*CONFERENCES AND SYMPOSIA*

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# Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (October 25, 2000)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held on October 25 2000 at the P L Kapitza Institute for Physical Problems, RAS. The following reports were presented in the session:

(1) **Razumova K A** (Nuclear Fusion Institute, Russian Scientific Center 'Kurchatov Institute', Moscow) *Transport barrier formation in a tokamak plasma*;

(2) **Marchenko A V** (General Physics Institute, Russian Academy of Sciences, Moscow) *Model for the formation of ice hummocks in a drifting ice cover*.

Brief presentations of these reports are given below.

PACS numbers: **52.30.–q**, **52.35.–g**, 52.55.Fa
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## Transport barrier formation in a tokamak plasma

Razumova K A

It is a well-known fact that for many years research has been conducted worldwide on the problem of building a reactor for controlled fusion, a powerful and safe source of energy. The main avenue of research, which has already led to a technically feasible reactor project, uses plasma that has currents flowing through it and is placed in a toroidal magnetic field. The device became known as a tokamak. Here I will not discuss the technical achievements reached in this area of research, such as, say, plasma temperatures as high as 35 keV and the high coefficient of utilization of the magnetic field pressure. Rather, I will speak on the remarkable properties of hot magnetized plasma, an amorphous substance subject to all imaginable instabilities, which in practice exhibits an order that could be expected only in crystals.

In an ideal situation, a plasma placed in a strong magnetic field will have small transport coefficients since the particles participating in collisions can become shifted only by a distance $\Delta x = \rho_{\text{Lar}}$. Actually, even when placed in a strong magnetic field the plasma remains extremely mobile and is subjected to numerous instabilities, which worsens energy and particle confinement. I will not discuss the kinetic instabilities, but, instead, I will touch on large-scale magnetohydrodynamic (MHD) instabilities, the leading factor in determining the behavior of plasmas.

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Since in a tokamak there is a current flowing along the plasma ring, the magnetic lines of force wind around the toroidal axis. The spacing of this winding is given by the quantity

$$q = \frac{B_{\text{t}} r}{B_{\text{p}} R} ,$$

where $B_{\text{t}}$ and $B_{\text{p}}$ are the strengths of the toroidal and poloidal magnetic fields, and $r$ and $R$ are the small and large radii of the plasma torus. For some radii, the magnetic line of force can, circling the torus one or more times, close on itself. Such surfaces are called rational and are characterized by a number $m$ corresponding to the number of turns prior to closure. If, in addition, such a line of force has wound itself around the toroidal axis, it can be characterized by the number $n$ of turns around the axis. Thus,

$$q = \frac{B_{\text{t}} r}{B_{\text{p}} R} = \frac{m}{n} .$$

From the standpoint of energy, it is advantageous for the current to flow along a real line of force rather than along the torus, with the result that a plasma with a current is unstable against concentrating along a pencil of rational lines of force. Such a helical current bunch generates its own magnetic field, which forms a 'magnetic island'. The island will grow, but its nonlinear interactions with the rest of the plasma limits this growth, with the result that the island is of finite dimensions. The size of the island depends on the variation of the 'twist' of the magnetic lines of force around the radius of what is known as magnetic shear:

$$S = \frac{r}{q} \frac{\mathrm{d}q}{\mathrm{d}r} .$$

The larger the value of $S$, the smaller the island.

Neighboring islands may adjoin each other along their edges. Nonlinear interaction at the edges leads to granulation of the islands and even to the emergence of regions with damaged magnetic surfaces, i.e. regions where the lines of magnetic force are randomly mixed. Due to the very high transport along the magnetic field, the plasma pressure in the outer and inner parts of the island easily evens out. There is also good thermal contact between islands, with the result that the heat and the particles rapidly leave the area in a direction transverse to the magnetic field.

