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STUDY OF THE X-RAY SPECTRUM OF THE HEAVY-ION Z-PINCH

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Abstract

This paper presents a study of the X-ray emission of the heavy-ion Z-pinch carried out at the Angara-5-1 facility (current 3-4 MA, rise time ~10^{-7} sec). The tungsten wire arrays were used as the facility load. At the final stage of Z-pinch compression (n_e ~10^{20-21} cm^{-3}, T_e ~70-100 eV) a powerful X-ray with a pulse duration of ~10^{-8} sec and a peak power of ~10^{13} W arises. The experimental studies of the X-ray emission are made by applying different spectroscopic techniques:

-a transmission grid for the photon energy below 1 keV;

-a reflection mica crystal for higher energies.

It has been shown that the “thermal” part of the radiation spectrum for the high-current tungsten Z-pinch differs significantly from that of the “black body”.

The measurements of the high photon energy have displayed the presence of intense W^{44+} lines that corresponds to a very high temperature of a certain part of the pinch.

The mathematical simulations supposed isothermal homogeneous cylindrical column of tungsten plasma and collisional-radiative equilibrium. The comparison of the calculated and experimental spectra allows us to obtain some data about plasma parameters, such as electron temperature, density and ionization stage.

1. Introduction

Magnetic implosion of plasma liners in powerful electric generators allows one to obtain high-temperature dense plasmas of highly charged ions and to produce thermal radiation of high intensity. Such radiation can be applied for radiation physics experiments and, in particular, for emission of K-radiation of multiply charged ions with the photon energy *hv*>1keV [1], for inertial confinement fusion [2], X-ray lithography [3] and so on. Some impressive results have been obtained on the Z-machine (a current of 18 MA) at the Sandia Laboratory where at implosion of wire arrays has been obtained the emitted X-ray power equal to 280 TW. Fields of application for a particular Z-pinch are defined by characteristics of the power supply (emissive power, total output, radiation spectrum and configuration of radiation-producing object), which depends on temperature, density and atomic spectrum of radiating plasma. In the experiments aimed at studying different schemes of inertial fusion mainly liners of heavy elements, e.g., tungsten, are used since their radiation spectrum is close to that of the “black body”.

The given work describes the investigation results obtained for the emitted radiation characteristics of Z-pinch forming at implosion of tungsten wire arrays at the Angara-5-1 installation (current 3-4 MA, rise time ~ 100 ns). In the process of liner implosion by magnetic field tungsten ions take the basic fraction of energy. At the final stage of radial compression of the tungsten shell there appears a Z-pinch emitting sufficiently high X-radiation for 5-10 ns. The typical pinch parameters are the following: electron density $n_e \sim 10^{20-21}$ cm^{-3}, electron temperature $T_e \sim 70 - 100$ eV, pinch radius ~ 0.1 cm and length ~ 1.5 cm. Different schemes of using Z-pinch emission to ignite a thermonuclear target have been suggested and studied [2]. The emission spectrum is one of the main parameters which define the process of target-radiation interaction.

2. Investigation methods

In the current experiments together with routine measurements (e.g., current, dynamics of liner implosion, power and total X-radiated output), special diagnostic channels for measuring the X-ray emission spectrum were made. As the main plasma radiation spectrum of high-current Z-pinches lies within the transition region between UV and soft X-ray, only two techniques, shown in Fig.1, were applied to study spectral characteristics:

-transmission diffraction grid for the photon energies below 1 keV;

-diffraction on the reflective mica crystal for the photon energies above 1 keV.

