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Tokamak foundation in USSR/Russia 1950–1990

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In the USSR, nuclear fusion research began in 1950 with the work of I.E. Tamm, A.D. Sakharov and colleagues. They formulated the principles of magnetic confinement of high temperature plasmas, that would allow the development of a thermonuclear reactor. Following this, experimental research on plasma initiation and heating in toroidal systems began in 1951 at the Kurchatov Institute. From the very first devices with vessels made of glass, porcelain or metal with insulating inserts, work progressed to the operation of the first tokamak, T-1, in 1958. More machines followed and the first international collaboration in nuclear fusion, on the T-3 tokamak, established the tokamak as a promising option for magnetic confinement. Experiments continued and specialized machines were developed to test separately improvements to the tokamak concept needed for the production of energy. At the same time, research into plasma physics and tokamak theory was being undertaken which provides the basis for modern theoretical work. Since then, the tokamak concept has been refined by a world-wide effort and today we look forward to the successful operation of ITER.

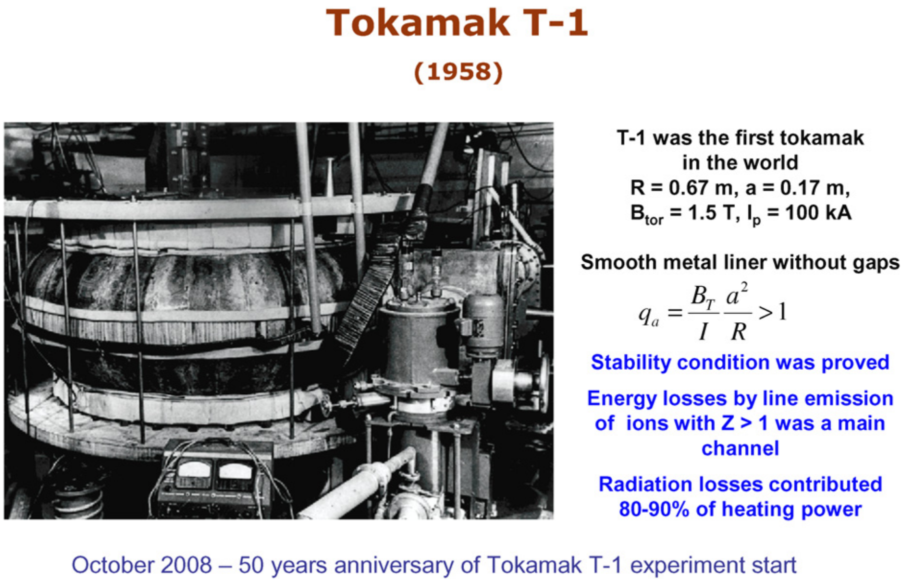
(Some figures in this article are in colour only in the electronic version)

At the opening ceremony of the United Nations First International Conference on Peaceful Uses of Atomic Energy held in Geneva in 1955, the outstanding Indian physicist Homi Bhabha stated that the conference would only be discussing the use of energy from heavy nuclear splitting but that the future would lie with the fusion energy of light nuclei. Having said this, Bhabha paused, but with no reaction from the assembled delegates. Today we know that many scientists among those present had already worked on the controlled nuclear fusion (NF) research problem, but that all these works were strictly classified.

The initiative to declassify came from the USSR. I.V. Kurchatov's lecture in Harwell in April 1956 about fusion related high current pulsed discharges was the first step in this direction. Two years later, at the Second Geneva Conference on the NF problem, 105 papers were presented, detailing work performed in the USSR, USA, UK, Germany and other countries. Thus it was shown that, despite the regime of classification, and apparently without any leakage of information, research had been conducted in practically identical directions. The conference did not result in an immediate collaboration in scientific research between different countries, but it demonstrated a common scientific approach and that the regime of research classification in the field was unnecessary given the lack of potential uses of magnetic confinement facilities for defence-oriented work. This was a solid basis to begin the wide international collaboration in fusion in the future.

