Theoretical and experimental studies of radiative and gas dynamic properties of substances at high energy density in matter

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Abstract. Mathematical modelling of radiative and gas-dynamic processes in substances at high energy density is carried out for experiments, where both laser and heavy ion beams are used. Important features of the theoretical model, known as the ion model (IM), which is used for quantum mechanical calculations of radiative opacity, are discussed. Reliability of (IM) results is tested with experiment, where measurements of x-pinch radiation energy yield for two exploding wire materials, NiCr and Alloy 188 were made. Theoretical estimations of radiative efficiency are compared with experimental results, and (IM) calculations agree well with the experimental data. Subsequently, the theoretical approach was used for temperature diagnostics of CHO plasma target in combined laser–heavy ion beam experiments. Joint radiative and gas-dynamic calculations are performed for comparison with experiment, where hohlraum radiation transmits through the CHO plasma target, and the share of absorbed radiation energy is compared with experiment. Study of radiative properties of CHO plasma with little admixture of gold is carried out as well. Specific dependence of the Rosseland mean on plasma temperature is discussed for gold plasma.

1. Introduction

Theoretical and experimental studies of matter at high energy density require extensive theoretical and experimental investigations of processes, where high power laser, x-ray or heavy ion beams interact with matter, transforming substances into a high energy density state. The investigations, which have been performed for last years [1–5], provide progress in deep understanding of physical processes in matter, which is transformed into a high energy density state under heating and compression. Fundamental theoretical study of these physical processes has to include (i) gas dynamics, (ii) photon transport processes [6,7], (iii) equation of state [8,9], (iv) radiative opacities [10], where the radiative opacity data represent an important part of this study [11].

Different theoretical models can be used to calculate the spectral coefficients for x-ray absorption, the Rosseland and Planck mean free paths and other radiative opacity characteristics. Comparative analysis of the most frequently used models has been carried out based upon the density functional theory [12]. The general set of self-consistent field equations that describe the state of the whole ensemble of plasma atoms and ions has been obtained using this approach. The set contains (a) the Hartree–Fock equations for all atoms and ions with different electron configurations; (b) the unbound electron densities in phase space for all atoms and ions; (c) the Gibbs distribution; and (d) the electroneutrality condition. The main feature of this set is the general coupling of all equations for all plasma atoms and ions, including exited states. At first site, this circumstance creates an irresistible obstacle for its solution because of huge number of equations. Therefore, further physical approximations were used until recently in the framework of the most part of frequently encountered models to simplify these equations.

Meanwhile, any simplification of the equations leads to a restricted range of plasma temperature and density over which the model can be applied [12]. For instance, the Thomas–Fermi model (TF) [13] can be used only for very high plasma temperatures. A more late model, which is known as the Hartree–Fock–Slater model (HFS) [14, 15], uses so-called average atom approximation. That is a fictitious atomic system with nointeger numbers of bound electrons in the atomic shells. These numbers are calculated using the Fermi-Dirac formula. To calculate the properties of a real atomic or ionic system, this approach uses the theory of perturbations. This circumstance restricts the temperature range, and the model cannot provide accurate enough results if the temperature of the plasma decreases.

The Detail Configuration Accounting (DCA) model [16] uses the Hartree–Fock equations for real atomic and ionic systems and the Saha method for calculating their concentrations. This approach cannot be used for strongly coupled plasmas. The point is that the Saha approximation can be used to determine the atom and ion concentrations only in case of ideal plasma. Meanwhile, that approach is widely used until now in the framework (DCA) model, since the approach leads to more simple calculations of atomic and ionic characteristics.

It is necessary to keep in mind that high power laser pulse can produce intense shock wave and intense radiation wave in a laser target. As a result, strongly coupled plasma can be produced. It can lead to considerable deviation of atom and ion concentrations from the Saha distribution as well as to deviation of atomic and ionic characteristics from the characteristics, which were calculated or measured for ideal plasma. A modern version of (DCA), which was called as Detailed Level Accounting (DLA) model [17], uses experimental data from different databases to improve the mentioned characteristics. It should be noted that application of experimental data, which were measured at the ideal plasma conditions, and applied to strongly coupled plasmas calculations in the framework of (DLA) model could considerably increase the error bar of the (DLA) model results.

