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Low recycling operations and improved confinement in tokamaks

R. Cesario[1], M. Marinucci[1], P. Smeulders[1], R. Zagorski[2]

[1]Associazione EURATOM/ENEA sulla Fusione, Centro Ricerche Frascati, Italy

[2]Institute of Plasma Physics and Laser Microfusion, EURATOM Assoc. Warsaw, Poland

Abstract. It is summarised the wide phenomenology in fusion plasmas that indicates the link between physics of the edge, via the recycling, and confinement. An interpretation is proposed in which electrostatic waves excited by thermal background in the plasma core enhance the turbulence at the periphery, via a local non-linear mode coupling with ion-sound quasi-modes. This instability is favoured by low electron temperatures of the edge, which correspond to operations with high recycling.

Introduction. The H-mode is a high plasma confinement regime obtained in tokamak plasmas when a certain threshold of additional power is exceeded. It is accompanied by a global reduction of the level of the H-alpha emission, i.e., a recycling reduction. More in general, as shown in Ref. 1 (and in quotations in it) low recycling operations was found as useful condition for improved confinement in tokamak and stellarators. It was also the case of the ion Bernstein (IBW) wave heating on FTU (Frascati Tokamak Upgrade), in which an internal transport barrier (ITB) was successfully produced only when operating with a relatively big plasma-wall distance needed for reducing recycling [2]. Similarly, Ref 1 identifies the radial outer gap (ROG), at the beginning of the main heating phase, as one of the relevant operating parameters for achieving ITB performances in JET (Joint European Torus). The identified useful condition of ROG ($\approx$ 5 cm) was actually utilised in the experiments of JET that produced, for the first time, long lasting ITBs sustained by lower hybrid current drive (LHCD) performed during H-mode [3-6]. The effect of recycling is clear by comparison with similar experiments performed with higher recycling (of a factor ten), due to a smaller ROG (< 2.5 cm, useful for improving the LHCD antenna coupling). In the low recycling operations, higher toroidal velocities and electron temperatures (of a factor two) at the plasma periphery, more prompt access to H-mode and successful ITB formation were found [1]. A powerful tool for obtaining plasma configurations with low recycling and improved confinement was identified by operating with vessel coated by Lithium [5 and quotations in Refs. 6-7]. A key for understanding such general behaviour linking edge physics and transport is suggested.

Experimental results and modelling. Recent experiments of FTU show that a high electron temperature at the edge and quasi-quiescent MHD occur by operating with low recycling. Figure 1 shows the important features produced by lithizated vessel (at $B_T \approx 6$T, $I_P \approx 0.5$MA, $<n_e> \approx 0.65\ 10^{20}$ m^{-3}, $T_{e0} \approx 2.2$ keV): *i*) the electron temperature of the edge is higher (230 eV vs. 160 eV at r/a ≈ 0.82, with recycling a factor ten lower than in boronised vessel), *ii*) the internal MHD activity is quasi-quiescent (the amplitude of 2/1 modes is five times lower). A 2-D boundary modelling of scrape-off plasma layer, performed for the realistic operating parameters of FTU, explains the dependence of the edge temperature on the recycling: as consequence of the strong pumping effect of Li-coating of the walls, a very low recycling coefficient (*R*=0.02) is obtained, consistently with the experimental data. Similar indications of low MHD activity, higher temperature at the periphery and better confinement are provided also by recent experiments of JET [8] and NSTX [9].

We interpret such general behaviour in terms of the electron temperature at the edge that, when below a certain threshold, produces strong turbulence. It is a non-linear mode coupling of a parametric instability, which is pumped by the electrostatic waves originated by the thermal background in the core, and driven by low frequency quasi-modes at the edge. This scheme is similar to that producing the spectral broadening in LHCD experiments [6,7], with the important difference that much lower convective losses occur in the present case, due to the uniform "illumination" of the plasma periphery by the core. The condition of occurrence of such instability is found by following Refs [6,7] considering, as example, the aforementioned FTU plasma. The parametric dispersion relation for electrostatic waves:

$$\varepsilon(\omega,\mathbf{k}) - \frac{\mu_1(\omega_1,\mathbf{k}_1,\mathbf{k}_0,E_0)}{\varepsilon(\omega_1,\mathbf{k}_1)} - \frac{\mu_2(\omega_2,\mathbf{k}_2,\mathbf{k}_0,E_0)}{\varepsilon(\omega_2,\mathbf{k}_2)} = 0 \qquad 1$$

is numerically solved for a LH pump wave excited by thermal background at a frequency of about 1 GHz that propagate from the core ($\omega_{LH} \lesssim \omega_0$) to the extreme periphery ($\omega_{pe} \gtrsim \omega_0$). $\mathbf{k}_{2,1}=\mathbf{k}\pm\mathbf{k}_0$, $\omega_{2,1}=\omega\pm\omega_0$ are the selection rules provided by momentum and energy conservation of the coupled modes (the index 1, 2 refer to the lower and upper sidebands, respectively). μ_1 and μ_2 are the coupling coefficients referring to the lower and the upper sidebands respectively, and magnetised ions are considered for the calculation. The pump electric field E_0^2 can be approximated by the field energy contained in the wavenumber space limited by $k_{zMax} \cong \frac{\omega 0}{v_{the}}$, $k_{\varepsilon\ Max}\ \omega\sqrt{\frac{m_i}{m_e}}\ \frac{-0 k_{zMax}}{-LH}$. For electron temperatures in the core of about 5 keV: $E_0^2 \approx 2\ 10^{-3}$ (statvolt/cm)^2, and $k_{zMax} \approx 2$. For typical plasma edge with low enough electron temperatures ($\lesssim$200 eV, and $n_e \approx 5 \div 50\ 10^{17}$ m^{-3}), coupled modes with positive growth rate ($\frac{\varepsilon}{\omega_0} - 2\ 10^5$) and exceeding the linear damping are found. The trend of the frequency and growth rate of the low frequency driving mode is plotted in Figure 2 with respect to its wavenumber referred to the direction perpendicular to the confinement magnetic field. In these conditions, the sidebands are propagating LH waves, while the low frequency driving mode is damped on particles and however exists only in presence of the pump wave (quasi-mode). Conversely, only stable solutions of Eq. 1 (i.e, with negative growth rate) are found for higher temperatures of the edge, also by considering a wide range of plasma and involved mode parameters. The occurrence of such coupled mode growth at the edge for low temperature/high recycling operations is consistent with the experimental outcomes. Further details are contained in a dedicated paper that is in preparation.

