fastest economic growth and, accordingly, of fastest development of the scientific complex.

Lev Andreevich belonged to the generation of 'personalities of national significance', whose life and creative activity was motivated not only by their extraordinary spirit and scientific talent, but the entire course of history of our native land. They came as an embodiment of the aspiration to serve lofty and impersonal purposes, which is so typical of the Russian intelligentsia. The beneficial influence of these outstanding people who came to know well not only the blessing of scientific creative activity, but the innermost mechanisms of science organization and the top national priorities as well, persisted for many years after they were gone.

Lev Andreevich was in charge of the physics research in our country for 17 years since 1957, when our division has been renamed the 'Division of General and Technical Physics' and detached from the former Division of Physico-Mathematical Sciences of the USSR Academy of Sciences.

Lev Andreevich gave much consideration to the problems associated with the institution of research. He outlined his credo in a brilliant report presented at the meeting of the Presidium of the USSR Academy of Sciences on 3rd December 1964. He considered a proper decision upon the line of investigation to be the key point. He believed that astrophysics and the physics of elementary particles were those lines at that time. In his opinion, only in these fields could the discovery of fundamentally new phenomena be anticipated. This viewpoint was fully confirmed later. He also believed that solid-state physics had been thoroughly studied, so that no major discoveries would be forthcoming. But present-day research in this field steadily yields excellent results. Lev Andreevich would have supposedly assigned them to applied results. In general, the proper correlation between fundamental and applied sciences and the promotion of scientific results are rather intricate questions. Scientific results are introduced in life by no means easily or fast, and all attempts to speed up this process by passing government resolutions would meet with only limited success. Lev Andreevich was firmly convinced that academic institutes should pursue only fundamental research despite the fact that this viewpoint was not shared by the majority of scientists. They believed that detachment from real life was impermissible, that industrial branch institutes had for the most part insufficient qualifications to find the applications for the results of fundamental research, and that academic institutes should therefore pursue applied research, too. It is pertinent to note that the question of the interrelation between fundamental and applied sciences is still an open question.

Lev Andreevich placed particular emphasis on the staff. He reasoned correctly that new laboratories and institutes should not be established unless there is a bright personality who has achieved much success in science. A prominent example of this kind: the Candidate of sciences Yuriĭ Nikolaevich Denisyuk, one of the founders of holography, was elected a Corresponding Member of the USSR Academy of Sciences.

Lev Andreevich Artsimovich believed that scientific activity should not be confined to Moscow and Leningrad. Major academic research centers should encompass the entire territory and involve residents of many regions in scientific activity. The now-familiar research centers like those at Troitsk, Chernogolovka, and the Special Astrophysical Observatory were formed in the time of L A Artsimovich. The instrument making and technological basis for physics and astronomy made rapid strides. He devoted much effort and personal time to attain these ends and would use his authority in government circles. Were it not for active participation, our biggest telescopes, the optical BTA and radiowave RATAN-600, would never have been realized.

Also noteworthy is the remarkable style of supervision or, to be more precise, of education of the staff members of the Division of General Physics and Astronomy, RAS. Owing to this, after Lev Andreevich passed away, our division (as before, it is the largest in the RF Academy) remained stable and grew steadily for many years to come. This style is characterized by more than the quest for high scientific and organizational standards. Exacting to his collaborators, Lev Andreevich preserved, brought up, even 'cultivated' in them the spirit of independence, the ability to make quick and efficient decisions and to act under any circumstances and in any instances. He never allowed himself petty cares, was a man of his word, consistent in decisions and careful. His co-workers always had the feeling of a secure rear and could expect reliable backing, objectivity, and support.

Today our scientific community, together with the entire country, is living through one of the most arduous periods in its history. May the bright example set by Lev Andreevich Artsimovich keep up our spirits.

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Trends in magnetic helical systems for CNF

V D Shafranov

Introduction

This year, the 25th of February was the 90th anniversary of the birth and the 1st of March, the 26th anniversary of the decease of Academician Lev Andreevich Artsimovich, an outstanding physicist, a man of rare combination of logic and intuition, the first Academician-Secretary of the Division of General Physics and Astronomy of the USSR Academy of Sciences. He was a person of brilliant and aphoristically thinking mind; a man of extensive knowledge; an ironical, witty, and sarcastic critic; an irreconcilable opponent of publicity campaigns and superficial studies in science. Lev Andreevich was among the magnificent four of our physicists and outstanding personalities to whom the controlled nuclear fusion (CNF) research in our country owes its highest level since its inception. They are Academicians A D Sakharov and I E Tamm, who put forward and elaborated the basic principles of magnetic thermal insulation of a plasma, and Academicians L A Artsimovich and M A Leontovich, who instituted the studies which gave birth to the foundations of high-temperature plasma physics and controlled nuclear fusion. The task of supervising the experimental research and verifying theoretical predictions in the field of CNF as well as guiding the quest of real conditions of high-temperature plasma production and confinement fell to precisely the lot of L A Artsimovich.

