

# OBSERVATIONS OF UP-DOWN DIFFERENCES IN PLASMA RESPONSE DURING ECRH ON TCV

T.P. Goodman, **M.A. Henderson**, Z.A. Pietrzyk, A. Pochelon, M.Q. Tran, J-Ph. Hogge,  
J-M. Moret, H. Reimerdes, O. Sauter and W. van Toledo

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

**Introduction:** During initial experiments with electron cyclotron resonant heating (ECRH) on the TCV tokamak the plasma was swept vertically through a stationary microwave beam and the beam was swept vertically through a stationary plasma. Results from these vertical sweeps revealed an asymmetry in the plasma response when beam deposition was above or below the plasma midplane. The up-down asymmetry is observed on the sawtooth shape, soft x-ray intensity, central electron temperature and pressure, and ion tail temperature. The likely source of the asymmetry is the poloidal component of the magnetic field being either parallel or anti-parallel to the launched beam direction. For the current TCV geometry this introduces a counter electron cyclotron current drive (ECCD) component when the beam is above-below the plasma midplane, respectively. ECCD efficiencies ( $\eta$ ) from the ray tracing code TORAY, during these sweeps are comparable to those calculated for ECCD experiments performed earlier[1] with low x-mode coupling. Likewise, both experiments exhibited similar plasma response with respect to the sawtooth shape, soft x-ray intensity, central electron temperature and pressure, and ion tail temperature. Future experiments are proposed to further explore the asymmetry and isolate its source.

**Experimental setup:** The TCV ECW system[2] when complete, will provide 3MW X2 (six 82.6GHz gyrotrons) and 1.5MW X3 (three 118Ghz gyrotrons) for 2s. These experiments used 0.5MW up to 1s pulse lengths. Each gyrotron is equipped with a matching optics unit including a two mirror universal-polarizer, an evacuated transmission line (30m) which includes a multihole power monitor, and an antenna comprised of a four mirror system which allows the launching of the beam in both the poloidal and/or toroidal directions. The so-called poloidal motion allows the beam deposition to be swept vertically through a circular plasma or two-thirds of the way through an elongated ( $\kappa=3$ ) plasma several times during a shot. The toroidal rotation permits current drive experiments in either co or counter directions from shot to shot. The TCV vacuum vessel can accommodate various plasma shapes and elongations. These

experiments were performed on low density ( $2 \cdot 10^{-19} \text{ m}^{-3}$ ), low elongation ( $\kappa \approx 1.3$ ), moderate  $q_a$  ( $\approx 4$ ) plasmas; centered between the equatorial and upper lateral ports. The antenna used is located on an upper lateral port. Another antenna will be available on an equatorial port.

**Experimental results:** Scans of the deposition location through the plasma were performed to determine the optimum heating location. In particular three sweeps were performed: 1) “swept plasma” - sweep of the plasma position keeping the beam launching angle fixed, 2) “swept beam” - sweep of the beam launching angle keeping the plasma location fixed, and 3) “ $B_\phi$  sweep” - sweep of radial deposition by varying  $B_\phi$  while keeping  $q_a$  constant. Each sweep was performed in both directions with no noticeable hysteresis. The x-ray intensity, sawtooth shape and period, electron central temperature and pressure, and energy confinement time are all strongly dependent upon the heating deposition location relative to the inversion radius[3]. All of these parameters were optimal when heating was localized near or within the inversion radius. However, during the vertical sweeps an asymmetry in several of the above parameters was observed. The soft x-ray signal and sawtooth shape shown in Figure 1 exemplifies the up-down asymmetry. Humpbacks occur when heating on the bottom of the plasma; normal to partially saturated sawteeth when heating on the top. A corresponding asymmetry was observed with the central electron pressure (product of soft x-ray  $T_{e0}$  and FIR interferometer  $n_{e0}$ ; see Figure 2), which was at a maximum when the deposition was below the plasma midplane. An asymmetry on  $T_{e0}$  was confirmed with Thomson scattering when several similar swept plasma shots were plotted together (Thomson, @20Hz, can not follow the rapid evolution of a single

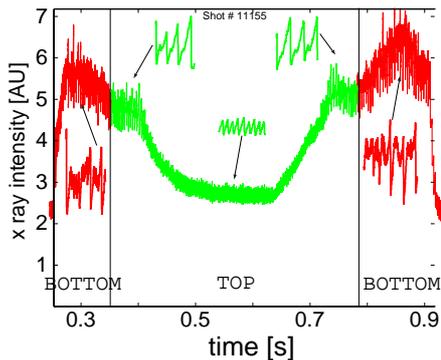


Figure 1 Up-down asymmetry in sawtooth shape and x-ray intensity while plasma is swept vertically. Humpbacks (normal sawteeth) are observed when beam deposition is below (above) the plasma midplane.

swept plasma). Since the ECRH power is dominate (500kW vs. 250kW ohmic) we can say that this may imply a significant asymmetry in confinement[3].

