

FORMATION OF A PERCOLATING NETWORK IN DENSE Z-PINCH PLASMAS

A.B. Kukushkin and V.A. Rantsev-Kartinov

INF RRC "Kurchatov Institute", 123182 Moscow, Russia

The present paper is aimed at demonstrating the percolatory networking of Z-pinch plasmas on the example of earlier experiments, using the method of multilevel dynamical contrasting [1]. The complexity of the method makes it difficult to illustrate the disclosing of structuring (because such a disclosing comes from watching a sort of an animated cartoon). However, the presentation of «static» images subject to a contrasting and «stripping» (i.e. to retaining only the regions brighter than a certain level) seem to be an appropriate illustration to the percolatory networking of Z-pinch plasmas.

The experimental set-up included: discharge tube 60 cm long, 20 cm diameter, with flat copper electrodes on the edges; low inductance capacitor, 60 μF ; initial voltage ~ 30 kV; energy store ~ 30 kJ, initial gas pressure (deuterium) 0.25 Torr. The stagnation stage, of ~ 100 ns duration and 150 kA current, takes place about 250-300 ns before first singularity of electric current (below time t is counted from this singularity). The peak density and temperature averaged over Z-pinch's main body at stagnation stage, as measured with the help of laser Thomson scattering and laser interferometry, amount to $n_e \sim 5 \cdot 10^{17} \text{ cm}^{-3}$, $T_e \sim 300$ eV. We present here typical visible light photographs, of 15 ns exposure and 50 μm space resolution. The optics collected the light in a perpendicular direction to facility's major axis, from a circular layer of 7.5 cm diameter (respective circle may be seen in the figures; their height normally is 7.5 cm) and 5 cm depth. This layer is located on major axis of facility.

The method [1] enabled us to suggest [1] Z-pinch plasmas to be a dynamical percolating network formed by the long-living filaments of electric current (see also [2a]). Here we illustrate the role of filamentation and networking of filaments in the following phenomena where, to our mind, the deviations of the networking-based approach from conventional interpretations provided by the 2-D MHD approaches are most significant (cf. [3]).

1. Formation of a filament-made magnetic stocking

The data suggest that a *magnetic stocking* forms at the very beginning of discharge and preserves its integrity for a long time, at least up to electric current disruption in the neck(s). The stocking is woven by the individual filaments (and appears to be most distinct in the case

of the presence of initial longitudinal magnetic field H_z). The matter is that the plasma tends to form a force-free like magnetic configuration (i.e. to direct the electric current along magnetic field) wherever and whenever possible, from internal structure of individual filaments to the network of filaments (see [2a]). In the Z-pinch at its implosion stage this manifests itself in forming the azimuthal electric currents. This leads to producing the transverse filaments, with respect to Z-pinch axis, which wound round longitudinal filaments and, thus, produce the filamentary current sheath in the form of a stocking (the much more perfectly woven magnetic stockings are believed [2b] to play special role in magnetically confined toroidal plasmas). Figure 1 taken at initial stage of stagnation ($t = -550$ ns, $H_z = 40$ G) shows a set of horizontal and vertical filamentary bonds (note that, because of the 5 cm depth of collecting the light from 7.5 cm circular layer, the picture gives a volumetric image of the stocking).

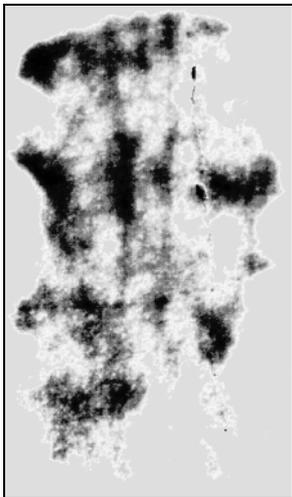


Fig. 1. ($t = -550$ ns)

