Third-harmonic X-mode, real-time controlled top-launch ECW experiments on TCV Tokamak

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Abstract. In the moderate magnetic field of TCV (1.5 T), the recently installed X3 system (3 gyrotrons @118 GHz, 0.45 MW/each, 2s) broadens the operational space with the possibility of heating plasmas at high density, well above the cutoff density of the X2 system (X2 cutoff at \( n_e = 4.2 \times 10^{19} \text{ m}^{-3} \)). To compensate the significantly weaker absorption coefficient compared to the absorption of X2, the top-launch injection allows to maximize the ray path along the resonance layer thus maximizing the optical depth. To maintain the maximum absorption in plasma discharges with a dynamic variation of both density (refraction) and temperature (relativistic shift) a real time control system on the poloidal injection angle has been developed and successfully tested on TCV. With a total injected power of 1.35 MW and using the mirror real-time control, full single pass absorption has been measured in an L-mode plasma. A significant fraction of the absorbed power is associated to the presence of suprathermal electrons generated by the X3 wave itself. In X3 heating experiments of H-mode plasmas it has been possible to enter into a different ELMy regime compared to the ohmic/low-power-heating ELMy regime. In these experiments a significant increase of the plasma energy is obtained with nearly full single pass absorption. Results on the comparison of the absorbed fraction calculated with the TORAY-GA ray-tracing code and the beam-tracing code, ECWGB, which includes diffraction effects, are discussed.

1. Introduction
The use of electron cyclotron (EC) waves in magnetically confined plasmas such as tokamaks or stellarators has demonstrated in the past years the applications of EC waves in fusion relevant plasmas in terms of highly efficient localized heating and current drive [1], MHD control [2, 3, 4, 5] and formation and control of improved core electron confinement [6]. However, in overdense plasmas \( \omega_{pe}^2/\Omega_{ce}^2 >> 1 \), \( \omega_{pe} \) and \( \Omega_{ce} \) being the electron plasma frequency and electron cyclotron frequency, respectively) EC heating (ECH) is restricted for wave frequencies \( \omega \) near the fundamental cyclotron frequency and second harmonic because the wave is reflected by a cutoff layer before it can reach the resonance. One option for overcoming the density limit is the mode conversion from the O-mode or X-mode to the electron Bernstein wave (EBW) [7] which is also considered in TCV. The alternative which is presented in this paper is the 3rd harmonic
in X-mode, which provides access to the density range frequently found in TCV (above the 2nd harmonic X-mode cutoff), especially in H-mode discharges.

For a Maxwellian distribution function and a harmonic number \( n \geq 2 \), the optical thickness \( \tau_{Xn} \) of the X-mode, launched from the low-field side (LFS) is proportional to the small term \((k_B T_e/m_e c^2)^{n-1}\) (in case of O-mode with quasi perpendicular injection the optical thickness \( \tau_{On} \) is proportional to \((k_B T_e/m_e c^2)^n\) for \( n \geq 1 \)); consequently the absorption of the X-mode at the third harmonic is significantly weaker than at the second harmonic. Contrary to the case of LFS injection, for a top-launch configuration with a grazing incidence of the rf beam on the resonant layer, the optical depth \( \tau_{X3\text{top}} \) scales as \( \tau_{X3\text{top}} \sim T_e L \) with \( L \) being a characteristic length along the resonance layer [8].

In the moderate magnetic field of TCV (1.5T), the X3 system broadens the operational space with the possibility of heating plasmas at high density, well above the cutoff density of the X2, where the cutoff for the X2 and X3 waves are \( 4.2 \times 10^{19} \text{m}^{-3} \) and \( 11.5 \times 10^{18} \text{m}^{-3} \), respectively. The top-launch injection of the X3 wave maximizes the ray path along the resonance layer thus maximizing the optical depth, but it has the disadvantage of weak localization and poor control of the heating profile [8]. With a top launch configuration, the aiming accuracy is very critical because the characteristic width of the rf beam, \( w_0 \), is comparable with the characteristic width of the resonance layer, \( w_{res} \). Hence, for maximizing the overlap of the rf beam on the resonance layer, a high accuracy of the launcher mirror angle is necessary. This aspect has motivated the implementation of a real-time feedback control on the mirror angle which will be described below. As explained in [8], the width of the resonance layer, \( w_{res} \), is an increasing function of the electron temperature, and, in presence of a suprathermal electron population (SEP), an equivalent resonance layer width can be defined \( (w_{res}^{\ast} \text{ in [8]} \) which satisfies the following inequality \( w_{res}^{\ast} > w_{res} \).

