Stability and Variation of Plasma Parameters in the L-2M Stellarator by Exciting Induction Current in ECR Heated Plasma

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Variation of parameters of ECR heated plasma was studied in the L-2M stellarator under conditions that the basic magnetic configuration was modified by exciting induction current. Experiments were carried out at ECRH power of ~200 kW (~1 MW m^{-3}) and average plasma density of ~$2{\cdot}10^{19}$ m^{-3}. The direction of the current was chosen such that the total rotational transform decreased, and its value was large enough (up to 17 kA) for rotational transform to change sign in the inner layers of the plasma column. Computer modeling predicts the formation of a multi-axis magnetic structure in the inner layers of the plasma column. Magnetic probe measurements show the presence of bursts in signals of Pfirsh-Schluter currents and variations of the spectrum and mode of MHD oscillations of the plasma column. The appearance of the n = 0 mode at currents above 10 kA is correlated to the appearance of the region where $\iota/2\pi = 0$. It is shown that, in the presence of the induction current, the electron temperature in the region $r/a \leq 0.6$ is lower by a factor of 1.3, whereas a characteristic jump in the temperature in the edge plasma remains; the density gradient at the plasma edge decreases. The behavior of turbulent density fluctuations was studied by using diagnostics of scattering of probing radiation. It is found that the probability density functions for increments of density fluctuations have heavier tails in the presence of a multi-axis structure. The spectral characteristics of turbulent fluctuations in the edge plasma and the poloidal plasma velocity were found to vary with radius. The experimental evidence suggests that the formation of the magnetic island structure in the core plasma leads to more intense transport in both core and edge plasma, but the change in transport is not catastrophic.

Keywords: stellarator, ECR heated plasma, plasma magnetic structure, omic current, MHD oscillations, plasma radial profiles, turbulence

1. Introduction

The straightforward method to study stability and confinement properties of stellarator magnetic configurations is the excitation of longitudinal (toroidal) currents.

Experiments with current were performed in the L-2 stellarator in the late 1970s, the results are presented in [1-3].

The present experiments in L-2M were carried out in the ECRH regime under conditions that an induced plasma current produced negative rotational transform with respect to the stellarator rotational transform. Calculations show that, at amplitudes of this "negative" current I/B > 0.25 A/G, the net rotational transform at the magnetic axis changes the sign in which case a flux surface with zero rotational transform should appear in the plasma. The higher the amplitude of induction current, the larger the radius of this flux surface. In toroidal geometry, such a magnetic configuration is topologically unstable. The transverse field of the current in the case $\iota/2\pi = 0$ is a perturbation resulting (even for $\beta = 0$) in a magnetic island with dimensions comparable to the minor radius of flux surfaces. In plasma with finite beta, such a magnetic configuration will be progressively modified

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and may be transformed into a multi-axes magnetic structure.

Plasma equilibrium under conditions that zero rotational transform exists inside the plasma column was studied experimentally in Heliotron-E [4]. Experiments showed that the appearance of zero transform in the plasma was accompanied by strong MHD activity and relaxation oscillations. The observed processes were attributed to activity of the m = 1, n = 0 tearing mode (m and n are the poloidal and toroidal indices, respectively).

In [5], the problem on equilibrium in the presence of a flux surface with zero rotational transform was studied numerically for the LHD configuration. Three-dimensional calculations, performed for various values of β, showed a possibility of one or two islands with zero rotational transform. In experiments [6] performed in configuration where islands might be expected, no apparent effect on plasma confinement was observed. At the same time, MHD activity of the m = 0, n = 0 was observed in the experiment.

The objective of the present work is to study the effect of such phenomena on plasma confinement and stability in the L-2M stellarator.

