Recent Results on Carbon Erosion, Migration and Re-deposition in DIII-D Tokamak using DiMES

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Summary

Part I: Temperature dependence of carbon erosion and re-deposition

- At 200º C we observed net carbon erosion at a rate of ~ 3 nm/sec from a plasma-facing surface under detached conditions, where normally net deposition is observed.
- At 200º C carbon deposition down a simulated tile gap was reduced by about a factor of 2 - 4 and D co-deposition by an order of magnitude compared to those at room temperature.
- Carbon deposition was observed on molybdenum mirrors recessed below the divertor floor at room temperature and was suppressed at elevated temperature between 90-175ºC.

Part II: Migration of artificially introduced carbon dust in the divertor

- Micron size carbon dust introduced in the lower divertor of DIII-D penetrated core plasma raising the core carbon density by a factor of 2-3.
- The amount of C that penetrated the core plasma following the dust injection was equal to 1.5-2 % of the total dust carbon content (equivalent to a few million of dust particles).
- Experimentally observed dust trajectories can be explained by combination of ion drag force, E×B drifts, and reflections from PFC surface corrugations.
DiMES system is used to insert material samples in the lower divertor of DIII-D for erosion and deposition studies.

A newly developed *in situ* sample heating capability allows us to study the temperature dependence of erosion/deposition.
Temperature dependence of carbon erosion and re-deposition in DIII-D divertor

Motivation:

- Chemical erosion rate of carbon and hydrocarbon films by hydrogen/deuterium is known to increase with surface temperature.
- Experiments with thermal ion beams have shown that the chemical erosion rate of carbon peaks at about 400°C.
- Transition from net erosion to net deposition was observed in low-temperature methane plasmas between 200-300°C.

Graph:

- Erosion by atomic H and D (0.2 eV)

References:


Motivation

- Tritium co-deposition/retention is one of the most critical issues for ITER
- High-priority ITPA topic
- One of the most troublesome carbon deposition regions for trapping tritium are the narrow tile gaps since such regions are not accessible to many of the proposed T-recovery methods
- In DIII-D co-deposition of deuterium (as a proxy for tritium) can be studied in a simulated tile gap using DiMES
- Altering the tile temperature may affect C deposition and D co-deposition rates
Tile Gap DiMES experimental concept and design

Concept features:

- radially oriented gap
- deposition on the silicon wafers
- defined geometry for modeling of the deposition profile

Built in heater and thermocouple for *in situ* temperature control
Two exposures at different temperatures were performed.

- Lower Single Null Simple-As-Possible Plasma (SAPP) shape
- DiMES located near the detached Outer Strike Point (OSP)
- Two exposures were performed, first at ~ 30º C, second at 200º C
- Each exposure was to 9 highly reproducible high-density L mode discharges for a total exposure time of about 32 seconds
Non-heated versus heated exposures: plasma-facing surface

- There were visible signs of plasma contact on the sample face upon removal, most likely deposits
- No net erosion/deposition measurements were available

- No visible signs of plasma contact on the sample face upon removal
- A graphite button with implanted Si marker was built into the sample face to measure net erosion/deposition on the plasma-facing surface
A high erosion rate was measured on the heated sample

- Ion Beam Analysis (IBA) at SNL Albuquerque has shown a total net erosion of about $90 \pm 4$ nm on the depth marked button from heated exposure.

- This corresponds to a net erosion rate of $\sim 3$ nm/sec = $1.2 \mu$m / ITER shot = 9 cm / burn year – rather high!

- We did not have erosion/deposition measurements on the non-heated sample, but it looked like there was some net deposition.

IBA data courtesy of Bill Wampler

Potentially bad news for ITER: surface erosion of C is strongly increased at elevated temperature.
No net erosion observed with detachment at room temperature

- A depth-marked DiMES sample exposed later to 7 comparable high-density SAPP L-mode discharges (but with OSP sweeps) showed no measurable erosion.

Previous DiMES experiments in detached H-mode showed net deposition around OSP and in the PF zone.

Erosion on heated sample must be due to the elevated temperature.

- Total time at OSP: Non-heated ~ 4 sec, Heated ~ 32 sec.

- Whyte et al., Nucl. Fusion 41 (2001) 1243
Carbon deposition inside the gap was a factor of 2 - 4 lower in the heated exposure.

