ENERGY and DENSITY INHOMOGENEITIES DRIVEN by TOROIDALLY LOCALIZED ECRH in W7-AS

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W7-AS is a modular stellarator with 5 field periods. Close to the plasma axis the poloidal Fourier components of the 3-D magnetic field tend to vanish and the configuration becomes similar to five "toroidally linked mirrors". During on-axis ECRH, the highly focused injected beam interacts, besides passing particles, with only the trapped particle population confined in the mirror where ECRH is launched. In low density ECRH discharges in magnetic configurations with high fractions of trapped particles, strong toroidal anisotropy in the electron distribution function may arise. Aim of this paper is the quantitative evaluation of the collisional redistribution of the deposited power between the different classes of trapped particles and an investigation of the possibility to detect experimentally the ECRH driven toroidal inhomogeneities by means of the ECE diagnostic.

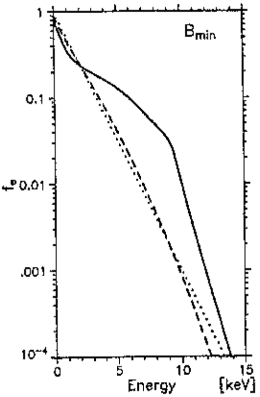
• ECRH DRIVEN TOROIDAL ANISOTROPIES •

The problem has been investigated by means of the bounce-averaged Fokker-Planck code FPTM /1/ suitable for the study of ECRH in periodic magnetic fields. The analyzed scenarios refer to second harmonic on-axis heating by a collimated beam of X-mode polarized waves injected perpendicularly from low-field-side in the "minimum B" and the "maximum B" magnetic configurations characterized by a local minimum or a local maximum, respectively, in the toroidal plane where the ECRH beam is injected /2/. While in the case of "maximum B", the power is mainly deposited to passing particles and redistributed toroidally in a rather uniform way, in the case of "minimum B" strong local perturbations of the distribution function can arise for the population of electrons trapped in the local toroidal mirror where ECRH is injected, as shown in Fig. 1 (for a target plasma with density $n_0 = 1 \cdot 10^{13}$ cm^{-3}, temperature $T_0 \simeq 1400$ eV, ECRH power density 5 W/cm^3). In this mirror, the deviations from the Maxwellian distribution are considerably stronger than those found in the other mirrors where heating appears only due to collisional energy transfer from passing particles.

In steady-state, the redistribution of density and energy between the different populations of particles is mainly determined by the balance between ECRH and collisions. The increase of the perpendicular energy of the electrons resonant with the ECRH beam, has two main consequences: the power absorbed by "barely" passing particles can cause their trapping, while the power deposited in the trapped particle region of velocity space tends to create an enhancement of trapped particles at higher energy and a depletion at lower energy. Due to the velocity dependence of pitch angle scattering, the anisotropy at low velocity is more efficiently counteracted than at high velocities, causing a net flux through the boundary between trapped and passing particles. On the other side, as trapped particles of higher perpendicular energy are poorly confined in Stellarators, losses will also play a role in the redistribution.

The ECRH driven density perturbation is shown in Fig. 2. In the "minimum B" configuration, the density of the population of directly heated trapped particles is increased mainly due to the collisional redistribution driven by ECRH. In the other mirrors loss effects are dominant and the number of trapped electrons is slightly reduced.

In the "maximum B"-scenario, the deviations are considerably smaller in amplitude (different scales are used for the ordinates in Fig. 2), as most of the power is now absorbed by passing particles and homogeneously redistributed toroidally. A qualitative similar toroidal dependence is obtained for the ECRH driven energy perturbation (the relative energy perturbation being three times greater in magnitude for the case under examination).



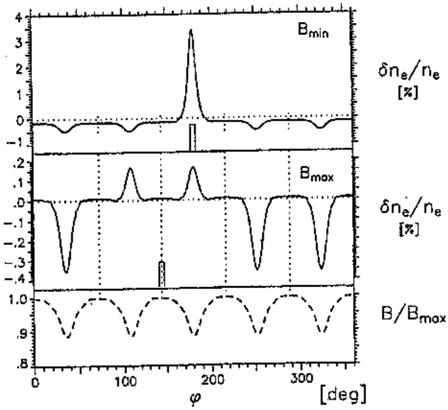


Fig. 1 *Energy spectra, along the line $v_\parallel = 0$, of the bounce-averaged distribution function. Solid line: toroidal mirror with ECRH launch; dashed-line: other mirrors; dotted line: initial Maxwellian (for reference).* **Fig. 2** *Toroidal dependence of the relative density perturbation driven by ECRH for the "minimum B"* (**top**) *and for the "maximum B"-scenario* (**center**). *The small rectangle in these figures indicates the toroidal position of the launching system. On the* **bottom** *the normalized magnetic field used for the bounce-averaging is shown.*

The inhomogeneity in the electron density generates toroidal electric fields. The density perturbation under stationary conditions is determined by the balance between the particle fluxes driven by ECRH and by these electric fields. As ions remain unperturbed, any perturbation of the electron density results in the generation of an electric field (proportional to the density gradient), that, in a self-consistent treatment, would tend to reduce the ECRH driven density perturbation.