2. Experimental conditions

Experiments for studying the effect of a negative induction current on plasma confinement and stability were carried out in the "standard" magnetic configuration of the L-2M stellarator (R = 100 cm, a = 11.5 cm), where the ratio of the amplitude of the main harmonic of helical field (l = 2) to the amplitude of toroidal field at the axis is equal to 0.228. In this case, the rotational transform is $\iota(0)/2\pi = 0.2$ at the axis at the magnetic axis and $\iota(a)/2\pi = 0.8$ at the last closed magnetic surface for the vacuum magnetic configuration. In [7], the dependence of the rotational transform $i/2\pi$ on the mean radius of the magnetic surface was calculated for various current values under the assumption that topology of the L-2M magnetic configuration is only slightly affected by the current. It was shown that, at negative currents I/B= 1 A/G, we have $\iota/2\pi<0$ for normalized radii $\rho = r/a \leq 0.65$. The induction current, excited using the ohmic heating transformer, was switched on simultaneously with the ECRH pulse. Electron cyclotron heating (2nd harmonic of gyrofrequency, X-mode) was performed using a gyrotron with power P = 200 kW, frequency f = 75 GHz, and pulse duration of 10-12 ms. A focused Gaussian beam of diameter ≈4 cm was injected in the equatorial plane. The magnetic field B_0 = 1.34 T corresponded to the position of cyclotron resonance at the magnetic axis, R = 100 cm. The plasma density varied in the range, the amplitudes of induction current varied in the range 3-17 kA.

3. Numerical simulation of the magnetic structure

To study the equilibrium of a plasma with a current, we used a mathematical procedure based on the combination of numerical codes [8, 9]. For modeling the effect of the current, we numerically solved the average problem of MHD equilibrium with free boundary for the averaged poloidal flux (a quasilinear elliptical differential equation in partial derivatives). The model current profile for calculations was taken in the form

$j = J_0(1 - r^2)^k$, with variable k.

The numerical calculation of the averaged problem of equilibrium with a current yields values of the poloidal flux on a grid of polar coordinates with the origin at the magnetic center of the averaged equilibrium configuration.

The structure of three-dimensional surfaces, affected by both the current and plasma pressure, was determined by solving the magnetic-line equation and by tracing the results on map. The maps were constructed for tree basic cross sections.

According to calculations, the zero rotational transform inside the plasma results in a complicated magnetic structure with islands. Island dimensions depend on radial profiles of current and plasma pressure, and also on vertical magnetic field controlling the plasma position. As an illustration, Fig. 1 shows the calculated flux surfaces for a plasma current of 7 kA with a radial current density profile $j_\alpha \sim (1-\rho^2)^2$. The structure with two magnetic axes contains magnetic islands occupying a good fraction of the cross-sectional area.

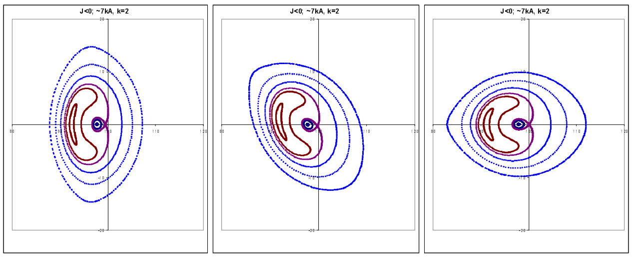


Fig. 1. Structure of flux surfaces in three cross sections of the L-2M stellarator in the presence of a "negative" induction current. The axis of the vacuum chamber is at R = 100 cm.

4. Time behavior of Pfirsh-Schluter currents, diamagnetic current and MHD oscillation during excitation of a negative induction current

Figure 2 shows the time behavior of the ECR heating power, induction current, derivative of equilibrium field determined by Pfirsch-Schluter currents (dPS/dt), average electron density (measured by a 2-mm interferometer over the central chord), and central electron temperature (measured from electron cyclotron emission at a frequency of 76 GHz). The quasi-steady state lasts from 50 to 60 ms. Characteristically, the dPS/dt signal in the regime with current shows sharp peaks of relaxation oscillations at ~1-ms intervals (Fig. 2c), which are absent in the currentless regime (Fig. 2d). It should be noted that such oscillations were always absent in the signal of diamagnetic flux derivative (dW/dt) in the regime with a negative current. The plateau current is also undisturbed. Hence, it may be concluded that the arising MHD perturbations are associated with Pfirsch-Schluter currents.

