Identification of the magnetic island structure in the HL-2A tokamak*

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The identification of the magnetic island structure in the HL-2A tokamak is presented. First, the perturbation current as a source for the perturbation flux can be determined by using Mirnov probe measurements. By superposing the perturbation flux and the equilibrium flux reconnected by equilibrium fitting, the structure and the width of the magnetic islands can be estimated. The method has been used in the HL-2A experiments.

Keywords: magnetic island, magnetohydrodynamic instability, tearing mode

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1. Introduction

Magnetohydrodynamic (MHD) instabilities, which can lead to confinement degeneration and even discharge disruption, play an important role in tokamaks. When MHD instabilities occur in the plasma, they usually bring a change to the magnetic topology, such as tearing modes. At rational surfaces, the magnetic field lines break and reconnect to form magnetic islands.[1−3] Identification of the magnetic island structure is important for understanding the MHD instability phenomena and for their control. In many fusion experiments, the MHD instabilities are investigated by using electron cyclotron emission (ECE) imaging[4] and soft X-ray tomographic imaging.[5] The Mirnov probe recording the accompanying magnetic perturbation field is another important diagnostic tool for the analysis of MHD instability.

In the HL-2A tokamak, MHD instabilities, especially the tearing modes, are investigated using Mirnov probes. Based on the experimental measurements, the frequencies and the amplitudes of the modes can be investigated. The mode numbers can also be determined easily.[6] However, the width of the magnetic island not only depends on the amplitude of the signal measured by the Mirnov probes, but id also affected by the distance between the q resonant surface and the probes, the magnetic shear at the rational surface, and so on, where $q = m/n$, m and n are the poloidal and the toroidal mode numbers, respectively. So it is difficult to estimate the mode structure and the island width directly with Mirnov probes. The spatial resolutions of the soft X-ray and the ECE diagnostics are not good enough to measure the island in the HL-2A. In order to analyse the structure of the magnetic island, an identification method of the magnetic island has been developed for the HL-2A.[7] With the help of a simulation of the perturbation field and a comparison with the Mirnov measurements, the structure and the width of the magnetic islands can be estimated. The results indicate that the width of the magnetic island is in good agreement with the theoretical prediction. The method is reliable for analysing the structure of the magnetic island. For convenience, some approximations, such as the cylindrical approximation and the simplified case of the vacuum field response, were used in that work. In addition, the equilibrium flux was calculated with an assumed plasma current profile. So the plasma displacement and the Shafranov shift affected the calculation accuracy. Moreover, the method can be used only for the limiter discharge. In this paper, using the MHD equilibrium[8] reconstructed by using the equilibrium fit (EFIT) code, these problems will be addressed.

The rest of the present paper is organized as follows. The experimental setup is described in Section 2. In Section 3, the method is presented in detail. Discussion and a conclusion are given in the last section.

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2. Experimental setup

The HL-2A tokamak[9] (with major radius $R_0 = 1.65$ m and minor radius $a = 0.4$ m) has an axisymmetric single-null divertor. A set of Mirnov probes is equipped on the HL-2A. A poloidal array of 18 pick-up coils is used to determine the poloidal mode number. The distance between two adjacent probes in the poloidal direction is about 10.5°, as shown in Fig. 1. They can be used to determine the poloidal mode number of $m \leq 17$. Ten Mirnov coils arranged along the toroidal direction are employed to detect the toroidal mode. The toroidal Mirnov coils can be used to recognize $n \leq 4$ mode. Based on the experimental data, the mode frequency and the mode amplitude are investigated. In addition, the mode number (m, n) can be determined by the correlation analysis of the measurements from the Mirnov probes.

