IAEA FEC 2012 — October 8-13, 2012, San Diego, California, USA

Comparative Study of Chemical Methods for Fuel Removal

A. Kreter[1], S. Möller[1], C. Schulz[1], D. Douai[2], H.G. Esser[1], A. Lyssoivan[3], V. Philipps[1], U. Samm[1], G. Sergienko[1], T. Wauters[3] and TEXTOR Team

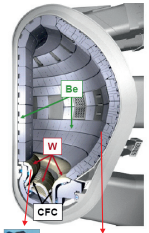
[1]*Institute for Energy and Climate Research - Plasma Physics, Forschungszentrum Jülich, Association EURATOM-FZJ, TEC, Germany*
[2]*CEA, IRFM, Association Euratom-CEA, 13108 St Paul lez Durance, France*
[3]*LPP-ERM/KMS, Association Euratom-Belgian State, 1000 Brussels, Belgium*

e-mail: A.Kreter@fz-juelich.de

FTP/P1-05

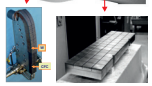
Introduction

Fuel retention in ITER

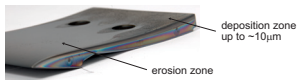


- Wall materials, i.e. carbon, are eroded and transported by plasma
- Materials accumulate in remote areas
- Co-deposition of tritium, i.e. in a-C:T layers
- Gaps are additional remote areas, distributed allover the vessel
- Total area of gaps in ITER ~1000 m²

→ **Fuel removal techniques need to be developed and optimized, i.e. for gap cleaning**



Limiter tile from TEXTOR after one campaign



Techniques for fuel removal and vessel wall conditioning

Application of heat loads
→ Desorb tritium from the surface or to ablate re-deposited layers
- Disruption cleaning
- Photonic cleaning by flash lamps and lasers

Physical desorption
→ Ion-induced desorption
- Conditioning plasma discharge

Exchange of hydrogen isotopes
→ Bring non-radioactive hydrogen isotopes in contact with the tritium containing surface in the form of:
- Gas
- Conditioning plasma discharge

Chemical etching
→ Based on the chemical reactivity of the removal gases towards the hydrogen isotopes and the wall materials as carbon
Activation energy is provided by:
- Active wall heating
  - Thermo-Chemical Removal (TCR), also known as baking in reactive gases
- Energetic incident particles
  - Conditioning plasma discharge: GDC, ICWC, ECWC

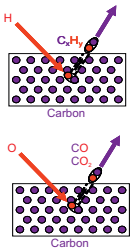
Studies in Forschungszentrum Jülich have been concentrated in recent years on chemical methods including
- Thermo-Chemical Removal (TCR)
- Glow-Discharge Conditioning (GDC)
- Ion-Cyclotron Wall Conditioning (ICWC)

Chemical erosion of carbon by hydrogen and oxygen

Chemical erosion of carbon:
formation of volatile compounds with impinging species

$H + C \rightarrow C_xH_y$

$O + C \rightarrow CO, CO_2$



Co-deposited D/T is released as hydrogen molecule, hydrocarbon or water

Removal rates are functions of
- Surface temperature: According to activation energy of the process
- Impact energy: Enhancement by bombardment with energetic particles (e.g. ions)
  - → Deeper penetration
  - → Creation of active sites for other species (synergistic effect)

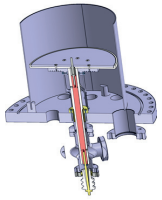
Aim of the study

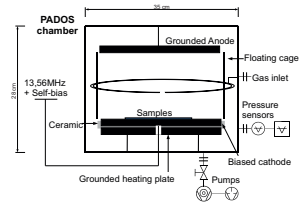
- Optimize the removal efficiency of each method
- Characterize application restrictions of methods
- Find alternatives to oxygen as removal gas
- Optimize removal from remote areas including gaps
- Propose an integral scheme of fuel removal in carbon containing environment

