Contribution ID: **1097** Type: **Regular Poster**

Effect of partially ionized high-Z atoms on fast electron dynamics in tokamak plasmas

Tuesday, 11 May 2021 12:10 (20 minutes)

The dynamics of fast electrons driven inductively or by resonant interactions with radio- frequency waves is known to be highly sensitive to the presence of impurities in hot magnetized hydrogen plasmas. The possibility to use tungsten for the ITER divertor, thanks to its low tritium retention and high melting temperature, has raised the question of the impact of partially ionized high-Z atoms on current drive efficiency by enhancing pitch-angle scattering but also collisional slowing-down. Pioneering work on the impact of the partial screening effect in kinetic calculations was carried out primarily for the problem of runaway electron mitigation in very cold post-disruptive plasmas [1]. In this paper the approach is adapted and extended to regular plasma regimes, allowing to take into account any type of high-Z metallic impurity in the plasma core on the fast electron dynamics. In addition, the enhancement of non-thermal bremsstrahlung by partially ionized high-Z atoms in the plasma is calculated.

Effect of partial screening is investigated in the framework of the Born approximation by calculating the usual form factor to account for the spatial extent of the high-Z ion using atomic electron densities deduced from simplified models (Thomas-Fermi, Yukawa potential) or from the Density Functional Theory (DFT) describing accurately many-body exchange and correlation interactions. In order to reduce computational effort either for kinetic calculations or bremsstrahlung emission, analytical formulas of the form factor deduced from Thomas- Fermi and Yukawa potential atomic models are used, with effective ion sizes determined for each ionization state by a best fit of the form factor deduced numerically from quantum relativistic calculations using the GAUSSIAN chemistry software package [2]. While Thomas- Fermi model form factor gives better results when high-Z atoms are weakly ionized, Yukawa potential model turns out to be more appropriate when the screened ion charge is greater than Z/3, where Z is the atomic number, a condition encountered for tungsten in standard core tokamak plasma conditions where electron temperature reaches few keV.

From the spinless relativistic Rutherford elastic scattering cross-section, the modified pitch-angle collision operator is used in Fokker-Planck calculations, taking into account of the partial screening for each species and all corresponding ionization states. It is proportional to the factor (Z-N)2lnΛ(p)+g(Z-N,p), where lnΛ(p) is the usual momentum-dependent Coulomb logarithm, N, the number of bound electrons, and g an analytical function describing the enhanced pitch-angle scattering by inner populated atomic shells. When g is small as compared to the usual Coulomb logarithm term, screening effect on pitch-angle is small. Inelastic scattering resulting from the mean excitation of partially-ionized high-Z atoms is also considered from the Bethe formula for the electron relativistic stopping power.

For non-thermal bremsstrahlung, Yukawa potential model is usually preferred for describing screening effect of bounded electrons, since inner atomic shells contribute significantly, whatever the ionization state [3]. In this case, an original semi-analytical formula is derived for the doubly differential quantum relativistic cross-section in photon energy and in photon emission angle from the most general Bethe-Heitler bremsstrahlung cross-section [4], which greatly enhances calculation speed, while keeping a high numerical accuracy. It is shown that bremsstrahlung scales like Zˆ2, with an enhanced reduction factor as the ratio k/Ec decreases, where k is the photon energy and Ec the incoming fast

electron kinetic energy (Fig. 1). Screening effects tends to disappear progressively when the angle between the photon emission and the incoming electron velocity increases.

Consequences on the current drive efficiency have been investigated using the kinetic solver LUKE of the 3-D linearized relativistic bounce-averaged electron Fokker-Planck equation [5] and on the fast electron bremsstrahlung using the quantum relativistic radiation code R5-X2 [6]. Thermal ionization states for all species are determined by ADAS code [7]. A full simulation of the high-power WEST tokamak discharge #55539 is investigated, where most of the plasma current is driven by the Lower Hybrid wave, taking into account of the tungsten level deduced from radiative power losses using the METIS tokamak code [8]. With an estimated concentration of tungsten of 4x10-4, it is shown that the reduction of the LH driven current is about 4%, while conversely, bremsstrahlung is increased by a factor 3 approximately as compared to the fully screened ion case. From simulations of high-power WEST tokamak Lower Hybrid discharges [9], the general impact of partially ionized metallic impurities on RF current drive is discussed, as well as on fast electron bremsstrahlung diagnosis capability.

Acknowledgements. This work has been partially funded by National Science Centre, Poland (NCN) grant HARMONIA 10 no. 2018/30/M/ST2/00799. We thank the PLGrid project for computational resources on the Prometheus cluster.

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Session Classification: P1 Posters 1

Track Classification: Magnetic Fusion Theory and Modelling