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Scrape-off Layer Plasmas

M. E. Fenstermacher, G. D. Porter, M. E. Rensink
T. D. Rognlien, S. L. Allen,
D. N. Hill, C. J. Lasnier
Lawrence Livermore National Laboratory
Livermore, CA

T. Léonard, T. Petrie
General Atomics
San Diego, CA

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UEDGE and DEGAS Modeling of the DIII-D Scrape-off Layer Plasma*

M. E. Fenstermacher, G. D. Porter, M. E. Rensink, T. D. Rognlien,
S. L. Allen, D. N. Hill, C. J. Lasnier, T. Leonard[†], T. Petrie[†]

Lawrence Livermore National Laboratory, Livermore CA.

[†]General Atomics, San Diego CA.

Abstract

This paper presents the results of work to develop benchmarked theoretical models of scrape-off-layer (SOL) characteristics in diverted tokamaks by comparing shot simulations using the UEDGE plasma fluid and DEGAS Monte-Carlo neutral particle transport codes to measurements of the DIII-D SOL plasma. The available experimental data include the radial profiles of electron density and temperature, the ion temperature, the divertor exhaust power, the intensity of H_α emission, and profiles of the radiated power. A very simple model of the anomalous perpendicular transport rates produces consistency between the calculated and measured radial profiles of the divertor power, and of the midplane densities and temperatures. Experimentally, measured exhaust power is now typically 80-90% of the input power. The simulated peak power on the outer leg of the divertor floor is now within about 20% of the measured power. Various sensitivities of the simulation and measurement comparisons to model assumptions are described. Finally, these benchmarked models have been used to examine the effects of various baffle configurations for the Radiative Divertor Upgrade in DIII-D.

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1.0 Introduction

Predicting the performance of the divertor has been identified as a critical component of the design of future high power tokamaks like ITER and TPX. To develop this predictive capability, an active program is underway in both scrape-off-layer (SOL) and divertor physics code development, and in benchmarking / validation of the code models against experimental data. Work on the former is described elsewhere [1]. This paper describes efforts to validate the complete 2-D solution from the UEDGE fluid plasma physics code [2] against DIII-D experimental data. As a first use of the validated models, this paper also describes the application of UEDGE and the DEGAS Monte-Carlo hydrogenic neutral transport code [3] to analysis of design options for a Radiative Divertor Program (RDP) upgrade of the divertor in the DIII-D tokamak.

The paper is organized as follows. Details of the benchmarking / validation work with UEDGE are described in Section 2. Applications of both UEDGE and DEGAS to the RDP designs are described in Section 3. Conclusions and plans for continued work are given in Section 4.

2.0 Validation of UEDGE with DIII-D Data

This effort focusses beyond validation of the code solution for a single parameter or profile at a single location, in an attempt to simultaneously simulate, with the 2-D code, multiple diagnostic measurements at multiple locations in the SOL and divertor. To do this, simulation results are compared with the extensive SOL data set from the DIII-D tokamak including measurements at multiple locations (see Fig. (1)). The electron temperature and density are measured by Thomson scattering and a Langmuir probe array as shown. The ion temperature is measured by the Charge-Exchange Recombination (CER) diagnostic, the divertor heating power by the IRTV diagnostic, and the H_{α} emission by a photo diode array. In addition, some electron density and

temperature data, measured 15 cm below the low field side of the midplane with an insertable Langmuir Probe array, is available.

INSERT FIG. 1 HERE

A very simple model of anomalous perpendicular diffusion for both particles and energy, with spatially constant diffusion coefficients over the entire computational domain, is used to compare the UEDGE SOL plasma simulation with the data. The value of these diffusion coefficients, $D_{\perp}$, χ_i , and χ_e , is varied to fit the radial profile of the measured upstream density and temperatures. Typically agreement is obtained with diffusion coefficients in the range $D_{\perp} \in (0.02, 0.25)$, and $\chi_{e(i)} \in (0.1, 0.5)$. The simulated midplane density and temperature profiles are compared with data for an ELM-free H-mode discharge in Figure (2). Note that the agreement exists within the uncertainty of the location of the separatrix (a few millimeters).

