Avoidance of $q_a = 3$ Disruption by Electron Cyclotron Heating in the JFT-2M Tokamak

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The typical MHD disruption at safety factor $q_a = 3$ has been suppressed by off-central electron cyclotron heating with power of 70–80 kW in the JFT-2M tokamak. For the suppression, the electron cyclotron resonance layer has to be placed radially in a very narrow region of width about 1 cm near the $q = 2$ surface. The observed narrow suppression window suggests that the basic mechanism responsible for the suppression is direct island heating. The actual time scale of the suppression is much faster than the time scale of the change of the overall current profile.

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In tokamak plasmas the electron cyclotron heating (ECH) yields a well localized deposition of power to the electrons. Therefore the ECH is a powerful tool in controlling MHD instabilities in these plasmas. Recently, ECH has been found to control sawtooth oscillations in the Doublet-III tokamak [1] and WT-3 tokamak [2]. On the other hand, the possibility of suppression of low-m (poloidal mode number) tearing modes by ECH has been pointed out by theoretical calculations [3–5]. In the TFR tokamak [6] the modes $m = 2$ and 3 which appear at $q_a = 3$ are suppressed by ECH. But these results have been reported to be rather irreproducible due to the change in plasma displacement. Instead, in the JFT-2M tokamak the plasma displacement and the q_a value can be well controlled and remain constant. We have found that the MHD modes (Mirnov oscillations) which appear around $2.8 < q_a < 3.3$ are always suppressed by ECH provided that the electron cyclotron resonance (ECR) layer is set correctly on a narrow region near the $q = 2$ surface. Furthermore, we found that the disruptions caused by these modes are avoided by ECH.

Conventionally, disruptions are avoided by the fast control of plasma current. This report demonstrates, for the first time, a reliable and active way to avoid MHD disruptions using ECH.

The JFT-2M tokamak is a noncircular tokamak with major radius $R_0 = 1.31$ m and minor radii $a = 0.35$ m and $b = 0.53$ m. The maximum central toroidal field is $B_{t0} = 1.4$ T. The ECH system consists of two cw gyrotrons of frequency 59.8 GHz and total output power of 400 kW. The maximum injection power into the plasma is 250 kW. Waves are launched from two horn antennas on the equatorial plane. The second-harmonic ECR layer is located at the magnetic axis (plasma center) where $B_{t0} = 1.07$ T. The experiment was done with a circular plasma cross section and hydrogen as the filling gas. The plasma density is limited to below 2.2×10^{19} m^{-3} at the ECR layer to avoid the right-hand wave cutoff. The horn antennas radiate an electromagnetic wave which is linearly polarized (circular TE_{11} mode) with the electric field perpendicular to the toroidal magnetic field (extraordinary mode). The angle of injection is 81–82 deg with respect to the toroidal direction (almost perpendicular injection); the beam divergence was 9 deg. The Doppler resonance width increases with electron temperature, the width being calculated to vary from 6 to 12 mm for the experimental range with electron temperature from 100 to 300 eV [7]. Limiter configurations with $a = 0.34$ m were taken in this experiment. The typical plasma current for $q_a = 3$ was $I_p = 210$ kA.

The region of operation of plasmas in tokamaks can be represented by the Hugill diagram as shown in Fig. 1. The parameters of operation are bounded by the $q_a = 2$ disruption region and the density limit. The latter could be caused by imbalance of power input and large power losses. The density limit increases with $1/q_a$ which is proportional to the current density. At the density limit, the plasma disrupts.

