X-RAY LINE SPECTROMETRY IN EXPERIMENTS WITH THE ALUMINIUM Z-PINCH

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X-ray line spectrometry with temporal resolution was developed for registration of [He]- and [H]-like aluminium ions spectrum. It was chosen a scheme with scintillator converting X-ray spectrum into the visible image, which was transferred through the flexible optical fiber to the entrance slit of the streak camera. In Z-pinch experiment on the high current S-300 generator the aluminium line spectrum was registered with nanosecond time resolution. The simultaneous appearance of [He]- and [H]-like aluminium ions radiation was observed, that is the evidence of high electron temperature existence in the plasma for a long time before the main part of the load mass comes to the axis. The noticeably changing of radiating plasma parameters was found after the computer treatment of line spectra: the electron concentration is varied in five times ((3…14)·10^{19} cm^{-3}), electron temperature in three times (0.3…1 keV), ion temperature in five times (20…100 keV), – during 50 ns. The great difference between the electron and ion temperature holds during all radiation time and demonstrates the ineffective energy transfer from the kinetic energy of ions to electron.

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X-ray spectral lines registration with temporal resolution accompanied by standard diagnostic equipment [1] was carried out on S-300 high-current generator in wire-array implosion experiment. The nested Al wire array was of the next parameters: the height of 15 mm, outer array of 12 mm in diameter contains 48 wires, inner array of 6 mm in diameter contains 24 wires that were of 15-microns in thickness. The whole load mass was of 348 µg.

It was chosen a scheme with scintillator converting X-ray spectrum into the visible image, which was transferred through the flexible optical fiber to the entrance slit of the streak camera. The main advantage of this scheme is the convenient adjustment to the interesting spectral interval by ease varying of the X-ray incidence angle to the crystal and the distance between the crystal and scintillator. This principal scheme is presented in Fig. 1.

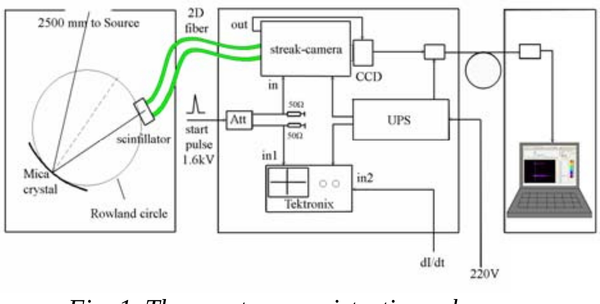

Fig. 1. The spectrum registration scheme

Spherically bent mica (d = 9.906973 Å) crystal was a dispersive element for [He]- and [H]-like aluminium ions spectrum. X-ray focusing ability both in the dispersive plane and in the sagittal plane favour to increase the gathering force of spectrometer in a few times. Scintillator film made of polystyrene with p-terphenyl of 20 µm in thickness and of 2.5 ns response time was placed immediately on the frontal surface of the optical fiber. X-ray spectrum was focused in sagittal direction on the scintillator plane at the distance of ~83 mm from the crystal. The fiber of 50 cm in length was round in cross section of 30 mm in diameter. It transfers the spectrum image with spatial resolution of ~20 µm. Vacuum-proof end of the fiber went out to the air through the annular sealing. To this round fiber end two rectangular fiber with cross section of 2×6 mm were optically connected. Owing to these two relocatable fibres one can transfer two interesting spectral intervals to the entrance slit of photocathode of the compact streak camera K008 [2]. The detailed description of the registration scheme is available in [3,4].

