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The current status of the stellarator program

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1. Introduction

Briefly reviewed in this report is the world stellarator program, i.e., a research program having the aim of developing a controlled fusion reactor based on a stellarator type magnetic trap. The main stages of program advancement, its current status, and plans for further research are discussed. The author took the liberty to omit, as far as possible, mathematical formulas and experimental data plots to make the subject of the report comprehensible to a wider audience of listeners (readers). I apologize to specialists for the unavoidable inaccuracy of certain my assertions and formulations.

2. The origin of the stellarator program and the main stages of its development

Studies to explore the possibility of using controlled thermonuclear fusion (CTF) as a source of energy were initiated in the Soviet Union and USA almost simultaneously circa 1951. However, up to 1958 this work was assigned a security label, and the first results were made available for the world's scientific community only at the 2nd International Congress on Peaceful Uses of Atomic Energy (September 1958, Geneva). In the USSR, these studies were based on Tokamak machines invented by I E Tamm and Andrey D Sakharov, and in the USA on facilities of the stellarator type developed by Professor L Spitzer, an astrophysicist affiliated with Princeton University.

As the story goes, Spitzer, while on a ski holiday, happened to read a report saying that certain R Richter from the Argentine had successfully demonstrated the possibility of CTF. Understandably, this news agitated the scientific community. Upon his return to Princeton, Spitzer, assisted by coworkers, developed a research program to assess the possibility of CTF and advanced the scheme of an experimental reactor for its realization. This facility, called the stellarator (from Latin stella — 'star'), was actually a toroidal magnetic trap of tokamak type. Spitzer appears to have proposed this system on the following theoretical grounds: (1) magnetic field lines should not extend beyond a closed volume (topological torus); (2) they should lie at the surfaces of toroids inserted into each other; (3) the turn angle of a line of force should not be too small (the turn angle or rotational transform angle is the angle by which a line of force turns with respect to the torus small azimuth upon its complete revolution about the principal axis of the torus), and (4) the system should be suitable for operating in a steady-state regime.

Both tokamak and stellarator facilities meet all but the last of these conditions. However, tokamaks are distinct from stellarators in that their magnetic surfaces, as surfaces of constant plasma pressure, appear due to ohmic current running through a plasma; in stellarators, magnetic surfaces are created by a system of external current-carrying conductors wrapped around a vacuum chamber. These currents are responsible for the rotational transform necessary to compensate for toroidal drift of the particles and confine them within the closed volume (toroid). It should be recalled that the last requirement is very important because an industrial power plant must operate in the steady-state regime, which is difficult to maintain in a tokamak machine, where ohmic current creating the magnetic field to ensure the plasma equilibrium is generated by an eddy electric field. There is no such problem with stellarators, where the magnetic field is created by external conductors that may be superconducting and fed from a regular current generator.

The Princeton Plasma Physics Laboratory (PPPL) designed and built a family of stellarators (A, B, C models) and proposed model D (the project has yet to be implemented) with a view to demonstrating CTF.

Unfortunately, model C experiments have failed. Despite expectations and theoretical predictions, the plasma lifetime in this system proved too short, whereas experiments on the Soviet tokamak T3 demonstrated rather efficient plasma heating and confinement. As a result, the US stellarator research program was abandoned in 1969, stellarator C was transformed into a tokamak, and tokamaks gained triumphant worldwide approval. To cite H Furth, the then PPPL Director, "each housewife in America wished to have her own small tokamak."

Such tremendous growth of tokamak developments had a negative impact on the stellarator program: its funding was curtailed and further progress slowed down. Meanwhile, despite skepticism about stellarator systems and some loss of interest in them amongst the world fusion community, stellarator research continued in the USSR [P N Lebedev Physical Institute (FIAN), A M Prokhorov Institute of General Physics (IOFAN), Khar'kov Physico-Technical Institute (KhFTI)][1], Germany, and Japan, soon yielding interesting and promising results. This provided an incentive to revitalize stellarator projects in the USA and to build the Advanced Toroidal Facility (ATF) at the Holifield National Laboratory[2] (Oak Ridge, 1988–1994). At that time, it was the largest stellarator having the powerful heating sources and continuously maintaining the discharge as long as 1 hour, i.e., operating practically in the steady-state regime. However, ATF experiments inexplicably ceased 6 years after their onset, and the facility was decommissioned despite a number of interesting results obtained with this machine. Figures 1 and 2 give an idea of the ATF stellarator, showing its helical conductors (inducing a magnetic field) and the shape of confined plasma, and illustrating its general view, respectively.

