Density limit studies in the tokamak and the reversed-field pinch

G. Spizzo, G. Pucella[1], O.Tudisco[1], M. Zuin, M. Agostini, F. Auriemma, P. Buratti[1], L. Carraro, R. Cavazzana, G. Ciaccio, G. De Masi, C. Galperti[2], G. Granucci[2], M. Marinucci[1], L. Marrelli, E. Martines, C. Mazzotta[1], A. Moro[2], M. E. Puiatti, P. Scarin, C. Sozzi[2], M. Spolaore, O. Schmitz[3], N. Vianello, and R. B. White[4]

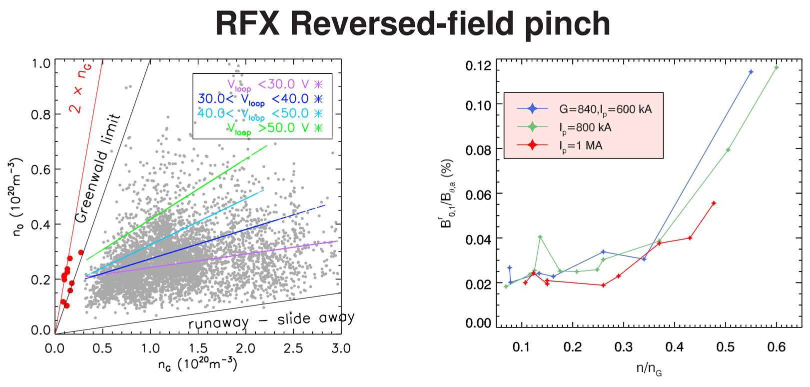
Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, Corso Stati Uniti 4, 35127 Padova, Italy
[1]ENEA, Centro Ricerche di Frascati, Italy
[2]IFP-CNR, Via R. Cozzi 53, 20125 Milano, Italy
[3]Department of Engineering Physics, University of Wisconsin - Madison (USA)
[4]Plasma Physics Laboratory, P.O.Box 451, Princeton, New Jersey 08543 (USA)

Introduction

The ITER scenarios and the project of DEMO [1] involve stable operation above the Greenwald density [2], which justifies efforts to understand and overcome the density limit, observed as a disruptive termination of tokamak discharges [3] and a thermal crash (with no disruption) of stellarator and reversed-field pinch (RFP) ones [4]. Both in the tokamak and the RFP, new finds show that the high density limit is not governed by a unique, theoretically well-determined physical phenomenon, but by a combination of complicated mechanisms involving the strength of the magnetic field $\vec{B}$ [5], electrostatic plasma response to magnetic islands [6] and plasma-wall interaction [7]. In this paper we will show new evidence challenging the traditional picture of the "Greenwald limit", in particular with reference to the role of thermal instabilities and the edge radial electric field E^r in the development of this limit.

1. Phenomenology of the Density Limit

RFX Reversed-field pinch



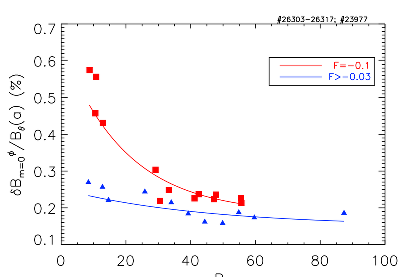
In the RFX RFP, data points in the plane (n_G, n_0), with n_0 the central density, seem to follow a Hugill-Greenwald scaling, with scarce data points for $n_0 > n_G$, as published several times in the past [4] – no disruptions

The straight lines in the plot correspond almost exactly to curves at constant V_{loop}, with $V \approx 13 + 190\, n/n_G$

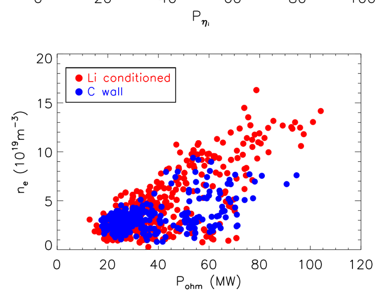
No real Greenwald limit is present

Instead, by increasing density we destabilize the $m/n = 0/1$ mode, which is responsible for the development of a MARFE

