PACS numbers: **01.65.+g**, **28.52.–s**, 52.55.Fa
DOI: 10.3367/UFNe.0179.200907f.0767

Academician B B Kadomtsev and the International Thermonuclear Experimental Reactor (ITER)

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Kadomtsev Boris Borisovich (1928–1998), physicist, Full Member of the Russian Academy of Sciences (1970). Main works on plasma physics (stability, transport processes, thermal insulation, etc.) and controlled thermonuclear fusion. USSR State Prize (1970), and Lenin Prize (1984).
Great Russian Encyclopedia, 2007

Academician Boris Borisovich Kadomtsev belonged to a group of physicists of whom their colleagues can speak only in superlatives. The spectrum of his scientific interests is astonishing. The posthumous collection of his works in two volumes contain not only the widely known publications on high-temperature plasma physics that became classical but also those on quantum mechanics (his first and lifelong love as a disciple of D I Blokhintsev), the behavior of matter in superstrong magnetic fields, the theory of nonlinear and stochastic processes, magnetic reconnection, the theories of solitons and ball lightning, and above all controlled thermonuclear fusion. Boris Borisovich treated all these issues with plenty of original thinking. The seeds sown by him will bring forth fruit at some time or another. Suffice it to mention his interpretation of the known *Sokolov effect* (appearance of coherent addition to an excited hydrogen atom flying near a metallic surface). Boris Borisovich expounded his vision of quantum mechanics and the Sokolov effect in the book *Dynamics and Information* [2][1] that he finished not long before his death. In a way, he had cast a glance 'behind the horizon'. It is as likely as not that in some 20 years an encyclopedia will mention B B Kadomtsev not only as a founder of the theory of thermonuclear plasma transport and stability, but also as an author of a new interpretation of quantum mechanics.

I happened to collaborate with Boris Borisovich only in a relatively narrow area of his scientific interests, namely plasma stability and transport in tokamaks, hence the choice of the subject of this report. Despite the seeming narrowness of this subject, it was B B Kadomtsev's focus of attention for a long period of his scientific and administrative work as Director of the Nuclear Fusion Institute (NFI) in the Russian Research Centre 'Kurchatov Institute'. That period was a time of rapid progress in research on controlled thermonuclear fusion carried out abroad after the powerful incentive given by the tokamak concept suggested by Andrey D Sakharov and I E Tamm in the early 1950s and universally accepted in the mid-1960s through efforts of L A Artsimovich, B B Kadomtsev's predecessor in the capacity of Director of the Kurchatov Institute's NFI.

Figure 1, borrowed from display materials of the Princeton Plasma Physics Laboratory (PPPL), USA, illustrates the growth dynamics of deuterium–deuterium (DD) and deuterium–tritium (DT) thermonuclear fusion power achieved in tokamaks of different countries from 1970 to 1996. The lower portion of the curve shows the results

[1] See also Refs [3–8].

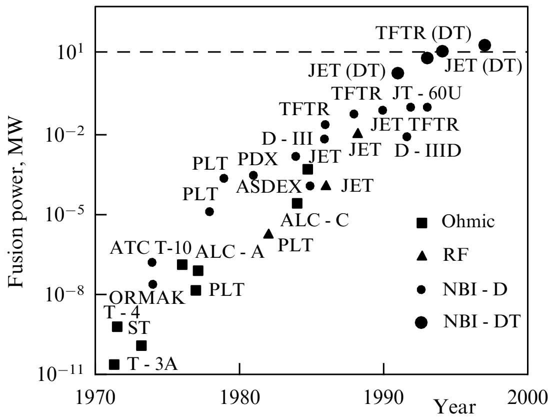

Figure 1. Progress of tokamaks: Ohmic — ohmic heating alone; RF — high-frequency heating; NBI-DT and NBI-D — heating by neutral deuterium beams with and without tritium, respectively.

obtained with Soviet tokamaks (T-3A, T-4, and T-10) in the late 1960s and early 1970s.

The overall success of the tokamak program, i.e., the construction of fusion facilities as the first demonstration nuclear power plants, provided a physics basis for the world's first industry-scale International Thermonuclear Experimental Reactor (ITER) currently under construction in France through the joint efforts of Europe, India, China, Russia, USA, South Korea, and Japan. It is appropriate to recall that diplomatic and organizational activities concerning this project were initiated by our country and translated into meaningful proposals at the well-known meeting of Mikhail Gorbachev and Ronald Reagan in 1985. Further coordination of these activities from the Russian side was entrusted to E P Velikhov, while B B Kadomtsev acted in the capacity of key native expert in tokamak research as a recognized founder of modern high-temperature plasma physics.

