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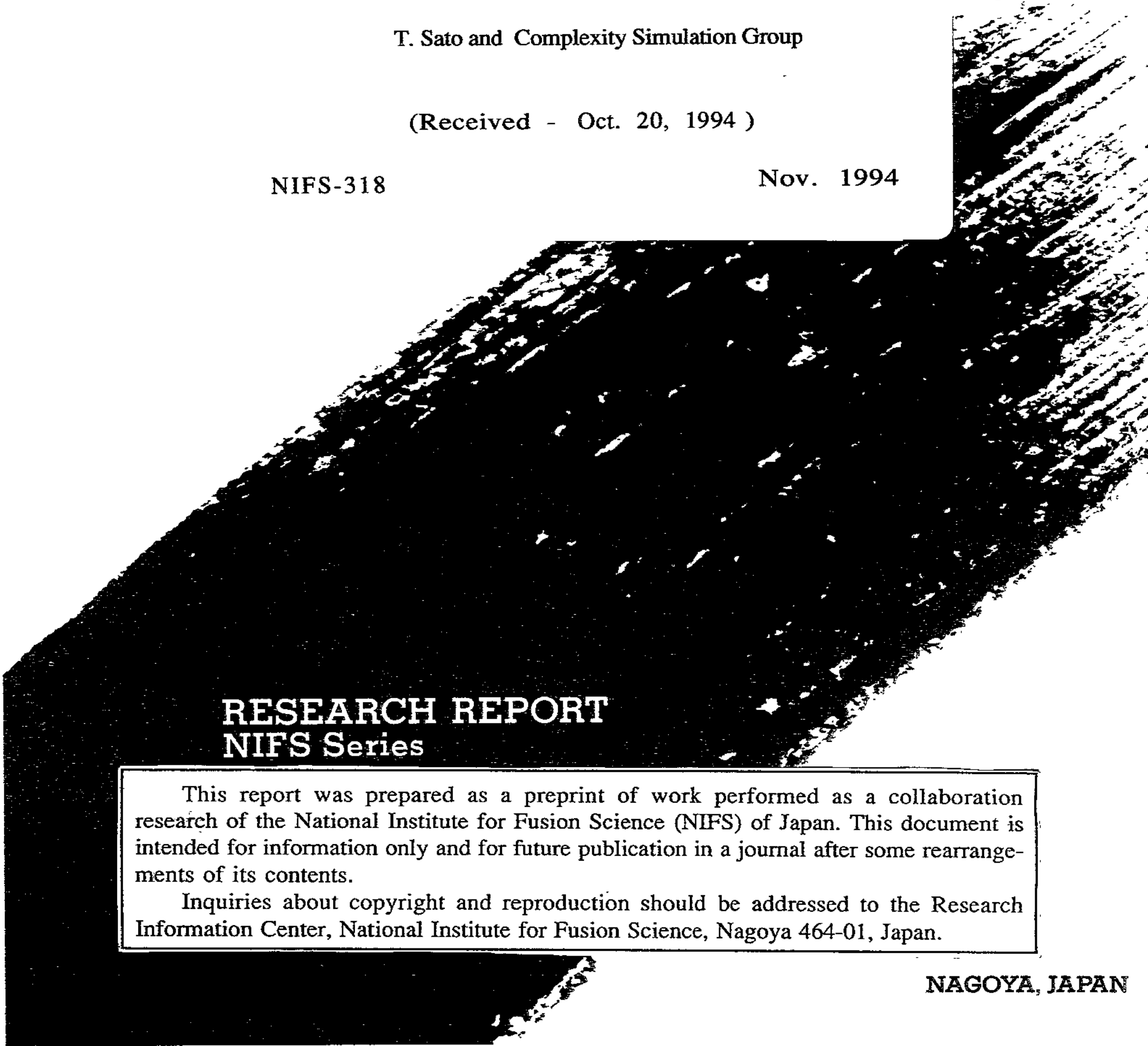

RESEARCH REPORT
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NAGOYA, JAPAN

COMPLEXITY IN PLASMA – A GRAND VIEW OF SELF-ORGANIZATION

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Abstract

The central theme of the Complexity is the inquest of the creation of ordered structure in nature. Extensive computer simulations on plasmas have revealed that self-organization is governed by the three key processes, i.e. energy pumping, entropy expulsion and nonlinearity. A system exhibits characteristically different self-organization, depending on whether the energy pumping is instantaneous or continuous, or whether the produced entropy is expulsed or reserved. The nonlinearity acts to bring a nonequilibrium state into a bifurcation, thus resulting in a new structure along with an anomalous entropy production.

Keywords : complexity, self-organization, intermittency, recurrence, energy pumping, entropy expulsion, nonlinearity, bifurcation, anomalous extropy production

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The way, i.e. *modus operandi*, of Modern Science is to reduce a system into its elements and to reveal the fundamental function of every element. The underlying philosophy is that the mechanism of a system is fully understood by assembling all the fundamental functions of the elements. The elementary particle physics is, in this sense, the extremity of Modern Science.

This Science has already obtained a rather high level of maturity. Then, one may ask, had all fundamental interactions of a system been revealed, then can one really predict what will happen in a system? The answer will be "no" in most cases. Even if a system is described by a complete set of fundamental equations, one cannot get a full comprehension of its dynamical behavior. This means something missing in the underlying philosophy.

Speaking in terms of mathematics, the very root of unpredictability lies in the nonlinearity. Since any system in nature can never be isolated in a strict sense, it inevitably suffers unpredictable, internal and external, fluctuations. Furthermore, it exchanges information, good or bad, with an external world. Because of the nonlinearity and the openness of the system, the behavior of the system becomes very complex and mathematically intractable.

The present-day supercomputer technology has vastly increased the possibility of handling a complex system and has given us a hope, at least technically, that the behavior of a complex system can be elucidated.

Science is directed toward a deeper and deeper stratum of nature by cutting off the mutual interactions among the linked strata. Consequently, we have already acquired an abundant knowledge on the fundamental laws governing the elementary processes in physics and chemistry. Based on the accumulated fundamental knowledges it is the time to turn our eyes from a lower to a higher stratum where the interactions with lower strata are never ignored. The interactions are, as a matter of course, so complicated and complex that the methodology of computer simulation may be the most viable one.

