Set of electromagnetic instabilities observed in Mercier stable plasmas of the L-2M stellarator

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Abstract. Electromagnetic instabilities that have been experimentally observed at the L-2M zero net current stellarator and their theoretical analysis are discussed in this paper. We report the structure of the magnetic surfaces and the numerical calculation results. Under experimental conditions, the ideal internal MHD (magnetohydrodynamic) modes are stable. However, the external ideal peeling modes, which start to increase only if the plasma pressure gradient exceeds some particular threshold value, are unstable. If the peeling mode is stable, an electromagnetic mode, which starts to increase only if the plasma density and pressure exceed some particular threshold values, is observable. The characteristic frequency of the unstable modes was in the range of 70–90 kHz, and the direction of its rotation coincides with the direction of the ion diamagnetic drift. An instability was observed at \( n(0) > 1.5 \times 10^{13} \text{ cm}^{-3} \) and at \( \beta > 0.14\% \), where \( n(0) \) is the plasma density averaged over the central chord and \( \beta \) is the volume-averaged ratio of the gas kinetic pressure to the magnetic pressure. This phenomenon cannot be described within the framework of the theory of resistive interchange MHD modes. Analytical estimates have been performed within the framework of two fluid magnetohydrodynamics, and the calculations and experimental data are in reasonable agreement.

1. Introduction

Here, electromagnetic instabilities that have been observed in the L-2M experiments are presented and discussed. The L-2M device is a classical stellarator with a high magnetic shear and planar geometric axis. The total number of the helical field periods is \( N = 14 \), the multipolarity is \( l_0 = 2 \), and the major radius of the magnetic axis is \( R_0 = 100 \text{ cm} \). To describe the magnetic surfaces, we will use the dimensionless parameter, \( x = a/a_p \) (see, e.g., [1]), where \( a \) is the average radius of the magnetic surface and \( a_p (11.5 \text{ cm}) \) is the average radius of the separatrix. The reported experiments were carried out at \( \beta \leq 0.25\% \). The plasma was created and heated with the help of an electron-cyclotron resonance heating (ECRH) system. A detailed numerical analysis of the plasma stability in the L-2M configuration [2] showed that the ideal internal magnetohydrodynamic (MHD) modes are stable under the given experimental conditions. Thus, an ideal MHD mode is an instability that survives when the plasma conductivity in the MHD equations tends to infinity. Even if the internal MHD modes are stable, unstable external peeling modes can exist, which have been previously analyzed numerically and analytically in refs. [2, 3] and observed experimentally in ref. [4]. Within the framework of ideal
magnetohydrodynamics, the number of instabilities that can appear in plasma is limited by those that are mentioned above. In tokamaks where the longitudinal current is an additional source of instabilities, unstable modes are often observed in plasma that should be stable according to the ideal MHD theory (see e.g., refs. [5, 6] and references therein). In contrast, in the TJ-II heliac [7], an electromagnetic instability was observed in the configuration with a deep magnetic well, and in these experiments, the pressure was more than an order of magnitude lower than the theoretical pressure threshold for both the ideal and resistive MHD modes.

Of note, in many stellarators (and the L-2M is no exception), there are magnetic configurations with a magnetic hill at the plasma edge. Therefore, the resistive interchange modes are sure to be unstable there. In ref. [8], the properties of these modes, which can be observed in the L-2M stellarator, were studied in detail (both experimentally and theoretically). However, sometimes, the resistive interchange modes are erroneously involved to explain all the electromagnetic activity at the plasma edge [9], as was shown at the TJ-II heliac, which is characterized by a high stability of the MHD modes.

Here, we briefly present the properties of the magnetic configuration, the possible electromagnetic instabilities and the experimental results obtained at the L-2M stellarator. In cases in which numerical analysis of instabilities is impossible, the experimental results are discussed on the basis of analytical estimates.

2. Experimental setup, experimental results and analytical estimates
The properties of the plasma under consideration have been presented above. Here, we outline the geometrical properties of the plasma instabilities. As an example, Figure 1 shows a self-consistent magnetic field structure of the boundary magnetic surface in a magnetic configuration that is centered with respect to external conductors at a linear pressure profile of $p \sim (1 - s)$, where $s$ is the normalized toroidal magnetic flux. This example demonstrates that in the configuration under study the structure of the magnetic field is rather complicated. There are components that are conditional on the average curvature of the system and on 3D effects. Therefore, the structure of the possible unstable perturbations is not a priori obvious, and this problem requires a detailed numerical analysis (see e.g., ref. [2]).

