Abstract. In recent experiments on the Tokamak à Configuration Variable (TCV) \( \approx 1.35 \text{ MW} \) of vertically launched third harmonic extraordinary mode electron cyclotron resonance heating (ECRH) was coupled to a diverted ELMy H-mode plasma. In cases where \( \geq 1.1 \text{ MW} \) of ECRH power was coupled, the discharge either transitioned to a H-mode in which large ELMs dominated confinement or into an ELM-free H-mode with approximately constant electron density and energy confinement similar to or better than that of the large ELM regime. These H-modes operated at \( \beta_N \approx 2, \pi_e/n_G \approx 0.25 \) and had \( H_{IPB}^{98}(y,2) \) up to \( \approx 1.6 \). Despite being purely electron heated and having no net particle source these discharges maintained peaked electron density profiles \( (n_{e,o}/\langle n_e \rangle \approx 1.6) \). This paper presents an overview high power electron cyclotron resonance heated H-modes on TCV.

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1. Introduction

The Tokamak à Configuration Variable (TCV) [1,2] is a medium sized toroidal fusion experimental machine. Ohmic ELMy H-mode has been routinely achieved on TCV for some years [3]. Recently a set of three 500 kW gyrotrons, that produce radiation at the third harmonic of the electron cyclotron resonance frequency, have been installed. These gyrotrons operate at 118 GHz in the extraordinary mode and their power is launched vertically along a line of constant magnetic field. In this way the third harmonic extraordinary mode (X3) absorption is maximised and it is possible to heat the core of the ELMy H-mode on TCV. Over the past three years two of these gyrotrons have been used and it has proven very difficult to heat these H-modes when the additional RF power, $P_{RF}$, is less than or of the order of the ohmic power, $P_\Omega$, in anything other than a transitory manner [4].

During 2005 the third X3 gyrotron became available and this opened the door to ELMy H-mode on TCV with significantly increased stored energy and toroidal plasma beta; $\beta_{tor} \equiv <P>/(B_{tor}^2/2\mu_0)$ where $<$ denotes a plasma volume average, $P$ is the plasma kinetic pressure and $B_{tor}$ is the on-axis toroidal magnetic field. In some cases an ELM-free H-mode with stationary density has also been obtained that operates at elevated $\beta$ ($\beta_N \approx 2$).

This paper is organised as follows. In section 2, TCV and the X3 heating system are briefly described. The general properties of X3 absorption are described in section 3. In section 4 high power, $P_{RF} \geq P_\Omega$, X3 heating of H-mode experiments are described. Emphasis is placed on the description of the quasi-stationary ELM-free H-mode phase. Conclusions are presented in section 6 with our plans for future work.

2. TCV and the X3 ECRH system

2.1. The Tokamak à Configuration Variable (TCV)

Operation in TCV is generally conducted with a toroidal magnetic field, $B_\phi$, $\leq 1.54$ T and a plasma current, $I_p$, $< 1$ MA with an elongation, $\kappa$, $< 2.7$. The plasma facing wall is made entirely of graphite and is routinely boronised.

The tokamak is equipped with 6 gyrotrons that operate at 82.7 GHz to provide X2 heating and current drive. Cut-off and refraction limit the range of density over which the X2 system can be used is limited to $n_{max} < n_{X2, cutoff} = 4.2 \times 10^{19} m^{-3}$. Up until 2000 the X2 system was the sole source auxiliary heating available on TCV.

Stationary Type III ELMy H-mode is routinely achieved on TCV but the central electron density exceeds the cut-off for X2 and these discharges exhibit only modest $\beta_{tor} \approx 1.4\%$.

One of the main aims of TCV is to achieve high $\beta$ and to approach the ideal beta limit ($\beta_{limit,ideal} \approx 3.5\%$ for the discharges examined in this paper). Another aim is to heat ions; the ions can be heated collisionally by electrons if the density is high enough. Both of these goals can be achieved by heating H-mode at density ($\approx 7.0 \times 10^{19} m^{-3}$)
using vertically launched X3. A third aim is to enlarge the operational space in which ELMy H-modes can be achieved on TCV and to change the ELM phenomenology; the ELMs in ohmic H-mode on TCV are probably of Type III [12].