There is a third disruption region with constant plasma current (region B in Fig. 1). This disruption is caused by

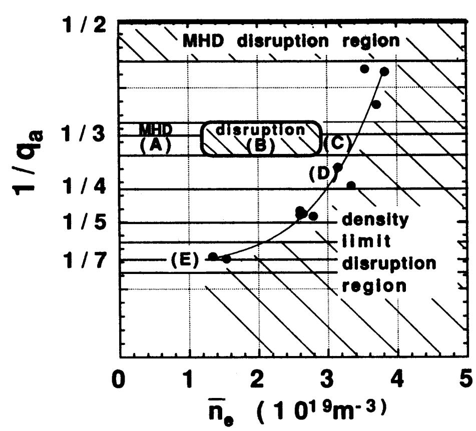

FIG. 1. Hugill diagram. Hydrogen plasma. Circular cross section (ellipticity 1.04, volume 3.05 m^3). Plasma current $I_p = 93$–285 kA. Dots show the parameters where density-limit disruptions occurred.

the MHD oscillations at $2.8 < q_a < 3.3$, $\bar{n}_e > 1.1 \times 10^{19}$ m^{-3} (region B). In JFT-2M this instability does not cause plasma disruption when the line average density is less than 1.1×10^{19} m^{-3} (region A). The mode numbers have been identified to be $m/n = 2/1$ (n is the toroidal mode number) by a magnetic probe array. The mode frequency is typically 2.5 kHz. The mode amplitude has been found to increase almost linearly with the plasma density.

Typical time traces of a shot in which the ECH suppresses the $q_a = 3$ MHD instability are shown in Fig. 2. Plasma current is set constant in such a way that the Mirnov oscillations which appear at $q_a = 3$ remain stationary. With application of ECH at a specific radial position, the envelope of the magnetic probe signal reduces as shown in Fig. 2(b), while the frequency of the MHD instability increases slightly during the suppression. Therefore this decrease is due to the decrease in amplitude and not to mode locking. Both the q_a value and the plasma displacement stay constant during ECH. There is a large decrease in Shafranov lambda value, $\Lambda = \beta_p + l_i/2 - \frac{1}{2}$, where the β_p is the poloidal beta value and l_i is the plasma internal inductance, as shown in Fig. 2(d). The stored energy measured by diamagnetism shows a slight increase with the introduction of off-central ECH (the density has been raised after 800 ms to avoid excess x rays). Therefore the plasma internal inductance decreases as a consequence of ECH. We observe that ECH suppresses the MHD instability on a time scale much faster than the time scale of the decrease of the lambda value (which means a decrease in the internal inductance). Moreover, the MHD instability returns to the initial magnitude after the ECH is turned off, while the lambda value remains small. Therefore, this suppression by ECH is not caused by a global change in the current profile, but by a local ECH effect. We propose that direct island heating is the mechanism of suppression by ECH. The observed degradation of suppression after 50 ms from the introduction of rf may be due to the movement of $q = 2$ island out of the ECR layer. This migration could be due to a change in the global current profile which is caused by the suppression of the MHD instability. Therefore the effectiveness of the ECH may decrease in the latter part of the pulse.

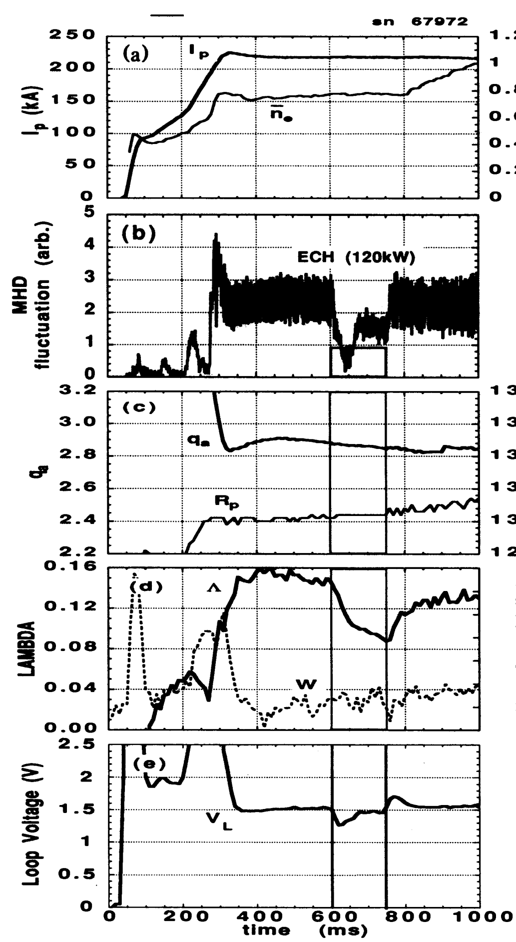

FIG. 2. Typical time traces of a shot in which MHD instability at $q_a = 2.86$ is suppressed by ECH.

