Third Harmonic X-mode Electron Cyclotron Resonance Heating on TCV using Top Launch

L. Porte, S. Alberti, G. Arnoux, Y. Martin, J.P. Hogge, T.P. Goodman, M.A. Henderson, E. Nelson-Melby, A. Pochelon, M.Q. Tran

Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, Association EURATOM-Confédération Suisse, CH-1015, Switzerland

Email contact of main author : laurie.porte@epfl.ch

Abstract. A third harmonic electron cyclotron resonance heating system (X3) has been installed, commissioned and brought into service on the Tokamak à Configuration Variable (TCV). It comprises three 118 GHz, 0.5 MW gyrotrons designed to produce pulses up to 2 seconds long. In the present configuration, 1.0MW is launched vertically from the top of the vessel into the plasma and the remaining 0.5MW is launched horizontally from the low field side. X3 has been used to heat plasmas at density exceeding the 2nd harmonic cut-off significantly extending the operational space of additionally heated TCV plasmas. Studies have been performed to determine the optimal plasma/launcher configuration for X3 absorption for various plasma conditions and to find methods for real time feedback control of the X3 launcher. First experiments have been performed aimed at heating H-mode plasmas on TCV. First results show that the ELMs in TCV ohmic H-mode plasmas exhibit all characteristics of Type III ELMs. If, at moderate X3 power (<0.3MW), the additional heating is increased and then decreased, the ELM frequency first decreases and then increases again. At higher X3 power (>0.45MW) the Type III ELMs disappear and the H-mode discharge exhibits different MHD phenomena eventually disrupting.

1. Introduction

TCV has had a powerful and versatile 2nd harmonic electron cyclotron heating system (X2) for a number of years [1]. This system has been used to study many aspects of tokamak physics. These studies have been performed at density not exceeding the second harmonic cut-off ($n_e = 4.25\text{x}10^{19}\text{m}^{-3}$) and in practice the plasma density has been kept $<3.0\text{x}10^{19}\text{m}^{-3}$ to minimise refraction effects. The 3rd harmonic electron cyclotron heating system (X3) significantly extends TCV operations by allowing access to density up to $\approx 10^{20}\ \text{m}^{-3}$.

The linear ray tracing code TORAY-GA has proven useful as a tool in designing X3 experiments even at the high density associated with H-mode operation. In particular it is capable of predicting the optimal X3 mirror launch angle for a given plasma configuration. It has become obvious that active feedback control of the X3 launcher mirror is required to maintain X3 absorption. Experiments have been performed to determine which diagnostics are most useful for feedback control and to test methods of real-time signal analysis.

A routinely accessible ‘gateway’ to the ohmic, quasi-stationary ELMy H-mode regime has been found on TCV [2]. Using this ‘gateway’ a series of experiments has been performed to determine the best plasma/launcher geometry for heating an ELMy H-mode on TCV and to examine the effects of the heating on ELM behaviour.

In section 2, of this paper, the X3 heating system is briefly described. In section 3, the results of experiments designed to examine the feasibility of real-time feedback control of the launcher mirror are described. In section 4 the preliminary H-mode heating experiments are described. Section 5 presents a summary and conclusions.

2. The X3 heating System

A detailed description of the gyrotrons has been given by Alberti et al in [3]. The entire system is described by J.P. Hogge et al [4]. Three gyrotrons operating at 118 GHz and rated for 500 kW, 2-second-operation have been installed on TCV. A matching optical unit (MOU) is used to manually set the polarisation of the gyrotron output beam with arbitrary, controllable ellipticity. The elliptically polarised beam, from each gyrotron, is transmitted to the tokamak or a calibrated load along ≈40m of evacuated corrugated waveguide. Each gyrotron has its own transmission line. The three separate waveguides of the top launch system converge in the direction of the single launcher mirror that has a focal length of 700mm and is made of copper; Fig 1b. The mirror can be translated, on a shot to shot basis along a major radius between 800mm and 965mm (the vacuum vessel axis is at 880mm) and can be rotated poloidally, during a shot, between 40^o and 50^o. Figure 1 shows the experimental layout with the beam trajectory following the cyclotron resonance and antenna system.

(1a)

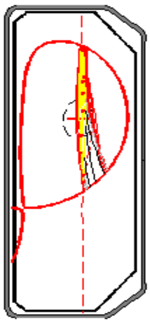
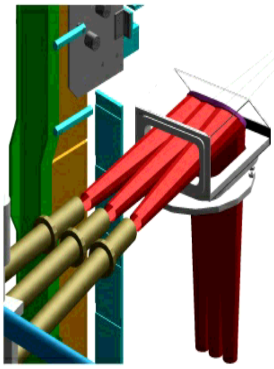


Figure 1: X3 radiation is projected into TCV from the top and traverses the cyclotron resonance; dashed red line in (1a). Radiation is delivered to the top launcher along three separate evacuated waveguides that converge to a point behind the single mirror (see 1b) of the top launcher.