2.2. Third Harmonic Extraordinary Mode Electron Cyclotron Resonance Heating (X3)

In order to use ECRH to achieve the aims outlined above, a third harmonic ECRH system has been installed on TCV [5]. In the experiments described here only extraordinary mode polarisation was launched into the plasma. The gyrotrons can be pulsed for two seconds. The RF power from any gyrotron may be continuous or it may be modulated with a duty cycle of 50%.

Gyrotron radiation is transported along \( \approx 25 \) m evacuated, oversized corrugated waveguide. Each gyrotron has a dedicated transmission line. The three transmission lines are directed toward a single plasma facing mirror the radial position \( (R_L) \) of which can be adjusted in the range 900 mm to 800 mm between shots and its launch angle \( (\theta_L) \) may be swept from 40° to 50° during a discharge. The launcher angle can be controlled either under feed forward control or under real time feedback control [6]. Figure 1 shows the layout of the X3 launch mirror on the top of the TCV device. Figure 1a shows a poloidal cross section of the TCV machine where the X3 launcher is situated. Shown, also, are the upper lateral X2 launchers. Radiation from the three gyrotrons is projected onto one plasma facing copper mirror of focal length 700 mm as shown in Figure 1b. The mirror produces a beam spot size of \( \approx 33 \) mm in the plasma. The efficiency of the transmission line is \( \approx 90\% \) so that \( \approx 1.35 \) MW of X3 power is available at the plasma.

Detailed experimental studies of third harmonic absorption have recently been performed on TCV and details are to be found in [6, 8, 9]. The salient point for
Figure 2. Overview of a typical ohmic H-mode target plasma. Showing from top to bottom, $D_\alpha$ light, the ratio of average electron density to the Greenwald density (N.B. the maximum density is constant at $\approx 7 \times 10^{19} \text{ m}^{-3}$), the stored energy, $\beta_{\text{tor}}$ and the electron temperature.

Vertically launched X3 heating is the linear dependence of the absorption on electron temperature. Once an electron temperature $\approx 2 \text{ keV}$ has been obtained, and for an electron density $\approx 7 \times 10^{19} \text{ m}^{-3}$ the single pass X3 absorption reaches $\approx 80\%$ and effective heating is possible. The optimum density for X3 heating is $\approx 7 \times 10^{19} \text{ m}^{-3}$.

It has also been shown [6] that, in H-mode plasmas, estimates of X3 power absorption, obtained using TORAY-GA [10], are in good agreement with measurements made using a diamagnetic loop [7]. All estimates of X3 absorbed power, presented in this paper, have been obtained using TORAY-GA.

Vertical launch X3 heating, as described here, is not localised. The region over which the power is deposited is large, covering normalised radius ($\rho = \sqrt{\psi}$ where $\psi$ is the poloidal flux) range $0.1 \leq \rho \leq 0.7$.

Using the vertical launch geometry, the X3 power is launched with wavevector perpendicular to the magnetic field and therefore there is no net current drive.
3. X3 Heating of ELMy H-mode on TCV

3.1. The ELMy Ohmic H-mode Target

Ohmic ELMy H-mode has been selected as target because of its inherent relatively high, compared to L-mode, temperature ($T_e \approx 1 \text{ keV}; T_i \approx 550 \text{ eV}$) and high confinement ($\tau_E \approx 45 \text{ msec.}$) both of which help increase the X3 absorption.

