UNIVERSIDADE DE SÃO PAULO

INSTITUTO DE FÍSICA
CAIXA POSTAL 20516
01498 - SÃO PAULO - SP
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WALL CONDITIONING BY ECR PLASMAS IN A SMALL TOKAMAK

J.I. Elizondo and **I.C. Nascimento**
Instituto de Física, Universidade de São Paulo

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Abstract

The electron-cyclotron resonant discharge cleaning process (ECR-DC) was tested in the small tokamak TBR-1. The main parameters of the conditioning plasma were measured with a Langmuir probe. Using a zero dimensional model it was concluded that initially low T_e (1 eV) is important for the cleaning but the n_e value is not. In the final part of the conditioning moderately low T_e (10-30 eV) and high n_e (in excess of 10^{11} cm^{-3}) are necessary to optimize the cleaning. The efectiveness of the conditioning, as evaluated by a quadrupole mass analyzer, is roughly the same of the Taylor discharge cleaning system. More than 15 monolayers of oxygen were converted into water and pumped out during the cleaning operation.

I. Introduction

The investigation of high temperature magnetically confined plasmas has been concentrated on toroidal devices, mainly tokamaks. One of the main problems, not satisfactorily solved yet, in this type of device, is the hydrogen plasma contamination with atoms of O, C, Fe, etc., during the discharges, due to plasma-wall interaction. The presence of those impurities in the hydrogen plasma influences strongly the most important plasma parameters: temperature, stability, energy confinement, etc. [1]. To minimize the contamination it is necessary to control simultaneously the discharge parameters and the actual state of the surfaces interacting with the plasma.

In small-size machines the main impurity is oxygen, but carbon is also important [1]. To diminish the O and C densities on the wall surface a variety of cleaning processes was proposed [2]. The discharge cleaning is one of them, and is widely used. It works with a hydrogen plasma with low temperature and density and low ionization degree (T_e~5 eV, n_e~10^{10}-10^{12} cm^{-3}, $\alpha < 10^{-2}$). The neutral atoms generated in the reaction $H_2 + e^- \rightarrow H + H + e^-$, strike the wall producing H_2O, CH_4 and other molecules wich are easily desorbed and pumped out by the vacuum system.

In the TDC (Taylor discharge cleaning) system [3,4], the conditioning plasma is inductively generated by the OHT (ohmic heating transformer). Recently it was developed the ECR-DC (Electron cyclotron resonant discharge cleaning) process; in this process the cleaning plasma is generated by the interaction of microwaves with electrons in the presence of a magnetic field and has been used successfully in a variety of tokamaks [5,6,7,8] substituting the Taylor system or operating with other conditioning systems.

It is still necessary a lot of experimental work to determine the main ECR plasma parameters and also more accurate models describing the conditioning process. In the small TBR-1 tokamak of the University of São Paulo [9] a ECR-DC system was recently developed and tested. The n_e and T_e radial profiles were measured. The density profile shape was explained by the cyclotronic and upper hybrid resonant absorption. The efficiency of the cleaning process, monitored with a residual gas analyzer, was compared with that of the Taylor system, and shown to be roughly the same. A simple model [6] was used to investigate the n_e, T_e and P_2 (hydrogen pressure) influence on the conditioning process.

2. Experimental set-up and results

The main TBR-1 parameters used in this work are in the table 1. The 316 L stainless steel vessel is evacuated with a turbomolecular pump. The effective pumping velocity for N_2 is 55 *l*/s in the vessel.

TABLE 1

Major radius	R_o	30 cm
Minor radius	b	11 cm
Base pressure	P_b	1×10^{-4} Pa
Wall internal area	A_w	1.3 m^2
Vessel volume	V	80 l

The microwaves, generated by a magnetron (f=2.45 GHz, P=800 W DC) are coupled with a rectangular waveguide in the TE_{10} mode, and injected from the external part of the torus, perpendicularly to the toroidal magnetic field with ordinary polarization. The magnetic field necessary for the resonance -875 G- is

