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Recent Heating and Current Drive Results on JET in View of ITER

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ABSTRACT.
Recent progress in heating and current drive on JET in preparation of ITER is summarized. The paper reports new results on the following topics: high power coupling of Ion Cyclotron Resonant Heating/Lower Hybrid Current Drive (ICRF/LHCD) at ITER relevant antenna/launcher-separatrix distances, use of 3dB couplers for ELM tolerance of the ICRF system, influence of ICRF on LHCD operation, fast beam ion transport, rotation studies in plasma without external momentum with standard and enhanced JET toroidal field ripple, studies of different ICRF heating schemes and of Neoclassic Tearing Modes (NTM) avoidance schemes using Ion Cyclotron Current Drive (ICCD). Future plans for further tests and developments of load tolerant ICRF systems at JET are presented.

1. INTRODUCTION
For the success of ITER, reliable operation of the heating systems at high power levels is of utmost importance. For Lower Hybrid Current Drive (LHCD) and Ion Cyclotron Resonant Heating (ICRF), the problem of coupling high levels of power to ITER plasmas consists in finding a reliable solution to make RF power propagation efficient over the large distance between the launcher or antenna strap and the plasma separatrix. Sections 2 to 4 of this paper will summarize progress on these topics. For ICRF, in addition a solution needs to be developed to improve the load tolerance of the antenna system in order for the antenna straps to uninterruptedly radiate high levels of ICRF power. Results of the use of 3dB couplers to address this problem are presented in Section 5. Plans to implement and test conjugate-T systems on JET in the near future are summarized in Section 11. Not only the individual heating systems have to show reliable performance, but combined operation as well. In JET simultaneous operation of the LH and ICRF heating systems can lead to a degradation of the LH wave coupling due to the presence of RF sheaths created by the ICRF antenna when the LH launcher and ICRF antenna are magnetically connected. This is described in Section 6. A correct understanding of the transport of injected fast ions is important to verify the predictions for ITER. Results of dedicated studies on this topic are presented in Section 7. A heating scenario that can contribute to heat directly the ions is important for ITER. One such scenario is ICRF heating at the majority D-ion cyclotron resonance. It is found that the usual drawback, being the poor wave coupling with the thermal bulk ions can be overcome by injecting fast D ions by Neutral Beam Injection (NBI). Advanced modelling has resulted in an enhanced understanding of the specific role of the fast beam ions and results are summarized in Section 8. Rotation in plasmas is another important topic, as it can contribute to stabilising various instabilities. However, this topic is far from being well understood and time has been devoted to the study of the influence on plasma toroidal rotation of ICRF and LH. A significant dependence of plasma rotation on the plasma current and the level of toroidal field ripple was found and results are summarized in Section 9. Fusion born alpha particles in a reactor have the potential to induce Neoclassical Tearing Modes (NTMs). This is the case if alpha particle stabilisation of the sawtooth would occur and give rise to large sawtooth crashes, which in turn would create seed islands for NTMs. Developing methods which could lead to a

destabilisation of such long sawteeth periods is, therefore, important. One method consists in applying Ion Cyclotron Current Drive (ICCD) close to the q=1 surface. In previous years we learnt that the positioning of the ICCD resonance layer with respect to the q=1 surface is rather critical, especially in plasmas where the equilibrium is evolving leading to a change in absolute position of the q=1 surface. Therefore, the ICRF system was modified this year in order to keep the ICCD layer well positioned relative to the evolving position of the q=1 surface by applying small frequency changes. Results of this study are summarized in Section 10. Finally, Section 11 gives a brief outlook of the future plans for JET related to the heating and current drive systems, in view of ITER and Section 12 concludes this paper.

