Thermalization of the plasma arising during counter collision of high-energy plasma flows in a longitudinal magnetic field

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Abstract. This work is devoted to the study of thermalization of plasma created by head-on collisions of high-energy plasma flows in a longitudinal magnetic field of 0.5–2 T. Hydrodynamic flows contained the energy of 200 kJ with velocities from $2 \times 10^7$ to $4 \times 10^7$ cm/s and ion density from $2 \times 10^{15}$ to $4 \times 10^{15}$ cm$^{-3}$ were created inside the 2MK-200 facility by two electrodynamic plasma accelerators equipped by a system of pulsed gas injection. Nitrogen, neon and their mixtures with hydrogen and deuterium were implemented as working gases. A process of plasma creating was investigated by near-wall magnetic probes situated in different parts of the interaction chamber. Temporal evolution of the plasma electron temperature had been traced by X-ray photodiodes covered by different filters. It was discovered that the plasma electron temperature changed insignificantly during 6–8 µs after it reached the maximum value, which means that it ionization state can be considered as quasi-stationary.

1. Introduction

It is well-known that performance properties of materials and components applied in energetic, machine-, aero- and space engineering can be improved by pulsed irradiation of their outer layers when exposed to powerful pulsed energy fluxes, including short-wavelength radiation ones. A source applicable for that purpose can be created during counter collision of high-energy plasma flows as a result of kinetic energy conversion to energy of soft X-ray radiation. The topic of the plasma flows kinetic energy transformation during the collision of these flows has been considered for quite a long time. It was shown in [1] that the directed energy of the flows can be effectively thermalized as a result of ion scattering on Alfvén waves. In [2–4] main mechanisms of the conversion of the plasma kinetic energy into radiation during the interaction of a plasma stream with different obstacles (condensed substance, dense gas, plasma, magnetic field or solid-state target) were considered. Various aspects of the transformation process of the plasma flows kinetic energy into other types of energy were studied experimentally in [5–13]. In particular, the work...
[6] is devoted to conversion to ultraviolet radiation, and the work [7] generation of neutrons in plasma flows collision was investigated. In [12] it was shown that the electron density at a collision region of two plasma bunches increases 1.3–3.8 times compared with the density in the single stream. However, all these experiments were carried out with plasma flows of relatively low energy. For example, in [12] the energy stored in capacitors of the experimental setup was at the level of 1 kJ.

In [14, 15] experiments on collision of high-energy nitrogen and neon plasma flows with full energy of 200 kJ, velocities from $2 \times 10^7$ to $4 \times 10^7$ cm/s in a longitudinal magnetic field with $B = 2$ T are described. As a result of these works predictions of preliminary theoretical and numerical analysis were confirmed. It was demonstrated that a considerable part of the plasma flows kinetic energy converts to the thermal energy of a plasma bunch arises in the zone of interaction. The plasma flows were created by pulsed plasma accelerators. The energy emitted in a form of photons with energies over 100 eV amounts up to 2 kJ for the case of neon–deuterium mixture and up to 10 kJ for pure nitrogen. The pulse duration was about 10–15 µs for both cases.

Energy, spectral and temporal properties of the source created in the described way depends largely on thermalization dynamics of the created plasma bunch. Investigation of this process is the main goal of this work.

2. The 2MK-200 facility
The experiments were carried out using the 2MK-200 facility [14–18]. It consists of two pulsed plasma accelerators and an interaction chamber [figure 1]. The chamber is a tube made of stainless steel with inner diameter of 21 cm and 3 mm thick walls. The full length of the system is about 4 m; 10$^{-4}$ Torr pressure were maintained inside.

The plasma flows with full energy of 200 kJ had been colliding in a longitudinal magnetic field, which was created in the chamber by a system of eight solenoids. All of them were installed symmetrically relatively the central cross-section (four on each side). The solenoids current rise time was 3.5 µs. A magnetic field distribution in the chamber was selected to provide a source with maximum lifetime and diameter less than 15 cm. These parameters were controlled by x-ray photodiodes and magnetic probes correspondingly. The initial magnetic field had been rising from 0.5 T in edge sections to 2 T in the central one.

