

PFC/RR-95-9

**First Annual Report of the Divertor Task Force:
Progress and Plans**

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October 1995

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Preamble

Recognizing that a practical solution for a high fusion power divertor design will have to come from new physics rather than engineering alone, the Divertor Task Force (DTF) was established in August 1994 as a focused and innovatively organized cooperative of scrape-off-layer (SOL) and divertor plasma theorists and computational experts (with guidance from DIII-D and Alcator C-Mod experimentalists and "ITER experts"), volunteering to collaborate as one group across institutional boundaries working toward a common objective (in contrast to the traditional highly competitive mode of operation of separate national lab and university groups). The common goal is to obtain an increasingly complete physics understanding of existing divertor plasmas, to build analytical and numerical models of the SOL divertor plasmas and to extrapolate them to find design solutions for the high power divertors of ignited tokamak plasmas such as ITER and other high performance future tokamaks.

This process is facilitated through mutual code sharing, person to person collaborative visits to other facilities and periodic working meetings, in addition to task force group presentations at the major US meetings. (A list of first year DTF working meetings and special sessions at conferences is given in Appendix 1.) The DTF members accept the obligation to work on the programmatically most pressing topics (sometimes sacrificing productive personal research interests) and to commit to completion dates for code developments (often difficult in leading edge research). Commitment to this task force is entirely voluntary and does not preclude participation in other groups such as the less structured divertor edge plasma group originated by H. Weitzner(1) in December 1992 as a first step at shifting attention to this important topic.

(1) H. Weitzner, editor "A Survey of Problems in Divertor and Edge Plasma Theory," Report MF-125, Courant Institute, NYU (December 1992).

I. Founding Meeting, Original R&D Needs List and Organization

At the August 1994 founding meeting the roughly 30-member task force organized itself into three teams governing the main themes of (1) detachment and divertor physics; (2) core plasma interaction with the SOL; and (3) code development and validation. These 3 teams consist of a balanced mixture of analytical theorists and numerical specialists. An R&D needs list was compiled driven by the corresponding lists from existing divertor tokamaks plus ITER and TPX. These lists in themselves presented the worldwide state-of-the-art (formulated, e.g., by the "ITER experts"). To secure strong ties to divertor experiments Ron Stambaugh (DIII-D) and Garry McCracken (Alcator C-Mod) were invited into the task force from the start.

The following list of work topics established in August 1994 reflects both the premier R&D needs at that time and the DTF members original commitments:

In the area of detachment the plans called for improved physics in the big 2D codes, together with development of simple 1D codes to scope various physics elements quickly, in conjunction with experiments. An urgent need for a fluid (Navier-Stokes) description of the neutral particles in the divertor chamber was recognized to model detachment, in parallel with further Monte Carlo neutrals code development. The importance of $E \times B$ drifts due to the ambipolar electric field were recognized as well as edge plasma turbulence which determines the width of the SOL plasma. Kinetic theory (rather than fluid) model descriptions were found as essential to understand plasma phenomena near the divertor target as well as "upstream" in the long mean free path regime prevailing near and above the X-point but reaching into the divertor target area.

The core plasma SOL interactions were recognized as essential for ELM evolution, H-mode formation, the density limit, and the formation of the ambipolar field and edge turbulence across the separatrix.

Concerning code development and validation, the following codes were at hand but in various (often early) stages of development. The 2D fluid codes UEDGE and B2, the original 1D fluid NEWT1D coupled with early impurity models, the PIC kinetic W1 code in a version running on a PC, the beginnings of a turbulent neutral fluid 3D code ISAAC, the Monte Carlo code DEGAS and its successor DEGAS-2 (under development), a just begun core SOL coupling code CORSICA, and a plasma wall ablation code FOREV.

The task force committed itself to further develop/validate/benchmark these modelling tools to bring them closer to a confident application stage, with first deliverables within one year, agreed upon by the participants.

The original workplan outline is given in Appendix 2

II. Achievements of the DTF in the first year-Summary

At the August 1995 Working Meeting at MIT the following summaries of first year accomplishments were presented(or deposited with the chairman).

While the listing follows the lab/university group's presentations, the work presented can, and must -- by the very construct of the Task Force -- be attributed to many DTF members working across institutional boundaries.

II.1 Detachment and Divertor Physics

The efforts in this team were concentrated during the first year (8/94-8/95) on eight areas of edge plasma physics:

1. Theory of detachment mechanisms
2. Neutral particle fluid models and coupling to the plasma models
3. Divertor similarity and scaling laws
4. Impurities and ELMs
 - 5a. Fluid code modelling
 - 5b. Kinetic modeling, i.e. PIC and F.P.(Fokker Planck) finite element codes
6. Kinetic theory development
7. Turbulent effects in the edge plasma
8. Electric field effects

SELECTED HIGHLIGHTS OF OBTAINED RESULTS

The leadership of the detachment and divertor physics team is predominantly at MIT's divertor plasma theory center, but contributions from other team members were essential here. The corresponding references are listed at the end of this section.

1. Detachment

- A comprehensive analytical theory of various models of plasma detachment was developed based on plasma-neutral-impurity interaction, ExB drift effects, and plasma recombination[1,3,7,10,15,17,22,26].

2. Neutral Particle Fluid Model Development

- First coupling of the full Navier-Stokes neutral fluid model retaining neutral-neutral collisions to the UEDGE plasma fluid code. C-MOD and ITER modeling reproduce detailed features of the detached divertor regimes (in collaboration with D. Knoll and T. Rognien) [1,16,18].
- Initial benchmarking of the DEGAS Monte Carlo (MC) code in the short mean free path limit by employing the exact analytic results from a coupled ion-neutral treatment [16].
- Future Plan-Hybrid Approach for Neutral Transport Modeling in SOL Plasma:

The ratio of the neutral mean free path, λ_N , to the scale length of plasma parameter variation, L_p , in the SOL plasma can vary over a wide range. Close to the divertor targets, for the high recycling regime it may be very small ($\sim 10^{-2}$), while far from the targets, or near the side walls it may be very large ($\sim 10^2$). This circumstance makes impossible to apply a very efficient fluid neutral description in the whole SOL volume with reasonable accuracy. On the other hand, a comprehensive MC method becomes very inefficient for neutral transport modeling in the dense plasmas especially if neutral-neutral collisions must be retained.

A hybrid approach which can be efficiently applied for whole SOL volume is highly desirable. At present, two possible approaches may be pointed out: i) application of the MC method upstream and fluid description in a separate region closer to the divertor target, and their matching at the boundary, ii) application of the coupled MC and fluid descriptions in the whole SOL regions adding into both sets of the equations sink/source terms depending on the λ_N/L_p ratio. It should be noted that at present it is not yet clear if any of these hybrid approaches can be applied for neutral transport modeling in the SOL/divertor plasmas. A feasibility analysis of their applicability is needed before the development of the hybrid code commences.

3. Divertor Similarity and Scaling Laws

- Similarity transformation techniques were employed for divertor plasma models extending the "Lackner Divertor Scaling". These results can be used for code benchmarking and interpretation of the experimental data. (In collaboration with J. Connor, Culham) [2].

4. Impurity and ELMs

- Adapting the earlier Hirshman-Sigmar "method of reduced charge states" for the SOL, the reduced-ion description for computing the parallel forces and heat fluxes in a fluid-regime impurity plasma has been encoded in a module FMOMBAL for use in plasma edge transport codes. This code package has been coupled to the UEDGE code. For high Z impurities, Krashennnikov's earlier "continuum model" has been further developed. (Sherwood 1995, collaboration with S. Hirshman) [29].
- The effects of the ELM bursts on the SOL plasma parameter evolution have been investigated with kinetic and fluid models. It was found that this transient effect can result in strong departure of the distribution function from Maxwellian with important consequences for divertor

probe measurements as well as application of fluid model codes to such plasmas. Also, a nonlinear radiative instability with concomitant stratification of the SOL plasma has been investigated (in collaboration with UNAM, Mexico) [8].

5a. Fluid code modelling

- Starting with the 2-D UEDGE plasma fluid code and coupling the neutral fluid model by Helander, Krasheninnikov and Catto [16] it has been possible for the first time to simulate successfully the experimental details of partial detachment in the Alcator C-MOD divertor plasma, to be presented at the APS 1995 meeting. The abstract of this important step forward reads:

Simulation of Detachment in the Alcator C-Mod Divertor
with an Improved Neutral Model

F. Wising, D.A. Knoll, S. Krasheninnikov, T. D. Rognlien

We have recently improved the neutral physics in the 2-D edge plasma fluid code UEDGE, allowing us for the first time to simulate detachment in the strongly curved C-Mod geometry. A neutral momentum equation has been added which is fully coupled to the ion momentum equation through ion-neutral collisions, ionization, and recombination. This allows parallel plasma momentum to be converted into neutral momentum, which is dispersed to the material walls due to the high neutral viscosity. The model is relevant and appropriate for high density, short mean free path conditions such as in Alcator C-Mod and ITER, and includes both ion-neutral and neutral-neutral collisions.

