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Impact of detailed radiation transport on volume recombination

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Abstract

Recently both the Alcator C-Mod and DIII-D tokamaks observed significant recombination of major ion species in the divertor region during detachment. For sufficiently low temperatures the mixture of neutral atoms and ions can be optically thick to line radiation. The optical depth of the recombined region to Ly_α radiation can be very large and opacity effects and radiation trapping can dramatically change the heat flux to the divertor walls. This paper presents an analysis of the effect of line radiation on volume recombination using CRETIN, a multi-dimensional, non-local thermodynamic equilibrium (NLTE) simulation code that includes the atomic kinetics and radiative transport processes necessary to model this complex environment.

Keywords: Recombination; Line radiation; Radiative divertor; Radiation transport

1. Introduction

In detached and/or highly radiating divertor conditions [1,2], achieving low temperatures [3,4] in the plasmas away from the material surface results in a significant amount of recombination of plasma ions and electrons. This insulates the divertor plate by reducing the incident ion flux to the material surface. The production of a strongly recombining region of major ion species in the divertor region away from the material surface is called "volume recombination" and has been observed recently on the Alcator C-Mod [5,6], ASDEX-Upgrade [7], JET [8], and DIII-D [9] tokamaks. However, to assess the impact of volume recombination and to be able to predict the degree of heat flux reduction to the divertor plate in a fusion reactor, we need a more detailed understanding of the phenomenology of this recombining region.

One of the major uncertainties in the ionization and recombination of plasmas away from the material surface is the effect of line radiation. The mean free paths of the Lyman lines are inversely proportional to the neutral population. For a neutral density of $\sim 10^{14}$ cm^{-3}, the mean free path of a Ly_α photon is <0.2 cm, which is significantly shorter than typical scrape-off layer thickness. In a radiatively trapped case, line radiation can significantly alter both the excited state distribution and the ionization balance [10]. Radiative transitions produce an enhanced excited population, which can then be collisionally ionized. Even if the ionization balance is not changed significantly, opacity effects must be accounted for when calculating radiative energy fluxes or interpreting spectral information from optically thick lines.

Past edge modeling using collisional-radiative models used either optically thin or crude escape factor approximations. However, to assess the impact of line radiation in complex geometries where photons are absorbed and re-emitted in regions of varying optical depth and line profiles, simulations must also include line transport. The primary purpose of this paper is to present a sample calculation, using the non-local thermodynamics equilibrium (NLTE) code CRETIN, that illustrates how this can be used to assess the importance of line and continuum radiation in the recombining region of a divertor. We will address the collisional and radiative processes that are included in our atomic

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models which are important in the relevant regime in the divertor regions of present-day tokamaks. We then present a sample analysis of a two-dimensional (2D) configuration representing the scrape-off layer (SOL) region just outside the magnetic separatrix with dimensions similar to the DIII-D tokamak. A UEDGE [11] simulation corresponding to low-power DIII-D operation, which easily yields a detached divertor plasma, provides the plasma profiles.

2. Code description and relevant atomic physics

CRETIN is a multi-dimensional NLTE simulation code [12] that includes the atomic kinetics and radiative transport processes necessary to model the complex environment of a divertor. Atomic processes include electron–ion and ion–ion collisions, photo-ionization and photo-excitation, and Auger processes. Rates for inverse processes are done via detailed balance. Radiative processes include treatments of bound–bound, bound–free, and free–free processes. CRETIN does not include hydrodynamics, but does include transport of neutral particles using a diffusion model [13]. Since the code does not transport ions, the diffusion is supplemented with the condition that the total mass density profile remains unchanged from the input profile. Transport of neutral particles can significantly affect the ionization balance near the divertor plate and is included in our analysis. The flux of the reentrant neutrals at the boundary is assumed to be proportional to the ion flux at the boundary.

3. Case study of a radiative divertor

We present here a case study demonstrating the inclusion of radiation transport effects in simulating the DIII-D-like radiative divertor. Plasma density and temperature profiles calculated with the UEDGE [11] code were fed into CRETIN, which then calculated distributions of ions, atoms, and radiation. Neutral hydrogen was modeled with ten atomic states, characterized by principle quantum number, which were connected to every other state plus the hydrogen ion via collisional and radiative transitions. No molecular transitions were considered.

The geometry of a typical DIII-D-like tokamak with the SOL and divertor region is depicted in Fig. 1(a). The SOL and divertor regions are idealized as a rectangular domain for this initial investigation. The UEDGE plasma simulation is performed over a 100 cm poloidal length corresponding to the outer half of the SOL/divertor regions with a distance of 25 cm between the magnetic X-point and the divertor plate. CRETIN then uses the plasma solution in the X-point-to-plate subdomain as depicted in Fig. 1(b) to do the radiation transport calculation. A more realistic geometry will be used in future studies.

