ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

Ball Lightning as Self-Organization Phenomenon

B.B.Kadomtsev

(Received - Jan. 31, 1995)

NIFS-337 Feb. 1995

RESEARCH REPORT
NIFS Series

This report was prepared as a preprint of work performed as a collaboration research of the National Institute for Fusion Science (NIFS) of Japan. This document is intended for information only and for future publication in a journal after some rearrangements of its contents.

Inquiries about copyright and reproduction should be addressed to the Research Information Center, National Institute for Fusion Science, Nagoya 464-01, Japan.

NAGOYA, JAPAN

Ball Lightning as Self-Organization Phenomenon

B. B. Kadomtsev

National Institute for Fusion Science, Nagoya 464-01, Japan
Permanent address : RRC Kurchatov Institute, Moscow 123192, Russia

Abstract

The Ball lightning formation is considered as a process of self-organization in a cold dust plasma with electrical-chemical active dust particles. Such particles in their chemical reactions can generate electric and magnetic fields which can be responsible for the resilience property of the gas bubble. Two types of plasma ball formation are possible : electrostatic and magnetostatic ones. Their properties are discussed qualitativly.

Keywords : ball lightning, dust plasma, magnetic reconnection, spheromacs.

1 Introduction

Ball lightning is a rare and unusual natural phenomenon. It was observed many times over so that we can consider it as a real fact. Ball lightning looks like a luminous sphere with a volume of one to several liters. It can exist many seconds. Sometimes its life is finished by an explosion. Observers estimate the energy of ball lightning at the order of a few kilojoules, with a large spread from event to event.

Ball lightning floats in air, so that its mass density is not very much different from the air density. It means that its temperature is not higher than air temperature and its total mass is of the order of a few grammes. The energy release in the form of a small-scale explosion is accompanied sometimes by an electric discharge akin to a tiny flash of lightning. Namely on this reason it was called a ball lightning.

We can assume that the energy carried by ball lightning is of chemical origin. For instance, the energy of water vapour condensation is about 2kJ per gramme, and the energy of explosives is about 4kJ per gramme. The most striking feature of ball lightning is its stable spherical shape, which is retained almost rigidly even in the presence of external perturbations. This feature looks like the result of a kind of surface tension that forces the conservation of the spherical shape with a minimum surface area. To understand the physics of ball lightning we have to discuss its misterious features.

We will proceed in this way step by step with the main attention to the ball elasticity. Our starting idea is that the ball lightning matter is a dust plasma with dust particles chemically active ones. We assume that the corresponding chemical reactions can generate electric charges and electric currents in such a plasma. Therefore electric and magnetic fields can be generated and the generation of these fields looks like some kind of selforganization.

We shall discuss the mechanisms of fields generation and the corresponding properties of an gas cloud with the electric and magnetic fields.

2 Gas battery phenomenology

To generate electric and magnetic fields by chemical reactions we need something similar to the usual Galvanic battery. But in our case this is not a solid-state but a gas battary. In the absence of fields it is completly symmetical one. Hence we have to accept that such a gas is unstable in respect to small initial perturbations of the charge and current densities. We shall consider this instability with the help of pure phenomenological approach.

Let us start with the passive cold plasma. We can assume that in such a plasma there is no free electrons but only heavy positively and negatively charged ions are present. Such ions can be aggregated in some complexes together with the water molecules. But this is not so important for us.

The electric properties of such gas can be described by a very simple relation $j = \sigma_0 E$ between the current density j and electric field E. The factor σ_0 here is the plasma electrical conductivity. We can plot this relation by a very simple linear dependence in Fig. 1.

Any initial perturbation of the charge density ρ_0 or the magnetic field B_0 of the plane-wave type decay according to laws :

$$\rho = \rho_0 \exp(-4\pi\sigma_0 t) \; ; \; B = B_0 \exp(-e^2 k^2 t/4\pi\sigma_0) \tag{1}$$

where k^2 is the square of the wave number.

We have used here the Gaussian units. In (1) expressions σ_0 is positive une. But if the plasma is chemically active the possibility for negative values of conductivity is not exluded. Of course at large value of electric field the plasma conductivity has to be positive again because an external field produces the positive work in this case. But at small E values electric conductivity could be negative one giving rize to possibility for small perturbations to be build up. Thus the $j(E)$ characteristics of active plasma could have the positive values of the derivative dj/dE at high values of E and negative ones at low values of E.

There are two types of possibilities for such kind of characteristics (Fig. 2a, b). The first of them, Fig. 2a, can be called $N-$type of characteristics and the second one, Fig. 2b, is called $S-$type of characteristics. We shall see that both of them can lead to a self-organization but of slightly different types.

It is clear from Fig. 2ab, that in both cases the point $E = 0, j = 0$ is unstable one because $\sigma < 0$ there and according to (1) relations both electric and magnetic field perturbations increase with time.

Now we see that in the case of $N-$type characteristics, Fig. 2a, the current density $j = 0$ at $E = E_0$ value. The absence of current means the possibility for the steady state with the nonzero value of electric field. Such a state can be called the electrostatic self-organized state. As for the case of the $S-$type characteristics, Fig. 2b, the statationary current $j = j_0$ can be maintained here even in the absence of electric field E. This current is produced by some driving force of the chemical nature . Such a state can be called the magnetostatic self-organized steady state.

These two possibilities correspond to the different plasmas with the different dust particle compositions. They have to be considered separately one by one. The physics mechanisms for the characteristics of Fig. 2a and Fig. 2b will be considered later. As for macroscopic gas behavior it can be considered without detailed analysis of the physics reason for such characteristics. We start with the electrostatic self-organization.

