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# Review of L-2M Experiments

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## Abstract

The paper presents results of ECRH experiments carried out in the L2-M stellarator. The initial stage of the ECR discharge was studied, and the minimum breakdown time was observed when resonance conditions were satisfied at the vacuum magnetic axis. The results of the influence of plasma pressure on the shape of magnetic surfaces are presented. Scraping off the large-shear region by a limiter has shown that the shear at the plasma boundary affects weakly plasma confinement. Analysis of the electron temperature profiles has shown that the heating picture is in poor agreement with the ray-tracing calculations of the energy deposition profile.

## Keywords:

stellarator, electron cyclotron resonance, gyrotron, magnetic surface, Shafranov shift, magnetic shear

## 1. Introduction

The paper presents the results of recent ECRH experiments carried out in the L2-M stellarator ($R=1$ m, $a_p \leq 0.115$ m, $l=2$, $\iota(0)=0.2$, $\iota(a)=0.8$, $B<1.5$ T). For creating and heating a current-free plasma, we used two 75 GHz gyrotrons ($\lambda=4$ mm) with the power P=0.4 MW. For the magnetic field $B=1.34$ T, the resonant conditions for the ECR at the second harmonic of gyrofrequency ($\omega=2\ \omega_{Be}$, X-mode) were fulfilled for R=1 m. The experiments were carried out with hydrogen or helium plasma. The heating pulse duration was 10–12 ms; during the heating pulse, B varied by no more than 1%. Plasma parameters typical of our experiments are $n_e \approx (1 \div 2)10^{19}$ m$^{-3}$, $T_e(0) \approx 1$ keV, $T_i \approx 0.1 \div 0.15$ keV.

## 2. ECR Breakdown

Gas breakdown and formation of the plasma column were produced by means of the microwave beams. After switching-on the heating power, breakdown began after a certain delay time. As the experiments showed, the delay time was dependent on the value of the magnetic field, *i.e.*, on the position of the resonant region in the stellarator cross section (see Fig. 1(a), where $B_0$ is the magnetic field at point $R=1$ m). This dependence shows a clear resonant character. The breakdown time is the minimum at $B_0=1.32$ T, which corresponds to position of the resonant region on the magnetic axis of vacuum magnetic surfaces, at $R=0.975$ m. To verify whether the minimum breakdown time corresponds to the resonance on the

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*Corresponding author's e-mail: greben@fpl.gpi.ru magnetic axis, we carried out test experiments with shifting the magnetic axis by applying a vertical magnetic field $B_v$. Figure 1(b) shows the results obtained for the magnetic axis shift of about ± 2 cm. Here again the breakdown occurs more rapidly if the resonant region is located on the vacuum magnetic surfaces axis. The possible explanation is that, near the magnetic axis, magnetic field ripples are minimum, and a number of trapped electrons which can drift out from the resonant region is minimum as well.

## 3. Limiter Experiments and β Effect

As the plasma is heated and the equilibrium currents are generated, the magnetic surfaces deform and shift outward (the Shafranov shift). The experimental value of the Shafranov shift was measured by a multichord X-ray diagnostics. In the ECRH experiments in L2-M, the measured values of the Shafranov shift lie between 1.8 and 3.3 cm, depending on the values of plasma density and electron temperature. These values agree with theoretical estimation under reasonable assumption about the radial β-profile. For more correct comparison of the theory with the experiment, the inverse problem was solved: the equilibrium plasma configurations were calculated for the experimental values of the Shafranov shift of plasma center and values $<\beta>$, obtained from diamagnetic measurements. A magnetic surfaces map and β(r) were calculated by using a numerical procedure described in ref. [1]. Such a map with superimposed lines of sight of the SXR diagnostics allows us to reconstruct the profiles $T_e(<r>)$, where $<r>(\psi)$ is the mean radius of the magnetic surface with the given magnetic flux $\psi$. The detailed description of the reconstruction procedure and some examples are presented in [2]. Comparison of the experimental profiles $T_e(r)$ with the calculated profiles $\beta(r)$ shows that these may be in agreement if the plasma density profile $n_e(r)$ is more flat. Note that the

