-driven flow organization usually requires access to complex mult-field correlations such as turbulent stresses and then relating these microscopic quantities to macroscopic system behavior. Small scale experiments can provide direct access to these quantities, but the approaches used in these facilities can not in general be used in large fusion experiments. We will therefore focus attention on comparing non-invasive imaging diagnostics – which can be used in the core of fusion plasmas – against direct but invasive probe diagnostics which do provide direct access to the relevant turbulent microphysics. The hope is that by making such comparisons we can identify markers or signatures of the microphysics in imaging datasets, and then use those diagnostics in large scale fusion experiments to confirm the physics origin of flow organization in these systems.

We describe our plans for research into these two themes in the following sections.

PV Homogenization as a Universal Principle of Flow Organization: The motivation for studying the Rossby wave-Zonal Flow and Drift Wave-Zonal Flow systems stems from the analysis of Hasegawa and Mima [Hasegawa:1977] and Hasegawa et al. [Hasegawa:1979] which noted an identity relation between the equations for nonlinear drift wave evolution and geostrophic Rossby waves in the shallow water limit. It was this realization which led to the notion that the complex dynamics of the tokamak pedestal may be approached from the well trod grounds of geophysical research, and perhaps even explored experimentally. The nonlinear evolution of these equations shows that when the system is stirred at small scale (i.e. turbulence is stimulated), in the presence of inhomogeneity, leads to driving motion at much larger scales [Horton:1994]. This is the essential element of the theory which leads to generation of zonal flows that arise out of and provide a saturation mechanism for drift wave turbulence. Furthermore, as discussed in the Progress section of this report, and reported in the literature [Diamond:2008], the potential vorticity, which is a generalized form of the vorticity specific to the Rossby wave and Drift wave systems, can be cast as an organizing mechanism that links these disparate systems. In this theory, flows in these systems form into a "staircase" of sheared flows. The step is associated with a zonal flow, and the regions located between the steps are then regions of constant, or uniform, potential vorticity. The PV then takes a jump, or step, at the zonal flow shear layer. Mesoscale avalanche and/or streamer transport events then mediate transport from one zonal flow to the next.

CMTFO researchers working on laboratory devices will compare the Rossby-wave/Zonal Flow and Drift-wave/Zonal flow systems using the HTX and CSDX devices. Specialized diagnostics (multipoint probe arrays in CSDX; laser sheet beam with particle velocimetry in HDX) will be implemented to measure the potential vorticity in these devices, and we will then try to test this picture directly via experiment.

Published work from CDSX has shown the generation of zonal flows from drift-interchange turbulence [Holland:2006, Tynan, 2006: Yan:2008, Yan:2009a, Yan:2009b, Xu:2010, Xu:2011, Manz: 2011]. This work forms the basis for our planned experiments on CSDX. In order to have better separation between the turbulence scales and the zonal flow scales, we have recently fabricated a large plasma source and have installed it on the device. In addition, with separate funding we have upgraded the magnetic field to now operate up to 2.5 kG. These changes, along with switching from argon discharges to neo or helium discharges will permit more than an order of magnitude increase in the dimensionless system size, and thus should permit measurements of PV profiles across the plasma and across zonally driven sheared flows to be made. These measurements will then test the hypothesis.

In HTX, Rossby waves are expected to be excited when the endcaps are modified to include sloped or curved upper or lower surfaces as was observed in earlier experiments [Busse, 1994]. When a source of stirring is applied to drive small scale turbulence, say from a set of jets mounted on the inner cylinder, we anticipate the formation of zonal flows at much larger scale. The advantage of this experiment is that we will provide direct non-perturbative measurements of the turbulent momentum flux via measuring the Reynolds stress with a two-component LDV diagnostic as discussed earlier in this report.

- What is the rate of angular momentum transport measured by the two-component LDV system due to the action of Rossby waves stimulated by perturbations in solid body rotation with sloped endcaps? What structure do the Rossby waves and zonal flows take? How does the zonal flow amplitude scale with the amplitude of the driving perturbation?

- Can Rossby waves and zonal flows be excited is sheared systems? How does the amplitude of these structures scale with some measure of the global shear?
- How do the measured experimental results compare with the numerical and theoretical predictions?
- What new physical understanding can be achieved on the interactions between global shear and local turbulence? What di_erences and similarities can be identified with interactions between turbulent transport and zonal flow?
- What similarities exist between the Rossby waves produced in the hydrodynamic system and the drift waves observed in tokamak pedestals?

Studies of Rossby waves will begin in HTX once a set of modified interior surfaces is manufactured and will complement zonal flow studies on CSDX which has a longer history of such work.

In the second year, with the installation of sloped boundaries to the HTX experiment we will begin studies of the interaction of Rossby waves and zonal flows. These structures will be characterized in terms of spatial distribution, intensity, and temporal behavior as a function of the amplitude of the driving perturbation, azimuthal structure of the perturbation, and Reynolds number. The transition to weakly sheared cases will be explored. Multiple sets of fluid facing surfaces with different shapes will be manufactured and implemented to explore the system response as the driving parameter is changed. Measurements of Rossby wave structures will be compared with theoretical predictions of potential vorticity conservation, providing a test of fundamental momentum theorems derived for plasmas by P.H. Diamond recently.

With knowledge gained from hydrodynamic studies in HTX, in the third year we will design and implement sloped surfaces for integration in the MRI Experiment. The physics of magneto-Rossby waves will be explored begin in the MRI Experiment as a function of the applied magnetic field and background rotation, characterized in terms of the Hartmann and Elsasser numbers. Additional studies of hydrodynamic Rossby waves in HTX may be performed as appropriate to further the overarching mission of the center. We will explore of magneto-Rossby waves by incorporating similar modifications in the existing MRI Experiment which uses liquid metal in a separate Couette flow device. The following list of questions encompasses experiments in both of these devices.

- What are the characteristic growth rates of zonal flows as a function of background rotation, perturbation amplitude, and if possible, the slope of the end caps?

- What is the spatial structure of the zonal flows? Are they steady, oscillatory or chaotic?

- How are the Rossby waves modified by MHD effects? How do these changes affect the development of the zonal flows?

- How are Rossby and magneto-Rossby waves modified in the presence of weak shear in the background flow?

Development of Diagnostic and Data Analysis Approaches to Study Flow Organization Physics in Hot Plasmas: Key tests of turbulent-driven flow organization usually requires access to complex mult-field correlations such as turbulent stresses and then relating these microscopic quantities to macroscopic system behavior. Small scale experiments can provide direct access to these quantities, but the approaches used in these facilities can not in general be used in large fusion experiments. However diagnostic advances in fusion experiments now permit direct visualization of the spatiotemporal structure – i.e. imaging – of plasma turbulence with sufficient resolution to observe structure evolution, development of anisotropy in the turbulence, propagation of structures, and so force. Thus the question emerges: could these types of datasets be used to extract key tests of the physics that lead to flow organization in MFE plasmas?

In order to address this question, we plan to continue the work of the Colorado group and explore various velocimetry techniques and their range of validity. Workers at CU have developed a "linear optical flow" code, which calculates smooth velocity maps while accurately assessing local regions of high curl. This is critical for separating spatial scales of velocity behavior, and thus transport. This code has recently come on-line, and we are currently using it to revisit a number of older datasets. Additionally, they have begun work on developing pattern-recognition techniques for imaging diagnostics, based on established digital image compression algorithms. This has the potential to open the analysis of turbulent plasma behavior beyond the well-trodden Fourier and wavelet approaches. They will also continue initial proof-of-principle experiments at CSDX and LAPD to look at various aspects of turbulent momentum transport and techniques for its measurement.

Collaborative experiments will be continued on the CSDX device at UCSD. Initial experiments in 2011 compared two methods of measuring turbulent Reynolds stress, known to be a significant contributor to cross-field momentum transport. Data was taken with a multi-tip probe and compared to stress measurements from velocity fields derived from fast-framing images of line emission, the brightness of which depends on local electron density. Analysis of this experiment is ongoing, but initial results demonstrate a very close match between the two techniques (see Figure 25). This is an extremely significant result, as it opens up the possibility of using a whole suite of modern imaging techniques for turbulent stress measurements (including GPI or other fast-camera based diagnostics, or even other multichannel instruments such as photodiode arrays, BES, or microwave imaging). We need to continue these experiments to confirm this preliminary result and determine under what range of conditions fast imaging can be used to successfully infer the transport of momentum (and perhaps of particles and heat as well(!)). Once the ability to infer momentum transport physics is better understood, we can then begin to apply these results to hot fusion plasmas, e.g. to the formation of the H-mode pedestal, to the formation of ITBs, and other such phenomena.

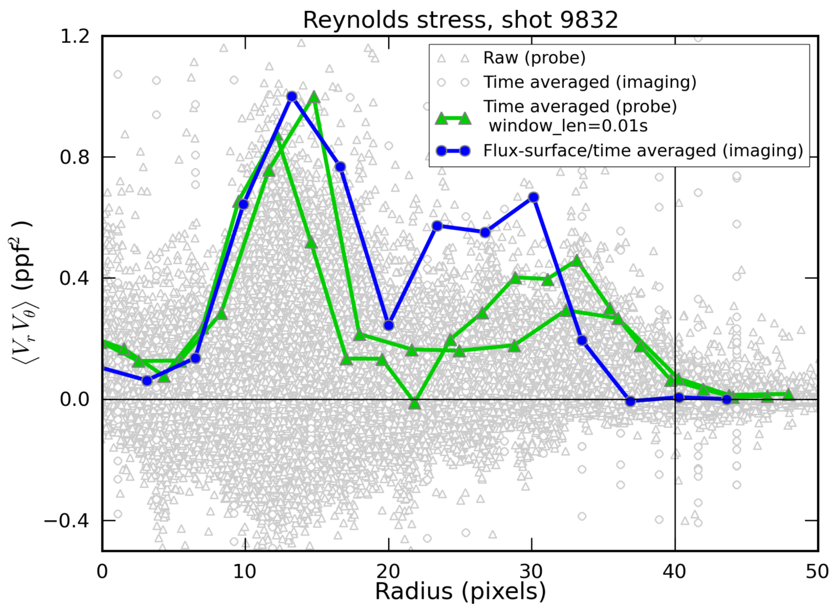

Figure 25: *Comparison of Reynolds stress in CSDX measured by multi-tip probe (green) and derived from velocimetry analysis of fast camera imaging (blue). Black triangles and circles represent individual spatial/temporal datapoints within the profile averages.*