3 Electrostatic field self-organization.

Electrostatic field self-organization for the case of $N-$type characteristics was discussed by author in [1]. According to Fig. 2a any initial perturbation of the electric charge and electric field is unstable due to the negative value of the electrical conductivity. These small perturbations increase up to the level when nonlinear effects start to play role.

Let the initial charge density perturbation looks like Fig. 2, a, b and the corresponding electric field perturbation looks like Fig. 3c. These perturbations increase in time but only up to level $E = E_0$. According to Fig. 2a the ohmic power jE starts to be positive at electric field values larger than E_0, so that the corresponding electric field patterns decay in time. It means that the initial perturbation of Fig. 3 will rise very quickly up to the level of an electric bubble formation (Fig. 4). Inside this bubble the electric field is equal to $E = E_0$ and it is equal to zero outside this ball. To maintain $E = E_0$ relation the definite positive electric charge density has to be provided:

$$\rho = \frac{1}{4\pi} div \bar{E} = \frac{1}{4\pi}\frac{1}{r^2}\frac{d}{dr} r^2 \bar{E_0} = \frac{E_0}{2\pi r}. \tag{2}$$

The total positive charge inside the ball is equal to $q_0 = r_0^2 E_0$. Exactly the same but of negative sign value of the charge has to be maintained at the ball boundary surface.

If to take into account the diffusion of ions-current carriers then the r_0 boundary has to propagate in the radial direction with some velocity v_0 [1]. Thus the bubble of Fig. 4 will expand in time trying to cover all the active plasma volume. If we assume that the homogeneous plasma is present only inside some spherical volume of radius $r = R_0$ while the initial perturbation is placed at its center then the pattern of Fig. 4a structure is extended over the all volume of the active dust plasma : we have an electrostatically self-organized ball with $E = E_0$ inside and $E = 0$ outside the active volume.

The radial electric field $E = E_0$ inside the ball attracts the negative charges at its surface so that the gas is compessed inside the ball up to the value $\Delta p = E_0^2/8\pi$. As we see something like a surface tension appears : the role of surface tension value is played by the $R_0 E_0^2/16\pi$ expression.

The effective surface tension restores the spherical shape of ball at any external perturbation of this shape. We can estimate the characteristic time of the restoring process by a simple relation $\tau \cong R_0/v_E$. Here v_E is the electrostatic analogue of the well known Alfven velocity : $v_E = E_0/(4\pi m n_0)^{1/2}$. Here n_0 is the air molucle number density and m is the average mass of air molecules. For a reasonable value of the spherical shape restoring time of the order of 1 sec the value of $E_0 = 1esu = 300\, Volts/cm$ is sufficient (the air mass density $mn_0 = 10^{-3} gcm^{-3}$ when the ball radius $R_0 = 10cm$. The energy of the electric field E_0 in the volume of the order of several liters is of the order of $10^{-5} joules$.

For the active matter to maintain an electric field a driving force has to be present. But if the electric field $E = E_0$ exists in plasma an Ohmic current $\sigma_0 E_0$ has to flow inside the matter, where σ_0 is the differential conductivity at the point $E = E_0$ of Fig. 2a : $\sigma_0 = (dj/dE)_{E_0}$. This current leads to energy disipation with a rate

$$\dot{\varepsilon} = -8\pi\sigma_0\varepsilon, \text{ where } \varepsilon = VE_0^2/8\pi. \tag{3}$$

Here V is the total plasma volume. If the ball plasma consists of negatively and positively charged ions at room temperature (the ball's luminosity is assumed to be produced by the chemical luminiscence rather than by thermal), its conductivity can be estimated at $\sigma_0 = e^2 n/n_0 m\sigma_a C_s$, with n the plasma density, m the ion mass, σ_a the atomic collision cross section, and C_s the speed of sound. At $m = 5 \cdot 10^{-23} g$, $\sigma_a = 10^{-15} cm^2$, $C_s = 3 \cdot 10^4 cm/\sec$ the value of σ_0 can be estimated as being of the order of $10^{14} n/n_0 \sec^{-1}$. If the plasma density is of the order $10^{13} cm^{-3}$ and n_0 of the order of $10^{19} cm^{-3}$, the rate of energy decay $\dot{\varepsilon}$ is of the order of $-10^8\varepsilon$. This is about $1kW$ at the $E_0 \cong 1esu$ and the ball volume of the order of several liters. Thus, for an initial energy capacity of the order of several kilojoules the electric field energy dissipation yields a lifetime of the order of several seconds. If the plasma density is below $10^{13} cm^{-1}$, the lifetime of ball lightning with electrostatic self-organization is greater than this value.

4 Magnetic field self-organization

Now let us consider $S-$type characteristics of Fig 2b. In this case the shortest wave-length perturbations grow with the higher rate. They reach a saturation at the current density $j = j_0$ when no external Ohmic power supply is needed. We can imagine that such a saturated state looks like a set of many small-size current loops (Fig. 5a). Each elementary current loop generates a magnetic field $B \approx l j_0 / c$, where l is the linear size of the current loop (in esu units). It can be considered as a small magnet with some momentum M. If l is not extremely small, the magnetic forces can influence the plasma's behavior. By magnetic forces tiny loops attract each other and then can merge leading to the net magnetic momentum increase (Fig. 5b).

When a big current loop is produced by such merging it can swallow small loops (Fig. 6ab). At first it orients the small loops along the magnetic field lines, then it attracts the small loops toward the median plane and there it stretches out the small loop. Finally it swallowes a small loop by reconnecting its magnetic field and joining it to the main current loop.

