Plasma confinement properties at high density in TCV and T-10 tokamaks

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1. Introduction. Experimental investigation of the plasma behavior in a high density range is still important question since it gives additional information on the analysis of plasma stability and confinement in reactor relevant conditions. Comparison of the plasma confinement in a high density range close to the limit value has been done in T-10 and TCV tokamaks. Limiter discharges with similar q_{95} values in range of 2.5-6 have been considered. Both machines are medium size tokamaks: major radius of TCV tokamak is 0.88 m, minor radius a=0.25m; major radius of T-10 tokamak is 1.5 m, minor radius is 0.3 m. Feature of the TCV tokamak is the possibility to develop different plasma shapes in a wide range of plasma elongations and triangularities including negative triangularities [1]. An advantage of the T-10 tokamak is the possibility to compare experimental results obtained in regimes with the different plasma facing materials: graphite, tungsten and tungsten with lithium coating. So, intermachine comparison allows us: i) to find general features of confinement behaviour in vicinity of the density limit in regimes with the different plasma shaping and different plasma-facing componts; ii) to distinguish specific features caused by the configuration or first wall material. In all cases ohmic discharges are considered. Discharges with ECRH are added for the illustration of the general regularity in the density limit value on T-10.

2. The value of the density limit. Experiments on both tokamaks have been performed with the gas puffing from the plasma periphery. The values of the limit density reached in T-10 and TCV are presented in Figure 1. Results of the T-10 experiments with ohmic heating have been obtained with different limiter materials. TCV data are given for the medium elongation for both negative and positive triangularity cases. Data from both tokamaks demonstrate clear dependence of the ratio of $(n_e)_{lim}/n_{Gw}$ on q_{95} ($(n_e)_{lim}$ – the limit density value, n_{Gw} – Greenwald limit, q_{95} – edge safety factor value). It is seen that the Greenwald density can be easily reached in high q_{95} discharges.

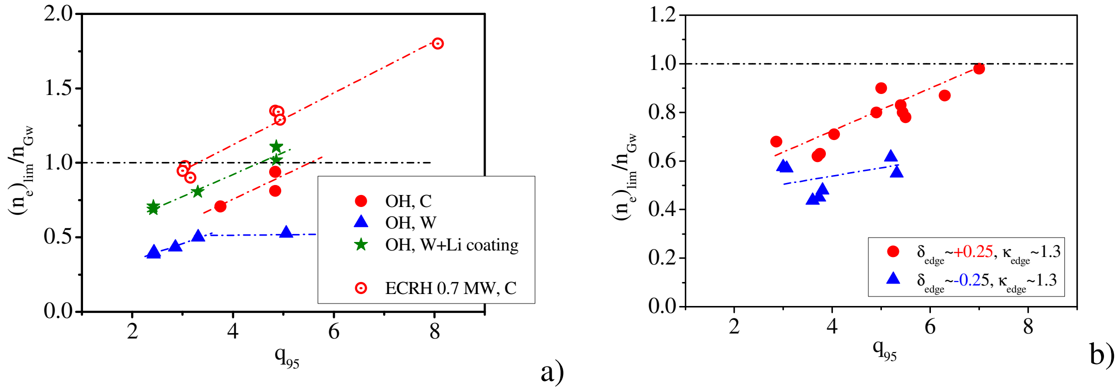

FIG. 1 Dependence of the limit density value on edge safety factor in T-10 (a) and TCV (b) experiments.

The limit density value in limiter configuration depends on the plasma facing material (FIG. 1,a). Li coating leads to the increase of the limit density in a whole q_{95} range. TCV data presented in FIG. 1,b demonstrate the difference of the maximal achievable density on the plasma triangularity. In elongated plasmas with the positive triangularity the value of limit density is ~40% higher than in the similar discharge with the negative triangularity. It is important to note that similar dependence of the $(n_e)_{lim}/n_{Gw}$ on q_{95} has been also reported in T-10 ECRH heated plasmas and has been explained by the effect of the radius of plasma current channel [2].