Thus, one can indicate the range of plasma temperature and density over which the mentioned models cannot provide accurate enough results [12]. The solution of the general set of self-consistent field equations, which describe the state of the whole ensemble of plasma atoms and ions, is the way to solve the problem in general. To achieve this aim, the set of equations was solved at first for pure substances in the framework of the Ion Model of a plasma (IM) [18], which has been created and developed for some years. Subsequently, it was applied to compound chemical compositions. As a result, reliable quantum mechanical calculations of radiative opacity became possible over a wide range of plasma temperature and density. Finally, the optimization problem was solved for compound plasma compositions. A specific theoretical method and effective computer code were created to optimize radiation yield from complex materials that can be used as x-ray source materials in practice. Efficiencies these materials can be estimated for optically thick and optically thin plasma.

As known, optically thick plasma can be produced by laser interaction with a hohlraum wall. It was shown [19], that hohlraum wall loss energy increases proportionally to the square root of the Rosseland mean free path. Therefore, an optimal chemical composition for optically thick plasmas can be achieved by minimizing the Rosseland mean free path. Application of the optimization method, which is based on the (IM) model, to hohlraum wall plasma has been considered in detail at [20]. The case of optically thin plasma was considered at [21], where the (IM) results were tested with experiment of Cornell University, and experimental results confirmed the (IM) theoretical approach.

Thus, a theoretical approach, which is based on the (IM) of plasma application, has been formed, and this approach is used for different theoretical and experimental investigations of processes, where high power laser, x-ray or heavy ion beams interact with matter, transforming substances into a high energy density state.

2. Theoretical and experimental study of radiative and gas dynamic processes in plasma for experiments, where both intense laser and heavy ion beams are used

The theoretical approach can be used for studies of radiative and gas-dynamic processes in plasma, which is produced in laser and heavy ion beams experiments. In particular, it can be applied for temperature diagnostics of low-Z foams, which is used at this experimental scheme. As known, intensity of heavy ion beam interaction with a target increases if the target is heated to plasma [22–24]. The experiment needs creating a plasma target, which can keep the temperature and density during further interaction with heavy ion beam. Indirect heating of CHO-foam with laser pulse can be used to this end. In this scheme, the laser pulse interacts with the wall of the Au cylindrical converter—hohlraum for effective conversion of the laser energy into soft x-rays energy, and then soft x-rays heat the low-density CHO polymer slab. A new temperature diagnostics method, which is based on experimental measurements of photoabsorption K-edge energies in carbon, was developed for this scheme [25]. Indeed, if the temperature increases, the state of the whole ensemble of plasma atoms and ions is changed. It leads to appearance of new ions with more high ionization degree, and states with low ionization vanish. As a result, K-edge energies are considerably changed. Comparison of the theoretical and experimental results can be used to estimate plasma temperature.

3. Mathematical modelling of radiative and gas dynamic processes in CHO plasma. Radiative properties of TAC and Au compositions

Another application of the ion model (IM) is connected with mathematical modeling of radiative and gas-dynamic processes in plasma for experiments where triacetate cellulose (TAC, $C_{12}H_{16}O_8$) foam slab was used for indirect heating with laser pulse. The temperature and density in (TAC) plasma target depend on coordinate and time. Joint radiative and gas-dynamic calculations were used to determine these characteristics with regard for photon transport processes, and the ion model (IM) was used to calculate the radiative opacity characteristics. In this experiment, the hohlraum radiation transmits through (TAC) plasma target during definite time interval, which was equal to 5 nanoseconds, and the transmitted spectrum is compared with experiment. The comparison shows good enough agreement of the theoretical and experimental result over the most part of energy interval [26].

The share of the hohlraum radiation energy, which has been absorbed in the target, was found 75 percents, and this value coincides with experiment. The share can be increased by using a little admixture of gold to TAC polymer [27]. Indeed, the heating process can be divided into same stages. On the initial stage, the temperature is small in the target, and the Rosseland mean free path is small too. As a result, practically all hohlraum radiation is absorbed in the target. On the next stage, the temperature increases and the Rosseland mean free path increases as well. Some part of photons can go through the target taking away energy. To suppress this effect, one can add a little admixture of gold to TAC polymer. As shown in [27], a little admixture of gold 0.7 percents in mass fraction leads to double decrease of the Rosseland mean.