The results of research conducted in the USSR, Germany, and Japan proved highly impressive, which allowed, in my opinion, regarding the stellarator program as a plausible alternative to the tokamak project. These results, both theoretical and experimental, are briefly discussed below.

3. Main results of the theoretical studies

I. Fundamentals of the neoclassical transport theory have been developed (*Galeev, Sagdeev*; *Kovrizhnykh*, 1967–1969 [1, 2]). The theory predicts that the plasma lifetime at high temperatures characteristic of thermonuclear reactors is longer in tokamaks than in stellarators. However, lifetimes examined experimentally proved very close in these

[1] Present names of research institutions.
[2] Oak Ridge National Laboratory before 1975.

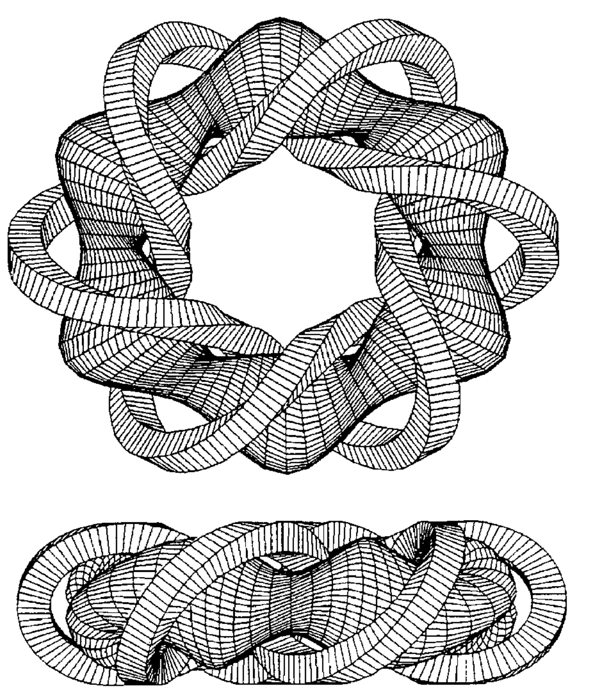

Figure 1. Helical conductors creating a magnetic field and shapes of magnetic surfaces in the ATF stellarator.

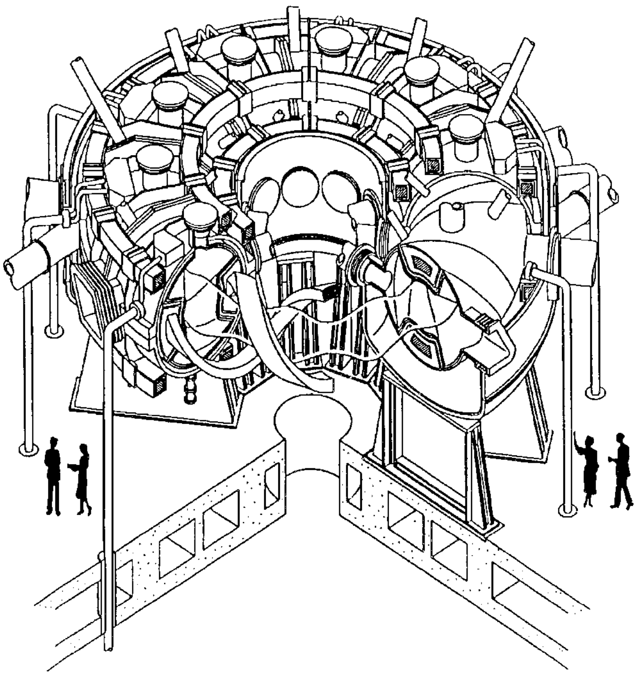

Figure 2. General view of ATF machine.

two facilities, which points to the occurrence of some additional mechanism of losses common to both magnetic systems.

