Effect of magnetic field on density limit in FTU

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Introduction

Greenwald limit is an empirical law that has been originally found in plasmas fuelled by gas puffs and states that the maximum line averaged that can be obtained in tokamak plasmas is given n_G~kJ [1] (where k is the plasma elongation and J the averaged plasma current density) . This limit, however, has been exceeded when different fuelling methods as pellet injection [2], mainly due to the change of the peaking of the density profiles. Using the edge density instead of the line averaged one, a limiting density can be recovered even for strongly peaked profiles[2].

In present FTU experiments, line-averaged density in high-q ohmic discharges with gas puff only, can systematically exceed the Greenwald limit, while for low-q discharges this limit can only be approached. This behaviour seems to be due to the presence of MARFE [3], that appear at a fixed fraction of Greenwald limit in almost all the discharged considered here.

In order to have a more clear and detailed frame of the experimental data, a dedicated campaign has been done in 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), for a total of 15 different (I_p, B_T) configurations. FTU is a compact high field tokamak with a circular cross section (Ro=0.935m, a=0.3 m) and a toroidal molybdenum limiter that covers the vacuum vessel at the high field side. Oxygen level is kept low by coating the wall with boron. Recently, a liquid Lithium limiter has also been inserted and it has been used for wall conditioning. Boron and Lithium wall conditioning produces very clean deuterium plasma (typically $Z_{eff} = 1.0 - 1.5$). All discharges considered here had gas puffing and ohmic heating only. Disruptions have been obtained by a continuous gas flow in the plasma current flat top.

Experimental results

A set of 15 discharges has been made with continuously increasing density till a disruption has been obtained. Magnetic field and current have been selected in order to have scans at fixed currents (that should have all the same Greenwald limit) and scans at fixed magnetic field. All discharges have $Z_{eff}<1.5$. The magnetic fields and currents and corresponding cylindrical safety factor of these discharges are listed in table I.

Table 1

I_P(MA) B_T(T)	0.5	0.7	0.9
4.0	$q_{cyl}=3.4$	$q_{cyl}=2.4$	$q_{cyl}=1.9$
5.2	4.4	3.1	2.4
6.0	5.0	3.6	2.8
7.2	6.0	4.3	3.4
8.0	6.7	4.8	3.7

The density at the disruption is shown in the usual Hugill plot (fig 1) where the expected Greenwald limit is also drawn. It can be seen that only few discharges are in agreement with the predicted limit. Discharges with high q_{cyl} tends to have a higher density limit, whilst discharges at very low q_{cyl}, disrupt before the expected limit.

When the line central density at the limit is plotted versus the magnetic field (fig 2) the data spread reduces enormously. A best fit gives $n_{lim} = 0.19\times B_T^{1.5\pm0.1}$. This behaviour is associated with an increase of the density profile peaking with q_{cyl}. Actually, MARFE highly affects density profiles that tend to become more peaked at high q (see next section). The global effect is to cancel the dependence of the limiting density from the current introducing a dependence on B_T.

A different picture arises when considering the edge density (line averaged at r/a~0.8) at the disruption instead of the central (along the plasma diameter) line average, in fact, the former increases linearly with the current (as it is for the Greenwald limit) and shows no dependence on B_T. So, we can confirm that the density that limits the plasma operations is the edge one[2] and that it scales with the plasma currents density.

Effect of MARFE on density

In FTU present plasma facing configurations (with Molybdenum toroidal Limiter and wall conditioned with Boron or Lithium), the formation of MARFEs occurs in almost all discharges with sufficiently high density, with an impact on plasma characteristics that depends on edge safety factor and density [4,5].

MARFE is a poloidally asymmetric edge thermal instability, caused by the reduced parallel electron conductivity, that prevents the energy from redistributing along the flux surface, and let the formation of local cold regions with strong line emission, in the low field side where the heat flux from the core is lower. In fig 3, the evolution of temperature (a), density (b), its peaking factor(c) and Bremsstrahlung(d) is reported. The abrupt emission observed Bremsstrahlung is the marker that the MARFE has formed; this typically occurs after the edge temperature (r/a~0.8) has dropped to few eV. Afterwards, the MARFE develops, increasing its poloidal extension and the density in the plasma core start to increase, with a consequent increase of the density peaking factor (fig 3c) that continue to increase till the disruption[5]. Density and temperature in the annular ring remains strongly asymmetric, forming a dense cold plasma at the high field side, that oscillates rapidly in the poloidal direction modulating density and Bremsstrahlung. The global effect on density profile is an increase of the peaking ($n_e(0)/<n_e>_{vol}$), as the volume density increases less due to the unchanged background density in the region where the MARFE is located. The density at which the MARFE appears in FTU is a fixed fraction (0.4) of the Greenwald density limit, and profile peaking at this time do changes slightly with q_{cyl}, whist the peaking before the disruptions has a strong variation with q_{cyl}, from 1.5 at $q_{cyl} = 2$ to 3 at $q_{cyl}=7$ (fig 4). As said before, this dependence is the cause of the different scaling low on the central line averaged density with the current and magnetic field.

