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JÜLICH FORSCHUNGSZENTRUM

Atomic and Molecular Spectroscopy in the Scrape-Off Layer of High Temperature Fusion Plasmas

- Results from TEXTOR and JET -

IAEA Atomic, Molecular and Plasma-Material Interaction Data for FS&T

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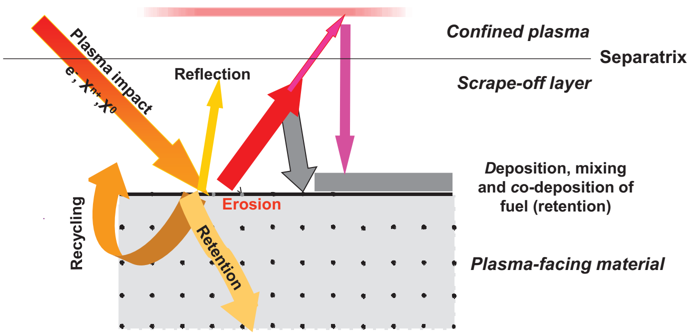
Plasma-Surface Interaction Processes

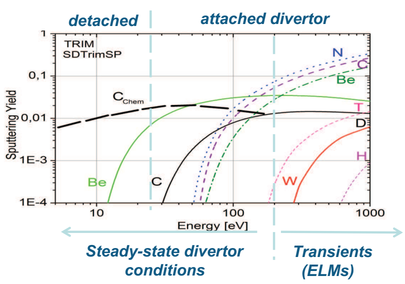


Processes depend on material mass, projectile mass, material mix and concentration, impact energy (E_{in}), impact angle (α), surface roughness and temperature (T_{surf})

Here: focus on recycling, erosion and impurity fluxes in the SOL and edge layer

Plasma-Facing Materials

Sputtering Yields



Low-Z: strong wall erosion (also at low E_{in})

High-Z: low sputtering / mainly by impurities energetic threshold for each species

… from all-C to Be/W mix ….

Particle-Flux Determination

Line emission

$$\varepsilon = \frac{1}{4\pi} n_A^* A_{ij}$$

$$n_A^* \sum_{k \le i} A_{ik} = n_A n_e < \sigma_{Exg} \upsilon_e >$$

with B as branching ratio:

$$B = A_{ik} / \sum_{k \le i} A_{ik}$$

$$I_{tot} = B \frac{h\nu}{4\pi} \int_{r}^{r_2} n_A(r) n_e(r) < \sigma_{Exg} \upsilon_e > dr$$

Particle flux <=> number of ionisation events

$$\frac{d\Gamma_A}{dr} = \frac{d(n_A \upsilon_A)}{dr} = -n_A(r) n_e(r) < \sigma_I \upsilon_e >$$

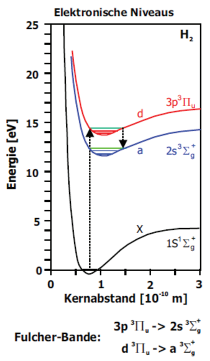
$$\Gamma_A = \int_{r_1}^{r_2} n_A(r) n_e(r) < \sigma_I \upsilon_e > dr$$

$$\Gamma_A = 4\pi \frac{I_{tot}}{B h\nu} \frac{\int_{r_1}^{r_2} n_A(r) n_e(r) < \sigma_I \upsilon_e >_{(r)} dr}{\int_{r_1}^{r_2} n_A(r) n_e(r) < \sigma_{Exg} \upsilon_e >_{(r)} dr}$$

Assumption of a fully ionising plasma & almost constant local plasma conditions in the region of emission. Otherwise corrections factor or full rate coefficients.

$$\Gamma_A = 4\pi \frac{I_{tot}}{B h\nu} \frac{< \sigma_I \upsilon_e >}{< \sigma_{Exg} \upsilon_e >} = \frac{4\pi I_{tot}}{h} \frac{S}{B X}$$

Outline



- Introduction
- Hydrogen spectroscopy
  - D_2 molecules in front of W PFCs
  - Tritium molecules in JET
- Hydrocarbon spectroscopy
  - Molecular break-up chain
  - Effective sputtering yields
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  - Chemical-assisted physical sputtering
- Tungsten spectroscopy
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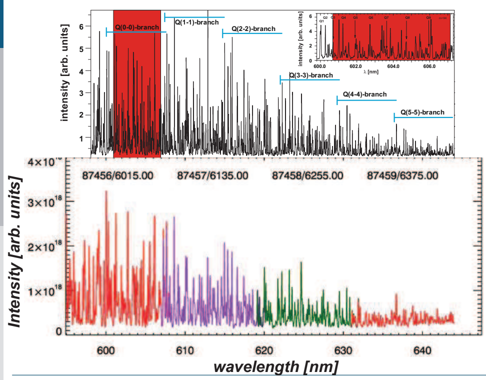
Fulcher-α Spectroscopy

