Hydrogenic Fuel Recovery & Retention with Metallic Plasma-Facing Walls
In the Alcator C-Mod Tokamak

D.G. Whyte, 1, 2)∗, B. Lipschultz 2), J. Irby 2), R. Granetz 2), B. LaBombard 2), J. Terry 2) G.M. Wright 1)
1) University of Wisconsin-Madison, Madison, WI 53711, USA
2) MIT Plasma Science and Fusion Center, Cambridge, MA 02139 USA (* present address: e-mail contact of main author: whyte@gsc.mit.edu

1. Introduction

Controlling the hydrogenic fuel inventory in plasma facing materials will be necessary for successful operation of future burning plasmas that use tritium (T) as a fuel. In ITER, the on-set of a T burning plasma is of paramount importance, while ~100 g is fueled into the vessel for a full power discharge [1], indicating the requirement for low retention for carbon and boron deuterium-plasma deposited C-films to store large amounts of T (T0 ≈ 10-15 g). Tungsten is also proposed for use as PFCs in ITER and reactors due to its expected lower T retention necessary for the successful operation of burning plasmas that use tritium as a fuel. In ITER, the on-site limit of tritium is 350 g for safety reasons, experience with regards to hydrogenic fuel retention in high-Z material is limited.

Alcator C-Mod has only high-Z molybdenum as the PFC material with significant areas of Mo PFCs applied (boronization). A study documented the negative response of plasma performance to the removal of the B film from Mo PFCs [2]. The method of removal of boron from the molybdenum tiles provided a valuable opportunity to study H/D retention in purely high-Z materials (Section 3).

An in-situ tritium recovery method has been proposed for ITER that uses plasma disruptions as a termination of the plasma (referred to as ‘post-boronization’). The resulting rapid radiative heating of plasma-viewing surfaces causes the DT to be released as molecules to be recovered by the vacuum pumps, while the underlying substrate material is undamaged. We describe successful recovery of retained H/D from the C-Mod wall using planned disruptions demonstrating global control of the fuel inventory in the wall (Section 4).

2. Experiments

Particle balance: All valves to vacuum pumps are closed for the duration of the shot. Gas is injected in known quantities through calibrated valves (cross-checked by injection into an empty vessels). The pumps were turned off and then re-started for 5-10 minutes after the discharge in order to measure the equilibrium vessel pressure and hence recovered fuel particle inventory, which is then evaporation by opening the pump valves.

The particle balance inventory is very accurate (+/− 3×1016 D) due to several key sources of C-Mod.
- No other external fuel sources (e.g. neutral beams)
- No open particle sinks (e.g. cryopumps)
- No intra-dish cleaning

Therefore, any deficiency in recovered Deuterium as compared to the injected Deuterium must reside in the PFC surfaces. One possible explanation could be that the excess of D recovered is a result of net out-gassing or depletion of the wall.

Discharges: Diverted and fueled with D2 gas injection only.
- In-vessel gas composition: quadrupole mass spectrometer
- Auxiliary heating: H/million ICRF
- Typical plasma parameters:
  - Major radius: 1.68 m ± 0.02 m
  - Plasma current: Ip = 0.8 - 1 MA
  - Toroidal field: Bt = 5.3 T
- Shot duration: 1-2 s

Boron films: C-Mod has intermittently applied boronization films since ca. 1998. For most of these present experiments, the boron films were removed from all inter-vessel areas using wires or ultrasonic cleaning [2]. Surface analysis of the cleaned tiles showed ~90-90% Mo surface with the remainder being made up of boron. This is in stark contrast to the situation before cleaning, where the surface Mo coverage was < 1%, and the B film thickness 6-10 microns thick over most of the Mo surface. The post-boronization element facing the plasma, except at the outer divertor with surface B:Mo ~ 1:1.

3. Deuterium Fuel Retention

Experiments were carried out to compare the D retention of cleaned Mo walls (‘pre-boronization’) to the retention after the application of boronization (‘post-boronization’). The D retained per shot shows several interesting features (Fig. 1).

1. The retention is relatively large compared to the typical C-Mod fueling level ~ 2×1015 D/shot, indicating a high global retention rate.

2. Most surprising, there is no significant difference in the D retention between the ‘pre-boronization’ and ‘post-boronization’ Mo wall films. This indicates that the Z boron films are not directly causing the D retention, despite the ability of boron films to cause codeposition of H-atoms (up to 20%) [5]. Boronization films therefore must be the cause of the D retention, which is important at all locations.

3. D retention is ~ 25-50% of D+ per shot and constant with repeated shots.

4. The retention is dependent on plasma line-averaged density, exhibiting a rather sharp threshold at n~1020 m−3 towards higher retention rates. This suggests a link between retention and ion/recycling flux to the wall which increases monotonically with linear retention rate ~0.5% D per ICRF heating.

5. Conclusions

- Global fuel retention rates are high in C-Mod, ~30% of fuelled deuterium even with quite high preliminary molybdenum walls.
- Codeposition in boron is not the cause of the retention.
- Most surprising is the finding that the C-Mod experiments can find no sign of saturation in the D uptake into the Mo walls.


- Technique: Exploit rapid surface heating during disruption to desorb trapped H/D as molecules from wall. A remove from vessel by standard pumps.
- ITER: Radial terminations lead to disruption of entire vessel surface area to de-Tritate wall [3].
- C-Mod: Rather sharp threshold at n~1020 m−3 towards higher retention rates. This implies deep diffusion, trapping & retention; implications for recovery?

5. Conclusions

- Global fuel retention rates are high in C-Mod, ~30% of fuelled deuterium even with quite high preliminary molybdenum walls.
- Codeposition in boron is not the cause of the retention.
- Most surprising is the finding that the C-Mod experiments can find no sign of saturation in the D uptake into the Mo walls.
- Disruption H recovery more efficient than other recovery techniques

References

[1] ITER Physics Basis

Acknowledgments

This work is supported by the United States Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award DE-AC02-09CH11437 and the National Science Foundation under Grant DMS-1007111.

Fig. 1 Deuterium fuel retention on Mo walls: (a) Total D+ flux to wall is kept constant (Fig. 4); (b) D+ flux to wall = ~50 times larger than D2 fueling due to recycling; (c) Wall retention evolves over few shots but becomes constant at high retention rates.

Fig. 2 Plasma density at shot t=2 s, cleaned Mo walls. (a) Total D ion flux to the wall is kept constant (Fig. 4); (b) D+ ion flux to wall = ~50 times larger than D2 gas fueling due to recycling; (c) Wall retention evolves over few shots but becomes constant at high retention rates.

Fig. 3 Deuterium fuel retention with varying divertor magnetic geometries. LSN/USN: lower/upper single-null.

Fig. 4 Cumulative D retention per shot (1023 D/shot) with varying divertor magnetic geometries. LSN/USN: lower/upper single-null.

Fig. 5 Cumulative D retention in cleaned walls versus Td. Plasma conditions are as in Figs. 2 and 4.

Fig. 6 Dependence of H retention on target plasma temperature. H recovery has strong threshold with max. surface temp. ~ 1/3 of starting D retention is recovered at higher rate than fueling.