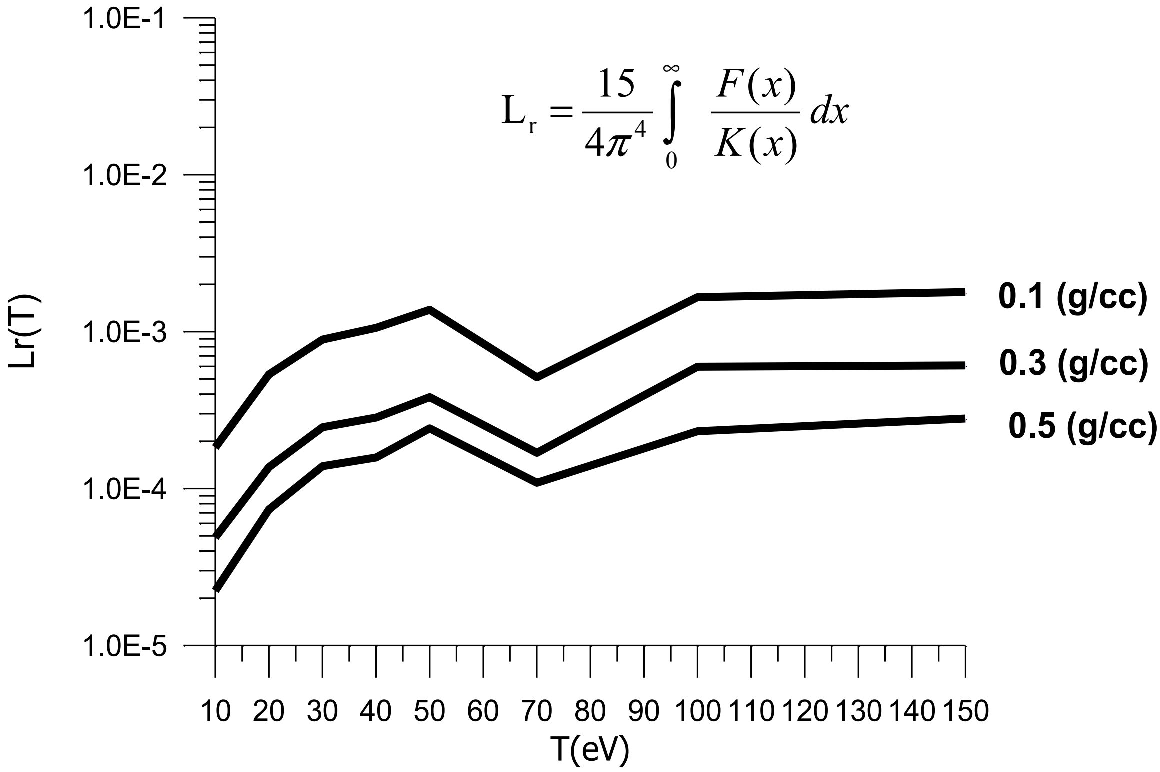

Figure 1. The Rosseland mean free path $Lr(T)$ (cm) vs plasma tevperature T (eV) calculated for gold plasma at different densities 0.1 (g/cc), 0.3 (g/cc) and 0.5 (g/cc).

4. Radiative opacity of gold plasma

Finally, the radiative opacity of gold plasma was calculated over the wide range of plasma temperature and density. The graph (figure 1) presents the Rosseland mean free path in dependence on temperature calculated for three different densities. As usual, the Rosseland mean has steady increase with temperature increasing. However, one can see a definite decrease of this value at the temperature 70 (eV) (see figure 1). The explanation of this effect is connected with specific spectral coefficients for x-ray absorption for gold plasma.

Indeed, the Rosseland mean free path is calculated using the formula (figure 1), where $K(x)$ is the spectral coefficients for x-ray absorption, $x = E/T$. Here E is photon energy and T is plasma temperature.

Function $F(x)$ has the form:

$$F(x) = x^4 \exp(-x)/((1 - \exp(-x))^2).$$

The function F attains the maximum if photon energy $E = 3.7T$. We denote this value by $Emax$. If the temperature increases, the value $Emax$ moves along the energy scale. If $Emax$ position on the energy scale coincides with the spectral line group position of the function $K(E)$, the Rosseland mean decreases.

Figure 2 presents the spectral coefficient for x-ray absorption $K(E)$, which was calculated at the temperature 70 (eV) and the density 0.1 (g/cc) (thin line), and function $F(E)$ (bold line). One can see the spectral line group position of $K(E)$ on the energy scale coincides with $Emax$ position.