INSERT FIG. 2 HERE

The SOL plasma parameters are determined throughout the computational domain by the choice of the diffusion coefficients and by boundary conditions (eg. density and temperatures at the innermost flux surface (consistent with the diagnostic measurement), plate recycling coefficients, and wall properties). The validity of the full 2-D plasma solution is assessed by comparison with data at several locations: first the calculated power across the separatrix is consistent with that measured within 20–30%. Secondly, as shown in Figure (3), the calculated peak power at the outer strike point on the divertor floor agrees well with that measured on the experiment. The width of the calculated profile is somewhat broader than that measured, suggesting an inconsistency in the power flow in the ion channel (perhaps due to the incomplete ion temperature measurements in the SOL on this shot). Finally, agreement within a factor of two is typical between the simulation and measurements of the amplitude of the H_{α} emission near the inner and outer strike points. The measured emission in the private flux region is generally higher than found in the simulation.

INSERT FIG. 3 HERE

The simulation significantly overestimates the power at the inner strike point. There is evidence that the discrepancy in the power there arises from radiation effects. The effect of impurities is only crudely included in the UEDGE simulations. A specified fraction of impurity atoms is assumed throughout the plasma, and the radiative electron energy loss in the plasma is self-consistently included. The non-equilibrium emissivity is calculated as a function of electron temperature using tabulated data from a series of runs of the MIST code [4]; charge exchange between impurity ions and neutral hydrogen is included in the MIST code results, so the impurity charge state distribution and emissivity also depend on the neutral hydrogen density. Simulations with small carbon concentrations ($\sim 1.5\%$) show more than a factor of 2 increase in the in/out power asymmetry, mostly due to reduction of the power to the inner strike point.

The quality of the UEDGE simulations in the areas of power balance, peak divertor power and radial profiles has improved significantly over previous work [2]. To improve the models in other areas, the sensitivities of the simulations to various assumptions have been explored. Results are summarized below:

- The in/out asymmetry of the divertor power is increased (inner power reduced) by including the effect of parallel currents in the SOL.
- The H_{α} emission in the private flux region is increased by increasing the plate recycling coefficient (R) from the range of 0.98 (used for the best simulations) to 1.0. However, the agreement between the measured and simulated emission near the strike points is poorer with $R=1.0$.
- Variation in the simple model of flux limits, used in UEDGE to allow for kinetic effects, produces changes primarily in the ion temperature near the divertor, a parameter which is not measured in the experiment.

3.0 Application to the Radiative Divertor

Present plans call for the installation of a new Radiative Divertor configuration in DIII-D in FY96 [4]. The goal of the design is to simultaneously achieve advanced divertor and advanced tokamak operation in a single device, *ie.* to reduce the heat flux to the divertor plates and to control the plasma density in H- and VH-modes for the high triangularity plasma shapes which give the best performance in DIII-D.

To accomplish this, the present ADP ring/baffle structure will need to be replaced with new structures which confine neutrals in the divertor region for the high triangularity AT shapes. UEDGE and DEGAS have been used to simulate the behavior of the plasma and the neutral hydrogen in various generic shapes to determine the effect of x-point to strike point length, and of the width of the plasma channel between the structures, and to guide engineering design decisions to a conceptual design. Results from the generic configurations and for some of the conceptual design options will be described below.

3.1 Plasma Simulations with UEDGE for Generic Equilibria

The lower half of assumed up-down symmetric double null divertor configurations is modeled. Radial transport is anomalous with constant values for the particle and thermal diffusivities. The orthogonal mesh extends radially from a flux surface 0.3 cm inside the separatrix to a flux surface 3.5 cm outside the separatrix at the outboard midplane. Fixed plasma density ($3.5 \times 10^{19} \text{m}^{-3}$) and plasma temperature (175-200 eV) are specified on the innermost flux surface to obtain a total power flow of 9 MW across the separatrix into the scrape-off layer. Zero-gradient boundary conditions are imposed at the outermost SOL flux surface and at the innermost private-flux surface. At the divertor plates, standard sheath boundary conditions and unity recycling for the ion particle flux striking the plate are applied. Pumping boundary conditions for the

hydrogen neutrals at the private flux wall and outermost side walls of the mesh are specified by a fixed albedo of 0.95.

Three divertor configurations are compared with different plasma shapes and lengths for the outboard divertor leg (x-point to separatrix strike point at the divertor plate): 40cm, 20cm and a "reference case". The particle and heat flux profiles at the outboard divertor plate are shown in Figs. 4 and 5. The peak plate electron temperatures were 16 eV, 36 eV and 48 eV for the three cases, respectively. The longer slot length yields lower divertor plate temperatures, but higher peak heat fluxes because of the smaller radial expansion of the flux tube (from midplane to divertor plate).