The list of instabilities in plasma is extremely long. To each action the plasma responds by generating an instability, which changes the plasma's transverse transport path. But each instability, drawing its energy from the unfortunate gradient of a plasma parameter, leads to changes in this gradient and to stabilization. Thus, the plasma tends to organize its profile in such a way so as to become as stable as possible, i.e. to acquire a configuration with minimum internal energy. One can expect that for different tokamaks and a broad class of tokamak operational regimes the dimensionless plasma pressure profiles are similar, provided that one is able to find the correct normalization for the plasma radius. This is demonstrated by Fig. 1 [1].

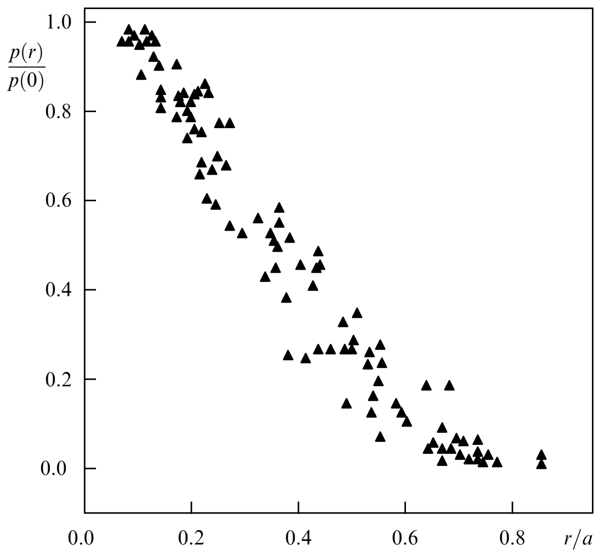


**Figure 1.** Dependence of the renormalized plasma pressure on the dimensionless radius $\rho = r/a$, where $a = (IR/B_t)^{1/2}$, for different tokamaks and a broad class of operational regimes (T-10, T-11, TFR, TM-3, PLT, PDX, ASDEX).

It was found that the 'current' radius must be normalized to the radius of a magnetic surface with a given $q$. B B Kadomstev explained this phenomenon and showed that a profile close to a self-consistent one corresponds to the minimum of internal energy [2]. This leads to a situation in which the transport coefficients depend not only on the local characteristics but also on the state of the plasma as a whole.

Naturally, there can be no ideal profile, since the plasma is constantly exposed to various factors. The strongest of these are the boundary conditions, which distort the self-consistent profile and, hence, increase the energy and particle flux to the chamber wall. If we could create a narrow layer with small transport coefficients near the edge of the plasma, the wall would be separated from the plasma and the profile would be closer to the optimal one.

No matter how fantastic this idea sounds, it was actually realized once.

A group of researchers working with the German ASDEX tokamak discovered an operational regime with an external transport barrier (a local minimum of transport coefficients). The electron temperature $T_e$ and electron concentration $n_e$ were found to have steep gradients at the edge of the plasma. This type of regime became known as the H-mode, and in it the plasma confinement is longer by a factor of roughly two. Although empirically the conditions under which such a regime is formed have been thoroughly studied and although this regime has been adopted as the main one for the reactor, the physics of this formation is far from clear. Why, in a narrow zone near a certain magnetic surface, are the conditions for plasma confinement much better?

One of the reasons for this is the formation of rapid poloidal rotation ($V_p \approx 1-5 \times 10^6$ cm s$^{-1}$) within a small layer of the plasma periphery. The most probable instability responsible for the loss of heat from ions and particles proper is the drift – gradient mode, in which the plasma is ejected in the form of relatively long-wave 'tongues'. Nonuniform rotation along the radius smears these tongues and prevents the development of the instability. Experiments have corroborated this result. But where does the rotation come from? Why does the electron confinement time increase?

Nature prepared another present for the researchers— local internal transport barriers. The theory predicts than many MHD instabilities can be stabilized if $S < 0$, i.e. the current has a hollow profile. Such a configuration emerges either because of a skin-effect or in generation of a noninductive current in the proper zone of the plasma.

