Kukushkin A.B., Rantsev-Kartinov V.A., Terentiev A.R., Formation of a spheromak-like magnetic configuration by a plasma focus self-transformed magnetic field // Fusion Technology, 1997, vol. 32, pp. 83-93.

FORMATION OF A SPHEROMAK-LIKE MAGNETIC CONFIGURATION BY A PLASMA FOCUS SELF-TRANSFORMED MAGNETIC FIELD

A.B. KUKUSHKIN, V.A. RANTSEV-KARTINOV, and A.R. TERENTIEV

Institute for Nuclear Fusion, Russian Research Center "Kurchatov Institute", 123182 Moscow, Russia

Dr. A.B. Kukushkin,
Institute for Nuclear Fusion,
Russian Research Center "Kurchatov Institute", 123182 Moscow, Russia
Fax: 7 (095) 9430073
E-mail: kuka@qq.nfi.kiae.su

Pages, Figures

Kukushkin A.B., Rantsev-Kartinov V.A., Terentiev A.R., Formation of a spheromak-like magnetic configuration by a plasma focus self-transformed magnetic field // Fusion Technology, 1997, vol. 32, pp. 83-93.

FORMATION OF A SPHEROMAK-LIKE MAGNETIC CONFIGURATION BY A PLASMA FOCUS SELF-TRANSFORMED MAGNETIC FIELD

A.B. KUKUSHKIN, V.A. RANTSEV-KARTINOV, and A.R. TERENTIEV

Institute for Nuclear Fusion, Russian Research Center "Kurchatov Institute",

123182 Moscow, Russia

Topical category: PLASMA ENGINEERING

KEYWORDS: Plasma Focus, closed magnetic configuration, plasma self-compression

ABSTRACT

Experimental results are presented which verify the possibility, formerly predicted,[1] of the formation of a closed, spheromak-like magnetic configuration (SLMC) by the natural magnetic field of a plasma focus discharge. The model is based on the self-generated transformation of a toroidal (i.e. azimuthal) magnetic field into a poloidal one. At the final stage of the discharge, the SLMC takes the form of a squeezed spheromak, which includes a combined Z-ϑ pinch at its major axis, exhibiting a power density several orders of magnitude larger than that measured experimentally on a force-free flux-conserver-confined spheromak formed by helicity injection. The results suggest a possibility of further concentrating the plasma power density by means of compressing the SLMC-trapped plasma by the residual magnetic field of the plasma focus discharge.

A qualitative model is given for the scenario of the SLMC-producing plasma focus discharge. Special emphasis is placed on the difference of this approach from conventional approaches to the role of magnetic field reconnection processes in plasma focus dynamics. The operational conditions necessary to stimulate SLMC formation in high-current gaseous discharge systems and the uses of SLMC-trapped plasmas are discussed briefly.

I. INTRODUCTION

Producing a stable Z-pinch in a plasma focus discharge is primarily dependent on the dynamics of the current sheath as it converges on the axis. (See, for example, Refs. 2 and 3). It was earlier predicted[1] that an SLMC would be formed by the natural magnetic field of the plasma focus discharge, without helicity injection at any stage of the discharge. In its final stage, the SLMC takes the form of a squeezed spheromak, with a combined Z-ϑ pinch at its major axis. The SLMC produces closed electric currents with strong filamentation, both in the inner region of the SLMC (i.e., in the combined Z-ϑ pinch) and in its periphery. The current driven by the residual magnetic field is filamented as well.

The essential feature of this paradigm[1] is the self-consistent generation of a poloidal magnetic field (i.e. dynamo effect) as a result of the partial transformation of the azimuthal field of a plasma focus (in general, of a non-cylindrical Z-pinch). (Here, the toroidal field of the eventual spheromak-like configuration is formed by the azimuthal field.) Such an effect does not require additional (i.e. mechanisms independent of the inner dynamics of the magnetic field in the plasma focus discharge) production of a poloidal magnetic field, as distinct from the experiments employing coaxial plasma guns to produce a spheromak as a force-free configuration. (Cf. Ref. 4 and the latest survey in Ref. 5).

Data from an earlier experimental program carried out at the Filippov-type plasma focus facility[6] in the Kurchatov Institute during 1980-84 are presented. Some of the results presented here have not been previously published, as they were not fully understood before. The present analysis of this experimental database in terms of the SLMC model[1] reveals evidence of SLMC formation and further clarifies the conditions or regimes in high-current gaseous discharge (HCGD) systems favorable to SLMC formation analysis (see also Ref. 7). Further, it is now possible to identify the role of the enhanced rate of the magnetic field propagation along the anode resulting from the Hall effect in plasmas.[8-10] Significantly, the identification of the SLMC as an essentially three dimensional formation is available only from combining the diagnostics with different (and complementary to each other) spatial and spectroscopic scales.

A qualitative model is given for the SLMC-producing plasma focus discharge in Section II. Special emphasis is given to the differences between this model and conventional approaches to the role of magnetic field reconnection processes in plasma focus dynamics. Experimental results are presented in Section III, and experimental problems in identifying the SLMC are given in Section IV. The characteristic features of an SLMC-producing discharge are described in Section V. Operating conditions necessary to induce SLMC formation in HCGD systems and applications of SLMC-trapped plasmas are discussed briefly.

II. A QUALITATIVE MODEL FOR THE SLMC FORMATION

A qualitative description of the formation of the SLMC is based on an energy transformation model.[1] The most important physical mechanism for the formation of the SLMC is the production of a sufficiently strong solenoid-like magnetic field or an equivalent poloidal field (in terms of toroidal topology) within the plasma volume (i.e. the dynamo effect). The optimal mechanism for this production is the natural transformation of a part of the azimuthal magnetic field H_ϑ, which is the primary accumulator of energy in the discharge chamber, into radial-longitudinal, r-z components of a poloidal magnetic field. The possibility of this transformation may be assumed by the fact that the dynamics of the plasma and its magnetic field in a plasma focus discharge appear to meet the necessary conditions for the dynamo effect. (See Refs. 11 and 12.) Indeed, the helical hydrodynamic motion of the filamented current sheath exhibits differential rotation (caused by the inhomogeneity of the current sheath along its major axis) and possesses an essentially three-dimensional structure. Motion picture of the magnetic field front (and electric current sheath) in a spheromak-producing plasma focus discharge is shown in Fig. 1.

The progression of input energy transformations in a plasma focus discharge under enhanced rates (in contrast to conventional diffusion) of magnetic field propagation along the anode is as follows[1] (see Fig. 2).

The breakdown in the discharge chamber transforms the energy stored in the external capacitors into an azimuthal magnetic field H_ϑ. The H_ϑ magnetic pressure forms a moving current sheath, which is subject to filamentation. The filamentation as itself produces favorable conditions for transforming the topology of the magnetic field. Further improvement of the background for the dynamo effect stems from the production of the three-dimensional field of the hydrodynamic velocities of the plasma (and that of the magnetic field which is not completely frozen in plasma). The hydrodynamic motion of the current sheath is unstable with respect to rotation. Here, the breakdown (either spontaneous one or unduced by the geometry of the facility) of axial symmetry of hydrodynamic motion at the initial stage of the discharge eventually increases the “richness” of spatial distribution of hydrodynamic velocities. In addition to this effect, the transfer of H_ϑ with the electric current velocity leads to the accumulation of H_ϑ at the anode, and consequently to the enhanced propagation rate of the magnetic field and the current sheath along the anode.[8-10] This in turn leads to a strong z-dependence of both azimuthal and radial hydrodynamic velocities. This results ultimately in a differential rotation of the currrent sheath.

