ABSORPTION PROPERTIES OF X3 TOP-LAUNCH ECH ON TCV

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The TCV EC system has been recently completed with three 450 kW gyrotrons operating at the frequency of 118 GHz for 3^{rd} harmonic X-mode heating. For maximizing the X3 absorption a top-launch is used implying that absorption strongly depends on the launcher poloidal angle, the plasma density, temperature and injected power. In order to characterize the X3 absorption properties, a set of experiments has been performed and the resulting sensitivity on the launcher poloidal angle as well as the absorption dependence on the density and the injected power are discussed. Simulations using the linear ray-tracing code TORAY-GA are compared to the experimental results. The optimal launcher angles predicted by TORAY-GA are in good agreement with the experiments at low power injection ($P_{inj} = 450$ kW). At a central electron density $n_{e,0} = 4 \cdot 10^{19}$ m^{-3} full single pass absorption is measured when the total X3 power is injected (1.35 MW). At this power level a significant discrepancy is found between the TORAY-GA prediction and the experiment. This dicrepancy is partly due to the presence of a supra-thermal electron population generated by the X3 itself.

Introduction

In the moderate magnetic field of TCV (1.45 T), the X3 ECH system extends the accessible plasma density range up to its cutoff density $n_{e,cutoff}^{X3} = 11.5 \cdot 10^{19}$ m^{-3} compared to the cutoff density of $4.2 \cdot 10^{19}$ m^{-3} for the X2 system. The X3 absorption coefficient is lower than the X2 absorption coefficient by a factor $(k_B T_e)/(m_e c^2)$ and a top-launch injection system (see Fig.1) has been chosen in order to maximize the ray path along the resonance layer [1]. The low absorption coefficient and the particularity of the top-launch imply that the absorbed power strongly depends on the launcher poloidal angle θ_l. The linear temperature dependence of the X3

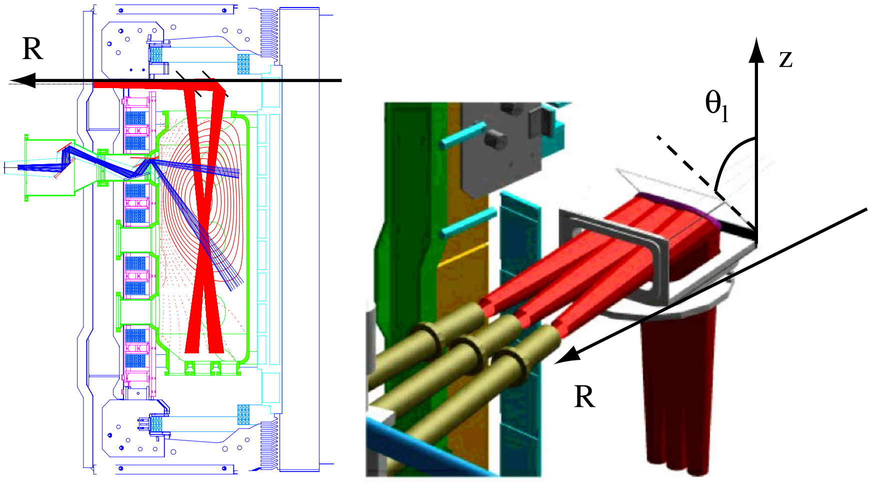

Figure 1: The X3 launcher is a single elliptical mirror focusing the three gaussian beams inside the plasma. The mirror can be moved in the radial direction R from shot to shot and the launcher poloidal angle θ_l can vary during the shot. The vertical injection corresponds to $\theta_l = 45^o$ and if $\theta_l > 45^o$ (resp. $< 45^o$), the beam propagates from the LFS to the HFS (resp. from the HFS to the LFS).

absorption coefficient, $\alpha_3^{(X)}$, suggests that the single pass absorption can be improved increasing the injected power. This is experimentally confirmed by absorption measurements versus injected power. The $\alpha_3^{(X)}$ dependence on density predicts that the absorption is maximal at $n_e = 7 \cdot 10^{19}$ m^{-3} [2]. This has been measured and is compared to TORAY-GA calculations. At a central density of $4 \cdot 10^{19}$ m^{-3} it is shown that the suprathermal electron population generated by X3 itself allows to reach full single pass absorption [3] with an injected power as high as 1.35 MW.