Experimental

Laboratory device PADOS

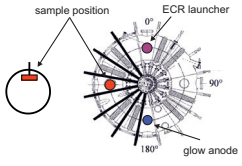
- Used for coating of samples by amorphous deuterated layers a-C:D and for TCR
- Capacitive RF discharge between two circular electrodes, ∅ 25 cm, distance 7 cm
- Option of biasing for lower electrode
- Lower plate is heatable, e.g. for TCR
- a-C:D layers are produced by Plasma Enhanced Chemical Vapour Deposition (PECVD) in methane

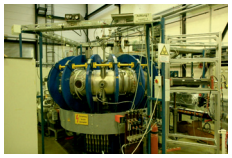




TOMAS toroidal plasma device

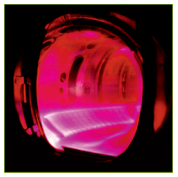
- Toroidal vacuum chamber with R = 0.78 m, a = 0.26 m, B_t ~ 0.1 T
- RF-assisted DC glow discharge between cylindrical anode and grounded wall as cathode: p ~ 10^{-2} mbar, U_{DC} = 300 V, I_{DC} ~ 1 A, Γ_i ~ 10^{14} cm^{-2}s^{-1}, B_t off
- ECR discharge at 2.45 GHz, P = 1.5 kW, p ~ 10^{-4} mbar, Γ_i ~ 10^{15}-10^{16} cm^{-2}s^{-1}
- Installation of samples at upper vessel wall

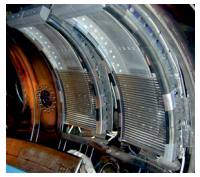




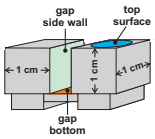
Tokamak TEXTOR equipped with ICRF antennae

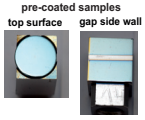
- R = 175 cm, a = 46 cm
- Circular plasma cross-section
- All limiters made of carbon
- Test limiter locks to expose samples
- Frequency 25 - 38 MHz
- Typical ICWC power 2 x 50 kW
- Operational at B_t = 0.2-2.5 T





Examples of a-C:D coated samples

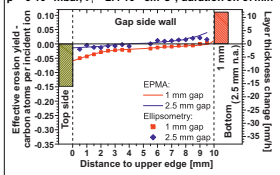




Removal from castellated structures

GDC in hydrogen

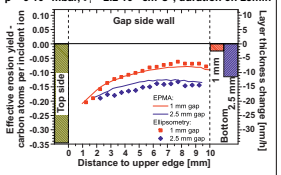
H_2 GDC 470 K



- Erosion of top surface
- Erosion in upper part of gap, deposition in deeper parts

→ Net source of C from the plasma (vessel walls)

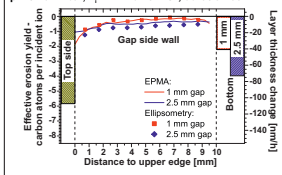
H_2 GDC 620 K



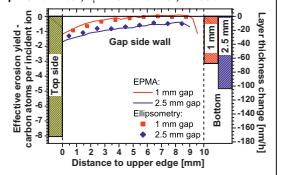
- Erosion of all surfaces
- Higher erosion in wider gap

GDC in oxygen

O_2 GDC 470 K



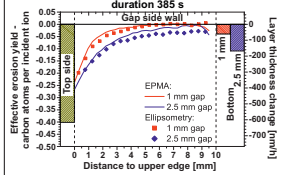
O_2 GDC 620 K



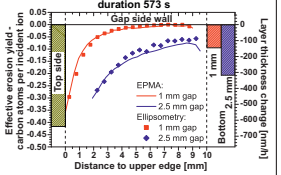
- Higher erosion than in hydrogen, especially top side and gap bottom
- Removal at 620 K slightly more efficient that 470 K