The time behavior of the MHD amplitude, under the application of ECH, depends critically on the radial position of the ECR layer. The suppression of the amplitude of the MHD instability is observed only at a specific radial position of the ECR layer [Fig. 3(a)]. In fact the suppression occurs only when the ECR layer is located at $r_0/a = 0.70 \pm 0.03$ (r_0 is the radial coordinate of the ECR layer). In order to suppress the mode the radial position of the ECR layer should be tuned within 1–2 cm. An enhancement of the mode occurs when the ECR layer is located inside $r_0/a < 0.60$. The lambda value decreases

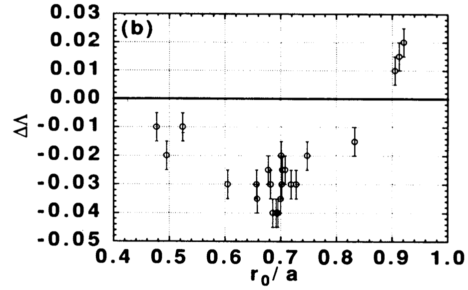

FIG. 3. (a) Increment in the MHD amplitude (envelope) by the application of ECH. $P_{rf} = 140$ kW. Circles, $2.9 < q_a < 3.1$; squares, $2.8 < q_a < 2.9$; triangles, $3.1 < q_a < 3.25$. (b) Change in lambda values.

as shown in Fig. 3(b).

The suppression is also dependent on the q_a value and is almost complete when the q_a value is close to the stability boundary. The suppression of the MHD instability persists after the ECH pulse when q_a is 3.2, as shown in Fig. 4. The continuation of the MHD suppression after the ECH pulse might be due to the global change of the current profile by the ECH stabilization.

In practice the power to suppress the MHD mode may be of importance. Actually, 70–80 kW from a single gyrotron only could suppress the MHD mode almost equally well as power from two gyrotrons. This is because the difference in the gyrotron frequencies (one was 59.75 GHz and another was 59.90 GHz) and the resultant difference (4 mm) in the power deposition radii affected the result of suppression.

Plasma disruptions induced by this MHD instability (in region B) are avoided by ECH as shown in Fig. 5. In fact, the plasma disrupts at $t=470$ ms when the density reaches 1.1×10^{19} m^{-3} (broken lines), but by the application of ECH at $r_0/a=0.7$, the MHD instability is suppressed and disruptions are avoided [Fig. 5(c)]. Disruption reoccurs after the ECH has been switched off, with the value of Λ becoming 0.3 which is almost the same as the value at disruption without ECH. When the position of the ECR layer is not set at the correct position, disruption could not be avoided by the ECH.

With the MHD instabilities suppressed by ECH we could ramp up the plasma density, and we found that the disruption region which is indicated by region B (in Fig. 1) no longer exists. The plasma did not disrupt even after the ECH pulse when the density reached 3×10^{19} m^{-3} (region C). Region C is found to be a disruption-free region. The plasma only disrupted when raising the density further and entering the density-limit disruption region.

Suppression of MHD instabilities is considered to be caused by the suppression of the magnetic island width. The $m/n=2/1$ mode grows at the $q=2$ surface. In these experiments we do not know the exact position of this surface. We can only estimate the position of the $q=2$ surface from the measured electron temperature profile. Assuming the Spitzer resistivity which is proportional to $T_e^{-1.5}$ and a uniform effective charge $Z_{\rm eff}$ we calculated the $q=2$ surface to be $r/a=0.77$–0.81 in the target plasma. Actually there is a slight discrepancy between the calculated position and that found in the experiment, $r_0/a=0.70$. Considering the observed very narrow suppression window of stabilization in the radial position of ECR layer, $r/a=0.7$ could be more reliable for the $q=2$ surface. Then our experimental result means that island heating produces a very fast suppression of the MHD instability, much faster than the time scale of the change of the current profile.