The differential rotation of the filamented current sheath produces a poloidal magnetic flux and the corresponding azimuthal electric current j_ϑ. The current j_ϑ tends to be concentrated mainly in those regions of the current sheath which move to the axis fastest (i.e. at the front edges of the current sheath). Thus, in the local framework, this leading edge of the magnetic field takes a form close to that of a finite-length solenoid created by the front edges of the current sheath. The formation of such a finite-length solenoid is strongly stimulated by the disruption of the current sheath in the region undergoing enhanced-rate propagation of the magnetic field along the anode. Here, the magnetic pressure of the H_ϑ field and the sharp hydrodynamic rotation gradient of the current sheath tears the rapidly moving/rotating front portion of the current sheath away from the slower moving portion. This disruption of the current sheath leads to the reconnection of the magnetic field lines around the finite-length solenoid described above. As a result, a closed, spheromak-like magnetic configuration (SLMC) emerges. The poloidal field of the SLMC is formed by this solenoid-like magnetic field, in contrast to the toroidal field, which is formed by a part of the azimuthal field H_ϑ. The residual H_ϑ field forms a spatially distributed electric current, which closes the outer electric circuit of the discharge, while the magnetic pressure of the residual H_ϑ tends eventually to form the standard plasma focus current sheath, now called the residual current sheath (RCS). The resulting magnetic configuration is shaped like a tokamak, with an elliptical cross-section strongly elongated toward the nearly radial direction. As this configuration is squeezed toward the plasma focus major axis, both by the SLMC's own magnetic pressure and by the pressure of the RCS, it is transformed into a spheromak-like plasma with a non-circular and asymmetric (with respect to its equatorial plane) cross section.

The SLMC model of the magnetic field evolution of a plasma focus plasma differs substantially from conventional understanding of this phenomena on one key point: namely, that the essential transformation of the magnetic field occurs long before the current sheath converges on its major axis. Specifically, for a wide range of plasma focus facilities, 200-300 nanoseconds (ns) before the peculiarity of time dependence of electric current or its derivative. The reconnection of the magnetic field is signaled by the simultaneous short pulses of x-rays and visible light and (with a proper retardation) of accelerated particles, as well as by the very conservation of the SLMC structure while it eventually is forced away from the anode (see below).

The internal structure of the SLMC-trapped plasma is characterized by (i) a combined Z-ϑ pinch (i.e. a pinch having both azimuthal and longitudinal magnetic field) at the SLMC major axis, and (ii) strong filamentation of electric currents in both the Z-ϑ pinch area and in the peripheral regions of the SLMC. Thus, the Z-ϑ pinch has a rather complex internal structure distinguished by a helical configuration of the current filaments. The closure of the "inner currents" in the peripheral regions of the SLMC is characterized by a fairly inhomogeneous formation composed of thick filaments of electric current. (For experimental observations of filamentation in gaseous discharges see Refs. 13 and 14.)

The pressure of the RCS strongly influences SLMC's geometry by squeezing the SLMC in the radial direction, thus elongating it in the longitudinal direction. The RCS's pressure either drives the SLMC towards the cathode or squeezes it toward the anode, until the build-up of the residual magnetic field at the anode repels it. The development of the residual magnetic field and the RCS may be repeated over and over, provided the stored energy and the gas media in the discharge chamber are sufficient for a multiple-stage regime.

Significantly, the compression of the SLMC by the RCS may result in the formation of a quasi-steady-state configuration in the central region of the SLMC which being observed separately from the peripheral areas of the SLMC, may be interpreted as a quasi-steady-state Z-pinch. Such an effect makes the identification of the SLMC a complicated diagnostic task which requres simultaneous observations in a wide range of spacial and spectroscopical scales. Besides this, because of the strong filamentation of such plasmas, spectroscopical measurements, both of visible light and of x-ray emission, are extremely complex and may lead to appreciable errors unless such effects are taken into account.

It should be noted that, in general, reconnection of the magnetic field lines and formation of the SLMC may also be achieved without breaking the current sheath by the magnetic field. Such a reconnection may also result from the collision of the edges of the current sheath at the axis. One more possibility for producing a closed magnetic configuration stems from nonlinear development of helical modes at the stage of quasi-steady-state Z-pinch. A comparative analysis shows that the progression of input energy transformation[1] is most favorable for controllable production of a closed magnetic configuration.

Because of the self-organization character of the SLMC formation, which results from strong nonlinear coupling of the various factors affecting SLMC formation in a plasma focus discharge, there is a non-monotonic dependence of the output parameters (emission rates of light, x-rays, charged particles, etc.) on the input parameters (geometry, voltage, current, etc.). This manifests itself in a “quantization” of optimal values for the SLMC formation. Spontaneous and non-controllable formation of the SLMC may prevent the attainment of higher discharge electric current values, thus limiting the power densities in HCGD systems (plasma focus, Z-pinch, etc.). On the other hand, just the SLMC formation suggests a possibility of further concentrating the plasma power density by means of compressing the SLMC-trapped plasma by the residual magnetic field. Such an approach is to combine the advantages of inertial confinement fusion (high peak values of power density) and magnetic confinement (enhanced stability due to closedness of magnetic configuration). This suggestion is supported by the fact that at the final stage of the discharge, the SLMC takes the form of a squeezed spheromak, which includes a combined Z-ϑ pinch at its major axis, exhibiting a power density several orders of magnitude larger than that measured experimentally on a force-free flux-conserver-confined spheromak (cf. Ref. 5).

III. EXPERIMENTAL RESULTS

A great deal of experimental data obtained in neon gas studies carried out at the Filippov-type plasma focus facility[6] supports the SLMC model formerly predicted[1], and permits the extension of this model to incorporate the important role of the enhanced propagation rate of the magnetic field along the anode.

A diagram of the facility and its diagnostics array is shown in Fig. 3. The mushroom-shaped anode (11-cm diam.) is located inside a coaxial metallic chamber 80-cm long and 30-cm high, which acts as the cathode. The distance between the anode and the cathode along the major axis was varied between 6 cm to 12 cm, depending on the initial gas pressure and energy store, in order to match the time of sharp substantial drop of total electric current with its rather broad maximum (thereby consuming as large amount of energy as possible). The main discharge parameters are: capacitance, 180 μF; initial inductance, 55 nG; initial voltage, 16-24 kV, varying with energy of 20-50 kJ, respectively; maximum current, 600 kA; neon gas pressure, 0.5-4.7 Torr.

The discharge electric current and its derivatives are recorded using a Rogowski coil and a magnetic probe, respectively. Typical time dependencies of electric current and voltage in SLMC-producing discharges are shown in Fig.4. The second time peak of the time derivative of electric current takes place 500-550 ns after the first one. The time Δt in the figures below corresponds to the time shift from the first peak of the time derivative of the current.

Figures 5.1, 5..2, and 5..3 are visible light photographs of the SLMC (an electronic optical converter is synchronized with the current to an accuracy of <50 ns). Figure 5.1 exhibits strong filamentation of the outer electric currents of the SLMC. Filament helicity varies in different discharges from weak to relatively strong, with an essentially three-dimensional formation.

Figure 5.2 shows that the pressure of the RCS transforms the SLMC-trapped solenoid-like section of the broken current sheath into a plasma disc, and the combined Z-ϑ pinch forms a rod of dense plasma attached to the disc.

Figure 5.3 shows the crown-like structure of current filaments of the spheromak. The RCS has also broken into filaments, which spread along the anode disc and extend to its lower side. (The elliptical image of the anode disc itself is seen in the background. For comparison see Fig. 6.)

Figures 7.1 - 7.15 (space scale 1:1) are frames of a motion picture of the evolution of SLMC formation, taken with the help of a ruby-laser-based interferometer operating in the Bates regime (0.01-J laser pulse energy; 2-ns duration; pulse direction perpendicular to the system axis). The system axis is located 3.7 cm from the left side of the pictures (cf. Fig. 7.4). Note that the horizontal line projects the current sheath's upper boundary. The heel-like form of the current sheath in Figs. 7.1 and 7.2 (Δt = -360 ns and -300 ns, respectively) is caused by the enhanced rate of the magnetic field propagation along the anode, due to the Hall effect-induced build-up at the anode. (For a comparison of experimental data with the results of numerical modeling, see Refs. 9 and 10.)

