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Plasma-wall self-organization in magnetic fusion

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This communication introduces the concept of plasma-wall self-organization (PWSO) in magnetic fusion [1]. The basic idea is the existence of a time delay in the feedback loop relating radiation and impurity production on divertor plates. Both a zero and a one-dimensional description of PWSO 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-plate 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*, in particular for machines using high-Z materials. Two basins of attraction of PWSO are shown to exist for the tokamak during start-up, with a 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, 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 that of more margins for ITER and of smaller reactors.

The L-mode density limit increases with rising heating power P like $P^{0.4}$ ([2] and five papers published between 1986 and 1999 quoted in the introduction of [3]); figure 4 of [5] shows with a data base of 6 tokamaks that a scaling like $(IP/a^4)^{4/9}$, 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 [3-5], which are in much better agreement with the tokamak and RFP databases. They apply to the stellarator too [5-6]. They describe the density limit as a radiative one, and therefore include naturally a clear explicit dependence on P. A large part of the radiative density limit comes from the radiation of impurities [3-5]. Their amount is governed by plasma-wall interaction. We provide a self-consistent description of this interaction and introduce the concept of PWSO.

Both zero and one-dimensional descriptions lead to a delay equation whose simplest expression is $R+ = \alpha (P-R)$, where P is the total input power in the plasma, R is the total radiated power, and R+ is its delayed value. This makes the plasma-wall system unstable for $\alpha > 1$. Since α is proportional to the density below detachment, this threshold defines a density limit. It can be reached for a ratio of total radiated power to total input power as low as 1/2. Building blocks of the derivation are expressions yielding the amount of sputtered atoms on the plates of a divertor and the corresponding amount of radiation in the plasma.

When detachment develops, the plasma temperature at the plates decreases, which makes α to vanish. This pushes the radiative density limit to very high values when physical sputtering dominates, in particular for tungsten. Hence density freedom.

In [4,6] it was found that a cylindrical description of the stellarator yields a good description of its density limit as a radiative one. References [4,5] show the same property holds for the reversed field pinch. Therefore, it is natural to extend the 0D and 1D models of PWSO to these two devices as well.

When physical sputtering dominates, a very high density limit can be predicted, 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 would trigger a virtuous circle enabling it. These vicious and virtuous circles are two basins of attraction of a second aspect of PWSO.

Unfortunately, usual tokamak operation is trapped into the bad basin of PWSO. 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 plates with high-Z materials. This would bring several benefits. Especially fulfilling more easily Lawson criterion, which might bring more margins for ITER and lead to smaller fusion reactors than expected presently. A strongly ECRH assisted ohmic start-up might be beneficial for the RFP as well. Stellarators might take advantage of improving their present start-up scenarios toward higher initial densities.

References

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