The magnetic energy of this current loop decreases when its size increases. Thus the current loop has a tendency to be stretched out (Fig.7a). But the narrow current filament is unstable in respect to the kink-type MHD-perturbations. This instability leads to a toroidal magnetic field being generated, so that a tiny spheromak [3] is created (Fig. 7b).

If several spheromaks are formed inside the active plasma they will again attract each other by their poloidal magnetic fields. Then they can merge by the magnetic reconnection mechanism [4]. If two spheromaks have different helicities they annihilate each other [4] transforming their magnetic energy into heat. But if they have the same helicity they can produce, by merging, a spheromak of somewhat larger size.

Thus we can say, that a mechanism exists which tends to combine all the elementary spheromaks into a single large spheromak encompassing the entire plasma. Similar configurations have been investigated by Koloc [5], who, however, attempted to explain the entire ball lightning energy as being solely of magnetic origin. It seems more realistic to believe that the magnetic energy is needed only for the ball lightning elasticity, while the main energy stored is of chemical origin.

It is easy to see that at a given current density $j \approx j_0$ the spheromak configuration tends to resotore its shape in spite of any external perturbation. For instance, if to imagine a pertuarbation which occurs at the frozen magnetic fluxes, then the toroidal flux Φ_T and the poloidal magnetic flux Φ_p can be considered as to be constant and the total magnetic energy $\varepsilon = \varepsilon_T + \varepsilon_p$ can be represented in the form

$$\varepsilon = \varepsilon_T + \varepsilon_p \approx const\{\Phi_T^2 R a^{-2} + \Phi_p^2 R^{-1}\}. \tag{4}$$

Here a is minor radius and R is major radius of the toroidal configuration. At a given plasma volume $V \approx 2\pi^2 a^2 R$ and $\Phi_T \sim \Phi_p$ the minimum of the (4) expression is reached at $a \approx R$, i.e. for the case of compact spheromak configuration. This configuration as a whole is maintained against the expansion by the air pressure, so that the pressure inside the spheromak is lowes than the external pressure by the amount of $\Delta p = -B^2/8\pi$. Thus, we can assume that the spheromak of almost spherical shape is produced by the magnetic fields. At the value of the Alfven velocity $v_A = B(4\pi n_0 m)^{-1/2}$ of the order of $10 cm/\sec$ the ball's stability is assured. It means that a value of the order $B \approx 1 Gauss$ is sufficient for the spheromak elasticity. At such field values the elementary spheromak coalescence can be influenced but not eliminated completely by the Earth's magnetic field.

For a volume of several liters the magnetic-field energy is again of the order of $10^{-5} joule$. Here, too, the plasma resistivity can lead to energy dissipation. The rate of dissipation can be estimated as $\varepsilon = -\varepsilon \cdot c^2/4\pi\sigma_0 R^2$ where σ_0 is the Ohmic resistivity and R is the major radius of spheromak. Repeating our estimations we obtain $\varepsilon \cong 10^{-5} n_0/nkW$ at $B \approx 1 Gauss$ for $V \approx 1$ liter. At $n \approx 10^{14} cm^{-3}$ and $n_0 = 10^{19} cm^{-3}$ we obtain $\varepsilon \approx 1kW$. If the amount of chemical energy stored in the lightning is of the order of several kilojoules the lifetime of such a plasma ball is of the order of several seconds.

Thus, we can say, very roughly, that the electrostatic self-organization preveils at $n < 10^{14} cm^{-3}$ whereas the magnetostatic self-organization is preferred at $n > 10^{14} cm^{-3}$.

5 Active dust plasma

Now we can discuss the problem of what kind of chemical reaction and the dust particle structure can lead to the electric current generation. Let us consider Fig. 2 once more. As we see at large values of electric field the $j(E)$ dependence looks like $j = \sigma_0(E - E_0)$ in the case of Fig. 2a and like $j = \sigma_0(E + j_0/\sigma_0)$ dependence in the case of Fig. 2b. In other words the driving force is directed opposite to the external field direction is the first case and along the external field direction in the second case. By analogy with magnetics we can say that the Fig. 2a case is similar to diamagnetism and the Fig. 2b case is similar to paramagnetism. It is evident that these two cases correspond to completely different plasmas with different chemical reactions and different dust particle compositions.

Let us start with Fig. 2a characteristics. The chemical reactions in this case have to generate the electric current which is directed oppositely to the external electric field. I shall discuss here only one of the different possibilities for such reactions.

To generate the current the corresponding chemical reactions have to be accompanied by the electric charge exchange between reactants as in an usual electric battary. In our case the cold plasma plays the role of an electrolyte and some dust particles can manifest themselves as electrodes. Let us consider the concrete example of reactions shown in Fig. 8. We assume that the cold plasma consists of heavy ion complexes, C_+ and C_-. When such complex ions collide with the chemically active dust particle D the chemical energy can be released so that the complex ion can be fragmentated in several, say Z, smaller-size ions of the same charge sign. Of course, the charge $(Z-1)e$ is delivered to the dust particle. But in average, if the ions of both signes, C_+ and C_-, are present the average charge of D particle can be zero.

The ion current density to the dust particle can be estimated as $j_c = env_{th}$, where n is the ion density and v_{th} is the thermal velocity of the ion complexes. The rejected current density is $Z-$times larger.