In the beginning the experiments followed the first path. During the current-growth phase the plasma was subjected to powerful additional heating: a flux of high-energy neutral atoms was injected into the plasma at an angle to the magnetic field, and the recharging of these atoms heated the plasma. Improvement of confinement was discovered by Synakowskiĭ et al. [4] (Fig. 2), but the zones with reduced transport coefficients proved to be not in the region where $S < 0$ but in the zero-shear zone. By such heating method torque is introduced into the plasma. This could serve as an explanation of the phenomena, as the presence an external barrier explains the H-mode. However, experiments were soon held in which heating did not introduce a torque into the plasma, while a local transport barrier still appeared.

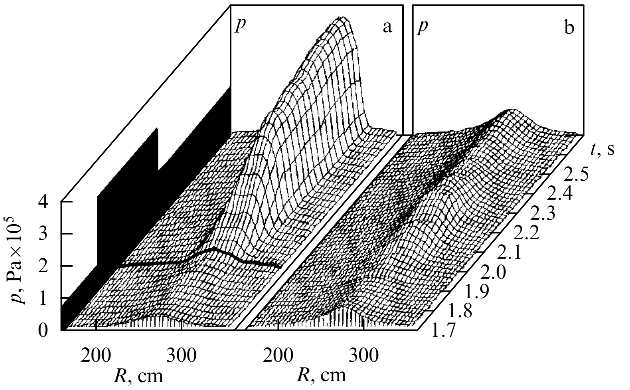


**Figure 2.** U.S. TFTR facility. Variations in the plasma pressure profile in the process of local transport barrier formation (the left diagram), and an ordinary regime with close initial parameters. The black contour depicts the power fed to the plasma as a function of time. (a) Discharge with a local barrier; (b) discharge without a local barrier.

The T-10 tokamak at the Russian Scientific Center 'Kurchatov Institute' uses electron cyclotron resonance (ECR) as a source of additional heating (naturally, only electrons are heated in this method). If the ECR waves are input at an angle to the magnetic fields, noninductive generation of a current in a given fairly narrow zone of the plasma is possible. Here no torque is introduced into the plasma. The zone of the introduced power and current generation amounts to three-tenths of the total radius of the plasma (such a zone can be made even more local). Thus, current may be generated at different radii both in the direction coinciding with that of the plasma current (CoCD) and in the opposite direction (CounterCD), which means that the profile $q(r)$ can be changed arbitrarily (Fig. 3).

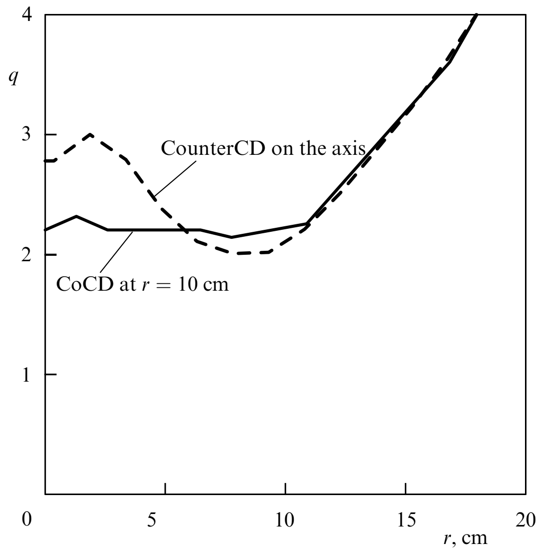


**Figure 3.** Calculated profiles $q(r)$ for measured profiles $T_e(r)$ and $n_e(r)$ in the generation of CounterCD at the center of the plasma and CoCD at one-third of the plasma radius.

