Particle Control and Transport Experiments

In the DIII-D Tokamak
With Graphite Walls

by
S.L. Allen

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The DIII-D AT Experiment with Graphite Walls

• Advanced Tokamak physics on DIII-D
  – Can recover from off-normal events between shots (GDC)
  – DIII-D has effective $n_e$ control in high-$\delta$ shapes

• Graphite walls, wall conditioning, divertor pumping
  – Baking to 350°C, GDC between shots
  – 3 divertor cryopumps can decrease H-mode density

• Pay attention to fuel retention in longer pulse experiments
  – Divertor pumping and 350°C bake removes shallow deposits
  – Thermo-Oxidation can remove fuel that is co-deposited with carbon – use UTIAS experiments
Summary of Results

• Dynamic (Time Dependent) particle balance shows no wall retention in H-mode plasmas
  – Strong divertor cryopumping
  – Well conditioned graphite
  – Dynamic agrees with shot-integrated “static” exhaust

• Significant wall retention in startup (20%)
  – Shot-Integrated retention averages

• Thermo-oxidation on DIII-D
  – Removes D at rates consistent with UTIAS results
  – Advanced Inductive plasma operation recovered quickly
  – No damage to tokamak components
Global Particle Balance Based on Measured Quantities

\[
\Gamma_{\text{wall}}(t) = \Gamma_{\text{gas}}(t) + \Gamma_{\text{NBI}}(t) - \left[ Q_{\text{pump}}(t) + \frac{dN_0(t)}{dt} + \frac{dN_{\text{core}}(t)}{dt} \right]
\]

**Particle input sources**
- gas puff values ⇒ *Gas flowmeter*
- NBI ⇒ *P_{NBI} & V_{NBI}*

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Global Particle Balance Based on Measured Quantities

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- **Particle input sources**
  - gas puff values \( \Rightarrow \) Gas flowmeter
  - NBI \( \Rightarrow P_{\text{NBI}} \) \& \( V_{\text{NBI}} \)

- **Particles exhausted**
  - (cryo-pumps)
  - Fast ion gauge

- **Rate change in un-pumped neutrals**
  - Fast ion gauge

- **Rate change in core particle content**
  - \( CO_2 \) interferometer
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Remainder
In Steady-state H-mode, Global Balance Reduces to a Few Terms

Main terms in NBI discharges

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- \( \Gamma_{\text{NBI}} \) is derived & has uncertainty ~20%
- \( Q_{\text{pump}} \) is measured directly; low uncertainty (~5%)
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**Main terms in ECH discharges**

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- Considered more accurate due to well calibrated quantities
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Dynamic Particle Balance Shows No Retention in H-mode

- High retention in ramp-up phase
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- High retention in ramp-up phase
- H-mode removes fuel

\[ Q_{PUMP} > \Gamma_{NBI} \]
\[ \Gamma_{WALL} < 0 \]
\[ \int \Gamma_{WALL} \text{ Decreasing} \]
High retention in ramp-up phase

H-mode removes fuel

\[ Q_{PUMP} > \Gamma_{NBI} \]

\[ \Gamma_{WALL} < 0 \]

\[ \int \Gamma_{WALL} \text{ Decreasing} \]
Validation of Dynamic Exhaust with Integrated Gas Balance

\[ \Gamma_{\text{wall}}(t) = \Gamma_{\text{gas}}(t) - Q_{\text{pump}}(t) \]

- Calibration of Exhaust
- After several shots:
  - Cryopumps regenerated
  - Pressure rise measured
  - Compared with Integral of exhaust

- Agreement ~5%

Set #1

Exhausted Particles [Torr-L]

- 4th shot
- 3rd shot
- 2nd shot
- 1st shot
- Pump Regeneration

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Validation of Dynamic Exhaust with Integrated Gas Balance

- ECH balance equation:

\[ \Gamma_{\text{wall}}(t) = \Gamma_{\text{gas}}(t) - Q_{\text{pump}}(t) \]

- Calculated vs measure exhaust within error of measurements
Details of Wall Inventory Sensitive to Small Changes in Rates

• Otherwise similar discharges have variation in wall inventory
  – Outside error bars

• Slight variation in exhaust rate
  – Small shape changes
  – Differences in ELMs
### Conclusions: Fuel Retention Rate is Phase Dependent and Large Fraction is Recovered by Baking

