LHCD-induced Soft X-Ray poloidal asymmetry during tungsten trace injection: investigating radiative processes

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Abstract A poloidal asymmetry of Soft X-Ray (SXR) emissivity, stronger on the High Field Side (HFS), was observed during a tungsten (W) injection in a Tore Supra (TS) pulse with Lower Hybrid (LH) heating only. It is shown that a small fraction of this asymmetry can be explained by purely radiative processes. Indeed, the interaction between W and trapped superthermal electrons results in asymmetric SXR emissivity. However, uncertainty regarding certain simulation inputs hampers an ultimate conclusion regarding the exact fraction of the asymmetry that can explained by this effect, and the simultaneous existence of an impurity density asymmetry remains to be investigated.

Introduction In tokamak plasmas, heavy impurities radiate significant amounts of energy out of the plasma core, impacting the local plasma resistivity or even resulting in a radiative collapse. In particular, the choice of a W divertor for ITER comes with the urgent need to understand heavy impurities transport and their suspected interactions with MHD. As a matter of fact, SXR diagnostics are a useful tool for studying both processes since SXR emissivity is partly due to impurities and since it is often considered a flux-surface quantity. However, this latter assumption does not always hold. Indeed, SXR poloidal asymmetries have been observed in plasmas polluted by medium-to-heavy impurities (Ni, Fe, W...) and heated by Neutral Beam Injection (NBI) [1] or off-axis Ion Cyclotron Resonance Heating (ICRH) [2]. These two types of SXR asymmetries rely on underlying impurity density asymmetries. This paper investigates a different kind of asymmetry, observed in TS during a W trace injection in a pulse with Lower Hybrid Current Drive (LHCD) only [3]. Understanding poloidal asymmetries is important for several reasons. First, MHD and impurity transport studies require proper interpretation of SXR measurements that can be significantly biased if asymmetries are not properly understood. Second, asymmetries may themselve have a direct impact on radial impurity transport [4].

Observation and similarities with a hard X-ray asymmetry In pulse TS # 47757, LHCD was used for its ability to add a strong superthermal tail to the electron distribution, and thus to efficiently drive the current profile. At $t \approx 18.99$ s, a W trace injection was performed in a stable phase with $T_e(0) \approx 6$ keV, $n_e(0) \approx 3.10^{19}\ m^{-3}$, $P_{LH} \approx 3.5$ MW and $I_P \approx 0.7$ MA. As W penetrates the plasma core, the background-subtracted SXR measurements revealed a W-generated SXR emissivity unexpectedly stronger on the HFS, as seen in fig.1. Asymmetry quantification is difficult (uncertain noise, magnetic equilibrium and tomography). However, it is clearly visible on line-integrated measurements (vertical camera), and the inversion yields a 10 % ($\pm$ 5 %) asymmetry (as defined by Eq. 1) inside $0.3 \leq \rho \leq 0.5$.

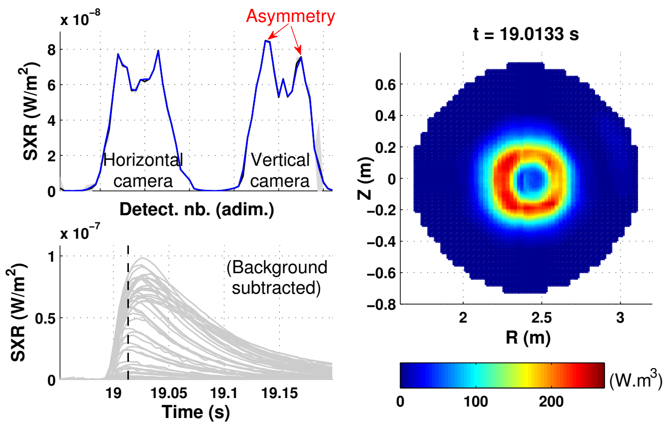

Figure 1: *Experimental observation of the SXR asymmetry both on line-integrated and inverted data*

$$\kappa_S^\eta(\rho) = \frac{\varepsilon_S^\eta(\rho,\pi) - \varepsilon_S^\eta(\rho,0)}{\varepsilon_S^\eta(\rho,0)} \qquad (1)$$

where ρ is the normalised minor radius, θ is the poloidal angle, ε_S^η is the SXR emissivity due to species S, spectrally filtered by detectors η. Such observations are new to the field of SXR diagnotics, but not to the field of Hard X-Ray (HXR). Indeed, low collisionality allows magnetic trapping of some superthermal electrons, making their perpendicular temperature poloidally asymmetric. Hence, poloidal asymmetry of perpendicular temperature results in a corresponding asymmetry of HXR emissivity (stronger on the HFS), as shown in [5]. In the following, simulations are run to compute the local SXR emissivity due to the interaction of impurities with the perpendicular part of the electron distribution, in which the dynamics of the asymmetry lies. Thus, the possibility that trapped superthermal electrons might cause a purely radiative SXR asymmetry is explored.