3. Evolution of sawtooth oscillations. Modification of sawtooth behaviour has been observed in both T-10 and TCV tokamaks at high density [2, 3]. Evolution of two T-10 discharges with different sawtooth behaviour due to the different gas-puffing rate is presented in FIG. 2. Decrease of the gas-puffing rate at high density is accompanied by the increase of soft X-ray emission from the core region (mostly inside of the q=1 zone), increase of radiation losses from the core and change of sawtooth period and amplitude. Existence of the positive feedback loop has been proposed [3]: density increase leads to the temperature decrease in the core, it leads to the current density redistribution, increase of the sawtooth period, further density and impurity peaking in the core which leads to the decrease of the core temperature and further flattening of plasma current in the core region. Effect of sawtooth modification has been observed in T-10 in regimes with $q_{95}>3$ at densities $n_e>0.8(n_e)_{lim}$ in discharges with graphite limiters and in regimes with tungsten limiters after lithium coating. In regimes with tungsten limiters (without lithium coating) sawtooth suppression has not been observed. Sawtooth suppression was found to be accompanied by confinement degradation. On TCV the effect of sawtooth suppression was found to be dependent on plasma shape and q_{95} value (FIG. 3). It is seen (FIG 3,b) that in ITER-relevant q_{95} range sawtooth suppression can be expected in the density range above $0.75(n_e)_{lim}$. At the same time increase of plasma triangularity to the ITER value leads to the restoration of sawteeth at high density at q_{95} up to 4.

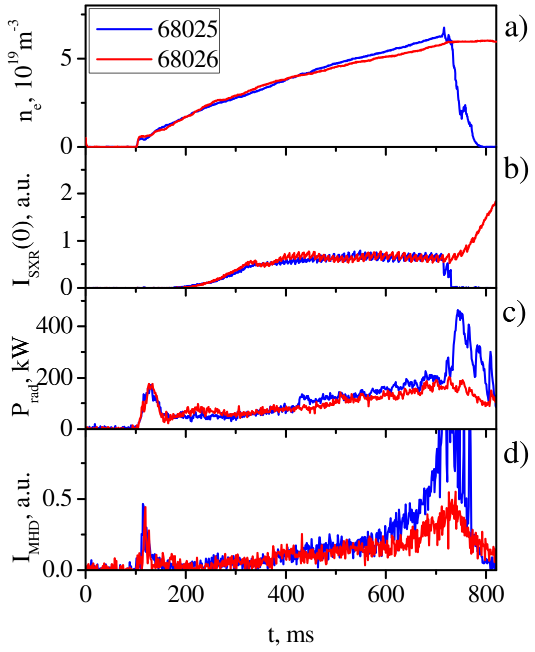

FIG. 2 Evolution of line average plasma density (a), SXR emission measured along the central chord (b), total radiation losses (c) and magnetic field perturbation with m=2 (d) for shot with high gas-puffing up to the density limit (68025) and with the decreased gas-puffing rate at the density slightly below the limit value (68026).

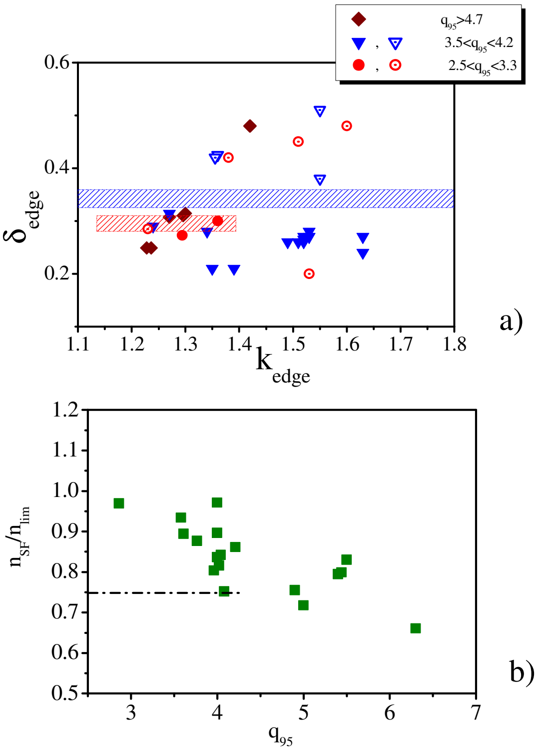

FIG. 3 TCV results. Dependence of the sawtooth stabilization on plasma shape (a). Dependence of the density of sawtooth suppression n_{SF} (as a part of limit density value) on q_{95}. Open points - discharges without sawtooth suppression up to the density limit, closed points – discharges with sawtooth suppression at the density below the density limit.

