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The Dynamics of Non-Equilibrium Plasmas of the Neck of X-pinch

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As result of experiments [1], the following sequence of events was found for X-pinch evolution (Fig. 1): mini-diode and micro Z-pinch formation, cascade process of the decreasing of plasma compression region, hot spot formation and its explosion-like spark, Z-pinch breakup phase, devastation of mini-diode and generation of accelerated electron and ion beams. During the last stages of the process, the intensive axial movement of plasma behind shock waves (SW) which propagate from the explosion region, is important. These complex processes have been, successfully, simulated by 2D MHD model [2] that demonstrated self-similar character of phenomena of hot spot formation and spark: at this stage, the processes are very similar for X-pinches of various masses. This model includes a sufficiently full set of radiation and MHD effects, but electron inertia effect was absent. The numerical simulation have discovered a main phenomena of hot spot micro-explosion, and allowed us to assume, that electron inertia effect not play a significant role at least before breakup of the neck. In the paper X-pinch spark model is developed on the base of numerical results [2].

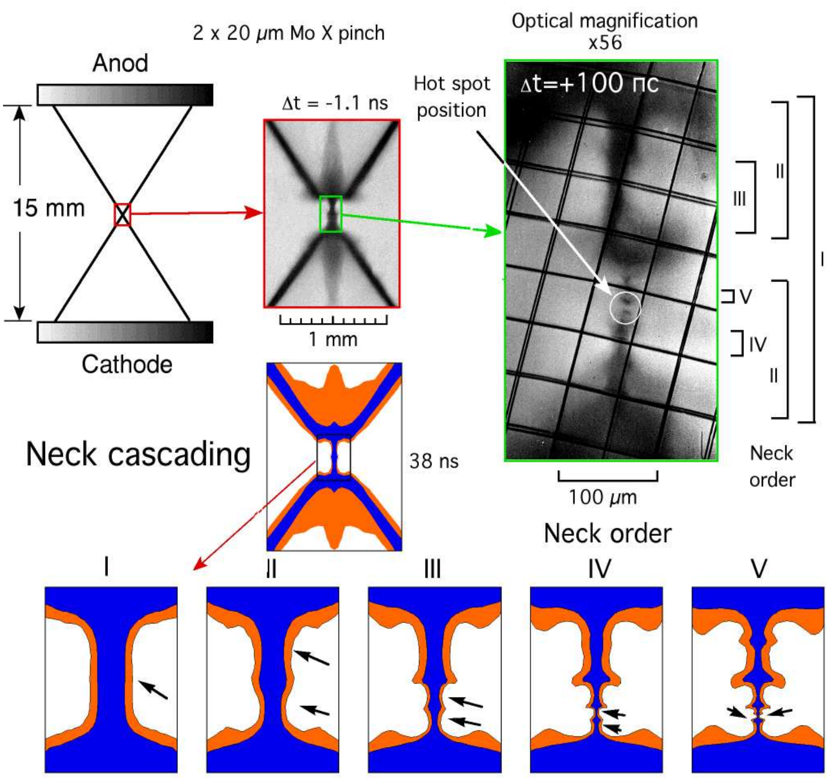

Fig. 1. Cascade process of X-pinch neck evolution and hot spot fo r-mation. The neck diameter 1.5 μm was estimate.

During cascade process, every new neck is reproduced from previous one as its reduced copy. From one cycle to another, gradually, a curvature of plasma free surface increases, and in the result of cumulation on the axis, oblique character of SW develops more and more. As the result, intensity of axial plasma flow behind the front of reflected SW must reach the level comparable with radial plasma motion.

This fact and also above noted self-similarity of the process is base of further inquiry.