In the USSR, NF research began in 1950. In October 1950 I.E. Tamm and his former postgraduate student A.D. Sakharov, who were participating at that time in the development of thermonuclear weapons at the then secret Arzamas-16 nuclear centre, formulated the initial principles of magnetic confinement of high temperature plasma and performed the first estimations of a possible thermonuclear reactor with magnetic confinement of plasma. Already, by the beginning of 1951, Sakharov had calculated provisional parameters of a toroidal thermonuclear D–D reactor, MTR, with a power capacity of 900 MW: the large radius—12 m, small radius—2 m, magnetic field—5 T, plasma density—$3 \times 10^{20}\,\mathrm{m}^{-3}$, ion temperature—100 keV. Rotational transformation of the magnetic field was provided by a superposition of a toroidal magnetic field and a magnetic field of electrical current along a conductor located in the chamber axis (more recently, such installations have been known as Levitrons). Another way to create such a magnetic configuration was also proposed: driven current directly in the plasma itself. Parameter comparison of that D–D reactor with those of today's projects based on a deuterium–tritium mixture reveals close coincidence of reactor dimensions.

The papers of Tamm, Sakharov and their collaborators were first published in a four-volume book 'Physics of Plasma and Controlled Thermonuclear Reaction Problem' [1–3] published just before the Second Geneva Conference in 1958. The authors had noted that MTR could be used for tritium breeding (100 g per day) or ^{233}U production (8 kg per day).



Tokamak T-1

(1958)

T-1 was the first tokamak in the world
R = 0.67 m, a = 0.17 m,
B_{tor} = 1.5 T, I_p = 100 kA

Smooth metal liner without gaps

$$q_a = \frac{B_T}{I}\frac{a^2}{R} > 1$$

Stability condition was proved

Energy losses by line emission of ions with Z > 1 was a main channel

Radiation losses contributed 80-90% of heating power

October 2008 – 50 years anniversary of Tokamak T-1 experiment start

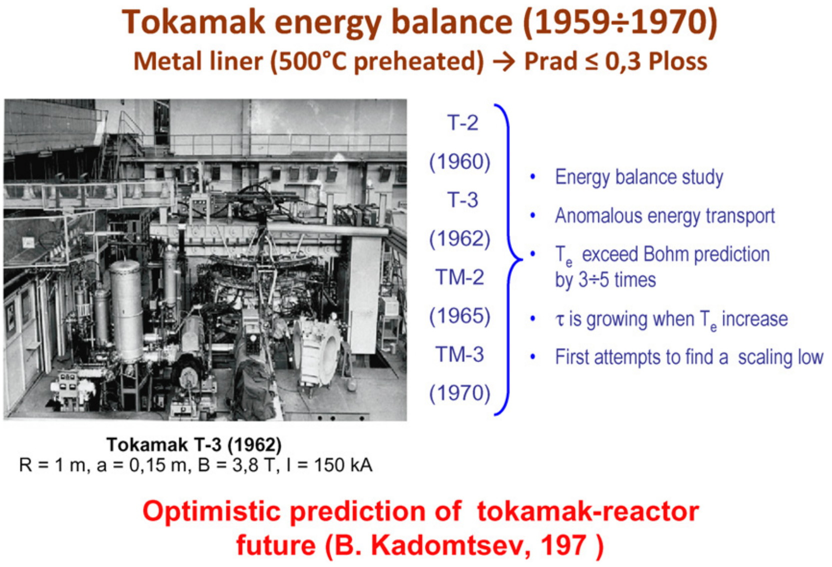
Figure 1. The T-1 tokamak.

Experimental research on plasma initiation and heating in toroidal systems began in 1951 at the Kurchatov Institute. Originally, these were experiments with toroidal chambers made from glass, porcelain or metal with insulating inserts. The largest installation of this series (TMP), with major radius $R = 0.8$ m, minor radius $a = 0.13$ m, $B_o = 1.5$ T, $I = 0.25$ MA, was in many respects already close to the scheme of the future classical tokamak, with the creation of rotary magnetic transformation by superposition of a toroidal magnetic field and a field of an electric current raised in a plasma core, and an external conducting casing for stabilization of the plasma. In these experiments, the first data on hot toroidal plasma were collected [4]. The first machine with an all-metal chamber, without insulating inserts, was the T-1 device, which should be considered to be the first tokamak (figure 1). It was started at the end of 1958 and so in 2008 we marked the 50th year anniversary of the world's first tokamak. On its installation, it was shown that, despite lacking arcing on dielectrics, the dominant role in the power balance of hot plasma was played by the losses caused by vacuum ultraviolet radiation of impurities [5].

