AVOIDANCE OF DENSITY LIMIT DISRUPTIONS USING ELECTRON CYCLOTRON HEATING

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1. Introduction

During the energy quench of a major density limit disruption, the energy confinement of a tokamak plasma discharge is abruptly destroyed. As a consequence, the temperature of the plasma core drops significantly. Loss of energy by impurity radiation, which was already substantial, on the edge of the plasma before the quench, extends all over the plasma after the quench. This enhances the fast increase of the electron resistivity which provokes the decay of the plasma current by Ohmic dissipation.

For large tokamaks, where the energy content can be considerable, the loss of energy confinement leads to a intense heat load on some parts of the vessel which can be vaporized. Moreover large values of dI_p/dt reached during the current quench, induce currents in the vessel, which in large tokamaks give rise to huge forces (up to 2 MN) on the vessel and its supporting structure. These forces can cause severe damage to the machine. Therefore the research on the physics of the disruption and on ways to control or avoid its destructing effects is of great interest [1].

In this paper we present the results of experiments done in RTP (major radius 0.72 m and minor radius 0.164 m), where electron cyclotron resonance heating (ECRH) at 110 GHz, was used to avoid the major disruption or to soften the current quench on discharges with a major disruption.

Density limit disruptions were produced by puffing with He gas in a He plasma, with $I_p = 100$ kA, 1.58 T$<B_\phi<$2.39 T. Whenever it was necessary to lower the density limit well below the cut-off density for ECRH, Neon was puffed to increase losses by radiation. A gyrotron, that can deliver up to 350 kW of power through a steerable mirror that focuses the beam, launched from the low field side, into a deposition area with a diameter of 2 cm was used to heat the plasma. This gyrotron, was triggered on a magnetic signal, that follows the evolution of the amplitude of the m=2 mode, which increases prior to disruption. By setting the threshold to a low level (small amplitude of the m=2 mode) the avoidance of the disruption could be studied. A higher level threshold was used to trigger the gyrotron immediately after the energy quench, to study the softening of the current quench. These two types of experiments are described below.

2. Softening of the current quench

The current decay that follows the energy quench of a major density limit disruption is caused by strongly enhanced Ohmic dissipation, due to the high value of the resistivity reached at that phase. We have investigated the possibility of decreasing, or even reversing, the current decay rate by attempting to heat the plasma and so decrease the electron resistivity. To do this ECRH was applied at the end of the energy quench when the electron temperature is typically in the order of 100 eV.

Although the temperature decrease can be as much as 90%, the electron density is just 30% to 40% lower at this phase of the disruption. If the pre-disruption central electron density is $\approx 10 \times 10^{19}$ m^{-3}, after the energy quench it falls to just below 7.5×10^{19} m^{-3}, the cut-off density for central heating with the 110 GHz gyrotron. In these conditions, it was already reported [2] that it was found that the decrease, or even inversion, of the current decay showed a dependence on the position of the resonance layer on the plasma radius, as well as on the angle of injection of the EC beam. To clear out possible interference of the high electron density, on the propagation and absorption of the EC beam, the same experiments were repeated with Ne gas puff, and $I_p = 60$ kA in order to decrease the central density to $\approx 5 \times 10^{19}$ m^{-3}.

At these lower densities, neither a dependence on the radial position of the resonance layer nor a dependence on the angle of injection of the EC beam, was observed. Moreover, the observation of a decrease on the current decay rate, when the injection angle of the beam was in the counter current drive direction clearly indicates that the main mechanism involved in this process is electron cyclotron resonance heating and that electron cyclotron current drive is not important. On RTP, the behavior of the horizontal position control system, (HPCS), plays an important role in the success of this process. The vertical magnetic field, B_v, increases with the plasma pressure. Since the HPCS is to slow to adjust the value of B_v to the fast drop on the pressure during the energy quench, the plasma is driven into the inner wall. If the pressure drop is very large the plasma will be squeezed into the wall. If the pressure drop is smaller or if it can be quickly inverted by ECRH, the plasma reverses its motion and moves into the outer wall. At RTP the difficulties usually start at this phase since the HPCS is again to slow to increase B_v on time to stop the plasma motion before it reaches the limiter on the outer wall. When the plasma touches the outer limiter a minor disruption follows. Its associated decrease in the pressure, provokes again the plasma movement into the inner wall. This cycle is repeated three or four times, with a growing amplitude of the horizontal displacement at the natural oscillation frequency of the position control feedback loop. When this oscillation can be stopped then the current decay can be reversed as shown in Fig. 1, at 240 ms. The typical current decay time for disruptions on RTP, is between 5-10 ms. On the example of Fig. 1 the plasma was kept for 80 ms after the major disruption, a period 8 - 16 times longer than normal. After the onset of the ECRH the plasma current decayed from 93 kA to 67 kA in 22 ms. This produced a decay rate of 1.2 MA/s, which is much smaller than the usual 10 - 20 MA/s. The current increased then