Conclusions

A density limit that depends on the magnetic field only has been found in FTU, in presence of MARFE, in clean plasma conditions ($Z_{eff}<1.5$). This dependence is similar to the so-called "Murakami limit" [6], where the limit is scaling as B_T/R, but it has a stronger dependence on B_T ($n_{lim} = 0.19 \times B_T^{1.5}$). Actually, as the authors states [6], the "Murakami limit" was obtained on a set of discharges with the same edge safety factor ($q_a=5$), so it was impossible to discriminate between the dependence on I_P or B_T, the authors used this fact to claim the true limit depended on the current (total input power). In the past, FTU has had density limit not dependent on the plasma current [2], due to the fact that the plasma was contaminated by carbon and oxygen, but this limit was below the usual Greenwald one, and was extended injecting deuterium pellets in the plasma. In the present experiments the plasma was clean and Greenwald limit has been passed with gas puffing only.

In our program, we plan to inject pellets in the already peaked density profiles, in order to understand if higher density limit can be obtained. However, plasma can bear pellets better at high current where the peaking effect of the MARFE is small, so that a compromise must be found working at high field. It would be also interesting to apply auxiliary heating in this discharges but both FTU system (LH and ECRH) have small effects at such density and most of the plasmas here considered would be centrally overdense for the 140 GHz frequency, preventing the ECH.

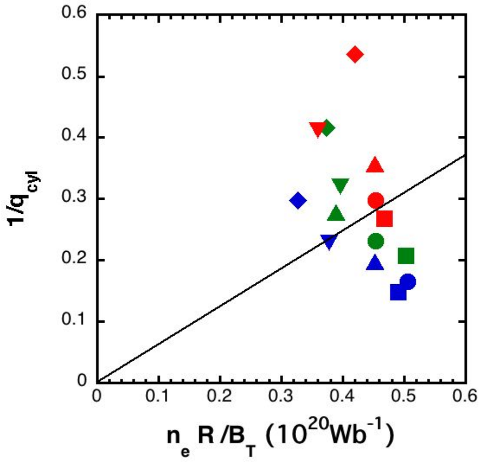

Figure 1: *Hugill plot of FTU discharges at the density limit. Different symbols represent different magnetic field, whilst currents are represented with colors.*

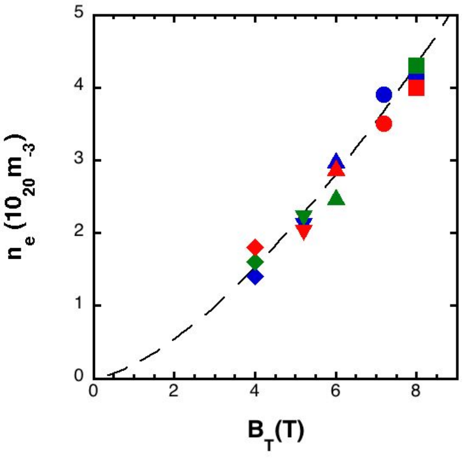

Figure 2: *Central line averaged density at the disruption versus the toroidal magnetic field.*

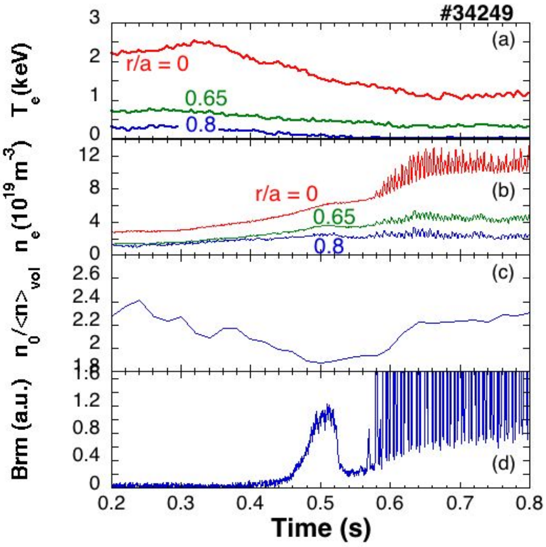

Figure 3: *Time traces of some relevant quantities at the MARFE appearance. a) temperature at r/a=0,0.65 and 0.8, b) line density at the same radial position, c) peaking factor of density profile, d)Bremsstrahlung in a vertical chord (no. 3) looking at the high field side*

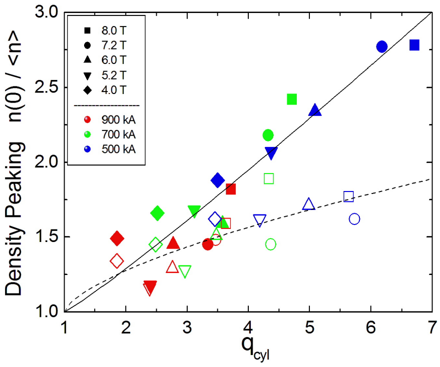

Figure 4 : *Density peaking factor at the MARFE appearance (open symbols) and at the disruption (full symbols).*

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