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RECENT, ONGOING AND PLANNED WORK IN PLASMA EDGE AND ROTATION PHYSICS AT GEORGIA TECH IN SUPPORT OF DIII-D

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I. RADIATIVE EDGE

The Georgia Tech plasma group efforts were directed to radiative edge physics in the early 1990s. Injection of low-to-intermediate-Z impurities into the plasma edge to radiatively exhaust over a larger area the outflowing power that would otherwise flow onto the ITER divertor plate was first suggested in 1996 [1] (from which the later idea of a radiative divertor naturally evolved), and in 1998 the Georgia Tech group was invited by the then DIII-D program leader, Tom Simonen, to work with the DIII-D team on the development of this and related topics. This work quickly expanded to the modeling of edge radiative instabilities (MARFEs, disruptive collapse of radiative edge) in DIII-D and the confirmatory prediction of plasma density limits imposed thereby [2,3].

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II. NON-DIFFUSIVE TRANSPORT IN THE PLASMA EDGE

RECENT WORK: Fluid momentum balance requires that the radial particle flux consists of a diffusive part proportional to the pressure gradient and a convective part made up of the EM and external force terms[1,2]. The resulting *pinch-diffusion particle transport* equation obtained by substitution of this radial particle flux into the continuity equation has non-diffusive pinch terms as well as diffusive terms [2,3], indicating that the commonly used pure diffusion particle transport equation does not satisfy momentum balance and should be replaced by the new “pinch-diffusion” equation.

A second “non-diffusive” modification to the conventional particle transport equations results from the *ion-orbit-loss* (IOL) of particles, energy and momentum from the outflowing thermalized ion distribution due to particles that can access orbits that leave the confined plasma [2,4,5]. These IOL particle and energy losses, and the compensating return currents necessary for neutrality, must be represented in the fluid continuity and energy balance equations [6,7], further changing the conventional particle and energy transport equations. We predict that most thermalized ions and their energy cross the separatrix into the SOL on IOL orbits and that these loss orbits strongly concentrate the ions and energy into the SOL about the outboard midplane, at least in part explaining the higher outboard divertor heat flux observed experimentally, and suggesting the possibility of redistributing this heat towards the inboard SOL by the judicious use of shim coils and divertor biasing.

The effect of non-diffusive transport on the interpretation of DIII-D experimental results involving the L-H transition [8,9], the recovery of profiles between ELMs[10], the effect of RMP [11] and the effect on the interpreted heat diffusivity [2,12] have been investigated. We find that the inward particle pinch increases dramatically and the ion-orbit-loss of particles and energy decreases dramatically at the L-H transition, that the rebuilding of the pedestal after an ELM event is associated with a strong inward particle pinch, that one effect of RMP is to reduce the inward particle pinch (relative to H-mode) and thereby lower the particle density in the pedestal below the ELM threshold, that in general the net radial ion particle flux is the difference between larger outward diffusive and inward pinch components, and that electromagnetic forces dominate neutral ionization effects in determining the pressure gradient in the edge pedestal.

The momentum IOL is primarily of counter-current particles, leaving the thermalized plasma with predominantly co-current ions, which explains the edge peaking of co-current *intrinsic rotation* seen in DIII-D [13,14] and other experiments. The formalism [7] predicts the new result of poloidal intrinsic rotation not yet identified experimentally.

This work is summarized in a paper given at the 2015 PET meeting to be published in Contrib. Plasma Phys. this spring.

ONGOING WORK: The IOL model was extended to an analytical elongated up-down asymmetric flux surface model[15] and to include IOL of NBI ions, X-transport[16] and loss particle return effects in the recently completed PhD thesis of Theresa Wilks[17]. Investigation of the change of the ion-orbit loss of particles, momentum (intrinsic rotation) and energy across the L-H and the back H-L transitions are being carried out presently as MS theses by Nicholas Piper and John Norris, respectively. The possibility of modifying the IOL so that energy loss is redirected from the outboard midplane to the inboard midplane is being examined by Rafaele Tatali of Politechnico Milano in a collaborative MS Thesis.

