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ABSTRACT

In ITER, the requirement for the ICRF antenna is to deliver 20 MW in ELMy H-mode plasmas with an averaged antenna - plasma separatrix distance of 14 cm [1]. Two major problems will have to be solved: the very fast change in antenna loading during ELMs and the decrease of the loading when the plasma is pushed far away from the antenna. JET has the capability to combine these conditions and for the first time, experiments were performed in ELMy H-mode at antenna - separatrix distance, referred as ROG, varied from 10 to 14 cm. When ROG was increased, the perturbation caused by ELMs was found to decrease significantly and the loading between ELMs was found to deteriorate to very low values. In order to compensate the latter unwanted effect, different levels of deuterium gas were injected in the edge either from the divertor, the midplane or the top of the tokamak. Using this technique, the loading was increased by more than a factor 3 and up to 8 MW of ICRF power were coupled.

INTRODUCTION

The ITER requirement for the ICRF antenna is to couple 20 MW with two main challenges to be solved [1]. Firstly, the averaged distance between the antenna Faraday screens and the plasma separatrix distance will be around 14 cm. However, it is well known that ICRF antenna loading decreases exponentially with the position of the fast wave cut-off density that can be related to the radial outer gap (ROG) value, defined as the distance in the midplane between the separatrix and the poloidal limiters [2][3]. Secondly, the edge localised modes (ELMs) associated with the ITER reference scenario in H-mode, results in very fast change in ICRF antenna loading and several solution are envisaged to couple steady ICRF power during such changes [4-6].

For the first time, experiments were performed on the JET tokamak with both challenges combined. The variation of the JET A2 antennas' loading was monitored using a fast data acquisition system (up to 4 μs). The injection of deuterium (D2) gas in the edge was tested in order to improve the antenna coupling by bringing the fast wave cut-off layer closer to the antenna. Two sets of experiments have been performed with two different plasma configurations and edge behaviours. The main results are reported in this paper.

FIRST SET OF EXPERIMENTS: ITER-AT CONFIGURATION

The first set of experiments was performed in the so-called ITER-AT configuration (lower triangularity of $\delta_l \sim 0.50$, upper triangularity of $\delta_u \sim 0.38$). Because of its peculiar X-point legs position, this configuration has a very high recycling and then very low amplitude / high frequency type I ELMs. The following parameters were used: magnetic field of 3.1 T, plasma current of 1.9 MA, central electron density of $5\ 10^{19}\ m^{-3}$ and NBI power of 16 MW. The ICRF heating scheme used was hydrogen (H) minority heating with an ICRF frequency of 47 MHz and a "dipole" antenna phasing. Variations in ROG values were performed from 10 to 14 cm. The gas injector modules (GIMs) used to inject D2 gas were: GIM 9 and GIM 10 situated on a ring in the divertor and GIM 6 located in the midplane near the ICRF antenna B (see Fig. 3).

As illustrated on Fig. 1, on the time evolution of R_c(B3) and R_c(B4) (B3 and B4 straps coupling resistances defined as the loading resistances minus losses), a clear decrease of the perturbation caused by the ELMs was observed as the ROG was increased. Furthermore, a decrease of the baseline coupling (value between ELMs) was seen when gas injection from GIM 9 and GIM 10 was stopped at 17.7s. More precisely, the effect of the D2 gas injection is shown on Fig. 2, were the baseline of R_c(B4) is represented as a function of ROG and for different gas injection combinaison. First of all, one can see that the coupling without gas injection (triangle) was very low (~ 0.5 Ohm) and did not vary too much with ROG changing between 10 to 14 cm, which was to be expected due to the exponential decrease of the coupling with ROG [2,3]. Secondly, if gas injection from the divertor (GIM 9 and 10) at a rate of 1 10^{22} el/s led to a significant increase in the coupling (pulse 68112), it is clear that adding just 0.4 10^{22} el/s from GIM 6 in the midplane (pulse 68110) was much more efficient. Finally, in this configuration up to 8 MW of ICRF power was coupled with a ROG of 14 cm in ELMy mode and gas injected from GIM 9, 10 and 6 (total injection rate of 1.8 10^{22} el/s). Clear increase in the central electron temperature and plasma diamagnetic energy was observed, confirming a good absorption of the ICRF waves. Following this first set of experiments, more data were necessary in order to investigate further the effect of the gas injection position relative to the antennas positions. This was done in a second set of experiments described in the next paragraph.

