2012 ANNUAL REPORT

FUSION RESEARCH CENTER

GEORGIA INSTITUTE OF TECHNOLOGY

November, 2012

The Georgia Tech Fusion Research Center is a member of the National Team for the DIII-D National Tokamak Research Facility. Georgia Tech faculty and students collaborate with other DIII-D scientists in the interpretation of plasma physics experiments on DIII-D and in the development of supporting theory and computations*. The research performed during calendar year 2012 is summarized in this report.

Contents

*Partially supported by US Dept. of Energy, Office of Fusion Energy Science, under Grant DE-FG02-99ER54538.

Intrinsic rotation produced by ion orbit loss and X-loss

W. M. Stacey[1], J. A. Boedo[2], T.E. Evans[3], B. A. Grierson[4] and R. J. Groebner[3]

[1]*Georgia Institute of Technology, Atlanta, Georgia, 30332, USA*

[2] *University California San Diego, San Diego, California, 92093, USA*

[3]*General Atomics, San Diego, California, 92186, USA*

[4]*Princeton Plasma Physics Laboratory, Princeton, New Jersey, 08453 , USA*

Abstract A practical calculation model for the intrinsic rotation imparted to the edge plasma by the directionally preferential loss of ions on orbits that cross the last closed flux surface is presented and applied to calculate intrinsic rotation in several DIII-D discharges. The intrinsic rotation produced by ion loss is found to be sensitive to the edge temperature and radial electric field profiles, which has implications for driving intrinsic rotation in future large tokamaks.

Summary The preferential directionality of the loss of ions from interior flux surfaces by executing orbits that cross the last closed flux surface (or any other exterior loss surface) causes the remaining ions in the plasma to be predominantly of the opposite directionality, which constitutes an intrinsic plasma rotation in that direction. In the 'standard configuration' DIII-D discharges considered, with the current counter-clockwise and the magnetic field clockwise (looking down from above), the resulting intrinsic rotation is co-current. A calculation model for this intrinsic rotation was developed, and some applications to calculate intrinsic rotation in DIII-D discharges were performed. The magnitudes of the intrinsic rotation predictions just inside the seperatrix were similar to those observed in DIII-D ohmic discharges.

