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Soft X-Ray Measurements of the Electron Temperature in ECRH in L-2M

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ABSTRACT
Soft X-ray measurements of the electron temperature in the L-2M stellarator and a procedure for reconstructing the temperature profile are described. The radial profile of the electron temperature and the Shafranov shift were measured by using a single set of filtered diodes. We studied the behaviour of the profile $T_e(r)$ under various conditions of ECRH.

Keywords:
stellarator, electron temperature , soft x-rays, magnetic surfaces, Shafranov shift

1. Introduction

The electron temperature is the main parameter in ECRH experiments, and soft X-ray measurements of spatial and temporal behaviour of T_e gain in importance. For this purpose, we used a single device which measured T_e in 11 chords by the filter technique. In such a case, in contrast to tomography, a magnetic surfaces map is needed to reconstruct the profile $T_e(r)$. The magnetic surfaces were calculated on the basis of the experimental values of the average plasma pressure and Shafranov shift of magnetic axis.

Experiments were carried out on L-2M stellarator [1]. A plasma was created and heated by microwaves at the second harmonic of the electron cyclotron frequency ($f = 75$ GHz, which corresponds to the resonant magnetic field B_0 = 1.34 T). The heating power reached P_0 = 350 kW; the pulse duration was t = 10 – 12 ms, the line average plasma density was in the range n_e = (0.7 – 2) 10^{19} m^{-3} and the central electron temperature was $T_e(0)$ = 0.6 – 1.2 keV.

2. Measurement Technique

A SXR diagnostic complex on L-2M consists of two units: a semiconductor Si(Li) spectrometer and a multidetector system for measuring the electron temperature by the foil technique. The first one has a line of sight along the major radius. The second one is mounted in a bottom vertical port, which makes it possible to measure the plasma shift in the horizontal direction (Fig. 1). Its spatial resolution near the magnetic axis is Δr = 1.4 cm; the length of the viewing field in the toroidal direction is Δz = 6.5 cm. This unit is separated from the stellarator vacuum chamber by a 40 μm thickness Be foil; the pressure in its vacuum vessel is maintained at a level of 2×10^{-2} Torr. Two arrays of surface barrier diodes (11 diodes in each array) are arranged along an arc, and there are two frames with Be foils of various thickness in front of each array. These arrays are positioned so as two neighbour diodes covered by different filters have the same line of sight. The unit allows manipulation with the frames without breaking the vacuum.

The advantage of the multichord SXR diagnostics is the opportunity for measuring the time dependence of the $T_e(r)$ profile in each shot. As is known, the foil technique may provide erroneous results if the contribution from line radiation of impurity ions or from

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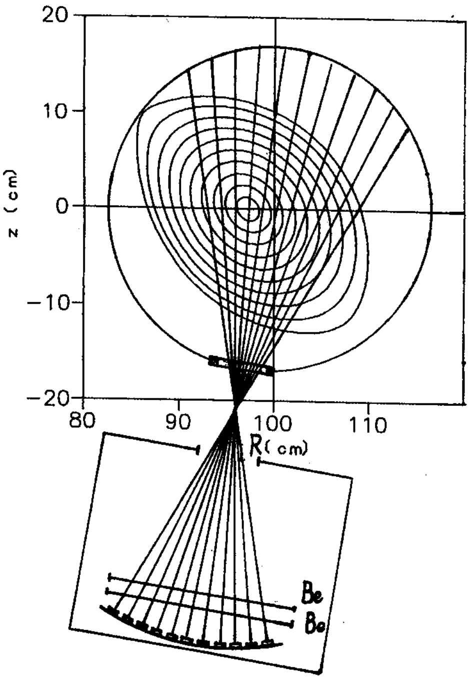

Fig. 1 Arrangement of SXR detectors in the cross section of the stellarator chamber. The vacuum magnetic surfaces are shown in the absence of a limiter.

suprathermal electrons into a signal is large. In order to estimate possible errors of T_e under our experimental conditions, we conducted simultaneous spectral measurements with the Si(Li) spectrometer with a time resolution of 2 ms. These test measurements showed that the electron energy spectrum was usually close to a Maxwellian, and the temperature determined from a slope of the spectrum differed from that determined by the foil technique by no more than 10%.

