EFDA–JET–CP(10)05/14

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M. Van Schoor, G. Van Wassenhove, M. Vervier, the TEXTOR Team,
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ICRF Physics Aspects of Wall Conditioning with Conventional Antennas in Large-Size Tokamaks

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A. Lyssoivan[1], R. Koch[1], D. Douai[2], J.-M. Noterdaeme[3,4], V. Philipps[5], V. Rohde[3],
F.C. Schüller[6], G. Sergienko[5], D. Van Eester[1], T. Wauters[1,2], T. Blackman[7], V. Bobkov[3],
S. Brémond[2], S. Brezinsek[5], E. de la Cal[8], R. Dumont[2], M. Garcia-Munoz[3], E. Gauthier[2],
M. Graham[7], S. Jachmich[1], E. Joffrin[2,9], A. Kreter[5], P.U. Lamalle[6], E. Lerche[1], G. Lombard[2],
F. Louche[1], M. Maslov[7], M.-L. Mayoral[7,9], V.E. Moiseenko[11], P. Mollard[2], I. Monakhov[7],
J. Ongena[1], M.K. Paul[5], R.A. Pitts[6], V. Plyusnin[11], W. Suttrop[3], E. Tsitrone[2], M. Van Schoor[1],
G. Van Wassenhove[1], M. Vervier[1], the TEXTOR Team, the TORE SUPRA Team,
the ASDEX Upgrade Team and JET EFDA contributors

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]LPP-ERM/KMS, Association Euratom-Belgian State, 1000 Brussels, Belgium
[2]CEA, IRFM, Association Euratom-CEA, 13108 St Paul lez Durance, France
[3]Max-Planck-Institut für Plasmaphysik, EURATOM-Association, Boltzmannstr. 2, D-85748, Garching, Germany
[4]Gent University, EESA Department, B-9000 Gent, Belgium
[5]IEF-Plasmaphysik FZ Jülich, Euratom Association, 52425 Jülich, Germany
[6]ITER International Organization, F-13067 St Paul lez Durance, France
[7]EURATOM/CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[8]Laboratorio Nacional de Fusión, Association Euratom-CIEMAT, 28040 Madrid, Spain
[9]EFDA-CSU, Culham Science Centre, OX14 3DB, Abingdon, UK
[10]Institute of Plasma Physics, NSC KIPT, 61108 Kharkiv, Ukraine
[11]Instituto de Plasmas e Fusao Nuclear, Association EURATOM-IST, Lisboa, Portugal
** See annex of F. Romanelli et al, "Overview of JET Results",*
(Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

Preprint of Paper to be submitted for publication in Proceedings of the
19th International Conference on Plasma Surface Interactions, San Diego, California, USA.
(24th May 2010 - 28th May 2010)

ABSTRACT.

This paper focuses on a study of the principal operation aspects of standard ICRF heating antennas in the Ion Cyclotron Wall Conditioning (ICWC) mode: (i) ability of the antenna to ignite the cleaning discharge safely and reliably in different gases including those most likely to be used in ITER – H_e, H_2, D_2 and their mixtures, (ii) the antenna capacity to couple a large fraction of the RF generator power (>50%) to low density (~10^{16}–10^{18} m^{-3}) plasmas and (iii) the RF power absorption schemes aimed at improved RF plasma homogeneity and enhanced conditioning effect. The ICWC discharge optimization in terms of RF plasma wave excitation/absorption resulted in successful simulation of the conditioning scenarios for ITER operation at full field (JET) and half field (TEXTOR, TORE SUPRA, ASDEX Upgrade).

1. INTRODUCTION

Encouraging results obtained in present day tokamaks and stellarators (reviewed in Ref. [1]) have elevated ICWC to the status of one of the most promising techniques available to ITER for routine wall conditioning in the presence of the permanent, high toroidal magnetic field resulting from operation with superconducting magnets. The ability to operate in ICWC mode has recently been confirmed as a functional requirement of the ITER main ICRF heating and current drive system [2]. This paper focuses on multi-machine (TEXTOR, TORE SUPRA (TS), ASDEX Upgrade (AUG) and JET) study of the principal RF physics aspects of conditioning plasma production with standard ICRF heating antennas. It comprises (i) ability of the antenna to generate Ez-field (along the toroidal magnetic field lines) and ignite the RF cleaning discharge safely and reliably in different gases including those most likely to be used in ITER – H_e, H_2, D_2 and their mixtures, (ii) antenna capacity to couple a large fraction of the RF generator power (>50%) to low density (~10^{16}–10^{18} m^{-3}) plasmas and (iii) the RF power absorption schemes (mainly collisional e-absorption) aimed at ICWC discharge performance with improved plasma homogeneity and enhanced conditioning effect at ITER relevant conditions.