II. It is theoretically demonstrated that neoclassical transport coefficients in stellarators can be reduced (optimization) by the special choice of external conductors creating a helical magnetic field (*Kovrizhnykh*, 1982 [3]). The idea of optimization has recently acquired wide recognition; special mathematical codes are being developed and powerful modern computers used for its realization (*Nuhrenberg et al.*).

III. Studies on the influence of magnetic field perturbations on the structure of magnetic surfaces suggest the existence of 'magnetic islands' that may, under certain conditions, be responsible for strong degradation of magnetic surfaces (*Kovrizhnykh, Morozov, Solov'ev*, 1961 – 1963 [4, 5]). These studies imply that current conductors should be manufactured with a high degree of accuracy if good magnetic surfaces are to be obtained.

IV. A simplified system (averaged over helical harmonics) of magnetohydrodynamic equations for stellarators, characterized by axial symmetry (as in the case of tokamaks), has been derived; this made possible the application of the methods previously developed for tokamaks to stellarators (*Kovrizhnykh, Shchepetov*; *Strauss*, 1980 [6, 7]).

V. The newly discovered self-stabilization effect was used to confine plasma in a stellarator at rather high β values (up to 10%, with $\beta = 8pNT/B^2$, where N is the plasma density, T is its temperature, and B is the magnetic field induction (*Kovrizhnykh, Shchepetov*, 1981 [8]). This finding is very important in that one of the main drawbacks of stellarators, for which they could not be regarded as prototype thermonuclear reactors, was too low (as was believed in those days) a critical value of β; the plasma became unstable as this value was surpassed.

VI. Mathematical codes have been developed for calculating magnetic surfaces, plasma equilibrium, and plasma stability in different, very complicated magnetic configurations (mostly by foreign researchers).

In my opinion, the period from the late 1970s to the early 1980s was especially productive for the development of stellarator theory. Those years were a time of fierce disputes and heated debates, sometimes with strong language, so strikingly different from the politically correct atmosphere prevailing at today's forums. Nevertheless, they were purely scientific discussions and never upset personal relations between the participants.

4. Main experimental findings

I. The methods developed for the measurement of magnetic surfaces allowed the cause of the failure of stellarator C to be elucidated. It appears to have been due to the bad quality (destruction) of magnetic surfaces (FIAN).

II. It was shown that plasma can be produced, heated, and confined in a stellarator without ohmic current.

III. The effect of plasma self-stabilization was confirmed and transition to the second stability zone was accomplished (ATF).

IV. Different methods of plasma heating were developed and verified. Steady-state plasma confinement was achieved [for over 1 hour; ATF, Large Helical Device (LHD)].

V. The subthermonuclear parameters of the plasma were obtained in the LHD stellarator (*although not all of them at the same time!*): $\beta = 4.5\%$, $N(0) = 10^{15}$ cm^{-3}, $T_{\rm i}(0) =$ 13.5 keV, $T_{\rm e} = 10$ keV, $NT\tau = 4.4 \times 10^{19}$ m^{-3} s keV, $\tau > 0.02$ s (τ is the hot plasma lifetime), and discharge duration 1 h. It should be remembered that the triple product $NT\tau$ should be 1.5 – 2 orders of magnitude greater for a thermonuclear fusion reaction to be ignited.

5. Merits and demerits of stellarators

Let us formulate the advantages and disadvantages of stellarators in comparison with tokamaks.

Advantages of stellarators:

— ability to operate in the steady-state regime;

— avoidance of rather hazardous disruption instabilities characteristic of tokamaks due to ohmic current;

— presence of a natural diverter (a special system to remove impurities from the plasma and reduce the thermal load on the chamber);

— potential for optimization of the magnetic configuration in order to weaken neoclassical transport processes (diffusion and heat conduction);

— absence of plasma density cut-off limit. In all likelihood, such a limit does exist but as found experimentally it is higher than 10^{15} cm^{-3} (an acceptable value for a future thermonuclear reactor);

Drawbacks of stellarators:

— higher neoclassical transport coefficients in the region of low collision frequencies. Nevertheless, as noted above, there are optimization methods to reduce these coefficients. True, efficacious optimization is hardly possible if anomalous losses are commensurate with or exceed neoclassical ones;

— more complicated system of magnetic field windings and a high degree of accuracy needed to manufacture them;

— smaller experimental database attributable to the successful development of tokamak programs and failure of stellarator experiments in the late 1970s and the early 1980s.

