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Numerical models and scaling laws for MHD and radiation processes in X-pinch.

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X-pinch is a plasma object produced by electrical explosion of two or more intersecting thin wires having a common point of contact in a vacuum high-current diode. Its main feature is the high capability to energy concentration in the plasma, which is used to develop X-ray sources. The results of 2D numerical simulations of the evolution of X-pinch plasma produced by electrical explosion of two crossed wires (Fig.1) allow one to develop a physical model of plasma implosion, MHD cumulation, and X-ray emission processes. The point-like regions of strongly compressed high-temperature plasma in the region of X-pinch neck (hot-spot) are formed. The MHD model describes a radial compression of plasma by the magnetic field; outlet of plasma on axis; the nonequilibrium multiple ionization and transport phenomena in magnetic field, such as two-temperature processes of electron-ion relaxation; diffusion of magnetic field in plasma and Joule heating; MHD-instabilities; radiation transfer in the diffusion approach in the axial and radial directions with the vacuum losses of radiation on radius. The initial conic plasma configuration is shown in Fig. 1.

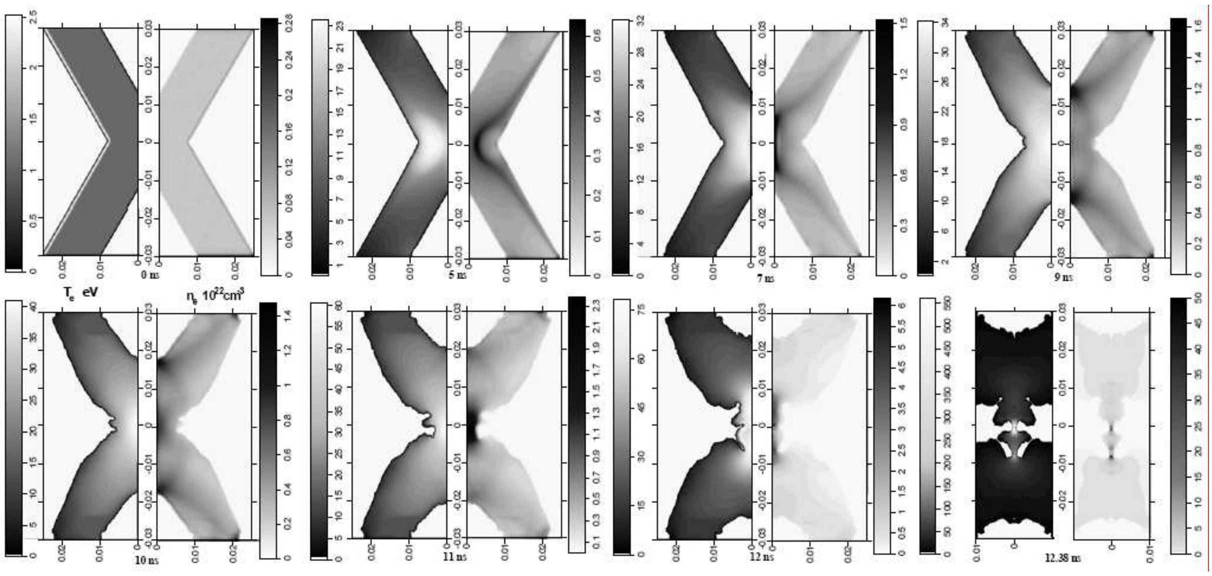

Fig. 1. Example of calculated evolution of X-pinch.

The model describes a hot-spot plasma formation as the process of the neck cascading due to the MHD-instability phenomena. One can observe here a progressive reduction of the plasma compression scales both in space and time. An elementary cycle is determined by dynamics of an oblique shock wave (OSW). The number of the cascade cycles is finite, and at final cycle the lifetime of hot-spot plasma is determined by a break of the neck at generation of the axial shock waves. The scaling laws for X-pinch cascade evolution are determined in the model, in particular, for the hot-spot plasma parameters and X-ray burst. In a final process of the hot-spot development, that has very small subnanosecond scales, the hot-spot plasma is strongly non-ideal, $n_i^{1/3}\, r_{Di} < 1$, and some new features of the plasma dynamics must be taken into account in the X-pinch model.