Figure 1. Schematic plot of the 2MK-200 facility: 1—pulsed plasma accelerators; 2—cylindrical vacuum chamber; 3—solenoids; 4—plasma bunches; 5—diagnostic windows for spectrometer, photodiodes and magnetic probes; 6—magnetic probes.
Figure 2. Temporal evolution of the magnetic probe (dashed line) signal and x-ray photodiodes signal obtained in the central section of the interaction chamber for two different types of a plasma-forming gas: (a) mixture of neon and deuterium (partial pressures are 75% for neon and 25% for deuterium); (b) pure nitrogen. In the case (a) the photodiodes were covered by 25 $\mu$m (thick line) and 50 $\mu$m (thin line) beryllium filters. Aluminum filters with thicknesses of 3.0 $\mu$m (thick line) and 7.1 $\mu$m (thin line) were applied for the case (b). In that case the amplitude obtained for the thicker filter was multiplied by 7 for convenience. Time is counted from the moment the plasma accelerators are started.

Power supply of the accelerators were provided by 1 mF capacitors. Electrical voltage on the capacitors had been varied in the 20–23 kV range. The plasma-forming gases had been injecting in a region between electrodes by a pulsed gas valve. Nitrogen, neon and mixtures of them and deuterium or hydrogen were used. Soft x-rays emitted by the plasma were registered with a time resolution of 0.02 $\mu$s by semiconductor photodiodes covered by different filters. Absolute spectral sensitivity of them can be found in [19]. Data obtained by means of the photodiodes allowed characterizing the plasma thermalization process. Under these words we mean conversion of the flows kinetic energy to thermal energy of the plasma in the collision zone. Also, the photodiodes data was used to obtain the plasma electron temperature temporal evolution.

Magnetic probes were also used for plasma diagnostics. There were three probes in different positions: one in the central section and two in the side sections 40 cm far from the center. Distance between the probe and the chamber wall did not not exceed 1 cm. Electric voltage in the magnetic probe circuit was proportional with 2% accuracy to variation of magnetic induction $\Delta B$ in the region close to the chamber wall. It allowed characterizing a process of magnetic field displacement by the gas-kinetic pressure and the internal magnetic field of the plasma.

3. Experimental results

Experimental data analysis is based on collation of the magnetic probes and x-ray photodiodes (situated in the central section) signals obtained for different injected gases. As it was mentioned above the signal of the magnetic probe is associated with the plasma generation process in the interaction zone and the signal of photodiodes relates to the heating of plasma electron component. The data obtained with these detectors for the different plasma-forming gases are shown in figure 2.

As we can see, in the case of neon plasma the x-ray signals started to arise simultaneously with the magnetic probe signal, but a 5 $\mu$s lag was observed for the nitrogen plasma. Such behavior was obtained for all carried experiments with neon- and nitrogen-containing plasma.
Figure 3. Time profiles of signals obtained by the magnetic probe (dashed lines) and the x-ray detector (solid curve), which were installed in the side section of the interaction chamber during the experiments with two different plasma-forming gases: (a) neon–deuterium mixture; (b) pure nitrogen. The x-ray radiation was registered behind the 3 µm aluminum filter. Time is counted from the moment the plasma accelerators are started.

Figure 4. Time profiles of signals from the magnetic probe (dashed line) and the x-ray detector (solid line) installed in the central section of the interaction chamber during the experiments with two different plasma-forming gases: (a) nitrogen–deuterium mixture (partial pressures are 25% for nitrogen and 75% for deuterium); (b) pure deuterium. The x-ray radiation was registered behind the 3 µm Al filter. Time is counted from the moment the plasma accelerators are started.

A very similar situation takes place for signals obtained by the magnetic probes and x-ray photodiodes installed in one of the side sections 40 cm far from the central section (figure 3). As one can see the x-ray signal also lags a little for the case of the nitrogen plasma.

For experiments with mixture of nitrogen and deuterium it was also found that the signal associated with the x-ray radiation of the hot nitrogen-containing plasma lags relatively the magnetic probe signal approximately for 5 µs. Figure 4(a) demonstrates a sample of data obtained for the experiments with the mixture of nitrogen and deuterium. Temporal profiles obtained for pure deuterium as plasma-forming gas are shown in figure 4(b).
Figure 5. Time profile of plasma electron temperature in the central section of the interaction chamber obtained by means of the absorber-foils method for the experiments with two different plasma-forming gases: (a) neon–deuterium mixture; (b) nitrogen. Temperature measurement accuracy is ±15%. Dashed line is a signal of the magnetic probe installed in the central section of the interaction chamber. Time is counted from the moment the plasma accelerators are started.

In experiments with neon and nitrogen, the time course of the electron temperature of the plasma formed during the collision of flows and the thermalization of their directed kinetic energy was determined [figure 5] in the central section of the interaction chamber. It was calculated on the base of the x-ray signals registered behind filters, which material and thickness were chosen in such a way to provide complete absorption of possible lines emission of multicharged ions. It allowed to implement the classical absorber-foils method [20].