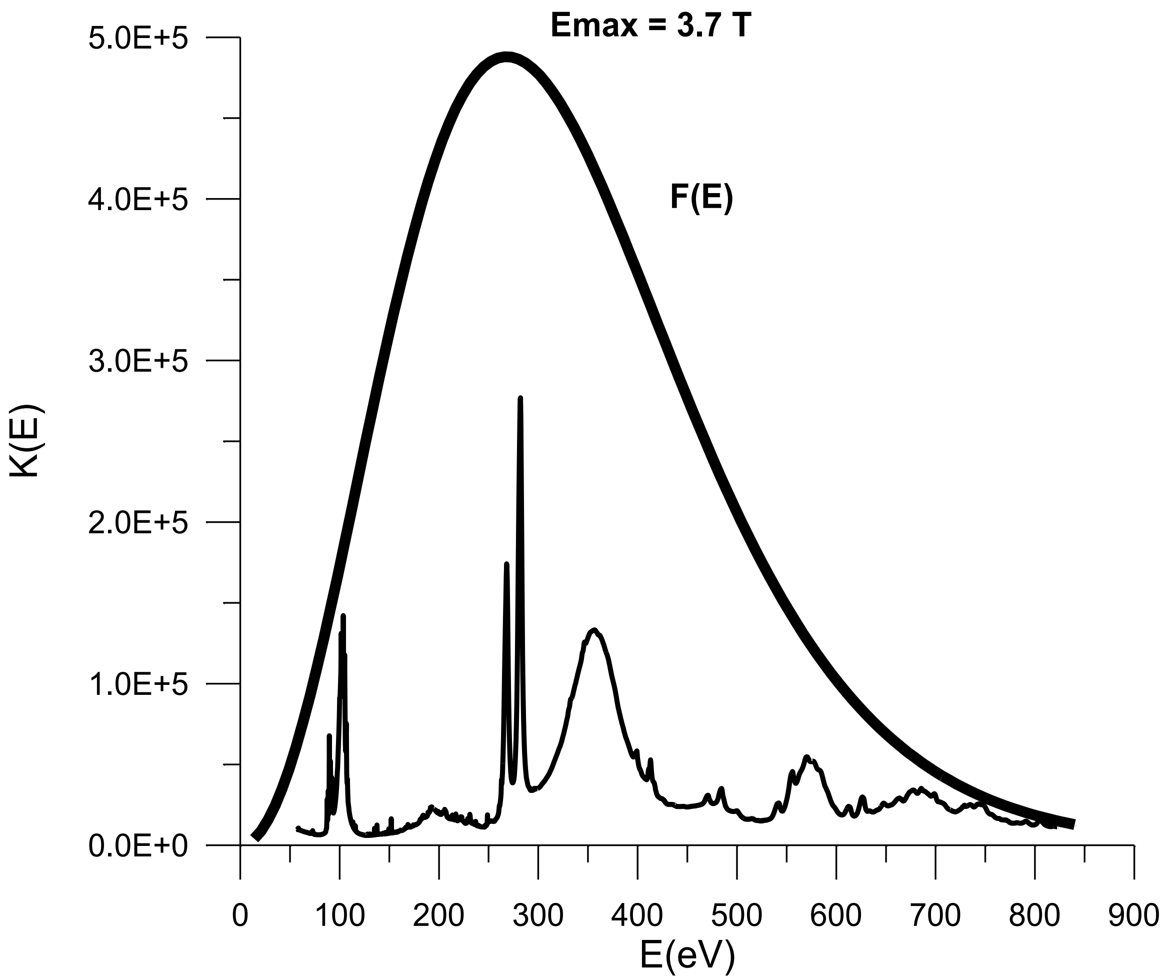

Figure 2. The spectral coefficients for x-ray absorption $K(E)$ (cm^2/g) vs photon energy E (eV) calculated for gold plasma at the density 0.1 (g/cc) and temperature $T = 70$ (eV) (thin line). Function $F(E)$ (bold line).

5. Conclusion

One can conclude that theoretical approach, which is developed for last years at Joint Institute for High Temperature RAS, provides reliable quantum mechanical calculations of radiative opacity over a wide range of plasma temperature and density. The theoretical approach can be used for temperature diagnostics of low-Z plasma and for mathematical modeling of radiative and gas dynamic processes in plasma.

Acknowledgments

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