If to apply the external field E the ions of both kind start to drift and the Ohmic current is generated with the density $j_0 = \sigma_0 E$. If both sign ions, positive and negative, have similar structures then their drift velocity u is equal to $u = j_0/2en$. Ions rejecting from the dust particle provide the opposite current density near the dust particle being equal to $-j_0 Z$. This current density is produced in the vicinity of the dust particle, i.e. in the volume $V \sim r_0^3$ where r_0 is the dust particle radius. We can assume that the small ions can be recombined and transformed into large complex ions outside this volume. Thus, the total current density can be estimated as

$$j = \sigma_0(1 - ZV_D N_D)E. \tag{5}$$

Here V_D is the volume near the dust particle where opposite sign currents are generated and N_D is the number of dust particles per unit volume. We see that the effective electric conductivity can be negative one at a very high dust density, when $V_D N_D \sim 1$. So that the electrical-chemical reactions of such type can produce negative electric conductivity. At large values of E the drift velocity increases and the dust particles start to screen each other so that the mechanism for negative j value is weaken.

Now let us consider the $S-$type characteristics of the Fig. 2b. It has a similarity with the paramagnetics so that it is reasonable to consider nonisotropic dust particles. In principle such particles can have a very complicated fractual structure [6], but we consider here much more simple particles. One of such particles is shown in Fig. 9a. It has a chemical anisotropy so that being immersed into the cold plasma it becomes positively charged at one ends and negatively charged at the opposite end. Such a particle collects the ions of the cold plasma. If both ends are coupled each other with " a wire " all the structure together with plasma looks like a tiny short-circuit battary. If to apply an external electric field E the dust particle is oriented in such a way that it can produce an additional current along the E field. Let the particle looks like two spheres connected by tiny wire (Fig. 9b). If each ball has the charge q it will collect the current $I_S = 4\pi q\sigma_0$. Thus, if the particle density is equal to N_D and each particle has the length l the total current density is equal to

$$j = \sigma_0 E + 4\pi q l N_D. \tag{6}$$

As we see an additional driving force appears which can lead to a $S-$type characteristics. If the anisotropic particles continue to be oriented they can provide the current density $j = 4\pi\sigma_0 q l N_D$ even in the absence of the averaged electric field E. Thus, anisotropic dust particles can simulate

$S-$type characteristics of Fig. 2b which looks like a " superconductor " simulation.

6 General discussion

As we have shown the resiliency property of the ball lightning can be provided by the electric or magnetic field when the ball lightning is " a chunk " of cold dust plasma. The dust particles have to be chemically active to generate the fields inside the plasma cloud. In principle, both types of configurations, magnetic and electric ones, can exist. But they differ each other quite substantially. In both cases the fields $E \sim B \sim 1$ (in Gaussion units) are needed. But to maintain $B \sim 1Gauss$ is not an easy matter. If the ball volume is of the order of one liter the current density $j \approx 10mA/cm^2$ is needed. This is a quite high value of current density at the atmosphere pressure of gas. Therefore, it seems that the electrostatic selforganization is much more realistic one. If the electric conductivity of plasma is very low the life-time of a selforganized state can be long enough even in the case when the chemical energy storage is not very high. In this case the electric field E_0 can be maintained at a very low power of chemical reaction.

If the electrical conductivity decreases then both the chemical reaction power and the Ohmic power decrease. In this case the configuration restoration time becomes larger so that the hydrodynamic instabilities can destroy this configuration. The destroyment is more violent near the plasma boundary where the cold active plasma is in contact with the air. The delute plasma in vicinity of surface can " boil up " producting small " droplets " of charged plasma chunks which can be ejected outwards.

The electrostatically organized ball lightning has many other interesting features which were discussed qualitatively in the author's paper [1]. Of course, it would be reasonable to check all this qualitative deliberations with the help of direct numerical simulations.

Acknowledgement

I would like to express my sincere appreciation to National Institute for Fusion Science where this work was completed.

References

[1] B. B. Kadomtsev, Comments Plasma Phys. Contr. Fus. 5 (1990) 277.

[2] B. B. Kadomtsev, J. Moscow Phys. Soc. 1 (1991) 335.

[3] M. N. Rosenbluth and M. N. Bussac, Nuclear Fusion 19 (1979) 489.

[4] Y. Ono, paper D2-C11, sixth Int. Toki Conference, Toki, Japan (1994).

[5] P. M. Koloc: " The plasma configuration and ball lightning " in " Science of Ball Lightning ", ed. Y. N. Ohsaki (Singapore: World Scentific 1989).

[6] B. M. Smirnov, Usp. Fis. Nauk 160 (1990) 45.

Figure Captions

Fig. 1. Electric field-current density characteristics in the case of passive plasma.

Fig. 2. Two possible nonlinear characteristics with $dj/dE < 0$ at small values of E : (a)- $N-$type characteristics, (b)- $S-$type characteristics.

Fig. 3. Initial perturbation (a) of the electric charge density ρ with profile (b) produces the initial electric field perturbation of the form (c).

Fig. 4. Saturated state in the case of an electrostatic self-organization looks like a sphere filled by the constant radial electric field $E = E_0$.

Fig. 5. Tiny current rings being attracted each other (a). After two loops merging a new larger size loop appears which has the double value of momentum.

Fig. 6. A big current ring with the large magnetic momentum M_0 makes the small magnet M to be oriented along the magnetic field lines (a). Then it attracts the small loop toward the median plane and stretches it there to merge with the main current loop.

Fig. 7. The big current loop is stretched out by the magnetic forces (a). Later on a kink-type instability develops and the current loop is transformed into a small spheromak.

