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ABSTRACT.

In this study, the most likely causes of the enhanced radiation in front of the LHCD launcher are investigated: fast ions from the warm plasma, fast electrons parasitically accelerated in front of the grill and arcs. Evidence for the presence of each of these mechanisms is discussed.

INTRODUCTION

The Lower Hybrid Current Drive (LHCD) system in JET is used to pre-form and maintain the *q*-profile of the discharge by the production and sustaining of a negative magnetic shear which leads to formation of Internal Transport Barrier (ITB) plasmas [1]. The operation of the LHCD system requires avoidance of harmful plasma-launcher interactions, characterised by increased radiation in front of the LHCD antenna. This radiation, measured by a bolometer and UV spectrometer, is due to impurities from the LHCD launcher, and its enhancement indicates possible damage to the grill. Since first operation in 1994, the present JET LHCD launcher has accumulated damage like blobs and protuberances on its top left corner and melted material in the middle of the rows, visible in Fig.1. A recent visual inspection of the grill has again proved that the damage continues to accumulate, and determining the causes is relevant to future applications of LHCD in fusion devices. In this study three causes of impurity radiation from the LHCD launcher —fast electrons, arcs and fast ions — are investigated and evidence for their occurrence in JET assessed. The experimental conditions favouring the appearance of these phenomena and their impact on the launcher have also been highlighted. The main approach adopted in the study is to investigate the accumulated database of LHCD experiments in JET and attempt to find a correlation between the impurity generation from the launcher and the heating sources and plasma parameters. However, this is quite complicated due to the fact that some of the parameters utilised in the analysis are closely related each other. For example, the high additional heating power and consequent H-mode plasma are related to the use of near launcher gas injection for improving the coupling, whilst at low power and in LHCD-only pulses, gas was very rarely used. This makes it impossible to separate the effects of gas injection and additional heating power on the impurity radiation from the grill.

THE STATUS OF THE LHCD LAUNCHER AND THE UTILISED DIAGNOSTICS

The LHCD system on JET consists of 24 3.7GHz klystrons, each of which produces up to 650kW for pulses of up to 20s, arranged in 6 modules (A-F). The power coupled to the plasma strongly depends on the launcher power handling, the operating scenario and the plasma conditions. Each klystron feeds two hybrid junctions, ordered in 6 rows and 8 columns at the grill mouth as shown in Fig.1. The grill is surrounded by a protective guard frame made of Carbon (*C*). A poloidal limiter on the right hand side of the launcher separates it from the nearby ICRH antenna B and the launcher is kept radially behind this limiter at all time. On the left hand side of the launcher there is a gas pipe used for improving the coupling.

The radiated power in JET is measured by a bolometric diagnostic. The vertical camera of the JET bolometer is situated above the LHCD grill and two lines of sight were used in the study: one which looks at the plasma in front of the launcher and another one which measures the radiation from the main plasma. The difference between them, referred to as *d35*, is used as an estimate for the enhanced radiation in front of the grill during plasma operation. In addition, UV spectrometry is used to measure the line radiation of the impurities in the plasma. The launcher grill contains Iron (*Fe*) and Nickel (*Ni*) and increased UV radiation of these elements indicates their release from the grill. Although *Fe* and *Ni* impurities can be generated by other in-vessel components, e.g. RF antennas, we assume that the enhanced signals from both the bolometer and the UV spectrometer point out that the radiation comes from the LHCD grill. These two diagnostics are also included in the LHCD radiation protection system.

As a plasma facing component the LHCD launcher is subject to several potential destructive processes including: (*i*) melting and evaporation by bombardment with highly energetic electrons or runaways, which increase the heat load on the materials, (*ii*) evaporation and sublimation caused by arcing between different in-vessel components and (*iii*) physical and chemical sputtering by energetic ions and atoms. All of these processes generate impurities in the Scrape Of Layer (SOL) which diffuse into the plasma, where they are ionised and radiate.

In the study, data from JET campaigns C7-C14 have been investigated. Data are taken at the time of the maximum of the *d35* signal and *FeXXIII* UV radiation during LHCD operation. Events during disruptions, which lead to high radiation signals, are discounted following identification from instant changes of the plasma current.

ASSESSMENT OF THE MOST LIKELY CAUSES.

