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**UCLA Program in Theory and Modeling
of Edge Physics and Plasma Material Interaction**

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Progress Report for Period 6/91 through 6/92

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UCLA-SCIENCE

Our research activity in edge plasma modeling is directed towards understanding edge plasma behavior and towards innovative solutions for controlling the edge plasma, as well as the design and operation of impurity control, particle exhaust, and plasma facing components. During the last nine months, we have made substantial progress in many areas, as will be described below. The highlights are: (A) Development of a second-generation edge-plasma simulation code (Section II); (B) Development of models for gas-target divertors, including a $1\frac{1}{2}$ -D fluid model for plasma and Monte Carlo neutral-transport simulations (Section III); and (C) Utilization of the RF ponderomotive force and electrostatic biasing to distribute the heat load on a larger area of the divertor plate, and the development of analytical and numerical transport models that include both ponderomotive and electrostatic potentials (Section IV). A list of publications by the UCLA scientists is given in Section V.

I. Overview

The first generation of two-dimensional (2-D) edge-plasma simulation codes (such as the B2 and EPIC codes) demonstrated the value of edge-plasma simulations of the scrape-off layer, and they have been used extensively for simulating divertor tokamaks. The experience with these codes has also exposed many shortcomings and underlined the need for the second-generation edge-plasma simulation codes. During the last year, we started to develop a second-generation code that is more accurate and includes improved physics models. At the same time, this new code should be flexible enough to be utilized for machines ranging from small laboratory experiments to full-scale fusion devices. Our modeling goals for this second-generation simulation code are described in detail in Section II.

Radiative and/or "gas-target" divertors potentially offer an attractive solution to the divertor heat-load problem. A key element of this concept is enhanced radiative-power

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loss in the divertor area, which is accomplished by injecting neutral deuterium and/or impurities close to the divertor target. As a result, the power flow may be redistributed over a larger surface area and the peak divertor heat load may be reduced substantially. Simultaneously, the target electron temperature can be decreased to acceptable values (~ 10 eV). The gas-target regime has been simulated in linear plasma facilities (PISCES-A), and a substantial reduction of the electron temperature downstream from the plasma source has been demonstrated.

Modeling efforts are under way at UCLA to evaluate possible gas-target divertor scenarios (Section III). Since high hydrogen neutral density (or some lower-density impurity content) is required close to the divertor target (so that a substantial fraction of the input power to the scrape-off layer is radiated), modeling ultimately requires a self-consistent approach that incorporates a plasma fluid model and a neutral transport model. A 2-D fluid code with a multi-group neutral model is under development at UCLA (Section II) and will be available for the modeling of the gas-target regime in the fall of 1992. So far, we have employed a simple $1\frac{1}{2}$ -D fluid code (solving the electron heat-flux equation along with the plasma momentum and continuity equations) to obtain solutions for the axial density and electron temperature profile at a gas-target divertor (Section III). The axial profile of the hydrogen neutral density is prescribed initially, based on PISCES-A experimental measurements in the gas-target regime and on results from the DEGAS code (Section III). We are using the plasma density and temperature profiles calculated from the $1\frac{1}{2}$ -D fluid code as an input to the DEGAS code in order to obtain a more accurate neutral-density distribution. This two-stage simulation process can be iterated several times until convergence is achieved.

One of the recent and exciting innovations is the application of RF ponderomotive forces to the scrape-off layer in order to control edge-plasma characteristics and to affect the global particle and energy confinement. Initial experiments of this technique were successful on PISCES and experiments are now planned for TEXTOR and PBX-M. We have developed, for the first time, an analytical and numerical transport model that includes both ponderomotive and electrostatic potentials. Our model is designed to allow detailed comparison with experiments that have been performed on the PISCES linear edge simulator and that are proposed for the PBX experiment, which includes both electrostatic biasing and the RF ponderomotive divertor. Our initial estimates also show that, for a device like ITER, the application of RF ponderomotive forces can reduce the peak heat flux substantially with only a small amount of RF power. Our modeling activity in this area is described in detail in Section IV.

