

## Poloidally Asymmetric Plasma Response during ECH Experiments in TCV

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**Introduction:** Plasma experiments using absorption of radiation in the range of the electron cyclotron frequency are often grouped under two separate headings: electron cyclotron heating (ECH) or electron cyclotron current drive (ECCD). The division is based, roughly, on the toroidal angle-of-incidence between the beam and the toroidal magnetic field direction. In practice, ECH experiments are those in which there is no projection of the  $\mathbf{k}$ -vector on the toroidal field,  $\mathbf{B}_\phi$ . For the flexible launching systems of present day tokamaks, this rough division is not strictly correct; although, for the purpose of indicating the intent of an experiment it may still be valid.

Due to the presence of the poloidal field, a beam launched with no toroidal angle can nevertheless have a non-negligible projection of its  $\mathbf{k}$ -vector along the total field and thereby produce Doppler-shifted absorption leading to ECCD; that is, a so-called ECH experiment can produce ECCD when absorption is off-axis. The direction (co/counter) and quantity of ECCD will depend on the absorption location, launch direction (HFS versus LFS) and toroidal field direction but not the plasma current direction. Both the poloidal field and the plasma current producing the poloidal field, change direction at the same time therefore simply reversing the plasma current will not change the relative direction of the ECCD (e.g. co-ECCD will remain co-ECCD). The toroidal field must be reversed. Because it is the poloidal field that creates the asymmetry, the effects are seen only during off-axis absorption.

Previous experiments on TCV have produced poloidally asymmetric plasma responses during so-called ECH experiments[1]. Here, we give experimental evidence that the asymmetry is due to the presence of ECCD.

**Experimental setup:** Up to 1.5 MW second harmonic heating (X2, 82.7 GHz) from three 0.5MW gyrotrons was directed to the plasma by three independent launching antennas (launchers). One launcher is mounted in an equatorial port (L1) and two launchers (L2 and L3) are mounted in upper lateral ports. Each launcher has 2 degrees of freedom, one of which provides steering of the beam in a fixed plane during a shot; the other allows that plane to be rotated about the TCV major radius (pointing out through the center of the launcher port) between shots. Each gyrotron can be independently switched to the torus or to a calorimetric load from shot to shot, such that power can be delivered from any possible combination of three launchers for a given shot.

The TCV vacuum vessel can accommodate various plasma shapes and elongations; however, 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. This provides geometric symmetry. The beam was swept through a stationary plasma so that all external conditions remain constant (e.g. location of plasma on the limiter, geometric configuration between diagnostics and the plasma, induced currents required to move the plasma, etc.) and only absorption-induced plasma changes are produced. Sweeps allow comparison of heating at different locations in the same plasma during a single shot. Experiments were performed for

both toroidal field directions and with various combinations of launchers to allow any systematic asymmetries (e.g. gyrotron output power, beam power density, etc.) to be clarified.

Optimum coupling of the beam to the plasma would require modification of the polarization during such sweeps since the location at which the beam enters the plasma changes in time; however, with the proper choice of a constant polarization the coupling can remain acceptably high (e.g. >95% X-mode) and symmetric at all times.

As expected, TORAY [2] X-mode ray-tracing calculation with injection in the poloidal plane (no toroidal injection) show linear current drive efficiencies which change sign when heating above or below the plasma midplane: purely perpendicular incidence on the field line at the resonance cannot be assured for all poloidal angles. Previous ECCD experiments [3] have demonstrated that the X-ray tomography diagnostic shows clear differences in sawtooth shape and period suggesting that a signature for co- and counter-ECCD exists even at low ECCD efficiencies like those

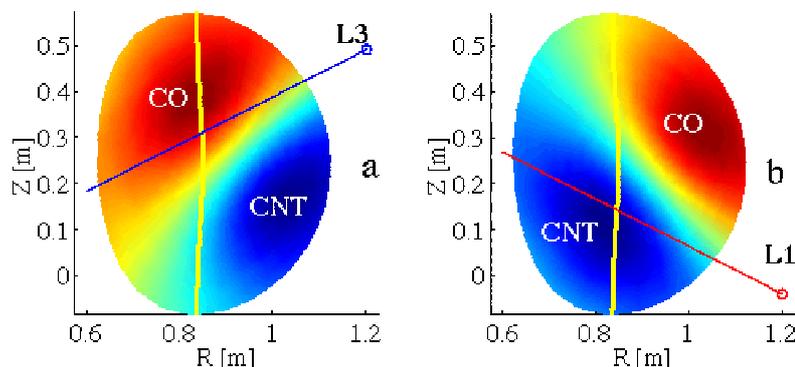


Figure 1. Poloidal cross-section showing the  $k_{||}$  contours for a so-called ECH experiment (shot 16053,  $t=1.189s$ ). Red indicates co-ECCD and blue indicates counter-ECCD. Both launcher L3 (a) and launcher L1 (b) produce co-ECCD above midplane and counter-ECCD below, although of different magnitudes, when the beams (L3-blue and L1-red lines) are swept along the resonance (yellow line).

calculated by TORAY for no toroidal injection. Ray-tracing shows that refraction may make it difficult to superimpose different beams at the same height in the plasma; therefore, launch angles were preprogrammed to sweep the refracted beams vertically along the resonance

at a constant rate.

