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Trapping of Pellet Cloud Radiation in Thermonuclear Plasmas

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Abstract

The experimental and theoretical data on radiation trapping in clouds of pellets injected into thermonuclear plasmas are presented. The theoretical modeling is performed in terms of equivalent Stark spectral line widths under condition of LTE (Sakha-Boltzman) in pellet cloud plasmas. It is shown that a domain of blackbody radiation could exist in hydrogen pellet clouds resulting in "pellet disappearance" effect which is absent in a case of impurity pellet clouds. Reasons for this difference are discussed.

Keywords:

pellet, cloud structure, ablation, radiation, trapping, LTE

1. Introduction

Pellet clouds are low temperature and high density plasma structures driven by a hot thermonuclear plasma (see review ref. [1]). The experimental results show that the hydrogen pellet position in the direction across and along magnetic field becomes undistinguishable at some distance from the pellet surface resulting in "pellet disappearance" effect. The effect seems to be due to a blackbody radiation which covers all the radiation within that distance hiding the exact pellet position. The effect exists for hydrogen and is absent for impurity (in particular carbon) pellet clouds.

A complete analysis of these effects requires an account of the pellet cloud dynamics and radiation trapping effects self-consistently. However, there is no reason to do it at the present state of the problem because the pellet dynamics is not clear up to the end. So the dynamic parameters of pellet clouds extracted from the dynamic theoretical models and the experimental observations [1,2] are used below as input parameters for radiation trapping phenomena.

The goal of the present paper is to perform theoretical estimations for radiation trapping in pellet clouds and to compare them with experimental observations in thermonuclear installations.

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2. Experimental Data

The pellet cloud intensity distributions deduced from the fast photography measurements in T-10 [2] are shown in Fig. 1. Measurements have been done in the total visible range of light (400–700 nm) with exposure times of about 7 μs for hydrogen pellet clouds shown in Fig. 1a and 40 μs for carbon ones shown in Fig. 1b. Distributions of cloud intensities both along (longitudinal) and across (transverse) to the magnetic field are shown in Fig. 1. It is seen from Fig. 1b that intensities of the carbon pellet cloud have a sharp maximum corresponding to the current pellet position in the plasma. The striking phenomenon is an appearance of "plateau" region of intensity in the hydrogen pellet cloud (Fig. 1a). This "plateau" region has $R_{\rm pl} \approx$ 3–4 mm in the transversal and $Z_{\rm pl} \approx$ 30–40 mm in the longitudinal direction resulting in "pellet disappearance" inside the domain It is supposed that this region is due to a transition of the radiation observed into Black-Body

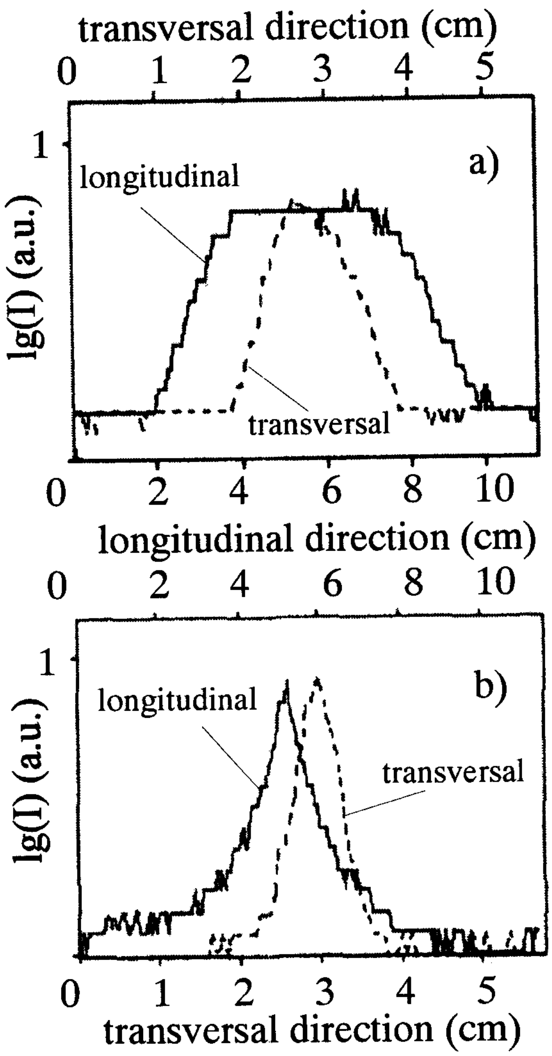

Fig. 1 Distributions of cloud intensities in the 400–700 nm spectral range in longitudinal (solid) and transversal (dashed) direction for hydrogen (a) and carbon (b) pellets injected in T-10 plasmas [2]. Cloud scales are shown in horizontal axes.

