Midplane Neutral Density Profiles in NSTX

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• Describe a simulation based method for inferring midplane neutral density profiles from visible camera data.

• Get a range of values for 2010 NSTX discharges: 
  \[ n_D \sim 10^{16} \text{ m}^{-3}, \quad n_{D_2} \sim 10^{17} \text{ m}^{-3}. \]

• Validation quantifies uncertainties in simulation results \( \Rightarrow \) error bars and pointers for improving model & experiment.

• If you leave / fall asleep:
Multiple Needs for Main Chamber Neutral Density Profiles

- For other diagnostics & analyses
  - Neutral beam charge exchange loss power,
  - Interpretation of CHERS data.
- & for study of SOL & pedestal physics,
  - H-mode pedestal formation,
  - Edge plasma turbulence.

[S. Medley, NF (2004)]
Visible camera $\Rightarrow$ line integrated emission rates.
Abel inversion $\Rightarrow$ volumetric rate $S$.
Balmer-$\beta$ emission rate:

$$S_\beta = n_D(1s) \left[ \frac{n_D(n = 4)}{n_D(1s)} \right] A_{4\rightarrow2} \equiv n_D F(n_e, T_e),$$

$\Rightarrow n_D = S_\beta / F(n_e, T_e).$

But, $S_\beta$ & $F$ both significant only in narrow radial region,
DEGAS 2 based “forward” method for inferring $n_D(R), n_{D_2}(R)$ provides more information, smaller uncertainties.
DEGAS 2 Monte Carlo Neutral Transport Code

- Simulate behavior of neutral species in a plasma.
  - Plasma-wall interactions generating neutral atoms & molecules, e.g., recycling.
  - Interactions between those neutral species with plasma ions & electrons as they penetrate.
- Input to DEGAS 2:
  - Geometry: 2-D or 3-D outline of hardware & flux surface aligned mesh for plasma.
  - Plasma density, temperature, flow velocity everywhere.
  - Source of neutrals: recycling, gas puff, recombination, . . . .
- \( \Rightarrow \) Volumetric sources / sinks of plasma mass, momentum, & energy due to those interactions (e.g., for coupling to plasma codes).
- & Synthetic diagnostic data for experimental comparison,
  - Neutral pressure,
  - Light emission,
  - Wall fluxes.
Method Leverages Off Successful Midplane Gas Puff Imaging Simulations

- See: [B. Cao et al., Fusion Sci. Tech. 64, 29 (2013)].
- Relies on nearby $n_e(R) \& T_e(R)$ from Thomson scattering,
  - & assuming $n_e(R) \& T_e(R)$ constant on flux surface $\Rightarrow$ know everywhere.
- Flux surface shapes from EFIT,
  - Thomson profiles mapped via $R \Rightarrow$ not sensitive to separatrix location.
Validated DEGAS 2’s Description of D$_2$ Penetration from Far SOL

- D$_\alpha$ radial profiles from D$_2$ puff matched within estimated uncertainties.
- & matches absolute magnitude,
  - Camera absolutely calibrated,
  - Know total amount of gas injected
    ⇒ compare photons recorded / D injected.
  - GPI: $1/89 \pm 34\%$,
  - DEGAS 2: $1/75 \pm 18\%$.
- ⇒ DEGAS 2 provides adequate model for D$_2$ penetration of NSTX midplane.
Key Data: Passive Light Emission from Edge Neutral Density Diagnostic (ENDD)

- Absolutely calibrated tangential camera,
  - ⇒ Radial profile, 1.6 mm resolution.
- 3.7 ms exposure time = 268 frames / second.
  - ⇒ integrates over ELMs.
- 20 cm radial × 9 cm poloidal.
- Has $D_\beta$ filter for shots considered here.
- Complete spatial calibration ⇒ can build DEGAS 2 synthetic diagnostic.

[Bay I diagram]

Set Up DEGAS 2 Simulations Similar to Those Used for GPI

• Geometry & plasma setup procedures derived from those used for GPI [B. Cao et al., Fusion Sci. Tech. 64, 29 (2013)],

• Geometry based on EFIT flux surface contours,

• Plasma profiles from Thomson & CHERS,
  – Use CHERS to estimate $n_{D^+}/n_e$ & $T_i/T_e$,
  – $T_i = T_e$ for shots used here.

• Primary differences from GPI:
  – Nature of D$_2$ source,
  – Synthetic diagnostic for D$_\beta$ ENDD,
  – Baseline runs ignore D$_\beta$ from molecules.
Source Characterization & Analysis
Procedure Specific to ENDD

- Actual sources difficult to characterize:
  - Neutral flow from divertor,
  - Main chamber recycling,
  - Or outgassing.

- Postulate vertically uniform $D_2$ source coming from vessel walls,
  - Will show results very insensitive to this assumption.
  - Assign arbitrary magnitude: $\Gamma_{D_2} = 10^{20} \ D_2/(m^2 \ s)$ at wall.

- Compare synthetic ENDD signal with experimental image:
  - Use horizontal row of simulated ENDD pixels at $Z = 9 \ cm$,
  - Overlay with row from calibrated experimental ENDD smoothed over vertical 10 pixels (1.4 cm)
    - Overall scale factor for simulation.

