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ABSTRACT.

Hot spots in the divertor region have been observed on JET during Lower Hybrid (LH) Current Drive (CD) experiments. The most probable reason is the fast electron generation by parasitic absorption of LH power in front of the grill, as observed in LHCD experiments on Tore Supra and TdeV tokamaks. With parasitic absorption we here mean the absorption of the very high $n_{||}$ modes of the spectrum, with $n_{||} > 20$. The parallel heat fluxes on Tore Supra grill limiters were typically 5–10MW/m^2 but in extreme cases up to 30MW/m^2 were measured. In recent JET experiments, series of hot spots have been detected on the inner and outer divertor apron, which are magnetically connected to the LH grill region. The LH power level in these experiments was between $P_{LH} = 1$ and 3MW and strong gas injection near the grill was used to improve the coupling. However, in some cases excess of gas in front of the grill may increase the heat flux to the magnetically connected components.

1. EXPERIMENTAL SET-UP

A CCD camera was used to observe hot spots on the divertor aprons with good spatial resolution. Since the line of sight of the CCD camera is fixed, the hot spots can only be seen at specific q_{95}-values even though they are assumed to be created in most of the LH shots. Consequently, the best possibility to see hot spots is in the current ramp up or down phases with changing edge q-values. The q95-value is important because it defines the magnetic field line connection from the LH grill to the divertor region.

Three sets of shots, where hot spots were seen, were analysed. In order to get the q_{95}-values needed for the observation of the spots, a current ramp-up was used in the pulses. In the first two sets the current was ramped up during the whole pulse and in the last one just at the end. At the beginning of the shots, the q_{95} was about 7 times larger than the values (4.3, 3.4, or 3.1) in experiments where hot spots were previously observed. The current ramp up brought the q_{95}-value down to the level, where the spots are visible by the CCD camera. The connection then takes place after N turns, where N = 3.5 for example for Pulse No: 55761 for which the connection length is then about 65m. After 5 turns the connection length is 92m. In some shots the ramping rate was limited by MHD activity, which would have led to disruptions. The magnetic field varied from set to set between B = 3 and 3.5T. In order to have better coupling, gas injection was used near the lower hybrid grill. The grill position was varied from 1 to 2cm behind the limiter and the distance from the wall to the Last Cosed Flux Surface (LCFS) varied from 4 to 8.5cm

2. HOT SPOTS ON DIVERTOR APRONS

In the first set of pulses clear trains of hot spots were seen on the divertor apron. The trains were moving as the q-value was ramped down. This rotational transform $d\varphi/dq_{95}$ on the CCD camera is consistent with the width of the connection lines on the divertor apron obtained from a field line tracing code. Moreover, the $\Delta\varphi$ of the train is consistent with the poloidal height of the antenna after rotational transform. The absolute values of connection do not agree very well with the computation but after 3.5 to 5 turns this is not surprising since the error per turn is large. However, it is clear that these hot spots are signatures of effects of magnetic connections between the grill and the inner apron after a few toroidal turns.

The Infra Red Movie Analyser, IRMA, software [3] was used to analyse the CCD videos of the pulses that showed hot spots on the divertor apron. Unfortunately, the software has not been calibrated at JET to measure the temperature. Consequently, only the brightness can be obtained. Two or three measuring points have been used on the inner divertor apron and one on the wall for the background brightness. Figure 1 shows the measuring points and the result of the analysis for a recent JET pulse. The analysis shows clear increases in the brightness of the measuring points in the second phase of the shots. Pulse No's: 58666 to 58668 show clearly three peaks in the brightness on the inner apron. The peaks are denoted by arrows in Figure 1. There is a clear correlation with the termination of the brightness of the hot spots and the end of LH power at t = 12.5s. A comparison to the q_{95}-values is also shown in the figure. In these shots, three windows with spots are seen. In each of the three shots, these windows are roughly at the same values. The first window is $q_{95} = 5.1$ to 4.5, the second one at $q_{95} = 4.1$ to 3.8 and the last one around $q_{95} = 3.8$ just before the end of LH power. The other sets also show clear peaks at the times of the spots seen in the CCD camera. They show spots also around $q_{95} = 3.4$ and $q_{95} = 3.13$.