A specific geometry and high initial density of the X-pinch matter lead to localization of the main processes of evolution in a tiny region of intersection (a mini-diode), where the matter axial motion is important. To formulate the problem it is sufficient to consider this region. Such a behavior is a kind of self-organization, that is, during and after the mini-diode formation, the X-pinch evolution goes as a process of neck cascading, and this is shown in Fig. 1. A new neck being formed in each of the cycles presents a diminished and slightly distorted copy of a previous configuration. In the course of heating, ionization, and diffusion of the magnetic field caused by the current flow there occurs an OSW, which is followed by the plasma implosion. The center of the OSW front curved due to the complex geometry is nearing the axis at 5 ns, and the main volume of the wire crossing area is heated up to 15÷20 eV. But at a periphery, the front changes its slope sharply, and penetrates the plasma only slightly. This is the moment of the cumulation start at the axis. In frame 7 ns, one can observe the reflection of an oblique front of compression from an axis, but the peripheral part of the front continues its motion to the cone inner surface. The cumulation zones, where the oblique incidence and reflected fronts are crossing, move along the axis in the direction of both electrodes. Up to 9 ns one can clearly observe the cumulation zone coming to the inner boundary and, as a result, the plasma expands. Here the central part has already been heated, the reflected front reached the surface, and the implosion has formed a typical picture of a minidiode. The formation of such a picture is associated also with a transverse motion of a part of the reflected front, which has already come outside the formed neck. At this stage of implosion the neck is strongly stretched along the axis, and the limiting "minidiode electrodes" are noticeably deformed, and the cumulative jets are formed inside a vacuum cone. The OSW shape at 10 ns is indicative of a new stage of compression that is axially nonuniform. As a result, the neck takes a classical form after being narrowed in a cross-section and elongated along the axis as a result of convergence of a new implosive wave. The temperature T_e and density n_e of the axial region of dense and hot plasma achieve 100 eV and 10^{23} cm^{-3}, respectively (frame 12 ns). Then within a short time two compression regions are formed in the neck, and the plasma that flows out of them is forming an expansion region between them. The evolution of the narrowing regions is accelerated up to sub-nanoseconds, and in frame 12.38 ns only one of them is noticeably developed.

The effects that determine the shock wave structure are such [1] that the dimension $c_s\tau_{ei}$ of the *ei*-relaxation zones, behind the shock wave, and the *e*-heat conductivity, in front of it, are much greater than the scale $c_s\tau_{ei}/Z$ of the energy transfer from ions to electrons, and much greater than thickness of the compression front $v_{Ti}\tau_{ii}$. The implosion process can be characterized by the Reynolnds magnetic number, $\mathrm{Re}_m = 4\pi\sigma c_s a/c^2 = (a/\delta_s)^2$, where $\delta_s = c(a/4\pi\sigma c_s)^{1/2}$ is the skin-layer thickness. The skin layer becomes thin during implosion, and $\mathrm{Re}_m = (2c_s\tau_{ei}/Za)(\omega_{pi}a/c)^2 > 1$. The first term is the ratio of radius to the ion-electron heat transfer layer thickness, and the second term is the quadruple ratio of the linear ion density, $N = \pi a^2 n_i$, to its critical value N_*/Z^2, where $N_* = m_i c^2/e^2 = 7\cdot 10^{15}A$ 1/cm. It turns out that $a/c_s\tau_{ei} = 8NZ/N_*\mathrm{Re}_m$. The growth of Re_m and the outlet of plasma make the ratio $a/c_s\tau_{ei}$ lower. At first it is greater than 1, and at $N > N_*/Z^2$ it should become less than 1 in the region of minimal cross-section.

At $a < c_s\tau_{ei}$ the *e*-thermal conductivity heats up the whole area of the neck, and the electron temperature takes a smooth distribution, the more uniform the better inequality is fulfilled. The electron heating capabilities become exhausted, and a further cumulation consists in the ion heating in a thin compression layer that can be regarded as a rupture. Immediately behind it, in the layer of thickness $c_s\tau_{ei}/Z$ at $T_i > T_e$, the heated ions are intensively cooled down by electrons. In the region of $a/c_s\tau_{ei} < 8/Z < 1 < NZ/N_*$, the *ei*-heat exchange becomes restricted, and the temperature separation of ions increases rapidly. The plasma becomes strongly nonequilibrium. One can go beyond the mechanisms of the Coulomb collisions, i.e. the lengths of the *ii*- and *ei*-paths become less than distances between the ions $n_i^{1/3}$. The calculation performed in [2] verifies this. The number of the cascade cycles proves to be finite.

The synergetics tells the difference between organization and self-organization. The organization is the linear response to the action of external forces, and the self-organization is the formation of the ordered structures in the stochastically disordered media due to their inherent features. The new structures are born due to the bifurcations in a nonlinear dynamic system, where the initial conditions are the random noises, and instability is the mechanism of development. A nonlinear evolution of the complex systems may be determined by such features as the competition between the fluctuation structures, the subordination of the short-living structures to the long-living ones, the appearance of the hierarchy, etc.

The evolution shown in Fig.1 allows one to suggest the presence of self-organization in the dynamics of the X-pinch necking. This can be attributed to the class of dissipative structures in the thermodynamically nonequillibrium media. The examples can be found in the hydrodynamics of liquid and plasma, see also the evolution shown in Fig.1. A succession of bifurcations at the cascade development of the neck is due to the frontal reorganization of shock waves in the course of cumulations at the axis output. A further extension and axial motion of the plasma provide conditions for the MHD instability that are necessary for the development of new compressions of a smaller scale. This determines the hierarchy structure of the necking. The final X-ray flash is accompanied by the radiative collapse. This leads to the rupture of necking and also to the bifurcation. A new structure is born, that is, a gap of a spatial charge with the self-consistent fields and the flows of electrons and ions in a pinching magnetic field of the current.

An up-to-date model of the collapse assumes a two-stage compression of the Z-pinch. This requires a sufficiently large axial scale of the pinch and corresponds to a plasma focus condition. But it needs to be essentially corrected as applied to the radiative X-pinch flash. Instead of the MHD compression one should apply the self-organized compression cascade, which is terminated by the neck rupture in a final cycle.

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