

# Impact of suprathermal electrons on ionization and radiation properties of fusion plasma with high-Z impurities

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## 1. Introduction & Motivation

The use of tungsten (W) as plasma-facing components material is a well-established routine in modern existing fusion devices such as WEST, EAST and is also foreseen for ITER. For high-Z impurities like W, ionization is partial and nucleus charge is partially screened by bound electrons. As a result, impurity cooling factor rapidly increases with atomic number in the expected  $T_e$  range 1 – 20 keV and is dominated by line radiation. W cooling factor so high in this  $T_e$  range that small W concentration  $c_w = n_w/n_e$  at level 0.01 % ( $10^{-4}$ ) is enough to compromise core plasma performance [1]. It is therefore critical to ensure that core W concentration remains below a certain level, established of the order of few  $10^{-5}$ . This triggers several needs for tokamak research:

- Well-characterized W ionization balance, see Fig. 1, and radiation features;
- Including effect of local phenomena: particle transport, energy deposition by heating systems leading to a non-Maxwellian electron velocity distribution function;
- Diagnostics and reconstruction methods to estimate W distribution and spectral features;
- Strategies to identify and use actuators that can mitigate W central accumulation.

When dominant electron heating prevails, the electron velocity distribution function deviates from being Maxwellian, developing a distinct suprathermal tail. Therefore, theoretical and numerical tools should be developed to calculate the ionization equilibrium and radiation features of high-Z impurities in plasmas with non-Maxwellian electron velocity distributions and moderate particle transport, as typically occurs in tokamaks with strong electron heating.

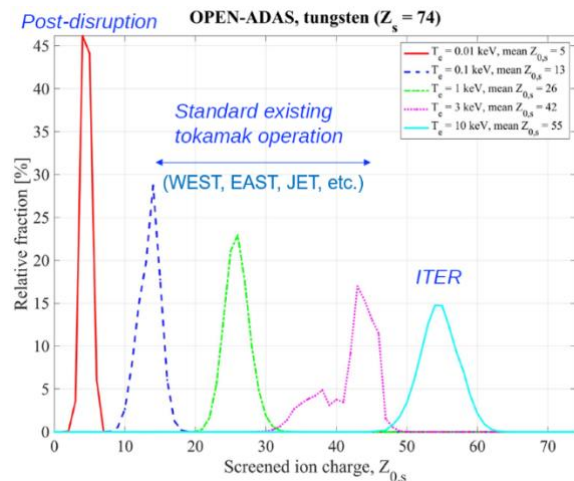


Figure 1: Relative fraction of W ionization states at different  $T_e$  values [2].

The effect of such impurities on the suprathermal electron population can be studied using a Fokker-Planck solver. In this case, it is necessary to modify the electron-ion collision operator to account for the influence of partially ionized high-Z elements resulting from the uncontrolled impurity influx [3]. This, in turn, requires atomic models that are sufficiently accurate yet also allow for fast and efficient calculations for all elements present in the plasma, regardless of their local ionization level.

## 2. Outcome of recent current drive and X-ray studies

Kinetic and bremsstrahlung calculations describing electron physics for Ohmic or RF heating and current drive in tokamaks must now cover a very wide range of parameters:

- Kinetic energies from 10 eV to 30 MeV (runaway regime with relativistic effects);
- Plasmas with fully or partially ionized atoms ranging from H ( $Z = 1$ ) to W ( $Z = 74$ ), thus involving complex atomic physics;
- Standard to strongly shaped plasmas (e.g. spherical tokamaks).

All the electron dynamics must be described continuously and consistently regardless the operating regime start-up, ramp-up, flat-top, post-disruption. The reference tools for this are LUKE [4], solver of the 3D guiding-centre averaged linearized relativistic Fokker-Planck equation, and the quantum relativistic bremsstrahlung synthetic diagnostic R5-X2 [5].

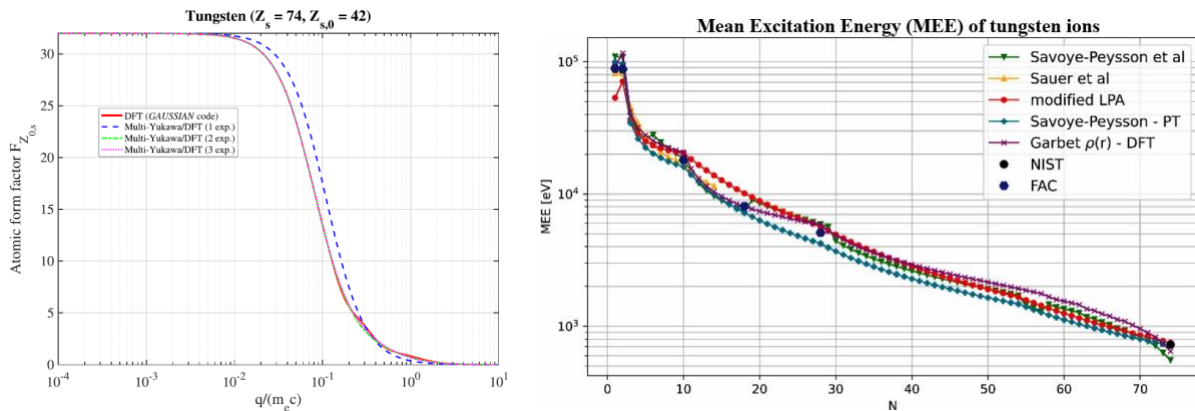


Figure 2. Left: Atomic form factor of  $W^{42+}$  ions, calculated by DFT and multi-Yukawa models [6].

Right: Mean excitation energy (MEE) of W ions estimated with different models [8].