Threshold for the destabilization $n_0 \sim 0.35\, n_G$

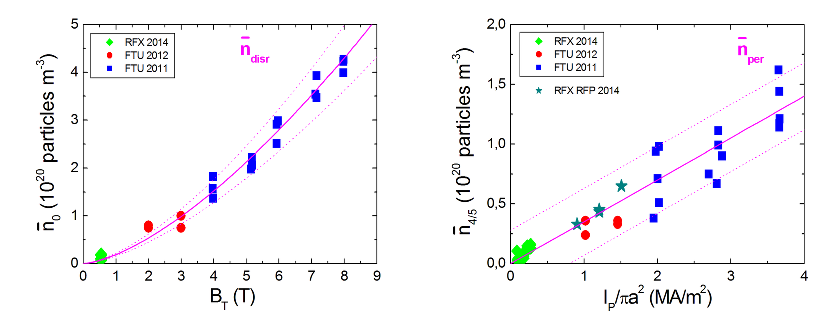


The threshold $n_0 = 0.35 n_G$ has been recently put into relationship with a threshold in Prandtl number, $P \sim 30$ [8]



Once the threshold is crossed, density depends on input power and wall conditioning [7]

FTU and RFX Tokamaks



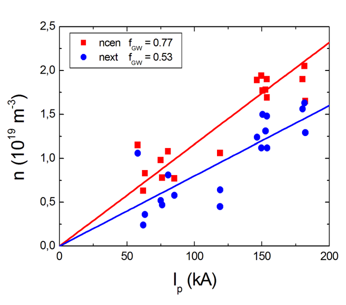
In the FTU tokamak a Greenwald-like scaling $n_{edge} \sim 0.35\, n_G$ holds for the edge density $(r/a = 0.8)$

Instead, the core density follows a Granetz-like [9] scaling $n_0 \approx B^{1.5}$ with the magnetic field [5]

The dependence on $|\vec{B}|$ is lost in the original 1988 Greenwald paper! In the Hugill plane (safety factor vs Murakami parameter [10])

$$\frac{1}{q_a} \propto n_c \frac{\mu_0 R}{2B} \rightarrow n_c = \frac{I_p}{\pi a^2}$$

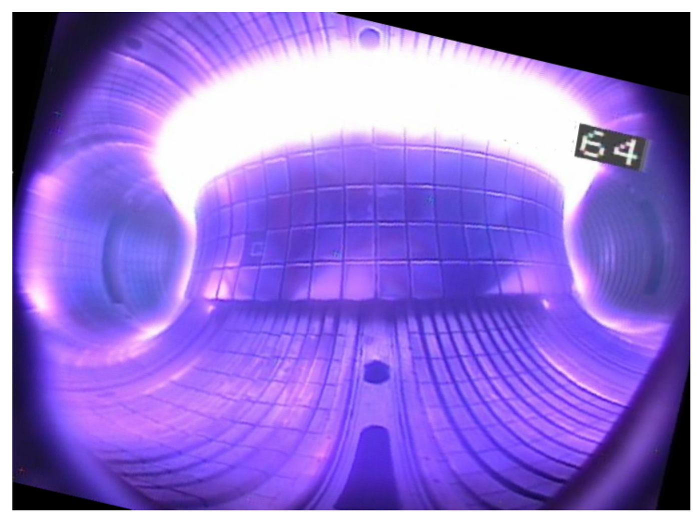
The scaling with $|\vec{B}|$ is followed also in the RFX device, operated as a tokamak [8]