Figures 7.3 and 7.4 (Δt = - 260 and -190 ns) show that the magnetic field line reconnection and the development of electric current formations which are unique to a closed magnetic configuration take place before the current sheath converges on the axis. This fact is suggested by

(i) the helical structure of the filaments clearly seen in the middle and especially the lower part of these figures;

(ii) the detection of a number of precursors caused by the reconnection process (viz. short pulses of soft and hard X-rays, visible light etc.) long before (200-300 ns) the major peak of the time derivative of total electric current;

(iii) the convergence of the current sheath at the axis long before (200 ns) the major peak of the time derivative of total electric current (Fig. 7.3.); and

(iiii) the conservation of the structure, which has detached itself from facility circuit current, while it eventually is forced away from the anode (see Figs. 7.5 - 7.7).

Figures 7.5 - 7.7 (Δt = +200, +290, and +360 ns, respectively) show the displacement of the SLMC away from the anode by the residual magnetic field accumulated at the anode due to the Hall effect. Figures 7.8 - 7.14 (Δt = +400, +450, +510, +550, +710, +790, and +810 ns, respectively) show the formation and squeezing of the second SLMC. This phase stops with the second peculiarity of the current derivative. Figure 7.15 (Δt = +850 ns) shows decay of the plasma formation.

The above interferograms allow to trace dynamics of the spatial profiles of electron density at large space scales. Though plasma exhibits strong azimuthal inhomogeneity -- due to a strong filamentation -- nevertheless it makes sense to evaluate electron density averaged over space scales of the order of the current sheat thickness, assuming axial symmetry and making Abel inversion. Thus, for initial pressure 3 Torr and initial voltage 16 kV, at Δt = -500 ns and at a point behind the current sheath and 1 cm over the anode surface, this gives electron density values $n_e \sim 5\ 10^{17}$ cm^{-3}. The corresponding electron temperature T_e , evaluated from NeI and NeII line intensities ratio, amounts to few/several eV. As to the peak values attained at the stage of maximum compression (and maximun soft X-ray radiation yield), at $\Delta t \sim$ +500 ns, the values of T_e -- within 0.05-0.1 cm radii -- determined from SXR line spectra, are about 1 keV, with $n_e \sim 10^{19}$ cm^{-3}, i.e. peak values exhibit well-known weak dependence on the capacitance and discharge geometry.

Self-organization character of the SLMC formation manifested itself in a non-monotonic dependence of the output vs. output parameters. The most significant fact here is a sharp drop of the SXR yield, by a factor 2-3, with exceeding the optimal value of discharge initial voltage by 5% only.

IV. EXPERIMENTAL PROBLEMS IN IDENTIFYING SLMC

Identification of an SLMC in plasma experiments is a complex problem, requiring plasma observations and measurements in a wide range of spatial scales, luminosities, etc. It appears that the observation of the longer wavelength (i.e. in the visible light range) emission pattern of the SLMC is even more important than the examination of short-scale (i.e. in the x-ray range) formations within it, because the formation of the combined Z-ϑ pinch at the discharge major axis may occur regardless of SLMC formation and its corresponding magnetic reconnection processes and closure of electric currents at the periphery of the plasma. Indeed, that part of the formation close to the inner region of the SLMC may be caused by the instability m=1, n=1, and the filamentation of the current at the final stage of a conventional, linear Z-pinch. Thus, even repeated observations of a strongly emitting, quasi-steady-state Z-ϑ pinch in the central region of the discharge still leave unresolved questions about the evolution of the overall formation of the plasma with its rapidly changing and weakly emitting peripheral regions. Therefore, in order to identify the SLMC, passive diagnostics for the central region must be combined with active diagnostics for the rapidly changing visible-light formation.

The importance of this conclusion may be illustrated by the results of the search for a helical structure in a plasma focus discharge, which has been stimulated by the well-known success of the Taylor theory[4] in experiments on reversed-field pinches. For instance, soft x-ray diagnostics have been used to observe a helical track with separate bright spots,[15] which has been interpreted as a probable manifestation of the Taylor force-free configuration. This track is believed to have appeared simultaneously with the second neutron burst. Application of the Taylor concept[4] to the quasi-steady-state phase of a plasma focus discharge revealed possible existence of a small-scale cell-like formation, composed of coaxial force-free configurations.[16] Here, the schlieren image of the formation, inhomogeneous in z-direction (similarly to the image of the pinch seen in the interferogram of Fig. 7.14), has been interpreted in Ref.16 to be the central region of such a cell-like formation.

V. CONCLUSIONS

The model[1] and the analysis of experimental results obtained from earlier experiments on high-current gaseous discharge (HCGD) systems, which included Filippov- and Mather-type plasma focus devices, non-cylindrical Z- and Z-ϑ pinches, and plasma guns, has allowed the identification of the unique characteristics of a spheromak-like magnetic configuration

(SLMC). (For current state of the HCGD physics, see e.g. Ref. 17.) These attributes of a SLMC include:

(1) The self-consistent generation of a poloidal magnetic field (the dynamo effect, see Refs. 11, 12), solely by the internal dynamics of the magnetic field in the discharge.

(2) Strong filamentation (cf. Refs. 13, 14) of electric currents, which occurs both in the inner region of the SLMC (i.e. in the combined Z-ϑ-pinch) and in its periphery. The electric currents driven by the residual magnetic field are also strongly filamented.

(3) SLMC formation is stimulated by the enhanced propagation rate of the magnetic field along the anode, due to the Hall effect in plasmas[8] (see also Refs. 9 and 10).

(4) A magnetic field reconnection process leading to the formation of the SLMC as a closed configuration, appears to occur before the current sheath converges on the axis.

(5) In its final stage, the SLMC takes the form of a squeezed spheromak configuration, forced away from the anode by the pressure of the residual azimuthal magnetic field.

(6) The power density in the combined Z-ϑ-pinch at the major axis exceeds the peak power density of a force-free flux-conserver-confined spheromak formed by helicity injection by several orders of magnitude (cf. Ref. 5).

(7) The SLMC exhibits a cyclical, evolutionary tendency to form, be repelled away from the anode, and reform repeatedly.

(8) Self-organization (non-monotonic "input vs. output" dependence, "quantization" of discharge energy).

The primary conditions which have been identified which may stimulate SLMC formation in HCGD systems are:

(a) the differential rotation of the hydrodynamic motion of the current sheath,

(b) filamentation of the current sheath, and

(c) the essentially three-dimensional character of the non-steady-state, non-ideal-magnetohydrodynamics of the plasma and the magnetic field.

It follows from the item (c) that even the most advanced existing numeric codes are insufficient to provide adequate computational modeling of the evolution of an SLMC.

Applications of the SLMC formation in a plasma focus dicharge could be of importance for achieving an enhanced yield of the SXR radiation in a moderate-voltage plasma focus facility, making it possible to design a high-efficiency low-cost SXR source. Another, much more promising application of the present concept relates to achieving the fusion ignition in a high current gas discharge experiments in a plasma focus facility that is based on (i) self-production, by the plasma focus discharge, of the pre-fusion magnetized plasma in a closed magnetic configuration and (ii) its further compression by the residual magnetic field of the discharge. Regular type of magnetic compression of a closed magnetic configuration by an open magnetic configuration at large space scales (several cm size) -- in contrast to irregular formation of a single “hot spot” -- opens a possibility to control/optimize self-compression of the SLMC-trapped plasma in a SLMC-producing discharge. Such an approach is to combine the advantages of inertial confinement fusion (high peak values of power density) and magnetic confinement (enhanced stability due to closedness of magnetic configuration).