SECOND SET OF EXPERIMENTS: HT3 CONFIGURATION

In order to document the ICRF coupling at large ROG with different edge conditions, a second set of experiments was performed in the so-called HT3 configuration (lower triangularity of δ_l~0.35, upper triangularity of δu ~ 0.45) which has a very low recycling and then very high amplitude / low frequency type I ELMs. Because of the lack of NBI power at the time of the experiments and in order to have large ELMs, the following parameters were used: magnetic field of 1.55 T, plasma current of 1.5 MA, central electron density ~ 6 10^{19} m^{-3} and NBI power of 8 MW. The ICRF heating scheme used was 2nd harmonic H minority heating with an ICRF frequency of 47 MHz and a “dipole” antenna phasing. Focus was given in studying the effect of gas injection from different GIMs in the midplane and on top of the tokamak. The position of the GIMs used and the field line connection with the different ICRF antennas is represented on Fig. 3. The change in baseline coupling for antenna A, B and C as a function of the gas injection rate for different GIMs, is shown on Fig. 4. Interestingly, improvement on all the antennas independently of the gas injection position was observed i.e. an improvement was observed even if the antennas were not magnetically connected to the GIMs location (Fig. 3). This suggests that D2 injection either from the midplane or from the top led eventually to an increase of the scrape-oflayer (SOL) density throughout the whole equatorial plane. Nevertheless, antenna A coupling improvement was noticeably higher from GIM2 and GIM8. In order to inject gas as efficiently as possible and minimize any detrimental effect on the confinement, one need to develop our understanding of gas ionization and related modification of the SOL. Finally, one has to note that in this configuration and without gas injection the averaged antenna coupling resistances were around a critically low value of 0.2 Ohm. By injecting 2.3 10^{22} el/s from GIM 8, a maximum ICRF power of 5 MW was coupled with an increase in coupling up to a factor 6.

CONCLUSIONS

Experiments have been performed for the first time at JET in ELMy mode and ITER-relevant antenna-separatrix distance. These experiments showed firstly that during ELMs, the coupling perturbation was minimized as the antenna – separatrix distance was increased. Secondly, between ELMs it was shown that the extremely poor coupling could be improved by injecting D2 gas with the best results obtained with injection from the midplane or top of the tokamak. It is also clear that in order to optimize the gas injection (position and level), a better understanding of the gas ionization process in the SOL is required and that 3D edge modelling tools should be developed. High ICRF power (up to 8 MW) was successfully coupled and resulted in an efficient plasma heating and increase in plasma diamagnetic energy.

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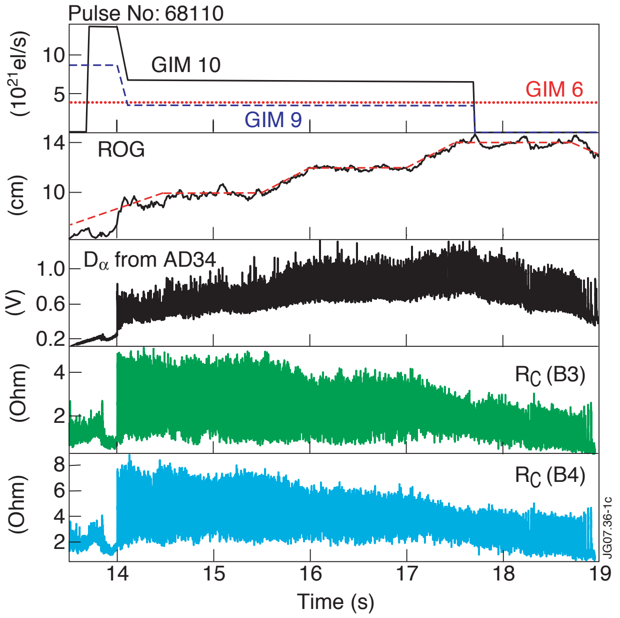

FIGURE 1. Time evolution of gas injection, ROG, ELMs behaviour, B3 and B4 antenna strap coupling (loading minus losses) for a typical pulse.