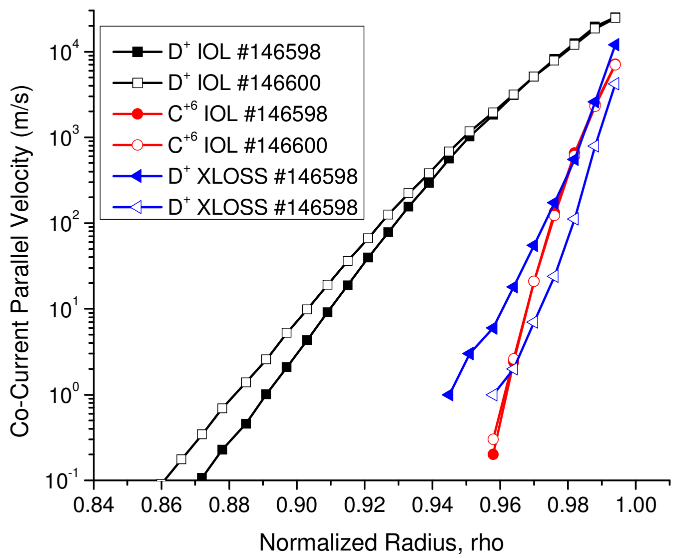


Fig. 1 Calculated Intrinsic Deuterium Rotation in DIII-D Ohmic Discharges

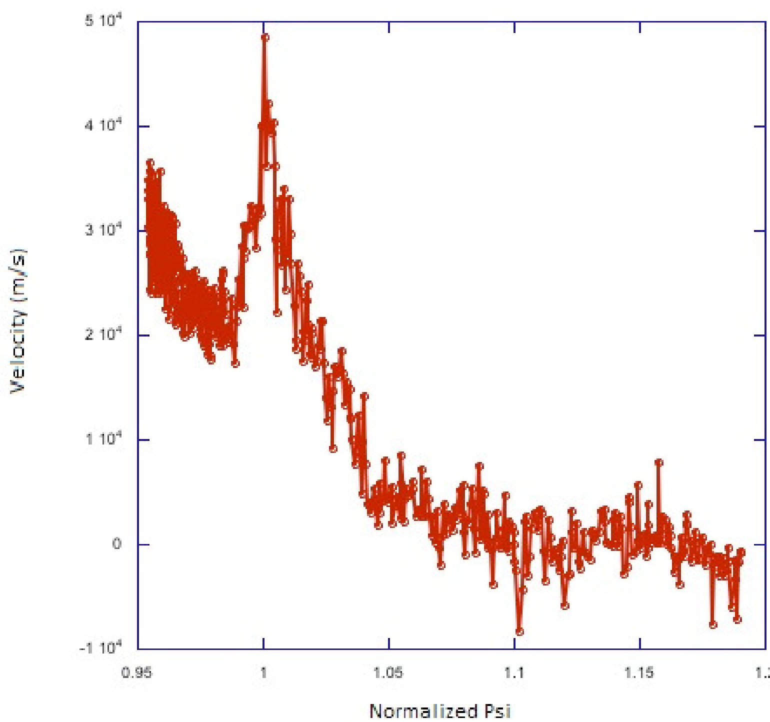


Fig. 2 Measured Intrinsic Deuterium Parallel Velocity in an Ohmic DIII-D Discharge

Differences in rotation in NBI-driven discharges with and without Resonance Magnetic Perturbations were found to be comparable to those predicted from intrinsic rotation due to ion orbit loss for carbon. These differences were of sufficient magnitude that intrinsic rotation due to ion orbit loss should be taken into account in comparisons of rotation theories with measurements in the edge plasma, certainly in DIII-D and probably in other strongly rotating experiments as well.

Some interesting relationships between the radial electric field and the intrinsic rotation were found. This raises the possibility of generating intrinsic rotation by controlling the electric field in the edge plasma, which could be useful in future tokamaks such as ITER.

(paper published Phys. Plasmas 19, 112503, 2012)

Interpretation of changes in diffusive and non-diffusive transport in the edge plasma during a Low-High (L-H) transition in DIII-D

W. M. Stacey[1], M-H. Sayer[1], J-P. Floyd[1] and R. J. Groebner[2]
[1]*Georgia Tech, Atlanta, GA 30332,* [2]*General Atomics, San Diego, CA 92186*

Abstract The evolution of diffusive and non-diffusive transport during a L-H transition has been interpreted from a particle-momentum-energy balance analysis of the measured density, temperature and rotation velocity profiles in the plasma edge $(0.82 < \rho < 1.0)$ of a DIII-D discharge. It was found that the majority of edge pedestal development occurs within the first 100 ms following the L-H transition, for this discharge. There appears to be a spatio-temporal correlation among the measured torodial and poloidal rotation, the formation of a negative well in the measured radial electric field, the creation of a large inward particle pinch, the calculated intrinsic rotation due to ion orbit loss and the measured formation of steep gradients in density and temperature in the outer region $(\rho > 0.95)$ of the edge pedestal.

Summary The evolution of diffusive and non-diffusive transport during a L-H transition has been interpreted from a particle-momentum-energy balance analysis of the measured density, temperature and rotation velocities in the plasma edge $(0.82 < \rho < 1.0)$ of a DIII-D discharge.

The measured density, temperature and rotation velocities in the plasma edge and the radial electric field constructed from them changed dramatically from their L-mode profiles during the first 30-70 ms after the L-H transition and then slowly evolved over another few hundred ms, non-monotonically, as the H-mode fully developed. These data and calculated radial heat and particle fluxes were used in the heat conduction relation to interpret experimental thermal diffusivities, and these data were used with the particle and momentum balance equations to interpret experimental particle diffusion coefficients and pinch velocities.

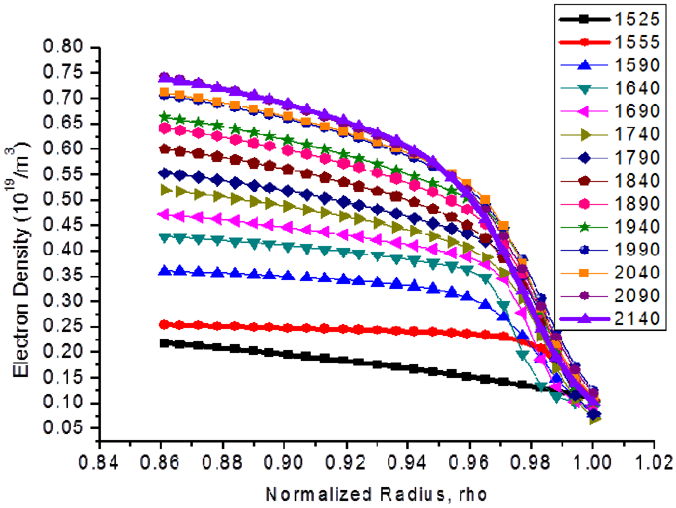


Fig. 3 Electron Density Before (1525ms) and After L-H Transition

Momentum balance requires that the radial particle flux satisfies a "pinch-diffusion" relation and defines the values of the diffusion coefficient and the pinch velocity in terms of quantities that can be determined from experiment. The deuterium diffusion coefficient can be determined from measured quantities--the ion-impurity collision frequency, which can be determined from the measured densities and temperatures, and the momentum transport frequency, which can be inferred from the measured toroidal rotation velocity. The unmeasured Deuterium rotational velocity profile and the Deuterium and Carbon momentum transport frequencies were determined from the measured Carbon toroidal rotation velocity by using first order perturbation theory.