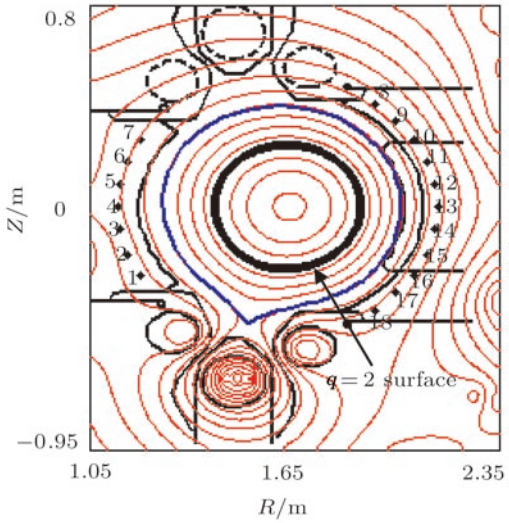


Fig. 1. (colour online) Locations of poloidal Mirnov probes and MHD equilibrium reconstructed by EFIT in the HL-2A.

3. Method

Figure 2 displays the scenario of shot No. 10049. Figures 2(a) and 2(b) show the raw data from the 13-th probe located in the midplane on the low field side and its spectrogram, respectively. Figure 2(b) shows the dominant mode ($m = 2$), the second and the third harmonics of the dominant mode, other modes and the fixed noise supplied by the ohmic coil current. An ideal filter, which is based on the fast Fourier transform (FFT), is used to extract the perturbation field of the dominant mode. Figures 2(c) and 2(d) show the perturbation field of the dominant mode ($m = 2$) $\tilde{B}_{m=2}$ and its spectrogram, respectively.

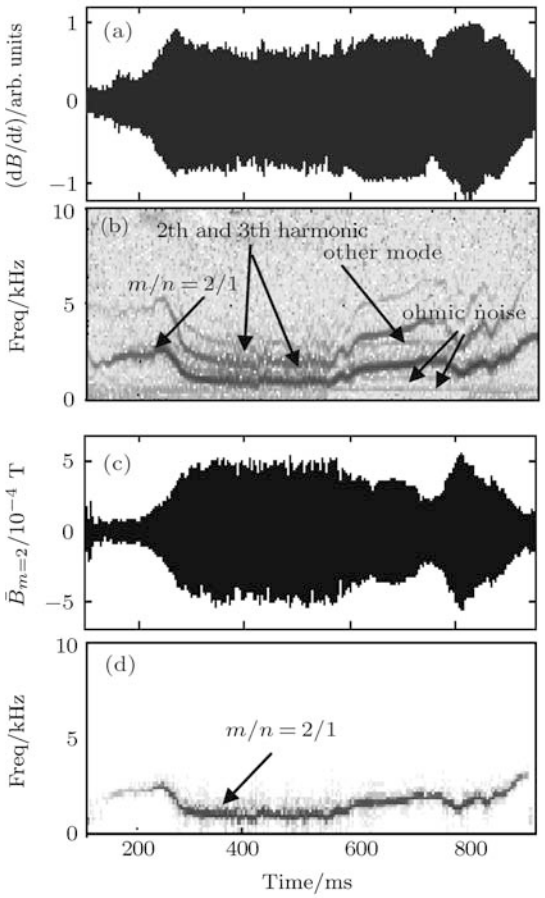


Fig. 2. Measurements of the Mirnov probe and the perturbation field of the $m = 2$ mode extracted from the raw signal. (a) and (b) are the raw data from the 13-th probe and its spectrogram, respectively. (c) and (d) show respectively the perturbation field and its spectrogram of the $m = 2$ mode extracted from raw data using an ideal filter method.