A general understanding of the potential for ECCD is gained by calculating the projection of the  $k$ -vector on the field, since it is the Doppler shifted absorption by electrons streaming along the field that is ultimately responsible for the current drive. This is shown in Figure 1 for the plasma-beam configuration used in these experiments and a given toroidal field direction (recall that the sign of the driven current depends on the sign of  $\mathbf{B}_\phi$ , only). It is important to remember that the figure pertains to the  $k$ -vector in the poloidal plane of the tokamak (zero toroidal injection angle).

**Experimental results:** Sweeps of each launcher individually show that when crossing the  $q=1$  surface, a) density pump-out occurs and central temperature rises sharply such that line-integrated X-ray emission, as seen on the central X-ray tomography channels, increases significantly, b) the sawtooth period and amplitude increases at the transition from outside to inside, c) the change in period and amplitude is much larger on the side nearer the launcher than on the opposite side, d) the width of the transition region is larger when passing from inside to outside (rather than outside to inside) the  $q=1$  surface, e) the amplitude of the peak in sawtooth period increases with co-ECCD and decreases with counter-ECCD (produced by intentionally introducing small toroidal angles) and f) the width of the transition region is of the order of the free-space beam width projected on the resonance at the heating location ( $\sim 3cm$ ). Since the experiments perturb the density (a) and the transition region is small (f), it is very difficult to superimpose beams even with preprogramming. On the other hand, this region is a highly localized,

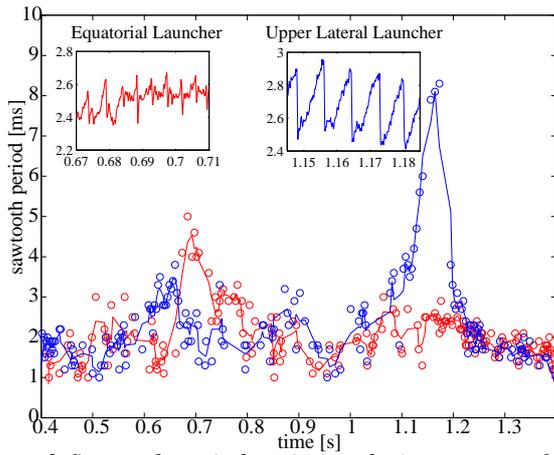


Figure 2 Sawtooth period variation during sweeps of L1 (red) and L3 (blue) separately from below to above mid-plane ( $dz/dt=0.35\text{m/s}$ ). The peaks correspond to the lower and upper  $q=1$  regions. The sawtooth shape is seen in the insets. Note that the peak is clearly larger on the side nearer the corresponding launcher.

L3 and vice versa. Therefore, we can conclude that for the same launcher, *a*) the near-side sawtooth shape depends on the driven current direction and *b*) similar sawteeth changes cannot be produced on the opposite side of the plasma. Taking the large regular sawteeth, the fact that the roles of an upper lateral and equatorial launcher are reversed when the field is reversed, suggests that it is either *a*) the current driven (proportional to the power density) or, *b*) the beam width, that determines whether or not these sawteeth can be created. By fixing the beam absorption on the transition region and varying the beam power, we keep the beam width constant and vary the power density. Sawteeth do not change shape but become larger with power density. This suggests that in the case of heating on the opposite side of the  $q=1$  surface (i.e. far side transition region for a given launcher), the beam width plays the dominant role in determining the sawtooth shape (Note: the *sign* of the ECCD for the far-side transition region for a given launcher is the same as for the opposing launcher's near-side transition region when  $\mathbf{B}_\phi$

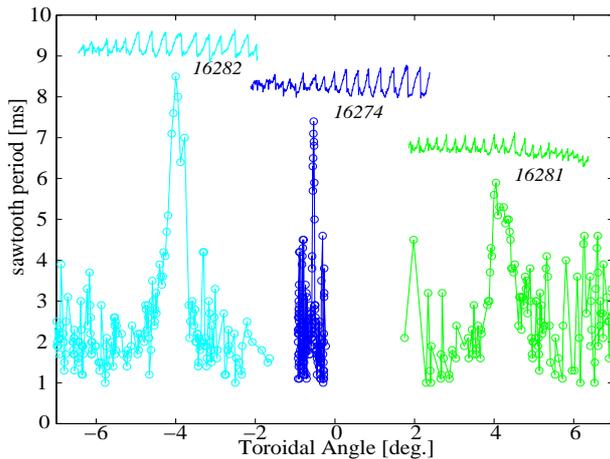


Figure 3 Elimination of co-ECCD component at near-side transition region for L1 with  $\mathbf{B}_\phi$  reversed. Shot 16281 is pure ECH at the sawtooth period peak. The beam is swept over the same range as in Figure 2 passing through both the near and far side transition regions. The plane of sweep is rotated by  $\pm 8^\circ$  relative to the poloidal plane of the tokamak. (Insets have equal scales).

easily recognizable target location in the plasma and can be used as a diagnostic for in situ testing of the relative alignment between launchers.

