Neutral Transport Simulations of Gas Puff Imaging Experiments on Alcator C-Mod

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Note: This poster is available on the Web at:
http://w3.pppl.gov/degas2/
INTRODUCTION

• Tokamak edge ideal for comprehensive study of turbulence,
  – Accessible with probes
    ⇒ directly measure $n_e$, $T_e$, and other properties.
  – Relatively low $T_e$ facilitates use of atomic physics as basis for diagnostics.
  – Potential payoff great because edge sets boundary conditions for core transport,
    * E.g., internal transport barriers, H-mode pedestal.

• Gas Puff Imaging (GPI) experiments designed to measure 2-D structure of edge turbulence,
  – Compare with 3-D nonlinear simulations.
  – And with turbulence measured by probes,
  – Puff neutral gas (e.g., D$_2$) near outer wall,
    * View with fast, high res. camera light from electron impact excitation of gas,
    * Use sightline $\parallel \vec{B}$ to see radial & poloidal structure,

• Explore relation between images & plasma fluctuations with DEGAS 2 neutral transport code,
  – Straightforward because puff does not perturb plasma,
  – Emitted light brighter than background,
  – Material surface interactions should not be important.

• Experimental presentation: O-02 J. L. Terry et al.
Fig. 1 - Zweben APS ‘01
Fig. 2 - Zweben / APS ‘01
DESCRIPTION OF DEGAS 2 SIMULATIONS

• Alcator C-Mod Geometry:
  – Start with outline of vacuum vessel,
    † Including gas puff nozzle & surrounding structures.
  – EFIT equilibrium for time of interest ⇒
    † 2-D plasma mesh set up using DG & Carre,
    † Bunch surfaces & grid points to get resolution
      3 mm or smaller in region of interest.
  – Divide puff region into ∼ 3 mm triangles
    using Triangle.

• Simulations 2-D axisymmetric for now,
  – Output is averaged over toroidal angle.
  – ⇒ poloidal plane variation of photon emission rates.
  – Plan to add toroidal resolution ⇒
    † Can directly simulate fast camera views,
    † Quantitative comparison of image intensity,
    † Evaluate toroidal spatial averaging.
DEGAS 2 Geometry for C-Mod Shot 1010622
• Simulations assume steady-state.

  – Compare time scales:

    ∗ Autocorrelation time for turbulence
      = 10 – 20 \( \mu \)s,

    ∗ Time for 3 eV D to travel across cloud
      = 1 \( \mu \)s (2 cm),

    ∗ Timescale for emission of D\( \alpha \) photon
      = 1/A\( 3\rightarrow2 \) = 0.02 \( \mu \)s,

    ∗ Note that camera exposure times
      = 2 \( \mu \)s (60 frame/s) or
      4 \( \mu \)s (5 \times 10^6 frames / s),

    ∗ \( \Rightarrow \) assumption of stationary plasma OK.
• Physics:
  
  – $D_2$, $D_2^+$ dissociation, including
    
    * $e + D_2 \rightarrow e + D(1s) + D(1s)$
    * $e + D_2 \rightarrow e + D(1s) + D^*(n = 3)$
    * $e + D_2 \rightarrow 2e + D_2^+$
    * $e + D_2 \rightarrow 2e + D(1s) + D^+$
    * $e + D_2^+ \rightarrow 2e + 2D^+$
    * $e + D_2^+ \rightarrow e + D(1s) + D^+$
    * $e + D_2^+ \rightarrow e + D^+ + D^*(n = 3)$
    * $e + D_2^+ \rightarrow D(1s) + D^*(n = 3)$
  
  – $D + D^+$ elastic scattering (i.e., charge exchange),
  
  – $D_2 + D^+$ elastic scattering,
  
  – $e + D$ ionization,
    
    * “Multi-step”, i.e., collisional-radiative model.
  
  – Neutral-neutral collisions not included,
    
    * May not be negligible,
    * Need realistic neutral density to treat,
    * Can only be computed in 3-D.
- Emission rate \((m^{-3} s^{-1})\) written as:

\[
S_{D\alpha} = \sum_{j=D,D_2,D_2^+} n_j f_j(n_e, T_e),
\]

* Where \(n_j = \) ground state atom & molecule density,

\[
f_D = \frac{n_D(n = 3)}{n_D(n = 1)} A_{3\rightarrow 2},
\]

* \([n_D(n = 3)/n_D(n = 1)](n_e, T_e)\) from CR model,

* Largely determines \(n_e, T_e\) dependence of \(f_D\).

\[
f_{D_2}, f_{D_2^+} = n_e \sum_k \langle \sigma v \rangle_k(T_e),
\]

* \(k = \) reactions leading to \(n = 3\).