Although the X-ray intensity is integrated over the sightline, the most contribution comes from the magnetic surface to which this line is tangent when the electron temperature monotonically decreases with radius. As calculations showed [2], for temperature and density profiles close to parabolic ones, the foil technique provides a value which is only by 5% lower than a maximum T_e for each chord.

For the plasma parameters typical of the ECRH experiments, the sensitivity of the available system allows measurements only in the central part of the plasma column ($r/a \leq 0.5$).

3. Reconstruction Procedure

The magnetic surfaces for $\beta = 0$ are shown in Fig. 1. However, when the plasma heating is substantial, the finite beta effect must be taken into account. In calculations of shifted magnetic surfaces, we used the model of a "current-free" plasma. A value of $<\beta>$ (where $<\beta>$ means the averaging over volume) is known from diamagnetic measurements. Preliminary calculations by the numerical procedure described in [3,4] showed that, for experimentally observed b, the magnetic axis remains close to a planar curve, and the calculated value of the Shafranov shift equals to the experimental one for reasonable profiles $\beta(r)$. For more accurate comparision of the theory with the experiment, the inverse problem was solved. The pressure profile $p(\Psi)$ (where Ψ is the poloidal flux) was selected using the one-parameter set of functions:

$$P \approx P(\Psi) \approx P(0) \times \left(\frac{\Psi - \Psi_{\min}}{\Psi - \Psi_{\max}}\right)^{\gamma},$$

where $\Psi_{\max}$ and $\Psi_{\min}$ are the poloidal fluxes on the magnetic axis and boundary, correspondingly. For the given $<\beta>$, the parameter γ was chosen such that the calculated shift of the magnetic axis was equal to the experimental one. Since the plasma pressure falls off sharply outside the separatrix or in the limiter shadow, we used the following boundary conditions: $P > 0$ for $\Psi > \Psi_{\min}$ and $P = 0$ for $\Psi < \Psi_{\min}$; and all plasma fields vanish at the infinite distance from the plasma column. The plasma boundary was given by the separatrix or the limiter. A magnetic surfaces map was calculated by using the iteration numerical procedure described in [4].

The sightlines of the SXR diagnostics were then superimposed on the magnetic surfaces map, and the mean radii of magnetic surfaces that were the main contributors into the SXR intensity were determined. This allowed us to reconstruct the profiles as $T_e(<r>)$, where $<r>(\Psi)$ is the mean radius of the magnetic surface with the given magnetic flux Ψ. We believed that such reconstruction was correct since the resulting profile satisfied the condition T_e = const on a given magnetic surface, *i.e.*, the profile was symmetric (measured value the electron temperature was the same inside and outside of magnetic axis on the given magnetic surface).

4. Experimental Results

The experiments on ECRH have shown that the value of Shafranov shift lied between 1.8 and 3.2 cm, depending on the heating power, plasma radius and magnetic field and was in good agreement with the theoretical calculations.

To reduce radiation losses and growth of the plasma density during the ECRH pulse, the moveable graphite limiter (which changed not only the plasma radius but also the rotational transform and shear at the plasma edge [5]) was used in some experiments. A knowledge of the radial distribution of the electron temperature, in this case, is of great importance for an understanding of the plasma transport properties.

Figure 2 shows the profiles $T_e(r)$ in the absence of a limiter, when the plasma radius is limited by the separatrix (a_p = 0.115 m), and in the presence of the limiter (a_p = 0.078 m). Here, the normalized radius (which is the mean magnetic-surface radius divided by the mean plasma radius) is laied off as abscissa. It is seen that the profiles are symmetric. In the absence of a limiter (curve 1 in Fig. 2), the electron temperature profile is sharper and is described sufficiently well by a square parabola ($T_{e0}[1-x^2]^2$, where $x = r/a$), whereas in the presence of the limiter (curve 2 in Fig. 2)., the profile is close to a simple parabola ($T_{e0}[1-x^2]$). As is seen, the central temperature is higher in the presence of the limiter, although the energy lifetime is smaller in this case, $\tau_E \sim a^2$ [5]. Apparently, this is related to a decrease both in the radiation losses and plasma density. From the calculated pressure profile we can estimate the density profile for these two cases. For simplicity, we neglect the contribution from the ion component into the pressure, because this contribution is usually no more than 10 − 15%. In the central part of the plasma column, the density profiles turn out flatter than the electron temperature profiles. It should be noted that simulation of the ECR plasma heating in the L-2M stellarator by the TRANSZ hybrid neoclassical code [6] gives also a flat density profile which even has a dip in the centre in some cases.