INSERT FIGS. 4 AND 5 HERE

With sufficiently hydrogen gas puffing from the private flux side wall of the outboard divertor leg a plasma 'detachment' is observed from the outboard plate in the sense that the peak of the recycling ionization region moves upstream toward the x-point with increasing gas puff current. Figs. 4 and 5 show steady state results for the 20 cm configuration with moderate (1000 Amps) and strong (2200 Amps) gas puffing that correspond to attached and detached plasmas respectively. Total (plasma+neutral) parallel pressure is approximately constant along the separatrix, so as the plate temperature collapses with increasing gas, the plasma and/or neutral density rises. The total hydrogen radiation remains small (less than 20 percent) compared to the total power crossing the separatrix into the SOL even for strong gas puffing. The radiative energy loss per ionization event is reduced to less than 5 eV for high density ($1.0 \times 10^{21} \text{ m}^{-3}$) low temperature (5 eV) plasmas due to efficient multi-step ionization processes. Thus, it appears that radiation from impurities is necessary to significantly reduce the total power flow to the divertor plates.

3.2 Neutral Transport with DEGAS for the Generic Equilibria

DEGAS simulations are used to calculate the penetration of neutrals from the divertor region back into the core plasma. This represents an uncontrolled particle fuelling source which is undesirable for the AT operating modes. The figure-of-merit used in comparisons of candidate Radiative Divertor designs is the total ionization source (neutral current) inside the separatrix fuelling the core. The simulations showed that two processes contributed to this current: neutrals leaking radially out of the SOL in the divertor and migrating to the midplane where they penetrated the thin SOL plasma, or a small fraction of the large recycling current managing to propagate to the core against the divertor plasma flow. The scoping studies compared this ionization source to the neutral beam source in DIII-D ($I_{nb} = 300 - 400$ particle amperes at high power).

The scoping studies were focussed around three generic questions: 1) how long must the baffled region be, 2) must the baffles be shaped to conform closely to flux surfaces or would structures which slanted into the divertor plasma be sufficient, and 3) how narrow must the opening be near the divertor strikepoints? Baffle configurations used in the studies (Fig. 6) included close conformal walls, narrower conformal walls for which the recycling source at the top of the slot was taken into account, a "gas bag" configuration, and a completely open divertor (vacuum vessel only).

INSERT FIG. 6 HERE

To understand many of the effects seen in the DEGAS simulations it is important to keep in mind two properties of the UEDGE plasma solutions. First, the particle and power flow radial profiles peak just on the SOL side of the separatrix and have radial scale lengths on the order of about 1 cm, so a much larger recycled neutral flux occurs on a baffle intercepting a 1 cm flux line (mapped to the midplane) compared with the 2 cm flux line. Second, the ionization mean free path tends to be nearly a flux function in most of the divertor region except near the strikepoint, so neutrals in the outer SOL with

velocities directed towards the separatrix have a much higher probability of ionization after a short flight than those directed along flux lines.

To examine the effect of divertor leg length, the UEDGE cases for the generic 20 cm and 40 cm x-point to outer strike point lengths were used in DEGAS simulations with all four of the generic baffles. Results are summarized in Table 1, which describes the core ionization current (Amp) for each configuration. As expected, the close conformal slot, without any recycling off the side walls or the top of the slot, produced the greatest reduction in the core ionization source. A simple "gas bag" shape was sufficient in the 40 cm configuration to reduce the source well below the beam source, and was marginal in the 20 cm configuration. In the narrower slot case with recycling off the top of the slot, the recycling was an important source of core influx. This study showed that proper shaping of a baffle in a configuration with an x-point to strikepoint length of 20 - 30 cm would be sufficient to reduce the core source below the beam source.

INSERT TABLE 1 HERE

Though conformal slots work well to restrict neutrals from the core, they have many disadvantages from an operational viewpoint including limited diagnostic access and reduced operational flexibility to run plasmas of different shapes, currents, I_i profiles etc. Also the recycling from the top of the slot where the horizontal structure intercepts plasma flow can produce a significant core source. For these reasons a slanted baffle geometry (Fig. 6) was examined, in which the surface intercepting plasma flow is slanted in the SOL so that the neutrals emitted from the surface are directed toward the hotter regions of the SOL where they can be ionized and entrained by the plasma flow. Baffles with slanted surfaces crossing flux surfaces from 3.5 cm (outer boundary of the UEDGE plasma solution) to 2.0 cm off the separatrix were compared with tighter baffles spanning the 2.0 to 1.0 cm flux surfaces. In the latter case the effect of the shape of the upper knee of the baffle was also examined. All of these baffle configurations were

simulated with DEGAS using three UEDGE plasma solutions in the 20 cm configuration; no puff, 1.0 kA puff (attached) and 2.2 kA puff (detached).

