A local solution to a global problem: treating radial profile variation and intrinsic momentum transport in a flux tube gyrokinetic code

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Tokamak plasmas are routinely observed to rotate even in the absence of an externally applied torque. This `intrinsic' rotation exhibits several robust features, including rotation reversals with varying plasma density and current and rotation peaking at the transition from low confinement to high confinement regimes. Conservation of toroidal angular momentum dictates that the intrinsic rotation is determined by momentum redistribution within the plasma, which is dominated by turbulent transport. For up-down symmetric magnetic equilibria, the turbulent momentum transport, and thus the intrinsic rotation profile, is driven by formally small effects that are usually neglected in simulations and analysis.

We present a gyrokinetic theory that makes use of the smallness of the poloidal to total magnetic field ratio to self-consistently treat the dominant effects driving intrinsic turbulent momentum transport in tokamaks. These effects (including slow radial profile variation, slow poloidal turbulence variation, and diamagnetic corrections to the equilibrium Maxwellian) have now been implemented in the local, delta-f gyrokinetic code GS2. We describe important features of the numerical implementation; in particular, the novel WKB-like method used to capture 'global' effects in a flux tube simulation domain. Finally, we present numerical results illustrating the impact of these formally small effects on intrinsic turbulent momentum transport and compare with experimental observations of intrinsic rotation reversals.

Oral

Designing a Tokamak Fusion Reactor
No Plasma Physics Required

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This work describes some basic tokamak reactor results that are well known by a small portion of the fusion community, but not by most others, particularly the new generation of plasma physicists. Specifically, the work demonstrates that the overall design of a tokamak fusion reactor is actually determined almost entirely by the constraints imposed by nuclear physics and fusion engineering. Virtually no plasma physics is required to determine the main design parameters of a reactor: n, T_i, T_e, a, R_0, B_0. Instead, the "nuclear physics – fusion engineering" designed reactor makes **demands** on the plasma physics that must be satisfied in order to generate power. It is the job of the plasma physics community to discover ways to meet these demands. If the demands cannot be met, the design must be altered to accommodate the plasma physics, and this is always in a direction to make the final reactor less desirable economically. Since the design without worrying about plasma physics is already not very attractive economically, there is not a lot room to cure poor plasma performance.

As implied, many of the results presented here have already been obtained by sophisticated and detailed numerical design studies, for instance as in the ARIES series of fusion reactors. What is new in the present work is that the basic design can be carried out entirely analytically with the final parameters being semi-quantitatively accurate. That is, they are much more accurate than what might be expected from simple scaling relations and back-of-the-envelope estimates. The calculation thus provides a crisp, compact, logical design procedure for a tokamak fusion reactor in a simple-to-understand analytical framework.

Once the design is determined the resulting plasma physics demands are substituted into the well-known constraints arising in tokamak physics, for example the Troyon limit, Greenwald limit, kink stability limit, H-mode confinement time limit, etc. Some of these constraints are satisfied, while some are not. This is crucial information, since knowledge of the unsatisfied constraints defines a set of "show-stopping" plasma physics issues. These issues must be solved in order for the tokamak to lead to a power reactor. They, therefore, define several critical areas of fusion research which should probably be carried out on existing facilities in order to learn, sooner rather than later, whether solutions are possible. If solutions do exist, they may involve clever plasma physics. However, the reactor design presented here also suggests that certain high leverage fusion engineering innovations can, perhaps surprisingly, lead to plasma physics solutions while simultaneously improving reactor reliability. The specific plasma physics show stoppers and high leverage engineering innovations have been identified and will be presented at the conference.

Poster but could be an oral tutorial type talk if so desired by the selection committee

Alpha Heating in ICF Implosions at the National Ignition Facility*

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The National Ignition Facility (NIF) has been conducting experiments using the indirect drive approach, with the goal of achieving thermonuclear burn in the laboratory. In these experiments, up to 1.8 MJ of ultraviolet light (0.35 micron) is injected into a 1 cm scale, gas-filled hohlraum, to implode a 1 mm radius capsule that contains a solid DT fuel layer.

Research at NIF has made good progress over the course of the last year. An increase in laser power early in the pulse (i.e., "High Foot") makes the capsule more robust by preventing hydrodynamic instabilities, which mix cold ablator material into the central hotspot, thereby quenching the ignition process. These "high foot" NIF shots have achieved record yield. In these implosions, the amount of fusion yield that derives from alpha-heating is almost equal to the yield from compression alone, nearly doubling the total number of neutrons.