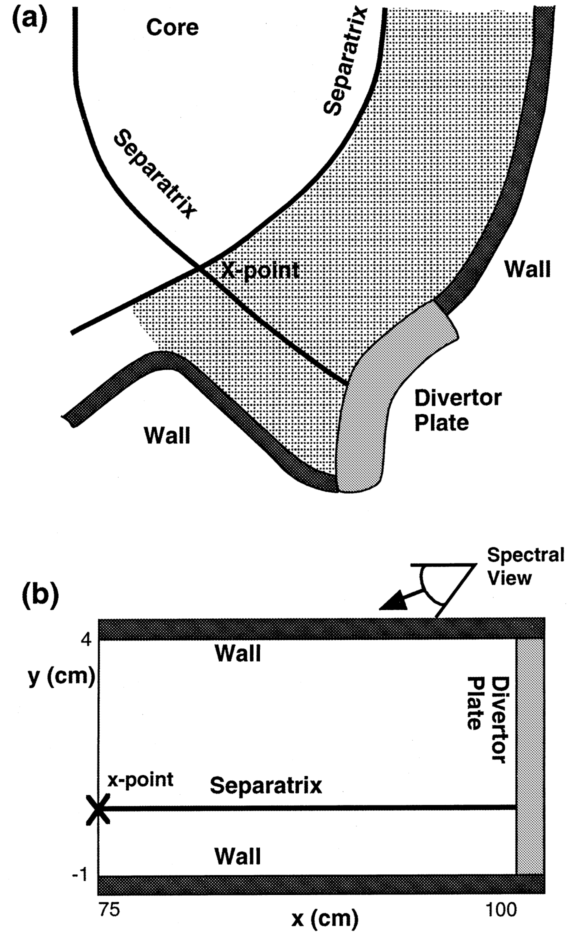

Fig. 1. Rectangular geometry used in this study (b) is an idealized simplification of a more realistic 2D divertor shown in (a). Also indicated in (b) are the detector position and orientation used to calculate the spectrum shown in Fig. 6. The detector was positioned at $x = 95$ cm, $y = 5$ cm and aimed 14° below the x-axis with an opening angle of 0.1 sr.

The configuration chosen for study corresponds to a detached plasma with a moderately cold dense plasma (where radiation trapping should be important) extending roughly halfway to the X-point. The plasma electron temperatures and number densities, as calculated by UEDGE, are shown in Fig. 2(a) and (b). The boundary conditions for the CRETIN simulation were: (1) radiation could freely escape from all boundaries, (2) zero flux of neutral particles through the walls and back towards the main plasma, and (3) a recycling condition at the divertor plate, where ions hitting the plate are reintroduced as neutrals.

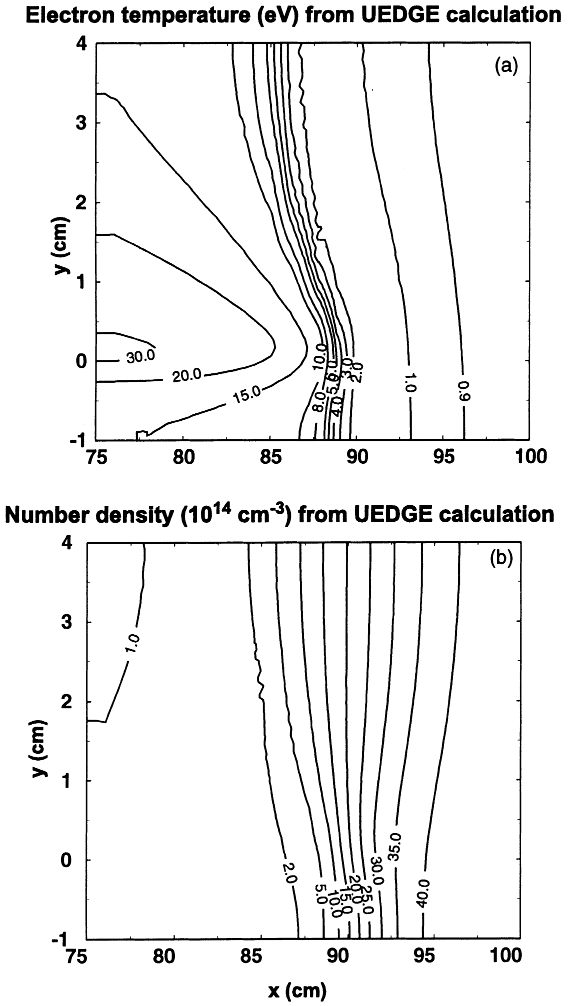

Fig. 2. Contours of constant electron temperature (in eV): (a) and hydrogen number density (ions + neutrals, in units of 10^{14} cm^{-3}); (b) in the divertor region from a UEDGE calculation. The temperature distribution, and a similar distribution for ion temperature, was held constant for the radiative transfer calculation. The number density distribution was also held constant, although the ionization balance and excited state distributions were allowed to vary.

