Theory of Non-Diffusive and Non-Axisymmetric Transport in the Edge Pedestal of Tokamaks

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This paper will review the work of the author and colleagues over the past decade on plasma edge theory, in particular on i) edge pedestal structure. **[1]**; ii) non-diffusive transport arising from electromagnetic particle pinches **[2]** and ion-orbit-loss **[3]** which dominate diffusive transport in the edge pedestal, requiring an extension of conventional diffusive transport theory to include the dominant non-diffusive effects; iii) intrinsic rotation produced by ion orbit loss **[4]**; and iv) a theory for the edge viscosity and rotation caused by non-axisymmetric magnetic geometry (field errors, magnetic islands, field ripple, etc.) which introduce dominant parallel viscosity effects into the damping of toroidal angular momentum in the edge plasma **[5]**. These new phenomena should be included in extended rotation and radial particle transport models for the plasma edge.

[1] Theory of edge pedestal structure [*Phys. Plasmas,* **8**, 4073 (2001); *Phys. Plasmas*, **8**, 5199 (2001); *Contr. Plasma Phys.*, **42**, 283 (2002); *Contrib. Plasma Phys.* **44**, 100 (2004); *Phys. Plasmas,* **11**, 4295 (2004); *Phys. Plasmas*, **11**, 5487 (2004); *Contrib. Plasma Phys.*, **46,** 597 (2006); *Phys. Plasmas* **17**, 052506 (2010); *Phys. Plasmas* **20**, 092508 (2013); *Phys. Plasmas* **21**, 014502 (2014); *Contrib. Plasma Phys*. **54**, 524 (2014).]

[2] A new edge transport theory that incorporates electromagnetic (pinch) forces [*Contrib. Plasmas Phys*., **48**, 94 (2008); *Phys. Plasmas*, **16**, 102504 (2009); *Nucl. Fusion*, **50**, 064004 (2010); *Fusion Sci. & Technol.* **61**, 227 (2011); *Nucl. Fusion*, **52**, 114020 (2012)].

[3] A new theory for ion orbit loss from and X-transport in the edge of tokamaks [*Phys. Plasmas* **18**, 102504 (2011); *Phys. Plasmas* **18**, 122504 (2011); *Nucl. Fusion* **53**, 063011 (2013); *Phys. Plasmas* **21**, 014502 (2014)]; *Phys. Plasmas* **22** (2015).

[4] A theory for intrinsic rotation in the edge plasma due to ion orbit loss [*Phys. Plasmas* **19**, 112503 (2012); *Nucl. Fusion* **54**, 073021 (2013)].

[5] An extension of plasma rotation theory in the edge to incorporate non-axisymmetric magnetic field (NTV) effects in the viscous stress tensor [*Phys. Plasmas* **21**, 092517 (2014)]; *Phys. Plasmas* **22** (2015).

Invited Talk

Gyrokinetic Theory and Dyanmics of the Tokamak Edge

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A capsule review of phenomena faced in the tokamak edge from turbulence to equilibrium and flow relaxation is given. The elements of gyrokinetic theory required to cover these effects are outlined, with correspondence to more familiar models including reduced MHD and Braginskii treatments. The nonlinearity of tokamak edge turbulence and its resilience against flows is explained. Comparisons to the familiar MHD interchange model and some in-between models are used to outline the qualitative differences. Physical processes including adiabatic coupling of Alfvénic turbulence to pressure dynamics and flows, and diamagnetic flow compression in the perturbed equilibrium, are explained via energetic analysis. The inability of computational turbulence models to properly explain the L-H transition in tokamaks, despite 25 years of hopeful claims, is given qualitative and quantitative physical basis. A list of phenomena involved in the L-H transition that are commonly ignored is given. The current status of gyrofluid and gyrokinetic computation of the tokamak edge including self-consistent magnetic and flow equilibrium is shown. The role of neoclassical processes is explained, generally as well as within the parameter situation of the tokamak edge. The physical scale ratio hierarchy in the edge is very different from familiar modelling and is decisive in any of the results.

Three-dimensional transport analysis of plasma, neutrals and impurities in LHD peripheral regions with impurity gas-puff

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Modelling of particle and heat transport in peripheral plasma is a key issue for analysis and prediction of not only peripheral but also core plasma in a fusion device. The three-dimensional transport code, EMC3-Eirene [1,2], has been employed to simulate peripheral plasma of Large Helical Device (LHD) [3,4]. Transport of impurities injected with gas-puff is solved by EMC3-Eirene code in this work. Two-dimensional imaging with infrared imaging video bolometer [5] is available during impurity gas-puff experiments. Plasma, neutrals and impurities are closely linked to each other, therefore measurements with controlled impurity gas-puff give important information to understand physical effects of modelling parameters such as transport coefficient, impurity amount and gas pumping.