On an orthogonal C-Mod geometry, with divertor plates normal to the poloidal field, we have shown that this model produces detachment as a fixed fraction of carbon impurities is added to the plasma [F. Wising, D. Knoll, T. Rognlien, 1995 Sherwood Theory Conference]. It was found that the heat flux to the plate as well as the ion saturation current both were reduced by one to two orders of magnitude at detachment.

The new simulations, carried out in the full **nonorthogonal geometry**, investigate detachment in the C-Mod vertical target divertor. They reproduce, for the first time, the pervasive experimental feature that the plasma detaches gradually, starting at the strike point, while always remaining attached above the "nose" of the divertor channel.

The strikepoint heat flux and current drop by an order of magnitude as 0.5% of carbon is introduced to induce detachment. At detachment, the plate temperature remains at or above about 1 eV all the way out to the nose, i.e. higher than in the orthogonal plate simulations and in agreement with the experimental data. The separatrix T_e remains low over an extended region between the target and the X-point.

• See the simulation results in Figs 1a, 1b at the end of this report.

5b. Kinetic Models -- Numerical Tools (PIC and finite element F.P. codes)

- We have developed (in collaboration with LLNL) the 1D+2V PIC code W1 and obtained the first results of kinetic modeling of detached divertor regimes. Strong departure of the electron distribution function from Maxwellian is found near the target, which affects the interpretation of the probe data for the electron temperature found for C-MOD like conditions (which are also typical for ITER like plasma parameters) as well as correct evaluation of reaction rates. Both attached and detached solutions are found in agreement with analytic predictions [10]. Slot -- as well as gas box geometry was modelled [23b].

W1 Work Underway/Plans:

Parallelized version of code PW1 is under construction (with LLNL)

ELM burst simulation with real mass ratio

Influence of radiative impurity on detachment

Gas-box model -- further modifications

- We have developed a 1D+2V finite element Fokker Planck (F.P.) code ALLA. We have benchmarked ALLA with the exact self-similar solutions of the collisional kinetic equation (in collaboration with M. Shoucri, Canada) [27]

ALLA Fokker-Planck code results:

1. The 1-D,2-V code Alla was built on an adaptive grid in space and non-uniform grid in velocity space with cubic splines and a conservative collisional operator solver .
2. 1D and 2V versions of code are benchmarked on:
 - propagation of sharp function across adaptive mesh
 - full Rosenbluth potentials solver
 - self-Maxwellisation of non-Maxwellian distribution function
 - self-similar solutions of kinetic equations
3. 1V non-stationary model of ELM burst including energy source and particle sink terms is simulated.

ALLA Code Work Underway/Plans:

- a. Benchmarking of full 1D2V version.
- b. Simulation of C-Mod and TdeV electron transport.
- c. Parallelization of ALLA massively parallel computers using the MPI environment.

6. Kinetic Models -- Analytic Results

- Several kinetic equation solutions based on the self-similar variables technique have been developed for neutral and plasma species. These solutions are being used for the benchmarking of fluid and kinetic, neutral and plasma codes [13, 28].
- Long mean free path effects on the divertor plasma parameters were investigated using different kinetic SOL models. Strong (i.e. non-negligible) effects are found [6,18,23a].

7. Turbulent effects in the edge plasma

- The effects of the turbulent neutral gas flow on the heat conduction in the divertor region have been investigated for the ITER relevant parameters with the ISAAC code. It is found that neutral gas heat conductivity can be strongly affected by the turbulence even at low Reynolds numbers (< 1000) (in collaboration with L. Vahala and G. Vahala). [5]
- We have shown that the Reynolds stress term in the divertor plasma can strongly affect the plasma parallel momentum balance and can induce plasma pressure drop along the magnetic field line similar to that found in the detached divertor plasmas. [12]

8. Electric Field Effects

- In Alcator C-MOD, the Tde V and other tokamaks, a strong effect is observed on the heatload-asymmetry to the inner/outer divertor target upon reversing the magnetic field and hence the ExB flow. For this and further reasons including the influence of the ExB induced Reynolds stress on detachment, a series of analytical and numerical studies were completed on this topic. [9,12,20,21,25,4]

References-this section (MIT):

- [1] S. I. Krasheninnikov and T. K. Soboleva, "Plasma-Neutral Interaction in Tokamak Divertor for "Gas-Box" Neutral Model," PFC report JA-95-13 (June 1995), submitted to Phys. Plasmas.
- [2] P. J. Catto, S. I. Krasheninnikov and J. W. Connor, "Scaling Laws for Two-Dimensional Divertor Modeling," PFC report JA-95-10 (May 1995), submitted to Phys. Plasmas.
- [3] D. A. Knoll, P. R. McHugh, S. I. Krasheninnikov and D. J. Sigmar, "Simulation of Dense Recombining Divertor Plasma with a Navier-Stokes Neutral Transport Model," accepted in Phys. Plasmas (1995).
- [4] L. Gauthier and S. I. Krasheninnikov, "Radial and Poloidal Electric Field Effects on Particle Trajectories in a Tokamak," submitted to Plasma Phys. Reports.
- [5] G. Vahala, L. Vahala, J. Morrison, S. I. Krasheninnikov and D. J. Sigmar, "Effects of Neutral Three Dimensional Turbulence in the Gas Blanket Regime for Divertors," Phys. Letters A 205 (1995) 266.
- [6] P. J. Catto, S. I. Krasheninnikov and R. D. Hazeltine, "Flux Limiting Due to Electron Impact Excitation Energy Loss," PFC report JA-95-8 (May 1995), submitted to Phys. Plasmas.
- [7] A. S. Kukushkin and S. I. Krasheninnikov, "Modeling of the Transport of the Plasma and Neutrals in the Divertor Layer with 1D GARMIT Code," PFC report JA-95-7 (March 1995), submitted to Phys. Plasmas.
- [8] P. Helander, S. I. Krasheninnikov, D. Kh. Morozov and T. K. Soboleva, "Radiative Instabilities in the Tokamak Scrape-Off Layer During Edge-Localized Mode Activity," PFC report JA-95-6 (March 1995), Phys. Plasmas 2, 3769 (1995).
- [9] G. Manfredi, M. Shoucri, I. Shkarofsky, P. Bertrand, A. Ghizzo, S. Krasheninnikov, D. Sigmar, O. Batishchev and A. Batishcheva, "Study of a Divertor Plasma in ExB Flow," CCFM report RI 452e (March 1995).
- [10] S. I. Krasheninnikov, P. J. Catto, P. Helander, D. J. Sigmar and T. K. Soboleva, "Thermal Bifurcation of Scrape Off Layer Plasma and Divertor Detachment," PFC report JA-94-28 (January 1995), Phys. Plasmas 2, 2717 (1995).
- [11] T. H. Rider and P. J. Catto, "Modification of Classical Spitzer Ion-Electron Heat Transfer Rate for Large Ratios of Ion to Electron Temperatures," Phys. Plasmas 2, 1873 (1995).
- [12] S. I. Krasheninnikov, D. J. Sigmar and P. N. Yushmanov, "Effect of ExB Drift on Divertor Plasma Flows," Phys. Plasmas 2, 1972 (1995).
- [13] P. J. Catto and J. W. Connor, "A Two-Dimensional Ion Kinetic Model of the Scrape-Off Layer of a Diverted Plasma with a Private Flux Region,"

Phys. Plasmas 2, 218 (1995).

[15] S. I. Krasheninnikov, P. J. Catto, D. J. Sigmar, P. N. Yushmanov, R. D. Hazeltine, P. Helander, J. W. Connor, D. Knoll, P. R. McHugh, S. P. Hirshman, Š. E. Attenberger, J. J. Martinell, D. Kh. Morozov and T. K. Soboleva, "On Divertor Detachment in Current Tokamaks and ITER and Kinetic and Fluid Descriptions of Scrape-Off Layer Plasmas," Fifteenth International Conference on Plasma Phys. and Controlled Fusion Research, Seville, Spain, 26 September - 1 October 1994.