For these densities and temperatures, the cold plasma is very optically thick to Ly$_\alpha$ radiation. The optical depth from the X-point to the plate is of order 10^3. The optical depth between the walls through the cold plasma is also of order 10^4. Most of the Ly$_\alpha$ emission occurs on the edge of the cold dense region. Fig. 3 shows the distribution of the $n = 2$ excited state population, which is proportional to the emission coefficient. The temperature quickly becomes high enough towards the main plasma so that line photons can freely escape, but the flux of line photons towards the wall is severely attenuated.

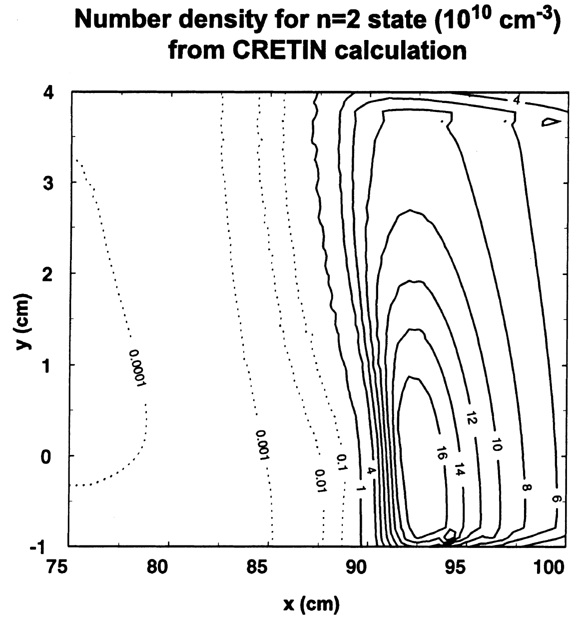

Fig. 3. Contours of constant number density of the $n = 2$ excited state of neutral hydrogen (in units of 10^{10} cm^{-3}) from the CRETIN calculation. This quantity is proportional to the Ly$_\alpha$ emission coefficient.

The radiation trapping and optical depth effects are quite important for understanding the performance of the divertor. Fig. 4 shows the radiative energy flux along the divertor plate which is primarily (~90%) due to continuum radiation. The solid line is from an optically-thin calculation that neglected attenuation of the Ly$_\alpha$ radiation through the cold plasma, including both absorption and re-emission. The optically thin calculation over estimates the radiative flux to the divertor plate due to line radiation by two orders of magnitude, and over estimates the total radiative flux by two orders of magnitude. When attenuation is included, 90% of the radiation reaching the plate is from continuum emission.

The dot–dashed line in Fig. 4 is from a calculation that accounted for attenuation of the line through the cold plasma, but did not include re-emission. The difference is due to radiation trapping effects in the cold plasma. The trapped radiation results in ~10% higher in electron densities which produces ~20% more recombination radiation.

Fig. 5 shows the radiative energy flux along the inner wall ($y = -1$ cm in the simplified geometry). The dotted line gives the total flux from an optically thin calculation, while the solid line gives the total flux from a self-consistent calculation. Again, the optically thin calculation overestimates the total flux by 2 orders of mag-

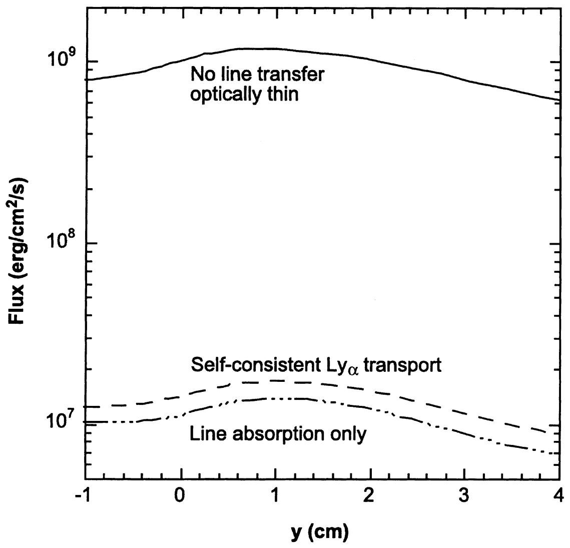

Fig. 4. Radiative energy flux incident upon the divertor plate as a function of position along the plate. The solid curve assumes that the plasma is optically thin to Ly_α radiation. The dot–dashed curve accounts for absorption of the radiation by intervening plasma. The dashed curve includes both absorption and re-emission of the Ly_α radiation.