By thus revealing the complex behaviors for a variety of natural phenomena and making mutual comparisons of the revealed processes, a common and universal relationship that governs a complex system is sought for.

A new paradigm from reduction to integration is dawning. This is the Science of Complexity. As the vocabulary of Complexity, Nicolis and Prigogine [1] pick up the following: nonequilibrium, instability, bifurcation, symmetry-breaking, and long-range order. Crudely speaking, the first two terms, nonequilibrium and instability, describe the initial evolution of a complex system and the last three concepts, bifurcation, symmetry-breaking and long-range order, appear in the subsequent evolution. In short, the first ones are the cause and the last are the effect. The cause comes essentially from the nonequilibrium and the effect arises as a result of the nonlinearity of a system. Therefore, the Complexity may well be described by the two key concepts of a system, i.e., the far-from-equilibrium and the nonlinearity.

Fusion plasmas and space plasmas are always non-uniform, thus they are in a nonequilibrium state. To release the free energy, therefore, the system becomes unstable. Because of its nonlinearity the evolution becomes highly complex and results in bifurcation, symmetry-breaking and long-range order. In this sense, Plasma Physics is potentially a Physics of Complexity. Most of the fundamental laws are already established in the classical electrodynamics. Therefore, plasmas will be a good target for the study of Complexity.

Central Problem of Complexity – Self-Organization

Self-organization is a generic process which describes a spontaneous formation of an ordered structure. It may not be an exaggeration to say that the central concern and problem of our universe is the creation of an ordered structure against the second law of the thermodynamics. It is a mystery how an orderliness is created in nature. Is there any universal law for creating the orderliness? This is the central problem of the Science of

Complexity.

Incidentally, Taylor's theory[2,3] has casted light on the concept of self-organization in a plasma. The theory is based on the conjecture of conservation of the magnetic helicity and the selective dissipation of the magnetic energy. Its strong attractiveness and impact have focused the plasma physicist's attention on the relationship of self-organization with the behavior of the helicity and magnetic energy[4-15]. The concept of self-organization forecasts a much broader concept than the Taylor's relaxation concept, however. In this article, self-organization is studied with a view to generalize the concept of self-organization.

Self-Organization by Instantaneous Energy Pumping

We start with a Taylor self-organization process which takes place in an instantaneously pumped-up system. Given initially a higher force-free energy state which is far beyond a minimum energy state, we solve its nonlinear evolution. We consider a rectangular box in which the side boundaries of the box is made of conductors and the axial boundaries are periodic. Fig. 1 shows a structural evolution of the magnetic field [15]. The final spiral structure is the self-organized one. The evolutions of the magnetic helicity and energy are given in Fig. 2. It is observed that the relaxation occurs in two steps for the magnetic energy but not for the magnetic helicity. The two-step relaxation reflects the fact that there was another force free state between the given initial state and the final minimum energy state.

We emphasize here that each stepwise relaxation occurs in about ten of the Alfven transit time τ_A, which is quite a fast process compared with the classical diffusion time (ten thousands of the Alfven transit time). During each relaxation process the magnetic energy is rapidly converted into the thermal energy (entropy). We here assume that the produced entropy is instantaneously expulsed from the system. The main process involved in this energy conversion is the ohmic process. However, the initial magnetic Reynolds number (normalized electrical conductivity) was 10^{-4} . Thus, we can conclude that some nonlinear process, which enormously enhances the conversion rate (thousand times in this case), must have happened. This is realized by the driven magnetic reconnection which is caused by strongly excited kink flows [16].

In this self-organization process one notices an important fact regarding the Taylor's conjecture. A careful examination of the helicity evolution in Fig. 2 exhibits that the helicity is never conserved in a strict sense, though the conservation has been firmly believed. On looking at the helicity curve in Fig. 2, one can readily recognize that the helicity dissipation exhibits a critical slowing-down in accordance with the stepwise relaxation of the magnetic energy. In the initial phase the magnetic helicity experiences a rather strong dissipation, which is the same as that of the magnetic energy. The dissipation rate of the helicity is slowed down critically at the first stepdown relaxation of the magnetic energy ($t \approx 23\tau_A$). The dissipation rate keeps an almost constant value for a while and then it experiences again a critical slowing-down at the second stepwise relaxation ($t \approx 46\tau_A$). Thereafter, the dissipation rate is slower but constant. The dissipation rate of the magnetic energy also becomes much slower than the initial one. These slow dissipation rates for both the magnetic energy and helicity indicate that the system has reached to a stable self-organized state. We note here that both the critical slowing-down of the magnetic helicity and the stepwise relaxation of the magnetic energy are explained by the driven reconnection process.

Intermittency in Self-Organization by Continuous Energy Pumping

One may consider that the example given in the above is a typical self-organization process in the sense that a system relaxes in a transient fashion into a steady minimum energy state starting from an initial non-minimum energy state. A question, then, arises as to how such an initial far-from-equilibrium state can be realized without suffering any instability on the way to it. The answer will be that the state is realized if the external pumping of energy into the system is reasonably fast action and the system cannot react upon the pumping. Namely, the pump-up time scale is shorter than the dynamic response time of the system. We call such a self-organization process as an instantaneously pumped self-organization.

In the instantaneously pumped self-organization process the system relaxes in a stepwise fashion but monotonously into a steady ordered structure. The process is a transient from the initial state to the minimum energy state. In nature, however, the energy pump in a local system from an external world is not always a fast process. It often happens that an energy gradually and continuously flows from an external world. In such a situation no Taylor type variational method would be applied. Generally, any mathematical methodology would not be able to predict what will happen in the system. The evolution would be strongly dependent on the nonlinearity of the system and also would be strongly influenced by the processes of information exchange between the system and the external world.

Based on the above consideration, we shall present a simulation result of a new self-organization process which is stimulated by an external energy reservoir that has an ability to supply a continuous energy flow. The thermal energy generated during the evolution is assumed to be instantaneously pumped out in the same way as in the previous example.