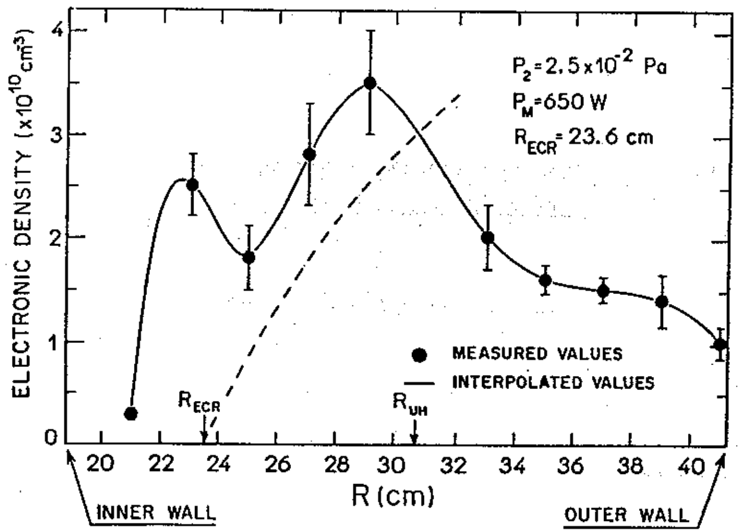

Fig.1 - Radial density profile of the ECR plasma in the horizontal direction. The intersection of the dashed line (equation 3) with the full line determines the upper hybrid resonance position.

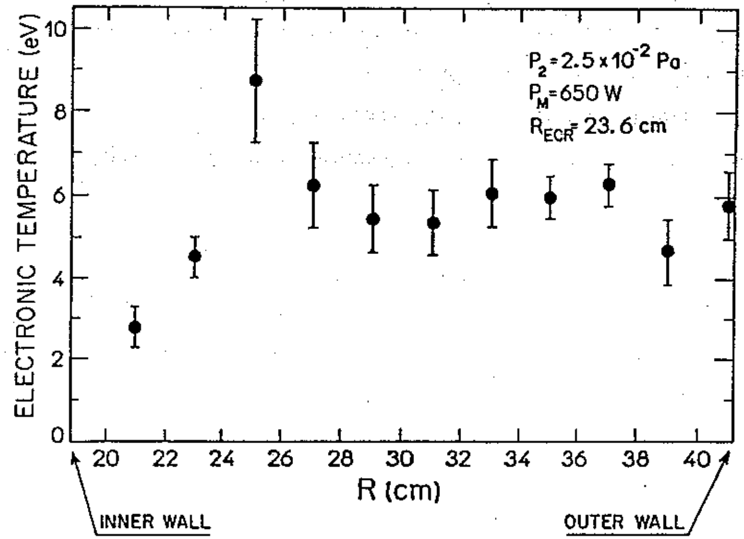

Fig.2 - Radial electron temperature profile of the ECR plasma in the horizontal direction.

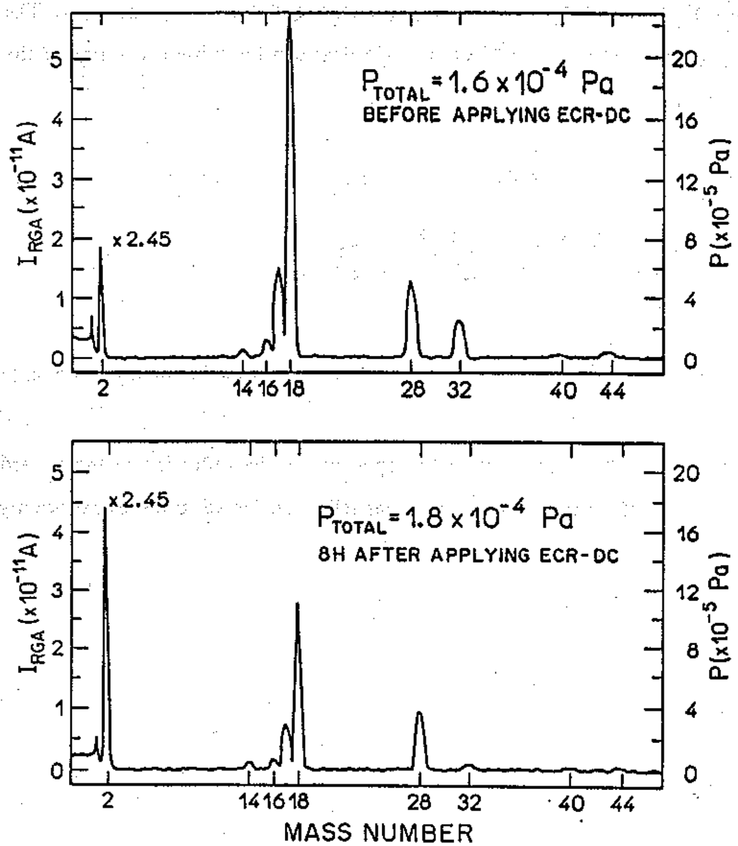

Fig.3 - Residual gas spectrum before and 8 h after the ECR-DC operation.

generated by a current flowing on the toroidal coils. Since $B_T \sim 1/R$, the cyclotronic resonance region is a vertical cylinder surface whose radius is linearly dependent on the toroidal coils current.