(1b)

3. Launcher Optimisation and Feedback Control

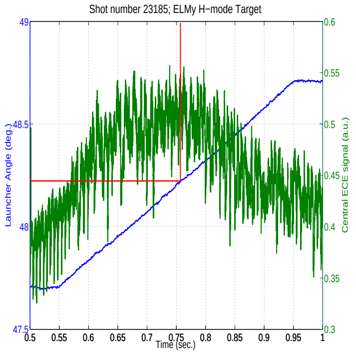


Figure 2: The plasma response measured using a central ECE channel is plotted with the X3 launcher angle.

With a long narrow resonance layer (see Figure 1a) it is important that one can, a priori, predict the optimal launcher angle for X3 and control the mirror launch angle in real time to adapt to changes in the plasma profiles. TORAY-GA has been used to predict the optimal launch angle and experiments have been performed to study the best means of real time mirror control.

Sweeping the X3 poloidal launch angle while heating stationary plasma allows one to determine the optimal launcher angle. By comparing the experimentally deduced optimal launcher angle with the TORAY-GA predicted angle one can benchmark the code for the plasma parameter range of interest. This has been done for steady-state H-mode plasma. Figure 2 shows the plasma response measured using a central ECE channel that has a line of sight through the plasma centre. The peak in the ECE signal is interpreted as representing the moment of maximum power absorption and the launcher angle at this time is assumed to be the optimal angle. Here the maximum response is at a launcher angle of ≈48.2^o; TORAY-GA predicted an optimal angle of 48^o for this discharge. TORAY-GA may be used as a tool in designing H-mode experiments with X3 top launch heating.

During the heating phase, plasma profiles change and the position of the maximum electron cyclotron absorption may move. If the launch mirror does not move to accommodate this, the absorbed power may decrease: real time launcher mirror control is required. Experiments were performed to test means of real time data analysis and to determine the best signals for use in real time control. The launcher mirror was swept linearly through the cyclotron resonance but superimposed on the linear sweep were sinusoidal oscillations. The oscillations perturbed the absorption and allowed one to determine the maximum response by examining the phase and amplitude of the perturbations. Figure 3a, top, shows the mirror sweep while 3a, bottom, shows the plasma response measured by a soft X-ray camera with a line of sight through the plasma centre. Figure 3b displays the measured plasma response (top), with filtered perturbation and filtered response signals. Shown, also, is the deduced phase of the response. At the peak of the measured response, the phase of the response attains a value of π/2 radians and exhibits a π radians phase change as the peak is traversed. Locking the phase response would allow real time control of the mirror. The centrally viewing SXR camera signal can be used as a source for real time control. Algorithms that can be implemented, in real time, on a digital signal processing (DSP) card are being developed.

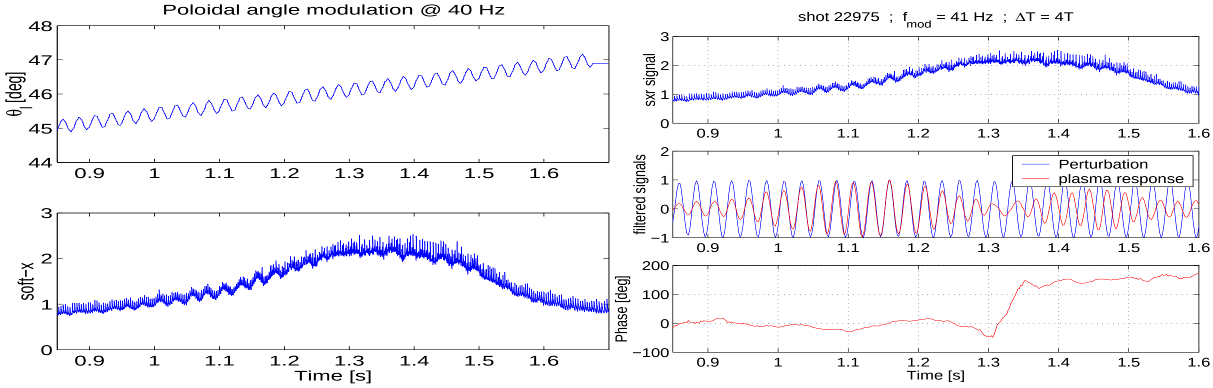


Figure 3a *Figure 3b*

Figure 3: Fig 3a (top) shows the mirror sweep with the sinusoidal perturbation and 3a (bottom) shows the plasma response measured using a centrally viewing SXR camera. By post processing the SXR signal it is possible to extract the amplitude and phase of the plasma response w.r.t. the imposed perturbation. The phase response is shown in Fig 3b along with the SXR signal and the digitally filtered signals. The deduced phase signal shows where the maximum plasma response is located. By phase locking the response it will be possible to control in real time the launcher mirror.