The simulation system is the same rectangular box as the previous simulation. Uniform straight field lines are applied in the axial direction. The axial boundaries are not periodic but are the suppliers of a continuous energy flow. Specifically, at the boundaries a circular motion is steadily applied in a limited region at both ends with the opposite polarity to each other, so that the magnetic field lines are kept on twisting[17]. This problem may find some application in the problem of solar flares[18–20].

We have accumulated sufficient simulation data where the field lines are twisted at both boundaries under various conditions, single-twisted flux tube, twin-twisted flux tubes, etc. Among them we exemplify the case where the twisting is given at two circular flux tubes because every case gives essentially the same behavior, i.e., a twin-twisted flux tube case. Fig. 3 illustrates the topological change of two bundles of the field lines starting from one axial boundary. The two bundles of straight field lines are twisted and squeezed toward the center in the initial phase. As the twisting proceeds, the stored tension energy of the twisted bundle of field lines is released in terms of a knot-of-tension type of instability (t=8). The instability develops in such a way that the kinked parts of the two flux tubes approach to each other (t=9). As a consequence, reconnection is driven to take place between the two flux tubes (t=10) and relaxes toward an interconnected structure (a local minimum energy state)(t=11). As the twisting continues, reconnection advances stepwise to an outer untwisted region (t=18) by intermittently generating knot-of-tension instability and alternating a tensioned (supersaturated) state with a relaxed state (local minimum state). As the twisting goes further, the flux tube linked with distant untwisted field lines reconnects with a companion twist-untwist flux tube to come back to the original straight topology (t=20). This is because the straight structure of the field lines is energetically lower than the linked structure between the twisted field lines and the distant untwisted ones, presumably the global minimum energy state. Thereafter a similar process to that of what we have observed is repeated. This indicates that the topological evolution exhibits a recurrence to a topology closer to the original one (global minimum energy state) and reproduces a similar behavior thereafter. Fig. 4 shows the temporal evolution of the kinetic energy converted from the twisted magnetic tension energy for a single-twisted flux tube case. One can see that the magnetic energy is converted into the kinetic energy in bursts ($1 \sim 2\tau_A$) in an intermittent fashion and exhibits a recurrence to the original topology after several intermittent bursts. The intermittency and the recurrence are the common features observed for the continuous pumping.

Energy Pumping and Entropy Expulsion

The above two examples have shown that the system manifests an essentially different evolution depending on the difference in the energy pumping process. When it is instantaneously pumped up to a far-from-equilibrium state, the system relaxes into the final global minimum energy state in a transient way and keeps its state in a steady way. In contrast, when it is in contact with a continuous energy supplier, the system repeats intermittently an energy burst and exhibits a recurrent behavior, changing the state from a supersaturated (tensioned) state to a local, or global, minimum energy state.

On top of the way of energy pumping there is another crucial element which would change the fate of the self-organization. In the present examples, we have assumed that the thermal energy produced during the relaxation process is instantaneously pumped out. Knowing that the produced thermal energy is the entropy which is the superfluous quantity for the created ordered structure, it is rather prudent to clarify the role of the entropy on the self-organization.

We present two different simulations. In the first we attempt to examine how seriously the maintenance of the produced entropy in the system influences upon the fate of the self-organization. For this purpose we take as an example the instantaneously pumped MHD self-organization which was previously presented. Without pumping out the produced thermal energy we solve the pressure dynamics self-consistently with the plasma motion and the magnetic field evolution[21]. The thermal conduction effect is discarded.

The simulation result has shown that the magnetic structure evolves in a very similar way to the previous case where the pressure is discarded. Nevertheless, two important new facts have been discovered. The first one is that the structure of the pressure exhibits a very similar structure to that of the magnetic field intensity. An example is shown in Fig. 5.

The other discovery is that the magnetohydrodynamic (MHD) self-organized state is not the force-free minimum energy state, but a force-balanced state, i.e., $\boldsymbol{J} \times \boldsymbol{B} = \nabla p$.

the current $\boldsymbol{J}$ consists of the perpendicular and parallel components. As the relaxation proceeds, the parallel (force-free) component decreases, while the perpendicular component increases inversely. They approach nearly to the same level in the self-organized state. This result indicates that unless some pumping out of the thermal energy or a fast perpendicular thermal conduction does exist, the Taylor relaxation does not occur. Instead, the system relaxes to a force-balanced, non-Taylor, minimum energy state.

Next, We shall attempt to look for what will happen when the produced entropy is filtered out. We take the ion-acoustic double layer for this purpose. What we have obtained is a remarkable and striking new self-organization phenomenon caused by filtering out the produced unnecessary entropy from the system. It is well known by particle simulation that weak ion acoustic double layers are generated in a one dimensional collisionless plasma where electrons have a shifted Maxwellian distribution and ions have a normal Maxwellian[22]. In the previous simulations, however, particles were regarded as periodic in one dimensional system. This periodic condition implies that the particles leaving from the downstream boundary enter into the system from the upstream boundary as they are and vice versa, no matter how seriously they are disturbed by the generation of ion acoustic double layers. In other words, the disturbed information, or disorderliness, is retained in the system.

A new particle simulation code is developed in which fresh particles continuously flows into the system from each boundary in place of dirty particles leaving the system[23]. We can thus filter out the superfluous information (entropy), when produced. The result is really striking. A giant double layer is generated. In the initial phase of the ion acoustic instability the normal ion acoustic double layers are generated. They disappear after a while, as we observed in the previous simulation. However, new ion acoustic double layers emerge at different positions. They again disappear after a while. Once again a double layer is generated. At this time, the double layer grows singly and the potential reaches to a surprisingly large amplitude (see, Fig. 6). Compared with the conventional ion acoustic double layer, the potential difference of which is of the order of one electron thermal energy, the potential amplitude of this giant double layer reaches to a surprisingly large level, say, larger than ten times of the thermal energy. This giant double layer has much longer lifetime than that of the normal weak ion acoustic double layer and exhibits a recurrent generation. In view of the fact that the drifting electron energy was only 0.36 of the electron thermal energy in this example, the obtained potential difference is really huge. This giant ion acoustic double layer can be an efficient electron accelerator.