Fig. 8. The chemically active dust particle D is immersed in the plasma electrolyte which consists of heavy complex ions with charges $\pm e$. When the heavy ion interacts with the particle D the charged " droplets " are produced and ejected in plasma so that Z small-size ions appear instead of a single heavy ion.

Fig. 9. Anisotropic particle looks like a tiny short-circuit battary with anode A and cathode C immersed into plasma which plays the role of an electrolyte (a). Such a dust particle, being oriented

by the external electric field E, collects the ions and drives an additional electric current along E.

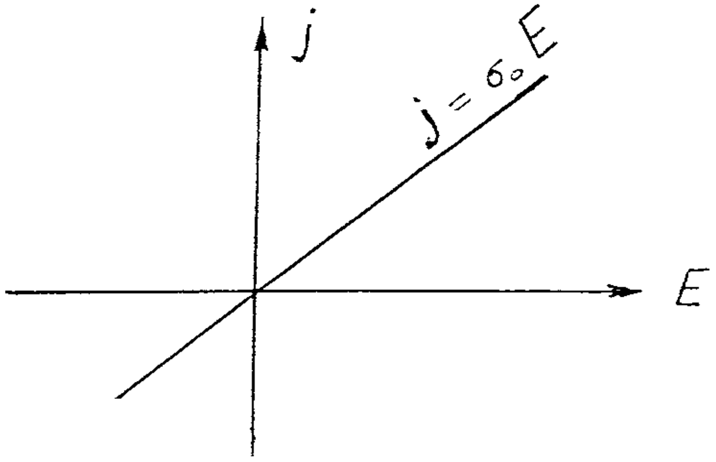

FIG.1.

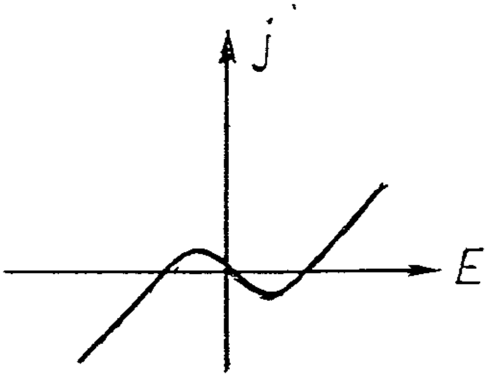

FIG.2.(a)

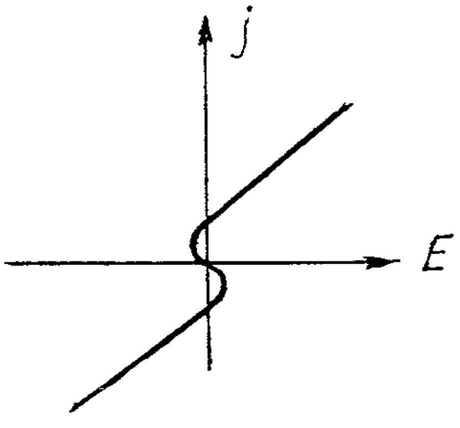

FIG.2.(b)

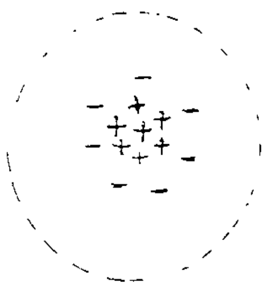

FIG. 3. (a)

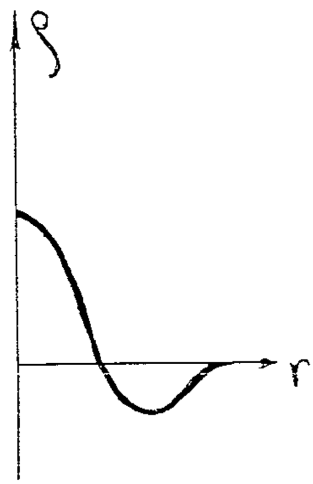

FIG. 3. (b)

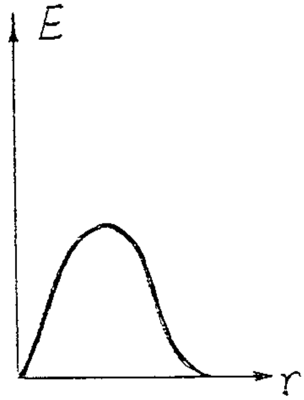

FIG. 3. (c)

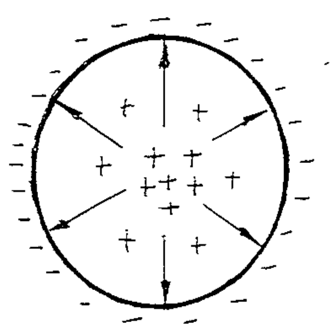

FIG. 4. (a)

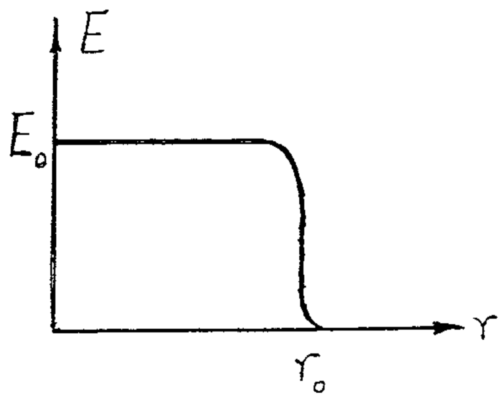

FIG. 4. (b)

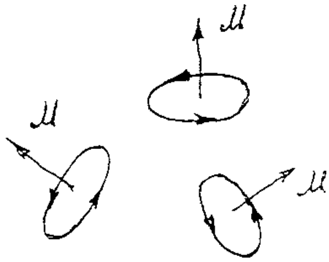

FIG.5.(a)