It is believed that Kadomtsev first addressed the physical aspects of tokamaks as potential candidates for fusion reactors in the paper published by *Sov. Physics – Uspekhi* in 1967 under the title of "Plasma instability and controlled thermonuclear reactions" [9]. There is little doubt that the paper was inspired by L A Artsimovich, who prefaced it by his own review in the same issue concerning the state of the art of thermonuclear research and reporting the absence of so-called Bohm diffusion in Soviet T-3 and TM-3 tokamaks where the plasma energy lifetime was 10 times the calculated 'Bohm' lifetime. Artsimovich summarized the review [10] with the following conclusion: "This result affords ground for cautious optimism with which we are now looking at prospects for the development of future research in this area [i.e., tokamak physics]."

Despite the delicate form of this assertion, it was a rather radical statement for that time: the most promising foreign thermonuclear facilities (stellarators) almost universally suffered substantial anomalous plasma leakage across the strong magnetic field, i.e., turbulent diffusion named after the American scientist D Bohm, who observed it in gas discharges in a strong magnetic field in the 1940s. Had this diffusion really been universal, the idea of thermonuclear fusion in closed magnetic traps (tokamaks and stellarators) would have had to have been abandoned. Many serious theorists of that time tried to prove the universal character of Bohm diffusion. Boris Borisovich was among them.

In this context, the downfall of Bohm universality in relation to tokamaks looked like sheer nonsense. The point is that many Russian and foreign physicists of that period regarded the tokamak concept as physically ungrounded, in contrast to the stellarator one. Electron flux forming current that traverses plasma along the direction of the strong tokamak magnetic field and giving it a helical shape was thought to be an additional energy reservoir for a battery of magnetohydrodynamic and kinetic instabilities. Moreover, if tokamak plasma were macroscopically stable, the longitudinal electric field applied to a plasma turn would gradually convert all current-carrying electrons into a relativistic electron beam (plasma betatron). Tokamaks would be a step down 'from the Bohm' rather than an improvement.

However, the real situation proved more complicated than *a priori* considerations. In 1962, E P Gorbunov and K A Razumova showed for the first time that current-carrying electrons did not enter betatron acceleration in the usual macroscopically stable regime of the TM-2 tokamak. This is a fundamental physical phenomenon underlying the current tokamak concept. Later studies demonstrated that the passage of electrons to acceleration was hampered by certain electron beam instability scattering electrons being accelerated over a range of angles. Spontaneous suppression of this instability in certain exotic regimes immediately transformed the tokamak into a superpowerful betatron.

The first explanation of the nature of this tokamak-saving kinetic instability of electrons was offered by B B Kadomtsev and O P Pogutse [11] in 1967 by invoking the mechanism of the anomalous Doppler effect. It removed a major restriction from tokamaks. The absence of universal Bohm diffusion opened up prospects for using these magnetic traps as thermonuclear reactors. It appears that Artsimovich wanted to emerge together with Kadomtsev as a leading expert in plasma turbulence that many regarded as limitless at that time. Now, what conclusions did Kadomtsev arrive at in his keynote paper?

"Some time ago, a pour of publications reporting more and more new instabilities gave reason to think that we shall never have a complete description of rarified plasma instability in a strong magnetic field. Fortunately, the situation is beginning to improve. Despite continuing extensive studies of plasma instabilities, it is becoming clear that only few of them pose a real threat to hot plasma confinement in the magnetic field" [9]. In other words, the number of dangerous instabilities was argued to be limited. This conclusion was not universally accepted, since pessimism about the stability of high-temperature plasma was a given at that time. Kadomtsev considered drift-temperature instability to be the most dangerous among remaining instabilities; it was expected to manifest itself as enhanced plasma leakage across the magnetic field, functionally resembling Bohm instability but multiplied by the ratio of the Larmor ion radius to the minor radius of the plasma column. Today, transfer of this type is referred to as gyroBohm transport and accepted as the most probable one to occur in the ITER based on experimental data obtained with operating tokamaks for the last 40 years, rather than on theoretical predictions (see Fig. 1).