ACKNOWLEDGMENTS

The authors are grateful to V.A.Khrabrov and M.M.Orlov for their valuable contribution to obtaining the experimental database presented in Ref. 6 and the present paper; V.V. Vikhrev and O.Z.Zabaidullin, for helpful discussions of the Hall effect issues. The authors appreciate valuable discussions of the present concept with N.V.Filippov, J.Davis, G.H.Miley, A.I.Morozov, S.L.Nedoseev, A.A. Rukhadze, H.Schmidt, V.P.Smirnov, L.I.Rudakov, B.A.Trubnikov, A.Velikovich, V.V. Vikhrev. The authors are grateful to E.E.Trofimovich for preparing the Figure 6.

REFERENCES

1. A. B. KUKUSHKIN., V. A. RANTSEV-KARTINOV, “On the Pos sibility of Formation a Spheromak-Like Magnetic Configuration in a Plasma Focus Discharge,” *Preprint of the RRC “Kurchatov Institute*”, IAE 5646/6, Moscow (1993).

2. N. V. FILIPPOV, “Plasma Focus Experiments in the Kurchatov Institute,” *Sov. J. Plasma Phys*., **9**, 14 (1983).

3. V. V. VIKHREV, S. I. BRAGINSKII, “Dynamics of Z-pinch,” *Reviews of Plasma Physics*, vol.10, p.425, Ed. M. A. Leontovich, Consultants Bureau, New-York, (1986).

4. J. B. TAYLOR, " Relaxation of Toroidal Plasma and Generation of Reverse Magnetic Fields", Phys. Rev. Lett., **33**, 1139 (1974); ." Relaxation and Magnetic Reconnection in Plasmas," *Rev. Mod. Phys*., **58**, 741 (1986).

5. T. R. JARBOE, “Review of Spheromak Research,” *Plasma Phys. and Control. Fusion*, **36**, 945 (1994).

6. M. M. ORLOV, A. R. TERENTIEV, V. A. KHRABROV, “Some Results on Laser Sounding of a Non-Cylindrical Z-Pinch,” *Fizika Plazmy (Sov. J. Plasma Phys*.), **11**, 1268 (1985); “Measurements of the Magnetic Field in a Plasma Focus, “*Ibid*., **11**, 1517 (1985).

7. A. B. KUKUSHKIN, V. A. RANTSEV-KARTINOV, A. R. TERENTIEV, “Formation of a Spheromak-Like Magnetic Configuration by the Plasma-Focus-Self-Transformed Magnetic Field,” *Preprint of the RRC “Kurchatov Institute*”, IAE 5737/7, Moscow (1994).

8. A. I. MOROZOV, A. P. SHUBIN, “On the Theory of Electromagnetic Processes in the Presence of the Hall Effect,” *Zh. Eksp. Teor. Fiz. (Sov. Phys. JETP)*, **46**, 710 (1964).

9. V. V. VIKHREV V.V., O. Z. ZABAIDULLIN, A. R. TERENTIEV, “Investigation of the Enhanced-Rate Propagation of Magnetic Field Along the Anode in a Z-Pinch,” *Proc. 20th*

EPS Conf. on Contr.Fusion and Plasma Phys., Lisbon, July 26-30, 1993,. Contrib. Papers, Part II, p.523, European Physical Society (1993).

10. V. V. VIKHREV, O. Z. ZABAIDULLIN, "Modeling of the Enhanced Rate of Magnetic Field Propagation Along the Anode ," *AIP Conference Proceedings* #**299,** Dense Z-pinches 3rd Int. Conf., London, April 1993, p.165, Eds. Malcolm Haines and Andrew Knight, AIP Press, New York (1994).

11. H. K. MOFFAT, *Magnetic Field Generation in Electrically Conducting Fluids*, Cambridge U. Press, Cambridge (1978).

12. S. I. VAINSHTEIN, YA. B. ZELDOVICH, A. A. RUZMAIKIN, *Turbulent Dynamo in Astrophysics* (in Russian), Nauka, Moscow (1980).

13. I. F. KVARTSKHAVA, K. N. KERVALIDZE, YU. S. GVALADZE, G. G. ZUKAKISHVILI, "Space-Periodical Plasma Structures Formed in a Fast High-Current Discharge,*"* *Nucl. Fusion*, **5**, 181 (1965).

14. S. I. SYROVATSKY, A. G. FRANK, A. Z. KHODZHAEV, "Development of the Current Layer During Plasma Motion in Magnetic Field with Zero Point," *Pis'ma Zh. Eksp. Teor. Fiz. (JETP Lett.)*, **15**, 138 (1972).

15. A. SESTERO, B. V. ROBOUCH, S. PODDA, "Suggested Relaxation of Plasma Focus Discharge to Helical Force-Free Configurations", *Plasma Phys*., **22**, 1039 (1980).

16. R. DEUTSCH, W. GRAUF, H. HEROLD, H. SCHMIDT, "Self-Organization Phenomena in the Plasma Focus," *Plasma Phys*., **25,** 833 (1983).

17. *AIP Conference Proceedings* #**299,** Dense Z-pinches 3rd Int. Conf., London, April 1993, Eds. Malcolm Haines and Andrew Knight, AIP Press, New York (1994).

FIGURE CAPTIONS

Figure 1. Motion picture of the magnetic field front (and electric current sheath) in a spheromak-producing plasma focus discharge (1, cathode; 2, insulator; 3, anode).

Figure 2. The progression of input energy transformations in a spheromak-producing plasma focus discharge.

Figure 3. Experiment Scheme: 1, 30 kV rectifier circuit; 2, Ballast resistor; 3, Cable-line pulse generator (15 ns, 15 kV); 4, High pressured, coax, broadband laser switcher; 5, Manometer; 6, Pressured nitrogen cylinder; 7, Ruby laser λ = 6943 A; 8, Objective lens; 9, Oscilloscope; 10, Broadband electrical divider; 11, Photocamera shutter's power supply; 12, Electron-Optical Converter; 13, 100% reflecting mirror; 14, see 8; 15, see 7; 16, Deflexing buffer; 17, Signal timing system; 18, Circuit of discharger ignition; 19, see 9; 20, Coax photo-element; 21, see 8; 22, 50% reflecting mirror; 23, Flat-parallel glass plate; 24, see 22; 25, Optical filters; 26, Photo-camera; 27, see 13; 28, see 23; 29, see 22; 30, Iris; 31, see 13; 32, see 8; 33, Vacuum chamber (cathode); 34, Insulator; 35, Mushroom-like anode; 36, Discharge capacity; 37, Vacuum power switcher.

Fig. 4. Time dependence of the discharge electric current (squares) and voltage (triangles) in the SLMC-producing discharges.

Fig. 5.1. Visible light photograph, Δt = -250 ns, taken using an electronic optical converter with a 15-ns exposure. The photographic angle is 45 degrees below the system axis. Space scale 1:1.82.

Fig. 5.2. Visible light photograph, Δt = +150 ns (all else the same of Fig.5.1). Space scale 1:1.82.

Fig. 5.3. Visible light photograph, Δt = +320 ns (all else the same of Fig.5.1). Space scale 1:1.82.

Fig. 6. Schematic drawing of a single-loop electric current corresponding to large-scale filamentation of the current driven by the magnetic field of a spheromak (shown at the bottoom is the mushroom-shaped anode, seized by the filaments of the current driven by the residual magnetic field).

Figs. 7.1 - 7.15 (space scale 1:1) are frames of a motion picture of the evolution of SLMC formation, taken with the help of the ruby-laser-based interferometer (2-ns pulse duration; pulse direction perpendicular to the system axis). The system axis location is indicated.