Figure 3 shows the dependence of $T_e(r)$ on the magnetic field B_0 at the axis of the magnetic system (R = 1 m). Curve 1 corresponds to the case of the low magnetic field, where the resonance point is shifted by about 3 cm inwards from the magnetic axis. In this case, the flat radial profile typical of the off-axis heating was observed. Curve 2 corresponds to the case of the on-axis heating, where the resonance point lies near the magnetic axis. The temperature profile is peaked, and the central temperature increases. It was expected that, for the higher magnetic fields, in which the resonance point shifts outwards from the magnetic axis, flat profiles should again take place in accordance with the ray-tracing calculations [7]. However, as the measurements showed (curves 3, 4), the profile becomes sharper and the central temperature increases as the magnetic fileld increases, although the resonant point is

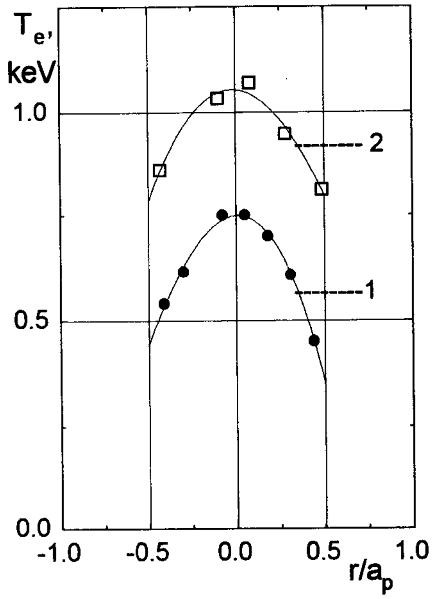

Fig. 2 Electron temperature profiles in ECRH regime, P_0 = 200 kW, for two limiter positions: 1—the limiter is outside the separatrix; n_e = 1.4×10^{19} m^{-3}, P_{rad} = 120 kW; 2—the limiter is positioned inside the separatrix at a distance of 3 cm, n_e = 1.0×10^{19} m^{-3}, P_{rad} = 85 kW.

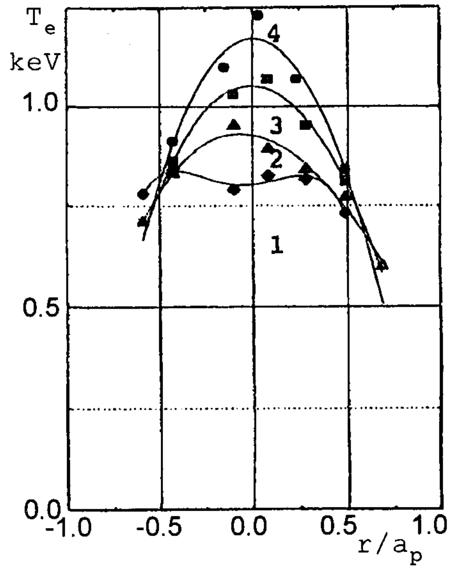

Fig. 3 Electron temperature profiles in ECRH regime for various magnetic fields: 1 - B_0 = 1.31 T, 2 - 1.34 T, 3 - B_0 = 1.36 T, 4 - B_0 = 1.37 T, P_0 = 200 kW, n_e = 1.0×10^{19} m^{-3}.

shifted outwards from the magnetic axis. This behaviour contradicts the results of the ray-tracing calculations of the heating power absorption.

5. Conclusion

The method for reconstruction of the electron temperature profile measured by a single multichord SXR diagnostic device has been developed. The present technique is capable to follow the main effects of the ECR plasma heating in the L-2M stellarator. The distributions of the electron temperature in the central part of the plasma column have been measured. The radial profile was found to flatten when the resonance is displaced inwards from the axis of the magnetic system. When the resonance is displaced outwards, the peaked profile is observed as in the case of central heating. At present, we cannot explain this effect.

Acknowledgements

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