In 1966, the available experimental database was too small for such generalizations. However, it allowed for reasoning 'in Bohm fractions'. Kadomtsev calculated the minimal size of a DT-fuelled reactor-tokamak proceeding from the maximally possible (from the theorist's standpoint) magnetic field induction ($B_{\mathrm{T}} = 10$ T) created by superconductors and unbelievably high (at that time) plasma temperature ($T = 10$ keV). He found that in the case of Bohm leakage, the minor torus radius a should be unreasonably large (14 m). In the case of a two-order-of-magnitude-lower leakage (lifetime of '100 Bohms'), the minor radius had an acceptable size of 1.4 m. Thus, the values of $a = 1.4$ m and $B = 10$ T were chosen as the tentative parameters of the DT-fusion reactor-tokamak.

In 1967, the possibility of reducing plasma losses to $1/100$ of the Bohm ones seemed practically unattainable. In conclusion, Kadomtsev cautioned enthusiasts of thermonuclear fusion [9]: "In order to achieve controlled thermonuclear fusion by this approach [i.e., in tokamaks], it will be necessary to overcome huge technical difficulties of creating a magnetic field on the order of 10 T in a cubic meter-scale volume. These are preliminary conclusions. Extensive physical surveys are needed to verify them... ."

Indeed, later research clarified the situation. Within a year after Kadomtsev's publication, L A Artsimovich reported at a conference held under the auspices of IAEA (Novosibirsk, 1968) that the plasma energy lifetime obtained in domestic T-3 and TM-3 tokamaks was 40 times the Bohm lifetime. Certain suspicious foreign researchers wished to check our measurements of the electron temperature, a key parameter of the T-3 experiment, by the direct laser scattering method then developed in the UK. In a year (in 1969), the joint British-Soviet team successfully repeated these measurements and gave reporters cause to announce with much ado that "the results proved even higher than those reported by the Russians." (The Russians measured average temperature by plasma diamagnetism, while the laser-assisted method offered a local temperature. The results obtained by the two methods were in good agreement within the scatter of measurements.)

Direct existence proof of an electron temperature around 1 keV in tokamaks caused sensation and led to restructuring several major research programs abroad. New specialists were recruited and newly built large tokamaks (see Fig. 1) were equipped with additional sources of plasma heating, such as beams of neutral atoms (NBI, Fig. 1), high-frequency heating systems (RF, Fig. 1), and present-day diagnostic facilities. As a result, the ion temperature of about 10 keV was recorded in the Princeton Large Torus (PLT) tokamak (USA, 1979) and the so-called breakeven condition was achieved in 1997 in experiments with a DT-mixture (NBI-DT, see Fig. 1) in the Joint European Torus (JET) tokamak (rough equality of thermonuclear fusion power (ca. 17 MW) and heat flux from the hot zone of the plasma column, i.e., thermal plasma losses). These experimental results constitute the basis for ITER. The gap between the Bohm lifetime and real energy lifetime of the plasma (ca. 1 s) amounted to hundreds of times, which allowed the ITER toroidal field to be reduced from 10 to 6 T at a minor plasma column radius of 2 m. As a result, the concept of the reactor-tokamak acquired concrete features remaining in the same energy limits as declared by B B Kadomtsev in 1967. (To recall, the first toroidal magnetic reactor proposed by Andrey D Sakharov and I E Tamm in the early 1950s had a similar minor radius (2 m) and magnetic field (5 T) but was designed to be used for DD-fusion instead of DT-fusion!)

After the death of L A Artsimovich in 1973, B B Kadomtsev took up his post of Head of the Plasma Studies Division at I V Kurchatov Institute of Atomic Energy (later the

Nuclear Fusion Institute at the Kurchatov Centre). Kadomtsev was in a way forced to take this position by his colleagues, who did not wish to see it occupied by an 'outsider'.