In recent years, several atomic models have been proposed and implemented in LUKE and R5-X2. These semi-empirical atomic models for elastic and inelastic collisions involving fast electrons and ions have been calibrated and optimized [6–9]. Thanks to this, significant progress has been made to include the physics of non-fully ionized impurities in Lower Hybrid Current Drive (LHCD) simulations, upgrade Fokker-Planck operator and Hard X-ray (HXR) synthetic diagnostics to study impact of heavy impurities on current drive and HXR radiation [10]. The following effects were included: (1) Elastic collisions with partial screening effect, including atomic form factor [6, 7]; (2) Inelastic collisions with the Mean Excitation Energy (MEE), cf. Bethe-Bloch stopping power [8], see Fig. 2; (3) Fast electron bremsstrahlung (in HXR range)

on heavy impurities [10, 11]. Moreover, W cooling rate and elastic/inelastic collisions were included in disruption simulations with the DREAM code to observe the impact of W impurities on runaway electron generation, see [12].

LHCD simulations with these effects have shown that the current driven by fast electrons is not significantly affected – only slightly reduced – by W impurities at their usual level ( $cw < 10^{-3}$ ). By contrast, fast electron bremsstrahlung is enhanced by a factor  $\sim 2$  with W, see Fig. 3. As a result, HXR signal is no longer a straightforward signature of fast electrons, but high-Z impurity level also has a significant influence.

### 3. Discussion & Next Steps

These studies assumed that W ionization equilibrium results from a local Maxwellian electron velocity distribution function defined by its electron temperature, but the impact of suprathermal electrons on ionization, radiation and transport of heavy impurities were not considered. Therefore, it is planned to use the theoretical and numerical tools developed in recent work and extend them to study how a fast electron population can influence ionization, transport and radiation properties of fusion plasmas with high-Z impurities. While direct impact of fast electrons on current drive is likely low, influence on W radiation features and cooling rate may be important. This may impact  $T_e$  distribution and in turn power deposition profile or runaway generation rate (for disruption studies). So, indirect effects can have important consequences on discharge evolution and on associated diagnostic methods.

Different numerical tools are considered to achieve this goal, see Fig. 4. The outcome of this work will involve the development of synthetic diagnostic tools, tomographic reconstruction, and X-ray spectroscopy for the experimental visualization of the spatial distribution of impurities and their spectral emissivity characteristics [13, 14], as well as for the identification of particle transport and ionization induced by non-Maxwellian effects. For instance, an X-ray tomography algorithm with real-time capabilities based on neural networks, was validated on WEST against Tikhonov regularization [15]. Simultaneous ( $T_e$ ,  $cw$ ) reconstructions from several line-integrated X-ray measurements in different energy bands were also proven feasible [13]. Diagnostics with spectral resolution such as spectroscopy, or Gas Electron Multiplier (GEM) will offer promising possibilities for such studies [14].

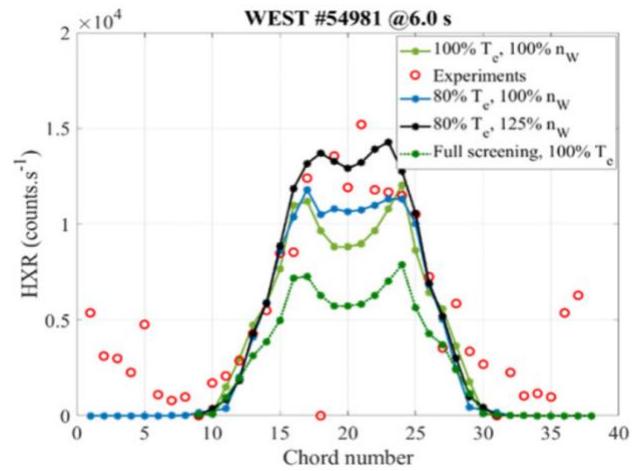


Figure 3: HXR line-integrated signal from WEST – comparison of experiment and simulations, including partial or full screening [11].

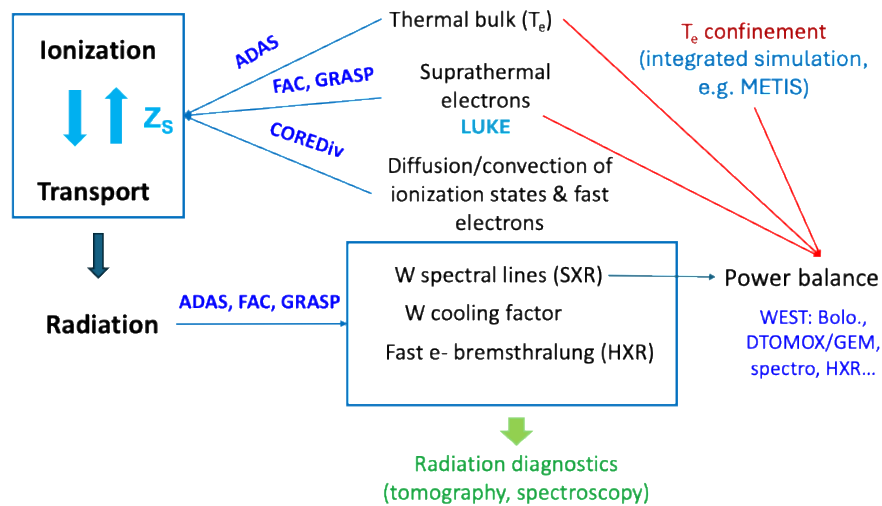


Figure 4. Scheme of interaction between suprathermal electron effects and impurity ionization, radiation and transport in tokamak plasmas, with related numerical tools.

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