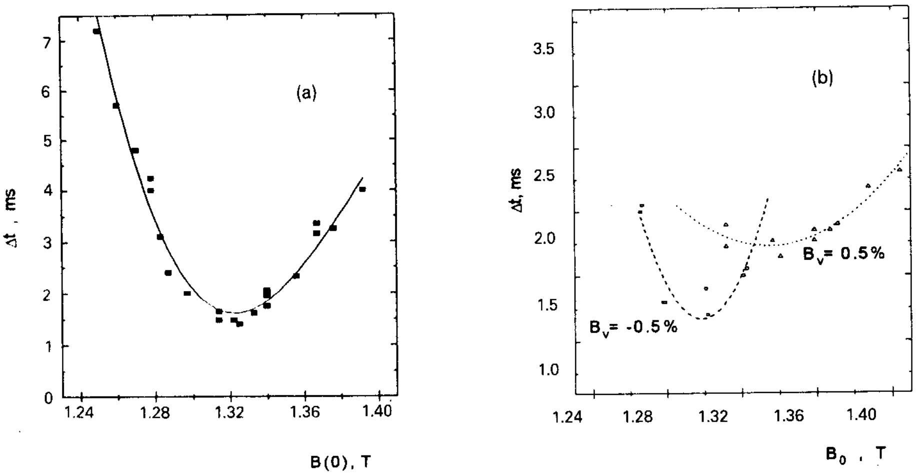

Fig. 1 The time delay of breakdown vs magnetic field value $B_0$; (a) - standard configuration, (b) - shift of magnetic axis by vertical magnetic field.

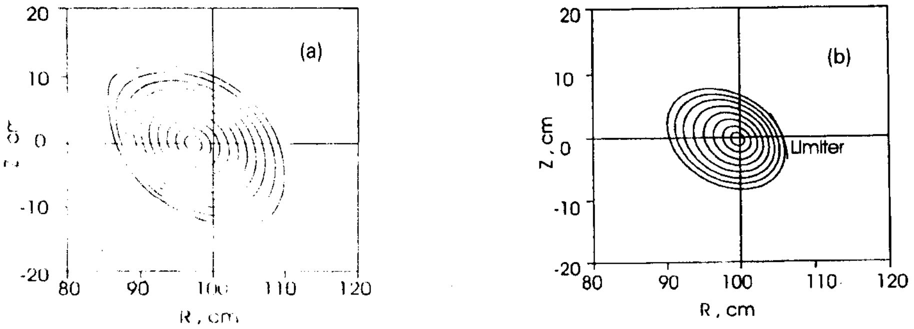

Fig. 2 The magnetic surfaces for L2-M, (a) - without limiter (β = 0), (b) - with limiter 3 cm inside separatix ( $<\beta>$ = 0.15%).

calculation by the TRANSZ code [3] yields a flat density profile as well.

In a number of experiments, a graphite limiter was used to decrease the plasma-wall interaction and the radiation growth. This movable limiter can be introduced from the outside of the torus inward up to 3 cm from the separatrix. While limiting the plasma radius, the limiter cuts off the large shear and largest rotational transform region at the plasma edge. In the absence of a limiter, the outward shift of the separatrix is much smaller than that of the center of the plasma column; for the plasma parameters typical of L2-M experiments, this effect is negligible. In limiter experiment, in which the rotational transform at the plasma edge decreases, the plasma boundary shifts outward noticeably, which leads to an additional decrease in plasma radius. The resulting magnetic field structure inside the plasma differs substantially from the initial one. Figure 2 shows the vacuum magnetic surfaces in the absence of a limiter and those for the limiter positioned at 3 cm distance from the separatrix. The radial profiles of $\iota$ for both cases are shown in Fig. 3. The limiter experiments have shown that under the same heating conditions, the energy confinement time is proportional to the square of mean plasma radius. Thus we did not find any influence of either the value of shear at the plasma edge or that of rotational transform on the confinement in the stellarator.

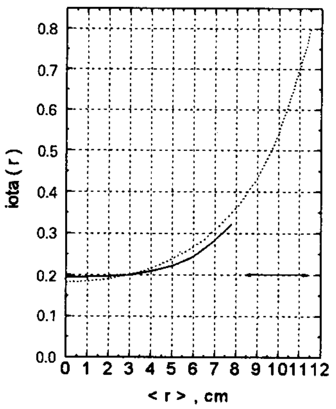

Fig. 3 The rotational transform profiles for two configurations shown in Fig. 2.

## 4. Local Heating and High-Energy Electrons

Ray-tracing calculations for the L-2M experiments on ECRH at $\omega = 2\ \omega_{Be}$ show that the total power absorption coefficient should be close to unity for a rather wide interval of the magnetic field [4,5]. As the value of the magnetic field $B_0$ varies, the position of the energy deposition region in the plasma should vary together with the power deposition density (see Fig. 4). When the resonance occurs at the magnetic axis, the specific power deposition reaches about 30 W/cm$^3$ which value is by order of magnitude higher than in the case where the resonant region is displaced outward or inward by ~3 cm. The measured electron temperature distributions in the central part of the plasma column for various magnetic fields are shown in Fig. 5. For low magnetic fields, the temperature profile is flat, which is typical of the off-axis heating. When the resonant region approaches the magnetic axis, the profiles sharpen; however, the absolute values of the central temperature increase slightly in spite of 10-fold increase in the specific power deposition. It is likely that the energy deposition region becomes larger due to trapped electrons, as has recently been shown in the experiments on W7-AS [6]. Paradoxical situation occurs when the magnetic field is higher, and the resonant region is expected to be shifted outward. In this case however, the electron temperature profile remains peaked at the magnetic axis. Working from the ray-tracing calculations, we cannot explain this case. The X-ray data are supported by the ECE data (Fig. 6). Emission from

