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THRESHOLD EFFECTS IN PELLET-PLASMA INTERACTION IN T-10 TOKAMAK

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Introduction. Plasma fuelling by hydrogen pellets and plasma diagnostics by impurity pellets are widely used in tokamaks and stellarators [1,2]. The pellet penetration depth into high-temperature plasmas is the main issue in pellet-plasma interaction. This length is determined by neutral gas shielding effects [3,4], effects of suprathermal electrons [5] and MHD events in the plasma including those initiated by pellets [6]. The fast transport of the density delivered into the plasma by pellets is another basic problem of pellet-plasma interaction. Toriodal drifts of the pellet produced plasmoids [7] and MHD processes [6,8] may be responsible for the delivered density transport into the core plasma. Understanding the influence of both mechanisms on the ablation and transport is very significant for development of fueling and diagnostic systems. This paper is devoted to studying the pellet-plasma interaction in T-10 tokamak experiments with carbon pellets of different sizes. The study was aimed at the effects of MHD processes on pellet ablation and accompanying transport phenomena.

Experimental setup. Spherical carbon pellets of diameters gradually varied in 0.20–0.62 mm range (that corresponds to $1.9\text{x}10^{17} - 5.1\text{x}10^{18}$ of carbon atoms in the pellets) were accelerated to ~400 m/s velocities and injected to the plasma core [6]. Penetrations beyond the plasma center were reached. Plasma parameters in Ohmic discharge were as follows: $\langle n_e \rangle \approx 2\times10^{13}$ cm^{-3}, Te=1.2 keV, I_{pl} = 270 kA, B_t = 2.4 T, a=30 cm, q=3. The pellet ablation was observed by a CCD camera and a wide-view photo-detector.

Experimental results. The main goal of experiments was to detect the pre-cooling effect, conditions when the cooling front spreads faster than the pellet and correlations of pre-cooling with ablation rate fluctuations. The study of enhanced ablation zones for different pellet diameters has shown the obvious size-threshold effect. Ablation rates for pellets larger than 0.3 mm demonstrated bursts/drops of ablation near rational magnetic surfaces where smaller pellets ablated smoothly being in agreement with Neutral Gas Shielding Model (NGSM) (see Fig. 1).

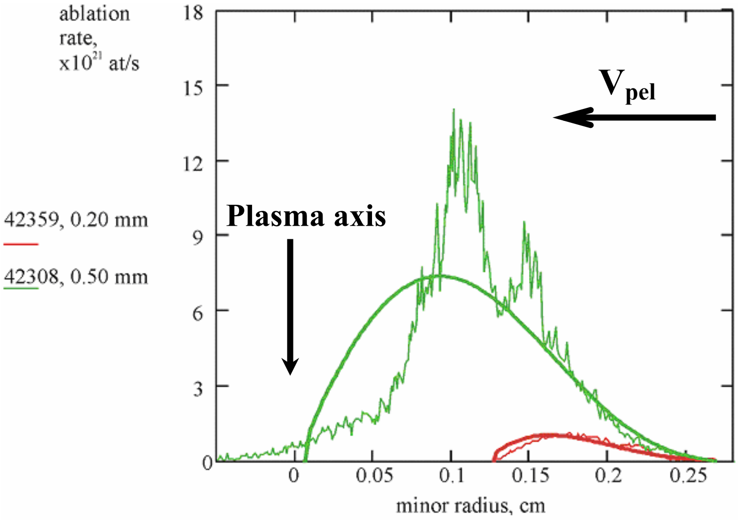

Fig. 1.