In this paper, the experimental configuration is presented in section 2. The real time control system of the mirror angle is presented in section 3. The X3 absorption studies performed with the real-time control of the mirror on L-mode plasmas are presented in section 4. In section 5, with 1.35MW of X3-ECH injected into an ELMy H-mode, results on a new ELMy regime (compared to the ohmic/low-power-heating of ELMy H-modes) are presented. A comparison of the experimental results with two different models: ray-tracing and beam-tracing are presented in section 6.

2. Experimental configuration

The recently completed ECH system on the TCV Tokamak, has a total of 4.5MW of installed power (4.05MW of injected power). It consists of 9 gyrotrons grouped in three "clusters" of three gyrotrons each [9]. Two of the clusters operate at 82.7GHz (0.5MW/gyrotron, 2s) and are used for heating and/or current drive, coupling to the X-mode EC plasma wave from the low-field side and being absorbed at the 2nd harmonic resonance (X2). The third cluster operates at 118GHz (0.5MW/gyrotron, 2s), couples to X-mode from the top of the vacuum vessel and provides the ECH power which is absorbed at the 3rd harmonic resonance (X3) [10].

As shown in Fig. 1, on the left, the three X3 waveguides radiate the rf beams onto a single toroidal mirror with a maximum incident power of 1.35MW. For the maximum rf pulse length in TCV of 2s, no cooling of the mirror is needed. The mirror is made of OFHC (Oxygen Free High Conductivity) copper \((246 \times 182.6 \times 10 \text{mm}^3, 4 \text{kg})\) and has a 700mm focal length, focusing the beam inside the plasma. Assuming a gaussian distribution, its waist is \( w_0 = 3.3 \text{cm} \) in E-field and is located approximately at the vacuum vessel center. The mirror can be steered radially from 800mm to 960mm from pulse to pulse and the mirror angle \( \theta_l \) can vary from 40° to 50° during the shot with a maximum speed of \( d\theta_l/dt = 20 \text{ deg/s} \).

Drawings and pictures of different parts of the top-launch housing and its motorization are shown in Fig.2a-d. The friction-less flexure-pivots shown in Fig.2c are a key element for the real-
time control of the mirror angle. Fatigue tests of this entire system over two years of operation has demonstrated very high reliability of this design. Similar flexure pivots are presently part of the design of the ITER front-steering launcher [11]. Fig. 2 d, shows the transfer function represented in a Bode diagram (amplitude and phase versus frequency) of the mirror system and its motorization. A strongly damped resonance is observed around the frequency of 13Hz which is chosen as the driving frequency for the harmonic perturbation. The red curves represents an analytical fit with a second order pole ($G_2(s)$ in Fig. 4). In general for real time control of such mirror systems, and in particular for the different EC launchers in ITER (upper port and equatorial) such a transfer function needs to be determined for each mirror to allow a proper design of the real-time feedback.

A key characteristic of the X3 top-launch heating is its sensitivity of the absorption to mirror angle as shown in Fig. 3 [8, 12]. For a given plasma equilibrium shown in Fig. 3b and a fixed mirror radial position the plasma response versus mirror angle is shown in Fig. 3a. With 0.45 MW of injected power, the level of absorption is indicated on this figure by the variation of the central temperature ($T_{eX}$, blue curve) deduced from the soft X-ray emission measurement along a central vertical view line by using the two-foil method (the method is based on the ratio of X-ray emissivities passing through two different low-pass filters [13]). As a comparison, the calculated absorption with the TORAY-GA code is shown in red. The optimum injection angle and the width of the absorption curve are in good agreement between the experiment and the simulation. The calculated X3 top-launch absorption versus mirror angle and radial position of the launcher is shown in Fig. 3c. The target plasma cross section is shown in the inserts and the absorption has been calculated on an experimentally obtained plasma equilibrium having a central electron density and temperature of $4 \times 10^{19} \text{m}^{-3}$ and 2.7 keV, respectively. One notices that the FWHM of the absorption versus mirror angle is weakly dependent on the radial position.

