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INTRODUCTION

Runaway electrons (RE) with energies of several megaelectronvolts have been observed during disruptions in JET [1] and other large tokamaks. These intense electron beams are the result of the toroidal electric field induced by the sudden cooling in connection with disruptions and may cause severe damage to the plasma facing components. Therefore REs are considered to be a potential threat to the operation of tokamaks with high currents, such as ITER [2]. Reliable runaway electron (RE) mitigation after disruptions is one of the most important challenges for safe ITER operation. A proper understanding of the generation and loss of REs is therefore essential.

This paper investigates the effect of the ITER-like wall (ILW) on RE generation in JET. The ILW comprises solid beryllium limiters and a combination of bulk tungsten and tungsten-coated carbon fibre composite divertor tiles. Similar JET disruptions in Lmode limiter discharges are compared with different wall materials: carbon (Carbon Fibre Composite, CFC) and beryllium (for ILW). In both cases the disruption was induced by slow argon injection. Typically with the ILW, a significantly lower fraction of energy is radiated during the disruption process, yielding higher plasma temperatures after the thermal quench (illustrated in figure 1a) and thus longer current quench times [3, 4], as illustrated in figure 1b. As a consequence, in the carbon wall case, a runaway electron plateau is observed, while with the ILW the runaway current is negligibly small. Runaway electron dynamics is a complicated process [5], therefore numerical modelling is necessary to provide a deeper insight into the physics. Detailed modelling was carried out to study which factors affected the RE formation in these two cases [6].

1. MODELLING

The post-disruption current profile is calculated by a self-consistent onedimensional model of electric field, temperature, density and runaway current taking into account impurity evolution. The details of the model can be found in refs. [5, 6]. The time evolution of the current density profile is determined by the runaway electron generation and the diffusion of the electric field governed by the parallel component of the induction equation. The changes of the electric field are mainly determined by the short time scale changes of the conductivity, which strongly depends on temperature ($\sigma \propto T_{3/2}$). The model also includes a conducting plasma vessel but neglects coupling to the coils. The primary generation is calculated via the Dreicer process [7] and the seed runaways are amplified via avalanching [8]. Hot tail generation is efficient if the cooling rate is comparable to the collision frequency and has been predicted to be important in ITER disruptions, but in the cases studied in this paper, the cooling times are long enough for the Dreicer generation to dominate over hot-tail generation.

As inputs, the GO code requires the predisruption electron density- and temperature profiles (obtained by High Resolution Thomson Scattering) and a specification of the neutral impurity density as function of time and radius. The time evolution of the neutral impurities is often assumed to be an exponential ramp-up, with a characteristic time on the ms timescale in agreement with numerical modelling [9]. The exact amount of impurities penetrating the plasma is unknow and therefore impurity amounts are scanned in our modelling while searching for an agreement with the experimentally measured runaway current and radiated energy. The temperature and density evolution is modeled separately for each plasma component – electrons and Zi ions. Ohmic heating, line radiation, ionization, recombination and Bremsstrahlung losses were also taken into account. Due to the different collision times the different species are modeled separately. The energy balance equations are coupled with collisional energy exchange terms between Maxwellian species. The heat diffusion coefficient is assumed to be constant ($\chi = 1\ m^2/s$). Radiation has the strongest cooling effect on the electrons. To describe the line radiation the ionization of the impurities is taken into account by calculating the density of each charge state for every ion species solving the rate equations with density- and temperature dependent radiation rates extracted from the ADAS database.

2. RUNAWAY GENERATION WITH THE ITER-LIKE WALL

One of the major differences compared to disruptions with the carbon wall is that a lower fraction of energy is radiated during the disruption process, yielding higher plasma temperatures after the thermal quench. This will in turn affect the runaway formation. Drawing definite conclusions from the experiments at present time is difficult due to the limited number of runaway experiments carried out with the ILW so far. In the CFC case the temperature after the thermal quench is ~10eV, which gives rise to runaways with a significant current plateau. In the ILW case the post thermal quench temperature is significantly higher, which results in a slower current quench and only a negligible amount of runaways. As the result of relatively low plasma density coupled with increased wall sputtering in L-mode, these discharges have substantial steady-state wall impurity content. However, the level of impurity sputtering from the walls as well as the efficiency of argon mixing during the disruption is not well known. The argon content can be estimated based on the total injected argon amount with a reasonable assumption of *O*(30)% for the mixing efficiency [10].