[16] P. Helander, S. I. Krasheninnikov and P. J. Catto, "Fluid Equations for a Partially Ionized Plasma," Phys. Plasmas 1, 3174 (1994).

[17] P. Helander and P. J. Catto, "Two-Dimensional Kinetic Modeling of a Tokamak Scrape-Off Layer with Recycling," Phys. Plasmas 1, 2213 (1994).

[18] P. J. Catto, "A Short Mean Free Path, Coupled Neutral-Ion Transport Description of a Tokamak Edge Plasma," Phys. Plasmas 1, 1936 (1994).

[19] P. J. Catto and R. D. Hazeltine, "A Two-Dimensional Kinetic Model of the Scrape-Off Layer," Phys. Plasmas 1, 1882 (1994).

[20] P. N. Yushmanov, J. Q. Dong, W. Horton, X. N. Su and S. I. Krasheninnikov, "Plasma Rotation and Electrostatic Potential Formation at the Edge Due to Suprathermal Particle Losses," Phys. Plasmas 1, 1583 (1994).

[21] S. I. Krasheninnikov and P. N. Yushmanov, "The Influence of a Radial Electric Field on Neoclassical Orbits and Ion Prompt Losses from Tokamak Edge Plasmas," Phys. Plasmas 1, 1186 (1994).

[22] S. I. Krasheninnikov, D. J. Sigmar, T. K. Soboleva, A. B. Kukushkin, O. V. Batischev and Yu. S. Sigov, "Regimes with Recombining Plasma in the ITER Divertor," Contrib. Plasma Physics 34, 442 (1994).

[23a] O. V. Batischev, S. I. Krasheninnikov, D. J. Sigmar, Yu. S. Sigov and T. K. Soboleva, "Influence of Kinetic Effects on Particle and Energy Flows in the ITER Divertor," Contrib. Plasma Physics 34, 436 (1994).

[23b] O. V. Batischev, X. Q. Xu, J. A. Byers, R. H. Cohen, S. I. Krasheninnikov, T. D. Rognlien and D. J. Sigmar, "Kinetic Study of Divertor Plasma Detachment with PIC Code "W1"," submitted to PFC report JA-95-24 (July 1995), submitted to Phys. Plasmas.

[24] S. I. Krasheninnikov and R. Chodura, "Kinetics of Plasma Flow in Recycling Region," Contrib. Plasma Physics 34, 210 (1994).

[25] S. I. Krasheninnikov and P.N. Yushmanov, "Radial Electric Field Influence on Neoclassical Orbits in a Tokamak," Contrib. Plasma Physics 34, 186 (1994).

[26] S. I. Krasheninnikov, "Kinetics of Tokamak Edge Plasmas: Problems and Progress," Contrib. Plasma Physics 34, 151 (1994).

[27] A. A. Batishcheva, O. V. Batishchev, M. M. Shoucri, S. I. Krasheninnikov, P. J. Catto, I. P. Shkarofsky, and D. J. Sigmar, "Modeling of the Kinetic Features of ELM Propagation in the Tokamak SOL Plasmas with Fokker-Planck Code "ALLA"," PFC report JA-95-23 (July 1995), submitted to Phys. Plasmas.

[28] P. Helander, S. I. Krasheninnikov, "Kinetic Theory in Self-Similar Variables for Neutral Atoms in Plasma," PFC Report JA-95-26 (June 1995) accepted for publication in Phys. Plasmas.

[29] A. B. Arutunov, S. I. Krasheninnikov, D. Yu. Prokhorov, "Simplified models of distributions of impurities in ionized states in a tokamak plasma," Sov. J. Plasma Phys. 17 (1991) 668.

II.2 Further Code Developments and Core-SOL Interactions

(as presented at the August 1995 DTF Working Meeting)

Dana Knoll (INEL):

A combined edge plasma/Navier-Stokes neutral model has been developed within the UEDGE code for simulation of ITER dissipative divertor scenarios. The model includes both ion-neutral and neutral-neutral collisions. The full model (3 momentum equations for neutrals) is functional on Cartesian grids, while a reduced model (1 parallel momentum equations for neutrals) is functional on nonorthogonal curvilinear grids.

This Model has been able to reproduce all salient features of detachment in CMOD-like plasmas on rectangular grids. Volume recombination and neutral-neutral collisions are required to correctly simulate plate characteristics.

A 4 meter long (poloidal) ITER-like problem was modelled whose divertor length is 1 meter, slot width is 30 cm, with a 0.5% carbon admixture. The result shows complete thermal and momentum detachment.

Only 20% hydrogen line radiation was allowed to escape to account for the to high density ($4 \times 10^{19} \text{ m}^{-3}$). Approximately 40% core power is radiated

by impurities (carbon), and 15% is radiated by hydrogen neutrals. The bulk of the remainder goes to side walls.

Baffling the neutral flow (in a Cartesian grid) has shown a significant increase in the operating window (allowing higher T_{sep} , lower n_{sep} for a dissipative divertor).

•The results of the simulation are shown in Fig2 at the end of this report and is published in D. A. Knoll, P. R. McHugh, S. I. Krasheninnikov and D. J. Sigmar, "Simulation of Dense Recombining Divertor Plasma with a Navier-Stokes Neutral Transport Model," accepted in Phys. Plasmas (1995).

•A new code permitting a fully implicit Vlasov Fokker-Planck solution of collisional plasmas has been written and applied to the ion species in the plasma edge (submitted to J. Comput. Phys. 1995).

G. Vahala (William and Mary), L.Vahala (Old Dominion Univ.):

- ISAAC: Numerical modelling of the K-epsilon equations for the 3D turbulence neutral fluid flow in a toroidally notched/recessed divertor chamber shows a remarkably large ratio of turbulent heat transfer coefficient over laminar heat transfer coefficient. Before the beginning of the wall recess the ratio is 2. At the end of the recess it is as much as 30. This indicates a large enhancement of the effective heat and momentum transfer through the neutral gas to the walls: the eddy enhanced transport coefficient can be 15 times larger than the classical value.

[5] G. Vahala, L. Vahala, J. Morrison, S. I. Krasheninnikov and D. J. Sigmar, "Effects of Neutral Three Dimensional Turbulence in the Gas Blanket Regime for Divertors," Phys. Letters A 205 (1995) 266.

LLNL Divertor/Edge Plasma Program

The LLNL work has focused on the following areas:

1. ExB detachment, current, and boundary conditions
2. Kinetic modeling

3. Core-SOL coupling
 4. Plasma turbulence
 5. Integrating new models into 2-D fluid codes
 6. Improved numerics
 7. Code validation
-

(Note: Numbers in parenthesis following paragraphs refer to subject of the original workplan outline listed after the references)

1. ExB detachment, current, and boundary conditions

We have developed analytic models of the effect of ExB drifts in producing poloidal density asymmetries in the SOL [1L] that could lead to detachment-like profiles. We have also generalized the Bohm sheath condition and clarified the closing of currents on the divertor plate [1L,2L]. In response to these ExB effects, rippled divertor plates are predicted to broaden the width of the SOL [3L]. (1.1.1) We have modeled a typical DIII-D discharge including ExB effects with UEDGE using the improved models [1L,2L]. There is a competition between the radial and poloidal drifts that cause reduced thermal collapse for either direction of the toroidal B-field, and this investigation is continuing. (1.1.1)

2. Kinetic modeling

As part of the LLNL/MIT collaboration, we have performed numerous calculations with the W1 1-D kinetic for both Knudsen and gas box neutral models to show the transition to detached divertor operation.

Parallelization of W1 is discussed under item 6. Comparisons have also been made between the W1 and fluid UEDGE to highlight the kinetic differences. (1.2.2; 3.2)

A previous analytic model of kinetic thermal transport [4L] has been extended to allow efficient implementation in fluid codes. (1.2.2; 3.2)

3. Core-SOL coupling

A new model for the L-H transition based in part on instabilities in the SOL has been developed [5L]. A preliminary version has been incorporated into UEDGE that does show a natural bifurcation of the SOL equilibrium;

refinement to obtain the power threshold predicted by the theory is in progress. We have also analyzed the effect of core drift-wave turbulence which could propagate to the edge region [6L]. (2.1)

Coupling between the core and SOL transport models have been achieved with the CORSICA-2 code which integrates 1-D core transport with 2-D SOL transport through a common flux-surface interface near the plasma edge. So far, three variables (n , T_e , and T_i) have been coupled. (2.3)

A description of radial plasma current has been obtained from the toroidal momentum balance equation that includes anomalous momentum transport consistent with damping of toroidal rotation. This current allows a solution of the current continuity equation to obtain the electrostatic potential which is now valid both inside and outside the separatrix. (2.4)

Initial UEDGE calculations have been done at LLNL and INEL to understand the SOL time response to a disruption. The anomalous diffusion coefficients are increase one to two orders of magnitude to produce the observed energy flux on the divertor plate. For ITER, these calculations can provide input conditions for ablation codes such as FOREV, and subsequently can provide impurity transport back into the core.

