WHITE PAPER FOR DOE-OFES INTEGRATED SIMULATION BOUNDARY (B) WORKSHOP (April 10, 2015)

W. M. Stacey (weston.stacey@nre.gatech.edu), Georgia Tech, Atlanta, GA 30332-0405 (www.frc.gatech.edu)

BACKGROUND The Georgia Tech group has collaborated with other DIII-D physicists for many years in the modeling and interpretation of edge physics phenomena and their cause-effect relations with observed phenomena. We found that:

i) *electromagnetic* (Er, VxB) forces produce non-diffusive transport-- an inward *radial particle pinch* --that increases sharply at the L-H transition (Ref 1, fig 15; Ref 2, fig 8), that is reduced by RMP causing density pumpout in ELM suppression (Ref 3, fig 10), that is responsible for greater particle pumpout with 60^o than 0^0 RMP phasing (Ref 4, figs 4 & 12) and that went from slightly outward immediately after an ELM event to strongly inward just before the following event (Ref 5, fig 12);

ii) *ion-orbit-loss* of mostly CTR-current thermal ions results in an edge plasma with predominatly CO-current ions which *produces an intrinsic CO-rotation* just inside the LCFS similar to observation (Ref 6, figs 3 & 5; Ref 7, figs 1&5; Ref 8, fig 9);

iii) the *fluxes of ions and ion energy* from the core across the separatrix into the SOL consist mostly of ion-orbit-loss ions and *are strongly peaked about the outboard midplane* (Ref 8, fig 8);

iv) the *interpretation of experimental diffusive transport coefficients* from measured temperature and density profiles strongly depends on taking the electromagnetic (EM) pinch (Ref 9, fig 5) and ion-orbit-loss (Ref 2, figs 5a & 6a; Ref 10, figs 23 & 24) into account;

v) *toroidal angular momentum transport frequencies*, needed to construct particle diffusion coefficients and EM particle pinch velocities, *can be inferred from measured rotation velocities* in axisymmetric tokamaks (Ref 11);

vi) extended *neoclassical rotation models for axisymmetric tokamaks agree reasonably well with measured rotation velocities* in DIII-D and KSTAR *in the plasma core but not edge* (Refs 12-14), suggesting that it is necessary to extend the rotation models to treat the 3D magnetic field structure in the plasma edge--which has begun (Refs 15 & 16) ;

vii) the *rotation and radial electric field* which are involved in the EM particle pinch *are related via momentum balance to the radial particle flux, hence to ion-orbit-loss and X-los*s, suggesting ways to control the EM pinch and hence the non-diffusive transport in the edge plasma (Refs 17 & 18);

viii) the particle diffusion equation used in many edge and boundary codes does not conserve momentum. Momentum-conserving fluid particle transport theory can be derived by solving the momentum balance equations for the particle flux, which involves pressure gradients and the EM pinch, and using this particle flux in the continuity equation to obtain a "pinch-diffusion" equation and define D (Ref 19). The diffusion equation obtains when the EM forces, temperature gradients and other ion species are neglected. Inclusion of drifts may partially offset the problem.

ix) the *GTNEUT neutral particle transport code*, which can use either an input grid or the UEDGE grid extended to the wall to represent the edge and boundary plasma, can achieve *accuracy comparable to Monte Carlo with two orders of magnitude less cpu time* (Refs 20 & 21);

x) *MARFEs and radiative collapse of the edge* can be modeled as radiative thermal instabilities which impose *edge density limits* (Ref 22) and

xi) seeding the edge plasma with impurities that are a few times ionized in the edge but fully ionized in the core provides radiative power exhaust, which reduces the divertor heat load problem (Ref 23 & 24). This idea has been incorporated in the ITER design and also led to the radiative divertor concept.

PROPOSED RESEARCH Only models which have been tested against experiment should be implemented. Several implementations are suggested. Also, several coordinated experimental-modeling plasma edge physics efforts are suggested to build upon the recent advances described above towards a predictive capability for the control of the tokamak edge pedestal that can be implemented at a later date.

 # 1 Control of rotation and radial electric field in order to control the EM pinch in the plasma edge. First efforts to compare the radial electric field calculated with the methodology of Refs 17 & 18 with the measured (carbon) radial electric field in a DIII-D discharge show qualitative but not quantitative agreement between radial electric field profiles (Ref 25). A coordinated model improvement effort and experimental program to test various aspects of the predictive model for the radial electric field is suggested for developing a predictive capability for the EM pinch.

 # 2 Rotation in the plasma edge of a non-axisymmetric tokamak. We believe that the quantitative disagreement mentioned in the previous paragraph may be due to failure of the rotation model in Ref 11 to take into account 3D magnetic fields (from errors, ripple, etc.) which can have profound effects on rotation via the viscous stress (Ref 15 & 16). A coordinated model improvement effort and experimental program to test various aspects of the rotation model is suggested for developing a predictive capability for rotation in the plasma edge.

 # 3 Ion-orbit-loss and X-loss in the plasma edge. The loss of particles, energy and momentum from the edge plasma and the compensating return currents play a major role in determining the radial ion flux, which torques rotation in the edge plasma that produces a motional electric field. The momentum loss causes intrinsic edge rotation. Relatively simple computational models for these phenomena are available today (Ref 8). A coordinated model improvement effort and experimental program to test various aspects of the model is suggested for developing a practical predictive capability for ion-orbit-loss and X-loss in the plasma edge.

 # 4 ELM control by control of the EM pinch. We have found (Ref 3) that one difference between ELMing and RMP discharges is the EM particle pinch profiles. This suggests that any means of controlling this EM particle pinch might be used to control ELMs. A coordinated modeling and experimental program to test various ways of suppressing ELMS by controlling the EM particle pinch is suggested.

 # 5 Control of heat and particle flux distribution into SOL by control of ion-orbit-loss. Our present calculations (Ref 8) predict that most of the ions and ion energy that cross the separatrix from the edge into the boundary plasma are ion-orbit-loss and sharply concentrated about the outboard mid-plane, creating large particle and energy fluxes incident on the outboard divertor plate. A coordinated modeling-experimental effort should investigate the possibility of changing this ion-orbit- loss distribution to lessen the heat flux problem on the outer divertor plate.

 # 6 Interpretation of diffusive/conductive transport coefficients in the plasma edge. Once the non-diffusive EM pinch and ion-orbit-loss transport effects are fully modeled it will be possible take them into account in the interpretation of measured density and temperature profiles to determine experimental values of diffusive transport coefficients (D and χ) that can be compared with theoretical models and with gyrokinetic/gyrofluid code predictions.

#7 Implement particle transport codes that conserve momentum. The "pinch-diffusion" model (Ref 19) has been implemented in 1D using the same solution algorithms conventionally used to solve the 1D diffusion equation (Ref 26), but it may be necessary to develop modified solution algorithms for 2D codes.

 # 8 Implement a fast and accurate neutral particle transport capability. A fast, accurate and detailed neutral particle transport code, GTNEUT, has been developed, benchmarked against experiment and Monte Carlo, and used for analysis of DIII-D (Refs 20 & 21). This code should be extended to also include molecular transport and implemented in the major codes used for plasma edge and boundary calculations.

 # 9 Implement calculations of edge density limits for MARFEs, radiative collapse, etc. See Ref 22.

 # 10 Implement models for impurity seeded radiative edge and divertor.

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