Contribution of the Hall effect to radial electric field and spontaneous/intrinsic rotation in tokamak core plasmas

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1. Introduction. Observations [1] of radial electric field E_r in the T-10 tokamak and TJ-II stellarator may be interpreted as evidence of the role of two-fluid magnetohydrodynamics (2F-MHD) effects in plasma equilibrium. Large negative values of E_r in the core plasmas (~ 100 V/cm) and, especially, its fast increase and even the change of E_r sign during strong ECRH, despite the small changes of ion pressure, suggest that the commonly used estimates of E_r from MHD radial equilibrium for ions (p – pressure; V - hydrodynamic velocity, B - magnetic field, their poloidal and toroidal components are labeled with subscripts),

$$\frac{\partial p_i}{\partial r} = e n_e E_r - \frac{e n_e}{c}\left(V_{tor} B_{pol} - V_{pol} B_{tor}\right), \qquad (1)$$

may not work well, so the role of the MHD radial equilibrium for electrons in the generation of E_r (j – electric current density)

$$\frac{\partial p_e}{\partial r} = -e n_e E_r - \frac{1}{c} j_{tor} B_{pol} + \frac{1}{c} j_{pol} B_{tor} + \frac{e n_e}{c}\left(V_{tor} B_{pol} - V_{pol} B_{tor}\right), \qquad (2)$$

should be revised. Here we show that the Hall effect, defined as the separation of electric charges of opposite sign when they move in a magnetic field, may contribute substantially to the observed negative radial electric field E_r in the core plasma in tokamaks and, respectively, to the spontaneous/intrinsic rotation of plasma.

A detailed study of the Hall effect in plasmas began with a study in [2] — within the framework of 2F-MHD — of the effect of frozenness of magnetic field mainly in the electron component of the plasma. This effect is important for stationary plasma flows [3] and plays a dominant role in plasma open switches, Z-pinches, plasma foci, and is widely studied in the literature (see, e.g., [4]). In the 2F-MHD, the tokamak poloidal magnetic field compresses only the plasma electrons (the pinch by toroidal electric current), and this separation of electric charges produces E_r which, in turn, generates "spontaneous" plasma rotation in the crossed ExB fields. A simple way to evaluate the Hall effect contribution to the E_r value, using independently measured space distributions of magnetic field, electron pressure and plasma rotation velocity, may be suggested and applied to data analysis.

2. Estimation of contribution of the Hall effect to radial electric field in tokamaks. Here we consider the case when there is no substantial contribution to the plasma rotation from external, auxiliary (with respect to the Ohmic mode of tokamak operation) sources such as the neutral beam injection. Thus, we consider only the case when the plasma rotation is called spontaneous or intrinsic one. Under these conditions, the electric current velocity is much higher than the plasma rotation velocity, and the Ampère force (2nd and 3rd terms in the right-hand side of (2)) dominates over the contribution of plasma rotation (4th and 5th terms in (2)). This case is certainly applicable to tokamak operation for Ohmic heating and/or ECRH with low or moderate ECCD.

In literature, the value of electric field, which equates the Ampere's force, is called the Hall electric field. For a quasi-steady-state E_r in tokamaks, it would be natural to redefine this field via including the electron pressure gradient, because the latter weakens (saturates) the (driven by the Lorentz force) separation of electric charges, to give the net electric field. In the single-fluid (1F) ideal plasma, the motion of plasma with the MHD velocity $\boldsymbol{V}$ across magnetic field also produces the electric field due to the Lorentz force (equivalently, in ideal 1F-MHD, the plasma moves with E-cross-B drift velocity in the crossed electric and magnetic fields). Thus, the terms in (2) may be rewritten as radial components of the following vectors:

$$\text{(a)} \quad \boldsymbol{E}^{*}_{Hall} = \frac{1}{en_e}\left\{\frac{1}{c}[\boldsymbol{j},\boldsymbol{B}] - \nabla p_e\right\}, \qquad \text{(b)} \quad \boldsymbol{E}_{idealMHD} = -\frac{1}{c}[\boldsymbol{V},\boldsymbol{B}]\,. \tag{3}$$

It follows from (2) that the poloidal magnetic field, B_{pol} , is responsible for the following effects:

- in the Ohmic mode, B_{pol} is pumped into the main chamber from the poloidal current coils (the source of volt-seconds), and the influx of B_{pol} produces the toroidal electric current;
- B_{pol} compresses electrons (the pinch effect) and separates the electric charges because ions are magnetized much less than electrons; this separation produces radial electric field which pulls ions after electrons, and as a result, B_{pol} compresses the plasma as a whole;
- as far as B_{pol} compresses the plasma with the (almost frozen-in) toroidal magnetic field, B_{tor}, the compression of B_{tor} produces the poloidal electric current and the force against the pinch effect caused by the poloidal magnetic field.

Note that all these effects are well recognized in the physics of magneto-inertially confined plasmas (cf. e.g. [4]).

The estimates of the Hall effect contribution to the E_r value, using the independently measured spatial profiles of electron pressure, magnetic field and plasma rotation velocity in tokamaks TM-4 and T-10, are presented in Figs. 1 and 2 (for more details, see [7]). For TM-4 tokamak, we use the data [5]: minor radius a = 0.085 m, $T_e(0)$ = 0.5 keV, $n_e(0)$ = 3.0 10^{19} m^{-3}, plasma toroidal electric current $I_p(a)$ = 0.025 MA, $B_{tor}(0)$ = 1.45 T, $V_{pol}(\rho=0.5)$ ~ 2 km/s (cf. Fig. 4 in [5]). For T-10 tokamak, we use the data [6]: a = 0.3 m, $T_e(0)$ = 0.8 keV, $n_e(0)$ = 4.0 10^{19} m^{-3}, $I_p(a)$ = 0.15 MA, $B_{tor}(0)$ = 2.1 T, $V_{pol}(\rho=0.5)$ ~ 3 km/s (cf. Figs. 2, 4 in [6]).