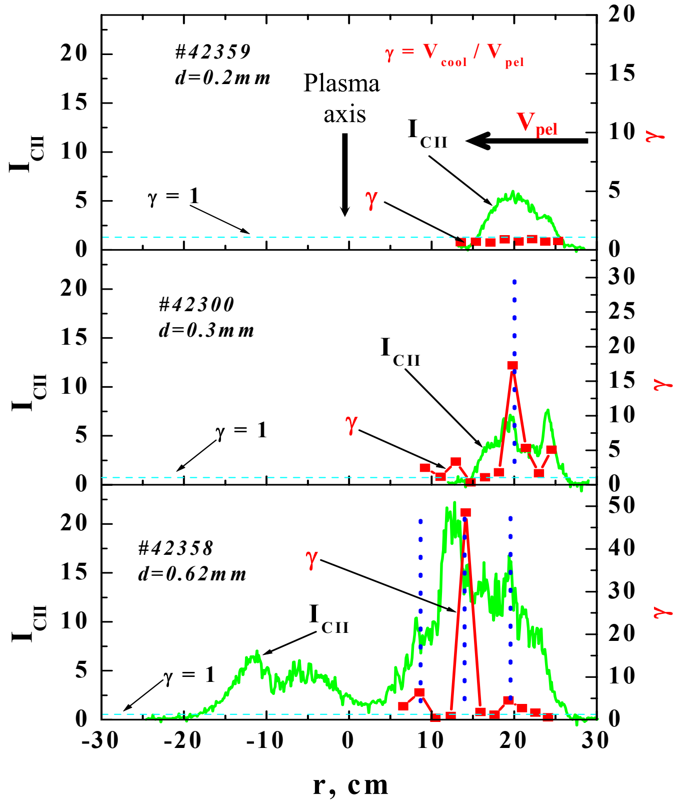

Fig. 2.

The ECE signals show the similar “threshold” character of the cooling front propagation. The ratio γ of the cooling front velocity $\mathbf{v}_{cool}$ and the pellet velocity $\mathbf{v}_{pel}$ are presented in Fig. 2. For pellets smaller than 0.3 mm the velocities are close and γ=1. Jumps of the γ-ratio were detected near rational magnetic surfaces for larger pellets. The highest ratio γ>10 was observed in the core region totally governed by the Kadomtsev reconnection.

Similar fast propagation of the pellet material ahead of the pellet was detected by semiconductor arrays AXUVD [8].

Discussion. It is clear from the data obtained that MHD processes determine basic features of the pellet ablation and deposited material transport during the pellet penetration into plasma. The pellet forced reconnection mechanism is formulated below for explanation of the observed phenomena.

Pellet cools the magnetic tube and adds the impurity into it increasing the effective plasma charge Z_{eff}. Both factors lead to growth of the electric field and formation of x-points for reconnection of the helical magnetic flux at rational magnetic surfaces. The effect is very strong. For typical tokamak conditions the resistive time $\tau_R=r^2/\eta$ may reduce by a factor of

10^3-10^4. This means that tearing mode islands with a few centimeters width ***w*** may grow up in a time shorter than 100 μs, and the Kadomtsev reconnection time may convert into μs-range instead of 100 μs without pellets.

The assumption that characteristic times for the pellet forced tearing processes and Kadomtsev reconnection are much smaller than the pellet ablation time has allowed us to propose an algorithm of the ablation model including the reconnection effects. NGSM [2] is used for calculations of the ablation rate under local plasma parameters. Electron density n_e, temperature T_e and safety factor q define the ablation rate N(t) stating from the plasma boundary r=a. We assumed that tearing mode islands with width w=3 cm (speculative value) are formed instantly when pellet reaches rational magnetic surfaces q=2 and 1.5. Mixing the n_e and T_e in the reconnection zone formed new n_e and T_e profiles ahead of the pellet. Ablation rate N(t) after tearing process was calculated using new profiles. Instant ionization to Z=6 was assumed. The Kadomtsev reconnection approach was used to get modified profiles n_e, T_e when pellet has reached q=1 magnetic surface. Beyond the plasma center n_e,T_e profiles were calculated accounting for the pellet ablated material. No reconnection events were considered there (however may be added).

Fig. 3 illustrates results of the model developed where experimental ablation rate (blue) is compared with NGSM (black) and NGSM upgraded by the reconnection effects (red).

