High resolution n_e and T_e profiles during the energy quench of density limit disruptions in RTP

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The power yield of a tokamak reactor increases with plasma density as does the ratio of edge radiation over heating power. Both effects are beneficial except that at high density the plasma can be abruptly lost during a so-called plasma major disruption [1]. This event is initiated with the energy quench, where the energy confinement is totally lost. Despite the large difference in sizes and different geometry's between today's tokamaks, the precursors and the current quenches of disruptions show similar behaviour in the different devices. The innocuous effects of disruptions in small tokamaks make these very suitable for their study. Besides of its small size, RTP (Rijnhuizen Tokamak Project, $a = 0.16$ m, $R_0 = 0.74$ m) was equipped with a set of very good diagnostics that allowed to probe the energy quench with high spatial and temporal resolution. In this paper we analyze the energy quench phase in density limit disruptions of RTP plasmas ($I_p = 100$ kA, $q_a \simeq 4$) that come after the growth of a $m = 2$ mode. The density was increased by puffing Ne gas in a He plasma ($\bar{n}_{e\Omega}^{max} \approx 3.9 \times 10^{19}$ m^{-3}). This recipe made the disruption events very reproducible and kept the density limit below cut-off of the ECE-channels. The time evolution of $T_e(r)$, was measured with a 20 channels ECE radiometer, with 1 μs time resolution, along a horizontal chord throughout the equatorial plane. Perpendicularly, along a vertical chord, $T_e(r)$, $n_e(r)$ profiles with 3 mm spatial resolution were measured by Thomson scattering (TS). In order to scan the energy quench the TS was triggered by a signal proportional to the amplitude of $\tilde{B}_{\theta,m=2}$. In RTP there are two types of $m/n = 2/1$ precursors [2]. Here we will only discuss the type that is characterized by an exponential increase of $\tilde{B}_{\theta,m=2}$ for a short period of ≈ 0.5 ms prior to disruption. However, the findings here reported are common, irrespective of the type of precursors[3]. Mode locking was never observed *i.e.*, the mode rotation slowed down but never came to rest.

Events before the negative voltage spike. The evolution of $T_e(r)$ measured by the ECE radiometer is shown in Fig. 1(a). With the purpose to simplify the discussion, the time origin ($t = 0$) was set to coincide with the last time the $m = 2$, X point passes in front of the ECE radiometer, before the observed collapse in T_e at the plasma core. From the excursion of the isothermals in Fig. 1(a) outside the $m = 2$ mode towards the edge, it becomes clear that some degradation in energy confinement starts already at approximately $t = -250$ μs. This degradation originates in the plasma core with a slight erosion of the $m = 1$ mode cold point. The heat lost in the core flows to the edge provoking the expansion of the temperature profile. At half radius, erosion of the T_e profile is observed at $t = -50$ μs, $\rho = 0.5$. At this time the 262 eV isothermal describes a slight, excursion towards the plasma core. This excursion originates at the same angular position of the $m = 2$, O point (see arrow A) and it is symmetric in time around the O point. Around $t = 0$ μs in the plasma core, the energy confinement degrades faster, as can be seen by the widening of the dark gray region in the cold point of the $m = 1$ mode at $\rho \approx -0.25$. At the same time, the 262 eV isothermal crosses the $m = 2$, X point and advances towards the plasma edge in the LFS.

From $0 - 40$ μs, as the O point passes in front of the ECE radiometer, it is observed that erosion of the T_e profile is already significant (see arrow B). The temperature in the cold point of the $m = 1$ mode decreased 50% and is equal to the temperature in the $m = 2$, O point, in

