Simulation of turbulent plasma toroidal rotation evolution in tokamak with ECR heating switch-on

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The paper continues our research on a low frequency nonlinear turbulent convection and the associated anomalous transport of heat, particles and momentum. The main goal of this paper is the analysis and simulations of toroidal momentum transport in tokamak in various regimes with ECR heating. The simulations are performed with CONTRA-C code, which is based on adiabatically reduced MHD-like model [1, 2].

The complete set of equations is presented in [1, 2]. It consists of transport equations for the surface averaged values of pressure p, plasma density n, electric potential ϕ and momentum and equations those determine temporal and 2D spatial behavior of fluctuations for these values. Transport equations include both background (typically neoclassical) fluxes and turbulent fluxes which are determined by fluctuations.

All equations in this model are written in the terms of flux coordinates: minor plasma radius $\rho = \sqrt{\Psi(r,t)/\pi B_0}$, where $\Psi(r,t)$ is the toroidal magnetic flux and B_0 is the toroidal magnetic field at magnetic axis, and toroidal angle φ. We introduce the specific toroidal momentum of the plasma sheath of thickness $d\rho$:

$$M'(t,\rho) = m_i n V' \left\langle r^2 \right\rangle \Omega(t,r) \tag{1}$$

where $V' = \oint \sqrt{g} d\theta d\varphi$ is the specific volume of the plasma sheath, $\left\langle r^2 \right\rangle = (1/V') \oint \sqrt{g} r^2 d\theta d\varphi$ is the square of major radius averaged over the plasma sheath and Ω is the frequency of toroidal rotation.

The toroidal momentum transport is governed by equation:

$$\begin{aligned} \partial_t M' - \partial_\rho \left(m_i n V' \left\langle r^2 \right\rangle \left(c\frac{h}{\rho} \right)^2 \overline{(\partial_\rho \phi)(\partial_\varphi \phi)} \right) = \\ = \frac{3}{20} \partial_\rho \left(m_i n V' \left\langle r^4 \right\rangle \left(X \frac{n}{\sqrt{T_i}} \right) \frac{h\rho}{\rho^2 + \rho_0^2} \partial_\rho \Omega \right) + Q_M \end{aligned} \tag{2}$$

The second term on the left-hand side has the form of toroidal momentum radial turbulent flux divergence. This term vanishes at the simulation domain boundaries, hence it does not change the integral momentum of a system, but redistributes its profile. Also this term is responsible for the energy interchange between toroidal rotation and fluctuations.

The first term on the right-hand side is a background flux caused by collisional ion viscosity with factor $X = 0.4\sqrt{\pi m_i} e^2 c^2 \Lambda$, where Λ is Coulomb logarithm, $\rho_0^2 = 4q_0\rho_{L_i}R$, R is major plasma radius averaged over plasma sheath, ρ_{L_i} is ion gyro radius at the magnetic axis. The viscosity term also has flux form and returns some kinetic energy of the toroidal rotation into heat.

The second term on the RHS denotes torque sources (e.g. neutral beam injection). The integral momentum changes only due to momentum flux over boundaries and external sources (or sinks) such as neutral beam injection. Thus equation (2) has the form of the conservation law for the integral momentum $M = \int_0^a M' d\rho$ and the integral dynamic vorticity $W(t) = m_i n V' \Omega \Big|_0^a$.

We suppose that there is no momentum flux at the magnetic axis. The external boundary of our simulation domain is located on the last closed magnetic surface. This surface contacts with material limiter, so we assume that due to the friction with the wall there is no rotation at the external boundary of simulation domain, i.e. standard "boundary layer" condition in hydrodynamics.

