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MARFE and Density Limit Detachment with the Tore Supra Actively Cooled Limiter

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In the long pulse scenarios envisaged on Tore Supra with the actively cooled toroidal pump limiter, high densities triggering a MARFE [1] or detachment might lead to difficulties in pumping and coupling the RF additional heating sources to the plasma. During the last campaign a preliminary ohmic experiment was dedicated to studying high density plasmas up to the MARFE onset. The MARFE characteristics are described here, and MARFE precursors are identified.

1. Radiation and impurities during the density ramp

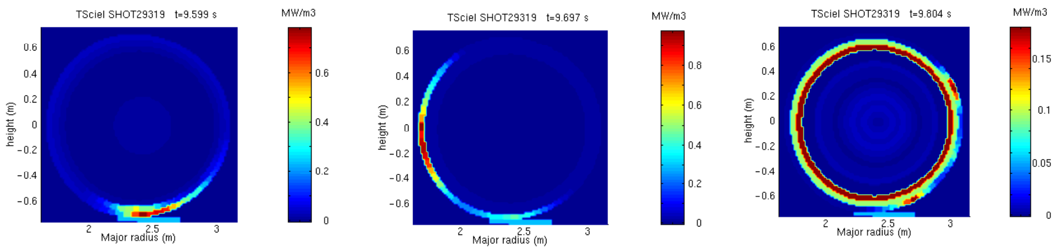

Figure 1: Tomographic reconstruction of the radiated power (left) before the MARFE, (center) during the MARFE and (right) after symmetrisation, from bolometric measurements

A series of deuterium ohmic discharges was performed, in which the D_2 gas injection was fed back on the line integrated electron density. The target density was set to a value above the density limit and the gas injection rate was set to such a value as to reach this density limit at the end of the current flat top. This scenario allowed us to follow the approach to the MARFE and detachment. For the present study the total radiated power distribution was reconstructed from the measurements by a set of 16 horizontal bolometric chords. A high resolution visible spectrometer was used to analyse the emission collected by two lines of sight: one with a perpendicular view of the limiter surface and the other one traversing the plasma on the midplane and viewing the inner wall (and the MARFE). No Langmuir probe was available for this experiment.

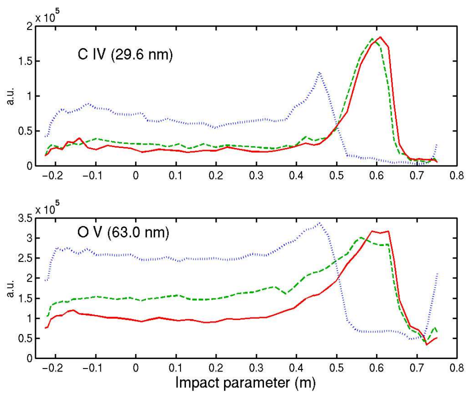

Figure 2: C IV (top) and O V (bottom) brigthness profiles 0.4 s (solid line), 0.2 s (dashed) before the MARFE and after symmetrisation (dashed-dotted).

Before the MARFE onset (Fig.1, left), the power is radiated mainly from a region (volume 1.4 m^3, 6% of the total plasma volume) located in front of the limiter. We deduce from the Dα lineshape emitted in front of the limiter the energy distribution width of the cold atoms produced by molecular dissociation [2]. It is around 2.6 eV, constant during the density ramp. Brightness profiles of C IV and O V (Fig. 2) have been measured on a duochromator equipped with an oscillating mirror which allows to scan the lower half of the plasma in 200 ms, including the region of interaction between the plasma and the limiter. The C IV emission is known from previous experiments to be located very close to the carbon source (i.e. the limiter) and poloidally asymmetric because of its relatively low ionisation potential (64.5 eV). The C IV emission profile shape remains stationary up to the MARFE occurrence, indicating that no change in the carbon source (and thus presumably in the production mechanism) occurs. The O V emission is located farther in the plasma because of its higher ionisation potential (113.9 eV) and thus more poloidally symmetric. As the density is increased, the inner side of the O V profile peak broadens continuously inward and the profile peaking (peak height compared to flat part of the profile) decreases. This behaviour, characteristic of the increasing penetration of the O V radiation is consistent with a continuous flattening of the radial T_e gradient profile, as observed by the ECE radiometer (Fig. 3), rather than to a transport modification during the density ramp-up. In these discharges, a small but unknown nitrogen gas (not air) flow was continuously injected due to a leak in the D_2 injection line. The behaviour of a N IV line at 28.4 nm shows that it is similar to C IV, in that the profile shape is constant almost up to the MARFE (it starts broadening only about 400 ms before the MARFE onset). However, the peak is broader and its radial position is closer to the O V peak position. The continuous increase of the power radiated by oxygen is thought to trigger the thermal instability responsible for the MARFE (see below). Note that the vessel was poorly conditioned, which resulted in an unusually high oxygen to carbon concentration rate.