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III. FIRST-PRINCIPLES CALCULATION OF RADIAL ELECTRIC FIELD

RECENT WORK: Many edge plasma parameters are correlated with the radial electric field in the plasma edge, so understanding E_r raises the possibility of controlling it and other important parameters. We have suggested theoretically [1] that the radial electric field is determined via Ohm's law (Maxwell's equations and momentum balance) largely by the ion pressure gradient and the motional electric field due to plasma rotation, which latter in turn is determined by the torque of radial particle fluxes associated with ion orbit loss and the compensating return current as well as external particle and momentum sources. This suggestion recently has been confirmed by comparison with DIII-D experiments [2], when the motional electric field is constructed from experimental rotation velocities. However, present models for the calculation of rotation velocities, hence of the motional electric field, lead to small but significant discrepancies in the predicted radial electric field. We suspect that the assumption of toroidal axisymmetry in the viscous model used in the momentum balance may be causing part of the discrepancy in modeling rotation velocity in the plasma edge [3]. Comparison with the full delta-f XGC0 calculation for a different DIII-D shot further confirms the calculation of some of the model assumtions[2].

FUTURE WORK: We intend to follow up on this initial success in calculating the radial electric field by refining the models used for the ion orbit loss calculations and for the fluid momentum balance calculation of toroidal and poloidal rotation velocities of the thermalized ions in the plasma edge. The objective is a fully first-principles calculation of the radial electric field and the plasma rotation in the edge plasma. I believe this is within grasp and would like to recruit an outstanding PhD student to work on it.

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III. PLASMA ROTATION AND POLOIDAL ASYMMETRIES

RECENT WORK: We have long worked on a momentum balance model for plasma rotation based on the Braginskii decomposition of the viscous stress tensor extended to a low collisionality plasma and a Fourier expansion of poloidal dependencies[1,2,3]. Results to date are encouragingly close to DIII-D measurements of toroidal rotation, except in the edge [4,5,6], and we believe that the difficulty in the edge region arises in part from the failure to take into account intrinsic toroidal and poloidal rotation, in part from failure to take into account the effect of toroidal asymmetries on the viscous damping [7], and in part from the use of an approximate flux surface geometry model. We have recently extended the Miller model for elongated plasma flux surfaces to handle up-down asymmetries and to correctly treat non-orthogonal geometry [8], which provides an improved flux surface geometry representation for such calculations.

ONGOING AND FUTURE WORK: A recently initiated MS thesis (Richard King) is applying the methodology of [8] to calculate poloidal rotation velocities to compare with DIII-D measurements. This work should be extended to a PhD thesis to extend the momentum balance calculation of plasma toroidal and poloidal rotation and poloidal asymmetries in the plasma edge, taking into account toroidal non-axisymmetries.

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IV. **INTERPRETATION OF DIFFUSIVE/CONDUCTIVE EXPERIMENTAL TRANSPORT COEFFICIENTS**

RECENT WORK: We have previously developed a procedure and an interpretive code (GTEDGE) for calculating conductive and convective radial particle and energy fluxes needed to evaluate the experimental particle and energy diffusivities in the plasma edge from the continuity and energy balance equations, using measured density and temperature profiles to calculate ionization particle sources and atomic physics cooling rates[1]. The GTEDGE code also evaluates theoretical expressions for particle and thermal diffusivities for comparison with values interpreted from experiment [2]. The importance of taking into account non-diffusive transport mechanisms (EM pinch, ion orbit loss, rotational energy convection, work done against pressure and viscosity) was demonstrated [3,4] and included in GTEDGE. The GTEDGE code has recently been extended to include improvements in the ion-orbit-loss theory [5,6] and an asymmetrically elongated Miller model flux surface representation [7] which matches the EFIT flux surfaces very closely.

ONGOING WORK: A recently initiated PhD Thesis research by Jonathan Roveto is undertaking to interpret the experimental particle and energy diffusion coefficients in a variety of DIII-D shots in different confinement modes, using these new features for treating non-diffusive transport effects. The interpreted experimental particle and energy diffusion coefficients will be compared with theory.