- *Fulcher-α routinely used for vibrational population and plasma analysis* [see talk by U. Fantz]
- *Impact of material on D_2 population and release studied in TEXTOR (T_e~30-100eV) and labs*



TEXTOR D_2 reference spectrum (T_e~30eV)

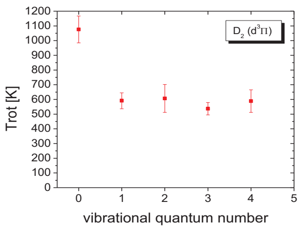
(S. Brezinsek et al. JNM PFR 2008)

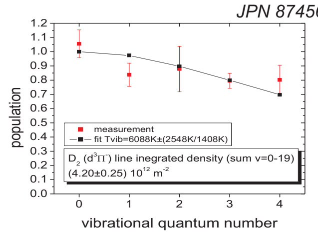
JET-ILW D_2 spectrum in outer divertor (T_e~30eV)

D_2 Recycling in JET W Divertor

- *Contribution of reflected ions (neutralised at the PFC) is larger for W than for C PFCs*
- *Increase in atom-to-molecule ratio of the recycled deuterium*
- *Strong variation of surface temperature is changing the fuel content AND release species*
- *Non-Boltzmann population in the vibrational ground state measured – different population to previous JET-C measurements. Detailed analysis started.*

JPN 87456-58





G. Sergienko et al.

JET-C T_2 in Trace Tritium Experiment

- *Detailed studies of D_2, H_2, HD rovibrational population in TEXTOR, JET-C, AUG etc.*
- *T_2 injection in the main chamber and local observation of molecular emission*
- *Injected amount of 2.5mg is recycled/pumped in JET-C. A fraction ends up in the divertor PFCs (CFC) and can be detected as TD and T_2 Fulcher-α emission*
- *Tritium surface content down to 0.1% of recycling flux measurable via DT molecules*

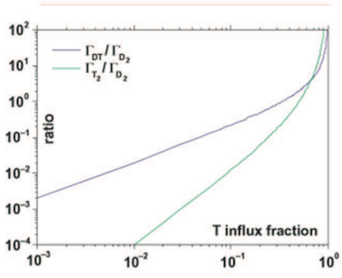


Figure 3(a): A tritium puff into a D-plasma

A. Pospieszczyk et al. J. Nucl. Mater. 2007

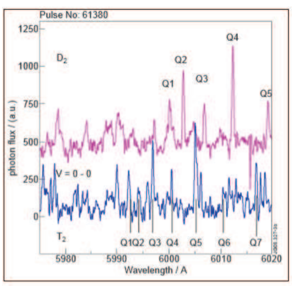
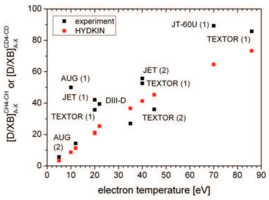


Figure 3(b): D_2 and T_2 spectra before / during the T_2 puff

Outline



S. Brezinsek et al. JNM 2007

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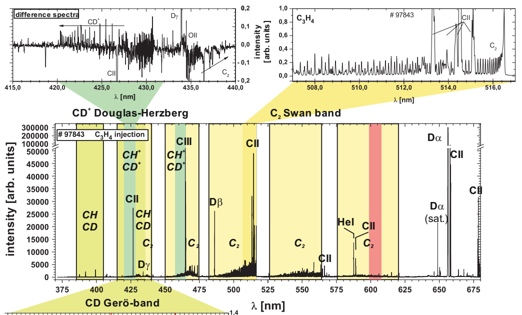
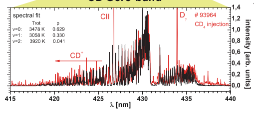
Hydrocarbon Break-up