A rather surprising feature was found in the measured toroidal rotation profile in the edge plasma. The measured Carbon toroidal rotation velocity profile and the Deuterium toroidal rotational velocity profile calculated from it were rather flat in L-mode, increased sharply within 30 ms of the L-H transition for $\rho < 0.95$, but decreased sharply during this same time for $\rho > 0.95$, indicating either a torque or an increased radial transport of toroidal momentum in the region $\rho > 0.95$ within the first 30 ms after the L-H transition.

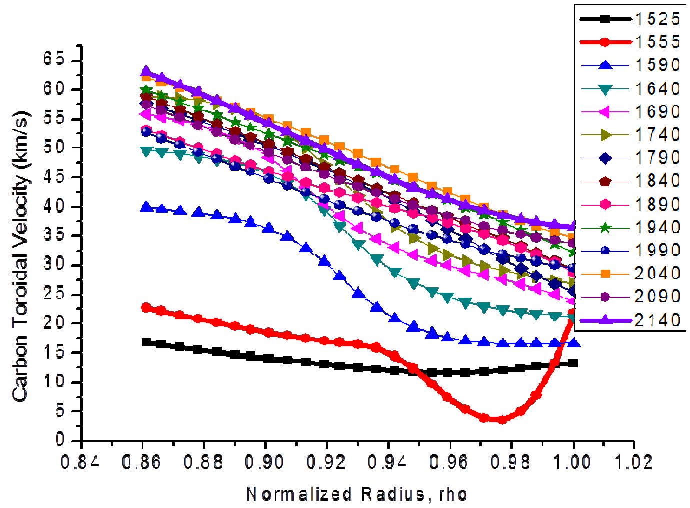


Fig. 4 Carbon Toroidal Rotation Before (1525ms) and After L-H Transition

This increase in the interpreted momentum transport frequencies for $\rho > 0.95$ produced a sharp peaking in the interpreted Deuterium diffusion coefficient immediately after the L-H transition. This structure for $\rho > 0.95$ gradually disappears from the measured rotation velocity and the interpreted diffusion coefficient profiles at later times. The overall effect is a transition from a diffusion coefficient profile in L-mode that increases sharply with radius for $\rho > 0.95$ to a fully developed H-mode diffusion coefficient profile in which the H-mode value is about twice the L-mode value for $\rho < 0.95$, but for $\rho > 0.95$ there is a pronounced reduction relative to L-mode and a 'transport barrier' well-like structure of the diffusion coefficient caused by the radial structure in the collision and momentum transport frequency profiles.