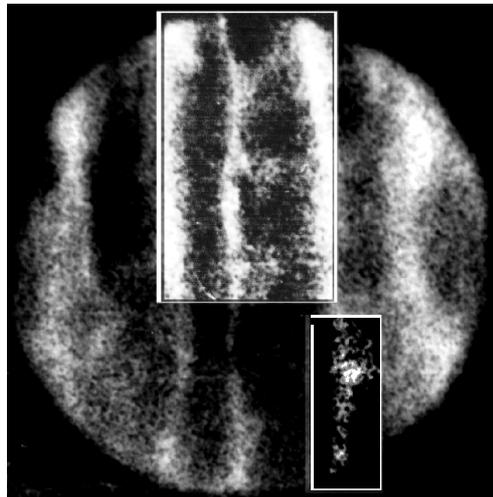


Fig. 2. ($t = -950$ ns)



Fig. 3. ($t = -550$ ns)

2. Formation of a precursor

In these experiments the electric current sheath preserves its filamentary structure, with dramatic deviations from axial symmetry, during both implosion and stagnation stages. This «shortcoming» allows to resolve both the filamentation as itself and the fine structure of filaments. Figure 2 ($t = -950$ ns, here and below $H_z = 0$) shows typical picture of filamentation at implosion stage of discharge. Significantly, axial non-uniformity of the current sheath opens a possibility for magnetic field to reach the axis and form there an electric current structure, far in advance of the moment when major current sheath converges on the axis. This is seen as a precursor which was observed even in the case of the most perfect implosion ever achieved, namely in the experiments on multi-wire array Z-pinch [4]. Fine structure of the

precursor in the present experiments, of relatively much less effective compression, may be seen in the less contrasted image in central window in Figure 2.

3. Development and saturation of Rayleigh-Taylor instability **Fine structure of Z-pinch's main body and halo**

Figure 1 shows typical regular inhomogeneity produced by the large-scale stocking which predetermines future large-scale axial stratification (cf. Figure 5). Magnetic field in the interstrata space compresses the current sheath faster so that at stagnation stage the Z-pinch takes the form of a fur-like tree, see Fig. 3 ($t = -550$ ns). Indeed, the largest filaments when compressed on the axis form its trunk (in rough imaging, the so called main body of Z-pinch) while the largest heteromacs form the branches of the tree, roughly perpendicular to the trunk (for the definition of the heteromac see Figs. 1 and 2 in Ref. [2a]). The smallest heteromacs form the leaves of the tree (in rough imaging, the halo of Z-pinch). The neck looks like an inter-branch space. At stagnation stage magnetic field moves the branches along the trunk to make the necks narrower.

It follows that the interpretations of the necking in terms of magnetically-driven Rayleigh-Taylor instability in non-filamentary plasmas, in essence, mimics a more complicated dynamics. For instance, the saturation of the Rayleigh-Taylor instability in the filamentary current sheath at stagnation stage looks, in the present approach, merely like a direct implication of the resilience/stiffness of the trunk.

Sometimes the branch takes the form of an unexpectedly long, thin rectilinear stick, with a thinner helical winding (Fig. 4, $t = -500$ ns, image height 2 cm, time exposure 60 ns; see the window of a stronger «stripping» the image). We called this a *magnetic needle*, because a strong magnetic flux is accumulated on major axis of such a heteromac. It is easy to trace the motion picture of magnetic needles, and this enabled us to suggest that (i) the observed lifetimes of the filamentation and networking largely exceed those predicted by the conventional theories of plasma kinetics and magnetohydrodynamics, and (ii) the filaments, therefore, are the non-fluctuative, non-chaotic formations. Note also that the heteromac is obviously more stiff than its mother filament, and this could explain its unique stiffness.

4. Disruption of the necks

Under conditions of relatively low filament number (and particle density) and relatively high magnetic compression the «overloaded» filaments of electric current are being destroyed just in the neck (this looks like a disruption of the trunk in neck's region) that leads to a singularity of circuit electric current. Therefore, the neck appears to be a region of depleted particle

density (see Fig. 5, $t = +125$ ns). Note that the existing 2-D MHD codes predict peaking of particle density in the necks (or, at best, around the neck) whereas experiments show that the most of radiation comes from the spike regions (especially, from «hot spots» in these regions) because particle density is not peaked in the necks.