Experiments and simulations

A set of experiments has been performed injecting 450 kW (1 gyrotron) of X3 power and sweeping the launcher poloidal angle in order to make the beam passing across the X3 resonance layer. This implies that a maximum absorption can be observed from the global electron temperature measurement as shown on Fig.2. The optimum launcher angle, $\theta_{l,opt}$, corresponds to the maximum single pass absorption and is experimentally determined by the maximum of T_e-X. A good agreement is found between experiment and the simulation with TORAY-GA. According to this optimal angle, one define the launcher angle sensitivity $\delta\theta_{mes}$ (resp. $\delta\theta_{toray}$) as the FWHM of the smoothed T_e-X measurement (resp. the P_{abs} dotted curve). TORAY-GA predicts an absorption sensitivity $\delta\theta_{toray} = 0.8^o$ and the measurements give $\delta\theta_{mes} = 1.4^o$. The strong sensitivity on the launcher poloidal angle implies that a real time feedback control on θ_l is required in order to maximize the absorption during the discharge. The principle of such a control system has been shown using a software package [4, 5] and experiments have shown that an error signal can be obtained in real time using synchronous demodulation technique. The next step is to close the feedback loop via an analog PID controller and this is foreseen in the current experimental campaign.

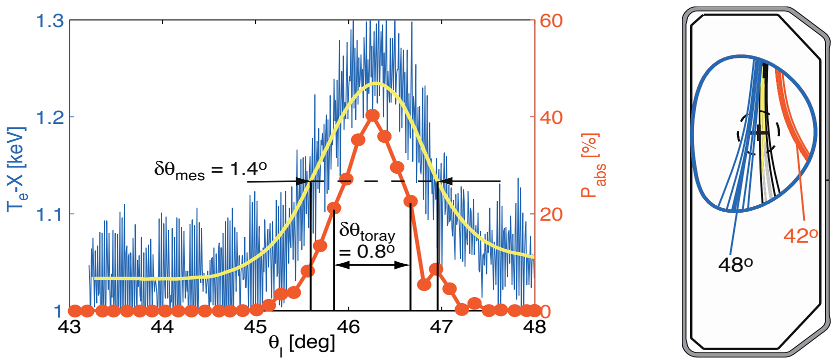

Figure 2: Definition of the launcher poloidal angle sensitivity using the T_e-X measurements as well as the absorbed power predicted by TORAY-GA (Dots). Both curves give also the optimal launcher angle $\theta_{l,opt}$. The poloidal view of TCV shows the TORAY-GA beam trajectory during the launcher angle sweep.

The dependence of $\theta_{l,opt}$ on the density has been measured reproducing the scenario shown in Fig. 2 for various densities ($3.3 \leq n_{e,0} \leq 8.0 \cdot 10^{19}$ m^{-3}). Fig. 3 b) shows that $\theta_{l,opt}$ increases with the density because the injection direction has to compensate refraction effects. TORAY-GA calculation and measurements are in good agreement for determining the optimal launcher angle. Note that the ”error bars” represent the sensitivity $\delta\theta_{toray}$ and from Fig.3 b), one observes that $\delta\theta_{toray}$ is independent of n_e.

Fig. 3 a) shows the comparison between the measured global electron energy increase $\Delta W_e = W_e(\theta_{l,opt}) - W_{e,min}(\theta_l)$ (circles) and the absorption calculated by TORAY-GA at $\theta_{l,opt}$ (diamonds) as a function of the central density $n_{e,0}$, $W_{e,min}$ being the electron energy during the non heated (ohmic) phase. Both curves show that the optimal density for X3 heating is around $n_{e,0} = 7 \cdot 10^{19}$ m^{-3}.

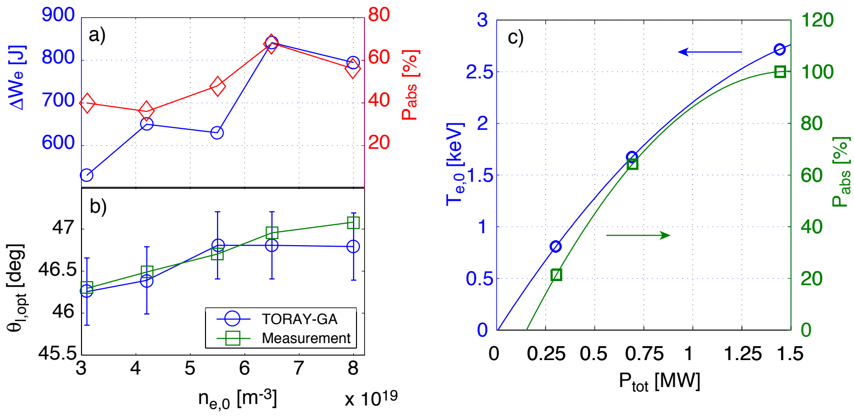

Figure 3: a) The electron energy increase (circles) and the absorption calculated by TORAY-GA (diamonds) both predict an optimal density of $n_{e,0} \simeq 7 \cdot 10^{19}$ m^{-3}. b) The optimal launcher angle determined from both TORAY-GA and T_e-X measurements are in good agreement independently of the density. c) The measured X3 absorption (squares) and the central temperature versus the total power ($P_{tot} = P_{oh} + P_{abs}$) of the plasma for a central density of $n_{e,0} = 4 \cdot 10^{19}$ m^{-3}.