The n_e and T_e radial profiles of the conditioning plasma were obtained with an electrostatic probe (Fig.1,2) horizontally movable in the major radius direction in the entire cross section. The density is maximum in the upper hybrid layer and has a secondary maximum in the cyclotron resonant layer.

Before every cleaning operation the vessel was vented for one day. After two days of pumping a 20 h cleaning operation was started with duty cycle of 10% and 8 s of pulse width. The duty cycle was limited by the heating of the toroidal coils. In this case the wall temperature was not higher than 70 °C.

The partial pressures of the vessel atmosphere before, during and after the cleaning operation were monitored with a quadrupole residual gas analizer (Fig.3,4). In these figures the formation and desorption of compounds, mainly H_2O and CO (or N_2) can be seen. When the conditioning starts up the water pressure is two orders of magnitude greater than in the base vacuum. The time dependence of the water pressure is like $t^{-0.4}$ (Fig.5), in agreement with other works [3]. It is important to remark that the decrease of the water pressure during the long run reflects the diminishing of the surface density of oxygen in the wall. Comparing the partial pressures spectra before and after the conditioning (Fig.3) a great reduction of the contaminant peaks is observed, particularly in the oxygen one, and an enhancement in the hydrogen peak, both observations being consistent with the model.

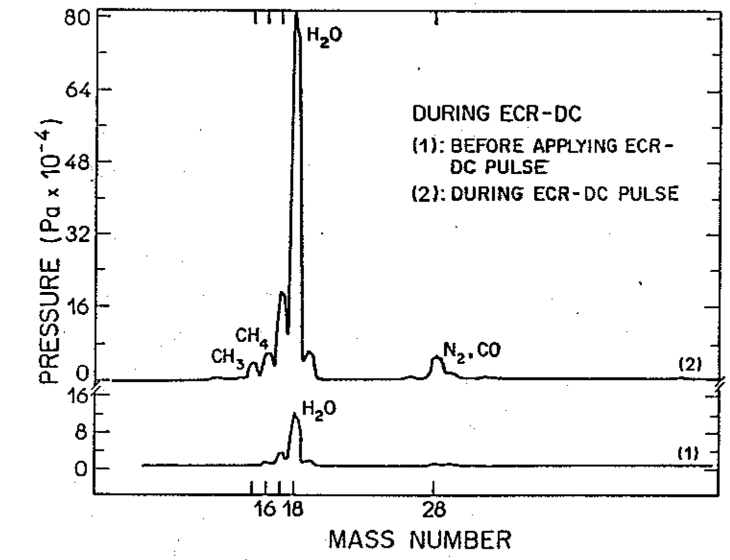

Fig.4 - Residual gas spectrum before and during ECR-DC pulse.

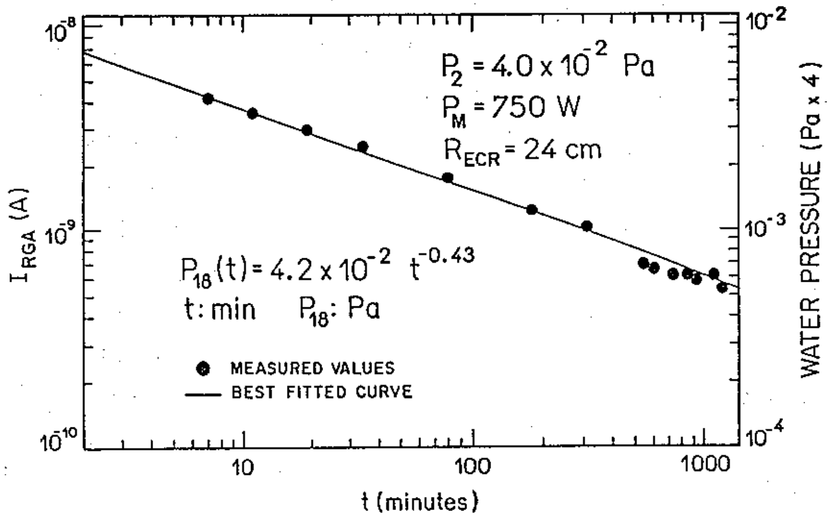

Fig.5 - Dependence of the water pressure, in the ECR-DC pulse during the cleaning.

