Determination of the heat flux structure after switch-off (-on) ECRH in T-10

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Introduction

Determination of the heat flux structure is important for understanding of the transport physic. At the steady state we can not decompose the heat flux, thereby we should study a transient process. In this report we determine the transport coefficients from the variation of the electron temperature profile after ECR heating switch-off (-on).

Statement of the problem and numerical algorithm of the solution

The dynamic process, which happens during the gyrotrons switch-off (-on), can be described as follows. The heat conductivity equation for the steady-state electron temperature $T^S(r)$, (with index 's') before switch-off (-on) can be written as:

$$\frac{3}{2}\frac{\partial}{\partial t}\left(n^S T^S\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(r\chi_e^S n^S\frac{\partial T^S}{\partial r}\right)+P_{OH}^S+Q^S+P_{EC}, \tag{1}$$

$$\frac{\partial T^S}{\partial r}(r=0,t)=0,\ T^S(r=1,t)=T_0,\quad 0<r<1,\ t=t_S,$$

The heat conductivity equation for the electron temperature $T(r,t)$, corresponding to the transient process after the gyrotrons switch-off (-on) (without index) is

$$\frac{3}{2}\frac{\partial}{\partial t}(nT)=\frac{1}{r}\frac{\partial}{\partial r}\left(r\chi_e n\frac{\partial T}{\partial r}\right)+P_{OH}+Q, \tag{2}$$

$$\frac{\partial T}{\partial r}(r=0,t)=0,\ T(r=1,t)=T_0,\ T(r,t=t_S)=T^S(r),\ 0<r<1,\ t>t_S.$$

Here $n(r,t)$ is the electron density, t_S is the gyrotron switching-off (-on) time, T_0 is the boundary temperature, χ_e is the effective heat conductivity, P_{OH} is the ohmic heating power, Q is another heat losses, P_{EC} is the additional heating power.

During the transient process the electron temperature $T(r,t)$ and effective heat conductivity χ_e can be presented as the sum of its steady state values $T^S(r), \chi_e^S(r)$ and the variations $\Delta T(r,t), \Delta\chi_e(r,t)$, i.e.

$$T(r,t)=T^S(r)+\Delta T(r,t), \chi_e(r,t)=\chi_e^S(r)+\Delta\chi_e(r,t). \tag{3}$$

We suppose that the effective heat conductivity χ_e can be presented by following way:

$$\chi_e(T)=\chi_e\left(T^S+\Delta T\right)=\chi_e(T^S)+\left(\chi_e(T^S)\right)'_{T^S}\Delta T+O(\Delta T^2),$$

$$\Delta\chi_e(r,t)=\left(\chi_e(T^S)\right)'_{T^S}\Delta T. \tag{4}$$

We subtract Eq. (1) from Eq. (2) and expand the ohmic heating power P_{OH} and the heat loss power Q relatively ΔT, omitting the second order terms $O(\Delta T^2)$. We also assume that the variation of the electron density is much less than the variation of the electron temperature, i.e. $n\approx n^S$. Thus we obtain the following equation:

$$\frac{3}{2}\frac{\partial}{\partial t}(n\Delta T)=\frac{1}{r}\frac{\partial}{\partial r}\left(r\chi_e^S n\frac{\partial\Delta T}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\chi_e^S\right)'_{T^S} n\left(\frac{\partial T^S}{\partial r}+\frac{\partial\Delta T}{\partial r}\right)\Delta T\right]- \tag{5}$$
$$-P_{EC}+P'_{OH}(T^S)\cdot\Delta T+Q'(T^S)\cdot\Delta T.$$

In this report we study shots where the ohmic heating power P_{OH} and heat loss Q are considerably less than the deposited power P_{EC}, therefore we can omit the terms describing the variation of P_{OH} and Q. As a result, we obtain the approximate linear equation for ΔT :

$$\frac{3}{2}\frac{\partial}{\partial t}(n\Delta T)=\frac{1}{r}\frac{\partial}{\partial r}\left(rK\frac{\partial\Delta T}{\partial r}\right)-\frac{1}{r}\frac{\partial}{\partial r}(rV\Delta T)-P_{EC},$$
$$\frac{\partial\Delta T}{\partial r}(r=0,t)=0,\ \Delta T(r=1,t)=0,\ \Delta T(r,t=t_0)=0, \tag{6}$$

where $K=\chi_e^S n,\ V=-\left(\chi_e^S\right)'_{T^S} n\left(\frac{\partial T^S}{\partial r}+\frac{\partial\Delta T}{\partial r}\right)$.