The implication of this simulation is of incalculable value. If the system owns a proper filtering function of the superfluous disorderliness, then a well-organized structure can be realized and sustained for a longer period. Also, this example supports a recurrent behavior for a continuous energy flow as we observed for the continuously twisting magnetic flux.

Along with the first simulation of the MHD self-organization where the produced entropy is confined, the present simulation filtering out the produced entropy leads us to an assertion that the expulsion of the produced entropy plays a crucial role in the self organization.

Scenario of Self-Organization

We are now in a position to draw a somewhat integrated picture of the grand view of self-organization when a system is pumped up to a far-from-equilibrium state. The evolution exhibits a remarkably different feature depending on the way of energy pumping. When externally pumped up faster than its dynamical response time, the system relaxes in a transient fashion to a steady self-organized state. Upon a continuous supply of an external energy flow, on the other hand, the system exhibits a recurrence in the structure and energy state while repeating intermittent bursts.

It is also seen that whether a superfluous entropy or disorderliness can be pumped out or not, the evolution and the created structure are largely changed. When the entropy or a superfluous material is filtered out, a well-organized structure can be created. The pumping way of energy and the expulsing way of entropy are both closely related to the interrelation of the system with the external world. They are thus considered to be the crucial controlling external elements of the self-organization.

On top of these controlling elements there are several important internal natures that govern the self-organization. They are the instability, bifurcation (phase transition), anomalous dissipation, etc. When a system gains an energy, gradually or instantaneously, from an external world, beyond a threshold (marginal) point, an instability arises. When the instantaneously gained energy or the energy supplied from a continuous energy budget becomes far beyond the instability threshold, the instability develops sufficiently. The nonlinearity is enormously enlarged thereby and gives rise to a large deformation of the structure. The deformation progresses in such a way that the excessively deposited energy is released in the shortest (most effective) way. In order to release it in the shortest way an anomalous dissipation, or an anomalous entropy production, must take place in one way or another. Simultaneously, the structure (topology) must be drastically changed, namely, a bifurcation must take place.

In the magnetohydrodynamic self-organization, the driven magnetic reconnection plays these roles at once, namely, the anomalous magnetic energy conversion into the thermal energy and the topological change of the magnetic field. In a collisionless plasma with drifting electrons, the localized anomalous resistivity plays the roles of the current redistribution and the formation of an electrostatic potential structure.

These results and others have led us to an assertion that a natural system tends to boost up itself to a bifurcation (phase transition) point and give rise to an anomalously enhanced dissipation there, or an anomalous entropy production rate, when a far-from-equilibrium state is realized by whatever process it may be.

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Figure Captions

Fig. 1 A typical example of a magnetohydrodynamic (MHD) self-organization when the system is instantaneously pumped up to a high energy state (far-from-equilibrium). We choose a rectangular cylinder which is periodic in the axial direction and bounded by a conducting wall on the four sides. A small resistive MHD plasma is filled in it. Initially, an unstable, ideal MHD equilibrium state is instantaneously set up in the system. The six panels show the time evolution of one aspect of the magnetic structure. The brown color represents an isosurface of the axial magnetic field. The initial state consists of five straight flux tubes (t=0). Each straight flux tube suffers from a helical kink instability and is deformed by its nonlinear evolution (t=9). The further nonlinear evolution causes driven magnetic reconnection between neighboring flux tubes and the structure becomes complicated and disordered (t=12). Driven reconnection rapidly proceeds and creates a double-helix-like structure (t=15) which immediately relaxes to a single helix of three pitches (t=30). In the meantime, this three-pitch helix is transformed into a two-pitch helix by the second instability (t=60) which is the Taylor minimum energy state and no more deformation occurs.

Fig.2 Time evolutions of the magnetic energy (W), the magnetic helicity (K) and the ratio (W/K) for the same simulation shown in Fig. 1. One can notice that the magnetic energy experiences twice a stepwise relaxation. In contrast, the dissipation rate of the magnetic helicity shows a critical slowing-down in accordance with the stepwise enhancement of the magnetic energy dissipation. The three-pitch helix state shown in Fig. 1 represents an intermediate state between the first and second anomalies.

Fig. 3 An example of MHD simulation exhibiting an intermittency in self-organization when the system is in contact with a continuous energy supplier. A small resistive MHD plasma is filled in a rectangular cylinder in which initially the magnetic field is uniform and directed in the axial direction. We impose two pairs of circular motion with the same polarity on one axial boundary and the opposite polarity at the other boundary, whereby the magnetic field lines are twisted in the same direction. Each panel of the figure consists of a composite of a top (axial) view (upper) and a side view (lower) where the dotted lines represent the demarcation between the twist and untwist regions. When the field lines are twisted to a certain degree, a knot-of-tension instability takes place in such a way that the distortions of both twisted flux tubes approach to each other. (t=8,9). Reconnection is driven with each other (t=10) and the system relaxes to a local minimum energy state (t=11). A tension-relaxation evolution is intermittently repeated and reconnection advances stepwise to a distant untwisted region (t=18). In the meantime, the linked twist-untwist field lines reconnect with one another to retrieve the original topology (t=23).

Fig. 4 Intermittent bursts of the kinetic energy in the self-organization of a continuously twisted flux tube. One can clearly recognize the intermittency in self-organization when the system is in contact with a continuous energy supplier. In the present twisted magnetic flux case, a recurrence in the magnetic topology is also observed after several intermittent bursts, as indicated by a vertical arrow at τ_{rec}.

Fig. 5 A non-Taylor MHD self-organization. All previous MHD simulations where $\nabla p=0$ is *a priori* assumed have demonstrated that the system relaxes to a force-free Taylor minimum energy state. However, the present simulation, which does not assume $\nabla p=0$ but solves the pressure evolution self-consistently, has revealed that a force-balanced ($J \times B= \nabla p$), non-Taylor state is achieved. The figure represents a non-Taylor self-organized magnetic structure (left) and pressure structure (right). It should be noted that the pressure (hollow) exhibits a double-helix structure. The brown helix and green helix on the left represent the isosurfaces of a positive axial magnetic field and a negative one, respectively.

