Combined Onion Skin Method (OSM) and EIRENE Modeling of the Alcator C-Mod Edge

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Summary

• A new method of analyzing the tokamak edge plasma is illustrated for an example of a C-MOD L-mode discharge, using Onion-Skin Method (OSM) modeling of the plasma, combined with EIRENE Monte Carlo modeling of the neutral hydrogen.

• The OSM approach directly incorporates a substantial amount of experimental data to constrain the plasma solutions, specifically Target Langmuir Probe measurements across the targets and $D_\alpha$ and $D_\gamma$ spatial profiles from several viewing locations.

• The plasma solutions were cross-checked by comparison with other experimental data, specifically upstream Fast Scanning Probe radial profiles and Stark broadening measurements of $n_e$ and $T_e$ in the divertor.

• The ‘plasma background’ thus generated will be used in future studies to analyze the behavior of hydrogen (using EIRENE), and the impurity behavior (using DIVIMP).
Motivation

*we would like to know….*

- 2D distributions of D, D₂ throughout plasma and non-plasma volumes

- *fluxes* of D, D₂ onto all solid surfaces and impact energies

- D₂ throughput of *pumps*, bypass *leaks*

- 2D distributions of *impurities, intrinsic and non-intrinsic, recycling and non-recycling*, throughout plasma and non-plasma volumes

*unfortunately….*

- Much of this can not be directly measured
Fortunately….

- All these quantities can be calculated using Monte Carlo (MC) neutral hydrogen codes, e.g. EIRENE and DEGAS, and MC impurity codes like DIVIMP

- All known atomic and molecular processes can readily be included.

- MC codes are obedient bookkeepers that just keep track of the cumulative effects of a very large number of basic, well-understood processes. \(\therefore\) should be *reasonably reliable*

However….

The validity of the MC output is controlled by the fidelity of the ‘plasma background’ - the 2D (or 3D) distributions of \(n_e, T_e, T_i, v_{i\parallel}\) - which they need as *input.*
Providing the ‘Plasma Background’

- Standard approach: 2D edge fluid code such as UEDGE, EDGE2D and B2

- An alternative approach: Onion-Skin Method, OSM, modeling.

- OSM uses *more experimental input* to constrain the solution - e.g. $n_e(r)$ and $T_e(r)$ across the targets from Langmuir probes

- Thus, in principle, OSM can achieve *more fidelity to the actual experimental conditions, particularly near the divertor targets*, where important neutral hydrogen and impurity, sources and sinks, (including the pumps) are located.

*however…*

We need to actually show that we can find *any* plasma background consistent with the available experimental data.
C-Mod shot number 990429019: lower single null, L-mode, \( <n_e> = 1.4 \times 10^{20} \text{ m}^{-3} \)

An array of Langmuir Probes built into the divertor measured \( T_e \) and \( I_{sat}^+ \) across the targets.

The radial and vertical distributions of \( D_\alpha \) emission across the divertor were measured by the \( B_{top} \) and \( K_{bottom} \) calibrated reticon arrays.

The 2D poloidal distribution of \( D_\gamma \) radiation was measured by a calibrated toroidal CCD camera equipped with a filter centered at 4340A. Integrations over this 2D data were performed to construct line of sight (LOS) views equivalent to the reticon \( D_\alpha \) data since calibrated LOS spectrometer data were unavailable.

Upstream \( n_e(r) \) and \( T_e(r) \) across the SOL were measured at two locations by the Horizontal and Vertical Fast Scanning Probes.

Stark broadening measurements of \( n_e \) and \( T_e \) were available for certain viewing chords through the PFZ region.
OSM Analysis of the Different Edge Regions

1. **Outer divertor** is *attached* and ‘standard’ OSM analysis, based on Target Langmuir Probe boundary conditions, is used to model the outer SOL - “SOL Option 22” in the DIVIMP Code.

2. **Inner target** may be *detached* and a simple model/prescription of detachment, with several adjustable parameters, is used to model the inner SOL - “SOL Option 21” in the DIVIMP Code.

3. The physics of the **PFZ** is poorly understood, however, “SOL Option 21” was used there also.

**Independent Cross-check of solutions:**

(a) *for outer SOL*: by comparing with upstream $n_e(r)$ and $T_e(r)$ profiles from 2 Fast Scanning Probes.

(b) *for PFZ*: by comparison with Stark broadening measurements.
‘Standard’ OSM Analysis

(“SOL Option 22” in the DIVIMP Code)

• Solve the 1D, along-\( B \), plasma conservation equations using across-\( B \) boundary conditions from experiment, e.g. \( I_{\text{sat}}^+ \) and \( T_e \) across targets from Langmuir probes to produce a 2D solution

• The plasma solver is iterated with a 2D neutral code, EIRENE, to provide the particle, momentum and power terms associated with hydrogen recycling.