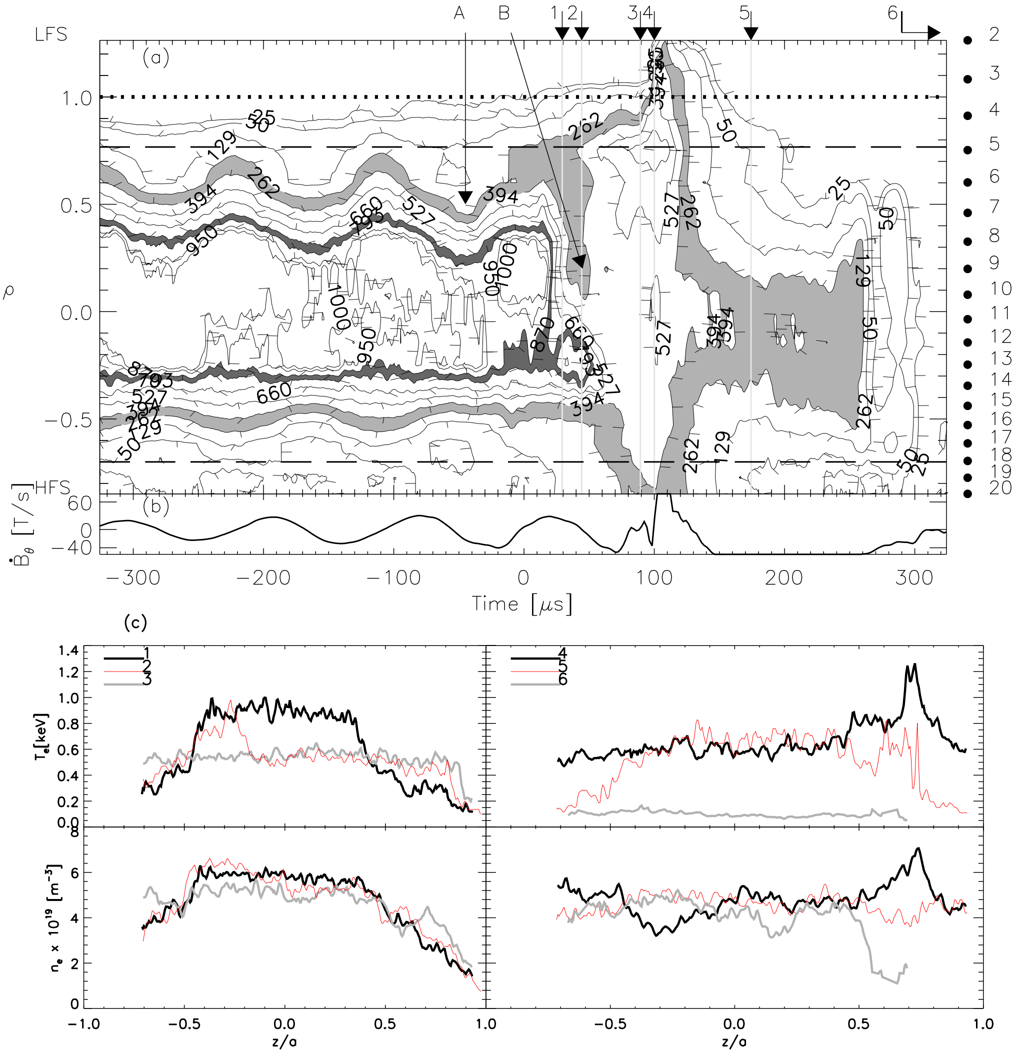

Figure 1: (a) Time evolution, with 1 μs time resolution, of the radial temperature profile measured by the ECE radiometer. The position of the channels is indicated at the right. The arrows indicate the time of the TS profiles shown in (c) measured during identical but separate discharges. The TS profile 6 is at $t \approx 700$ μs. The horizontal dashed lines indicate the position of the $q = 2$ surface. The dotted line indicates the vertical position of the top/bottom rail-limiter. (b) $\dot{B}_\theta$ at the equatorial plane in the LFS and displaced a toroidal angle of 150° from the ECE radiometer. (c) TS T_e and n_e profiles at times indicated in (a) 3 mm spatial resolution.

the LFS. During this period, T_e in the $m = 2$ mode appears to be rather homogeneous, but that is a consequence of the low spatial resolution of the ECE radiometer. As seen in the first TS profile in Fig. 1(c) (T_{e1}^{TS}) the temperature profile inside the island is irregular. In T_{e2}^{TS} the T_e profile between the $m = 2$, X point and the $m = 1$, hot point, is eroded. After this, within 40 μs the erosion is complete and the T_e profile becomes flat, up to $\rho = 0.9$ (see T_{e3}^{TS}) with a value of about 500 eV.