Results are summarized in Table 2. Puffing does increase the core ionization source somewhat. In the wider opening case, the core source at the maximum puff is still well below the beam source. With the narrower configuration the source rate approaches the beam rate in the highest puffing case, especially when the upper baffle region is not optimized because the surfaces intercept regions of higher plasma flow (closer to the separatrix) at locations closer to the x-point and core boundary. Finally, a noticeable decrease in the core source was observed with only a minor change in the shape of the upper knee of the baffle. Two conclusions can be made: 1) slanted baffles seem to be a viable option since all of these configurations at least marginally satisfy the goal of reducing the core ionization source below the beam source, and 2) from a core fuelling standpoint a slanted baffle extending in to the 2.0 cm flux line is sufficiently narrow to control the neutral source; tighter baffles produce greater core source due to recycling from the upper part of the structure.

INSERT TABLE 2 HERE

3.3 Analysis of the Reference RDP Configuration

Results from the studies described above helped guide the development of a reference engineering design for the RDP. The reference design has an x-point to outer strikepoint length of 23cm, a slanted outer baffle with a 1.0cm opening near the strikepoint (chosen to optimize pumping performance), careful shaping of the upper knee of the baffle, a baffle on the 0.25cm flux line in the private flux region and a cryopump to pump the private flux and inner strikepoint regions (see [5]) for design flexibility.

The UEDGE result for this configuration is shown in Figs. 4 and 5. The corresponding DEGAS simulation produced a core ionization source of 65 ± 15 Amps, well below the beam source. In addition, the beneficial effect of impurity radiation with

carbon impurities artificially constrained to the regions near the divertor plates is shown in Figs. 4 and 5. The total power and peak power are significantly reduced (factor of 3) by a 3% Carbon concentration. For this case the electron temperature is low enough that the effective Z of the plasma remains below about 1.5 in the divertor region.

4.0 Conclusions and Plans for Continued Work

A simple model of anomalous perpendicular diffusion of particles and energy (constant diffusion coefficients) produces good agreement between experimental measurements and UEDGE calculated plasma and heat flux profiles. Agreement within a factor of two is also achieved for the measured and calculated divertor H_α emission. Using this model in conjunction with DEGAS showed that the goals of the RDP upgrade for DIII-D could be met with a modest x-point to outer target length (20-30 cm) and a slanted baffle structure.

Near term plans include installation of algorithms for impurity transport and non-orthogonal grids in UEDGE, validation of DEGAS solutions against DIII-D H_α and neutral pressure data, benchmarking of UEDGE neutrals solutions against DEGAS, and continued analysis of optional configurations for the RDP

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Table 1. Comparison of the core ionization currents (Amp) found for generic baffle designs with two plasma configurations.

Configuration	20 cm	40 cm
Open	880 ± 57	711 ± 65
Gas Bag	287 ± 33	73 ± 21
Close Conformal	37 ± 12	5 ± 5
Narrower Conformal with Recycling	57 ± 15	92 ± 23

Table 2. Comparison of cases with and without deuterium gas puff (20 cm configuration, slanted baffle).

UEDGE Plasma Case	3.5 to 2.0 cm	2.0 to 1.0 cm	
		Unoptimized	Partially Optimized
No gas puff	63 ± 15	160 ± 24	114 ± 21
1.0 kA D ₂ puff	77 ± 24	263 ± 45	207 ± 40
2.2 kA D ₂ puff	115 ± 37	264 ± 57	234 ± 54

Figure Captions

- Figure (1) SOL-relevant diagnostics on a typical single null discharge in DIII-D (1.0 cm flux surface spacing at the outer midplane).
- Figure (2) Comparison of UEDGE simulation of the midplane density and temperature profiles for an ELM-free H-mode discharge.
- Figure (3) Comparison of the UEDGE simulated divertor power profile at the outer strike point with that measured by the IRTV system.
- Figure (4) Particle flux profiles on the outer plate calculated by UEDGE for the 20 cm, 40 cm and reference cases.
- Figure (5) Heat flux profiles on the outer plate calculated by UEDGE for the 20 cm, 40 cm and reference cases.
- Figure (6) Generic baffle configurations used in DEGAS for the RDP studies; a) a conformal slot, b) "gas bag" baffles and the outer vacuum vessel, c) a narrower conformal slot, and d) slanted baffles.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

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Scrape-off Layer Plasma***

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* This work supported by the USDOE under contracts W-7405-ENG-48 at LLNL, and DEA-C093-89ERS51114 at General Atomics.