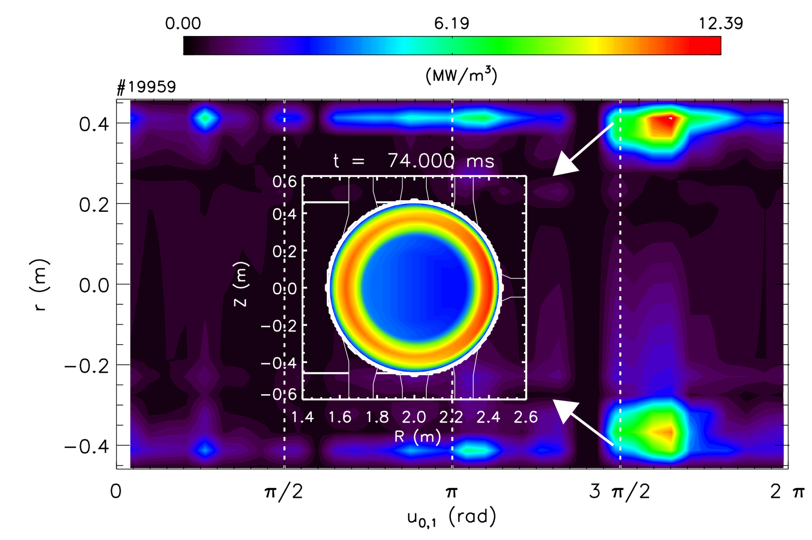


In the RFX tokamak the core density n_0 follows also a Greenwald scaling, which disappears at large B in FTU

The critical density for the destabilization of the $0/1$ mode in RFX operated as RFP (MHD threshold) follows the same Greenwald-like scaling of the edge density of the RFX-tokamak and FTU.

2. Role of Thermal Instabilities



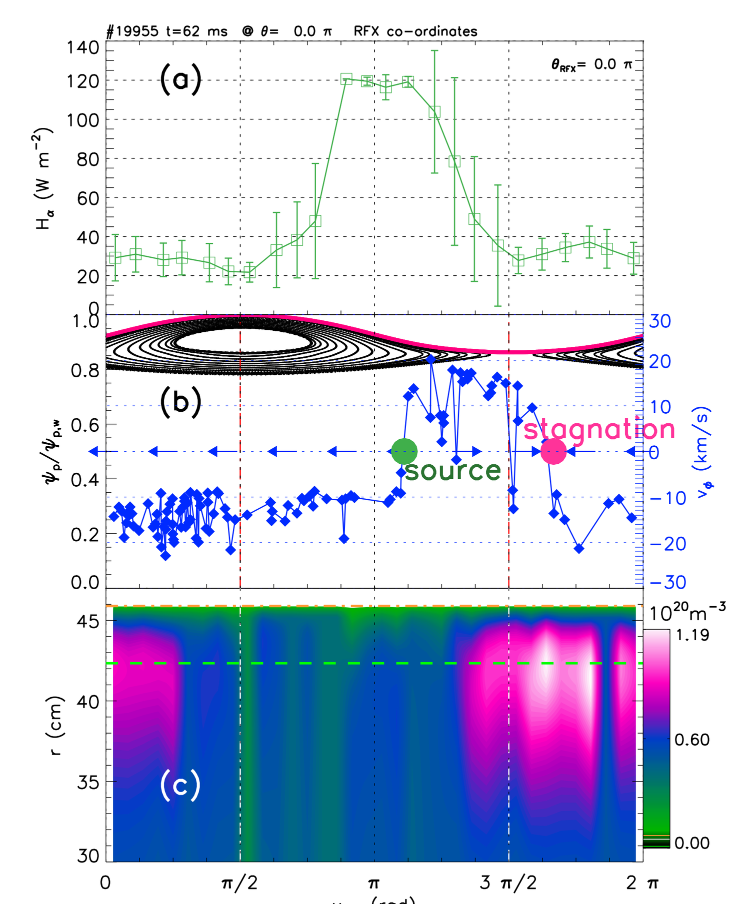


In both FTU (left) and RFX (right) the density limit is associated with the appearance of the multifaceted asymmetric radiation from the edge (MARFE) [11]

In FTU the MARFE = local cold regions at the HFS with strong line emission.
It appears as a toroidal ring, poloidally localized at a threshold $n_0 > 0.4\, n_G$

In the RFX RFP the MARFE appears at $n_0/n_G > 0.7$ as a poloidal ring of high radiation, toroidally localized