The absorption sensitivity on the mirror angle $\theta_l$ has been experimentally studied in previous experiments and is also modelled by numerical simulations with TORAY-GA. For
Figure 2. a) Schematic of the top-launch mirror. b) Picture of the frictionless bearings (Flexure-pivots) used for the mirror angle movement. c) Picture of the mirror with shown the chain system allowing the radial movement between shots. d) Frequency response of the mirror+motorization system represented in a Bode diagram (amplitude and phase).

a given plasma with fixed temperature and density profiles, the numerical simulation shows that the optimum mirror angle (at a fixed mirror radial position) depends on the central temperature and density with a sensitivity of $\frac{d\theta}{dT_e|_{n_e}} = 0.2 \text{ deg/keV}$ (relativistic shift) and $\frac{d\theta}{dn_e|_{T_e}} = 0.18 \text{ deg/}(n_e 10^{19} \text{ m}^{-3})$ (refraction). This high sensitivity has motivated the development of a real time control of the mirror angle.

3. Real time control of the mirror angle
The real-time control is based on a sinusoidal modulation of the mirror angle and a synchronous demodulation of the plasma response. With this system it is possible to generate an error signal which is proportional to the derivative $dI_x/d\theta_l$ (or $dT_{eX}/d\theta_l$ in Fig. 3a) where $I_x$ is the soft-X ray emissivity measured along a vertical chord passing through the plasma axis. A schematic of the analogue feedback system is shown in 4. The harmonic perturbation at 13Hz is used both for applying the sinusoidal perturbation on the launcher mirror and also as an input of the synchronous demodulator which is placed after a pass-band filter centered at 13 ± 5Hz. At the output of the demodulator the AC component is filtered out by a low-pass filter ($f_{cutoff} = 2\text{Hz}$) with the resulting signal being proportional to the derivative of the plasma response function, $dI_X/d\theta_l$. The dynamic response of the closed-loop system can be adjusted by the parameters of the PID (Proportional, Integral, Derivative) controller.

The dynamic response of the open-loop system is shown in Fig.5, where the different traces, labeled from a) to d), correspond to the points a) to d) indicated on Fig.4. Trace d) is the error signal which is proportional to the slope $dI_x/d\theta_l$. On trace c) one notices that the envelope of the signal at the pass-band filter output crosses zero exactly at the time ($t_1 = 1.41s$) when the mirror is at the optimum angle. The small time delay between this time, $t_1$, and the time of
Figure 3. a) Blue trace: plasma temperature, $T_e X$, versus mirror angle (the yellow trace is the result of low-pass filtering the blue trace). In red, the absorbed fraction as predicted by TORAY-GA. b) Cross section of the plasma with ray trajectories for different injection angles. c) Contour plot of calculated absorbed fraction (ray-tracing code TORAY-GA) versus mirror angle and radial position of the mirror.

Figure 4. Schematic of the complete closed-loop feedback system.

zero crossing of trace d) ($t_2 = 1.47s$) is caused by the low-pass filter. This small difference can be compensated by adjusting the level of the reference signal $R(s)$.

In the closed loop system, this error signal is compared to an externally preset reference ($R(s)$ in Fig.4). The difference between the error signal and the reference is fed to a PID controller. For both, a P-term and a PI-term in the PID controller, studies of the dynamic response of the closed-loop system have been carried out on a wide variety of plasmas and mirror radial launching positions. The I-term has the property to bring to zero the steady state error as it is shown on Fig.6 (left figure third trace from top). It has also been verified that the system is able to track the optimum angle when an external preprogrammed ramp forces the mirror angle to move away from its optimum value[12]. It is planned to transform this analogue feedback system to a digital one.

The dynamic response of the closed-loop system with a PI controller is shown in Fig.6 where the external preset mirror angle was fixed at a value of 45.5deg. After a transient period of approximately $\tau_t = 250ms$, the mirror angle has reached a stationary optimum value. For fixed parameters of the PI-controller, the experimentally measured characteristic time for the transient period is linearly increasing with the plasma density[12].
Figure 5. Open-loop signals during a linear sweep of the mirror angle where a linear angular sweep is performed such to cross the optimum mirror angle. On this linear sweep there is superimposed the sinusoidal modulation at 13Hz. The different traces labeled a) to d) correspond to the points a) to d) indicated on Fig.4.

