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** See annex of F. Romanelli et al, "Overview of JET Results", (23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).*

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1. INTRODUCTION

Previously, oscillations between low and high density plasma was reported at JET [1]. In present work we have attempted to develop this further based on the new discovery of Dielectronic Recombination (DR) in singly ionized carbon, C II, at the divertor of the JET tokamak. It is observed at the CFC outer target plate by a direct imaging spectroscopic system covering the far UV up to IR with a wavelength resolution of less than 1 Å. Unlike the direct electron capture processes Radiative Recombination (RR) and Three Body Recombination (TBR), DR is an indirect resonant electron capture process with two electrons simultaneously participating and therefore not allowed for hydrogen, deuterium, tritium and hydrogen-like ions. In the DR process studied in the present work, a free electron is captured by the ground state $1s^22s^2\ ^1S_0$ of C III, the lowest ionization limit of C II, with a simultaneous inner-shell 2s-2p excitation forming doubly excited doublet and quartet states of C II of the $1s^22s2p(^3P)nl\ ^{2,4}L$ terms. characters. If a state of this kind is lying above $1s^22s^2\ ^1S_0$ it might be subject to auto-ionization due to spin-orbit configuration interaction between the LS-allowed doublet and LS-forbidden auto-ionizing quartet states in C II. Although the interaction may be weak, in the order of $10^{-1} – 10^{-2}$ percent, the high auto-ionization rate (A_a) in the order of $10^{13} – 10^{14}\ s^{-1}$ is sufficient for inducing appreciable auto-ionization into quartet states. In present work we have focused on the metastable and the highly auto-ionizing $1s^22s2p(^3P)4s\ ^4P$ and $1s^22s2p(^3P)3d\ ^2F$ resonant states of C II by analyses of the $2s2p(^3P)3p\ ^4D$ - $1s^22s2p(^3P)4s\ ^4P$ and $2s2p(^3P)3p\ ^2D$ - $1s^22s2p(^3P)3d\ ^2F$ transitions lying at 3581-3590 Å and at 7996-8000 Å, respectively, schematically shown in figure 1. The resonant states of the 4s ^4P and 3d ^2F terms are lying 1.60 and 0.41 eV above the $1s^22s^2\ ^1S_0$ ground state of C III, respectively. The level structure of the $2s2p(^3P)3p\ ^4D$ – $2s2p(^3P)4s\ ^4P$ multiplet in Fig.2a is typical at lower electron density (n_e) whereas the one for the same multiplet in Fig.2b is typical for higher n_e. Further details, which are central, on this matter will be specified further on in the paper.

2. THE PROCESS OF DIELECTRONIC RECOMBINATION OF C III

In summary, the DR process is started by interaction between a free electron and a positive ion with production of continuous bremsstrahlung resulting by the energy loss with an amount depending on the distance between the electron and the ion. If the resulting kinetic energy of the free electron, relative to the rest system of the ground state of the ion and its binding energy is matching the energy required for excitation of an inner shell electron, a resonant radiation-less Dielectronic Capture (DC) creating doubly excited configurations of the next lower ion takes place. In the theoretical expression for the intensity (I_{pb}) of an auto-ionizing satellite line is given by equation (1) below, where p and b mean upper and lower levels respectively. The intensity is proportional to electron density (n_e) and to the density of the ground state of C III (n_{CIII}) multiplied with the dielectronic capture rate coefficient (C_d) and branching ratio of captured states that stabilize before auto-ionization.

$$I_{pb} = \cdot n_e \cdot n_{CIII} \cdot C_d \ \frac{A_r}{(A_a + A_r)} \qquad (1)$$