Over the course of the next year, plans to further improve this yield include improving the shape of the implosion (keeping it more spherical as it converges by a factor of ~ 30), and improving hohlraum performance (by changing the shape of the hohlraum from cylindrical to rugby). This campaign also plans to push the capsule to higher velocity (and thus higher yield), and further plans to explore "medium foot" options.

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Prefer Oral Presentation

Rapid Change of Field Line Connectivity and Reconnection in Stochastic Magnetic Fields

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Abstract

Magnetic fields depending on three spatial coordinates generally have the feature that neighboring field lines exponentiate away from each other and become stochastic. Such a generic condition can occur in a number of contexts in fusion plasmas such as tokamaks or reversed-field pinches in the presence of multiple tearing modes, or in the solar corona. Under the condition of large exponentiation, the ideal constraint of preserving magnetic field line connectivity becomes exponentially sensitive to small deviations from ideal Ohm's law, which may potentially lead to rapid magnetic reconnection. This idea of breaking field line connectivity by stochasticity is tested with numerical simulations based on reduced magnetohydrodynamics equations with a strong guide field line-tied to two perfectly conducting end plates. Starting from an ideally stable force-free equilibrium, the system is allowed to undergo resistive relaxation. During the early phase when the system evolves quasi-statically, it is found that regions of high field line exponentiation (akin to quasi-separatrix-layers) are associated with rapid change of field line connectivity and strong induced flow. However, although the field line connectivity of individual field lines can change rapidly, the overall pattern of footpoint mapping appears to deform gradually. From this perspective, field line exponentiation appears to cause enhanced diffusion rather than reconnection during this phase. At a later time, it is found that resistive quasi-static evolution can cause the ideally stable initial equilibrium to cross an ideal stability threshold. Onset of the instability causes formation of intense current filaments, followed by rapid change of field line mapping into a qualitatively different pattern. It is in this phase that the change of field line connectivity may be more appropriately designated as magnetic reconnection. Our results reveal and address the difficulty in distinguishing magnetic reconnection from enhanced diffusion in the presence of field line stochasticity. Rapid change of field line connectivity appears to be a necessary, but may not be sufficient, condition for fast reconnection.

[Oral]

An enstrophy minimizing method for 3D MHD Equilibrium with Flow

Samuel A. Lazerson,* Stuart Hudson, and David Gates
PPPL
(Dated: January 2, 2014)

A variational technique for finding steady state solutions to the set of ideal MHD equations, with finite velocity terms, is described. In this formulation it is assumed that flows self-organize into minimum enstrophy states and no axisymmetric assumptions are made. As a result the derived equations are applicable to both axisymmetric and 3D systems (stellarators and perturbed tokamaks). The resulting minimized quantity is no longer the energy of the system but rather a linear combination of the flow enstrophy and magnetic energy. The constraints of magneic helicity, flow helicity, cross helicity, and mass are invoked to ensure the extremized states are non-trivial. This avoids the ill-posed problem of minimizing the ideal MHD kinetic energy term subject to such constraints. The resulting set of coupled Beltrami-like equations then define the system with three helicity multipliers. The constraint of flow helicity may then be relaxed, resulting in a similar system of equations (with two helicity multipliers). The analysis presented focuses on the incompressible limit ($\nabla \cdot \vec{v} = 0$) which is relevant to many perturbed tokamaks, stellarators, and reverse field pinches (RFP). The force free limit ($\nabla p = 0$) is directly applicable to the RFP and may be expanded to tokamaks and stellarators (by invoking a stepped pressure). The cylindrical limit is explored to develop connections between the angular momentum and flow vorticity. The physical implications of minimizing this functional are discussed.

On the formation of phase space holes and clumps

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We show that the formation of phase space holes and clumps in kinetically driven, dissipative systems is not restricted to the near threshold regime, as previously reported and widely believed. Specifically, we observe hole/clump generation from the edges of an unmodulated phase space plateau, created by the excitation, phase mixing and subsequent dissipative decay of a kinetically driven, linearly unstable bulk plasma mode in the electrostatic bump on tail model (the standard paradigm transferable to the general wave-particle interaction processes). This has now allowed us to elucidate the underlying physics of the hole/clump formation process for the first time. Holes and clumps are side-band negative energy waves, which arise due to the sharp gradients at the interface between the plateau and the nearly unperturbed, ambient distribution, which destabilise in the presence of dissipation in the bulk plasma. We confirm this picture by demonstrating that the formation of such nonlinear structures does not in general rely on a “seed” wave. In fact regimes of linear stability for the bulk plasma can still generate holes and clumps, so long as a plateau exists. In addition, we observe repetitive cycles in which 1) a large plateau is first formed; 2) it is gradually eroded as hole/clump pairs detach, making the plateau smaller; 3) nonlinear interactions within the smallest plateau initiates a rebuild process to a large plateau state. This cycle appears insensitive to initial conditions and persists for a long time