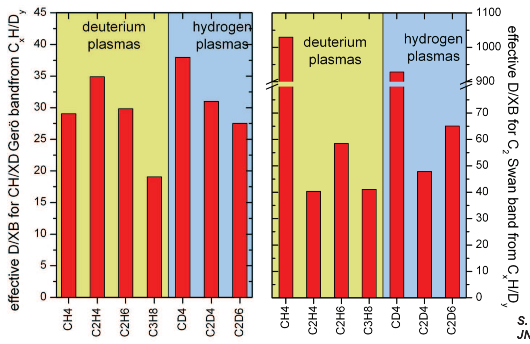


S. Brezinsek et al. JNM 2007

TEXTOR hydrocarbon injection experiments:
- CD, CD^+, C_2, D_2, $D\beta$, $D\gamma$, CI, CII, CII lines
- Comparison with HYDKIN and ADAS
- Production efficiency between 20 and 100%
- Break-up chain & excited states

Hydrocarbon Break-up Footprints: CD & C_2

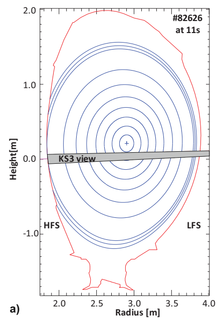
Isotope experiment – surface influences minimised



S. Brezinsek et al. JNM 2007

Simple plasmas in TEXTOR (3.0-4.0 $10^{18}m^{-3}$ and 60-65eV at the LCFS)
Injection in the SOL, gas inlet 1.5cm -2cm behind the LCFS

Outline



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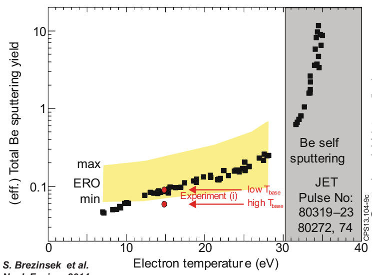
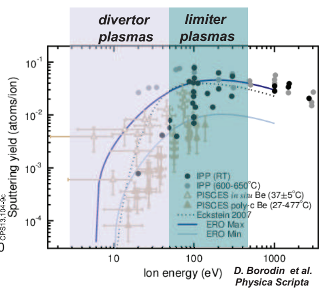
Effective Beryllium Sputtering Yields



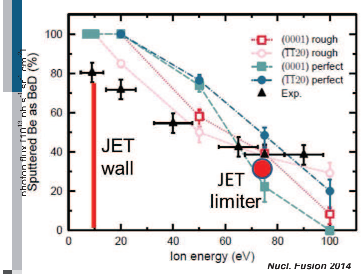
S. Brezinsek et al. Nucl. Fusion 2014



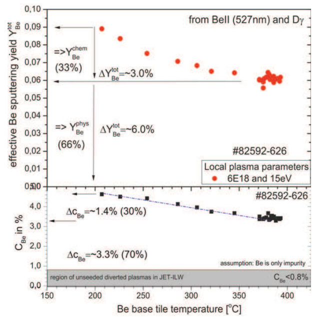
D. Borodin et al. Physica Scripta

- Determination of Be sputtering yields in limited configuration to verify data base and ERO code used for ITER Be wall life-time predictions [D. Borodin PS2014].
- Spectroscopy averages over observation spot (Tsurf, ion flux, geometry)
- Dominant self-sputtering observed at high electron temperatures / impact energies
- Energetic threshold at low impact energies

Chemical Assisted Physical Sputtering of Be via BeD_x



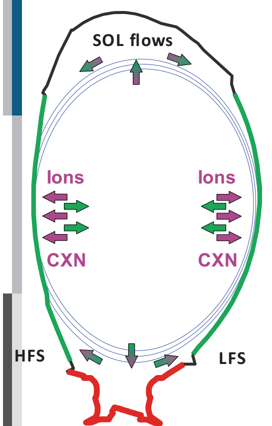
Nucl. Fusion 2014



- Physical sputtering process which releases from near surface molecules: BeD_x, x=1,2,3
- Energetic threshold at low impact energies – not like carbon chemistry!
- Confirms Molecular Dynamics predictions [C. Björkas] and PISCES results [D. Nishijima PPFC 2008]

- Chemical-assisted physical sputtering causes an increase of the net source
- Lower binding energy of Be in the D supersaturated Be surface likely