2. PHASES OF RF DISCHARGE INITIATED WITH STANDARD ICRF ANTENNA

The initiation of an ICRF discharge in a toroidal magnetic field B_T results from the absorption of RF energy mainly by electrons. The RF $\tilde{E}_z$-field (parallel to the B_T-field) is considered to be responsible for this process [3]. However, in the typical ICRF band (~10–100 MHz) in the present-size fusion devices, for most of the antenna zϰ-spectrum, the RF waves (cylindrical modes) cannot propagate in the vacuum torus: ${}_\perp^2 = {}^2/c^2 - {}_z^2 < 0$, where ${}_\perp$ is the perpendicular wave-vector, $\omega = 2 f$, f is the RF generator frequency. Hence, the neutral gas breakdown and initial ionization may only occur locally at the antenna-near $\tilde{E}_z$-field (evanescent in vacuum). Simplified analytical description of the antenna-near $\tilde{E}_z$~-field generation in vacuum [4] was found in a good agreement with numerical simulations done for the real antenna configurations (JET A2 antenna [5]) using 3D electromagnetic codes (Fig.1). Former analysis of the gas breakdown phase led to the following local ionization condition [6]:$(/e)(2m_e \, {}_i)^{1/2} \le \tilde{E}_z(r) \le m_e \, {}^2 L_z/e$. Here ε_i is the ionization energy threshold for the molecules/atoms, $L_z = \tilde{E}_z/(d\tilde{E}_z/dz)$ is the parallel length scale of the RF ponderomotive potential. Further analysis of the JET A2 antenna-near $\tilde{E}_z$-field amplitude in frame of this model showed that the ionization condition in He (E_z~10kV/m at ~1cm outside the Faraday screen) may be achieved with ~10kV of applied RF voltage. This estimation was found in agreement with the RF voltage operational range (≈12–14kV) used for JET A2 antenna operation in the RF plasma production mode [7]. After the first pre-wave local ionization phase, as soon as plasma frequency ω_{pe} becomes of the order of generator frequency, $\omega_{pe} \ge \omega$, (it occurs at a very low density ~10^{12}–10^{14} m^{-3} in the frequency range 10–100MHz), the plasma waves (slow waves, SW) can start exciting/propagating in a relay-race regime governed by the antenna $_z$-spectrum, causing further space ionization of the neutral gas and plasma build-up over the torus (plasma wave phase). If plasma density becomes high enough ($n_e > 10^{18}$ m^{-3}), the usual Fast magneto-sonic Wave (FW) can become propagating for the typical antenna π-phasing operation. Because of the very low and frozen plasma temperature during the ionization process (T_e~2–5 eV [6]), the RF power is expected to be dissipated mostly collisionally (random e-collisions with gas molecules, atoms or ions) either directly or through conversion to SW and Ion Bernstein Waves (IBW) if $\omega > \omega_{ci}$ or by conversion at the Alfvén resonance if $\omega < \omega_{ci}$. Such a non-resonant coupling allows RF plasma production at any B_T [8].