Fig.2 presents the usual set of the experimental data obtained during the wire array implosion. Chronograms of the resonance [H]-like ion and [He]-like ion lines and intercombination line of [He]-like ion of aluminum are shown there. There are traces of the soft X-ray radiation in the figure; voltage (right scale) and the current through the load (left scale) overlapped with the light streak image of the plasma. Soft X-ray traces have usually one or two spikes so as the first one always correlates with the most constricted phase of the plasma. Small discrepancy of 2…3 ns between the soft X-ray detectors maximum and aluminum characteristic line maximum could be explained by more wide spectral interval hν>150 eV registered by the filtered AXUV-5 detector in comparison with the narrow K-spectrum of aluminum, which is attributed to the most hot region of the plasma. Next spikes of soft X-ray signals detected by AXUV-5 detectors coincide satisfactory with the spectral lines intensities maxima. Both [He]-like and [H]-like ions radiation appear simultaneously in all experiments; at this moment time resolution of the recorded system is determined mainly by the scintillator and is ~2 ns. Moreover, sometimes [H]-like ions intensity rises more rapid then intensity of [He]-like ion (Fig. 3). But following the model of the plasma implosion where the electron temperature of the cold moving plasma rises

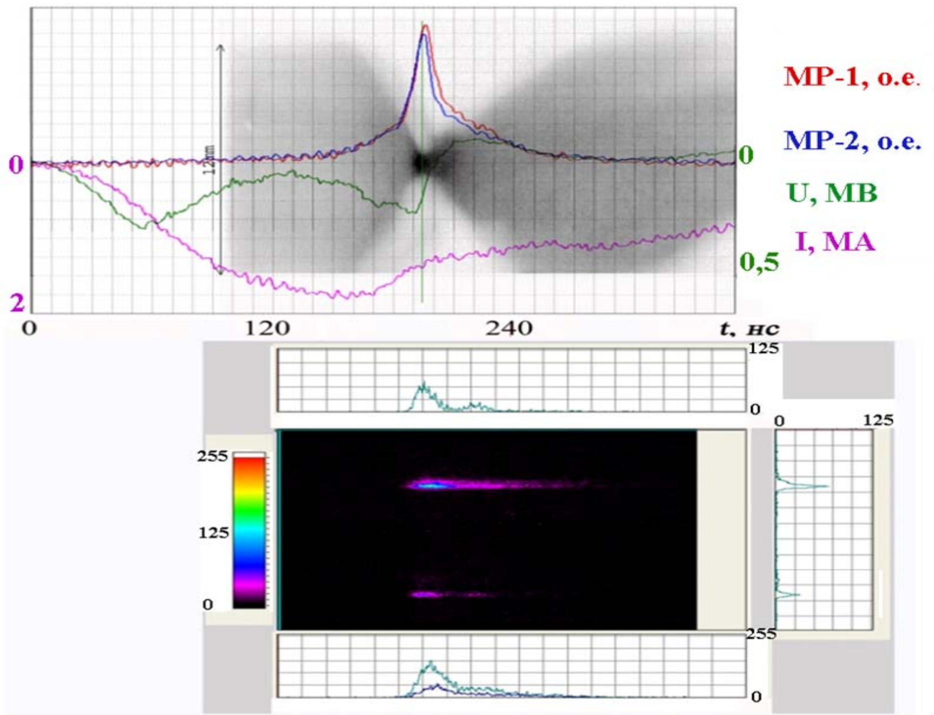

Fig. 2. Experimental data from the shot 06_5#2. Overhead: traces of two identical AXUV-5 detectors of soft X-ray; voltage (right scale) and current (left scale) through the load overlapping with the light streak image of the load. At the foot: X-ray characteristic lines streak synchronized with traces. Intensity of lines is expressed in the conditional colors; the scale of intensity is left from the streak. Time is in ns. Right hand side is placed the intensity profile at the moment of the maximal [He]-like ion radiation. Upside of streak: time evolution of the line Res AlXIII 1s-2p; downside – Res and Int AlXII 1s^2-1s2p

owing to heat flux from the ions heated in its turn after the implosion to the axis. So, [He]-like ion radiation should appear first. And then after the consequent ionization stage will appear line radiation of [H]-like ion.

