Recent Results from L-2M Stellarator

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Abstract. The results of recent experiments in the L-2M stellarator are presented. The experiments were carried out with the use of boronization of the stellarator vacuum chamber. This made it possible to change the conditions of the plasma experiment substantially, reducing the radiation loss power to 10 - 15% of the power input. Under these conditions, at a heating power above 120 kW, a jump (pedestal) by 100 - 150 eV appears in the electron temperature at the separatrix. When operating with a high heating power and plasma density above n > 10^19/m^3, we observed a spontaneous, sudden and very fast (about 0.2 ms) drop in the plasma energy by 5-10% of its value, measured by the diamagnetic diagnostics. After this fast drop, the plasma energy slowly restores or even increases somewhat. The probability of such events increases with increasing density and heating power. The fast change in the plasma parameters occurs only at the edge while not influencing the core plasma parameters. The fast drop is followed by a slow increase in the plasma energy, which correlates with an increase in the plasma density, which may be considered as a demonstration of somewhat better confinement of particles. The report presents the results of ion temperature measurements from a Doppler broadening of emission lines of impurity ions and their comparison with calculations using a TRANSZ transport code. Results of measurements of the microwave scattering by plasma fluctuations are discussed in the context of the relation between anomalous and neoclassical transport. The electron energy distribution function was reconstructed from the measured SXR spectra and was found to be essentially non-Maxwellian at low plasma densities.

1. Introduction

This report presents results of recent experiments on ECR plasma heating and confinement in the L-2M stellarator. The L-2M is a classical l = 2 stellarator with a major radius R = 1 m, and the total number of magnetic field periods N = 14. In a standard magnetic configuration, the rotational transform is $\iota(0) = 0.18$ at the magnetic axis and $\iota(a) = 0.78$ at the last closed flux surface. The average minor plasma radius in this case is a = 11.5 cm. Plasma is produced and heated by one of two gyrotrons at a frequency f = 75 GHz for a magnetic field at the axis of B = 1.34 T (X-mode, the second harmonic of the electron cyclotron frequency). Experiments were carried out in the range of average plasma densities n=(0.5 - 2.5) x 10^19/m^3 and ECR heating power P = 100 - 300 kW. The electron temperature in the center of plasma column is about 1 keV and the ion temperature is 0.1-0.15 keV. The use of the boronization of the stellarator vacuum chamber changed the conditions of the plasma experiment substantially, resulting in a several-fold decrease in the intensity of emission spectral lines of impurity ions and integral plasma radiation [1]. For boronization we used the glow discharge in the mixture of He gas (60%) and carborane ($C_2B_{10}H_{12}$) vapor (40%) at the pressure of $2x10^{-3}$ torr. In the present experiments, the radiation loss power does not exceed 10 - 15% of the power input.

2. Some effects in the edge plasma region

The reduction in radiation loss power in experiments with boronization involved some changes in characteristics of the edge plasma. These changes are most evident in the electron

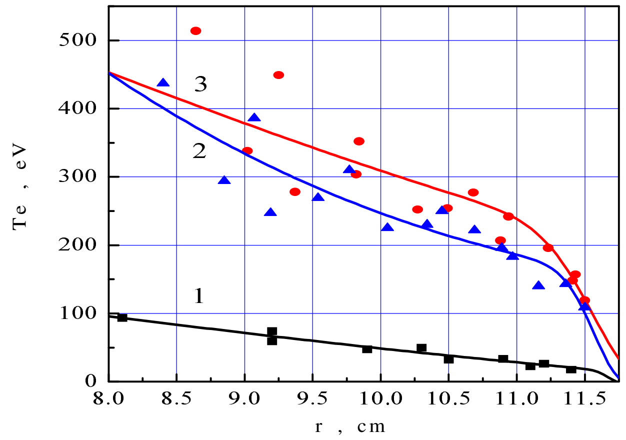

FIG.1.Radial electron temperature distribution at the plasma edge.