The next step of the experimental programme was focused on searching for ways to mitigate radiating losses. To this end, the T-2 tokamak was created in the following year [6, 7]. This installation had an inner vacuum chamber (liner) made of corrugated metal that could be heated up to 550 °C. In the chamber there was a diaphragm for limiting the area of the discharge current. In the macroscopically stable regimes (according to Shafranov's criteria $q > 1$) the fraction of radiating losses did not exceed 30% of the full power delivered to the plasma. For the next generation of tokamaks, the presence of a limiter and the use of various methods of liner surface degassing were characteristic features. The concept of replacing a metal chamber wall with a smaller atomic number material was realized in the 1970s on the TMG tokamak which had a fully graphite chamber first wall [8]. The value of the effective charge of plasma ions in this machine was noticeably lower than the same value for the TM tokamak series with metal chambers.

The problem of plasma equilibrium in the vertical (top–bottom) and horizontal (over a big radius) directions was investigated in more detail on the T-5 installation [9]. In order to do this, the machine was equipped with a system of coils, allowing one to create magnetic fields perpendicular to the plasma current direction for control of the plasma magnetic axis position. These investigations were further developed on the TO-1 installation where plasma equilibrium without a conducting shell and suppression of MHD instabilities by means of a feedback system was investigated [10]. At that time, the power balance of plasma was investigated on practically all tokamak installations; however, the problem of plasma thermal confinement in tokamaks was studied in more detail by experiments on T-3, T-3a, TM-1, TM-2, TM-3 and T-4 in the 1960s and in early 1970s (figure 2).

In those years, the results of experiments on stellarators and other fusion machines were considered by many scientists as the evidence of thermo-isolation of plasmas in toroidal systems corresponding to the so-called empirical Bohm's formula. From this formula it follows that thermo-isolation worsens with the rise of plasma temperature. The basic result of the research performed in these years on tokamaks was the conclusion that plasma thermo-isolation in toroidal systems does not worsen with the growth of plasma temperature. Experimentally measured values of plasma energy confinement time in tokamaks exceeded those predicted by the Bohm formula by an order of magnitude [11] (figure 3). This contradiction was a theme of scientific discussions within the plasma community for several years. Debate reached the greatest acuteness at the Third International Conference on the Physics of Hot Plasma and Nuclear Fusion in 1968 in Novosibirsk [12]. Even before that, L. Spitzer, the Director of the Princeton Plasma Physics Laboratory, had stated his opinion that the temperature measurement techniques used in Soviet experiments did not allow for authentic results. In response, the Head of the Russian NF programme, Lev Artsimovich, offered R.S. Pease, the Head of the Culham Laboratory of Plasma Physics,



Tokamak energy balance (1959÷1970)