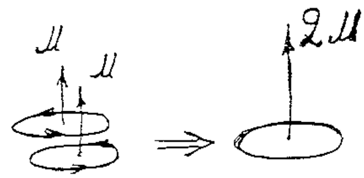

FIG.5.(b)

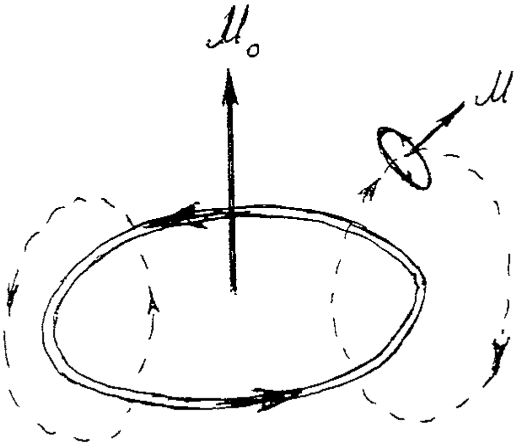

FIG.6.(a)

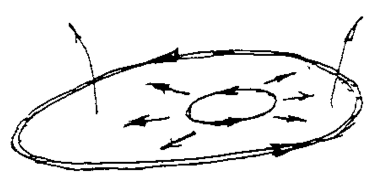

FIG.6.(b)

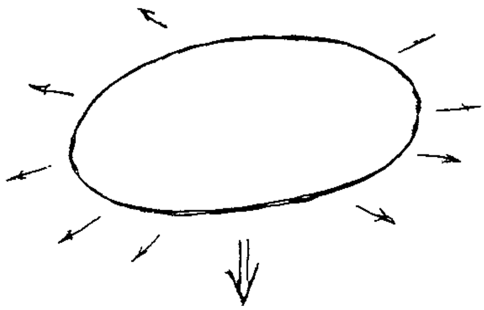

FIG. 7. (a)

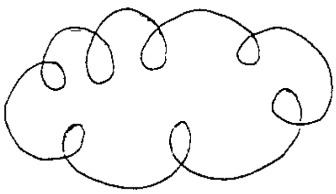

FIG. 7. (b)

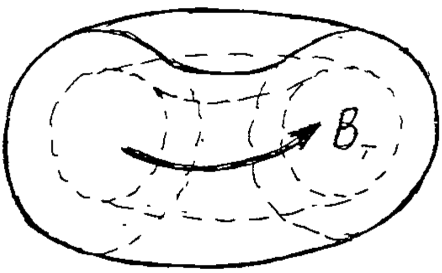

FIG. 7. (c)

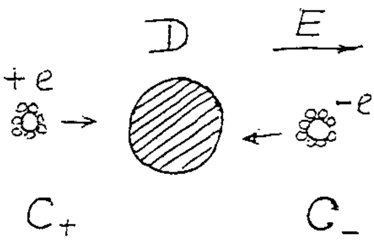

FIG. 8. (a)

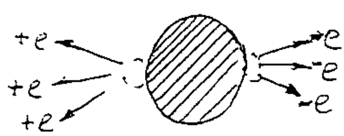

FIG. 8. (b)

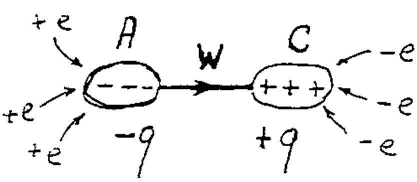

FIG. 9. (a)

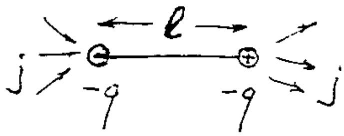

FIG. 9. (b)

Recent Issues of NIFS Series

NIFS-295 S. Bazdenkov, T. Sato, R. Horiuchi, K. Watanabe,
Magnetic Mirror Effect as a Trigger of Collisionless Magnetic Reconnection, Aug. 1994

NIFS-296 K. Itoh, M. Yagi, S.-I. Itoh, A. Fukuyama, H. Sanuki, M. Azumi,
Anomalous Transport Theory for Toroidal Helical Plasmas,
Aug. 1994 (IAEA-CN-60/D-III-3)

NIFS-297 J. Yamamoto, O. Motojima, T. Mito, K. Takahata, N. Yanagi, S. Yamada, H. Chikaraishi, S. Imagawa, A. Iwamoto, H. Kaneko, A. Nishimura, S. Satoh, T. Satow, H. Tamura, S. Yamaguchi, K. Yamazaki, M. Fujiwara, A. Iiyoshi and LHD group,
New Evaluation Method of Superconductor Characteristics for Realizing the Large Helical Device; Aug. 1994 (IAEA-CN-60/F-P-3)

NIFS-298 A. Komori, N. Ohyabu, T. Watanabe, H. Suzuki, A. Sagara, N. Noda, K. Akaishi, N. Inoue, Y. Kubota, O Motojima, M. Fujiwara and A. Iiyoshi,
Local Island Divertor Concept for LHD; Aug. 1994 (IAEA-CN-60/F-P-4)