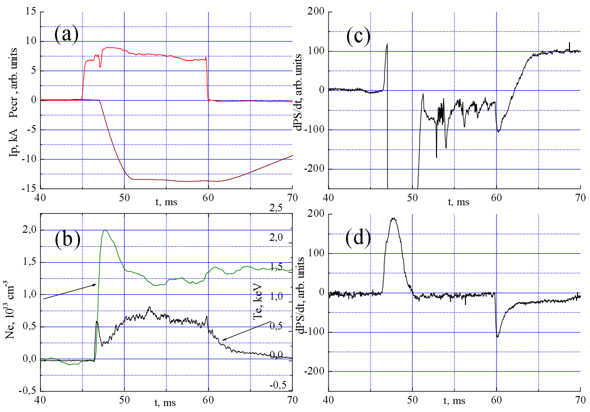


Fig. 2. Time behavior of signals in a discharge with a "negative" current: (a) gyrotron power P_{ecr} (red) and induction current I_p (brown), (b) average density N_e (green), central electron temperature T_e (ECE, 76 GHz) (black), (c) derivative of transversal magnetic flux dPS/dt (for current 13 kA), (d) derivative of transversal magnetic flux dPS/dt (without current).

To clear up the cause of perturbations in the Pfirsh-Schluter currents, we compared the data of this diagnostics with data of a set of Mirnov coils. The Mirnov coils were placed outside the vacuum chamber, in front of the quartz windows in order to reduce the shielding effect of the chamber, and were so oriented as to measure the poloidal component of the magnetic field.

Figure 3 shows the signals from Mirnov coils for different regimes. The signal amplitudes are of the same order for the regimes with and without current. Fourier spectra of the signals span the range 1-150 kHz. Analysis revealed a time correlation between the appearance of relaxation peaks in the dPS/dt signal and the appearance of a peak in the range 5-15 kHz in the spectrum.

Data of Mirnov coils showed that the mode composition of MHD perturbations changed in the regime with negative current, specifically, perturbations with toroidal index n = 0 were observed in the plasma. It should be noted that the perturbations in Pfirsh-Schluter currents and the n = 0 mode were observed when the magnitude of the negative current exceeded the threshold value of 10 kA.

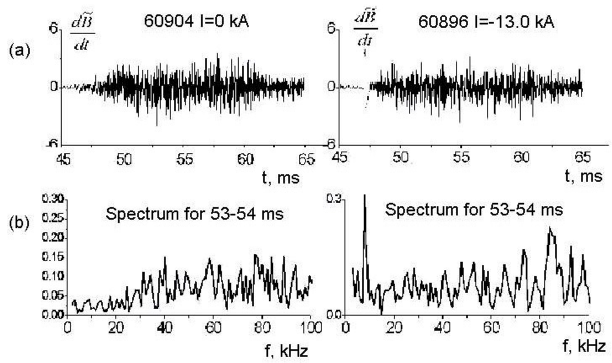


Fig. 3. Time evolution of magnetic field fluctuations:
(a) Mirnov coil signal, $d\tilde{B}/dt$.
(b) Fourier spectra of Mirnov coil signals.

5. Measurements of the radial electron temperature and density profiles

Figure 4 shows the radial electron temperature profile (on semi-log scale) in the ECRH regime in the absence of an induction current. The electron temperature was measured from the intensity of ECE at the second harmonic of the gyrofrequency in the central region (r/a≤0.6) and from intensity of impurity lines BIV (282.2 nm) and CIII (464.7nm) at the periphery (0.6≤r/a≤1.0). The half-with of the profile is estimated as (0.4-0.5) a. A characteristic feature of the temperature profile is the temperature jump near the last closed flux surface, within a region Δr/a ≤ 0.1. The temperature jump may be interpreted as a thermal barrier [10].

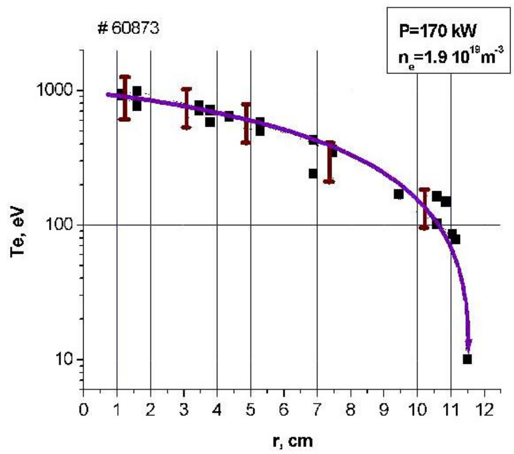


Fig. 4. Radial electron temperature profile in currentless plasma. ECRH power 170 kW, average density $1{,}9{\cdot}10^{13}$cm^{-3}.