In all cases under study, the largest components of an unstable perturbation are the harmonics that arise as a result of the coupling caused by the poloidal inhomogeneity (the toroidal effect). These are harmonics with poloidal mode numbers of $m \pm k$, where $k$ is a positive integer. The amplitudes of these harmonics decrease with increasing $k$. The harmonics that appear due to 3D coupling are relatively small. This result has a rather simple physical interpretation. The unstable perturbations are almost constant along the magnetic field line. In this case, multiple regions with favorable and unfavorable curvatures are averaged along the field line. As a result of this averaging, an effective curvature of the magnetic field line arises that is responsible for the poloidal coupling of harmonics.

The transport transitions provoked by the peeling mode were observed in the L-2M plasma [2–4] at densities of $n(0) > 1.0 \times 10^{13} \text{ cm}^{-3}$ and at
 plasma energies of $W = 200\text{–}600 ~\text{J}$. At $n(0) > 1.5 \times 10^{13} ~\text{cm}^{-3}$ and $\langle \beta \rangle > 0.14\%$, a mode with a characteristic frequency in the range of $70\text{–}90 ~\text{kHz}$ was observed. This phenomenon was analyzed in detail in ref. [10]. Here, we discuss some additional details. Figure 2 presents a typical discharge where the magnetic probe signal has a considerably high frequency component. In this frequency range, correlations between the signals from the magnetic and Langmuir probes were weak. It is natural to assume that the perturbations are localized not too close to the plasma boundary. By analyzing the signals of four magnetic probes installed in the toroidal direction, it was established that the frequencies of perturbations with even toroidal numbers were in the {sense is not OK}frequency range of the order of 30 kHz and in the frequency range of the order of 75 kHz. As shown in the map of the rational magnetic surfaces, only the poloidal number equal to seven is reasonable. Thus, $m = 5$, $n = 4$ is the external peeling mode; $m = 6$, $n = 4$ is located at the magnetic surface of $\mu = 2/3$; here, the leading mode is $m = 3$, $n = 2$. In the estimates, we assume a definite $m$ number and use the averaged cylindrical approach. Then, we obtain

$$w = 4 \left( \frac{\delta B_p}{B_0} \frac{a_z}{a_s} m \mu \right)^{1/2},$$

where $w$ is the island width ($w = 0.41 ~\text{cm}$ at $m = 7$), $\delta B_p$ is the poloidal magnetic field oscillation, $\delta B_p/B_0 = 1.12 \times 10^{-6}$ at the point of the magnetic probe location at $W = 600 ~\text{J}$, and subscripts $z$ and $s$ denote the average radii of the probe location and resonance magnetic surface, respectively. Locations of the probes are the same as in ref. [1]. Eq. (1) can be used at $\mu/\mathcal{N} \ll 1$.

Let us consider the possible mechanisms that could be responsible for the observed phenomena. In calculations performed in the framework of an ideal MHD model, it is impossible to obtain instability. We complicated the model and performed our estimates in the framework of two-fluid magnetohydrodynamics [18]. Therefore, we also took into account the combined effect of the drift and acoustic modes. In the estimates, we set $x = 0.7$. According to ref. [1], at $\langle \beta \rangle \sim 0.2\%$, here a small magnetic hill is present. No instability was observed at sufficiently low densities, which suggests that the ion temperature plays an important role in this process. At $\langle \beta \rangle = 0.2\%$ and $n(0) = 2.0 \times 10^{13} ~\text{cm}^{-3}$, we set $T_{\text{io}} = 300 ~\text{eV}$, $T_{\text{io}} = 150 ~\text{eV}$, and $n = (1 - x^2)n(0)$ for the estimations.