We shall study an energy cumulation phenomenon in the result of a density jump appearance on the axis at final stage of cascade implosion. In accordance of [3], the SW front structure in plasma is determined by the following spatial scales: *ei*-relaxation length behind a density jump and *e*-heat conductivity before it $c_s\tau_{ei} >> c_s\tau_{ei}/Z$ (size of area of energy transfer from ions to electrons) >> $v_{Ti}\tau_{ii}$ (width of compression jump); here, $c_s = [(5T_i/3 + ZT_e)/m_i]^{1/2}$ is a sound speed. When plasma compressed to radius $a < c_s\tau_{ei}$, electrons are heated in whole volume of neck, and their temperature is distributed more uniform, than better above presented inequality is realized: the possibility of electron heating is saturated, and a subsequent cumulation consists in the heating of decelerating ions. The region of corresponding processes localized in a thin layer of compression, which one may consider as jump. Here, viscous ion heating is in m_i/Zm_e times greater than electron one, and the temperature $T_e \approx T_{e0}$ is, approximately, continuous, plasma density increases in about 4 times, and, therefore, the time of relaxation $\tau_{ei}/Z \sim T_e^{3/2}/Z^3\rho$ decreases as $1/\rho$. Behind of jump, that moves toward the axis with velocity $\approx c_{s0}$, the temperature of ions $T_i > T_e$ is limited by the value $T_{i1} \approx m_i c_{s0}^2/3 = Z_0 T_{e0}/3$. Ions transfer its energy to electrons during the time τ_{ei}/Z. For radius of neck $a \approx c_s\tau_{ei}/Z$, whole volume of plasma is involved into the process. And the process can't be completed before density jump returning after its reflection from the axis. In comparison with previous case, this jump moves faster, because of the sound speed is higher. Therefore, the ions are heated up to the temperature $T_{i2} \approx Z_0 T_{e0}$. For example, for T_{e0} = 0.1 keV, when Z_0 = 10÷15, $T_{i1} = 0.3 \div 0.5$ keV and $T_{i2} = 1 \div 1.5$ keV. The heating of electrons is more complicated by the radiation and ionization process. The number of electrons in *Z* times more, than ions one, and electrons take away the energy more slowly.

Appearance of the oblique SW front on the axis is happen not simultaneously, and on this reason cumulation process has 2D character. It is necessary to distinguish the stage of motion of SW to the axis before the formation of cumulation region and after that, when two areas of reflected matter expanding in opposite directions appears. The axial plasma flow takes place in the region between the density jumps, and an expansion of X-pinch neck begins when reflected SW reach its surface. Deceleration of the expansion by magnetic field leads to development of instability in this region, and a new implosion starts when the density in the volume between two cumulation regions decreases. The formation of hot spot and