A similar measurement on the outer apron also shows an increase in the brightness at the end of the LH phase in Pulse No's: 58666 to 58668. However, these spots are weaker and only recognised by the IRMA software. Unfortunately, lower q-values could not be obtained in this set and the hot spots do not reach very far in the visible region.

The spots were also analysed as a function of various parameters. The brightness of the spots was ranked on a scale from 0 to 5 in order to give it a measure. Figure 2 shows the brightness versus the distance between the last closed flux surface and the limiter, and versus the LH power. The brightness clearly decreases with the distance between the limiter and the LCFS. This is beneficial for ITER, which is designed to work at a large LCFS to limiter distance. The dependence on the LH power is not as clear as the one on the distance. However, the brightness increases with the LH power, which has also been seen on Tore Supra and on TdeV [1,2] as well as in theoretical analysis [4].

The brightness seemed not to depend on the overall NBI or ICRH power. In this analysis we did not distinguish between the ICRH antenna modules, which may have an effect. The analysis is left for a further study. The grill position behind the limiter also did not affect the brightness too much, though the brightest points were obtained when the grill was 15mm behind the limiter. The stronger magnetic field gives a slightly larger brightness. This could be due to the particles being better confined around the magnetic field line since the Larmor radius decreases with increasing magnetic field.

SUMMARY AND DISCUSSION

The hot spots due to parasitic absorption of LH power in the near field of the LH grill have been studied at JET. The spots were observed with a CCD camera and analysed with IRMA software. The brightness obtained from IRMA is clearly increased on the divertor apron at the times the spots are seen moving in the CCD video. Moreover, it decreases rapidly down to the background when the LH heating ends. The analysis of the observed hot spots and of the magnetic field connections demonstrates that the fast particles produced in a thin layer in front of the grill mouth can travel several times around the torus, similarly as in Tore Supra. According to the analysis versus various parameters, the main effect is due to the plasma – wall distance, i.e. the distance between the last closed flux surface and the poloidal limiter. The maximum attainable brightness of the spots clearly decreases with increasing distance. A lower density in front of the grill is not likely to be the reason, since the coupling is very good in most cases due to the gas puffing. Since the coupling well above the cut-off density is a very weak function of the density, this should be investigated in more detail in further work. The preliminary study did not show a clear dependency on the reflection coefficient. However, the propagation of the particle beam further away from the grill could be affected by non-linear effects due to the lower density there. Moreover, the interaction point is changed and further out on the apron the beam hits less recycling surfaces and the brightness is lower for the same heat flux. Indeed, the flux on the apron can also be lower, but there are no measurements to verify that.

ACKNOWLEDGMENTS

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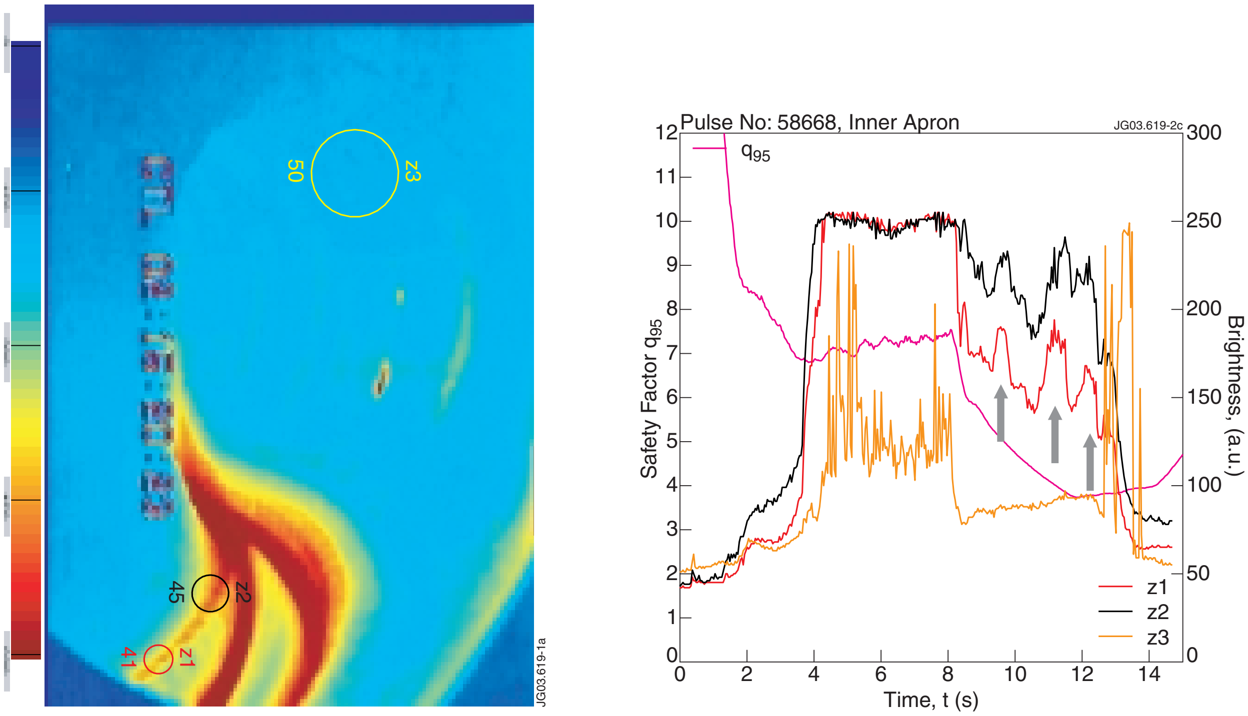