Let us estimate the effect of the diamagnetic drift. In this case, the characteristic angular velocity of the perturbation is $\omega_{D_\parallel} = mc (- p_\parallel) / \mu e B_0$, where $m$ is the poloidal mode number, the prime denotes the differentiation with respect to $a$, $c$ is the speed of light, $e$ is the elementary charge, $B_0$ is the mean longitudinal magnetic field, and $T_0$ is the equilibrium ion temperature. For these plasma parameters, we obtain $f_{D_\parallel} = \omega_{D_\parallel} / 2 \pi = 5 m ~\text{kHz}$. To estimate the correction due to the electric field, $\omega_{E}$, it is
necessary to replace \((-p)\) with \(enE\) in the expression for \(\omega_{0i}\). The electric field is directed toward the plasma boundary and is approximately equal to 30 V/cm. If we take this value when estimating \(m\), then we will obtain \(m \sim 7\)–8. According to the theory, in this case, the perturbation should rotate in the direction of the ion diamagnetic drift, which agrees with the experiment. In our case, three ranges of longitudinal wave numbers are possible. At large poloidal mode numbers, they are \(k_{\parallel} = \mu m \delta a / R_0\), \(k_{\perp 2} = \mu / R_0\), and \(k_{\parallel 3} = N / l_0 R_0\), where \(k_{\parallel} << k_{\perp 2} << k_{\parallel 3}\). Here, \(\delta a\) is the characteristic radial size of the perturbation, \(k_{\parallel}\) is the wave number corresponding to the fundamental radial mode, and \(k_{\perp 2}\) and \(k_{\parallel 3}\) are the wave numbers corresponding to the toroidal and three-dimensional satellites, respectively.

Hence, we obtained \(f_{\perp 2} = k_{\perp 2} V_{fi} / 2\pi = 9\) kHz \(< \sim \) \(f = 75\) kHz \(< \sim \) \(f_{\parallel 3} = k_{\parallel 3} V_{fi} / 2\pi \approx 136\) kHz. In the estimates, we assumed \(m = 7\). Thus, the observed frequency is on the order of \(f_{\perp 2}\) which corresponds to three-dimensional satellites, which is highly questionable [согласен, но так наверное лучше] For a high-shear system, the analytical estimate of the ion pressure [7] overestimates the necessary value. Thus, the problem demands correct quantitative calculations. Such an analysis will be presented in a separate paper.

3. Conclusions
In this study, we considered electromagnetic instabilities that are observed in the three-dimensional configuration of the L-2M stellarator. In the framework of a MHD approach, the largest components of an unstable perturbation are the harmonics that arise as a result of coupling caused by the poloidal inhomogeneity (the toroidal effect). These are harmonics with poloidal mode numbers of \(m \pm k\), where \(k\) is a positive integer. The amplitudes of these harmonics decrease with increasing \(k\). The harmonics that appear due to 3D coupling are relatively small. This result has a rather simple physical interpretation. Unstable perturbations are almost constant along the magnetic field line. In this case, multiple regions with favorable and unfavorable curvatures are averaged along the field line. As a result of this averaging, an effective curvature of the magnetic field line arises that is responsible for the poloidal coupling of the harmonics. The external peeling mode is the only ideal MHD mode that was experimentally observed. When the external peeling mode is stable, another unstable mode is observable. The characteristic frequency of the unstable modes is in the range of 70–90 kHz, and the direction of its rotation coincides with the direction of the ion diamagnetic drift. This mode has definite thresholds for the plasma density and pressure. The observed phenomenon was analytically analyzed in the framework of two-fluid magnetohydrodynamics.

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References
[1] Shchepetov S V et al. 2008 Plasma Phys. Controlled Fusion 50 045001
[2] Mikhailov M I, Shchepetov S V, Nührenberg K, Nührenberg J 2015 Plasma Phys. Rep. 41 1016
[3] Shchepetov S V 2016 Plasma Phys. Controlled Fusion 58 114002
[4] Shchepetov S V, Vasilkov D G 2017 Plasma Phys. Rep. 43 720
[5] Mikhailovskii A B, Sharapov S E 1999 Plasma Phys. Rep. 25 803
[6] Hastie R J, Ramos J J, Porcelli F 2003 Phys. Plasmas 10 4405
[7] Jimenez J A, Luna de la E, Garcia-Cortes I and Shchepetov S V 2006 Plasma Phys. Controlled Fusion 48 515
[8] Shchepetov S V, Kholnov Yu V, Vasilkov D G 2013 Plasma Phys. Rep. 39 130

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[9] Oyama N 2008 *J. Physics: Conf. Series* **123** 012002
[10] Shchepetov S V, Vasilkov D G, Kholnov Yu V 2018 *Plasma Phys. Rep.* **44** 539
[11] Braginskii S I 1965 *Reviews of Plasma Physics*, Ed. by M. A. Leontovich (Consultants Bureau, New York, 1965) 1 205