4. Plasma turbulence

We have expanded from 2-D to 3-D our numerical model of edge/SOL turbulence based on the conducting wall mode [7L,8L]. The model again includes propagation into the core region, and now allows low density regions near the divertor plates to simulate detached plasmas. (1.1.4; 2.5) A model has been developed to describe the influence of the poloidal magnetic field variation near the x-point on conducting-wall type modes [9L].

5. Integrating new models into 2-D fluid codes

Several important physics modules have been added to the public UEDGE fluid code. With the assistance of Hirshman (ORNL), we have installed the multi-species impurity package FMOMBAL which calculates the parallel collisional force between ion species in the non-trace limit. This provides a more rigorous model to evaluate impurity retention in the divertor region. (1.1.3; 3.5).

We collaborated with Knoll (INEL) and Wising (MIT) to include a fluid neutrals model with parallel inertia and neutral-neutral collisions in the public UEDGE. This model produces the same type of detachment with low ion current to the plate as seen in the full Navier Stokes neutrals model. (1.1.2; 1.2.3; 3.3)

A new model for the electrostatic potential valid into the core region has been implemented. The model calculated the radial current by using the toroidal momentum equation with anomalous viscosity. The model reproduces the change from a positive radial electric field outside the separatrix to the negative one inside, as observed experimentally. (2.4)

A first hand-iteration between UEDGE and DEGAS-2 has been achieved. (3.4)

6. Improved numerics (3.7)

As part of the LLNL/MIT collaboration on the W1 1-D kinetic code, we have developed a version (PW1) that runs on the T3D parallel computer at NERSC. There is a nearly linear increase in speed with the number of processors until a saturation begins beyond 16 processors; we are working to improve this further, and have developed plans for a 2-D version of PW1. (3.2)

A nonorthogonal mesh version of UEDGE has been developed that allows one to assess the role of tilted divertor plates and other structures (baffles) that protrude into the SOL [10L] (3.7)

In our continuing effort to improve the method of solution for fluid codes, we have extended the reordering of the Jacobian matrix reported previously [11L] to include automatic scaling of the Jacobian columns. This procedure results in a better conditioned matrix, and allows the code developer to use physical variables rather than normalized variables, making detailed knowledge of previous normalization unnecessary. (3.7)

A new version of the time-dependent solver DASPK by Petzold, et al. has been included in UEDGE which treats the boundary conditions as pure algebraic constraints rather than stiff ODE's. This package was available previously, but was difficult to use because the initial conditions needed to be consistent; this consistency is now automatically generated. (3.7)

The pseudo-transient method introduced by Knoll has been included in UEDGE. This gives the user the option to trade the rate of convergence for an increased radius of convergence. Work is continuing on optimizing this procedure. (3.7)

7. Code validation (3.8)

As an outgrowth of the Adaptive Mesh Workshop at Livermore in December, 1994, we setup a simplified 2-D fluid benchmark calculation with UEDGE so various new codes could compare their solutions. A successful comparison on an orthogonal mesh has only been made with the LANL code (Kuprat).

We have continually worked to benchmark UEDGE with experimental data from DIII-D and are beginning to do this with C-Mod (Wising, MIT). Typical DIII-D comparisons are given in Ref. [12L-14L]. Thermally collapsed solutions that arise from a bifurcation in the equilibrium [15L], preferentially on the inner divertor plate are now routinely found, and can lead to a hydrogenic MARFE-like solution. An assessment of the trapping of Lyman radiation from excitation of the hydrogen case has been carried out using the stand-alone version of the CRETIN radiation transport code [16L].

REFERENCES this section (LLNL)

- 1L. R.H. Cohen and D. Ryutov, "Electric Drift, Plasma Current, and the Bohm Condition in the SOL of a Tokamak with a Toroidal Limiter," *Comm. Plasma Phys. Controlled Fusion* 16, 255 (1995).
- 2L. R.H. Cohen and D. Ryutov, "Plasma Sheath in a Tilted Magnetic Field: Closing of the Diamagnetic Currents: Effect on Plasma Convection," submitted to *Phys. Plasmas* (1995).
- 3L. R.H. Cohen and D. Ryutov, "Spreading Particle Trajectories Near a Perfectly Reflecting Surface in a Tilted Magnetic Field," submitted to *Phys. Plasmas* (1995).
- 4L. R.H. Cohen and T.D. Rognlien, "Finite Mean-Free-Path Effects in Tokamak Scrape-Off Layers," *Contr. Plasma Phys.* 34, 198 (1994).
- 5L. R.H. Cohen and X.Q. Xu, "A Model for a Scrape-Off-Layer L-H Transition," *Phys. Plasmas* 2, 3374 (1995).

- 6L. N. Mattor, "Drift Wave Propagation as a Source of Plasma Edge Turbulence," *Phys. Plasmas* 2, 766 (1995).
- 7L. X.Q. Xu and R.H. Cohen, "3D Fluid Simulations of Turbulence in Detached SOL Plasmas," submitted to *Phys. Plasmas* (1995).
- 8L. X.Q. Xu, "Fluid Simulations of Electron-Temperature-Gradient-Driven Turbulence in Tokamak Boundary Plasmas," *Phys. Fluids B5*, 3641 (1993).
- 9L. N. Mattor and R.H. Cohen, "How Fluctuations Continue through an X-Point," submitted to *Phys. Plasma* (1995)
- 10L. D.A. Knoll, V.A. Mousseua, T.D. Rognlien, and M.E. Rensink, "Modeling of Divertor Plasma with a Nonorthogonal Finite-Volume Method," to be submitted to *J. Comp. Phys.* (1995).
- 11L. G.R. Smith, P.N. Brown, R.B. Campbell, et al., "Techniques and Results of Tokamak-Edge Simulation," *J. Nucl. Mat.* 220-222, 1024 (1995).
- 12L. G.D. Porter, T.D. Rognlien, S.L. Allen, "Scrape-Off Layer Plasma Modeling for the DIII-D Tokamak," in *Plasma Physics and Controlled Nuclear Fusion Research (Proc. 15th Int. Conf. Plasma Phys. and Controlled Fusion Res., Seville, Spain, (to be pub., IAEA, Vienna, 1995), IAEA-CN-60/D-P-I-1.*
- 13L. M.E. Fenstermacher, G.D. Porter, M.E. Rensink, et al., "UEDGE and DEGAS Modeling of the DIII-D Scrape-Off Layer Plasma," *J. Nucl. Mat.* 220-222, 330 (1995).
- 14L. G.D. Porter, M. Fenstermacher, R. Groebner, et al., "Benchmarking UEDGE with DIII-D Data," *Contr. Plasma Phys.* 34, 454 (1994).
- 15L. T.D. Rognlien, P.N. Brown, R.B. Campbell, et al., "2-D Fluid Transport Simulations of Gaseous/Radiative Divertor," *Contr. Plasma Phys.* 34, 362 (1994).
- 16L. A.S. Wan, H.E. Dalhed, H.A. Scott, et al., "Detailed Radiative Transport Modeling for ITER Radiative Divertor," *J. Nucl. Mat.* 220-222, 1102 (1995).

Gary Craddock et al (NERSC):

- Demonstrated capability of FOREV/CRETIN codes to couple plasma ablation/radiation hydro and non-LTE, nonlocal atomic physics/radiation transfer codes. The FOREV/CRETIN codes do vapor shielding and ablation for disruptions in ELMs and radiative divertor modelling.
- Sensitivity studies in UEDGE concerning collapsed state solutions with respect to turbulent diffusion coefficient and low T_e atomic physics.
- Workshop on adaptive mesh methods for fusion plasmas

The following list of works (NERSC) performed/reported/published comes from Alice Koniges, Gary Craddock, Marc Day, Jose Milovich, also, with input from Dave Eder and Alan Wan, of LLNL X and A Divisions :

"Role of Radiation Vapor Shielding of First Wall During Disruption,"
A. E. Koniges, et al., J. Nucl. Mater. 220-222 1116 (1995).

"UC San Diego PISCES Edge Physics and Modelling Program",
B. Merriman and M. Day, Plasma Facing Components Workshop, Pleasanton CA, September 19-20, 1995

"Summary of Recent NERSC Divertor Results and Directions: Radiation Transfer, Adaptive Grids, and UEDGE Sensitivity Studies," G. G. Craddock, et al. Working Meeting for the Divertor Task Group, MIT, August 15, 1995.