Metal liner (500°C preheated) → Prad ≤ 0,3 Ploss

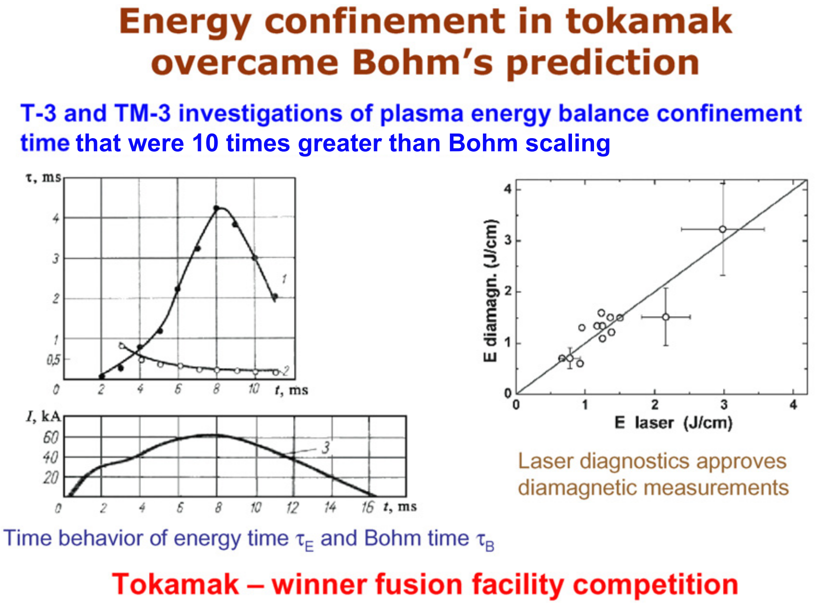
T-2
(1960)
T-3
(1962)
TM-2
(1965)
TM-3
(1970)

- Energy balance study
- Anomalous energy transport
- T_e exceed Bohm prediction by 3÷5 times
- τ is growing when T_e increase
- First attempts to find a scaling low

Tokamak T-3 (1962)
R = 1 m, a = 0,15 m, B = 3,8 T, I = 150 kA

Optimistic prediction of tokamak-reactor future (B. Kadomtsev, 197)

Figure 2. The T-3 tokamak and research into the energy balance, 1959–1970.



Energy confinement in tokamak overcame Bohm's prediction

T-3 and TM-3 investigations of plasma energy balance confinement time that were 10 times greater than Bohm scaling

Laser diagnostics approves diamagnetic measurements

Time behavior of energy time τ_E and Bohm time τ_B

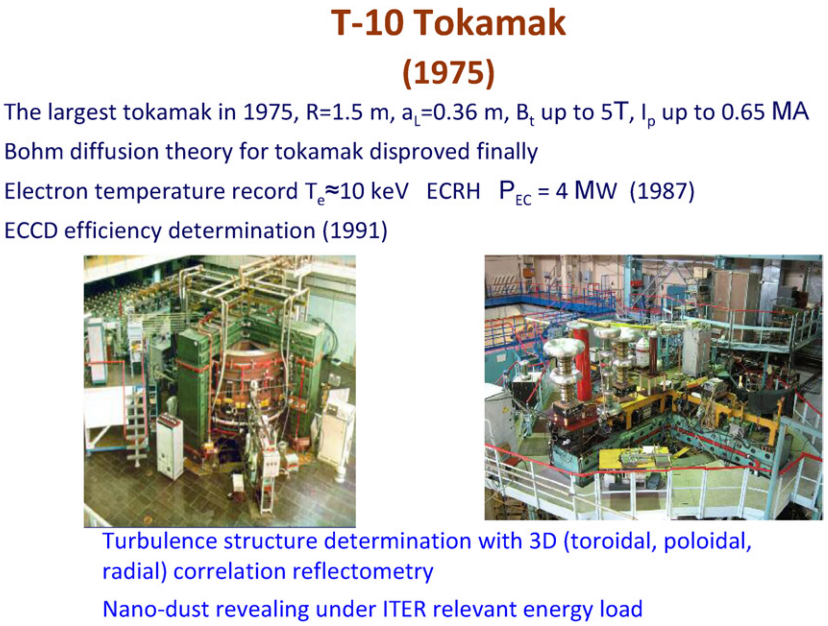
Tokamak – winner fusion facility competition

Figure 3. Energy confinement in tokamaks.

the opportunity to check the results of Soviet tokamaks in a joint experiment. It was suggested to measure an electron temperature in the T-3a tokamak by laser scattering diagnostics, with the use of equipment developed in the Culham Laboratory. This work was carried out under the supervision of D. Robinson, later the Director of the Culham Plasma Physics Laboratory and a Fellow of the Royal Society.

The results of a joint experiment on T-3a were reported at the International Conference on Plasma Confinement in Closed Systems (Dubna, USSR, 1969). The electron temperature measured by the laser scattering method was consistent with the data obtained earlier in the Kurchatov Institute by the diamagnetic measurements and charge exchange analysis of atoms escaping from the plasma [13, 14]. The results of this international experiment, the first in NF history, established tokamaks as the basic direction for further research on magnetic plasma confinement, worldwide.

