



HAL
open science

PLASMA-WALL SELF-ORGANIZATION IN MAGNETIC FUSION

Dominique Franck Escande, F Sattin, Paolo Zanca, Jiaxing Liu, Ping Zhu, Junli Zhang, Donghui Xia, Yuhan Wang, Jiaming Wang, Qinghu Yang, et al.

► **To cite this version:**

Dominique Franck Escande, F Sattin, Paolo Zanca, Jiaxing Liu, Ping Zhu, et al.. PLASMA-WALL SELF-ORGANIZATION IN MAGNETIC FUSION. 29th IAEA Fusion Energy Conference (FEC 2023), Oct 2023, Londres (Grande Bretagne), United Kingdom. hal-04208384

HAL Id: hal-04208384

<https://hal.science/hal-04208384>

Submitted on 15 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

PLASMA-WALL SELF-ORGANIZATION IN MAGNETIC FUSION

^{1,2}D.F. ESCANDE, ²F. SATTIN, ²P. ZANCA, ³J.-X.LIU, ^{3,4}P. ZHU, ³J.-L. ZHANG, ³D.-H. XIA, ³Y.-H. WANG, ³J.-M. WANG, ³Q.-H. YANG, ³J.-G. FANG, ³X.-Q. ZHANG, ³L. GAO, ³Z.-F. CHENG, ³Z.-P. CHEN, ³Z.-J. YANG, ³Z.-Y. CHEN, ³Y.-H. DING, ³Y. PAN, and the J-TEXT team

¹Aix-Marseille Université, CNRS, PIIM, UMR 7345, Marseille, France

²Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete Spa), Padova, Italy

³IFPP, Huazhong University of Science and Technology, Wuhan, China

⁴Engineering Physics, University of Wisconsin-Madison, Madison, USA

Email: dominique.escande@univ-amu.fr

Abstract

The paper introduces the theory of plasma-wall self-organization (PWSO) in magnetic fusion and its first experimental check. The basic idea is the existence of a time delay in the feedback loop relating radiation and impurity production on divertor or limiter targets. Both a zero and a one-dimensional description of PWSO *at flat-top* are provided. They lead to an iterative equation whose equilibrium fixed point is unstable above some threshold. This threshold corresponds to a radiative density limit, which can be reached for a ratio of total radiated power to total input power as low as 1/2. When detachment develops and physical sputtering dominates, this limit is progressively pushed to very high values if the radiation of non-target impurities stays low. Therefore, PWSO comes with two basins for this organization: the usual one with a density limit, and a new one with *density freedom*. Two basins of attraction of PWSO are shown to be possible for the tokamak *during start-up*, with the high density one leading to this freedom. This basin might be reached by a proper tailoring of ECRH-assisted ohmic start-up in present middle-size tokamaks using high-Z materials, by mimicking present stellarator start-up. In view of the impressive tokamak DEMO wall load challenge, it is worth considering and checking this possibility, which comes with fulfilling more easily Lawson criterion, and consequently more margins for ITER and smaller reactors. Recent experimental data of the J-TEXT tokamak with Ohmic or ECRH-assisted ohmic start-up confirm that cleaner plasmas provide higher density limits. These limits agree with those predicted from the 0D and 1D PWSO models.

1. INTRODUCTION

The L-mode density limit increases with rising heating power P like $P^{0.4}$ ([1] and five papers published between 1986 and 1999 quoted in the introduction of [2]); figure 10 of [2] shows with a data base of 5 tokamaks that a scaling like $(I.P/a^4)^{4/9}$, with a the small radius and I the total current, organizes much better the data than Greenwald's one in I/a^2 ; especially device per device. This scaling is a part of those derived in [2-4], which are in much better agreement with the tokamak and reversed field pinch (RFP) databases, and apply to the stellarator too [2,4,5]. They describe the density limit as the loss of power-balance due to excessive radiation, and therefore include naturally a clear explicit dependence on P .

Having a basic character, this *power balance density limit* might be considered as the 'ultimate radiative density limit'. The loss of power-balance can be reached for R/P as low as $1/2$ [3]. This is important to notice, since the fact that the density limit is not always associated with a very high radiated fraction was used as an argument against the radiative origin of this limit [6]. Reference [7] shows that translating the scaling of [2] in terms of separatrix density limit makes the scaling work as well for the H-mode density limit in ASDEX Upgrade. The power balance density limit was found to correspond to the threshold for the occurrence of non-monotonic temperature profiles [3]. Such a threshold had been found previously as that where the temperature profile becomes unstable with Bessel-like oscillations [8].

