Journal of Nuclear Materials 390–391 (2009) 907–910

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Influence of toroidal and vertical magnetic fields on Ion Cyclotron Wall Conditioning in tokamaks

A. Lyssoivan [a,*], G. Sergienko [b], V. Rohde [c], V. Philipps [b], G. van Wassenhove [a], M. Vervier [a], V. Bobkov [c], J. Harhausen [c], R. Koch [a], J.-M. Noterdaeme [c,d], D. van Eester [a], M. Freisinger [b], H.-U. Fahrbach [c], H. Reimer [b], A. Kreter [b], D. Hartmann [c], J. Hu [e], R. Weynants [a], O. Gruber [c], A. Herrmann [c], D. Douai [f], Y.D. Bae [g], H.G. Esser [b], J.G. Kwak [g], E. Lerche [a], O. Marchuk [b], V. Mertens [c], R. Neu [c], U. Samm [b], A. Scarabosio [c], C. Schulz [b], S.J. Wang [g], TEXTOR Team and ASDEX Upgrade Team

[a] *LPP-ERM/KMS, Association EURATOM-BELGIAN STATE, B-1000 Brussels, Belgium* [1]
[b] *Institut für Energieforschung, FZ Jülich, EURATOM Association, D-52425 Jülich, Germany* [1]
[c] *Max-Planck Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany*
[d] *Universiteit Gent, EESA Department, B-9000 Gent, Belgium*
[e] *Instituite of Plasma Physics, CAS, 230031 Hefei, PR China*
[f] *CEA, IRFM, Association EURATOM-CEA, F-13108 St Paul lez Durance, France*
[g] *Fusion Engineering Center KAERI, 1045 Daedeokdaero, Yuseong, Daejeon 305-353, Republic of Korea*

ARTICLE INFO

PACS:
52.40.Hf
52.50.−b
52.55.Fa
52.80.Pi

ABSTRACT

In the present paper, inter-machine studies of Ion Cyclotron Wall Conditioning (ICWC) have been performed in limiter (TEXTOR) and divertor (ASDEX Upgrade, AUG) tokamaks in the presence of toroidal (0.2–2.35 T) and vertical (0–0.04 T) magnetic fields using the conventional ICRF antennas without modifications in hardware. The ICWC effect on both machines was studied by analyzing the removal rate of marker gases which have been loaded to the walls by glow discharge beforehand. Several factors were identified which could have a crucial impact on the conditioning efficiency: (i) RF power coupled to the plasmas; (ii) RF power absorption scheme; (iii) superimposing an additional vertical magnetic field on the toroidal field ($B_V << B_T$). All the observed effects are analyzed in terms of RF plasma wave excitation/absorption and compared with the predictions from 1-D RF and 0-D transport codes. ICWC scenarios for ITER are proposed and analyzed.

1. Introduction

ITER and future fusion devices need the availability of wall conditioning techniques for routine operation and to control the in-vessel long term tritium retention. The presence of *permanent high magnetic field* in present and next generation *superconducting* fusion machines will prevent the use of conventional glow discharge conditioning (GDC) due to short-circuit occurring between anode and cathode along the magnetic field lines.

Wall conditioning based on the ICRF discharge (ICWC) is fully compatible and needs the presence of the magnetic field. The ICWC technique was recently approved for integration into the ITER baseline using the ITER ICRF heating system [1]. Therefore, further development of the ITER relevant ICWC scenarios with conventional ICRF antennas is an important and urgent task. The present paper focuses on the impact of toroidal and poloidal magnetic fields on antenna coupling, RF plasma homogeneity and wall conditioning, e.g. removal rate of selected 'marker' masses. The outcome of the ICWC study in the present-day tokamaks TEXTOR and AUG was used for elaboration first proposals for ICWC scenarios in ITER using main ICRF antenna.

2. Antenna-plasma loading and RF discharge homogeneity

Antenna-plasma coupling defines the fraction of the generator power coupled to the plasma, $\eta = P_{RF-pl}/P_{RF-G}$. Usually, the coupling of the conventional ICRF antenna designed for dense plasma heating through excitation of the fast magneto-sonic wave (FW) was seen to be very low ($\eta < 30\%$) during the generation of RF plasmas with low-density $n_e \sim 10^{16}$–10^{17} m^{-3}, at which FW is non-propagating. To achieve better coupling and improve homogeneity of the low-density plasmas, several recipes based on plasma wave propagation have been found and successfully tested: (i) operation

* Corresponding author. Present address: Laboratory for Plasma Physics ERM/KMS, 30 Avenue de la Renaissance, 1000 Brussels, Belgium.
E-mail address: A.Lyssoivan@fz-juelich.de (A. Lyssoivan).