Helical magnetic systems is an extended name of the stellarator systems of magnetic plasma confinement. Since their declassification in 1958, stellarators (toroidal facilities in which the system of nested magnetic surfaces necessary for plasma confinement is established by external currents, not requiring the induction of current in the plasma) have competed with tokamaks. These two systems have always been in invisible competition with each other. Lev Andreevich Artsimovich as the one in charge of the national program of controlled nuclear fusion and the direct supervisor of experimental tokamak research (since 1962) joined in the race recklessly and won. At the 3rd International Conference on Plasma Physics and Controlled Nuclear Fusion Research in Novosibirsk (1968), he reported that an electron temperature of about 1 keV was obtained in the T-3 tokamak [1]. When summarizing the results of the conference, he spoke confidently as follows: "We have found escape from the gloomy ghost of tremendous losses, which is embodied by the Bohm formula, and have opened up the way for a further rise in temperature up to the physical fusion level". But our foreign colleagues did not perceive the tokamak facility seriously at that time. Just as they disregarded the report made four years before at the preceding conference in Culham that the T-3 tokamak was devoid of that enhanced Bohm diffusion which repeatedly showed up in the Princeton C stellarator, so was the then fantastic temperature of 1 keV met with disbelief by some of them. That is why Lev Andreevich proposed to R S Pease, Director of the Culham Laboratory, that a group of physicists who had elaborated the method of local temperature measurements from Thomson scattering should be sent to the Kurchatov Institute of Atomic Energy. This September will be the 30th anniversary of the Second International Symposium on Toroidal Systems in Dubna (1969), so memorable to its participants, at which the results were reported on this Soviet-British experiment on the local measurements of electron temperature [2]. They confirmed the conclusions sounded the year before in Novosibirsk. The Dubna Symposium marked the commencement of the advance towards the fusion plasma parameters and became, it is safe to say, the finest hour of Lev Andreevich.

In the quarter of a century that has passed since the decease of Lev Andreevich, tokamaks world-wide have become the primary system for obtaining high-temperature plasmas. But in connection with the production of genuine fusion plasmas in big tokamaks, interest has also quickened in helical (stellarator) magnetic systems of plasma confinement.

Two of the participants of the British-Soviet experiment, D Robinson (now the Director of the Culham Laboratory) and V Sannikov, with L A Artsimovich after Robinson's report about the experimental results from the T-3 tokamak. Second International Symposium on Toroidal Systems (Dubna, September 1969).

The early history of tokamaks and stellarators

The CNF research commenced in the early 50s with magnetic confinement systems in the three countries: UK, USSR, and USA. Each of these countries pioneered CNF research along one of the lines involving toroidal systems:

UK became the forefather of toroidal pinches with stabilization by a relatively weak toroidal magnetic field, which gave birth to the reversed field pinch [1];

USSR became the forefather of a tokamak;

USA became the fatherland of a stellarator, or helical systems, in a broader sense.

Both tokamaks and stellarators are systems topologically equivalent to a torus, with primarily the toroidal, i.e. going around the principal torus axis, direction of the magnetic lines of force. With the axial symmetry of the system, the toroidal magnetic field is similar to the magnetic field of a direct current, i.e. it falls off with distance from the principal torus axis as $1/r$. In this field, positively and negatively charged particles drift parallel to this axis in opposite directions. The resulting charge separation in the plasma gives rise to an electric field aligned with the torus axis, which is responsible for the plasma drift in the grad r direction, i.e. away from the torus axis. In the macroscopic description, this drift corresponds to the action of the force of balloon expansion of a toroidal plasma column. In the initial (1950) calculations of a toroidal magnetic fusion reactor (MFR) with a deuterium plasma (the minor model with a continuous power input [3] and the major model with a self-sustaining fusion reaction [4]), I E Tamm and A D Sakharov neglected the effects of toricity. It was only at the end of his paper dated 1951 that A D Sakharov put forward two proposals for the 'stabilization' of toroidal drift: (i) suspension of the current-carrying ring on ropes in a toroidal magnetic field (the precursor of a levitron proposed in the USA in the 60s), and (ii) the second proposal, which brought tokamaks into being, sounds as follows: "An alternative way of antidrift stabilization, which is incomparably more acceptable and should therefore receive careful consideration, is the formation of an axial current directly in the plasma by the induction method".