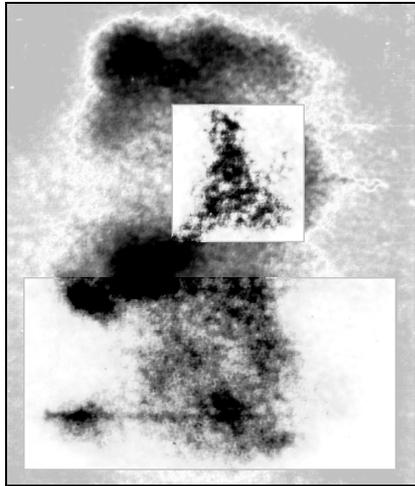


Fig. 4. ($t = -500$ ns)

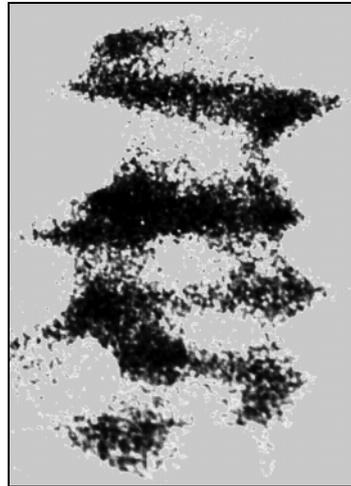


Fig. 5. ($t = +125$ ns)

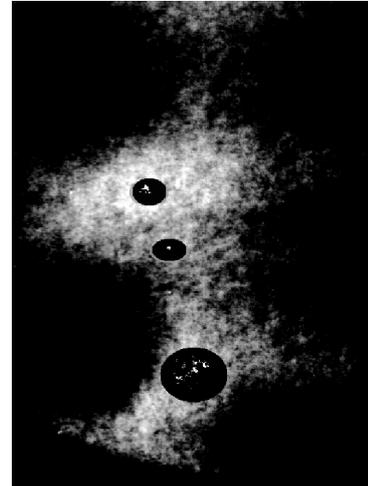


Fig. 6. ($t = +250$ ns)

5. Fine structure of «hot spots»

The fractal structure of the plasma manifests itself in the self-similarity of structuring at different length scales. Extrapolation of the resolved structuring [1] to a smaller length scale suggests that the hot spot is a bunch of heteromacs of respective length scale. Such a bunch can be formed by the heteromacs which branch off mother filament at the same or very close points and, thus, produce a region of the enhanced density of magnetic energy, because of efficient confinement of magnetic field in the heteromac. The brightest spots shown in small elliptic windows of Fig. 6 (via enhanced contrasting the image in these windows) appear as a rule to be located inside relatively bright regions (strata) whereas the neck is much poorer with bright spots (image height 5 cm, size of hot spots is about $100 \mu\text{m}$, $t = +250$ ns).

References

- [1] A. B. Kukushkin, V.A. Rantsev-Kartinov: Preprint of the RRC “Kurchatov Institute”, IAE 6045/7, Moscow, 1997; *Laser and Particle Beams* **16**(3) (1998, *to be published*).
- [2] A.B. Kukushkin, V.A. Rantsev-Kartinov: (a) «Self-similarity of plasma...», these proceedings; (b) «Plasma networking in magnetically...», *these proceedings*.
- [3] *AIP Conference Proceedings #409, Dense Z-pinchs 4th Int. Conference*, Vancouver, Canada, May 1997, edited by N. R. Pereira, J. Davis, and P. E. Pulsifer (AIP Press, New York, 1997).
- [4] T.W.L. Sanford, et. al.: in Ref. [3], p. 561; *Phys. Plasmas* **4**, 2188 (1997); *Rev. Sci. Instrum.* **68**, 852 (1997); *Phys. Rev. Lett.* **77**, 5063 (1996).