Plasma dynamics in different X pinches loads of megaampere range

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The experiments were performed in the S-300 facility (2.3 MA, 0.15 Ω, 150 ns). The results of experimental investigations into the dynamics of plasma produced in the multiwire X pinch at currents up to 2.3 MA are presented. The materials, diameters, and the number of wires are varied. At such currents, the power of the soft x-ray radiation with the photon energy from 1 to 3 keV increases to 120 GW, and, since the size of a hot spot is less than 20 μm, it corresponds to a source brightness of ~10^{15} W/(cm^2 sr). The energy recorded in lines of neon-like molybdenum (in the range of 2.5–3 keV) is higher than 10 J. Hard x-ray radiation detected in experiments with tungsten and molybdenum X pinches has the photon energy > 800 keV.

1. Study of the Mega-Ampere Multiwire X-Pinch

The results of experimental study X-pinch plasma dynamics and plasma parameters on the high-current generator S-300 with the current in the load up to 2.3 MA and the risetime ~ 150 ns are presented. X-pinch experiments with so high currents were first carried out by us; see the communication [1]. We operated by X-pinches with the length 10–12 mm formed by different numbers (N = 2–20) crossed wires (the angle of wire cross is υ =60°) of different diameters (d = 55–300 μm) made of W, Mo, Nichrome, and stainless steel. Thus, the broad range of linear masses was provided (m_l = 3.6–40 mg/cm).

Diagnostic complex included pinholes, X-ray spectrograph with convex mica crystal, X-ray detectors operating in different spectral ranges, optical chronograph with the time-analyzing slit directed along X-pinch axis. The X-ray radiation in the range of energy from hundreds electronvolts up to several kiloelectronvolts was recorded by the calibrated semiconductor diodes AXUV-5 and by the vacuum XRD with the Ni cathode supplied by a set of filters. The X-ray radiation in the range of E > 200 keV was recorded by the scintillation detectors with the plastic scintillators and photo-multipliers. They were absolutely calibrated at the energy 1.25 MeV, their time resolution was about (3–4) ns. An example of temporal dependencies for both soft x ray (SXR) and hard x ray (HXR) synchronized with the current is given in Fig. 1.

In most experiments, several regions radiating in SXR range were recorded; their size was varied in the range of 20–500 μm with the object spatial resolution ~ 15 μm. In the regimes presented here, several SXR (1–3 keV) pulses observed; it is reasonably to correspond that to the hot spot radiation (see, e.g., [2]). The maximal power in the SXR range (summarizing 250–300 eV and 1–3 keV ranges), measured by means of XRD with the Ni photo-cathode was

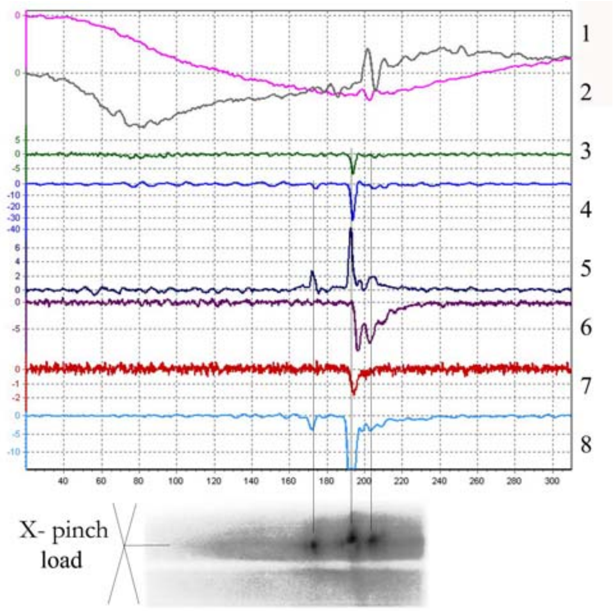

Fig.1 Time dependences of the current and its time derivative and x-ray radiation of NiCr X pinch 16×100 μm in size. Chronogram synchronized with time dependencies are shown below. Waveforms denoted by figures present the following: 1 – I, MA; 2 – dI/dt, arb.un; 3 – XR (E = 10–40 keV), arb.un., AXUV5; 4 – XR (E = 6.9–40 keV), arb.un., AXUV5; 5 – XR (E = 1–3 keV), arb.un., XRD-diode; 6 – XR (E > 600 keV), arb.un., scintillation detect; 7 – XR (E > 800 keV), arb.un., scintillation detect; 8 – XR (E = 3–40 keV), arb.un., PIN diode.

about ~ 100 GW. As far as the time resolution of the vacuum XRD is ~ 1 ns, and it is possible a hot spot with the lifetime significantly shorter exists [3], the real power may be much more than that given above.