[1] These systems are the first remarkable example of plasma 'self-organization' — the stabilization of current instability is accomplished in them through the continuous generation of toroidal magnetic flux in the plasma, which exceeds the initial flux inside the conductive chamber. In this case, the conservation of the magnetic flux inside the conductive chamber is provided by the reversal of the magnetic field in the domain between the wall and the hot plasma. The mechanism of magnetic flux generation is also responsible for the enhancement of plasma diffusion. At present, studies are underway to find ways of improving the plasma confinement by sustaining externally a poloidal electric current, which is a source of the toroidal magnetic flux.

In the USA, while contemplating the method for plasma confinement in the magnetic field, Lyman Spitzer abandoned the use of current in a torus [2]. Recognizing the problem of toroidal drift, he proposed a solenoid in the form of a spatial figure eight for its neutralization [6]. This simplest stellarator of circular section had a spatial axis but was void of the of magnetic field lines shear of force and the 'average magnetic well' required for MHD plasma stability. Enhanced (Bohm) diffusion was repeatedly observed in it. In September 1958, the Second International Conference on the Peaceful Uses of Atomic Energy was held in Geneva, where previously strictly classified papers on controlled nuclear fusion were reported. The Spitzer stellarator was the highlight of this, according to L A Artsimovich, 'fair concept'. The feasibility of principle of toroidal plasma confinement in the magnetic field without inducing an internal current, revealed by Spitzer, then appeared to be the only viable trend of CNF research. Suffice it to say that in 1959 the pursuance of the tokamak program at the Kurchatov Institute of Atomic Energy was jeopardized. The salvation was the awareness that the initial plasma heating in stellarators should be accomplished, like in a tokamak, by the electric current induced in it (other methods of heating, namely, high-frequency heating and neutral-beam injection had not yet been developed). But in so doing the system of minimum torus length L (in this case the condition for the helical instability allows higher currents to provide a sufficiently strong plasma heating even without recourse to additional heating techniques) and maximum radius of plasma cross-section (plasma energy and particle losses reduce and the impact of sputtering of the chamber walls on the plasma weakens) is an advantage. Together with I N Golovin, N A Yavlinskiĭ actively promoted the tokamak concept (by then formulated in essence in Ref. [7]), which developed A D Sakharov's idea, and gave it the name tokamak in 1957. N A Yavlinskiĭ upheld the T-3 tokamak project elaborated by the end of 1958. And it was precisely in this tokamak where a plasma temperature of 1 keV was attained in the late 60s. That was the commencement of the entry of a tokamak to the international scene and of the termination of other lines of CNF research (straight pinches, systems with internal circular currents, magnetic mirror traps, etc.) in several laboratories.

Tokamaks 30 years later after the Dubna Symposium

Advances of tokamaks. Since the 70s, tokamaks have been disseminated widely and now they number about a hundred world-wide. JET (Western Europe), the largest of them, is characterized by a plasma torus of radius $R = 3$ m and a D-like plasma cross-section of diameter $2a = 2.5$ m and height $2b = 4.2$ m. A fusion power of 16 MW for 0.85 s was obtained in the deuterium-tritium plasma experiments in this facility in 1997 [8]. The power gain coefficient Q (the fusion-to-heating power ratio) ran right up to the first milestone in the production of controlled fusion energy, $Q = 1$. A somewhat lower fusion power of 10 MW with $Q = 0.25$ in a deuterium-tritium plasma was obtained in the TFTR tokamak ($a = b = 0.85$ m, $R = 2.5$ m) of the Plasma Physics Laboratory at Princeton University in 1994 [9]. On the big Japanese JT-60M tokamak ($a/b = 0.95/0.75$, $R = 3$ m), deuterium plasma parameters were recently obtained for which the Q value in a deuterium-tritium plasma would have been $Q = 1.25$. The plasma temperature and density in these biggest-tokamak experiments were $T = 30-40$ keV and $n = 10^{19}-10^{20}$ m^{-3}. Therefore, the tokamak experiments have proved in effect the feasibility of the controlled fusion reaction with a power sufficient for a fusion reactor.

[2] "... He preferred steady-state operation and chose not to use an internal current to set up the magnetic field in closed devices as in pinches or tokamaks ..." [5].

Tokamak plasma physics news. A progressive movement towards the attainment of fusion plasma parameters in tokamaks has served as the whys and wherefores of the development of the project of the International Tokamak Experimental Reactor (ITER). This does not signify that the experimental and theoretical studies of tokamak plasma confinement have come to a close. During the construction and putting into service, a lot of physical problems are to be solved to increase the reliability of operation of the first fusion reactor. Many teams of physicists from different countries now espouse this work. Undeniably, tokamaks owe their world-wide distribution to the relative simplicity of the design and small bulk. Though simple in geometry, a tokamak has proven to be a challenge as regards plasma physics. The plasma is sufficiently well confined only for a special shape of the distribution of the toroidal current density. Fortunately, extensive research has revealed several remarkable properties of the tokamak plasma. First and foremost, it turned out that the self-organization of stable plasma confinement modes could be realized in a tokamak plasma [10]. Moreover, in addition to the retention of a stable current profile, under certain conditions there develop regimes with an improved thermal plasma insulation due to the spontaneous origination of a 'thermal barrier' — a toroidal tubular layer with strongly retarded transport processes. The study of these regimes now commands the attention of researchers.