The current project of a prototype thermonuclear reactor [International Thermonuclear Experimental Reactor (ITER)] is based on the tokamak concept. However, future research must show whether the above advantages of stellarators outweigh their drawbacks to enable the choice of one system or the other as the basis on which to build a commercial fusion reactor. Thus far, both programs have been developing successfully, providing plausible and significant mutual rewards because, for all the difference between stellarators and tokamaks, many processes in them are similar and likely to have a common nature.

Today, nine stellarators are operating throughout the world (see Table 1).

In what follows, only the main characteristics of these stellarators and the most interesting photos of them are presented without reference to the results obtained with each of them.

1. *Large Helical Device* (LHD) is currently the largest operating stellarator in the word, comparable in terms of size to such large tokamaks as Tore-Supra (France), JT-60 (Japan), DIII-D (USA), and TFTR (USA; dismantled). In terms of total plasma volume, the LHD is a disadvantage in relation to the JET tokamak (UK) only. The National Institute of Fusion Studies (NIFS) was established in Japan to accommodate the LHD and the device itself was built in a relatively short time.

Table 1. Stellarators operated in different countries.

Facility	Country	Startup	$V_p B$, m^3 T *
LHD	Japan	1998	80
Heliotron J	Japan	1999	1.4
TJ-II	Spain	1997	1.4
HSX	USA	1999	0.66
U-3M	Ukraine	1981	0.6
H-1	Australia	1998	0.7
L-2M	Russia	1975 (1993)	0.4
WEGA	Germany	1975 (2001)	0.16
STH	USA	2005	0.2

* Product of plasma volume V_p and magnetic field induction modulus determining the lifetime of the hot plasma: the higher this value the better its confinement and the higher its temperature.

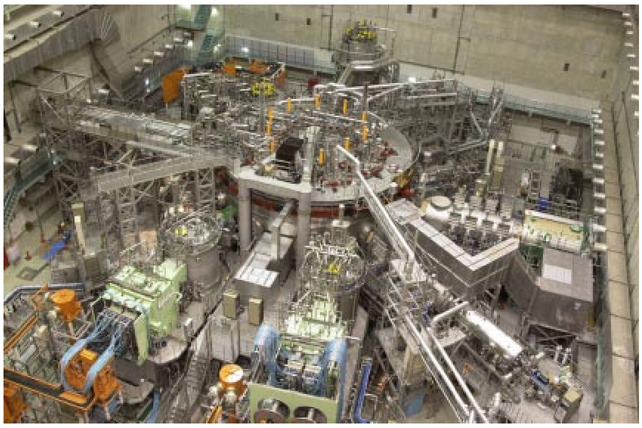

Figure 3. Overall view of the hall accommodating the LHD and accessory equipment.

In principle, a LHD is a classical stellarator designed similarly to the aforementioned ATF machine (see Fig. 1). However, it employs superconducting external winding, and our Japanese colleagues call it a heliotron or torsotron. The following characteristics give some idea of the size of the LHD.

Major plasma radius $R = 3.6$ m, minor radius $r = 0.6$ m, magnetic field induction $B = 3$ T, plasma volume ~ 30 m^3, magnetic field energy on the order of 1 GJ. The device is equipped with various plasma heating sources, such as powerful microwave and high-frequency generators for heating at electron cyclotron resonance (ECR) and ion cyclotron resonance. Also, it has injectors for high-energy beams of neutral atoms and a large set of modern diagnostic tools. Further enhancement of heating power is necessary to improve the plasma parameters. Temperatures close to magnitudes needed to trigger a fusion reaction have been reached, however plasma density remains 1.5 – 2 orders of magnitude lower than that sought for the purpose. Clearly, the probability of igniting the reaction in the LHD is a negligibly small value, but it is quite possible to come close to this goal but it will require substantially increasing the heating power. A general view of the LHD and accessory equipment is shown in Fig. 3.