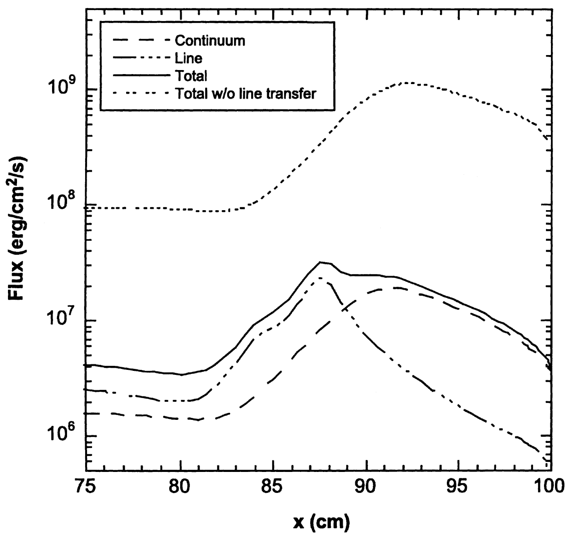

Fig. 5. Radiative energy flux incident upon the bottom wall ($y = -1$ cm) as a function of position along the wall. The dotted curve assumes that the plasma is optically thin to Ly_α radiation. The solid curve includes both absorption and re-emission of the Ly_α radiation. The dot–dashed and dashed curves show the portion of the flux carried by Ly_α and continuum radiation, respectively.

nitude. The dashed and dot–dashed curves represent the contributions of continuum and Ly_α radiation, respectively. Radiation trapping does not significantly affect

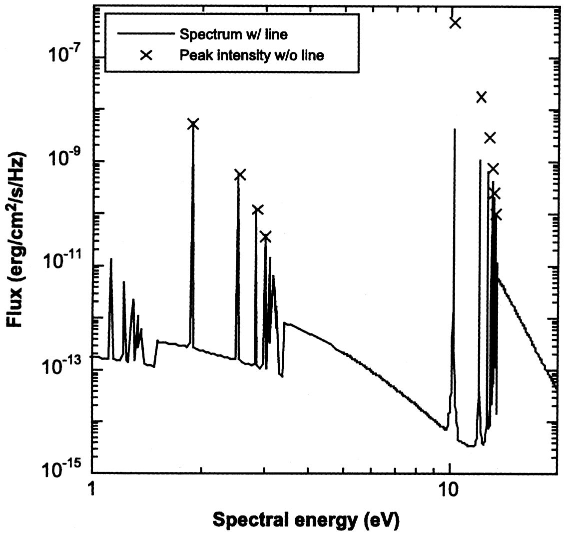

Fig. 6. Simulated spectrum which would be observed by a detector with an acceptance of 0.1 sr placed at ($x = 95$ cm, $y = 4$ cm) and oriented 15° below the x-axis [see Fig. 1(b)]. The detector is assumed to have a flat response curve and negligible broadening. The ×s mark the peak flux densities that would be predicted for the Lyman line and Balmer line series in the absence of absorption.

these results since most of the flux is still due to line radiation.

The calculations performed by CRETIN are self-consistent with respect to the Ly_α radiation and the ionization balance and excited population distribution. However, the temperatures and total plasma densities were calculated by UEDGE under the assumption that the plasma was optically thin and radiation would escape. Since this is far from consistent with the results of the radiation transfer calculations, the energy balance in the divertor region may be quite different than that obtained by UEDGE. Future work will focus on providing a method to address this problem.

The geometry and non-uniform distribution of populations also affect the interpretation of spectral diagnostics, since a given line of sight will pass through regions of differing emission and opacity. Fig. 6 shows a simulated spectrum that would be observed by a detector oriented as pictured in Fig. 1(b). The crosses indicate the values that would be predicted by an optically thin calculation. Attenuation significantly affects the peaks corresponding to the first four members of the Lyman series (above 10 eV). The amount of attenuation will depend on the configuration of the plasma with respect to the detector. The line wings are optically thin and unaffected by attenuation, but will still depend on the particular region of plasma sampled by the detector.

4. Summary

Recombining divertor plasmas can quickly become optically thick to line radiation. We have done some preliminary NLTE radiative transfer calculations for a simplified DIII-D configuration simulated with UEDGE to assess the consequences of this fact. The very large attenuation of the line radiation can dramatically alter the energy balance in the divertor region, with a much smaller impact from radiation trapping. A full evaluation of this effect will require a self-consistent simulation of the divertor plasma that includes radiative transfer.

Acknowledgements

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