Material Migration: Main Chamber

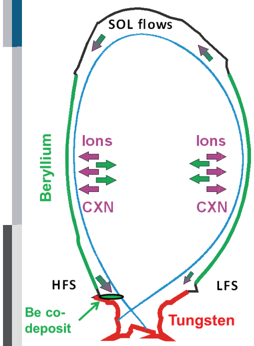


Limiter configuration
- At high E_{in}: Be sputtering yield (JET-ILW) is larger than C sputtering yield (JET-C)
- Moderate increase of total limiter source (25%) with respect to C in JET-C
- Campaign averaged erosion rate at centre tile: Spectroscopy : $4.1x10^{18}$ Be/s gross erosion Post-mortem analysis: $2.3x10^{18}$ Be/s net erosion
- Majority of eroded Be remains in the main chamber and is redistributed on limiter/wall

A: Widdowson Phys. Scr. 2013
S. Brezinsek IAEA2014, ICFRM2013
I. Bykov PSI2014

Global Material Migration in JET-ILW

Migration in the JET-ILW with Be wall and W divertor



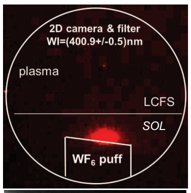
Divertor configuration
- Sputtering at recessed wall at low T_e / impact energies (E_{in}<10eV) and by CX neutrals
- At low E_{in}: Be sputtering yield (JET-ILW) is lower than total C sputtering yield (JET-C)
- Factor 4-5 smaller primary source with ILW (Be in JET-ILW vs. C in JET-C)
- Absence of low energy erosion in the ILW case (chemical erosion in case of C in JET-C!)
- Majority of eroded Be transported in SOL towards inner divertor.

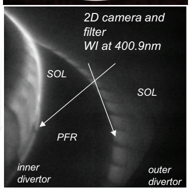
S. Krat JNM 2014
S. Brezinsek PSI2014, IAEA2014
M. Mayer et al.

Fair balance between Be eroded (21 g) in main chamber and Be deposited (28 g) in divertor after first year of ILW operation

Outline

TEXTOR W limiter





JET W divertor

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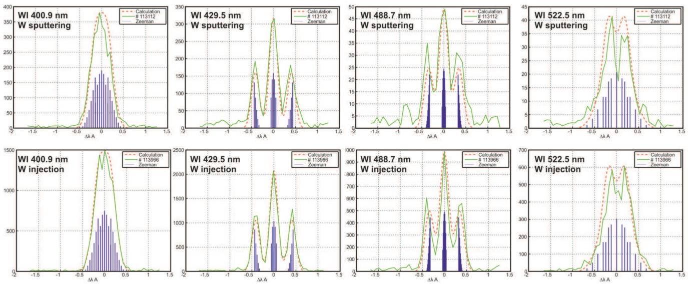
TEXTOR Experiments: W Sputtering and WF_6 Injection

- *Twin Limiter experiment with variation of impact energies of impinging impurities*
- *Determination of the W sputtering yield and the impurity composition*
- *Effective S/XB values from corresponding WF_6 injections (into comparable plasmas)*

- *WF_6 injection experiment with gas inlet and negligible limiter surface*
  - *Well-known amount of W injected / direct dissociation at about T_e~0.1eV*
  - *Prompt re-deposition minimised / no impact from local deposition of W*

TEXTOR: Comparison of W Atoms from Sputtering and Injection

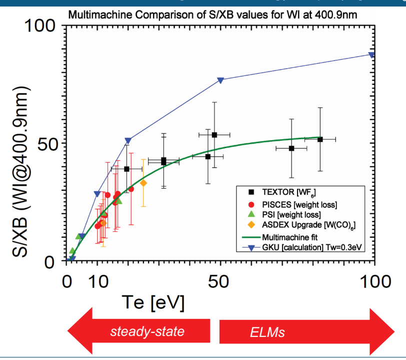
- *Is W from WF_6 dissociation representative for W from sputtering?*
  - *No difference in line shape of different WI and WII lines*
  - *Line ratios of WI lines with same lower level comparable in sputtered and injected W*
  - *WII lines measured and quantified in WF_6 injections*



S. Brezinsek Phy. Scripta 2011

Inverse Photon Efficiencies for WI

- *Multimachine fit of effective S/XB values for 400.9 nm applied for quantification of W fluxes*
- *Contrast to AUG data which uses constant 20 (but works only in the range od 5-15 eV)*
- *JET outer divertor hotter and has larger ELM energy drops (higher T_e)*