Fig. 6 A particle simulation creating a giant potential structure by filtering out the disturbed part of the outgoing particles. The upper panel shows the potential structure of normal (weak) ion acoustic double layers generated by a shifted Maxwellian electron stream with the average velocity of 0.6 V_{eth} (V_{eth} is the electron thermal velocity) under the condition that particles are periodically circulated. We remove the periodicity that retains the disturbed particles and devise a simulation model in which the disturbed particles are replaced by the shifted Maxwellian particles at the boundaries. Then, a surprising result is obtained where an enormously enhanced ion acoustic double layer is generated (the lower panel). Note the difference in the vertical scale between the upper and lower panels.

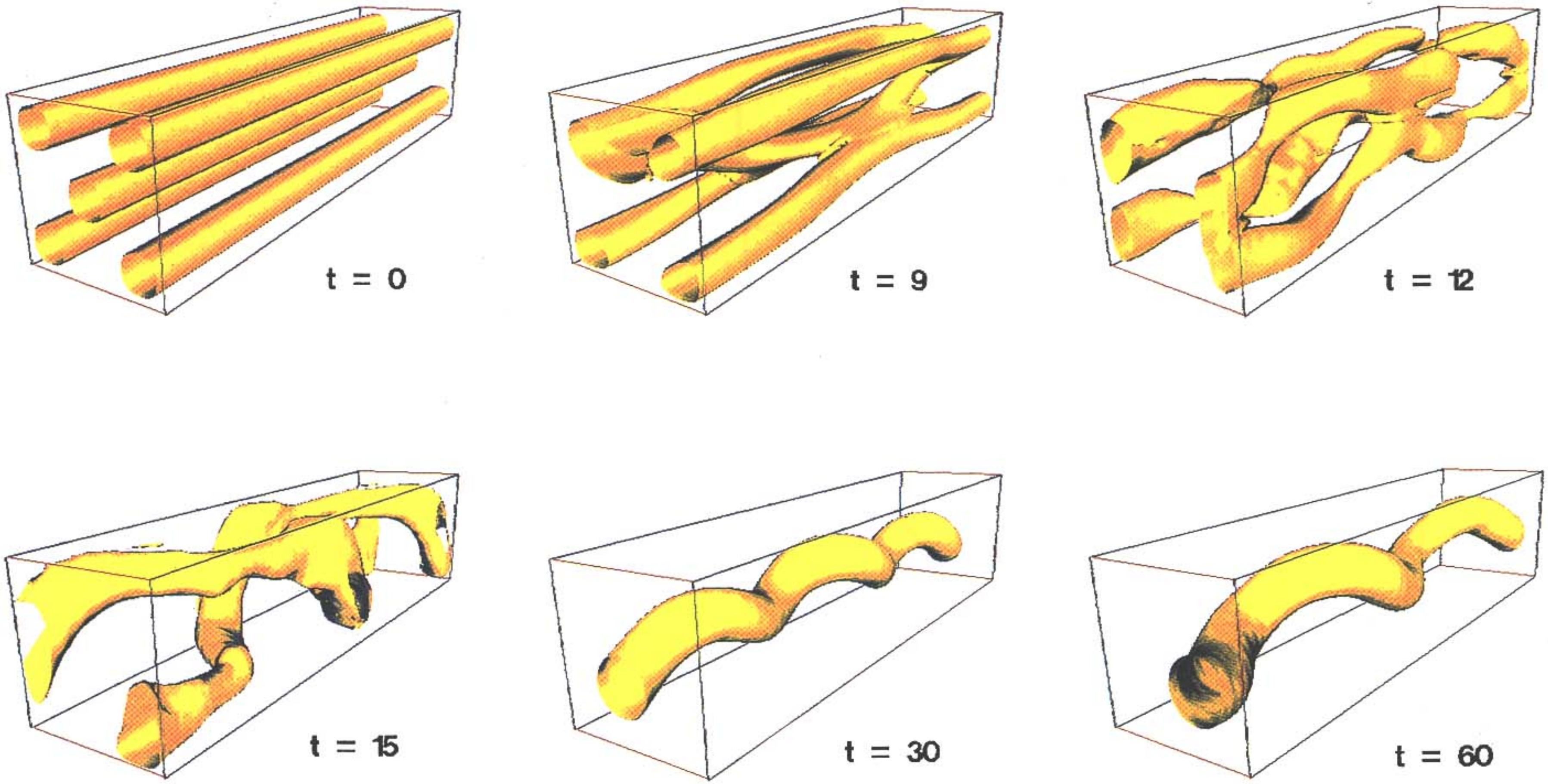
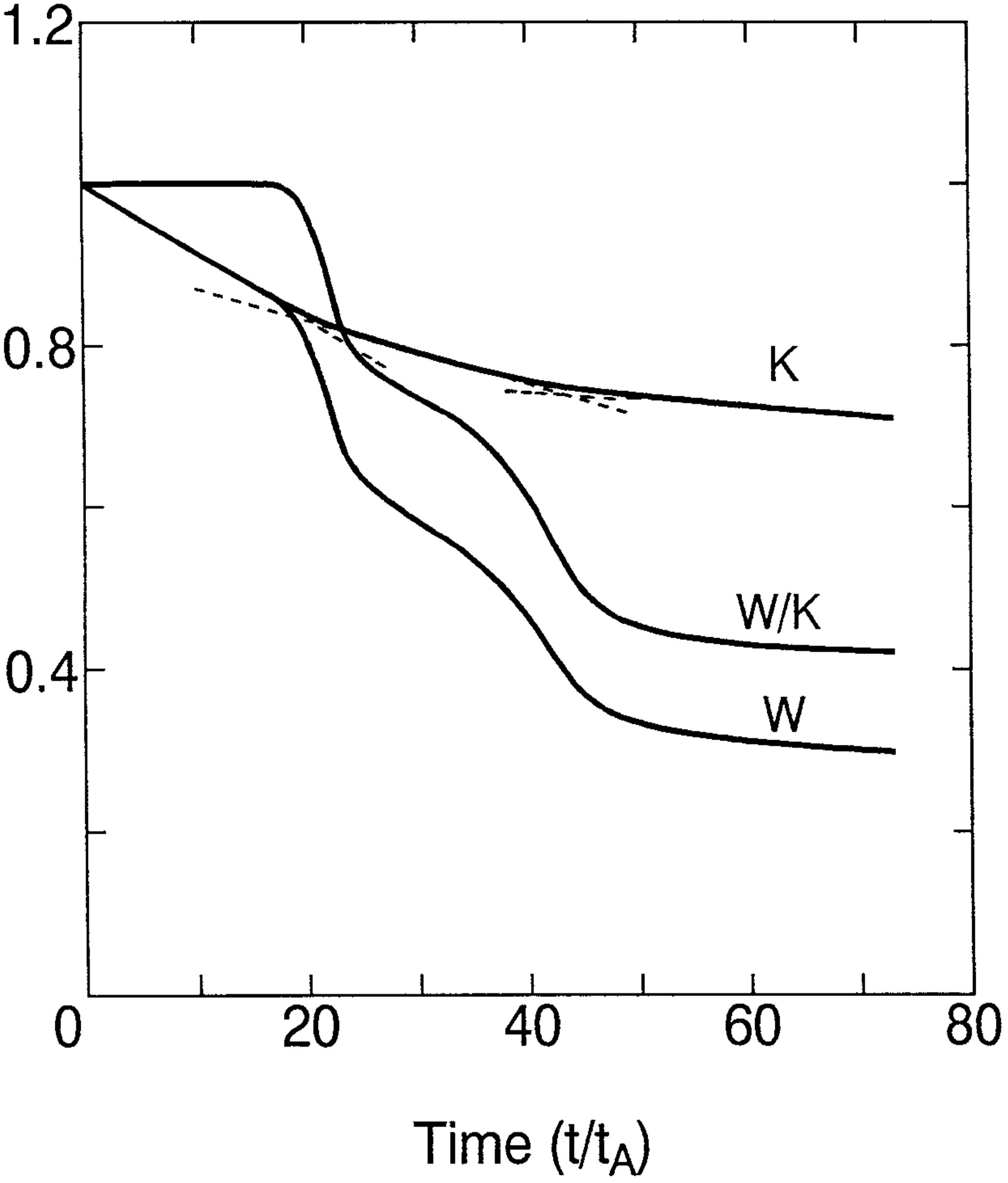