- C deposition inside the gap was ~ 2 - 4 times lower in the heated exposure.
- The deposit thickness profiles from ellipsometry are in good agreement with the carbon areal density from IBA.
- Ellipsometry failed to resolve the deposit thickness in the heated exposure.
- Some C may have been absorbed into the wafers to form silicon carbide.
D co-deposition inside the gap was an order of magnitude lower in the heated exposure

- Potentially good news for ITER: by controlling the PFC temperature it may be possible to control WHERE the T co-deposition would occur

- However, increased carbon impurity production at high temperature may offset the advantage of higher re-erosion rates in the gaps
Motivation

- Optical mirrors are foreseen in ITER for many diagnostics, and will be used in infrared, visible and ultraviolet wavelength ranges
- High-priority ITPA topic
- Mirrors in the ITER divertor will likely suffer from deposition, and dedicated experiments in tokamak divertors are urgently needed
- Using DiMES, we had a chance to perform first ever tests of ITER-relevant mirrors in a tokamak divertor under well-diagnosed plasma conditions
Mirror DiMES experimental concept and design

- Molybdenum Mirrors
- Protective flap
- Thermocouple
- Heater
- Stainless steel holder

DIIF-D National Fusion Facility San Diego
Mirror DiMES exposure geometry

- Lower Single Null SAPP-like shape
- DiMES located at the Private Flux Region
- Highly reproducible ELMing H-mode discharges with detached outer strike point
Three exposures at different temperatures

- 1st set of mirrors was exposed at ambient temperature for a total of ~25 s
- Visible deposits were found on both mirrors and holder upon removal
- 2nd mirror set was exposed for a total of ~70 sec at elevated temperature changing from 140º C to 90º C (planned exposure at 400º C but heater failed)
- Upon removal, practically no deposits were visible on the mirrors
- Recently 3rd mirror set was exposed at ~150 º C for a total of ~36 sec.
- No visible deposits were found on the mirrors

Note: in 1st and 2nd exposures the thermocouple measured the bulk temperature of the holder. In the 3rd exposure thermocouple measured temperature at the back of a mirror.
Deposition is suppressed at elevated temperature

Set #1 non-heated

Set #2 heated

Secondary Ion Mass Spectrometry (SIMS) measurements locations
SIMS shows significant C deposition on the cold mirror and virtually no deposits on the heated mirror.

Potentially very good news for ITER: it may be possible to mitigate carbon deposition by moderate heating of diagnostic mirrors.

Deposition rate of ~4 nm/sec at room temperature

Negligible deposition at elevated temperature
Elevated temperature mitigates the reflectivity drop

- Elevated temperature mitigates the reflectivity drop
- The reflectivity of the heated mirrors was essentially preserved in the wavelength range above 500 nm
- Between 250-500 nm the reflectivity of the heated mirror was slightly degraded due to a thin (<15 nm) oxide film formed on the mirrors, presumably from long term storage in air

Measurements made on downstream mirrors are shown

Note that heated exposure was almost 3 times longer
Part I Summary

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  ~ 3 nm/sec from a plasma-facing surface under detached 
  conditions, where normally net deposition is observed

- At 200º C carbon deposition down a simulated tile gap was 
  reduced by about a factor of 2 - 4 and D co-deposition by an 
  order of magnitude compared to those at room temperature

- Carbon deposition was observed on molybdenum mirrors 
  recessed below the divertor floor at room temperature and 
  was suppressed at elevated temperature between 90 - 175º C
Motivation

- Micron size dust is commonly found in tokamaks
- Dust can be a serious problem for ITER for a number of reasons:
  - Tritium retention and co-deposition with Carbon dust
  - Accumulation of toxic and radioactive materials
  - Be dust in the divertor may cause hydrogen explosion hazard
  - Dust can cause core contamination and degrade performance
- In DIII-D dust is commonly found during vents in ports, between tiles etc.

Possible sources include:

- Flakes from deposited a-C:D films
- Blistering
- Leading edges
- Monopolar arcs
- Thermal Stress Induced Fracture
- Particles left over from entry vent
- Degradation of grafoil under tiles
- Volume condensation

Due to acceleration by plasma flows (ion drag) and reflections from PFC surfaces, micron size dust particles can acquire velocities of 10-100 m/s.

Transport of dust particles can be an important mechanism of core plasma contamination by impurities.

