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Time-resolved measurement of the temperature of a pinched dense plasma by the ratio of the signals of two X-ray diodes with different spectral response

S.A. Sorokin[*]

Institute of High Current Electronics SB RAS, Tomsk, Russia
[*]*s.sorokin@rambler.ru*

Abstract. When liners (hollow cylindrical shells) are imploded by the current of a pulsed generator, the density of particles and energy of the pinched plasma are largely determined by the implosion time (initial radial size) of the liner, which should be longer than the rise time of current through the liner. Due to the preliminary injection of plasma into the region of the liner load, the rise time of the current through the liner can be reduced to several nanoseconds, and the initial radius of the liner can be reduced to 1 mm or less. This approach makes it possible to obtain a plasma column with a particle density higher than the particle density in a solid, and a plasma energy density of more than 10^8 J/cm^3 already at a generator current of 1–2 MA. The spectrum of thermal X-ray emission from such a plasma can be close to the Planck spectrum, which makes it possible to determine the plasma temperature from the ratio of the signals of radiation sensors with different spectral responses. In this paper, under the assumption of the Planck radiation spectrum, the temperature dependence of the signal ratio of two photoemission X-ray diodes (XRDs) with an aluminum photocathodes and polypropylene filters 10 μm and 20 μm thick is calculated. The calculation results were used to determine the temperature of the pinched plasma in experiments on the implosion of thin aluminum foil liners.
Keywords: current sharpening, liner implosion, temperature measurement.

1. Introduction

One of the most effective ways to create a hot dense plasma is the implosion of cylindrical shells (liners) by the current of a high-current generator. The radial dimensions of the pinched plasma and, accordingly, the density of particles and plasma energy are largely determined by the time (initial radial size) of the liner implosion, which should be longer than the rise time of current through the liner. At a fixed compression ratio, the initial and final radii of the liner are proportional to the time of its implosion. In [1, 2], at a generator current rise time of about 80 ns, the rise time of current through the liner was reduced to several (1–3 ns) nanoseconds due to preliminary injection of plasma into the region of the liner load. The injected plasma is swept away by the magnetic field towards the liner. The current starts to switch to the liner just as the current sheath reaches the liner. With a liner implosion time of 5–10 ns and an initial liner diameter of 0.6–1.0 mm, the diameter of the pinched plasma was 30–60 μm. An order of magnitude decrease in the implosion time and, accordingly, in the pinch diameter corresponds to an increase in the plasma density (and energy density) in the pinch by two orders of magnitude. At a current through the liner of about 2 MA, the aluminum plasma density in the pinch is several times higher than the density of solid aluminum, and the plasma energy density is (3–6)×10^8 J/cm^3 [3, 4].

One of the features of pinches with a diameter of less than 100 μm is that the active resistance of the pinch ranges from fractions to a few ohms and is close to or exceeds the impedance of high-current generators used for liner implosions. That is, Joule heating essentially determines the energy balance in a pinched plasma.

Another feature of such pinches is the high mass thickness of the plasma (the product of the plasma density and the pinch radius nr is inversely proportional to the liner implosion time τ). The Collisional Radiative Equilibrium (CRE) model calculations [5] show that at a plasma ion density of about 10^{23} cm^{-3}, a plasma temperature of less than 1 keV, and a krypton plasma column diameter of 20 μm, the plasma becomes optically thick, the radiative power approaches the blackbody radiative power, and the spectrum – to the Planck spectrum. The universal spectrum determined only by temperature provides a unique opportunity to measure the electron temperature of a plasma from the ratio of the signals of two (or more) radiation sensors with different spectral responses. In this work, the temperature dependence of the signal ratio of photoemission X-ray diodes (XRDs) with an aluminum photocathode and polypropylene filters 10 µm and 20 µm thick was calculated for the Planck spectrum. The calculation results were used to measure the plasma temperature of an imploded liner about 1 mm in diameter, made of 2.5-µm thick aluminum foil. The experiments were carried out on the MIG pulse generator [6] at a current through the liner of about 2 MA.

2. Calculations

The XRD signal is proportional to the integral over the spectrum of the product of the spectral function, spectral transmission of the filter and photocathode sensitivity

$$\int_0^{h\nu_{max}} \frac{(h\nu)^3}{e^{\frac{h\nu}{kT}}-1} e^{-\mu(h\nu)\rho d_i} \eta(h\nu) d(h\nu) \tag{1}$$

where $h\nu$ is the quantum energy, T is the electron temperature, µ is the mass-absorption coefficient of x-ray filter, ρ is the density of the filter material, d_i is the filter thickness and η is the photocathode quantum efficiency. The data on the sensitivity of an aluminum photocathode from the work [7] were used in the calculations. With the Planck spectrum, the main part of the radiation belongs to the region of photon energies from ~T to ~6T (here, the temperature is in energy units). To obtain a significant dependence of the ratio of XRD signals on temperature, a significant dependence of the filter transmission on the photon energy in the region $T < h\nu < 6T$ is required. For the temperature range from 100 eV to 350 eV, a 10 µm thick polypropylene filter can be selected as a basic filter (Fig.1).