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II. A Second-Generation Edge-Modeling Simulation Code

Fluid-based computational simulations are effective tools for studying the edge plasma of a tokamak and for determining conditions at the contact points of the plasma with the vacuum vessel. However, practical applications (computer codes) have not yet been sufficiently developed for the production analysis that is required for designing reactor systems such as ITER, ARIES, and TPX. The available edge-modeling codes are slow (*i.e.*, they require considerable supercomputer resources) and, therefore, they are ineffective for the necessary parameter-variation studies (including modifications in both geometry and boundary conditions). Furthermore, uncertain physical (and numerical) models are routinely “hardwired” into the algorithms of these codes, which makes it difficult to analyze the influence of the models and solution techniques on computed solutions.

After carefully considering the special requirements for modeling the edge plasma of tokamaks and the shortcomings of the previous codes, we have begun to develop a second-generation modeling platform, the UCLA Edge-Modeling System (UCLA-EMS) to address these issues.

General goals: To date, the development of the UCLA-EMS code has focused on implementing a unique, non-orthogonal spatial discretization and on utilizing modern, robust, linear and nonlinear matrix-solution techniques. The code is written to be easily operated and modifiable and general enough to support future generalizations; thus it will serve as a development platform for future modeling efforts. The code will be freely dispersed in the fusion community and will be supported with full documentation and a graphical user interface (GUI).

The generalized model equation: The UCLA-EMS code is designed to accept a system of time-dependent fluid equations in two spatial dimensions of the general form

$$\frac{\partial C(x, t, s)}{\partial t} + \nabla \cdot \mathbf{F}(x, t, s, \nabla s) = S(x, t, s, \nabla s),$$

where C is the concentration of a physically conserved quantity (*e.g.*, energy, number particles, *etc.*), $\mathbf{F}$ is a general flux (convective, diffusive, or otherwise), and S is the source of C . A typical set of equations that is encountered in modeling a tokamak edge plasma includes a diffusion model for the fluid neutral density and plasma radial velocity. Standard anisotropic convection-diffusion models are then added to couple to the plasma density, n , parallel velocity, $v_{\parallel}$, and temperatures, T_i and T_e . Likely extensions to this “standard” model include coupled drift convection and multi-group diffusive neutrals. The number of such equations simultaneously solved by the code is limited only by the available com-

putational resources and not by the numerical algorithms (this philosophy represents a significant departure from that employed in earlier codes).

Boundary conditions are specified in the form

$$G(x, t, s, \nabla s) = 0.$$

The expected range of boundary conditions includes specified values (*e.g.*, plasma density at the separatrix), specified total flux (*e.g.*, heat flux from the core), specified normal derivatives (*e.g.*, zero at symmetry planes), and specified relations between unknowns (*e.g.*, the sheath condition $v = \sqrt{kT/m}$ at the target).

The UCLA-EMS code is designed such that the physics models are separated from the numerical algorithms. Therefore, to extend the code to include new physics models, the user merely provides coded routines to the calling program for the functions C , F , S , and G . For the purpose of testing of the numerics on relevant physical models, a standard anisotropic convection-diffusion operator is used as the default F .

Gridding and discretization: There are two opposing criteria for the computational grids: (1) They should be flexible enough to easily grid scrape-off layer and target plate regions found in the limiter and single- and double-null divertor geometries. (2) They must also be structured enough to allow the grid to be aligned with the magnetic flux surfaces when possible. The structure should allow simple discretization of fluid equations and the use of organized solution techniques for the discrete equations (such as line by line relaxation or incomplete factorization methods).

We have chosen to allow arbitrary quadrilateral grids—grids composed of four-sided cells, but otherwise arbitrary cell shape and connectivity. While the local structure of the grid is logically rectangular, the global structure may in general be arbitrarily connected, allowing complex gridding strategies. A general connectivity allows for gridding of the entire scrape-off layer, both inside and outside the last closed flux surface. Flexible cell shape allows the grid to conform to the details of target plate geometry without necessarily following orthogonal field lines. The four-sidedness is useful for aligning with the flux surfaces when convenient. Two sides can be parallel and the other two perpendicular, to better represent the anisotropic transport on the grid. Triangular cells are ruled out by their inability to align properly with the flux surfaces under any situation.