Abstract

This paper presents the results of work to develop benchmarked theoretical models of scrape-off-layer (SOL) characteristics in diverted tokamaks by comparing shot simulations using the UEDGE plasma fluid and DEGAS Monte-Carlo neutral particle transport codes to measurements of the DIII-D SOL plasma. The available experimental data include the radial profiles of electron density and temperature, the ion temperature, the divertor exhaust power, the intensity of H_{α} emission, and profiles of the radiated power. A very simple model of the anomalous perpendicular transport rates produces consistency between the calculated and measured radial profiles of the divertor power, and of the midplane densities and temperatures. Experimentally, measured exhaust power is now typically 80-90% of the input power. The simulated peak power on the outer leg of the divertor floor is now within about 20% of the measured power. Various sensitivities of the simulation and measurement comparisons to model assumptions are described. Finally, these benchmarked models have been used to examine the effects of various baffle configurations for the Radiative Divertor Upgrade in DIII-D.

Approach of this Paper

- Section 1: Results from the 2-D fluid plasma physics code UEDGE are compared with experimental measurements from DIII-D as a means of validating model assumptions.
- Section 2: The validated plasma model is used to calculate plasma parameters for candidate configurations of the Radiative Divertor Program (RDP) upgrade for DIII-D.
- Section 3: The Monte-Carlo neutral transport code DEGAS is used to determine the effect of various baffle geometries on the migration of hydrogenic neutrals in the fixed plasma background calculated by UEDGE.
- Section 4: UEDGE and DEGAS are applied to the current reference engineering design for the RDP.

Validation of UEDGE

- Objective: Simultaneous simulation of multiple diagnostic measurements at multiple locations in a tokamak SOL and divertor.
 - * Comparisons of code solutions with data for single parameters or profiles at a single location have been successful in the past (eg. midplane profiles, scaling of peak divertor heat flux with x-point height, etc.)
 - * SOL / divertor is really a 2-D problem so validation must examine 2-D effects.
 - * A 2-D plasma fluid model with a diffusive neutrals model and non-equilibrium radiation from a fixed concentration of impurities is used.
- Data used:
 - * midplane electron density, electron and ion temperature profiles
 - * divertor heating power profile
 - * H_{α} emission
- Variables used to match simulation to the data:
 - * Diffusions coefficients (spatially constant):
 $D_{\perp}$, χ_e , χ_i
 - * Boundary conditions:
 $n_{e,sep}$, $T_{e,sep}$, $T_{i,sep}$
Recycling coefficient
Wall absorption

Sensitivities to Other Parameters

- The sensitivities of the results to several other parameters in the UEDGE model (eg. parallel SOL currents, recycling coefficients, flux limits) have been examined.
 - * Only small changes are seen in the midplane plasma and outer divertor power profiles; the quality of the fits is retained.
 - * Large changes are seen in the in/out power asymmetry and emission from the private flux region.
- When parallel currents in the SOL are included in the model, the in/out asymmetry of the divertor power is increased (inner power reduced closer to the measurement).
- When R is increased from 0.98 to 1.0, the H_{α} emission from the private flux region is increased (closer to the measurement). However, the agreement between measured and calculated emission near the strike points is poorer with $R=1.0$.
- Variations in the simple UEDGE model of flux limits produces changes primarily in the ion temperature near the divertor, a quantity which is not measured.

UEDGE Plasma Model*

GENERAL ATOMICS

- Multi-fluid equations for plasma quantities, n_e , n_i , $u_{||i}$, T_e , T_i , Φ .
- Fluid equations for up to two species of neutrals (Frank-Condon and charge-exchange neutrals).
- Classical parallel and anomalous perpendicular transport models.
- Sheath boundary conditions at divertor plates.
- Fully implicit numerical methods.
- Orthogonal mesh from realistic MHD equilibria.
 - * Separatrix location determined from EFIT with finite separatrix current.
 - Strike point locations are consistent with IRTV
 - Location in the gradient region of Thomson edge profiles as expected.
 - Calculated power across the separatrix agrees with experiment when the SOL profiles match.
 - Remaining uncertainty ~ 1 cm.

*(see G.R. Smith *et. al.*, poster PD-16 for details)

Important Diagnostic Views for Code Validation with DIII-D Data

ELM-free H-mode

Shot 78037 @ 2800 ms

- Plots of plasma current, injected beam power, deuterium gas injection, line averaged density, line integrated H_{α} emission and outer divertor power are shown.

