

Opacity Effect on Photon Emissivity Coefficients (PECs) of Neutral Helium Line Emissions and Its Impact on Line Ratios

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Motivation

In our recent work, we developed a spectroscopic method to determine the plasma parameters simultaneously from the visible spectrum and then the obtained results are used to calibrate a VUV spectrometer-detector system [1]. The obtained results with few approximations were encouraging because spectral fits were very consistent. However, it requires further investigations in particular to identify the role of poorly determined electron temperature from the proposed analysis. Inclusion of other atomic processes such as dielectronic recombination of ions, opacity effect and also losses due to diffusion to the walls of the discharge source may improve the analysis. In this work we are motivated to understand the opacity effect in our pre-existing model.

Objective

➔ To investigate the helium spectral line excitation keeping the influence and consequences of opacity.

Introduction

➔ Spectral line emissions of atomic and molecular species from various plasmas (Tokamak, Penning discharge source etc) have been promoted as a key diagnostic to plasma electron density, plasma electron temperature and transport characteristics of the plasma.

➔ Interpretation of spectroscopic measurements is not straight-forward. The delicacy lies in the complex nature of plasmas and subsequently the manifold atomic processes. In order to infer the plasma parameters from spectroscopic studies, one requires efficient experimental tools as well as large databases of pertinent atomic data, often from theory, to model the emission through a collisional-radiative (CR) model [2] calculation.

➔ If the plasma is optically thick, the radiation which is coming from the plasma can not be used for 'true' parameter estimation. Moreover, to infer the plasma parameters correctly one has to check the effect of opacity on the working spectral lines prior to apply the spectroscopic method like – line ratio method [3], simultaneous parameters estimation [1] etc.

Pre-existing CR-Model & Opacity inclusion

➔ According to CR model the rate of change of population of a given level (say level p) with respect to time can be written as:

$$\frac{dN_p}{dt} = \text{populating terms} - \text{depopulating terms} \quad (1)$$

Populating Terms:

Collisional De-excitation, Collisional excitation, Spontaneous decay, Electronic three body recombination, Radiative three body recombination.

Depopulating Terms:

Collisional De-excitation, Collisional excitation, Ionization, Spontaneous decay

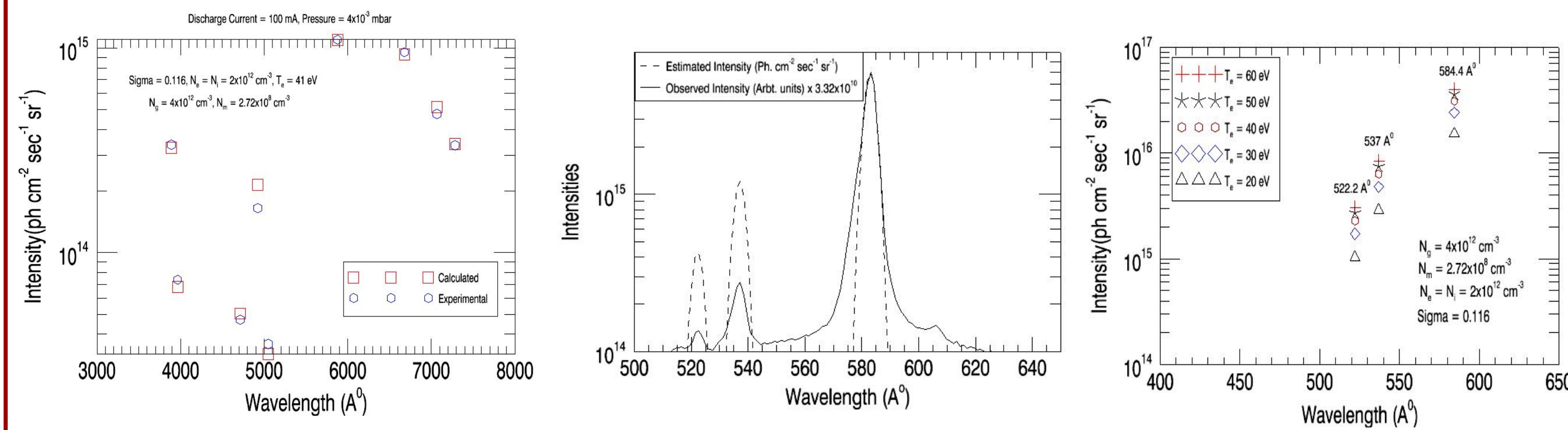
➔ With all these rate coefficients and using CR model, in quasi-steady-state the intensity equation for a given transition can be written as:

$$I(\lambda_{ul}) = \frac{L}{4\pi} \left[\text{PEC}_{\text{reco}} N_e N_i + \text{PEC}_{\text{exct}} N_e N_g + \text{PEC}_{\text{meta}} N_e N_m \right] \quad (2)$$

Here PECs are the Photon Emissivity Coefficients (effective rate coefficients x Einstein's A Coefficients) for a given line and are complicated functions of electron plasma temperature and density. Moreover, for a given set of electron temperature and density the PECs values can be retrieved from the ADAS database.

Pre-existing model:

Equation (2) is used to develop a model for the estimation of plasma parameters like plasma electron temperature, plasma electron density, neutral density, ion density, metastable state density and we found the following results [1];



➔ The estimated densities are consistent with other studies of penning plasma discharge source [4], but the estimated electron temperature is not consistent. This inconsistency in the temperature may be due to the opacity of plasma or it may be due to the diffusion of metastable state atoms or it may be due to both of the processes.

Opacity Inclusion:

➔ The opacity changes the population of excited states and hence the effective collisional-radiative ionization and recombination rate coefficients. The change in effective rate coefficients will change the emitted radiance of spectral lines

➔ Escape factor approach is widely used to include the effect of opacity in rate coefficients. The escape factor is the mean escape probability that a photon emitted anywhere in the source travels directly to the surface of the source in any direction and escapes. More specifically the escape factor can be interpreted as the ratio between the total rate of emergent flux of photons and the total rate of emission of photons within the source. The inclusion of opacity in the CR model calculations causes the net reduction in Einstein's A coefficients.

➔ The spectral radiance $L_\lambda(\lambda)$ in a plasma along a line of sight x is given by the equation of radiative transfer (without scattering into the line-of-sight)

$$\frac{dL_\lambda}{dx} = \varepsilon_\lambda - \alpha' L_\lambda \dots (3)$$

Opacity inclusion contd.

$$\varepsilon_\lambda \rightarrow \text{Spectral Emission Coefficient} = \varepsilon_\lambda P_\lambda(\nabla\lambda) = \frac{n_u A_{ul} h\nu}{4\pi} P_\lambda(\nabla\lambda)$$

$$\alpha' \rightarrow \text{Effective absorption coefficient} = \alpha \left(1 - e^{-\frac{h\nu}{kT}} \right) \quad (\text{If the population ratio of the upper and lower states can be described by Boltzmann distribution.})$$

➔ If the plasma extends over co-ordinate x from zero to b , the escaping radiance at b is given by [5],

$$L_\lambda(b) = \int_0^b \varepsilon_\lambda(x) \exp\left[-\int_x^b \alpha(x') dx'\right] dx + L_\lambda(0) \exp\left[-\int_0^b \alpha(x) dx\right] \dots (4) \quad \text{with the assumption } L_\lambda(0)=0 \text{ and } \alpha \text{ is independent}$$

of x , equation (4) will take the form $L_\lambda(b) = \int_0^b \varepsilon_\lambda(x) \exp[-(b-x)\alpha] dx \dots (5)$

