

# PECULIARITIES OF ELECTRON HEAT BALANCE IN TOKAMAKS AT TRANSIENT PROCESSES WITH PINCH DOMINATING

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## 1. Introduction and background

Spontaneous inward plasma fluxes in tokamaks were discovered in the early 1980s while analysing experimental data for some non-stationary processes like gas puffing and sawteeth oscillations (see, for example, [1]). Later the same phenomenon had been found in experiments on off-central injection of small pellets into the plasma of T-10 tokamak (Kurchatov Institute, Moscow) [2,3] and at  $L \rightarrow H$  transition in TUMAN-3 tokamak (Ioffe Institute, St.Petersburg) [4]. Experimentally it manifested itself through fast building up central zone of radial plasma density profile which occurred just after beginning of the non-stationary events. In all the cases the density increase could not be explained with aid of ionization and diffusion only.

Velocities of the pinch obtained from particle balance calculations turned out to be by 2 to 5 times higher than those of the Ware pinch predicted by the standard neoclassical theory developed for stationary plasma. This was a reason for the discoverers to give name “anomalous” to the pinch.

Another unexpected feature of the pinch had been discovered during analysis of loop voltage behaviour in the above mentioned experiments on T-10 [2,3] and TUMAN-3 [5]. The transient processes, when the plasma influx was observed, turned out to be accompanied by a loop voltage excess which in some cases [2,3] could not be explained in conventional way, i.e. with plasma temperature variations (measured or assumed) and according redistribution of plasma magnetic flux or/and changes in equilibrium status. In the analysis the voltage excess had been found to be proportional to the radial plasma flux velocity:  $\Delta U_l \propto 2\pi R(V_r B_p) / c$ . The same relation exists at the plasma magnetic compression [6], when  $V_r = -0.5r(dB_t / dt) / B_t$ , and in the neoclassical theory, where neoclassical correction in the resistivity may be attributed to the Ware pinch and the boot-strap current may be related to the neoclassical diffusion [7,8]. In the case of the plasma influx it implies a counter-current generation and according increase in the voltage induced by the transformer.

Local plasma heat balance for such transitory processes needs a careful consideration. Typically heat fluxes due to both the heat conductivity and the plasma convection are joined together (see, for example, [4]) to deduce an effective heat diffusion coefficient,  $\chi^{eff}$ . This would be reasonable for a situation when both the parts of the heat flux had a diffusion nature, were proportional to density or/and temperature gradients. But at the pinch dominating this approach may lead to some paradoxes like negative heat conductivity and does not yield a proper comprehension of the processes.

In the present work the  $L \rightarrow H$  transition in TUMAN-3 [4] is analysed. Terms due to the radial plasma velocity in the heat balance equation for electron component are taken into

account in explicit form and genuine electron heat diffusivity,  $\chi_e$ , is derived both for quasi stationary state before the transition and for the dynamic phase just after.

## 2. Electron heat balance for $L \rightarrow H$ transition.

### 2.1. Experimental data

In TUMAN-3 the  $L \rightarrow H$  transition occurred spontaneously during pure ohmic heating. On Fig.1 the experimental data taken from [4] are reproduced. Arrow stands at  $t = 27ms$  when the transition starts.

Fast, more than twofold increase in the plasma density in area  $r/a < 0.4$  is clearly seen at simultaneous twofold drop in the ionization rate (see  $D_\alpha$  behaviour). Numerical solving the continuity equation performed in [5] had yielded  $r-t$  evolution of plasma flux velocities during the transition (Fig. 2). While the pre-transition phase was dominated by outward diffusion plasma flux, after  $t = 27ms$  inward plasma velocities which amounted to more than  $-500cm/s$  were computed. They exceeded the Ware pinch velocity by factor of 2.5. A noticeable hump on the loop voltage waveform arose within  $27ms < t < 30ms$  time period.

### 2.2. Computational methods

Following to [7] the heat balance equation for electrons was taken in form

$$1.5\partial(n_e T_e) / \partial t + div(1.5n_e T_e V_r) + n_e T_e div V_r + div(-\kappa_e \nabla T_e) = j_p E - p_{ei}. \quad (1)$$

The second and the third terms in the left hand side describe, respectively, heat transport by plasma convective flux and its work, and the fourth term is the heat conductivity flux. Terms in the right hand side are Joule heat and electron-ion heat exchange. Following to the authors of [4] radiation losses were considered to be negligible. Electron heat diffusion coefficient,  $\chi_e(r) = \kappa_e / n_e$ , was deduced from integrated form of Eq. (1).

To obtain the current distribution, the  $1D$  equation for diffusion of the poloidal magnetic field [2] was solved at the neoclassical conductivity (the boot-strap current was taken into account as well) which deduced from the measured electron temperature and density, with  $Z_{eff}$  being a fitting parameter to match calculated loop voltage to the experimental one. Sawteeth, current ramp-up prehistory and persisting skin-effect were considered in the simulation.