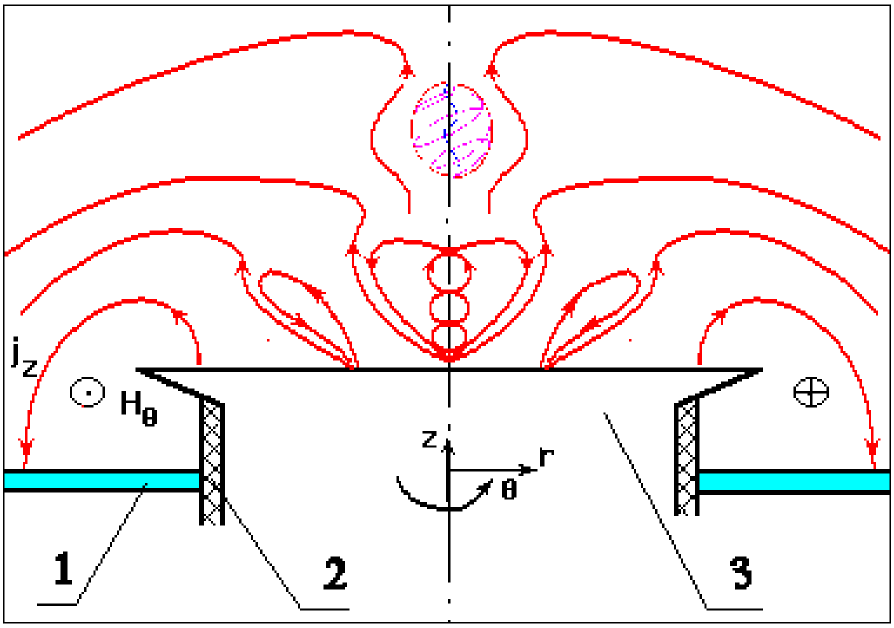


Figure 1. Motion picture of the magnetic field front (and electric current sheath) in a spheromak-producing plasma focus discharge (1, cathode; 2, insulator; 3, anode).

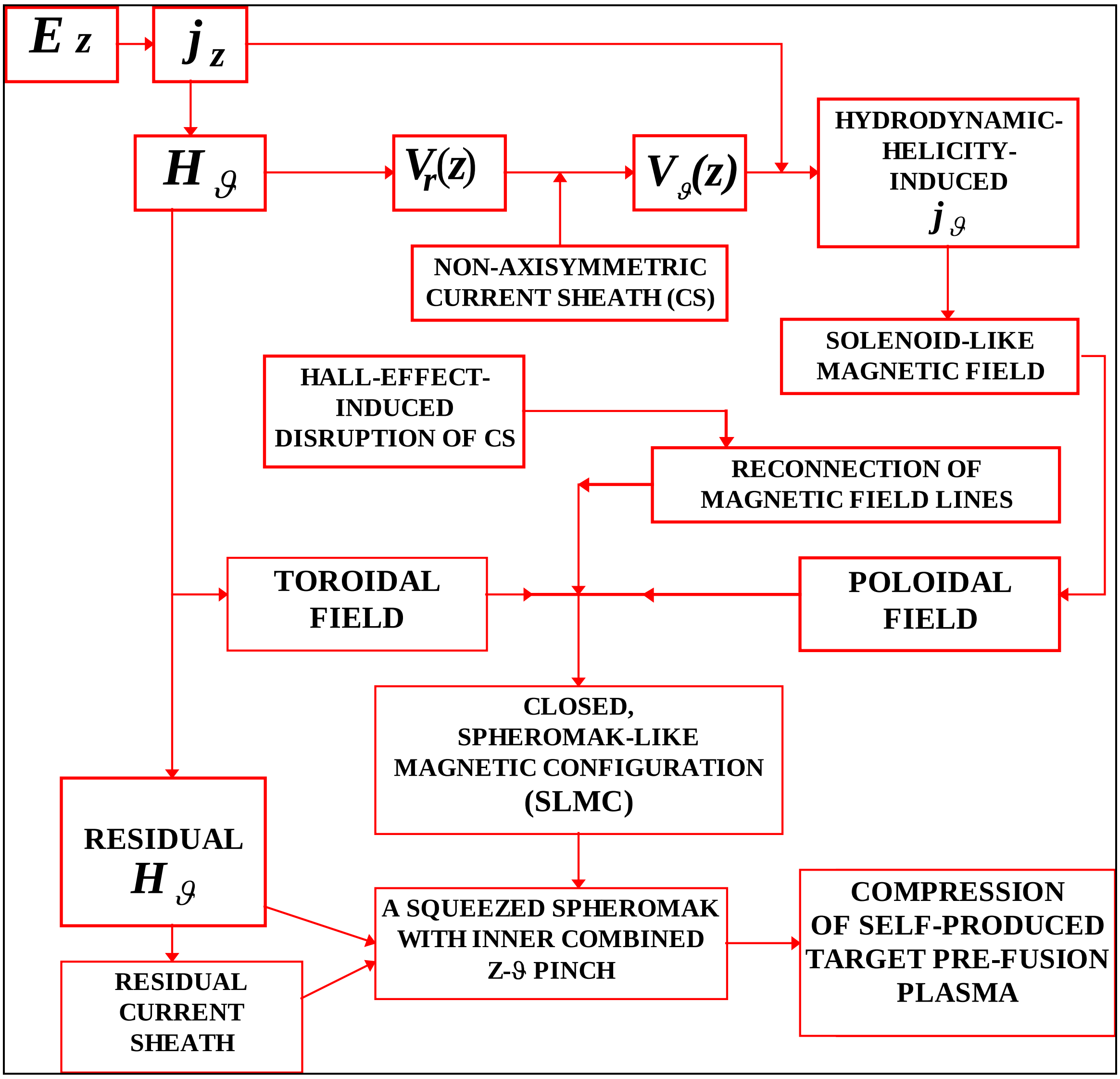


Figure 2. The progression of input energy transformations in a spheromak-producing plasma focus discharge.