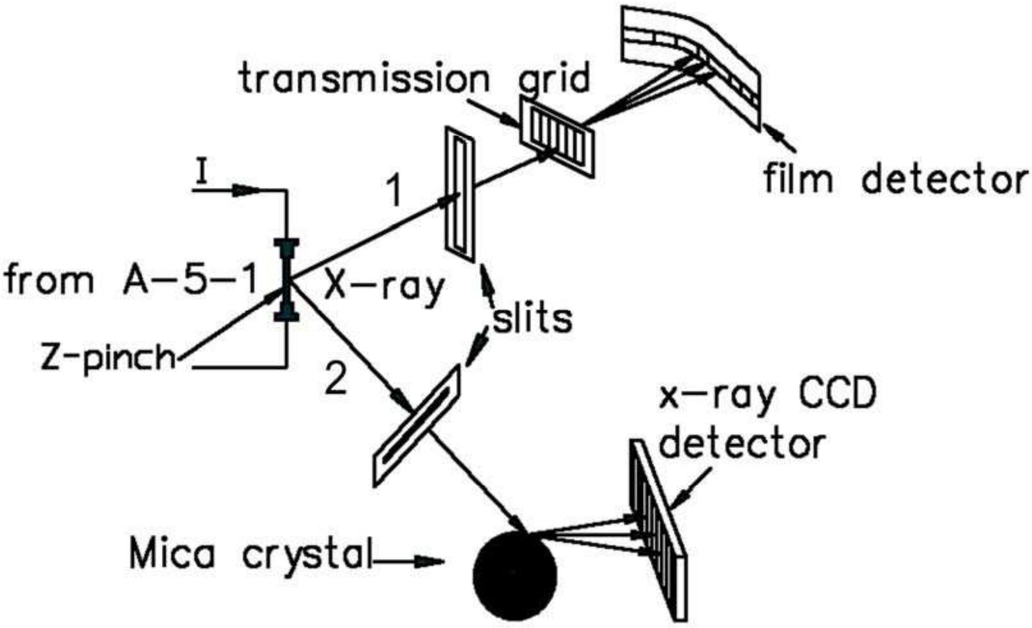


Fig.1. Experimental setup of Angara-5-1 spectral measurement diagnostics
1 - transmission diffraction grid for the photon energies below 1 keV;
2 - diffraction on the reflective mica crystal for the photon energies above 1 keV.

The radiation spectrum detectors were as follows: a photographic film in the transmission grid channel and an X-ray CCD linked to PC in the reflection crystal channel.

Modeling of the radiation spectrum of the tungsten plasma pinch was based on level-by-level kinetics consistent with the processes of radiation transfer [4]. Earlier on theoretical [5] and experimental [6] grounds it was shown that at the current 3 MA in the tungsten liner the electron temperature ranges from 50 to 100 eV. So, when modeling, attention was paid to the given range of electron temperatures. By using the techniques and codes THERMOS & BELINE [4] (level kinetic and radiation transport) [5] the calculations of the tungsten radiation spectra have been performed. Calculation was made for both plane and cylindrical plasma layers of different thickness at temperatures of 30-150 eV and densities of $n_e \sim 10^{20-21}$ cm^{-3}. As a rule, average atom model was used, but for a number of most important cases the obtained data were verified for both the spectral line position and the more real cylindrical geometry of the liner which requires much more computation time. In these cases the detailed calculations with FAC atomic data [7] were fulfilled.

A self-consistent solution for an optically thick cylindrical layer of tungsten plasma was obtained by iterations as a result of subsequent solution of the equations of level-by-level kinetics for ion concentrations and of the equation of radiation transfer in the axisymetric formulation.

Radiation characteristics were obtained for different pinch parameters. As an example the calculated spectra for two different temperatures are presented on Fig.2.

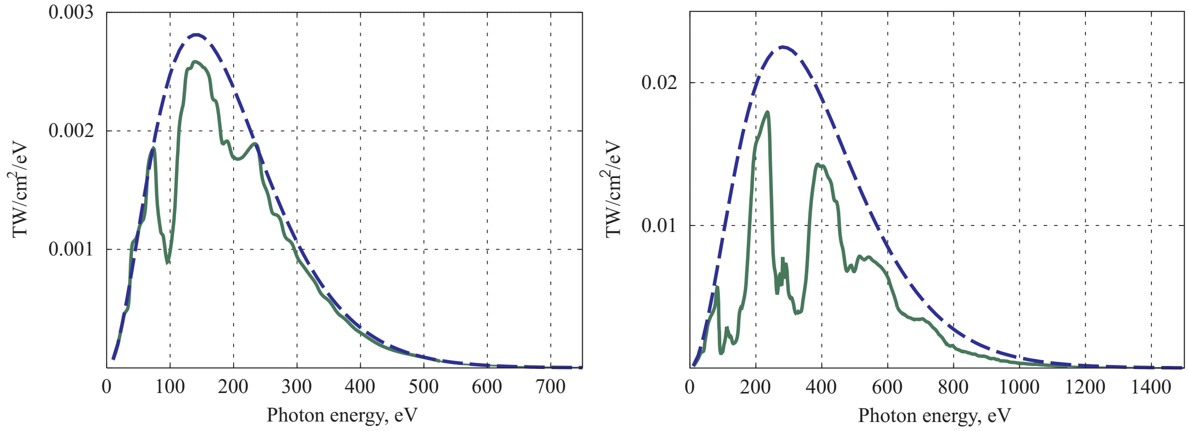


Fig.2. Simulation of Z-pinch spectra for a plane tungsten layer with electron density $n_e=10^{21}$ cm^{-3} and different electron temperatures T_e (left - T_e =50 eV; right - T_e =100 eV). The Planckian at the corresponding temperature is shown by dashed line.