Figure 5 compares the temperature profiles (ECE frequency spectra) averaged over 10 shots for the regimes without and with currents -(13-15) kA. The profile shape does not change in the regime with current, but the maximum temperature drops by a factor of ~1.3.

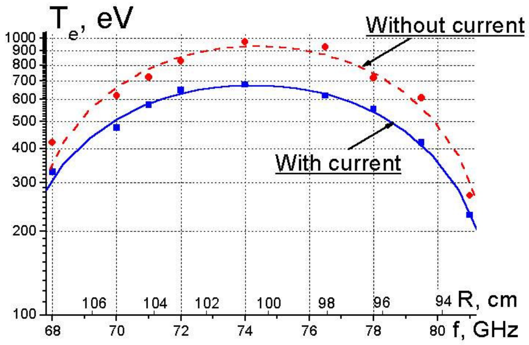
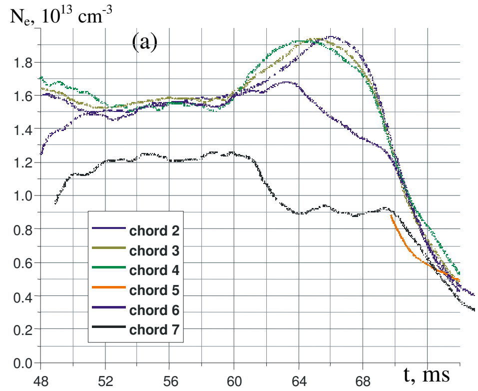


Fig. 5. Comparison of electron temperature profiles (ECE) in the core plasma for regimes without/with negative current 13-15 kA Average density without current $1{,}7\cdot10^{13}$cm^{-3}, with current $1{,}5\div1{,}7\cdot10^{13}$cm^{-3}

From spectral measurements of the BIV line (the ionization energy of B^{+3} ions is about 250 eV), it may be deduced that the characteristic form of the profile at the edge is retained. Thus, the intensity of this line drops very steeply on the interval R = 89-87 cm in the currentless regime, and so does it in the regime with current -(8-15) kA, but on the interval R = 88-86.5 cm (spectral measurements are made on the inside of the magnetic axis, R < 100 cm). The intensity distribution shifts by ~1 cm toward smaller R. This result is consistent with the expected shift of flux surfaces under the action of the transverse field produced by negative current. Therefore, it may be concluded that a temperature jump at the edge takes place.

Figure 6 shows the average density values measured by an HCN laser interferometer over 7 chords in the regimes with and without current of -13 kA. From Fig. 6a, it is seen that the density on central chords initially drops somewhat at the beginning of the ECRH pulse. After 52 ms, the radial density profile changes only slightly. Characteristically, the radial profile in the currentless plasma in L-2M is flat, with a sharp drop near the plasma boundary.

The electron density profile and its evolution change markedly in the presence of a negative induction current: the profile is less flattened as compared with the currentless plasma. A sharp drop in the density over all the central chords is observed at the beginning of the ECRH pulse, which indicates substantial losses of electrons from the core plasma. Besides, we observe substantial (up to 20%) irregular changes in the average density for all of the central chords, including in the ohmic phase of the discharge (after 60 ms).



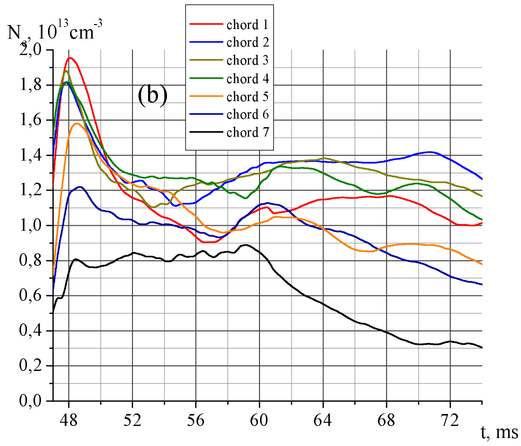


Fig. 6. Time evolution of average electron densities measured over 7 chords:
(a) currentless plasma,
(b) regime with current 13 kA.