In trying to understand the up-down asymmetry different potential sources are identified; sys-

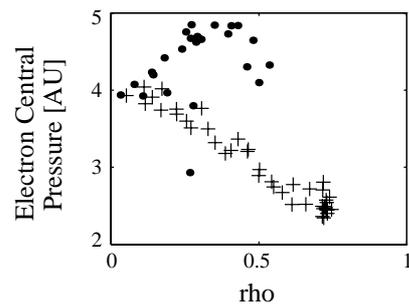


Figure 2 An up-down asymmetry is evident in the central electron pressure during a swept plasma shot. Pressure is significantly higher when heating below(•) than above(+) the plasma midplane.

tem geometry, ion drift direction and ECCD due to  $B_\theta$ , among them. The asymmetry of sawtooth shape during ECRH is similar to the behavior observed during co/counter ECCD experiments in which a significant difference on the sawtooth shape between co and counter ECCD was observed. Despite a low theoretical (TORAY) efficiency  $|\eta| < 15 \cdot 10^{-3}$  A/W (~15% of optimal coupling), normal and partially saturated sawteeth were seen during co ECCD and

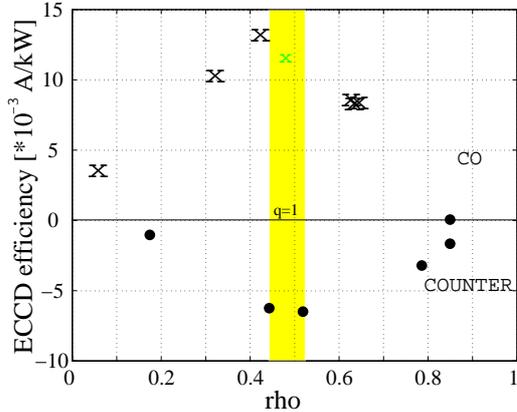


Figure 3 Co/counter ECCD efficiencies computed from TORAY during a swept plasma shot, with ECRH beam deposition above(X)/below(•) the plasma midplane.

humpbacks during counter ECCD. This difference is similar to the up-down asymmetry during the swept plasma: normal sawteeth with deposition on top correspond to co ECCD and humpbacks on the bottom correspond to counter ECCD (as expected due to  $B_\theta$ ). Furthermore, TORAY ray tracing code models a small co/counter ECCD component with similar  $\eta$  ( $13.1/-6.55 \cdot 10^{-3}$  A/W) when the deposition location was on the top/bottom half of the plasma (see Figure 3).

To further suggest that co-counter ECCD as the source of the up-down asymmetry, the behavior on the central electron and ion tail temperatures during the sweeps are comparable with the low  $\eta$  ECCD discharges.  $T_{e0}$  increased with the x-mode coupling fraction and rose above ohmic during counter ECCD, while  $T_{e0}$  remained constant with x-mode coupling fraction during co ECCD. The same behavior is seen when heating below (counter) and above (co) the midplane during the plasma sweep: highest  $T_{e0}$  occurred when deposition was located below the midplane (see Figure 4). The ion temperature, which is Maxwellian during ohmic plasmas, develops a hot tail during both co and counter ECCD. The tail temperature is larger for counter

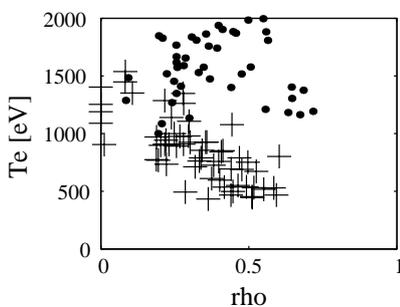


Figure 4 The asymmetry is seen on the  $T_{e0}$  when heating below(•) versus above(+) the midplane. The high  $T_{e0}$  signal when deposition is on the bottom corresponds with the increase in  $T_{e0}$  during counter ECCD above ECRH levels.

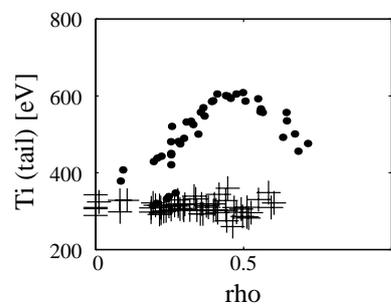


Figure 5 The ion tail temperature is higher when heating below(•) the plasma midplane than above(+). This corresponds with the ECCD experiment when counter ECCD produced larger ion tail temperatures than co ECCD.

ECCD than for co, which is also seen when heating below or above the midplane respectively (see Figure 5).

**Future experiments:** During the next campaign on TCV experiments are planned to fully characterize the up-down asymmetry and determine its source. For example: a shot to shot scan of the vertical deposition with an improved time resolution (x3) on Thomson scattering and with particular attention to possible confinement asymmetry; reversing  $B_\phi$ ; utilizing the equatorial launcher to separate out system asymmetries; etc.

**Conclusion:** An up-down asymmetry in central electron temperature and pressure, sawtooth shape and ion tail temperature has been observed when scanning the beam deposition along a vertical cord of the plasma. The plasma response in the bottom/top ECRH experiments follow the behavior for counter/co ECCD experiments. Only a small co-counter current drive was needed during the ECCD experiments to change from normal sawteeth to humpbacks. It follows that the sawtooth shape asymmetry may be due to the poloidal component of the magnetic field which introduces a counter/co ECCD component when heating on the bottom/top. TORAY ray tracing calculated  $\eta = -6.55 / +13.1 \cdot 10^{-3}$  A/W when heating on the bottom /top (these values for  $\eta$  are comparable to the low  $\eta$  discharges of the ECCD experiments). The highest central electron temperatures occur when heating off axis on the bottom side of the plasma (counter ECCD). Large differences in co/counter ECCD temperatures occurred only with full sawtooth stabilization due to high  $\eta$ . In contrast to the present results which show high  $T_{e0}$  difference even at low  $\eta$ . This may be due to the high first pass absorption in the present experiments compared with the low  $\eta$  ECCD experiments. Further experiments are planned to fully characterize the asymmetry and isolate its source during the next TCV campaign.

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## References

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