OSM-EIRENE Modeling of Neutral Pressures in the Alcator C-Mod Divertor

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The **ITER divertor** will be more **collisional** than those in existing tokamaks.

**Estimate of collisionality:** $n_e R$
- $n_e$ – Divertor plasma density ($10^{20} \text{ m}^{-3}$)
- $R$ – Major radius (m)

Strong **neutral-plasma, neutral-neutral** (viscosity) and **neutral-photon** (trapping) interactions

Need to **validate neutral modeling codes** for ITER-like conditions

Most collisional divertor available: **Alcator C-Mod**

![Graph comparing $n_e R$ for JET, C-MOD, and ITER](image)
Factor ~10 smaller than ITER, similar shape

**High magnetic field** (9 Tesla max.) → **high density**
- \( n_e \approx 10^{21} \text{ m}^{-3} \) in divertor from Stark broadening data

**Trapping** of Lyman series **photons** observed from line ratio measurements [Terry]
- “Stong” Ly\( _\alpha \) trapping implied by data

High divertor neutral pressures: \(~100\) mTorr max.
- Neutral viscosity is important

Excellent **opportunity** for **evaluating neutral codes** in a **highly collisional divertor**
Motivation
Previous Efforts to Model the Measured Divertor Neutral Pressure in C-Mod

Measured pressure: $25 \pm 3$ mTorr (shot 990429019, 950 ms)

**DEGAS2 Monte-Carlo neutral code** [Stotler]

- **First attempt: 1–2 mTorr**
  - Simple plasma model [Pitcher]

- **Second attempt: 2–3 mTorr**
  - Onion-Skin Method (OSM) plasma solution input to DEGAS2 [Elder]
  - OSM: an interpretive reconstruction of the divertor plasma based on experimental data (more later) [Stangeby]
  - General agreement with spectroscopic data

**Most likely problem: plasma solution**

- Partial detachment observed experimentally
- Spectroscopy indicates $T_e < 1$ eV, $n_e \approx 10^{21}$ m$^{-3}$ in the divertor [Lipschultz]
- Volume recombination very sensitive to $T_e$, $n_e$ for these plasma conditions
- Long ionisation MFP → need accurate plasma solution for **entire** divertor
**MOTIVATION**

Most Recent Attempt…

**Objectives:**

1. Develop an improved OSM plasma solver for generating a detailed and “sufficiently accurate” description of the detached regions of the divertor plasma.

2. Input the plasma solution to the EIRENE neutral code and quantitatively assess the dominant processes governing neutral dynamics in the C-Mod divertor.
MOTIVATION

EIRENE Monte-Carlo Kinetic Neutral Code

D. Reiter and coworkers, IPP Jülich, Germany

“Official” hydrogenic neutral code for ITER

**Photon transport** included
- Pressure, Doppler and natural broadening
- Zeeman splitting in development
- Validated for high pressure lamps

**Neutral viscosity** included

Also:
- D–D$^+$ elastic collisions
- D ionisation
- D$^+$–D$_2$ elastic collisions
- D$_2$ ionisation and dissociation
- D$_2$+ (equilibrium approx.)
- D$_2$(ν) (kinetic and equ. approx.)

Benchmarks well with DEGAS2

www.eirene.de
OSM based “empirical reconstruction” of the detached divertor plasma

Interpretive method, not predictive
**Onion-Skin Model (OSM) Formulation of the Divertor Plasma Solution**

- **OSM** based “empirical reconstruction” of the detached divertor plasma
- Interpretive method, not predictive
- Use a simple parameterized model of detachment

**Constrain detached plasma solution:**
Set model parameters based on comparison with (ideally) all of the available diagnostic data for the plasma, everywhere in the divertor

**Validity** of the plasma solution is determined by the level of agreement with experiment and the amount of data confronted
PLASMA SOLUTION

Divertor Plasma Diagnostics

HIGH RESOLUTION DIODE ARRAYS WITH $D_\alpha$ FILTER

TARGET LANGMUIR PROBES AND UPSTREAM RECIPROCATING PROBE FOR $n_e$ AND $T_e$

DIVERTOR GAS PRESSURE (25±3 mTorr)

TOROIDALLY VIEWING CCD CAMERA WITH $D_\gamma$ FILTER

SPECTROMETER FOR VOLUME $n_e$ AND $T_e$

C. BOSWELL
B. LaBOMBARD
B. LIPSCHULTZ
A. NIEMCZEWSKI
S. PITCHER
J. TERRY

UNIVERSITY OF TORONTO
Comparison with Camera $D_\gamma$
PLASMA SOLUTION

$T_e$ and $n_e$ Profiles Input to EIRENE

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Detailed OSM plasma solution with broad agreement between model and experiment - (almost) within uncertainties