2. STATIONARY COUPLING OF LH POWER AT LARGE DISTANCE BETWEEN PLASMA SEPARATRIX AND LAUNCHER

A solution to couple LH waves to JET plasmas at large distances between the launcher and the plasma separatrix in JET has been developed using a specially designed gas pipe, which provides a gas flow near the LH launcher to increase the electron density in front of it. In previous experiments, CD_4 and later D_2 were used, allowing the coupling of several MW of LH power to the plasma, including at distances between the Last Closed Flux Surface (LCFS) and LH launcher up to 10 cm, in H-Mode plasmas with low triangularity (δ) [1]. However, in order to provide the necessary flexibility for ITER plasma operation good coupling needs to be realized at distances between the LH launcher and the LCFS larger than 10cm. Recent experiments in JET have shown that it is possible to obtain good coupling with distances between the LCFS and the launcher of up to 15cm, using even less D_2 gas than in earlier experiments. This has been done both in a newly developed plasma configuration for advanced scenario operations at high triangularity δ, (δ_{lower} = 0.49 and δ_{upper} = 0.4) [2], and in a hybrid scenario (δ_{lower} = 0.38 and δ_{upper} = 0.50). In the hybrid scenario, about 3MW of LH power could be coupled for over 8s in a stationary way. This is illustrated in Fig. 1. The beneficial effect of gas puffing near the launcher was demonstrated in experiments where the near gas injection was either switched off or on during the LH phase. Without gas puffing, the power reflection coefficient increases and the LH power is switched off due to the launcher safety system. However, good coupling could be obtained even in cases without gas injection near the launcher, provided that the total gas injection in the tokamak was high enough [2]. This suggests that recycling plays a role, which is in accordance with results obtained in JT-60U [3]. In the recent JET experiments it was also shown that the LH power density plays a role in the increase of the far SOL electron density. Modeling with a modified version of the EDGE2D code (calculation grid extended in order to model the plasma 10cm beyond the separatrix) shows that in order to simulate the far SOL density increase, enhanced ionization due to an increased electron temperature (presumably caused by LH power loss in the SOL) has to be included in the calculations [4].

3. LH CURRENT DRIVE EFFICIENCY WITH NEAR GAS PUFFING AND LARGE LAUNCHER-SEPARATRIX DISTANCE

Possible deleterious effects due to parasitic absorption of the LH power in the local gas cloud created by injecting gas in the region near the LH launcher could be an important issue. Such effects could translate into increased heat flux carried by the electrons accelerated near the grill mouth and possibly a decrease in the LH current drive efficiency [5]. This has been addressed in a recent experiment in JET (carried out in L-Mode plasmas only), in which real-time control of the boundary flux was used, in order to keep the loop voltage constant and leave the plasma current floating. The amount of gas puffed near the LH launcher and the plasma-launcher distance was varied, while parameters such as electron density, temperature, total gas puffing and LHCD power, were kept constant. In such a way, a variation in the LH current drive efficiency should be detected by a variation in the plasma current. The plasma current obtained in a discharge with plasma-launcher distance of 11cm, assisted by near gas puffing to improve the LH coupling, was slightly smaller (by less than 70kA) than a reference discharge at 1.4MA with plasma-launcher distance of 5cm and without near gas puffing. If one assumes that the non-inductive current produced by LHCD was 50% of the total current, this would result in $\Delta I_{LH}/I_{LH} < 10\%$ at worst compared to the discharge with small plasma-launcher distance without near gas puffing. The second harmonic non-thermal ECE emission was similar in the discharges, which indicates that there was no loss of current carrying electrons with increasing gas puffing near the launcher. One of the possible mechanisms by which LH power is lost parasitically in the SOL is by acceleration of electrons in front of the grill [6]. These cause hot spots on components magnetically connected to the launcher, and is also observed in JET [2]. In the experiment described here, the surface temperature of the poloidal limiter magnetically connected to the launcher was measured using the IR camera. There was no difference in the hot spot temperature in the two discharges described above. The analysis of the experimental data is still preliminary, but these observations all indicate that the amount of LH power lost in the SOL varies little with increasing plasma-launcher distance or amount of gas puffed.

4. COUPLING HIGH POWER ICRF IN H-MODE PLASMAS WITH ITER RELEVANT SEPARATRIX-STRAP DISTANCE

Coupling 20MW ICRF power on ITER H-Mode plasmas will be a major challenge because of (i) fast changes in antenna loading during Edge Localized Modes (ELMs) and (ii) because of the large antenna-strap distance of ~19cm. In order to compensate the decreasing antenna loading with increasing antenna plasma distance, D_2 gas puffing in the edge has been applied on H-Mode plasmas with a radial outer gap ROG (defined as the distance in the midplane between the separatrix and the JET poloidal limiters, and approximately equal to the distance between plasma separatrix and Faraday Screen) of up to 14cm. Two high triangularity plasma configurations with significant differences in recycling and ELM behaviour were used and allowed a first evaluation of the effectiveness of gas puffing under rather different plasma conditions. The effect of the gas puff location was studied using gas puff from the top of the machine, midplane and divertor. In both configurations D2 gas puff led to a significant improvement of the ICRF antenna loading (up to a factor of 6) allowing to couple high levels of ICRF power. Up to 8MW of ICRF power was applied in this way with a ROG of 14cm using gas puff from the midplane (GIM6) and the divertor (GIM9 and 10), see Fig. 2. This was accompanied by an increase in the central electron temperature and diamagnetic energy, showing that the launched ICRF power is indeed efficiently coupled to the plasma. The best gas puff positions were from the midplane and the top of the machine. Improvement in loading was observed even for those antennas that are not magnetically connected to the position of the gas inlet. Finally, one could clearly observe a decrease in the loading perturbation caused by ELMs as the plasma-antenna distance was increased [7].

