Density Limit Experiments on FTU

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Abstract:
One of the main problems in tokamak fusion devices concerns the capability to operate at high plasma density, which is observed to be limited by the appearance of catastrophic events causing loss of plasma confinement. The commonly used empirical scaling law for the density limit is the Greenwald limit, predicting that the maximum achievable line-averaged density along a central chord depends only on the average plasma current. The aim of this work is to present the results of dedicated density limit experiments performed on the Frascati Tokamak Upgrade (FTU) in which the high density domain was explored in a wide range of values of plasma current ($I_p = 500 - 900$ kA) and toroidal magnetic field ($B_T = 4 - 8$ T). These experiments confirm the edge nature of the density limit, as a Greenwald like scaling holds for the maximum achievable line-averaged density along a peripheral chord. However, when the central line-averaged is considered, the dependence of the density peaking on the edge safety factor, associated to the presence of MARFEs, give rise to a new density limit scaling law in which the central line-averaged density is solely dependent on the toroidal magnetic field. The behaviour of the density limit with the magnetic field in presence of pellet injection and with strong lithium coated wall will be studied in FTU in the next future, possibly including lower magnetic field discharges.

1 Introduction

In tokamak fusion devices it is of great interest to operate at high plasma density, which is observed to be limited by the appearance of catastrophic events causing of plasma disruption [1, 2]. In 1988 Greenwald and co-workers [3], analysing data from many ohmically heated tokamak experiments, obtained an experimental limit for the maximum line-averaged density (expressed in units of $10^{20}$ particles m$^{-3}$) given by $\tilde{n}_G = I_p/\pi a^2$ for an

\textsuperscript{*}See Appendix of P. Buratti et al., paper OV/P-01, this Conference.
elliptical plasma cross section with minor radius \( a \) (in m), where \( I_p \) (in MA) is the plasma current. In this paper we will present the study of the density limit on the Frascati Tokamak Upgrade (FTU) in ohmic discharges fuelled with gas puffing, where the Greenwald limit is regularly exceeded for high values of the edge safety factor \( q_{cyl} \). Such study has shown that actually the density limit has a clear dependence solely from the toroidal magnetic field for all the plasma current values. The reason of this behaviour must be searched in the increase of the density profile peaking factor with the \( q_{cyl} \), confirming that edge density is a better parameter to describe the density limit [4].

2 Experimental Results

In order to understand why high \( q_{cyl} \) discharges routinely exceed the Greenwald limit in FTU (circular cross section, metallic first wall, \( R_0 = 0.935 \) m, \( a = 0.28 \) m), some dedicated density limit experiments were performed, in which the high density domain was explored in a wide range of values of plasma current \( (I_p = 500 - 900 \) kA) and toroidal magnetic field \( (B_T = 4 - 8 \) T). For 15 different \( (I_p, B_T) \) configurations we performed a discharge where a continuous gas flow was injected into the plasma to produce an increasing density up to the disruption for density limit. All discharges considered here had gas puffing and ohmic heating only and were performed under clean machine conditions (typically \( Z_{eff} = 1.0 - 1.5 \)).

\[ \text{FIG. 1: Time traces of some relevant quantities for a specific discharge with } B_T = 7.2 \text{ T and } I_p = 700 \text{ kA: (a) toroidal magnetic field, (b) plasma current, (c) line-averaged density at } r/a = 0, 0.8, (d) temperature at } r/a = 0, 0.8. \]
FIG. 2: Line-averaged density for a central chord \((r/a = 0)\) at the disruption versus the plasma current density. Different colors are used for different \(I_p\) and different symbols are used for different \(B_T\) (see box on the figure). The solid line corresponds to the Greenwald density limit \(\bar{n}_G\).

FIG. 3: Line-averaged density for a central chord \((r/a = 0)\) at the disruption versus the toroidal magnetic field. Different symbols are used for different \(B_T\) and different colors are used for different \(I_p\) (see box on the figure). The solid line corresponds to the new scaling law \(\bar{n}_{\text{new}}\).

In FIG. 1 the time traces of some relevant quantities are reported for a specific discharge with \(B_T = 7.2\) T and \(I_p = 700\) kA: (a) toroidal magnetic field, (b) plasma current, (c) line-averaged density at \(r/a = 0, 0.8\), (d) temperature at \(r/a = 0, 0.8\). As we can see, starting from \(t = 0.5\) s there is a peaking of the density profile, as evidenced by the strong change seen on the central chord of the interferometer while the value of the peripheral chord remain almost unchanged: we will see that the density profile effect plays a crucial role in the determination of the density limit scaling law. The results of this experimental campaign are summarized in FIG. 2 and FIG. 3, where the line-averaged density for a central chord at the disruption is reported versus the plasma current density and the toroidal magnetic field respectively. As we can see, the data show a substantial independence of the maximum achievable central line-averaged density on the average plasma current density, while we find a more than linear dependence on \(B_T\). In particular, the best fit of the values of density corresponding to the disruption (expressed in unit of \(10^{20}\) particles \(\text{m}^{-3}\)) as a function of \(B_T\) (in T) is given by \(\bar{n}_{\text{new}} = 0.19 \times B_T^{1.5 \pm 0.1}\).

