A Collisional-Radiative Study of Low-temperature Tungsten Plasma

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A detailed fine structure collisional radiative model with thousands of levels is developed to calculate the radiative properties of tungsten plasma in the low temperature range of 1–2 eV and a nominal ITER electron density of 10^{14} cm^{-3}. A large configuration average model is used to choose the important configurations for the fine structure model. Calculations including the effect of configuration interaction and cross sections with various levels of approximation are compared. The calculations presented here should be of interest to the continuing efforts to model the radiative losses in large magnetic fusion devices, where relatively cold tungsten is found in the divertor region.

The use of tungsten in large-scale tokamak devices has recently motivated a number of theoretical and experimental investigations of its radiative properties over a rather large temperature range. As a wall material, tungsten can enter the main core plasma as an impurity and cause an unwanted energy loss mechanism. Plasma electrons collide with tungsten ions that produce excited states and radiate high-energy photons. Tungsten can also promote significant cooling in the divertor region.

The results of collisional radiative modeling of tungsten for the low temperature range of 1–2 eV have been reported. These temperatures are typical lower limits for the divertor region of a tokamak device. The modeling of tungsten in this region represents a computational challenge because the first few near-neutral ion stages of tungsten have partially filled 5d shell ground states, which produce many atomic levels. The authors are unaware of any previous detailed modeling of this kind in this temperature range.

The calculations are made at an electron density of 10^{14} cm^{-3}, which is a typical tokamak plasma density. The plasma is considered to be optically thin throughout. The LANL collisional-radiative code ATOMIC is employed to solve the rate equations and produce populations and fractional abundances of tungsten ions, radiative losses, and emission spectra for selected temperatures. The atomic structure and collisional data are generated using the LANL suite of atomic physics codes. The atomic data used in the calculations presented here were generated from the LANL suite of computer codes developed over many years to calculate atomic structure and atomic scattering quantities. The CATS code, which is an adaptation of Cowan's atomic structure codes, was used to calculate wave functions, energy levels, oscillator strengths, and plane-wave Born (PWB) collision strengths for tungsten. CATS was used to generate data in both the configuration-average and fine-structure (level-to-level) approximations, the latter of which includes intermediate-coupling and configuration-interaction effects.

Electron-impact ionization, photoionization, and autoionization cross sections were calculated using the multipurpose ionization GIPPER code. These processes were calculated explicitly with distorted-wave continuum functions while most of the electron-impact ionization calculations used scaled hydrogenic cross sections that were designed to reproduce distorted-wave calculations. Three-body, radiative, and dielectronic recombination rate coefficients were obtained from detailed balance. For selected transitions (usually from the ground state), the ACE code was used to calculate electron-impact excitation cross sections in a first-order many-body perturbation-theory (FOMBT) approximation. These more accurate data replaced the corresponding plane-wave Born results mentioned above.

Two atomic models were chosen for this study. A configuration-average model including many configurations was used as a guide for choosing the important features for another model consisting of a smaller set of configurations for more detailed fine-structure calculations. Both models included contributions from ion stages WI–WV. Note that the effects of electric and magnetic fields, charge exchange, and molecular effects are neglected.

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As an example of the results obtained from this study, calculated spectra produced by the various models at 2 eV are shown in Fig. 1. Spectra are shown for the CFG-AVE (configuration average), FS-NOCI (fine structure without configuration interaction and including PWB cross sections) and FS-FOM (fine structure including configuration interaction and FOMBT cross sections) models. The CFG-AVE spectrum was constructed using unresolved transition arrays (UTA) to statistically represent the envelopes of spectral lines. Lorentzian line shapes with a half width at half maximum (HWHM) of 0.002 eV were used for all lines in the FS models. The HWHM was chosen to be large enough to obtain sufficient resolution.

Figure 1 shows that the CFG-AVE UTA model provides a adequate description, without detail, of the envelope of spectra lines. In general, the effect of configuration interaction (FS-FOM) raises the background of the spectral distribution compared to the FS-NOCI result. This occurs because there are more participating transitions with slightly different energies due to level mixing that creates more overlapping lines in the FS-FOM case. Also, in the region of maximum power near 5^{-10} eV, the line intensities are significantly reduced due to the introduction of improved collisional excitation cross sections.

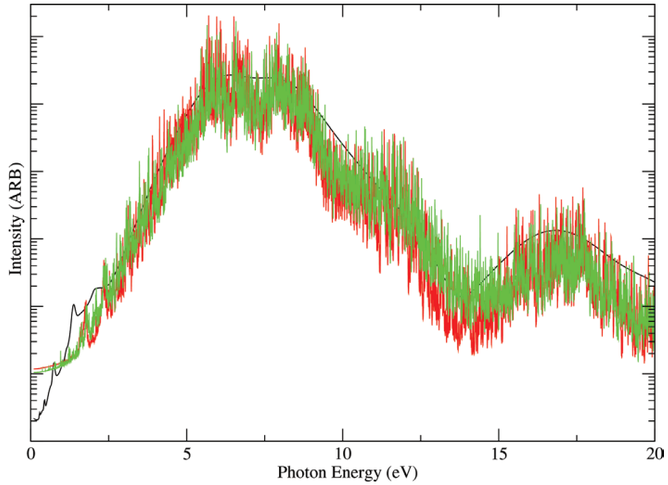

Fig. 1. The calculated emission spectrum for an electron temperature of 2 eV and an electron density of 10^{14} cm^{-3} using various models. The black curve corresponds to the CFG-AVE model using a UTA spectral distribution, the red curve corresponds to the FS-NOCI model, and the green curve corresponds to the FS-FOM model.

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