These first experiments show the potential of gas puffing to improve ICRF coupling conditions at large antenna-plasma separatrix distance and ELMy H-mode. However, before being able to extrapolate to ITER, more extensive experiments are needed as well as the development of 3D modeling tools to optimize gas puffing (minimize gas puff by using the best located gas inlet).

5. USE OF 3DB COUPLERS FOR ELM TOLERANCE OF THE ICRF SYSTEM

One of the possibilities to realise ELM tolerance of ICRF antennas is the use of 3dB couplers, as first shown on ASDEX-Upgrade [8]. 3dB couplers have been installed between the antenna A and B ICRF arrays. An example of the results obtained for the A1 and B1 antenna straps is shown in Fig. 3. The four ports of the 3dB coupler are: A1 and B1 transmission line going to A1 and B1 antenna straps (A1 and B1 STL), the transmission line going to the generator (B1 OTL) and the coupler dummy load. As expected the fast changes in coupling occurring during ELMs led to high levels of reflected power on the A1 and B1 transmission lines (A1 and B1 STL). Because of the properties of the 3dB coupler, the reflected power is directed to a dummy load connected instead of going back to the generator. As no reflected power is seen by the generator (see B1 OTL reflected), the generator is not tripped which leads to increased averaged coupled power during ELMs [9]. However, ICRF operational experience with 3dB couplers on JET [9] has clearly shown the limitations of traditional Voltage Standing Wave Ratio (VSWR) arc detection methods, the problem being low voltage arcs at voltage-node locations in the antenna vacuum transmission lines. Parasitic low VSWR activity, difficult to detect with the present arc detection system, was indeed observed in the Vacuum Transmission Lines (VTL) that could indicate voltage-node arcing [10]. Low-voltage RF breakdown in the VTLs for the JET antennas has been under scrutiny since 2004 (i.e. before the use of 3dB couplers) when undetected arcing at a voltage-node location most likely caused a perforation in a bellow leading to a vacuum leak. Parasitic low-VSWR activity triggered by ELMs was observed during commissioning of the 3dB couplers and caused concerns about the vulnerability of bellows at voltage-node positions [10]. Restrictions in the use of the 3dB coupler system are now in place at JET, which unfortunately limit its usefulness. These observations emphasize the need to develop new arc detection methods for ICRF ELM-tolerant systems. This includes arc detection development for the ITER-like antenna (S-matrix arc detection (SMAD), sub-harmonic arc detection (SHAD) and for the external conjugate T system (advanced wave amplitude comparison system - AWACS) [11].

6. EFFECT OF ICRF ON LH WAVE COUPLING

The LH launcher at JET is magnetically connected to ICRF antenna B at all time and in some configurations also to antenna A. Operating the ICRF antennas simultaneously with LH results in a degradation of the LH wave coupling. A detailed study [12] shows that the effect is not toroidally/ poloidally homogeneous and depends on the ICRF power and antenna phasing applied, with worst effects being seen for -90∫ and monopole antenna phasing. LH coupling in these conditions can be improved by puffing D_2 from the gas pipe close to the LH launcher. These observations are compatible with the presence of RF sheaths created by powering the ICRF antennas. Rectified sheath potentials created by interaction of the RF field with the surrounding materials build up at the boundaries of the Faraday Screen, septum, limiters, etc. These sheath potentials are shown to scale with the coupled RF power, consistent with observations. The spatial gradients of the sheath potential give rise to ExB drifts and RF sheath induced convection. Similar effects were also observed and modelled in the Tore Supra tokamak [13, 14]. This study shows the importance of a detailed understanding of the RF induced sheath effects in the edge when trying to optimise simultaneous operation of LHCD with ICRF, to get a better understanding of power losses in the SOL and hot spots generation on magnetically connected components. For those reasons, it is expected to be an important topic during the commissioning of the new ITER like ICRF antenna in JET (see Section 12), which is magnetically connected to the LH launcher. These studies are also of direct importance for ITER, where the LH launcher is currently planned to be next to the ICRF antenna.