Calculations of the flux surfaces in plasma with current (Fig. 1) show that the outer flux surfaces retain their structure. This allows us to compare the regimes with and without current by using data for the peripheral chord ("7"), normalized to the central-chord density. Estimates show that the density gradient near the boundary is 1/4 less in the regime with current.

Thus, according to interferometric measurements, the electron density profiles in the core plasma are less flattened, with smaller gradient near the plasma boundary in the regime with current.

6. Fourier spectra and statistical characteristics of turbulent plasma density fluctuations

To study turbulent plasma density fluctuations in the central region of the plasma column, we used scattered ordinary microwaves arising as a result of double refraction of the gyrotron radiation, produced and heated the plasma column (the radiation wavelength is 4 mm). In this method, the probing radiation passes through the central chord and allows measurements in the central regions. Fluctuations of the wave phase are averaged over the central chord, whereas geometric sizes of the beam and the detector ensure measurements of scattered radiation in the near wave zone.

Turbulent density fluctuations in the edge plasma were studied with the help of a Doppler reflectometer using the scattering of a low-power probing beam (wavelength from 8 to 9 mm) at total reflection of radiation incident obliquely on the plasma column (see, e.g., [11-13]). Geometry of this diagnostic allows measurements of scattered signals from density perturbations with wavelengths of 4-6 cm; the growth rate of these perturbations is three times smaller than for the ion drift-temperature mode.

Typical Fourier spectra of small-angle scattering are presented in Figs. 7. The Fourier spectra for regimes with and without current are essentially different. In the absence of current, we observe a continuous spectrum with feebly marked wide bands. In the regime with current, the spectral density is maximal in the low-frequency range 5-15 kHz decreases toward 50 kHz and there is wide band with a maximum at 100-150 kHz.

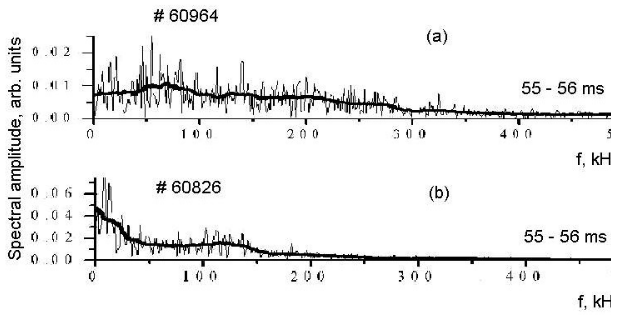


Fig. 7. Fourier spectra of small-angle scattering signals. Average density $1,4 \div 1,5 \cdot 10^{13}$cm^{-3}, ECRH power 200 kW.

The reflectometer measurements in the edge plasma were performed with probing frequencies of 30.9, 34.8, and 37.6 GHz, at angles of incidence of 4^0, 8^0, and 12^0 with respect to the normal to the plasma boundary. These frequencies correspond to the scattering regions with plasma densities $1.73 \cdot 10^{13}$, $1.48 \cdot 10^{13}$, and $1.17 \cdot 10^{13}$ cm^{-3} at the edge of the plasma column, $0.8 \le r/a \le 0.9$. The reflectometer measured density fluctuations with poloidal wavenumber $k \approx 2$cm^{-1}.

Figure 8 compares Fourier spectra of the complex signals for regimes without and with current (-14 kA). The probing frequency is 30.9 GHz, the angle of incidence is 8^0. Gray lines are for a time resolution of 1.22 kHz; black lines are for a time resolution of 25.62 kHz. Both spectra are averaged over the time interval 819.2 μs. The spectral peak is shifted into the red region by ~250 kHz, which is a Doppler shift in frequency and corresponds to a poloidal velocity of ~~10^6 cm s^{-1}. The Fourier spectra for probing frequencies of 34.8 and 37.6 GHz are very similar in shape and shift value. From these results it may be inferred that the poloidal rotation velocity is uniform over the region with density from ~$1.7 \cdot 10^{13}$ to ~$1.1 \cdot 10^{13}$ cm^{-3}.