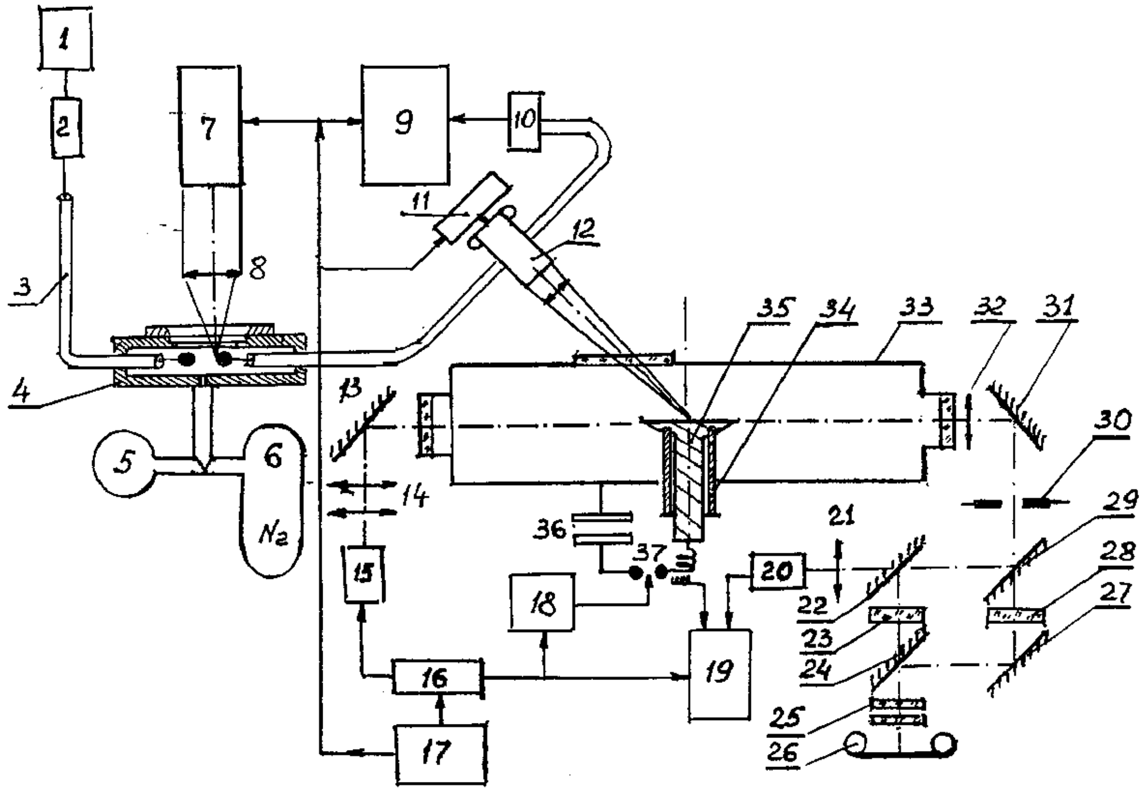


Figure 3. Experiment Scheme: 1, 30 kV rectifier circuit; 2, Ballast resistor; 3, Cable-line pulse generator (15 ns, 15 kV); 4, High pressured, coax, broadband laser switcher; 5, Manometer; 6, Pressured nitrogen cylinder; 7, Ruby laser λ = 6943 A; 8, Objective lens; 9, Oscilloscope; 10, Broadband electrical divider; 11, Photocamera shutter's power supply; 12, Electron-Optical Converter; 13, 100% reflecting mirror; 14, see 8; 15, see 7; 16, Deflexing buffer; 17, Signal timing system; 18, Circuit of discharger ignition; 19, see 9; 20, Coax photo-element; 21, see 8; 22, 50% reflecting mirror; 23, Flat-parallel glass plate; 24, see 22; 25, Optical filters; 26, Photo-camera; 27, see 13; 28, see 23; 29, see 22; 30, Iris; 31, see 13; 32, see 8; 33, Vacuum chamber (cathode); 34, Insulator; 35, Mushroom-like anode; 36, Discharge capacity; 37, Vacuum power switcher.

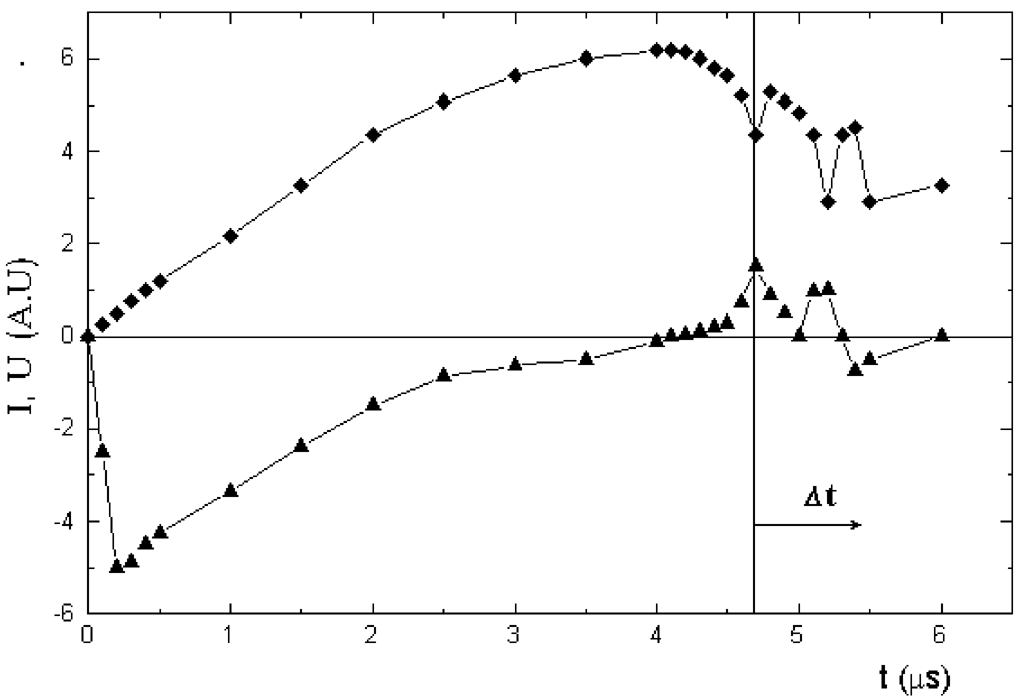


Fig. 4. Time dependence of the discharge electric current (squares) and voltage (triangles) in the SLMC-producing discharges.

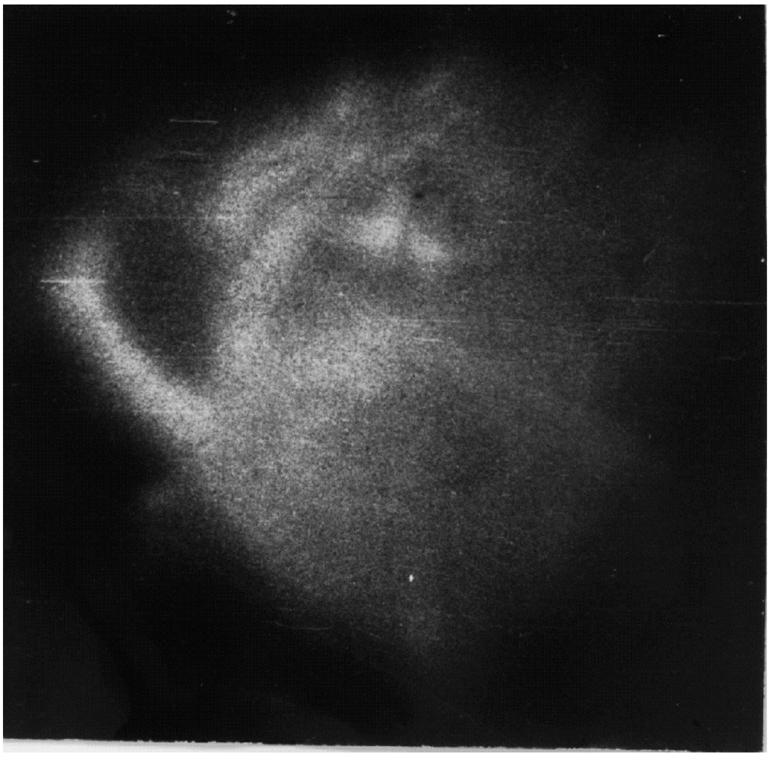


Fig. 5.1. Visible light photograph, Δt = -250 ns, taken using an electronic optical converter with a 15-ns exposure. The photographic angle is 45 degrees below the system axis. Space scale 1:1.82.

Fig. 5.2. Visible light photograph, Δt = +150 ns (all else the same of Fig.5.1). Space scale 1:1.82.