7. STUDY OF ANOMALOUS FAST ION TRANSPORT WITH OFF-AXIS NBI

The understanding of fast ion physics in tokamak plasmas is important for modelling and interpretation of neutral beam injection (NBI) in tokamaks and required for the derivation of transport coefficients and the validation of the predictions for ITER. ASDEX-Upgrade have reported [15] anomalous behaviour above a given threshold power when using off-axis NBI. On JET, the 2-D neutron camera has been used to diagnose NBI fast ion behaviour by providing time and space resolved neutron profiles from fusion reactions caused by fast ions in a Deuterium (D) plasma. Previous experiments [16] injected short Tritium (T) beam blips (~300ms) with both on- and off-axis beam trajectories into a D plasma with plasma current 1.0 MA and toroidal fields 1.2 T (q_{95}≈3.3) and 3.0T (q_{95}≈8.5). Reanalysis of this T beam data now shows agreement between TRANSP [17] Monte Carlo simulation and the experimental neutron profiles from DT reactions. Experimental investigations have continued this year with dedicated fast ion studies extending the parameter space towards that of the ASDEX-Upgrade pulses in which the beam ion anomaly was observed. This required a plasma current of 820kA, toroidal field of 1.4T (q_{95}~5.4) and low plasma densities of <n>~$1.5*10^{19}$ m^{-3}. The effect of increasing plasma beta on off-axis fast ion dynamics has been studied in such pulses by gradually stepping up the off-axis D beam power up to the available maximum of 7.7MW, reaching a maximum β_N=1.8. Comparison of the experimental DD neutron profiles with TRANSP simulations at each D-beam power step shows no significant deviation from classical fast ion physics, though orbit smearing caused by the low toroidal field would obscure the effect of low levels of anomalous diffusion (up to ~1m^2/s) and thus it is impossible to rule it out in this scenario. Such is not the case, however, in a hybrid mode pulse from the Trace Tritium Experiment which, at a toroidal field of 1.7T, plasma current of 1.4MA (q_{95}≈3.8) and 13.4MW D beam heating reached beta values of up to β_N=2.5. Here the analysis of the†DT neutron profiles and measured neutron rates†obtained with an off-axis T blip showed that even small values of anomalous diffusion (0.5m^2/s) degrades agreement with TRANSP. We conclude that with the (low density) experiments done so far on JET we have been unable to confirm anomalous fast ion behaviour.

8. ICRF HEATING SCENARIOS INVOLVING MAJORITY IONS

The possibility to heat the plasma majority ions at their fundamental cyclotron resonance frequency in tokamaks is of significant scientific and practical interest and is especially important for the understanding of its potential perspectives in ITER D-T plasmas.

ICRF heating of deuterium majority ions was successfully tested in JET [18], despite the rather challenging operational conditions required by this heating scenario: the lowest accessible ICRF frequencies (f ~ 25MHz) at which only a reduced amount of RF power is available. Modeling (with TOMCAT [19], CYRANO [20,22] and PSTELION [21]) indicated that various ITER relevant heating mechanisms occur simultaneously: fundamental ion cyclotron resonance heating of majority D ions, parasitic impurity cyclotron heating and electron heating due to Landau damping and Transit Time Magnetic Pumping (TTMP). All these mechanisms were observed in JET experiments with a ~90% D, 5% H plasma including traces of Be (relying on Be evaporation prior to the experiments) and Ar (puffed in the machine during the experiment). Both the simulations and the experiment showed that majority D ion ICRF heating without some ‘preheating’ of the D ions was unlikely to be successful at JET, as it is impossible to realize the ITER conditions simultaneously (sufficiently high densities and temperatures) to make this scheme efficient: the typical bulk ion temperatures are not large enough to allow significant ICRF absorption far from the cold ion-cyclotron resonance layer. A solution is to move the particle wave resonance away from the cold resonance for the majority ions, where E_+ is nearly zero. For the ion temperatures expected in ITER, on the other hand, the simulations show that due to the broader Deuterium velocity distributions the efficiency of the fundamental D heating scheme is considerably higher. The solution adopted to increase the efficiency of this heating scenario in JET was to exploit the Doppler shift of high energy D ions injected with NBI. Indeed, the D majority ICRF experiments showed that the Doppler-shifted beam particle absorption plays a crucial role in enhancing the rather poor wave coupling with the thermal bulk ions, as indicated by the depositions profiles shown in Fig.4, calculated with a coupled fullwave/QLFP code, which properly accounts for the non-Maxwellian beam distribution [22]. Central ion and electron temperatures increased from T_i~ 4.3 and T_e ~4.5 keV (NBI-only phase) to T_i ~ 5.5 and T_e ~4.8 keV (ICRF+NBI phase), respectively, with only ~1.5MW of ICRF power applied to the plasma. Simulations predicted that a small fraction of the D beam particles could be accelerated up to 200keV at these ICRF power levels, well above the source energy, as is confirmed by observations from NPA and γ-spectroscopy.

