Time- and spatially resolved spectra of X-ray radiation of Z-pinch of tungsten multiwire arrays

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Abstract. Studies of the spectra of the radiation source based on the Z-pinch of multiwire arrays on the Angara-5-1 facility are presented. Their intensity and character change drastically during the radiation pulse. The instantaneous spectra of Z-pinch radiation differ substantially from time-integrated spectra close in shape to Planck's, their shape depends on the time of their recording and is characterized by the presence of bands which, according to calculations, correspond to the 4d-4f transitions (in the wavelength range greater than 120 Å) and 4d-5p (less than 120 Å) in tungsten plasma with an average ionization ~14 and a temperature of ~40 eV.

1. Introduction.

It has been shown that a thermal X-ray source with a power of hundreds of TW is created in the pulsed multimega-ampere range during the current implosion of cylindrical wire arrays in the fast Z-pinch discharge mode [1]. Such a source has found wide application in studies on inertial confinement fusion [2] and in high energy density physics [3].

The significant non-stationarity of the processes during the implosion of wire arrays leads to a non-equilibrium of the radiating plasma, deviation of the ionization composition and the level populations from the local thermodynamic equilibrium. In such plasma, the radiation transfer is determined by the absorption in the arrays of overlapping spectral lines. Because of the large number of transitions in multicharged ions and mutual overlapping of the lines, an almost continuous spectrum of radiation is formed. This radiation is nonequilibrium, and its spectrum is not Planckian. To describe such plasma, it is necessary to use kinetic models in which level-by-level kinetics and radiation transfer are taken into account [4, 5].

An experimental study of the spectral characteristics of the X-ray emission of such sources is extremely important, since it allows us to use experimental data on the radiative properties of Z-pinch plasma for comparison with the results of calculations simulating spectral opacity and emissivity of a dense high-temperature plasma from substances with a high atomic number in order to verify initial conditions and calculation codes. The data can also be used to calibrate programs designed to obtain spectral opacity and emissivity of dense high-temperature plasma. Measurements of the soft x-ray spectra with temporal and spatial resolution give unique information about the plasma...
characteristics of the central part of the pinch and the physical processes taking place within it. To interpret these experimental data, it is necessary to improve the theoretical model of pinch implosion in order to simulate non-stationary spectra and emission power of soft x-ray pinch with spatial resolution.

2. Results

2.1. Experimental Layout

At the Angara-5-1 facility [6], experiments were carried out to study the spectra of Z-pinch radiation from tungsten plasma with temporal and spatial resolution. Wire arrays with a diameter of 10 mm consisting of 6 μm W wires were used as generator loads. The amplitude of the current pulses of the generator was 3.5-4 MA at a current rise time of about 100 ns. In this case, pulses of soft x-ray radiation (SXR) with a power of 6-7 TW and a duration of 9-10 ns were obtained.

To study the spectral composition of the soft X-ray radiation (SXR) in the wavelength range 20-400 Å, the grazing incidence spectrograph GIS-3d was used. It had an entrance slit of 50 μm and a concave grating of 20 × 30 mm (curvature radius R=1 m, grazing angle 4°, 600 grooves/mm, W/Re coating) as a dispersion element of the spectrograph [7]. It was placed 170 cm away from the axis of the facility. An off-Rowland scheme is applied where the spectrum is recorded in the plane normal to the diffracted beams. To provide spatial resolution, a 70-μm slit was placed between the spectrograph and the radiation source. The slit produced a demagnified image of the source on the grating. To record the spectra of radiation with a time resolution in the GIS-3d spectrograph, a system is used based on the three-stripe micro-channel plate (MCP). The spatial resolution of the spectrograph was about ~300 μm, the exposure time of the frames was ~1.5 ns.

2.2. Experimental results and discussion

The experiments carried out at the Angara-5-1 and Z [8, 9, 10] facilities show that the emission spectrum of a wire tungsten array is a superposition of two sources: a compact high-temperature pinch and a "halo" of a substantially larger transverse dimension producing a much softer emission spectrum. The large effective size of the radiation source is explained by the fact that the radiation from a compressed compact pinch re-emits on the trailing plasma located outside the compressed region [8].

The emission spectra of the Z-pinch of a tungsten wire array were obtained at different times relative to the maximum of the radiation. Fig. 1a shows emission spectra of the Z-pinch at times -9 ns, +1 ns and +14 ns with respect to the maximum SXR. They are characterized by the presence of bands which, as follows from the calculations of Refs [4, 5], correspond to the 4d-4f transitions (in the wavelength range greater than 120 Å) and 4d-5p (less than 120 Å) in tungsten ions with average ionization ~14, which corresponds to electron temperature ~40 eV.

A comparison of the instantaneous spectra of the Z-pinch emission with a time-integrated spectrum is shown in Fig. 2.
Fig. 1. a) The emission spectra at time -9 ns (curve 1), 0 ns (curve 2), and +14 ns (curve 3). b) curve 1 is the time profile of the current, curve 2 is the time profile of the X-ray signal of the XRD (> 100 eV). The arrows indicate the time of registration of the spectra shown in Fig. 1a.

Fig. 2. Comparison of the emission spectra measured at -9 ns (curve 2), 0 ns (curve 3), and +14 ns (curve 4) relative to the peak of the SXR pulse with the time-integrated emission spectrum (curve 1) of the Z pinch of tungsten wire arrays. Exposure time of frames at registration of time resolved spectra 1.5-2 ns.

A comparison of the time-resolved spectra of the Z-pinch emission with a time-integrated spectrum shows that the “dips” between the emission bands in the time-resolved spectra are closed due to a change in their position with time due to a change in the temperature of the radiating plasma.

The time-resolved spectra were compared with the calculations of [4] (Fig. 3).
Fig. 3. The Z-pinch spectrum (curve 1) at the maximum of the SXR pulse calculated for plasma with an electron density $N_e = 3 \times 10^{20} \text{ cm}^{-3}$ and a temperature $T_e = 40 \text{ eV}$, and an experimental Z-pinch spectrum (curve 2), also obtained at the moment of maximum SXR.

Thus, the spectral information on the X-ray source, obtained for the first time with a time and spatial resolution, indicates a change in the spectral composition of the Z-pinch plasma during a short radiation pulse. The obtained features on the spectra and their time variation are important for the verification of computational codes that take into account the kinetics and transport of radiation.

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