"ITER Divertor Damage during ELM's and Disruption, A. E. Koniges and D. C. Eder, (invited talk) ITER San Diego Co-Center, August, 1995.

"Benchmarking Radiation Transport Calculations Important for ITER Divertor Ablation ," H. Wuerz, B. Basylev, I. Landman, D. C. Eder, A. E. Koniges, and A. S. Wan, IEEE Conference of Plasma Science, Madison, WI, May, 1995.

"Atomic Physics at LLNL," Workshop on Modeling of Plasma Stream Target

Interaction for Tokamak Disruptions," D. C. Eder and A. E. Koniges, Karlsruhe, Germany, May 15, 1995.

"Effect of Line Radiation in Vapor Shielding during Disruption," D. C. Eder, (invited talk) ITER-Garching Co-Center, Germany, May 22, 1995.

"Plans and Algorithm Development for an Adaptive Grid Divertor Simulation Code," A. E. Koniges, M. S. Day, J. L. Milovich (invited talk) Max-Planck Institute fur Plasmaphysik, Garching, Germany, May 1995

"Ablation Modeling and Coupling Issues for ITER Disruptions," Workshop on Disruption Modeling, A. E. Koniges and D.C. Eder General Atomics, San Diego, CA, April 19, 1995.

"First Steps in the Development of Adaptive Grid Algorithms for Divertor Tokamak Plasmas," J. L. Milovich and A. E. Koniges, 1995 International Sherwood Fusion Theory Meeting, April 3-5, 1995, Incline Village Nevada, Poster 2D40.

"The Role of Line Emission in Radiation Transport Calculations of Divertor Ablation Mitigated by a Vapor Shield," A. E. Koniges, et al., 1995 International Sherwood Fusion Theory Meeting, April 3-5, 1995, Incline Village Nevada, Poster 3C21.

"A Multi-Variable Core-Edge Simulation via 1D-2D Coupled Non-Linear Transport Codes," A. Tarditi, R. H. Cohen, G. G. Craddock, et al., 1995 International Sherwood Fusion Theory Meeting, April 3-5, 1995, Incline Village Nevada, Poster 2D32.

"Aspects of Computational Thermally Collapsed States," G. G. Craddock, A. E. Koniges, and J. L. Milovich, 1995 International Sherwood Fusion Theory Meeting, April 3-5, 1995, Incline Village Nevada, Poster 1D27.

"Numerical Studies of the Tokamak Edge Fluid Equations", PhD. dissertation, UCLA February 28, 1995.

"Fluid Modelling of Divertors using the FMS code", M. Day and B. Merriman, Bull. Am. Phys. Soc. vol. 39, p. 1531 (1994).

"Aspects of Computational Thermally Collapsed States and Time Dependent Behavior," G. G. Craddock, A. E. Koniges, J. L. Milovich, and T. D. Rognlien, Bull. Am. Phys. Soc., vol. 39, p. 1711 (1994).

"Adaptive-Grid Development for Divertor Tokamak Plasmas," J. L. Milovich, D. Marcus, A. E. Koniges, and J. Bell, vol. 39, p. 1711 (1994).

"Scrape-off Layer Plasma Modeling for the DIII-D Tokamak," G. D. Porter, G. G. Craddock, ..., A. E. Koniges, ..., J. L. Milovich, ..., IAEA International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madrid, Spain, Sept 26 - Oct. 1 1994, LLNL Report UCRL - 117107.

"Vapor Shielding Calculations for ITER-Scale Disruptions Including Line Transfer and Magnetic Field Inhibited Evaporation," A. E. Koniges, D. E. Eder, and A. S. Wan, Bull. Am. Phys. Soc, vol. 39, p. 1594 (1994)

R. Harvey (General Atomics):

FPET Development (Bob Harvey, Olivier Sauter, Ken Kupfer).

- The Fokker-Planck Edge Transport (FPET) code has been developed over the past year, building on past Fokker-Plank work [1,2,3].

- FPET is a 2D-in-velocity, 1D-in-space along the magnetic field, collisional code with the parallel streaming (advection) term, sources and sinks, and boundary conditions appropriate to divertor conditions. It is multi-species (several ions and electrons) and solves for the self-consistent ambipolar electric field along the field line.

- The well-benchmarked bounce-averaged Fokker-Planck operator in the CQL3D FP code was "de-bounce-averaged" and is used in FPET.

- The code has been benchmarked against Branginskii transport, in the collisional limit.

- The code has been parallelized on the T3D using the CRAFT parallelization model, giving near linear speed up with number of processors, up to 32 processors (for a 32 space-point calculation). CRAFT uses compiler directives to obtain parallelization (these directives start with "c" in column 1, are ignored by workstation fortran, and therefore permit the code to run on a workstation with no changes).

•So far the code has been run for electrons and ions, separately. The objective is to do the combined electron-ion problem by APS, 1995.

•FPET is being combined with results from the comprehensive DDiC divertor, moment code[4]. The objective is to further quantify the regions of parameter space where kinetic effects must be accounted for in accurate modeling of the divertor physics or in diagnostics for the divertor region.

References for this section (General Atomics)

- [1] G.D. Kerbel and M.G. McCoy, PF 28, 3629 (1985).
R.W. Harvey and M.G. McCoy, IAEA TCM on Adv. in Sim. of Plasma, Montreal (1992).
- [2] O. Sauter, R.W. Harvey and F.L. Hinton, Contrib. Plasma Physics 34, 169 (1994).
- [3] K. Kupfer, R.W. Harvey, O. Sauter, G. Staebler, and M.Schaffer, Sherwood Oral, Incline Village (1985); paper in preparation. [4] A.Yu. Pigarov, and V.A. Pozharov, Kurchatov Institute report IAE-5803/6 (1994).

Karney, Stotler, Kanzleiter, Vesey (PPPL):

- DEGAS-2: Initial coupling of DEGAS-2 present preliminary version with UEDGE, by Rensink
- Generalized atomic physics models, Pigarov
- Improved treatment of elastic scattering, Kanzleiter
- Implementation of atomic and material surface reactions, Stotler
- H-alpha modelling of C-Mod, Vesey

Concluding Remarks

After one year of high intensity cross institutional collaborations of the Divertor Task Force a first balance can be drawn. Several urgent SOL and divertor physics questions have been answered and several new tools (i.e. codes) have been brought into application. To mention some of the "globally" significant highlights again:

- Several Divertor plasma detachment mechanisms analytically understood and implemented in simulation codes(including multi-species impurity transport and nonorthogonal grids),exhibiting plasma detachment and natural formation of Marfes.
- Laminar and turbulent neutral fluid model developed analytically and numerically, and coupled to plasma fluid modelling code. This is essential for success in modelling experimental observation of "partial detachment" (Figs. 1a,b) and demonstration that ,with certain baffling designs ,a 500 MW/m² parallel heatflux ITER divertor plasma remains detached from the divertor target (Fig. 2).
- With the very large step from present divertor tokamaks to ITER-like machines depending on divertor scaling laws a major contribution was the derivation of more comprehensive theory based SOL/divertor scaling laws than the existing P/R "Lackner divertor scaling".
- Dynamic ELM and major disruption modelling and analysis of effects on the divertor plasma has begun. For ITER, these calculations provide input conditions for existing ablation codes (e.g. FOREV).
- Atomic physics advances determining divertor plasma detachment included incorporation of 3-body and molecular (negative ion) recombination, a compact reformulation of multi-charge state impurity transport, interaction between divertor ELMs and impurity-seeding including radiative condensation, and divertor heat flux limiting due to electron impact excitation loss.
- 2 and 3D modelling of the plasma edge/SOL turbulence shows a dominant conducting wall mode to persist for detached plasmas.

- A new model for the L-H transition based in part on instabilities in the scrape-off layer (SOL) has been developed. First implementation into the UEDGE code shows a natural bifurcation of the SOL equilibrium
- The subject of plasma core-SOL interaction has received serious attention through the construction of a coupled core-SOL transport code
- In order to capture important kinetic (i.e. energetic charged particle) effects a particle-in-cell code (1D in space, 2D in velocity space ["2V"]) was brought into application on dedicated workstations as well as on the massively parallel T3D NERSC computer.

Similarly, two complimentary new 1D-2V Fokker-Planck codes were brought on line (also running on the T3D).

