Impact of partial screening effect on fast electron dynamics in WEST tokamak plasmas with high Z impurities

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1. Introduction

The ITER divertor will use tungsten (W) monoblocks as plasma-facing components, causing the release of W impurities into the plasma due to erosion processes. However, in tokamaks, W impurities might impact the dynamics of fast (suprathermal) electrons being carriers of current, for example, in the case of ECCD in ITER or LHCD in WEST. In the case of WEST tokamak, the divertor is entirely made of tungsten, and the first walls are W coated. WEST gives thus the perfect opportunity to investigate such interaction between W impurities and fast electrons. The existing default suit of codes used for simulation of LHCD on WEST tokamak is METIS/C3PO/LUKE/R5X2 [1-4]. This suite of codes has been recently upgraded with the physics of W impurities [5]. A crucial element of this upgrade was the implementation of a key phenomenon in the case of collisions of fast electrons with W ions, namely the partial screening effect [6]. In this context, the primary goal of the present work is to estimate the impact of W ions on the fast electrons induced current and non-thermal bremsstrahlung for selected WEST plasma discharge.

2. Partial screening effect

Let us consider a single collision between a non-fully ionized impurity atom j and a fast electron in a hot tokamak plasma. In such a situation, it is necessary to consider that the fast electron can partly probe into the electron cloud bound to the ion, as depicted in Figure 1. If so, only part of the electron cloud (the green region in Figure 1) of $N_{e,j}$ electrons is screening the ion nucleus of charge Z_j. This is partial screening effect, and it results in a higher effective ion charge $Z = Z_j - F_j(\vec{q})$, where $F_j(\vec{q})$ is the atomic form factor ($0 \leq$

$F_j(\vec{q}) \leq N_{e,j}$) and $\vec{q} = \vec{p}_f - \vec{p}_i$ denotes the momentum transferred to the electron during the collision.

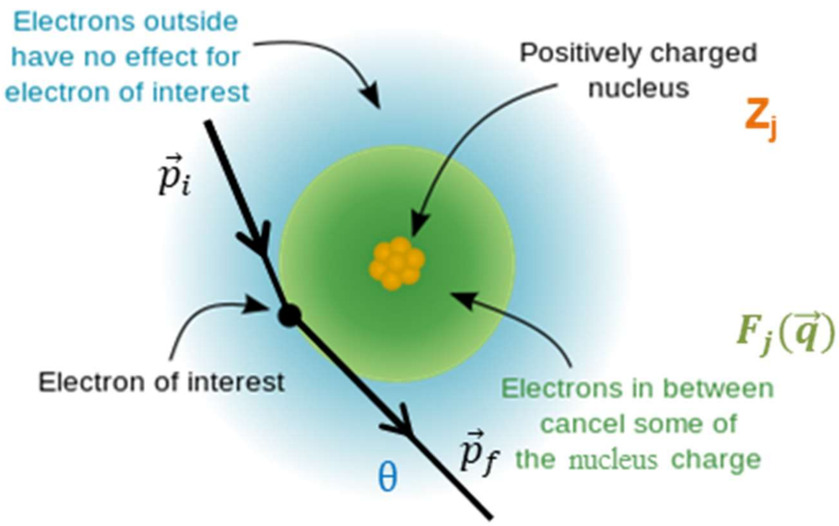

Figure 1. Partial screening effect in the case of a collision between a fast electron and an ion.

The atomic form factor can be expressed as the Fourier transform of the electron density distribution $\rho_{e,j}(\vec{r})$ around the nucleus in the momentum space:

$$F_j(\vec{q}) = \int \rho_{e,j}(\vec{r}) e^{-\frac{i\vec{q}\circ\vec{r}}{a_0}} d\vec{r}, \tag{1}$$

where $\vec{r}$ denotes the position vector of electron and a_0 the Bohr radius. We considered two approximations of $\rho_{e,j}(\vec{r})$ to obtain fast and sufficiently accurate estimations of $F_j(\vec{q})$ in our work: the Thomas-Fermi and Tseng-Pratt-Botto models. We investigated which approximation among these two will suit the best needs of accurate description for the case of a hot tokamak plasma, using the Density Functional Theory (DFT) with GAUSSIAN code as a reference [5]. Among all three approximations, only DFT captures atomic shells and thus gives the most accurate $\rho_{e,j}(\vec{r})$ estimations. The Tseng-Pratt-Botto approximation of form factor gives the closest results to the reference DFT approximation for middle-ionised tungsten atoms. Thus, this approximation was chosen and used in the performed simulation.