The transmission of such a filter reaches 0.9 at a photon energy of about 2.6 keV. At higher energies of quanta, the transmission of the filter changes only slightly. Fig.2 shows the spectral response of a XRD with an aluminum photocathode and polypropylene filters 10 µm and 20 µm thick. The main part of the emission spectrum of plasma with a temperature of 350 eV is below 2.6 keV. Fig.3 shows the results of calculating the signal ratio of two XRDs with polypropylene filters 10 µm and 20 µm thick. It can be seen that in the temperature range from 100 eV to 350 eV there is a strong dependence of the signal ratio on temperature.

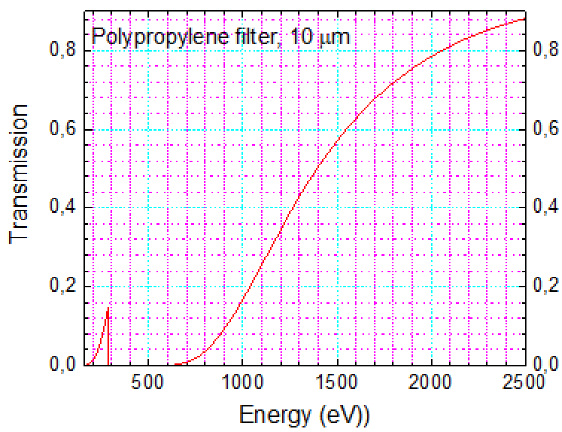

Fig.1. Spectral transmission of a 10-µm thick polypropylene filter.

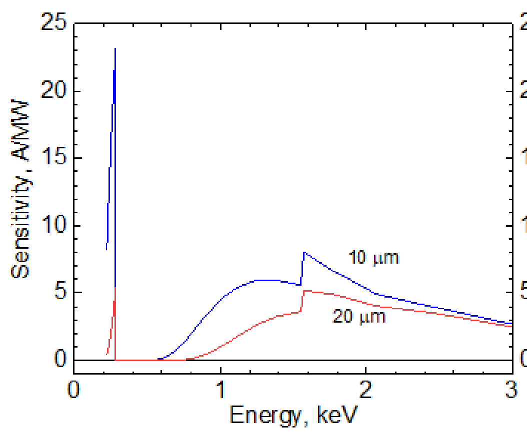

Fig.2. Spectral response of a XRD with an aluminum photocathode and polypropylene filters 10 µm and 20 µm thick.

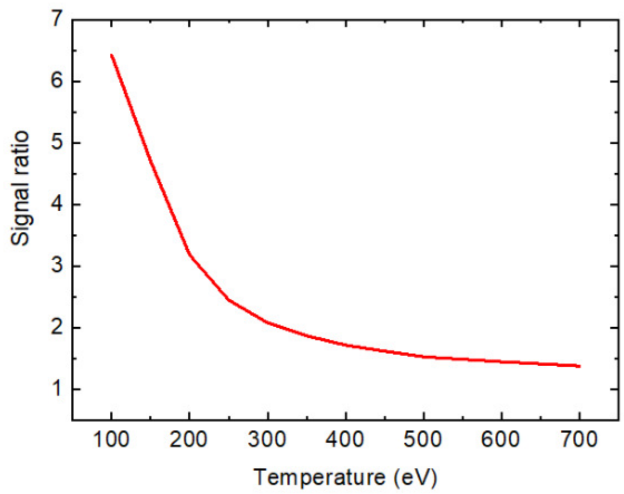

Fig.3. Results of calculating (under the assumption of the Planck radiation spectrum) the temperature dependence of the signal ratio of two photoemission X-ray diodes (XRDs) with an aluminum photocathodes and polypropylene filters 10 µm and 20 µm thick.

3. Experiment

Fig.4 shows the current and signals of two XRDs with polypropylene filters of 10 µm (XRD1) and 20 µm (XRD2) for imploding a 2.5-µm thick aluminum liner. Liner diameter is 1 mm. The current sheath reaches the liner at about 76 ns. The X-ray peaks at 80 ns and 87 ns correspond to the emission from the exploded surface of the liner [1, 2, 8] and the imploded liner. Subsequently, the liner oscillates around the equilibrium position. The process of the first and subsequent compressions is accompanied by the development of the Rayleigh-Taylor instability. The time-integrated pinhole picture shows a plasma column with a radial size of about 50 µm, as well as several hot spots. The ratio of the XRD signals in the time interval from 76 ns to 140 ns (when the level of the signal of the XRD with a 20-µm filter significantly exceeds the noise level) is shown in Fig.5. During the first liner compression (87 ns), the ratio of the XRD signals is 4.6, which, according to the calculation (Fig.3), corresponds to a temperature of about 150 eV.

