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 the high density range is still important to collect 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 the T-10 and TCV tokamaks. Limiter discharges with similar q_{95} values in the range 2.5-6 have been considered. Both machines are medium size tokamaks: the major and minor radii of the TCV tokamak are 0.88 and 0.25 m respectively; the corresponding values of the T-10 tokamak are 1.5 and 0.3 m. The TCV tokamak features 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 different plasma facing materials: graphite, tungsten and tungsten with lithium coating. In all cases ohmic discharges are considered. Discharges with ECRH are added for 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 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 in both negative and positive triangularity cases. Data from both tokamaks demonstrate a clear dependence of the ratio of $(n_e)_{lim}/n_{Gw}$ on q_{95} ($(n_e)_{lim}$ – the limit density value, $n_{Gw}=I_p[MA]/\pi a^2$ – Greenwald limit, q_{95} – edge safety factor value). It is seen that the Greenwald density can be easily reached in high q_{95} discharges. It is important to note that a similar dependence of the $(n_e)_{lim}/n_{Gw}$ on q_{95} has also been reported in T-10 ECRH heated plasmas and has been explained by the effect of the radius of plasma current channel [2].

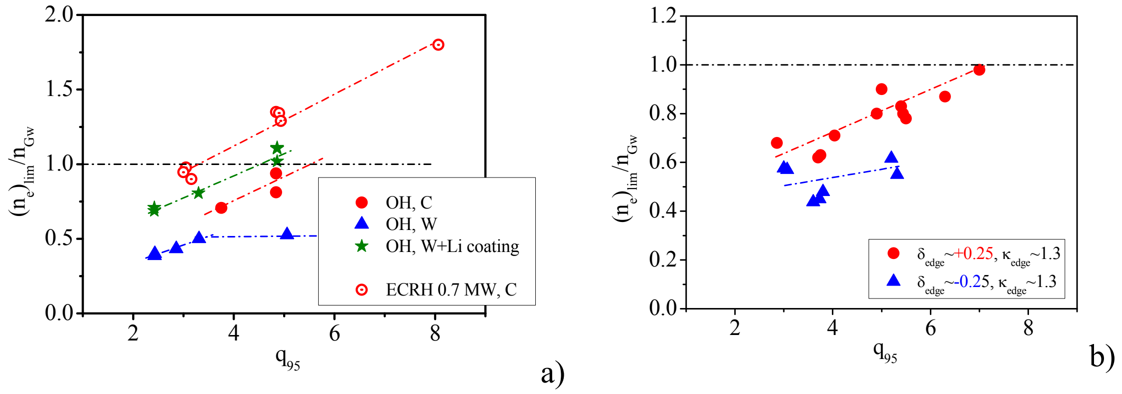

FIG. 1 Dependence of the limit density value on edge safety factor in T-10 (a) and TCV (b) experiments.

The limit density value in limiter configuration depends on the plasma facing material (FIG. 1,a). Li coating leads to an increase of the limit density in the whole q_{95} range. TCV data presented in FIG. 1,b demonstrate the dependence of the maximal achievable density on the plasma triangularity. In elongated plasmas with positive triangularity the value of limit density is ~40% higher than in a similar discharge with negative triangularity.

3. Evolution of sawtooth oscillations. A modification of sawtooth behaviour has been observed in both T-10 and TCV tokamaks at high density [2, 3]. The evolution of two T-10 discharges with different sawtooth behaviour due to a different gas-puffing rate is presented in FIG. 2. The decrease of the gas-puffing rate at high density is accompanied by an increase of soft X-ray emission from the central region (mostly inside of the q=1 zone), an increase of radiation losses from the centre and a change of sawtooth period and amplitude. A positive feedback loop has been proposed to explain the effect [3]: the density increase leads to a temperature decrease in the core, which leads to a current density redistribution, an increase of the sawtooth period, and further density and impurity peaking in the core; this in turn leads to a decrease of the core temperature and further flattening of the plasma current in the core region. The 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 the 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 and q_{95} up to 4.

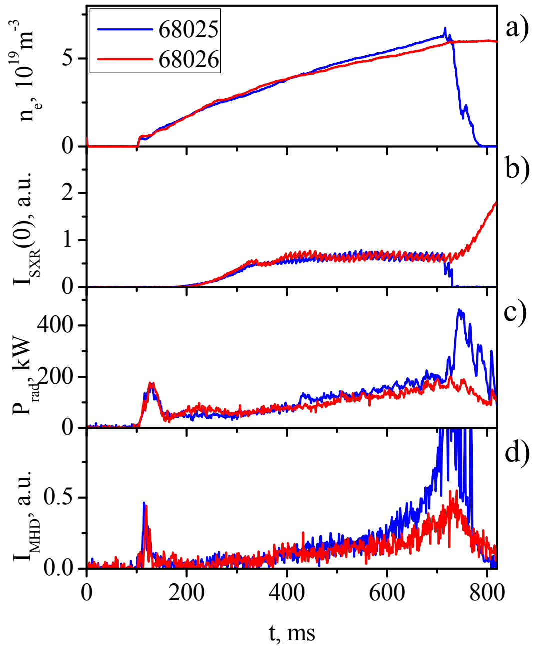

FIG. 2 Evolution of line average plasma density (a), SXR emission measured along the central chord (b), total radiation losses (c) and magnetic field perturbation with m=2 (d) for shot with high gas-puffing up to the density limit (68025) and with decreased gas-puffing rate at the density slightly below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