Analysis of the experimental data shows that the enhanced impurity radiation from the LHCD launcher depends in a complex manner on a number of parameters. This is attributed to the fact that many different processes are involved in the impurity release from the launcher. This conclusion is also consistent with the assorted damage to the grill, i.e. the melted top left corner and the scratch-like formations in the middle of the rows. The most likely causes of the impurity radiation from the LHCD launcher, not arranged in a particular order, are summarised here.

IMPURITY RADIATION RELATED TO THE LHCD POWER.

The main causes of enhanced radiation associated with the LHCD operation are the parasitic fast electrons in the SOL and the arcs. Both of these are related to the electric field at the grill mouth, which is proportional to the square root of the applied LHCD power, $P_{\mathrm{LH}}{}^{1/2}$, and also depends on the reflection coefficients. An example of a radiation event when LHCD alone was applied is given in Fig.2(a). The dependence of the radiation on the applied LHCD power at the moment of maximum of *d35* signal is shown in Fig.2(b), according to which, it is less probable to observe enhanced radiation at small LHCD power, $P_{\mathrm{LH}} < 1.5$MW.

In general LH aims at driving current by interaction with the electrons in the plasma core. The parallel refractive index $1.4 < N_{||} < 2.3$ ensures that the LH wave is absorbed via Landau damping by electrons in the keV range, which in divertor configurations can not spread beyond the separatrix and hence they are excluded from considerations. However, because of the launcher geometry and in particular because of the sharp edges of the waveguides' walls, a part of the RF power is launched at quite large parallel refractive index $N_{||} > 30$. The phase velocity $v_{||} = c / N_{||}$ at that refractive index decreases thus allowing less energised electrons to absorb energy from the wave. For $N_{||} \approx 100$ those could be electrons with energy some tens eV, i.e. electrons in the SOL. These can gain further energy by interaction with lower $N_{||}$ mode numbers, because of the resonances overlap [2], [3]. The fast electrons can act on the protruding parts of the LHCD launcher, e.g. the blobs and the protuberances of the grill and the inner walls of the protective frame and the surrounding limiters, as they increase the heat load and ease the melting and evaporation of the targeted components. A radiation event associated with the fast electrons can be discriminated from arc occurrence by the large C impurity influx in LHCD-only experiments.

Although the last visual inspection of the surrounding limiters showed no indication of damage due to parasitic electrons, the grooves-like damages to the grill, observed on all of the rows, are in the same direction as the magnetic field lines in front of the launcher for the most typical JET experiments, Fig. 1, and this is consistent with interaction with fast electrons. Hotspots, which are observed [4] on the divertor components, magnetically connected to the LHCD grill, are another evidence for the presence of fast electrons in the SOL.

An arc can deposit enough energy in the waveguides to melt the grill. Impurity ions of *Fe* and *Ni* could be expected to enter the plasma, thus increasing the radiation. Arcs are more likely to occur between structures with sharp edges since these result in high electric fields. A high rate of gas puffing near the launcher will also increase the possibility of arcs because of the increased neutral pressure in the vicinity of the launcher and inside the multijunctions. For that reason, the gas injection rate in LHCD experiments is optimised to provide good coupling but not to increase the pressure in front of the launcher too much. A statistical analysis of radiation events, in which no C impurities were observed, shows that arcs occur less often during operation with a well conditioned launcher.

INTERACTION OF THE LAUNCHER WITH THE FAST IONS CREATED BY ICRF AND/OR NBI.

The enhanced radiation in the front of the LHCD launcher is partially a result of the fast ion bombardment of the grill, especially when high ICRH and NBI power is applied. Fast ions are either fusion products, e.g. H(3.02MeV), T(1.01MeV), He^3(0.82MeV) for D plasmas, or can be created by the additional heating of ICRH and NBI, e.g. 1 MeV protons are typical for $(H)D$ minority heating schemes. Factors which enhance the radial excursion of their banana orbits, are larger energies, heavier ions such as T or He^3 and smaller poloidal magnetic field B_p at smaller plasma current I_p. The non-confined fast ions leave the plasma and sputter the in-vessel components: divertor, limiters, RF antennas, etc. thus producing impurities, which are at low ionisation state in the SOL, where the plasma temperature is small. These impurities further radiate through atomic processes of line radiation and recombination.