The transition region is of particular interest because it allows the confirmation that ECCD is responsible for the non-axisymmetric plasma response. Figure 2 shows the plasma response when heating with either an upper lateral (L3) or equatorial (L1) gyrotron alone ( $\mathbf{B}_\phi > 0$ ). Large more-or-less triangular sawteeth appear *only* when heating near the upper  $q=1$  surface with L3 and not with L1. Non-triangular, but nevertheless large, sawteeth occur when heating near the lower  $q=1$  surface with L1 and not L3. When  $\mathbf{B}_\phi$  is reversed, these results are reversed as well, with L1 playing the role of

L3 and vice versa. Therefore, we can conclude that for the same launcher, *a*) the near-side sawtooth shape depends on the driven current direction and *b*) similar sawteeth changes cannot be produced on the opposite side of the plasma. Taking the large regular sawteeth, the fact that the roles of an upper lateral and equatorial launcher are reversed when the field is reversed, suggests that it is either *a*) the current driven (proportional to the power density) or, *b*) the beam width, that determines whether or not these sawteeth can be created. By fixing the beam absorption on the transition region and varying the beam power, we keep the beam width constant and vary the power density. Sawteeth do not change shape but become larger with power density. This suggests that in the case of heating on the opposite side of the  $q=1$  surface (i.e. far side transition region for a given launcher), the beam width plays the dominant role in determining the sawtooth shape (Note: the *sign* of the ECCD for the far-side transition region for a given launcher is the same as for the opposing launcher's near-side transition region when  $\mathbf{B}_\phi$

is reversed). For the near side transition using L1 with  $\mathbf{B}_\phi$  reversed, the co-ECCD Doppler component which exists at resonance for launch in the poloidal plane can be eliminated or enhanced by intentionally adding a toroidal angle to the launched beam. The resulting peaks in sawtooth period as well as the sawtooth shapes are shown in Figure 3. Positive angles decrease the ECCD component:  $+4^\circ$  corresponds to pure ECH. For each shot, the same mirror range was swept and the beam passes through both the upper and lower transition regions. However, since the beam lies in a plane which is rotated about the major radius passing through the launcher ports, the sweep range in toroidal angle increases as the

plane is tilted more relative to the poloidal plane of the tokamak. The time at which the beam crosses the near-side transition region will change by less than one sawtooth period. Large triangular sawteeth only occur with a co-ECCD component and when the absorption occurs over a narrow extent in minor radius (near-side). Similarly, large triangular sawteeth can be created by over-compensating the inherent counter-ECCD offset on the near-side with the standard  $\mathbf{B}_\phi$ , leading to co-ECCD

The narrow range over which the large regular sawteeth occur allows the determination of the beam absorption location if one admits that there exists a correlation with some yet-to-be-determined but physically relevant location in the plasma. If this location can be proven to be tied to a physical relevant location of interest such as the  $q=1$  radius by simultaneous measurements of  $q$ , for example using the MSE diagnostic on DIII-D, it could provide a tool for testing and refining the details of models describing the sawtooth instability [4]. Tokamaks with ECH but not equipped to measure the  $q$ -profile could then find this location by sweeping the heating location and constrain equilibrium reconstruction codes accordingly.

In any case, without specifying the exact location, *a*) differences of heating location of 10mm ( $\sim 2.5\%$  of plasma radius) are easily measured based on these transitions even though most diagnostics have a spatial resolution of  $\sim 3$ -4cm, *b*) individual beam-plasma aiming is confirmed to be reproducible to  $0.2^\circ$  ( $\pm 3$ mm at resonance near the middle of the launcher's angular range) and *c*) the two upper lateral launchers are confirmed to heat the same location within this reproducibility for the same angle settings, producing large sawteeth. However, refraction limits the ability of aiming an upper lateral and an equatorial launcher with the necessary accuracy to cause reliable beam overlap at a given height even though attempts were made to correct for refraction a priori. In this heating scenario, the large sawteeth become less regular, perhaps beam-width dominated.

**Conclusion:** Poloidally asymmetric plasma responses, particularly sawtooth shape and amplitude, have been shown to be consistent with the presence of ECCD during sweeps of the heating location in the poloidal plane of a tokamak plasma. Large regular sawteeth are produced over a very narrow spatial range, provided the beam absorption width is narrow and some co-ECCD is present. Broad absorption appears to perturb the triangular sawtooth shape.

It seems reasonable to expect that local ECCD applied at the  $q=1$  surface lowers the shear so as to produce sawtooth stabilization, extending the period and increasing the amplitude. The one dimensional code PRETOR has simulated the effect of pure ECH. The sawtooth period increases when passing inside the  $q=1$  radius, but shows no peaking of the sawtooth period near the  $q=1$  radius [5]. Simultaneous measurement of the  $q$ -profile and heating location would help to clarify the physical mechanisms at work in producing different sawtooth shapes: for example, a precise knowledge of the heating location relative to  $q=1$  is necessary to allow direct comparison between experiments and the 2D model of sawtooth dynamics recently proposed by Porcelli [4].

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