- All puffs are 300 K with cosine distribution,

* Examined sensitivity in preliminary runs,

* Run with \((\cos \theta)^4\) distribution,

* One with 150 K puff.
• Plasma profiles:
  – All are taken from measured data mapped to midplane,
  – Assume constant on a flux surface,
    * In triangulated region, estimate $\rho = \text{distance between zone center \& nearest flux surface mesh zone}$.
  – Assume $n_i = n_e$, $T_i = T_e$. 
Scanning Probe Data from C-Mod
Shot 1010622006, 700 ms

Electron Temperature (eV)

Electron Density \((m^{-3})\)

R (m)

0.88 0.89 0.9 0.91 0.92 0.93

0.88 0.89 0.9 0.91 0.92

Electron Temperature vs. R (m)

Electron Density vs. R (m)

Compare DEGAS 2 Result with Experimental Data
Radial Slice at \(Z = -0.034\) m

Normalized \(D_{\alpha}\) Emission Rate

Measured

DEGAS 2

R (m)
Peak Location & Width of Simulated Emission Insensitive to Details of $D_2$ Distribution

Radial Slices, $Z = -0.0255$ m

Vertical Slices, $R = 0.905$

⇒ Vertical extent can be affected
C-MOD RESULTS

- Alcator C-Mod shot 1010622006 at 700 ms.
- Baseline computed with time-average plasma profiles,
  - 10 – 20% of atoms in cloud undergone reflection,
  - “CX fraction” have had a CX,
  - Rest from dissociation ⇒ ballistic trajectories.
  - ⇒~ 50 – 65% of D emission
- At peak, molecular D_α's contribute ~ 40%,
  - < 10% for \( R \lesssim 0.9 \) m.
- Compare with time-average experimental GPI images,
  - Emission peak near nozzle not seen experimentally,
  - Probe data assumed constant for \( R > 0.91 \) m,
  - Nozzle peak \( \downarrow 10^{-2} \) if \( T_e < 2.5 \) eV
  - Or if \( n_e < 3.6 \times 10^{16} \) m\(^{-3}\),
  - Both consistent with exponential extrapolation of probe data.
DEGAS 2 Baseline

D$_\alpha$ Rate (10$^{19}$ photons m$^{-3}$ s$^{-1}$)

CX Fraction = 0.30
Fraction of $D_{\alpha}$ Due to Atoms
• Impose 2-D perturbation on $n_e$ and $T_e$,
  
  – Important to understand relation between spatial variation in emission & underlying plasma fluctuations,

  – Consider ad hoc perturbation:

  $$n_e'(R, Z) = n_e(R, Z)[1 + \frac{1}{2}\sin(\frac{\pi Z}{0.01})]$$

  $$\times\{1 + \frac{1}{2}\sin[\frac{\pi(R - R_{sep} + 0.0035)}{0.005}]\}$$,

  – where:

    * The $1/2$ factors make this a 50% perturbation,
      · Factor ranges from 0.25 to 2.25.
    * 2 cm wavelength for poloidal ($\sim Z$) variation,
      · Typical size of observed emission structures.
    * Used only 1 cm in $R$ because of limited radial width,
      · 0.0035 shift so innermost data point unchanged.

  – Try same perturbation on $T_e$,

    * Only difference: $T_e$ bound between 5 and 100 eV.
2-D Perturbation to Electron Density

\[ R \ (m) \]

\[ Z \ (m) \]

\[ D_\alpha \ Rate \ (10^{19} \ photons \ m^{-3} \ s^{-1}) \]
2-D Perturbation to Electron Temperature

![Image of a 2-D perturbation to electron temperature graph with color scale showing $D_\alpha$ rate in units of $10^{19}$ photons m$^{-3}$ s$^{-1}$]
Effect of 2-D Perturbation
Normalized to Unperturbed Value
Vertical Slice

