STUDIES OF IMPURITIES BEHAVIOUR FOR THE OPTIMIZATION OF PLASMAS AND HEATING SCENARIOS AT TOKAMAKS IN PERSPECTIVE FOR ITER

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This contribution reports on the recent progress of integration methods to control and minimise W and mid-Z impurity content for the optimization of plasmas and heating scenarios at tokamaks. The operational setup of diagnostics for impurity control is briefly described. It was found out that different parameters such as auxiliary heating power, deuterium gas injection rate, impurity seeding, density profile, and ELM's frequency affect the behavior of impurities. Furthermore, ICRH use is reviewed and methods for optimisation simultaneously RF coupling and impurity control are presented.

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INTRODUCTION

The Joint European Torus (JET) can make unique contributions to fusion research due to its capability to operate with hydrogen (H), deuterium (D), tritium (T) and deuterium-tritium (DT) mixtures. Its main mission is to support ITER and DEMO. Since 2011 JET has been operating with an ITER-like wall (ILW) comprises beryllium (Be) limiters and a combination of bulk tungsten (W) and W-coated CFC divertor tiles [1]. JET is currently equipped with four A2 Ion Cyclotron Resonance Heating (ICRH) antennas and with the ITER-like antenna (ILA) installed in 2015 [2]. Using both systems up to 6 MW of heating power was coupled in H-mode JET-ILW plasmas and maximum of 8 MW in L-mode discharges. ILA contributed to ~1/3 of the total power in average. Up to 2020, the main objective of the JET campaigns is the preparation of the DT campaigns and development of high performance scenarios in a full metal environment in view of ITER. The goal for new DT campaign at JET with the ILW (DTE2) is demonstrating fusion power in the range of 10…15 MW in stationary conditions (~5 s) representing a fusion energy between 50…75 MJ [3]. In connection with the above, deuterium operation at tokamak JET in 2015-2016 focused on the development of the ITER baseline and hybrid scenarios. Baseline scenario is a proxy for the Q = 10 ITER reference scenario at high plasma current (I_p = 15 MA) and, hence, low safety factor q_{95} (q_{95} ~ 3). To achieve high performance, this plasma scenario takes advantage of the favorable scaling of plasma energy confinement with I_p. Hybrid scenario is a proxy for the ITER long-pulse operation Q = 5, t > 1000 s, at reduced plasma current (I_p = 12 MA) and, hence, higher q_{95} (q_{95} ~ 4.3). In this domain higher normalized pressure (β_N) can be achieved. At higher β_N, higher confinement factor H98(y,2) can be accessed, which helps to compensate the reduction in I_p in terms of the energy confinement. The reduction in I_p tends to result in reduced n_e, which has potential advantages for JET DT because of the improved beam penetration and, hence, central heating. In both baseline and hybrid scenario a new ILW fusion record of 2.9×10^{16} DD neutrons/s was achieved in 2016 experiments [4]. The ICRH is used for scenarios development in preparation of the DT campaign at JET and for development of ICRH scenarios in the ITER non-active phase. The use of ICRH heating is often accompanied by an increased metallic impurity content in plasmas [5-7] therefore, optimisation of ICRH coupling and characterization of plasma wall interaction (PWI) is an important aspect. The major challenge is the integration of high confinement operation with the tungsten (W) divertor constraints at full applied heating power with low core W concentration. To reach these high level objectives, high-Z impurities control and avoidance of their accumulation in the plasma core has become crucial for extending the duration of the high-performance phase.

1. IMPURITY SOURCES AND CORE

1.1. IMPURITY DATA DIAGNOSTICS

During high power ICRH at tokamak JET, W impurities come mainly from main chamber W components (such as the NBI shine-through protection plates) and the divertor apron tiles (W-coated tiles covering the entrance of the divertor) rather than the main part of the divertor (bulk W) [7]. Mid-Z impurities such as nickel (Ni) and iron (Fe) come from Inconel or similar based alloys components at the outer main chamber wall. The presence of copper (Cu) in JET-ILW plasmas is associated with the use of the NBI heating. It must be noted, that the high-Z and mid-Z impurities migrate throughout the vessel and are deposited in the divertor and main chamber limiters.