3. DISRUPTION STUDIES FOR ITER

Plasma pulses during the C 20-25 at the JET-campaign devoted to "Disruption Studies for ITER" were analyzed. In the present work we give results from analysis of Pulse No: 77660, a low q disruption. Machine parameters during the measurements were neutral beam (NB) of 14.5MW, an average flat-top value of the current $I_p = 2.0$MA and magnetic field $B(t) = 1.1$T. The development of plasma parameters and spectroscopic measurements can be seen in figure 3 between 23.5 and 26.0s. The intensity pattern of the D_α line (ELM), with its oscillation between ionization and recombination (time resolution of 4ms), is shown between 23.5 and 26s in figure 3d. Figure 3e shows the oscillation of the intensities of the spectral line features of the $2s2p(^3P)3p\ ^4D_{7/2} - 2s2p(^3P)4s\ ^4P_{5/2}$ at 3589.657 Å and the closely lying $2s2p(^3P)3p\ ^4D_{5/2,3/2} - 2s2p(^3P)4s\ ^4P_{3/2,1/2}$ transitions at 3590.86 Å denoted na (non-auto-ionizing upper state) and ma (metastable auto-ionizing upper states), respectively. In figure 3f, the ratio of the line intensities of ma and na (ma/na) between 23.5 to 26s of the pulse can be seen, varying between 0.3 and 0.4. As the maximum value of ma/na at pure LS coupling is 0.73,this means about 50% of recombination and ionization thus being in ionization equilibrium. It is worth noting that the metastable auto-ionizing $^4P_{3/2,1/2}$ levels are being populated by DR only if n_e is getting a value at which the electron collision rates are quenching the metastable auto-ionization probability (A_a) which is a constant and lying around $10^{10}\ s^{-1}$ and thereby may induce fast cooling. Reaching this stage, the plasma must undergo two important steps. In the first one, labelled L-H or transition from low to high confinement plasma mode, depicted in figures 3d for D_α and 3e for C II, we note a sudden but gentle increase of the background (bremsstrahlung) due to closer distance between electrons and ions. Losses of kinetic energies of electrons means a sudden and rapid decrease (in the order of ms) of bremsstrahlung at 23.63s due to electron capture into the interaction zones of the ions. Some captured electrons may have sufficient kinetic energy for population of D_α and C II by RR and DR, respectively, with subsequent formation of high frequent line features labelled ELM III, which was not the case in present pulse, however.

With sufficient increasing of n_e a so called H-L (high to low confinement transition) may occur which can be seen at 23.97s in figures 3 and 4. In the case of C II, the L-H transition is triggered at a certain n_e at which the metastable autoionization rate $A_a \sim 10^{10} s^{-1}$ is quenched by the rate of collisions. In figure 4 we can see the regular behaviour of the ma line between H and L modes or C^{2+} and C^+ made possible by the energy reversed Auger electron and electron capture processes.

The pulse is ended through a disruption which can be seen in figure 5 which shows the saturated ma feature. At the disruption the ma line has obtained its full LS value labelled giant C II-ELM which was about 15 times stronger than at ionization equilibrium. We can also see that at the disruption the highly auto-ionizing $2s2p(^3P)3d\ ^2F$ states, situated 0.41eV above $1s^22s^2\ ^1S_0$, the lowest limit, is a proof on the low temperature at the disruption. As in the the case for radiatively activation of the metastable autoionizing states with $A_a \sim 10^{10}\ s^{-1}$, there is an analogous case for the highly auto-ionizatio levels of 3d ^2F with a quenching of $A_a \sim 10^{12} s^{-1}$ by the rate of particle collisions inducig a $T_e \sim 0.4$eV at the disruption. Notable in figure 6 is the influence of STARK effect on 3p ^2D -3d ^2F and the D(3-12) line (see figure 6).