Figure 6. On the left, dynamics of the closed-loop feedback system on a plasma shot where the external reference has been set to a constant angle of 45.5°. In this shot a PI controller was used and one can see that after a transient period of approximately 250ms the error signal reaches a constant zero value consistent with the presence if the integral term in the controller. On the right, simulated dynamics of the closed-loop feedback system using the @MATLAB’s Simulink software package. In this simulation an analytic expression of the different transfer functions $G_i(s)$ has been used.
4. X3 Absorption studies on L-mode plasmas with mirror-angle real-time control

Results on the top-launch X3 absorption properties on L-mode plasma has been already reported in an earlier work [12] and a summary is presented in Fig.7. This study has been performed with the real-time control of the mirror angle and the measurement of the absorbed fraction is based on the measurement of the diamagnetic flux (DML) perturbation during a modulated portion of the injected rf power (full-power modulation of one gyrotron at 237Hz) [14]. The main conclusions of this study are: a) the real-time feedback is fully operational with L-mode plasmas, b) full single-pass absorption has been measured (DML) for central plasma densities lower than $5 \times 10^{19}$ m$^{-3}$.

At these plasma densities the calculated absorbed fraction (TORAY-GA), based on a maxwellian distribution function, is significantly lower than the measured one. The difference is to be associated with a suprathermal electron population created by the X3 itself. Evidence for this SEP is found on diagnostics sensitive to suprathermal electrons such as the high-field-side ECE\[15\] and a hard X-ray camera\[16\]. Similar results of an absorption enhancement in presence of a SEP have been obtained with a X3 low field side injection in presence of X2 CO-ECCD\[17\].

For a Maxwellian electron distribution function with a temperature of $T_e = 2keV$ and a characteristic width of the rf-beam ($w_0 = 33$ mm) the ratio $w_{res}/w_0 \approx 1/2$. In presence of a SEP with a distribution assumed to be Maxwellian, depending on the temperature and density of the SEP, the ratio $w^{*}_{res}/w_0$ can become significantly larger than $w_{res}/w_0$ and therefore yield to an improved absorption. Without the presence of a SEP, as it is the case for H-mode plasmas, the ratio $w_{res}/w_0$ can be increased by decreasing $w_0$. This point will be discussed below.

5. X3 heating of H-mode plasmas

In recent experiments dedicated to heating of H-mode plasma it has been possible to reach nearly full single-pass absorption on a target plasma with a central density of $n_{e0} = 8 \times 10^{19}$ m$^{-3}$. In these experiments the real-time feedback on the mirror angle could not be used due to perturbations on the $I_X$ signal associated with ELM induced density perturbations as well as fast density variation in ELM free periods occurring during the X3 rf pulse. It is planned to eliminate these effects by using, instead of the $I_X$ signal ($I_X \sim n_e^2$), the $T_{eX}$ signal which has no $n_e$ dependence.

The temporal evolution of the relevant physical quantities of a typical shot are shown in Fig.8. As previously reported [12], with a total injected power of 1.35MW, an ELMy regime that is significantly different to ohmic/low-power-heating ELMy H-mode [18], has been found. This new regime of ELMy H-mode is highly reproducible and the measured absorbed X3 fraction, is in excess of 85% at central densities of $n_{e0} = 8 \times 10^{19}$ m$^{-3}$. The measured level of absorption is in good agreement with the value calculated with the ray-tracing code TORAY-GA. This result is consistent with the fact that no SEP is observed at these high densities.

The ratio between the ohmic power and the X3 absorbed power is typically $P_{ECH}/P_\Omega = 4−5$, which level is significantly higher than the preliminary results obtained with X3-heated H-modes [19]. The plasma stored energy is significantly increased to give a plasma $\beta$ of 2.4%. Contrary to the case of L-mode plasmas, as shown in Fig.8, at these higher density levels a significant ion heating is observed which can be explained by both: a significantly higher coupling with the electrons (equipartition) together with an improved energy confinement during the X3 heated phase. Detailed analysis of these results is presently ongoing.