- $n_e'/n_e$ or $T_e'/T_e$
- $D_\alpha$ with $n_e$ perturbation
- $D_\alpha$ with $T_e$ perturbation
Effect of 2-D Perturbation Normalized to Unperturbed Value Radial Slice
– Both simulations shows same 2-D structure,
– ⇒ wavenumber spectrum at least similar to that of plasma turbulence,
  * Expect autocorrelation function & frequency spectra similar also,
  * Will subsequently investigate quantitatively.
– Ratio of perturbed / unperturbed emission $\neq n_e'/n_e$ because $\partial \ln f_D/\partial \ln n_e, \partial \ln f_D/\partial \ln T_e < 1$.
– Further complicated by molecular contributions,
  * $f_{D_2}$ and $f_{D_2^+} \propto n_e$,
  * $T_e$ dependence not simple,
  * Effective scaling varies radially.
• Simple interpretation of GPI: image patterns $\propto n_e'/n_e$,
  – And insensitive to $T_e$,
  – Valid only if $n_e \lesssim 10^{18}$ m$^{-3}$ and $T_e \gg 10$ eV,
  – Not the case here!
  – $\Rightarrow n_e, T_e$ dependence of $S_{D\alpha}$ not different enough to infer perturbation amplitudes,
  – Would be simpler if $n_e, T_e$ in phase.
The dependence of $D_\alpha$ emission rate contained in the ratio of $n=3$ density to $n=1$.

Scaling of $f(n_e, T_e)$ varies across radial profiles of 1010622.
Shadow Fraction

• Above focussed only on effect of perturbation on $f_j$,
• They also impact $n_j$!
• “Shadowing effect”: ionization caused by local $n_e$, $T_e$ peak reduces light at smaller $R$.
• Compare images with and without shadowing,
  – “With” shadowing is as above,
  – To eliminate, use perturbed $f_j$ and unperturbed $n_j$,
  – “Unshadowed” clearly shows $n_e$ perturbation structure,
  – Shadowed image smeared out,
    * Due to $n_j$ reductions by $n_e$ peaks,
    * And $n_j$ increases by $n_e$ minima.
Runs with Electron Density Perturbation Shadowing:

with

without

\( D_\alpha \) Rate (10^{19} \text{ photons m}^{-3} \text{ s}^{-1})

(a)

(b)
• Estimate by computing:

\[ F_s = \left[ \sum_j (n'_j - n_j)f'_j \right] / \sum_j n_j f_j, \]

– Where prime indicates perturbed value.
– Evaluate separately for both “perturbed” simulations.

• Structure is complicated!

• Main observations:

1. \(|F_s| \gtrsim 0.5\) in many places
   ⇒ too large to ignore in GPI analysis.
2. Most of \(F_s\) due to molecules,
   – Analogous quantity based on atoms only \(\leq 0.2\).

• To understand \(F_s\) look at radial slices,

  – \(Z = -0.034\): peak in \(n'_e/n_e\),
  – \(Z = -0.025\): at nozzle & a minimum in \(n'_e/n_e\).
  – Compare with \(1 - n'_e/n_e\),
    * \(1 - n'_e/n_e < 0\) ⇒ local \(n_e >\) unperturbed value,
    * \(1 - n'_e/n_e > 0\) ⇒ local \(n_e <\) unperturbed value,
    * \(T_e\) perturbation differs at edges.
  – \(F_s < 0\) ⇒ \(n_j\) locally reduced,
    * \(F_s\) drops are in “shadows” of largest \(n'_e/n_e\).
  – \(F_s > 0\) ⇒ \(n_j\) locally increased,
    * \(F_s > 0\) at \(Z = -0.025\) since \(n_e\) modulation near min.,
    * Not so in perturbed \(T_e\) case due to smaller dissociation rate & strong \(T_e\) dependence of \(f_j\).
Shadow Fraction with Density Perturbation
Shadow Fraction with Temperature Perturbation
Shadow Fraction Significant

Radial Slices

Normalized Values

$Z = -0.034 \text{ m}$

$Z = -0.025 \text{ m}$

$Z = -0.025 \text{ m}$

$R (\text{ m})$
CONCLUSIONS

- **DEGAS 2** simulations show that spatial variation of $D_\alpha$ emission reflects that of $n_e, T_e$ turbulence.

- But, $n_e, T_e$ dependence of emission rate complicated,
  - $\Rightarrow$ no simple scheme to get plasma fluctuations.

- Contributions from molecules significant,
  - Further complicating $n_e, T_e$ dependence,
  - Densities significantly affected by perturbation.

- $\Rightarrow$ will need neutral transport code to interpret GPI,
  - Must do careful benchmarks first,
  - To verify these conclusions,
  - Validate atomic & molecular physics models.