As Boris Borisovich Kadomtsev himself said in an interview to *Literaturnaya gazeta* (*Literary Gazette* magazine) soon before these dramatic events, he was a loner type of researcher, choosing to work with no more than one or two postgraduate students. In his new capacity, he had to alternate social, administrative, and other nonscientific activities, but in fact remained inwardly a skeptical researcher always concerned about the possibility of developing new spontaneous plasma instability able to reduce to nought his efforts as director. It seemed to hang heavy on him. He did not have inborn leadership qualities, and this fact proved highly beneficial for the tokamak program. Intense thinking about scientific problems being developed in his Institute brought forth fresh fruitful ideas that gave new impetus to experimental and theoretical research. In my opinion as an experimentalist in the field of plasma stability, two most popular ideas of B B Kadomtsev had the greatest influence on the understanding by plasma physicists of processes responsible for the macroscopic stability of tokamaks ('tokamak limits'). These ideas are indispensable components of the ITER physical concept:

(1) The idea of magnetic reconnection during development of large-scale instabilities in tokamaks (*Kadomtsev's internal disruption model*, 1975);

(2) The idea of ideal kink instability of the *vacuum bubble* type in the presence of low magnetic shear (in co-authorship with O P Pogutse, 1973).

The idea of magnetic reconnection was derived by Kadomtsev from astrophysics to account for transition of an ideal (without a change in the total magnetic flux) kink instabilities to resistive ones developing with a substantial loss of magnetic fluxes. The first example of successful application of this idea was interpretation of the so-called internal disruption or 'sawtooth' oscillations, i.e., characteristic instability at the center of a tokamak plasma column, manifesting itself as strictly periodic relaxation oscillations of its electron temperature.

It was shown in experiment that relaxations were preceded by the development of helical $m = 1$ perturbation resonant (i.e., having the same geometry) with the closed helical magnetic structure created by plasma current near the center.

In order to clearly demonstrate the mechanism of this phenomenon, Kadomtsev made use of the so-called additional magnetic field $\mathbf{B}^*$ (introduced earlier jointly with O P Pogutse) defined in the vicinity of a certain chosen closed helical magnetic structure as the vector difference between the real magnetic field $\mathbf{B}$ and calculated field, i.e., the magnetic field of the said magnetic structure extended over the entire region of interest. In other words, field $\mathbf{B}^*$ is identically equal to zero in the zone occupied by this structure. All magnetic lines in this zone have a similar helical geometry and therefore do not cross as they move relative to one another. Such a magnetic configuration was called configuration with *zero magnetic shear*.

The departure of the field $\mathbf{B}^*$ from zero means that the magnetic lines of force have a pitch angle different from that given by a closed magnetic structure; therefore, they ought to intersect during their motion relative to one another, i.e., to reconnect (*nonzero shear* case). The electroconducting plasma frozen into a magnetic field must hamper such an intersection

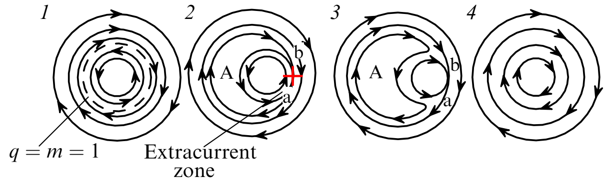

Figure 2. Schematic of internal disruption in a tokamak as postulated by Kadomtsev.

and reconnection. In other words, electric currents (*extracurrents*) must be induced in the putative intersection zone to hinder intersection of magnetic lines of force. By this means, magnetic fluxes and the plasma-confining magnetic configuration are retained in tokamaks. Abnormally fast dissipation of induced currents implies equally rapid reconnection of magnetic fields $\mathbf{B}^*$, loss of magnetic fluxes, and (accordingly) magnetic and plasma energies.

Evidently, really observable anomalously fast dissipation of extracurrents has a collisionless nature; in all likelihood, it is underlain by a certain variety of electron beam kinetic instability in the plasma. In astrophysics, anomalously fast magnetic reconnection is described in terms of the known Sweet – Parker model. Unfortunately, the same processes in tokamaks proceed more abruptly. Their physics is the subject of ongoing research.