In the model the amount of injected argon and carbon/beryllium is scanned, which had an impact of the modelled runaway current as can be seen in figure 2. Figure 2 shows the effect of argon and carbon (a) / beryllium (b) content on the modelled runaway currents, where the impurity amounts are expressed as a fraction of the predisruption plasma electrons. Increasing the argon content resulted in a larger runaway current, while a lower value was found for higher carbon/beryllium contents. The differences are due to the nonlinear nature of the runaway evolution that amplify the differences in the initial temperature- and density profiles, injected argon amount and the presence of different background impurities, all of which amplify each others' effect. The presence of beryllium effectively reduces the runaway current at argon contents of experimental relevance. As low as 10% beryllium leads to a factor of two decrease in runaway current. The obtained runaway current values from the model can be compared with those obtained in the experiment, as shown with magenta rectangles in figure 2, suggesting the actual impurity concentrations in these discharges. The presence of impurities also decreases the relative fraction of primary runaways. Beryllium increases the avalanche fraction more than carbon, that can be useful as the characteristic growth rate of avalanche is an order of magnitude lower than for Dreicer generation. This means that runaway loss mechanisms have more time to have an effect. The simulations indicate that the impact of the wall impurities on the runaway current and Dreicer fraction reduces with increasing argon content (for the plasma parameters in these shots) . At values of 50% argon content the behaviour in comparable. This suggests that REs will probably return in future experiments regardless of the ILW when argon is used in large quantities in massive gas injection (MGI) experiments on JET.

3. THE EFFECT OF RUNAWAY DIFFUSION

In general, magnetic perturbations can come from deliberate external perturbations, MHD activity, error fields, the response of the control system to the disruption, instabilities enhanced by the gradients during runaway evolution; all of which can lead to increased radial runaway transport. The Rechester-Rosenbluth diffusion [11] was used to demonstrate the effect of magnetic perturbations on runaway current evolution. The magnetic perturbations are kept constant in space and time as this is sufficient to demonstrate the effect and only requires one free parameter, B/B. For simplicity, the evolution of the main plasma parameters such as temperature is taken from the experimental data and Zeff = 1 is assumed. Without runaway losses due to magnetic perturbations, the simulations end with a considerable runaway current in both shots, although its value is higher in the C wall case than in the ILW case. The current evolution is best matched with the experiment at a perturbation level of $\delta B/B = O(10^{-3})$. With a constant perturbation the runaway plateau cannot be reproduced, but otherwise the main features of the current evolution (such as the current decay rate) are similar. With a perturbation level of $\delta B/B = 10^{-3}$ the runaway redistribution rate is comparable to the generation rate and the runaways spread out in the plasma before they can form a strong runaway population. Even if the runaways are not completely removed, the runaway current density is decreased which in turn decreases the avalanche generation rate.

Figure 3 shows the modelled peak runaway current normalized to the predisruption current for the CFC and ILW cases for which the δB/B value was varied. The obtained results can be compared with the experimental values (measured in the plateau) as shown by the shaded areas in figure 3. It was found that the maximum value of the runaway current drops exponentially as a function of δB/B for both cases, but the relative RE current peaks reached are significantly different for the two walls cases. The reason why in the simulation the ILW case is more sensitive to magnetic field perturbations, is not only because for the CFC case the toroidally induced electric field is larger, but also through a different evolution of the plasma density-, temperature- and effective charge profiles yields a stronger Dreicer mechanism. As the Dreicer generation is approximately one order of magnitude faster than the avalanche mechanism, radial diffusion losses (as well as other loss mechanism) can be more easily counteracted by the runaway growth if primary generation overwhelms avalanching.

SUMMARY

Our simulation results show that the differences between the CFC wall and ILW cases are due to the positive feedback effect between (1) the different plasma parameter profiles due to the different wall, (2) the difference in the injected/mixed argon amount, and (3) the different radiation characteristics of beryllium and carbon. Variations in the argon content in these simulations have a considerable effect on the runaway generation. The Dreicer fraction is reduced by the presence of beryllium, but is almost unaffected by the presence of carbon. This results in a lower Dreicer current generation in the ILW case compared with the CFC wall case. The runaway population in the ILW case consists mostly of slowly growing avalanche runaways and they are effectively transported out from the plasma by a low level of magnetic perturbations or other losses. Note, that the presence of beryllium is beneficial only if the amount of argon is not too large. Above ~50% argon content the radiation of the argon takes over and the differences due to the wall material eventually vanish. In view of the results of this paper, upcoming massive gas injection experiments with the ILW on JET will most probably have to face with the reoccurance of runaways for the scenarios that produced runaways using MGI with the carbon wall. Dedicated runaway experiments with the ILW on JET are necessary to be able to better estimate the runaway behaviour in ITER.