3. ANTENNA-PLASMA COUPLING IN ICWC MODE OF OPERATION

The antenna-plasma coupling efficiency is the fraction of the generator power coupled to the plasma, $\eta = P_{RF\text{-}pl}/P_{RF\text{-}G}$. The conventional ICRF antenna is designed for dense target plasma ($n_e > 10^{18}$ m^{-3}) heating through excitation of FW with high coupling efficiency ($\eta > 0.9$). Being operated in the RF plasma production mode with the "plasma heating settings" (high k_z-spectrum of the radiated RF power), the conventional ICRF antenna gives evidence of poor coupling ($\eta_0 \sim 0.2$–0.3) to the low density RF plasmas n_e~10^{16}–10^{17} m^{-3}, at which FW is typically non-propagating. The present-day solutions for ICRF antenna enhanced coupling in the ICWC mode are based on the development of scenarios with FW close to propagation or propagating in low density plasmas: (i) antenna phasing to low k_z-spectrum of the radiated RF power, (ii) FW-SW-IBW Mode Conversion (MC) in RF plasmas with two ion species, (iii) operation at High Cyclotron Harmonics (HCH), typically $\omega \approx 10\omega_{ci}$. It should be noted that the FW cutoff frequency strongly depends on the antenna kz-spectrum [9]. For the case of TEXTOR ICRF antennas, it results in a dramatic reduction (about two orders) in the threshold density for FW excitation results from changing the phase between RF current straps is changed from π-phasing ($n_{e\text{-}FW} \approx 2.7\times10^{18}$ m^{-3}, $k_z \approx 6$ m^{-1}, f = 32.5MHz) to zero-phasing ($n_{e\text{-}FW} \approx 7\times10^{16}$ m^{-3}, $k_z < 1$ m^{-1}, f = 32.5MHz), respectively. The recent ICWC experiments have clearly demonstrated this effect as shown in Fig.2 for monopole-phasing (low k_z, $\eta/\eta_0 \approx 3$–4) and for higher kz. Another solution for rising the coupling is based on the effect of FW conversion to SW and IBW in low density/temperature plasmas containing two ion species, e.g. $D^+ + H^+$, ${}^4He^+ + D^+$ or ${}^4He^+ + H^+$ [8]. Generally, FW may be non-propagating over the plasma cross-section except for the narrow conversion area located closer to the fundamental Ion Cyclotron Resonance (ICR) of the principal species, protons ($\omega = \omega_{cH+}$) or deuterons ($\omega = \omega_{cD+}$), depending on ICWC scenario. In this regime, antenna coupling becomes sensitive to the radial location of MC layer: the closer MC layer to the antenna surface the higher antenna-plasma coupling. This coupling effect is more pronounced for the standard π-phasing antenna operation ($\eta/\eta_0 > 3$) [8]. Antenna coupling to low density plasmas may also be enhanced by increasing the ion cyclotron harmonic number by ~10 times either by decreasing the BT-value or increasing the generator frequency. In terms of FW excitation, this effect is attributed to strong shrinking of the wave evanescent layer at the plasma edge [4] and its possible propagation even in the high kz-spectrum case, giving rise to the standard antenna coupling, $\eta/\eta_0 \approx 4$ (Fig.3).

4. IMPACT OF RF POWER ABSORPTION SCHEMES ON WALL CONDITIONING OUTPUT

The progress achieved in the understanding of the antenna-plasma coupling characteristics in the ICWC mode enabled to extend the ICWC operation window over a large range ($B_T = 0.2$–3.3 T, $B_V = 0$–0.04 T, gas pressures $p_{tot} \approx (0.2$–$8.0)\times10^{-2}$Pa, coupled power $P_{RF\text{-}pl} \approx 10$–230kW and coupled power density $P_{RF\text{-}pl}/V_{pl} \approx 0.3$–$3.0$kW/m^3) and successfully simulate ITER ICWC scenarios at half-field (TEXTOR, TS, AUG) and full field (JET) [10]. Simulation of the ITER ICWC scenarios in the present-day fusion machines means scaling of the foreseen ITER B3T-field (2.65T or 5.3T) and generator frequency band (40–55MHz) to the presently available values keeping the same ITER f/B_T-ratio and on-axis location of the fundamental ICR for protons/deuterons thus crossing over the divertor. The conditioning output was studied by measuring the overall outgassing rate of several marker gases using mass spectroscopy and/or optical penning gauges. Here we define the outgassing rate of a given species as the quantity [11]: $Q_{RR}(t) \sim V\,(dp/dt) + p \cdot s + V\,(k^d + k^i)pne$, where V is the volume, p and s are the partial pressure of the given mass and its pumping speed, respectively, k^i and k^d are the ionization rate and dissociation rate and is the electron density.

In the case of H_2 preloading at JET, analysis of the partial pressures for the mass 3 (HD) and mass 2 revealed a noticeable increase in outgassing after the RF pulse termination for the antenna low k_z-spectrum case (0000-phasing) compared to 00$\pi\pi$-phasing (JET D_2-ICWC, Fig.4). The net power coupled to the plasma was doubled (at the same generator power) and (possibly partly due to this) higher and more homogeneous density was obtained. The H_2-injection into He plasmas made the conditioning more effective in the presence of the fundamental ICR for protons (AUG (He + H_2)-ICWC, Fig.5). The observed effect may be attributed to the beneficial MC scenario [8]: (i) higher coupled power (~2 times) and (ii) the improved plasma homogeneity due to radially extended (towards HFS) power deposition profile for the electrons. The hydrogen induced chemical erosion/isotope exchange could also contribute to the obtained result [12]. The conditioning effect at low $B_T \approx 0.2$T (HCH regime) was comparable to that at high $B_T \approx 2.0$–2.3T (ICR presence). It may be related to the strongly increased (~1.5–2 times) coupled power which is absorbed by the electrons through collisional dissipation as TOMCAT code predicts [8]. The performed comparison of the ICWC output indicates indirectly the minor role in conditioning process of the high energy Charge eXchange (CX) atoms/ions usually generated in ICWC plasmas in the presence of ICR and needs further investigation.

