Investigation of suprathermal electron transport induced by Electron-Cyclotron waves in tokamak plasmas

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Electron-Cyclotron (EC) waves are routinely injected in tokamak plasmas to increase electron temperature and drive current. The resonant absorption of EC waves occurs in a narrow region of real and velocity spaces, allowing for very accurate power deposition. For this reason, it is foreseen as the main tool for MHD mode control or mitigation in future large devices such as ITER. However, it has been observed that the suprathermal electron distribution is broader than the power deposition calculated by numerical simulations with linear ray-tracing and quasi-linear drift-kinetic codes [1, 2, 3]. The experimental driven current appears to be also smaller than calculated. This may potentially hamper the efficiency of MHD mode mitigation by driving current outside magnetic islands, and the underlying mechanisms need to be understood. A possible explanation being explored, both numerically and experimentally, is the scattering of the EC beam before its absorption by density fluctuations, resulting in a broader deposition profile [4]. This effect is expected to be significant in larger devices, such as ITER, where the beam path from scattering location to absorption is large [5, 6, 7, 8]. Another possibility, on which this contribution focuses, is the transport of the accelerated electrons outside the absorption area due to local turbulent transport enhanced by EC wave absorption itself. This has been suggested by previous studies performed at TCV, using drift-kinetic models augmented by ad-hoc radial transport of fast electrons [3]. Indeed, the transport model that most successfully recovers the experimental data from Hard X-Ray Spectroscopy (HXRS) is a model proportional to the local deposited power in phase space. It may suggest a local enhancement of turbulent transport by the wave-particle interaction, without excluding the impact of beam scattering, self-consistent turbulence being the missing key ingredient of LUKE drift-kinetic simulations [9]. This has motivated the development of a realistic EC source in a flux-driven gyro-kinetic code, enabling turbulent transport studies from first principles [10, 11]. This new tool, implemented in ORB5 [12], has been tested and compared to drift-kinetic simulations performed with LUKE, by disabling turbulent transport effects in ORB5. It is planned to experimentally study the transport

*See author list of H. Reimerdes *et al* 2022, *Nucl. Fusion* **62** 042018 induced by EC waves, using power-modulated EC beam and HXRS-constrained LUKE modeling, extending the work performed in [3] and testing the new ORB5 EC module in actual experimental situations. The experimental setup and methodology are introduced in this contribution.

Benchmark of flux-driven gyro-kinetic ORB5 against drift-kinetic LUKE. Both ORB5 and LUKE are based on the Fokker-Planck theory, although the codes are very different in the way they treat the problem. The Fokker-Planck equation for the electron distribution f_e can be written

$$\frac{\partial f_e}{\partial t} + \{f_e, H_e\} = \sum_s C(f_e, f_s) + \sum_n Q^n_{EC}(f_e) \tag{1}$$

where s are the different species, n the harmonic numbers, H_e the Hamiltonian and $\{\cdot,\cdot\}$ the Poisson brackets. The quasilinear diffusion operator $Q^n_{EC}(f_e) = \nabla \cdot [D_n \cdot \nabla f_e]$ describes the wave-particle interaction, with D_n the diffusion tensor [10]. The quasilinear nature of this operator stems from the fact that the deposited wave power depends on the electron distribution, which is, in turn, affected by the deposited power. The main differences between LUKE and ORB5 are their collision operators $C(f_e, f_s)$ and their treatment of wave propagation and absorption. ORB5 is limited to 2D propagation and absorption, with a new model able to treat current drive configurations [11]. The power deposition is inferred from the theoretical linear prediction [13]. LUKE is coupled to the 3D ray-tracing code C3PO [14], and there is therefore no limitation with respect to EC configurations. Unlike ORB5, LUKE distribution functions and EC power deposition are calculated self-consistently. Finally, for this study, turbulent transport coming from Poisson bracket non-linear terms has been filtered out in ORB5 and is not present in LUKE by construction. The two codes have been compared in a TCV-like plasma equilibrium, with flat density, quadratic safety factor profile and realistic temperature profile, with an EC beam propagating on the equatorial midplane, for varying input EC power. The absorbed power for pure heating and a current drive configuration is shown in figure 1. In the linear regime (low power), the agreement between both codes and linear calculations, both analytical and from ray tracing, is very good, especially with pure heating. There is a $\sim 10\%$ offset in the current drive case, which is acceptable. At high power, quasilinear effects become significant. The wave absorption is distorting the electron distribution away from Maxwellian, while collisions tend to bring the distribution back to Maxwellian. The increase or decrease in absorbed power comes from the competition between the increase in number of fast particles (targets for wave absorption) and the flattening of the distribution in the direction of the quasilinear diffusion. Overall, the agreement remains qualitatively good, especially with pure heating. The remaining discrepancy between ORB5 and LUKE can be explained by their major differences described earlier.