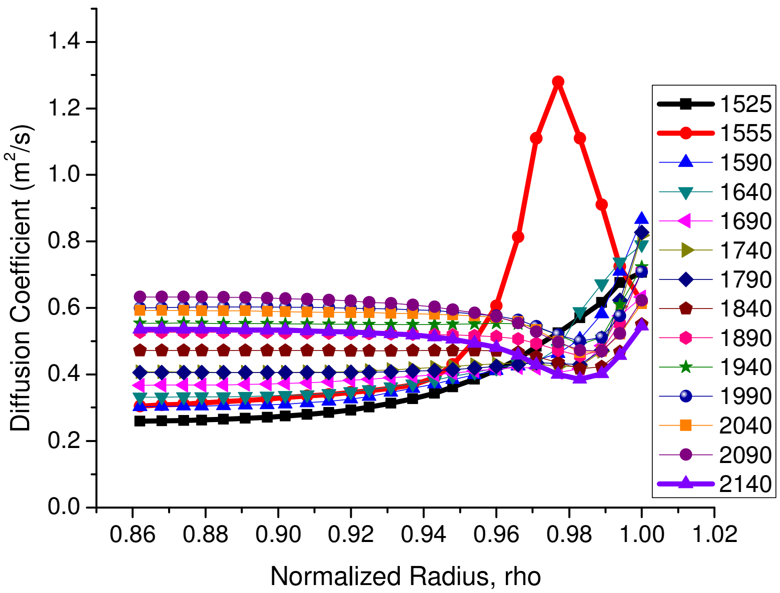


Fig. 5 Diffusion Coefficient Before (1525ms) and After L-H Transition

One possibility for the sharp reduction in co-current rotation for $\rho > 0.95$ within 30 ms after the L-H transition is ion orbit loss of preferentially counter-current ions, which was calculated to produce a co-current intrinsic rotation which increased with radius in the plasma edge. This intrinsic rotation was significant in L-mode, decreased significantly for $\rho > 0.95$ within the first 30 ms after the L-H transition, then increased with time after the first 30 ms. The magnitude of this change in intrinsic rotation was similar to the measured magnitude of the difference in toroidal rotation over the first 30 ms after the L-H transition.

The radial electric field, which was calculated from the radial momentum balance using measured Carbon density, temperature and rotation velocities, changed dramatically from the small, positive and relatively flat L-mode profile to a profile which increased to positive values an order of magnitude larger (10-20 kV) for $\rho < 0.95$ but became strongly negative (-10-20kV) for $\rho > 0.95$ within 30 ms following the L-H transition. The electric field profile further evolved after 30 ms, non-monotonically but retaining these features, as the H-mode developed.

The pinch velocity is a collection of normalized electromagnetic forces, specified by momentum balance requirements, in which there are terms proportional to the toroidal and poloidal rotation velocities, a term proportional to the radial electric field, and (smaller) terms proportional to external momentum torques and the induced toroidal electric field. In this discharge, the radial electric field and the poloidal velocity terms were dominant.

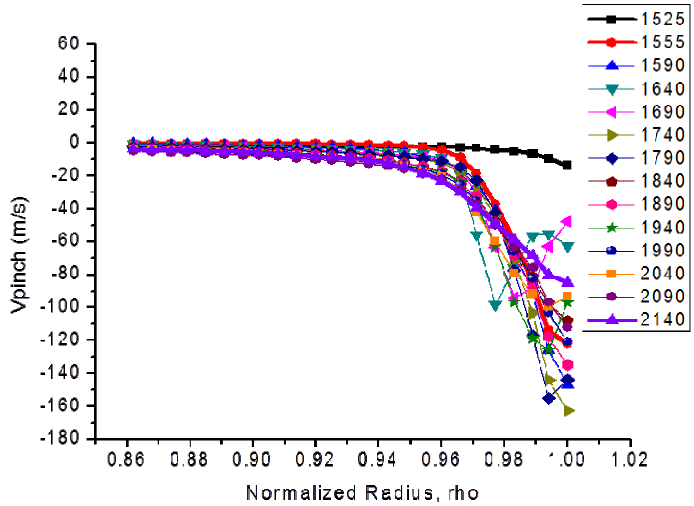


Fig. 6 Particle Pinch Velocity Before (1525ms) and After L-H Transition

The variation in the radial electric field profile was the principle reason that the ion particle pinch velocity, which was only slightly inward $(\sim 10 m/s)$ for $\rho > 0.95$ in L-mode, became strongly inward $(\sim -100 m/s)$ in this region within 30 ms after the L-H transition and then remained strongly inward but of non-monotonically varying magnitude as the H-mode evolved. The Deuterium poloidal rotation velocity (calculated from the Deuterium radial momentum balance) also changed dramatically from the small, positive and relatively flat L-mode profile to a H-mode profile strongly peaked (20-30 km/s) for $\rho > 0.95$.

The interpreted electron thermal diffusivity profile was relatively flat across the plasma edge in L-mode, but decreased sharply within 30-70 ms after the L-H transition to form a "transport barrier" structure and then varied somewhat, non-monotonically, as the H-mode fully developed.