[1] Partners in the Trilateral Euregio Cluster (TEC).

0022-3115/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2009.01.233

at low B_T-field and standard generator frequency (regime of the FW excitation at high ion cyclotron harmonics $\omega = n\omega_{cH+}$, $n >> 1$ [2]) and (ii) plasma wave mode conversion (MC) at high B_T in plasmas with two ion species in the presence of the fundamental ion cyclotron resonance (ICR) for minor species, $\omega = \omega_{cH+}$ [3]. In the TEXTOR case, the ICWC plasma production was studied in the wide range of the B_T-variation (Fig. 1). Several obvious effects are important: (i) the high ability of the ICRF power to produce plasmas at any B_T-field (no B_T-limits were found), (ii) a considerable improvement (about 1.5–2 times) of the antenna coupling and the associated density rise over the total vessel volume at the low $B_T \approx 0.2$–0.5 T ($\omega \approx 10\omega_{cH+}$) compared with the high $B_T \approx 1.4$–2.4 T ($\omega = \omega_{cH+}$). Further analysis of the FW dispersion relation [4] and its evanescent layer [2] showed that the discovered effect was related to the gradual excitation of FW in low-density plasmas starting from LFS with decreasing the magnetic field.

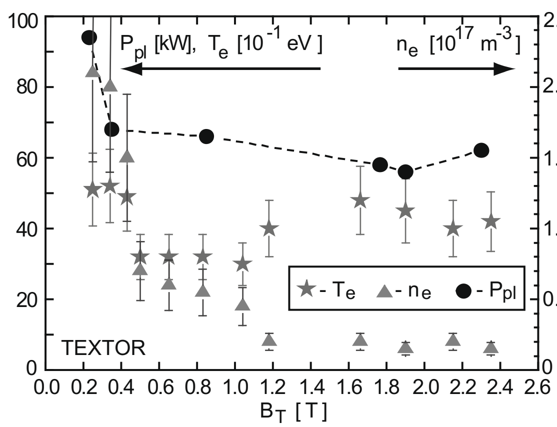

Fig. 1. Dependence of n_e, T_e (measured by Langmuir probe at the plasma edge, $r = 0.45$ m) and RF power coupled to $(He + H_2)$-plasma on B_T in TEXTOR: $P_{RF-G} \approx$ 120 kW, $p_{tot} \approx (4–6) \times 10^{-2}$ Pa.

Antenna coupling at high B_T can be improved with conversion of the non-propagating FW into propagating ion Bernstein wave (IBW) in plasmas with two ion species. This scenario can be achieved in e.g., deuterium/hydrogen or helium/hydrogen gas mixtures. This The effect was predicted from modeling with the TOMCAT 1-D RF code [5], demonstrated in JET [3] and further developed in AUG. Fig. 2 shows the *calculated* energy deposition profiles for different plasma species and the related *images* of the RF plasmas from the top CCD cameras for three AUG cases: (I) RF plasma in helium at $B_T = 2.4$ T and $f = 30$ MHz, (II) RF plasma in a gas mixture, $H_2/(He + H_2) \approx 0.2$–0.3 at the same field and frequency and (III) RF plasma in the same gas mixture and B_T but at two different frequencies, $f_1 = 36.5$ MHz and $f_2 = 30$ MHz. It is clearly seen that a transition occurs from localized plasma production at the LFS (antenna side) towards a more homogeneous filling of the AUG vessel with the plasma reaching the vessel center (marked by dashed curve) in the He/H$_2$-mixture using the MC scenario. Further plasma extension towards HFS in this scenario was achieved with simultaneous operation at two frequencies. The impact of the MC scenario on the antenna coupling was very strong: $\eta_{He+H2} \geqslant 3\eta_{He}$ when the conversion layer was located closer to the antenna.

Superposing an additional vertical magnetic field ($B_V << B_T$) may improve the performance of the ICRF discharge against operation in pure B_T-field due to: (i) better particle/energy confinement [6], (ii) better coupling with the poloidally polarized antenna [7], (iii) wider poloidal plasma extent [3] and (iv) if B_V is oscillating, improved ionization by inductively induced toroidal electric field.