To provide a quantitative measurement of the W-concentration at JET, the XUV spectrometer has been installed, with vertical line-of-sight (l-o-s) from the top of the machine towards the divertor. This spectrometers register a quasicontinuum radiation of the W-ions W^{27+}-W^{35+} at 5 nm, and the line radiation form W^{41+}-W^{45+} ions. Provided W impurities concentrations are valid only in a limited radial range, where the ambient T_e allows the ions emission. To determine W concentration profiles, the SXR diagnostic is routinely used. The large number of SXR cameras l-o-s, allows determining the 2D-radiation map of SXR-radiation. From the observed poloidal in-out asymmetry the rotation velocity is evaluated. Quantitative diagnosis of the W content in both approaches is described in detail in [8]. The short wavelength range (between 10…40 nm) of JET's VUV spectra are dominated by different mid-Z impurities like Ni, Fe, Cu, chromium (Cr), molybdenum (Mo) making this range particularly valuable

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from the point of view of diagnosing high temperature plasmas. The mid-Z impurity concentrations is determined based on method described in [9]. Besides, quantitative determination of radiated power from plasmas, and deconvolution of 2D radiation maps is made base on bolometry data.

2. EXPERIMENTAL RESULTS

2.1. THE ROLE OF COMBINED ICRH AND NBI HEATING

Dedicated plasmas were examined at JET in conditions as close as possible of ITER scenarios dimensionless parameters. It was found that combined ICRH and NBI heating is crucial for extending the duration of the high-performance phase and plays a key role in achieving the new ILW fusion record [4]. Pulses without ICRH suffers impurity accumulation in the subsequent discharge phase. With the increased radiated power, a deterioration of the fusion performance (decrease in neutron rate, β_N, H98(y,2)) was observed. Such behavior is explained by peaked electron density and changes of the convection sign which drives impurities inward and then accumulation on-axis is observed (see Fig. 1). Application of ICRH resulted in a more peaked electron temperature profiles (higher T_e peaking) and a flatter density profiles (small effect on n_e peaking) which were favorable for the avoidance of impurity accumulation [10, 11]. Impurity peaking was well correlated with T_e peaking and strong reduction of SXR (W) peaking with ICRH power was observed [10]. This is consistent with an outward neoclassical convection of high-Z impurities near the plasma center and off-axis peaks occurrence (see Fig. 1, with stronger radiation at mid-radius region) when the radial transport across flux surfaces has a sign inversion.

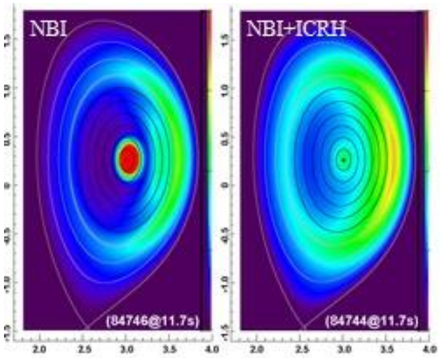

Fig. 1. Comparison of 2D radiation maps for two similar discharges with only NBI and NBI+ICRH heating

Required minimum of ICRH power is scenario dependent. For example for med. n_e/I_P baseline H-modes, P_{ICRH} >4 MW is needed for impurity control [11]. Additionally, with the ICRH, the sawteeth stabilization was observed [10]. In order to optimize the ICRH in different scenarios, aiming at minimizing W radiation in the very core of the plasma, the ion cyclotron resonance position (R_{IC}) was varied by ramping the toroidal field (B_T) [4, 10, 11]. It was found that the core T_e peaks [10] and both the bulk radiation and the peaking of the W radiation are minimized when the R_{IC} is located close to the magnetic axis.