Plasma Profiles and Fits, Shot 78037 at 2800 ms

- UEDGE simulation profiles (solid) and data profiles (dashed) for electron density and temperature (Thomson) and ion temperature (CER).
- Diffusion coefficients $D_{\perp} =$, $\chi_e =$, $\chi_i =$

Divertor Power Simulation, Shot 78037 @ 2800 ms

DIVERTOR POWER SIMULATION FOR 78037 ask Gary

- Calculated peak power at outer strike point is within 30% of experimental measurement.
- Outer profile shape is consistent with experiment to half power point.

ELMing H-mode before Gas Puff

Shot 79342 @ 2500 ms

- Plots of plasma current, injected beam power, deuterium gas injection, line averaged density, line integrated H_{α} emission and outer divertor power are shown.

ELMing H-mode

Fits to Midplane Profiles

- UEDGE simulation profiles (solid) and data profiles (dashed) for electron density and temperature (Thomson) and ion temperature (CER).
- Diffusion coefficients $D_{\perp} =$, $\chi_e =$, $\chi_i =$

ELMing H-mode

Shot 79342 at 2500 ms

- UEDGE outer (solid) and inner (dashed) divertor power profile, and data (circles) [IRTV].
* No impurities

- * 0.8% Carbon impurity

H α Emission

Shot 79342 at 2500 ms

- Private flux H α emission is more like that measured for higher R, but agreement at the strikepoints is poorer.
- Scan of divertor plate recycling coefficient:

* Run pr47: R = 0.981, P_{out/in} = 3.1
* Run pr48: R = 0.989, P_{out/in} = 3.3
* Run pr49: R = 0.995, P_{out/in} = 1.4
* Run pr50: R = 1.0, P_{out/in} = 1.0

High Power H-mode

Shot 78076 at 3000 ms

- Plots of plasma current, injected beam power, line integrated H_{α} emission, and line averaged density, are shown.

UEDGE Simulation with Carbon

Shot 78076 at 3000 ms

- Uniform concentration of Carbon (1.4%) used throughout the computational grid.

Figure (f:5.1) Mid plane density and temperature profiles for UEDGE run w110, compared with experimental data.

Figure (f.5.2) Radial profile of divertor power flux for UEDGE run w110, compared with experimental data.

UEDGE Run without Carbon

Shot 78076 at 3000 ms

- In / out asymmetry of the divertor power measured is not reproduced by the simulation.

Figure (f:3.1) Mid plane density and temperature profile from UEDGE run w103, compared with experiment.

Figure (f:3.2) Radial profile of divertor power, versus major radius (left), and normalized flux (right).

UEDGE with Parallel SOL Currents

Shot 78076 at 3000 ms

- Parallel currents increase the in/out asymmetry but not to the extent measured in the experiment.

Figure (f:4.1) Mid plane density and temperature profile from UEDGE run w104, with parallel currents included.

Figure (f:4.2) Radial profile of divertor power for UEDGE run w104 compared with experimental result

Calculated H_α Emission

Shot 78076 at 3000 ms

- Run model assumptions:

- * Run w103: No carbon or parallel SOL currents
- * Run w104: Parallel SOL currents only
- * Run w110: Uniform Carbon concentration (1.4%)

FUTURE WORK/IMPROVEMENTS

- Simulate radiative divertor experiments with detached plasmas.
- Couple UEDGE and DEGAS calculations for DIII-D shot simulations
 - Provides validation of UEDGE neutrals model.
 - Permits more thorough examination of plate recycling and wall pumping models.
- Implement non-orthogonal differencing schemes*.
 - Permit simulation of more realistic plate geometry.
 - Permit better examination of recycling and wall pumping models.
- Add impurity transport physics*.
 - Attempt to better match divertor power in/out asymmetry.

*(see G.R. Smith *et. al.*, poster PD-16 for details)

SUMMARY AND COMMENTS

- Real improvement has been made in the ability of UEDGE to simulate characteristics of the DIII-D SOL and divertor plasmas.
 - Using $D_{\perp}$ and χ 's which provide good fits to the measured midplane density and temperature profiles gives good agreement (code to measurement) in:
 - Power across the last closed flux surface.
 - Peak outer divertor power density.
 - Half width of the outer divertor power profile.
 - D_{α} emission near the divertor strike points.