A large part of the radiative density limit comes from the radiation of impurities [2-4]. Their amount is governed by plasma-wall interaction. A self-consistent description of this interaction was proposed in [9] with the introduction of the concept of plasma-wall self-organization (PWSO). This paper introduces the corresponding theory and its first experimental check [10].

2. THEORY

2.1. Basics of plasma-wall self-organization

The basic idea of PWSO theory [9] is that there is a time delay in the feedback loop relating impurity radiation and impurity production on divertor/limiter plates. Both zero and one-dimensional descriptions of *flat-top* lead to a delay equation whose simplest expression is

$$R^+ = \alpha (P - R) \quad (1)$$

where P is the total input power in the plasma, R is the total radiated power, and R^+ is its delayed value, where

$$\alpha = \frac{f l}{a D T'} I(T') \int_0^a n(r) \text{Rad}[T(r)] dr \quad (2)$$

where $n(r)$ and $T(r)$ are respectively the density and temperature profiles, D is the perpendicular diffusion coefficient, T' is the plasma temperature at the target plate location, f is the fraction of the sputtered atoms that reach the main plasma and become ionized at a distance l inwards from the plasma target location, $\text{Rad}[T]$ is the impurity radiation rate coefficient, and $I(T')$ is an average of the yield function of the target material over the energies of the impinging particles. The coefficient α quantifies the delayed radiation power R^+ generated by the impurities produced from the plasma-wall interaction; the amount of these impurities is proportional to the outflow power (P-R) onto the wall targets.

The fixed point of equation (1), $R = R^+$, corresponds to the plasma-wall self-organization equilibrium. Close to the threshold, R oscillates about the equilibrium below and above threshold. Section 5 of [9] provides experimental hints of the oscillating instability in the literature. Equation (1) shows this equilibrium is unstable for $\alpha > 1$. Therefore, the threshold $\alpha = 1$ defines a *radiative density limit*

$$n^* \sim \frac{D T'}{f l \text{Rad}[T^*] I(T') a^*} \quad (3)$$

at the radius with temperature T^* where $\text{Rad}[T]$ is maximum; a^* is the radial width of $\text{Rad}[T(r)]$. Section 4.1 of [9] shows this limit can be reached for a ratio of total radiated power to total input power as low as $1/2$. This section showed that such a threshold was compatible with present density limits with both carbon and tungsten targets. Several scaling laws of the L-mode density limit in tokamaks display a favourable power dependence [7], in particular that in [2,3,4]. However, for ASDEX Upgrade a naive extrapolation of these scalings raises false expectations for reaching higher density limits [7]. Since the limit (3) has no obvious scaling with the power, it might be a limiting factor when the power is increased.

If there is detachment, the plasma temperature at the plates decreases, as well as $I(T')/T'$, since sputtering does too. This pushes the radiative density limit (3) to a very high value, especially when physical sputtering dominates the contribution to radiation. As a consequence, there are two basins of PWSO at the flat top of plasma current. The usual one is the regime of density limit corresponding to the higher temperatures of targets, whereas the other is a *regime of density freedom* corresponding to the lower temperatures of targets, in particular in machines where the target plates are made of high-Z materials, since physical sputtering decreases strongly with the plate temperature.

This freedom might be reached by plasma detachment at high density, which would come with a low target temperature, where the whole input power would be radiated in the SOL by neutrals. Then, neutral radiation would be produced very close to the targets where recycling is occurring. This would make irrelevant the finite distance and time delay, which are essential in the iterative model, and no unstable feedback would be present.

Such a freedom is more likely to be obtained, if the plasma is set at a high enough density at the end of start-up. The maximum possible density at this moment is bounded by the amount of impurities, which are produced during start-up. This amount is high for the traditional ohmic start-up of the tokamak, which is performed at low density. This sets the system in a vicious circle where a low density limit prevents reaching the high densities enabling detachment. To the contrary, a high density during start-up might trigger a virtuous circle enabling it. These vicious and virtuous circles are two basins of attraction corresponding to *start-up*.

2.2. PWSO models

The theoretical assumptions are now made more precise. The time delay between R and R^+ is made of (i) the finite time of flight of sputtered atoms to reach the ionization position, (ii) the diffusion/propagation time for impurities to produce their full radiation, (iii) the diffusion/propagation time for heat from the impurities to the targets. The simplest version of the iterative model for radiation considers R as due only to the total radiation due to target impurities.