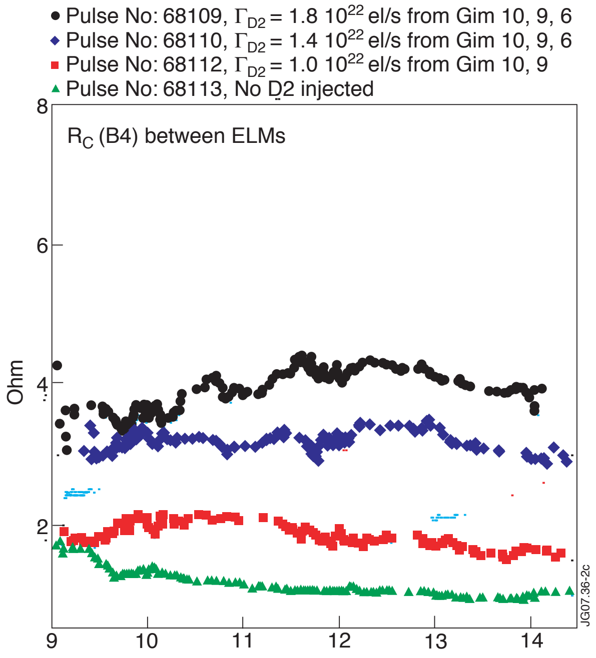

FIGURE 2. Evolution of B4 antenna strap coupling with ROG and for different level of D2 gas injected.

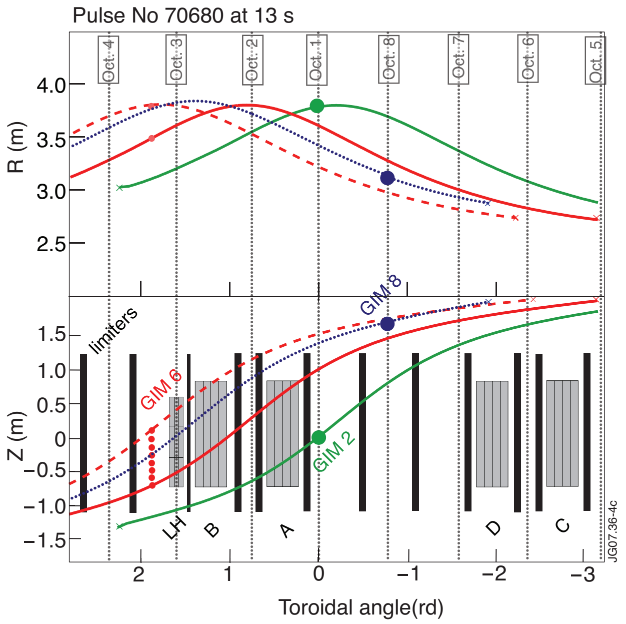

FIGURE 3. Illustration of field line connection between GIM 6 , GIM 8 , GIM 2 and the RF antennas for a typical shot in HT3 configuration.

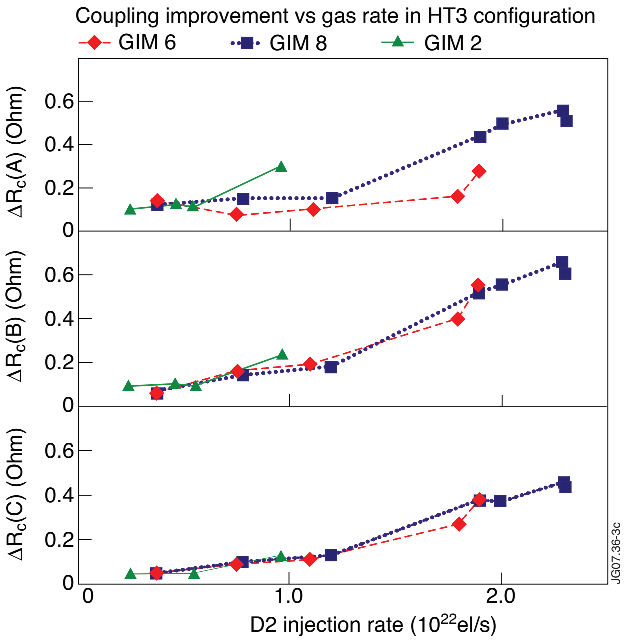

FIGURE 4 Effect D2 gas injection from GIM 6 and GIM 8 of the baseline coupling (= between ELMs) of antenna A, B and C.