The future goal is to couple these kinetic effect results as updates to much faster but physics-limited fluid divertor codes. Applying these codes to Alcator C-Mod and TdeV important kinetic deviations from the simpler fluid simulations are observed.

- The effects of the ambipolar electric field and ensuing $E \times B$ drifts have been analyzed analytically and numerically coupled to UEDGE, beginning to unravel their influence on the observed inner/outer divertor asymmetry, and on detachment. Relatedly, a theory determining the radial ambipolar field across the separatrix was implemented, in agreement with experimental observations.

Conclusion-Management Aspects

The organizational model of the DTF has proven to be workable and fruitful. The momentum of the Task Force comes from the strong technical leadership of the "teamleaders". Most of the accomplished highlights originated from collaborations aimed toward a common objective rather than in group to group competition. This modus operandi was particularly productive in bringing together analytic theorists with numerical simulators and with state-of-the-art supercomputer/parallel processor specialists. Throughout, the divertor experimentalists and "ITER Divertor Experts" were constantly "at our heels" and were invited to report about their progress and open questions at all of our formal and informal meetings. Through organization of special DTF working meetings and dedicated sessions at the major meetings combined with regular e-mail exchanges inbetween a constant flow of communications was maintained.

Appendix 1
Chronology of Divertor Task Force Events 8/94-12/95

August 1994 Founding meeting, ~30 participants, formation of three teams:

1. Detachment and divertor physics
2. Core plasma SOL interaction
3. Code validation/improvement

APS Nov 1994
Special Session

3 overviews and 30 two-minute talks

Sherwood 1995
Special Session

5 thirty-minute talks

1. Working meeting on kinetic effects in fluid codes/models in San Diego
4/18/95

2. Working meeting on status/validity of divertor SOL-core codes at MIT
8/15-16/95

APS 1995
SOL/
Special Session

2-1/2 hour evening session reporting on recent physics progress in divertor and Scrape off Layer

PET-V 1995

2 invited, several oral talks and many posters by DTF members

Appendix 2

Original Work-Area Outline from the August 1994 founding meeting

1. DETACHMENT

1.1 Compare Present Analytic and Numerical Models with Experimental Detachment

1.1.1 Plasma hydrogen particle and energy balance

1.1.2 Neutral hydrogen particle and energy balance

1.1.3 Impurity transport and radiation

1.1.4 Instabilities and turbulence

1.2 Physics Improvements to Detachment-Related Models

1.2.1 Turbulence

1.2.2 Kinetic plasma effects

1.2.3 Advanced neutral models

1.2.4 Helium transport for detached plasmas

2. CORE-SOL

2.1 Improvement and validation of L-H transition model

2.2 Development of ELMs' model

2.3 Density limit

2.4 Structure of the fluid equations in the presence of turbulence

2.5 Edge turbulence

3. CODE DEVELOPMENT AND VALIDATION

3.1 Fluid-Plasma Codes

3.2 Kinetic Plasma Edge Code Development

3.3 Fluid-Neutrals Codes Navier-Stokes (3-D fluid). k-epsilon turbulence modeling

3.4 Monte Carlo Neutrals Codes DEGAS, EIRENE

3.5 Impurity Transport Code Modules

3.6 Hybrid Codes; Develop codes for SOL/core coupling, edge disruption modeling

3.7 Numerical Techniques

3.8 Code Validation

3.9 Fluctuations (including MHD) code development in SOL/core

FIGURE CAPTIONS

Figure 1a: Alcator C-Mod electron temperature for pulse 940623018. The plasma is detached from the strikepoint to the nose of the divertor channel, and attached further out. Convergence is monitored and accomplished over all cells of the nonorthogonal grid.

Figure 1b: Ion saturation current to the outer divertor plate in Alcator C-Mod. Partial detachment is observed as 0.5% of carbon is added, featuring an order of magnitude drop of the ion saturation current near the separatrix and an outward shift of the peak current density. The plasma remains attached above the divertor "nose".

Figure 2: A 2-D fluid plasma Braginskii model coupled to a full Navier-Stokes advanced neutrals model is employed to obtain the neutral flows and electron temperature profiles for a baffled rectangular model of the ITER divertor. A parallel heatflow of 500 MW/m^2 is seen to remain detached due to strong neutral fluid circulation.

C-Mod, 0.5% Carbon

Wising, MIT, 10/04/95, UEDGE

Electron Temperature (eV), #940623018

1.000E+00
2.000E+00
4.000E+00
6.000E+00
8.000E+00
1.000E+01
1.200E+01
1.400E+01
1.600E+01
1.800E+01
2.000E+01
3.000E+01
4.000E+01
5.000E+01
6.000E+01
7.000E+01