Much more important, D tails were also observed during mode conversion studies in D (^{3}He) plasmas heated with combined ICRF and 130keV D-NBI heating, applying gradually increasing ^{3}He concentrations [23]. At a concentration of about 18%, the time of flight neutron diagnostic TOFOR [24] detected an unexpected fast particle population. These fast particles were identified as not being ^{3}He but rather D-ions with energies above 300keV. This was confirmed with gamma spectroscopy [25], giving an estimate of the average D tail temperature of about 400±100keV. Although the cold D cyclotron layer was at the far high field side and thus thermal D ions were not expected to be significantly heated (because of the limited power density in this region of the plasma), the 130keV D beam particles, with a Doppler shift between 0.4-0.5m, could absorb the ICRF power much closer to the plasma core. Due to this fast "preheated" population injected into the machine, D heating became an important ingredient of this scenario. Similar effects have been seen before, though less clear as the D-NBI heating was at a much lower level [26]. Nevertheless, the analysis of these experiments suggests that a reassessment of previous pulses heated with D-beams and (low frequency) ICRF is likely going to be instructive, as considerable heating could take place well away from the region where it was "classically" expected with models assuming Maxwellian distributions in the wave equation solver, and hence may explain some temperature increase at previously non-expected locations.

9. ROTATION IN ICRF HEATED PLASMAS

Rotation in plasmas with little or no external momentum injection [27-32], often referred to as intrinsic rotation, is an interesting phenomenon that is not well understood. In view of the fact that rotation can have a beneficial effect on a fusion plasma, e.g. by enhancing the stabilising effect of a resistive wall, it is of interest to consider different mechanisms that can give rise to rotation. Plasma rotation without significant external momentum injection is in this context particularly interesting since, unlike in today's experiments, Neutral Beam Injection in ITER is not expected to give rise to significant rotation.

Experiments [33] aimed at studying plasma rotation in ICRF heated plasmas with little or no external momentum input in both plasmas with ICRF and LH have been carried out. The rotation profiles have been measured by CXRS (Charge Exchange Recombination Spectroscopy), using short diagnostic NBI pulses. In order to minimise the perturbation introduced by the diagnostic NBI itself, only the first spectrum of each NBI diagnostic pulse is considered. While most of the measurements were focussed on ICRF heating, the LHCD results are particularly interesting since they present the first results from JET using the above technique and allowed studies of rotation with a safety factor above one (slightly reversed magnetic shear) and consequently without sawteeth. Present measurements indicate that in the outer part of the plasma rotation is co-current and fairly flat up to about mid radius. This is the case irrespective of the scenario studied (different antenna phasings, cyclotron resonance positions, ICRF only, combined ICRF and LHCD etc.). On the other hand, in the central part of the plasma, a hollow rotation profile was observed in many circumstances. Such profiles appeared particularly at low current and with off-axis (both low and high field side) ICRF heating. In plasmas with LHCD only, a relatively flat profile was observed also in the centre, which became hollow when adding ICRF, as illustrated in Fig. 5. This demonstrates importance of measuring rotation profiles (as opposed to the velocity at a single point).

In a special campaign the toroidal magnetic field ripple was varied on JET. This can be realised on JET as the 32 toroidal field coils consist of 2 groups of 16, and the current in these groups can be varied separately. Up to 4MW of ICRF was applied in discharges at 1.5MA/2.2T with a toroidal field ripple (defined as $(B_{max} - B_{min})/(B_{max} + B_{min})$ in the equatorial plane at R=3.8m) varying from 0.08% (standard JET conditions) to 1.5%. A first striking result is that the rotation profile under those conditions changes from fully co-rotating at a ripple of 1% to mainly counter rotating at a ripple of 1.5%. Only minor losses were observed, at least not in the positions where the lost ion detectors are located. Thus, it possible that other effects than fast ion losses to the wall could have played a role. Various hypotheses are under investigation. This study also shows that it is important to correctly take into account the influence of plasma current and toroidal field ripple in inter-machine studies of plasma toroidal rotation.

10. NTM AVOIDANCE BY SAWTOOTH CONTROL USING ION CYCLOTRON CURRENT DRIVE

Fusion born alpha particles in a reactor have the potential to induce sawteeth with long periods. Their crashes can provide seed islands for Neoclassical Tearing Modes (NTMs) [34, 35], which can degrade the performance of a fusion plasma significantly. In view of ITER it is therefore desirable to develop strategies to avoid NTMs. One possibility consists in keeping the sawtooth period short. According to the Porcelli model [36], this can be achieved if the local shear s_1 at the q = 1 surface is increased sufficiently. In JET this can be realised by applying Ion Cyclotron Current Drive (ICCD) close to the q=1 surface. Sawtooth control by localized current drive has been demonstrated on several tokamaks [37-42] and was also demonstrated on JET for fast ion induced long sawteeth [33-45]. In the JET experiments reported in the latter references, a fast ion population was created in the centre by accelerating H ions by ICRF (H minority heating) with a central resonance while ICCD near the q = 1 surface was realized by simultaneously applying high field side ICRF with –90 phasing. During the past experimental campaign these experiments have been repeated with more additional heating power (mainly NBI) such as to increase the normalized beta, β_N to levels which allowed triggering of NTMs. It was confirmed that when the ICCD resonance layer was correctly positioned, the sawteeth remained short throughout the ICCD phase despite the fast ion population in the centre of the plasma. Most importantly, no NTMs were triggered at the crashes of the shortened sawteeth. Without applying ICCD long sawteeth were systematically present and NTMs were triggered at several instances. Furthermore, the experiment showed that the positioning of the ICCD resonance with respect to $q = 1$ is rather critical and hence the need to control this relative position in real time to maintain sawtooth destabilization throughout an evolving discharge. A second set of experiments was therefore dedicated to the development of a feedback scheme where the ICRF frequency is varied in real time, to allow the ICCD resonance layer to follow movements of the $q = 1$ surface. To this aim the ICRF system was modified allowing real time variations of the ICRF frequency by +/-500kHz corresponding to movements of the ICCD resonance position by +/-4cm. The actuator of the feedback loop was the sawtooth period, for which a real time algorithm was developed. The real time detection of the sawtooth period was robust and the ICRF frequency could be varied in real time provided the frequency variation was not too fast. The final step, proof of real time feedback control of the sawtooth period under evolving plasma conditions, thereby preventing NTMs, is planned for future experiments.