The excitation of the induction current causes changes in the scattered spectra, but these changes are different for different probing frequencies. For a frequency of 30.9 GHz, the spectrum becomes narrower and the Doppler shift decreases. For a frequency of 37.6 GHz, the Doppler shift increases, which corresponds to an increase by 50% in the poloidal velocity.

Thus, the excitation of the magnetic island structure in the core plasma affects the edge plasma. The Doppler shift of the spectrum varies with radius, which is evidence for the radial shear of the poloidal velocity.

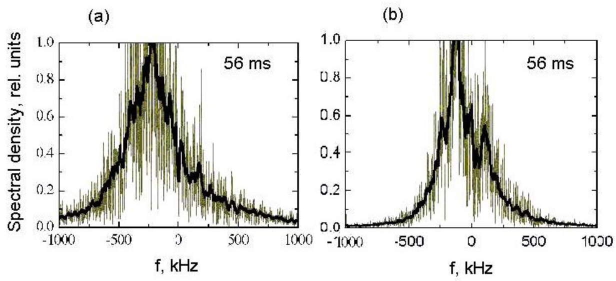


Fig. 8. Comparison of Fourier spectra of scattered signals for frequency 30.9 GHz of the Doppler reflectometer with a 5-kHz filter for regimes without (a) and with (b) negative current 14 kA. Average density $1,4 \div 1,5 \cdot 10^{13}$cm^{-3}, ECRH

The time behavior of the scattered signals and the form of their Fourier spectra reveal stochastic nature of plasma density fluctuations. Statistical analysis of signals of small-angle scattering showed that the probability density functions (PDFs) of signal increments are non-Gaussian and broaden out in the presence of a current. Similar effects were observed for the reflectometer signals measuring density fluctuations in the edge plasma.

Thus, the spectral-statistical characteristics of turbulent plasma turn out to be sensitive to changes in the magnetic field structure. It may be assumed that this is a manifestation of interrelation between turbulence and transport processes.

7. Conclusions

Experiments in the regime of simultaneous ECR and ohmic heating have been carried out in the L-2M stellarator for studying the effect of a negative induction current decreasing the rotational transform. The amplitudes of induction current were properly chosen to achieve zero rotational transform on some flux surface in the plasma column.

A numerical analysis of the magnetic structure demonstrated a possibility for multi-axis structure with magnetic islands whose dimensions reach one-half the plasma radius.

Characteristic oscillations in the Pfirsh-Schluter currents and changes in the mode composition of MHD perturbations (the excitation of MHD fluctuations with toroidal index n = 0) were observed at currents above 10 kA.

The excitation of the current leads to a decrease in the electron temperature in the core plasma to 0.7 of its value for currentless plasma, the temperature jump near the plasma boundary is retained. The radial density profile and its evolution change in the presence of the current: the density profiles in the core plasma are less flattened, the density gradient decreases near the boundary. A density by 1/3 of its initial value was observed at the initial stage of the discharge. These data constitute evidence of more intense heat transport processes in the core plasma and more intense particle transport in the edge plasma.

The excitation of the current involves changes in the characteristics of turbulent density fluctuations in the core plasma as well as in the edge plasma. The probability of large amplitudes in the PDF of increments of density fluctuations in the core plasma increases, resulting in wide deviations and the normal (Gaussian) law. The turbulent spectra and poloidal velocity in the edge plasma turn out to be nonuniform over a narrow plasma region $\Delta r/a \approx 0.1$, in contrast with the currentless plasma where the poloidal velocity is uniform. The PDFs become asymmetric, which is indicative of convection transport. From these results it may be concluded that MHD processes occurring in the core plasma influence turbulent fluctuations at the edge.

Thus, the formation of the multi-axis magnetic structure with islands in the L-2M magnetic configuration leads to more intense transport and changes turbulence characteristics, but the change in transport is not catastrophic.

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