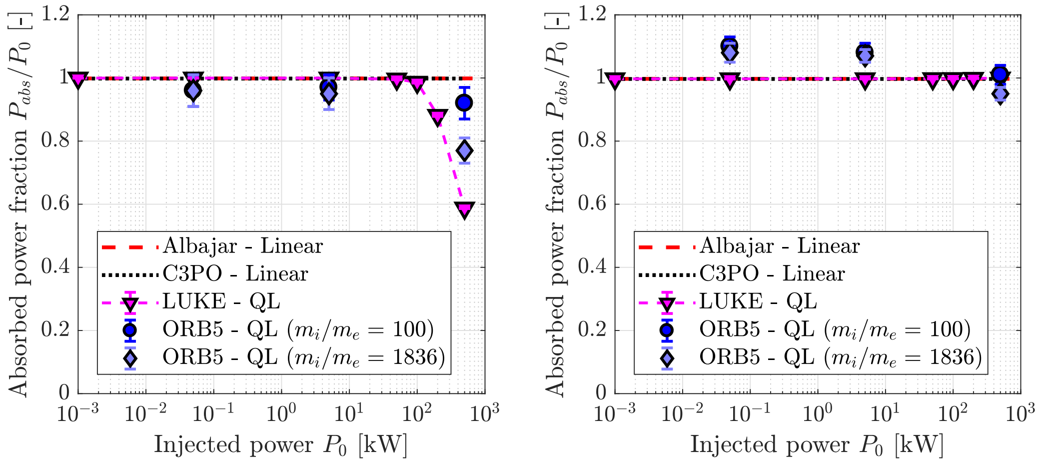

Figure 1: *Absorbed EC power for pure heating (left) and current drive (right), for ORB5, LUKE, C3PO and theoretical linear prediction.*

Experimental setup and methodology A direct measurement of the deposited EC power profile is not possible. In TCV, the Bremsstrahlung photons from suprathermal electrons are measured instead, using a solid-state cadmium telluride Hard X-Ray Spectrometer (HXRS) [15]. This spectrometer is composed of 4 compact cameras, with 24 tungsten-collimated lines of sight per camera, associated with a $2 \times 2 \times 2$ mm CdTe photodiode each, thus covering a complete poloidal view. The typical energy range of the HXRS is 20-300 keV, with a resolution of $\sim$ 8 keV. Thermal contribution is cut off by the mean of aluminum filters (in TCV $T_e \sim$ 2-4 keV). These measurements are used to constrain LUKE simulations. Indeed, the electron distribution calculated by LUKE is used to estimate the Bremsstrahlung emissivity through a HXRS synthetic diagnostic [16]. Ad-hoc radial transport of electrons is modeled by an additional diffusion operator in Eq.1, the coefficients being adjusted to match the experimental data. In TCV, experimental transport studies are performed by modulating the power of a gyrotron firing into the plasma. Over a shot, a total of 48 11-ms long cycles, with 2-ms at high power, is achievable. Pulses are assumed to be physically identical so data can be conditionally averaged to increase statistics. Pulses are designed to be short enough that the plasma current remains frozen, and the duty cycle is such that the plasma can relax between subsequent pulses [3]. Preliminary results for a reference shot are shown in figure 2. The EC beam is injected in the equatorial midplane. This configuration is expected to minimize the impact of beam broadening by density fluctuations on the power deposition profile as the absorption is perpendicular to the magnetic flux gradient. As expected, the HXR signal increases during the high power phase of the pulse, and starts decreasing when the power decreases. Different channels are displayed, 2 channels viewing the power deposition location and 1 channel viewing the magnetic axis. Experimental HXRS data are compared to transport-less dynamical LUKE simulations. The experimental HXR signal is maximum on the central channel while the LUKE HXR signal is maximum on channels viewing the absorption location. The flattened experimental HXR distribution suggests a radial transport of the suprathermal electrons. This plasma scenario seems to be a good case for testing turbulent transport enhancement by EC waves, and transport studies with LUKE have to be performed, as well as ORB5 simulations at high and low power. Experiments extending the work of [3] to higher power and different EC parallel wavenumber have also been performed, but both experimental and numerical analysis remains to be done.