Appendix A: Bibliography and References Cited

[Abbett:2007] Abbett, W. P. (2007), The magnetic connection between the convection zone and corona in the quiet sun, Astrophys. J., 665(2), 1469
[Antar:2007]G. Y. Antar et al., Phys. Plasmas 14, 022301 (2007)
[Artemova:2006] Artemova, Yu.V., Bisnovatyi-Kogan, G.S., Igumenshchev, I. V., & Novikov, I. D, Black Hole Advective Accretion Disks with Optical Depth Transition, (2006) Astrophys. J., 637, 968
[Balbus:1991] Balbus, S. A. & Hawley, J. F. A POWERFUL LOCAL SHEAR INSTABILITY IN WEAKLY MAGNETIZED DISKS .1. LINEAR-ANALYSIS. Astrophysical Journal 376, 214-222 (1991).
[Balbus:1996] S. A. Balbus, J. F. Hawley, and J. M. Stone. Nonlinear stability, hydrodynamical turbulence, and transport in disks. Astrophys. J., 467:76-86, 1996.
[Balbus:1998] Balbus, S. A. & Hawley, J. F. Instability, turbulence, and enhanced transport in accretion disks. Reviews of Modern Physics 70, 1-53 (1998).
[Balbus:2003] S. A. Balbus. Enhanced Angular Momentum Transport in Accretion Disks. Annu. Rev. Astron. Astrophys., 41:555-597, 2003.
[Batchelor:1956] Batchelor, G. K. ON STEADY LAMINAR FLOW WITH CLOSED STREAMLINES AT LARGE REYNOLDS NUMBER. Journal of Fluid Mechanics 1, 177-190 (1956).
[Beauchemin:1995] S. Beauchemin and J. Barron, ACM Computing Surveys 27, 433 (1995).
[Belli:2008] E. A. Belli and J. Candy, Plasma Phys. Cont. Fusion 50, 095010 2008.
[Bergerson:2010] W.F. Bergerson, et al., Bull. Amer. Phys. Soc. 55, 24 (2010).
[Betti:1998] Betti, R. Beta limits for the N=1 mode in rotating-toroidal-resistive plasmas surrounded by a resistive wall. Physics of Plasmas 5, 3615-3631 (1998).
[Bisnovatyi-Kogan :1974] Bisnovatyi-Kogan, G. S. & Ruzmaikin, A. A. (1974), The accretion of matter by a collapsing star in the presence of a magnetic field, Astrophys. Space Sci., 28, 45
[Bisnovatyi-Kogan :1976] Bisnovatyi-Kogan, G. S. & Ruzmaikin, A. A. (1976), The accretion of matter by a collapsing star in the presence of a magnetic field. II. Self-consistent stationary picture, Astrophys. Space Sci., 42, 401
[Bisnovatyi-Kogan :2007] Bisnovatyi-Kogan, G. S., & Lovelace, R. W. E. (2007), Large-Scale B-Field in Stationary Accretion Disks, Astrophys. J., 667, L167
[Bisnovatyi-Kogan :2011] Bisnovatyi-Kogan, G. S.; Lovelace, R. V. E. (2011), Accretion disks with a large scale magnetic field around black holes, and magnetic jet collimation, e-print arXiv:1104.4866
[Borovikov :2009] Borovikov, S. N., Kryukov, I. A., & Pogorelov, N. V. (2009), Adaptive mesh refinement on curvilinear grids, in Astronomical Society of the Pacific Conf. Ser. 406, Numerical Modeling of Space Plasma Flows: ASTRONUM-2008, ed. N. V. Pogorelov, E. Audit, P. Colella, & G. P. Zank, 127 (ASP: San Francisco)
[Brito:2001] D. Brito, H.-C. Nataf, P. Cardin, J. Aubert, and J.-P. Masson. Ultrasonic doppler velocimetry in liquid gallium. Experiments in Fluids, 31:653-663, 2001.

[Burin:2005] Burin, M. J., Tynan, G. R., Antar, G. Y., Crocker, N. A. & Holland, C. On the transition to drift turbulence in a magnetized plasma column. Phys. Plasmas 12, 14 (2005).
[Burin:2006] M. J. Burin, E. Schartman, H. Ji, R. Cutler, P. Heitzenroeder, W. Liu, L. Morris, and S. Raftopolous. Reduction of Ekman circulation within a short circular couette flow. Experiments in Fluids, 40:962-966, 2006.
[Burrell:1997] K. H. Burrell, Phys. Plasmas 4, 1499 (1997)
[Busse:1976] F. H. Busse. Generation of planetary magnetism by convection. Phys. Earth Planetary Inter., 12(4):350-358, 1976.
[Candy:2008] J. Candy, R. E. Waltz, and M. Fahey, "TP6.00016 Hybrid TGLF-GYRO Steady-State Transport Calculations with TGYRO," Bull. Am. Phys. Soc., vol. 53(14), p. 187 (2008)
[Carmody:2011] D. Carmody and P.W. Terry, APS-DPP, 2011.
[Chagelishvili: 2003] G. D. Chagelishvili, J.-P. Zahn, A. G. Tevzadze, and J. G. Lominadze. On hydrodynamic shear turbulence in Keplerian disks: Via transient growth to bypass transition. Astron. Astrophys., 402:401-407, 2003.
[Chang:2004] C.S. Chang et al, Phys. Plasmas 11, 2649 (2004)
[Colebrook: 1938] C. F. Colebrook. Turbulent flow in pipes with particular reference to the transitional region between smooth and rough pipes. J. Inst. Civil Eng., 11(133-156), 1938.
[Conway:2008] G.D. Conway et al, PPCF 50, 085005 (2008)
[Conway:2011] G.D. Conway et al, Phys. Rev. Lett. 106, 065001 (2011)
[Corpetti:2002] T. Corpetti, E. Memin, and P. Perez, IEEE Trans. on Patt. Anal. and Mach. Intel. 24, 365 (2002).
[Diamond:1994] P.H. Diamond et al, IAEA Proceedings (1994) IAEA-CN-60/D-2-II-6
[Diamond:1995] Diamond, P. H. & Hahm, T. S. ON THE DYNAMICS OF TURBULENT TRANSPORT NEAR MARGINAL STABILITY. Physics of Plasmas 2, 3640-3649 (1995).
[Diamond:2005] Diamond, P. H., Itoh, S. I., Itoh, K. & Hahm, T. S. Zonal flows in plasma - a review. Plasma Phys. Control. Fusion 47, R35-R161 (2005).
[Diamond:2007] P.H. Diamond, S. I. Itoh, K. Itoh, and L. J. Silvers. The Solar Tachocline, pages 213-240. Cambridge University Press, 2007.
[Diamond:2008] Diamond, P. H., McDevitt, C. J., Gurcan, O. D., Hahm, T. S. & Naulin, V. Transport of parallel momentum by collisionless drift wave turbulence. Physics of Plasmas 15, (2008)
[Diamond:2009] Diamond, P. H. accepted for publication. Plasma physics and controlled fusion (2009).
[Diamond:2009] Diamond, P. H. in press. Nuclear Fusion (2009).
[Dritschel:2008] Dritschel, D. G. & McIntyre, M. E. Multiple jets as PV staircases: The Phillips effect and the resilience of eddy-transport barriers. Journal of the Atmospheric Sciences 65, 855-874, doi:10.1175/2007jas2227.1 (2008).
[Dubrulle:1993] B. Dubrulle. Differential rotation as a source of angular momentum transfer in the solar nebula. Icarus, 106:59-76, 1993.
[Dubrulle:2005] B. Dubrulle, O. Dauchot, F. Daviaud, P.-Y. Longaretti, D. Richard, and J.-P. Zahn. Stability and turbulent transport in Taylor-Couette flow from analysis of experimental data. Physics of Fluids, 17:095103-19, 2005.
[Ebrahimi:2008] F. Ebrahimi, V.V. Mirnov, and S.C. Prager 15, 055701 (2008).

[Eckert:2002] S. Eckert and G. Gerbeth. Velocity measurements in liquid sodium by means of ultrasound Doppler velocimetry. Experiments in Fluids, 32:542-546, 2002.
[Estrada:2010] T. Estrada et al, EPL 92, 35001 (2010)
[Feng:2010] Feng, X. S., Yang, L., Xiang, C., Wu, S. T., Zhou, Y., and Zhong, D.K., (2010) Three-dimensional solar wind modeling from the Sun to Earth by a SIP-CESE MHD model with a six-component grid, Ap., J., 723:300 doi: 10.1088/0004-637X/723/1/300
[Feng:2011] Feng, X.S. Zhang, S., Xiang, C., Yang, L., Jiang, C., and Wu, S. T. (2011) A hybrid solar wind model of the CESE+HLL method with a yin-yang overset grid and an AMR grid, Ap., J., 734:50, doi:10.1088/0004-637X/734/1/50
[Finlay:2005] C. Finlay. Hydromagnetic waves in Earth's core and their influence on geomagnetic secular variation. PhD thesis, University of Leeds, May 2005.
[Fromang:2002] S. Fromang, C. Terquem, and S. A. Balbus. The ionization fraction in models of protoplanetary discs. Mon. Not. Astron. Soc., 329:18-28, 2002.
[Gammie:1996] C. F. Gammie. Layered accretion in T Tauri disks. Astrophys. J., 457:355-362, 1996.
[Garaud:2005] P. Garaud and G. I. Ogilvie. A model for the nonlinear dynamics of turbulent shear flows. J. Fluid Mech., 530:145-176, 2005.
[Goldreich:2004] Goldreich, P., Lithwick, Y. & Sari, R. Planet formation by coagulation: A focus on Uranus and Neptune. Annual Review of Astronomy and Astrophysics 42, 549-601, doi:10.1146/annurev.astro.42.053102.134004 (2004).
[Greenspan:1968] H.P. Greenspan. The Theory of Rotating Fluids. Cambridge University Press, 1968.
[Grierson:2011] B. A. Grierson, Bull. Am. Phys. Soc. 56(16), 2011; & private communication.
[Groebner:2009] R.J. Groebner et al, Nucl. Fusion 49, 085037 (2009)
[Groebner:2010] R.J. Groebner, private communication 2010
[Gruzinov:1994] Gruzinov, A. V. & Diamond, P. H. SELF-CONSISTENT THEORY OF MEAN-FIELD ELECTRODYNAMICS. Physical Review Letters 72, 1651-1653 (1994).
[Gurcan:2007] Gurcan, O. D., Diamond, P. H., Hahm, T. S. & Singh, R. Intrinsic rotation and electric field shear. Physics of Plasmas 14, (2007)
[Guttenfelder:2011] W. Guttenfelder et al., Phys. Rev. Lett. 106, 155004 (2011).
[Hahm:2007] Hahm, T. S., Diamond, P. H., Gurcan, O. D. & Rewoldt, G. Nonlinear gyrokinetic theory of toroidal momentum pinch. Physics of Plasmas 14 (2007)
[Hallatschek:2001] K. Hallatschek and D. Biskamp, Phys. Rev. Lett. 86, 1223 (2001)
[Hatch:2011a] D.R. Hatch, et al., Phys. Rev. Lett. 106, 115003 (2011).
[Hatch:2011b] D.R. Hatch, et al., Phys. Plasmas 18, 055706 (2011).
[Heerikhuisen : 2010] Heerikhuisen, J., Pogorelov, N. V., Zank, G. P., Crew, G. B., Frisch, P. C., Funsten, H. O., Janzen, P. H., McComas, D. J., Reisenfeld, D. B., & Schwadron, N. A. (2010), Pick-up ions in the outer heliosheath: A possible mechanism for the Interstellar Boundary Explorer ribbon, Astrophys. J., 708, L126
[Heerikhuisen :2011] Heerikhuisen, J., Pogorelov, N. V. (2011), An estimate of the nearby interstellar magnetic field using neutral atoms, Astrophys. J., 738, 29
[Hide:1966] R. Hide. Free hydromagnetic oscillations of the earth's core and the theory of the geomagnetic secular variation. Proc. R. Soc. Lond. A, 259(1107):615-647, 1966.
[Hinton:1991] F.L. Hinton, Phys. Fluids B 3, 696 (1991)