• DETECTION BY ECE •

The ECE intensity, I, can be evaluated from the "radiative transfer equation" /3/:

$$N_r^2 \frac{d}{ds}\left\{\frac{I}{N_r^2}\right\} = \eta - \alpha I \qquad \Rightarrow \qquad \frac{I(s)}{N_r^2} = \int_0^s ds' \, \frac{\eta(s')}{N_r^2(s')} \, e^{-\int_{s'}^{s} \alpha(s'')ds''} \tag{1}$$

where N_r is the ray refractive index, η and α, the emission and absorption coefficients, respectively, and s the space coordinate along the ray trajectory.

For a Maxwellian distribution function, η and α are related by a simple multiplicative constant, in agreement with Kirchhoff's law:

$$\frac{\eta(\underline{k}, \omega)}{\alpha(\underline{k}, \omega)} = N_r^2 \, \frac{\omega^2 T}{8\pi^3 c^2}. \tag{2}$$

In the general case the evaluation of η and α requires the determination of the (warm) polarization of the wave and an integration along the resonance curve $\omega - k_\parallel v_\parallel - \frac{n\omega_{ce}}{\gamma} = 0$ in velocity space /4/. While for the emission coefficient the integrand is proportional to the electron distribution function, in the expression for the absorption coefficient a differential operator appears (corresponding to the derivative of the distribution function along the "diffusion path" in velocity space) /4/. In this paper the wave polarization has been evaluated from the Maxwellian bulk, while for the integration in velocity space the deviation of the electron distribution function predicted by the FPTM-code has been taken consistently into account.

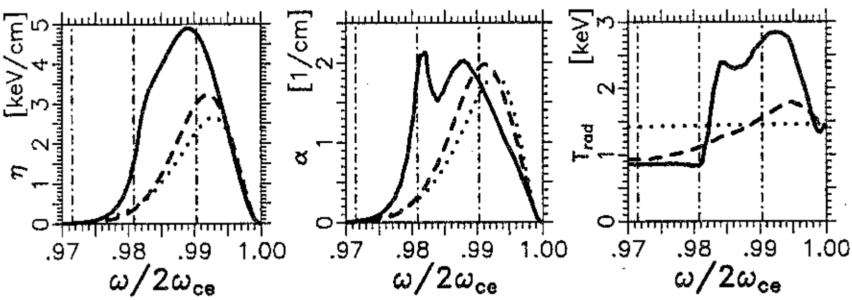


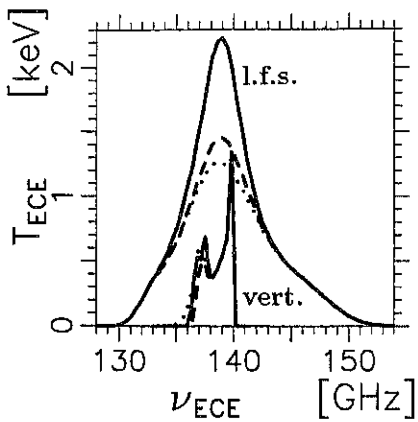
Fig. 3 left *(normalized) emission coefficient,* **centre** *absorption coefficient and* **right** *"radiative temperature" for the scenario of Fig.1. The same line notation as in Fig.1 is used and the vertical lines corresponds to resonant electrons with energy 15,10,5 keV, respectively.*

The normalized emission $\bar{\eta}(\underline{k},\omega) = \eta(\underline{k},\omega)\cdot(8\pi^3c^2)/(N_r^2\omega^2)$ and the absorption coefficients are shown in Fig.3, together with the "radiative temperature", $\bar{\eta}(\underline{k},\omega)/\alpha(\underline{k},\omega)$, for the distribution function in Fig.1.

