H-mode accessibility in ohmic discharges on RFX-mod

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I. Introduction

RFX-mod is a toroidal device originally designed as a reversed field pinch, presently operated also as a low current tokamak. The major radius of this device is 2 m, minor radius 0.46 m. The on-axis toroidal magnetic field is 0.55 T. The device is equipped by 8 independent shaping coil pairs symmetric with respect to the midplane that allow generation of several types of discharges: limiter discharge with both circular and elongated plasma, double null discharge and as some of the 8 pairs can be disconnected, it is possible to generate single null discharges either with upper or with lower X-point. RFX-mode is also equipped with 192 independent saddle coils for MHD control. Using the saddle coils and sophisticated control algorithms, RFX-mod can operate with the edge safety factor below two or avoid 2/1 mode locking in circular discharges [1]. In future, the same experiments should be performed also for single null discharges, possibly in H-mod. In addition, if the H-mod were reached, RFX-mod saddle coils could be useful tool for ELM mitigation.

Presently, RFX-mod can routinely perform single null discharges. The plasma shape can be computed using the algorithm presented in [2] with precision of several millimetres compared to independent simulations using the Grad-Shafranov solver MAXFEA [3]. The boundary reconstruction method can also provide the value of poloidal magnetic field everywhere in the vacuum. The boundary reconstruction works also in real time and provides the values of the gaps between the plasma and the first wall for 8 lines of sight connecting the centre of the vacuum vessel and the flux loops. Using the real time gap computation, a controller of the plasma shape was designed. It allows following the desired plasma shape reference signals also if the plasma parameters changes [4]. These two tools are useful for the design and performance of the experiments focused on L to H-mod transition. The shape control algorithm can modify the shape during the discharge to modify the L-H threshold power [5] that strongly depends for example on the distance between the X-point and the first wall. The offline boundary reconstruction is useful for evaluation of quantities related to the energy confinement (this property is expected to improve after the LH transition) such as β_p. Another important parameter that is evaluated is the power through separatrix carried by particles. The computation of these macroscopic plasma parameters is described in the paper.

II. β_p evaluation

In this section, the evaluation of β_p for RFX-mod diverted discharges will be presented. The most common method of β_p evaluation is based on the diamagnetic measurement. Unfortunately, this method is not reliable for RFX-mod diverted discharges due to hardware limitations. Thus, an independent method to evaluate β_p presented in [6] was implemented and used. This method is based on computation of the following integrals along the plasma boundary:

$$s_1 = \frac{2\pi}{V\langle B_p^2\rangle}\int R(s)B_p^2(s)\mathbf{n}(s)\mathbf{p}(s)ds, \qquad (1)$$

where V is the plasma volume, s is the curvilinear coordinate along the plasma boundary, R is the major radius, B_p is the poloidal magnetic field, **n** is the normal vector to the plasma boundary and **p** is the vector connecting the magnetic axis and the plasma boundary. As we know the plasma boundary and the magnetic field everywhere in the vacuum, the computation is straightforward. The other needed integrals are

$$s_2 = \frac{2\pi R_0}{V\langle B_p^2\rangle}\int R(s)B_p^2(s)\mathbf{n}(s)\mathbf{e_r}ds, \qquad (2)$$

$$s_3 = \frac{2\pi R_0}{V\langle B_p^2\rangle}\int z(s)B_p^2(s)\mathbf{n}(s)\mathbf{e}_z ds, \qquad (3)$$

where R_0 is the major radius, z is the vertical coordinate and $\mathbf{e}_{r,z}$ are the unit vectors in radial/vertical direction. Using these integrals, one can estimate the following:

$$\frac{s_1}{2} + s_2 = \beta_p + \frac{l_i}{2} \qquad (4)$$

and

$$l_i = \frac{1}{\alpha - 1}\left(\frac{s_1}{2} + \frac{s_2}{2}(R_t - R_0) - s_3\right), \qquad (5)$$

where R_t is the plasma centroid position and $\alpha = 2k^2/(1+k^2)$, where k is the elongation. The validity of this computation was tested in a few diverted discharges by puffing the gas. After the gas puff, the plasma pressure and thus also β_p are expected to increase. A minor increase of l_i is expected as well, since the plasma edge is cooled and thus the peaking of the current increases. The time evolution of β_p, l_i and $\beta_p + l_i/2$ is shown in Fig. 1. The results of the computation meet the theoretical expectations.