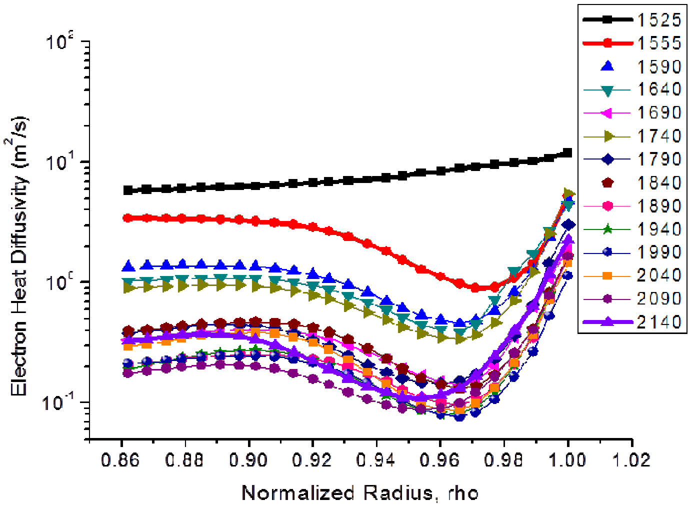


Fig. 7 Electron Thermal Diffusivity Before (1525ms) and After L-H Transition

The interpreted ion thermal diffusivity profile was also relatively flat across the plasma edge in L-mode, and decreased sharply within 30-70 ms after the L-H transition (but did not discernibly form a "transport barrier" structure) and then also varied, somewhat non-monotonically, as the H-mode fully developed. Calculation of ion-orbit loss effects in the edge plasma, which indicate steady increase in both particle and energy loss fractions as a function of time as the plasma enters the H-mode, were included in the ion heat diffusivity calculation.

Based on these results, we conclude that the majority of edge pedestal development occurs within the first 100 ms following the L-H transition, for this discharge, and suggest that in future investigations it would be useful to obtain more highly time-resolved data over the first 50-100 ms after the L-H transition in such discharges.

Finally, we note that the apparent spatio-temporal correlation among the calculated intrinsic rotation due to ion orbit loss, the measured torodial rotation and the measured radial electric field is suggestive that changes in ion orbit loss could be playing a major role in the dynamics of the L-H transition, perhaps via the return edge current (necessary to compensate the ion orbit loss in order to maintain charge neutrality) setting the radial electric field in the plasma edge.

(paper submitted to Phys. Plasmas)

Evolution of edge profiles between ELMs

J. P. Floyd[1], W. M. Stacey[1] and R. J. Groebner[2]

1) Georgia Tech, Atlanta, GA 30332, 2) General Atomics, San Diego, CA 92186

Abstract The purpose of this ongoing research is to understand the evolution of transport in the edge pedestal between Edge Localized Modes (ELMs) in DIII-D. CER and Thompson data from the same inter-ELM time periods between ELMs (e.g. 5-10%, 10-20%..80-95%) were collected from a sequence of ELMs in DIII-D H-mode discharge 144977. Profiles were fit, using splines for the CER data and hyperbolic tangent fits for the Thomson data, to obtain composite profiles of electron density and temperature and carbon density, temperature and rotation velocity in the plasma edge in different time intervals between ELMs. These profiles will be interpreted in terms of the underlying diffusive and non-diffusive transport mechanisms (by requiring that they satisfy the particle, momentum and energy balance equations and the heat conduction relation) in order to investigate the evolution of these transport mechanisms over the interval between ELMs.

Summary The work to date has emphasized selecting and fitting the data to obtain an accurate representation of its evolution in time, taking into account averaging periods used in the initial processing of the data. Care was taken to choose inter-ELM intervals that excluded data taken at the time of the ELMs.

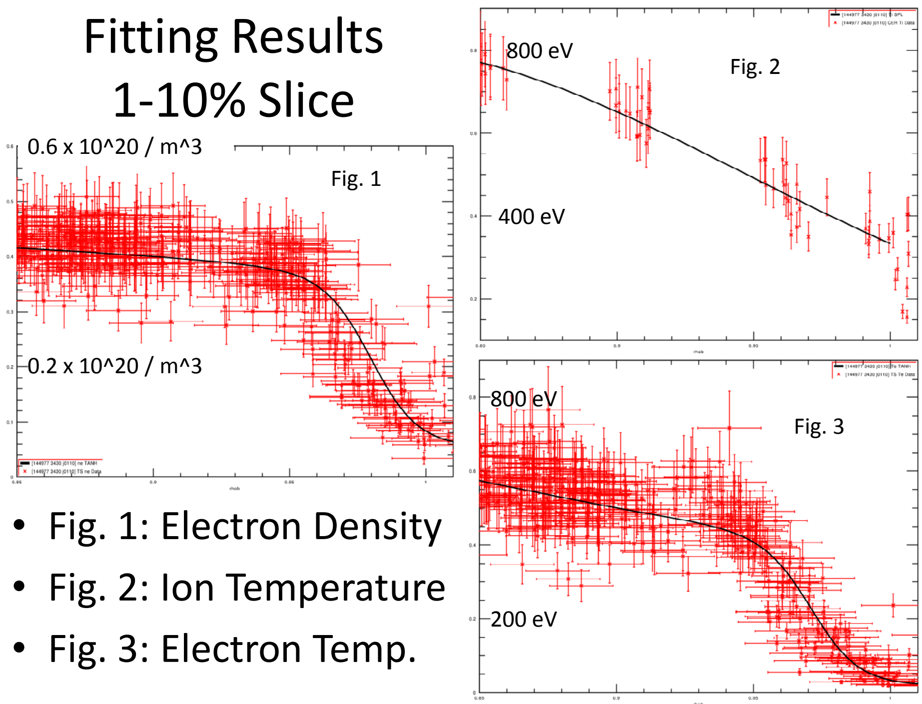


Fig. 8   Data fits for 0-10% interval between ELMs.