Figure 2 presents a schematic of internal disruption in a tokamak as postulated *by Kadomtsev*. According to this model, the physical cause of internal disruption is an excessive concentration of plasma current close to the axis of the column due to a preferred heating of the plasma at the center and the resulting enhancement of its electric conduction. Concentration of plasma current in the central part of the column gives rise to a closed helical magnetic structure (shown by the dashed line in Fig. 2) formed by magnetic field lines that close up on themselves every other turn around the torus ($m = 1$). This is the first necessary condition for internal disruption to occur. Figure 2 illustrates the evolution of field $\mathbf{B}^*$ distributions at the center of the plasma column as inferred by Kadomtsev. There are four characteristic positions. Position *1* is the starting stationary position with an annular closed magnetic structure (dashed line), the maximum magnetic flux and energy accumulated at the center of the column. Current density dies away from column center to periphery; accordingly, field $\mathbf{B}^*$ changes sign as it crosses the dashed line. Position *2* corresponds to the evolution of the central ideal (i.e., retaining total magnetic flux) kink ($m = 1$) instability provoking internal disruption. The appearance of this instability is the second necessary condition for disruption; it is due to the accumulation of excessively high plasma energy near the axis and manifests itself as a helical ($m = 1$) displacement of the current axis with respect to the column center. Region a – b is the extracurrent generation zone (shown by the cross); the extracurrent prevents further outward shift of helical current perturbation as yet on retention of the total magnetic flux enveloped by perturbation helical axis. Position *3* displays the internal disruption proper or dissipation of extracurrent, implying reconnection of oppositely directed magnetic fields $\mathbf{B}^*$ on either side of the region of a closed helical magnetic structure ($m = 1$), *pressing-out* of the hot plasma of the former column center to the outside, loss of magnetic flux, and the formation of a central relatively cold *magnetic island* A with uniformly

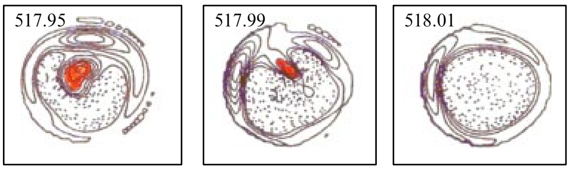

Figure 3. Time (in microseconds) sequence of SX-profiles during development of internal disruption in the Tokamak de Varenna [12].

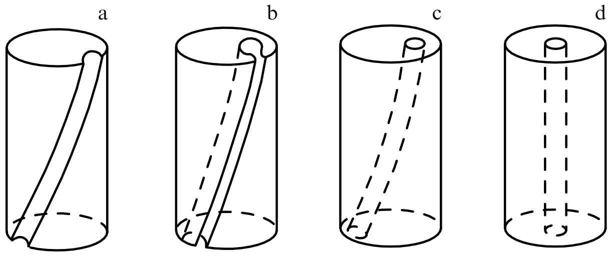

Figure 4. Successive steps of the penetration of a vacuum bubble into the center of the column [13].

distributed field $\mathbf{B}^*$, i.e., elimination of the closed structure ($m = 1$) within the entire central region (position *4*), signifying the appearance of the flattened current distribution at the column center. Thus, the process that started from ideal instability passes to dissipative instability accompanied by the loss of plasma magnetic and thermal energies. A distinctive feature of internal disruption is its local nature. It does not cause radical deterioration of the state of the plasma column as a whole. Flattening of current distribution at the center is followed by a smooth phase during which the flattened current profile gradually sharpens, and the process repeats itself in the form of quasistationary relaxations.

The *Kadomtsev model* has received wide recognition. Its validity was confirmed in numerous experiments, and the magnetic reconnection concept is extensively exploited by tokamak physicists.

Figure 3 presents X-ray tomographic images of the column central region obtained during the course of internal disruption in the Canadian Tokamak de Varenna. Equal-intensity contours of soft X-ray radiation roughly correspond to equal electron temperature. Evidently, the hot plasma core is pressed out from the center within tens of microseconds and substituted by a cold zone, closely following the scheme displayed in Fig. 2.

Another constructive idea of Kadomtsev suggested jointly with Pogutse permits us to explain the nature of major disruption in tokamaks. The authors hypothesized the development of ideal kink instability of the vacuum-bubble type under small magnetic shear conditions.

Unlike internal disruption, major disruption (or simply disruption) in a tokamak affects the entire zone through which the current flows and cools the whole column from the edge to the center for a few hundred microseconds. This is the most serious instability threatening the tokamak as a reactor. The zone where disruption instability develops bounds the region of permissible operating conditions and determines limiting parameters of the device ('tokamak limits'). The first question that arises is: what causes the rapid development of instability and fast transport of the cold plasma from the periphery to the center of the column? The vacuum-bubble capture model gives an answer to this question. It is schematically represented in Fig. 4.