4. Plasma confinement. Energy confinement time has been analysed in vicinity of the critical density value in all regimes under discussion. In both machines energy confinement time, τ_E, rises linearly with the density in the low density range. In T-10 τ_E is close to or below the neo-Alcator scaling [4] predictions. In TCV the energy confinement time in the low density range is well above the neo-Alcator scaling predictions. Confinement saturation is observed above some critical value, $n_{LOC\text{-}SOC}$. Comparison of the critical density of LOC-SOC transition with the scaling prediction [4] is given in Figure 4. It is seen that in TCV the critical density value is close to the scaling prediction. Agreement between experimental result and scaling prediction is better for the configuration with positive triangularity. In T-10 experiments the critical density of LOC-SOC transition is close to the scaling predictions in regime with tungsten limiters after lithium coating. In regimes with graphite or tungsten limiters it was lower.

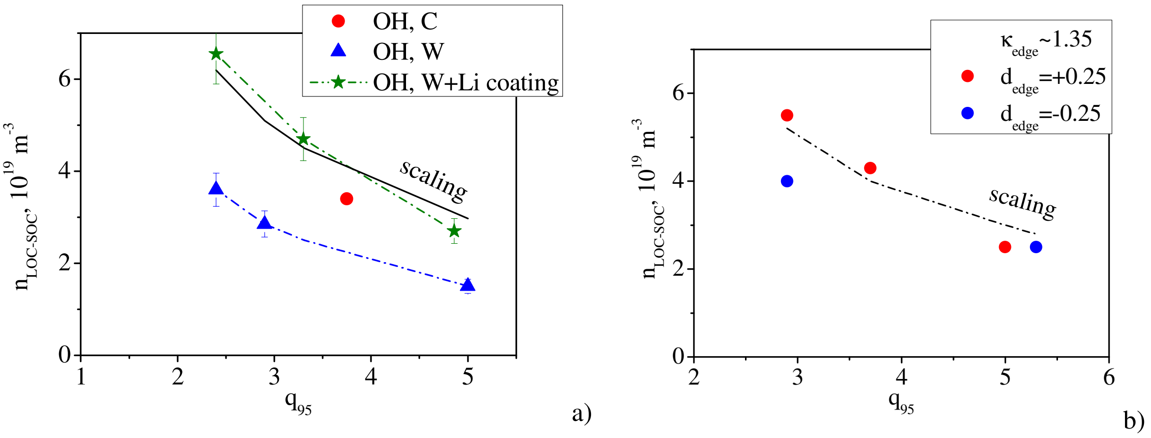

FIG. 4 Dependence of the critical density of the LOC-SOC transition in T-10 (a) and TCV (b) tokamaks.

5. Conclusions. Plasma behavior at high density has been compared in ohmic regimes in TCV and T-10 tokamaks in a wide range of q_{95}. General regularities have been found. The ratio of $(n_e)_{lim}/n_{Gw}$ depends on the q_{95} value in all investigated magnetic configurations and plasma-facing materials. Advantage of the plasma configuration with W limiter and lithium coating is the increase of the maximal achievable density with the factor of 1.3. Sawtooth suppression has been observed at high density leading to impurity accumulation and confinement degradation. Increase of the triangularity and q_{95} value matching the ITER-relevant condition prevents sawtooth stabilization in vicinity of the density limit.

This work was partially carried out in the framework of the Scientific and Technological Cooperation Programme Switzerland Russia and was supported in part by the Swiss National Science Foundation and by ROSATOM State Atomic Energy Corporation (Russia), Contract H.4x.44.9Б.16.1021.

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