Extension of neoclassical rotation theory for tokamaks to realistically account for the geometry of magnetic flux surfaces

C. Bae,[1] W. M. Stacey,[1] and W. M. Solomon[2]

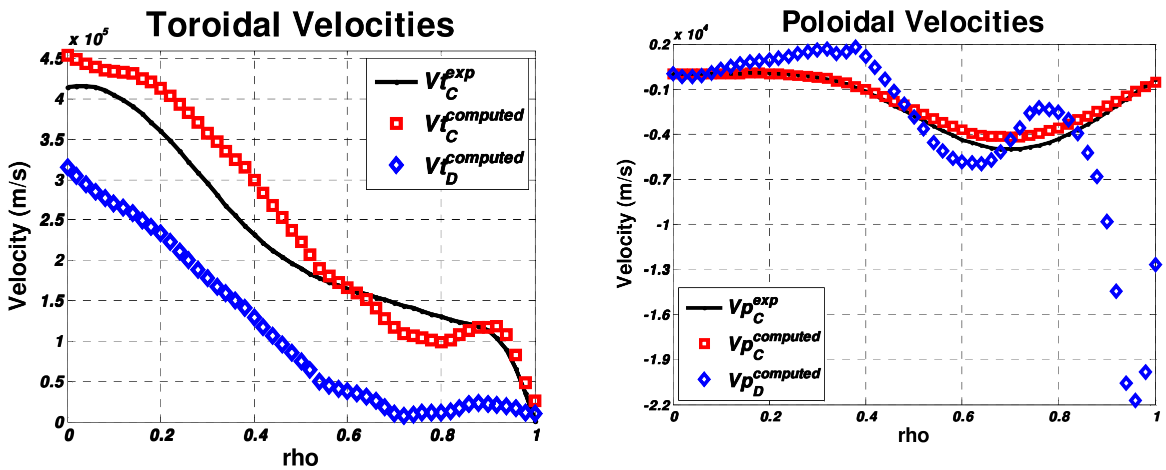
[1] *Georgia Institute of Technology, Atlanta, GA 30332, USA*

[2] *Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA*

Abstract A neoclassical rotation theory (poloidal and toroidal) was developed from the fluid moment equations, using the Braginskii decomposition of the viscosity tensor extended to generalized curvilinear geometry and a neoclassical calculation of the parallel viscosity coefficient interpolated over collision regimes. Important poloidal dependences were calculated using the Miller equilibrium flux surface geometry representation, which takes into account elongation, triangularity, flux surface compression/expansion and the Shafranov shift. The resulting set of eight (for a two-ion-species plasma model) coupled nonlinear equations for the flux surface averaged poloidal and toroidal rotation velocities and for the up-down and in-out density asymmetries for both ion species were solved numerically. Comparison of prediction with measured carbon poloidal and toroidal rotation velocities in a co-injected and a counter-injected H-mode discharge in DIII-D indicates agreement to within <10%, except in the very edge (ρ > .90) in the co-injected discharge.