3. Discussion of the results

In the ECR-DC operating conditions in TBR-1 -n_e and T_e low-, there is a low absorption of the ordinary mode in the electron cyclotron resonant layer. The fraction F_o of the power absorbed on a single pass can be written in terms of the optical depth Γ_o:

$$F_o = 1 - e^{-\Gamma_o} \cong \Gamma_o \qquad (\text{for } \Gamma_o \ll 1) \qquad (1)$$

$$\Gamma_o \cong \frac{\pi}{2} R_o \frac{\omega_p^2}{\omega_c^2} \left(1 - \frac{\omega_p^2}{\omega_c^2}\right)^{\frac{1}{2}} \frac{\omega_c}{c} \frac{v_t}{c^2} \qquad [10]$$

where ω_c is the electron-cyclotron frequency, ω_p is the plasma frequency and v_t is the thermal velocity of the electrons. The value of F_o for the TBR-1 is of the order of 10^{-5}: the plasma is almost completely "transparent". In the reflection at the inward wall of the vessel, the microwave power is partially transferred to the extraordinary mode, which is absorbed in the upper hybrid layer.

From the resonant equation

$$\omega^2 = \omega_{UH}^2 = \omega_p^2 + \omega_c^2 \qquad (2)$$

it is obtained a relation between R_{UH}, the upper hybrid resonance position, and n_e:

$$R_{UH} = \frac{e \mu_o N}{2\pi m \sqrt{\omega^2 - \frac{n_e e^2}{\epsilon_o m}}} i_T \qquad (\text{in SI units}) \qquad (3)$$

where i_T is the current flowing in the N toroidal coils, ω is the microwave frequency and ω_{UH} is the upper hybrid frequency. In fig.1 the dashed line is a plot of R_{UH}

versus n_e. The point where the plot intercepts the real n_e profile determines the position of the upper hybrid resonance layer, which coincides aproximately with the maximum of the density profile, as it is expected. Thus, the absorption of microwave power injected perpendicularly at B_T from the outside of the vessel, with T_e and n_e relatively low, is explained by the absorption of the ordinary mode (for $\omega=\omega_c$) and extraordinary mode (for $\omega=\omega_{UH}$), attempting to the multi-reflection in the wall of the vessel. The slow decrease of the electron density between R_{UH} (upper hybrid resonant layer position) and the outer wall, contrasts with the fast decrease between R_{ECR} (electron-cyclotron resonant position) and the inward wall. This difference is due to the electron drift, which occurs in the outward horizontal direction.

From the temperature and density profiles it is possible to estimate roughly the atomic neutral flux on the wall (10^{16} cm^{-2}.s^{-1}) and the density of H° ($n_o \sim 10^{10}$ cm^{-3}) [7]. The dissociation rate of H_2 by electrons is two orders of magnitude higher than the H_2 influx by the gas feeding. The pressure is mantained by the recombination of the hydrogen atoms which do not react on the wall surface. However, the H_2 pressure decreases by a factor of aproximately two when the plasma is generated.

Because the oxygen is the main contaminant in small tokamaks, this work emphasizes the diminishing of the oxygen density in the wall surface, via water formation followed by pumping. Supposing that an oxygen monolayer corresponds to 2×10^{15} at.cm^{-2} [4] it is possible to calculate the number of monolayers pumped out during the conditioning process

$$Q_{18} = \int_{t_0}^{t_1} s_{18} P_{18} \, dt \qquad (4)$$

where s_{18} is the pumping velocity for water and P_{18} is the water pressure. Calculating the integral in (4) it is obtained $Q_{18}=15$ monolayers, supposing that the pumping velocity for water is the same for N_2.