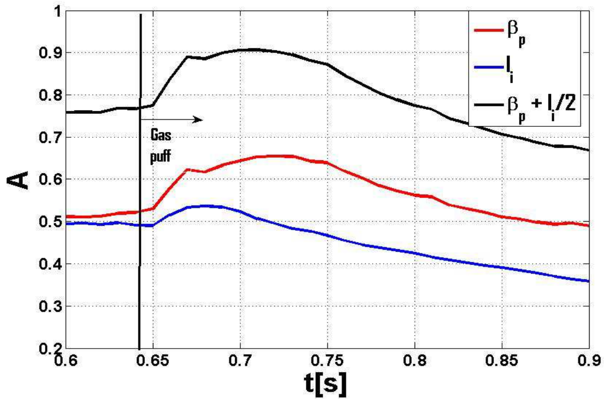

Fig. 1: The time evolution of β_p, l_i and $\beta_p + l_i/2$ *after gas puff for discharge 37925.*

III. Estimate of power through separatrix carried by particles

For the L-H transitions, two basic conditions must be met. The electron density and the power through separatrix carried by particles P_{sep} have to be above a certain threshold [7]. The critical density for RFX-mod according to scaling laws presented in [7] is $8 \cdot 10^{18}$ m^{-3} (the real density is usually below this value). The power threshold needed for the LH transition P_{LH} is around 100 kW for the critical density. This value can be exceeded especially in transient phases of the discharge. However, these two values can be different in reality, since the scaling provides just approximate values. The difference between the result of scaling and reality can be easily by a factor of 2. In RFX-mod, the H-mod is not achieved in the flat-top phase of the discharge. Thus, we conclude that the density or P_{sep} are below the threshold: both quantities need to be increased during the experiments focused on LH transition on RFX-mod. The way of increasing the density is out of the scope of this paper.

Let us discuss the possibilities of increasing P_{sep}. As there are no additional heating sources on RFX-mod, the only possibility to increase the P_{sep} (besides operation on higher plasma current and reducing radiation) is taking advantage of some transient events such as current ramp-downs when the value of P_{sep} can be temporarily increased. To model this situation, we start from the power balance equation [8]:

$$U \cdot I_p = P_{sep} + I_p \left(L \frac{dI_p}{dt} + \frac{dL}{dt} I_p\right) + \frac{dW}{dt} + P_{rad}, \qquad (6)$$

where U is the applied loop voltage, L is the plasma inductance, W is the plasma energy and P_{rad} is the power radiated by the plasma. All the quantities besides P_{sep} in (6) can be either measured (this is the case of U, I_p, P_{rad}), or computed by the combination of the boundary reconstruction method mentioned in section 1 and the β_p and l_i computation described in the previous section. This is the case of L and W. The plasma inductance is given by the sum of internal inductance l_i determined in previous section and external inductance that can be computed by elliptic integrals using the knowledge of plasma boundary coordinates. The plasma kinetic energy W can be computed using the value of β_p: the ratio of the plasma kinetic pressure and the poloidal magnetic field pressure on the plasma boundary. As β_p is known and magnetic field at the plasma edge can be provided by the boundary reconstruction code, the computation of W is straightforward.

The time evolution of P_{sep} is in Fig. 2. One can see that it is significantly increased in the plasma current ramp-down phase. This property determines one possible strategy to reach H-mode on RFX-mod: try to obtain the LH transition during the ramp-down phase. As the power required to sustain the H-mode is lower than the power required for the L-H transition, the H-mode might be sustained even after the plasma current value is stabilized. Unfortunately, none of the attempts performed up to now was successful in sustaining H-mode after the current ramp-down, but several cases that could be LH transition were observed transiently during the ramp-down phase.

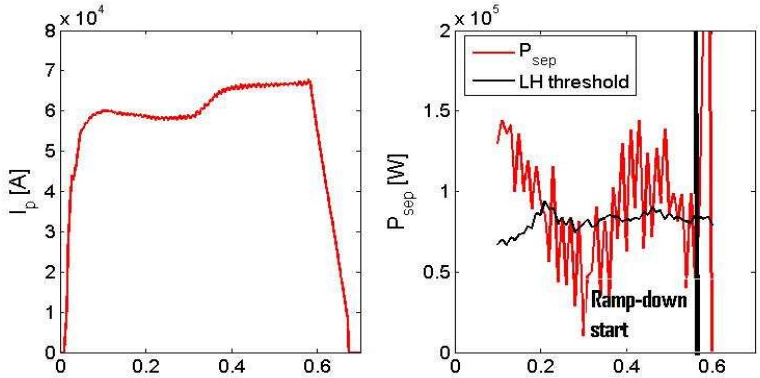

Fig. 2: The estimate of the P_{sep} power during the plasma current ramp-down phase of discharge number 36914.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 633053 and from Erasmus Mundus International Doctoral College in Fusion Science and Engineering. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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