THE “POSITIVE“ MAGNETIC ISLANDS CONCEPTION AND ITS APPLICATIONS TO T-11M EXPERIMENTS

S.V. MIRNOV, I.B.SEMENOV, A.M.BELOV, E.A.AZIZOV

State Research Center TRINITI, Troitsk, 142092 Moscow Region., Russian Federation

Abstract

A situation in tokamaks is analyzed in which the development of strong plasma current filamentation leads to nonlinear magnetic islands formation near resonant magnetic surfaces. It is shown that, along with the usual “negative” magnetic islands, in which the modulation of the perturbation currents is negative, “positive” islands can form in local regions with the positive current modulation. The “positive” magnetic islands can be a reason of the “hot spot” in plasma center during sawtooth crash. Also the “positive” islands, probably, plays the important role in m=2 development during the major disruption and in the locked modes dynamics.

1. INTRODUCTION. THE “POSITIVE” MAGNETIC ISLANDS CONCEPTION IN TOKAMAKS.

Usually, the sizes of magnetic islands are estimated by taking into account the perturbations of the initial poloidal magnetic field of the plasma column. Figure 1a[1] shows the magnetic field lines of so-called auxiliary magnetic field $\mathbf{B}^*$ near a certain resonance magnetic surface $q(r_s)$ [2]: $\mathbf{B}^* = \mathbf{B}_\Theta - \frac{rB_T}{R_q(r_s)}\mathbf{e}_\Theta = -\mathbf{B}_\Theta \frac{r_s dq}{qdr}\delta r$. Here $\mathbf{B}_\Theta$ is the field of the plasma current in the vicinity of the rational magnetic surface $q(r_s)=m/n$, where m and n are the integer numbers, e_Θ is a unit vector in the Θ direction, r is the minor radius, R is the major radius, B_T is the toroidal magnetic field, q is the safety factor, and δr is the deviation of the radial coordinate from r_s. If $q(r_s)$ increases toward the plasma edge (as in most tokamak regimes), then the field $\mathbf{B}^*$ coincides with the field $\mathbf{B}_\Theta$ of the plasma current inside the magnetic surface q(r) and is oppositely directed outside this surface. If we introduce the resonant helical perturbations of the current $\pm J_\Theta$ with density j_Θ at the rational surface of radius r_S (Fig. 1a), the radial component b_r of the magnetic field of these perturbation causes the formation of magnetic islands (O-points) in regions in which the modulation of the current j_Θ^- is negative (i.e., the perturbed current is oppositely directed to the main plasma current J_P) and the appearance of X-points in regions with the positive modulation of j_Θ^+ (Fig. 1b). In this case, the component b_Θ of the magnetic field of the current perturbations enhances the field B_Θ^* near the O-points and weakens it near the X-points. When this weakening is small, the increase in J_Θ causes the width of the islands to grow in the radial direction, without changing their geometric structure. This can be regarded as a linear stage. However, the situation changes radically when the component b_Θ becomes larger than B_Θ^*. In this case, the X-point should be splitted into two X-points (Fig.1b), and, in the region between them, in which the current density j_Θ^+ is positively modulated, a new island forms (Fig.1c). The displacement of X-point to the plasma center should cause an intense cooling of the central plasma. What is the level of perturbations J_Θ corresponding to this process?