11. FUTURE PLANS

Future plans consist in testing various options for ELM tolerant operation of ICRF systems at JET, in view of ITER. The first option is the ELM tolerant ITER like High Power Prototype Antenna, in which ELM tolerance is achieved using a conjugate-T matching circuit, with internal capacitors as matching elements. This antenna, designed to deliver a power density of $8MW/m^2$, has been characterized with first matching studies on a dedicated test bed at JET [46, 47]. The antenna is currently being installed. This will be followed by a commissioning campaign. A second option under development at JET is an External Conjugate T system on between the ICRF antenna C and D arrays, with trombones as matching elements [11]. This system is also currently implemented on JET in order to compare its functionality with the internally matched JET-EP antenna and later for use in the experimental campaigns. Together with the 3dB couplers already in operation, JET will in this way be equipped with various ELM tolerant systems that can be tested under a large variety of plasmas conditions at JET. This should allow a clear assessment of advantages/disadvantages of the different options and provide important input for ITER.

12. CONCLUSIONS

Recent JET experiments have contributed to progress on several important topics in the field of heating and current drive of tokamak plasmas. A new series of experiments have demonstrated the possibility of coupling high levels of ICRF and LH power to plasmas under ITER like conditions, i.e. with a large distance between the antenna-strap or launcher and the plasma separatrix in plasmas at ITER like triangularities. This can be done by puffing a well-dosed amount of gas in the SOL, leading to an enhanced propagation of the RF waves. In this way, it has now been possible to couple 3MW of LH power in a stationary way and over 8MW of ICRF power in H-Mode plasmas with ELMs. A clear increase has been observed in plasma temperature and energy when applying 8MW ICRF at a distance between the antenna-strap and plasma-separatrix of 20cm and the efficiency of LH current drive under at a launcher/plasma-separatrix distance of 15cm is only minimally (<10%) decreased. Modelling of the gas puff in the case of LH show that small parasitic losses of LH power, leading to increased temperatures in the SOL, and thus to enhanced ionization, must be included in the modelling to explain the observed electron densities before the LH launcher. Research on these topics will continue in future experimental campaigns, in order to further optimize the gas puff and minimize its influence on given plasma conditions. The use of 3dB couplers to reach more steady ICRF power delivery to H-mode plasmas with ELMs at JET has been investigated. These studies illustrate the effectiveness of the 3dB couplers, but also show the shortcomings of traditional arc detection methods based on VSWR detection, as the likelihood of arcs at voltage-node locations in the transmission lines is increased. This limits the use of the 3dB coupler system at JET, and shows clearly the need for new arc detection methods when using ICRF ELM-tolerant systems. Both an external conjugate-T system (between antennas C and D), and the ITER like High Power Prototype Antenna, a conjugate-T system with internal matching capacitors are foreseen on JET for the next campaigns. This will allow the testing of a wide range of load tolerant systems at JET and it will deliver important inputs for ITER. Dedicated studies to investigate anomalous transport of injected fast ions when using off-axis beams, as reported on ASDEX-Upgrade, have until now failed to show the effect in JET plasmas. In the current JET experiments, the 2D neutron camera was used as the main detection tool for possible anomalies. However, this method cannot rule out small deviations from a purely classical behaviour, and future experiments are planned aiming at further increasing the precision of the measurements, by using additional detection methods to characterize the beam deposition. ICRF heating at the fundamental resonance of Deuterium ions has been studied, being one of the scenarios that directly heat the fusion fuel ions. For the experimental conditions that allow studying this scenario at JET, the ICRF power is rather limited and the wave absorption is rather weak. However, the absorption is significantly improved in the presence of fast D ions injected by NBI, which interact with the ICRF waves far away from the cold resonance of the majority ions, due to their enhanced Doppler shift. Advanced modelling methods, including realistic non-Maxwellian particle distributions, allowed to reach a much more detailed understanding of the various heating mechanism at play in this scenario, and also helped to explain similar effects observed in ^{3}He ICRF minority (mode conversion) heating in D plasmas with combined D NBI injection. Studies of rotation in plasmas with low external momentum using ICRF and LH have demonstrated the importance of the plasma current and toroidal field ripple on the induced rotation. It also shows that such effects should be correctly quantified in multimachine studies of induced rotation in order to reach valid conclusions and possible predictions for ITER. Previous studies using ICCD to destabilize long sawtooth periods induced by the presence of fast particles showed the importance of the relative positioning of the current drive layer with respect to the q=1 surface. This is especially important as the stabilizing effects are easily lost whenever the position of the q=1 surface evolves even by a few cm, due to evolving plasma equilibrium conditions. The experiments this year have been further extended by implementing a programmable frequency shift around the main frequency in the ICRF system. This now allows moving the ICCD resonance position over +/-4cm around its initial position. The next step is to implement a feedback control system (with the sawtooth period as actuator), and is foreseen for future experiments.