It should be emphasized that the electron temperature remains permanent during 6–8 μs (within the margin of error) thereafter maximum values had been reached. It means that the ionization state of the plasma can be considered as quasi-stationary. This fact increase the level of confidence for the results of detailed kinetic calculations for spectral distribution of the plasma x-ray radiation which were carried out in [14, 15].

The observed delay between the magnetic probe and photodiode signals can be explained by several different reasons. Among them can firstly be ones associated with different dynamics of the thermalization process for different chemical composition of the colliding flows and, secondly, associated with features of the ionization process kinetics for different plasma types. In this work we have tried to investigate an influence of the last ones.

Time-resolved calculations of the ion kinetics were held for nitrogen and neon plasma by means of the collisional-radiative spectral analysis code PrismSPECT [21]. 11481 energy levels for neon ions and 8180 levels for nitrogen ions of all possible charge states and all transitions due to radiation processes, electron collisions and autoionization were included in the calculations. At the same time gas-dynamical parameters of the plasma were defined by a quite crude model. It was assumed that the plasma object is spatially homogeneous and time-dependencies of the ion density $N_i$ and the electron temperature $T_e$ can be described by the Heaviside function $\sigma(t)$ [figure 6(a)]:

$$T_e(t) = T_0 + T_{\text{max}}[\sigma(t-t_m) - \sigma(t-t_m-\Delta t)],$$

$$N_i(t) = N_0 + N_{\text{max}}[\sigma(t-t_m) - \sigma(t-t_m-\Delta t)],$$

(1)

where $T_0$, $T_{\text{max}}$ and $N_0$, $N_{\text{max}}$ are initial and maximum values of the plasma temperature and density correspondingly, $t_m$ and $\Delta t$ are time of the magnetic probe signal beginning and its
Figure 6. (a) Parameters of the plasma model which were used for the kinetic calculations. (b) Calculated time profiles of the x-ray intensity emitted by the neon plasma (solid line) and nitrogen plasma (dashed line) after the start of the flows interaction.

duration. The value of the parameter $T_0$, which determines the initial stage of ionization of the plasma bunch, was set in such a way that the average charge in the bunch was approximately $\approx 1$. Other parameters values were determined by the experimental data.

Calculation results for the intensity of x-rays with photon energy higher than 900 eV emitted by neon and nitrogen plasma with parameters shown in figure 6(a) are shown in figure 6(b). The low limit for the photon energy was chosen in correspondence with the absorption properties of the filters, which were used in the experiments. It is obvious that the ion kinetics calculations results show a significant difference in the considered plasma luminosity dynamics. It results in slower growth of the x-ray signal for the case of nitrogen plasma. Nevertheless these results still can not explain completely so dramatic difference between the start moments of the x-ray signals arising, i.e., so essentially different dynamics of the thermalization process on the initials phase of the flows interaction.

We guess that the main disadvantage of the described simplified model is infinite temporal gradients of the plasma parameters in the initial moment of the plasma flows collision. Obviously, the gradients should be finite and determined by the chemical composition of interacted plasma, because ion-ion collisions cross-sections depends on these ions charge. The detailed model development requires additional real and numerical experiments.

### 4. Conclusions

Our findings are as follows:

- The simultaneous growth of the pressure and electron temperature was observed for the high-temperature plasma generated in the interaction zone during experiments on the collisions of high-energy plasma flows, which consisted of neon and deuterium. In the case of the nitrogen plasma flows interaction the electron temperature growth was approximately 5 µs behind the pressure increasing.

- Electron temperature temporal profile was obtained for the plasma created in the central part of the high-energy neon- and nitrogen-containing flows collision zone. It was shown that for the both cases the temperature varied insignificantly during the time period of 6–8 µs: 160–180 eV for the nitrogen plasma and 180–200 eV for neon-containing. It means that the state of the plasma was quasi-stationary.
• Time-resolved calculations of the ion kinetics were held for nitrogen and neon plasma by means of the collisional-radiative spectral analysis code. The obtained temporal profile of the x-ray intensity was in a good agreement for the case of neon plasma, but such a good correspondence was not observed for the nitrogen plasma. Additional investigations are required to answer the question about significant difference of the thermalization process during counter collision of plasma flows with neon or nitrogen ions.

Acknowledgments
The reported study was funded by the Russian Foundation for Basic Research according to the research project No. 18-29-21013 and also by the Program of Competitiveness Enhancement of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute). The authors are sincerely thank an employee of the State Research Center of Russian Federation Troitsk Institute for Innovation and Fusion Research I K Fasakhov for the code, which had been applied to obtain the plasma electron temperature.

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