To accommodate the non-orthogonal gridding structure, we developed a set of discrete operators based on a nine-point local stencil. This unique hybrid scheme is designed to preserve the conservation properties of finite volumes while retaining the geometric flexibility of finite elements. The stencil operator is based on isoparametric bilinear interpolations of

the mesh values, and it is extensible to three dimensions. Note also that the discrete operator tools are coded functions, so that details of the nine-point formulation are, therefore, shielded from the disinterested user.

For the special case of a uniform Cartesian grid, our discretization scheme reduces to centered finite differences. Centered differences are numerically unstable in the presence of the anticipated physics (strong advection) and require a corrective stabilization technique. There are several general candidates: slope limiters, upwind differencing, and artificial diffusion (all of which can be applied in our general setting without much difficulty). We have used a streamline-weighted artificial diffusion during the code development, because it is the simplest and most robust option. This technique is tailored to our hybrid scheme from the historically successful SUPG finite-element approach. However, because it has the drawback of a rather low accuracy, one of the more accurate techniques will be added in the final stages of the code development. Support for several corrective stabilization techniques may be needed for edge plasma codes since certain regimes (*e.g.*, coupled drift and parallel-momentum equations) are strongly convection dominated.

A more flexible geometry capability has left grid generation issues in need of development attention. In conjunction with a graphical user interface (GUI) that is under development, an automated mouse-driven grid generator has been prototyped. At start-up, flux surfaces generated by an equilibrium code are displayed for the model geometry. The user then “clicks” on primary grid locations and can locally refine areas known to require resolution.

Equation solvers: The time- and space-discretized fluid equations, along with the discretized boundary conditions, form a nonlinear system of N equations, where N is the total number of unknowns, which is typically around 10,000 [N is the number of states per cell (n , $v_{||}$, T_i , and T_e , for example) times the number of grid cells]. The system may be strongly nonlinear, because of the strong temperature dependencies in transport coefficients and neutral-plasma source terms. Furthermore, diffusion time scales in the plasma system are such that *implicit* time evolution is unavoidable. To solve the system, we use a multidimensional Newton method. Here, the nonlinear problem is linearized about the current state, and the slope is used to formulate a subsequent guess to the nonlinear problem. The process is iterated until the guess satisfies the full system, and it is substantially more robust than the semi-implicit iterative methods employed in most of the present edge codes.

Modern iterative solution techniques are used to solve the intermediate linear systems in each Newton iterate. The work of these algorithms, such as BiCGSTAB and QMR, is

proportional to N and, therefore, they scale suitably for larger problems. We additionally find that combining these iterative methods with a preconditioner is essential for obtaining fast convergence. Using a line-by-line relaxation, we can reduce the required iteration count by a factor of 10 or more.

Finally, we note that Newton methods are convergent only if the initial guess is "reasonably" close to the true solution. To improve the robustness of the solver in finding a steady-state solution, a pseudo-time is employed effectively as a damping to the pure Newton iteration process. The pseudo-time method allows the system to relax according to the dominating physical time scales, while requiring minimal operator intervention.

Numerical experiments: Even though the UCLA-EMS code is still under active development, many of the component features have already been successfully tested. Examples are presented below for the case of verifying the grid independence.

At least to the accuracy order of the discrete operator, a solution should reflect limited dependence of a particular gridding scheme. This property can be tested qualitatively by comparing the computed solutions of the same plasma condition for drastically different grids, or by rotating the action of a physical process with respect to a fixed grid. The discretization algorithm was tested in regimes dominated by convection, diffusion, and nonlinear convection-diffusion. These were chosen to bracket all cases of relevance to plasma simulation. In some cases, a model domain was constructed to include the effects of a target plate inclined with respect to an imposed ambient magnetic field.