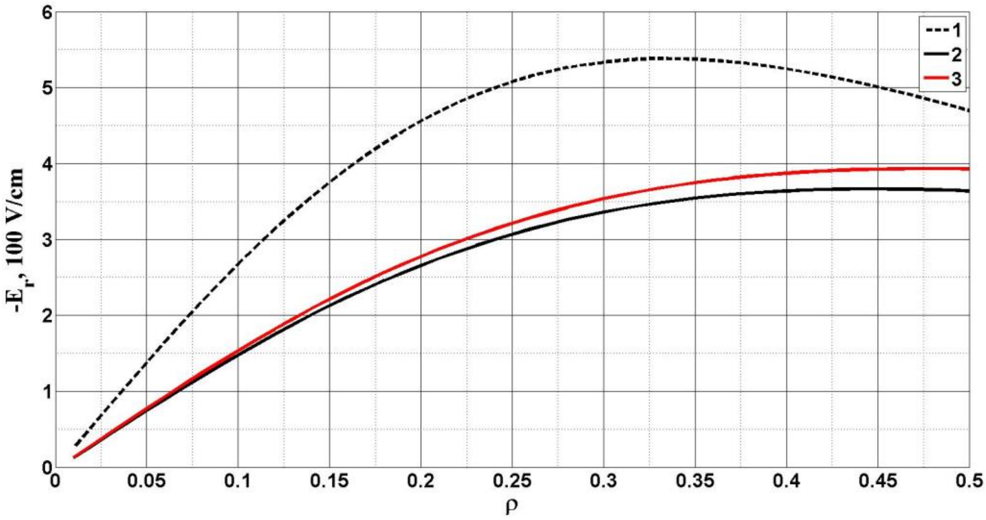

Figure 1. The profile of radial electric field, E_r, evaluated from Eq. (2) for TM-4 tokamak data [5]: effective Hall electric field from Eq. (3a) with account of toroidal electric current only (dashed black curve); the result of (3a) for the total Ampere's force (black curve), the result of all the terms in (2) (red).

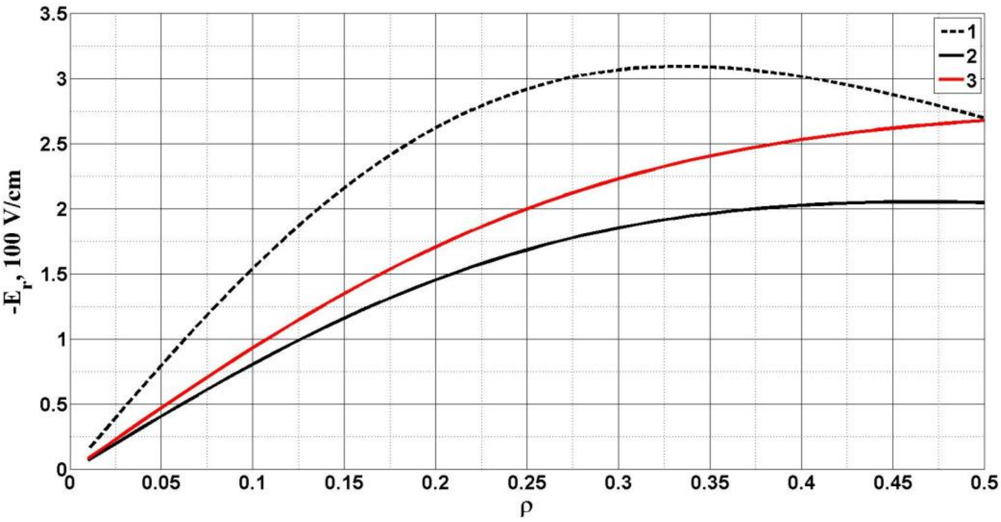

Figure 2. The same as in Fig. 1 but for T-10 tokamak data [6].

Thus, the balance of radial forces on electrons in (2), for small ion MHD velocity as compared to that of electrons, is as follows:

- ✓ compression of electrons by the poloidal magnetic field gives negative values of the force and the strongest contribution to E_r ,
- ✓ repulsion produced by the compressed toroidal magnetic field gives positive values of the force and only partly compensates the above-mentioned compression force,
- ✓ repulsion force due to an excess of negative electric charge in the core is positive for negative values of E_r,
- ✓ repulsion produced by the electron pressure (diamagnetic effect, positive values of the force) plays a significant role and, if increased, may change the sign of E_r .

3. Conclusions.

The estimates of radial electric field in the core plasma, based on the equation of MHD radial equilibrium for electrons and experimental data for electron pressure, magnetic field and plasma rotation, give – for the data from TM-4 and T-10 tokamaks – high negative values of E_r in the core plasma (~ few hundreds of V/cm), which are in qualitative agreement with the measured values (~ 100 V/cm).

Contribution of other mechanisms (e.g., neoclassical kinetics) to E_r (and spontaneous/intrinsic plasma rotation) in tokamaks should be treated with account of a strong hydrodynamic effect of the Ampère force, described in the framework of the 2F-MHD.

Fast increase and even the change of the E_r sign during strong ECRH, despite the small changes of ion pressure, may be explained with the increase of electron pressure gradient. In stellarators, this mechanism may work as well, because (instead of the Ampère force in tokamaks) the confinement is produced by the geometry of magnetic field.

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