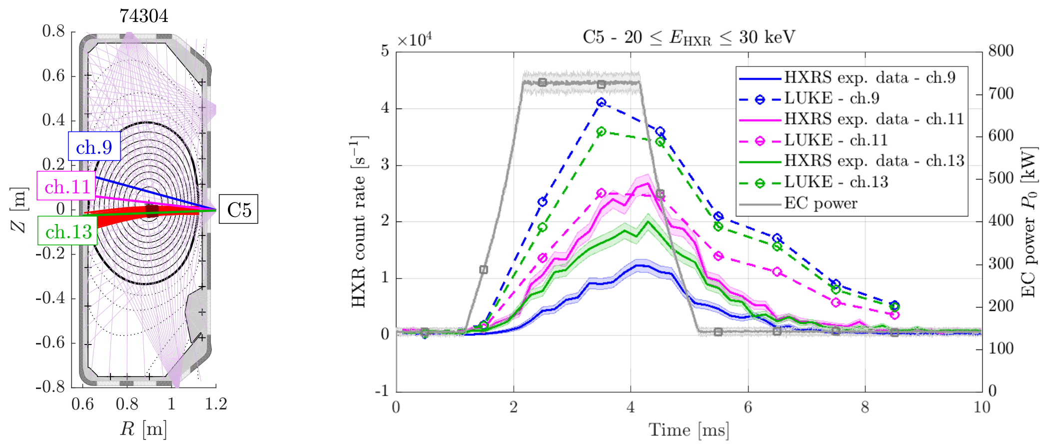

Figure 2: *Plasma poloidal view with HXRS lines of sight and C3PO ray tracing with absorbed beam in red (left) and conditionally averaged HXRS signal for highlighted channels compared with LUKE, without additional transport (right).*

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References

[1] S. Coda *et al*, Nucl. Fusion **43**, 1361 (2003)

[2] P. Nikkola *et al*, Nucl. Fusion **43**, 1343 (2003)

[3] D. Choi *et al*, Plasma Phys. Control. Fusion **62**, 115012 (2020)

[4] O. Chellaï *et al*, Nucl. Fusion **61**, 066011 (2021)

[5] Y. Peysson *et al*, Plasma Phys. Control. Fusion **53**, 124028 (2011)

[6] J. Decker *et al*, EPJ Web Conf. **32**, 01016 (2012)

[7] A. Snicker *et al*, Nucl. Fusion **58**, 016002 (2017)

[8] A. Köhn *et al*, Plasma Phys. Control. Fusion **60**, 075006 (2018)

[9] Y. Peysson *et al*, Fusion Science and Technology **65**, 22 (2014)

[10] P. Donnel *et al*, Plasma Phys. Control. Fusion **63**, 0640011 (2021)

[11] P. Donnel *et al*, submitted to Plasma Phys. Control. Fusion (2022) hal-03538335v1

[12] E. Lanti *et al*, Computer Physics Communications **251**, 107072 (2020)

[13] F. Albajar *et al*, Plasma Phys. Control. Fusion **49** (2006), 15

[14] Y. Peysson *et al*, Plasma Phys. Control. Fusion **54**, 045003 (2012)

[15] S. Gnesin *et al*, Rev. Sci. Instrum. **79**, 10F504 (2008)

[16] Y. Peysson, J. Decker, Phys. Plasmas **15**, 092509 (2008)