3. Effect of toroidal and vertical magnetic fields on ICWC output

These results enabled to extend the ICWC operational range to the following parameters: $B_T = 0.2$–2.35 T, $B_V = 0$–0.04 T, gas mixture $H_2/(He + H_2) \approx 0.2$–0.3, $p_{tot} \approx (2–8) \times 10^{-2}$ Pa, $P_{RF-pl} \approx 10$–135 kW from two (TEXTOR) to four (AUG) ICRF antennas powered in a single-pulse mode ($\tau_{RF} \approx 5$–8 s) without any modifications in hardware. The wall conditioning effect on both machines was studied by measuring the overall removal rate of several *marker gases* using mass spectroscopy. (Here we define the removal rate as

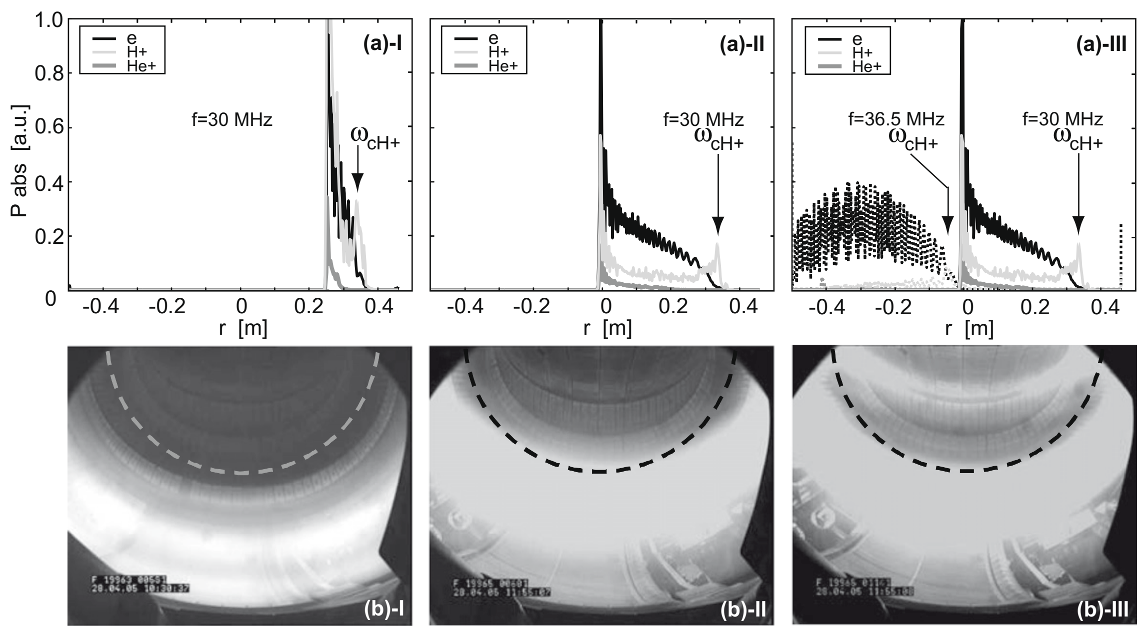

Fig. 2. (a) Evolution of the calculated energy deposition profiles for different plasma species and (b) AUG plasma CCD images for pure He ICWC (case I), for gas mixtures with $H_2/(He + H_2) \approx 0.3$ (case II) and for dual frequency 30 MHz (solid curves) and 36.5 MHz (dashed curves) operation, same gas mixture (case III): $B_T = 2.4$ T, $p \approx 4 \times 10^{-2}$ Pa, $P_{RF-pl} \approx 50$ kW.

the quantity: $Q_{RR}(t) \sim V(dp/dt) + p \cdot s$, where V is the plasma volume, p and s are the partial pressure of the given mass and its pumping speed, respectively.) The walls were loaded with the marker gases, Ar in AUG (W-coated vessel) and an Ar-D_2 mixture in TEXTOR (C-coated vessel), prior to each ICWC conditioning cycle by standard GDC [9]. Also a standard GDC in helium procedure was used for wall cleaning of the residual marker gas that was not removed by the ICWC conditioning.