According to [2], we write the expression for the auxiliary field in cylindrical approximation: $B_\Theta^* = 0.2\pi\langle j\rangle_r \frac{rdq}{qdr}\delta r$, where $\langle j\rangle_r$ is the mean ohmic current density inside the magnetic surface of radius r. On the other hand, if we assume that, the perturbation current flows through the circular filament with radius δr and current density j_Θ^+ (Fig. 1a), then the magnetic-field component corresponding to this current is $b_\Theta = 0.2\pi j_\Theta^+ \delta r$. The field B_Θ^* becomes equal to the perturbed field b_Θ when $j_\Theta^+ = \langle j \rangle_r \frac{rdq}{qdr}$. We can see that, in the case, till the plasma cooling is insignificant and the reduction in the magnetic shear near the resonant magnetic surface of radius r_s is small (rdq/qdr=1), a transition to the nonlinear stage can occur only if the perturbations j_Θ^+ are relatively strong (comparable to $\langle j \rangle_r$). For tokamaks operating in conventional modes with $j_p(r)$ profiles peaked about the plasma axis, this indicates that for $q(r_s)>2$ the amplitude of the negative modulation of $j_\Theta^- \approx - j_\Theta^+$ should exceed the local magnitude of $j_p(r_s)$.

When $j_\Theta^+ > \langle j \rangle_r \frac{rdq}{qdr}$, the "positive" magnetic island is positioned along the radius r, unlike conventional negative islands, which are positioned in the Θ direction (Fig. 1b) [1].

This feature of the "positive" magnetic islands can be used to identify them. It should manifest itself, in particular, as an asymmetry in the perturbed magnetic field $b_\Theta(\Theta)$ outside the plasma column, which can be inferred from the magnetic probe measurements, because the positive perturbations b_Θ should be stronger and highly localized than the negative ones (note that the integral of these perturbations over the entire poloidal circumference Θ should be equal to zero).

When j_Θ^+ becomes higher than $\langle j \rangle_r$ the local condition q(δr)<1 should be satisfied on the surface of the current tube that winds q times around the torus. This can lead to the onset of a conventional ideal kink instability (analogous to the Shafranov-Kruskal instability with *m*=1 and *n*=1) and, ultimately, to the decay of the current tube, i.e., to the self-decay of the perturbations j_Θ.

Hence, "positive" magnetic islands can exit in the range:

$$(1 + \frac{rdq}{qdr})\langle j \rangle_r > j_\Theta^+ > \langle j \rangle_r \frac{rdq}{qdr}.$$

II. THE POSSIBLE MANIFESTATIONS OF "POSITIVE" MAGNETIC ISLANDS.

Obviously, the "positive" magnetic islands could be develop in the region with minimum rdq/qdr. Fig. 2 shows the distributions of rdq/qdr for two typical j(r) (solid curve - j(r) has maximum , and dashed curve - j(r) has minimum in plasma center). Estimations show that in the discharge with maximum current density in the center the appearance of the "positive" magnetic islands is most probable near the plasma center during sawtooth crash [1], Fig. 3 [3] shows the reconstructed volume distribution of the soft X-ray and Te(r) (ECE data) in TFTR during sawtooth crash. Both distributions show elongated in r direction structure ("hot spot") which is typical for the "positive" magnetic islands. So it is possible to explain the appearance of the "hot spot" in the plasma center during sawtooth which was observed in [3].

Transition of the distribution 1 to distribution 2 (Fig. 2) probably takes place during the major disruption in tokamaks. The potential possibility of the "positive" magnetic islands development appears in disruption near integer q=2,3. The corresponding current perturbations have to be elongated in r direction. In this case the external observer have to measure the visible amplitude of n=2 harmonic (m=2q). The development of the high m (particularly m=4 together with m=3 or before m=3) was observed in earlier experiments in T-11M [4]. Fig 4 shows the mode dynamics (m=2,3,4) during disruption instability in T-11M. The m=4 perturbation appears during degradation of the perturbation m=2 together with m=3. The analysis of the magnetic perturbations along the torus shows [5] that the sufficient intensity of n=2 (probably m=4/n=2) exists in this moment. Probably that is result of the "positive" magnetic islands appearance near q=2.

Finally the locked mode maybe gives an example of the non-linear development of the positive magnetic islands. It is known that the magnetic (and current) perturbations are large in locked mode.