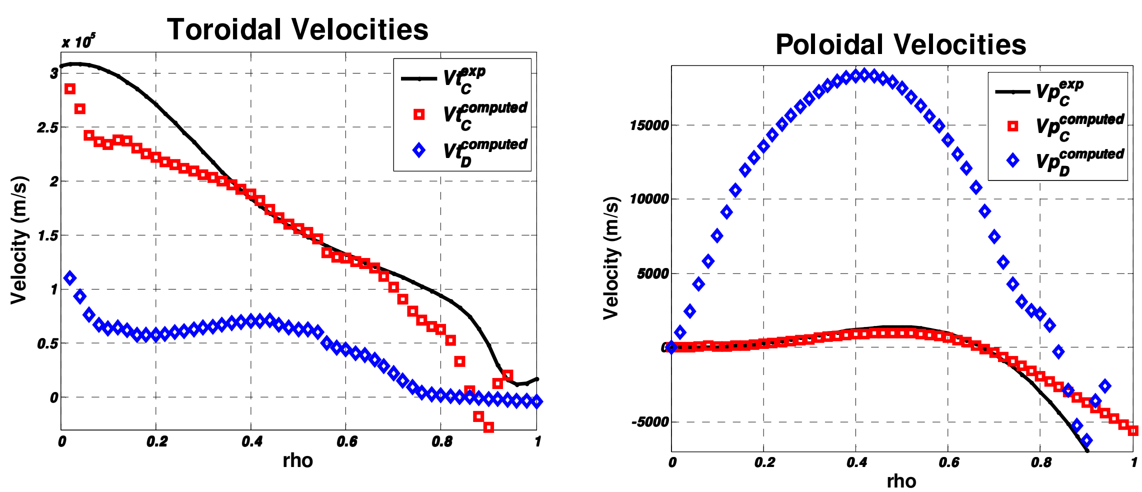
Summary An Extended Neoclassical Rotation and momentum plasma transport theory based on the Stacey-Sigmar model with the more accurate Miller equilibrium flux surface geometry was developed. It was shown that the gyroviscous contribution to viscous transport, $\left(R^2\nabla\phi\cdot\nabla\cdot\vec{\vec{\boldsymbol{\Pi}}}\right)_{gv}$, accounts for most of neoclassical toroidal angular momentum damping in this model. Comparisons of the predictions of this new theory with experiment for two DIII-D discharges indicate that the new theory predicts the measured carbon poloidal and toroidal rotation very well (<10%) everywhere except in the very edge, for the co-injected shot, where the neglect of recycling neutrals and of the divertor effect on geometry geometry and the assumption of strong rotation ordering may be expected to cause difficulty. It was shown that the more accurate poloidal representation of the flux surfaces provided by the Miller equilibrium

model is responsible for a significantly more accurate prediction than is possible with the similar neoclassical rotation theory based on the usual circular model.



(a) $\overline{V}_\phi$ (CCW positive) (b) $\overline{V}_\theta$ (positive upward at outer mid-plane)

Fig. 9 Calculated and measured velocities for carbon and deuterium for counter-injected upper SN shot #138639



(a) $\overline{V}_\phi$ (CCW positive) (b) $\overline{V}_\theta$ (positive downward at outer mid-plane)

Fig. 10 Calculated and measured velocities for carbon and deuterium for co-injected lower SN shot 142020.

The good agreement of prediction with experiment found on the two shots examined leads us to tentatively conclude that the extended neoclassical theory, when all important terms are retained and properly evaluated, is capable of accounting for most of the rotation and momentum transport in tokamaks. Such a conclusion must, of course, be confirmed by a more extensive comparison of prediction with experiment. Also, improved accuracy in the plasma edge requires extending the model further to represent charge-exchange of recycling neutrals, the effect of the divertor on poloidal asymmetries, and the weak rotation ordering of Mikhailovskii.

(papes submitted to Nucl. Fusion)

Toroidal phasing of resonant magnetic perturbation effect on edge transport in the DIII-D tokamak

T. H. Wilks[1], W. M. Stacey[1] and T. E. Evans[2]

[1]Georgia Tech, Atlanta, GA 30332, [2] General Atomics, San Diego, CA 92186

Abstract Resonant Magnetic Perturbation (RMP) fields produced by 3D control coils are considered a viable option for the suppression of Edge Localized Modes (ELMs) in present and future tokamaks. Repeated reversals of the toroidal phase of the I-coil magnetic field in RMP shot 147170 on DIII-D has generated uniquely different edge pedestal profiles, implying different edge transport phenomena. The causes, trends, and implications of RMP toroidal phase reversal on edge transport are analyzed by comparing various parameters at φ=0° and φ=60° with an I-coil toroidal mode number of n=3. An analysis of the diffusive and non-diffusive transport effects of these magnetic perturbations in the plasma edge has been performed. The change in the diffusive and non-diffusive transport in the edge pedestal for this RMP shot is characterized by interpreting the ion and electron heat diffusivities, the angular momentum transport frequencies, the ion diffusion coefficients, and the pinch velocities for both phases.

SUMMARY Resonance Magnetic Perturbations of different toroidal phases in DIII-D shot 147170 generate different edge densities and different radial profiles of edge density, temperature and rotation velocity. Measured density, temperature, and rotation profile differences can be interpreted as differences in diffusive and non-diffusive transport, resulting in a theoretical basis for a better understanding of the underlying differences in transport associated with difference in toroidal phase of the RMPs.

Very large outward diffusive particle fluxes and very large inward electromagnetic particle pinches are found, for both RMP toroidal phases, to largely compensate each other to produce an order of magnitude smaller net outward particle flux. This net outward particle flux is found to be larger for the higher density 0^{o} than for the 60^{o} RMP phase. The particle fluxes found from evaluating the pinch-diffusion relation using experimental data agree with the fluxes obtained by solving the continuity equation, for both toroidal RMP phases, confirming the internal consistency of the analysis.