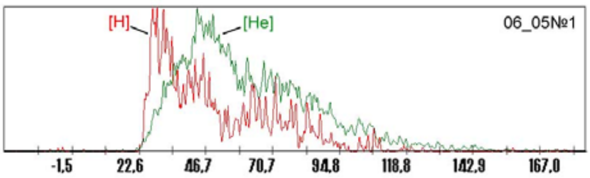

Fig. 3. Normalized to unity intensities of Res AlXIII 1s-2p and Res AlXII 1s^2-1s2p lines in shot 06_5#1. Time in ns is counted from the electrical current maximum

If we evaluate the time required to this ionization, than according to the W. Lotz formula we find $t_{ion} \sim 12$ ns at T_e=600 eV и N_e=10^{20} cm^{-3} [5, p.163]. The absence of such a delay gives a support to think that a long enough time before the radiation of the characteristic radiation could be detected, plasma with the electron temperature of a few hundred electron-volts exists. This plasma could be originated from the precursor plasma generated in the very beginning of the load implosion. Considering the next evolution of line radiation, it's seen the diminishing of the [H]-like ion radiation and the increase radiation of [He]-like ion, indicating some plasma cooling (see Fig.3). Computer simulation was used for the treatment of obtained spectra. It is based on the colliding-radiation plasma model taking into account radiation transport in the form of escape factor [6]. Plasma is considered as a steady-state uniform cylinder, T_i and T_e are not linked. Fig. 4 shows the simulation results when input parameters were experimental ratios of spectral line intensities and one spectral line width. It was found that plasma parameters noticeably vary during the radiation time of 50 ns as follows: N_e in 5 times ((3…14)·10^{19} cm^{-3}), T_e– in 3 times (0.3…1 keV), T_i – in 5 times (20…100 keV). The minimal radius of plasma was calculated as 1 mm, which correlates with the image size of the constricted plasma "rope". Plasma ion pressure n_iT_i exceeds the magnetic pressure $B^2/8\pi$ of the electric current at the calculated radius of plasma. The linear mass of the radiating plasma is counted up of the interval from a few percents till the whole initial mass of the load.

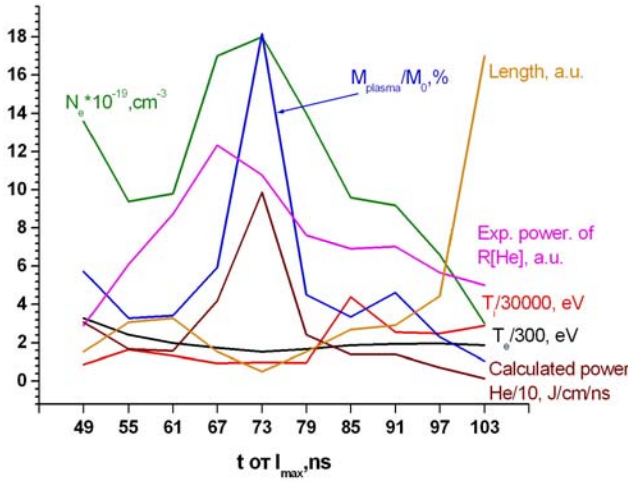

Fig. 4. Calculated plasma parameters in shot 06_05#1

This fact testifies to the reliability of the performed treatment in spite of the low spectral resolution of the registration system and plasma volume averaging of the obtained spectra. The time required for the temperature equilibrium between ions and electrons in plasma can be evaluate according to the L. Spitzer – V.I. Kogan [7] as follows

$$\tau_{ei} \approx 6.4 \cdot 10^{8} \frac{A T_{e[eV]}^{3/2}}{\Lambda N_{e\,[cm^{-3}]} Z^{2}} \sim 1.5\ \text{ns}$$

for electron concentration $N_e=10^{20}cm^{-3}$, and temperature $T_e \approx 400$ eV, Λ- Coulomb logarithm, A- atomic weight of the ion. For concentration of $N_e<10^{20}$ cm^{-3} the energy exchange between ions and electrons becomes slow in comparison with the stagnation time $t \approx R_{pl}/v = 0.1/5\cdot10^{7}=2$ ns and ineffective. The great contrast between T_i and T_e demonstrates the heat flux from ions to electrons in aluminum plasma is not as high as the electron radiation loses. It is worthy to note, the calculation results often show the abrupt changing in the plasma parameters during the shot that is the evidence of the radiation attribution to different regions of the plasma, which is multipoint in the structure. This structure is well seen in X-ray snap images of the plasma.