The 1D model makes more explicit the physical mechanisms underlying the 0D one. It uses a slab model describing the radial direction of the plasma. It couples an impurity transport equation and a heat transport equation, which are respectively of the kind used in the Engelhardt and Feneberg [11], and in the Zanca et al. [2,3,4] models. These equations decouple below threshold. Then, the self-consistency of impurity and heat transport can be neglected and a thermal equilibrium can be computed by the Power Balance Model [2,3,4]. If the plasma-wall system is in the basin of density freedom defined by PWSO, then this freedom is kept by this model, since the radiation of target impurities vanishes.

The simplest model (1) can be refined by accounting for other contributions to PWSO. In particular, there may be more radiation than that due to target impurities, especially with impurity seeding. For instance, neutral particles

can be strong contributors. This can be taken into account by adding a constant term in the right hand side of Eq. (1). This modifies the simple iterative model, but keeps its main features: fixed point unstable for $\alpha > 1$ and with $R < P$. Impurity accumulation in the plasma centre can be accommodated too. Also the case where a part of the impurities does not originate from the targets. If the part of emission due to non-target impurities becomes large enough, condition $R = P$ can be reached with $\alpha < 1$, limit (3) cannot be reached, and the density limit is provided by the power balance model.

2.3. Theory part: summary and conclusion

Experiments in the tokamak, the stellarator, and the RFP show the density limit to be a radiative one. The concept of plasma-wall self-organization (PWSO) is introduced by simple 0D and 1D models. The basic idea of the theory is the existence of a time delay in the feedback loop relating radiation and impurity production on divertor plates. The amount of radiation becomes unstable above a density limit. This limit can be reached for a ratio of total radiated power to total input power as low as $\frac{1}{2}$. The calculation works for the stellarator and the reversed field pinch too.

When detachment occurs, the radiative density limit (3) might be pushed to very high values when physical sputtering dominates radiation (high Z materials). PWSO comes with two basins for this organization *at flat-top*: the usual one with a density limit, and a new one with density freedom, because of the collapse of impurities, in particular for machines using high- Z materials. Two basins of attraction of PWSO exist for the tokamak *during start-up*, with a high density one leading to density freedom. Pure ohmic breakdown sets the tokamak in a bad basin of PWSO from the outset: too many constraints (low density, slow ramp up) leading to strong impurity production.

In [3,5] it was found that a cylindrical description of the stellarator yields a good description of its density limit as a radiative one. References [3,4] show the same property holds for the RFP. As yet, PWSO leads to better basins of operation in stellarators, with a higher density limit than in pinches. This is likely due to their ECRH start-up, and suggests that a strongly ECRH assisted ohmic start-up might enable reaching the high-density scenario, especially for targets with high- Z materials. In view of the impressive tokamak DEMO wall load challenge, it is worth considering and checking this possibility, which comes with that of more margins for ITER and of smaller reactors. In general, the start-up phase of tokamak discharges should get more attention: adults are strongly defined by genetics and education, also flat-top plasmas!

3. EXPERIMENTS

In order to investigate the impact of start-up conditions, including pre-filled gas pressure and ECRH power, on the flat-top density limit in ECRH assisted Ohmic discharges, a series of experiments were conducted on the J-TEXT tokamak (a medium sized iron-core tokamak with a major radius $R_0 = 1.05\text{m}$, minor radius $a = 25\text{-}29\text{cm}$, and a silicon-carbide-coated graphite limiter), as reported in [10]. This paper is now summarized.

The typical J-TEXT discharge in the limiter configuration is performed with a toroidal magnetic field about 2 T, a plasma current about 200 kA, plasma density in the range $1\text{-}7 \times 10^{19} \text{ m}^{-3}$, and an electron temperature about 1 keV. The material of limiter targets in J-TEXT is carbon whose chemical sputtering by hydrogen is not negligible in comparison to the physical sputtering. The limiter target can absorb a large amount of gas in high electron density discharges, thus cleaning discharges have to be carried out during the experiments. Since non-standard start-up settings are used for this study, a noticeable amount of discharges fail or disrupt. Gas puffing can be applied to inject hydrogen with various pre-filled gas pressure and gas puffing rate. The ECRH auxiliary heating system operates at the second harmonic frequency with X mode for a magnetic field between 1.7 T and 2 T; the maximum output power is 500 kW and the frequency is 105 GHz. The primary diagnostics for this experiment include a photo-diode array, a Langmuir probe, a polarimeter-interferometer, and a vacuum gauge.