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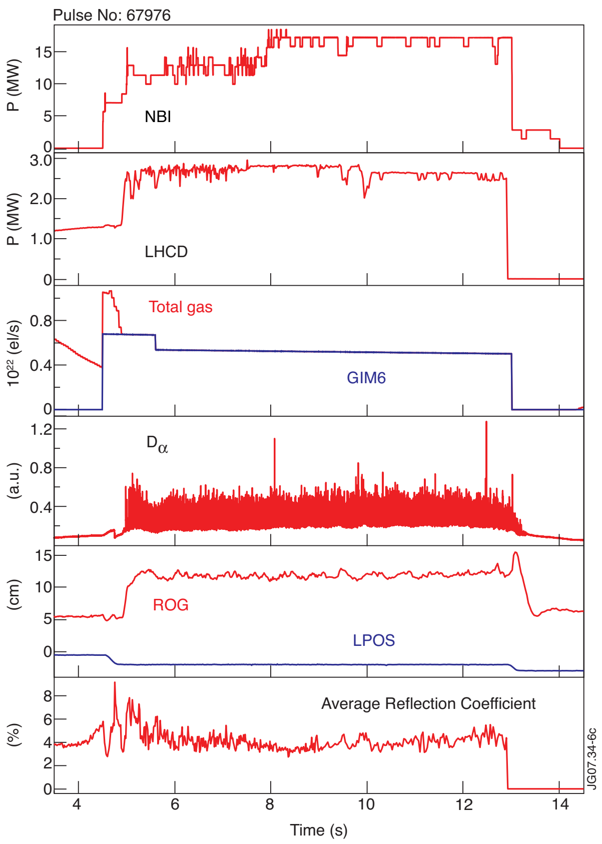

Figure 1: Illustration of long pulse high power LH coupling at large plasma-launcher distance in a hybrid scenario. Shown are as a function of time: NBI and LH power delivered, total gas puffing rate and gas puffing rate from the gas pipe (GIM6), the D_α signal showing the ELM activity, position of the LCFS (ROG) and LH launcher (LPOS) relative to the poloidal limiter (a negative distance means that the launcher is behind the limiter), and the reflection coefficient.

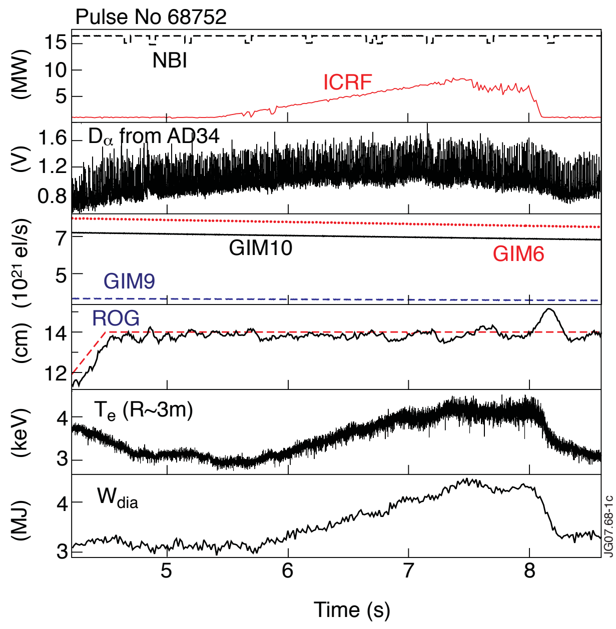

Figure 2 : Illustration of high power ICRF coupling at large plasma-antenna distance in an ELMy H-Mode plasma. Shown are as a function of time: total ICRF power, D_α signal showing the ELM activity, gas puffing rate from the different gas inlets, position of the LCFS (ROG), central electron temperature and diamagnetic energy.