4. MODEL DESCRIPTION OF POPULATION BY DIELECTRONIC RECOMBINATION.

The rates of $A_a(n)$ and $A_r(n)$, varying as $1/n^3$, implies high probability of population of high lying meta-stable and highly auto-ionizing states as it might be expected that these rates then will be superseded by the rate of collision processes. In order to theoretically describe the influence of DR, inclusion of a large number of doubly excited states with n ranging up to ~ 100 has been proposed [2] Cascading will progress stepwise downwards the doubly excited term system with a simultaneous low rate of the auto-ionization channel $1s^2 2s2pnl' \rightarrow 1s^2 2s^2 + \varepsilon l''$. The cascade population contributions may reach a level for which A_a is comparable or larger than the rate of collision processes the so called Saha-Boltzmann limit or the thermal limit [bb]. States above this limit are considered to be in LTE (Local Thermodynamic Equilibrium) or Saha-Boltzmann equilibrium. States below the limit subject to auto-ionization are much less populated. With increasing n_e, A_a may be quenched by the increasing rate of electron collisions and the level population by dielectronic recombination may proceed downwards in the term system in a stepwise and accelerated manner, so called continuum lowering. The acceleration of the cascading is due to the fact that still higher n_e, produced by the powerful cooling property by the DR process, is needed to compete the rising A_a, due to the $1/n^3$ dependence, downwards the term system. Finally the continuum lowering will reach the lowest resonance states with a subsequent inducing of a larger accumulation of level population with higher decay rate being in the nanosecond range made possible by the quenching of the lowest metastable auto-ionization probability A_a. The accumulative population is thus contributed both by cascading and population by DR of the lowest resonance levels with transition lines ranging from UV up to and beyond the IR wavelength region.

CONCLUSIONS

In present work we have for the first time, to the best of our knowledge, identified Dielectronic Recombination (DR) at the edge of the JET tokamak. The resonant behaviour of DR could be a clue for the atomic physics behind the L-H transition, ELM and disruption.

References

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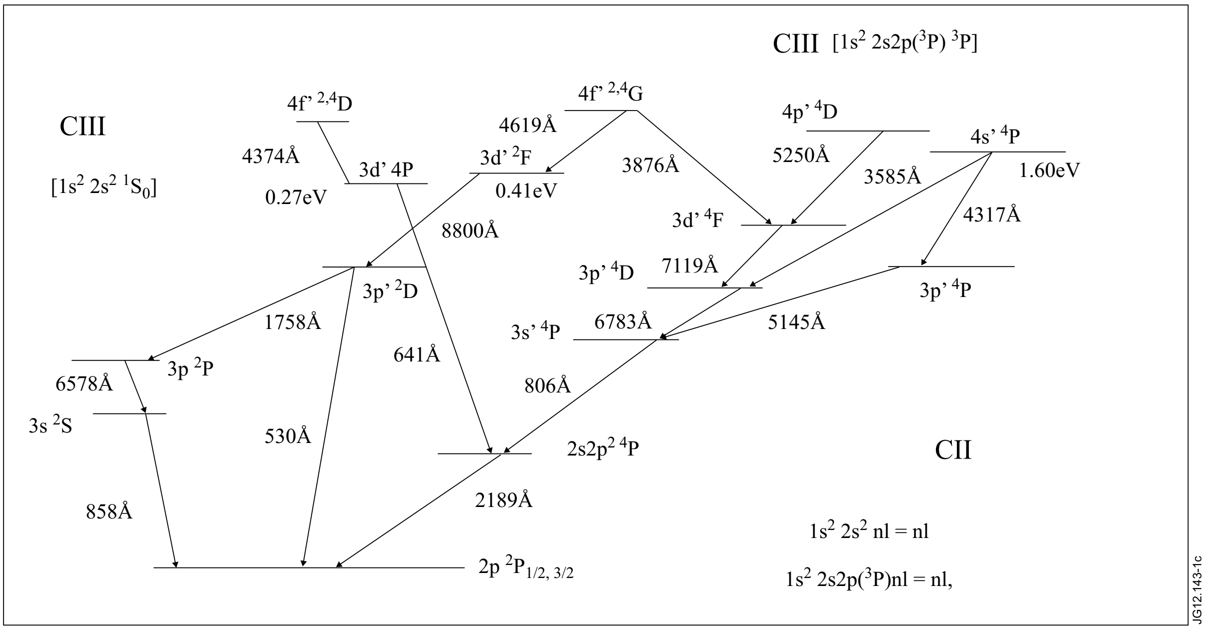

Figure 1: Schematic energy level diagram showing the low lying levels above the first ionization limit of C II subject to metastable and highly autoionization quartet and doublet states respectively.