ORAL

Simulated flux rope evolution and relaxation during non-inductive startup in the Pegasus ST[1]

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The dynamics and relaxation of magnetic flux ropes produced during non-inductive startup of the Pegasus Toroidal Experiment [Eidietis, *J. Fusion Energy.* **26**, 43 (2007)] are simulated with nonlinear MHD and two-fluid plasma models. A single injector is represented by a localized source-density for magnetic helicity and thermal energy. Results show development of a hollow tokamak-like profile of average $J_{\|}$ from a sequence of co-helicity merging events, wherein adjacent passes of the helical flux rope merge and reconnect, releasing flux-rope rings from the driven flux rope.[O'Bryan, *Phys. Plas.* **19**, 080701 (2012)]. Accumulation of poloidal flux over multiple relaxation events redirects the driven flux rope so that its path traces a toroidal surface. The presence of a quasi-separatrix layer during ring formation events is supported by analysis of the squashing-degree parameter (Q), where magnetic field-lines launched from the bottom surface of the domain produce a rolled surface of large Q. The layer bifurcates twice, once between non-reconnecting passes and again between reconnecting passes of the driven flux rope. Chaotic scattering during ring formation is also apparent from the distribution of magnetic field-line lengths. The longest magnetic field-lines correlate well with the largest values of Q. Scaling studies demonstrate that the topological evolution of the flux ropes is robust to variation in the viscosity and number diffusivity parameters.

The merging of adjacent passes of the driven flux rope constitutes coherent dynamo action that affects the global distribution. The effective MHD dynamo loop voltage–primarily from the vertical displacement of the flux rope–concentrates symmetric poloidal flux during ring formation and transfers significant energy to the flux-rope ring. Computations with the two-fluid plasma model produce qualitatively similar plasma evolution. The Hall dynamo effect acts over a much smaller region than the MHD dynamo and primarily contributes to the shaping of the current ring. Similar to experimental results, the magnetic fluctuations during helicity injection are approximately 5% of the toroidal field with significant activity in the 10-20 kHz range. After cessation of the simulated current drive, temperature and current profiles broaden and closed flux surfaces form rapidly, leaving a tokamak-like plasma suitable for transition to other forms of current drive.

[1]Work Supported by the U.S. Dept. of Energy

Oral Session Requested

Nonlinear Gyrokinetic Simulations of the Tokamak Edge Pedestal

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Gyrokinetic turbulence simulations are finely tuned to accurately capture the low fluctuation levels and weak density and temperature gradients typical in core tokamak plasmas. In contrast, the tokamak edge pedestal has relatively short gradient scale lengths and large electromagnetic fluctuations. This makes direct gyrokinetic simulation of the edge extremely challenging. In this talk we discuss these challenges and the significant progress made in this research area. Global gyrokinetic simulations find an unstable intermediate-n mode that resembles the MHD "peeling-ballooning mode" (PBM), thought to be responsible for the ELM. Linear simulations show that the kinetic PBM is an electromagnetic instability, propagates in the electron diamagnetic direction, has a real frequency in the drift-Alfven range, and is sensitive to the q-profile.[1,2] With the experimental q-profile, the intermediate-n kinetic PBM dominates over the high-n "kinetic ballooning mode" in most cases. Simulations with the unstable kinetic PBM nonlinearly saturate at high levels, with amplitudes peaking in the intermediate-n range. This qualitative behavior is found for simulations of several different DIII-D and C-Mod plasma discharges near the end of an ELM cycle. The general numerical magnetic equilibrium is used including up-down asymmetry. The stabilizing effect of the equilibrium radial electric field (Er) is found to be relatively weak both linearly and nonlinearly. While the linear growth rate of the KPBM is sensitive to the magnetic equilibrium, we found that except for the q-profile, the effects of the magnetic parameters are only quantitative. The results indicate that the density gradient, the q-profile, and hence the bootstrap current, are crucial for determining the stability of the KPBM.