A second set of experiments has been performed scanning the injected power ($0.45 \leq P_{inj} \leq 1.35$ MW). The optimal launcher angle is previously determined sweeping θ_l and the discharge is then repeated injecting the X3 power at the fixed angle $\theta_{l,opt}$. Within the ECH phase (1s), one gyrotron (0.45 MW) is fully modulated at 237 Hz during 200 ms in order to determine the X3 absorption measured via the diamagnetic flux variation associated to the modulation [6]. Fig. 3 c) shows the measured X3 single pass absorption measurement (squares) as a function of the total power in the plasma ($P_{tot} = P_{oh} + P_{abs}$). Superimposed to this curve, the central temperature $T_{e,0}$ obtained during the heating is shown. Full single pass absorption is obtained if $P_{inj} = 1.35$ MW ($P_{tot} \simeq 1.45$ MW) and

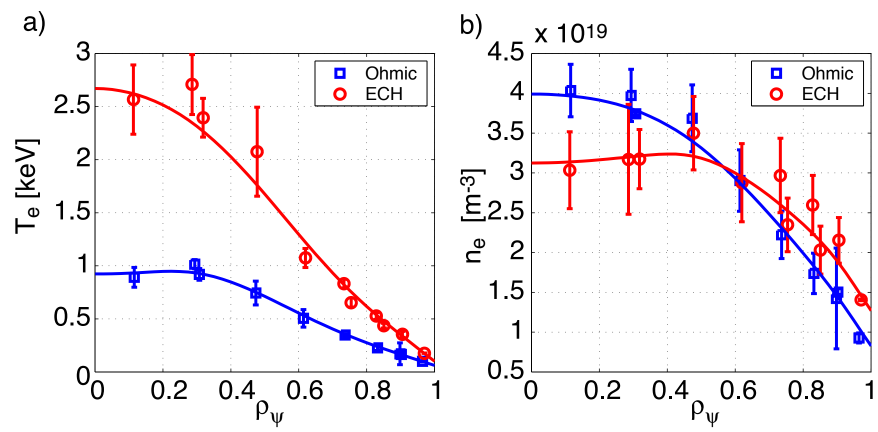

Figure 4: a) The temperature profiles during the ohmic and ECH phases. b) The density profile is significantly flattened when $P_{inj} = 1.35$ MW but this is not observed at lower injected power.

$T_{e,0} = 2.7$ keV. At this level of injected power the stored plasma energy is increased by a factor of 3 compared to the ohmic level. In this latter case, $\theta_l = 46.4^o$ and TORAY-GA calculation predicts an absorption of 50%. The discrepancy might be partly explained by the presence of suprathermal electrons generated by the X3 heating itself. With an angle sensitivity of $\delta\theta_{toray} = 0.8^o$, part of the discrepancy might also be associated to the accuracy of the reconstructed equilibrium, especially concerning the plasma radial position. With the maximum injected power of 1.35 MW Fig. 4a) and b) show the time averaged temperature and density profiles during the ohmic (squares) and the ECH (circles) phases. A significant density flattening is observed during the ECH phase. Similar effects have been observed on TCV with X2 ECH/ECCD and on ASDEX Upgrade in ECH/ECCD experiments [7, 8, 9]. In previous experiments [10] on highly elongated plasmas, it has been shown that the X3 power deposition occurs inside the region $\rho_\psi = 0.5$. This result is in good agreement with the deposition profile predicted by TORAY-GA

The results presented in this paper have shown that X3 full single pass absorption can be obtained with the injection of the total installed X3 power and for a central density equal to the X2 cutoff. The dependence of the X3 absorption on the injected power and the density will be completed in order to explore the whole $[n_e, P_{inj}]$ parameters domain. Further investigations will be performed to determine the limits of the linear ray-tracing code TORAY-GA. In particular, the top-launch mirror focuses the RF beam inside the plasma and cannot be properly described by the ray tracing model. Simulations using the beam tracing code ECWGB [11, 12], which include diffraction effects are presently underway.

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