Fig. 1



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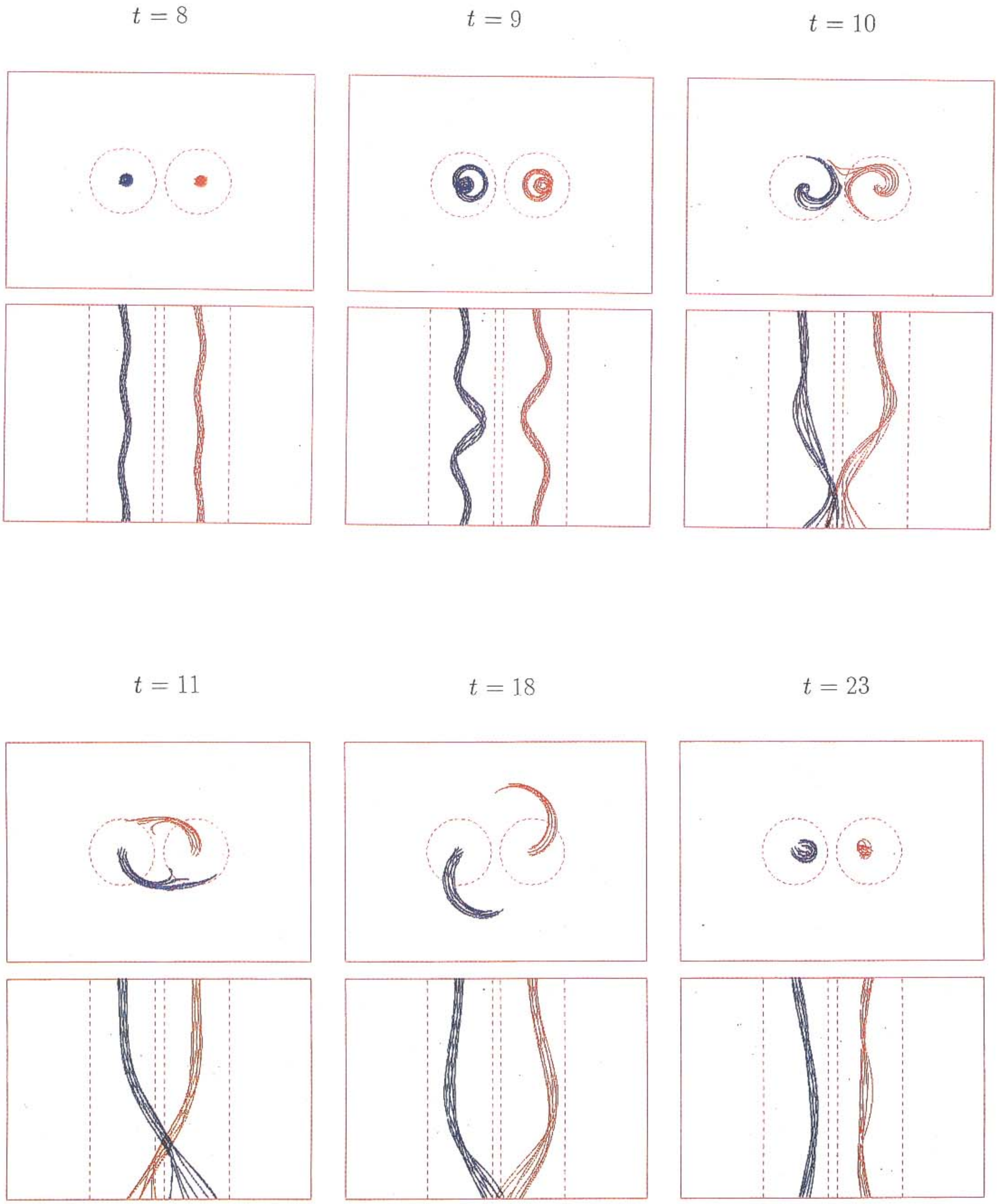