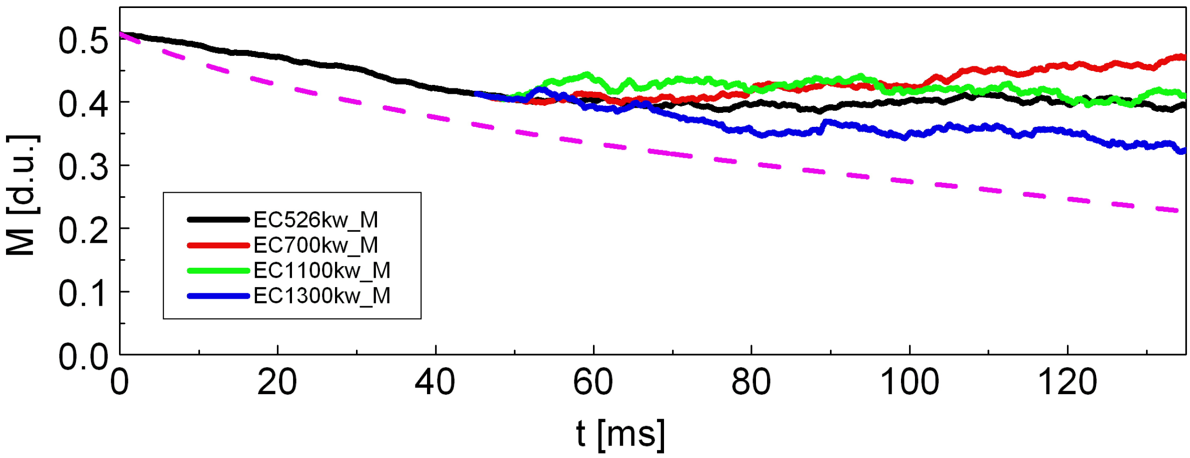

Figure 1: *Evolution of toroidal momentum in the regimes with different ECRH powers*

The simulations of plasma turbulence temporal evolution were performed for rather typical tokamak T-10 regimes plasma parameters $n_0 = 3.1 \cdot 10^{-19} m^{-3}$, $T_e = 1\,keV$, $T_i = 0.47\,keV$, minor radius $a = 30\,cm$, major radius $R = 150\,cm$. Ohmic heating(OH) power was about 250kW during OH stage and was reduced by half on ECRH stage. The energy confinement time on OH stage was about 32ms. The duration of OH stage in simulations was 45ms. It exceeded energy confinement time and is quite sufficient for fluctuations to reach their saturation levels. The simulations were performed for the central ECR heating with the variety of heating powers: 526kW, 700kW, 1100kW, 1300kW. The main distinctions of ECR heating source from other heat sources in our model are its relatively narrow profile and higher heating power.

The temporal evolution of total momentum for the variety of heating powers is shown on Fig. 1. The magenta dashed line shows a simulation test case (with additional ECR power 526kW) where the turbulent flux in equation (2) is forced to zero. In this simulation series the integral momentum decreases during OH-stage and after additional heating switching on it starts to oscillate near quasi-stationary level, which depends on the heating power. In the test case the integral momentum is decreasing monotonically.

The integral momentum maintenance in case of boundary condition $\Omega|_{\rho=a} = 0$ and without external source of momentum may seem a little bit surprising.

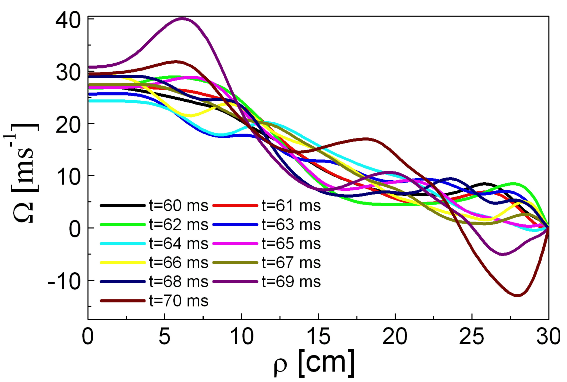

Figure 2: Ω *profiles at different time moments during ECRH stage for ECH power 526kW.*