In JET, early investigations showed that at high ICRH power (> 4.5MW), with the LHCD antenna positioned very close to the plasma, an increased radiation level and large impurity influx from the LHCD grill were observed. An illustrative example of the impurity production by fast ions is shown in Fig.3(a) for a case where LHCD power was switched off but enhanced radiation from the LHCD antenna was detected and the bolometer and UV spectrometer signals were correlated with the launcher movement, i.e. changing distance launcher-limiter.

The impurity radiation tends to increase with the additional heating power in both cases with and without gas injection, Fig.3(b). Investigation of the JET pulses at low LHCD power, $P_{\mathrm{LHCD}} < 1.5$MW, which excludes fast electrons and arcs as a possible cause of radiation, shows that the fraction of the shots with enhanced impurity radiation from the LHCD launcher increases above 5% when $P_{\mathrm{NBI}} + P_{\mathrm{ICRF}} > 8$ MW, Fig.3(c). The reduction of the radiation events for $P_{\mathrm{NBI}} + P_{\mathrm{ICRF}} > 12$MW can be attributed to the fact that in this case LHCD operated with launcher retracted further from the plasma, which can be seen by the increase of the averaged distance launcher-limiter, Fig.3c. Analysis of ICRH-only experiments in JET shows increasing *Fe* and *Ni* line radiation with P_{ICRF}. Orbit calculations of the fast ions for typical experimental configurations in JET show that the non-confined fast particles are moving from left to right in front of the launcher. Taking into account that the second and the third rows are almost always the closest to the plasma ones we conclude that the most likely part of the launcher to suffer fast particle bombardment is the upper left corner, where the most serious harm has been observed.

CONCLUSIONS

The impurity generating processes and their impact on the LHCD launcher are summarised in Table.1.

SOURCES	PROCESSES AND IMPURITIES	ENHANCING FACTORS	IMPACT ON LAUNCH
Fast electrons: 1. Parasitically created in SOL by LHCD (E_e<5keV); 2. From bulk plasma (not likely in divertor configurations);	Increased heat load on the in-vessel components leading to evaporation and/or sublimation: *Fe, Cu, Ni, C*	1. High $N_{\|\|}$ spectrum of the launched LHCD power; 2. High electric field at the grill mouth and in front of launcher; 3. High n_e in front of launcher.	Melted material and grooves-like formations in direction parallel to the magnetic field lines.
Arcs	Evaporation: *Fe, Cu, Ni*	1. High neutral pressure in frontof launcher; 2. High electric field at the grill mouth and in the multijunctions; 3. Non-conditioned launcher.	Melted material and grooves-like formations in the middle of the rows.
Fast ions: 1. Fusion products: *H*(3.02MeV), *T*(1.01MeV), He^3(0.82MeV); 2. ICRH/NBI created: *H*(1MeV); 3. Charge exchange.	Increased heat load on the in-vessel components, physical and chemical sputtering: *Fe, Cu, Ni, C*	1. High ICRH+NBI power; 2. Small plasma current; 3. Launcher positioned near plasma.	Severe damage to the upper-left corner of the grill.

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Table 1.
Possible causes of the enhanced radiation in front of LHCD launcher and their impact on it.

The analysis of large number of pulses shows that the impurity radiation in front of the LHCD launcher depends in a complicated manner on the operating conditions. The latter is confirmed by the different types of damages to the grill. The fast ions are found to be responsible for the enhanced radiation for $P_{\mathrm{NBI}} + P_{\mathrm{ICRF}} > 8$ MW, whilst the destructive action of the other two candidates — the fast electrons and the arcs — depends on the launched LHCD power and the launcher power handling. New diagnostics, which will be available later in 2005, are expected to contribute significantly to better understanding of the radiation causes discussed here.