(BB) one for the hydrogen pellet cloud. A number of experimental observations (see Ref. [1]) makes possible to accept the following values of pellet cloud parameters: typical electron density measured using Stark broadening of pellet intensity lines is order of 10^{17} cm^{-3}; electron temperature is about of 2–3 eV measured by a ratio of line to continuum intensities with its increase up to $T_{cl0} \sim 5$ eV at the pellet cloud boundary.

3. Modeling

To make a model consistent with the experimental observations mentioned above, let us consider a

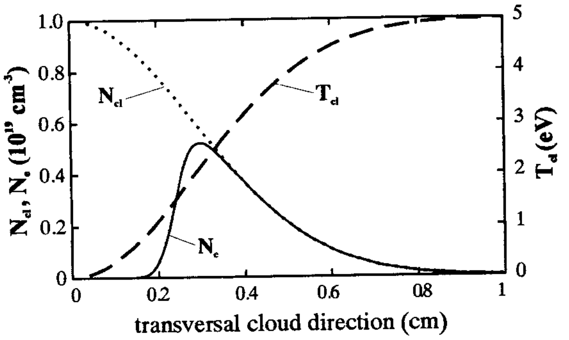

Fig. 2 The neutral, electron densities and electron temperature profiles used in simulations.

hydrogen pellet cloud with a given distribution of the total neutral density $N_{cl}(r)$ in the transversal direction 'r' with 1 cm total cloud radius (see Fig. 1a). We consider only domain ("plateau" region) part of the cloud taking into account that the toroidal density distribution in this part of the cloud is expected to be a weak function of a longitudinal co-ordinate [3]. Here, the cloud density toroidal distribution is assumed to be uniform. Then, a fairly large density of $N_{cl0} \approx 10^{19}$ cm^{-3} of the cloud domain could be estimated as $N_{cl0} \approx N \cdot 2 \cdot R_{pl}/(R_{pl}^2 \cdot Z_{pl} \cdot V_p)$ using a pellet ablation rate value $N \approx 5 \cdot 10^{23}$ at/s (calculated using the conventional Parks's scaling for $T_e \sim 900$ eV and $N_e \sim 3 \cdot 10^{13}$ cm^{-3} measured for the minor radius position of pellet for Fig. 1a) and pellet velocity $V_p \sim 5 \cdot 10^4$ cm/s.

The Sakha-Boltzman equilibrium is assumed through all the estimations below. Validity of this approach was confirmed by estimations done using Ref. [4]. The density $N_{cl}(r)$ and temperature $T_{cl}(r)$ profiles in he cloud were varied in the model with a goal to satisfy experimental data and estimation of N_{cl0} presented above:

$$T_{cl}(r) = T_{cl0}\,[1 - \exp(-(r/L_{cl})^2)]\,,$$
$$N_{cl}(r) = N_{cl0}\exp(-(r/L_{cl})^2)$$

Here L_{cl} is a characteristic decay length of the cloud parameters that is varied in simulations. The neutral and electron density distributions together with the electron temperature profile in the cloud are presented in Fig. 2. As shown below, under such plasma conditions a strong trapping of radiation measured in H_α and H_β spectral lines is possible at a specific cloud radius $r \approx R_{pl}$.