2. *TJ-II stellarator*. This facility is substantially different from the so-called classical stellarator in terms of design and methods for the creation of the magnetic field. Nevertheless, it is ranked as a stellarator because its magnetic field is generated by a system of external conductors rather than plasma current. The size of this stellarator is relatively small: major plasma radius $R = 1.5$ m, average minor radius $r = 0.22$ m, and magnetic field induction $B = 1.2$ T. The heating sources comprise a microwave generator using electron cyclotron resonance and beams of neutral atoms. The plasma electron temperature reached thus far is 1 keV, and a plasma density of several units of [10^{13} cm^{-3}] has been attained. Although plasma parameters obtained with such small and relatively low-cost facilities are much lower than those in the LHD, they may be used in experiments to gather novel and very useful information about various processes proceeding in hot plasma and the influence of magnetic field structure on transport processes. A schematic of field-generating conductors and a general view of TJ-II are shown in Figs 4 and 5.

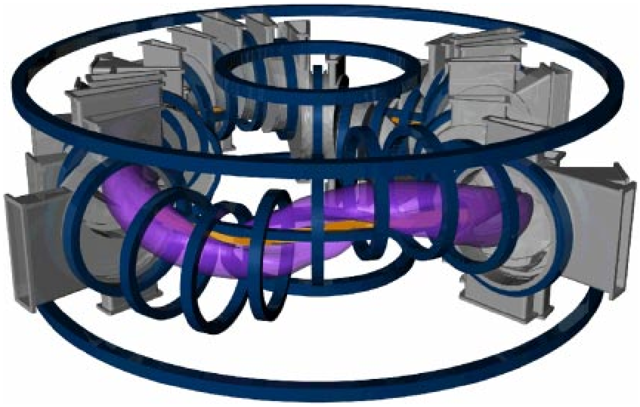

Figure 4. Schematic arrangement of conductors creating a magnetic field in the vacuum chamber of the TJ-II stellarator.

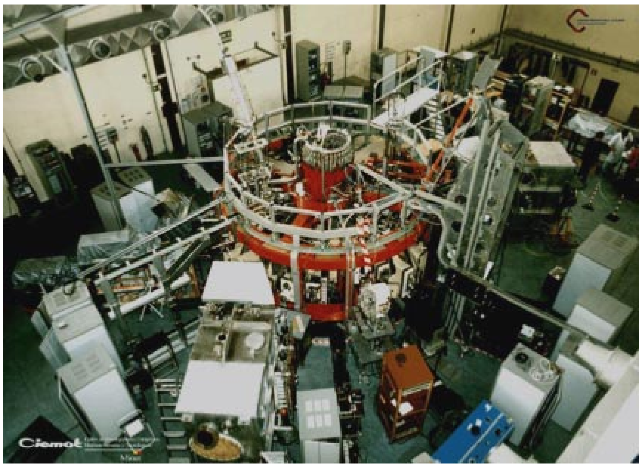

Figure 5. General view of TJ-II and accessory equipment.

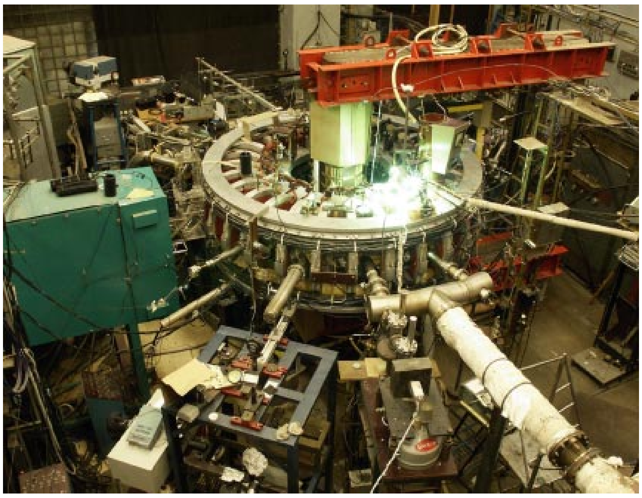

Figure 6. Russian L-2M stellarator.