The first tests were aimed at understanding the effectiveness of the nine-point formulation in allowing convective transport skew to the mesh. Artificial dissipation is applied directly in the upwind direction for a convection dominated problem (*i.e.*, the only dissipation present is numerical). The exact solution to this problem is the unsmoothed propagation of a "square" waveform. The nine-point results have been compared to a less efficient five-point scheme (Figure 1), wherein the dissipation is applied component-wise. The results indicate that, whereas the nine-point scheme is consistently diffusive regardless of the flow direction, the five-point scheme is absolutely intolerable for convection at 45° to the mesh. Though the poor first-order accuracy is apparent in these results, the nine-point scheme is notably less dependent on grid orientation, and its results could, therefore, be sharpened by localized grid refinement.

A more physical problem was then constructed to test the above results. A region was gridded in two distinctively different ways, as is shown in Figure 2. In the first grid, one grid coordinate was maintained along the magnetic field. In the second grid, one grid coordinate was maintained perpendicular to the target for expected gradient resolution

(irrespective of the field line geometry). Also note that the second mesh is constructed with an intentional "kink" in the grid lines.

The diffusive cases were run with fixed (Dirichlet) boundary conditions, as shown in Figure 3 (hyperbolic tangents in elevation). The convection case had fixed upper and lower boundaries and zero-flux (Neumann) side conditions. The qualitative solutions to these model problems are obvious, and the computed solutions, shown in Figure 3, are too close to distinguish in ordinary surface plots (all cases agree to $\pm 10\%$)

The ability to grid essentially irrespective of the ambient magnetic field is vital in modeling tokamak edge plasmas. Edge boundaries are intentionally constructed to meet the field lines at extreme angles in order to reduce impinging heat and particle fluxes. However, the UCLA-EMS is the first code designed to correctly allow for this situation.

Future direction: Development of the code is continuing with the full implementation of the nonlinear-system solution techniques. The algorithms have all been written and tested and await insertion into the EMS platform. Upon completion, direct comparisons can be made against the speed and accuracy of existing codes. It is expected that the UCLA-EMS code will be fully operational on a desktop workstation, while all the other codes require significant supercomputer resources. This functionality will be essential for the parameter scans and sensitivity analyses involved in typical fusion-device design programs.

Figure 1. Results of (A) five-point and (B) nine-point schemes for the convection of a square wave up and to the right. The exact solution is a square wave with its trailing corner at (3.54,3.54); a nine-point scheme, therefore, demonstrates significant improvement. Departure from a square wave is characteristic of a first-order convection scheme.

Figure 2. Non-orthogonal meshes used for the numeric tests. The grids were generated (A) to follow the imposed vertical field lines and (B) to be perpendicular to the target plate (bottom) for resolution away from the target.

Figure 3. Solutions of (A) diffusion- and (B) convection-dominated regimes for the domain of Figure 2. Solution to each problem differed by $< \pm 10\%$ for the two different grids of Figure 2, verifying the grid independence of our new nine-point discretization.

III. The Modeling of Gas-Target Divertors

Control of divertor plate erosion and thermal loading are critical issues for achieving long-pulse or steady-state tokamak operation at reactor-relevant power levels. Typically, the power flow parallel to the magnetic field in the scrape-off layer plasma is expected to reach values of 30 to 100 MW/m², and the power is deposited in a narrow region around the divertor strike point. Radiative and/or "gas-target" divertors potentially offer an attractive solution to the divertor heat-load problem. A key element of this concept is enhanced radiative-power loss in the divertor area, which is accomplished by injecting neutral deuterium and/or impurities close to the divertor target. As a result, the power flow may be redistributed over a larger surface area, and the peak divertor heat load may be reduced substantially. Simultaneously, the target electron temperature can be decreased to acceptable values (~ 10 eV). The gas-target regime has been simulated in linear plasma facilities (PISCES-A), and a substantial reduction of the electron temperature downstream from the plasma source has been demonstrated.