Given perturbation at the edge of the plasma column in the form of a vacuum bubble or a vacuum tube (Fig. 4a) oriented along the tokamak helical field created by superposition of toroidal magnetic field $\mathbf{B}_{\mathrm{T}}$ and poloidal current field $\mathbf{B}_{\mathrm{p}}$, the magnetic energy stored in such a bubble must equal $(B_{\mathrm{T}}^2 + B_{\mathrm{p}}^2)/8\pi$ multiplied by the tube volume. The energy of a similar tube at the center of the column (Fig. 4d) will be proportional only to $B_{\mathrm{T}}^2/8\pi$ (the poloidal magnetic field at the center being negligibly small). Therefore, it is energetically advantageous for the bubble to pass from the periphery to the center of the plasma column; in other words, the vacuum bubble created at the edge of the column appears to be potentially unstable. Such motion of the bubble is illustrated in Figs 4b, c. What can hamper it? It can easily be shown that the answer is: the magnetic shear can. Such a passage of the vacuum tube is feasible only under zero shear conditions over the entire cross section of the column, when perturbation propagating toward the center draws the magnetic lines of force apart but does not intersect them. In this case, magnetic fluxes remain virtually unperturbed. In other words, ideal kink instability takes place with an inherently high increment. But zero shear in a tokamak must correspond to the ideally flat current distribution over the cross section, unattainable in experiment, where current density changes in parallel with electron temperature (i.e., electrical conduction) of the plasma that takes dissimilar values in different parts of the column. Under real conditions, it is the magnetic shear that maintains the existence of plasma column in a tokamak by preventing penetration of peripheral cold plasma into the core. As exemplified above by the development of internal disruption, internal instability may lead to the flattening of current distribution at the center of the column, i.e., cause local lowering of magnetic shear. Experiments (S V Mirnov, I B Semenov, T-4 tokamak, 1976) demonstrated the development of a powerful single analog of internal disruption at the column center a few dozen microseconds before the onset of major disruption; it spreads not only over an $m = 1$ perturbation region but also over $m = 2$. As a result, magnetic shear decreases practically across the entire hot zone of the plasma column; this signifies fulfillment of the condition of 'cold bubble' penetration into its center set by the Kadomtsev – Pogutse model. Elucidation of the mechanism of disruption, identification of its precursors and the safe operation zone of the reactor-tokamak were priority issues for B B Kadomtsev at the time of developing the physical basis of the ITER.

What gives us reason to expect that the planned power (500 MW) of DT-fusion will be achieved in the ITER? The necessary plasma temperature (above 10 keV) has already been obtained and the necessary plasma density n on the order of 10^{20} m^{-3} is not too high for tokamaks (the highest reported $n \approx 10^{21}$ m^{-3}). What remains to be reached is the record energy lifetime τ_E, which must be as large as 3 – 5 s against the present 1 s.

Parametric analysis of databases obtained with different tokamaks of ITER-like magnetic geometry allowed deriving the ITER's scaling law for τ_E:

$$\tau_{E,98} = 0.0365\, I_{\mathrm{p}}^{0.97} B_{\mathrm{T}}^{0.08} P_{\mathrm{H}}^{-0.63} n^{0.41} M^{0.20} R^{1.93} \left(\frac{a}{R}\right)^{0.23} k^{0.67}\ \mathrm{s}\,,$$

where $2a$ is the lateral dimension in meters, R is the major radius of the torus [m], I_{p} is the current [MA] flowing through

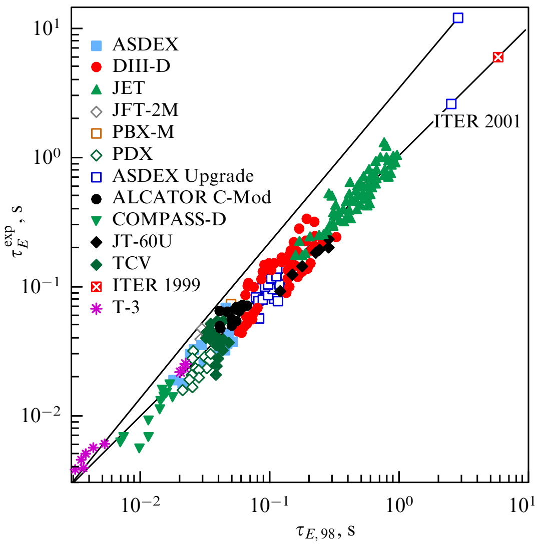

Figure 5. Experimental τ_E values and extrapolations of $\tau_{E,98}$ and $\tau_{E,68}$.