Continuous current maintenance. Nature also looked with favor at the researchers who were attempting to sustain a continuous current. It proved to be possible due to two remarkable discoveries: the passive and active generation of noninductive current. The generation of the passive noninductive current is inherent in a tokamak owing to diffusion of 'banana' (at the torus cross-section) drift trajectories of charged particles trapped due to the nonuniformity of the toroidal magnetic field. The banana width determined from the law of conservation of the toroidal momentum of the guiding center of a Larmor circle does not depend on the toroidal magnetic field. Therefore, the process of plasma diffusion, which involves the transit-to-trapped particle transformation (owing to collisions) and particle jumps from one banana trajectory to another (for the same reason), proceeds as if in a purely poloidal magnetic field and, hence, with the generation of a toroidal current ('bootstrap' current). However, the bootstrap current alone fails to confine the tokamak plasma continuously. The aid comes from the current generation by momentum transfer to ions from the atoms injected or to electrons from the electromagnetic radiation. The use of a narrow beam of electromagnetic radiation generated by a gyrotron makes it possible not only to maintain the required magnitude of the current but to control its distribution as well, and hence controlling improved confinement regimes is in sight. Continuous maintenance and control of the current distribution do call for serious expenditure.

Moreover, in a tokamak plasma there persists the possibility of a catastrophic current disruption instability, when the hot plasma core as if turns inside out to release the stored energy at the chamber wall. This instability is one of the most serious tokamak problems. A search is now being conducted, and not without success, for methods meant for controlling its development and prevention. But the cardinal solution for CNF would be stationary systems of magnetic plasma confinement.

The role of a tokamak in the development of stationary CNF systems. Among the stationary systems in the CNF problem are the following, alternative with respect to a tokamak: helical toroidal systems of magnetic plasma confinement — stellarators; open systems with magnetic mirrors (magnetic bottles, or mirror traps), and internal-ring toroidal devices ('Galateas' [11]) [3]. Most advanced among them are stellarators — the nearest relatives of the tokamak. They have much in common with tokamaks: the system of topologically toroidal nested magnetic surfaces; toroidal and poloidal magnetic fluxes as an invariant measure of the strength of toroidal and poloidal magnetic fields; rotational transformation as the limit of the ratio of the rotation numbers of a magnetic field line in the poloidal (around the magnetic axis) and toroidal (along the magnetic axis) directions — these are the general characteristics of the systems. The primary dissimilarity from a tokamak is in the geometry: in a stellarator, the plasma column is helically goffered rather than smooth. The shape of magnetic coils to set up the needed magnetic surfaces is far more complex than in a tokamak. Therefore, a stellarator is a system less versatile than a tokamak. But this complexity is purely technical. A multitude of difficulties encountered in reaching fusion plasmas are common to all thermonuclear reactors with magnetic plasma confinement. And they have been or are solved in more flexible tokamaks. Among them are: development of the diagnostic techniques for determining plasma parameters and studying the physical processes which affect the energy and particle transport in high-temperature plasmas; reduction of the inevitable plasma doping with high-Z impurity atoms by selecting the appropriate low-Z material to be coated onto the vacuum chamber walls; prevention of wall disruption by diverting external magnetic field lines into a special 'divertor' volume with a dense neutral gas to reradiate the energy of the plasma particles escaping the main confinement volume and flowing along the magnetic field lines into the divertor volume; development of plasma heating and refueling systems; mastering the vacuum technology of large volumes, and, finally, operation on cryogenic systems and superconducting magnetic coils. By solving a variety of problems of this kind, tokamaks have done more than pave the way for the advent of the first experimental fusion reactor around a tokamak. They have also fostered the development of other, probably more reliable, stationary magnetic systems in which the fusion plasma may be confined without excitation of the electric current in the plasma whatsoever.

[3] These systems can be referred to as stationary with the following reservation: on loss of superconductivity the internal ring and the surrounding plasma sink, so that the reactor operation is most likely to be cyclic.