NIFS-299 K. Toi, T. Morisaki, S. Sakakibara, A. Ejiri, H. Yamada, S. Morita, K. Tanaka, N. Nakajima, S. Okamura, H. Iguchi, K. Ida, K. Tsumori, S. Ohdachi, K. Nishimura, K. Matsuoka, J. Xu, I. Yamada, T. Minami, K. Narihara, R. Akiyama, A. Ando, H. Arimoto, A. Fujisawa, M. Fujiwara, H. Idei, O. Kaneko, K. Kawahata, A. Komori, S. Kubo, R. Kumazawa, T. Ozaki, A. Sagara, C. Takahashi, Y. Takita and T. Watari,
Impact of Rotational-Transform Profile Control on Plasma Confinement and Stability in CHS; Aug. 1994 (IAEA-CN-60/A6/C-P-3)

NIFS-300 H. Sugama and W. Horton,
Dynamical Model of Pressure-Gradient-Driven Turbulence and Shear Flow Generation in L-H Transition; Aug. 1994 (IAEA/CN-60/D-P-I-11)

NIFS-301 Y. Hamada, A. Nishizawa, Y. Kawasumi, K.N. Sato, H. Sakakita, R. Liang, K. Kawahata, A. Ejiri, K. Narihara, K. Sato, T. Seki, K. Toi, K. Itoh, H. Iguchi, A. Fujisawa, K. Adachi, S. Hidekuma, S. Hirokura, K. Ida, M. Kojima, J. Koog, R. Kumazawa, H. Kuramoto, T. Minami, I. Negi, S. Ohdachi, M. Sasao, T. Tsuzuki, J. Xu, I. Yamada, T. Watari,
Study of Turbulence and Plasma Potential in JIPP T-IIU Tokamak;
Aug. 1994 (IAEA/CN-60/A-2-III-5)

NIFS-302 K. Nishimura, R. Kumazawa, T. Mutoh, T. Watari, T. Seki, A. Ando, S. Masuda, F. Shinpo, S. Murakami, S. Okamura, H. Yamada, K. Matsuoka, S. Morita, T. Ozaki, K. Ida, H. Iguchi, I. Yamada, A. Ejiri, H. Idei, S. Muto, K. Tanaka, J. Xu, R. Akiyama, H. Arimoto, M. Isobe, M. Iwase, O. Kaneko, S. Kubo, T. Kawamoto, A. Lazaros, T. Morisaki, S. Sakakibara, Y. Takita, C. Takahashi and K. Tsumori,
ICRF Heating in CHS; Sep. 1994 (IAEA-CN-60/A-6-I-4)

NIFS-303 S. Okamura, K. Matsuoka, K. Nishimura, K. Tsumori, R. Akiyama, S. Sakakibara, H. Yamada, S. Morita, T. Morisaki, N. Nakajima, K. Tanaka, J. Xu, K. Ida, H. Iguchi, A. Lazaros, T. Ozaki, H. Arimoto, A. Ejiri, M. Fujiwara, H. Idei, A. Iiyoshi, O, Kaneko, K. Kawahata, T. Kawamoto, S. Kubo, T. Kuroda, O. Motojima, V.D. Pustovitov, A. Sagara, C. Takahashi, K. Toi and I. Yamada,
High Beta Experiments in CHS; Sep. 1994 (IAEA-CN-60/A-2-IV-3)

NIFS-304 K. Ida, H. Idei, H. Sanuki, K. Itoh, J. Xu, S. Hidekuma, K. Kondo, A. Sahara, H. Zushi, S.-I. Itoh, A. Fukuyama, K. Adati, R. Akiyama, S. Bessho, A. Ejiri, A. Fujisawa, M. Fujiwara, Y. Hamada, S. Hirokura, H. Iguchi, O. Kaneko, K. Kawahata, Y. Kawasumi, M. Kojima, S. Kubo, H. Kuramoto, A. Lazaros, R. Liang, K. Matsuoka, T. Minami, T. Mizuuchi, T. Morisaki, S. Morita, K. Nagasaki, K. Narihara, K. Nishimura, A. Nishizawa, T. Obiki, H. Okada, S. Okamura, T. Ozaki, S. Sakakibara, H. Sakakita, A. Sagara, F. Sano, M. Sasao, K. Sato, K.N. Sato, T. Saeki, S. Sudo, C. Takahashi, K. Tanaka, K. Tsumori, H.Yamada, I. Yamada, Y. Takita, T. Tuzuki, K. Toi and T. Watari,
Control of Radial Electric Field in Torus Plasma; Sep. 1994 (IAEA-CN-60/A-2-IV-2)

NIFS-305 T. Hayashi, T. Sato, N. Nakajima, K. Ichiguchi, P. Merkel, J. Nührenberg, U. Schwenn, H. Gardner, A. Bhattacharjee and C.C.Hegna,
Behavior of Magnetic Islands in 3D MHD Equilibria of Helical Devices; Sep. 1994 (IAEA-CN-60/D-2-II-4)

NIFS-306 S. Murakami, M. Okamoto, N. Nakajima, K.Y. Watanabe, T. Watari, T. Mutoh, R. Kumazawa and T. Seki,
Monte Carlo Simulation for ICRF Heating in Heliotron/Torsatrons; Sep. 1994 (IAEA-CN-60/D-P-I-14)

NIFS-307 Y. Takeiri, A. Ando, O. Kaneko, Y. Oka, K. Tsumori, R. Akiyama, E. Asano, T. Kawamoto, T. Kuroda, M. Tanaka and H. Kawakami,
Development of an Intense Negative Hydrogen Ion Source with a Wide-Range of External Magnetic Filter Field; Sep. 1994

NIFS-308 T. Hayashi, T. Sato, H.J. Gardner and J.D. Meiss,
Evolution of Magnetic Islands in a Heliac; Sep. 1994