2.2. INFLUENCE OF GAS INJECTION RATE AND GAS INJECTION LOCATION

The radio frequency (RF) electric filed gives rise to RF sheath potentials in which ions can be accelerated producing localized heating (hot-spots) [12]. In some hybrid pulses, hot-spot were developed on the narrow poloidal limiter close to the ICRH antenna B, causing a stop by the real-time wall protection system. Local deuterium (D_2) gas injection allowed reducing hot-spot temperature. The largest hot-spots temperature (T_{max}= 940°C) was observed at lowest gas rate (Γ_{D2} =3.5×10^{19} e/s) in the discharge stopped by the wall protection system. It was shown that D_2 gas injection had also beneficial impact on core impurity control. Decrease of high-, and mid-Z impurities with D_2 injection rate was observed. Different impurity trends were observed for plasmas with different I_p, It is because changes in the I_p have a strong impact on the plasma-wall interaction due to modifications in the edge density. It was found that at constant gas injection rate, both the hot-spot temperature and the core impurity content decreased with the separatrix density $n_{e\ (sep)}$. Besides, higher central SXR radiation for lower $n_{e\ (sep)}$ was observed. In all cases poloidal asymmetry in SXR radiation, caused by the centrifugal forces. However, with higher $n_{e\ (sep)}$ lower on-axis W accumulation and higher off-peak W radiation was observed. The main ion density gradients determine the direction of neoclassical convection [13, 14]. As it is presented in [10, 15], the ICRH performance was improved by enhancing the antenna-plasma coupling with dedicated main chamber gas injection. For mid-plane gas injection, the highest RF coupling and the lowest RF-induced impurity content were observed. Local gas injection to increase antenna coupling is routinely used as a part of the scenario development to maximize the benefit of ICRH.

2.3. IMPURITY CONTROL IN H-MODE EXIT

Recently attention has been given to issues related to impurity control during termination of the H-mode phase [16]. This phase, which is particularly problematic in JET Be/W wall environment, will be an important aspect of ITER operation [17]. Impurity accumulation can lead to the loss of the H-mode, the radiative collapse of plasmas and disruption. Experience in JET-ILW, as well as in AUG, have shown that, in order to maintain stationary ELMy H-mode conditions without impurity accumulation, the ELM frequency can be controlled using ELM pacing methods by gas fueling, vertical kicks or pellets [16]. In general, with a gas fueling, the ELM frequency increases. For the same gas injection rate top injection leads to a somewhat higher ELM frequency than divertor fueling. This may also partially contribute to the lower levels of impurity content in the plasma core. Experiments have shown that without ELM control long ELM-free periods tend to appear during the transition from H- to L-mode. This situation frequently leads to an uncontrolled impurity accumulation. The development of long ELM-free phases can be effectively prevented by triggering additional ELM's via vertical kicks. This method relies on fast (~2…3 ms) vertical plasma motion [18]. Fig. 2, is showing comparison of two H-mode discharges ramped down. In one of them vertical kicks (at 43 Hz) are applied. Successful ELM control using kicks was demonstrated during the H-mode termination, and the build-up of impurities in the core is avoided. It was found that with vertical kicks good impurity and density control was achieved, but with pellets density control was poor and ELM pacing efficiency was < 40 %.

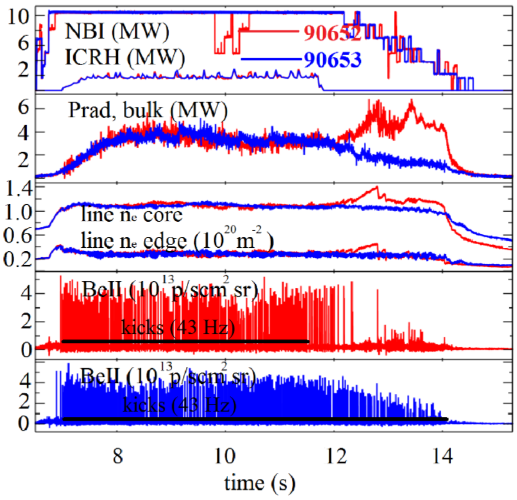

Fig. 2. Time evolution of NBI and ICRH power, bulk radiated power, electron density and BeII signals for two discharges with (blue) and without (red) ELM control via vertical kicks