• \( D_{\perp}^{\text{SOL}} \) and \( \chi_{\perp}^{\text{SOL}} \): not required as input. The cross-field information is implicitly contained in the cross-field boundary conditions. In fact, they can be extracted from OSM analysis (\( \Rightarrow \) ‘Edge TRANSP’)

• OSM has been tested using input (target conditions) from standard 2-D edge fluid codes (EDGE2D), Fundamenski et al, PSI 2000, replicating the rest of the 2-D fluid code solutions.
Simple OSM Model/Prescription for Detachment

(“SOL Option 21” in the DIVIMP Code)

- $T_e$ and $I^+_{\text{SAT}}$ profiles across target taken from Langmuir probes.
- pressure $p(s_{\parallel})$: for the PFZ: $p$ is taken to rise to some specified value (parameter) at $s_{\parallel}^*$ with a specified profile; for the inside SOL, the pressure rise is not a free parameter since the upstream pressure is required to equal that calculated on the outside, for the same flux tube.
- $T_e(s_{\parallel})$ taken to be flat from target out to some specified location, $s_{\parallel}^*$ (parameter).
- starting at $s_{\parallel}^*$ the standard conservation equations are assumed to hold (in simplified form) and assuming some specified volumetric power loss term (parameter).
- the parameters can be specified independently for each flux tube
- the parameters are varied to obtain a match to the $D_\alpha, D_\gamma$ profiles.
EIRENE


- **EIRENE** includes:
  - Backscattering, as computed using the TRIM code, with the remainder of the recycling particles released as thermal molecules
  - All known ionization and dissociation processes for hydrogen
  - Transport of atoms and molecules
  - Reflection from surfaces
  - Charge exchange collisions
  - Atom-atom, and atom-ion scattering collisions
  - Thermalization processes for atoms and molecules due to wall and particle collisions
Cross-Check of OSM Solution for Outer SOL

• Comparison with upstream radial profiles measured by Horizontal and Vertical Fast Scanning Probes

• Comparing the profiles is entirely dependent on the validity of the EFIT analysis, i.e. of the resulting computational grid

• **EFIT** uncertainties in location of, e.g. upstream separatrix, may be of order mm’s, or more

• Matching the OSM and Fast Probe profiles was found to be extremely sensitive to the location of the separatrix

• **Shifting** the Fast Probe data relative to the fixed grid by $\Delta \rho \approx +3$ mm for the Horizontal Probe, and by $\Delta \rho \approx -1$ mm for the Vertical Probe, was found to give close matches with the OSM profiles.
Effect of Shifting the Data relative to the Grid

Horizontal Scanning Probe Comparison

EXPT/OSM PROBE PLOT: 990429019 LP1 952ms - A56 - A33
Effect of Shifting the Data relative to the Grid

Vertical Scanning Probe Comparison

EXPT/OSM PROBE PLOT: 990429019 LP1 952ms - A56 - A33
Matching the $D_\alpha$, $D_\gamma$ Profiles in the Inner SOL and PFZ

- The EIRENE code was used to calculate $D_\alpha$, $D_\gamma$ profiles and the simulated spectroscopic signals to compare with the measured signals.

- The plasma conditions in the inner SOL and PFZ were adjusted, giving different ‘plasma backgrounds’ for EIRENE and thus different simulated spectroscopic signals.

- Adjustment was continued until approximate matches to the measured $D_\alpha$, $D_\gamma$ signals were obtained.

- The $n_e$ and $T_e$ obtained were then cross-checked with Stark broadening measurements.
B-top Straight Dalpha Comparison

990429019 LP1 952ms - A56 - A33

LINE RADIATION (PHOTONS/M^2/S)  X10 21

THETA (DEGREES)  X10 2

- CODE HALPHA
- B top straight

EXPT

EXPT
Btop Straight Dgamma Comparison

990429019 LP1 952ms - A56 - A33

- CODE H GAMMA
- 2D Dgamma

LINE RADIATION (PHOTONS/M^2/S)

THETA (DEGREES)
Kbottom Dalpha Comparison

990429019 LP1 952ms - A56 - A33

LINE RADIATION (PHOTONS/M^2/S) X10 21

THETA (DEGREES) X10 1

CODE HALPHA

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K bottom straight Dalpha
Simulated Kbottom Dgamma Comparison

