Non-equilibrium radiative properties of fluctuating Helium plasmas

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Abstract

Turbulent magnetized plasmas have been studied with transient temperature, density and HeI line emission measurements. Correlation effects and phase shifts have been analyzed with fully time dependent SOPHIA simulations. The simulations indicate significant phase correlations that are in qualitative agreement with the observations.

I. Introduction

Helium is identified as one of the most important species for plasma fusion magnetic confinement devices. In ITER recombining α-particles produced from fusion reactions lead to the formation of He^{1+} and He^{0+} and corresponding line emission. The analysis of the He radiation emission provides the possibility for a wide and unique non-perturbing characterization of the plasma: particle transport, supra-thermal electrons and charge exchange coupling with the neutral hydrogen background. For these purposes, a complex atomic physics code SOPHIA [1,2] has been developed. In this work, simulations are compared to the experimental results obtained at the experiment MISTRAL.

II. Experiments on MISTRAL

The MISTRAL experiment of the PIIM laboratory allows the optical diagnostics of turbulent magnetized plasmas [3, 4]. In the case of flute-type non-linear low frequency waves [5], the experimental time evolution of the following emission lines have been recorded with a photomultiplier tube coupled to interference filters: HeI(1s3d ^{3}D-1s2p ^{3}P) at 587.56 nm, HeI(1s4d ^{3}D - 1s2p ^{3}P) at 447 nm and HeI(1s3d ^{1}D-1s2p ^{1}P) at 667.8 nm. The corresponding optical line of sight LOS is parallel to the magnetic field lines, in the shadow of the limiter located between the source chamber and the study chamber, 5 mm away from the central plasma column (diameter: 100 mm). These optical measurements have been synchronized to an electrostatic Langmuir probe located in the LOS. The time fluctuations of the electron density n_e and temperature T_e are then deduced from the time resolved Langmuir probe characteristics.

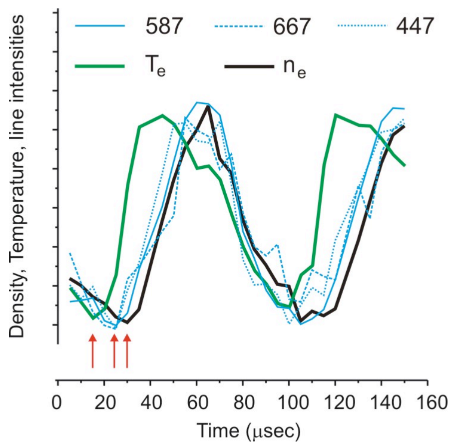

Figure 1: Probe measurements of electron temperature (solid green curve) and electron density (solid black curve) showing a phase shift of about 15 μsec (see left and right red arrow), blue curves are intensities of HeI emission lines: blue solid curve HeI(587 nm), dashed blue curve HeI(667 nm), dotted blue curve He(447 nm).

Figure 1 shows that temperature and density oscillations ($T \approx 80$ μsec) are out of phase: the maximum of the density oscillation arrives about 15 μsec later relative to those of the temperature. Line emissions are about in phase relative to each other (differences less that 5 μsec). However, a significant phase shift of the line emission relative to temperature is observed (about 10 μsec). The phase shift of light relative to density seems less pronounced: middle and right red arrows in Fig. 1 indicate differences less than 5 μsec.

III. SOPHIA: a fully transient atomic kinetics code for arbitrary fluctuation analysis

The study of the impact of arbitrary turbulence to radiative properties of plasmas can be transformed to the general problem of time dependent atomic population kinetics where no assumption is made neither about the time scales of time dependent temperature $T_e(t)$ and density $n_e(t)$ nor about its phase relations:

$$\frac{\partial n_j(t)}{\partial t} + \nabla\left(\Gamma_j(n_e(t),T_e(t))\right) = \sum_{i=1}^{N} n_i(t)\left\{ W_{ij}(n_e(t),T_e(t)) + A_{ij}\,\Lambda_{ij}(n_e(t),T_e(t))\right\} - n_j(t)\sum_{k=1}^{N}\left\{ W_{jk}(n_e(t),T_e(t)) + A_{jk}\,\Lambda_{jk}(n_e(t),T_e(t))\right\} \quad (1)$$

n_j is the population density of state j. It is important to note that the arbitrary character of $T_e(t)$ and $n_e(t)$ also requests that j runs not only over all levels of one charge stage but over all atomic levels irrespective of the ionization stage. This permits to consider not only photon relaxation effects but ionization dynamic effects of arbitrary type [1, 5]. N is the total number of atomic states, Γ_j is the related flux, A_{ji} is the spontaneous transition probability for a transition j → i and Λ_{ji} (depending on the photon effective path length L_{eff} and the level populations n_j and n_i) the related radiation transport operator. The elements of the collisional-radiative transition matrix W_{ij} are given by