[Hinton:1999] F. L. Hinton and M. N. Rosenbluth, Plasma Phys. Control. Fusion 41, A653 (1999)

[Hitt:1995] D. Hitt, M. Lowe, and R. Newcomer, Phys. Fluids 7, 6 (1995).

[Holland:2006] Holland, C. et al. Observation of turbulent-driven shear flow in a cylindrical laboratory plasma device. Phys. Rev. Lett. 96, 195001 (2006).

[Hollerbach:2003] R. Hollerbach. Instabilities of the stewartson layer part 1. the dependence on the sign of . J. Fluid Mech., 492:289-302, 2003.

[Hollerbach:2004] R. Hollerbach, Birgit Futterer, Tamar More, and Christoph Egbers. Instabilities of the stewartson layer part 2. supercritical mode transitions. Theoret. Comput. Fluid Dynamics, 18(2):197-204, 11 2004.

[Horn:1991] B. Horn and B. Schunck, Artificial Intelligence 17, 185 (1981).

[Horn:1993] B. Horn and B. Schunck, Artificial Intelligence 59, 81 (1993).

[Hubbard:2011] A. E. Hubbard et al, Phys. Plasmas 18, 056115 (2011)

[Hughes:1996] Hughes, D. W., Cattaneo, F. & Kim, E. J. Kinetic helicity, magnetic helicity and fast dynamo action. Physics Letters A 223, 167-172 (1996).

[Hughes:2007] Hughes, D. The Solar Tachocline. (Cambridge University Press, 2007).

[Idomura:2009] Idomura, Y. to be published. Nuclear Fusion (2009).

[Ilgner:2006] M. Ilgner and R. P. Nelson. On the ionisation fraction in protoplanetary disks. I. Comparing different reaction networks. Astron. Astrophys., 445:205-222, January 2006.

[ITER:1999] ITER Physics Basis, Nucl. Fusion 39, 2137 (1999)

[Itoh:2004] K. Itoh et al, J. Phys. Soc. Japan 73, 2921 (2004)

[Jensen:1983] Jensen, T. H. & Chu, M. S. A LINEAR-MODEL FOR THE TEARING MODE OF A TOKAMAK PLASMA WITH FLOW AND A RESISTIVE WALL BOUNDARY-CONDITION. Journal of Plasma Physics 30, 57-63 (1983).

[Ji:2000] H. Li, J. M. Finn, R. V. E. Lovelace, and S. A. Colgate. Rossby wave instability of thin accretion disks -ii. detailed linear theory. Astro. Phys. J., 533(2):1023-1034, 2000.

[Ji:2001] H. Ji, J. Goodman, and A. Kageyama. Magnetorotational instability in a rotating liquid metal annulus. Mon. Not. Astron. Soc., 325:L1-L5, 2001.

[Ji:2005] H. Ji, W. Fox, D. Pace, and H. Rappaport. Study of small-amplitude magnetohydrodynamic surface waves in liquid metal. Phys. Plasmas, 12:012102, 2005.

[Ji:2006] H. Ji, M.J. Burin, E. Schartman, and J. Goodman. Hydrodynamic turbulence cannot transport angular momentum effectively in astrophysical disks. Nature., 444:343-346, 2006.

[Kageyama:2004] A. Kageyama, H. Ji, J. Goodman, F. Chen, and E. Shoshan. Numerical and experimental investigationof circulation in short cylinders. J. Phys. Soc. Jpn., 73:2424-2437, 2004.

[Kamiya:2010] K. Kamiya et al, Phys. Rev. Lett. 105, 045004 (2010)

[Kim:2003] E. Kim and P.H. Diamond, Phys. Rev. Lett. 90, 185066 (2003)

[King:2011] J. King, Ph.D. Thesis, University of Wisconsin, 2011.

[Klepnev: 2010] Klepnev, A. S., & Bisnovatyi-Kogan, (2010)G. S, Models of high-luminosity accretion disks surrounding black holes, Astrophysics, 53, 409

[Ku:2011] Ku, S. et al, Sub. Nuc. Fusion (2011)

[Kulikovskii:2001] Kulikovskii, A.G., Pogorelov, N.V., Semenov, A.Y. (2001) Mathematical Aspects of Numerical Solution of Hyperbolic Systems, CRC Press, Boca Raton, Florida

[Kuritsyn:2009] A. Kuritsyn, et al., Phys. Plasmas 16, 055903 (2009).
[LaBombard:2004] B. LaBombard et al, Nucl. Fusion 44, 1047 (2004)
[LaBombard:2008] B. LaBombard, J. W. Hughes, N. Smick, A. Graf, K. Marr, R. McDermott, M. Reinke, M. Greenwald, B. Lipschultz, J. L. Terry, D. G. Whyte, S. J. Zweben, and Alcator C-Mod Team, Phys. Plasmas 15, 056106 (2008).
[Larsen:1998] R. Larsen, K. Conradsen, and B. Ersboll, IEEE Trans. on Geosci. and Remote Sens. 36, 256 (1998).
[Lebedev:1997] V.B. Lebedev and P.H. Diamond, Phys. Plasmas 4, 1087 (1997)
[Leprovost: 2007] N. Leprovost and E.J. Kim. Effect of rossby and alfven waves on the dynamics of the tachocline. The Astrophysical Journal, 654(2):1166-1170, 2007.
[Lesur: 2005] G. Lesur and P.-Y. Longaretti. On the relevance of Subcritical Hydrodynamic Turbulence to Accretion Disk Transport. Astron. Astrophys., 444:25-44, 2005.
[Li:2001] H. Li, S. A. Colgate, B. Wendro_, and R. Liska. Rossby wave instability of thin accretion disks. iii. nonlinear simulations. Astro. Phys. J., 551(2):874-896, 2001.
[Lin:1998] Science, 1998
[Liu:2008] W. Liu. Numerical study of the magnetorotational instability in princeton mri experiment. Astrophys. J., 684(1):515-524, 2008a.
[Liu:2008b] W. Liu. Magnetized ekman layer and stewartson layer in a magnetized taylor-couette flow. Phys. Rev. E, 77(5):056314-11, 2008b.
[Longaretti:2002] P. Longaretti. On the Phenomenology of Hydrodynamic Shear Turbulence. Astrophys. J., 576:587-598, 2002.
[Lorenzini:2009] R. Lorenzini, et al., Nature Physics 5, 570 (2009).
[Lovelace: 2009] Lovelace, R. V. E., Rothstein, D. M., Bisnovatyi-Kogan, G. S. (2009), Advection/Diffusion of Large-Scale B Field in Accretion Disks, Astrophys. J., 701, 885
[Lovelace:1999] R. V. E. Lovelace, H. Li, S. A. Colgate, and A. F. Nelson. Rossby wave instability of keplerian accretion disks. Astro. Phys. J., 513(2):805-810, 1999.
[Malkov:2008] M. A. Malkov and P.H. Diamond, Phys. Plasmas 15, 122301 (2008)
[Malkov:2009] M. A. Malkov and P.H. Diamond, Phys. Plasmas 16, 012504 (2009)
[Mantica:2011] P. Mantica, et al., US-EU TTF Workshop, 2011.
[Mattor:1988] N. Mattor and P. H. Diamond, Phys. Fluids 31, 1180 (1988).
[Mattor:1991] Mattor, N. TOROIDAL ION TEMPERATURE GRADIENT-DRIVEN WEAK TURBULENCE. Physics of Fluids B-Plasma Physics 3, 1913-1926 (1991).
[McDevitt:2009] C. J. McDevitt and P. H. Diamond, Phys. Plasmas 16, 012301 (2009).
[McDevitt:2009] McDevitt, C. J. accepted for publication. Physics of Plasmas (2009).
[McKee:2009] G. McKee et al, Nucl. Fusion 49, 115016 (2009)
[Mestel:2003] Mestel, L. Stellar Magnetism. (Oxford University Press, 2003).
[Mike:2010] K. Miki et al, Phys. Plasmas 17, 032309 (2010)
[Mukhopadhyay:2005] B. Mukhopadhyay, N. Afshordi, and R. Narayan. Bypass to Turbulence in Hydrodynamic Accretion Disks: An Eigenvalue Approach. Astro. Phys. J., 629:383-396, 2005.
[Nakagawa:1987] Nakagawa, Y., Y. Q. Hu and S. T. Wu, (1987) The method of projected characteristics for evolution of magnetic arches, Astron. Astrophys., 179, 354
[Pogorelov:2000] Pogorelov, N. V. (2000), Nonstationary phenomena in the solar wind and interstellar medium interaction, Astrophys. Space Sci., 274, No. 1/2, 115