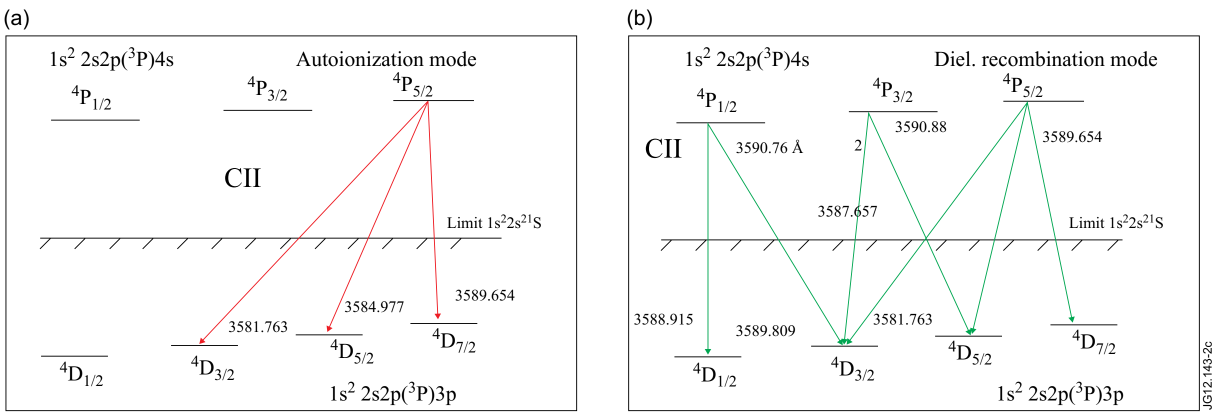

Figure 2: Figure 2a shows a level diagram of the resonant $2s2p(^3P)3p$ ^4D – $2s2p(^3P)4s$ ^4P transition in the auto-ionization mode. Figure 2b shows the transition in the dielectronic recombination (DR) mode.

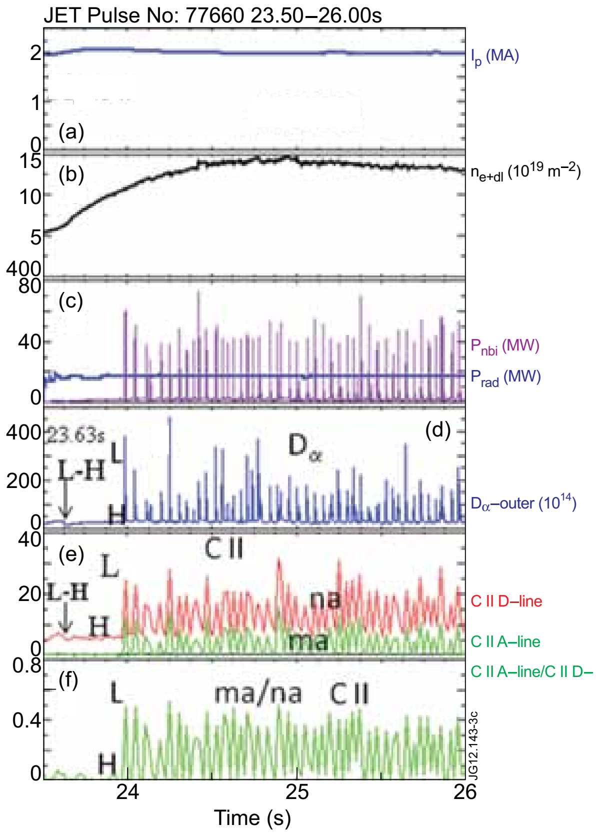

Figure 3: Parameter values of the Pulse No: 77660 rcorded during disruption studies for ITER, see text.