### 2.3. Results

Results of the heat balance calculations made for moments just before the  $L \rightarrow H$  transition ( $t = 27ms$ ) and after it ( $t = 27.5ms$ ) are displayed in Figs. 3 and 4, respectively. At quasi stationary  $L$ -mode the heat transport and work produced by the convective plasma flux compose a significant part of total transport heat losses at plasma periphery where the plasma velocities are high. They decrease the portion of the heat conductivity flux. Curve 1 on Fig. 5 presents the heat diffusion coefficient,  $\chi_e$ . If these two terms are included in an “effective heat flux” together with the genuine heat conductivity flux then the effective coefficient,  $\chi_e^{eff}$ , may be computed (curve 2). It is higher at least by two times than  $\chi_e$ .

So far as the transition period is concerned, sum of two large terms, time derivative of heat content and electron-ion heat exchange, is practically equal to the Joule heating, and the effective heat flux appears to be small value poorly defined because of errors in the three large terms. It randomly fluctuates near the abscissa axis. It can lead to a wrong impression about scale of the phenomenon discussed. Thus, in [4] reduction in  $\chi^{eff}$  by the order of magnitude is declared. However, the heat transport and the work produced by the plasma influx are negative now in a zone near the middle of the minor radius and contribute significantly to the heat conductivity flux. Then the electron heat diffusivity is quite valid value (Fig. 5, curve 3). The radial profile  $\chi_e(r)$  reveals a “heat conductivity barrier” at  $0.4 < r/a < 0.7$  where  $\chi_e$  is reduced by a factor of 3 in comparison with its value for the quasi stationary pre-transition *L*-mode. The high  $\chi_e$  level in the near-axis area is explained by sawteeth which were not triggered at  $t < 29ms$ .

In [4] the loop voltage excess during the *L* → *H* transition was explained with a hypothetical cooling of plasma periphery,  $r/a > 0.75$ , where the temperature measurements were not performed (see Fig. 1). However, there exists an alternative explanation due to Ohm’s law modification if the term  $V_r B_p / c$  is retained in it [5]. Then the profile  $\chi_e(r)$  will be changed a little (Fig. 5, curve 4) because of lesser Joule heating of the plasma column at the periphery and a plasma current redistribution over the minor radius.

### 3. Conclusion

**3.1.** Omitting terms containing radial plasma velocity in the heat balance equation for transient processes with pinch dominating is pregnant with a possibility to obtain a paradoxical value of the heat conductivity close to zero and  $\tau_E^{transp} \propto a^2 / \chi \rightarrow \infty$ . Whereas proper taking them into account yields a valid profile  $\chi(r)$  which, in the case of the *L* → *H* transition, for example, demonstrates the transport barrier with a reasonable depression in the heat conductivity by a factor of 3 that is typical of the *H*-mode.

**3.2.** The counter-current related to the plasma influx should be taken into account. This provides more correct distribution of the ohmic heating and, consequently, more correct heat conductivity profile.

### References

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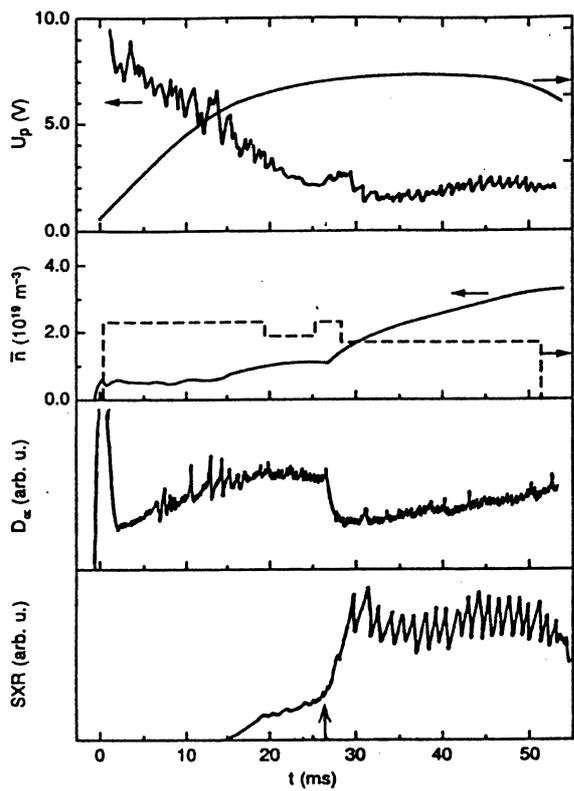


