# The Effect of Electron Cyclotron Heating on Density Fluctuations at Ion and Electron Scales in ITER Baseline Scenario Discharges on DIII-D

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The ITER Baseline Scenario (IBS) operates in reactor relevant regimes on the DIII-D tokamak using nearly balanced Neutral Beam Injectors (NBI) and Electron Cyclotron Heating (ECH), thus obtaining low applied torque and electron temperature close to that of ions. The main observation from the experiment is an increase in the intensity density of fluctuations, accompanied by a decrease in confinement, caused by torque-free direct electron heating compared to mixed electron-ion heating provided by beam sources at finite torque.

The IBS experiments reported in this paper were executed with plasma current $I_p = 1.3\,\text{MA}$, line averaged density $n_e \simeq 4-5\cdot 10^{19}$ m$^{-3}$, elongation $\kappa = 1.9$, top triangularity $\delta_T = 0.4$, bottom triangularity $\delta_B = 0.8$, normalized beta $\beta_N \simeq 2$ and confinement quality factor $H_{98y,2} \simeq 1$; the toroidal field was kept fixed at 1.8 T, resulting in $3.2 < q_{95} < 3.3$. Plasmas were heated with 110 GHz ECH as well as with NBI, whose applied torque could be modified from co-current to balanced, and were operated in such a way as to automatically alter the injected power in order to keep $\beta_N$ constant when the ECH power was varied.

**Effect of heating and torque on confinement and fluctuations**

The use of ECH allows one to mimic electron heating from alpha particles generated in a burning D-T plasma and to finely control the location of power deposition to study electron transport studies and turbulence. Density fluctuations were monitored by Beam Emission Spectroscopy (BES) in the spectral region $k_\perp < 3\ cm^{-1}$, Doppler Back Scattering (DBS) in the ragion $6 < k_\theta < 8\ cm^{-1}$, and Phase Contrast Imaging diagnostic (PCI) that measures line averaged fluctuations in the range $2 < k_R < 25\ cm^{-1}$ and a wide frequency bandwidth.

The most relevant result of the experiment is a significant reduction in confinement whenever ECH replaced beam power, at finite net torque, while maintaining a constant value of $\beta_N$; in particular, a much larger amount of EC power was required to replace NBI power, which translates into about 30% decrease in the confinement quality factor $H_{98y,2}$ at fixed $\beta_N$. All the afore-mentioned fluctuation diagnostics measured one effect qualitatively consistent with the dependence of confinement on the heating scheme, i.e. a drastic increase in the intensity of fluctuations when ECH was applied. The overall result of the measurements was reported in [1], while here we will describe in much greater detail the data and interpretation from the PCI diagnostic.

The PCI measures fluctuations in a broad range of horizontally propagating wave-numbers from $1-30$ cm$^{-1}$, which become a combination of $k_\rho$ and $k_\theta$ along the vertical line integral. Figure 1 displays the power spectrum of density fluctuations for a plasma heated with beams only and with a combination of beams and ECH at constant $\beta_N$. It can be seen that fluctuations with the largest intensity, which are below 100 kHz, are strongly enhanced by ECH, in agreement with what is observed by BES and DBS. However, for fluctuations between 100 and 500 kHz in the 'corner' of the spectrum this behavior reverses with stronger fluctuations being excited in the beam only heated part of the discharge. This may be understood by considering that beams in a high torque configuration cause the plasma to rotate faster toroidally, which suppresses ion scale fluctuations via larger $E\times B$ shearing rate and widens the apparent bandwidth of the fluctuations to larger frequencies via large Doppler shift. Since the PCI diagnostic does not need to integrate its signal over many energy confinement times to obtain acceptable signal-to-noise-ratio, it can compare the spectrum just before and after the EC power is turned-off to that obtained a few energy confinement times later. In a short time window across the turn-off time of the EC power, during which most of the profiles are still close to values they had before the switch-off, the low-frequency turbulence does not appear to change abruptly upon turning off the EC power, while the high-frequency corner increases up to a factor of three. By analyzing the frequency-wavenumber spectrum in response to the heat flux variation, it is concluded that the larger intensity of fluctuations at high frequency shown in Figure 1 is not due to an increased Doppler shift, but rather is due to the response of the electron temperature profile to the heat flux variation. Figure 2 shows the ratio of the two dimensional frequency-wavenumber power spectra, expressed as histograms, computed in short time windows right after the ECH removal to that computed before. It is seen that the intensity

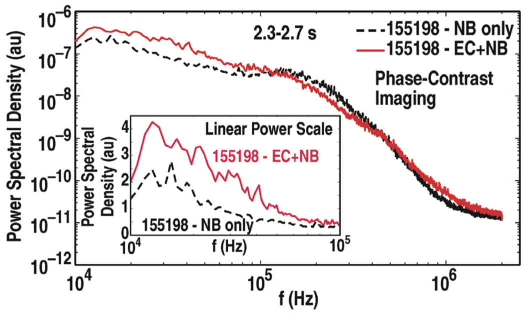


Figure 1: Frequency power spectra from the PCI diagnostic measured during phases without and with ECH replacing part of the beam power at fixed $\beta_N$.

of fluctuations increases in the frequency range 0.2-1 MHz and in the wavenumber range up to 15 $cm^{-1}$, corresponding to $k_y\rho_s < 8$, with actual values depending on where in the plasma the fluctuations collected along the line integral originate from.