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Oral

Dynamic boundary plasma-wall modeling of ELMy H-mode

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Physical processes in the boundary plasma and wall material strongly influence many of the most crucial issues of magnetic fusion science, such as: parameters of the edge plasma pedestal in H-mode (and, therefore, the core plasma confinement and fusion power); impurity contamination; divertor-plasma detachment; hydrogen isotope content in plasma and wall; transient and peak power load handling; and lifetime of plasma-facing components (PFCs). In current tokamaks the L-to-H mode transition as well as the recovery of H-mode pedestal after the ELMs involve simultaneous changes in both plasma transport and absorption/desorption processes of the working gas from PFCs.

The goal of our research is to study the roles of wall-related physical processes (adsorption, desorption, trapping, implantation, sputtering, etc) in the dynamics of ELMy H-mode discharges. Here we demostrate the dominant role of wall deuterium absorption and outgassing phenomena in the H-mode pedestal evolution during the ELM cycle.

In our studies, we use a new version of UEDGE code, called UEDGE-MB [A.Yu. Pigarov et al., PoP 18 (2011)], which implements the Macro-Blob approach allowing to simulate the spatiotemporal effects of highly intermittent, filamentary, non-diffusive transport observed during the ELMs. UEDGE-MB also incorporates time-dependent models for particle recycling, wall temperature, and deuterium inventory for each material boundary of the 2-D modeling domain.

We present the results of UEDGE-MB simulations of experimental data for H-mode DIII-D shots with type-I ELMs and with different pedestal plasma densities and ELM frequencies. Temporal evolutions of pedestal plasma profiles, divertor recycling, particle and power loads on divertor plates and chamber wall, surface temperature, and wall inventory in a sequence of ELMs are modeled and compared to the experimental time-dependent data. Short (during ELMs) and long (between ELMs) time scale variations of the pedestal and divertor plasmas are discussed. We show that the ELM recovery includes the phase of relatively dense and cold post-ELM divertor plasma evolving on a several ms scale, which is set by the transport properties of H-mode barrier. The global gas balance in these shots is analyzed. The calculated rates of deuterium deposition during the ELM and wall outgassing between the ELMs are compared to the ELM particle losses and NBI fueling rate, correspondingly. The sensitivity study of the pedestal and divertor plasmas to the model assumptions on the gas deposition and release on material surfaces is presented. The performed simulations show that the dynamics of pedestal particle inventory is dominated by the transit intense deuterium deposition into the wall during ELMs followed by the continuous gas release between ELMs roughly at constant rate. The dynamic deposition/release equilibrium attained in the saturated wall in a sequence of many ELMs and the roles of different plasma-material interaction processes in generating gas release are analyzed.

ORAL

Trapped particle precession and effective mass in Rosenbluth-Hinton type zonal flows

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Abstract

If an initial radial $\boldsymbol{E}$ field is set up in an axisymmetric collisionless tokamak, this results in GAMs. The latter Landau damp, leaving a residual steady $\boldsymbol{E}$ field[1,2] which is smaller than the initial field by a factor of $\approx 1.6q^2/\sqrt{\epsilon} \gg 1$ The final $\boldsymbol{E}$ field is consistent with conservation of toroidal angular momentum given the initial $\boldsymbol{E}$ field. It is well known that for a steady state $\boldsymbol{E}$, trapped particles (TPs) will undergo a rapid toroidal precession at the speed $\sim q u_E/\epsilon$, where u_E is the $\boldsymbol{E} \times \boldsymbol{B}$ drift. We observe, however, that the toroidal momentum in the precessing TPs is much larger than the residual Rosenbluth-Hinton (RH) toroidal momentum. Upon calculating the bounce-averaged TP toroidal flow from the RH distribution function, using conventional energy coordinates, we find the TP toroidal flow speed to be much smaller than the expected precession speed. Further, the calculation yields a nonzero poloidal flow for TPs. In addition, the RH effective mass is smaller than is expected from simple drift models: in particular, the origin of the effective mass can be described in analogy to the Lagrangian of two mass beads on a rigid massless rod pushed perpendicularly, with the beads free to slide along the rod, but one bead constrained to a linear 1-D channel to mimic the TPs. We show that the above-mentioned apparent discrepancies can be resolved by transforming to energy coordinates shifted with respect to the $v_{||}$ coordinate,with the shift[3] proportional to u_E. We show, in fact, that even in the limit of small $\boldsymbol{E}$, the corresponding first order shift in the phase space Jacobian must be retained as it acts on the zeroth order distribution function. Allowing for this Jacobian shift yields the correct precession and a zero poloidal flow of the TPs. The effective mass, if calculated separately for TPs and CPs, is in accordance with the precession based on the toy model Lagrangian. However, the composite effective mass is smaller and in agreement with the RH calculation. Underlying reasons for this are discussed. The calculations are essentially done in the sub-bounce-frequency limit, an assumption that fails near the separatrix. To explore the dynamics near the separatrix, a more general calculation based on action-angle coordinates has been commenced which may allow for low bounce frequency effects. This will be briefly described.