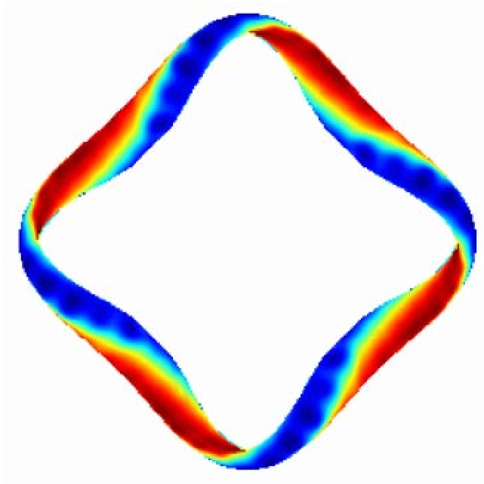

Figure 7. Shape of the plasma cord in the HSX (numerical simulation).

3. *L-2M stellarator*. I cannot help saying a few words about this (also small) facility for two reasons: first, it is accommodated at my Institute (IOFAN), and second, it is now the only stellarator operating in Russia. L-2M has the following characteristics: major plasma radius is 1 m, minor radius 11.5 cm, magnetic field induction 1.3 T, maximum electron temperature reached thus far 1.5 keV, and ion temperature is 150 eV at plasma density of 3×10^{13} cm^{-3}. Presently, installation and adjustment of a new powerful microwave complex are underway, consisting of two highly economical gyrotrons of 0.8 MW each expected to produce a record-breaking heating power density in excess of 5 MW m^{-3}. It should be mentioned that the L-2M team twice developed and proposed projects of even larger facilities that, however, could not be implemented for lack of funding. Project materials were used in other countries where similar reactors were built. The general view of L-2M is presented in Fig. 6.

4. *Helically Symmetric eXperiment* (*HSX*) *stellarator* is distinctive for the complexity of its system of conductors arranged so as to meet the quasihelical symmetry condition and thereby minimize (optimize) transport processes. In other words, its magnetic field structure was chosen in such a way that it reduces to a minimum the effect of toroidicity responsible for greater diffusion and heat conduction in stellarators compared with tokamaks. Note that prefix 'quasi' points to the impossibility of reaching total symmetry in stellarators. In fact, what can be done is to make the system close to a symmetric one, where the toroidicity effect is partly, albeit not totally, eliminated. Since the available photo of this facility conveys little useful information, I present here only a simulated profile of its plasma cord (Fig. 7) and main parameters, viz. major plasma 'radius' of 1.2 m, minor radius 0.12 m, magnetic field induction 0.5 T, and ECR heating power not more than 100 kW. Despite the rather long period of stellarator operation, the HSX collaboration still fails to answer the principal question of how, if at all, efficient the optimization procedure is.

6. Stellarators being designed and constructed

Several institutions are combining ongoing theoretical and experimental studies with designing and building new stellarators and developing a future thermonuclear reactor based on the stellarator concept. Although the reactor issues are beyond the scope of the present report, a few words about the stellarators under construction are certainly in order.

The project of a new superconducting, partly optimized stellarator with modular coils has been underway at the Max Planck Institute of Physics in Greifswald, Germany since the early 1980s. Let us recall that the stellarator magnetic field