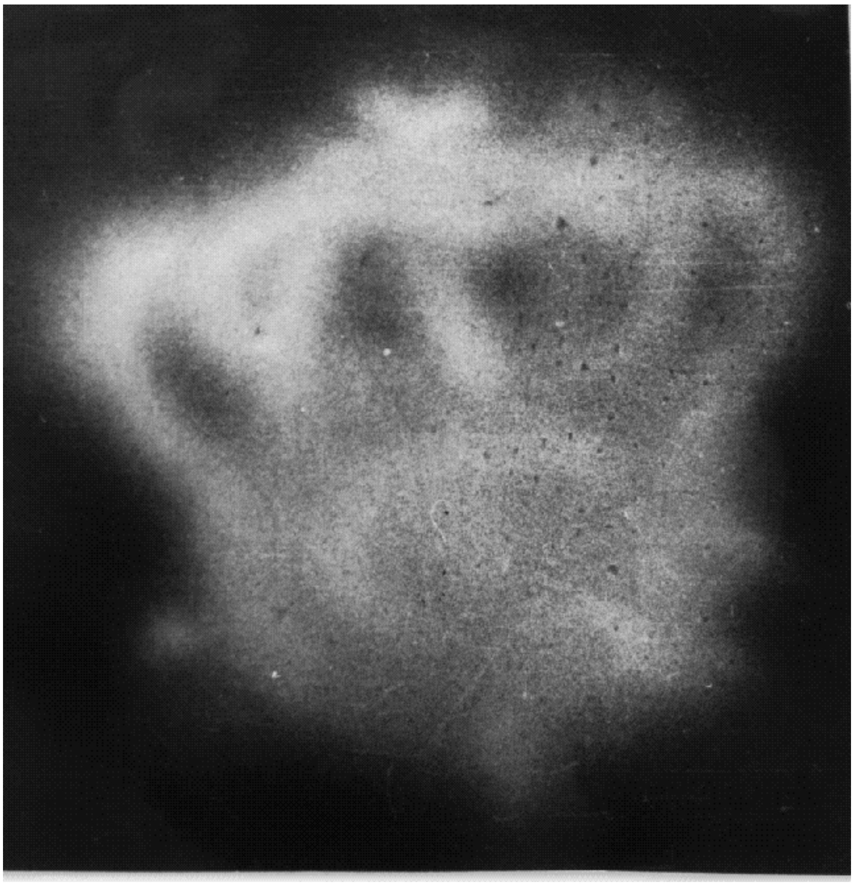


Fig. 5.3. Visible light photograph, Δt = +320 ns (all else the same of Fig.5.1). Space scale 1:1.82.

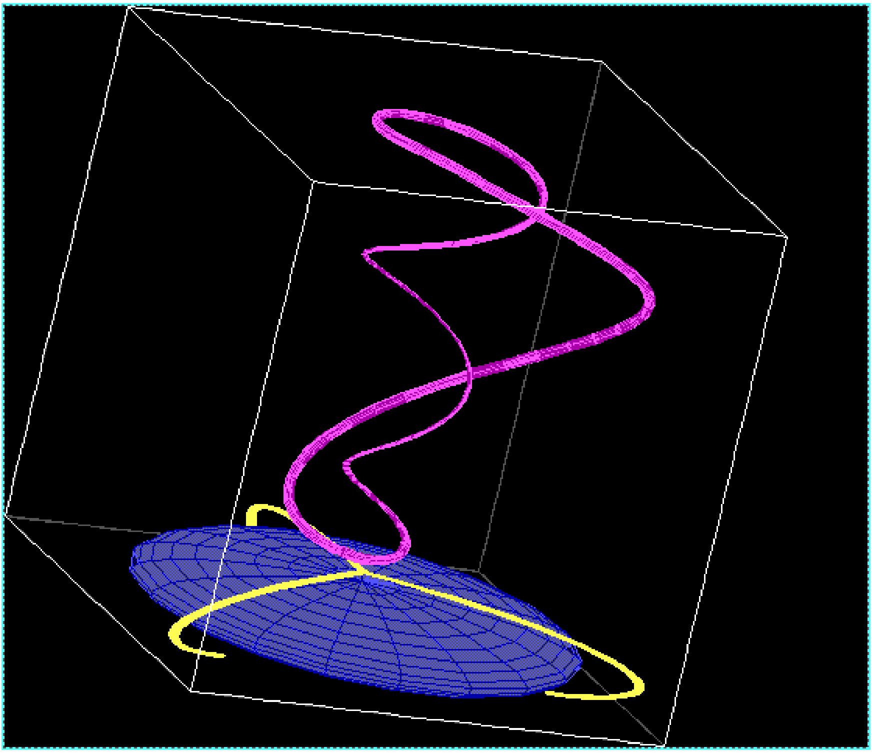
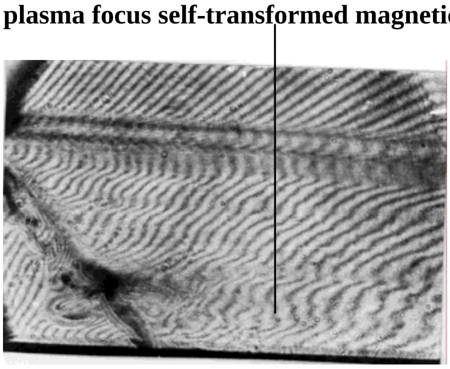
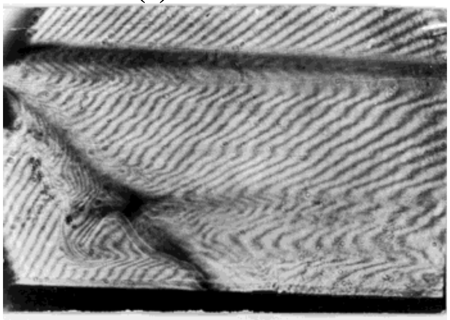


Fig. 6. Schematic drawing of a single-loop electric current corresponding to large-scale filamentation of the current driven by the magnetic field of a spheromak (shown at the bottom is the mushroom-shaped anode, seized by the filaments of the current driven by the residual magnetic field).

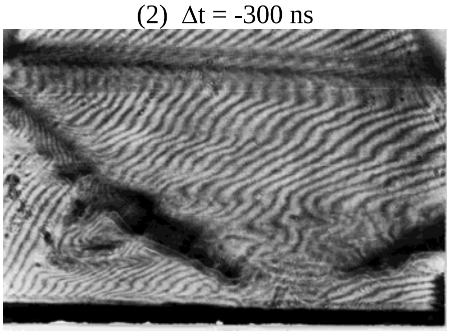
Kukushkin A.B., Rantsev-Kartinov V.A., Terentiev A.R., Formation of a spheromak-like magnetic configuration by a plasma focus self-transformed magnetic field // Fusion Technology, 1997, vol. 32, pp. 83-93.