Experiments conducted with T-10 by a group of researchers have shown [5] that local barriers can appear at a negative shear with a central CounterCD or with a noncentral CoCD, with the barrier always forming in the region with low shear and values of $q$ close to the rational one. Since the current is generated not immediately after ECR sets in but gradually increases due to the skin redistribution process, the $q(r)$ profile also changes gradually. When the region $dq/dr = 0$ approaches the rational value, the MHD instability level decreases sharply and a barrier begins to form. A further increase in $q_0$, which corresponds to the zero derivative, and its passage through the rational value lead to a new upsurge of MHD activity, followed by stabilization near the rational surface and formation of a new barrier (Fig. 4).

If the value of $q_0$ corresponds to the limit in the condition for barrier formation, the improvement of confinement in the inner zone and the corresponding redistribution of the current density can, as a result of $q$ decreasing within the barrier, force this quantity to leave the necessary range of values, so that the barrier disintegrates. In this case a periodic improvement and deterioration of confinement is observed.

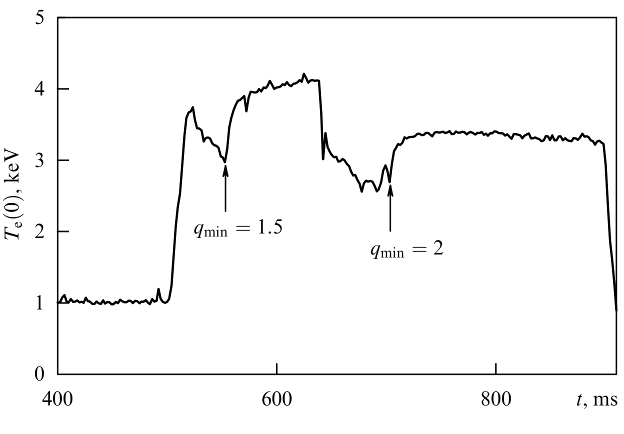


**Figure 4.** Consecutive emergence of an MHD instability and the formation of local barriers caused by changes in the profile $q(r)$ in the discharge process.

Let us follow the process of barrier formation using the example of the changes in the intensity of X-ray radiation (Fig. 5). What is interesting is that the process begins not only when the electron temperature begins to increase in the ring, where the barrier forms, but also with the simultaneous central region temperature begins to drop, even if the entire ECR power is input at the center (central CounterCD). Only after the barrier has completely formed will the central region of the plasma begin to fill.

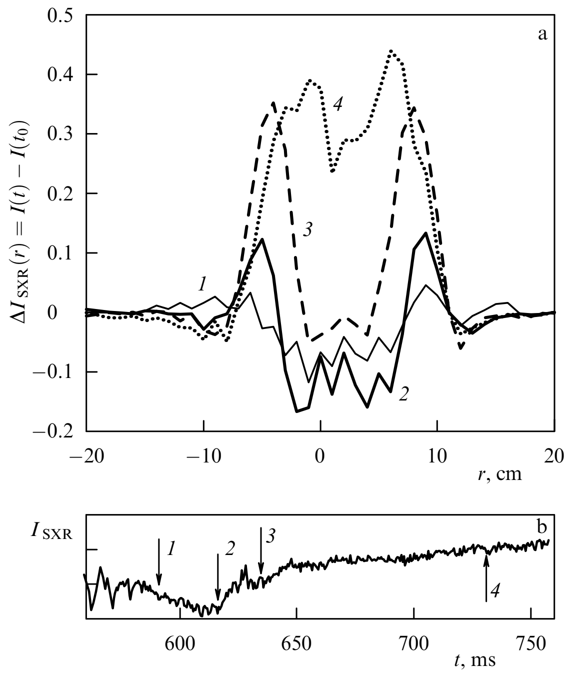


**Figure 5.** (a) Spatial distribution of the increase in intensity of soft X-ray radiation, $I_{SXR}$, measured along the chords in the process of barrier formation. The intensity $I(t_0)$ at the moment $t_0 = 570$ ms prior to barrier formation is subtracted from the measured intensity $I(t)$. Restoration of the profile by Abel's method substantially enhances the effect. (b) The arrows indicate the moments in time for which the profiles are given.