Innovative helical magnetic confinement systems

From Spitzer's figure 'eight' to well-optimized stellarators. Plasma 'pump out' from the confinement region was repeatedly observed both in the first stellarators of the 50s in the form of a spatial figure eight with a plasma of circular section and in a racetrack 'Stellarator C' with two-pole and three-pole helical windings ($l = 2$ on one side of the racetrack and $l = 3$ on the other) in Princeton in the 60s. The primary reason was the unfortunate choice of the magnetic system: (i) the arrangement of helical current-carrying conductors only at rounded parts and, what is more, a different number of poles does not ensure the formation of the system of nested magnetic surfaces required for plasma confinement, and (ii) the large ratio between the plasma column length ($L = 12$ m) and the perimeter of the plasma cross-section ($L/2\pi\langle a_{\rm p}\rangle = 40$, compared with the T-3 tokamak where the corresponding ratio is $R/a_{\rm p} = 8$) implies a small magnitude of the poloidal magnetic field which plays a leading part in plasma confinement. In a 'Stellarator C' it was not greater than 100 G while in T-3 no less than 10^3 G. In addition, the small chamber radius ($a_{\rm c} = 10$ cm) made a strong plasma–wall interaction inevitable. The consequences were a low plasma temperature, Bohm diffusion, and eventually an adverse effect on CNF, especially on helical (stellarator) systems. But the interest in stellarators was never lost. Stellarators were attractive because of the stationary state of the magnetic field for plasma confinement. For A D Sakharov and I E Tamm, who proposed the concept of a magnetic fusion reactor, intended precisely a stationary reactor. The use of an inductive toroidal current was a forced measure and even caused disappointment. It was not without reason that the emphasis in the CNF research pursued at the Kurchatov Institute of Atomic Energy (LIPAN at that time) was initially placed on simple pinches: if current is a necessity, what is the toroidal magnetic field for? Later it was addressed in effect as a means of stabilizing the necking and kink pinch instabilities. But immediately after the Geneva PUAE Conference (1958), when a wealth of ideas in the field of CNF became available, tokamaks did not appear to be simple. Moreover, it was not clear what innovations could be introduced in tokamak research, compared to that pursued at LIPAN. As for stellarators, they were widely diversified and allowed a variety of approaches. Therefore they began to progress rapidly. In the plasma laboratory of the P N Lebedev Physics Institute (FIAN), now a part of the Institute of General Physics, RAS, a two-pole stellarator with a circular axis was immediately adopted, the one which seemed to be most attractive. In the Khar'kov Physical-Technical Institute, research was undertaken on stellarators with both planar and helical axes. Initially, a three-pole racetrack-shaped stellarator was the basic one. A start was made on stellarator research in Novosibirsk and Sukhumi. Researchers at the Max Planck Institute for Plasma Physics in Garching (Germany) also counted on a stellarator. Somewhat later a start was made on stellarator research at the Universities of Kyoto, Nagoya, and Sendai (Japan), the Culham Laboratory (England), and more recently in Universities of Spain and Australia. The biggest stellarator programs are now pursued in Japan and Germany. Two-pole stellarators with a circular axis and approximately elliptic magnetic-surface cross-sections, which rotate along the length of the torus, proved to be the most fruitful. The needed magnetic configuration in the stellarators is produced when the transverse field of four continuous helical windings with currents of alternating directions ('conventional' stellarators) is imposed on the toroidal magnetic field. A version of a stellarator with only two helical windings with currents of the same direction, which does not require the coils of toroidal field, received the name torsatron. A more flexible system allowing for independent inclusion of the additional toroidal field is termed a heliotron. Gradually, the plasma parameters of two-pole stellarators were brought to the level of the tokamaks in their category (in geometric and physical parameters). With the availability of high-power sources of plasma heating (beams of accelerated neutral atoms and high-frequency techniques), attaining plasma temperatures up to 1 – 3 keV ceased to be a problem. On the fairly large Heliotron-E stellarator in Kyoto and a compact device CHS (Compact Helical System) of the heliotron – torsatron type, record magnitudes of the critical 'beta' parameter (the averaged plasma pressure-to-magnetic field pressure ratio) of 2% and 2.1% were attained.

One of the primary problems associated with helical systems resides in the enhanced diffusion in the range of low particle collision frequencies typical of the fusion reactor conditions, which was discovered in the neoclassical transport theory. By numerous numerical simulations and analytic treatment, theorists inquired to what extent the theoretically predicted transport can be reduced by optimizing the azimuth dependence of the pitch of continuous helical current windings. This line of investigation is supposedly completed by putting into service the biggest stellarator in Japan, namely, the LHD (Large Helical Device) heliotron with superconducting coils (the torus radius is 4 m and the plasma radius 0.6 m; the maximum heating power of 20 MW is intended for production of a plasma with the number density $n = 10^{20} - 10^{19}$ m^{-3} and temperature 3 – 10 keV).