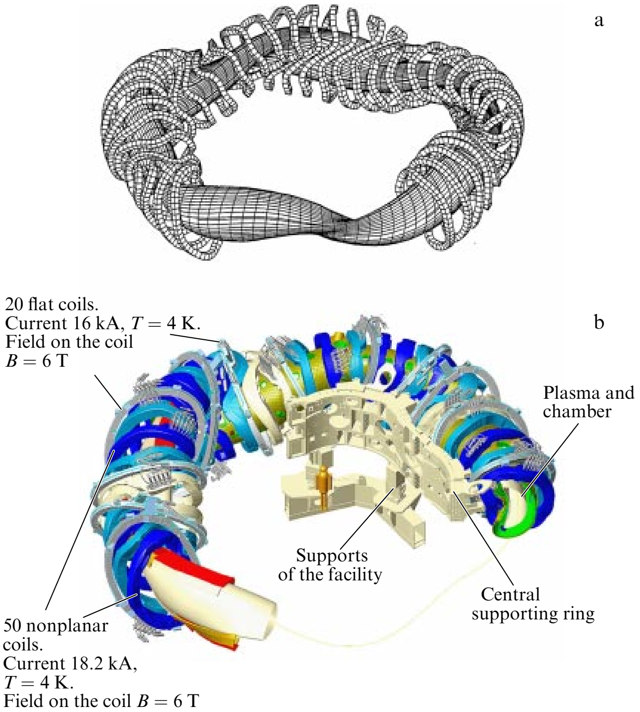

Figure 8. (a) Modular coils and shape of the plasma cord in the W-7X stellarator. (b) Mock-up of the W-7X stellarator as an assembly.

Figure 9. A fragment of the W-7X vacuum chamber (half the module).

can be generated not only by continuous helical conductors but also by properly shaped modular coils, as proposed for the first time by *Popov and Popryadukhin* [9] in 1966.

After thorough preparatory work that was, in my opinion, too long, the building of the W-7X stellarator was started in 2000. The reactor was planned for 2005 with preliminary experiments to start in the same year. However, technical difficulties encountered in manufacturing modular coils of intricate shape postponed completion of the project first till 2009 and thereafter till 2012. It is hoped that the work will be finished by this time.

W-7X has the following basic characteristics: major plasma radius $R = 5.5$ m, minor radius $r = 0.5$ m, magnetic field induction in the plasma core $B = 3$ T, and magnetic field energy $W = 620$ MJ. Figures 8 and 9 give a better idea of this grandiose machine.

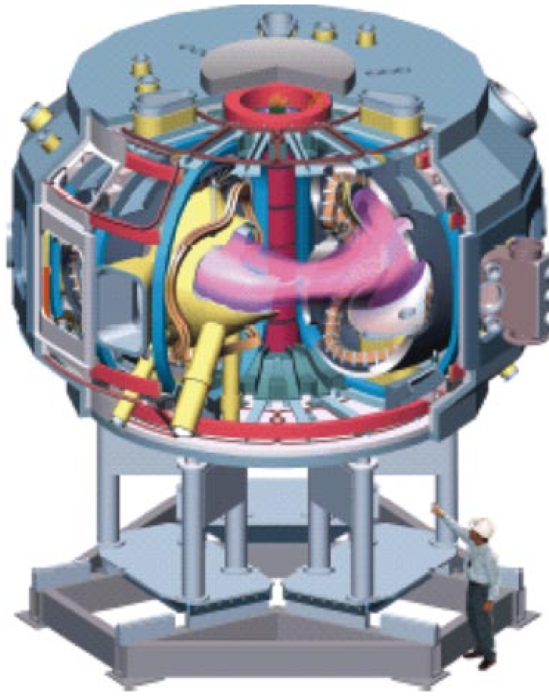

Figure 10. A full-size mock-up of the NCSX stellarator.

One more stellarator was designed for a much shorter time at PPPL (USA). It is called the National Compact Stellarator eXperiment or NCSX. The aim of the program is to address the following issues: the possibility of operations at high β with bootstrap current but avoiding the development of disruption instability, the reduction of neoclassical losses through establishing quasisymmetry conditions, and the possibility of imposing limits on beta. Although the NCSX is smaller than the LHD and W-7X, it is large enough to produce new interesting results owing to novel ideas employed in its construction. A mock-up of the NCSX is presented in Fig. 10. The average major radius of the plasma is 1.42 m, minor radius 0.33 m, magnetic field induction 2 T, and heating source power 3 – 12 MW. The completion of building the facility and the onset of experiments were planned as of 2009, but the project was suspended in 2008 (seemingly due to significantly overrunning an outlay) and the facility operation was stopped.

7. Pressing tasks and plans

I would formulate the goals of further studies as follows.