5. ICWC EXTRAPOLATION TO ITER

Modeling of the absorbed power scenarios for ICWC performance in ITER was performed with the TOMCAT 1-D full-wave RF code [13] upgraded to low density/temperature non-homogeneous plasmas and accounting for ion cyclotron, Landau damping and collisional absorption mechanisms. The foreseen ITER magnetic field variation ($B_T = 2.65–5.3$T) and designed frequency band for the ICRF Heating and Current Drive (HCD) system (f = 40–55MHz) gave a strong impact on selection of the ICWC operational parameters. The TOMCAT code predicts that a more homogeneous power absorption by the electrons over the ITER vessel may be achieved in the MC scenario at $B_T = 3.6$ T with two different frequencies ($f_1 = 40$MHz and $f_2 = 48$MHz) and low-kz-spectrum (π/3-, π/6- or monopole-phasing) between the RF currents in the toroidally adjacent antenna modules [8]. Performance of the MC scenario at half-field ($B_T = 2.65$ T) or at full field ($B_T = 5.3$ T) may result in less homogeneous ICWC discharge. However, plasma production with the antenna phased to low kz-spectrum of the radiated RF power looks beneficial: (i) FW is already propagating in low density plasmas; (ii) better antenna coupling is foreseen; (iii) larger fraction of the coupled RF power may be transported to the antenna distant (>2m) conversion layers. To improve the RF plasma homogeneity, an application of the poloidal magnetic field ($B_{V,R} << B_T$) and assistance with the on-axis ECRF ionization could be beneficial [8].

A 0-D plasma code [14] was used to simulate a scale of the RF power necessary to produce and sustain ICWC hydrogen/deuterium plasmas in ITER-size machine ($a_{pl} \approx 2.4$m, $R_0 = 6.2$m) in the presence of $B_T = 5.3$ T in the pressure range $p \approx (2–8)\times10^{-2}$Pa. The code predicts that RF plasmas with density of $n_e \approx (1–5)\times10^{17}$ m^{-3}, temperature $T_e \approx 1$eV and ionization degree $\gamma i \approx 0.05–0.10$ can be produced with the RF power coupled to the electrons in the range $P_{pl\text{-}ITER} \approx 0.3–1.5$MW depending on the gas pressure (Fig.6). Assuming an “optimistic” antenna coupling efficiency $\eta \geq 0.5$ at the “monopole”-phasing, this corresponds to the generator power range $P_{G\text{-}ITER} \approx 0.6–3.0$MW. The empirical direct extrapolation from the TEXTOR and JET ICWC data (coupled power $P_{pl\text{-}TEXTOR} \approx 12–30$ kW, $P_{pl\text{-}JET} \approx 230$ kW, similar power density scaling and antenna coupling) gives a power of $P_{pl\text{-}ITER} \approx 1–2$ MW and $P_{G\text{-}ITER} \approx 2–4$MW, respectively.

CONCLUSIONS

The results from ion cyclotron wall conditioning experiments with conventional ICRF antennas on several different tokamaks can be summarized as follows:

1. We have elaborated a general approach to the ICRF antenna functional requirements for operation in the plasma production mode and established reliable working parameters (antenna

RF voltage and power, frequency, phasing and gas pressure) needed for wall conditioning.

2. The found antenna operation solutions resulted in a successful simulation of ITER ICWC scenarios at half-field (on the tokamaks TEXTOR, TORE SUPRA and ASDEX Upgrade) and full field (on JET).
3. Extrapolation of the experimental data obtained on the various tokamaks, complemented by simulations with 1-D RF and 0-D plasma codes indicate that the currently planned ITER ICRF HCD system could be used for ICWC operations on ITER.

ACKNOWLEDGEMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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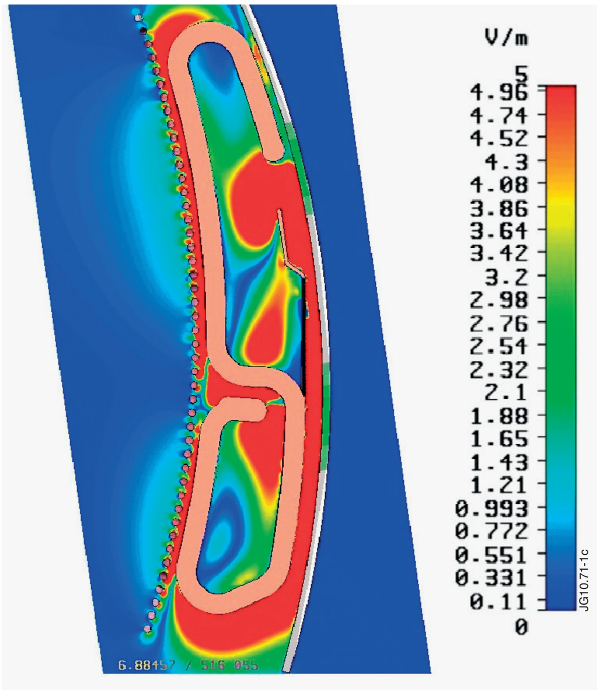

Figure 1. Ez-field simulation for the JET A2 antenna with 3-D MWS code (f = 30MHz, antenna straps in dipole-phasing, $P_{RF\text{-}input}$ = 1W).

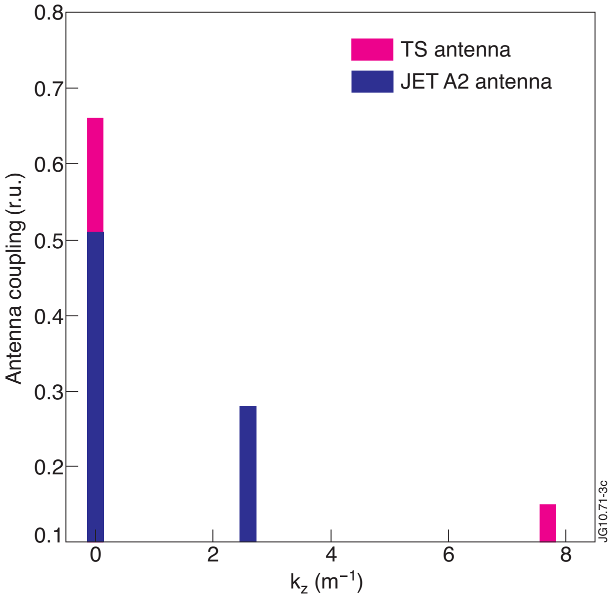

Figure 2. Antenna coupling efficiency to ICWC plasmas (ne~3×10^{17} m^{-3}) versus k_z-spectrum of the radiated RF power for standard ICRF antennas.

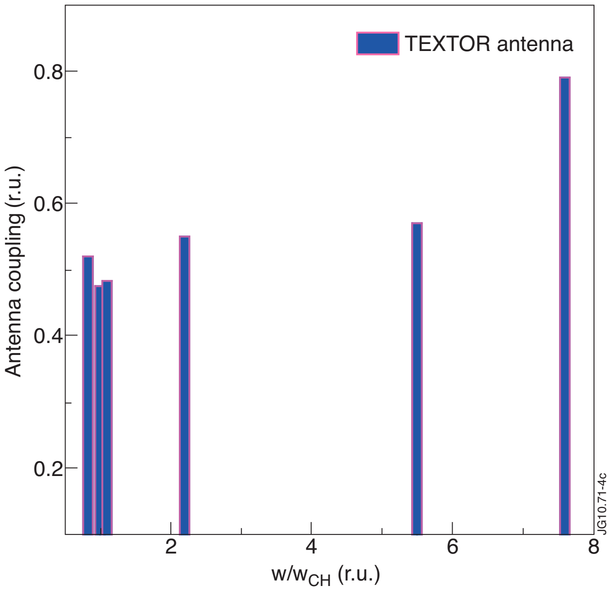

Figure 3: Antenna coupling efficiency to low density (ne~3×10^{17} m^{-3}) plasmas versus ion cyclotron harmonic number.