An ELMy H-mode target that is routinely accessible, exhibits good vertical stability and has a density close to the optimum for X3 heating has been developed. It is a single null diverted discharge with the ion-$\nabla |\vec{B}|$ direction away from the X-point. The plasma current is in the range $390 \text{ kA} \leq I_p \leq 420 \text{ kA}$ while the plasma density is typically $n_e \approx 7 \times 10^{19} \text{ m}^{-3}$ (≈ 25% of the Greenwald density). $B_{tor} = 1.45 \text{ T}$, $\kappa_{95} = 1.65$ and the plasma triangularity, $\delta_{95} = 0.36$ while the inner plasma wall gap, $d_{inner} = 3 \text{ cm}$ and $q_{95} \approx 2.4$. The stored energy is ($W_{dia}$) 20 $\text{kJ}$ and the energy loss per ELM is $\delta W_{dia,ELM}/W_{dia} \approx 4\%$. Figure 2 displays traces of the temporal evolution of several plasma parameters for a typical ohmic H-mode target. The energy confinement time in these discharges is well described by IPB08(y,2) [11] scaling and it is with reference to this scaling that H-factors are calculated in this paper.

It was shown in [12] that the ELMs in the ohmic H-mode of TCV are probably of Type III and they are essential for their role in maintaining the density close to the optimum for X3 heating.

3.2. High Power Heating of ELMy H-mode using X3

Using three X3 gyrotrons the available power at the plasma is $\approx 1.45 \text{ MW}$ and the absorbed fraction can greatly exceed the L- to H-mode transition power threshold ($\approx 500 \text{ kW}$). With this level of available power a new regimes of H-mode operation were obtained on TCV. The first of these regimes exhibits ELMs that are much larger than in the ohmic H-mode phase. During this phase the average stored energy and average electron density remain approximately constant. In the second regime, the H-mode is maintained but the ELMs are lost. Despite the lack of ELMs both the $W_{dia}$ and the $n_e$ remain approximately constant.

3.3. Characteristics of X3 Absorption in H-mode Plasma

At the start of the X3 heating phase, when the electron temperature is $\approx 1 \text{ keV}$, only 35 % of X3 power is coupled to the plasma. The single pass X3 absorption increases with electron temperature until a maximum absorption, typically in the region $70\% \leq P_{X3,abs} \leq 80\%$, is reached. Figure 3 shows the X3 power absorption as a function of $\rho$ as calculated using TORAY-GA in a case where the electron temperature is already high ($\approx 2.7 \text{ keV}$) and the density is near optimal. The power deposition region lies in the region $0.1 \geq \rho \geq 0.7$, straddles the $q=1$ surface and is clearly not localised. Figure 3b shows TORAY-GA calculated ray trajectories and the approximate location of the
X3 resonance. The RF beam is projected toward the high field side of the resonance to benefit from absorption on the relativistically broadened resonance.

Figure 4 shows how the X3 coupled power varies with time in a typical X3 heated H-mode case. Initially, the X3 absorption was low ($\approx 44\%$) but quickly increased to $\approx 70\%$ (1.0 MW of coupled X3 power) as $T_e$ (not shown) increased from 1.0 keV to 1.8 keV. At the same time the ohmic power fell from $\approx 500$ kW to $\approx 350$ kW. The total heating power therefore increased from 500 kW to $\approx 1.35$ MW.

The mirror-angular region over which good X3 absorption takes place is typically $\approx 0.5^\circ$ for an electron temperature of 1 keV. However, as the plasma heats this angular range increases, because of the relativistic dependence of the electron mass on energy. At 3 keV the angular width is $\approx 2^\circ$ and the heating efficiency is much less sensitive to fluctuations in density that would normally require adjustment of the mirror angle to compensate.

These discharges are extremely reproducible and the conditions are such that if the ELMs are maintained then the electron density remains, on average, approximately constant. Therefore refraction of the RF beam can be compensated for by adjustment of the mirror angle, a priori, using TORAY-GA as a predictive tool and because the

Figure 3. (a) Beam integrated, incremental X3 absorption as a function of normalised radius. The absorption, and hence the heating, occur place between $\rho \approx 0.7$ and $\rho \approx 0.1$. (b) TORAY-GA calculated ray trajectories superimposed on the flux contours of the discharge and the approximate location of the X3 resonance shown by the black line.
angular width of the resonance curve is rather large, the launch angle is left fixed during the discharge.