The calculations show that under typical conditions of high-current Z-pinch (current 3-4 MA and electron density n_e~$10^{20\text{-}21}$ cm^{-3}) the thermal radiation of the tungsten plasma may differ significantly from that of the "black body" spectra, which is due to a relatively small size of the radiation-producing region.

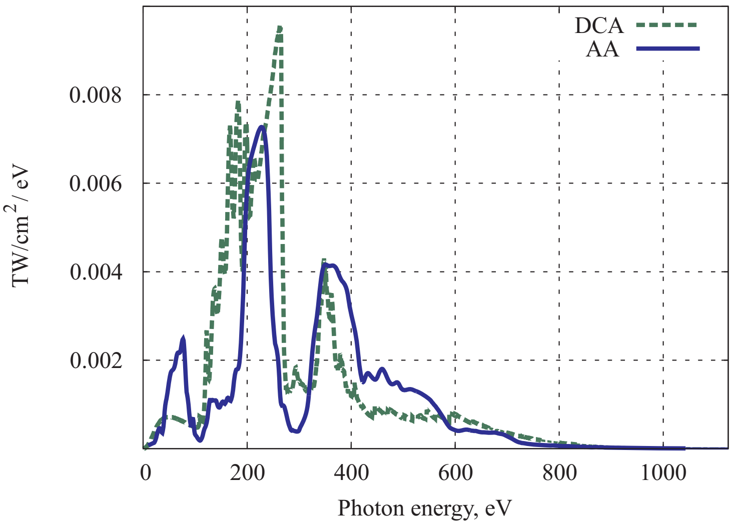
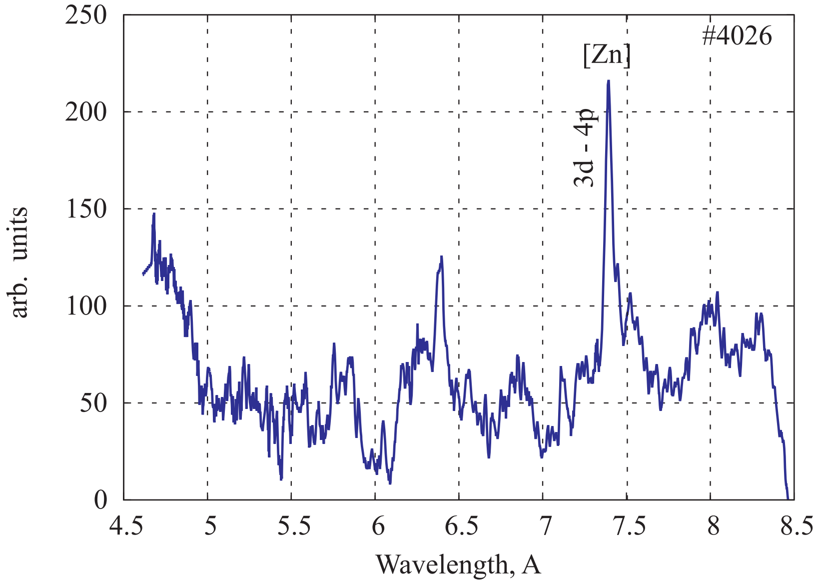


Fig.3. Comparison of the calculation results according to average atom model (AA) and detailed configuration accounting (DCA). Calculations were carried out for the electron density $n_e = 10^{21}$ cm^{-3} and temperature T_e = 75 eV.

3. Results

Comparison (see Fig.3) of the calculation results according to average atom model (AA) and detailed configuration accounting (DCA) shows similar results. The experimental data of spectral measurements in the low-energy spectrum region are being quantitatively processed now. However, the spectral pattern agrees with the predicted at the electron temperature of 75 eV.

The result of spectral measurements in a high photon energy region is shown inFig.4. We see a set of spectral lines in this energy interval, in particular, the lines of 3d - 4p transition of W^{44+} [Zn-like $3d^{10}4s^2$ - $3d^9 4s^2 4p$]. This fact can be explained by the high temperature of some part of Z-pinch plasma. To illustrate the presence of the hot regions in our pinch, a pinhole image is given in Fig.5, which was obtained with a Be filter.100 μ thick. The structure of the pinch is complicated and contains a set of small areas with hot temperature.



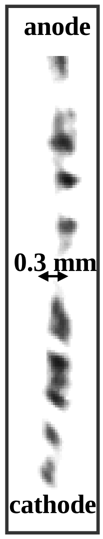


Fig 4. Spectrum of tungsten pinch in the photon energy range 1.5 - 2.5 keV obtained by the crystal spectrograph.

Fig.5. Pinch pinhole image - X-ray emission with the photon energy >2 keV.

Acknowledgements

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