[Pogorelov:2004] Pogorelov, N. V., Zank, G. P., & Ogino, T. (2004), Three-dimensional features of the outer heliosphere due to coupling between the interstellar and interplanetary magnetic fields. I. Magnetohydrodynamic model: Interstellar perspective, Astrophys. J., 614, 1007
[Pogorelov:2006] Pogorelov, N. V., Zank, G. P., & Ogino, T. (2006), Three-dimensional features of the outer heliosphere due to coupling between the interstellar and interplanetary magnetic fields. II. The presence of neutral hydrogen atoms, Astrophys. J, 644, 1299
[Pogorelov:2007] Pogorelov, N. V., Stone, E. C., Florinski, V., & Zank, G. P. (2007), Termination shock asymmetries as seen by the Voyager spacecraft: The role of the interstellar magnetic field and neutral hydrogen, Astrophys. J., 668, 611
[Pogorelov:2008] Pogorelov, N. V., Heerikhuisen, J., & Zank, G. P. (2008), Probing heliospheric asymmetries with an MHD-kinetic model, Astrophys. J., 675, L41
[Pogorelov:2009a] Pogorelov, N. V., Borovikov, S. N., Zank, G. P., & Ogino, T. (2009a), Three-dimensional features of the outer heliosphere due to coupling between the interstellar and interplanetary magnetic fields. III. The effects of solar rotation and activity cycle, Astrophys. J., 696, 1478
[Pogorelov:2009b] Pogorelov, N. V., Heerikhuisen, J., Mitchell, J. J., Cairns, I. H., & Zank, G. P. (2009b), Heliospheric asymmetries and 2--3 kHz radio emission under strong interstellar magnetic field conditions, Astrophys. J., 695, L31
[Pogorelov:2009c] Pogorelov, N. V., Borovikov, S. N., Florinski, V., Heerikhuisen, J., Kryukov, I. A., Zank, G. P. (2009c), Multi-scale fluid-kinetic simulation suite: A tool for efficient modeling of space plasma flows, in Astronomical Society of the Pacific Conf. Ser. 406, Numerical Modeling of Space Plasma Flows: ASTRONUM-2008, ed. N.V. Pogorelov, E. Audit, P. Colella, & G.P. Zank, 149 - 159 (San Francisco: ASP)
[Rhines:1982] Rhines, P. B. & Young, W. R. HOMOGENIZATION OF POTENTIAL VORTICITY IN PLANETARY GYRES. Journal of Fluid Mechanics 122, 347-367 (1982).
[Rhines:1986] Rhines, P. B. VORTICITY DYNAMICS OF THE OCEANIC GENERAL-CIRCULATION. Annual Review of Fluid Mechanics 18, 433-497 (1986).
[Rice:1998] J. E. Rice, M. Greenwald, I. H. Hutchinson, E. S. Marmar, Y. Takase, [Wolf:1998] S. M. Wolf, and F. Bomarda, Nucl. Fusion 38, 75 1998.
[Rice:2007] J. E. Rice et al., Nucl. Fusion 47, 1618 (2007).
[Rice:2011] J. E. Rice et al., Nucl. Fusion 51, 083005 (2011).
[Rice:2011] Rice, J.E. et al Phys. Rev. Letters 106 215001 (2011).
[Richard:1999] D. Richard and J.-P. Zahn. Turbulence in differentially rotating flows: What can be learned from the Couette-Taylor experiment. Astron. Astrophys., 347:734-738, 1999.
[Richard:2001] D. Richard. Instabilities Hydrodynamiques dans les Ecoulements en Rotation Differentielle. PhD thesis, Universitie Paris 7, 2001.
[Rossby:1939] CG Rossby et al. Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacements of the semi-permanent centers of action. J. Mar. Res, 2(1):38-55, 1939.
[Rudiger:1989] Rudiger, G. Differential Rotation and Stellar Convection. (Gordon and Breach, 1989).
[Schartman:2008] E. Schartman. Study of Anguular Momentum Transport of a Laboratory Flow. PhD thesis, Princeton University, 2008.

[Schmitz:2011] L. Schmitz et al., US-TTF 2011

[Schou:1998] Schou, J.; Antia, H. M.; Basu, S.; Bogart, R. S.; Bush, R. I.; Chitre, S. M.; Christensen-Dalsgaard, J.; di Mauro, M. P.; Dziembowski, W. A.; Eff-Darwich, A.; Gough, D. O.; Haber, D. A.; Hoeksema, J. T.; Howe, R.; Korzennik, S. G.; Kosovichev, A. G.; Larsen, R. M.; Pijpers, F. P.; Scherrer, P. H.; Sekii, T.; Tarbell, T. D.; Title, A. M.; Thompson, M. J.; Toomre, J. (1998), Helioseismic Studies of Differential Rotation in the Solar Envelope by the Solar Oscillations Investigation Using the Michelson Doppler Imager, Astrophys. J., 505(1), 390

[Schultz-Grunow:1959] F. Schultz-Grunow. Zur Stabilitat der Couette-Stromung. Z. angew. Math. Mech., 39:101-117, 1959.

[Scott:2010] B. Scott, Phys. Plasmas 17, 102306 (2010)

[Shakura:1978] Shakura, N. I., Sunyaev, R. A. & Zilitinkevich, S. S. TURBULENT ENERGY-TRANSPORT IN ACCRETION DISKS. Astronomy and Astrophysics 62, 179-187 (1978).

[Shu:2007] Shu, F. H., Galli, D., Lizano, S., Glassgold, A. E. & Diamond, P. H. Mean field magnetohydrodynamics of accretion disks. Astrophysical Journal 665, 535-553 (2007).

[Spence:2009] Spence, E. and Reuter, K. and Forest, C.B., Submitted to Astrophys. J., Numerical Simulations of a Spherical Plasma Dynamo Experiment, http://arxiv.org/abs/0901.3406,2009].

[Spiegel:1992] Spiegel, E. A. & Zahn, J. P. THE SOLAR TACHOLINE. Astronomy and Astrophysics 265, 106-114 (1992).

[Sun: 1995] Sun, M. T., Wu, S. T., & Dryer, M. (1995), On the time-dependent numerical boundary conditions for magnetohydrodynamic flows, J. Comput. Phys., 116, 330

[Takeda:1995] Y. Takeda. Velocity profile measurement by ultrasonic doppler method. Exp. Therm. Fluid Sci., 10: 444-453, 1995.

[Tangri:2008] V. Tangri, P.W. Terry, and G. Fiksel, Phys. Plasmas 15, 112501 (2008).

[Taylor:1936] G.I. Taylor. Fluid friction between rotating cylinders. i. torque measurments. Proc. Roy. Soc. London A, 157:546-578, 1936.

[Taylor:1986] Taylor, J. B. RELAXATION AND MAGNETIC RECONNECTION IN PLASMAS. Reviews of Modern Physics 58, 741-763 (1986).

[Terry:1992] P.W. Terry, D.E. Newman, and N. Mattor, Phys. Fluids A 4, 927 (1992).

[Terry:2007] P.W. Terry and K.W. Smith, Astrophys. J. 665, 402 (2007).

[Turner:2004] N. J. Turner, T. Sano, and N. Dziourkevitch. Turbulent Mixing and the Dead Zone in Protostellar Disks. ArXiv Astrophysics e-prints, December 2006.

[Tynan:1997] Tynan, G. R. et al. Characterization of an azimuthally symmetric helicon wave high density plasma source. J. Vac. Sci. Technol. A-Vac. Surf. Films 15, 2885-2892 (1997).

[Tynan:2006] Tynan, G. R. et al. Observation of turbulent-driven shear flow in a cylindrical laboratory plasma device. Plasma Phys. Control. Fusion 48, S51-S73, (2006).

[Tynan:2011] G. Tynan, private communication 2011

[Umurhan:2004] O. M. Umurhan and O. Regev. Hydrodynamic stability of rotationally supported flows: Linear and nonlinear 2D shearing box results. Astron. Astrophys., 427:855-872, 2004.

[Vainshtein:1992] Vainshtein, S. I. & Cattaneo, F. NONLINEAR RESTRICTIONS ON DYNAMO ACTION. Astrophysical Journal 393, 165-171 (1992).

[Vedenov:1962] Vedenov, A. A., Velikhov, E. P. & Sagdeev, R. Z. QUASI-LINEAR THEORY OF PLASMA OSCILLATIONS. Nuclear Fusion, 465-475 (1962).
[Vishniac:2001] Vishniac, E. T. & Cho, J. Y. Magnetic helicity conservation and astrophysical dynamos. Astrophysical Journal 550, 752-760 (2001).
[Wagner:1982] F. Wagner et al, Phys. Rev. Lett. 49, 1408 (1982)
[Wagner:2007] F. Wagner, Plasma Phys. Control. Fusion 49, B1 (2007)
[Waltz:2005] R. E. Waltz, J. Candy, F. L. Hinton, C. Estrada-Mila and J. E. Kinsey, Nucl. Fusion 45, 741 2005.
[Waltz:2007] R. E. Waltz, G. M. Staebler, J. Candy, and F. L. Hinton, Phys. Plasmas 14, 122507 2007
[Wang:2006] W. X. Wang et al., Phys. Plasmas 13, 092505 (2006).
[Wang:2010] W. X. Wang, P. H. Diamond, T. S. Hahm, S. Ethier, G. Rewoldt, W. M. Tang, Phys. Plasmas 17, 072511 (2010).
[Wang:2011] W. X. Wang, T. S. Hahm, S. Ethier, L. E. Zakharov and P. H. Diamond, Phys. Review Letters 106, 085001 (2011).
[Wang:2011] H. Wang et al, 1st APTWG 2011, BP-5
[Wang:2011] Wang, A. H., Wu, S. T., Tandberg-Hanssen, E. and Hill, F. (2011) Utilization of Multiple Measurements for Global Three-Dimensional Magnetohydrodynamic Simulations, Ap.J., 732:19 (12pp), doi:10.1088/0004-637X/732/1/19
[Wendt:1933] F.Wendt. Turbulente Stromungen zwischen zwei rotierenden konaxialen Zylindern. Ing. Arch., 4:577-595 1933.
[Wu:1987] Wu, S. T. and Wang, J. F., (1987) Numerical Tests of a Modified Full Implicit Continuous Eulerian (FICE) Scheme with Projected Normal Characteristic Boundary Conditions for MHD Flows, Comp. Methods in Appl. Mech. And Engineering, 64, 267-282
[Wu:2005] Wu, S. T., Li, B., Wang., S., and Zheng, H., (2005) A three-dimensional analysis of global propagation of magnetohydrodynamic (MHD) waves in a structured solar atmosphere, J. Geophys. Res., 110, A11102, doi:10.1029/2005JA011056
[Wu:2006] Wu, S. T., Wang, A. H., Liu, Y. and Hoeksema, J. T., (2006) Data Driven Magnetohydrodynamic (MHD) Model for Active Region (AR) Evolution, Ap. J., 652, 800
[Wu:2009] Wu, S. T., Wang, A. H., G. Allen Gary, Ales Kucera, Jan Rybak, Yang Liu, Bojan Vrsnak, Vasyl Yuchyshyn (2009) Analyses of Magnetic Field Structures for Active Region 10720 using a Data-Driven 3D MHD Model, Adv. Space Res., 44, 46-53, doi:10.1016/j.asr.2009.03.020
[Xu:2003] X.Q. Xu et al, Phys. Plasmas 10, 1773 (2003)
[Xu:2011] G.S. Xu et al, Nucl. Fusion 51, 072001 (2011)
[Xu:2011] G.S. Xu et al, Phys. Rev. Lett. 107, 125011 (2011)
[Xu:2011] M. Xu et al, Phys. Rev. Lett. 107 055003 (2011).
[Xu:2011b] M. Xu et al, submitted to Phys. Rev. Lett. 2011
[Yan:2008] Yan, Z. Turbulence-driven shear flow and self-regulating drift wave turbulence in a cylindrical plasma device PhD thesis, University of California San Diego, (2008).
[Yecko:2004] P. A. Yecko. Accretion disk instability revisited. Transient dynamics of rotating shear flow. Astron. Astrophys., 425:385-393, 2004.
[Yoshida:2008] Yoshida, M. et al. Role of pressure gradient on intrinsic toroidal rotation in tokamak plasmas. Physical Review Letters 100, doi:105002