The evolution of computer technologies made feasible a new formulation of the optimization problem for 3-D devices of magnetic plasma confinement, which was implemented by German physicists in the 80s. It proceeds from the plasma configuration rather than from the sources of a magnetic field. To be more specific, it proceeds from the parametric representation and optimization of the boundary toroidal magnetic surface (BMS). In the framework of this approach, numerical calculations involving 3-D equations of equilibrium, energy and particle transport equations, and criteria for plasma stability are used to determine the maximum permissible plasma pressure-to-magnetic field pressure ratio (the 'beta' parameter) for a fixed BMS. The optimum shape of the boundary magnetic surface is determined by varying the BMS parameters successively. The calculated distribution of the magnetic field outside the optimized BMS is used to determine the shape of the modular twisted windings whereby the optimum system is just realized. Modular windings minimize the 'scattered' magnetic field outside of the windings and thus differ advantageously from continuous windings in energy efficiency. The WVII-AS stellarator (with a major torus radius of 2 m and a mean minor radius of 0.2 m) in Garching, based on this principle, is in successful operation. It is used to obtain plasmas with a relatively high temperature of 3 keV. But the limiting 'beta' amounts approximately to only one percent, which is obviously insufficient for a fusion reactor. Subsequent passage from the planar circular magnetic axis to the spatial, helical axis resulted in a fundamental improvement of a stellarator performance [12]. The WVII-X stellarator (major radius of 5.5 m, mean minor radius of 0.53 m) embodying the new concept, with the limiting theoretical 'beta' = 5%, is now under construction in Greifswald. Simultaneously, a comprehensive project of an experimental reactor-stellarator with a helical axis is being elaborated, which exceeds the experimental WVII-X in linear dimensions by about a factor of four. A theoretical consideration of the optimization results on stellarators with a spatial axis led to the concepts of 'quasi-symmetry' [13 – 15] and 'pseudosymmetry' [16], which provide a recipe for producing 'omnigenous' (nested) or 'quasi-omnigenous' surfaces of charged particle's drift, i.e. for the elimination or depression of the radial excursion of plasma particles and thus for the optimization of 3-D magnetic plasma confinement devices. This approach to stellarator optimization has led to a new avenue of research in advanced or improved stellarator systems [17].

Advanced stellarator systems. Systems with a spatial (not planar) magnetic axis of the helix-on-imaginary-torus type and an optimized boundary magnetic surface are referred to as advanced devices. The spatial axis makes it possible to decouple the relation between the system length and the axis curvature. The point is that in the case of a 'planar' circular axis the equilibrium is improved with decrease in curvature while stability may be improved with increase in curvature of the axis [4]. What is more, in the case of magnetic configurations with a spatial axis the possibility appears to alter the topography of the $B =$ const lines on magnetic surfaces.

Significance of the topography of the $B =$ const lines on the magnetic surface. The theoretical basis for the new approach to the optimization of helical (and, more broadly, in general 3-D systems void of axial symmetry, unlike tokamaks) magnetic systems for plasma confinement is the study of the topography of B-lines (lines of an equal magnetic field strength on magnetic surfaces). It is the topography of precisely these lines that determines the character of the drift motion of the charged particles and hence the neoclassical transport in the regime of scarce particle collisions. In a perfectly symmetric tokamak, these lines have the form of circles centered on the principal axis of torus. In this case, the drift motion does not draw the charged particles far away from the magnetic surface. The discreteness of the coils of toroidal magnetic field gives rise to B-line island structure, which is responsible for additional bumpy losses of particles from plasma. In stellarators, the B-line island structure of this kind (not to be confused with the island structure of magnetic field lines!) appears due to the nonuniformity of the longitudinal (toroidal) magnetic field. In systems with a spatial axis, continuous variation of the B gradient direction, determined by the principal normal to the magnetic axis, along the length of the system permits the B-line closure into islands to be avoided. In this case, by selecting the BMS all the B-lines can be made topologically similar to those in the axially symmetric tokamak, i.e. being closed only after a complete detour in the toroidal direction. Such *pseudosymmetric* systems open up the possibility of decreasing substantially the neoclassical transport in a fusion plasma.

[4] This is achieved by selecting the BMS shape, for which a magnetic field line rotates slowly within the magnetic surface, on the side of it facing the center of curvature of the axis. As this takes place, the 'minimum-average-B criterion important for plasma stability is fulfilled: the average of the square of the field strength increases with distance from the axis.