Analysis of the mass 3 (HD) release in TEXTOR during the RF conditioning pulse revealed a noticeable rise in the Q_{RR} quantity at both, high and low B_T-fields (Fig. 3). The H_2-injection into He plasmas made the conditioning more effective, especially at high B_T. At high magnetic field ($B_T \approx 2.3$ T, presence of the fundamental ICR, $\omega = \omega_{cH+}$), the observed effect may be attributed to H_2 contribution to (i) the improved plasma homogeneity through the MC process, and (ii) the proton ion cyclotron acceleration at high B_T ($\omega = \omega_{cH+}$) and to (iii) the hydrogen induced chemical erosion/isotope exchange [8]. The noticeable conditioning effect at low B_T ($\approx$0.2 T, regime of high IC harmonic operation, $\omega \approx 10\omega_{cH+}$) was probably related to (i) the better plasma homogeneity and (ii) the chemical erosion. The HD removal rate further increased by applying a B_V-field in addition to B_T. Time variable ($\approx$0.008 T) and quasi-stationary (0.04 T) B_V-fields caused similar increase in the ICWC conditioning efficiency. Modeling of the power deposition profiles predicted a decrease of proton cyclotron absorption and increase of electron collisional absorption with decreasing the B_T (Fig. 4) and may be considered as an indirect evidence of the favourable impact of the fundamental ICR on ICWC output.

In the AUG case, the Ar removal rate was analyzed at the peak of the partial pressure after the termination of ICWC pulse. The Q_{RR} for Ar also decreased with B_T-decreasing (Fig. 5). The best result was achieved at $B_T \approx 2.4$ T, which locates the $\omega = \omega_{cH+}$ resonance at LFS, closer to the antennas. The conditioning became also more effective in the presence of B_V-field ($\approx$0.02 T). Contrary to the wide B_T-variations tested in TEXTOR (B_T = 0.2–2.3 T, gradual excitation of the IC harmonics in plasma in the range $\omega = (1–10)\omega_{cH+}$) the moderate B_T-varying in AUG (B_T = 1.6–2.4 T) resulted in the fundamental $\omega = \omega_{cH+}$ ICR excitation and gradual shifting of its location in the vacuum vessel (from LFS to HFS on decreasing B_T) for both operating frequencies.

The observed B_T-dependence of the ICWC yield correlated with the behaviour of the *measured* flux of the high-energy CX neutrals escaping the ICRF plasma and was found in agreement with the *calculated* reduction of the RF power absorbed by protons (Fig. 6). It is well known that the outgassing rate from the wall increases with the impact energy of the ions and their masses [9]. The ICWC experiments performed in TEXTOR and AUG give thus some indication for the importance of the ion cyclotron acceleration mechanism on the conditioning effect by the production of the fast particle impact on the walls. However more studies are needed to quantify this effect. The integrated Ar amount removed with ICWC cycle was compared with that during the subsequent He-GDC cycle. The analysis revealed that only ~25% of the total surface of the AUG vessel was affected by the ICRF discharge in the best regime ($B_T \approx 2.4$ T). Thus the homogeneity of the wall cleaning with ICWC is still a major concern and needs further optimisation.

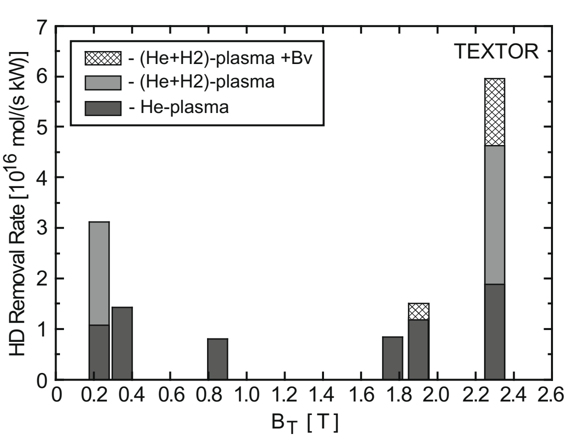

Fig. 3. Dependence of HD (m = 3) removal rate normalized to the plasma coupled power on B_T/B_V-in TEXTOR: He–H_2 mixture, $p_{tot} \approx (4–6) \times 10^{-2}$ Pa), $P_{RF-G} \approx$ 120 kW.