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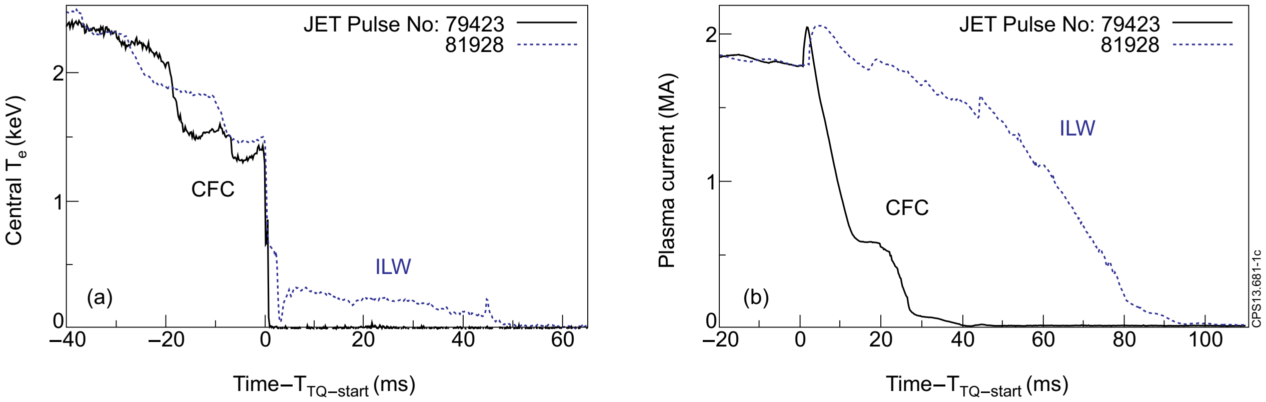

Figure 1: (a) Time evolution of the central electron temperature Te measured by ECE. (b) Time evolution of plasma current during the current quench. Significant runaway plateau for Pulse No: 79423 (CFC), slow and steady drop for Pulse No: 81928 (ILW).

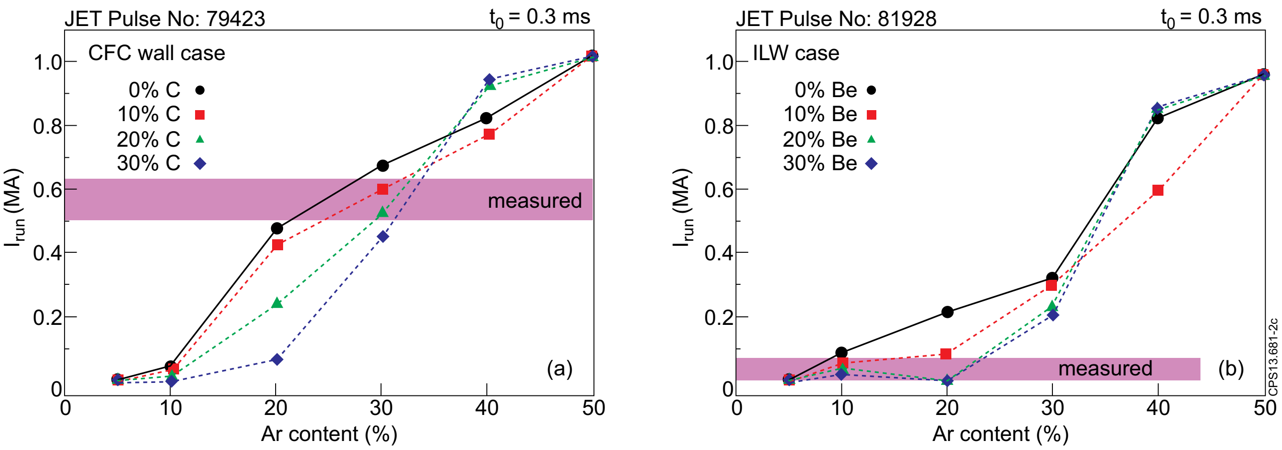

Figure 2: Runaway current for various argon and (a) carbon (CFC wall case) or (b) beryllium (ILW case) contents in the representative discharges. The magenta rectangle marks the experimentally measured range of runaway current.

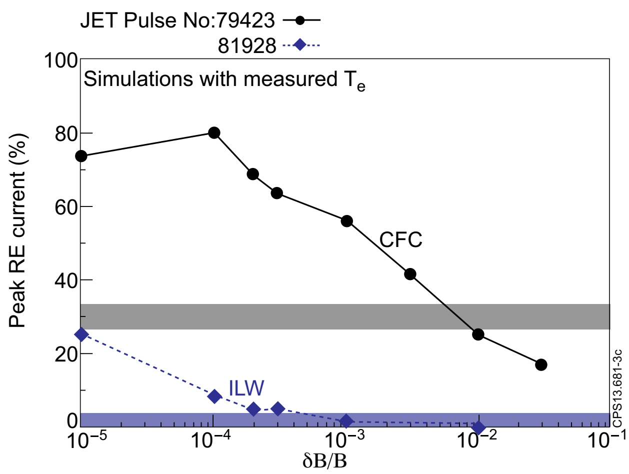

Figure 3: Peak runaway current normalized to the predisruption current as a function of δB/B for the two cases.