Fig. 3

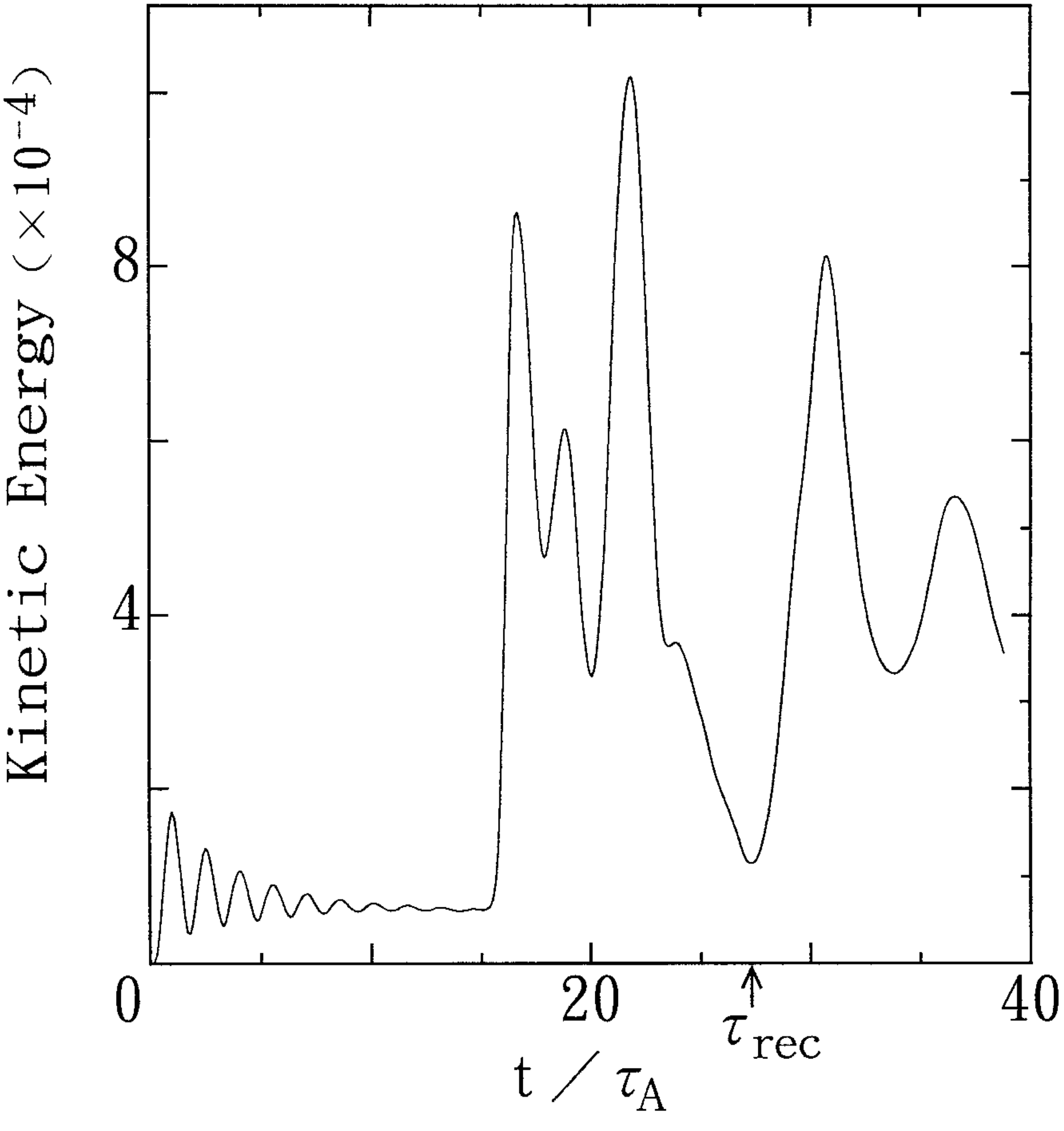
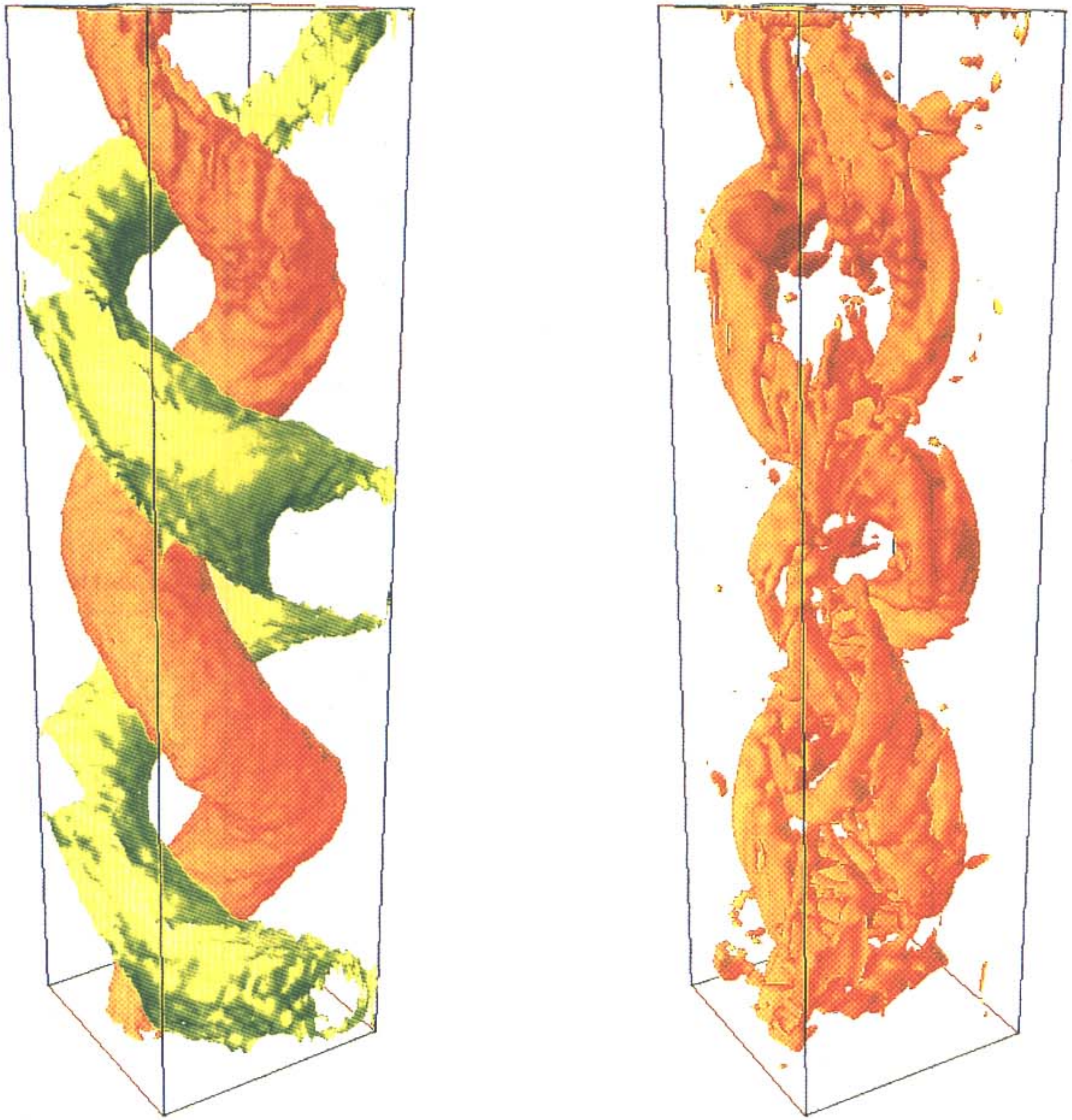