- Focus here on 2-D / axisymmetric calculations.
ENDD Geometry

- Scintillator Fast Lost Ion Probe [sFLIP, Darrow, RSI (2008)]: used for initial 3-D runs. But, not here.
Emission Profiles Agree Reasonably

- Apply to two NSTX H-mode plasmas:
  - 139412 \( t = 4 \) s: \( \delta = 0.3 \), ELMy,
    - Lull at \( t = 0.4 \) s.
  - 142214 \( t = 4 \) s: \( \delta = 0.6 \), ELM-free.

- High SOL density, \( n_e \sim 10^{18} \) m\(^{-3} \) \( \Rightarrow \) Thomson accurate at all points.

- Take ratios of profile peaks:
  - 139412: ENDD = 2.5 \( \times \) DEGAS 2,
  - 142214: ENDD = 1.6 \( \times \) DEGAS 2.

- Good match confirms approach to inverting ENDD & adequacy of uniform D\(_2\) source ansatz.

- But, what is “good”?
  \( \Rightarrow \) that’s the point of validation!
Simulated Peak Location Tracks $T_e = 100$ eV

- 12 runs from 7 shots.
$R_{\text{ENDD}} - R_{\text{DEGAS2}}$ Ranges from $-1 \rightarrow 4$ cm

- Discrepancy larger for smaller $R_{100}$!
Physics? Diagnostic problem? Simulation problem?
• \( \Rightarrow \) Ranges of values at vessel wall, \( R = 1.7 \) m. **Key result!**

• But, how uncertain are they???
Estimated Uncertainties from ENDD Itself Are Small

- Absolute calibration of camera: 3%.
- Spatial calibration of camera: 3 mm
- “Blue shifting”: 8% magnitude,
  - Negligible effect on peak location.
- Li coatings on mirror?
  - Expect insignificant & not evaluated.


- Thomson scattering profiles uncertain due to random & systematic errors, as well as finite sampling volume.
- Do Monte Carlo sampling of these errors ⇒ 100 $T_e$, $n_e$ profiles for 142214.
- ⇒ 100 runs ⇒ distribution of peak locations, neutral densities.
• Peak location standard deviation: 3 mm.
• Density standard deviations: $n_{D_2} : 6.6 \times 10^{16} \text{ m}^{-3}$, $n_{D} : 7.5 \times 10^{15} \text{ m}^{-3}$.
• Also, quantify sensitivity of densities to SOL $T_e$
Plasma & Separatrix Motion

1 cm Uncertainty in Peak Location

• Motion of plasma significant during 4 ms exposure
  \(\Rightarrow\) ENDD is an average.
• But, \(\sim 4\) frames between TS pulses. How to match up?
• 1 cm estimate from motion in 139396, 139432 & others.
Quantify Uncertainties Associated with Source Profile Assumption

- Relative deviations from baseline ENDD are \( \leq 18\% \),
- Density profiles differ by factor of 2 - 3 or less.
- Similar conclusions from runs with sources at bottom boundary.
Molecular Contributions May Be Important

\[ e + D_2 \rightarrow e + D(1s) + D^*(n = 4), \]
\[ e + D_2^+ \rightarrow e + D^+ + D^*(n = 4), \]
\[ e + D_2^+ \rightarrow D(1s) + D^*(n = 4). \]

- In GPI: \( D_2 D_\alpha \sim 40\% \) of emission at peak. Here?
- Problem: \( D_\beta \) rates not as well tested as \( D_\alpha \)
  \(\Rightarrow\) only an estimate.
- Contributes 35 → 50\% of total emission!
- Active at lower \( T_e \) than D emission
  \(\Rightarrow\) can shift emission peak!
Effect of Charge Exchange Surprisingly Small!

- Remove CX from reaction list: < 19% difference in ENDD profile,
  - $D, D_2$ densities at wall drop 17, 13%.
- Even though $\langle \sigma v \rangle_{CX} > \langle \sigma v \rangle_{ion}$ over most of volume.
- Dominant process is instead $D$ creation from $D_2$.
- CX is relevant for $R < R_{DEGAS2}$.
Summary

- Described method for inferring density profiles.
- Simulated ENDD profile peaks differ from measured by $\leq 4$ cm,
  - Uncertainty due to plasma motion: 1 cm,
  - From preliminary $D_2\ D_\beta$ emission model: $\leq 2$ cm.
- Factors preventing more complete resolution:
  - Plasma parameters in SOL,
  - Plasma motion & synchronization,
  - $D_2\ D_\beta$ model,
  - Unaccounted for camera calibration issues.
- Nonetheless, deviations small compared with problem scale $\Rightarrow$ can use results to get approximate densities.
- $\Rightarrow n_D = 1$ to $7 \times 10^{16}$, $n_{D_2} = 2$ to $9 \times 10^{17}$.
Can We Compare Vessel Densities with Micro-Ion Gauge Data?

- Survey C-mid, E-mid, IG 110 pressures in 17 shots,
  - Averaged over 0.1 or 0.2 s interval,
  - IG 110 shifted 0.18 s.

- No obvious correlation between them!
- Each is compromised:
  - C-mid very noisy (low end of operating range?),
  - E-mid direct view of plasma ⇒ affected by ELMs,
  - IG 110 slow to respond.

- Can only get an upper bound or range of vessel densities.
- Similarly, see no correlations with peak ENDD emissivity.