Thus, we see that the formation of a local electron transport barrier requires that a certain profile $q(r)$ exist in the vicinity of the resonance surface. And what role does rotation play? We know that it has been shown that namely plasma velocity shear determines the formation of local gradient of particle concentration and ion temperature.

Let us again turn to the experiments conducted on the T-10 tokamak. Here an important result was obtained thanks to the unique methods of plasma diagnostics developed in connection with these experiments, methods that made it possible to measure the changes in the potential profile in the plasma by probing the plasma with beams of heavy ions [6]. When the ECR power was input at one-half of the plasma radius, a barrier at the rational surface $q = 1$ was found to form in this region. Naturally, MHD instabilities, which appeared inside the region, reduced the energy confinement time. Nevertheless, a certain increase in the electron temperature was observed (Fig. 6). The experimenters were able to

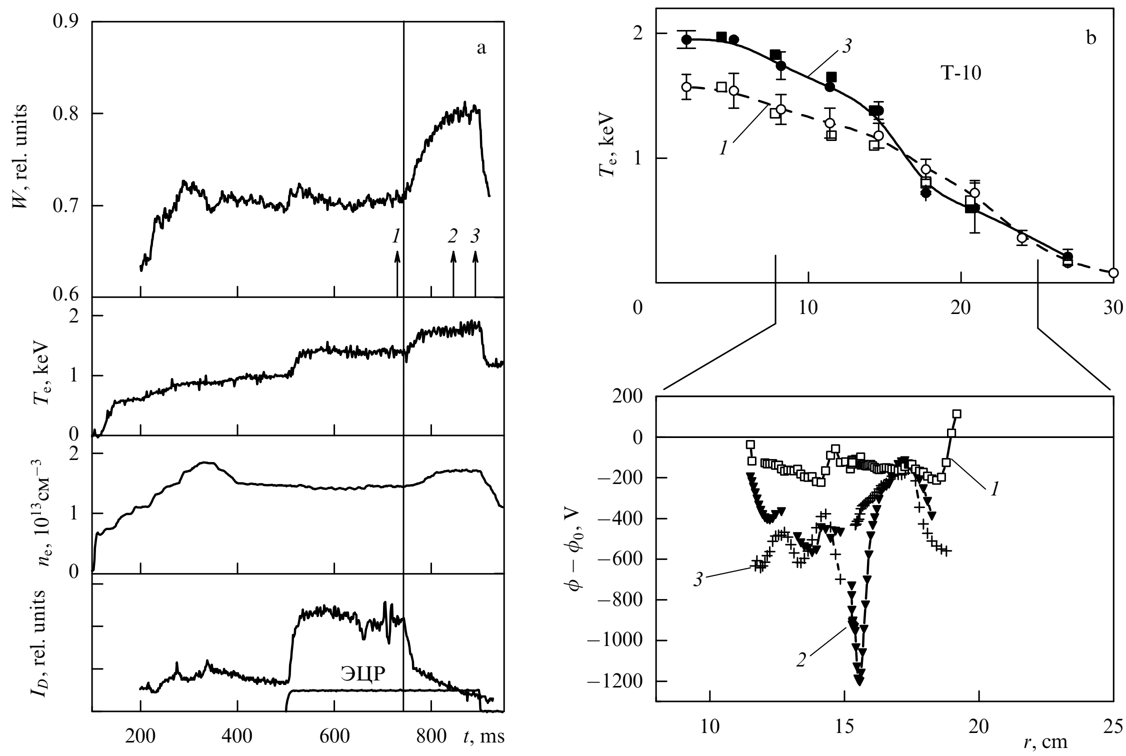


**Figure 6.** Formation of the local barrier with the ECR power input at one-half the plasma radius. (a) Downward: variation of the plasma energy content ($W$), variation of $T_e$ inside the barrier ($r = 17$ cm), the plasma concentration as a function of time, and the intensity of the deuterium line characterizing the influx of neutrals to the plasma; the time interval in which ECR is active is indicated in the lower part of this figure. (b) Electron temperature profiles and the variation of plasma potential with time in the process of barrier formation. The moments *1*, *2*, and *3* are as follows: *1*, prior to the formation of the local barrier; *2*, in the process of local barrier formation; and *3*, after formation of the local barrier has been completed.