2. Plasma parameters in hot points of X pinch

In the case of Mo X-pinch, the maximal value of radiation energy in the range of 2.5–3 keV estimated by the spectrograph film darkening exceeded 10 J. In the same experiment, XRD recorded the power 23 GW by the pulse duration 2 ns; that corresponds to the energy ~ 50 J in the range of quantum energy 1–3 keV. The qualitative comparison of calculated [4] and experimental spectra of the Ne-like MoXXXIII allows to estimate the electron temperature in the hot spots of Mo X-pinches as $T_e \sim 10^3$ eV and electron density exceeding 10^{21} cm^{-3}.

Experimental spectra of X pinches made from

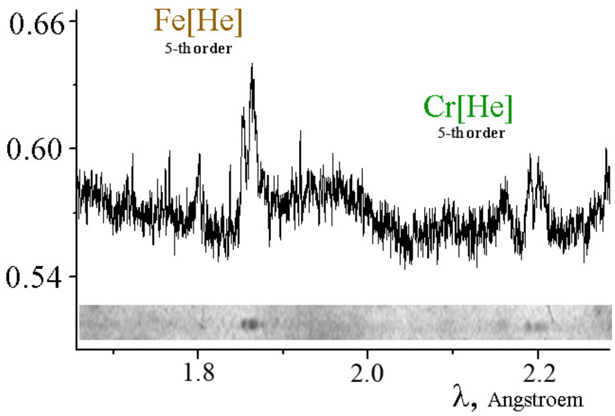

Fig.2 Spectrum and its densitogram in the experiment with 16×100 μm st. steel X pinch $m_l/I^2 = 3.24$ mg/(cm·MA^2), $I = 1.75$ MA.

stainless steel in the range from 1.4 to 2.5 Å (see Fig. 2, resonance, intercombination lines He-like Fe and Cr ions and their satellites are in this range) were compared with those calculated by using PrizmSPECT code [5] (see Fig. 3). The code used under the spherical symmetry approximation of radiating object, within the frames of collisional-radiative model with taking into account the plasma optical depth. In computational series, by both density ρ and temperature T varied, and the product ρR supposed to be constant. The spectra calculated were constructed under the assumption that the resolution is $(\lambda/\Delta\lambda) = 300$.

The calculated spectrum had completely reasonable form (compare Figs 2 and 3a), for the case of $\rho R = 0.0016$ g/cm^2, i.e. 1% of initial linear mass of the substance in the cross point. Hence, one could suppose that just this amount of substance becomes involved into the process of collapse while the hot spot formation. The calculated spectra were obtained in the following range of parameters: $T \sim 800$–2200 eV; $n_i \sim 10^{18}$–10^{23} cm^{-3}. It turned out (see Fig. 3b) that typical features of the calculated spectrum best of all coincided with those of experimental one by $T \sim 1200$–1400 eV, $n_i \sim 10^{22}$ cm^{-3} thus corresponding to $n_e \sim 2.5\times10^{23}$ cm^{-3}. The ratio of Li-, He-, H-like ion densities [Li]:[He]:[H] for the steel components of $T \sim 1400$ eV, $n_i = 10^{22}$ cm^{-3} equals to 0.12:0.79:0.08 for Fe, 0.08:0.67:0.25 for Cr and 0.19:0.79:0.01 for Ni. The spectral brightness of the resonance He-like CrXXIII line was $B_\nu \sim 6.5\times10^{11}$ W/(cm^2 sr eV). The minimum radius of the radiating region may be estimated from the calculated parameters as $R_r \sim 15$ μm.

Using experimental data on the energy value ($E = 0.16$ J) in the spectral range $\delta E \sim 70$ eV in the vicinity of the resonance He-like CrXXIII line, together with the calculated hot spot radius and the spectral brightness of the source, one could estimate the typical time of emission as $\Delta t = E/(4\pi\ S{\cdot}B_\nu{\cdot}\delta E) \sim 10$ ps (here $S = 4\pi R_r^2$ is the surface area of the radiating region). According to [3], such duration is typical for the radiation of the X pinch hot spot.

The maximal radiation power in the range of energy $E_\gamma > 800$ keV obtained in our experiments with X-pinch made from 16×100 μm Mo wires was $P \sim 0.8$ MW. The pulses of hard X-rays arose several nanoseconds later than pulses of SXR (1–3 keV). The harder are γ-rays, the more is this delay. This fact seems obvious enough within the frames of the following scenario: "neck – hot spot – mini-diode" [2]. Perhaps, this hard X-ray radiation is the Bremsstrahlung caused by the electron beam accelerated in this mini-diode. The growth of the resistance of such a diode results in the growth of accelerating voltage exceeding several times the output voltage of the generator.