The main objective of the conditioning is to maximize Q_{18}. For this P_{18} should be as high as possible. In order to study the combination of parameters for maximizing the oxygen pumping -via water- the model proposed in the reference 6 was used. In this model the molecules of water formed and desorbed from the wall surface may be pumped out, lost by plasma dissociation or readsorbed on the wall. Thus, in the equilibrium state, the molecular water flux emerging from the wall of the vessel, F_{18}, is:

$$F_{18}=F_p+F_d+F_{ad} \qquad (5)$$

and the fluxes can be writen as

$$\begin{aligned} F_{18}&=F_1 n_w p_{w18} \\ F_1&=n_e n_2 k_2 V_p \\ F_p&=s_{18} n_{18} \\ F_d&=n_e n_{18} k_{18} V_p \\ F_{ad}&=(1/4) n_{18} v_{18} A_w p_{st} \end{aligned} \qquad (6)$$

F_1 gives the H° production in the plasma, n_w is the oxygen surface density, p_{w18} is the probability of the water formation by H° impact on the wall surface, n_2 and n_{18} are the hydrogen and water densities in the plasma, k_2 and k_{18} are the dissociation rates of H_2 and H_2O by electron impact, V_p is the plasma volume, v_{18} is the thermal velocity of the water molecules and p_{st} is the wall readsorption probability -sticking probability- of H_2O, which must increase during the conditioning.

Substituting these fluxes expressions in the equation 5 it is obtained:

$$\frac{P_{18}}{P_2} = \frac{n_{18}}{n_2} = \frac{A}{1 + B/n_e} \quad (7)$$

where P_{18} and P_2 are the water and hydrogen pressures, n_{18} and n_2 are the corresponding densities and A and B are defined as

$$A = \frac{k_2}{k_{18}} p_{w18} n_w \qquad B = \frac{\frac{1}{4} p_{st} v_{18} A_w + s_{18}}{k_{18} V_P}$$

It is interesting to compare the water fluxes dissociated and adsorbed - F_d, F_{ad} - with the rate of water pumping:

$$\text{a)} \quad \frac{F_p}{F_d} = \frac{s_{18}}{n_e k_{18} V_P} \approx 10^{-2} \quad (8)$$

for the ECR-DC parameters in the TBR-1.

$$\text{b)} \quad \frac{F_p}{F_{ad}} = \frac{s_{18}}{\frac{1}{4} v_{18} A_w p_{st}} = \frac{3 \times 10^{-4}}{p_{st}} \quad (9)$$

F_p approximates to F_{ad} only for $p_{st} < 10^{-3}$.

From equations 8 and 9 it is concluded that a very little quantity of the water produced on the wall surface is effectively pumped. The great majority of the water molecules are lost by sticking on the wall surface or by dissociation by electron impact.

Equation 7 can be simplified for some cases:

a) $B << n_e$, since in the initial part of the cleaning $p_{st} << 1$:

$$\frac{P_{18}}{P_2} = \frac{A}{1 + B/n_e} \approx A = \frac{k_2}{k_{18}} p_{w18} n_e \quad (10)$$

The maximum of k_2/k_{18} is for $T_e = 1$ eV (Fig.6, Ref.11).

b) $B >> n_e$, because in the final part of the cleaning p_{st} approaches 1:

$$\frac{P_{18}}{P_2} = \frac{A}{1 + B/n_e} \approx \frac{A}{B} n_e = k_2 \frac{p_{w18} n_w}{\frac{1}{4} v_{18} A_w p_{st}} V_P n_e \quad (11)$$

Only k_2 depends on the electron temperature with a maximum for $T_e \sim 20$ eV (Fig.6).