WEDGE PARAMETER VARIATIONS FOR RADIATIVE DIVERTOR

- Configuration
 - 20 cm and 40 cm “reference” EFIT equilibria
 - Single and Double null
 - radial domain width (2 cm and 4 cm at midplane)
- Plasma
 - Separatrix boundary conditions
$$0.2 \times 10^{20} \text{ m}^{-3} < n_e < 0.7 \times 10^{20} \text{ m}^{-3}$$
$$175 \text{ eV} < T_e < 450 \text{ eV}$$
 - Anomalous radial transport
$$0.15 \text{ m}^2/\text{s} < D_{\perp} < 0.5 \text{ m}^2/\text{s}$$
$$0.5 \text{ m}^2/\text{s} < \chi_{\perp} < 2.0 \text{ m}^2/\text{s}$$
 - Side Wall boundary conditions
fixed value, zero flux, and extrapolation
- Diffusive neutrals model
 - one or two species
 - convective flux terms
 - particle flux limits
 - poloidal stretching
 - sidewall conditions (pumping, puffing, recycling)
- Hydrogen gas puffing
 - location (private flux side and outside side wall)
 - gas current (up to 2500 Amps)
- Impurity radiation (up to 3% Carbon)

40 cm

CONFIGURATION

EFITD 05/20/93 # 14077 , 1ms

40cm08

OUTBOARD DIVERTOR PLATE

20 cm

CONFIGURATION

EFITD

05/20/93

12077 , 1ms

2

20cm06

OUTBOARD DIVERTOR PLATE

"REFERENCE"

CONFIGURATION

EFITD

10/14/93

#930210 ,4011ms

rdp94.0 OUTBOARD DIVERTOR PLATE

Summary of DEGAS Applied to the RDP

- Goal:

To help guide the design of the Radiative Divertor Program (RDP) hardware by showing the effect of various baffle configurations on confinement of hydrogenic neutrals in the divertor regions.

- Questions Asked by RDP Physicists and Designers:

- * How long must the slot be ?

- Advantage: Intuition would say longer slots confine neutrals better in the divertor region.
 - Disadvantage: Longer slots are more restrictive for the Advanced Tokamak program.

- * How tightly "closed" must the slot be ?

- Advantage: Intuition would say narrow slots prevent neutrals from "sneaking" up the long mean free path sides of the divertor plasma.
 - Disadvantage: Even more restrictive for AT.

- * Is there any advantage to one baffle shape over another ?

Results from DEGAS Applied to the RDP

- DEGAS neutral transport simulations on fixed UEDGE background plasmas were used to give qualitative (and sometimes quantitative) answers.

- Quantitative Measure:

Core Ionization Current, $I_c = \Gamma_c * \text{Area}$

- Definition of Success:

$$S_{\text{recycling}} \leq S_{\text{nb}} \sim 10^3 P_{\text{inj}}(\text{MW}) / 45 \text{ keV} \sim 300 \text{ Amps}$$

- Results - the "Bottom Line":

* The proposed "slanted baffle" design reduces I_c by about a factor of 10 from the present "open" geometry to the range where $S_{\text{recycling}} \leq S_{\text{nb}}$:

- A candidate 20 cm outer divertor leg configuration is long enough.
- A baffle slanted in to 1-2cm midplane field line is narrow enough.
- Careful shaping of the baffle is important.

DEGAS / RECLUSE and the BASIS Post-processor

- DEGAS:

- * Monte-Carlo transport code for all hydrogenic neutral species.
- * 3D geometry (2D used in all calculations here).
- * Uses fixed plasma background ($n_{e,i}$, $T_{e,i}$, $V_{\text{flow}(x,y,z)}$ from UEDGE calculation).
- * Latest atomic physics data for wall interactions (Carbon walls in DIII-D).
- * Vectorized and multi-tasked; spawns 16 daughter processes on the C-90.

- BASIS Post-processor:

- * Converts information on DEGAS grid to the UEDGE grid at the BASIS parser level.
- * Plots DEGAS results for direct comparison with UEDGE (eg. 2D contours and cuts in div. legs, distribution of core ionization current, etc).
- * Allows comparisons between different DEGAS runs (eg. slot vs. open, puff vs. no puff).

Profiles of Plasma Parameters in the “Halo”

- The RECLUSE code (W. H. Meyer, LLNL) produces an arbitrary number of cells in the “halo” regions outside the UEDGE plasma grid.

- This allows profiles of plasma quantities to be specified in the far SOL for DEGAS calculations.
- Modeling of neutral transport in these outer regions, which was not routinely possible before RECLUSE, may be important in simulations of present experiments and for the radiative divertor.