MARFE and edge radial electric field E^r



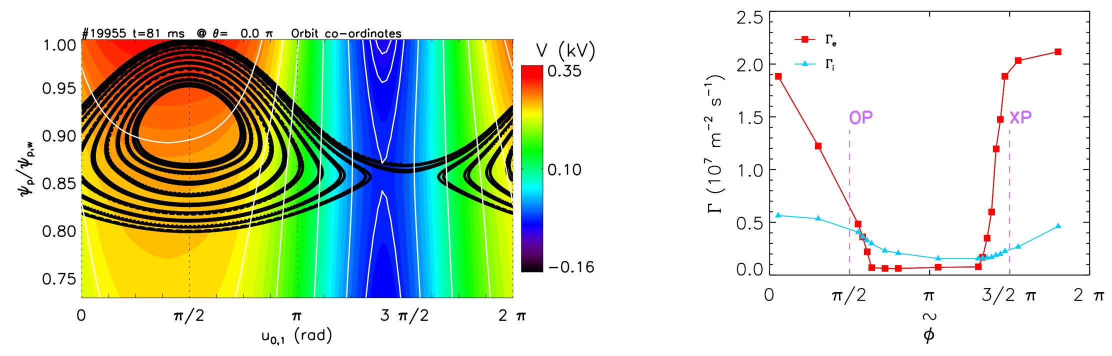
Crucial point: analyses as a function of the helical angle $u_{m,n} \equiv m\theta - n\varphi + \phi$, with ϕ phase of the mode [12].
In the 0/1 case $u_{0,1} = -\varphi + \phi$

- (a) Source = maximum H_α
- (b) The $0/1$ island resonates at $q = 0$ in the RFP edge, and determines a reversal of the flow v_φ = **convective cell**
- (c) The stagnation point corresponds to a very large density, which locally can reach $\sim 1.5\, n_G \rightarrow$ this is the MARFE

Edge measurements in RFX [12] suggest that the association edge island and convective cell (modulation of E^r) is a rather general feature of the RFP ($0/1$ and $1/7$ tearing modes) and tokamak ($2/1$ TM).

Patterns of E^r parent to a $3/1$ island are seen also during application of Resonant Magnetic Perturbations (RMPs) on TEXTOR [13]: this is quite relevant for the topic of ELM suppression [12].

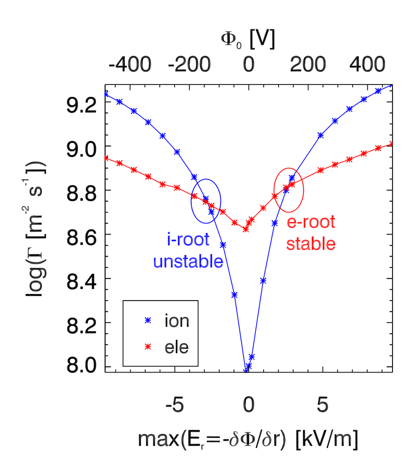
Simulations of the convective cell



The convective cell has been successfully modeled with the guiding-center code ORBIT [14]

It is generated by an ambipolar potential, balancing electron radial diffusion between the OP and XP of the island [15]

Algebraic solution to the ambipolar problem $\Gamma_e = \Gamma_i$ as a function of the potential phase $\tilde{\phi}$ shows two solutions ("roots"): a first one with the potential well at the O-point (OP) of the island, the second one at the X-point (XP).



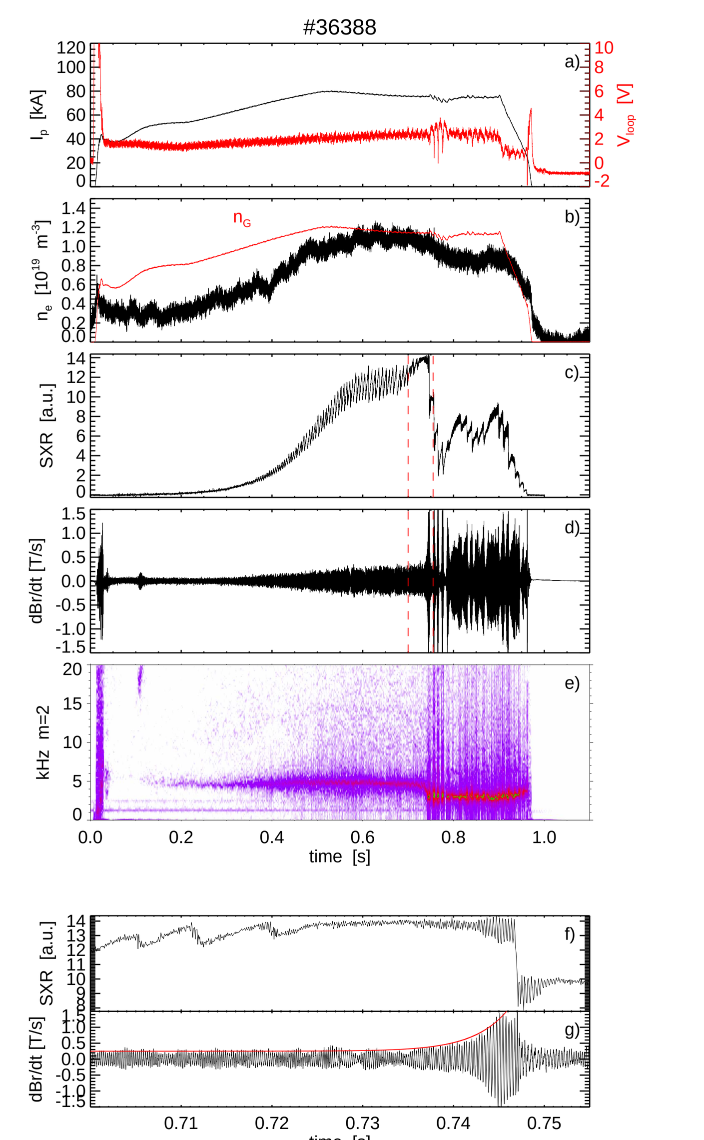
Amplitude scan:
In TEXTOR [13] we followed the stellarator criterion [16] for thermodynamic stability of the root