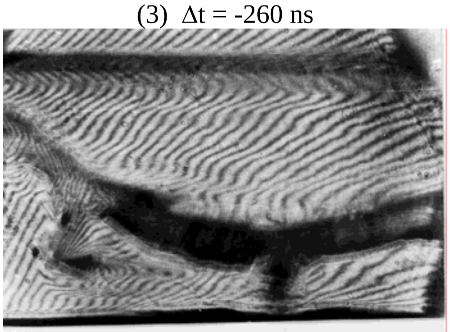
(1) Δt = -360 ns



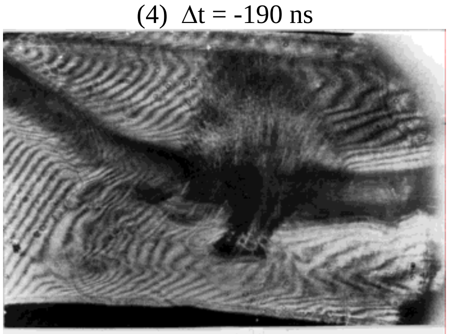
(2) Δt = -300 ns



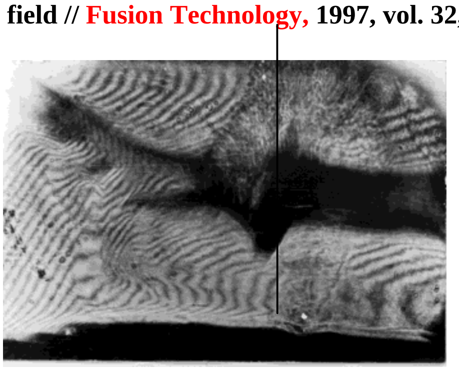
(3) Δt = -260 ns



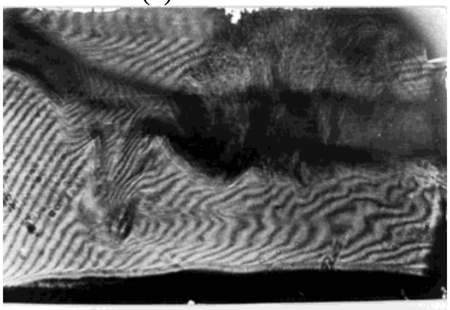
(4) Δt = -190 ns



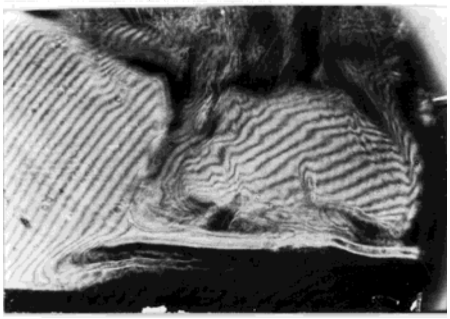
(5) Δt = +200 ns



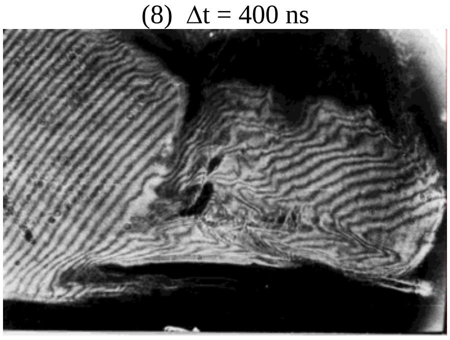
(6) Δt = 290 ns



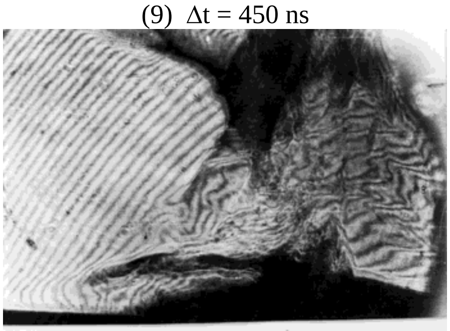
(7) Δt = 360 ns



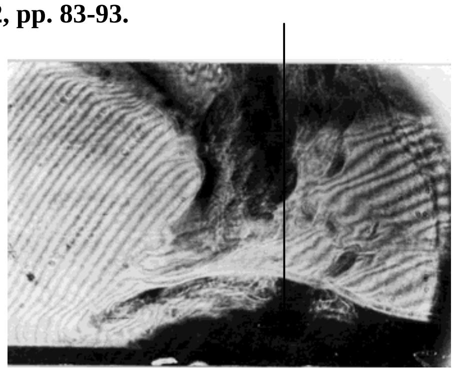
(8) Δt = 400 ns



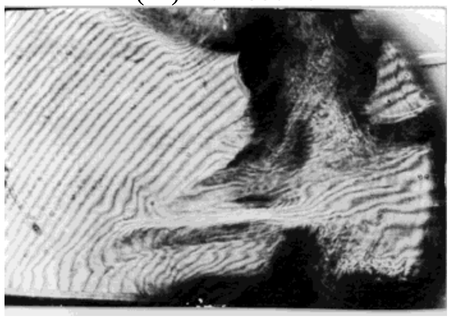
(9) Δt = 450 ns



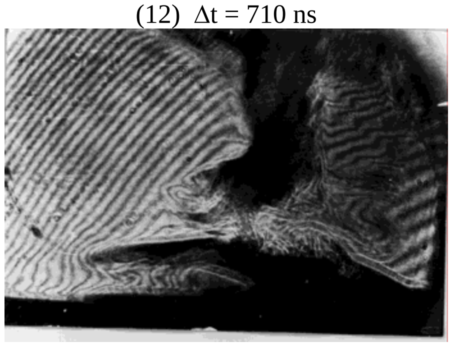
(10) Δt = 510 ns



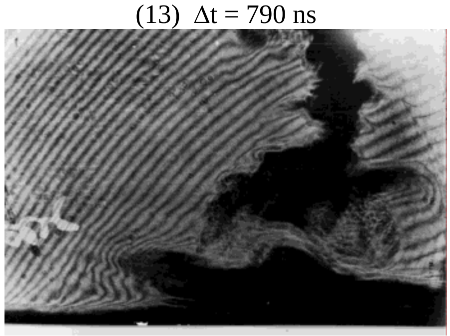
(11) Δt = 550 ns



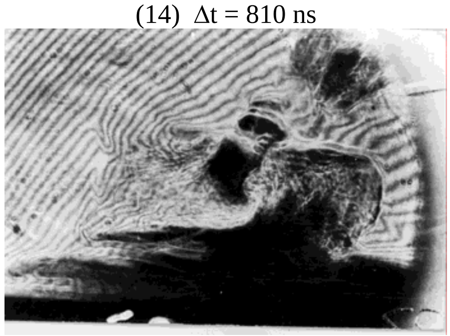
(12) Δt = 710 ns



(13) Δt = 790 ns



(14) Δt = 810 ns



(15) Δt = 850 ns

Figs. 7.1 - 7.15 (space scale 1:1) are frames of a motion picture of the evolution of SLMC formation, taken with the help of the ruby-laser-based interferometer (2-ns pulse duration; pulse direction perpendicular to the system axis). The system axis location is indicated.

Short biographies

Alexander B. Kukushkin (Ph.D., Plasma Physics and Chemistry, Moscow Physics Engineering Institute, 1982). Graduated from Moscow Physics Engineering Institute (theoretical physics, 1978). He is working for the Plasma Theory Division in the Institute for Nuclear Fusion of the Russian Research Center "Kurchatov Institute". Major topics of his research activity are as follows: quantum theory of radiation and radiative-collisional processes in plasmas with highly charged ions, including the processes in the presence of a strong laser field; laser diagnostics of thermonuclear plasmas (tokamaks, mirrors) and relativistic electron beams; radiative transfer in resonance atomic lines and lidar sounding of optically thick artificial clouds in space and upper atmosphere; nonlocal heat transport by electromagnetic waves (ECR, plasma waves) in tokamak plasmas; 3D two-fluid MHD in Plasma Foci and Dense Z-pinches.

Valentin A. Rantsev-Kartinov (PhD, Plasma Physics and Chemistry, RRC "Kurchatov Institute", 1996). Graduated from Moscow Physics Engineering Institute (experimental plasma physics, 1963). He is working for the Institute of Nuclear Fusion of the Russian Research Centre "Kurchatov Institute". He has carried out a series of plasma diagnostic experiments at various facilities: namely, plasma dynamics in plasma accelerators and continuous flow pinches; Stark effect diagnostics of turbulent electric fields in the Z-pinch and tokamak T-10; laser scattering in Z-pinch plasmas; designs of and experiments on the high-resolution X-ray line spectroscopy in tokamak T-10 and Plasma Focus plasmas; plasma dynamics in a highly radiating Dense Plasma Focus; impurity transport phenomena in tokamak T-10 plasma.

Arkady R. Terentiev (Ph.D., Plasma Physics and Chemistry, RRC "Kurchatov Institute, 1988). Graduated from Moscow Institute for Physics and Technology (experimental nuclear physics, 1975). He was working for the Institute for Nuclear Fusion of the Russian Research Centre "Kurchatov Institute" (former Plasma Physics Branch of the I.V.Kurchatov Institute of Atomic Energy) during 1975 - 1994. His interests were focused at a research and applications of the complex diagnostic methods in experiments on plasma accelerators, non-cylindrical Z-pinches and Plasma Foci. Special accent has been made to prove experimentally the Hall effect domination in the process of plasma acceleration in the above systems.