Modeling efforts are under way at UCLA to evaluate possible gas-target divertor scenarios. The plasma parameters of the proposed TPX/SSAT experiment are used for initial simulations. Since high hydrogen neutral density (or some lower-density impurity content) is required close to the divertor target (so that a substantial fraction of the input power to the scrape-off layer will be radiated), modeling ultimately requires a self-consistent approach that incorporates a plasma fluid model and a neutral transport model. A 2-D fluid code with a multi-group neutral model is under development at UCLA and will be available for the modeling of the gas-target regime in the fall of 1992 (Section II). So far, we have employed a simple $1\frac{1}{2}$ -D fluid code (solving the electron heat-flux equation along with the plasma momentum and continuity equations) to obtain solutions for the axial density and electron temperature profile at a gas-target divertor. The axial profile of the hydrogen neutral density is prescribed initially, based on PISCES-A experimental measurements in the gas-target regime and on results from the DEGAS code. The radial electron temperature, ion temperature, and plasma density profiles are assumed to be self-similar along the magnetic field. The ion temperature is assumed to be the same as the electron temperature. The profile of the neutral density inside the plasma is prescribed in such a way that the upstream neutral density at the $\times$ -point is not excessive ($n_0 < 10^{13}$ cm⁻³ at $\times$ -point). We are using the plasma density and temperature profiles calculated from the $1\frac{1}{2}$ -D fluid code as an input to the DEGAS code in order to obtain a more accurate neutral-density distribution. This two-stage simulation process can be iterated several times until convergence is achieved.

1 $\frac{1}{2}$ -D fluid modeling of gas-target divertors

We are using a 1 $\frac{1}{2}$ -D fluid model as a first approach to modeling gas-target divertors. In this model, we project the divertor slot onto the poloidal plane and treat this projected geometry as a 1-D slot with inlet at $z = 75$ cm and target at $z = 0$ cm. The model self-consistently calculates the neutral gas density, plasma density, plasma poloidal velocity, and plasma temperature (assuming $T_e = T_i$). We also include basic 2-D effects by allowing the plasma parameters to have radial profiles, with associated radial diffusion losses.

The plasma density, n , equation, which includes ionization gains and losses that are due, respectively, to radial anomalous diffusion and recombination, is

$$\frac{\partial n}{\partial t} + \frac{\partial(nv)}{\partial t} = nn_0\langle\sigma_{ion}v\rangle - n\frac{D_{\perp}}{\lambda^2} - \alpha n^2,$$

where σ_{ion} is the ionization cross section, $D_{\perp}$ is the anomalous perpendicular diffusion coefficient, and λ is the length scale for the radial density profile. We take $D_{\perp}$ to be the sum of the Bohm diffusion coefficient and the classical diffusion coefficient that is due to elastic neutral-ion collisions. Volume recombination (described by the last term) is only important at low temperatures ($kT < 1.5$ eV). As a boundary condition, the density is specified at the slot inlet.

The neutral gas density, n_0 , is modeled by a one-group neutral-diffusion model, which includes the losses to ionization and gains from ion recycling at the side walls and recombination,

$$\frac{\partial n_0}{\partial t} = \frac{\partial}{\partial z} D_{n_0} \frac{\partial n_0}{\partial z} - nn_0\langle\sigma_{ion}v\rangle + n\frac{D_{\perp}}{\lambda^2} + \alpha n^2,$$

where D_{n_0} is the one-group diffusion coefficient for neutrals at the plasma temperature. Neutral gas is assumed to be pumped at the target, which we model by the boundary condition of a specified neutral density at the target.

The plasma poloidal flow velocity, v , which is determined by the ion parallel-momentum equation, including the electric and thermal forces, momentum losses (due to charge exchange, neutral-ion collisions, and ionization), and radial diffusion,

$$\frac{\partial m_i n v}{\partial t} + \frac{\partial(m_i n v^2 + n k T)}{\partial z} = enE + 0.71n \frac{\partial k T}{\partial z} - m_i n v (\nu_{cx} + \nu_{in} + \nu_{ion}) - m_i n v_i \frac{D_{\perp}}{\lambda^2},$$

where m_i is the ion mass, T is the plasma temperature, and ν_{cx} , ν_{in} , and ν_{ion} are, respectively, the collision frequencies for charge exchange, neutral-ion collisions, and ionization.