As shown in [6], TORAY-GA estimates of the absorbed X3 power are in agreement with measurements of the absorbed power made using a diamagnetic loop. TORAY-GA calculates only first pass absorption. Absorption of the X3 radiation, after multiple passes through the plasma, is negligible.

3.4. Large ELM Regime

The large ELMy regime in the presence of X3 has already been described [13] so only a brief description is given here.

An ELMy H-mode that can last in excess of 30 energy confinement times and has constant average $n_e$ and constant average $W_{dia}$ is easily accessible on TCV using high power X3 heating. Figure 5 gives an overview of a typical example of such a discharge. During the X3 heating phase both the stored energy and $\beta_{tr}$ are doubled. The electron temperature increases from $\approx 1 \text{ keV}$ to $\approx 3 \text{ keV}$. The ELM character changes dramatically. In the ohmic phase the ELM frequency is $\approx 150 \text{ Hz}$ while it is closer to $50 \text{ Hz}$ in the X3 phase. The energy loss per ELM increases from $\approx 4 \%$ to $\approx 12 \%$. The average density remains approximately constant throughout the X3 phase.
These discharges exhibit good confinement with H-factors between \( \approx 1.0 \) and \( \approx 1.3 \).

The ELM type issue has still to be resolved since X3 power scans have yet to be performed. However, given that the heating power is much greater than the L- to H-mode transition threshold power, these large ELMs are probably Type I [14]. As yet no magnetic pre-cursors have been found associated with the big ELMs.

3.5. Quasi-Stationary ELM-free H-Mode Phase

Using the same launch geometry and the same plasma target as for the large ELMy H-modes, an H-mode regime that is ELM-free and is quasi-stationary. This regime is characterised by elevated \( D_\alpha \) light emission compared to the Type III ELMy H-mode, approximately constant \( n_e \), constant \( W_{\text{dia}} \), high \( \beta_{\text{tor}} \) and high \( \tau_E \). It is not yet understood why, in some cases, the ELM-free regime is accessed in preference to the ELMy regime.

3.5.1. General Characteristics

An example of this remarkable quasi-stationary ELM-free H-mode is shown in Figure 6. This discharge entered a quasi-stationary ELM-free phase at 0.85sec that lasted, uninterrupted, until 1.1sec; \( \approx 10 \) confinement times. At this time the discharge entered a brief ELM-free H-mode period more typical of the ohmic H-mode before entering a second quasi-stationary ELM-free H-mode phase that
ERCH of H-mode on TCV

Figure 6. Overview of TCV shot 29475. From top to bottom, the \(D_\alpha\) light, Greenwald ratio (\(n_e\approx\) constant at \(7.0 \times 10^{19} m^{-3}\)), the stored energy, \(\beta_{\text{tor}}\) and electron temperature. This discharge was an ELMy H-mode target heated with \(\approx 1.4 MW\) of total heating power in the period 0.6 sec. until 1.4 sec.

The electron pressure profiles were very similar in the ohmic H-mode phase, the X3 heated large ELM phase and the quasi-stationary H-mode phase (n.b. the high resolution thomson scattering diagnostic was not available for this campaign so changes in the extreme edge, \(\rho > 0.9\), pressure profile could not be resolved). Figure 7 compares electron temperature, electron density and incremental X3 absorption profiles from a discharge in which both the large-ELM regime and the quasi-stationary ELM-free H-mode regime were observed. There are no significant differences between the pressure profiles during the three phases.