the plasma, n is the number density [10^{19} m^{-3}], B_T is the toroidal magnetic field [T], P_H is the heating power [MW], M is the mass of ions measured in the proton mass, and k is the vertical elongation of the plasma column. ITER parameters allow τ_E to be around 4 s. Figure 5 gives an idea of the departure of real τ_E from this law in different tokamaks. Rounding off and neglecting power terms with exponents smaller than 0.2, this law can be written out in a simpler form:

$$\tau_{E,98} \sim I_\mathrm{p}\, n^{0.4} R^{1.7} a^{0.2} P_\mathrm{H}^{-0.6} k^{0.7} .$$

In this form, it closely resembles the similarity rule offered by L A Artsimovich at the IAEA Conference in Novosibirsk (1968): $\tau_{E,68} \sim B_\mathrm{p} a^2 n^{1/3}$ or $\tau_{E,68} \sim I_\mathrm{p} n^{0.33} a$, since $B_\mathrm{p} \sim I_\mathrm{p}/a$.

Substituting ITER parameters into this expression, a physicist of 1968 (when absolute τ_E values were 1–6 ms) would have had 12 s, i.e., only 3 times what the same physicist would obtain 30 years later. In Figure 5, extrapolation from 1968 is shown by the upper straight line. Thus, it can be concluded that even at a 1000-fold rise in τ_E, the tokamak as a physical object exhibits surprisingly stable similarity. Evidently, it ought to persist, i.e., τ_E will increase only 4-fold upon passage from current tokamaks to the ITER.

However, an important distinctive feature of the expression for $\tau_{E,98}$ (decreasing dependence on heating power $\sim P_\mathrm{H}^{-0.6}$) causes some concern. It was absent in the similarity law for $\tau_{E,68}$ because the latter was derived only for conditions of ohmic plasma heating, during which P_H varies but insignificantly. This feature allows a simple physical interpretation. Bearing in mind that $\tau_E = W/P_\mathrm{H}$, where W is the plasma thermal energy, P_H can be eliminated from the right-hand side of the expression for $\tau_{E,98}$, which then takes the form

$$\tau_{E,98} \sim \left(\frac{1}{\beta_\mathrm{T}}\right)^{1.7} V^{1/2} B_\mathrm{T}^{0.6} ,$$

where V is the plasma volume, β_T is the ratio of plasma pressure to toroidal magnetic field pressure ($B_\mathrm{T}^2/8\pi$) — the second most important parameter characterizing hot plasma confinement in tokamaks. In all likelihood, it is a rise in this parameter, i.e., the energy of the plasma being heated, that is responsible for $\tau_{E,98}$ degradation with increasing P_H. Evidently, its optimization will be the main problem facing the ITER experimental program, the more so as it directly determines the commercial attractiveness of the tokamak as a reactor.

With β_T remained at the planned level (2.5%), it would be commercially justified to use the tokamak as a breeder reactor for completely burning radioactive wastes of conventional nuclear power plants. It was estimated that the introduction of a ^{232}Th blanket into a fusion reactor analogous to the ITER would yield an electric power of up to 1 GW and annually produce up to 2 tons of ^{233}U as a fuel for nuclear reactors. This amount of ^{233}U would be sufficient to generate an additional 2 GW of electric power. To recall, a power of 3 GW roughly corresponds to half the total power of the Krasnoyarsk hydroelectric plant. Such are the stakes on the line. Evidently, the road from the ITER to commercially efficient energy-producing systems will be at least as long and hard as that from the first atomic reactors of Fermi and Kurchatov to modern industrial-scale nuclear power plants. However, the first psychologically most difficult step has been made: it was shown that such a conversion *is physically possible*.

We are proud that the first physical thermonuclear reaction was accomplished in this country and in our tokamaks in the late 1960s and early 1970s, that the world's scientific community took up and further developed this idea (see Figs 1 and 5), and that the theory of thermonuclear plasma behavior was for the major part developed by our scientists and was enthusiastically accepted by their foreign colleagues. Boris Borisovich Kadomtsev was a key actor in this global process.

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