4. X3 heating of H-mode discharges

Until X3 heating was installed on TCV the only quasi-stationary H-modes that were routinely available were ohmic H-modes that were approached through a narrow gateway in parameter space [2]. Experiments using X2 to heat the plasma, in H-mode, have been performed but these have only been used to heat the extreme plasma edge (ρ > 0.9) and have, for machine safety reasons, been limited to ECH pulse lengths no longer than 20ms. Using X3 to heat the core of ELMy H-modes, accessed through the gateway, experiments have been performed to establish quasi-stationary additionally heated ELMy H-modes and to study the effect of heating on the ELMs. Quasi-stationary ELMy and non-stationary ELM free H-modes have been established on TCV at densities far exceeding the X2 cut-off using X3 pulse lengths of several hundred milli-seconds. In all of these discharges the ohmic heating power was ≈500kW. In these experiments it was impossible to measure the coupled X3 power because the ELMs perturbed the diamagnetic measurement too much. Work is continuing to develop means of measuring the absorbed power in the presence of ELMs. Estimates of coupled power, stated in this paper, are from TORAY-GA calculations. Pochelon et al [5] describe experiments where they measure almost full absorption (>90%) of X3 using top launch.

Initial attempts to heat the ELMy H-mode on TCV often led to an ELM free period that transited back to L-mode finally disrupting after the formation of a locked mode: see Figure 4a. These discharges were non-stationary and the disruption limited the heating period to less than ≈200ms. This behaviour prevailed even at low additional heating power; <200kW. By reducing the gas feed ≈100ms before the start of X3 it has been possible to maintain the quasi-stationary H-mode in the presence of X3. The reduced gas feed increased the ELM frequency. The increased ELM frequency balanced the tendency of the heating power to decrease the ELM frequency and permitted the ELMy H-mode to be maintained. The MHD phenomena, that caused the locked mode and disruption, were avoided or at least delayed. Access to longer (> 700ms) additionally heated H-mode discharges was obtained. Figure 4b shows such a discharge.

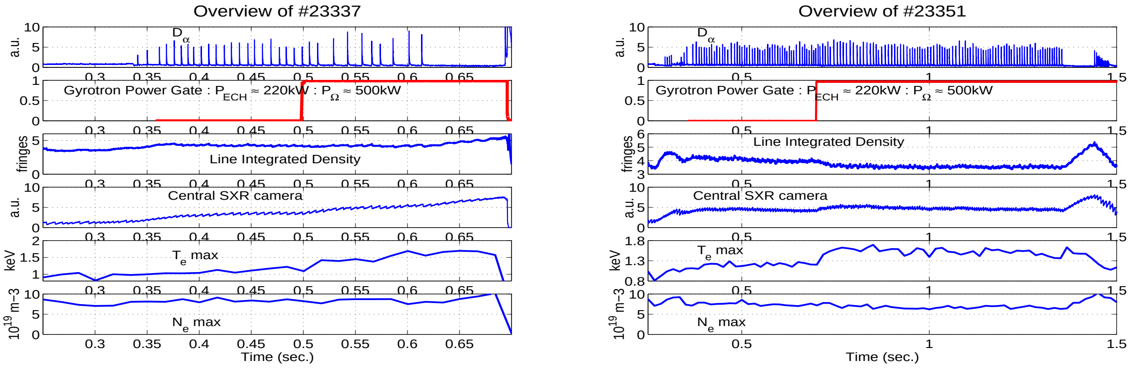


Figure 4a. *Figure 4b*

Figure 4: Fig. 4a shows the evolution of a X3 heated ELMy H-mode that exhibits the typical transition to ELM free H-mode (at ≈0.62sec.), MHD phenomenon (at 0.69sec.) followed immediately by a disruption. Fig. 4b exhibits the modified, more stable behaviour of a X3 heated ELMy H-mode with a modified gas feed. At ≈1.3 times higher additional heating power, the discharge remains ELMy.

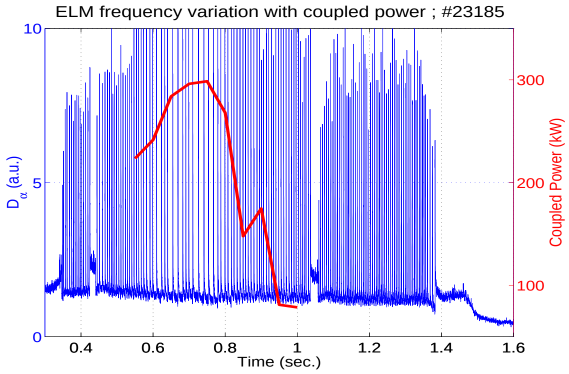


Figure 5: shown here are the power coupled to the plasma (from TORAY-GA) and the D_α signal. In this experiment the launch mirror was swept across the cyclotron resonance resulting heating power that first decreased, to ≈300kW, then increased. In response to the heating power the ELM frequency first increased and then decreased.