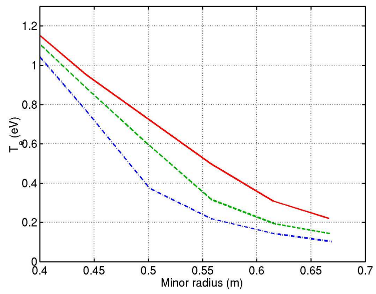

Figure 3: radial T_e profile as measured by ECE (minor radius 0.72 m)

In order to study the impurity behaviour, we have used the 1D core transport code MIST [3], with a modification of the MIST charge exchange model. The widely used scaling law ($R = 2\times10^{-15} Z^{1.14} T_i^{-0.35}$ [4]) has been replaced by the model proposed in [5], which uses recommended ion- and state-specific rates for carbon and oxygen. Using the improved CX rates, the observed steady increase in radiative power has been simulated in MIST under the assumption of constant impurity (C, N, and O) influx, by assuming a steadily rising neutral deuterium density as the MARFE is approached. This rise is simulated consistently with the observed radial T_e gradient flattening (Fig. 3), while an increase in C and O content caused by an increase of the sources is unlikely, as the edge temperature, for example, is expected to decrease with rising edge density. Fig. 4 shows the total radiation (C, N and O) from the simulation compared with the radiated power as reconstructed from the horizontal bolometer data, with and without the effect of CX. In the absence of the C VI and O VIII Lyα line measurements, the oxygen to carbon concentration ratio was assumed to be 1/3, a result obtained in previous experiments with similar plasma and vessel conditions. This assumption results in approximately equal carbon and

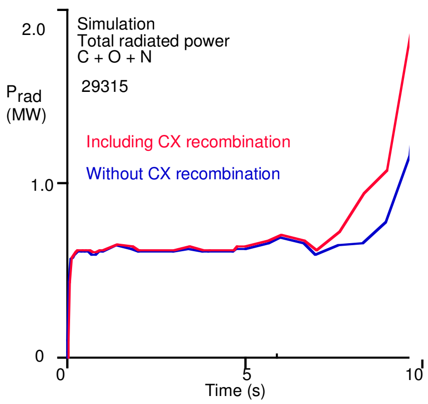

Figure 4: Simulated total radiated power with and without charge exchange

oxygen contributions to radiated power.

2. MARFE characteristics

The MARFE appears in these experiments as a radiating object which leaves the limiter radiating region (15% of the total radiated power remains in this region) and moves up to the high field side midplane (Fig.1, center) with a velocity of about 26 m/s deduced from the rise time measured on the bolometric lines of sight. According to tomographic reconstructions of the bolometric signals, the MARFE poloidal extension is variable but generally larger than the limiter radiating zone: about 45°(FWHM), with a smaller radial extension: less than 6 cm (spatial resolution of the reconstruction), which corresponds to about 4% of the plasma volume. Due to the reconstruction technique, the exact radial location of the radiation maximum is not determined but it can be inferred from the data that the radiation is emitted on both sides of the LCFS. During this phase of the discharge, the total radiated fraction rises from 90% just before the MARFE onset up to 100%, 44% being radiated in the MARFE volume. The trigger criterion $\rho = \pi a^2 n_e / I_p$ given in [1] varies from one shot to another from 0.62 down to 0.44, this variation representing fairly well the degradation of the plasma purity due to the nitrogen leak. On other occasions, stable MARFEs or detached plasmas have been observed with ρ between 0.57 and 0.76.

The bremsstrahlung emission used to deduce the plasma effective charge and measured by a set of horizontal lines of sight is seen to increase only when the MARFE is located in the field of view of these lines. This is an indication that this increase is due to the presence of the MARFE rather than to a core impurity content modification. At the same time we deduce from the Dα brightness that the recycling decreases on the limiter. The C II temperature on the limiter decreases from 15 eV down to 10 eV, which is attributed to a decrease of the physically sputtered flux relatively to chemically produced C atoms and/or a decrease of the sputtered atom kinetic energy, denoting in both cases a T_e decrease at the limiter. This is accompanied by a drop of the C II brightness. All these observations support the hypothesis of a constant impurity core content made for the simulation studies described above.