$$W_{ij}(n_e(t),T_e(t)) = n_e(t)C_{ij}(T_e(t)) + n_e(t)R_{ij}(T_e(t)) + n_e(t)I_{ij}(T_e(t)) + n_e^2(t)T_{ij}(T_e(t)) + n_e(t)DR_{ij}(n_e(t),T_e(t)) \quad (2)$$

where *C* denotes the collisional excitation/deexcitation rate coefficient, *I* is the collisional ionisation rate coefficient, *T* is the 3-body recombination rate coefficient, *R* is the spontaneous radiative recombination rate coefficient and *DR* is the dielectronic recombination rate coefficient. The currently implement level structure is rather detailed and allows also to keep track of collisional transfer processes between the levels: HeIII, HeII (nl for n=1-5 and l=0-4), HeI ($1s^2\ ^1S_0$, $1snl\ ^1L$ for n=2-5, l=0-4, L=0-4 and $1snl\ ^3L$ for n=2-5, l=0-4, L=0-4).

IV. Simulations of transient line emission in turbulent plasmas

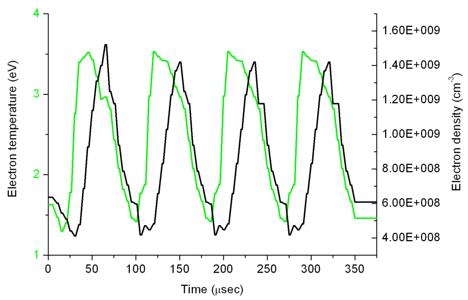

Figure 2: Transient evolution of temperature and density for the SOPHIA simulations.

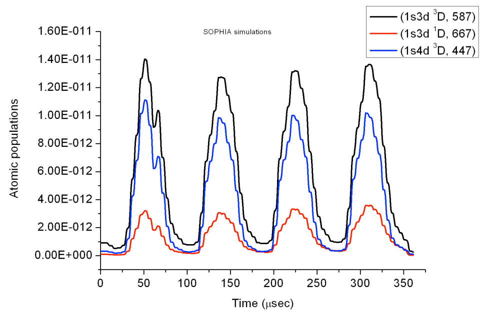

Figure 3: Transient evolution of different population densities. Population densities are probabilities; the sum is normalized to one.

Figure 2 shows the time dependent evolution of temperature and density (corresponding to the measurements presented in Fig. 1) used for the SOPHIA simulations, eq. (1). Figure 3 shows the time dependent populations of atomic levels from which the observed line emission originates. Figure 3 indicates, that for the time scales of $n_e(t)$ and $T_e(t)$ of Fig. 2, all line emissions are about in phase.

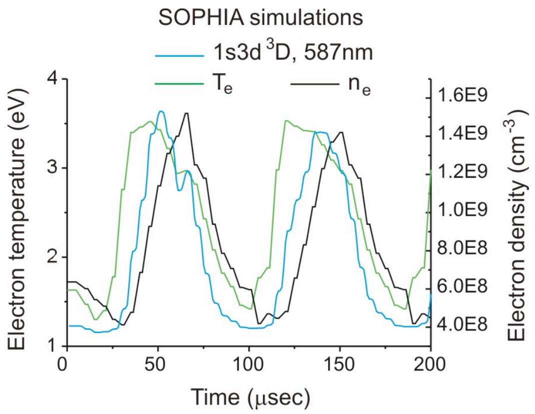

Figure 4: Transient evolution of the HeI level 1s3d ^{3}D (from which the 587 nm emission originates) relative to $n_e(t)$ and $T_e(t)$.

Figure 4 shows the transient line emission of HeI(587 nm) relative to $n_e(t)$ and $T_e(t)$. The comparison of the 3 curves shows that the phase shift of the line emission is located between those of $n_e(t)$ and $T_e(t)$ being slightly more close to $n_e(t)$. Figure 1 seem to indicate also line emission phase shift between $n_e(t)$ and $T_e(t)$, however, more close to $n_e(t)$ than seen in the simulations of Fig. 4.

V. Conclusions

Transient probe measurements of temperature and density as well as time dependent line emission have been compared with fully transient simulations carried out with the SOPHIA code. Observed dephasing effects of line emissions relative to temperature and density seem to be in qualitative agreement with the simulations.

VI. Acknowledgements

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VII. References

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