[Yuan:2007] J. Yuan, C. Schorr, and G. Steidl, SIAM J. Sci. Comput. 29(6) 2283 (2007).
[Zank:2009] Zank, G. P., Pogorelov, N. V., Heerikhuisen, J., Washimi, H., Florinski, V., Borovikov, S., Kryukov, I., Mueller, H. R. (2009), Physics of the solar wind--local interstellar medium interaction: Role of magnetic fields, Space Sci. Rev., 146, 295
[Zeldovich:1981] Y.B. Zeldovich. On the Friction of Fluids Between Rotating Cylinders. Proc. Roy. Soc. London A, 374:299-312, 1981.
[Zhao:2006] K.J. Zhao et al, Phys. Rev. Lett. 96, 255004 (2006)
[Zweben:2010] S. Zweben et al, Phys. Plasmas 17, 102502 (2010)
Carreras, B. A., Newman, D., Lynch, V. E. & Diamond, P. H. Self-organized criticality as a paradigm for transport in magnetically confined plasmas. Plasma Physics Reports 22, 740-753 (1996).

APPENDIX B: APS DPP 2010 Miniconference – Listing of Talks and Speakers

The CMTFO sponsored a mini-conference at the APS DPP 2010 meeting, focused on momentum transport in fusion and astrophysical systems. Speakers and titles of the talks given at this miniconference are included below.

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Session UM10: Mini-Conference on Momentum Transport in Magnetic Fusion and Astrophysical Systems II

Show Abstracts

Chair: George Tynan, University of California, San Diego
Room: *Columbus AB*

Thursday, November 11, 2010 2:00PM - 2:25PM	UM10.00001: Planet Formation in Magnetized Accretion Disks Andrew Youdin Preview Abstract
Thursday, November 11, 2010 2:25PM - 2:50PM	UM10.00002: Study of Angular Momentum Transport in Hydrodynamic and Magnetohydrodynamic Experiments H. Ji , E. Edlund , E. Spence , A. Roach Preview Abstract
Thursday, November 11, 2010 2:50PM - 3:10PM	UM10.00003: A new experiment for the study of hydrodynamic waves and turbulence E. Edlund , P. Humanik , A. Roach , E. Schartman , P. Sloboda , E. Spence , H. Ji Preview Abstract
Thursday, November 11, 2010 3:10PM - 3:30PM	UM10.00004: Convective Instability in the Plasma Couette Experiment Noam Katz , Cami Collins , Dave Weisberg , Ben Brown , John Wallace , Mike Clark , Cary Forest Preview Abstract
Thursday, November 11, 2010 3:30PM - 3:45PM	UM10.00005: Nonlocal Studies of the Magnetorotational Instability A. Bhattacharjee , F. Ebrahimi , B. Lefebvre , A. Vandenberg Preview Abstract
Thursday, November 11, 2010 3:45PM - 4:00PM	UM10.00006: Global Hall-MHD simulations of magnetorotational instability Fatima Ebrahimi , B. Lefebvre , C.B. Forest , A. Bhattacharjee Preview Abstract
Thursday, November 11, 2010 4:00PM - 4:15PM	UM10.00007: Kinetic Dissipation of Magnetized Relativistic Astrophysical Momentum Outflow Edison Liang , Markus Boettcher , Ian Smith Preview Abstract
Thursday, November 11, 2010 4:15PM - 4:30PM	UM10.00008: Turbulence Suppression in a coherent structure of localized current and vorticity Juhyung Kim , Paul W. Terry Preview Abstract
Thursday, November 11, 2010 4:30PM - 4:45PM	UM10.00009: Exact momentum conservation laws for gyrofluid and gyrokinetic models Alain Brizard Preview Abstract

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Session Index

Session TM10: Mini-Conference on Momentum Transport in Magnetic Fusion and Astrophysical Systems I

Show Abstracts

Chair: George Tynan, University of California, San Diego
Room: *Columbus AB*

Thursday, November 11, 2010 9:30AM - 9:50AM	TM10.00001: Overview of Toroidal Rotation Observations in Alcator C-Mod Plasmas John Rice , Matt Reinke , Yuri Podpaly , Yijun Lin Preview Abstract
Thursday, November 11, 2010 9:50AM - 10:10AM	TM10.00002: Intrinsic Rotation Drive on DIII-D W.M. Solomon , T.S. Hahm , K.H. Burell , J.S. deGrassie , A.M. Garofalo , R.E. Waltz , H. Reimerdes , P.H. Diamond , S.H. Muller Preview Abstract
Thursday, November 11, 2010 10:10AM - 10:30AM	TM10.00003: Generation of a Sheared Plasma Rotation by Emission, Propagation and Absorption of Drift Wave Packets Min Xu , George Tynan , Patrick Diamond , Stefan Muller , Christopher Holland , Jonathan Yu , Zheng Yan Preview Abstract
Thursday, November 11, 2010 10:30AM - 10:45AM	TM10.00004: Impurity Poloidal Rotation in DIII-D Under Low Toroidal Field Conditions K.H. Burrell , E.A. Belli , W.M. Solomon , B.A. Grierson , W. Wang , G.W. Rewoldt Preview Abstract
Thursday, November 11, 2010 10:45AM - 11:00AM	TM10.00005: Momentum studies with sources and sinks in fusion G. Dif-Pradalier , P.H. Diamond , V. Grandgirard , Y. Sarazin , J. Abiteboul , X. Garbet , Ph. Ghendrih , A. Strugarek , C.S. Chang , S. Ku Preview Abstract
Thursday, November 11, 2010 11:00AM - 11:15AM	TM10.00006: Advances in Velocimetry Techniques for Plasma Turbulence Studies T. Munsat , Y. Sechrest Preview Abstract
Thursday, November 11, 2010 11:15AM - 11:30AM	TM10.00007: Measurement of Momentum Transport in Magnetic Turbulence W.X. Ding , D.L. Brower , W.F. Bergerson , L. Lin , A. Almagri , G. Fiksel , D. J. Den Hartog , J.A. Reusch , J.S. Sarff Preview Abstract
Thursday, November 11, 2010 11:30AM - 11:45AM	TM10.00008: Characteristics of turbulence nonlinearly driven plasma flow and origins of empirical scalings of intrinsic rotation in experiments W.X. Wang , P.H. Diamond , T.S. Hahm , S. Ethier , W.M. Tang Preview Abstract
Thursday, November 11, 2010 11:45AM - 12:00PM	TM10.00009: Intrinsic rotation and residual stress in full-f ITG turbulence simulations S. Ku , E.S. Yoon , C.S. Chang , J.M. Kwon , S.M. Yi , P.H. Diamond Preview Abstract
Thursday, November 11, 2010 12:00PM - 12:15PM	TM10.00010: Intrinsic Rotation and Momentum Transport in Reversed Shear Plasmas with Internal Transport Barriers Hogun Jhang , S.S. Kim , P.H. Diamond Preview Abstract
Thursday, November 11, 2010 12:15PM - 12:30PM	TM10.00011: Gyrokinetic simulation of toroidal momentum transport in ITG and CTEM turbulence Ihor Holod , Zhihong Lin Preview Abstract

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APPENDIX C: List of Publications or Presentations of CMTFO Sponsored Work Arranged by Research Group

N. Brummel Group (UCSC)

1. Nic Brummell, Zonal flows? Relaxation? Self-organisation? Magnetic confinement? The solar tachocline has got it all!, 6th Festival de Theorie, Aix en Provence, France, July 2011

2. Céline Gervilly, Effects of magnetic boundary conditions on mechanically driven dynamos, 6th Festival de Theorie, Aix en Provence, France, July 2011

P.H. Diamond Group (UCSD and WCI/NFRI)

1. McDevitt, C.J. and *P.H. Diamond*, "Transport of Parallel Momentum by Drift-Alfven Turbulence", Phys. Plasmas 16(1), 012301, 2009 (18 pp).

2. Malkov, M.A. and *P.H. Diamond*, "Weak Hysteresis in a Simplified Model of the L-H Transition", Phys. Plasmas 16(1), 012504, 2009 (10 pp).

3. Wang, W.X., T.S. Hahm, S. Ethier, G. Rewoldt, W.W. Lee, W.M. Tang, S.M. Kaye and *P.H. Diamond*, "Gyrokinetic Studies on Turbulence-Driven and Neoclassical Nondiffusive Toroidal-Momentum Transport and the Effect of Residual Fluctuations in Strong E x B Shear", Phys. Rev. Letts. 102(3), 035005, 2009 (4 pp).

4. *Diamond, P.H.*, "Concepts and Themes in Confinement Physics - A Look Ahead Around and a Look Ahead", 2nd ITER International Summer School: In Conjunction with the 47th Summer School of JSPF for Young Plasma Physicists: Confinement, Eds. S.I. Itoh, S. Inagaki, M. Shindo, and M. Yagi, AIP Conference Proceedings, Vol. 1095, 2009 (9 pp).