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Oral session

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Modeling of tungsten and beryllium dust impact on ITER-like plasma edge

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With the progress of magnetic fusion toward increasing power and duration of plasma discharges, the plasma-wall coupling and its impact on performance of plasma edge and divertor, in particular, gain growing importance due to operational limits of wall materials. The large stationary or intermittent particle and heat fluxes can damage plasma-facing components, i.e. tungsten divertor and beryllium walls in ITER [1], leading to production and mobilization of metallic dust and droplets. Transport and ablation of such dust in the boundary plasmas is an important mechanism of impurity contamination, which can significantly affect fusion plasma operation.

In this work we investigate impact of tungsten and beryllium dust/droplets on edge plasmas in ITER-like discharge using computer simulations with the coupled dust-plasma transport code DUSTT/UEDGE [2]. The mixed Monte-Carlo/multi-fluid code allows to model self-consistently the dynamics of dust in tokamak peripheral plasma and the plasma response to the dust-impurity contamination. Various scenarios of the dust injection in divertor and upstream plasmas are modeled, taking into account the first 21 charge states of tungsten and all that of beryllium impurities. The dust of sizes ranged from 1μm to 100μm and mass rates of dust injection varied from 1mg/s up to ~1g/s are simulated. We demonstrate that injection of beryllium and tungsten dust with rates ~300mg/s and ~30mg/s, correspondingly, can significantly impact ITER operation leading to the divertor plasma detachment and degradation of the pedestal temperature. Larger amounts of dust can further cause divertor plasma thermal instability and discharge termination. The impurity radiation patterns, divertor heat load profiles, dust material in-core penetration and wall redeposition profiles are also analyzed for the considered dust injection scenarios. Significant differences in these effects caused by beryllium and tungsten dust, as well as by dust of different sizes are demonstrated. The implications of the obtained results on dust production limits in ITER are discussed.

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Prefer oral presentation.

Toroidal rotation produced by disruptions and ELMs

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In several experiments, including NSTX [1], Alcator C-Mod [2], and JET [3], it was observed that disruptions were accompanied by toroidal rotation. There is a concern that there may be a resonance between rotating toroidal perturbations and the resonant frequencies of the ITER vacuum vessel, causing enhanced damage. We present MHD simulations with M3D [4], as well theory, demonstrating that disruptions can produce toroidal rotation. Edge localized modes (ELMs) can also produce poloidal and toroidal rotation.

Net toroidal rotation requires [5] three conditions. (1) The poloidal magnetic field penetrates the wall, which is a condition that the plasma can transmit torque to the wall. (2) Rotation requires vertical asymmetry, which can be produced by a VDE. Simulations and theory indicate that the magnitude of the rotation is a stong function of VDE displacement. (3) Rotation requires MHD turbulence. In disruption simulations, the thermal quench and rotation generation occur at the same time, and are caused by toroidally varying MHD perturbations. The rotation persists into the current quench. Theory indicates that at least two modes, with poloidal and toroidal mode numbers $(m, n), (m + 1, n)$ must be present to cause toroidal rotation.

The toroidal velocity has a zonal structure, changing sign from the plasma core to the edge region. The maximum velocity can be an order of magnitude larger than the net velocity. Work is in progress to identify the scaling of the rotation with plasma parameters and assess its importance for ITER.

Rotation is also seen in MHD simulations of ELMs. It is possible that this mechanism is a cause of intrinsic toroidal rotation observed in H mode tokamaks. Theory gives toroidal rotation Alfvén Mach number, $M_\phi \approx 10^{-2}\beta_N$. This is consistent with a scaling [6] for intrinsic toroidal rotation.

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ORAL