temperature profile. A new effect was noted [2], namely, a jump by 100 - 150 eV in the electron temperature near the last closed flux surface, within a narrow radial region Δr~5 мм.. This is a threshold effect, which shows at a heating power P >120 kW, whereas at P = 100 kW a radial jump in the electric temperature is absent. As an illustration, Fig. 1 shows the electron temperature profiles in the edge plasma for different values of heating power. Curves 1,2 and 3 correspond to the ECR heating power P=100, 150 and 200 kW, respectively. For reference, the electron temperature profile across the plasma column is shown in Fig. 2. The appearance of such temperature pedestals at the plasma edge is characteristic of H-mode in tokamaks; in this case, the pedestal height increases as the energy lifetime increases, the enhancement factor being usually in the range 2-4. Usually the occurrence of the H-mode in stellarators is not accompanied by energy confinement times as large as this. The transition to H-mode is recognized from a substantial increase in the particle life time (see, e.g., [3]). However, the results are not yet sufficient to allow definite conclusions that the transition to H-mode occurs in L-2M with increasing heating power. Thus, diamagnetic measurements show that the plasma energy and, consequently, the plasma energy lifetime change but slightly in discharges with a pedestal. The dependence W(P) (here, W is the plasma energy and P is the heating power), to within the spread of experimental points (approx. 5%), has no stepwise changes. After all, we did not observed time-dependent transitions to H-mode followed by the inverse process. Since the pedestal tends to increase with increasing heating power in the range 120 – 250 kW, we intend to continue investigation of this effect over a much wider range of heating powers.

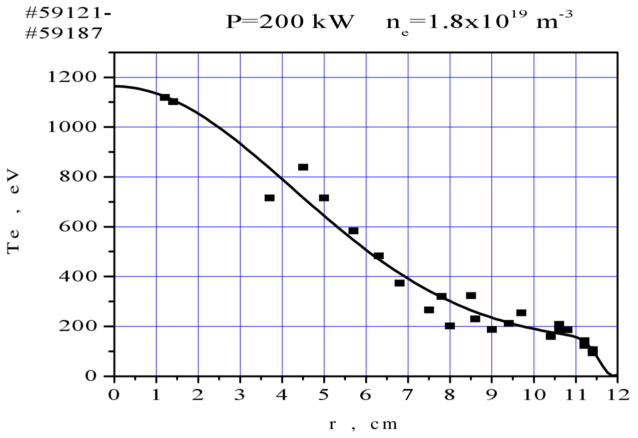

FIG.2. Typical electron temperature profile for ECR heated plasma

Another interesting effect was noted when operating with a high heating power and plasma density above $n_e > 10^{19}$ m^{-3}. This effect, which was never before observed in L-2M experiments, is a spontaneous, sudden and very fast (about 0.2 ms) drop in the plasma energy by 5-10% of its value, measured by the diamagnetic diagnostics. Such an effect is illustrated in Fig. 3 which shows the time behavior of the diamagnetic signals and its derivative for two similar ECRH pulses in L-2M. The upper signals correspond to a discharge without any energy drop in the steady-state phase, whereas the lower signals demonstrate the presence of a local minimum in the plasma energy. In the latter case, the plasma energy derivative shows a distinct spike estimated as 50-kW power losses from the plasma column. The occurrence of such an event itself and its time are unpredictable, we only note that the probability of this event increases as the heating power and the plasma density increase. The fast energy drop is followed by a slower phase of plasma energy restoration or, in most cases, by a faster energy growth. Figure 4 demonstrates the density dependence of the plasma energy attained by the instant at which the ECRH power is switched off. Asterisks corresponds to shots in which spikes were observed, whereas circles correspond to the absence of spikes. It can be seen that, for shots with fast energy drops, the plasma energy approaches its maximum values. Measurements show that only the outermost plasma layer is affected in this case. Thus, signals from a Mirnov coil for detecting the m/n = 2/1 MHD mode (developing near the magnetic flux surface with $\iota = 0.5$ at radius r/a ~ 0.7) do not undergo a change in the presence of a spike. At the same time, Langmuir probes measuring the floating potential at the plasma boundary indicate a drastic suppression of fluctuations after the fast energy drop. The correlation between MHD and potential signals, which is rather high before the energy drop, decreases several fold after this drop. It may appear that the effects observed in L-2M are similar to ELMs observed in tokamaks in the event of H-mode, but we did not observe oscillations preceding the energy drop. It is reasonable to assume that there exist two closely related steady states, and the transition from one to another is initiated by a certain process.
This effect cannot be explained in the frameworks of MHD theory, and probably the kinetic effects must be taken into consideration.