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V. A PARTICLE, ENERGY AND MOMENTUM-CONSERVING EDGE TRANSPORT CODE

BACKGROUND: To my knowledge, none of the codes presently used to calculate plasma transport take into account the non-diffusive transport effects that are important in the plasma edge—EM particle pinch, ion-orbit-loss of plasma ions and energy—or have a practical and accurate treatment of neutral particle recycling (both of which are of great importance in the plasma edge), hence are not capable of conserving particles, momentum or energy in the plasma edge. The Georgia Tech group is in a perhaps unique position to remedy this situation, i) having developed the momentum conserving pinch-diffusion theory [1] and the methodology for taking into account in the fluid equations the effect of ion orbit loss of particles and energy [2], and ii) having developed the computationally efficient and geometrically accurate GTNEUT 2D neutral particle transport code [3, 4] which has been shown to predict neutral densities in good agreement with the orders-of-magnitude more computationally intensive Monte Carlo method [5,6].

FUTURE WORK: We intend to develop an “edge” code that would incorporate the new non-diffusive transport (particle pinch, ion orbit loss), radial electric field and neutral particle transport representations discussed above, and would conserve particles, energy and momentum. The code would treat the “plasma edge” from rho = 0.85 to the plasma chamber wall and divertor plate, with “core flux” boundary conditions on the radial particle and energy fluxes at rho = 0.85 and “recycling/sputtering” boundary conditions at the material surfaces. The neutral transport code would treat injected and recycling deuterium atoms and molecules, sputtered intrinsic impurity (carbon) atoms and injected “seeded” impurity atoms. The ion transport calculation would include deuterium and the various charge states of the intrinsic and seeded impurities. The neutral transport calculation would be fully 2D for the edge, SOL and divertor. The plasma transport within the LCFS would be “1.5D”, meaning explicitly 1D radial pinch-diffusion theory corrected for ion orbit loss, but flux surface averaged over an asymmetrically elongated Miller model 2D flux surface (on which grid the neutral particle densities are calculated).. The plasma transport in the SOL and divertor would initially be based on the integrated particle, momentum and energy balances known as the "2-point" model [7], and then extended to a 1D numerical integration of the particle, momentum and energy equations along the SOL from inner to outer divertor plates [8]. Ultimately, a "2D" divertor-SOL transport model will be implemented, but this will require some development to retain the intended computational efficiency. The poloidal distribution of ions, momentum and energy from inside the LCFS into the SOL will be calculated explicitly, taking into account the poloidally asymmetric ion orbit loss[9] and the asymmetrically elongated flux surface representation[10,11]. The development and testing against DIII-D data of such a code would require 2 PhD thesis students and 1-2 MS thesis student over 3-4 years.

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VI. CONFINEMENT TUNING

BACKGROUND: The present practice is to use regression analysis to correlate measured energy confinement times in various experiments with various operating parameters in a confinement scaling law. Since the mix of experiments have different operating parameters and not all the important parameters may be included in the regression analysis, such confinement scaling laws are unlikely to model accurately the dynamics of future tokamaks, or for that matter of any one of the tokamaks included in the correlation, but they do provide a good baseline about which the confinement scaling of a given tokamak can be 'tuned'.

RECENT WORK: Using the ITER98 scaling law and a set of DIII-D shots, *confinement tuning parameters* have been regressed for a simple global plasma dynamics model against variables such as q95, type of heating power, triangularity, gas fueling rate, etc. When used to calculate the dynamics of a different set of DIII-D shots with different gas fueling and heating histories, calculations using these confinement tuning parameters match the measured temperature time histories much better than identical simulations without the confinement tuning factors[1]. This suggests that dynamics models can be "trained" by using the initial measurements in predicting the results of later discharges.

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*__NOTE__ on REFERENCES: CPP= Contr. Plasma Phys., FST=Fusion Sci.&Techn., MSGT=Georgia Tech MS thesis, NF = Nucl. Fusion, PoP = Phys. Plasmas, PF = Phys. Fluids, PhDGT = Georgia Tech PhD thesis. All references available on www.frc.gatech.edu.