Figure 1: The left-hand side image shows the measuring points in the IRMA analysis, which is shown on the right-hand side for Pulse No: 58668. The colours of the lines indicate the measuring points denoted by the coloured circles on the left-hand side. The right-hand side image also shows the safety factor versus time. During the first phase of the pulse, from t = 4 to 8s, the brightness is higher because of the ELMy phase.

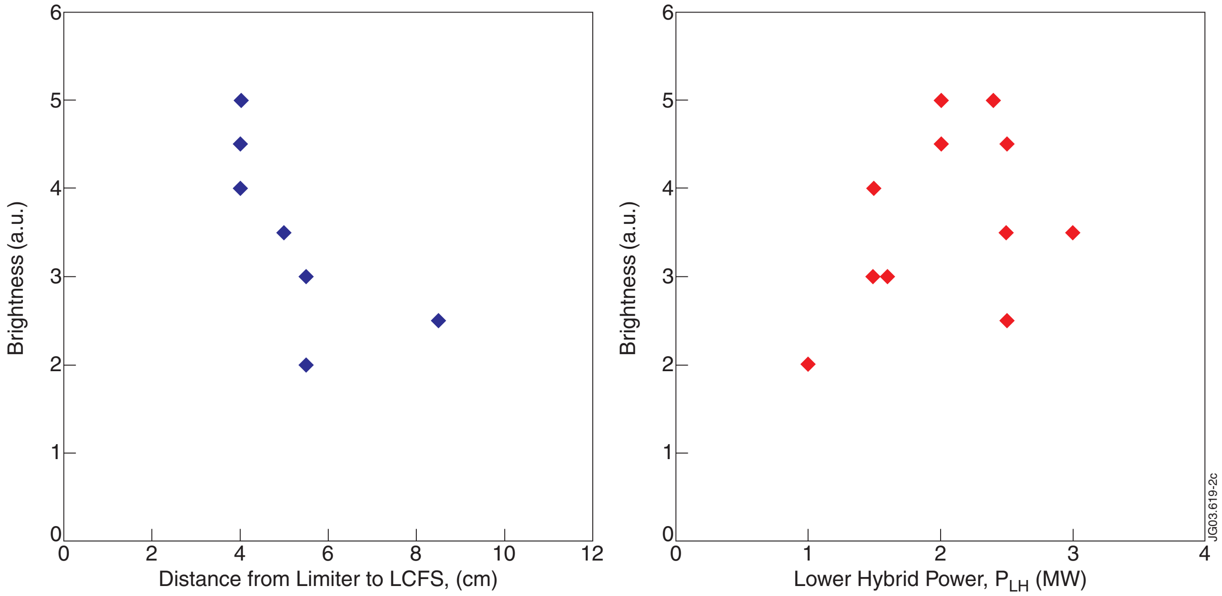

Figure 2: Brightness of the hot spots obtained on the CCD camera versus the distance from the limiter to the last closed flux surface (LCFS) and the LH power. The points may represent more than one shot. Shots with same power or distance may have different gas rate, current, magnetic field, grill position, overall power, etc.