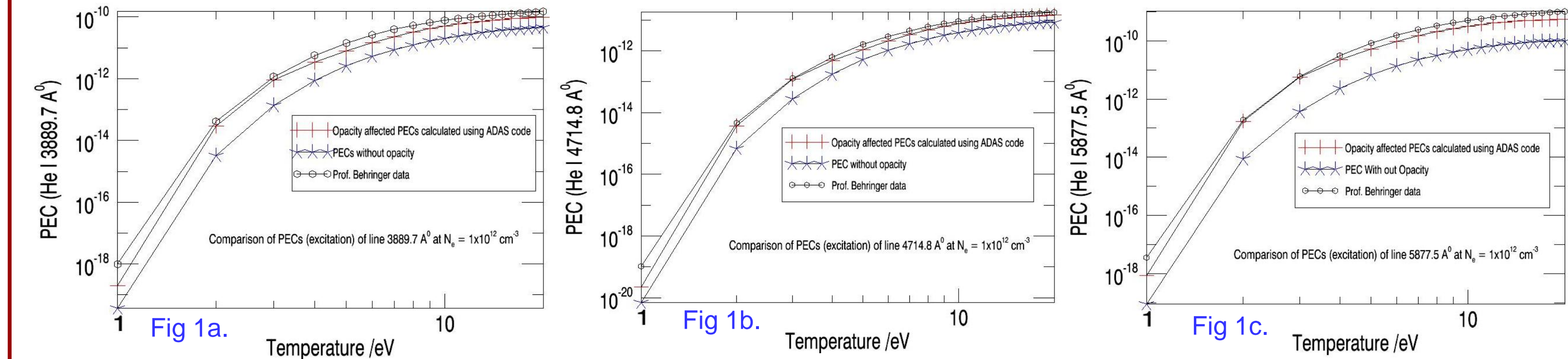
➔ The escape factor for the integral line emission in the direction of x is defined by relating the spectral integral over the self-absorbed line profile to the optically thin line radiance, which is expressed as [6], $\Theta = 1 - \frac{\int_{\Omega} \int_{\text{line}} \alpha(\lambda) \int_0^b \varepsilon_\lambda(x, \lambda) \exp[-(x-b)\alpha(\lambda)] dx d\lambda d\Omega}{4\pi \varepsilon_\lambda(b)} \dots (6)$

➔ For the cylindrical plasma geometry, Doppler line profile and parabolic emission spatial profile, it is found that the value of $\alpha(0)$ is proportional to neutral density n , oscillator strength f , wavelength λ and $\sqrt{\mu/T_g}$ [6] (where T_g is gas temperature and μ is atomic mass number). Hence the escape factor is expressed as [5,6],

$$\Theta = \alpha(0)b = n \frac{\lambda}{c} \frac{f e^2}{4\epsilon_0 m_e} \sqrt{\frac{\mu m_p}{2\pi k T_g}} b \dots (7)$$

Results

➔ The following input parameters are used in order to calculate the opacity affected PECs values from ADAS code: atomic mass number, electron temperature (this is only used to calculate the Boltzmann density distribution i.e. ~8 eV), gas temperature (~600 °K), neutral density (~10¹⁴), length of plasma b (1-10 cm), aspect ratio (0.5), plasma geometry (cylindrical), line profile (Doppler) and type of density distribution across plasma (parabolic).



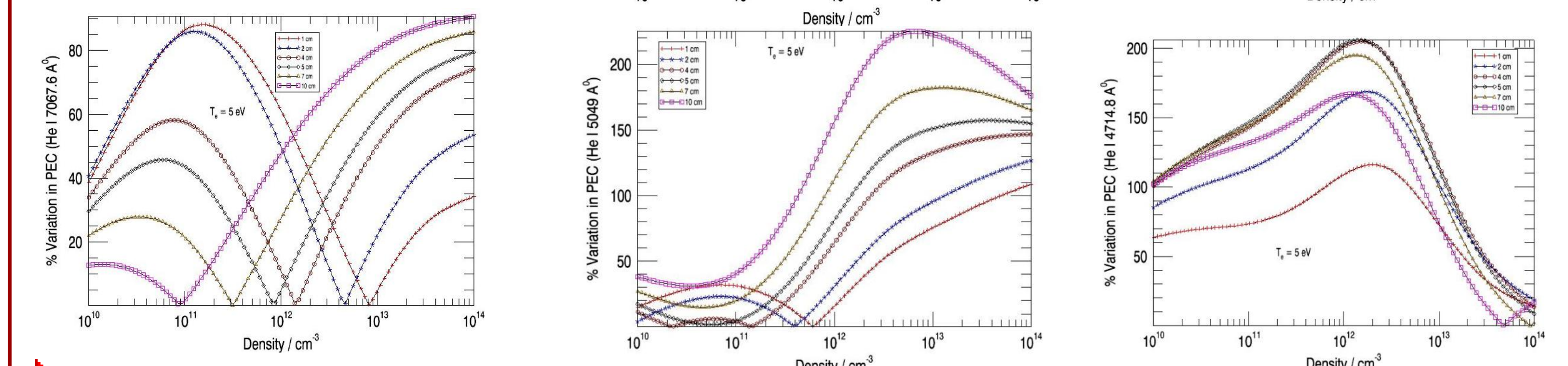
➔ Figure 1. Comparison of derived Photo Emission Coefficients under influence of opacity and without opacity obtained from the collisional-radiative model based ADAS code. The results are also compared with values of PEC's obtained using a code developed by Prof. Behringer, IPP, Garching, Germany. These figures are for neutral helium spectral lines at fixed $N_e = 1 \times 10^{12} \text{ cm}^{-3}$ and for the wavelengths a). HeI 3889.7, b). HeI 4714.7, c). HeI 5877.5 and d). HeI 7067.6.