Simulations and results Thanks to a ray-tracing code and relativistic Fokker-Planck solver [6], the non-Maxwellian electron distribution created by LH was simulated. It was approximated, in the perpendicular direction, by summation of a thermal and superthermal Maxwellians. For the needs of SXR computation, it was then issued in the form of an electron density (with small variations quantified by the dimensionless quantity $\tilde{N}$), a superthermal fraction in the perpendicular direction α and a thermal and superthermal Maxwellian distributions (cf. Eq. (2)).

$$n_\perp(\rho,\theta,p) = n_e(\rho)\tilde{N}(\rho,\theta)\left(f^{Th}(\rho,p)(1-\alpha(\rho,\theta)) + f^{Sp}(\rho,\theta,p)\alpha(\rho,\theta)\right) \qquad (2)$$

From this electron distribution, the local ionisation equilibrium of the injected impurity is approximated by computing the ionisation and recombination rates as the weighted average of their thermal and superthermal counterparts (weighted by the superhermal fraction). This local ionisation equilibrium is then assumed to be constant on each flux surface. Its interaction with the thermal and superthermal electron distributions gives rise to two independent sets of emission coefficients, hence to two filtered cooling factors $L_S^{Th,\eta}$ and $L_S^{Sp,\eta}$. Both the fractional abundances and emission coefficients were computed using the ADAS code suite [7] (with modified database for W [8]). The resulting local value of the impurity-generated SXR emissivity $\varepsilon^{\eta}_{\perp,S}$ writes as in Eq. 3.

$$\varepsilon^{\eta}_{\perp,S}(\rho,\theta) = n_S(\rho)n_e(\rho)\tilde{N}(\rho,\theta)\left(L_S^{Th,\eta}(\rho)(1-\alpha(\rho,\theta)) + L_S^{Sp,\eta}(\rho,\theta)\alpha(\rho,\theta)\right) \quad (3)$$

where the impurity density is assumed constant on a flux surface. At fixed ρ, three quantities change with the poloidal angle, resulting in three different processes that can contribute to the asymmetry. This can be seen in Eq. (4) where the flux-surface quantities have been grouped on the left hand side for simplification and normalisation $\hat{\varepsilon}^{\eta}_{\perp,S} = \frac{\varepsilon^{\eta}_{\perp,S}}{n_S n_e L_S^{Th,\eta}}$.

$$\frac{\partial \hat{\varepsilon}^{\eta}_{\perp,S}}{\partial \theta} = \underbrace{\left[\alpha\left(\frac{L_S^{Sp,\eta}}{L_S^{Th,\eta}} - 1\right) + 1\right]}_{A(\theta,S,\eta)} \frac{\partial \tilde{N}}{\partial \theta} + \underbrace{\tilde{N}\left(\frac{L_S^{Sp,\eta}}{L_S^{Th,\eta}} - 1\right)}_{B(\theta,S,\eta)} \frac{\partial \alpha}{\partial \theta} + \underbrace{\tilde{N}\alpha}_{C(\theta)} \frac{\partial}{\partial \theta}\left(\frac{L_S^{Sp,\eta}}{L_S^{Th,\eta}}\right) \quad (4)$$

These three processes can either compete against or add up to one another. In TS # 47757, both α and $\tilde{N}$ increase as θ goes from 0 to π. Besides, $A(\theta,S,\eta) \geq 0$ because $0 \leq \alpha \leq 1$. The relative weight of each term is mainly due to the shape of the filtered cooling function L_S^{η} (for a fixed ionisation equilibrium) as a function of θ (i.e.: of $k_B T_e$, see fig.2 (a)). Indeed, the second term becomes dominant when $L_S^{Sp,\eta} >> L_S^{Th,\eta}$, while the third term is positive only when the slope of L_S^{η} is positive in the superthermal domain, which never happens with a strong slope. It is then the second term that drives the asymmetry, as seen in fig.2 (b).

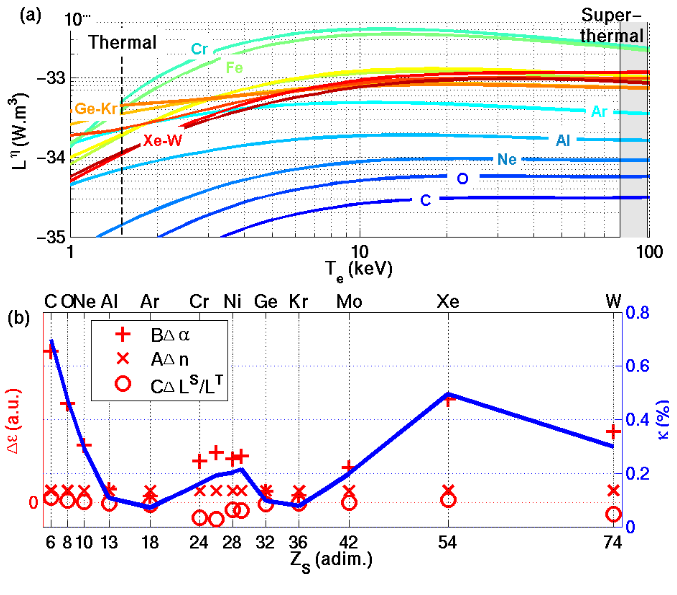

Figure 2: *(a) Evolution of L_S^{η} vs $k_B T_e$ (at fixed radius $\approx$ 0.5 and ionisation equiibrium) for several impurities. (b) Corresponding relative weight of the three terms driving the asymmetry and resulting total SXR asymmetry*

Conclusion and perspectives It appears that the process investigated (i.e.: radiation asymmetry due to impurity interaction with perpendicular electron distribution) accounts for a small part of the observed asymmetry. However, it can hardly be said at this point if the remaining discrepancy between observation and simulation is due to another process (i.e.: impurity density asymmetry due to a ye-to-be-determined transport process) or to computation error bars due to uncertainty on key inputs. In particular, it can be shown that accurate determination of the experimental filter function of SXR detectors is paramount for proper simulation of the asymmetry. While η was determined experimentally [9] and is probably more accurate than the standard "ideal" filter function, it remains an estimation carried out with limited ressources and future studies should include a systematic sensitivity study with respect to η. Furthermore, accurate extrapolation of atomic data to high temperatures is also very important, especially for heavy impurities. A tool for computing ionisation/recombination and emission coefficients directly with non-Maxwellian and anisotropic electron distributions would also be very useful. Finally, a larger database of experimental observations, which could be done with a W divertor, significant LH power and SXR detectors with well-determined spectral characteristics, would be welcome.

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