From these observations it is seen that it is not possible to ascribe a starting time for the onset of the energy quench. The degradation of the energy confinement seems to be a continuous process that accelerates in between -50 and $+90$ μs, as shown by the slope of the isothermal excursions. This phase of faster erosion of $T_e(r)$ appears to start from the LFS in between the $m = 2$, O point and the $m = 1$ cold point (arrow A) proceeding asymmetrically into the plasma core, first through the $m = 1$ cold point and then to the $m = 1$ hot point (arrow B). The behaviour of the electron density TS profile is shown in Fig. 1(c). From n_{e1} to n_{e3} the central density decreases $\approx 20\%$ in the plasma core and increases $\approx 50\%$ inside the $m = 2$ island. In the region between $z/a \approx 0.5$ to $z/a \approx 0.8$, the density gradient in the first three n_e profiles shows consecutively a perturbation moving outwards. This indicates that the density increase in the $m = 2$ island could be the result of the flow of particles from the plasma core. We should note that such a displacement of the density gradient is also apparent already in the last stages of the fast precursor [2]. In the center of the profiles n_{e2} and n_{e3} some asymmetry and structures in the density are visible. For n_{e2} the highest density is in between $z/a \approx -0.5$ to $z/a \approx 0$ that corresponds to the hot part of the $m = 1$ mode. The nature of this step is not understood. For $z/a > 0.8$ it is observed that the density does not change significantly. So during this period of the energy quench despite this internal rearrangements of the electron density profile, visible with TS, the global convex shape of $n_e(r)$ is still preserved, as was previously observed [5].

Events during the negative voltage spike. Shortly after the flattening of $T_e(r)$, *i.e.* when the $m = 1$ erosion is completed, a series of new phenomena is observed coinciding with the negative spike in the loop voltage occurs between +50 and +150 μs: (1) The remaining gradients in $T_e(r)$ and $n_e(r)$ at the plasma edge disappear. (2) The appearance of a short-lived extreme peak in the temperature at a radius between $0.7 < \rho < 0.8$ shows up. (3) An increasing deviation between T_e measured by TS and ECE can be noticed whilst normally these two diagnostics are very well in agreement with each other.

(1) The disappearance of the T_e gradients at the edge is only visible in T_e^{ECE},Fig. 1(a), between $t = +70$ μs and $t = +100$ μs. The TS profile 4 does not cover the very bottom edge of the plasma and at the top the 'peak' masks the effect. After the flattening of T_e, the electron density remains high. However the n_e profile is no longer convex. The density in the edge is in average as high as in the center as the gradients between $\rho = 0.5$ and 1 have disappeared. Except for the peak in n_{e4} the other profiles show large perturbations that do not have an apparent cause. Their occurrence is erratic with no apparent correlation with other observations. This fact together with the large size of these perturbations suggests that large scale turbulence inducing large scale convection in the plasma may be taking place during this last phase of the energy quench.

(2) At approximately 100 μs an intense increase in T_e^{ECE} at $\rho \simeq 0.77$ is observed in Fig. 1(a). This peak in T_e^{ECE} is localized at the same radius as the $m = 2$ island, just before that time. The peak is observed simultaneously in the top by TS and in the LFS by the ECE radiometer, but not in the bottom or in the HFS of the plasma. This means that poloidally it spans an angle that is larger or equal to 90° but is smaller than 180°. The peak value of the temperature measured in T_{e4}^{TS} is two times higher than the average electron temperature in the plasma center at the same time and it is 20% higher than the central temperature before the disruption. Also, the ECE radiometer measures a peak temperature but of only 600 eV when TS measures 1200 eV. The nature of this temperature peak is not understood. At the position of the peak in T_{e4}^{TS} the Thomson scattering spectrum shows a more pronounced high energy tail than at other positions of the viewing chord. This indicates the presence of fast electrons. It should be noted that also the density is higher at the peak position which gives an enhancement of the electron pressure in the peak with more than a factor 2 compared to the surrounding plasma and with a factor 1.5 above the central pressure before disruption.