3. LHCD simulation for WEST discharge #54981

The LHCD simulation using the METIS/C3PO/LUKE/R5X2 suit of codes has been performed for WEST discharge #54981 at t = 6 s. The time traces of the plasma current, heating powers and loop voltage are presented in Figure 2. The simulation was performed by taking into account the presence of W impurities in the plasma for full ($F_j(\vec{q}) = N_{e,j}$) and partial ($F_j(\vec{q}) < N_{e,j}$) screening cases.

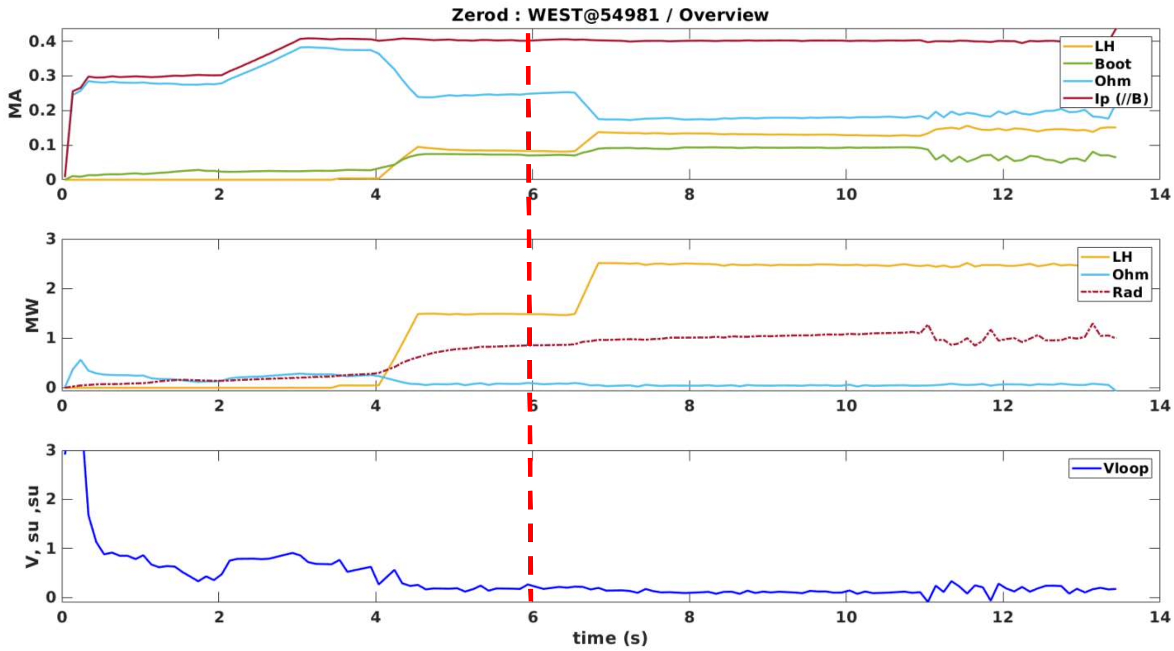

Figure 2. Plasma current, heating powers and loop voltage time traces for WEST shot #54981. The investigated time t = 6 s is marked by the red dashed line.