The observed phenomenology of low recycling produced by means of different operating tools, consisting in high temperature at the edge and low MHD activity that accompany improved confinement regimes, is interpreted in term of a non-linear mode coupling mechanism, which is expected to occur in conditions that can be met in the magnetized fusion plasma experiments.

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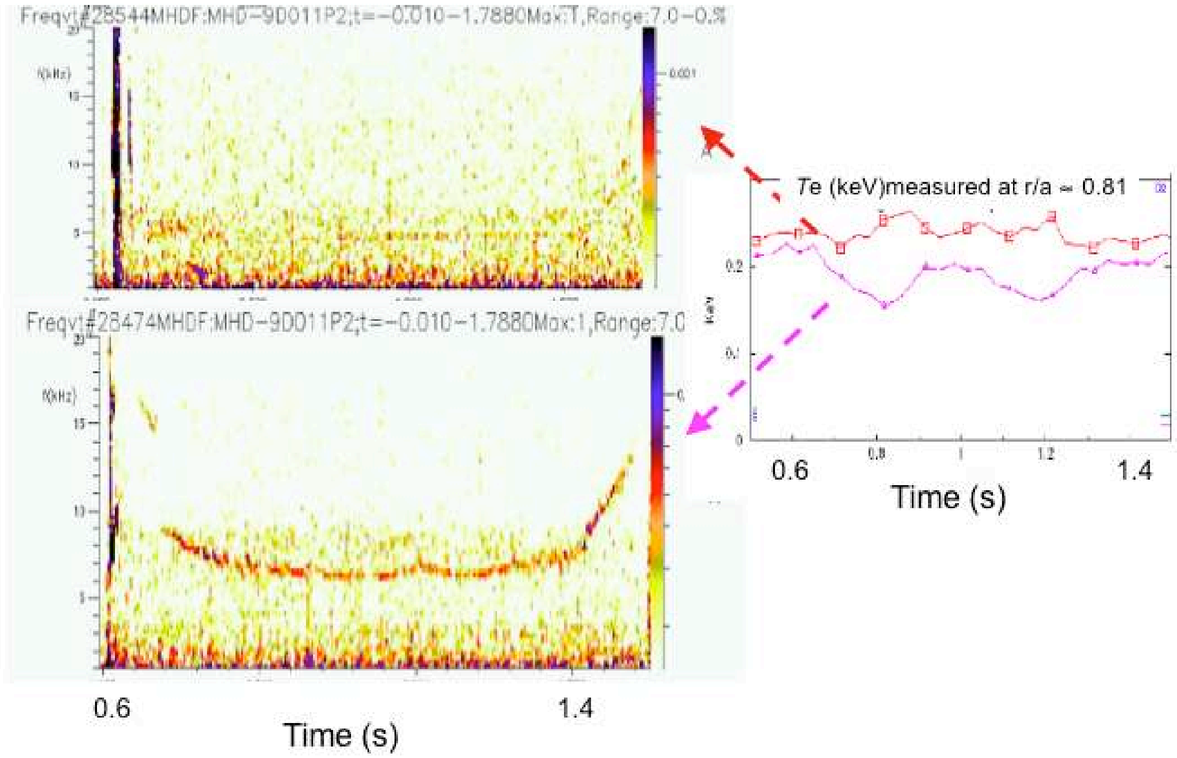

Figure 1. Comparison in similar shots of FTU performed with lithizated (low recycling) and boronised vessel of the time evolution of the MHD spectrograms (Fig. 1 a) and the electron temperature at the plasma periphery (Fig. 1 b), considering the same time window.

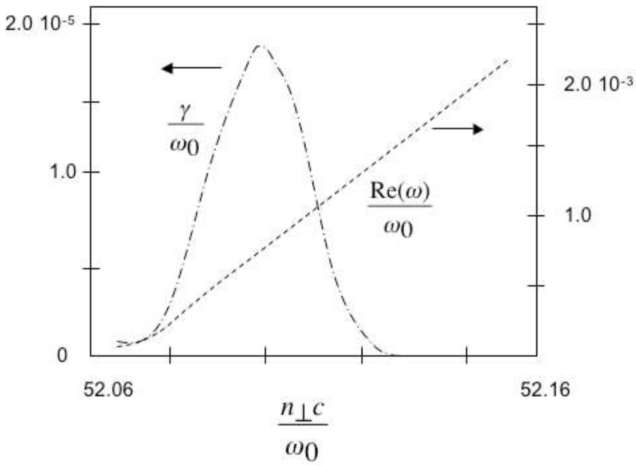

Figure 2. Solution of Eq. 1 for typical parameters of the FTU plasma periphery. For the low frequency driving mode, the frequency and growth rate (normalised to the pump frequency) are plotted vs. the normalised perpendicular wavenumber.