ACKNOWLEDGEMENTS

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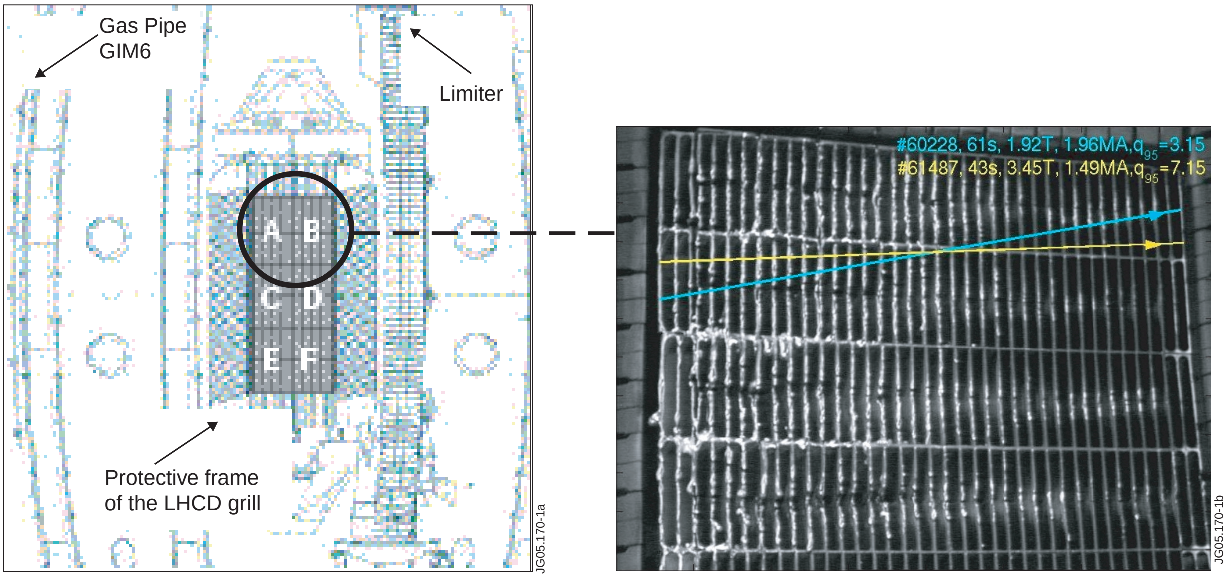

Figure 1: A drawing of the LHCD launcher and the surrounding in-vessel components and a picture of the most damaged upper part, modules A and B, of the grill with the reconstructed field lines in front of the launcher for two typical JET pulses.

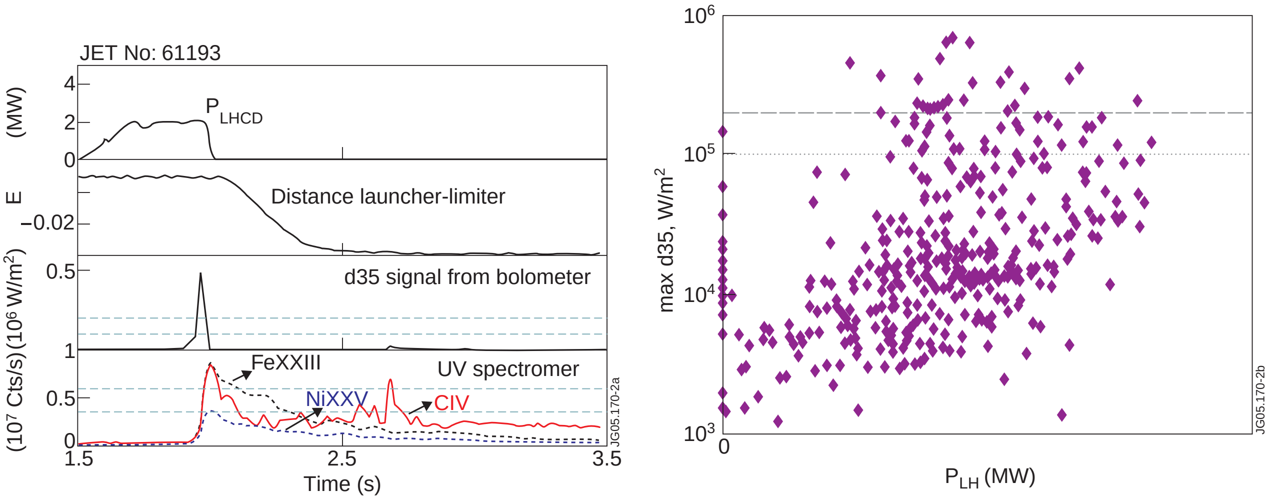

Figure 2: Radiation from the LHCD launcher when LHCD was applied alone a) and max. d35 *vs. LHCD power,* P_{LH}, *from the LHCD-only experimental database b). The present launcher protection limits of* d35 *and* FeXXIII *are given by dotted and dash-dotted lines.*