$$\omega = \frac{e}{\epsilon_\perp}\left(\frac{\partial \Gamma_e}{\partial E^r} - \frac{\partial \Gamma_i}{\partial E^r}\right)\bigg|_{E^r_{amb}} < 0$$

The stable root is that at the XP

This suggests a dependence of the root stability on T_e/T_i

3. Destabilization of MHD Modes



High-density disruptions in FTU are always preceded by a strong 2/1 activity [3].

A compared analysis can be done on both RFX and FTU

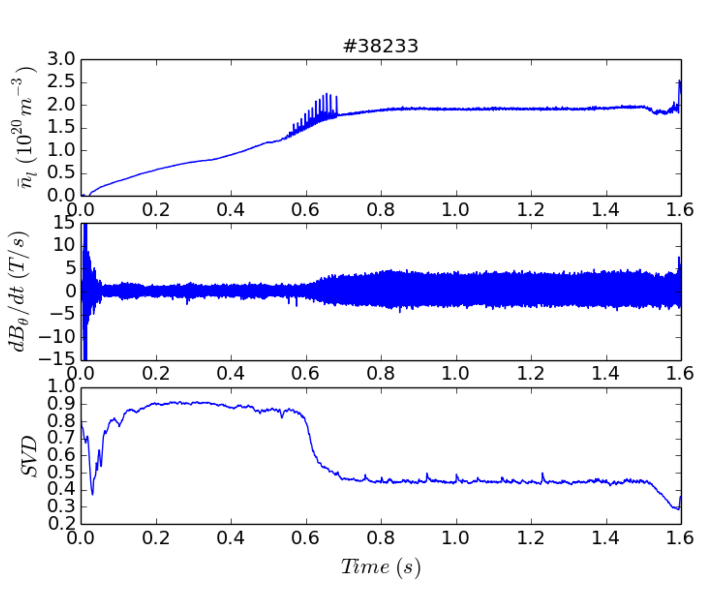
- (a) RFX: Plasma current and loop voltage
- (b) $\langle n \rangle \sim n_G$ at $t \sim 0.6$ s
- (c) SXR crash at $t \sim 0.75$ s, no current quench [see panel a)]
- (d) 2/1 mode amplitude: linear growth, then exponential increase
- (e) rapid braking of the mode at the SXR crash
- (f-g) inset during the final phase: the exponential growth rate is ~ 3 ms.