If we know the experimental values of the electron temperature variations f_i^k, measured in N radial points: i=1,…,N, and in M temporal points: k=1,…,M, we can formulate the inverse problem. We should find unknown functions P_{EC}, K and V for witch the solution of equation (6) $\Delta T(r,t)$, provides the minimum of the discrepancy functional:

$$J=\frac{1}{2}\sum_{k=1}^{M}\sum_{i=1}^{N}\gamma_k\left[\Delta T(\rho_k,t_i)-f_i^k\right]^2/\sum_{k=1}^{M}\sum_{i=1}^{N}\gamma_k\left[f_i^k\right]^2, \tag{7}$$

where γ_k are the weight factors, which are selected in accordance with the reliability of measurements in every radial points.

Let us expand the unknown functions K, V and P_{EC} over some given basis [1,2]:

$$K(r)=\sum_{j=1}^{M_K}k_j\cdot\varphi_j^K(r),\ V(r)=\sum_{j=1}^{M_V}v_j\cdot\varphi_j^V(r),$$
$$P_{EC}(r)=A\cdot\exp\left[-\beta\cdot\left(\frac{r-r_0}{2w}\right)^{\alpha}\right], \tag{8}$$

where $\varphi_j^K,\varphi_j^V=\{1,x,x^2,x^3,...\}$ are the polynomial, r_0, w are the position of the centre and half-width of the additional heating profile, $\beta=2^{\alpha}\ln 2$, A and α are the constants. Thus the solution of the inverse problem is reduced to the finding of the unknown parameters $\vec{P}=\{k_j,\ j=1,...,M_K,\ v_j,\ j=1,...,M_V,\ A,\ r_0,\ w,\ \alpha\}$ from the condition of minimum of the functional (7). This functional is minimized by the gradient method [3].

Results of numerical calculations

For excluding influence of magnetic surfaces reconnection only shots with suppressed sawtooth oscillations was analysed. Results of calculations for T-10 shot #23281 (I=75kA, B=2.35 T, $\bar{n}$ =1.2, off-axis CoCD) are presented in Figures 1-6.

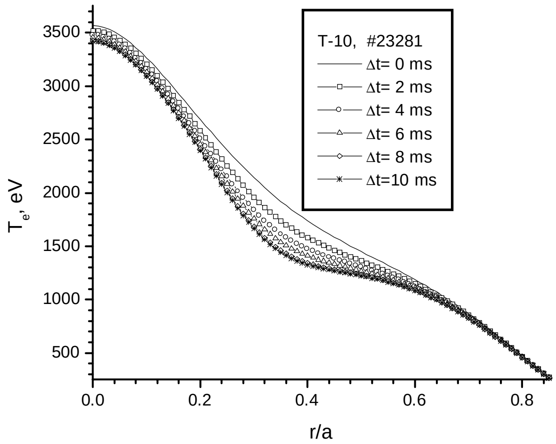

Fig.1. Electron temperature profiles for different times after gyrotrons switch-off.

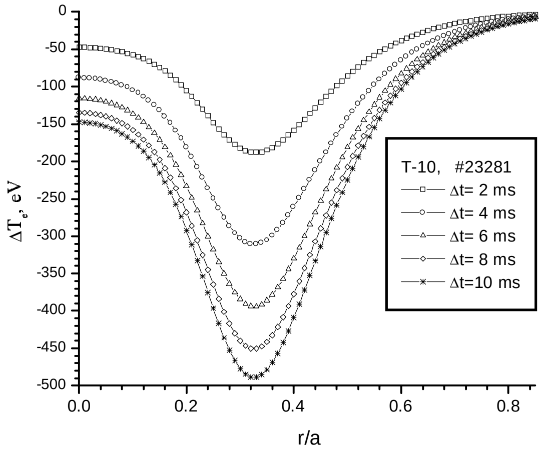

Fig.2. Variation of the electron temperature for the same times.

Figures 1 and 2 show the radial dependence of the electron temperature and electron temperature variation during 10 ms after gyrotron switch-off, which were reconstructed from variation of the experimental SXR intensity [2]. It can be seen that perturbation of the electron temperature does not spread. Such evolution of the electron temperature profile can be described by a parabolic heat conductivity equation only where heat conductivity coefficient is varied in time.

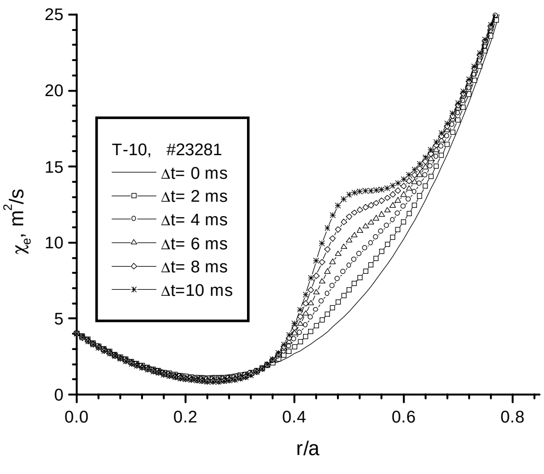

Fig.3. Radial dependence of the effective heat conductivity for different times.