The required power for the suppression seems to be smaller than that theoretically calculated [3,5], especially at the stability boundary. But the time behavior of the MHD amplitude during suppression seems to be similar to the result of calculation by Westerhof *et al.* [5].

Both electron heating and current drive in the island are considered to be effective for the suppression of the magnetic island [4]. The first mechanism decreases the resistivity of the island, and the second drives island

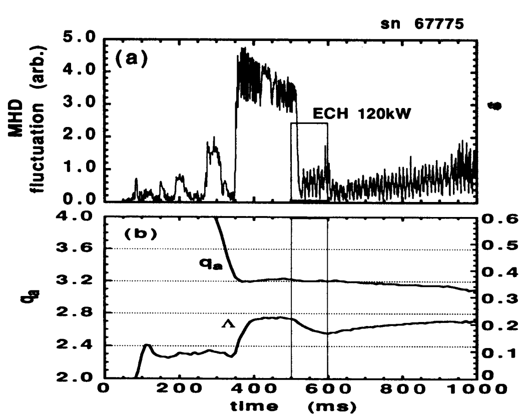

FIG. 4. Suppression of MHD instability near the stability boundary. $q_a=3.19$. $r_0/a=0.73$.

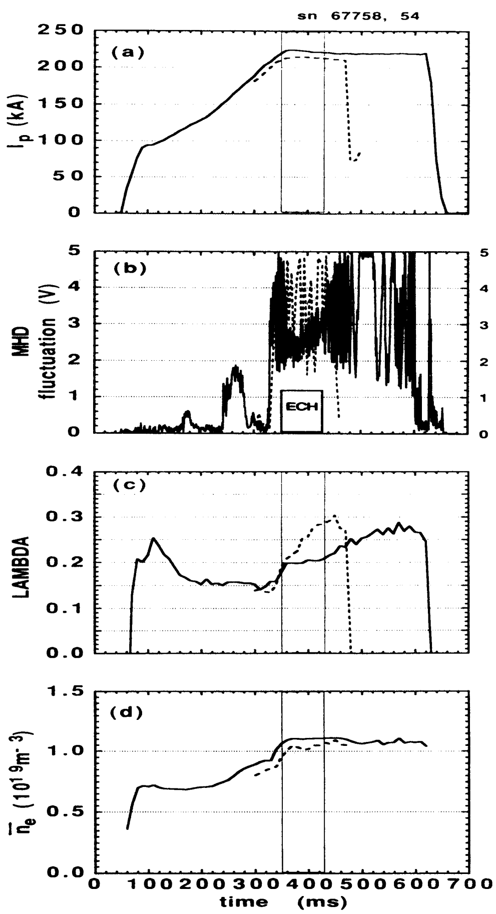

FIG. 5. Avoidance of disruption by ECH. The case without ECH is shown by the broken lines. $q_a=2.97$. $P_{\rm rf}=120$ kW.

current. From existing theories and the drive efficiencies already obtained we deduce that the ECH could at least drive island currents of order 1 kA with power 120 kW and $\bar{n}_e = 1.0\times 10^{19}$ m^{-3}. We changed the direction of the plasma current to see whether the driving of island currents plays a role or not. We found that ECH suppressed the MHD mode equally well for both plasma current directions. This result suggests that the suppression is caused dominantly by local heating of the magnetic island and not by the current drive. Then the characteristic time scales of the suppression may be the local heating time and the local current diffusion time at the island, which are both supposed to be values much shorter than the time scale for the change of the global current profile. This may explain our observations.

Our experimental results show that a region that is spatially very restricted has to be selectively heated for a sufficient time interval (longer than heating time) in order to suppress the MHD instability. Therefore, we need a fast tracking method in order to control the power deposition at a specified radial position for effective suppression of the MHD instability and avoidance of the disruption.

Finally, we would like to report that we have also observed suppression of the MHD instability which grows near the density limit (regions D and E in Fig. 1) and the resultant avoidance of disruption by off-central ECH in the high-q_a region. Thus we infer that ECH may be effective also for the avoidance of disruption near the density-limit region.

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