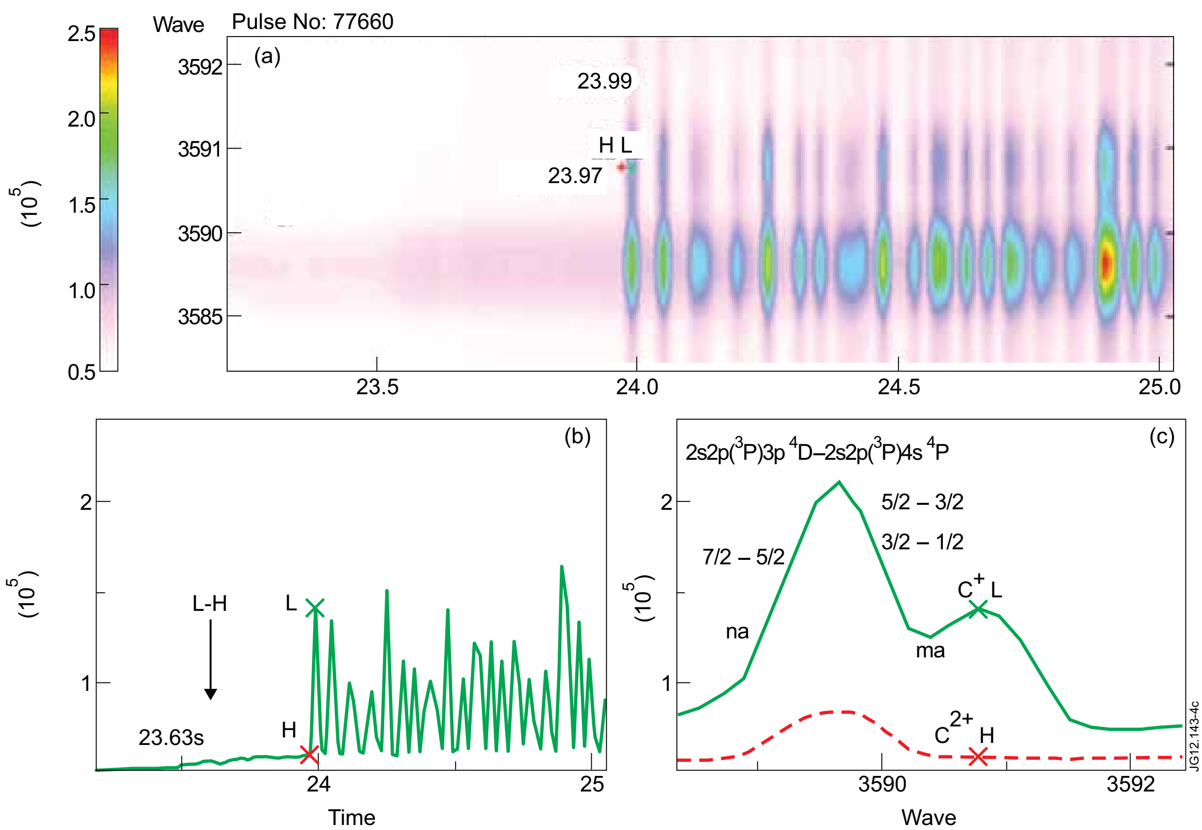

Figure 4: Initiation of the C II-ELMs at 23.97s. Note the oscillation between C^{2+}(H-mode) and C^{+} (L-mode).