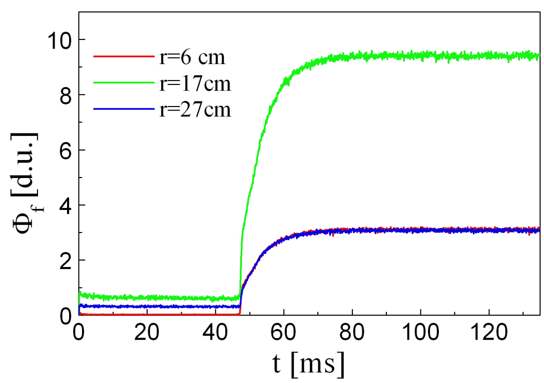

Figure 3: *Temporal evolution of* Φ *fluctuations levels at different radii.*

However, one can see that $\partial_\rho \Omega|_{\rho=a}$ (and hence the momentum flux over the external boundary) can change its sign (Fig. 2) with characteristic frequency higher than momentum dissipation rate. As a result the time-averaged momentum flux over the external boundary can vanish. It should be mentioned that these oscillations in the momentum flux occur due to momentum redistribution with the convective flux,which depends on potential fluctuations. The test case demonstrates that without such redistribution the total momentum decreases faster during the OH stage and additional heating does not affect this dissipation.

The temporal evolution of potential fluctuations levels at different radii is shown on Fig. 3. After ECRH switching-on the amplitudes of potential fluctuations grow. At the central radius potential fluctuations amplitude grow from almost zero values to rather significant.

The integral dynamic vorticity W is proportional to the difference between rotation frequencies at the external boundary and magnetic axis. So, in case of boundary condition $\Omega|_{\rho=a} = 0$, it demonstrates evolution of Ω at $\rho = 0$. For positive total momentum values the integral vorticity usually has negative value and vice versa. During OH stage central rotation slightly decreases,

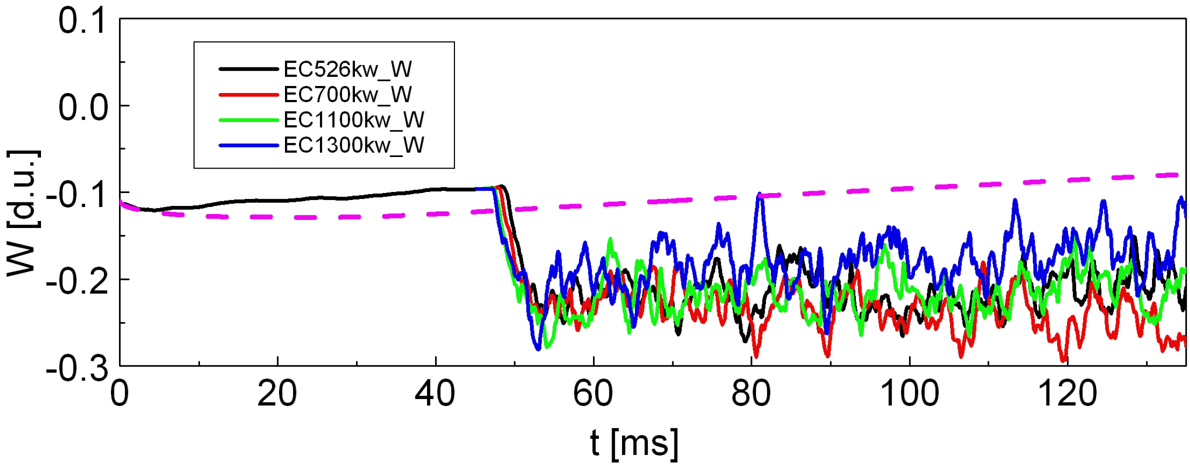

Figure 4: *Evolution of the integral dynamic vorticity in regimes with different ECRH power*

but after ECRH switching-on the central toroidal rotation increases and is maintained on some new level, which is almost the same for different ECRH powers (Fig. 4). The temporal behavior of the integral vorticity in the test case (the magenta dashed line) without the turbulent momentum flux is essentially different. The central toroidal rotation increases due to the initial Ω profile redistribution. Than, as expected, it monotonically decreases, because Ω profile relaxes to $\Omega(\rho) = 0$. Also there is no change in the temporal behavior after ECRH switching on.

The results of our simulations demonstrate the importance of turbulent fluxes caused by Reynolds stress for momentum transport and intrinsic rotation maintenance. Without the turbulent flux total momentum monotonically decreases due to the friction with the wall, while in the presence of this flux total momentum can be maintained in the regimes with relatively low viscosity [3] during OH stage or at ECH stage. Also the turbulent flux significantly affects the rotation at plasma center.

References

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