I. Studies of the nature of anomalous losses and modes of their suppression. Both stellarator and tokamak experiments have shown that the observed coefficients of heat conduction and diffusion are much higher than those predicted by neoclassical theory. The cause of this discrepancy is believed to be the presence of as yet unknown additional mechanism called anomalous losses. The physical nature of this mechanism awaits elucidation: can we influence it to totally or partially reduce anomalous transport? Given such a possibility, the development of transport-optimized systems should be continued. Otherwise, optimization is of little promise.

II. Simulation of transport processes and the development of increasingly more adequate numerical codes for investigations into plasma transport, equilibrium, and stability. There are two options for achieving this goal. One implies more or less the exact numerical solution of starting equations and then the transport equations. In principle, this option looks promising, but it requires powerful computers, sophisticated software programs, and a large amount of computing time. The other approach consists in elaborating a relatively simple analytical model that would phenomenologically take account of anomalous losses and allow a simple and rapid solution. In all likelihood, theorists will work along both lines.

III. Search for limiting density in stellarators. The fact that limiting density has not thus far been found in stellarators does not mean that it is altogether nonexistent. The solution to this problem is of primary importance because it would permit achieving the ignition conditions of a fusion reaction at lower temperatures.

IV. Diverter performance testing. A reactor cannot work without a diverter. However, an optimal design of a diverter remains to be developed and its efficiency needs to be assessed more thoroughly.

V. Extension of international collaboration, creation of comprehensive experimental database, and specification of scaling properties. Cooperation between different research groups in the framework of the stellarator program has been successfully developing in the past years in the form of exchange of scientists, the organization of joint working groups for the collection and analysis of experimental data obtained at different facilities, regular meetings to discuss newly obtained results, joint exploitation of powerful computers, and extensive use of Internet resources.

VI. Improvement of plasma parameters to be achieved by using more powerful facilities and enhancing power of plasma heating sources.

VII. Elaboration of a stellarator-based reactor project. Although building a stellarator-based fusion reactor is not a matter for tomorrow, the work toward this goal needs to be carried out today because many problems apart from purely physical ones (engineering, technological, economic, etc.) will have to be resolved. The development and construction of ITER would be of great help in this context.

I cannot help observing here that unfortunately the presence of Russian scientists in international efforts within the framework of the world stellarator program is rapidly decreasing. The same is true of the tokamak program and collaboration between Russian and foreign researchers. The causes are well known: from the lack of adequate financial support (and, as a consequence, the absence of new experimental devices and modern diagnostic equipment) to the aging of research groups, loss of interest, and unwillingness of young specialists to associate themselves with science, plus the waning prestige of the scientist at large. With this in mind, it appears safe to predict that the participation of Russia in the ITER program may end in complete failure for the simple reason that there will be nobody to recruit into it.

To conclude, I would like to say a few words about the man whose memory has brought us all together here.

I was not an intimate friend of Boris Borisovich Kadomtsev nor even his close associate, but I frequently met with him at numerous conferences, seminars, and workshops. What always impressed me was his remarkable physical intuition. Within a few days after a new experimental effect or phenomenon was reported, Boris Borisovich explained its physical nature in hand-waving terms speaking at a seminar or in a narrow circle of colleagues. Surprisingly, this first explanation of his was exactly in line with what was postulated after a time by a well-considered theory or in his own work. Surely, B B Kadomtsev was an outstanding scientist, a heaven-sent theorist. His death is an irreparable loss, not only for the plasma community but also for physics in general. He will be sorely missed by all who knew him. The sole consolation is the splendid reviews and those (alas!) few monographs [10–13] that he left to be studied, as I hope, by seasoned researchers and fledgling students alike.

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Nonlinear phenomena in the ionospheric plasma. Effects of cosmic rays and runaway breakdown on thunderstorm discharges

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1. Introduction

This article reviews some recent progress in the theory of cosmic rays and runaway breakdown (RB) along with new observations of their effects on thunderstorm processes in the atmosphere. An asymptotic solution of the linear kinetic equation is considered and similarity relations for runaway breakdown are proposed. The paper describes the Groza experimental installation measuring different forms of radiation during thunderstorms that is operated at the high-altitude cosmic ray station of the P N Lebedev Physical