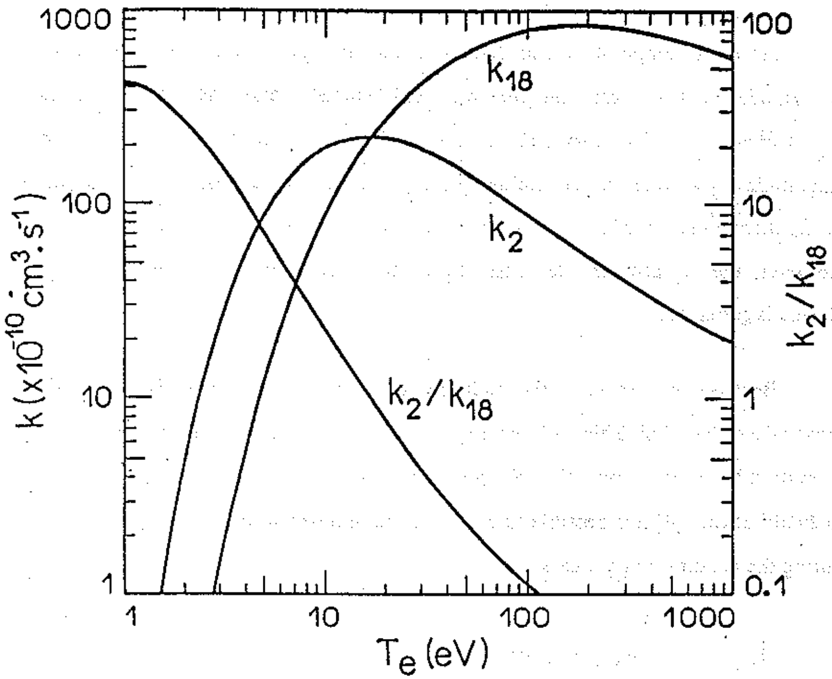

Fig.6 - Dissociation rate coefficients k_2 for H_2 and k_{18} for H_2O as a function of electron temperature.

The dependence of P_{18} with n_e (7) for several p_{st} values, is shown in fig. 7. In the beginning of the cleaning ($p_{st} << 1$), P_{18} changes slowly with n_e. In the final part ($p_{st} \sim 0.5$, Ref.6), it is absolutely necessary to work with high n_e for pumping out water efficiently. From equation 7 it is also concluded that P_{18} is proportional to P_2, if the other parameters remain the same.

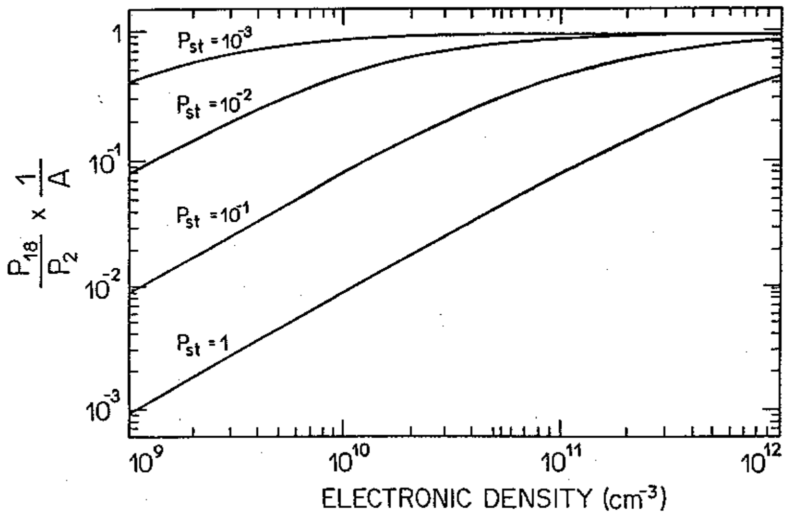

Fig.7 - Cleaning efficiency dependence with electronic density for various values of the sticking probability, p_{st}.

The results obtained in ECR-DC were compared with the measurements done in TDC, and it was concluded that their efficiencies are roughly the same. The main advantages of the ECR-DC are the low cost of the equipment and the low thermal load of the vessel walls, which make possible to operate with high duty cycle, and perhaps in continous operation. The main limitation of the used system is the relatively low density (10^{10} cm^{-3}) that can be achieved in this conditioning plasma, which limits the efficiency of this process in the final part of the cleaning (Fig.7). In fact the propagation condition for an ordinary ray in a plasma is

$$\omega \geq \omega_p \approx 5{,}6 \times 10^4 \, n_e^{\frac{1}{2}} \qquad (n_e \text{ in } cm^{-3}) \qquad (12)$$

For a frequency of 2.45 GHz, the maximum theoretical density is 7.4×10^{10} cm^{-3}, aproximately.

4. Conclusion

The ECR-DC system was tested in a small tokamak. Measurements performed with a quadrupole mass analyzer demonstrated the efficiency of the process for the reduction of the oxygen density in the wall surface.

Using a simple model it is concluded that for optimizing the conditioning process n_e must be high ($>10^{11}$ cm^{-3}), mainly in the final part of the cleaning. T_e must be initially low (1 eV) and grow up until 20 eV aproximately in the final part of the cleaning.

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