The measured electron density and temperature profiles (Thomson scattering) and the calculated absorption profiles (TORAY-GA) are shown in Fig.9. One notices that at the time of the X3 turn-on, the calculated absorbed fraction is approximately 30% and increases up to more than 90% once the stationary X3-heated phase is reached. The corresponding deposition profiles are shown on the right of Fig.9. During the stationary X3-heated-phase the deposition profile is more central compared to the one at the X3 turn-on.
Figure 7. On the left, temperature and density profiles measure by Thomson scattering for a typical L-mode plasma with central temperature and density before the X3 rf pulse of $n_e=4 \times 10^{19} \text{m}^{-3}$ and $T_e=0.9 \text{keV}$, respectively. The red curves correspond to the temperature and density profiles during the X3 heating. On the right is a summary the absorption studies on L-mode plasmas with two different injected rf power levels 0.675MW (blue curves) and 1.125MW (red curves). All the quantity are plotted versus the central electron density $n_{e0}$ for both rf power levels. On top is the mirror angle $\theta_l$, in the middle the electron temperature $T_{eX}$ and on the bottom the absorbed fraction measured with the DML (open circles) and calculated with TORAY-GA (open squares). The target plasma used in these experiments have the following parameters: toroidal magnetic field, $B_T=1.42 \text{T}$, major radius, $R_0=0.88 \text{m}$, minor radius, $a=0.25 \text{m}$ elongation $\kappa=1.53$, triangularity $\delta=0.15$, plasma current: $I_p=235 \text{kA}$.

With a top launch configuration, by the nature of the heating scheme, nearly no control of the deposition profile is possible. However, at the plasma density and temperature reached in these H-mode X3-heated plasmas, the single-pass absorption of an X3 rf beam injected from the LFS would be larger than 55% (TORAY-GA). With such a level of absorption, a significant control of the deposition profile would be possible. In addition, with a LFS injection, the square dependence of the optical depth with temperature ($\tau_{X3,LFS} \sim T_e^2$) would bring the single pass absorption at even higher values. Motivated by these results we are presently studying the possibility to upgrade the installed X3 power on TCV by increasing the unit power of each existing gyrotron by approximately 30% ($\sim 600 \text{kW/gyrotron}$) and by adding a fourth gyrotron with a LFS injection.

6. Comparison between ray-tracing and beam tracing models
To assess the importance of diffraction effects on the X3 power absorption in the top launch configurations, a comparison between the beam tracing code ECWGB[20, 21] and the ray-tracing code TORAY-GA has been performed. The beam tracing code ECWGB can also be used as a ray-tracing code, by numerically turning-off diffraction effects.

Two main effects have motivated this study: first, the top-launch mirror has been designed such to have a waist (converging beam) approximately at the center of the vacuum vessel and, secondly, refraction effect can generate additional focusing inside the plasma. In this situation,
Figure 8. Relevant quantities for an H-mode heated plasma with an X3 injected power of 1.35MW. From top to bottom: rf power for X3, $H_\alpha$ emissivity, diamagnetic flux $\phi_{\text{dia}}$, total plasma $\beta$ (calculated with the equilibrium code (every 50ms) and constrained by the DML measurement), Thomson scattering peak electron temperature (every 17.5ms), ion temperature at $\rho = 0.6$ measured by active charge exchange spectroscopy, line integrated density. The target plasma used in these experiments have the following parameters: toroidal magnetic field, $B_T = 1.42$T, elongation $\kappa = 1.6$, triangularity $\delta = 0.55$, plasma current, $I_p = 380$kA.

the WKB approximation, on which the ray-tracing is based, might fail, and a more accurate model such as beam tracing might be necessary. With respect to the converging beam optics inside the plasma, the ray-tracing modeling of the rf beam in vacuum has been performed by imposing a ray distribution corresponding to a constant cylindrical cross section (no convergence) with a gaussian electric field distribution with a waist, $w_0 = 33$mm. This assumption is somehow unphysical, but very convenient, since, as it will be shown later, is a good approximation of a diffractive beam.

A first comparison between the two codes is shown in Fig.10. The ECWGB code, compared to TORAY-GA, uses a higher number of rays with a better homogeneity in the rays spatial distribution. In the top-launch configuration, the condition on ray homogeneity is very important as explained in [8]. In Fig.10 a) and b) 61 and 432 rays have been used respectively (only a subset are represented in Fig.10 b) ). In Fig.10c) the total absorption (sum on all rays), is calculated along the central rays (in red in Fig. (a) and (b)) for each model and is represented in the $[\Psi_N, P_{\text{abs}}(\Psi_N)]$ plane. In this representation, the rf beam path in the plasma poloidal cross section is represented by the intersection of the central rays with the normalized flux surface, the rf beam enters the plasma at the point $P_{\text{abs}} = 0, \Psi_N = 1$, reaches the magnetic axis at $\Psi_N = 0$ and exits the plasma at $P_{\text{abs,max}}, \Psi_N = 1$. On notices that, for both models, the
absorption takes mainly place between the upper plasma edge and the plasma magnetic axis. We believe that the difference in global absorption shown in Fig. c) is to be associated to the different geometrical ray distribution. Further analysis on this aspect is presently ungoing.