(3) After the flattening of $T_e(r)$ a large discrepancy develops between the radiation temperature as measured with the ECE radiometer and the electron temperature as measured with TS. The ECE values fall more than a factor 2 below the TS values. The presence of fast electrons may also be the cause of the discrepancy between Thomson scattering and ECE radiometer which are normally in very good agreement. This effect starts only at the flattening of T_e, that is also after the onset of the large variations in the loop voltage between 50 and 150 μs. In the same period the oscillations of dB/dt are interrupted with a large spike as shown in Fig. 1(b). It is also in this period that the T_e profile suffers the largest expansion as can be seen at ≈ 100 μs.

Discussion. A widely spread model for the beginning of the energy quench evokes the stochastization of magnetic field lines between the $m = 2$ and the $m = 1$ modes. The nonlinear interaction of these two modes would lead to the destabilization of other modes in between, mainly the $m/n = 3/2$ mode, and when the width of the islands equals the distance between them the magnetic field lines would become stochastic destroying the magnetic flux surfaces. The strong point for this model is that it predicts rapid heat diffusivity throughout the stochastic region, that is comparable to the heat fluxes observed during a major disruption. Experimentally it is not possible to measure stochasticity directly. Its presence has to be inferred indirectly and its main effect is the expected flattening of the temperature in the regions that have stochastic field lines. The drawbacks of this model are the lack of a description for the time evolution of the process of stochastization and the lack of a self-consistent computation of the magnetic field and current. In the measurements previously described, the most clear observation of a flattened temperature profile between the $m = 2$ and the $m = 1$ mode is in T_{e2}^{TS}, Fig. 1(c), where it is observed that between the $m = 2$, X point in the top and the $m = 1$ hot point in the bottom, the T_e profile is flat. A closer look into the same profile, shows that although in the top the T_e profile is flat up to $z/a = 0.8$, in the bottom there is a gradient from $z/a = -0.45$ to $z/a = -0.7$, the position of the $q = 2$ resonant surface. This means that the neighbourhood of the $m = 2$ mode core-facing side is not all at the same temperature, which might be at variance with the complete stochastization of this region at this advanced phase of the profile erosion, as expected by some authors [4].

The evolution of the density profile during the erosion of T_e in the core, as mentioned before, shows a decrease in the core and an increase in the $m = 2$, O point, with the density perturbation travelling outwards, opposite to the density gradient. The causes of this particle flow, as well as the step in the center of n_{e2} and n_{e3} are not clear from these measurements. In Fig. 1(a), the deformation of the isothermals indicated by the arrow A seems to indicate the presence of a convective motion at the O point of the $m = 2$ mode of the same type as shown in [3]. A remarkable but very short-lived peak in T_e and p_e is observed at every disruption. The nature of this peak is not understood. After the flattening of T_e the kinetic energy is lost at a comparable rate as before the flattening, during the $m = 1$ erosion. In this phase no mode structures are observed any longer, and the electron density remains high.

The non-linear interaction between low wavelength MHD instabilities is clearly an important ingredient of the energy quench, as the $m/n = 1/1$ and specially the $m/n = 2/1$ mode are always present. Also the fact that with the use of only the reduced set of MHD equations together with simple transport assumptions the $m = 1$ erosion pattern of the T_e profile could be simulated [4], indicates the important role of MHD. But the discrepancy between the TS and ECE temperatures and the behaviour of the density, together with the transient but pronounced peak in the electron temperature and pressure, occurring after the flattening of the T_e profile, indicates that the energy quench is not a pure MHD event.

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