<table>
<thead>
<tr>
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<th>Particle Retention/Release</th>
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<td>Retention High ~ 85% un-pumped</td>
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Vacuum Bake Before and After Single Run-day Returned Large Fraction of Retained Particles

- **Particle balance summary**
  - Total injected: 2400 [torr-L]
  - Exhausted: 1010-1140 [torr-L]
  - Bake released: 1090 [torr-L]

- **Post-bake retention/total injected**
  - 170-300 [torr-L]/2400 ~7-12%

  *Bake was “short” due to Operational Constraints*
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- 170-300 [torr-L]/2400 ~**7-12%**

Remaining 7-12% is upper Bound on co-deposits
Conclusions: Fuel Retention Rate is Phase Dependent and Large Fraction is Recovered by Baking

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Two Thermo-Oxidations were Completed

- **Bake 1: Demonstrate Thermo-Oxidation on DIII-D**
  - 10 Torr Heliox (20% O$_2$/80% He), 350°C, 2 hours – UTIAS results
  - Demonstrate $^{13}$C removal on a few tiles with known $^{13}$C
  - High performance hybrid operations were recovered quickly
Oxidation Causes Hydrocarbon Release as Expected; Points to Successful Experiment

- CO, CO₂, D₂O form during O₂ bake from UTIAS lab results
- Novel new IR absorption measurement complements RGA

K. Umstadter UCSD
Fuel Removal on DIII-D Similar to UTIAS Lab Data

![Graph showing fuel removal on DIII-D](image-url)
Fuel Removal on DIII-D Similar to UTIAS Lab Data

DIII-D Divertor Tile Bake
UTIAS LAB 1.6 Torr O₂ 350°C
DIII-D 2 Torr O₂ Decreasing 350°C
Fuel Removal on DIII-D Similar to UTIAS Lab Data
High Performance Plasmas Recovered Quickly After DIII-D Oxygen Bake
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High Performance PlasmasRecovered Quickly After DIII-D Oxygen Bake

[Graphs showing time evolution of $\beta_N$, $H_{98y2}$, $O^{VIII}(CX)$, $C^{III}$, and $Prad/Pin$ with time in seconds.]
Two Thermo-Oxidations were Completed

- **Bake 1:** Demonstrate $O_2$ on DIII-D tokamak and recover high performance operation
  - Demonstrate $^{13}\text{C}$ removal on a few tiles with known $^{13}\text{C}$
  - High performance hybrid operations recovered quickly
  - All tokamak systems tested after bake

- **Bake 2:** Demonstrate removal of freshly deposited $^{13}\text{C}$ from several tiles
  - Repeat past $^{13}\text{C}$ deposition experiment with in-situ reference point (DiMES sample)
  - Tiles removed for NRA analysis at Sandia National Labs
**13C Deposition at Lower Inner Divertor When Injected at Top**

\[ ^{13}\text{C} (^{3}\text{He}, p) ^{15}\text{N} \] nuclear reaction analysis

W.R. Wampler, Sandia National Laboratories

- LSN Plasma, Inject \(^{13}\text{C}\) at top
- Remove tiles during vent
- Concentrated at inner divertor
$^{13}$C Deposition is Localized in Secondary Divertor
Conclusions: Fuel Retention Rate is Phase Dependent and Large Fraction is Recovered by Baking

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Summary of Results

• D retention occurs during startup

• Strongly pumped diverted H-mode, D species continuously removed
  – No evidence for retention
  – Continuously removed in DIII-D 5 s shots
  – Startup smaller fraction of discharge length in longer pulse machines

• DIII-D upper bound on co-dep retention 7%
  – Longer bake future experiment

• Fuel removal by thermo-oxidation
  – C, D removal rates similar to Toronto Lab results
  – No damage to DIII-D, Advanced Inductive plasma operation recovered quickly
Summary of Results

• **Dynamic (Time Dependent) particle balance shows ~0 wall retention in H-mode**
  – Well conditioned graphite with cryopumping
  – Dynamic agrees with shot-integrated “static” balance

• **Large wall retention in either startup or L-mode**
  – About 20%, dominates the discharge
  – Underscores need for dynamic measurements: shot-integrated can over estimate retention

• **Oxygen bake: 350°C, 1.3 kPa, 2 hours**
  – C, D Removal rates similar to Toronto Lab results
  – No damage to DIII-D, Advanced Inductive plasma operation recovered quickly