Formally, it is possible to estimate the plasma temperature during the X-ray peak at 80 ns. The XRDs signal ratio of 3.2 corresponds to T ~200 eV. However, the emission spectrum of the plasma expanding from the surface of the liner can differ significantly from the Planck spectrum. During the X-ray peaks at 102 ns, 107 ns, and 125 ns, the temperature is ~ 220 eV (XRDs signal ratio 2.9), ~250 eV (XRDs signal ratio 2.4), and ~180 eV (XRDs signal ratio 3.8), respectively. The higher temperature during radiation peaks after the first compression of the liner may be due to the contribution of Joule heating to the energy balance of the plasma, as well as the formation of hot spots as a result of the development of constrictions (m=0 perturbations). From 100 ns to 120 ns, the current through the liner is 2 MA, and the plasma temperature is in the range of 200–250 eV (the ratio of the XRDs signals is 2.4–3.2). Assuming that the plasma column is near the Bennett equilibrium, we estimate the temperature from the Bennett relation $(Z+1)N(\mathrm{cm}^{-1})T(\mathrm{eV}) = 3.12 \times 10^{21} I^2(\mathrm{MA})$. Here Z is the average ion charge; N is the line density for the plasma column. The Bennett relation in this form is valid for the case of non-degenerate plasma when the pressure is $p = n\,(1 + Z)\,kT$. At an electron temperature of about 200 eV and an electron density of $\sim 3\times10^{23}$ cm^{-3}, taking into account electron degeneracy gives a correction to the temperature estimate of no more than 5 percent (see, for example, [9]). With an average ion charge $Z = 10$ and current $I = 2$ MA, the Bennett equilibrium temperature is about 240 eV. That is, the temperature measured from the ratio of the signals satisfactorily corresponds to the temperature of the Bennett equilibrium.

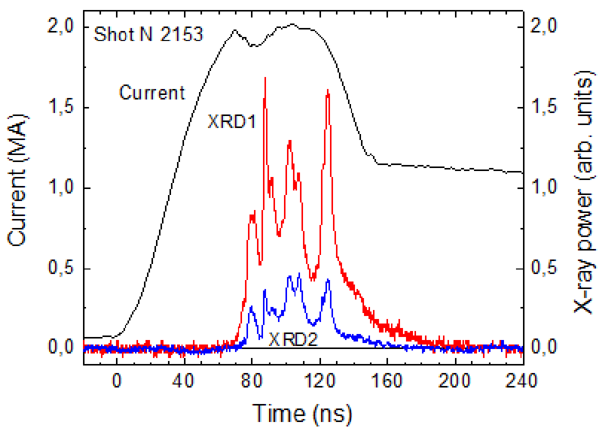

Fig.4. Current and signals of two XRDs with polypropylene filters of 10 µm (XRD1) and 20 µm (XRD2) for imploding a 2.5-µm thick aluminum liner. Liner diameter is 1 mm.

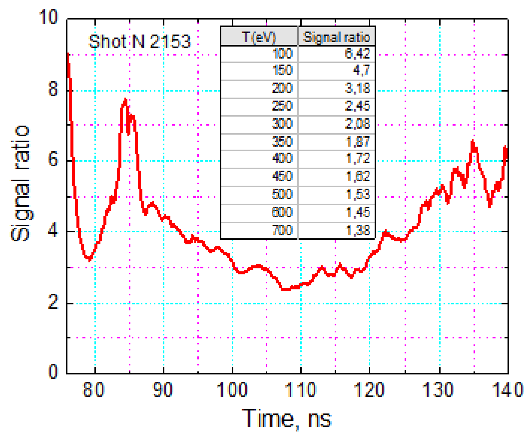

Fig.5. Ratio of the XRDs signals in the time interval from 76 ns to 140 ns for a shot with a 2.5-µm thick and 1-mm diameter aluminum liner.

4. Conclusion

In the case of an optically dense plasma, when the plasma emission spectrum is near-Planckian spectrum, the plasma temperature can be determined from the ratio of the signals of two radiation sensors with different spectral responses. To measure the temperature in the region of 100–350 eV, the temperature dependence of the signal ratio of two photoemission detectors (XRDs) with aluminum photocathodes and polypropylene filters 10 µm and 20 µm thick was calculated. The calculation results were used to determine the temperature of the pinched plasma column, which is formed after the implosion of liners about 1 mm in diameter, made of 2.5-µm thick aluminum foil. The temperature measured in this way during the evolution of the plasma after its first stagnation satisfactorily corresponds to the temperature estimate from the Bennett relation.

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