In FTU, at high density operation, the MARFE (Multifaceted Asymmetric Radiation From the Edge) [5-7] is always observed for density above a certain threshold depending on \(I_p\). This phenomenon is a radiative thermal instability of the edge plasma characterized by a toroidally symmetric and poloidally asymmetric belt of high density, strongly radiating, cold plasma localized at the high field side of the tokamak, with short poloidal and radial extent. From the complete dataset we have seen that the central line-averaged density at the MARFE onset, as measured by a dramatic increase of the \(D_a\) emission, is a linear function solely of the plasma current density (i.e. the MARFE occurs at a given
fraction of the Greenwald limit), in agreement with the usually observed scaling [8]. The density at the MARFE onset as measured by the $D_a$ emission (solid symbols) and by the interferometer (open symbols) is reported in FIG. 4 versus the plasma current. As we can see, the effects of the MARFE on the interferometer are visible at densities greater than that ones characterizing the increase of the $D_a$ emission, i.e. after the MARFE is more developed. In particular, the discharges with lower values of $q_{cyl}$ disrupt before the appearance of MARFE on the interferometer.

**FIG. 4:** Central line-averaged density at the MARFE onset versus the plasma current, as measured by the $D_a$ emission (solid symbols) and by the interferometer (open symbols). The discharges with lower values of $q_{cyl}$ disrupt before the appearance of MARFE on the interferometer.

From a closer inspection of the data, it turns out that the density peaking, obtained as the ratio between the central density and the volume-averaged density, is approximately constant at the onset of the MARFE. However, after the onset of the MARFE, with increasing density there is a spontaneous peaking of the density profiles, and the values of the density peaking at the disruption for density limit strongly depend on the edge safety factor $q_{cyl}$ (see FIG. 5). This behavior can help explaining the reason why the Greenwald density limit is exceeded in our data for high values of $q_{cyl}$ (see FIG. 2) and suggests that the edge density may be the actual limiting parameter as it influences directly the radiated power at the edge. In the following analysis, instead of the edge density we have considered the edge line-averaged density as measured by the interferometer vertical chord passing at $r/a \simeq 4/5$, as it is a direct measurement and is less affected by elaboration artefacts.
FIG. 5: Density peaking at the onset of the MARFE (open symbols) and at the disruption for density limit (solid symbols) as a function of \( q_{\text{cyl}} \), for discharges with different \( B_T \) and \( I_p \) (see box on the figure for the meaning of symbols and colours). The lines reported on the plot are only guides for the eyes.

Using the edge line-averaged density, both values corresponding to the onset of the MARFE and to the disruption for density limit recover the linear dependence from the plasma current density and therefore we can define an "edge Greenwald limit", \( \bar{n}_{\text{Gedge}} \approx 0.35 \times (I_p/\pi a^2) \) (see FIG. 6). On the other hand, when the central line-averaged density is considered, the density profile effect plays a crucial role in the determination of the density limit scaling law, providing a new scaling in which the central line-averaged density is solely dependent on the toroidal magnetic field (see FIG. 3). It is worth mentioning that the new scaling law found for the density limit on FTU implies a favorable scaling for large values of \( B_T \); for example, for a plasma current of 500 kA, according to the new scaling law \( \bar{n}_{\text{new}} \), FTU is able to operate at central line-averaged densities up to \( 4.3 \times 10^{20} \) particles m\(^{-3} \) (for \( B_T = 8 \) T), which is twice the value expected from the standard Greenwald scaling law \( \bar{n}_G \).

3 Discussion and conclusions

The Greenwald density limit is exceeded only in presence of a well developed MARFE in all discharges considered in this paper, so that the possibility that the MARFE is itself the cause of the peaking has been considered [6]. In this model, the temperature drop (below 10 eV) in a thick external layer, immediately after the MARFE onset and before
FIG. 6: Line-averaged density for a peripheral chord \((r/a = 4/5)\) at the disruption versus the plasma current. Different colors are used for different \(I_p\) and different symbols are used for different \(B_T\) (see box on the figure). The solid line corresponds to the edge Greenwald limit \(\bar{n}_{\text{Edge}}\).

the density peaking, increases the transparency of the plasma to neutral particles that can penetrate more deeply into the good-confinement region. The MARFE practically appears to form a channel for the penetration of the neutral particles into plasma deeper layers with an improvement of the gas fuelling efficiency and a consequent increase of the density profile peaking. The dependence on \(q_{cyl}\) is reintroduced by the MARFE dynamic that, being related to the parallel electron thermal conductivity, depends on the connection length in the scrape-off, \(l = 2\pi R_0 q_{cyl}\). It is to be noted that the analysis of particle flux in similar discharges [9], carried out by means of gyro-kinetic code (GWK), has found that a possible additional mechanism for density peaking is an increase of the particle pinch due to the presence of light impurities. The behaviour of the density limit with the magnetic field in presence of pellet injection and with strong lithium coated wall will be studied in FTU in the next future, possibly including lower magnetic field discharges.

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References