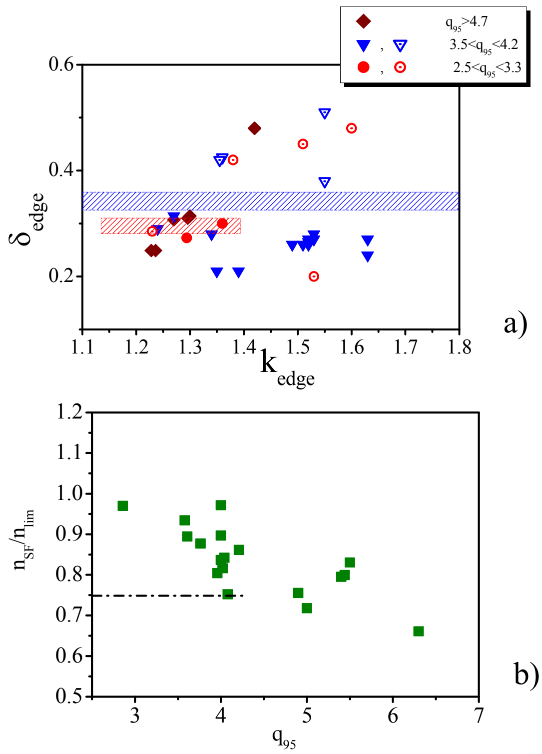

FIG. 3 TCV results. Dependence of the sawtooth stabilization on plasma shape (a). Dependence of the density of sawtooth suppression n_{SF} (as a fraction of the limit density value) on q_{95}. Open points - discharges without sawtooth suppression up to the density limit, closed points – discharges with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

4. Plasma confinement. The energy confinement time has been analysed in the vicinity of the critical density value in all regimes under discussion. In both machines, the energy confinement time, τ_E, rises linearly with 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, $n_{LOC\text{-}SOC}$. A comparison of the critical density for the LOC-SOC transition with the scaling prediction [4] is shown in FIG. 4. It is seen that in TCV the critical density value is close to the scaling prediction. Agreement between experimental results and scaling prediction is better for the configuration with positive triangularity. In T-10 experiments the critical density for the LOC-SOC transition is close to the scaling predictions for the regime with tungsten limiters after lithium coating. In regimes with graphite or tungsten limiters it is lower.

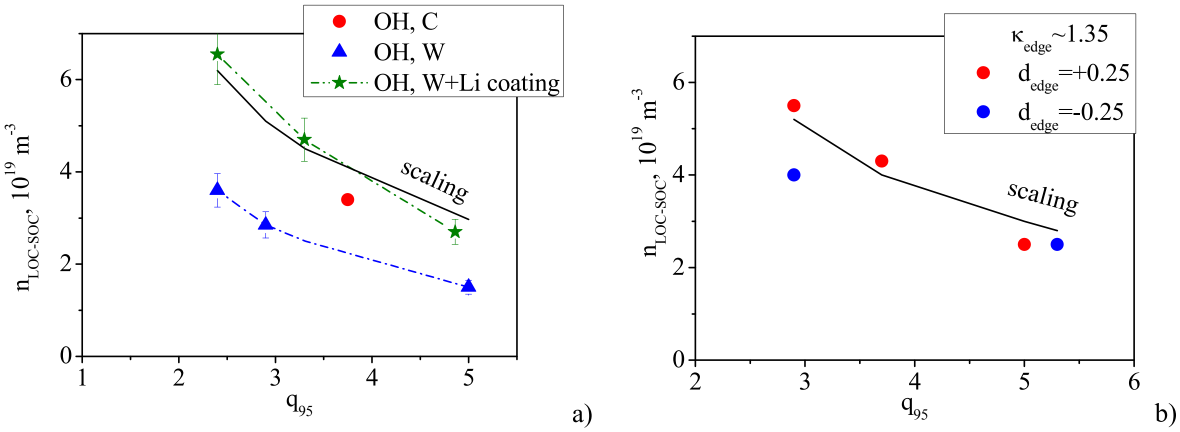

FIG. 4 Dependence of the critical density for the LOC-SOC transition in the T-10 (a) and TCV (b) tokamaks. Scaling is shown by black solid line.

5. Conclusions. The plasma behavior at high density has been compared in ohmic regimes in the 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, which means that the density limit has a weaker than linear dependence with plasma current and is near the Greenwald limit at small plasma current. An advantage of the plasma configuration with W limiter and lithium coating is the increase of the maximal achievable density by a factor 1.3. Sawtooth suppression has been observed at high density leading to impurity accumulation and confinement degradation. Increasing the triangularity and decreasing q_{95} to the ITER values prevents sawtooth stabilization in the vicinity of the density limit.

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