In this paper, the equilibrium flux is reconstructed by using the EFIT code, which was originally created by Lao *et al.* for the doublet III.[10,11] The purpose of the EFIT code is to obtain a solution to the equation for the equilibrium force balance in the tokamak plasma that is consistent with experimental measurements. It is currently used in many tokamaks all over the world, such as the TFTR, the JET, the D-IIID, the JT-60 and the TEXTOR. It has been also successfully applied to the HL-2A.[12] As shown in Fig. 1, the equilibrium configuration of Shot No.10049 is rebuilt by using the EFIT (for plasma current $I_p = 168$ kA, toroidal field $B_t = 1.33$ T and $t = 500$ ms). From the EFIT, the profile of safety factor $q(r)$ and the position of the $q = m/n$ resonant surface can also be determined. The q profile is important for the identification of the magnetic island

in our method. The position of the $q = 1$ surface estimated through soft X-ray diagnostics is used as the benchmark for the EFIT results.

In the calculation, the perturbation currents as the source of the perturbation flux mainly flow in the vicinity of the corresponding resonant surface. To simplify the calculation of the perturbation flux, it is assumed that the perturbation currents concentrate on the corresponding resonant surface and flow in a force-free manner along the equilibrium field lines of that surface. As force-free currents do not change the plasma equilibrium, the perturbation field is not influenced by the surrounding plasma.

Considering that the perturbation current on the rational surface q forms a helix, we can write the perturbation current distribution j' as

$$j'(R,Z) = j'_0 \cos(m\vartheta + n\varphi + \omega t + \Delta\Phi), \quad (1)$$

where ϑ and φ are the poloidal and the toroidal angles, $\vartheta = 0$ is in the midplane on the low field side, ω is the rotating rate and $\Delta\Phi$ is the initial phase of the perturbation current distribution.

The toroidal curvature can be described in the first order of the inverse aspect ratio by a transformation from ϑ to ϑ^*, namely,

$$\vartheta^* = \vartheta - \lambda \sin\vartheta.$$

The Shafranov approximation leads to

$$\lambda = \left(\beta_{\rm p} + \frac{l_{\rm i}}{2} + 1\right)\varepsilon,$$

where values of poloidal beta $\beta_{\rm p}$, internal inductance $l_{\rm i}$ and inverse aspect ratio $\varepsilon = r/R_0$ are those of the rational surfaces under consideration. To simplify the three-dimensional (3D) problem into a two-dimensional (2D) one, the toroidal component of the current is considered as

$$j'_\varphi(R,Z) = j'_0 \cos\left\{m\left[\vartheta - \left(\beta_{\rm p} + \frac{l_{\rm i}}{2} + 1\right)\varepsilon \sin\vartheta\right] + \Delta\Phi\right\}. \quad (2)$$

The parameters of the perturbation current, j'_0, λ, and $\Delta\Phi$, can be determined by a least-square fitting to the poloidal Mirnov measurements. A function is set as

$$\delta^2 = \sum_{i=1}^{k} \left(\tilde{B}_i - \tilde{B}_{i0}\right)^2, \quad (3)$$

where $\tilde{B}_i$ is the i-th Mirnov coil perturbation magnetic field calculated by using the perturbation currents (Eq. (2)), $\tilde{B}_{i0}$ is the measurement of the i-th Mirnov probe, k is the number of Mirnov probes and $k = 18$ in the HL-2A. The minimization of δ^2 result in suitable parameters for the perturbation current.

Figure 3 shows the comparison of the perturbation magnetic field of the Mirnov probes between measurement $\tilde{B}_{i0}$ and simulation $\tilde{B}_i$. The coefficients of the perturbation current, j'_0, λ and $\Delta\Phi$, for Shot No. 10049 at $t = 490$ ms (Fig. 3) are 9240, 0.1 and 2, respectively. Here λ ranges from 0.2 to 0.4 for the usual ohmic heated plasma in the HL-2A, which can be estimated by using the equilibrium fitting codes, such as the EFIT and the CF codes. The difference in λ between the simulation and the estimation is caused by the plasma horizontal displacement. Obviously, the simulation is in good agreement with the measurement. So, the perturbation currents are reliable to denote the dominant mode ($m = 2$) magnetic perturbation in the plasma. The perturbation flux produced by the perturbation current is demonstrated in Fig. 4.