The experiments are performed with initial pressures 2.5, 5.5, and 7.5 mPa, plasma current about 120 kA, and ECRH power 0, 100, 200 and 300 kW. During the current plateau period, gas injection continues until the plasma density limit is reached. 46 discharges were performed with varying pre-filled gas pressure and start-up ECRH power. The CIII radiation and target region plasma temperature at the current plateau phase can be adjusted by changing the start-up conditions. The experimental data indicates that lower CIII radiation and higher target region temperature generally lead to a higher density limit.

The CIII radiation power generally oscillates at the beginning of the current plateau phase and eventually approaches a steady level over time, which suggest that there may be a time delay in the development of radiation

as described in the PWSO model. And the target region plasma temperature is higher in the discharge with higher gas pressure after the radiation power stabilizes. This should be related to the lower radiation level which leads to more energy deposited on the limiter target in the higher pre-filled gas pressure discharge. When ECRH is applied, this is done in the first fourth of the start-up phase. This ionizes the pre-filled gas and leads to a higher target region plasma temperature subsequently.

The experimental results indicate that increasing either the pre-filled gas pressure or the ECRH power in the start-up phase can help achieve a reduction in impurity radiation, an increase in the boundary electron temperature during the flat-top phase, and an enhancement of the density limit in most of the shots.

Figure 1 displays the density limit n_{lim} normalized to the Greenwald density as a function of the CIII radiation power R_{CIII} for various pre-filled gas pressures and ECRH powers during start-up. n_{lim} increases when CIII radiation decreases, a signature of a cleaner plasma. This confirms the prediction of references [9,2-4] that a cleaner plasma provides a higher n_{lim} .

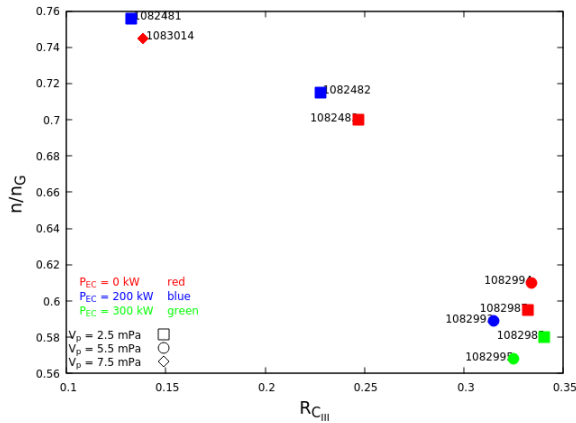


FIG. 1: Density limit versus CIII radiation.

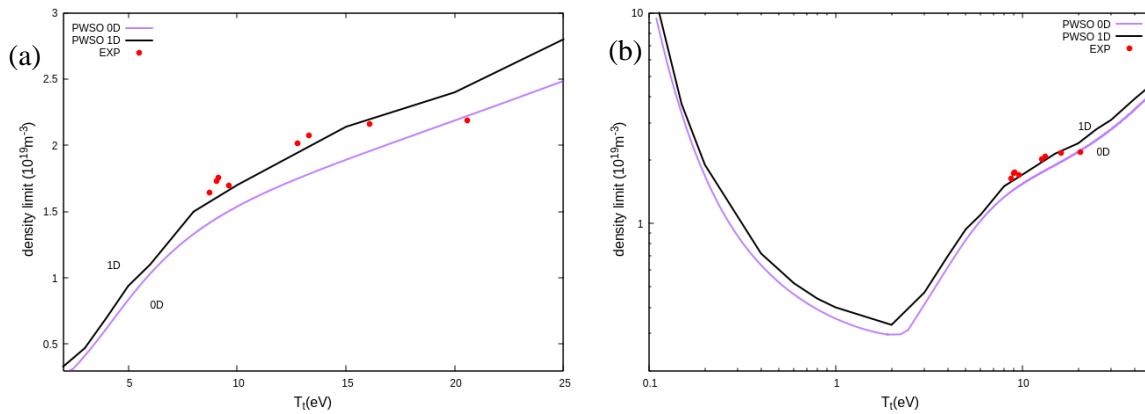


FIG. 2: Density limit versus target region plasma temperature (a) linear scales, (b) logarithmic scales.