ECR in oxygen

O_2 ECR poloidal 470 K



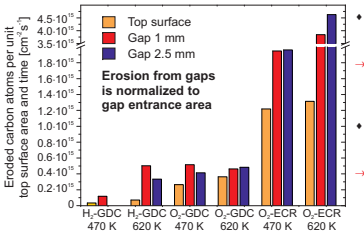
O_2 ECR poloidal 620 K



- Lower yields, but higher removal rate than GDC in O_2 (100x higher ion flux!)
- Removal at 620 K slightly more efficient that 470 K
- No significant difference between poloidal and toroidal gaps
- Significant erosion in deep regions of gap despite B field

→ Influence of neutrals deep in gap is crucial for ECR

Figure of merit for cleaning efficiency of GDC and ECR in gaps



- Higher normalized removal rates for gaps than for top surface

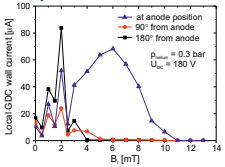
→ Reactive species are used more efficiently in gaps (multiple collisions with walls)

- Normalized removal rates are similar for 1 and 2.5 mm gaps

→ Integral removal efficiency is proportional to gap width

Influence of magnetic field

Toroidal symmetry of GDC in presence of low B field

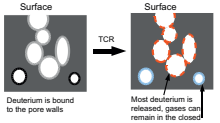


- TCR and ICWC are compatible with high magnetic field, GDC is not
- GDC can be operated at B field of up to ~3 mT
- GDC is compatible with residual fields from ferritic inserts planned for ITER to reduce B field ripple

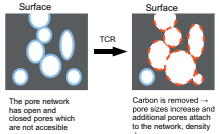
Thermo-chemical removal (TCR)

- Compatible with gap geometry
- TCR at 350°C in oxygen is at least one order of magnitude more efficient than in ammonia
- TCR in ammonia caused delamination of layer
  - → Potential source of dust
  - → Can by utilized for first mirror cleaning in ITER
- TCR in oxygen requires elevated wall temperature of >300°C, Arrhenius-type temperature dependence
- Removal is homogeneous in the entire layer due to its porosity
  - → **Removal rate is proportional to inventory**

TCR: mechanism of deuterium removal



TCR: mechanism of carbon removal



Summary

Removal rates are given for oxygen at wall temperature of 350°C

Removal method	Compatibility with B field	Minimum required wall temperature	Homogeneity of removal	D removal rate [at./m²h]	C removal rate [nm/h]
TCR (baking)	Yes	300°C	High, also for remote areas	$3 \cdot 10^{21}$ (for 200 nm)	50 (for 200 nm)
GDC	OK for <3 mT	Room temperature	High for plasma-wetted areas, limited for remote areas	$7 \cdot 10^{21}$	170
ICWC/ECWC	Yes	Room temperature	Limited on a part of plasma-wetted area	$20 \cdot 10^{21}$	600

Projection for ITER

Typical deposition rates in a tokamak discharge:
2 – 3 nm/s at top surface and upper edge of gap and 0.5 nm/s on gap bottom
→ 1000 nm deposition at top surface and at upper edge of gap and 200 nm on gap bottom within one ITER pulse of 400 s

Measured removal rates at 350°C and 1 mm gap:

hydrogen-GDC: 35 nm/h at top surface, 20 nm/h at upper edge and 2 nm/h on gap bottom
→ 100 hours to remove the layer from gap bottom deposited within one ITER pulse

oxygen-GDC: 170 nm/h at top surface, 30 nm/h at upper edge and 70 nm/h on gap bottom
→ 30 hours to remove the layer deposited within one ITER pulse

oxygen-ECR: 600 nm/h at top surface and at upper edge and 150 nm/h on gap bottom
→ 1.5 – 2 hours to remove the layer deposited within one ITER pulse

oxygen-TCR: removal rate is proportional to layer thickness: 50 nm/h at 200 nm, uniformly
→ for layer of >3 µm removal rate is higher than ECR

Proposed combined removal scenario, applied once a week
- Start cleaning of thick layers ~10-100 µm by oxygen-TCR for ~24 hours
- Continue cleaning of remaining layer by oxygen-ICWC and / or oxygen-GDC for ~10 hours

→ Thick layer can be removed within one weekend