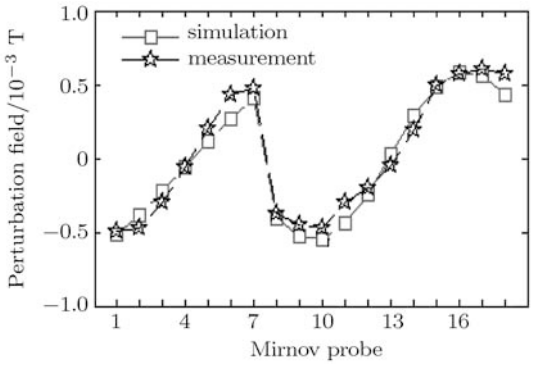


Fig. 3. Comparison of perturbation field between measurement and simulation for Shot No. 10049 at $t = 490$ ms.

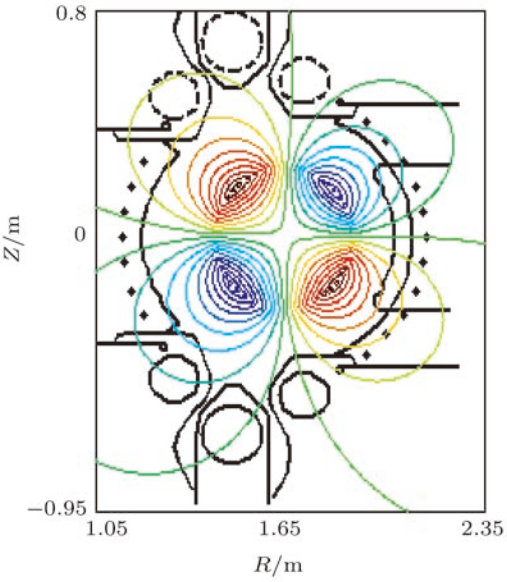


Fig. 4. (colour online) Perturbation flux calculated from the perturbation current, which is determined by the Mirnov measurements for Shot No. 10049 at $t = 490$ ms.

To identify the magnetic island structure, an artificial equilibrium flux $\Psi_{\rm h}$ is created as

$$\Psi_h = \Psi_0 - \Psi_{q=\rm const} = \Psi_0 - \frac{1}{q}\Phi_0, \tag{4}$$

where Ψ_0 and Φ_0 are the poloidal and the toroidal equilibrium flux functions, respectively.[13,14] A zero shear field $\Psi_{q=\rm const}$ (q=const. in each surface) is subtracted from the equilibrium field. According to the definition of q ($q = {\rm d}\Phi/{\rm d}\Psi$), the flux function $\Psi_{q=\rm const} = q^{-1}\Phi_0$. Since Ψ_0 and Φ_0 are constant in the initial flux surfaces, the resulting helical flux function $\Psi_{\rm h}$ has the same contour lines.

Unlike equilibrium flux functions Ψ_0 and Φ_0, each of which is a monotonic function in the radial direction and has an extremum at the magnetic axis, the helical flux $\Psi_{\rm h}$ has an additional extremum on the surface with safety factor q. Superposing the helical equilibrium flux $\Psi_{\rm h}$ and the perturbation flux, the equilibrium flux near the resonant surface $q = 2/1$ is modulated by the perturbation flux. The perturbation field changes the magnetic topology and the magnetic field lines break and reconnect to form the magnetic islands. As shown in Fig. 5, the magnetic island is reconstructed. The X points of the resulting islands are at the minima of the perturbation flux and the O points are at the maxima. The width of the magnetic island can be calculated to be $w = 0.065$ m.