5. Nagashima, Y., S.-I. Itoh, S. Shinohara, M. Fukao, A. Fujisawa, K. Terasaka, Y. Kawait, G.R. Tynan, *P.H. Diamond*, M. Yagi, S. Inagaki, T. Yamada and K. Itoh, "Observation of the Parametric-Modulational Instability Between the Drift-Wave Fluctuation and Azimuthally Symmetric Sheared Radial Electric Field Oscillation in a Cylindrical Laboratory Plasma", Phys. Plasmas 16(2), 020706, 2009 (4 pp).

6. *Diamond, P.H.*, C.J. McDevitt, O.D. Gurcan, T.S. Hahm, W.X. Wang, E.S. Yoon, I. Holod, Z. Lin, V. Naulin and R. Singh, "Physics of Non-Diffusive Turbulent Transport of Momentum and the Origins of Spontaneous Rotation in Tokamaks", Nucl. Fusion 49, 045002, 2009 (11 pp).

7. Hahm, T.S., *P.H. Diamond*, O.D. Gurcan and G. Rewoldt, Response to "Comment on Turbulent Equipartition Theory of Toroidal Momentum Pinch", Phys. Plasmas 16(3), 034704, 2009 (3 pp).

8. Chang, C.S., S. Ku, *P.H. Diamond*, Z. Lin, S. Parker, T.S. Hahm, W.W. Lee and N.

Samatova, "Compressed Ion Temperature Gradient Turbulence in Diverted Tokamak Edge", Phys. Plasmas 16(5), 056108, 2009 (11 pp).

9. McDevitt, C.J., *P.H. Diamond*, O.D. Gurcan and T.S. Hahm, "A Novel Mechanism for Exciting Intrinsic Toroidal Rotation", Phys. Plasmas 16(5), 052302, 2009 (12 pp)

10. Gurcan, O.D., X. Garbet, P. Hennequin, *P.H. Diamond*, A. Casati, and G.L. Falchetto, "Wave-Number Spectrum of Drift Wave Turbulence", Phys. Rev. Letts. 102, 255002, 2009 (4 pp).

11. Nagashima, Y., S-I. Itoh, K. Itoh, A. Fujisawa, S. Inagaki, Y. Kawai, S. Shinohra, M. Fukao, T. Yamada, K. Terasaka, T. Maruta, K. Kamatak, H. Arakawa, M. Yagi, N. Kasuya, G. Tynan, *P.H. Diamond* and Y. Takase, "Reynolds Stress Measurements for Investigation of Nonlinear Processes of Turbulence in the Large Mirror Device and in the Large Mirror Device-Upgrade", Proceedings of the 14th International Congress on Plasma Physics, 8-12 September 2008, Fukuoka, Japan, J. Plasma Fusion Res. Series, Vol. 8, 2009 (4 pp).

12. Ku, S., C.S. Chang and *P.H. Diamond*, "Full-*f* Gyrokinetic Particle Simulation of Centrally Heated Global ITG Turbulence From Magnetic Axis to Edge Pedestal Top in a Realistic Tokamak Geometry", Nucl. Fusion 49(11), 115021, 2009 (14 pp).

13. Tynan, G.R., *P.H. Diamond*, C. Holland, S.H. Muller, M. Xu, Z. Yan and J. Yu, "Nonlinear Dynamics of Shear Flows and Plasma Rotation in a Simple Laboratory Plasma System", Plasma Phys. Control. Fusion 51(12), 124055, 2009 (6 pp).

14. McDevitt, C.J., *P.H. Diamond*, O.D. Gurcan and T.S. Hahm, "Toroidal Rotation Driven by the Polarization Drift", Phys. Rev. Lett. 103, 205003, 2009 (6 pp).

15. Yan, Z., M. Xu, *P.H. Diamond*, C. Holland, S.H. Muller, G.R. Tynan and J. Yu, "Intrinsic Rotation from a Residual Stress at the Boundary of a Cylindrical Laboratory Plasma", Phys. Rev. Letts 104, 065002, 2010 (4 pp).

16. Miki, K. and *P.H. Diamond*, "Role of the Geodesic Acoustic Mode Shearing Feedback Loop in Transport Bifurcations and Turbulence Spreading", Phys. of Plasmas 17(3), 032309, 2010 (10 pp).

17. Gurcan, O.D., P. Hennequin, L. Vermare, X. Garbet and *P.H. Diamond*, "Shell Models and the Possibility of Application to Fusion Plasmas", Plasma Phys. Control. Fusion 52(4), 045002, 2010 (21 pp).

18. Gurcan, O.D., *P.H. Diamond*, C.J. McDevitt and T.S. Hahm, "A Simple Model of Intrinsic Rotation in High Confinement Regime Tokamak Plasmas", Phys. of Plasmas 17(3), 032509, 2010 (8 pp).

19. Solomon, W.M., K.H. Burrell, A.M. Garofalo, S.M. Kaye, R.E. Bell, A.J. Cole, J.S. deGrassie, *P.H. Diamond*, T.S. Hahm, G.L. Jackson, M.J. Lanctot, C.C. Petty, H. Reimerdes, S.A. Sabbagh, E.J. Strait, T. Tala and R.E. Waltz, "Mechanisms for Generating Toroidal Rotation in Tokamaks Without External Momentum Input", Phys. of Plasmas 17(5), 056108, 2010 (11 pp).

20. *Diamond, P.H.*, S.-I. Itoh and K. Itoh, "Modern Plasma Physics", Vol. 1: Physical Kinetics of Turbulent Plasmas, Cambridge University Press, 2010 (434 pp).

21. Kosuga, Y. and *P.H. Diamond*, "Collisionless Dynamical Friction and Relaxation in a Simple Drift Wave-Zonal Flow Turbulence", Plas. Fusion Research, Vol. 5, S2051, 2010 (4 pp.).

22. Ishizawa, A. and *P.H. Diamond*, "Ion-Temperature Gradient Modes Affected by Helical Magnetic Field of Magnetic Islands", Phys. Plasmas 17(7), 074503, 2010 (3 pp).

23. Gurcan, O.D., *P.H. Diamond*, P. Hennequin, C.J. McDevitt, X. Garbet and C. Bourdelle, "Residual Parallel Reynolds Stress Due to Turbulence Intensity Gradient in Tokamak Plasmas", Phys. Plasmas 17(11), 112309, 2010 (8 pp).

24. Wang, W.X., *P.H. Diamond*, T.S. Hahm, S. Ethier, G. Rewoldt and W.M. Tang, "Nonlinear Flow Generation by Electrostatic Turbulence in Tokamaks", Phys. Plasmas 17(7), 072511, 2010 (20 pp).

25. Dif-Pradalier, G., *P.H. Diamond*, V. Grandgirard, Y. Sarazin, J. Abiteboul, X. Garbet, Ph. Ghendrih, A. Strugerek, S. Ku and C.S. Chang, "On the Validity of the Local Diffusive Paradigm in Turbulent Plasma Transport", Phys. Rev. E 82, 025401, 2010 (4 pp.).

26. Kosuga, Y., *P.H. Diamond* and O.D. Gurcan, "On the Efficiency of Intrinsic Rotation Generation in Tokamaks", Phys. Plasmas 17(10), 102313, 2010 (11 pp).

27. McDevitt, C.J., *P.H. Diamond*, O.D. Gurcan and T.S. Hahm, "Poloidal Rotation and Its Relation to the Potential Vorticity Flux", Phys. Plasmas 17(11), 112509, 2010 (17 pp).

28. Wang, W.X., T.S. Hahm, S. Ethier, L.E. Zakharov and *P.H. Diamond*, "Trapped Electron Mode Turbulence Driven Intrinsic Rotation in Tokamak Plasmas", Phys. Rev. Lett. 106(8), 085001, 2011 (4 pp).

29. Wang, Z.H., *P.H. Diamond*, O.D. Gurcan, X. Garbet and X.G. Wang, "Turbulence Intensity Pulse Propagation with Self-Consistent Nonlinear Noise", Phys. Plasmas 18(3), 032306, 2011 (10 pp).

30. Wang, W.X., T.S. Hahm, S. Ethier, *P.H. Diamond*, G. Rewoldt, W.M. Tang and W.W. Lee, "Characteristics of Turbulence-Driven Plasma Flow and Origin of Experimental Empirical Scalings of Intrinsic Rotation", Phys. Plasmas 18(4), 042502, 2011 (12 pp).

31. Rice, J.E., J.W. Hughes, *P.H. Diamond*, Y. Kosuga, Y.A. Podpaly, M.L. Reinke, M.J. Greenwald, O.D. Gurcan, T.S. Hahm, A.E. Hubbard, E.S. Marmar, C.J. McDevitt and D.G. Whyte, "Edge Temperature Gradient as Intrinsic Rotation Drive in Alcator C-Mod Tokamak Plasmas", Phys. Rev. Lett. 106(21), 215001, 2011 (4 pp).

32. Wang, Z.H., *P.H. Diamond*, O.D. Gurcan, X. Garbet and X.G. Wang, "Turbulence Propagation in Heat Flux-Driven Plasmas: Implications for Temperature Profile Structure", Nucl. Fusion 51(7), 073009, 2011 (13 pp).

33. Kim, S.S., H. Jhang, *P.H. Diamond*, L. Terzolo, S. Yi and T.S. Hahm, "Intrinsic Rotation, Hystersis and Back Transition in Reversed Shear Internal Transport Barriers", Nucl. Fusion 51(7), 073021, 2011 (14 pp).

34. Rice, J.E., B.P. Duval, M.L. Reinke, Y.A. Podpaly, A. Bortolon, R.M. Churchill, I. Cziegler, *P.H. Diamond*, A. Dominguez, P.C. Ennever, C.L. Fiore, R.S. Granetz, M.J. Greenwald, A.E. Hubbard, J.W. Hughes, J.H. Irby, Y. Ma, E.S. Marmar, R.M. McDermott, M. Porkolab, N. Tsujii and S.M. Wolfe, "Observations of Core Toroidal Rotation Reversals in Alcator C-Mod Ohmic L-Mode Plasmas", Nucl. Fusion 51(8), 083005, 2011 (12 pp).

35. Wang, Lu and *P.H. Diamond*, "Kinetic Theory of the Turbulent Energy Pinch in Tokamak Plasmas", Nucl. Fusion 51(8), 083006, 2011 (8 pp).

36. Dif-Pradalier, G., *P.H. Diamond*, V. Grandgirard, Y. Sarazin, J. Abiteboul, X. Garbet, Ph. Ghendrih, G. Latu, A. Strugarek, S. Ku and C.S. Chang, "Neoclassical Physics in Full Distribution Function Gyrokinetics", Phys. Plasmas 18(6), 062309, 2011 (12 pp).