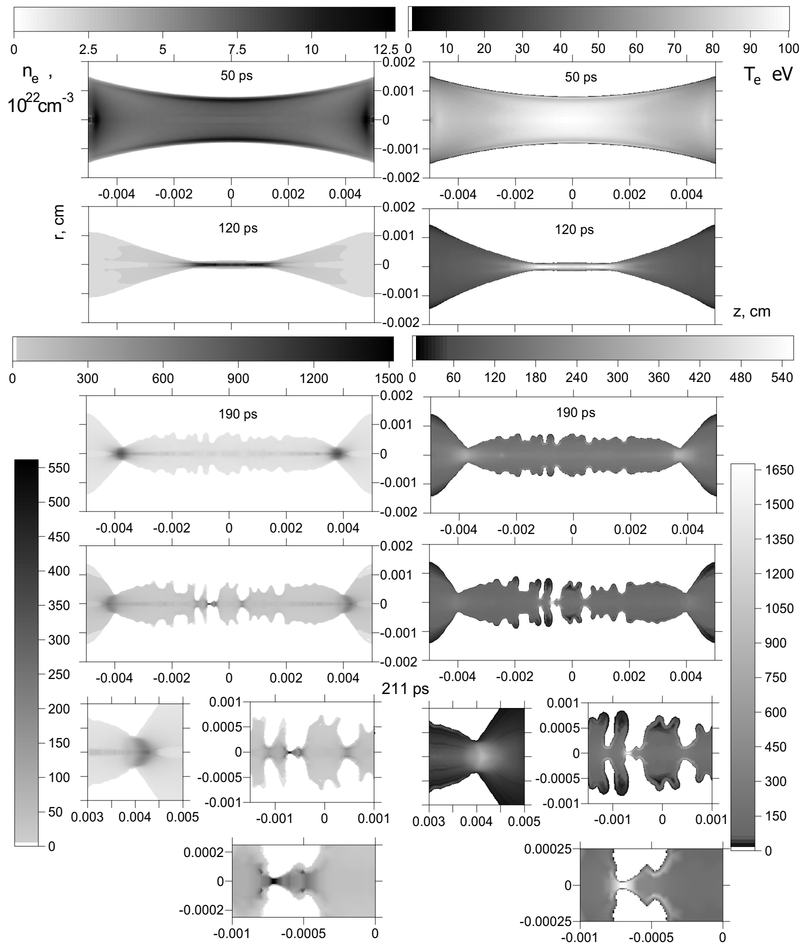

Fig. 2. The picture of hot spot formation processes at final stage of X-pinch implosion.

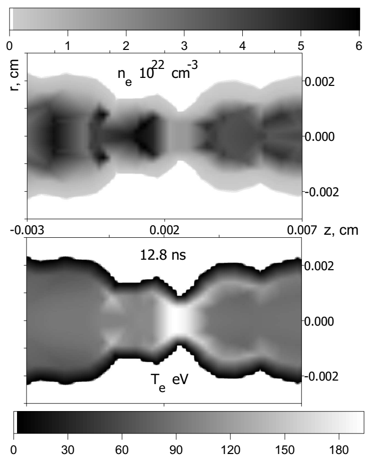

Fig. 3. The form of the neck of X-pinch at starting of final implosion, computed in [2].

its spark are happen on this, 3-rd stage of evolution.

That picture was reproduced in numerical simulation by model [2], applied to parabolic initial configuration of Mo plasma. The results are demonstrated on Fig. 2. The fragment of neck corresponds to a moment closed to finish of computation of [2] (Fig. 3). The statement parameters were following: current, 115 kA; ion density, $n_i = 3.5{\cdot}10^{21}$ cm^{-3}; average charge, Z =15; the temperatures, $T_e = T_i$ =100 eV. Spatial distributions of plasma parameters were uniform with random disturbances of 1% value. SW appears on the axis at 110 ps, and maximal values of plasma parameters are achieved at 120 ps, when two bright spots of density jumps are appeared. Instability significantly develops after 190 ps, and X-ray spark is observed at 210 ps. The maximal values of plasma parameters presented in Table 1:

t , ps	a, μm	T_e , keV	T_i , keV	T_γ , keV	n_e , cm^{-3}	Z
120	1	0.58	0.62	0.57	$1.5{\cdot}10^{25}$	21.6
210	0.1	2.1	8	0.8	$2{\cdot}10^{25}$	32.5

So, there are two X-ray sparks from X-pinch plasma. The first one is associated with cumulation regions due to appearance of curved front of SW on the axis. The parameters Z, T_i , a, T_e and n_e achieve the maximal values at this first spark. The difference of temperatures

$T_i - T_e < 70 \div 80$ eV in this stage, that isn't such large, as at the second spark . Second spark can be explained by fast implosion between the cumulation regions. Second spark begins at 205 ps, when the neck radius is $a \approx 1$ μm. Temperature and density of second hot spot are higher than those at SW appearance on the axis. During the following 5 ps X-pinch neck radius decreases by factor 10, and it is comparable now with Plankian free path of photons.

The existence of two sparks have been observed in experiments [4]. In accordance with numerical results , the first one responded to emission from more dense and cold plasma ($T_e < 1$ keV), than the second one ($T_e > 1$ keV). The investigations of time-resolved radiation spectrum shown the gradual increase of linear component fraction while, initially, continuum component have been dominant. For typical experimentally measured value of radiation yield is, approximately, 0.1 J and its duration -10 ps. So the radiation power closes to 10 GW. For size of emission region less than 1 μm, the radiation intensity exceeds 10^{17} W/cm^2.

Thus, it is shown, that hot and dense plasma of X-pinch can be considered as an interest example of strong non-equilibrium plasma object with high difference between electrons, ions and photons temperatures, high degree of ionization and radiation transfer, which is intermediate between black body and transparent medium cases..

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