Percentage Variation in PECs:

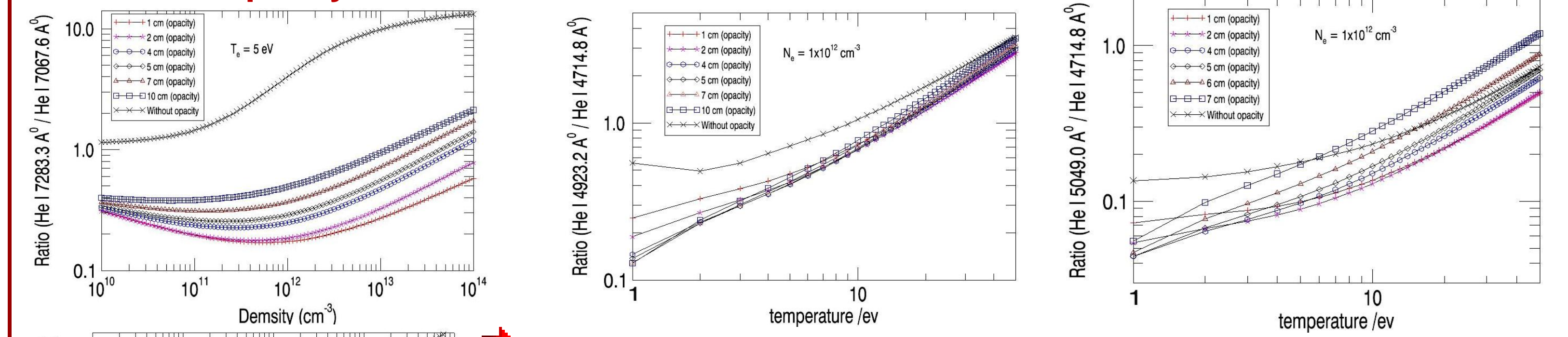
$$\% \text{ Variation} = \frac{(X_2 - X_1)}{X_2} \times 100$$

X_2 = PECs without Opacity

X_1 = PECs with Opacity



Effect of Opacity on Line Ratios:



Summary:

➔ The effects of opacity on the neutral helium spectral lines relevant to our penning discharge plasma system are estimated using an escape factor code of the ADAS database. A cylindrical plasma geometry similar to our earlier experimentation is used, assuming a parabolic emission profile (which peaks at the center of the cylinder) across the radius of the cylinder. Doppler line profile is used in the calculation as per the standard procedure of low density and low temperature plasmas. The code evaluates an optical depth for each transition and returns to a population escape factor. For a given set of escape factors, it became possible to perform collisional-radiative calculations using ADAS code with an account of opacity.

➔ It is done by parametrically modifying the Einstein's Coefficient A values in the Helium data file that are produced having the effects of opacity in the collisional-radiative model code. We evaluated a range of optically thick populations in terms of photon emission coefficients to be used in line ratio comparison and also in our earlier proposed analysis of basic plasma parameter estimations from number of spectral line in a penning plasma discharge source. The results show a significant variation in the PEC's values and so obviously in the plasma parameters.

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