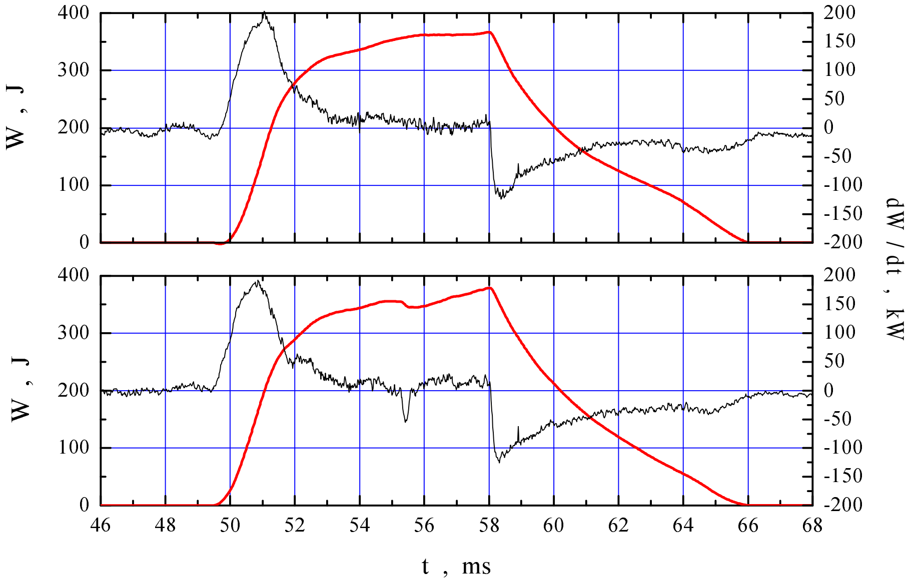

FIG.3. Time evolution of plasma energy (red curves) and its derivative (black)