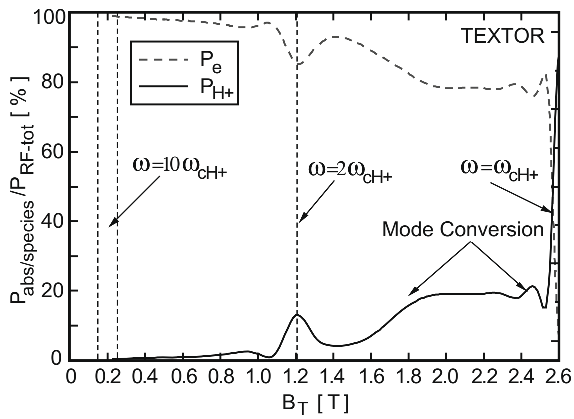

Fig. 4. Dependence of the calculated absorbed power in the (He + H_2)-plasma on B_T in TEXTOR: f = 29 MHz, $n_e(0) = 3 \times 10^{17}$ m^{-3}, $T_e(0)$ = 5 eV, main plasma species ratio $He^1_4:H^1_2:He^2_4$ = 0.6:0.2:0.05.

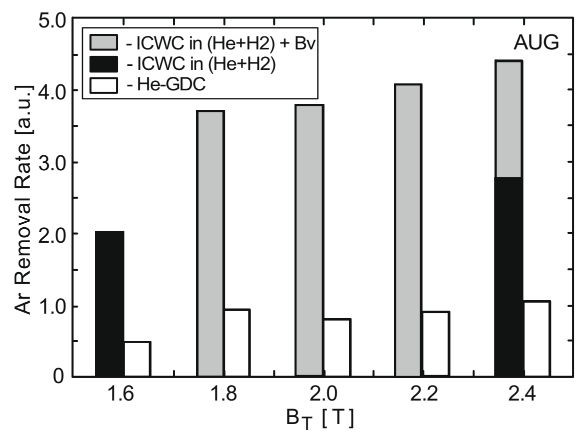

Fig. 5. Dependence of the Ar removal rate on B_T/B_V in AUG: $H_2/(He + H_2) \approx 0.3$, $p \approx 1.6 \times 10^{-2}$ Pa, $P_{RF-pl} \approx 85$ kW, f_1 = 36.5 MHz, f_2 = 30 MHz.

4. Modeling of ICRF conditioning plasmas in ITER

Modeling of the power absorption in RF plasmas of the ITER-size was performed for the MC scenario following the best results of the ICWC efficiency achieved in both tokamaks. The foreseen constraint on the magnetic field variation ($B_T \approx 2.6–5.3$ T) and designed frequency band for the ICRH system (f = 40–55 MHz) gave a strong impact on selection of the operational parameters. The TOMCAT code predicts that a more homogeneous power absorption by the electrons over the ITER vessel (Fig. 7) may be achieved in operation at two different frequencies (f_1 = 40 MHz and f_2 = 48 MHz) and two different phasing ($\Delta\varphi_{1-2} = \pi/3$ and $\Delta\varphi_{3-4} = \pi/6$) between the RF currents in the toroidally adjacent antenna modules.

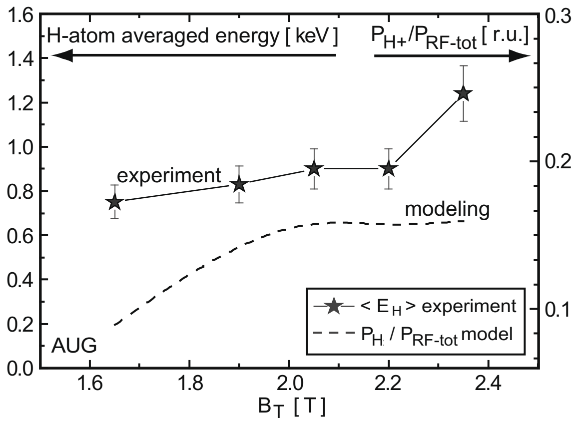

Fig. 6. Averaged energy of hydrogen CX-atoms in the energy range $E \approx 1$–5 keV measured in the AUG ICRF plasmas and calculated power absorbed by protons as function of the B_T-field.