37. Xu, M., G.R. Tynan, *P.H. Diamond*, C. Holland, J.H. Yu and Z. Yan, "Generation of a Sheared Plasma Rotation by Emission, Propagation, and Absorption of Drift Wave Packets", Physical Review Letters, Vol. 107, No. 5, 055003, 2011 (4 pp).

38. Miki, K. and *P.H. Diamond*, "Novel States of Pre-Transition Edge Turbulence Emerging from Shearing Mode Competition", Nucl. Fusion 51, No. 10, 103003, 2011 (13 pp).

39. Leconte, M. and *P.H. Diamond*, "Effect of Resonant Magnetic Perturbations on Secondary Structures in Drift-Wave Turbulence", Phys. Plasmas 18(8), 082309, 2011 (14 pp).

40. Sarazin, Y., V. Grandgirard, J. Abiteboul, S. Allfrey, X. Garbet, Ph. Ghendrih, G. Latu, A. Strugarek, G. Dif-Pradalier, *P.H. Diamond*, S. Ku, C.S. Chang, B.F.

McMillan, T.M. Tran, L. Villard, S. Jolliet, A. Bottino and P. Angelino, "Predictions on Heat Transport and Plasma Rotation from Global Gyrokinetic Simulations", Nucl. Fusion 51(10), 103023, 2011 (12 pp.)

41. *Diamond, P.H.*, Y. Kosuga and M. Lesur, "Dynamics of Structures in Configuration Space and Phase Space: An Introductory Tutorial", Festival de Theorie 2009 Volume - To Be Published (35 pp.)

C. Forest Group (UW Madison):

1. N. Katz, et al., Convective Instability in the Plasma Couette Experiment (talk) , Bull. Amer. Phys. Soc. 55, 369 (2010)

2. N. Katz, et al., Microwave Heating and LIF in the Plasma Couette Experiment (poster), Bull. Amer. Phys. Soc. 55, 218 (2010)

3. N. Katz, et al.,"Plasma Dynamo Experiments (talk)", AGU 2010.

4. N. Katz, et al., Towards a Parker Instability in the Plasma Couette Experiment (talk),
5. CMTFO Meeting, 2011.

6. C. Collins, et al., Flow generation in the Plasma Couette Experiment (poster), Bull. Amer. Phys. Soc. 55, 217 (2010).

T. Munsat Group (Colorado):

1. B.J. Tobias, R.L. Boivin, J.E. Boom, I.G.J. Classen, C.W. Domier, A.J.H. Donne, W.W. Heidbrink, N.C. Luhmann, Jr., T. Munsat, C.M. Muscatello, R. Nazikian, H.K. Park, D.A. Spong, A.D. Turnbull, M.A. Van Zeeland, G.S. Yun, and DIII-D Team, "On the application of electron cyclotron emission imaging to the validation of theoretical models of magnetohydrodynamic activity," *Physics of Plasmas* **18** 056107 (2011).
2. D.A. Russell, J.R. Myra, D.A. D'Ippolito, T.L. Munsat, Y. Sechrest, R.J. Maqueda, D.P. Stotler, S.J. Zweben, and the NSTX Team, "Comparison of scrape-off layer turbulence simulations with experiments using a synthetic gas puff imaging diagnostic," *Physics of Plasmas* **18** 022306 (2011).
3. Y. Sechrest, T. Munsat, S.J. Zweben, R.J. Maqueda, D. Russell, D.A. D'Ippolito, and J.R. Myra, "Flow and Shear Behavior in the Edge and Scrape-off Layer in NSTX L-Mode Plasmas," *Physics of Plasmas* **18** 012502 (2011).
4. S.J. Zweben, R.J. Maqueda, R. Hager, K. Hallatschek, S. Kaye, T. Munsat, F.M. Poli, L. Roquemore, Y. Sechrest, and D.P. Stotler, "Quiet Periods in Edge Turbulence Preceding the L-H Transition in NSTX," *Physics of Plasmas* **17** 102502 (2010).
5. S.J. Zweben, R.J. Maqueda, J.L. Terry, T. Munsat, Y. Sechrest, R. Hager, D.A. D'Ippolito, J.R. Myra, D.A. Russell, "Edge Zonal-like Flows in NSTX and Alcator C-

Mod," US-Japan Workshop on Turbulent and Neoclassical Flow Generation and Associated Transport Dynamics, Long Branch, New Jersey, September 9-10, 2011

6. A.D. Light, D.A. Schaffner, Y. Sechrest, S.H. Muller, G.D. Rossi, D. Guice, T.A. Carter, G.R. Tynan, S. Vincena, and T. Munsat, "Turbulent Stress Measurements in LAPD and CSDX," Innovative Confinement Concepts Workshop, Seattle, WA, August 16-19, 2011.
7. S. J. Zweben, T. Munsat, Y. Sechrest, D. Battaglia, S.M. Kaye, S. Kubota, and the NSTX Team, "Relationship between edge zonal flows and L-H Transition in NSTX," Workshop on Electric Fields, Turbulence and Self-Organization in Magnetized Plasmas (EFTSOMP), Strasbourg, France, July 4-5, 2011
8. Y. Sechrest, T. Munsat, S.J. Zweben, R.J. Maqueda, and the NSTX team, "Turbulence and Flow Interactions in the NSTX Edge," Joint US-EU Transport Taskforce Workshop, San Diego, California April 6-9, 2011.
9. H.K. Park, N.C. Luhmann Jr., A.J.H. Donne, B. Tobias, G.S. Yun, M. Choi, I.G.J. Classen, C.W. Domier, J.C. Kim, X. Kong, W. Lee, T. Liang, T. Munsat, L. Yu, and Asdex Ugrade Team, "Comparative Study of Sawtooth Physics and Alfven Waves via 2-D ECE Imaging on KSTAR, DIII-D, AUG and TEXTOR," 23rd IAEA Fusion Energy Conference, Daejon, Korea, Oct. 11-16, 2010.
10. T. Munsat, Y. Sechrest, "Advances in Velocimetry Techniques for Plasma Turbulence Studies," 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, Nov. 8 - 12, 2010.
11. A.Light, M. Schmidt, K. Laszlo, T. Munsat, "Flow and Fluctuations in the Colorado FRC Experiment," 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, Nov. 8 - 12, 2010.
12. Y. Sechrest, T. Munsat, S. Zweben, R. Maqueda, D. D'Ippolito, J. Myra, D. Russell, "Flow and Shear Behavior in the Edge and SOL in NSTX L-mode Plasmas," 52nd Annual Meeting of the APS Division of Plasma Physics, Chicago, Nov. 8 - 12, 2010.
13. A.Light, M.T. Schmidt, T. Munsat, "Latest Results from the Colorado FRC Experiment," Innovative Confinement Concepts Workshop, Princeton, NJ, February 16-19, 2010.
14. T. Munsat, I.G.J. Classen, C.W. Domier, A.J.H. Donne, N.C. Luhmann, Jr., H.K. Park, B. Tobias, "Temperature Fluctuations during Sawtooth Crashes in TEXTOR," 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, Nov. 2 - 6, 2009.
15. Y. Sechrest, B. Brown, T. Munsat, N. Sen, X. Xu, S. Zweben, "Validation of Velocimetry Techniques using Synthetic Diagnostics in Edge Turbulence Simulations," 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, Nov. 2 - 6, 2009.
16. A.L. Roquemore, S.J. Zweben, R.J. Maqueda, S. Kubota, T. Munsat, S. Kaye, R. Maingi, B.D. Scott, T.S. Hahm, "GPI Measurements of Edge and SOL Turbulence Across the L-H transition in NSTX," 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, Nov. 2 - 6, 2009.
17. Benjamin Brown, T. Munsat, Y. Sechrest, N. Sen, "Advances in Velocimetry Techniques for Plasma Turbulence," 51st Annual Meeting of the APS Division of Plasma Physics, Atlanta, Nov. 2 - 6, 2009.

P.W. Terry Group (UW Madison)

1. J.-H. Kim and P.W. Terry, "Turbulence suppression in a coherent structure of localized current and vorticity", Bull. Amer. Phys. Soc. **55**, 369 (2010).

2. J.-H. Kim and P.W. Terry, "Transport Barrier Formation in Quasi-Single Helicity RFP Plasmas", IEA Conference, 2011

3. J.-H. Kim and P.W. Terry, , "Turbulence suppression in a coherent structure of localized current and vorticity", TTF 2011

4. J.-H. Kim and P.W. Terry, , "Turbulence suppression in a coherent structure of localized current and vorticity", APS DPP, 2011

5. X. Chen, et al., "Advances in the measurement of electrostatic fluctuations and inference of particle flux with a heavy ion beam probe in improved confinement MST plasmas", Bull. Amer. Phys. Soc. **55**, 264 (2010).

6. D. Carmody and P.W. Terry, "Low Collisionality Destabilization of Microtearing Modes by Negative Magnetic Shear in the RFP", IEA Conference, 2011

7. P.J. Fimognari, D.R. Demers, and P.W. Terry, "Heavy Ion Beam Probe sample volume characteristics in the MST RFP and effects on single and multipoint measurements", APS DPP, 2011.

8. D. Carmody and P.W. Terry, "Gyrokinetic Studies of Microtearing Modes in the Reversed Field Pinch", APS DPP, 2011

G.R. Tynan Group (UCSD)

1. J. A. Boedo, E. A. Belli, E. Hollmann, W. M. Solomon, D. L. Rudakov, J. G. Watkins, R. Prater, J. Candy, R. J. Groebner, K. H. Burrell, J. S. Degrassie, C. J. Lasnier, A. W. Leonard, R. A. Moyer, G. D. Porter, N. H. Brooks, S. Muller, G. Tynan and E. A. Unterberg, *Poloidally and radially resolved parallel D(+) velocity measurements in the DIII-D boundary and comparison to neoclassical computations*, Physics of Plasmas **18** (3) (2011).

2. P. Manz, M. Xu, S. C. Thakur and G. R. Tynan, *Nonlinear energy transfer during the transition to drift-interchange turbulence*, Plasma Physics and Controlled Fusion **53** (9) (2011).

3. S. H. Muller, J. A. Boedo, K. H. Burrell, J. S. Degrassie, R. A. Moyer, D. L. Rudakov and W. M. Solomon, *Experimental Investigation of the Role of Fluid Turbulent Stresses and Edge Plasma Flows for Intrinsic Rotation Generation in DIII-D H-Mode Plasmas*, Physical Review Letters **106** (11) (2011).