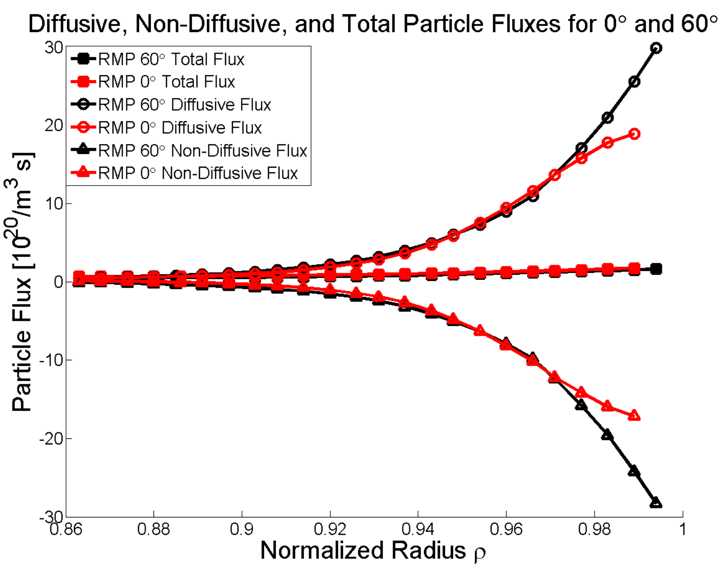


Fig. 11 Diffusive and pinch radial particle fluxes for Deuterium.

Electron and ion thermal diffusivities inferred from the density and temperature profiles were similar for the two toroidal phases in the steep-gradient pedestal region, but differed in the flattop region further inward, where the thermal diffusivities were greater for 60^o than for 0^o**.** The electron thermal diffusivity profiles exhibited a "transport barrier' well just inside the separatrix.

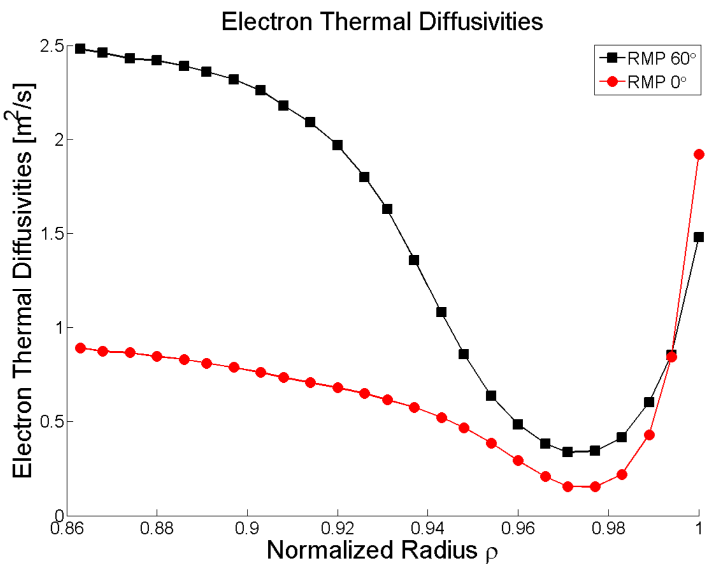


Fig. 12 Experimentally inferred electron thermal diffusivity.

Toroidal momentum transport, or "drag" frequencies were larger than interspecies collision frequencies, were different for the two RMP phases and had a major effect on both the diffusive and non-diffusive transport. This would seem to imply that one mechanism by which RMP affects edge transport is through exerting a torque on the edge plasma.

By interpreting the density and rotation velocity profiles, an argument can be made that the increased density for the 0° toroidal phase relative to the 60^o phase may be ultimately driven by the larger intrinsic rotation velocity attributable to ion orbit loss. The larger toroidal velocity for 0° leads to an inference of smaller momentum transport "drag" frequencies for 0° than for

60°, which in turn results (by using the momentum balance constraint) in smaller particle diffusion coefficients for 0° than for 60°. Since both the outward diffusive flux and the smaller inward pinch flux are both largely proportional to the momentum transport frequency, the smaller momentum transport frequency for 0° than for 60° leads to both smaller outward diffusive and inward pinch particle fluxes for 0° than for 60°. However, the net outward particle flux is larger for the 0^o than the 60^o toroidal phase of RMP, which can be attributed (at least in part) to differences in the edge radial electric field profiles for the 0^o and the 60^o toroidal phases.

(paper for Phys. Plasmas in preparation)