Qualitatively good agreement of radiation distribution calculated by EMC3-Eirene with bolometer measurements was obtained for a discharge with neon gas-puff and R_{ax}=3.6m magnetic axis position. Strong radiation was observed at the same location as the bolometer measurement, i.e. divertor legs in closed divertor sections and upstream plasma connected to them by the magnetic field. That is consistent with the fact that large recycling takes place due to a geometric effect on confinement of neutrals. Radiation region moves toward the last closed flux surface (LCFS) when neon amount is increased beyond a certain level while the other code input parameters are kept in the simulation. The shift is caused by reduction of the electron temperature with increasing impurity radiation. The low-T_e under intensive radiation leads to longer penetration length of neon atoms into the plasma. A systematic investigation of transport for different experiment conditions including different gas species and different magnetic axis positions will be presented in the paper.

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[5] B.J. Peterson et al., Plasma Fusion Res. **8** (2013) 2402037.

Roles of turbulence and pressure gradient driven flows in triggering the L-I-H transitions on HL-2A tokamak

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Understanding L-H transition mechanisms is essential for providing a predictable power threshold for a successful operation of fusion reactor [1]. The limit cycle oscillation (LCO), observed in slow L-H transition with expansion of time scale, provides opportunities for study of the nonlinear transition mechanism quantitatively. Early theoretical and experimental studies [2-3] have shown that plasma may enter an intermediate phase (I-phase) when heating power is close to the H-mode power threshold. Recently, a new type of limit cycle oscillation, in contrast with the prediction of predator-prey model, was found on the HL-2A [4], which is not consistent with the original predator-prey model of interaction between the low frequency zonal flow (ZF) and turbulence. The similar experimental results on the inversion of the LCO rotation were also reported on the JFT-2M [5]. Here, we report the extended study of mechanism of low-intermediate-high (L-I-H) confinement mode transitions on the HL-2A.

A physics model including three loops for the observed two LCO types and an eventual I-H transition is proposed. The roles of turbulence driven ZF and pressure gradient induced diamagnetic drift in L-I (type-Y LCO) and I (type-J LCO)-H transitions are identified. The pressure gradient induced diamagnetic drift is found to be the dominant contributor to the radial electric field in the I-phase of type-J LCOs and in the I-H transitions. The acceleration of the E×B flow from pressure gradient driving is shown to be much higher than that from Reynolds stress driving. The rate of energy transfer to E×B flow from the diamagnetic drift is also shown to be higher than that from turbulent Reynolds stress in I-H transitions.

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Self-consistent transport in SOLEDGE2D edge plasma modeling

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In the perspective of designing and operating ITER divertor, a dedicated effort is made to develop reliable numerical tools to estimate edge plasma properties. A special attention is paid to the development of so-called transport codes which aim at implementing most of the physical ingredients ruling the edge plasma behavior for a reasonable computation cost. Unlike, first principle codes, the transport codes require developing simplified models to account for a more complicated physics (for instance turbulence) which could not be included self-consistently without increasing significantly the computation time. Transport codes rely on fluctuation averaged fluid equations and are in that sense very similar to the Reynolds Averaged Navier-Stokes (RANS) description that have been used for many years in computational fluid dynamics. We propose here to present in this contribution the many similarities in the two approaches and to adapt some of the numerical methods that have been developed in the CFD community to edge plasma modeling.

A first point concerns the treatment of boundary conditions. We will present how numerical methods used to deal with fluid-structure interaction can be used to simulate complex plasma facing components geometry and to simulate the edge plasma up to the first wall.

Secondly, we will focus on the models to describe turbulent transport in the mean field equations. We will propose a set of two equations inspired from the k-epsilon model widely used in the CFD community. These new equations aim at taking into account the physical mechanisms generating and destroying edge plasma turbulence. Going beyond the empirical approach, they automatically generate profiles for the turbulent diffusivities and hence reduce the number of degrees of freedom for edge plasma transport codes. The model has proven to recover typical edge plasma turbulence features such as cross-field transport ballooning.

Applications to well-documented discharges on Tore-Supra and JET will be presented to compare simulation results and experimental measurements.

Outstanding issues in plasma-surface interaction research

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As nuclear fusion research programs across the world continue to progress toward burning plasma relevant operational scenarios, more and more stress is placed on the systems surrounding the confined plasma. Increased plasma parameters, coupled with longer pulse duration, focusses attention on the behavior of the surfaces required to remove the emerging power and interact with the escaping plasma particles. The importance of understanding the dominant processes involved at the plasma-material interface, to ensure the success of the plasma-facing components, consistently ranks high on lists of required research throughout the world's fusion research programs. This presentation summarizes recent PMI research results obtained using the PISCES linear plasma facility.

Linear plasma devices bridge the gap between single effect measurements (such as ion beam sputtering measurements, or electron beam high-heat flux measurements) and more complicated toroidal plasma confinement facilities. The PISCES linear plasma devices provide the opportunity to perform controlled, systematic investigations of the synergy and coupling between the variety of processes taking place at the interface between a material object and the incident high-energy plasma. This ability to systematically vary individual parameters is ideal for validation of various PMI models and theories.

Future directions of the PISCES research program will be described, along with the opportunities that exist for modelling of the experiments. The presentation will conclude with a more general description of outstanding research issues relating to the plasma-material interface.