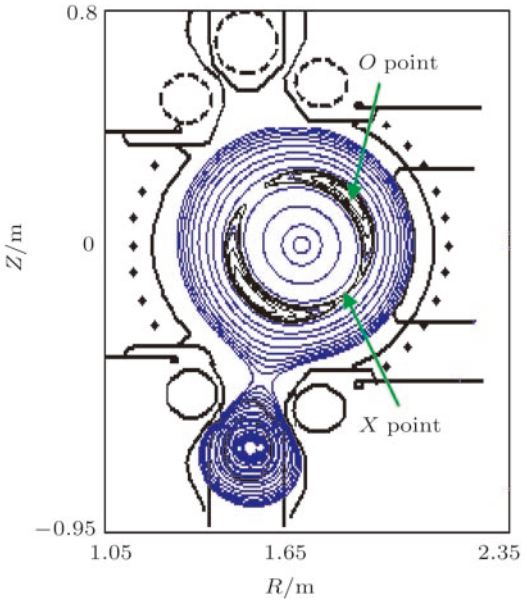


Fig. 5. (colour online) Superposition of the perturbation and the helical equilibrium flux. The magnetic island structure is identified to be $m = 2$ mode. The positions of the X and O points and the width of the magnetic island can be obtained.

Using the method described above, the widths of the magnetic islands corresponding to different amplitudes of the perturbation field measured by the 13-th Mirnov probe can be calculated. The non-linear relationship between the amplitude of the perturbation field $\tilde{B}_{m=2}$ and the width of the magnetic island is shown in Fig. 6 (denoted with star). The function $w = 0.0256 \times (\tilde{B}_{m=2})^{1/2}$ (the dashed line in Fig. 6) is shown to be the relationship between $\tilde{B}_{m=2}$ and w. This is in good agreement with the theoretical prediction, which is

$$w = 4\left(\frac{rq\tilde{B}_r}{mq'B_\vartheta}\right)^{1/2}_{\rm s} = 4\left(\frac{rq}{mq'B_\vartheta}\right)^{1/2}_{\rm s} \times \left(\tilde{B}_r\right)^{1/2}, \tag{5}$$

where r and B_ϑ are the minor radius and the poloidal magnetic field of the rational surface, respectively, and $\tilde{B}_r$ denotes the radial field perturbation and depends linearly on $\tilde{B}_{m=2}$.

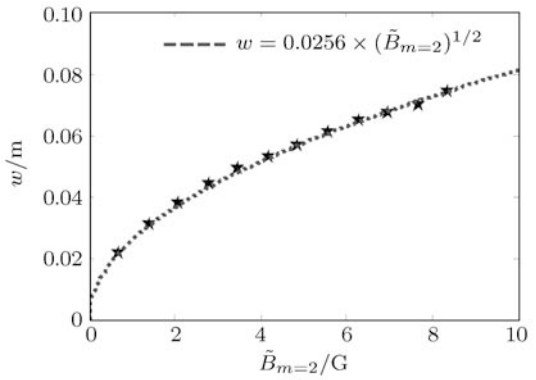


Fig. 6. Non-linear relationship between the amplitude of perturbation field $\tilde{B}_{m=2}$ and the width of the magnetic island w. The $\tilde{B}_{m=2}$ is measured by the 13-th Mirnov probe.

4. Discussion and conclusion

It is well known that the tearing modes in plasma can be measured by Mirnov probes. Although the amplitudes of the Mirnov signals can partially represent the intensity of the MHD instability, they are affected by the equilibrium configuration, such as the distance between the q surface and the Mirnov probe, and the magnetic shear near the corresponding surface. So, it is impossible to evaluate the width of the magnetic island directly. In this paper, the identification of the magnetic island structure in the HL-2A is described. With the help of a simulation of the perturbation current in the rational surface q and a comparison with the Mirnov measurements, the perturbation

flux can be calculated. By superposing the perturbation and the equilibrium (reconstructed by EFIT) flux, the structure of the magnetic island can be identified. The width of the magnetic island can also be estimated. This method has been used to identify the $m/n = 2/1$ mode in the HL-2A. In addition, it is useful for the investigation of MHD instability behaviour and its control.

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