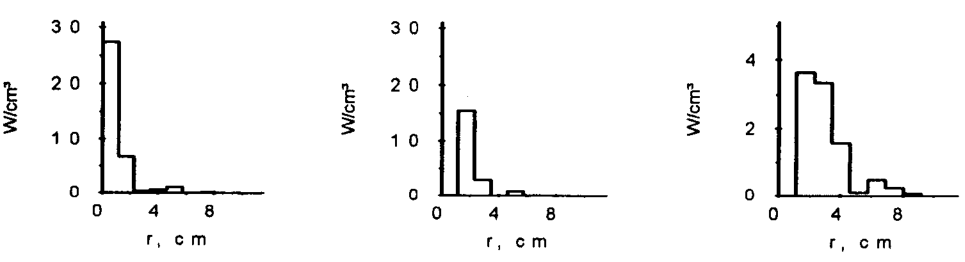

Fig. 4 The power deposition profiles according to the ray-tracing calculations.

thermal plasma component ($f$=77 GHz) slowly varies for the magnetic fields $B_0 > 1.34$ T. Emission at the frequency lower than the heating frequency ($f$=71 GHz), which is related to the suprathermal plasma component, shows different behavior. This emission increases continuously with increasing the magnetic field. The ECE measurements at $f$=71 GHz in the cross section in which the separatrix ellipse is extended in the vertical direction (see Fig. 7) allowed us to estimate the energy of fast electrons. There are two resonant regions for the given frequency which lie at a distance of more than 8 cm from the magnetic axis, outside the spot ( ~ 2 cm) of a receiving antenna. The reception on this frequency from the center of the plasma column is possible because of the relativistic shift of emission from the high-energy electrons with energies on the order of 30 keV, *i.e.*, some tens times as large as the electron temperature. The SXR measurements of the electron spectrum by the semiconductor spectrometer showed that, to high accuracy, this spectrum was a Maxwellian up to electron energies ~(6—7) $T_e$; farther, some suprathermal "tail" was observed. However, this technique could not provide sufficient statistics for measuring the electron energy spectrum for energies observed in the ECE measurements in order to estimate the portion of such particles. To determine the role of high-energy electrons in the microwave-power absorption should be the aim of our further studies.

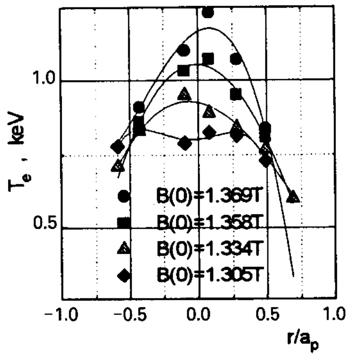

Fig. 5 The electron temperature distributions in the central part of the plasma column for various magnetic fields.

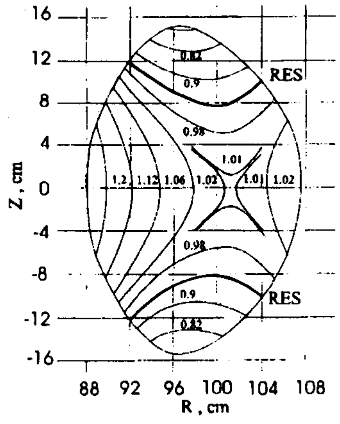

Fig. 6 The electron temperature determined by ECE measurements *vs* $B_0$: $T_1$ ($f$=77 GHz) and $T_2$ ($f$=71 GHz).

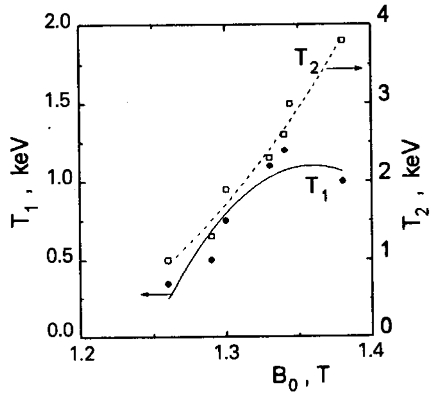

Fig. 7 The |B|=const lines and position of resonance regions for 71 GHz ECE measurements.

## 5. Conclusion

The ECRH experiments on L2-M have shown that:

(1) ECR breakdown is a resonance effect and develops more rapidly when the resonant region coincides with the vacuum magnetic axis.

(2) The experimental value of the Shafranov shift is in satisfactory agreement with theory.

(3) The experimental distribution of the electron temperature conflicts with the ray-tracing calculations.

(4) Essential decrease in the magnetic shear at the plasma edge has not any noticeable effect on plasma confinement.

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