Now we are unable to explain exact mechanism of the early electron heating. Probably, it is due to the specific plasma dynamics in the experiments with nested multiwire loads.

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REFERENCES

1. Yu.G. Kalinin, A.S. Kingsep V.P. Smirnov, et al.// *Plasma Physics Reports*. 2006, v. 32, N 8, p. 656–667.
2. http://www.bifocompany.com.
3. S.S. Anan'ev, S.A. Dan'ko, Yu.G. Kalinin// *VANT. Series "Thermonuclear synthesis*". 2009, N 2, p. 43-51 (in Russian).
4. Fan Ye, Yi Qin, Shuqing Jiang, et al.// *Review of scientific instrument*. 2009, v. 80, p. 106105.
5. L.P. Presnyakov, V.P. Shevel'ko, R.K. Yanev. *Elementary processes with multi-charged ions participation*. Moscow: "Energoatomizdat", 1986 (in Russian).
6. V.I. Derzhiev, A.G. Zhidkov, S.I. Yakovlenko. *Radiation of ions in the unstable dense plasma*. Moscow: "Energoatomizdat", 1986 (In Russian).
7. D.V. Sivuhin. Coulomb collisions in the fully ionized plasma // *Questions of plasma theory*. Moscow: "Atomizdat", 1964, Issue 4, p. 116 (In Russian).

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СПЕКТРОМЕТРИЯ РЕНТГЕНОВСКИХ ЛИНИЙ В ЭКСПЕРИМЕНТАХ С АЛЮМИНИЕВЫМ Z-ПИНЧЕМ

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Разработана методика для регистрации с временным разрешением рентгеновских линий [He]- и [H]-подобных ионов алюминия. Рентгеновский спектр преобразовывался с помощью сцинтиллятора в видимое изображение, которое переносилось гибким световодом на входную щель электронно-оптического преобразователя. Регистрация спектра проводилась с наносекундным разрешением в экспериментах с Z-пинчем на сильноточном генераторе С-300. Наблюдалось одновременное появление линий [He]- и [H]-подобных ионов алюминия, что является свидетельством наличия высокой электронной температуры в плазме задолго до момента прихода к оси основной массы Z-пинча. Компьютерная обработка спектров выявила значительные изменения параметров плазмы в процессе сжатия: концентрации в пять раз ((3…14)$\cdot10^{19}$ $см^{-3}$), электронной температуры в три (0.3…1 кэВ), ионной температуры в пять раз (20…100 кэВ) – за 50 нс. Большой разрыв между ионной и электронной температурами демонстрирует неэффективность передачи энергии от ионов к электронам.

СПЕКТРОМЕТРІЯ РЕНТГЕНІВСЬКИХ ЛІНІЙ В ЕКСПЕРИМЕНТАХ З АЛЮМІНІЄВИМ Z- ПІНЧЕМ

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Розроблено методику для реєстрації з часовим дозволом рентгенівських ліній [He]- і [H]-подібних іонів алюмінію. Рентгенівський спектр перетворювався за допомогою сцинтиллятора у видиме зображення, що переносилося гнучким світловодом на вхідну щілину електронно-оптичного перетворювача. Реєстрація спектра проводилася з наносекундним дозволом в експериментах з Z-пінчем на потужнострумовому генераторі С-300. Спостерігалася одночасна поява ліній [He]- і [H]-подібних іонів алюмінію, що є свідченням наявності високої електронної температури в плазмі задовго до моменту приходу до осі основної маси Z-пінча. Комп'ютерна обробка спектрів виявила значні зміни параметрів плазми в процесі стиску: концентрації в п'ять разів ((3...14)$\cdot10^{19}$$см^{-3}$), електронної температури в три (0.3...1кеВ), іонної температури в п'ять разів (20...100 кеВ) – за 50 нс. Великий розрив між іонною й електронною температурами демонструє неефективність передачі енергії від іонів до електронів.