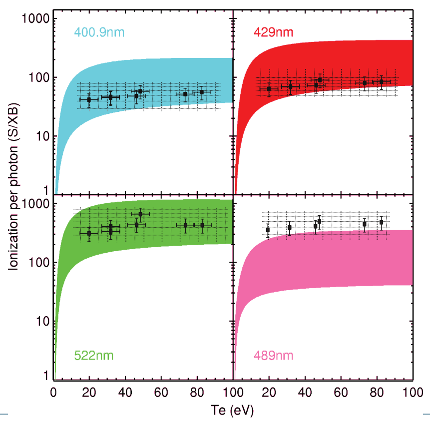


Different methods:
- ***Weight loss***
- ***Spectroscopy***
- ***WF_6 injection***
- ***$W(CO)_6$ injection***

S. Brezinsek ITPA 2012

Effectice S/XB for Different WI Lines

W I : 10^{18} m^{-3} → 10^{20} m^{-3}



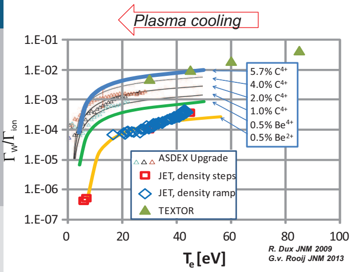
Modelling: ADAS/Mons data (O'Mullane/ Palmeri et al.)

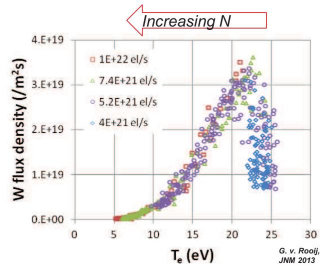
Experiment: TEXTOR data (Brezinsek/Laengner)

JET: Effective Tungsten Sputtering Yields

Plasma cooling leads to reduction of the W source down to physical sputtering threshold

Competition between higher impurity flux and local cooling in seeded discharges

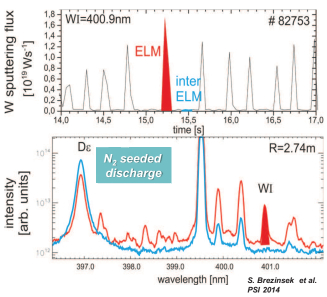


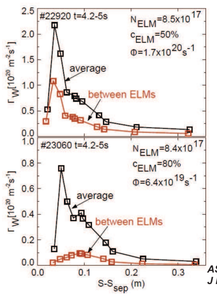


- *General W sputtering well described by Be ions / slight shift in energetic threshold*
- *Plasma cooling by N_2/Ar seeding till E_{in} drops below threshold* [AUG R.Neu JNM 2011/Giroud 2014]

JET: ELM-induced Tungsten Sputtering

- *Prediction of residual W source in ITER in H-mode plasmas*

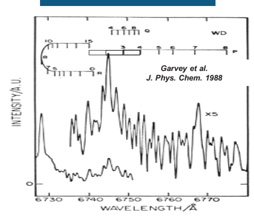


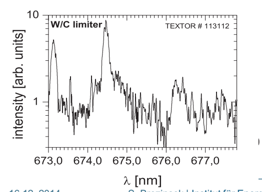


- *H-mode plasmas have energetic transients (ELMs) which hit the target at impact energies of 1keV or above*
- *Residual W in seeded plasmas determined by ELMs (Be+D+N impact)* [Guillemaut PPCF]

Chemical Assisted Physical Sputtering of W ?

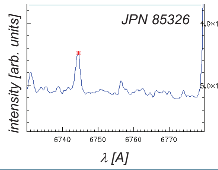
WD A-X transition





TEXTOR:
- Molecular emission solely in W sputtering experiment and not with WF_6 injection
- Molecular emission identified in high spectral resolution as WD molecules
- Surface reaction responsible for WD: Chemical assisted physical sputtering
  - fast D impacts on D saturated W surface and releases WD
  - C, O impacts on D saturated W surface and releases WD

JET:
- WD identified, but poor resolution



Summary

- ***Atomic and molecular species in the scrape-off layer of tokamaks observed***
- ***Focus on species related to ITER materials, fuelling and seeded species***

- *D_2 d-a transition: Recycling flux*
  => understood and good set of data (EIRENE)
  => impact of surface confitions / material needs to be investigated
- *BeD A-X band : Chemical-assisted physical sputtering / recombination*
  => empiric set of S/XB values
  => more work required
- *WD A-X band : Swift chemical sputtering*
  => just identified => no S/XBs
  => more work required
- *ND A-X band : Volume or surface reaction*
  => identified => S/XBs?
  => more work required
- *CN, N_2, N_2^+, CD, C_2 in minor quantities. Hydrocarbons well documented.*