measure the relative electric potential of the plasma, $\phi - \phi_0$. The measurements showed that a deep narrow potential well formed near the barrier as the temperature $T_e$ increased. This is an indication that near the barrier the balance between the ambipolar fluxes of electrons and ions was disrupted, while the Coulomb forces instantaneously brought the situation into balance again.

What initiated this disbalance? Did the ion flux increase in strength? No, the experiment showed that ion confinement had increased by a factor of 1.5. Hence the electron confinement improved. The new potential well generated a strong electric field that rapidly varied along the radius, with the result that a rotation velocity shear emerged, so that confinement of the ion component improved.

Thus, the process begins with the profile $q(r)$ and the increase in the electron lifetime. What is the relationship here? This question has still to be answered. In the steady-state phase of the process the well is transformed into a steplike decrease of potential toward the inner side of the torus (see Fig. 6).

One more remarkable phenomenon was observed in the experiments involving the T-10 tokamak. The formation of the local barrier is accompanied (simultaneously!) with the formation of an external barrier separated from the former by one-half of the tokamak radius.

The pattern of formation of this external barrier is quite similar to that observed inside — a potential well is formed. However, here particle confinement is improved, and the electron concentration gradient increases. A thorough examination shows that double and even triple barriers are observed in many experiments with different tokamaks. How are these surfaces connected? What a connection do exist between these surfaces? Indeed, there is not a single mode in a torus that can exist in pure form, since the harmonics of this mode are also generated. In the case at hand the local barrier was formed at $q = 1$, while the external barrier was formed at $q = 2$. Possibly, a substantial change in the profile of a magnetic island on one resonance surface may lead to a similar change on another such surface. But then we are forced to believe that the H-mode also begins its formation within a region with a given shear near the resonance surface. The scientific community is not yet ready for such a discovery, and so the question remains open. What is true is that plasma is capable of resounding like a cavity.

Thus, local barriers destroy the bonds in the plasma that (due to turbulence) determined self-consistent profiles and make it possible for steeper parameters gradients to set in local layers. The nonlinearity in the development of instabilities in the high-temperature plasma of a tokamak leads not to chaotization and disintegration of the plasma but to formation of self-organizing structures capable of producing high particle and energy confinement characteristics.

This makes it possible in terrestrial conditions to reach, within limited volumes, plasma temperatures ($T \leqslant 4 \times 10^8$ K) that exceed the temperature inside the Sun by tens of times.

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# Model for the formation of hummocks in a drifting ice cover

A V Marchenko

## 1. Introduction

Hummocks constitute a characteristic feature of the sea ice cover. They are produced by the deformations caused by the compression and shearing of the ice cover generated by wind and sea currents. The hummocks are formed in the open ocean and in the vicinity of the shores and greatly affect navigation in the ice-covered sea of the Arctic regions. The hummocks produced in the sea-shelf regions near the hydrotechnical structures greatly affect the distribution of the loads exerted by the ice on these structures.

The hummocks are pieces of ice pushed out under and over the surface of the surrounding flat ice cover. The above-water part of a hummock, the sail, may be several meters high while the height of the underwater part, the keel, may be tens of meters. Hummocks are fairly often extended horizontally [1]. Hummocks have a significant influence on the rheological properties of the ice cover and make it spatially inhomogeneous and anisotropic.

Theoretical modeling of hummock formation (the ridging process) may be classified into two types of analyses. In the studies of the first type (see, for instance, [2]) the ridging processes are taken into account in the large-scale simulation of the ice cover dynamics. Ridging is treated as the main mechanism for evolution of the ice cover thickness profile. The simulation yields the evolution of the thickness distribution for the ice cover under plastic strain. The structure and evolution of an individual hummock are ignored in the simulation process.