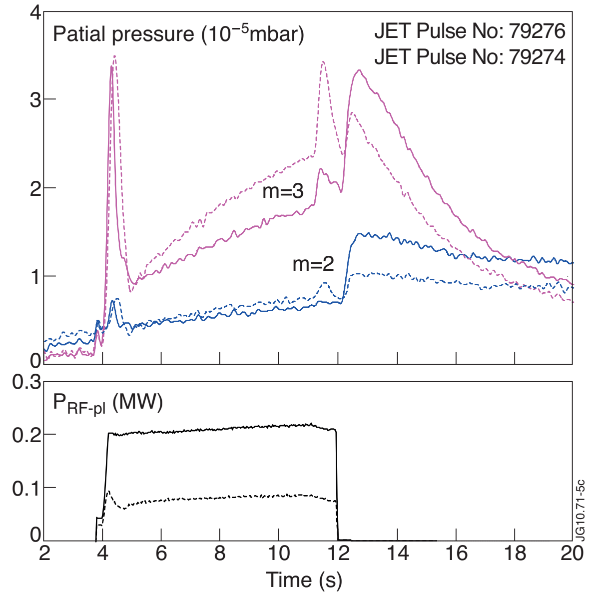

Figure 4: Effect of the antenna k_z-spectrum on JET D2-ICWC output (H_2 preloaded): 0000-phasing (solid) versus 00ππ-phasing (dashed), f = 25MHz, B_T = 3.3 T, p ≈ 2×10^{-3} Pa.

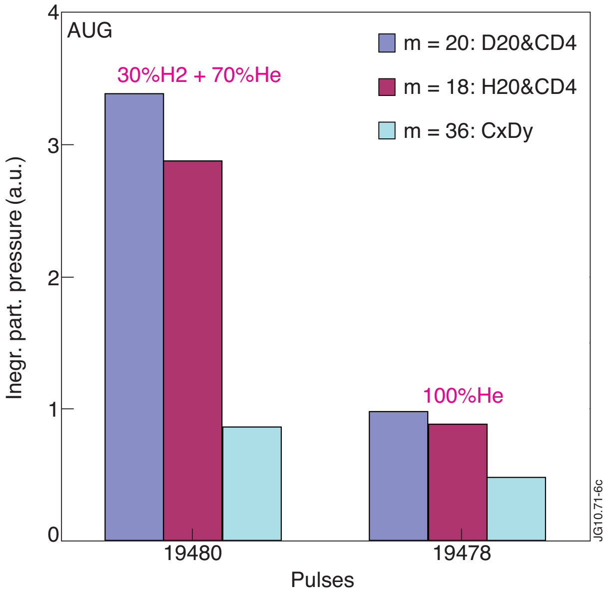

Figure 5: AUG (He+H_2)-ICWC versus He-ICWC: $f_1 = 30$MHz, $f_2 = 36.5$MHz, $B_T = 2.35$T, $p \approx 4\times10^{-2}$ Pa, $P_{pl(He+H2)} \approx 50$kW, $P_{pl(He)} \approx 30$kW, AUG wall composition: 50%C+50%W.

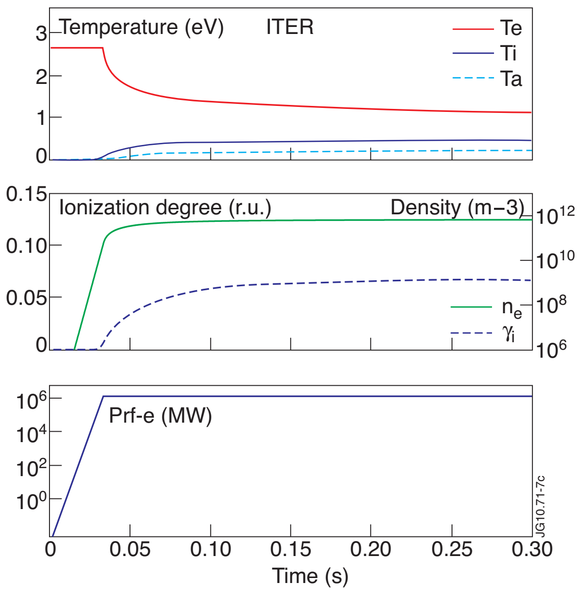

Figure 6: 0-D simulation of the H_2/D_2-plasma production in ITER-size machine for averaged power per neutral: $P/N \approx 70$ kW/(Pa·m^3), $p_{H2} = 8\times10^{-2}$ Pa, $P_{RF\text{-}e} = 1.3$MW.