2.4. INFLUENCE OF IMPURITY SEEDING

Both baseline and hybrid H-mode scenarios have explored the use of impurity seeding (e.g. Ne, N) as a technique for divertor heat load mitigation by radiating exhaust power from the plasma. Hence it has application to future devices such as ITER. Neon seeding is tested due to its operational compatibility with the JET tritium handling facility. In NBI heated hybrid plasmas, factor 3 reduction in peak divertor surface temperature was achieved without significant confinement degradation [19]. However, central radiation increased with Ne seeding and spectroscopic analysis showed increase in W and Mo concentration in the plasma core [20]. This was consistent with the role of ELMs, which frequency decreased with seeding rate [19]. It was also found, that stationary high-performance N_2 seeded H-modes could only be sustained when sufficient amount of ICRH (4…5 MW) was applied in the discharge [10]. With NBI-only heating gradual impurity accumulation leading to radiative collapse was observed [10]. At H-mode flat-top in NBI and NBI+ICRH discharges, similar T_e, n_e profiles and 2D SXR radiation pattern were observed. During impurity accumulation with NBI only, strong n_e peaking and hollow T_e profile were observed, which were a sign of the inverted convection from inward to outward in neoclassical transport.

2.5. INFLUENCE OF ICRH ANTENAS DESIGN

Comparison between impurity production, associated with A2 antennas and that with ILA antenna, for the selected shots [7, 15], and statistically was performed. In the first attempt, ILA antenna shows about 20 % less main chamber radiation than A2 antennas at the same heating power. Reduction is consistent with spectroscopic measurements of the impurity content for large data base presented in Fig. 3. It is assumed that enhanced sputtering leading to increased impurity sources is mainly driven by parallel component of RF antenna electric near-field $E_{||}$ (parallel to magnetic field of the tokamak B_T). JET A2 antenna assessment emphasizes importance to arrange ICRF near-fields and PFCs properly in reactor by reduction of $E_{||}$ at PFCs. The new 3-strap antenna in AUG was designed specifically to reduce the ICRH W sputtering by reduction of the near E-field at the W-coated limiters. Use of new 3-strap ICRF antennas with all-W limiters in AUG results in a reduction of the W sources at the antenna limiters and of the W content in the confined plasma by at least a factor of 2 compared to the W-limiter 2-strap antennas [7]. Apart from dedicated A2 vs. ILA comparison data from q_{95} scan were also used for this purpose and for testing influence of antennas magnetic connectivity on impurity production [15, 21]. It was found that RF sheaths can develop from a few cm up to several meters away from the ICRH antennas, and cause plasma ion acceleration along the magnetic field lines.