To examine the behaviour of the ELMs typical of a TCV ohmic, ELMy H-mode the X3 launcher mirror was scanned across the cyclotron resonance. With an X3 injected power of ≈420kW, the coupled power first increased from ≈220kW to ≈300kW then decreased to <100kW while the ohmic heating power remained approximately constant. The discharge stayed in the ELMy regime similar to that of the ohmic H-mode but the ELM frequency first decreased then increased with the ECH power. The energy loss per Type III ELM was measured to be ≈1 kJoule. ELMs in TCV ohmic H-mode exhibit the characteristics of the so-called Type III ELMs [6]. Chord averaged measurements from a soft X-ray camera reveal that, typically, these ELMs affect only the plasma edge (ρ > 0.6).

Experiments where $P_{ECH} \approx P_\Omega$, have been performed to explore the H-mode in a regime where the ohmic H-mode ELMs disappear. Figure 6 shows the overview of a typical discharge. The coupled power remained approximately constant at ≈520 kW (840kW launched power). The 'ohmic H-mode ELMs' disappeared after ≈50 msec. of heating. They were replaced by an event that caused a rapid loss of particles and energy and that affected the whole minor radius. Figure 6b shows the effect on the plasma of this instability as measured using a high-resolution soft X-ray camera. There is rapid (<150 µsec.) loss of particles and energy at normalised radii $\rho > 0.55$. At radii $\rho < 0.55$ the loss of energy and particles starts at the same time but the decay is somewhat longer (> 300 µsec.). Typically, the high power discharges end in a disruption after the formation of a locked mode.

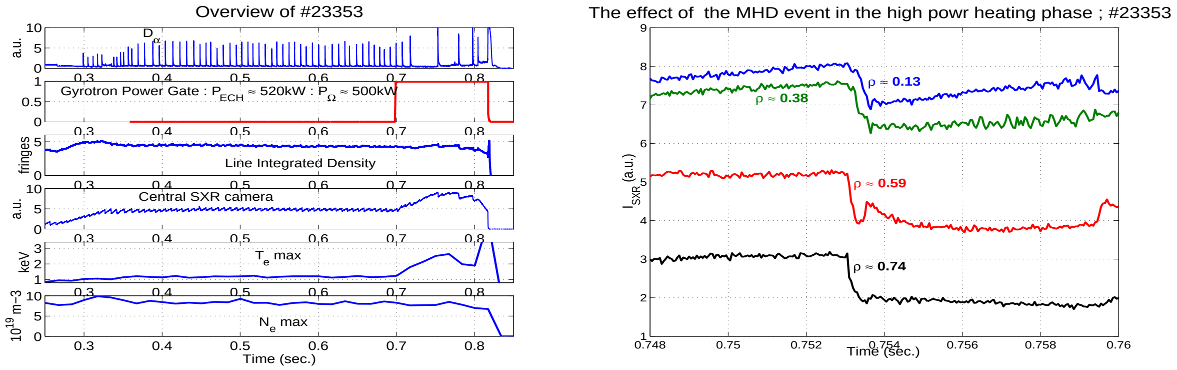


Figure 6a *Figure 6b*

Figure 6: 6a shows the overview of an ELMy H-mode subject to high additional heating power. The ohmic ELMs disappear after ≈50msec to be replaced by an instability that affects the whole minor radius. The new instability has no measured precursor and measurements show the loss of energy starts at the same time in the centre as in the edge. The heat loss from the edge happens more quickly than from the centre; see Fig 6b.

5. Summary and Conclusions

A 3rd harmonic ECRH system (X3) has been installed and commissioned on TCV. TORAY-GA has been found adequate for use in designing X3 in H-mode experiments. Real time launcher position control is required and experiments have been performed to explore data analysis techniques suitable for real time control and to decide which diagnostics are most useful. Soft X-ray cameras are promising candidates. Experiments have been performed to use X3 to heat H-mode in TCV. By varying the coupled X3 power in an ELMy H-mode plasma it has been observed that ELMs, of the sort observed in a TCV ohmic H-mode, exhibit the characteristics of Type III ELMs. Increasing the X3 power resulted in the H-mode going into an ELM-free phase and exhibiting MHD instability that affected the whole minor radius.

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Appendix 1: References

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