GAM evolution and LH-transition in TUMAN-3M tokamak

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Geodesic acoustic mode (GAM) does not participate in radial transport directly, although it transfers energy from high-frequency spectral components of ambient turbulence and creates strong inhomogeneity of radial electric field and transverse rotation, and thus affects anomalous transport through control of turbulence level [1]. GAM-induced shear of radial electric field is not constant in time, therefore possibility of LH-transition initiation in this case is not obvious and is to be studied. Interest for GAM studies has recently increased due to discovery of discharge scenario, which is intermediate between L- and H-mode (so called I-phase), characterized by interplay of GAM, ambient turbulence and confinement [2]. In previous experiments GAM were studied in TUMAN-3M tokamak by means of heavy ion beam probe [3] and Doppler reflectometry diagnostics [4].

To understand the possible role of GAM in LH-transition initiation, a simple numerical model of plasma density profile evolution under the influence of GAM-induced radial electric field shear was used. One-dimensional spatial and temporal evolution of plasma density profile was simulated:

$$\frac{\partial n(r,t)}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r} r \cdot \left(D(r,t) \cdot \frac{\partial n(r,t)}{\partial r} - v(r) \cdot n(r,t) \right) = S(r)$$

Here $n(r,t)$ – plasma density, $D(r,t)$ – diffusion coefficient, $v(r)$ – convection velocity, $S(r)$ – charged particle source density. Particle source and convection velocity were considered constant in time; diffusion coefficient was taken in a form $D=k(\omega(r,t))\cdot D_0(r)$, with radial electric field shear dependent factor $k(\omega)$ and spatial dependent part $D_0(r)$. In the L-mode, when radial electric field shear value is low, $k=1$ and stationary density profile is defined by transport coefficients D_0 and v. As shear increases, $k(\omega)$ value decreases, thus simulating local suppression of anomalous transport in the presence of strong radial electric field inhomogeneity.

There were used two different representations of $k(\omega)$ factor. The first representation of $k(\omega)$ is step-like semi-empirical dependence, used in work [5] for modeling of current ramp-up-induced LH-transition in TUMAN-3M tokamak. This coefficient has two «critical» shear values $\omega_{s1} = 0.25 \cdot 10^5$ s^{-1} and $\omega_{s2} = 1.25 \cdot 10^5$ s^{-1}, that were

chosen close to values of edge shear in L- and H-mode correspondingly; although k(ω) does not depend on any specific turbulence mode.

The second is analytical dependence $k(\omega) = \dfrac{1}{1+(\omega/\gamma)^2} + k_{NEO}$, similar to one proposed in [6]; here $k_{NEO}=0.05$ describes fully suppressed anomalous transport. If using this representation of k(ω), turbulence growth increment γ should be defined to determine the effectiveness of suppression. For the present modeling TEM mode with $\gamma = 0.7 \cdot 10^5$ s^{-1} (for characteristic edge plasma parameters in TUMAN-3M) was chosen due to banana electron transport regime, which corresponds with estimates for edge collisionality.
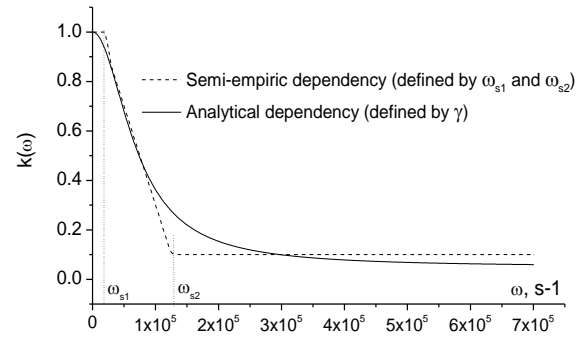

Fig. 1: Shear-dependent factor of diffusion coefficient

Total radial electric field was considered to be a sum of neoclassical and oscillating components $E = E_{NEO} + E_{GAM}$; GAM was modeled as a time- and space-localized traveling wave propagating radially outwards in a rectangular time window T:

$$E_{GAM}(r,t) = E_{GAM} \cdot \cos(2\pi \cdot f \cdot t - \frac{2\pi}{\lambda} \cdot r) \cdot \exp\left(-\frac{(r-r_0)^2}{w^2}\right) \cdot \mathrm{rect}(t_0, T)$$

Neoclassical electric field, provided toroidal rotation effect is neglected, depends on density and ion temperature gradients. There were no reliable measurements of ion temperature profile in TUMAN-3M tokamak, thus it was taken the same as density profile:

$$E_{NEO} = \frac{T_i}{e}\left[\frac{\partial \ln n}{\partial r} + k_T \frac{\partial \ln T_i}{\partial r}\right] \approx 2\frac{T_i}{e}\frac{d}{dr}\ln(n(r,t))$$

Simulations of density profile evolution were carried out for different combinations of amplitude, wavelength and frequency of GAM. It was found that as inhomogeneity of total electric field $E=E_{NEO}+E_{GAM}$ increases, formation of an area with suppressed diffusion is possible in a vicinity of GAM localization area. For specific combinations of GAM and plasma parameters, GAM-initiated transport barrier becomes self-sustaining and exists after GAM switching-off. This effect has a threshold nature – if GAM amplitude E_{GAM} (or burst

duration *T*) is too low, edge transport barrier decays after GAM switching-off, and system returns back to initial state with sloping density profile (L-mode).