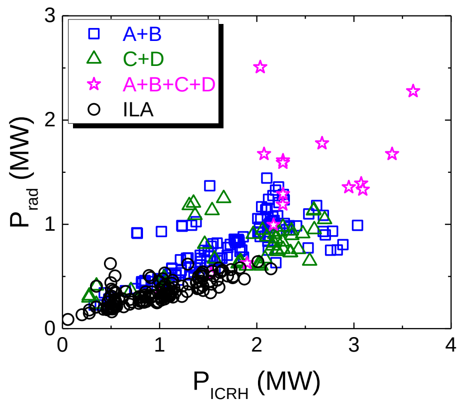

Fig. 3. Radiated power vs. ICRH power for different ICRH antennas at ILW-JET

2.6. INFLUENCE OF ICRH SCHEME

ICRH system in ITER will consist of two antennas able to deliver up to 20 MW of power each in ELMy H-mode plasmas in the frequency range of 40…55 MHz [22]. For minimizing neutron induced activation, the initial, non-active phase of ITER will start with L-mode H plasmas at half-field $B_0 = 2.65$ T and the plasma current Ip = 7.5 MA [23]. In H plasmas, the two ICRH schemes are available for central plasma heating, fundamental H majority (N = 1 H) at f ≈ 40 MHz and 2nd harmonic ^{3}He minority (N = 2 ^{3}He) at f ≈ 53 MHz. These two ICRH scenarios were closely reproduced in an experiment on JET with C-wall [24, 25], showing poor RF wave absorptivity in both cases and higher impurity content in ^{3}He scenario. For the ^{4}He plasmas fundamental H minority heating at f ≈ 42 MHz can be used. This heating scheme either with ^{4}He or, more often, with D plasmas (the D and ^{4}He ions have the same charge-to-mass ratio) was well established and tested in L-mode D plasmas with ILA [26]. The H concentration was varied from 5…30 % by injecting pure H_2 from a dedicated divertor gas injection module (GIM). Heating efficiency and plasma thermal energy (W_{MHD}) were not degraded below X[H]< 15 %, then started to decrease.

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Central electron temperature T_e (0) showed linear reduction with X[H] by factor 2-3. This was related to the reduction of the fast ion content and sawtooth activity. T_e measurements close to the magnetic axis were used as indicators of the sawtooth crashes. It was deduced that for higher X[H] values, more H ions have to share the same amount of RF power, that is absorbed in the plasma, and hence the power per particle is reduced leading to weaker RF acceleration responsible for enhanced plasma-wall interaction. Despite the higher edge losses which are related to poorer RF wave absorption, reduction of high-Z impurity content with X[H] was observed. However, the RF power (< 3.5 MW) was not high enough to keep the impurities out of the plasma core. Transport simulations confirmed that the global transport properties of the plasma are not strongly altered by the change in the H concentration. The impact of the H concentration on the plasmas performance in JET-ILW baseline H-modes was reported in [10]. It was shown that, the heating efficiency, T_e (0), W_{MHD}, decreased with X [H], but the W impurity peaking increased with X[H], which was related with T_e peaking decrease. Efficient core electron heating helped keeping high-Z impurities out of the plasma center. Different ICRH scenarios were tested in combination with NBI heating at JET: H minority heating at f=51 MHz, ^{3}He minority heating at f = 33 MHz and combined H+^{3}He minority heating simultaneously operating at 2 generator frequencies 51 and 33 MHz [15, 27]. H minority heating was proved the most efficient for electron heating and mixed heating for good overall and ion heating. Hints of high Z chasing have been obtained for P_{ICRH} > 4 MW [11, 27]. Similar core W concentrations were found for the various tested scenarios but two-frequency heating was the most optimal. Operation at too low X[^{3}He] yields a higher W concentration due to poor RF heating schemes necessitate bigger electric field amplitudes and typically gave rise to enhanced plasma-wall interaction and lower temperatures. Extra experiments are needed to establish firmer conclusions of this scenario in controled W accumulation in JET-ILW. Fundamental cyclotron ^{3}He minority ICRH scenario in L-mode hydrogen plasmas showed optimum heating efficiency, W_{MHD}, T_e (0) at X[^{3}He]=3...4 % [28]. Such maximum was also observed in W concetration at r/a=0 and W peaking. ^{3}He minority heating dominates the absorption until the mode conversion regime is reached, after which electron absorption is stronger than ion absorption. Independently, three-ion D–(^{3}He)–H absorption scenario was tested [29]. Three-ion scenario requires $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$, resonant ions with an ion charge to mass (*Z*/*A*) ratio in between that of the two main ions. In the JET experiments the H/(H+D) ratio was varied between 73...92 % and the ^{3}He concentration between 0.1...1.5 %. Both, ICRH absorption strength and impurity behaviour depended on plasma composition. It was founf that, small amount of ^{3}He ions (~ 0.2 %) can effectively absorb electromagnetic waves and heat the plasma for a rather large range of X[H] and X[^{3}He]. At the same time good RF performance and low impurity levels was observed. Three-ion scenario was very effective for the long-period sawteeth stabilization. Sawteeth period depended on ICRH antenna phasing. Longer-period sawteeth and higher $T_e(0)$ with $+\pi/2$ antenna phasing was observed. In this scenario W radiation was centralized (r/a < 0.3) approaching higher concentrations in between the sawtooth crashes. Change of such MHD activity is the underlying cause for the change of impurity transport. The three-ion species scenario at extremely low ^{3}He concentrations at AUG did not show such clear signs as on JET because of the reduced fast-ion confinement due to the smaller dimensions and lower plasma current at AUG. However, off-axis ^{3}He heating was successfully established in AUG experiments. Three-ion scenario is very promising for ITER application. It is because, several 3-ion heating schemes will be available (see Table).