The widths of spectral lines increase with the increase of optical depth of the media resulting in the BB radiation inside equivalent widths of these lines [4]. Moreover, the equivalent widths of these lines can overlap in the domain to approach a BB radiation in the total spectral range observed. The main mechanism responsible for the spectral line broadening in the cloud is the Stark effect in the electric fields of cloud plasma ions. Note that the static line shape can be assumed completely re-distributed over frequencies due to thermal motion of ions [5]. The equivalent width $\Delta\omega_{eq}$ for static line shapes in the far wings of spectral lines was estimated for large values of optical depth τ as follows [4]:

$$\Delta\omega_{eq} = 1.5 \cdot \Delta\omega_S(r) \cdot \tau^{2/5},$$
$$\Delta\omega_S = 2.6 \cdot C \cdot N_i^{2/3}, \quad \tau = \kappa_0 r,$$

where C is the Stark constant of the spectral lines observed, κ_0 is the absorption coefficient depending on the population of the lower atomic level, a line width and atomic parameters of the transitions (see Ref. [6]).

The dependence of the equivalent width of H_β-line on the cloud radius 'r' is shown in Fig. 3. One can see that the equivalent width more dominates over the Stark one when approaching the central parts of the pellet cloud whereas the conventional Stark broadening takes place at the cloud periphery. The radiation intensity outgoing from the optically thick pellet plasma in the 400–700 nm spectral range is shown in Fig. 4. It is seen that the cloud radiation reaches that of the BB one near a specific cloud radius $r \approx 0.27$ cm that is consistent with R_{pl} evaluations from Fig. 1a.

The main difference between hydrogen and impurity pellet clouds is that the oscillator strengths are localized in two (or three) spectral lines for hydrogen and are distributed over the observed spectral range for impurities. This results in the quadratic Stark effect for impurities in contrast with the linear one for hydrogen as well as in different values of absorption coefficients. One must take into account also the difference in neutral densities for both cases due to a difference in the pellet ablation rates together with a difference of ionization potentials in Sakha-Boltzman equilibriums.

Such estimations show that the equivalent optical widths for the hydrogen cloud are more than one order of magnitude larger than impurity ones. Therefore, when hydrogen lines are overlapped to create black body radiation, the impurity lines are still non-overlapped. This is a possible reason for existence of the "pellet disappearance" effect for hydrogen pellets and it's absence for carbon pellets.

4. Discussion

The consideration done above claims a possibility of radiation trapping inside pellet clouds. Due to the rough approach both for density and temperature distributions inside clouds as well as due to the simplified radiation trapping model used for strongly overlapping spectral lines, there are some uncertainties in simulated parameters of the problem. However, the presented model seems to be consistent with the experimental observations available. The measurements of electron densities of pellet clouds are consistent with the simulated values ~10^{17} cm^{-3} of electron density in the pellet cloud periphery where the equivalent width is close to conditional Stark one (Fig. 3). The temperature measurements seem to belong to the cloud domain near transformation of the intensity to the BB one (Fig. 4) where the temperature is near 2–3 eV (Fig. 3). At the same time the possibility of BB parts of the pellet clouds radiation is also consistent with "pellet disappearance" effect discussed above. The cloud parameters for these effects are not so far from the ones usually accepted for pellets.

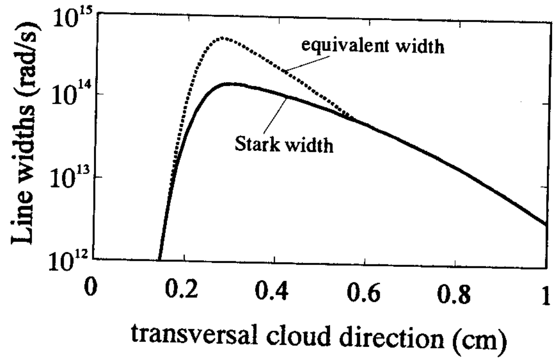

Fig. 3 Comparison of the equivalent and Stark width of H_β line at different radii inside the pellet cloud.

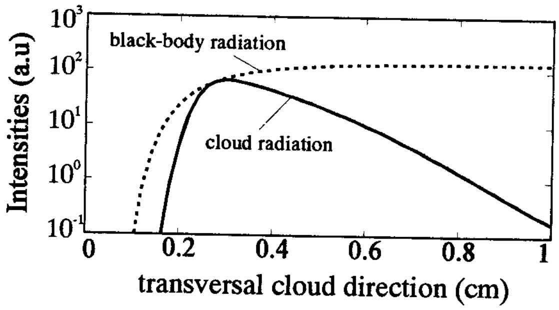

Fig. 4 Comparison of the pellet cloud and BB radiation intensity profiles in the 400–700 nm spectral range.

Acknowledgments

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