Hypothesis: The **basic picture** of the **divertor plasma** is correct and is sufficiently accurate for a **quantitative** investigation of neutral dynamics in the divertor

Measured neutral pressure: 
25 ± 3 mTorr

**Calculated neutral pressure** from OSM-EIRENE: 17 ± 2 mTorr

But… “**sealed**” plenum **approximation** in the model – calculated pressure is **artificially high** (more later)
Importance of Individual Neutral Processes

**CALCULATED DIVERTOR PRESSURE**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Torr</th>
</tr>
</thead>
<tbody>
<tr>
<td>STANDARD MODEL</td>
<td>15</td>
</tr>
<tr>
<td>Ly(_\alpha) TRANSPARENT</td>
<td>25</td>
</tr>
<tr>
<td>MAR OFF</td>
<td>15</td>
</tr>
<tr>
<td>VISCOSITY OFF</td>
<td>5</td>
</tr>
<tr>
<td>ION-MOLECULE ELASTIC COLLISIONS OFF</td>
<td>5</td>
</tr>
</tbody>
</table>
NEUTRAL SOLUTION

Effect of Lyman $\alpha$ Absorption

Pressure increases from $\sim 17$ mTorr to $\sim 30$ mTorr when photons removed.
Pressure drops to $\sim 10 \text{ mTorr}$ when removed.
Neutral Solution

Neutral Viscosity

Pressure drops to \(~10\) mTorr when removed.

Neutral-neutral collisions reduce the fraction of momentum influx lost to walls.

Pressure depends non-linearly on the neutral influx to the plenum:

\[ p \propto (\Phi_{\text{influx}})^{1.4} \]
NEUTRAL SOLUTION

Elastic Collisions Between Plasma Ions and Neutral Molecules

Pressure drops to \( \sim 5 \text{ mTorr} \)

- \( A \) – albedo
- \( \Phi_0 \) – “primary” neutral influx
- \( \Phi_1(A) \) – “secondary” influx
- \( \Phi_{\text{total}} \) – total influx
NEUTRAL SOLUTION

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\[
\Phi_{\text{total}} = \Phi_0 + \Phi_1(A) = \frac{\Phi_0}{1 - A}
\]

Cross-section \( \times 1.5 \), pressure increases to \( \sim 21 \text{ mTorr} \)

However, cross-section data from quantal calculations, \( \sim 20\% \) uncertainty
NEUTRAL SOLUTION
Including Additional Leakage Pathways

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Pressure drops from $17 \pm 2 \text{ mTorr}$ to $11 \pm 2 \text{ mTorr}$
SUMMARY

Progress Toward Objectives

1. Develop an improved **OSM method** for generating a **detailed** and
   **“sufficiently accurate”** description of the **detached** divertor
   **plasma**

   Broad agreement (almost) within experimental uncertainties,
   between the plasma solution and the available experimental data for
   the divertor

   Measured and calculated neutral pressures agree within a factor
   ~2 (3D EIRENE)

2. Input the plasma solution to EIRENE and **quantitatively** assess the
   **dominant processes** governing **neutral dynamics** in the C-Mod
   divertor

   The calculated neutral pressure is sensitive to volume
   recombination, \( \text{Ly}_\alpha \) opacity, viscosity and ion-molecule collisions

   Neutral modeling of a highly-collisional, “ITER-like” divertor must
   include these processes (V. Kotov)
SUMMARY

Principal Results

Given a (reasonably) accurate plasma solution as input, EIRENE reproduces the measured C-Mod pressure to within a factor ~2.

Possible explanations for the remaining discrepancy:

- Inaccuracies in the plasma solution
- Diagnostic interpretation
- Underestimation of volume rec.
- High frequency plasma oscillations
- \( \text{H}_2^+, \text{H}_3^+, \text{H}^- \) charge carriers
- Transport of \( \text{D}_2(\nu) \) into the plenum

Improved agreement due to a more detailed description of the divertor plasma → interpretive OSM modeling based on experimental data

- Previous DEGAS2 results: factor ~10 lower than experiment
- Introduction of detachment in the outer PFZ
- Improved resolution of the volume recombination source
- Not from refinement of neutral model (including opacity reduces pressure)

Controlling processes occur in the PFZ (for this discharge/geometry)

- 90% of neutrals contributing to the calculated pressure originate in the PFZ

Further refinement of plasma and neutral model required

- DIII-D study with divertor Thomson [P3-51]
- Want fewer parameters in the plasma model, more physics