The first model of hummock formation was developed by Parmeter and Coon [3] in 1973. Parmerter and Coon analyzed the observational data and put forward a hypothesis that there was a maximum hummock height depending on the thickness of the ice sheets making up the hummock. According to the hypothesis, a hummock grows in height and width if its vertical dimension is smaller than the maximum size and after its height has reached the maximum size only the hummock width grows. The maximum hummock height is determined by the bending load breaking down the edge of the floe pushing against the hummock owing to the lack of balance between gravity and the lifting force acting on the hummock edge in water. Parmeter and Coon estimated the compression stress required for the hummock formation from the equations for conservation of mass and energy.

Hopkins and co-workers [4, 5] used a different approach to modeling the ridging process. They treated a hummock as a pile of ice blocks of a given shape with viscous elastic forces acting between them. The motion of each ice block is described by a separate equation. New ice blocks are produced in the model when the floe edge pushes against the hummock. High-capacity computer simulations involved calculations of the motion for the large number of ice blocks making up the hummock yielding a realistic representation of the ridging process and confirming the hypothesis of the maximum hummock height.

It was only in 1998 that a hummock was produced under laboratory conditions [6] in the ice basin of the Technological University in Helsinki. The thickness of the artificially frozen ice was not more than 10 cm. The experimental results demonstrated that the growth of the hummocks under compression was accompanied by floes being pushed under hummocks so that these two processes cannot be monitored separately in practice. The results of the laboratory experiments are corroborated by the data of observations conducted in northern Baltic Sea which demonstrated that ice hummocks were largely composed of flat floes piled up on each other.

The objective of the present study was to develop a model of the ridging process that would make it possible to analyze the formation of hummocks in the ice cover consisting of an arbitrary number of floes. It is assumed that the hummocks are formed at the lines of contact between floes driven by winds. The suggested mechanism is valid for the sea ice cover in which the regions of flat and ridged ice can always be identified. A flat ice cover region is broken down under compression so that hummocks are produced while the flat ice regions are displaced with respect to each other. It will be demonstrated that the displacements are periodic owing to the self-sustained oscillations accompanying shifting of the drifting ice [7].

## 2. Basic equations

Let us consider the conservation of mass, momentum, and energy for an ice layer floating on a liquid surface. The appropriate differential equations for the one-dimensional case are

$$\frac{\partial m}{\partial t}+\frac{\partial mv}{\partial x}=0\,,$$
$$\frac{\partial mv}{\partial t}+\frac{\partial mv^2}{\partial x}=\frac{\partial \sigma}{\partial x}+f,$$
$$\frac{\partial E}{\partial t}+\frac{\partial Ev}{\partial x}=\frac{\partial \sigma v}{\partial x}+fv\,. \tag{2.1}$$

Here $m$ is the mass of the ice floating on the unit surface area of the ocean, $v$ is the ice drift velocity, $\sigma$ are the internal stresses in the ice, $E$ is the surface energy density of the ice, $f$ is the friction force of the atmosphere and the ocean acting on the ice, $x$ is the horizontal coordinate, and $t$ is the time.

The ice concentration on the ocean surface is assumed to be unity and we can write $m=\rho_i h(x,t)$ where $h(x,t)$ is the ice thickness and $\rho_i \approx 930$ kg m$^{-3}$ is the sea ice density. The surface energy density of the ice cover is given by the equation

$$E=K+P+W\,, \tag{2.2}$$

where $K=\rho_i h v^2/2$ is the surface density of the kinetic energy, and $P$ and $W$ are the surface densities of the potential and internal energies.

The surface density of the potential energy of the floating ice is given by the equation

$$P=\rho_i g\int_{z_-}^{z_+} z\,dz-\rho_w g\int_{z_-}^{0} z\,dz \tag{2.3}$$