Neutral Confinement and Core Fuelling, 4 cm SOL

- Integrated flux at the “core wall” is reduced with the “gas bag” configuration and further reduced with the slots.
- Recycling from the top of the narrower slot is an important source of flux to the core.

	40 cm	20 cm
Open divertor -	$710 \pm 65 \text{ A}$	$880 \pm 57 \text{ A}$
“Gas Bag” -	$73 \pm 21 \text{ A}$	$287 \pm 33 \text{ A}$
Standard slot -	$5 \pm 5 \text{ A}^*$	$37 \pm 12 \text{ A}$
Narrower slot -	$92 \pm 23 \text{ A}$	$57 \pm 15 \text{ A}$

* Large relative error - statistically 0 A.

Core Ionization is Still Acceptable with Gas Puffing

- "Slanted baffles" with recycling are used to model the radiative divertor design hardware.

- Core Ionization Flux

No Gas Puff - Conformal Slot	37 ± 12 A
No Gas Puff - Slanted Baffles	63 ± 15 A
1000 A D20 gas puff - Slanted Baffles	77 ± 24 A
2200 A D20 gas puff - Slanted Baffles	115 ± 37 A

- Ionization flux to the core depends on the detailed shape of the baffles.

Careful Shaping of the Baffle Can Reduce Γ_{core}

- For the tighter "slanted baffle", careful shaping of the upper shelf can reduce the core ionization.

- Cases with the upper shelf (3.5 --> 2.0 cm) normal to the flux lines show higher I_{core} than if it is slanted somewhat.

<u>Shelf</u>	<u>Normal</u>	<u>Slanted</u>
No Gas Puff	160 ± 24 A	114 ± 21
1000 A D20 gas puff	263 ± 45 A	207 ± 40
2200 A D20 gas puff	264 ± 57 A	234 ± 54

Application of DEGAS to the Reference Design

- A substantial upgrade of RECLUSE has been done to allow for studies of the RDP reference design.

- Initial DEGAS studies, for a UEDGE plasma with no gas puffing, show a core ionization flux of 65 ± 15 A

DEGAS Conclusions

- DEGAS studies have helped guide the design for the Radiative Divertor Program on DIII-D.
 - * Comparison of 20 vs. 40 cm configurations:
 - 40 cm config. has lower Γ_{core} than the 20 cm.
 - 20 cm gives $S_{\text{recycling}} \leq S_{\text{nb}}$ with proper baffling.
 - * "Slanted Baffles", Puff vs No Puff:
 - Slanted in from 3.5 to 2.0 cm, $S_{\text{recycling}}$ was:
37A (no puff), 77A (1kA puff), 115A (2.2kA puff)
 - Slanted in from 2.0 to 1.0 cm, $S_{\text{recycling}}$ was:

	Unoptimized	Partially optimized
no puff	160A	114A
1kA puff	263A	207A
2.2kA puff	264A	234A
- The proposed "slanted baffle" design reduces I_c by about a factor of 10 from the present "open" geometry to the range where $S_{\text{recycling}} \leq S_{\text{nb}}$:
 - A candidate 20 cm outer divertor leg configuration is long enough.
 - A baffle slanted in to 1-2cm midplane field line is narrow enough.
 - Careful shaping of the baffle is important.

DEGAS Future Directions

- DEGAS simulations need to be benchmarked in the same way that UEDGE is, by direct comparison with experimental data.

* Simulations of DIII-D shots are under way for Shot 78037.

- * DEGAS results will be compared with pressure measurements at several locations in DIII-D (private flux region, under the baffle, above the baffle and midplane wall).
- * DEGAS calculated D_{α} emission can also be compared with DIII-D photodiode array data.
- * Eventually we hope to compare 2D D_{α} measurements (tangentially viewing X-point TV) with DEGAS calculations.

Summary

- A process has been developed and implemented by which modeling assumptions in the 2-D fluid plasma physics code UEDGE can be validated against 2-D experimental data from DIII-D.
- The code with validated assumptions has been used to generate plasma solutions for options of the RDP upgrade for DIII-D
- DEGAS has been used to calculate the migration of neutral hydrogen in the fixed plasma solutions generated by UEDGE.
- Preliminary work has been done to develop methods to validate DEGAS against DIII-D data.
- Future plans include code upgrades for UEDGE (eg. non-orthogonal grids, impurity transport), completion of validation work with DEGAS, and work to bring the UEDGE / DEGAS solutions into iterative consistency.