Figure 2 displays n_{lim} as a function of the target region plasma temperature T_t (called T' in the theory part because of Word constraints in equations). Together with experimental data, it plots the value of n_{lim} predicted from the 0D (purple line) and 1D (black line) PWSO models. The 1D model predicts a density-free regime ($T_t < 2$ eV) where the density limit increases rapidly when T_t decreases and a density-limit regime ($T_t > 2$ eV) where the limit increase slowly when T_t increases (notice the logarithmic scales in figure 2b). The experimental points are located in the density-limit regime. There is a quantitative agreement with the 1D model by assuming an impurity radiation rate of 10^{-32} Wm^{-3} , impurities undergoing ionization at a distance $l = 0.01\text{m}$ away from the target, with a perpendicular diffusion coefficient $D=0.01 \text{ m}^2\text{s}^{-1}$, and that $f=1\%$ of the sputtered atoms penetrate the main plasma. Equation (3) shows n_{lim} for the 0D model scales like the former and inversely with the latter, while in the 1D model, for f/D constant n_{lim} is a growing function of f . The 0D predictions are similar to the 1D ones, but only qualitatively agree with the experimental points. These points are far from the density-free regime of both models, which may be due to the graphite targets of J-TEXT. In contrast, experiments in a tokamak with tungsten targets

might enter the density-free regime. Indeed, metallic walls should enable scans of initial neutral gas density and of ECRH power with less failures and disruptions at start-up than with carbon ones.

The 0D and 1D models have opposite trade-offs. The former is very simplistic and the latter is more elaborated, but with more parameters, whose experimental value is not precisely known. The experiment shows there is a lower CIII radiation power when using ECRH at start-up [10]. This confirms the improvement of purity expected in [9] due to a central breakdown of the discharge.

Summarizing the experimental section, the density limits predicted from the 0D and 1D PWSO models were compared and validated with J-TEXT experimental data. They are located in the density limit basin and demonstrate quantitative agreement with the PWSO model predictions under some parameter assumptions. Both theory and experiment suggest that a higher density limit corresponds to a lower impurity radiation state, which could be reached through increasing either the ECRH power or the pre-filled gas pressure at the start-up phase.

ACKNOWLEDGEMENTS

The theoretical part of this work [9] benefited from many useful advices. C. Arnas, L. Carraro, M.E. Puiatti, M. Valisa, and M. Wischmeier are thanked for information about plasma-wall interaction and impurity radiation. X. Bai, J. Bucalossi, S. Coda, H. de Oliveira, A. Fasoli, J. Graves, K. Nagasaki, Y. Peysson, H. Reimerdes, B. Shukla, and J. Stober are thanked for their help in discussing the experimental proposals. T. Klinger and H. Laqua are thanked for unpublished information about W7-X start-up. S. Cappello is thanked for an improvement in the large scale description of the theory. One of us (DFE) is grateful to the 2019 Festival de Théorie for the interaction with L. Howlett who pointed out to him reference [8]. The anonymous referees are thanked for their useful constructive comments.

REFERENCES

- [1] HUBER, A. et al, Impact of the ITER-like wall on divertor detachment and on the density limit in the JET tokamak, *J. Nucl. Mater.* **438** (2013) S139.
- [2] ZANCA, P. et al, A power-balance model of the density limit in fusion plasmas: application to the L-mode tokamak, *Nucl. Fusion* **59** (2019) 126011.
- [3] ZANCA, P. et al, A unified model of density limit in fusion plasmas, *Nucl. Fusion* **57** (2017) 056010.
- [4] ZANCA, et al, A power-balance model for the L-mode radiative density limit in fusion plasmas. *Plasma Phys. Control. Fusion*, **64** (2022) 054006.
- [5] FUCHERT, G. et al, Global energy confinement in the initial limiter configuration of Wendelstein 7-X, *Nucl. Fusion* **58** (2018) 106029.
- [6] GREENWALD, M., BADER, A., BAEK, S., et al., 20 years of research on the Alcator C-Mod tokamak, *Phys. Plasmas*, **21** (2014) 110501.
- [7] MANZ, P., EICH, T., and GROVER, O.. The power dependence of the maximum achievable H-mode and (disruptive) L-mode separatrix density in ASDEX Upgrade, *Nucl. Fusion* **63** (2023) 076026.
- [8] STACEY, W. M., Density limits in tokamaks. *Phys. Plasmas*, **4** (1997) 1069.
- [9] ESCANDE, D. F., SATTIN, F., and ZANCA, P, Plasma-wall self-organization in magnetic fusion, *Nucl. Fusion* **62**, (2022) 026001.
- [10] LIU, J., ZHU, P., ESCANDE, D. F., et al., Validation of the plasma-wall self-organization model for density limit in ECRH-assisted start-up of Ohmic discharges on J-TEXT, *Nucl. Fusion* **63** (2023) 096009.
- [11] ENGELHARDT, W., and FENEBERG, W., Influence of an ergodic magnetic limiter on the impurity content in a tokamak, *J. Nucl. Mater.* **76** (1978) 518.