The modeling with ECWGB has allowed to investigate the X3 top-launch injection for a beam optics with stronger focussing than the presently designed one which has, as mentioned earlier, a waist in electric field of \( w_0 = 33 \text{mm} \). Since, the ECWGB code has the flexibility to be used in “ray-tracing” or “beam tracing” mode, we have first checked the difference in calculated absorption for the two cases, where for the ray-tracing the rf beam has been approximated in vacuum as in TORAY-GA (constant cylindrical cross section with gaussian distribution). The rays distribution in vacuum are shown in Fig.11 left for the ray-tracing case and the beam tracing case.

The comparison between the ray-tracing and beam-tracing cases versus the focussing parameter \( w_0 \) is made in Fig.12. As it is shown on the left a), for the present waist of \( w_0 = 33 \text{mm} \), there is no difference between the two models and therefore justifies the cylindrical approximation made in TORAY-GA. At stronger focussing a relatively small difference between the two models is observed, but, more importantly, a significant increase of the absorbed power can be obtained. The increase of single-pass absorption with a stronger focussing is of particular interest for X3 heating of H-mode plasmas where the high density prevents the formation of a SEP. This is an important results since it would allow, by simply redesigning the launcher mirror, to significantly improve the single pass absorption.

In Fig.12 b), the absorption sensitivity versus mirror angle is shown for different waists. One observes that for stronger focussing the FWHM width \( \delta \theta_l \) decreases, but remains well within the accuracy at which the real time control operates.

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**Figure 9.** On the left, temperature (top-trace) and density profiles (bottom-trace) measured by Thomson scattering for a typical X3-heated H-mode plasma. In blue are represented profiles during the ohmic heated phase (before X3 turn-on) and in red profiles during the stationary phase of the X3 heating. On the right, with the same color coding, are the absorption profiles for the corresponding phases shown on the left.
Figure 10. Fig. a) and b), ray trajectories calculated with TORAY-GA and ECWGB (with diffraction effects included), respectively. The only ray which must be exactly the same for the two codes is the central ray (in red in Fig. a and b). The calculated absorbed fraction on these specific central rays is the same, demonstrating that the absorption calculation is the same in the two codes. On (c), the global absorption is shown in red for the ECWGB code (diffraction effects included) and in red for TORAY-GA.

Figure 11. Ray trajectories for the ray-tracing case (cylindrical cross section without diffraction in orange) and the beam-tracing case (blue) used with ECBGW for a strongly focused beam with $w_0 = 12$mm. On the left are the corresponding ray trajectories in vacuum. On the right with a plasma of central temperature and densities of $T_{e0} = 2.3$keV and $n_{e0} = 8.7 \times 10^{19}$m$^{-3}$. The density and temperature profiles correspond to the profiles of the L-mode plasma shown in Fig.7 left.
7. Conclusions

A top-launch X3 ECH system with a total injected power of 1.35 MW has been installed on TCV in order to heat high density plasmas. For this launching configuration, the numerically predicted and experimentally observed strong dependence of the X3 absorption on the mirror angle has motivated the development of a real-time control of the mirror angle. This real-time control is based on a mirror modulation technique which allows to generate via a synchronous demodulator an error signal proportional to the derivative of the plasma response versus mirror angle. Stationary control of the mirror have been achieved with a PI controller. Future plans include the implementation of such a system on the X2 launchers for EBW experiments and/or real time control of MHD activity such as sawteeth. This system has been successfully tested and has allowed to perform extensive absorption studies in L-mode plasmas. With a total injected power of 1.35 MW, full-single pass-absorption has been reached with a significant fraction of the power absorbed on a suprathermal electron population generated by the X3 wave itself. With 1.35 MW of X3 injected power we have demonstrated the accessibility to an ELMy regime that is significantly different to ohmic/low-power-heating ELMy H-modes.

Comparisons between the linear ray-tracing code TORAY-GA and the beam-tracing code ECWGB has allowed to validate the cylindrical cross section approximation used in TORAY-GA for the presently used launcher optics ($w_0 = 33$ mm). With a stronger focussing of the rf beam ($w_0 < 33$ mm), ECWGB predicts a significantly higher single-pass absorption. Plans to modify the top-launcher mirror with a stronger focussing are presently underway.

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