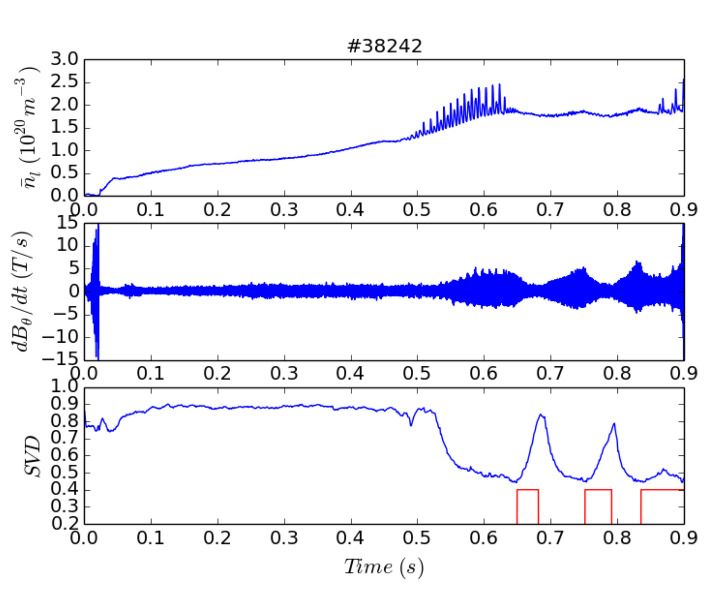
Stabilization of the $2/1$ mode with ECRH at high density

Experiments of real-time control of TM instability using ECRH have been recently done on FTU [see **Sozzi EX-P2-47, this afternoon**], on the wake of results obtained in FTU and ASDEX [17].

Reference discharge (bottom, left): $q_a = 5$, density ramp, $n_0 = n_G$ at the end of the ramp. The $2/1$ onset when $n_0 \sim n_G$ is evident (note that in this type of discharges the B-limit and Greenwald limits coincide).

Controlled discharge (bottom, right): when ECRH is targeted on the $2/1$ resonance, the mode disappears (although, not completely stabilized).





4. Summary & Work in Progress

Summary

- ★ In both tokamak and RFP we see a limit $n_{edge} \sim 0.35\, n_G$
- ★ Core density follows Granetz $n_0 \propto B^{1.5}$ (density peaking)
- ★ In the RFP the density limit is caused by the $\vec{E} \times \vec{B}$ flow (convective cells) associated with the edge $0/1$ island
- ★ also in FTU the $2/1$ TM is destabilized at high density
- ★ The $2/1$ mode can be stabilized by ECRH, which is consistent with an ambipolar mechanism at work

Work in Progress

- FTU: try to produce a density ramp with $n_0 > n_G$ & stabilize the $2/1$ mode with ECRH; measure E^r during suppression
- RFX: investigate the role of q at high density
- Simulation of ECRH heating with ORBIT

References

- [1] H. Zohm, C. Angioni, *et al.*, 2013 Nucl. Fusion **53** 073019
- [2] M. Greenwald, *et al.*, 1988 Nucl. Fusion **28** 2199
- [3] G. Pucella, *et al.*, *Proc. 40th EPS Conference on Plasma Physics*, Vol. 37D, P5.139
- [4] M. E. Puiatti, *et al.*, 2009 Nucl. Fusion **49** 045012
- [5] G. Pucella, O. Tudisco, *et al.* 2013 Nucl. Fusion **53** 023007
- [6] G. Spizzo, *et al.*, 2012 Nuclear Fusion **52** 054015
- [7] M. E. Puiatti, *et al.*, 2013 Nucl. Fusion **53** 073001
- [8] M. E. Puiatti, *et al.*, 2013 Plasma Phys. Control. Fusion **55** 124013
- [9] R. S. Granetz, *et al.*, 1982 Phys. Rev. Lett. **49** 658
- [10] M. Murakami, J. Callen, and L. Berry 1976 Nucl. Fusion **16** 347
- [11] U. Samm, *et al.*, 1999 J. Nucl. Mater. **266–269**, 666
- [12] N. Vianello, *et al.*, 2013 Nucl. Fusion **53** 073025
- [13] G. Ciaccio, submitted to Nucl.Fusion (2014)
- [14] R. B. White and M. S. Chance 1984 Phys. Fluids **27** 2455
- [15] G. Spizzo, *et al.*, 2014 Phys. Plasmas **21** 056102
- [16] D. Hastings, W. Houlberg, and K. Shaing 1985 Nucl. Fusion **25** 445
- [17] B. Esposito, G. Granucci, *et al.*, 2008 Phys. Rev. Lett. **100** 045006

gianluca.spizzo@igi.cnr.it