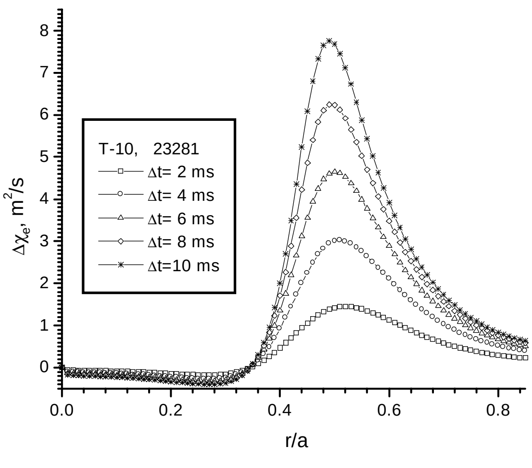

Fig.4. Radial dependence of the heat conductivity variation for different times.

Radial dependence of the effective heat conductivity χ_e and its variation $\Delta\chi_e$ founded from the solution of the inverse problem (6)-(8) are shown in Figures 3,4. The effective heat conductivity decreases inside the power deposition radius and increases outside it. This prevents variation of the heat flux after gyrotron switch-off and retards the radial spread of the electron temperature perturbation.

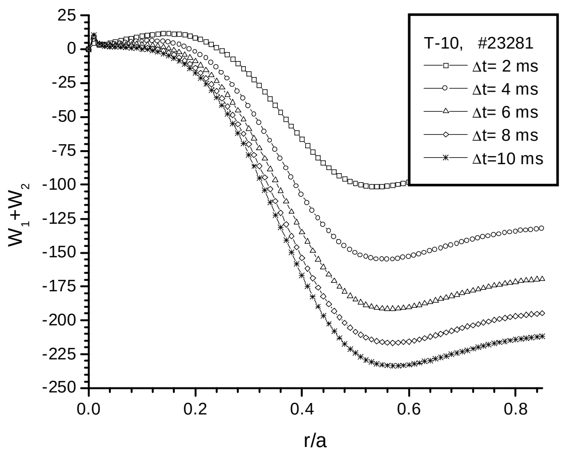

Fig.5. Radial dependence of the heat flux variation for different times after gyrotron switch-off.

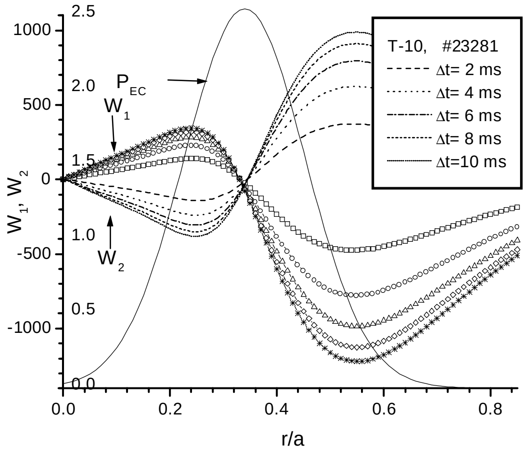

Fig.6. Variation of the heat flux components and EC power deposition profile.

Figure 5 shows radial profiles of the total heat flux variation $W_\Sigma = W_1 + W_2 = -\chi_e^S \cdot \partial\Delta T/\partial r - \Delta\chi_e \cdot \left(\partial T^S/\partial r + \partial\Delta T/\partial r\right)$. Figure 6 presents the radial dependence's of the heat flux variations $W_1 = -\chi_e^S \cdot \partial\Delta T/\partial r$, $W_2 = -\Delta\chi_e \cdot \left(\partial T^S/\partial r + \partial\Delta T/\partial r\right)$, and absorbed power profile P_{EC}.

Conclusion

The proposed method allows us to determine the absorbed power profile, heat conductivity and variation of the heat conductivity after additional power switch-off (-on). In all calculated shots with off-axis CoCD and suppressed sawtooth oscillations variation of the heat conductivity retard radial spread of the electron temperature profile perturbation.

Such a behaviour of the temperature perturbation and the heat flux variation can be represented by two different forms:

1) The heat flux consists of diffusion and convection parts which are constant in time. We analysed such a representation in Ref. [2].
2) The heat flux contains only the diffusion part with temporally and radial dependent effective heat conductivity. In this case the effective heat conductivity should be strongly nonlinearly dependent from the electron temperature variation.

It seems to us that the first form with convection (heat pinch) is more preferable, but it needs in additional analysis of more comprehensive database.

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