The performed LHCD simulation resulted in the Ohmic + LH current for the following cases: full screening – 492 kA and partial screening – 429 kA. At the same time, the experimental value of Ohmic + LH current is equal to 331 kA. Taking the partial screening effect into account increases the matching between simulation and experimental results. This single simulation gives a first guess of a probable general trend, i.e. decreasing fast electrons current because of the partial screening effect. The Ohmic + LH current density and the LH power absorption profiles could also be obtained from the simulation, as shown in Figure 3 (left). The partial screening effect also increases non-thermal bremsstrahlung emitted by fast electrons in the hard X-ray (HXR) range, as presented in Figure 3 (right). Also, in this case, considering the partial screening effect allows obtaining a better matching between simulation and experimental results.

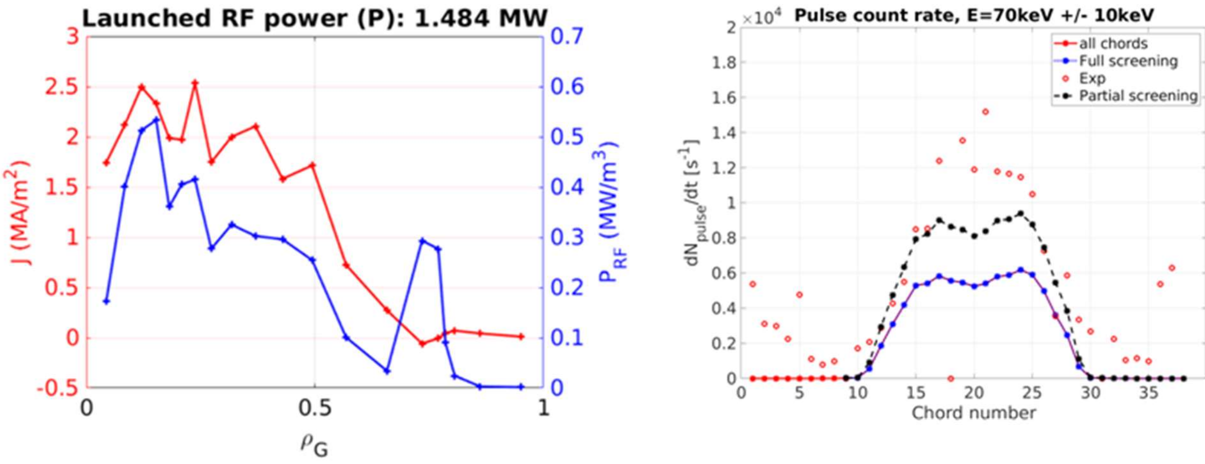

Figure 3. Simulation results of Ohmic + LH current profile and LH absorbed power profile (left). Non-thermal HXR profiles - comparison of simulation results with experimental data (right). All results were obtained for WEST discharge #54981, time t = 6 s.

4. Conclusions and perspectives

We implemented the partial screening effect in the suit of codes LUKE/R5X2. First results have shown that in WEST tokamak plasma with tungsten impurities, the partial screening effect decreases the LH driven current weakly and increases the non-thermal bremsstrahlung profile strongly by approximately two times. The remaining discrepancy between simulation and experimental results will require further investigations. In particular, a sensitivity analysis of the used W concentration profile must be performed, e.g. by validating the W profile using both HXR and SXR diagnostics. A parallel effort is ongoing to automatize the chain of codes in the prospect of statistical analysis.

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[1] J.F. Artaud et al., Nuclear Fusion, vol. 58, no. 10, 2018.
[2] Y. Peysson et al., Plasma Physics and Controlled Fusion, vol. 54, no. 4, 2012.
[3] J. Decker and Y. Peysson, MIT Plasma Science and Fusion Center, 2005, https://psfcsv10.psfc.mit.edu/~jliptac/research/modsim/decker2005.pdf (accessed 31.05.2021).
[4] Y. Peysson et al., Physics of Plasmas, vol. 15, no. 9, 2008.
[5] Y. Peysson et al., Effect of partially ionized high-Z atoms on fast electron dynamics in tokamak plasmas, IAEA-FEC Conference 2021, conference proceeding.
[6] L. Hesslow et al., Phys. Rev. Lett. 118 (2017) 255001.