The flow is assumed to be symmetric at the inlet ($\partial v / \partial z = 0$). The electric field, E , is determined from momentum balance of the electrons,

$$enE = -\frac{\partial(nkT)}{\partial z} - 0.71n\frac{\partial kT}{\partial z}.$$

The plasma temperature profile is determined from the electron temperature equation (since we assume $T_e = T_i$), which is

$$\frac{3}{2}n\frac{\partial kT}{\partial t} + \frac{3}{2}nv\frac{\partial kT}{\partial z} + nkT\frac{\partial v}{\partial z} = -\frac{\partial q}{\partial z} - nn_0\langle\sigma_{ion}v\rangle E_{ion}.$$

Here q is the poloidally projected, flux-limited Spitzer heat flux with a 50% harmonic flux limiter, and E_{ion} is the energy loss per ionization. The temperature and density dependency of both E_{ion} and $\langle\sigma_{ion}v\rangle$ are included. The temperature is fixed at the inlet boundary; and it is related to the flow velocity by the Bohm sheath criteria [$v = c_s(T)$] at the target boundary.

Because of the short time scale of the ionization process ($\approx 10^{-8}$ s), simulations require a small numerical time step and are, therefore, presently limited to a total elapsed time on the order of microseconds. This is much smaller than the time scale for convective equilibrium (milliseconds), but it is long enough to establish a quasi-equilibrium that is very robust on the microsecond time scale. Typical results are shown in Figure 4. Starting from a set of reasonable, simple initial conditions (exponential neutral profile, flat plasma density, temperature decreasing toward the target, and a sheath profile for the poloidal flow velocity), the system evolves to a quasi-equilibrium state in $\approx 1 \mu s$. The essential features of this state then persist for at least the next 40 μs . These robust features are: (1) The plasma is detached from the target by about 8 cm, where the density and temperature have collapsed; and (2) The neutrals are confined to this collapsed region and, at the neutral-plasma interface, there is an ionization zone containing a sharp peak in plasma density (because of ionization gains) and neutral density (because of localized recycling from the side walls). The plasma flow is strongly reversed at this interface, since the plasma is blown out by the high pressure at the density peak.

Convective effects may substantially alter this short time quasi-equilibrium, given sufficient time to act. Therefore, we are presently enhancing the code to achieve simulations on the millisecond time scale of the true equilibrium. Future plans also include the utilization of our new edge-simulation code (Section II) for gas-target divertor simulations.

(A)

 $t = 0.0 \mu\text{seconds}$

(B)

 $t = 2.0 \mu\text{seconds}$

Figure 4. (A) Initial and (B) evolved data for the gas-target divertor model. Shown are the neutral density, n_0 , plasma density, n , electron temperature, T , plasma pressure, $nk(T_e + T_i)$, parallel heat flux, $q_{\parallel}$, and poloidal Mach number, M_{pol} .

DEGAS Monte Carlo simulation of gas-target divertors

In order to radiate a substantial fraction of the scrape-off layer input power, high neutral density is required at the divertor target plate. The DEGAS code, which computes neutral transport effects in devices of general 3-D geometry, has been used in a preliminary calculation of the neutral density distribution for a gas-target divertor.

Plasma profiles input to the DEGAS code are from a $1\frac{1}{2}$ -D fluid calculation of axial density and electron temperature profiles (Section III), with the hydrogen neutral density initially prescribed based on experimental measurements in the PISCES-A gas-target regime. The DEGAS code provides a more accurate neutral distribution that can be iterated with the fluid calculation.

The DEGAS geometry [shown in Figure 5(A)] is a rectangular slab of 5 cm (in the radial direction) by 75 cm (in the axial direction, *i.e.*, parallel to the flux surface as projected on the poloidal plane). The latter dimension (75 cm) corresponds in tokamak geometry to a poloidal length for $B_\theta/B_t = 0.1$ and is consistent with the space limitations expected in TPX. A pump duct is located at $r = 5$ cm, $40 < z < 50$ cm. Neutrals can also exit the divertor channel through the upstream boundary ($z = 0$). Recycling from the side walls is included, consistent with the radial plasma loss by diffusion.