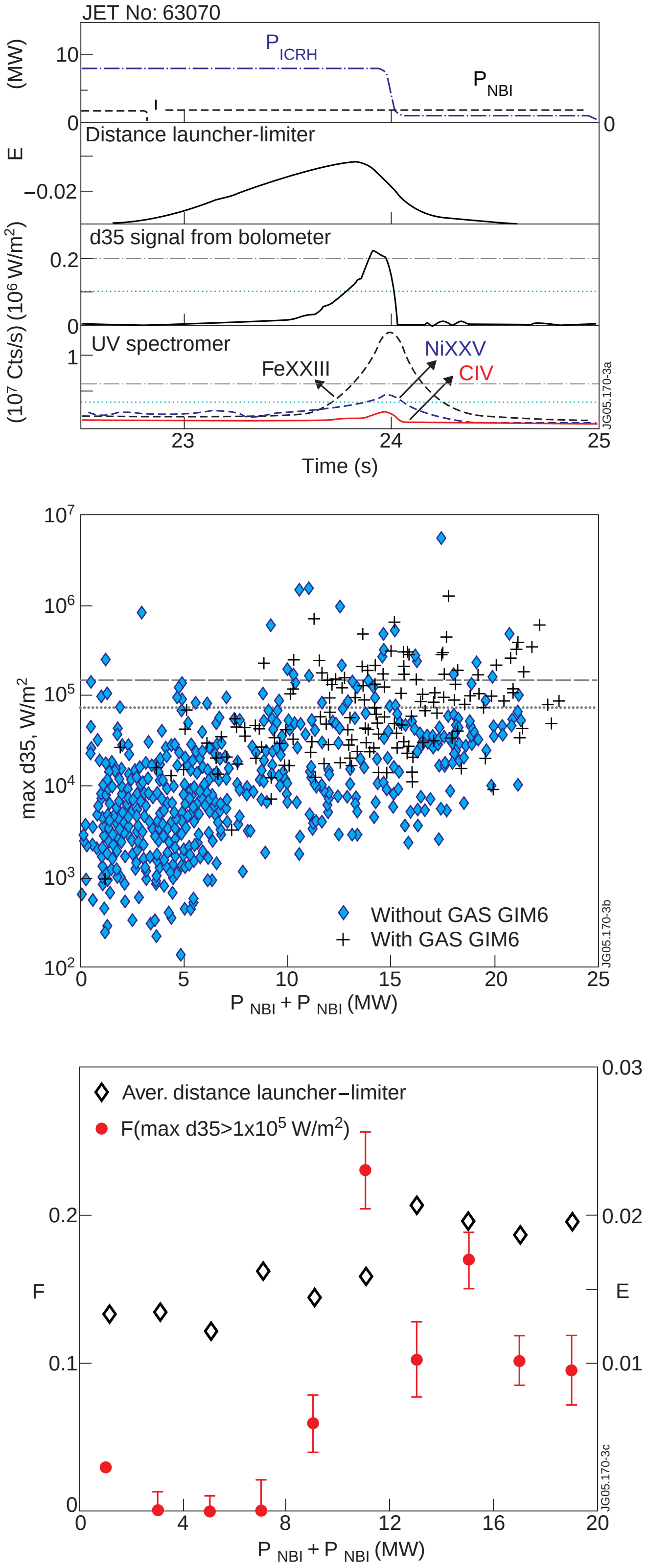

Figure 3: Radiation from the LHCD launcher caused by fast ions with NBI and IRCH applied a) and max d35 *vs. the additional heating power* P_{NBI} + P_{ICRH} *with and without gas injection b). The fraction* F *(points) of the low LHCD power,* P_{LHCD} *< 1.5MW, pulses with enhanced radiation, max.* d35 > *1¥*10^5 *W/*m^2*, and the averaged distance launcher-limiter (diamonds) for selected intervals of* P_{NBI} + P_{ICRH}*, given by vertical grid lines c).*