990429019 LP1 952ms - A56 - A33

![Graph showing simulated and experimental data for line radiation intensity vs. theta (degrees). The graph compares CODE HGAMMA and 2D Dgamma.]
Btop Dalpha Components

990429019 LP1 952ms - A56 - A33

H ionisation
H+ recombination
H2 dissociation
H2+ dissociation
CX of H and H+

THETA (DEGREES) x10^2
Btop Dgamma Components

990429019 LP1 952ms - A56 - A33

H ionisation
H+ recombination
H2 dissociation
H2+ dissociation
CX of H and H+

THETA (DEGREES) x10^2

Dgamma components (cumulative) (PH M-2 S-1) x10^20
Comparison with Stark Broadening

- A number of lines-of-sight pass through the PFZ and inner divertor plasma. The location of the maximum $D_\gamma$ mission along each LOS is extracted from the 2D $D_\gamma$ signals (both code and experiment). The plasma conditions at these locations are compared to the values obtained from the Stark broadening analysis.
- The experimental densities and temperatures are seen to be in overall agreement with those used in the modeling of the PFZ:

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<th>$D_\gamma$ [10$^{22}$ph/m$^3$/s]</th>
<th>$R,Z$ [m,m]</th>
<th>$n_e$ [10$^{20}$m$^{-3}$]</th>
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Background Plasma Solution

**DENSITY**
\[ \text{[m}^{-3}\text{]} \]
- 2.0E+21 TO 2.0E+21 (MAX)
- 1.6E+21 TO 2.0E+21
- 1.2E+21 TO 1.6E+21
- 1.0E+21 TO 1.2E+21
- 9.0E+20 TO 1.0E+21
- 8.0E+20 TO 9.0E+20
- 7.0E+20 TO 8.0E+20
- 6.0E+20 TO 7.0E+20
- 5.0E+20 TO 6.0E+20
- 4.0E+20 TO 5.0E+20
- 3.0E+20 TO 4.0E+20
- 2.0E+20 TO 3.0E+20
- 1.0E+20 TO 2.0E+20
- 1.0E+19 TO 2.0E+19

**TEMPERATURE**
\[ \text{[eV]} \]
- 7.5E+01 TO 7.5E+01 (MAX)
- 6.8E+01 TO 7.5E+01
- 6.0E+01 TO 6.8E+01
- 5.2E+01 TO 6.0E+01
- 4.5E+01 TO 5.2E+01
- 3.8E+01 TO 4.5E+01
- 3.0E+01 TO 3.8E+01
- 2.2E+01 TO 3.0E+01
- 1.5E+01 TO 2.2E+01
- 9.0E+00 TO 1.5E+01
- 6.0E+00 TO 9.0E+00
- 4.5E+00 TO 6.0E+00
- 3.0E+00 TO 4.5E+00
- 1.5E+00 TO 3.0E+00
- 7.5E-01 TO 1.5E+00
Further OSM Work To Be Done

- Discharges where the 2D spatial distributions (toroidal viewing camera) of both $D_\alpha$ and $D_\gamma$ are measured should be much more useful for constraining the solutions than the views used here.

- To avoid the inversion errors involved in the tomographic reconstructions of the $D_\alpha$ and $D_\gamma$ 2-D distributions, the code will simulate the toroidal lines-of-sight for direct comparison with measurements.

- The effect of wall reflection of the $D_\alpha$ and $D_\gamma$ light will be included in the modeling.

- More cases will be analyzed to try to establish if (the apparent) EFIT errors in locating the separatrix are systematic.

- The shifts required to obtain matches of OSM and Fast Probe profiles may be an indication of the effect of $\text{ExB and gradB drifts}$, rather than EFIT errors, so drifts need to be added to the OSM modeling.
Future Studies Using the ‘Plasma Background’

In future studies, the edge ‘plasma background’ generated by the foregoing procedure will be used with:

(a) **EIRENE** to analyze neutral deuterium behaviour in the CMOD edge, including plenum pressure modeling, leakage of neutrals through the divertor bypass to the main chamber, as well as main chamber recycling.

(b) **DIVIMP** to analyze the behaviour of intrinsic and injected, non-recycling and recycling, impurities.
Conclusions

• Combined OSM+EIRENE modeling of the tokamak edge provides an alternative to standard 2D edge fluid code modeling. It directly incorporates a substantial amount of experimental data as boundary conditions and as constraints on the plasma solutions.

• Combined OSM+Eirene can be used to find a ‘plasma background’ that is consistent with a broad set of experimental measurements.

• The method, however, is still in development and it remains to be demonstrated that these theoretical advantages can be realized over a wide range of experimental conditions.

Acknowledgements

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