back to 81 kA. There is a reproducible pattern on the behavior of the HPCS after a disruption. This indicates that an appropriate pre-programming of the HPCS for the post quench phase together with the use of ECRH, can be used to control the decay rate of the plasma current after a major disruption.
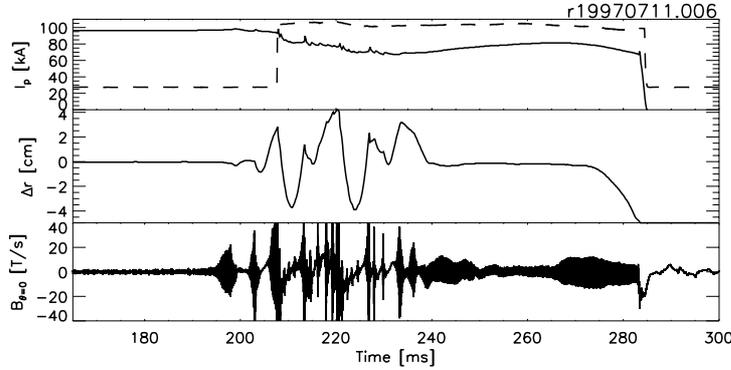

Figure 1. Plasma current and ECRH pulse (dashed line), horizontal displacement of the plasma and time derivative of the poloidal magnetic field, for a discharge where the current quench was softened and reversed. EC power was 330 kW and the resonance position was at r/a = 0. Ohmic heating was 260 kW just before the disruption and reached a maximum of 1 MW after the disruption at 212 ms.

3. Avoidance of the energy quench

Density limit disruptions provoked in these experiments, show sawteeth in their precursor phase. Just before the energy quench dB_θ/dt (that is mainly an m=2/n=1 mode) grows in less than 2 ms to an amplitude between 20 to 40 T/s. For $dB_\theta/dt \approx 20$ T/s minor disruptions are observed, whilst major disruptions occur when $dB_\theta/dt \approx 40$ T/s.

Setting a low threshold level ($dB_\theta/dt \approx 5$ T/s) on the trigger of the gyrotron, the EC beam was injected into the plasma at the q=2 surface, before the energy quench.
An EC power scan, from 60 kW up to 320 kW, was done on discharges where the Ohmic power before the onset of the ECRH was 280 kW.

When the EC power was between 1.14 P_{Ohmic} and 0.5 P_{Ohmic} the amplitude of the m=2 mode decreased to noise level and no major disruption was observed, as shown in Fig. 2. For $P_{EC} \approx 0.3P_{Ohmic}$, the amplitude saturated at 10 T/s and the energy quench was also avoided. When $P_{EC} \approx 0.2P_{Ohmic}$, the growth of the m=2 mode was not stoped and a major disruption occurred.

As Fig. 2 shows, the electron density keeps on increasing, after the m=2 mode is stabilized. In general it was observed that the density limit increased with the increase of total input power, $P_{EC} + P_{Ohmic}$. For $P_{EC} \approx 0.3P_{Ohmic}$, the density stabilized at the maximum value reached before the appearance of the m=2 mode. Probably with a large but saturated island amplitude, particle confinement deteriorates such that further density increase by gas injection is prevented.
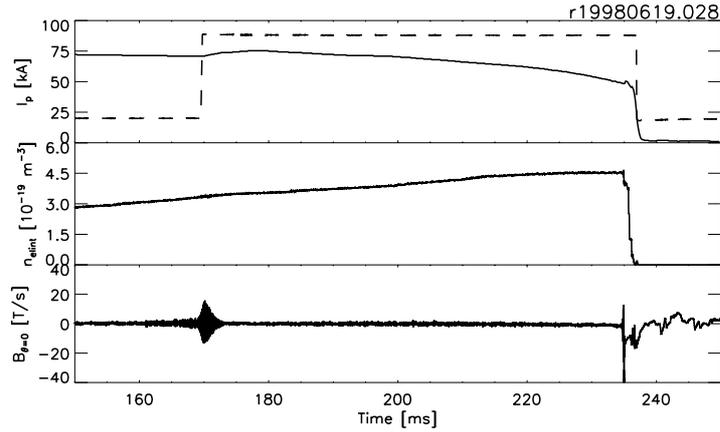
Figure 2. Plasma current, central line integrated density and time derivative of the poloidal magnetic field for a discharge where ECRH (dashed line) was applied at the q=2. $P_{EC} = 300$ kW and $P_{Ohm} = 280$ kW.

4. Conclusions

We have shown that electron cyclotron heating can be used to decrease or reverse the current decay rate of a tokamak plasma major density limit disruption. Previously reported dependence of this process on the position of the resonance layer and on the angle of injection [2] was not found anymore when the electron density is $\approx 2/3$ of the cut-off density. This indicates that heating gives the stabilizing effect:, and that the resistivity of the plasma can be decreased by any other effective method of heating the plasma, besides ECRH.

Due to interference of the present HPCS on RTP, it is not possible to be conclusive on the necessary minimum amount of EC power.

It was also found that a major density limit disruption can be totally avoided by depositing EC power in the q=2 surface. For $1.4\ P_{Ohmic} \leq P_{EC} \leq 0.5\ P_{Ohmic}$, the amplitude of the m=2/n=1 mode decreases to noise level and for $P_{EC} \approx 0.3\ P_{Ohmic}$ the m=2/n=1 mode saturates at a constant amplitude. At $P_{EC} \approx 0.2\ P_{Ohmic}$ ECRH did not prevent the mode growth and the disruption occurred.

References

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Acknowledgments