The appearance of diverging luminous regions (see the chronogram in Fig.1) may be corresponded with the plasma jets coming onto the X-pinch axis from the wire cores [2]. Indeed, in the case of the "underloaded" X-pinch (the mass less than the optimal linear mass for the given current amplitude), the energy store in the generator could be enough to provide the compression of plasma close to the axis except of the hot spot formation. By increasing the linear mass of the tungsten X-pinch per the current value squared, up to $m_l/I^2 = 4.3$ mg/(cm·MA^2), the matching becomes better. In addition, it is necessary to note that in the case of "overloaded" X-pinches ($m_l/I^2 >$ 7.5 mg/(cm·MA^2) for the 200 and 300 μm wires and $m_l/I^2 > 15.5$ mg/(cm·MA^2) for the 100 μm wires), diagnostics didn't demonstrated any peculiarities typical for the formation of the hot spot in X pinch: the vacuum diodes didn't recorded short intensive pulses of SXR radiation; the characteristic lines didn't recorded by the spectrograph; micron size radiating plasma regions didn't observed by the pinholes and optical streak camera.

Thus, we may state that experimental study X pinches with the current exceeding 2 MA results in the evidence

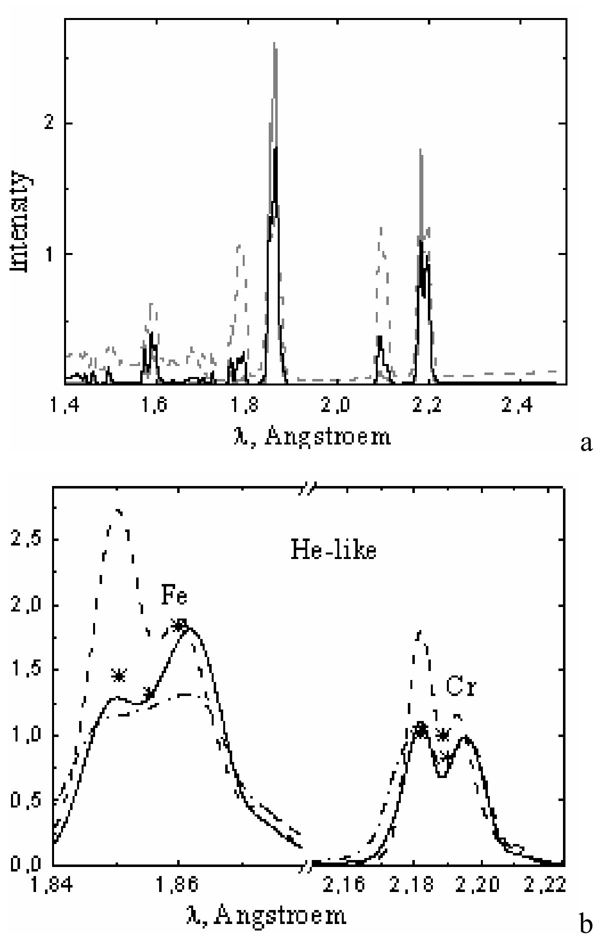

Fig.3 Relative intensities of the FeXXV and CrXXIII resonant lines for different values (a) $\rho\Delta L$ = 0.016 (dashed grey line), 0.0016 (black line) and 0.00016 g/cm^2 (grey line) at T = 1400 eV, $n_i = 10^{22}$ cm^{-3} and (b) ion density $n_i = 10^{21}$ (dashed line), 10^{22} (solid line) and 10^{23} cm^{-3} (dashed-dot line) at $\rho\Delta L$ = 0.0016 g/cm^2 T = 1400 eV. Experimental data are denoted by asterisks.

of applicability of the basic conclusions and dependences obtained by the current essentially less for this current range as well. For example, in [6] scaling the driver current up to 1 MA and x ray power based on an analysis of the Bennett equilibrium was published; besides in this paper compared theoretical, numerical and experimental data of minimum radius, mass per unit length and x ray power. Thereby, one could foresee the possibility of elaboration some unique source of radiation on the pulsed power machines with the current of multi-mega ampere range.

3. Conclusions

The experimental results on high-current multi-wire X-pinches made of stainless steel, nichrome, Mo, and W, confirmed basic features of their dynamics, as well as basic statements made on the base of earlier experiments with lower current.

The total energy of Mo X-pinch radiation in the range of the quantum energy 2.5–3 keV exceeds 10 J. The typical size of the hot spot $d \sim 20$ μm and the radiation power $P \sim 120$ GW. Using these direct measurements of space scales and radiated power we can estimate that the bright plasma regions have the brightness exceeding $B = P/(2\pi d)^2 \sim 10^{15}$ W/(cm^2 sr) in the range of the quantum energy 1–3 keV. It is important to note that such extreme plasma parameters determined from the time-integrated parameters (not from those resolved in time!) have been recorded for the first time.

Because the typical time of emission in SXR range of NiCr X-pinch was estimated as $\Delta t \sim 10$ ps, one may conclude that the real radiation power in this range is essentially higher than that recorded by the diodes (their resolution being ~ 1 ns).

The HXR radiation of an X-pinch in the range of the quantum energy > 800 keV has been recorded and studied.

4. Acknowledgments

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