Quasi-symmetry. This event will necessarily occur if the pseudosymmetry direction can be brought into coincidence with the invariant direction on the magnetic surface, determined by the quasi-symmetry vector [14]

$$\mathbf{Q}_{\text{tor}} = \frac{F\mathbf{B} + \mathbf{B} \times \nabla\Psi}{2\pi B^2} .$$

Here F and Ψ are the poloidal electric current and the poloidal magnetic flux that links the closed contour, aligned with the toroidal direction, on a magnetic surface. In the context of a tokamak, the $\mathbf{Q}_{\text{tor}}$ vector which has dimensions of length is expressed as $\mathbf{Q}_{\text{tor}} = \nabla\varphi/(\nabla\varphi)^2$, where φ is the polar angle of the cylindrical system of coordinates, with the axis made coincident with the principal torus axis. When the condition for toroidal quasi-symmetry is fulfilled, $\mathbf{Q}_{\text{tor}} \cdot \nabla B = 0$, the equations of the drift motion even have an integral (conservation of the canonical toroidal momentum of the guiding center)

$$\Psi + \rho_{\|}F = \text{const} .$$

In this formula, $\rho_{\|}$ is the Larmor radius calculated with respect to the longitudinal (along the magnetic field line) velocity of a charged particle and expressed in terms of B and the electric potential using the condition for conservation of energy. The quasi-symmetry condition cannot be met over the entire volume but it can be fulfilled approximately [by minimizing the harmonics in the spectrum of $B(\Psi, \theta, \zeta)$, which depend on the ζ-coordinate along the quasi-symmetry vector, yielding good results [18].

Poloidal quasi- and pseudosymmetries. By analogy with toroidal quasi- and pseudosymmetries, poloidal quasi- and pseudosymmetries can also be referred to. In this case, with the proviso that $\mathbf{Q}_{\text{pol}} \cdot \nabla B = 0$ the quasi-symmetry vector and the corresponding integral of motion are expressed by the formulas

$$\mathbf{Q}_{\text{pol}} = \frac{J\mathbf{B} + \mathbf{B} \times \nabla\Phi}{2\pi B^2} , \quad \Phi + \rho_{\|}J = \text{const} .$$

Here, J and Φ are the toroidal electric current and magnetic flux linking the cross-section contour on the magnetic surface. The case of poloidal quasi-symmetry is notable for the fact that the integral of motion is independent of the particle parameters in the absence of toroidal current. This case corresponds to the classical confinement of particles: all the particles drift over the magnetic surface, their Larmor centers are not displaced from this surface. This condition is realized when the B-lines and the magnetic lines of force are orthogonal. It can be fulfilled approximately in straight systems. As for curvilinear systems, only poloidal *pseudosymmetry* can supposedly be expected here. In the case of a stellarator, research conducted to date shows that the limiting values of the 'beta' parameter, as far as the plasma equilibrium and stability are concerned, in these systems are at least no smaller than in the optimized systems with toroidal pseudosymmetry. Poloidal pseudosymmetry is attractive for the following reason: it lets us combine, as regards the topology of $B = \text{const}$ lines, rectilinear mirror traps with curvilinear closures in a hybrid trap of the DRACON type [19]. The latter in principle admits of high average values of the 'beta' parameter, conceivably up to the values suitable for a $\mathrm{D-{}^3He}$ fuel reactor.

Conclusions

1. As a result of the tedious work pursued by large teams of physicists and engineers over an extended period of time, the initial arguments that tokamaks are 'unsuitable' for a fusion reactor owing to the necessity of exciting electric current have been rejected. The major rejected *physical* argument was as follows: the electric current required to ensure plasma equilibrium is a dangerous source of plasma instabilities. The major *engineering* argument was — continuous reactor operation is impossible. The following was established: there exist stable modes of plasma confinement in tokamaks; diffusion of the particles trapped due to a nonuniformity of the toroidal magnetic field is responsible for the generation of a toroidal bootstrap current which in combination with the feasibility of noninductive generation of electric current, e.g. by transfer of the momentum of gyrotron radiation to electrons, most probably solves the problem of stationary operation of a tokamak reactor. Controlling the current density distribution to sustain the stable mode was also found to be possible with the use of gyrotrons.

Tokamaks are self-sufficient as regards the fusion reactor. And yet they have set the stage for the development of other, conceivably more reliable stationary magnetic systems of stellarator type.