The amplitude of the locked mode was measured in T-11M for same extremal case by 24 magnetic probes. Fig. 4 shows the $B_\Theta(t)$ for several probes and $B_\Theta(\Theta)$ before and after the typical disruption. The maximum of the $B_\Theta(\Theta)$ amplitude relative to plasma current magnetic field was up to 25%. It means that we have strongly non-linear development of the magnetic islands. Estimation of the island size (according to linear formulas) gives the value ~0.8 of the minor plasma radius. So, it is possible to propose that in this case the "positive" magnetic islands can exist too.

III. CONCLUSIONS

The analysis of the experimental data gives the possibility to propose that the "positive" magnetic islands are really take part in extremal situations in tokamaks.

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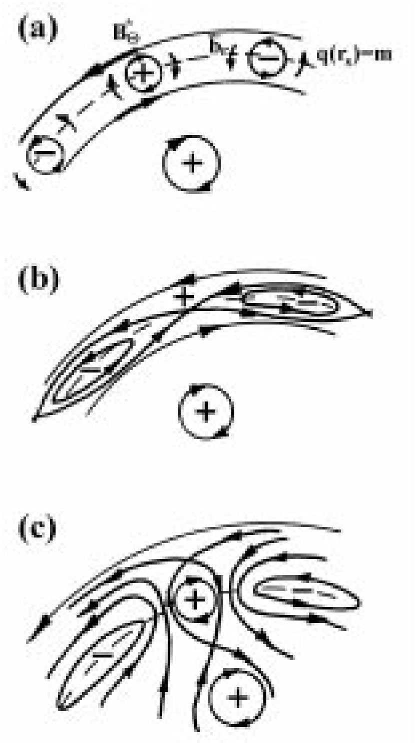

FIG. 1. (a) Geometry of the field ***B**** *and of the perturbation currents J near the rational surface* $q(r_s)=m$ *(*b_r *and* b_θ *are the components of the perturbing magnetic field) and (b) linear and (c) nonlinear scenarios of the formation of magnetic islands.*

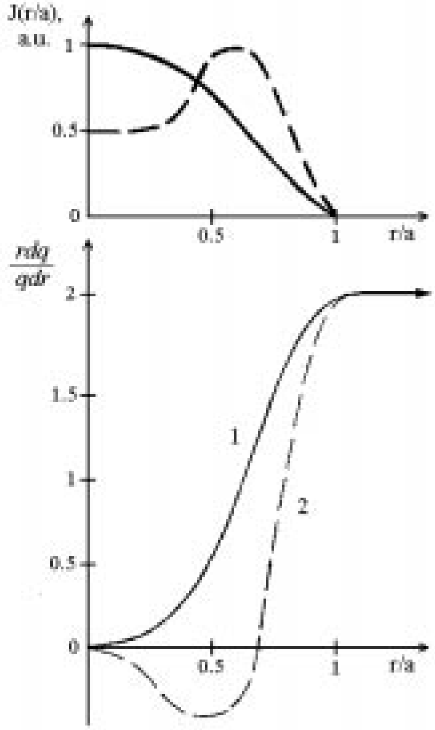

FIG. 2. The typical radial distributions of current density j(r) and rdq/qdr - parameters in tokamaks. The solid line - ,for conventional (dq/dr>0) case and dashed line - for negative shear case.