Fig. 1

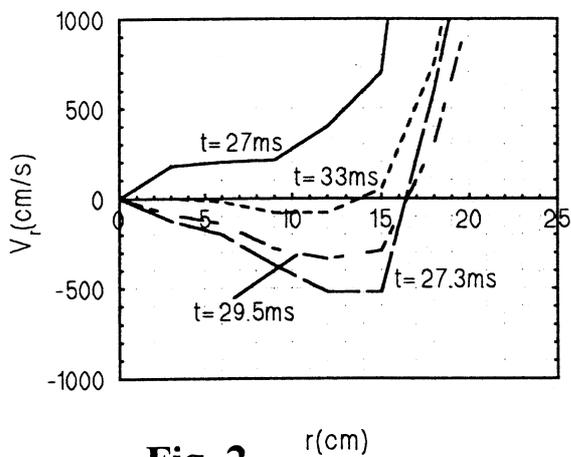
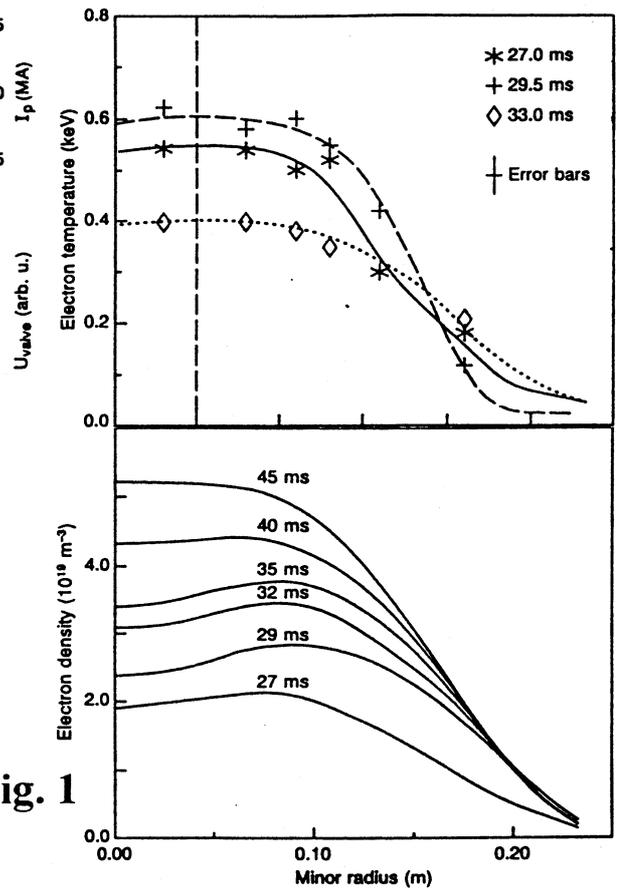


Fig. 2

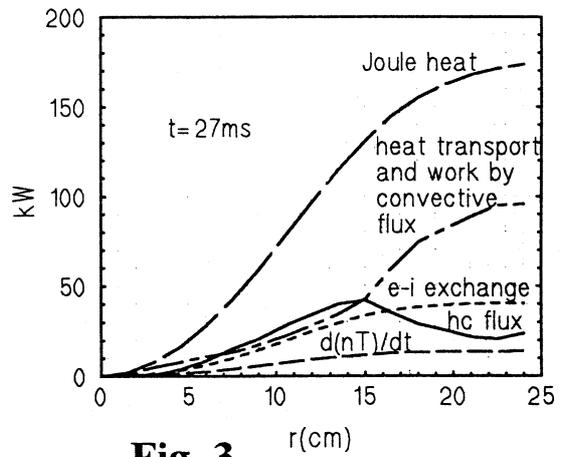


Fig. 3

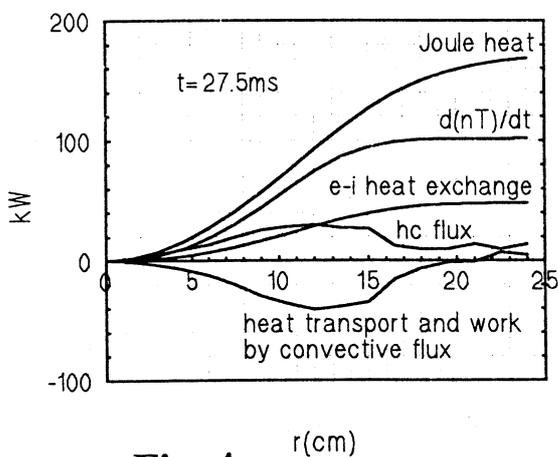


Fig. 4

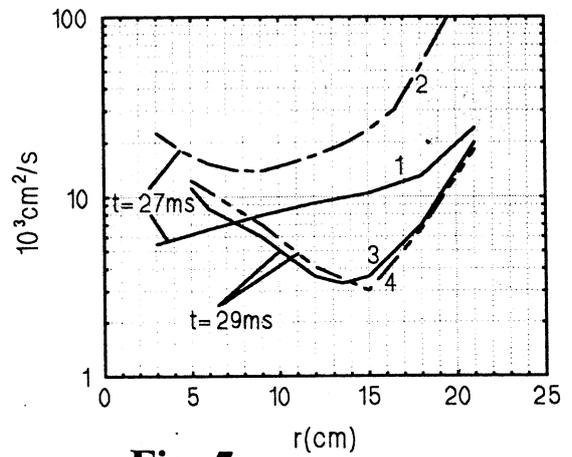


Fig. 5