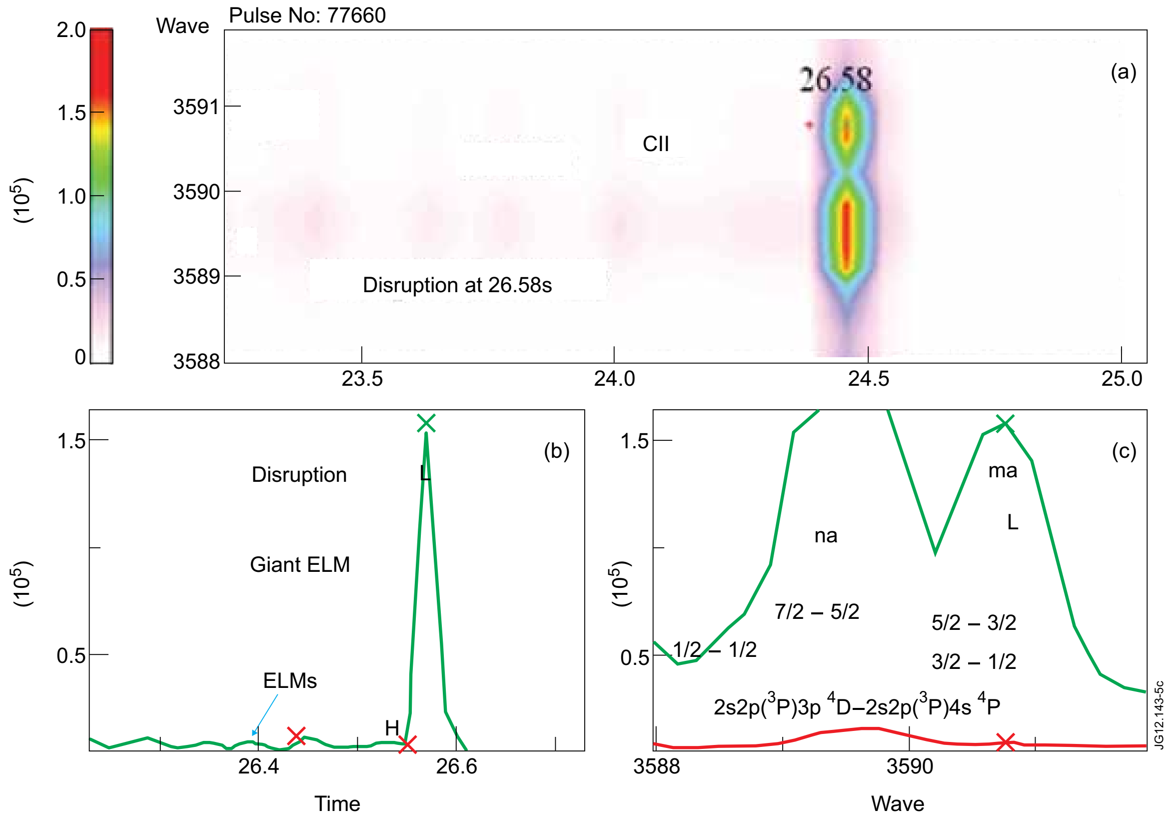

Figure 5: Note the size of C II-ELMs before the giant ELM being 15 times stronger and causing a disruption. The na-line (5/2-3/2 and 3/2-1/2 components) of the $3p^4D-4s^4P$ transition have achieved their full LS-intensities which means no autoionzation is "left over" indicating no possibility for achieving ionization equilibrium leading to disruption.

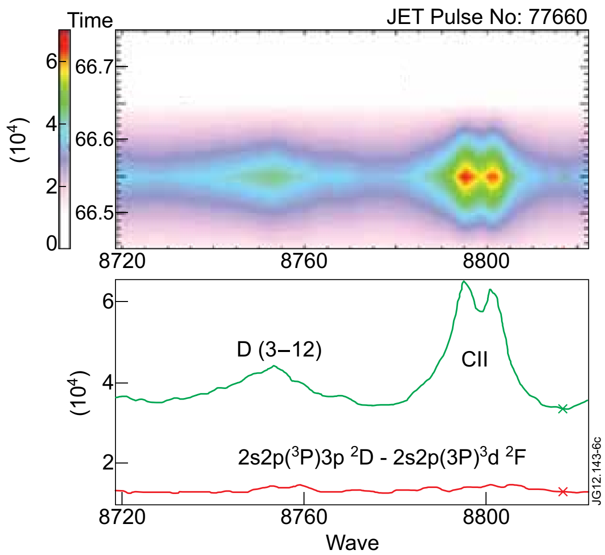

Figure 6: Another spectral feature becoming visible at disruptions is the $2s2p(^3P)3p\,^2D-3d\,^2F$ transition at 7996-8000 Å with the highly autoionizing ($A_a \sim 10^{12} s^{-1}$) with $3d\,^2F$ lying only 0.41 eV above the $1s^22s^2\,^1S$ ionization limit of C II, the groundstate of C III. This is an indication of the low T_e at the disruption (see also text).