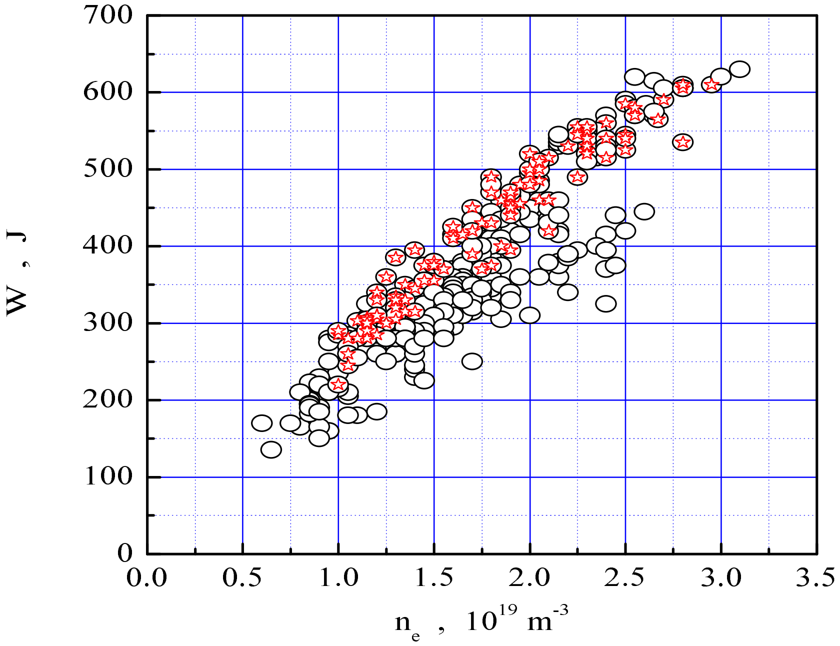

FIG.4. Plasma energy vs .plasma density for different regimes

The radial distribution and temporal evolution of the ion temperature at the periphery of the plasma column was measured from Doppler broadening of spectral lines of impurity ions (BIV, CIII, BII and HeII). Under conditions of ECR heating, the ions acquire energy at Coulomb collisions with electrons and from radial electric field. The measured values of ion temperature in the plasma region r = 9 - 11 cm are in the range from 40 to 100 eV. The temporal evolution of Ti during the process of heating was calculated with the TRANSZ code [4] in which only neoclassical transport coefficients were used for the ions. The calculated values of Ti agree satisfactorily with the measured values. Hence, there is no need to introduce extra heat losses (in addition to neoclassical losses) through the ion channel.

3. The problem of neoclassical and anomalies transport

In plasma investigations in stellarator configurations, the challenge is to elucidate physical mechanisms governing energy and particle transport in 3D-nonuniform magnetic fields and to determine contributions from neoclassical and anomalous transport. The L-2M stellarator has a rather large aspect ratio ($R/a_p \cong 8.7$). In this case, the $l = 2$ harmonic has a dominant role, in which case the available neoclassical transport theory [5] can be reliably used in modeling the plasma parameters. The relevant calculations show that neoclassical transport would suffice to explain the plasma parameters in the central region of the plasma column. For the peripheral plasma region, it is necessary to introduce anomalous thermal conductivity and electron diffusion. The most probable cause of anomalous transport is plasma turbulence. Plasma turbulence in the edge plasma of the L-2M stellarator has been the subject of much investigation (see, e.g., [6, 7]). In the course of experimental studies, plasma density fluctuations and floating potential were measured with Langmuir probes, MHD oscillations were measured with Mirnov coils, and density fluctuations were measured by using reflectometry. In particular, it has been shown that strong low-frequency turbulence is characterized by the presence of ensembles of stochastic plasma structures that are described by the probability density functions (PDF) different from a Gaussian distribution. An interesting and unexpected result was obtained when probing the plasma by microwave beams at the actual gyrotron frequency and its second harmonics (the second and fourth harmonics of the electron gyofrequency, respectively) [8]. Studies of scattering of this radiation by plasma fluctuations in the central region (ECR heating region) revealed a high degree of their correlation with fluctuations in the edge plasma. It would seem that this result demonstrates that different modes are involved in mode coupling so that turbulent processes play an important role over all the plasma column. However, this is contradictory to the results of simulation with our codes in the sense that the plasma parameters in the central region during ECRH are fairly described by neoclassical transport only, without any additions. To resolve this contradiction would require further development of diagnostic techniques and more careful comparison of experimental data with results of transport codes.

4. Deviation of the Electron Energy Distribution Function from Maxwellian during ECR Heating

Knowing the intensity distribution in SXR continuum emitted from the plasma, one can, in specific cases, find the electron energy distribution function. The SXR spectrum of L-2M plasma is measured with the help of a KEVEX spectrometer analyzing the energies of individual photons. Reliable measurements of the spectrum usually begin at energy E ~ 1.3-1.5 keV with energy resolution $\Delta E = 0.2$ keV. The pure bremsstrahlung intensity is defined by the expression [9]:

$$I(E) = \Sigma_i \alpha_0 n_i Z_i^2 \int_E^\infty \frac{f_e(E)}{\sqrt{E}} dE = A \int_E^\infty \frac{f_e(E)}{\sqrt{E}} dE \ ,$$

where $f_e(E) = dn_e/dE$ is the electron energy distribution function, n_i and Z_i are the density and charge of a given ion species, and α_0 is a numerical factor. For a Maxwellian electron energy distribution, we have $I(E) \sim \exp(E/T_e)$ and can easily find the plasma electron temperature. For non-Maxwellian distribution, the electron energy distribution function can be determined from the shape of the SXR spectrum:

$$f_e(E) = -\frac{\sqrt{E}}{A} \frac{dI(E)}{dE}.$$

If there are impurity ions in different ionization states in a hydrogen plasma, then the recombination radiation must be taken into consideration [10]. In this case, the factor A is equal to $\Sigma_i \alpha_0 n_e n_i \gamma_i$, where γ_i is the enhancement factor equal to the ratio of the total radiation intensity (the sum of bremsstrahlung and recombination radiation) to the pure bremsstrahlung intensity. If the SXR emission from the plasma is dominated by low-Z impurities (e.g., oxygen ions), then all the recombination transitions fall into a low-energy range that is not recorded by the spectrometer. In this case, the shape of the spectrum in the measurement region is similar to that for bremsstrahlung, but the intensities themselves are higher by the factor γ (average over all ion species). This situation that takes place in L-2M after the boronization of the stainless-steel vacuum chamber wall, because the influx of impurities, including high-Z impurities, from the wall into the plasma is reduced significantly. Even if there are high-energy tails, the SXR spectra have no characteristic K_α lines of Cr, Fe, and Ni entering into the composition of stainless steel. At plasma densities $n_e > 10^{19}$ m^{-3} and available ECR heating powers in these experiments, the function ln[I(E)] was always linear up to photon energies of E ~ 7 T_e. Measurements of the spectrum in the range of high energies usually involve difficulties because of very low radiation intensity and, hence, poor statistics.

That is, in this range of plasma densities, the electron energy distribution function over a wide energy range is Maxwellian. A different situation arises with low-density regimes $n_e<10^{19}$ m^{-3}. That the electron energy distribution tends to become non-Maxwellian with decreasing plasma density was clear from changes in the spectrum of electron cyclotron emission at the second harmonic of electron gyrofrequency [11]. Recently, we have undertaken detailed measurements of X-ray spectra in the range of photon energies 1.5 – 12 keV at plasma density n_e=0.5x10^{19} m^{-3} and heating power P=200 kW. The corresponding electron energy distribution function is presented in Fig. 5, curve 1. It is evident from the curve that this distribution differs markedly from Maxwellian (curve 2) over all the measurement range. This circumstance is of importance to the correct estimation of plasma energy.

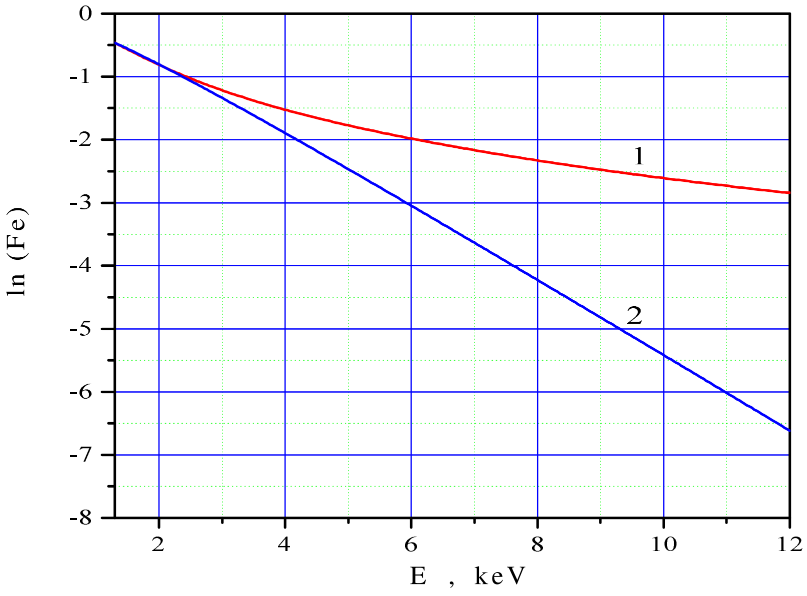

FIG.5 Electron distribution function. 1-experiment,
2- Maxwellian distribution for T_e*=0.7 keV case.*

5. Plans of Future Experiments in the L-2M Stellarator

The ECRH experiments at the stellarator are presently suspended because of mounting of a new system for ECR heating of plasma. Two gyrotrons of the old system will be replaced by new, high-performance gyrotrons with a frequency of 75 GHz and power of 0.8 MW each. It is anticipated that the energy deposition into a plasma will be increased substantially, attaining values more than 5 MW/@ over all the plasma volume. Experiments with the first gyrotron will start in 2007. The second gyrotron will permit the frequency change within 5 GHz.

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