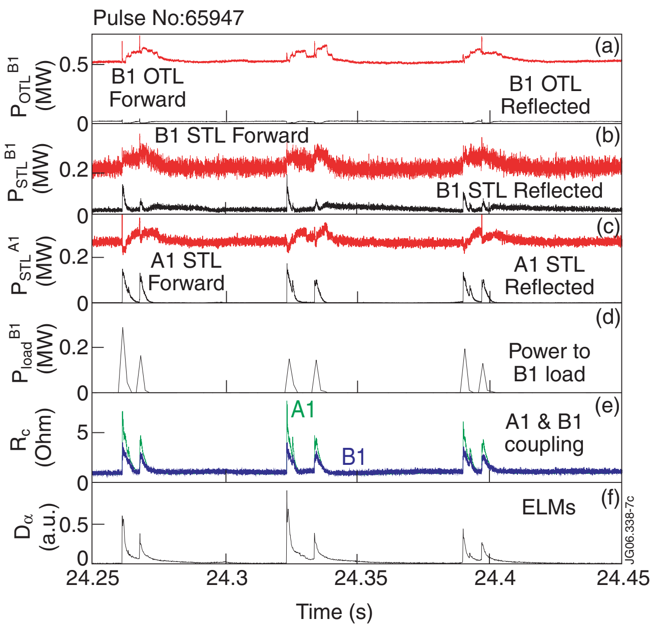

Figure 3: Illustration of the use of 3dB couplers to increase ELM tolerance for the ICRF system in JET. Shown are as a function of time: forward and reflected power at the generator, forward and reflected power on the A1 and B1 lines connected by the 3dB coupler, power to the 3dB dummy load, the A1 and B1 coupling resistance and D_α signal.

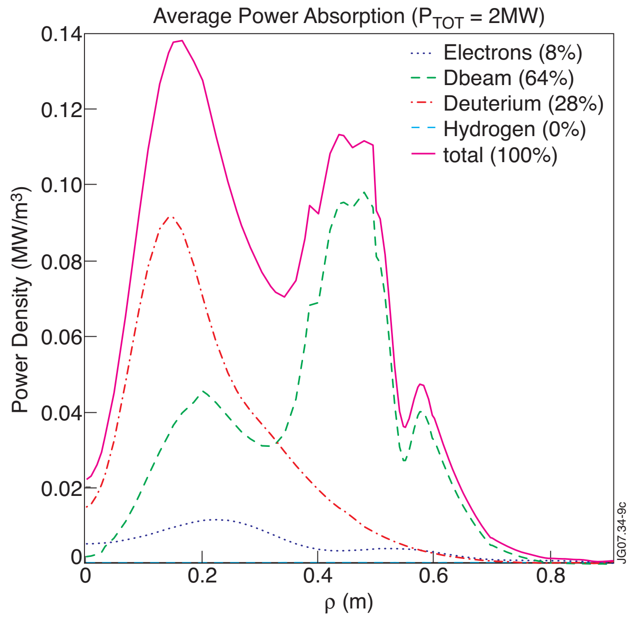

Figure 4: Power deposition (from CYRANO) profiles to the different plasma particles for the D majority fundamental cyclotron heating scenario tested at JET; parameters as in Pulse No: 68733.

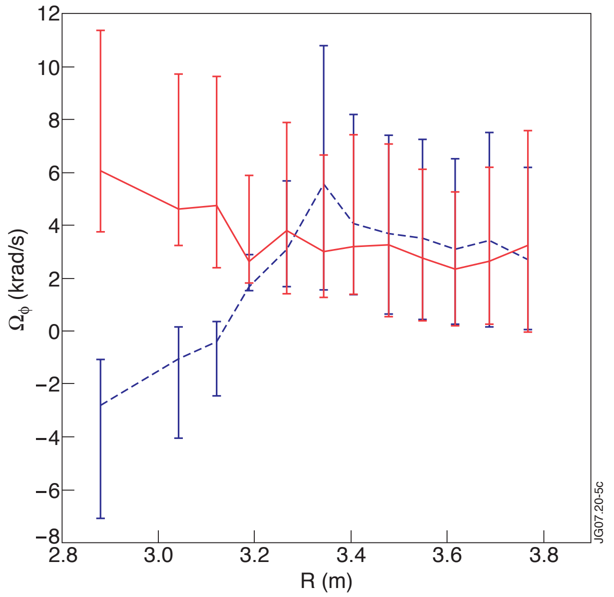

Figure 5: Rotation profiles for two discharges: (i) LHCD only (Pulse No: 68789) solid line and; (ii) combined ICRF and LHCD (Pulse No: 68782) dashed line