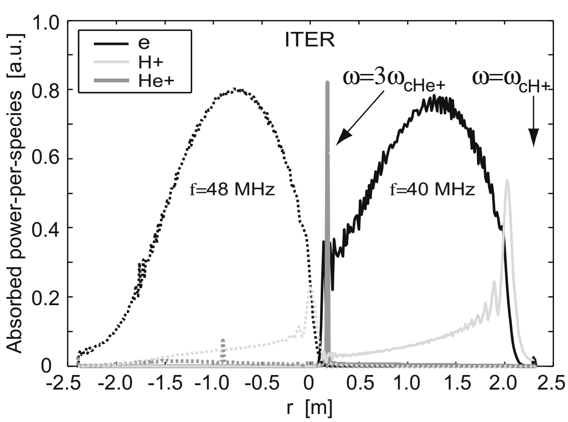

Fig. 7. Power deposition profiles in the ITER-like plasma predicted by TOMCAT code for two frequencies, 40 MHz (solid curves) and 48 MHz (dashed curves): $r_{pl} \approx 2.4$ m, $R_0 = 6.2$ m, $B_T = 3.6$ T, n_e, T_e and plasma composition as for Fig. 4.

To simulate the RF plasma production in the presence of toroidal and vertical magnetic fields, a set of updated energy and particle balance equations for the electrons, ions and atoms was solved numerically in the frame of the recently developed *homogeneous* 0-D model based on the electron collisional ionization [10]. The code predicts that the conditioning plasmas can be produced in ITER ($\bar{a}_{pl} \approx 2.6$ m, $R_0 = 6.2$ m, $B_T = 5.3$ T, $p \approx (2–8) \times 10^{-2}$ Pa) in a wide power range, $P_{RF-pl(ITER)} \approx 0.2$–1.5 MW depending on the gas pressure. It results in a density of $n_e \approx (1–4) \times 10^{17}$ m^{-3}, temperature $T_e \approx 1$–2 eV and ionization degree $\gamma_i = n_e/(n_e + n_0) \approx 0.01$–0.02. Assuming moderate antenna coupling efficiency $\eta \approx 40\%$, this corresponds to a generator power around $P_{RF-G(ITER)} \approx 0.5$–3.8 MW. The empirical direct extrapolation from TEXTOR ICWC data at low/moderate coupled power $P_{RF-pl} \approx 12$–30 kW for similar power density scaling and antenna coupling $\eta \approx 40\%$ gives a power of $P_{RF-pl(ITER)} \approx 1.0$–2.5 MW and $P_{RF-G(ITER)} \approx 2.5$–6.0 MW, respectively.

5. Conclusions

Inter-machine (TEXTOR, AUG) studies have been performed to develop wall conditioning technique based on ICRF plasma production for ITER in the presence of permanent high magnetic field. It has been found that:

(1) Wall conditioning in the mode conversion scenario (mixture of H_2, He) in the presence of high toroidal and low vertical magnetic fields (B_V << B_T) is considered as the most promising candidate for application in ITER using the main ICRF antenna. Both better radial/poloidal homogeneity of the ICWC plasma and the ability to accelerate ions at the fundamental ICR may contribute to improving the conditioning effect.
(2) ICWC at high cyclotron harmonics appears also to be attractive mainly due to high antenna-plasma coupling ($\eta \geqslant 80\%$) and better plasma homogeneity. However, the scenario needs working at high generator frequencies for the nominal magnetic fields. Also this method does not produce fast ions that may enhance the conditioning efficiency.
(3) Modeling with the 1-D RF and 0-D plasma codes and empirical extrapolation from existing machines give a good evidence for the feasibility of using ICWC in ITER with the main ICRF antenna.

Acknowledgements

This work was performed in the frame of the European Task Force on Plasma–Wall Interaction and EFDA Topical Group on Heating and Current Drive.

References

[1] ITER Team, ITER Design Change Request DCR-080, 2007.
[2] A. Lyssoivan et al., Report LPP-ERM/KMS, vol. 114, 1998.
[3] A. Lyssoivan et al., J. Nucl. Mater. 337–339 (2005) 456.
[4] R. Koch, Trans. Fusion Sci. Technol. 49 (2T) (2006) 177.
[5] D. van Eester, R. Koch, Plasma Phys. Contr. Fusion 40 (1998) 1949.
[6] L.E. Zakharov, G.V. Pereverzev, et al., Sov. J. Plasma Phys. 14 (1988) 75.
[7] A. Lyssoivan et al., Twenty second EPS Conference on CFPP, ECA, vol. 19C, Part III, 1995, p. 341.
[8] G. Sergienko et al., Eighteenth International Conference on Plasma Surface Interactions, Toledo, 2008, p. P2-45.
[9] J. Winter, Plasma Phys. Contr. Fusion 38 (1996) 1503.
[10] J. Buermans, T. Matthys et al., Diploma Thesis, ERM/KMS, Brussels, 2006.