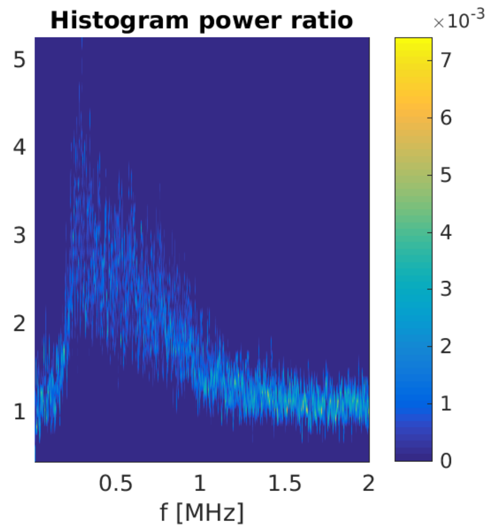


Figure 2: Frequency dependence of the histogram of the ratio of two-dimensional spectra computed in a time window right after the EC removal to that computed in a time window before it.

## Gyro-fluid modelling

Simulations were performed with the gyro-fluid code TGLF [2]. The temporal evolution of confinement and of the intensity of fluctuations reported in the previous section can be explained by computing the radial profiles of the Hahm-Burrell shearing rate [3]. While the observed shearing rate in the ECH-heated part of the discharge is well below the linear growth-rate of the most unstable mode in the ion scale region of the wave-number spectrum, which is where flow shear is expected to be effective in suppressing fluctuations, the two become quantitatively comparable in the ECH-free part of the discharge due to the toroidal acceleration. Turbulence quenching is expected to take place when the shearing rate $\gamma_E$ and the maximum linear growth rate in the absence of flow shear $\gamma_{max}$ satisfy the relation $\alpha\gamma_E \simeq \gamma_{max}$, where $\alpha$ is a numerical coefficient of order unity for the case considered. Therefore, the observed reduction of the intensity of fluctuations and the amelioration of confinement in the IBS without ECH are likely due to flow shear. This qualitative reasoning was confirmed by TGLF simulations, which showed that the inclusion of flow shear effects lowered the estimated non-linear fluxes to values close to those from the experiment.

A rough understanding of a transient phenomenon can be obtained by computing how the linear growth rates respond to the ECH removal. The time evolution of the radial profile of the growth rate of the most unstable modes at any wavelength in the region $0.01 < k_y\rho_s < 100$ was computed with the TGLF code, and showed that electron scale fluctuations in the radial region $\rho > 0.6$ and for wavenumbers such that $1 < k_y\rho_s < 50$ are enhanced by the ECH removal. This result suggests that the increase in the intensity of fluctuations observed by the PCI diagnostic at frequencies larger than 100 kHz is due to electron modes that originated from regions where the modification of the electron temperature gradient scale length in response to the heat flux variation is the largest. A comprehensive modeling of such plasmas would require the use of multi-scale simulations in order to capture the combined dynamics of ion and electron scale fluctuations [4] and are beyond the scope of this work. The modification to the electron temperature profile is predicted to promptly enhance the electron heat flux, without a significant effect on the ion channel. After a few energy confinement times, when profiles evolve to a new stationary state, the increased flow shear reduces the fluxes by quenching instabilities at ions scales. Interestingly, the simulations also show a prompt increased inward particle pinch, which is estimated to about one quarter of the outward particle flux generated by ion scale fluctuations. This increased inward pinch after the ECH removal might be connected to the well known ECH density pump-out effect [5] and is currently under study.

**Summary and conclusions**

We observed an increase in the intensity of fluctuations and a worsening of confinement caused by torque-free direct electron heating on DIII-D discharges in the IBS regime. Specifically, we used the Phase Contrast Imaging diagnostic to investigate the time evolution of density fluctuations across the turning-off of EC power. The time behavior of the characteristics of fluctuations is qualitatively consistent with linear gyrofluid modelling. After ECH is removed and the $E \times B$ shearing rate grows over several energy confinement times, the confinement time increases and the intensity of fluctuations below 100 kHz decreases. On a sub-energy confinement time scale, the intensity of fluctuations at higher frequencies increases. Linear gyrofluid modelling suggests that such an effect is localized to the outer third of the minor radius. Simulations also predict a larger heat flux and an inward particle pinch that might be related to the ECH density pump-out effect. Future work will attempt to quantify some of these results with synthetic diagnostics on non-linear gyro-kinetic simulations.

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