Estimates from Thomson scattering (TS) data show that in DIII-D under normal operation dust is not a significant contributor to core contamination [W.P. West et al., presented at PSI-17 (2006), submitted to J. Nucl. Matter.]

Naturally occurring dusts in DIII-D are hard to diagnose – typically 1-2 or less events per shot both from TS and TV cameras.

Size is not resolved by TS for particles larger than 0.25 microns in diameter.

We decided to artificially introduce pre-characterized micron-size carbon dust in DIII-D divertor to see whether any of the dust would make it into the core plasma.
Dust DiMES experiments

• Three individual experiments were performed
• About 1 mg of dust was used in the first experiment, not enough to cause any effect
• 25-30 mg of dust was used in second and third experiments
• A suspension of dust in alcohol was prepared and applied to a shallow dip in the holder
• Upon drying the dust formed a rather uniform layer clinging to the holder

• Carbon dust supplied by Toyo Tanso Company, Ltd., Japan
• 0.5–10 µm diameter flakes, ~6 µm median diameter from volume count
• ~10^{13} C atoms per median size dust particle
Diagnostic setup for the dust DiMES experiments

- DiMES TV and one of tangential TVs equipped with Kodak Wratten 89B IR filters with less than 1% transmission below 680 nm
- The second tangential TV equipped with CIII filter
Dust DiMES experiment No.2

Shot 122428

- High-power ELMy H-mode discharge with OSP swept inward and back
- Significant increase in C radiation during the first pass of OSP over DiMES!
- Cameras observed dust tracks
CER data show strong increase of core carbon content after OSP passes over DiMES around 2 sec.

Rough estimate of the amount of C that got into the core:

\[5 \times 10^{19} \text{m}^{-3} \times 0.02 \times 20 \text{m}^3 = 2 \times 10^{19} \text{atoms} = 4 \times 10^{-4} \text{g} \sim 10^6 \text{dust particles}\]

About 1.5% of the dust carbon made it into the core!
Dust velocities are 10 – 100 m/s

• From DiMES TV we can only make a low-bound estimate since most tracks go off screen

  Track length: $l_{\text{track}} \sim 20 – 40$ cm
  Exposure time: $t_{\text{exp}} = 16.7$ ms

\[ v \sim \frac{l_{\text{track}}}{t_{\text{exp}}} \sim 10 – 20 \text{ m/s} \]

• Tangential camera view is inclined, but we can still make an estimate

  Track length: $l_{\text{track}} \sim 10$ cm
  Exposure time: $t_{\text{exp}} = 1$ ms

\[ v \sim \frac{l_{\text{track}}}{t_{\text{exp}}} \sim 100 \text{ m/s} \]
Dust trajectories are consistent with ion drag force

- Toroidal direction is what one would expect – same as that of the plasma flow into the divertor
- Dust particles are accelerated by the plasma flow (ion drag)
- Apparent high field side inclination of trajectories may be either a projection effect or a drift effect
- Another mechanism that may accelerate the dust particles is the “rocket force” from asymmetric ablation due to the plasma heat flux coming preferentially from upstream side

Note: according to DustT modeling rocket force does not play a big role

- Both the flow and the rocket force should push dust particles towards the plate
- Particles can bounce from surface corrugations and fly towards the core

Comparison to modeling: Dust Transport *DustT* code

- *DustT* code solves equations of motion for dust particle in 3D self-consistently with ablation model given by equations for dust temperature and radius

- The code uses magnetic equilibrium mesh and plasma background from UEDGE code

- Based on UEDGE data, the forces acting on dust particle from plasma are calculated

- *DustT* employs Monte Carlo method for incorporating the dust collisions with walls and micro-turbulence

- *DustT* is capable of reproducing important features of tokamak experiments:
  - Dust particles preferentially move in the direction of plasma flow
  - Dust trajectories are “elongated” in toroidal direction
  - The “cruise” velocity of dust in plasma is 10-100 m/s

Micron size carbon dust introduced in the lower divertor of DIII-D penetrated core plasma raising the core carbon density by a factor of 2-3.

The amount of C that penetrated the core plasma following the dust injection was equal to 1.5-2 % of the total dust carbon content (equivalent to a few million of dust particles).

Experimentally observed dust trajectories can be explained by combination of ion drag force, $E \times B$ drifts, and reflections from PFC surface corrugations.

3D modeling of dust dynamics using $DustT$ code is capable of reproducing experimentally observed dust velocities and trajectory shapes.