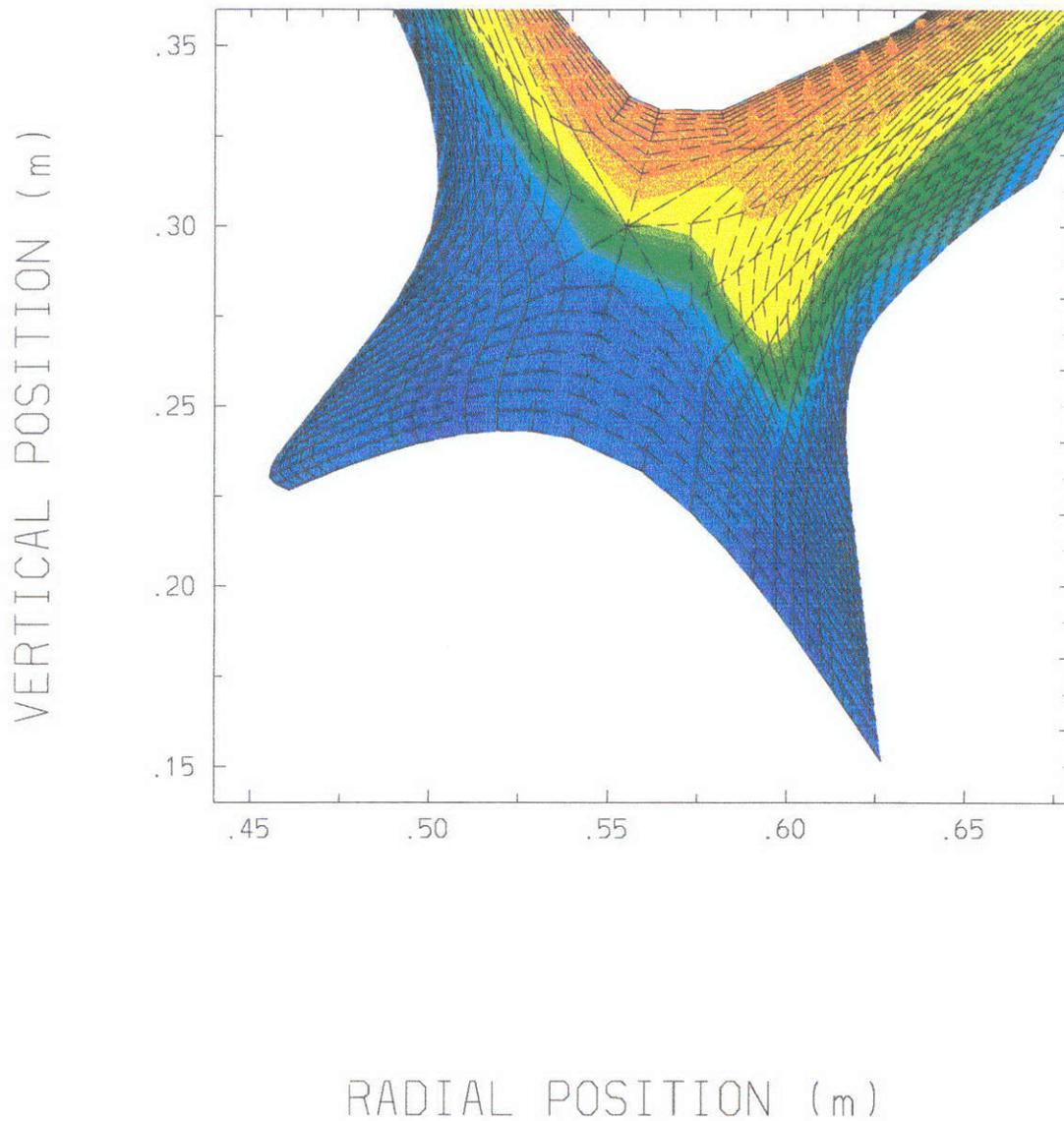


Figure 1a

C-Mod, Wising, MIT, 10/04/95, UEDGE
Outer target, Gradual detachment

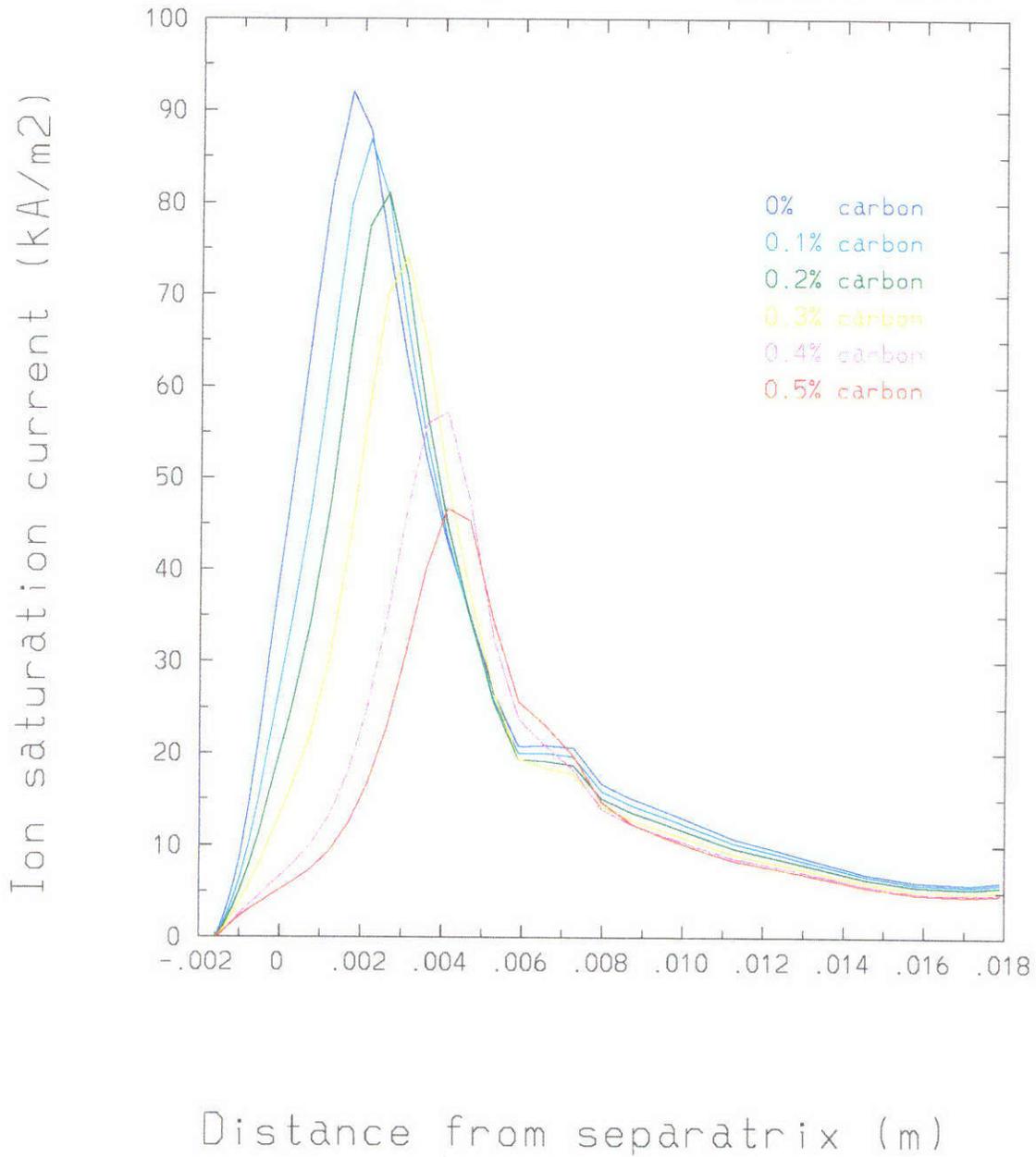


Figure 1b

Coupled Edge Plasma / Navier-Stokes Neutral Transport Model

(Includes Neutral-Neutral Collisions)

Te (eV)



Neutral Flux Vectors and Electron Temperature Contours
ITER Power Level and Upstream Density
Detached Plasma Through Baffling and Impurity Radiation
Neutral Knudsen Number in Slot is 0.01 to 0.1

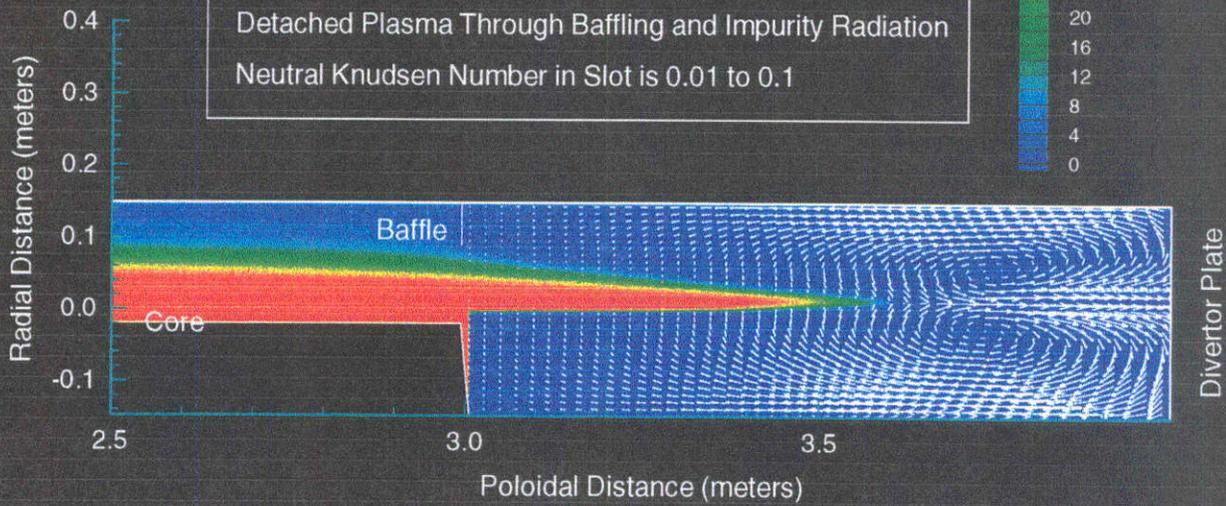


Figure 2

NOTE: COPY OF FIGURES IN BLACK AND WHITE FOLLOW.

C-Mod, 0.5% Carbon

Wising, MIT, 10/04/95, UEDGE

Electron Temperature (eV), #940623018

1.000E+00
2.000E+00
4.000E+00
6.000E+00
8.000E+00
1.000E+01
1.200E+01
1.400E+01
1.600E+01
1.800E+01
2.000E+01
3.000E+01
4.000E+01
5.000E+01
6.000E+01
7.000E+01