Measured \(\beta_{\text{tor}}\) was \(\approx 2.5\%\) (c.f. \(\beta_{\text{limit,ideal}} \approx 3.5\%\)) and the confinement time for these discharges was \(\approx 30 m\text{sec} \ (H_{\text{PB98}}(y,2) \approx 1.4)\) at full heating power. Values of \(H_{\text{PB98}}(y,2) \approx 1.7\) have been achieved.

In the ohmic phase the density peaking factor, \(n_{e,o}/<n_e>\), is \(\approx 1.68\) while in both the large ELMy phase and the ELM-free quasi-stationary phase it is reduced very slightly to between 1.5 and 1.6. Numerical simulation, using K1D code [15] indicates that edge fuelling plays no role in maintaining the density peaking in these discharges. The low loop voltage in these discharges also suggests that the Ware pinch cannot be invoked to explain the density peaking. Some anomalous pinch must be at work [16,17].
Measurements of soft X-ray emission revealed no sign of impurity accumulation during the quasi-stationary ELM-free phase; $Z_{\text{eff}} \approx 2.5$ in the ohmic phase and increased to $\approx 3$ in the X3 phase.

The $D_\alpha$ recycling light level was high during the ELM-free quasi-stationary phase; it was approximately equal to the level in the ohmic phase before the H-mode transition. The radiated power ($P_{\text{rad}}$) was $\approx 300$ kW and did not increase during the quasi-stationary phase.

The quasi-stationary ELM-free H-mode bears some resemblance to the quiescent H-mode found on DIII-D [18] and the EDA H-mode observed on ALCATOR C-MOD [19].

There are some fundamental differences between the quiescent H-mode observed on DIII-D and that observed on TCV. On DIII-D neutral beam injection and cryo-pumping are required. The quasi-stationary ELM-free H-mode on TCV has no direct ion heating, no active fuelling and no cryo-pumping. The DIII-D quiescent H-mode is accompanied by an Edge Harmonic Oscillation (EHO) that is believed to control the plasma density during DIII-D quiescent H-mode.

On ALCATOR C-MOD the EDA H-mode exhibits high energy confinement and high levels of recycling light as does the TCV quasi-stationary ELM-free H-mode. However, the EDA H-mode is generally obtained at $q_{95} > 3.7$ while on TCV the quasi-stationary ELM-free H-mode is obtained at $q_{95} \approx 2.5$. Also, the EDA H-mode
is accompanied by broad-band and coherent fluctuations in the edge density that are believed moderate the core plasma density.

The quasi-stationary ELM-free H-mode on TCV had approximately constant electron density. It is not known how the density was controlled and to date TCV has not had the diagnostic coverage to detect edge density fluctuations. However, no magnetic signatures, similar to the EHO, have been detected.

The quasi-stationary ELM-free phase of TCV H-mode discharges did exhibit some core MHD. They were typically dominated either by m/n = 1/1 modes associated with sawteeth (present throughout the discharges) or by m/n = 4/3 tearing modes that were associated with reduced energy confinement compared to the m/n = 1/1 dominated phases. The fluctuations observed on the $D_\alpha$ light during the quasi-stationary ELMy H-mode phase are not ELMs. Rather they are strongly correlated with the core MHD.

3.5.2. Ion Behaviour  During the quiescent H-mode phase it was possible to measure the carbon ion toroidal rotation, $v_{\text{tor},C}$, and carbon ion temperature profiles, $T_C$. These measurements were made using TCV Charge Exchange Recombination Spectroscopy (CXRS) diagnostic [20]. Due to the line of sight used by the CXRS system it was not possible to obtain measurements of $T_C$ and $v_{\text{tor},C}$ at $\rho < 0.6$.  

Figure 8. $D_\alpha$ light with the temporal evolution of the carbon ion temperature and carbon ion toroidal rotation velocity at $\rho \approx 0.6$ for shot number 29475. Shown also are the X3 heating phase (pink) and the three quasi-stationary H-mode phases (green) labelled 1, 2 and 3.
Figure 9. During the ELM-free quasi-stationary H-modes the carbon ion temperature, at $\rho \approx 0.6$ in this case, increased from $\approx 500 \text{ eV}$ to $\approx 1 \text{ keV}$. At the same time the carbon ion toroidal rotation, at the same location, increase from $\approx 5 \text{ kms}^{-1}$ to $\approx 50 \text{ kms}^{-1}$.