4. S. H. Muller, J. A. Boedo, K. H. Burrell, J. S. deGrassie, R. A. Moyer, D. L. Rudakov, W. M. Solomon and G. R. Tynan, *Intrinsic rotation generation in ELM-free H-mode plasmas in the DIII-D tokamak-Experimental observations*, Physics of Plasmas **18** (7) (2011).

5. G. R. Tynan, P. H. Diamond, C. Holland, S. H. Muller, M. Xu, Z. Yan and J. Yu, *Nonlinear dynamics of shear flows and plasma rotation in a simple laboratory plasma system*, Plasma Physics and Controlled Fusion **51** (12) (2009).

6. G. R. Tynan, A. Fujisawa and G. McKee, *A review of experimental drift turbulence studies*, Plasma Physics and Controlled Fusion **51** (11) (2009).

7. G. S. Xu, B. N. Wan, H. Q. Wang, H. Y. Guo, H. L. Zhao, A. D. Liu, V. Naulin, P. H. Diamond, G. R. Tynan, M. Xu, R. Chen, M. Jiang, P. Liu, N. Yan, W. Zhang, L. Wang, S. C. Liu and S. Y. Ding, *First Evidence of the Role of Zonal Flows for the L-H Transition at Marginal Input Power in the EAST Tokamak*, Physical Review Letters **107** (12) (2011).

8. M. Xu, G. R. Tynan, P. H. Diamond, C. Holland, J. H. Yu and Z. Yan, *Generation of a Sheared Plasma Rotation by Emission, Propagation, and Absorption of Drift Wave Packets*, Physical Review Letters **107** (5) (2011).

9. M. Xu, G. R. Tynan, C. Holland, Z. Yan, S. H. Muller and J. H. Yu, *Fourier-domain study of drift turbulence driven sheared flow in a laboratory plasma*, Physics of Plasmas **17** (3) (2010).

10. Z. Yan, G. R. Tynan, C. Holland, M. Xu, S. H. Muller and J. H. Yu, *Shear flow and drift wave turbulence dynamics in a cylindrical plasma device*, Physics of Plasmas **17** (3) (2010).

11. Z. Yan, G. R. Tynan, C. Holland, M. Xu, S. H. Muller and J. H. Yu, *Scaling properties of turbulence driven shear flow*, Physics of Plasmas **17** (1) (2010).

12. Z. Yan, M. Xu, P. H. Diamond, C. Holland, S. H. Muller, G. R. Tynan and J. H. Yu, *Intrinsic Rotation from a Residual Stress at the Boundary of a Cylindrical Laboratory Plasma*, Physical Review Letters **104** (6) (2010).

Appendix D: List of Collaborators

The following institutions and individuals would receive direct funding from OFES-DOE as part of their participation in the Center. Each listed institution is responsible for submitting their own budgets to DOE for the work, along with a statement of work that is consistent with the overall proposal being submitted by UCSD on behalf of the group.

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In addition to the above collaborators receiving direct funding from OFES-DOE, UCSD will be supporting post-doctoral researchers who will be based remotely at these institutions and will with the following groups:

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Princeton Plasma Physics Laboratory

Dr. Weixing Wang

Plasma Fusion Science Center, MIT

Dr. John Rice

Unfunded Collaborators

Professor Steve Tobias, University of Leeds, UK
Professor David Hughes, University of Leeds, UK

HL-2A Tokamak, Southwestern Institute of Physics, Chengdu China
EAST Tokamak, Academic of Sciences Institute of Plasma Physics, Hedei, China
DIII-D Natioanl Fusion Facility, General Atomics, San Diego CA
NSTX Experiment, PPPL
World Class Institute, NRFI, Rep. of Korea
Centre Energie Atomique, Cadarache, France
Kyushu University, Japan
LLNL, Livermore CA

Appendix E: Letters of Support from Large Collaborating Facilities

SWIP, Chengdu China
ASIPP, Hefei China
Dr. John Rice, MIT ALCATOR CMOD
Dr. Mickey Wade, DIIID National Fusion Facility

西 南 物 理 研 究 院
SOUTHWESTERN INSTITUTE OF PHYSICS
P.O.Box 432, 610041 Chengdu, P.R. China

To: Professor George Tynan
Director, Center for Momentum Transport and Flow Organization (CMTFO),
UC San Diego, USA

Subject: Continued collaboration on HL-2A

Chengdu，5/12/2011

Dear Professor Tynan,

As Deputy Director of the Southwestern Institute of Physics (SWIP) in charge of fusion research, I am pleased to confirm our interest in continuing experimental and theoretical collaboration with the Center for Momentum Transport and Flow Organization (CMTFO) on turbulence, momentum transport and flow organization. The work begun in 2011on HL-2A has provided a solid basis for this work. We are particularly interested in continuing our collaborative studies of the physics of the L-H transition, the origins of intrinsic toroidal rotation, and turbulence-zonal flow interactions on the device. In collaboration with Professor Patrick Diamond and his group at UCSD and at the WCI in the Republic of Korea, we also look forward to continued theoretical and computational studies of these and related problems.

You and your colleagues are most welcome at the SWIP and we look forward to our continued work together.

Sincerely,

Duan Xu

Dr. Xuru Duan
Deputy Director, Southwestern Institute of Physics (SWIP)
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中国科学院等离子体物理研究所
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Continuing collaboration between UCSD and ASIPP

The Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) at Hefei has begun operating the EAST tokamak device and is working to develop the capability of demonstrating steady-state tokamak operations in high performance fusion-grade plasmas. The plasma edge and scrape-off layer (SOL) region, and the accompanying plasma-material interactions (PMI) that occur at the first wall and in the divertor region of the device, play a critical role in achieving these objectives. Thus study of turbulence and transport in the edge and SOL, and of the PMI that occur in the EAST device are of interest to the ASIPP.

The University of California San Diego (UCSD) has several groups whose research interests and expertise lead them to propose a collaboration with the ASIPP. Professors Tynan and lead the newly established Center for Momentum Transport and Flow Organization (CMTFO), which is focused on studies of the physics mechanisms that lead to the formation of large scale well ordered flows in tokamak plasmas.

The collaboration has been established between UCSD and ASIPP since April, 2011. Since then, a series of co-operational activities have been carried out. Firstly, Dr. Min Xu visited ASIPP in May, in order to make preparations for the next joint experiments on EAST. Secondly, in June, Prof. Patrick Diamond visited USTC. We have discussed a lot about the Zonal flows and rotation. We also worked on the paper titled "First evidence of the role of zonal flows for the L-H transition at marginal input power in the EAST tokamak", which has been published on the *Physical Review Letters* in this September. And now, we are together preparing another paper which will also be submitted to the *Physical Review letters*, the data are from EAST, and UCSD are conducting the analysis and simulations. So we think it is very necessary and important to go on with the collaboration between us.

ASIPP:

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CMTFO C-Mod Plans for 2012

A paper on rotation reversals and Ohmic confinement, 'Rotation Reversal Bifurcation and Energy Confinement Saturation in Tokamak Ohmic L-mode Plasmas' by J.E.Rice, I.Cziegler, P.H.Diamond et al. has been recently accepted for publication in Phys. Rev. Lett. The paper describes the connection between core toroidal rotation reversals and Ohmic energy confinement saturation, including significant changes in turbulence characteristics at the transition. A high k, high frequency feature is present in the spectrum of density fluctuations at low density, which abruptly disappears when the rotation reversal occurs following a slight increase in the collisionality. The work plan for 2012 will be a comprehensive characterization of the turbulence changes at the linear Ohmic confinement (LOC) to saturated Ohmic confinement (SOC) regime transition. The following specific points will be addressed:

1.) What is the maximum wavenumber and frequency of the feature observed in the LOC regime?
2.) What is the mode propagation direction in the plasma frame?
3.) What is the spatial extent of the LOC turbulence feature?
4.) Are there any turbulent features which appear in the SOC regime?

These studies will be part of the C-Mod 2012 Joint Research Target on core confinement. The primary diagnostics will be the high resolution imaging spectrometer system, the Phase Contrast Imaging system, the reflectometer and the Gas Puff Imaging diagnostic.

Other related studies will involve the connection to non-diffusive thermal transport, up-down impurity asymmetries and particle transport. The dependence of the transition on collisionality will be explored.

-Dr. John Rice, ALCATOR C-MOD, MIT PSFC

DIII-D
NATIONAL FUSION FACILITY

December 4, 2011

Dr. George Tynan
Professor of Engineering Science
Department of Mechanical and Aerospace Engineering
456 EBU-II MC 0417
University of California, San Diego
9500 Gilman Drive
La Jolla CA 92093 USA

Dear Dr. Tynan:

This letter is to express the interest and support of the DIII-D research program in the continued funding of the DoE Plasma Science Center at UCSD on Momentum Transport and Flow. Research funded by this Center on DIII-D over the past several years has led to grown-breaking discoveries about the formation of localized regions of intrinsic rotation near the edge and the connection of this rotation with edge turbulence. I believe that continued funding of the Center will likely lead to a better understanding of the mechanisms leading to intrinsic rotation, which could be of potential importance in the realized performance on ITER. For this reason, the DIII-D program is interested in collaborating with this Science Center and will provide appropriate resources including experimental time, if necessary, towards the proposed research.

Sincerely,

Mickey R. Wade

Mickey R. Wade
Director, Experimental Science Division
DIII-D National Fusion Facility

Princeton University PLASMA PHYSICS LABORATORY
JAMES FORRESTAL CAMPUS
P.O. BOX 451, PRINCETON, NJ 08543–0451

August 18, 2011

Prof. George Tynan
Dept. of Mechanical and Aerospace Engineering
University of California at San Diego
9500 Gilman Dr., La Jolla CA 92093–0411

Dear Prof. Tynan:

In response to the recent conversation between you and Riccardo Betti, this letter is intended to confirm that the PPPL Theory Dept. will be happy to host a UCSD post-doc to work in the general area of momentum transport and flow generation in fusion plasmas. This person would be supervised by me and would be expected to apply the Gyrokinetic Tokamak Simulation (GTS) code to problems of current interest. The research would involve close coupling between theoretical and experimental studies; it would include verification against theory and validation against experiments of C-MOD, DIII-D, and NSTX. We view this opportunity as mutually beneficial for your Center for Momentum Transport and Flow Organization, for ongoing research at PPPL, and for the broader needs of the fusion program. Therefore, we are very happy to participate.

Sincerely,

Weixing Wang
Research Physicist