2. Optimization of the shape of the boundary toroidal magnetic surface (BMS) in lieu of optimization of the pitch of helical windings, opens the door to improvement of 3-D helical systems of magnetic plasma confinement; a case in point is the well-optimized system developed in Garching, which provided the basis for W7-X (Greifswald). This is correlated with the current quickening of interest in well-optimized stellarator systems of magnetic plasma confinement, which is similar to the quickening of interest in tokamaks in the 70s. Quite appropriate in this situation is L A Artsimovich's half-in-jest explanation for the unremitting effort to solve the fusion problem. According to him, the reason is that the self-confidence of physicists was jeopardized in this area of research. The same applies to the stellarator problem. But there is still another reason for the interest in stellarators. The construction period of large-scale reactor (or subreactor) type thermonuclear facilities is no shorter than ten years. Hence it is vital to preserve the accumulated scientific potential during this period. It is precisely this purpose that can be served by investigations to determine the potential of advanced helical or other stationary systems of magnetic plasma confinement. Work on devices of this kind would make it possible to relay the experience gained in plasma physics to the new generation, which is destined to complete the critically important mission of bringing into existence the foundations of safe energy production in the future. A fundamental contribution to this cause was made by Lev Andreevich Artsimovich.

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Leningrad Fiztekh Fellows in the tokamak team of Lev Andreevich Artsimovich (1962 – 1973)

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Fate decreed that a small group of Leningrad Fiztekh Fellows in the early 60s found themselves involved in the tokamak research supervised by L A Artsimovich at the I V Kurchatov Institute of Atomic Energy in Moscow. This happened owing to the following circumstance. At that time, a new method of considerable promise, intended for the diagnostics of hot plasmas, had been developed in our Leningrad Fiztekh. The method involved the analysis of atoms escaping from a plasma. It made use of the fact that in any, even very hot hydrogen plasma, which might seemingly be fully ionized, there exists a small fraction of neutral hydrogen atoms being in thermal equilibrium with the ions. The possibility of the occurrence of this phenomenon was first pointed out by A D Sakharov in the calculations of a toroidal fusion reactor with magnetic confinement [1]. "These atoms", Sakharov wrote, "should originate in a plasma due to the successive charge exchange of neutral hydrogen coming to the plasma interior from the chamber walls". Sakharov also noted that the fraction of atoms will be very small and will have no tangible effect on the energy balance of the plasma; nevertheless, a noticeable atomic flux will be emanating from the plasma and bombarding the wall. After publication of Sakharov's calculations, this phenomenon came to the attention of another outstanding physicist — B P Konstantinov, at that time Director of the Fiztekh [or in full, A F Ioffe Physical-Technical Institute (PTI), RAS]. He proposed using the atoms emerging freely from the plasma to diagnose ions and measure the ion plasma temperature, because the energy distributions of atoms are very close to that of ions. It is pertinent to note that the problem of measuring the ion plasma temperature was a pressing one at that time. No practical solutions of the problem were in sight. Starting from B P Konstantinov's proposal, in the PTI Laboratory directed by Prof. N V Fedorenko, under the supervision of V V Afrosimov during 1958 – 1960 the instrumentation was developed for detecting atoms emanating from the plasma (the so-called atom analyzers) and a technique was devised for determining the ion distributions from the measured atomic flux [2]. By the early 60s, this technique had successfully passed the tests at the legendary Leningrad fusion 'Alpha' facility, and the results were presented at the IAEA Conference in Salzburg in 1961 [3]. This report [3] attracted considerable attention in Salzburg. The result was that we at the PTI conceived the idea of testing the new technique in tokamaks, the tokamak research expanding vigorously at that time under the aegis of L A Artsimovich in Moscow. The PTI proposal was readily accepted, and a group of Fellows from Leningrad, including the author of this report, found themselves in the Department supervised by Artsimovich.

Lev Andreevich's attitude to us was determined primarily by the following two factors. First, he was deeply interested in the new method of plasma diagnostics. Second, Lev Andreevich himself had been a PTI staff member in the past (1930 – 1944). It had been at the PTI where he had turned into a prominent physicist. Therefore he was keenly interested in everything related to the Leningrad PTI. Moreover, this was an opportunity to establish with the PTI direct scientific cooperation, which Lev Andreevich appreciated highly, in addition to administrative and managerial relations (Artsimovich had already become the Academician-Secretary of the Division of General Physics and Astronomy of the USSR Academy of Sciences).

I saw Lev Andreevich for the first time at the tokamak sectorial (sector 44) seminar. At that time, after the tragic death of N A Yavlinskiĭ, V S Strelkov, a very young scientist, stepped in as the supervisor of the seminar. The seminar proceeded in Strelkov's office. I saw an athletic-looking, elegant man of medium height entering the office quickly and sitting down in the shabby oak armchair allotted to him. By the way, legend had it that the armchair, which had been brought from the Kaiser Wilhelm Institute in Berlin after the World War II, had belonged to W Heisenberg. It was striking how acutely and vividly Artsimovich reacted to everything discussed at the seminar. It was evident that he grasped the heart of the matter immediately, recognized the weak points quickly, and asked the speaker challenging questions. After the seminar, its participants crowded by the blackboard and continued to discuss what had just been heard. The young V Strelkov, A Razumova, D Ivanov and others crowded