Figure 8 shows the temporal evolution of the $D_{\alpha}$ recycling light, the $T_C$ and $v_{\text{tor},C}$, both at $\rho \approx 0.6$, for shot 29475. The X3 heating phase lasted from 0.6 sec to 1.4 sec. For the first time significant ion heating has been measured on TCV. At mid-radius the ion temperature increased from $\approx 500 \text{ eV}$ to $\approx 1 \text{ keV}$. At the same time the carbon ion toroidal rotation speed was measured to increase significantly; this is despite the fact that the X3 heating produces no net momentum.

In this discharge there were three ELM-free phases. The first (1), in the period 0.68 sec. to 0.83 sec., was dominated by a m/n=1/1 mode while the second (2), in the period 0.84 sec. to 0.9 sec., was dominated by an m/n=4/3 mode. The m/n = 4/3 mode degraded the plasma performance and both the $T_C$ and $v_{\text{tor},C}$ fell. In the third (3) quasi-stationary ELM free phase in the period 00.9 sec. to 1.37 sec. the discharge was again dominated by m/n = 1/1 modes and both the $T_C$ and $v_{\text{tor},C}$ partially recovered.

In Figure 9 are plotted ion rotation velocity profiles at various times during TCV shot 29475. The radial gradients of toroidal velocity were approximately the same, at $\rho < 0.92$, in all three quasi-stationary H-mode phases.

In both diverted ohmic H-mode and quasi-stationary ELM-free H-mode the plasma rotation is co-current contrary to what has been measured in L-mode on TCV [21].
4. Conclusions

To ensure good X3 heating it is necessary to have sufficient coupled power to increase the electron temperature to greater than $\approx 2.0 \text{ keV}$. Simultaneously it is necessary to ensure approximately constant density at $n_{e,\text{max}} \approx 7.0 \times 10^{19} \text{m}^{-3}$. When both these criteria are met then efficient X3 heating (absorption $\approx 80\%$) can be achieved.

Having satisfied these two requirements, high power additional heating ($P_{\text{add}} >> P_{\Omega}$) of ELMy H-mode plasma has been achieved on TCV using X3 with first pass X3 absorption up to 85 %.

This has enabled TCV ELMy H-mode plasmas to enter two different regimes. The first was an H-mode resembling a Type I ELMy H-mode. The ELM type is to be verified. The second regime was a quasi-stationary ELMy-free H-mode that had approximately constant stored energy and electron density. Both of these regimes were obtained at $\beta_N \approx 2$.

The mechanism for density control during the quasi-stationary H-mode is unknown. No magnetic signature similar to that of an EHO has been observed and, due to a lack of diagnostic coverage, it has been impossible to detect edge density fluctuations. The quasi-stationary ELMy-free H-modes did exhibit core MHD activity and the $D_\alpha$ recycling light was strongly correlated with it.

The electron density profiles were peaked ($n_{e,o}/<n_e> \approx 1.6$) in both the ohmic phase and the quasi-stationary ELMy-free H-modes. This suggests the presence of some anomalous particle pinch.

Ion heating has been demonstrated. The mid-radius ion temperature increased from $\approx 500 \text{ eV}$ to $\approx 1 \text{ keV}$ and the ion rotation increased from $\approx 5 \text{ kms}^{-1}$ to $\approx 50 \text{ kms}^{-1}$.

It is hoped, in future campaigns, to complement the measurements presented here with more complete measurements of ion temperature and impurity ion rotation by moving the plasma to the centre of the TCV machine. Work is underway to install both a reflectometer [22] and a phase contrast imaging diagnostic [23] on TCV.

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References


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