In the ECRH injection plane ("elliptical plane") the magnetic field topology is rather similar to that found in a Tokamak ($B \propto 1/R$). Two viewing geometries have been investigated for the ECE-antenna. The first refers to perpendicular viewing from the low-field-side and the second to vertical viewing. Low-field-side observation is characterized by a rather strong gradient of the magnetic field, while for vertical observation the changes in B are weaker and a local maximum appears close to the crossing of the viewing chord with the plasma axis /5/. In order to integrate Eq.(1), the distribution function, determined by the Fokker-Planck code only close to the plasma axis, has to be extended radially. The dominant broadening mechanism is related to ∇B-drift of ripple trapped particles. This kind of "convective losses" were examined in /2/. In this paper we use a simple analytical model, $f(r,\underline{v}) = f_{Max}(r,v) + [f_{FP}(0,\underline{v}) - f_{Max}(0,v)]\cdot exp(-r^2/\sigma^2)$, where f_{Max} is the Maxwellian, f_{FP} the Fokker-Planck distribution and σ a "broadening parameter" ($\sigma = 3$ cm, in this paper). The deviation of the distribution function from the Maxwellian is therefore distributed on the magnetic surfaces in a poloidal uniform way, only the amplitude of the ECRH-driven perturbation decreases with increasing radii.

The emission spectra obtained integrating Eq.(1) along these viewing chords, for the case of 2^{nd}-harmonic X-mode emission, are shown in Fig.4. Together with the emission of a Maxellian plasma the spectra for an antenna localized in the ECRH injection mirror and in a mirror where no ECRH is injected are shown too. As the deviations expected by Fokker-Planck simulations are found at relatively low energies (see Fig.1), the emission detected by the low-field-side antenna, sensitive to the bulk properties of the distribution function, can be strongly perturbed, especially for the mirror where ECRH is injected. On the other side, the vertical observation is generally "insensitive" to perturbations in the bulk of the distribution close to the plasma axis, as this emission tends to be reabsorbed by thermal optically thick plasma at outer radii, during its propagation towards the ECE antenna. Only emission at sufficiently down-shifted frequencies can reach the antenna. No ECRH power is expected to be directly absorbed at these resonant energies and collision and radial losses mainly determine the tail population /2/. The vertically observed ECE-spectrum is therefore determined by the balance between collisions and radial losses. The response to sudden changes in the injected ECRH power (switch-on, -off, modulation) can in principle be used to separate the two mechanisms, due to the different time scales and energy dependencies /6/.

In case of ECE at optically thin harmonics, reabsorption becomes negligible and the emission from the central region, where the deviation from Maxwellian are expected to be stronger, can reach the ECE antenna under any viewing geometry. Fig.5 refers to the case of emission at



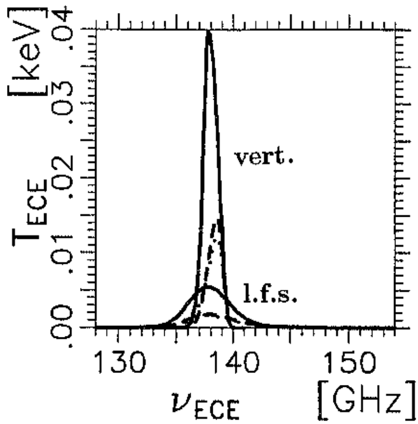


Fig. 4 *Simulated ECE-spectra for perpendicular viewing of X-mode 2^{nd} harmonic from a low-field-side antenna (l.f.s.) and for a vertically viewing antenna (vert.). The same line notation as in Fig.1 is used.* **Fig. 5** *Same as Fig. 4 but for X-mode 4^{th} harmonic emission.*

the (optically thin) 4^{th} harmonic (the magnetic field has been reduced from 2.5 to 1.25 T). The radiation temperature is relatively weak for these frequencies. The interpretation of the signals related to optically thin harmonics can be made critical due to possible contributions from wall reflection, making the presence of a "beam dump" mandatory.

• CONCLUSIONS •

Strong ECRH driven toroidal anisotropies are predicted by Fokker-Planck modelling. The deviations in the bulk of the distribution function in the toroidal mirror where ECRH is injected are expected to be strong enough to affect the ECE detected from low-field-side. The detected "radiation temperature" is expected to be substantially higher than the one detected in the other toroidal mirrors. Vertical ECE, along $B \simeq const$, due to the relation between emitting frequency and energy ($\omega - \frac{n\omega_{ce}}{\gamma} \simeq 0$) allows a more direct interpretation of the observed ECE-spectrum in terms of the "line averaged" distribution function. However, while emission at optically thin harmonics and/or high enough resonant energies can reach the vertical antenna, at optically thick harmonics, the emission related to low energy electrons located close to the plasma axis, i.e., where Fokker-Planck simulations predict the strongest deviations from Maxwellian, is generally reabsorbed during its propagation towards the antenna.

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