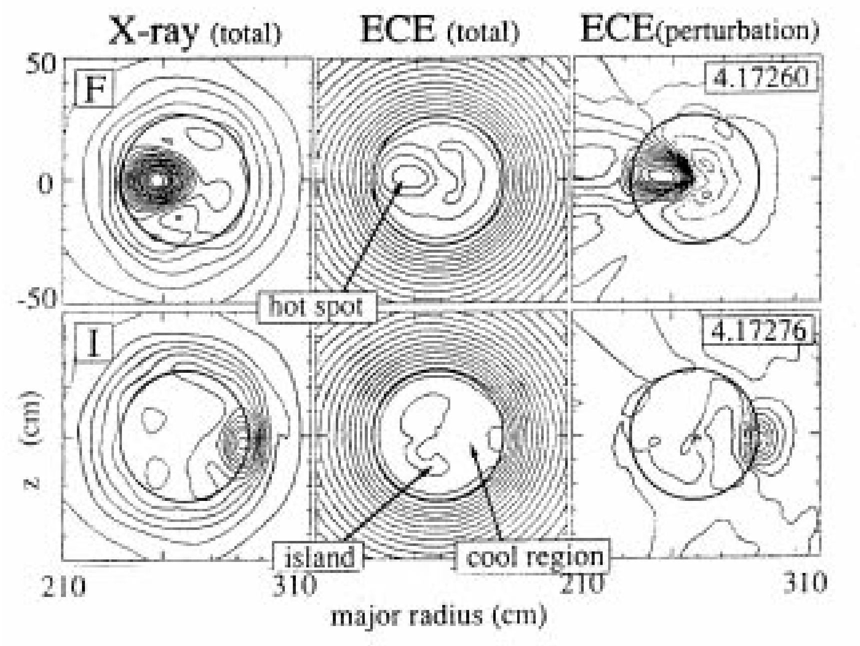

FIG. 3. TFTR [3]. Reconstructions of the X-ray, the ECE, and the perturbation of ECE during sawtooth. The contour step size is 300 eV an ECE (total), and is 60 eV in frames on ECE perturbation.

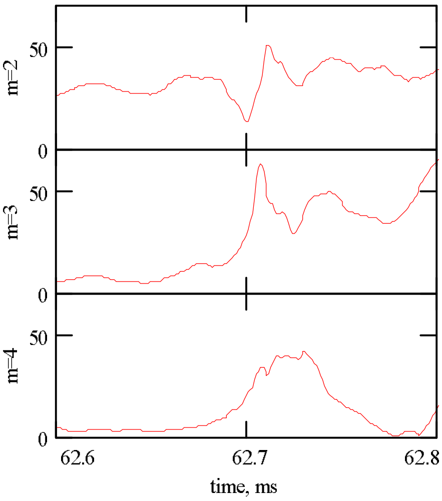

FIG. 4. T-11M [5]. The temporary behavior of m=2, m=3 and m=4 MHD-harmonics during disruption.

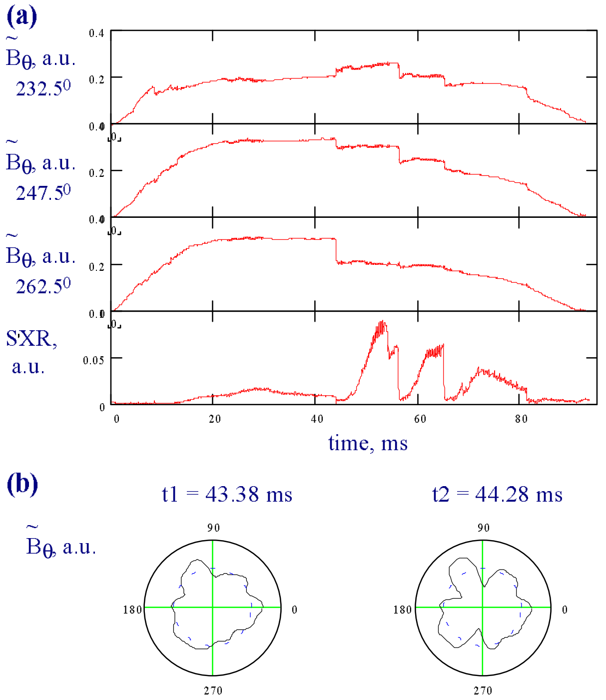

FIG. 5. The locked mode and disruption development in T-11M, (a) - the three typical magnetic probes signals and soft X-ray behavior, (b) - $B_\Theta(\Theta)$-structure before (t1) and after (t2) disruption.