The plasma separatrix is located at $r = 2$ cm. The input profile of the electron temperature, shown in Figure 5(B), decreases monotonically from $kT_{e,sep} = 250$ eV (at the slot entrance) to 25 eV (at the target) in the scrape-off layer zone (from $r = 0$ to $r = 2$ cm). In zones outside this region, although the temperatures are proportionately lower, they still decrease monotonically approaching the target. The radial density and temperature profiles are self-similar along the length of the channel. The plasma pressure is assumed to be constant along field lines, resulting in a density profile that has an $n_{e,sep} = 3 \times 10^{13}$ cm⁻³ and monotonically rises to 3×10^{14} cm⁻³ at the target [Figure 5(C)]. The density is taken to be constant for $0 < r < 2.5$ cm and decreases to 1/100th of that value in the scrape-off layer. Neutral hydrogen is puffed in at the target.

The DEGAS results, illustrated in Figure 6, show that the neutral density (both neutral hydrogen atoms and molecules) decreases by 3 to 4 orders of magnitude in the scrape-off layer zone in the axial direction approaching the divertor entrance. In the low density regions close to the channel walls, a reduction by 2 orders of magnitude is observed for H and H₂, so that the upstream neutral density is consistent with our earlier assumption for the plasma model. We are presently using the DEGAS code to determine the optimum location and geometry of the pumping duct(s). Additional efforts include iterations between the fluid model and DEGAS.

Figure 5. Input plasma parameters for the DEGAS simulation of a gas-target divertor: (A) geometry, (B) electron temperature, and (C) ion density.

Figure 6. Results of DEGAS simulations of a gas-target divertor: density of (A) neutral hydrogen atoms and (B) molecules.

IV. RF Ponderomotive Forces and Electrostatic Barriers for the Control of the Scrape-off Layer

Experiments have shown that particle and heat transport in the scrape-off layer can be significantly altered by externally imposing an electrical potential to the limiter and/or wall surfaces, or by imposing a ponderomotive potential within the plasma from an RF source. We have extended an analytical and numerical non-ambipolar two-fluid transport model to include both ponderomotive and electrostatic potentials. Unlike transport within the plasma core, cross-field electron and ion fluxes are not constrained to be ambipolar within the scrape-off layer. Currents may flow along field lines through the limiter, an effect that is enhanced by limiter biasing. These non-ambipolar boundary conditions can modify the density profiles that would ordinarily occur in an ambipolar plasma. In the presence of turbulence, this effect is not so clear and, to investigate it further, we have included such non-ambipolar effects within the framework of a phenomenological model of edge density and potential fluctuations. The contribution of neutral particle-plasma interaction is included in both analytical and numerical models. The model is developed to apply to toroidal magnetic geometry as well as to simple cylindrical geometry by retaining terms that arise from the gradient of the magnetic field, including curvature and radial inhomogeneity.

A set of coupled partial-differential equations are derived that describe density and electrostatic potential. Fluctuation-driven transport, which is experimentally observed to be largest in the edge plasma, may be due to instabilities that are governed by the radial dependence of the electric field. The effects of these fluctuations are included in the model by assuming that the density and potentials have a time-averaged term and a fluctuating term. The resulting equations are averaged so that only transport resulting from correlations is folded into a phenomenological, anomalous diffusion coefficient. Terms containing the magnetic field gradient arising from the $\vec{E} \times \vec{B}$, diamagnetic, and ponderomotive force drift are retained, so that the model can be used to describe transport in toroidal systems with magnetic shear. The equations are finite differenced on a 2-D grid and solved numerically. The condition of global ambipolarity is also imposed, which requires that the net current be zero (although locally there may be current flow).

The model has been applied to experiments that have been performed on the PISCES linear edge simulator and that are planned for TEXTOR and PBX-M. The ponderomotive barrier effect is readily seen in the contour plot of the wall current density (Figure 7), which resembles the experimentally observed contour topology.

Figure 7. (A) Schematic of the electron trajectory in the presence of a ponderomotive potential barrier and (B) contour plot of the wall current density, which demonstrates the ponderomotive barrier effect (departure from circular contours on the lower right-hand side).

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