Charge state to atomic mass ratio for different elements expected in ITER

ION	**T**	**^{9}Be**	**D, ^{4}He**	**^{3}He**	**H**
$(Z/A)_i$	1/3	0.43…0.45	1/2	2/3	1

For non-activated plasmas scenarios with energetic ^{4}He or ^{3}He ions, ^{9}Be-(*^{4}He*)-H, ^{9}Be-^{4}He-(*^{3}He*)-H. For activated ITER phase with ^{9}Be impurities, T-(*^{9}Be*)-D.

CONCLUSIONS

Central ICRF heating is the way of preventing impurity accumulation. Minority heating can be effective method for RF plasma heating and impurity control. Central ICRF heating with low H conc. confirmed to give the best results for high-Z impurity control. He^3 heating as well as combined H+He^3 ICRH heating also proved to be effective in few cases studied. Local gas injection have beneficial effect on ICRF coupling, RF-induced impurity content and hot-spots temperature. T_e peaking and n_e flattening are important for impurity screening due to outward neoclassical convection. The W accumulation in the core region can be prevented by increasing ELM's frequency via gas puffing or ELM pacing methods (kicks and pellets). ELM pacing is actuators to optimize exit from high confinement H-modes. Using antennas with different geometries influences an impurity production. Different impurity production is observed during A2 and ILA antenna operation at JET, and with the use of the new 3-strap antenna at AUG. Reduction of the near E-field at the antenna limiters reduces the impurity sputtering.

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ИЗУЧЕНИЕ ПОВЕДЕНИЯ ПРИМЕСЕЙ ДЛЯ ОПТИМИЗАЦИИ ПЛАЗМЫ И СЦЕНАРИЕВ НАГРЕВА В ТОКАМАКАХ В ПЕРСПЕКТИВЕ ДЛЯ ИТЭР

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Речь идет о недавнем прогрессе в развитии методов контроля и минимизации вольфрама и других примесей со средним Z для оптимизации плазмы и сценариев нагрева плазмы в токамаках. Коротко описан комплекс диагностики для контроля примесей. Обнаружено, что различные параметры, такие как дополнительная мощность нагрева, скорость впрыскивания дейтерия, источник примесей, профиль плотности и частота ELMов, влияют на поведение примесей. Кроме того, рассматривается использование ICRH и методов одновременной оптимизации RF связи и контроля примесей.

ВИВЧЕННЯ ПОВЕДІНКИ ДОМІШОК ДЛЯ ОПТИМІЗАЦІЇ ПЛАЗМИ ТА СЦЕНАРІЇВ НАГРІВУ В ТОКАМАКАХ У ПЕРСПЕКТИВІ ДЛЯ ІТЕР

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Мова йде про теперішній прогрес у розвитку методів контролю і мінімізації вольфраму та інших домішок із середнім Z для оптимізації плазми та сценаріїв нагріву плазми в токамаках. Коротко описано комплекс діагностики для контролю домішок. Виявлено, що різні параметри, такі як додаткова потужність нагріву, швидкість вприскування дейтерію, джерело домішок, профіль густини та частота ELMів, впливають на поведінку домішок. Крім того, розглядається також використання ICRH та методів одночасної оптимізації RF зв'язку і контролю домішок.