The D atom temperature deduced from the Dα lineshape to be 4 eV in the peripheral layer at the midplane before the MARFE decreases down to 2 eV when the MARFE is in the field of view of the line of sight. A preliminary analysis shows that the Stark broadening of the Dα line seems to be present, although very weak. We deduce that the electron density (assumed to be equal to the ion density) in the emission region is not higher than 5×10^{20} m^{-3}. The C^+ temperature also drops from 34 eV down to 10 eV. The radiation continues to extend toward the top of the plasma and then to its low field side with the same velocity, while it starts to extend more slowly (2.4π rad/s) back toward the bottom of the plasma a few tens of ms later. Radiation symmetrisation (Fig. 1c) is achieved in about 200 ms. When symmetrisation is achieved, the C^+ temperature in the limiter vicinity and the C II brightness remain constant, from which it is inferred that the carbon source does not recover the 'attached' level.

3. Precursors

One of the aims of the experiment is to identify criteria which could be used to feedback-control the deuterium injection and avoid the occurrence of MARFEs in high density scenarios. Since no Langmuir probe can be installed permanently on the limiter because of the expected high heat flux, the usual criterion of the ion saturation current drop is not available. The bolometric signals are used to define the MARFE onset but no early change in the signals is observed which could be used to prevent the MARFE occurence. Among the available measurements, a high spatial resolution infra-red camera provides measurements of the heat flux pattern evolution with the density. However, in these preliminary ohmic experiments, the total power is so low that the heat flux deposition pattern [6], clearly observed in visible light, cannot be seen with the IR camera. The measurement of the current I_{L-V} flowing between the limiter and the vessel (Fig. 5) [7] shows that it is proportional to the line integrated density in the lower density phase of the discharge. In the later phase it exhibits a systematic maximum about 1.5 s before the MARFE onset followed by a rollover, thus revealing a change in the plasma edge resistivity. The deviation of I_{L-V} from the linear expectation can be used to define a criterion but as the proportionality coefficient depends (among others) on the wall status, the linear part of the dependence has to be explored for each pulse. The Dα emission on the limiter, a measurement of the recycling, shows a behaviour similar to I_{L-V} both for the cold component due to molecular dissociation and of the warm component due to fast reflected and charge exchange atoms. The C II and C III emission exhibits a steep increase and a sharp maximum just before the MARFE onset, followed by a sudden drop, due to the quasi-suppression of the incident particle flux. We propose the C II to Dα brightness ratio as a 'detachment criterion'. Compared to the I_{L-V} criterion it has the advantage of being independent from the incident particle flux variation and the D wall content. However it seems to depend on the vessel condition.

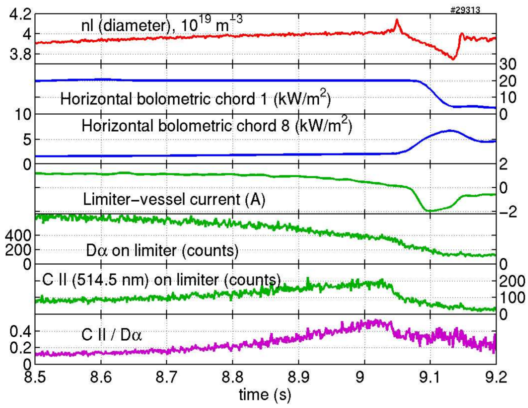

Figure 5: time traces for the identification of MARFE precursors

Conclusions

A series of preliminary ohmic experiment has produced classical MARFEs followed by transient detachment by means of gas injection. The impurity source decreases at the MARFE onset, and simulations show that the radiation increase is well reproduced with the only hypothesis of a T_e radial profile flattening leading to enhanced CX-populated ions. The C^+ temperature in the MARFE (10 eV) is three times lower than in the attached peripheral plasma. For these low power discharges, the IR thermographic measurements cannot be used to prevent the occurrence of MARFEs. Two criteria are proposed: the deviation of the limiter-vessel current from its linear dependence to the density, and the C II/Dα brightness ratio on the limiter, which has the advantage of being independent of the incident flux.

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