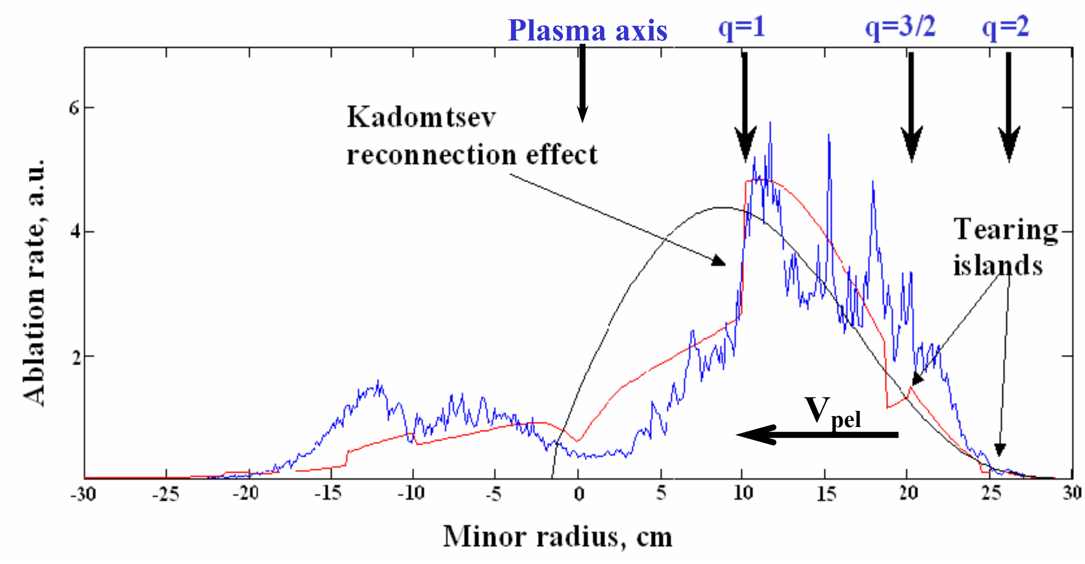

Fig. 3.

It is seen that the model describes reasonably the variation of the ablation rate due to tearing modes near q=2 and 3/2. The shape with initial jump of the ablation and following slow reduction is reproduced. (Two visible reconnections between q=1 and q=1.5 were not simulated). The Kadomtsev reconnection effect is clearly seen in the experimental data and well described by the new model. Even beyond the plasma center (negative radii) the experimental and simulated curves demonstrate similar behavior.

Summary. A threshold effect of the pellet size has been observed for appearance of the ablation bursts and drops in the T-10 experiments. Carbon pellets with size <0.3 mm do not affect significantly the magnetic structure of the tokamak. The ablation rate has small deviations from the smooth level predicted by Neutral Gas Shielding Model. Such pellets may be used for diagnostic purposes and studies of the toroidal drift effects.

The pellets larger than 0.3 mm initiate fast MHD processes in the plasma. Fluctuations of the ablation rate, formation of striations and pre-cooling fronts, are typical features of the pellet-plasma interaction at this larger level of plasma perturbations. The velocity of the pre-cooling fronts exceeds the pellet velocity up to an order of magnitude. The pre-cooling zones are localized in narrow regions (a few centimeters) near the low-value rational magnetic surfaces (q=2, 3/2, …). In the Kadomtsev reconnection zone (~10 cm) the ablation rate is significantly reduced by the pre-cooling front.

A mechanism of pellet effects on MHD stability and accounting it ablation model are proposed. The basic idea is that a pellet forms multiple x-points at the q=2, 3/2,… and a single x-point at q=1 magnetic surfaces and provokes the forced reconnection due to the conductivity reduction and expelling the current density from the x-points. Both the reduction of the electron temperature T_e and growths of the effective charge Z_{eff} in the pellet vicinity increase the increments of the tearing mode instability by a factor of 10^3-10^4 and reduce correspondingly the resistive reconnection time to the level below the pellet ablation time.

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