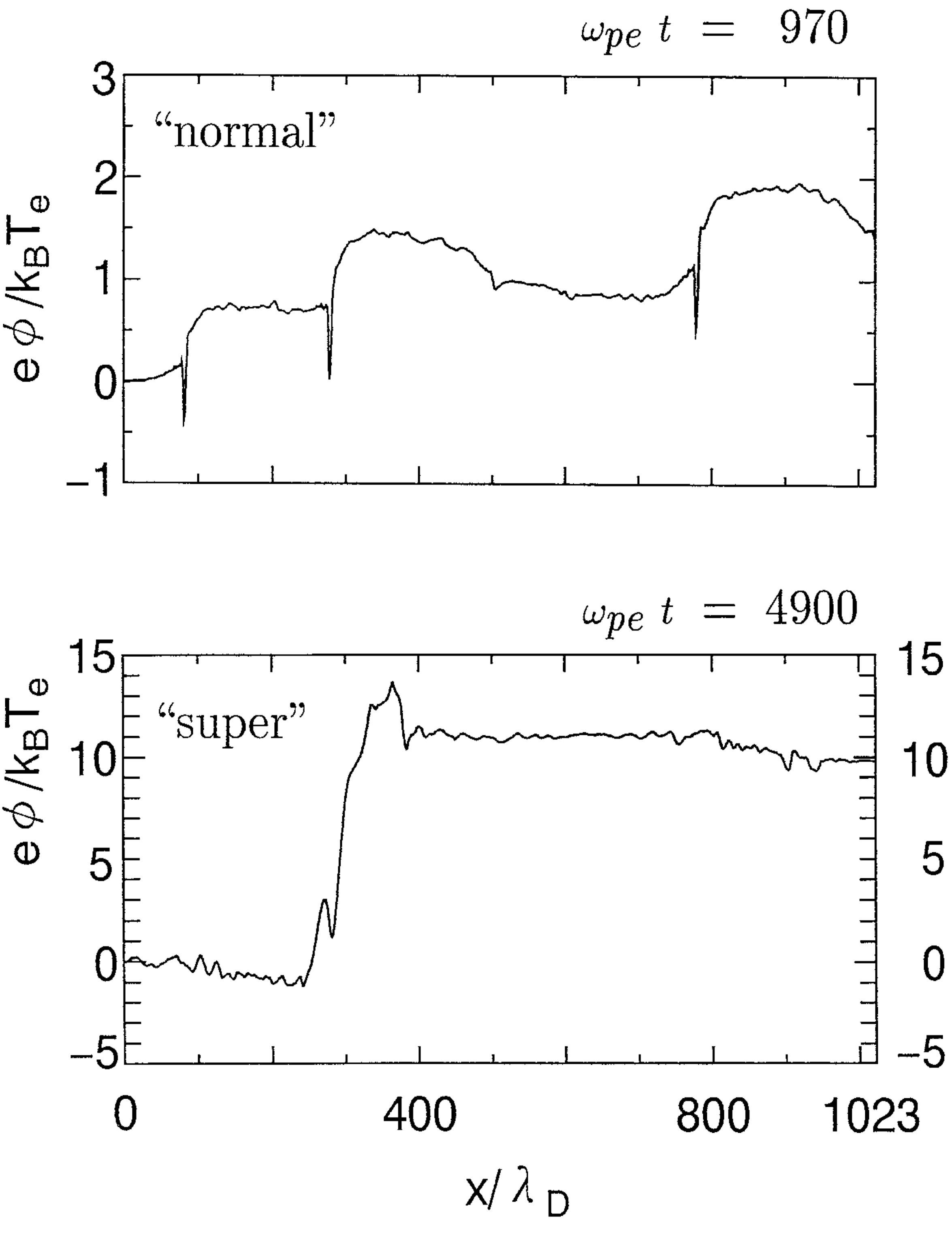
Fig. 4



Magnetic Field

Pressure

Fig. 5



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x/λ_D

Fig. 6

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