It was found in [7] that variable field shear has weaker effect on turbulence suppression: ratio of oscillation field frequency to turbulence linear growth increment $2\pi f/\gamma$ is crucial, the higher this value is, the lesser effective is suppression. As for analytical $k(\omega)$, TEM instability, which is likely to be responsible for anomalous transport in the TUMAN-3M plasma, with growth increment $\gamma = 0.7 \cdot 10^5 \ s^{-1}$ was used.

Semi-empirical $k(\omega)$ may seem convenient as it is not necessary to know turbulent mode, although considering the effect of suppression weakening by oscillating shear negates this convenience. Also, as it was found during simulations, LH-transition modeling with semi-empirical $k(\omega)$ may yield non-physical results, probably due to flat part after ω_{s2}. Thus, analytical $k(\omega)$ was found to be better for obtaining meaningful results.

In fig. 2a and 2b there are examples of peripheral shear evolution under the effect of GAM burst with analytical $k(\omega)$ dependence. If GAM amplitude and burst duration overcome certain threshold values, plasma goes into new state – the H-mode (red lines). Time required for the transition to the new state with self-sustained transport barrier and suppressed anomalous transport is labeled in fig.1 as t_{trans}. If amplitude or duration of GAM burst are insufficient, system returns to initial L-mode state after GAM is switched off, i.e. no LH-transition occurs (black lines in fig. 2). Drop and further increase of shear during the transition is related to profile transformation to steady-state H-mode.
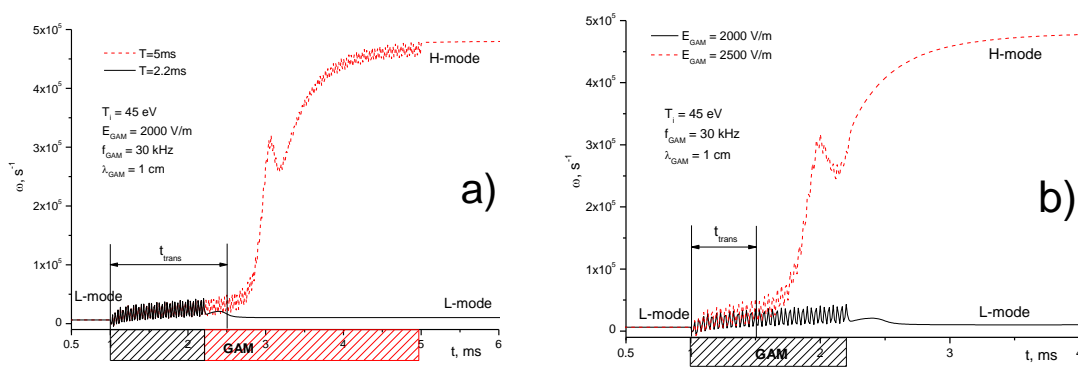

Fig. 2: Peripheral radial electric field shear evolution in the presence of GAM (analytical $k(\omega)$). Transition occurs if duration (a) or amplitude (b) of GAM exceeds threshold value

It is interesting to compare modeling results with experimental GAM observation in a low-density discharge with ohmic LH-transition in TUMAN-3M tokamak [3]. The HIBP-detected central potential oscillations with amplitude of ≈ 10 V and frequency about 30 kHz presumably were induced by alternating peripheral electric field of GAM. Central potential

perturbation $\Delta\Phi$=10 V may be obtained with different combinations of GAM amplitude and wavelength. For two characteristic combinations λ_{GAM} = 1 cm, E_{GAM} = 4.5 kV/m and λ_{GAM} = 2 cm, E_{GAM} = 2.5 kV/m GAM amplitude is higher than threshold value, if ion temperature is higher than 45 eV, which looks reasonable for the edge TUMAN-3M plasma.

Fig.3 Comparison of GAM experimental amplitude with LH-transition initiation threshold

To summarize, the results of numerical modeling of plasma density profile evolution with different dependencies of diffusion coefficient on radial electric field shear are presented. There discovered a possibility of GAM-initiated LH transition, if GAM parameters, primarily duration and amplitude, exceed certain values. Parameters of GAM oscillations, observed on the TUMAN-3M tokamak [3], are within the ranges necessary for the LH-transition initiation.
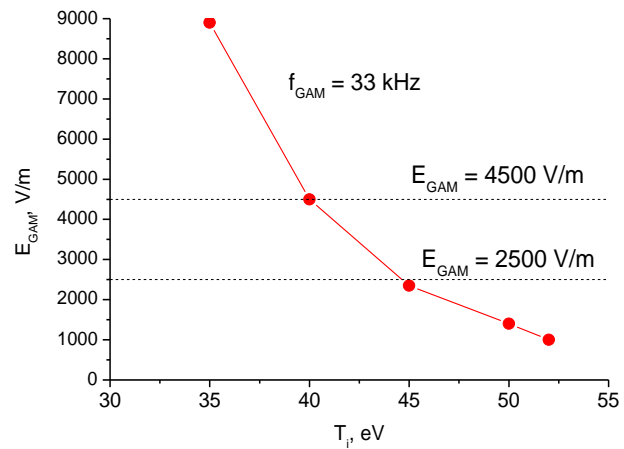
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