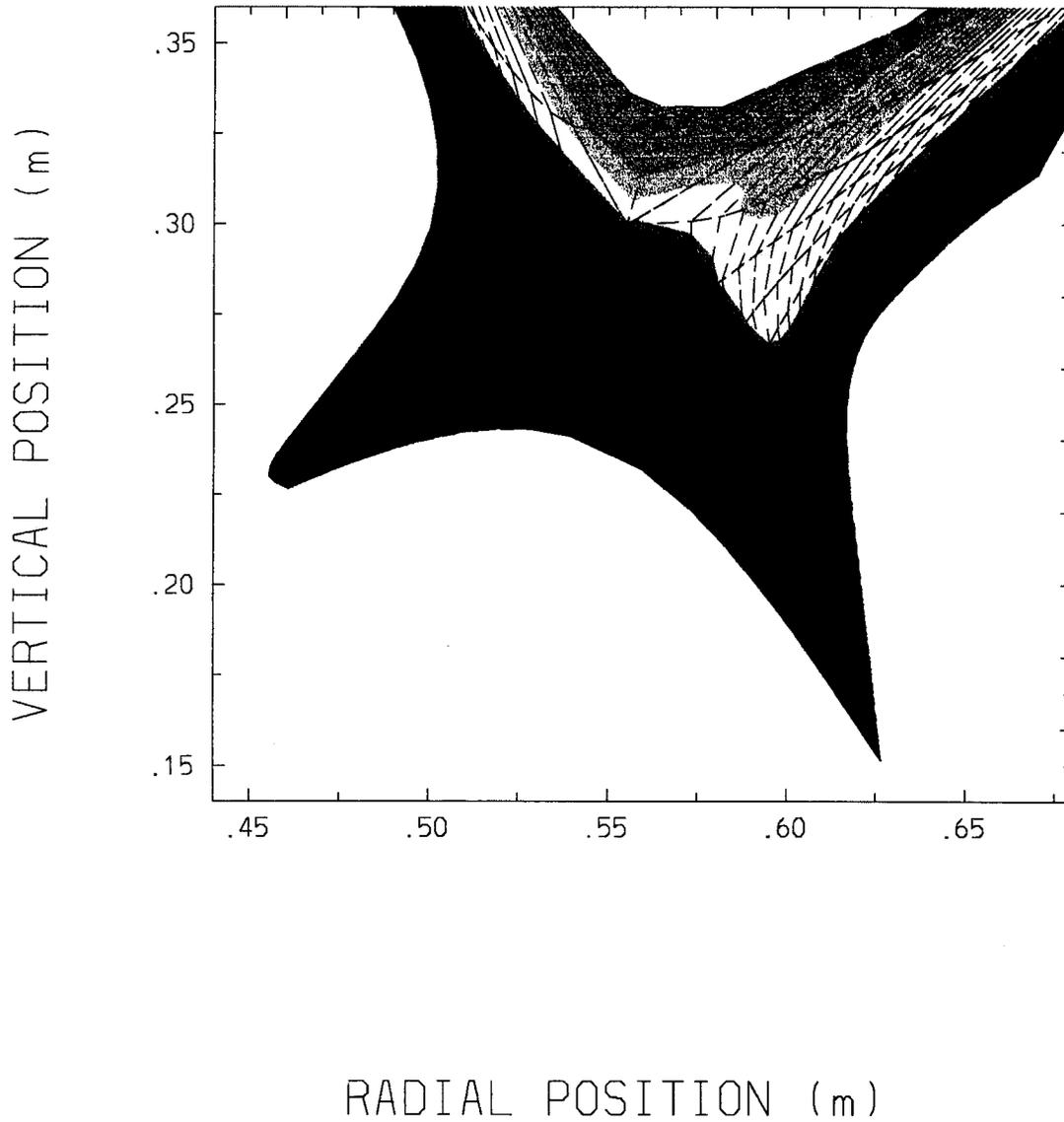


Figure 1a

C-Mod, Wising, MIT, 10/04/95, UEDGE
Outer target, Gradual detachment

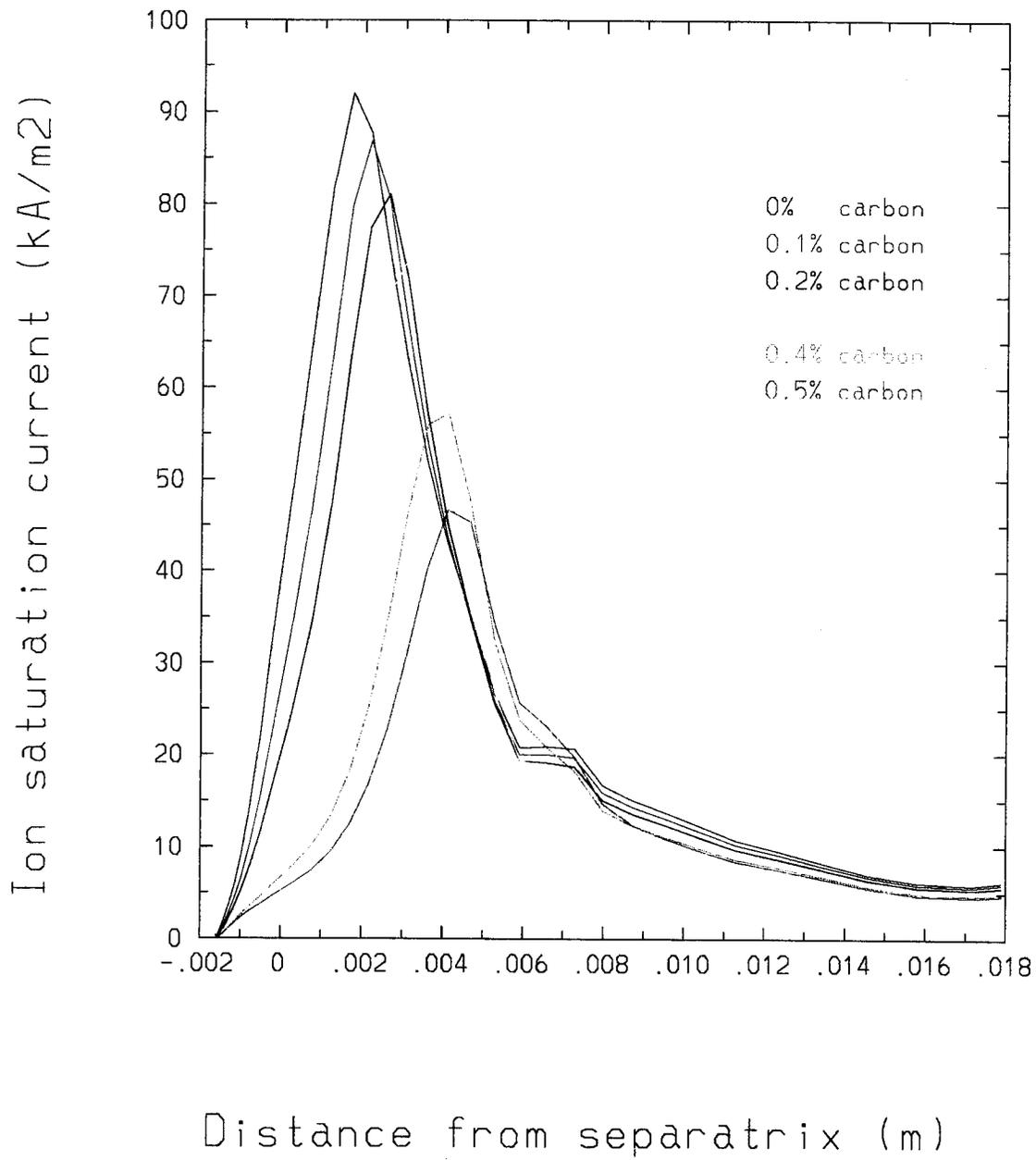


Figure 1b

Coupled Edge Plasma / Navier-Stokes Neutral Transport Model

(Includes Neutral-Neutral Collisions)

Te (eV)

- 40
- 36
- 32
- 28
- 24
- 20
- 16
- 12
- 8
- 4
- 0

Neutral Flux Vectors and Electron Temperature Contours
ITER Power Level and Upstream Density
Detached Plasma Through Baffling and Impurity Radiation
Neutral Knudsen Number in Slot is 0.01 to 0.1

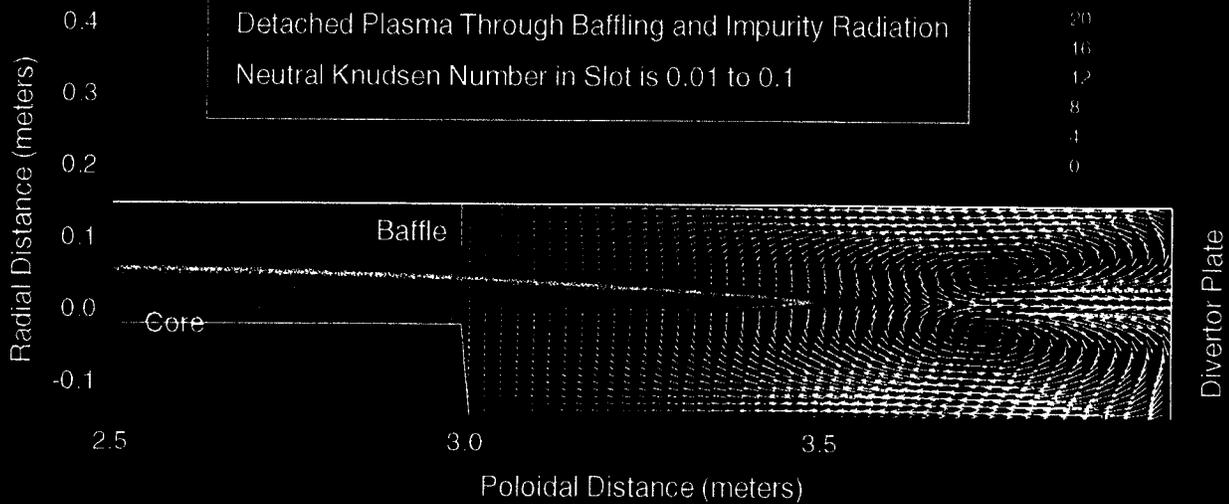


Figure 2