NIFS-309 H. Amo, T. Sato and A. Kageyama,
Intermittent Energy Bursts and Recurrent Topological Change of a Twisting Magnetic Flux Tube; Sep.1994

NIFS-310 T. Yamagishi and H. Sanuki,
Effect of Anomalous Plasma Transport on Radial Electric Field in Torsatron/Heliotron; Sep. 1994

NIFS-311 K. Watanabe, T. Sato and Y. Nakayama,
Current-profile Flattening and Hot Core Shift due to the Nonlinear Development of Resistive Kink Mode; Oct. 1994

NIFS-312 M. Salimullah, B. Dasgupta, K. Watanabe and T. Sato,
Modification and Damping of Alfvén Waves in a Magnetized Dusty Plasma; Oct. 1994

NIFS-313 K. Ida, Y. Miura, S -I. Itoh, J.V. Hofmann, A. Fukuyama, S. Hidekuma, H. Sanuki, H. Idei, H. Yamada, H. Iguchi, K. Itoh,
Physical Mechanism Determining the Radial Electric Field and its Radial Structure in a Toroidal Plasma; Oct. 1994

NIFS-314 Shao-ping Zhu, R. Horiuchi, T. Sato and The Complexity Simulation Group,
Non-Taylor Magnetohydrodynamic Self-Organization; Oct. 1994

NIFS-315 M. Tanaka,
Collisionless Magnetic Reconnection Associated with Coalescence of Flux Bundles; Nov. 1994

NIFS-316 M. Tanaka,
Macro-EM Particle Simulation Method and A Study of Collisionless Magnetic Reconnection; Nov. 1994

NIFS-317 A. Fujisawa, H. Iguchi, M. Sasao and Y. Hamada,
Second Order Focusing Property of 210° Cylindrical Energy Analyzer; Nov. 1994

NIFS-318 T. Sato and Complexity Simulation Group,
Complexity in Plasma - A Grand View of Self- Organization; Nov. 1994

NIFS-319 Y. Todo, T. Sato, K. Watanabe, T.H. Watanabe and R. Horiuchi,
MHD-Vlasov Simulation of the Toroidal Alfvén Eigenmode; Nov. 1994

NIFS-320 A. Kageyama, T. Sato and The Complexity Simulation Group,
Computer Simulation of a Magnetohydrodynamic Dynamo II: Nov. 1994

NIFS-321 A. Bhattacharjee, T. Hayashi, C.C.Hegna, N. Nakajima and T. Sato,
Theory of Pressure-induced Islands and Self-healing in Three-dimensional Toroidal Magnetohydrodynamic Equilibria; Nov. 1994

NIFS-322 A. Iiyoshi, K. Yamazaki and the LHD Group,
Recent Studies of the Large Helical Device; Nov. 1994

NIFS-323 A. Iiyoshi and K. Yamazaki,
The Next Large Helical Devices; Nov. 1994

NIFS-324 V.D. Pustovitov
Quasisymmetry Equations for Conventional Stellarators; Nov. 1994

NIFS-325 A. Taniike, M. Sasao, Y. Hamada, J. Fujita, M. Wada,
The Energy Broadening Resulting from Electron Stripping Process of a Low Energy Au⁻ Beam; Dec. 1994

NIFS-326 I. Viniar and S. Sudo,
New Pellet Production and Acceleration Technologies for High Speed Pellet Injection System "HIPEL" in Large Helical Device; Dec. 1994

NIFS-327 Y. Hamada, A. Nishizawa, Y. Kawasumi, K. Kawahata, K. Itoh, A. Ejiri, K. Toi, K. Narihara, K. Sato, T. Seki, H. Iguchi, A. Fujisawa, K. Adachi, S. Hidekuma, S. Hirokura, K. Ida, M. Kojima, J. Koong, R. Kumazawa, H. Kuramoto, R. Liang, T. Minami, H. Sakakita, M. Sasao, K.N. Sato, T. Tsuzuki, J. Xu, I. Yamada, T. Watari,
Fast Potential Change in Sawteeth in JIPP T-IIU Tokamak Plasmas; Dec. 1994

NIFS-328 V.D. Pustovitov,
Effect of Satellite Helical Harmonics on the Stellarator Configuration; Dec. 1994

NIFS-329 K. Itoh, S-I. Itoh and A. Fukuyama,
A Model of Sawtooth Based on the Transport Catastrophe; Dec. 1994

NIFS-330 K. Nagasaki, A. Ejiri,
Launching Conditions for Electron Cyclotron Heating in a Sheared Magnetic Field; Jan. 1995

NIFS-331 T.H. Watanabe, Y. Todo, R. Horiuchi, K. Watanabe, T. Sato,
An Advanced Electrostatic Particle Simulation Algorithm for Implicit Time Integration; Jan. 1995

NIFS-332 N. Bekki and T. Karakisawa,
Bifurcations from Periodic Solution in a Simplified Model of Two-dimensional Magnetoconvection; Jan. 1995

NIFS-333 K. Itoh, S.-I. Itoh, M. Yagi, A. Fukuyama,
Theory of Anomalous Transport in Reverse Field Pinch; Jan. 1995

NIFS-334 K. Nagasaki, A. Isayama and A. Ejiri
Application of Grating Polarizer to 106.4GHz ECH System on Heliotron-E; Jan. 1995

NIFS-335 H. Takamaru, T. Sato, R. Horiuchi, K. Watanabe and Complexity Simulation Group,
A Self-Consistent Open Boundary Model for Particle Simulation in Plasmas; Feb. 1995

NIFS-336 B.B. Kadomtsev,
Quantum Telegragh : is it possible?; Feb. 1995