The ion temperature was also studied in T-3a experiments. For this purpose, researchers at the Ioffe Physico-Technical Institute in Leningrad developed diagnostics of the energy spectrum of the fast neutral atoms escaping from the plasma core. The results of the measurements showed that the spectrum of hydrogen ions in the plasma core in T-3a was close to the Maxwellian with a temperature of 300–400 eV [15]. In stable modes of tokamak operation, no deviation from Maxwellian distributions was observed in the spectrum of plasma protons. In the experiments on deuterium plasma on T-3a and T-4 tokamaks the absolute measurements of intensity of neutron flux and its change in time for various modes were performed. The measured value of neutron flux intensity in the energy spectra was compared with that calculated



T-10 Tokamak

(1975)

The largest tokamak in 1975, $R=1.5$ m, $a_L=0.36$ m, B_t up to 5T, I_p up to 0.65 MA

Bohm diffusion theory for tokamak disproved finally

Electron temperature record $T_e \approx 10$ keV ECRH $P_{EC} = 4$ MW (1987)

ECCD efficiency determination (1991)

Turbulence structure determination with 3D (toroidal, poloidal, radial) correlation reflectometry

Nano-dust revealing under ITER relevant energy load

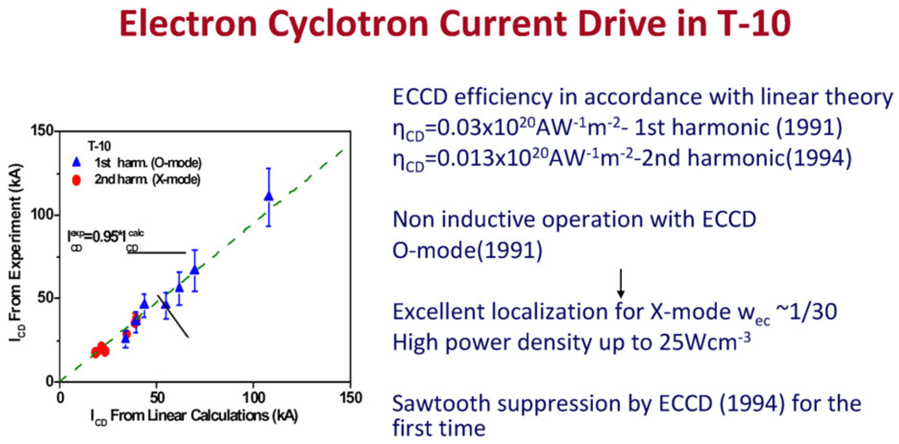
Figure 4. The T-10 tokamak.

using the known cross section of the D–D reaction and the measured values of ion temperature and plasma density. In these experiments the long thermonuclear neutron radiation of a stable toroidal plasma column was recorded for the first time [16, 17].

It is still impossible to calculate the energy and particle transport in tokamaks from first principles, due to the plasma turbulence. Energy losses through the electron component channel exceeded by tens times those predicted by a neoclassical theory. Many real mechanisms of losses are not clear. It was, and still is, therefore very important to establish scaling laws for energy confinement time. The analysis of experiments on T-3a, T-4, TM-2, TM-3 and T-11 has allowed us to find empirical dependences (scalings) of energy confinement time by deduction from the geometrical size, magnetic field value, discharge current and plasma density [18]. Subsequently, the results of similar studies on tokamaks in different countries were obtained and will be included in the ITER database.

The T-10 tokamak was designed as a final installation with only Ohmic heating (figure 4). The criterion of its parameters' optimization was to provide the maximum possible plasma temperature in Ohmic heating mode on the basis of previously determined energy confinement scalings and possible technical decisions. The second goal of the T-10 programme was to start the research on an auxiliary plasma heating technology. The experiments on T-10 ($R = 1.5$ m, $T = 0.4$ m, $B_o < 5$ T) began in 1975, see [19, 20] and references therein. Non-Ohmic heating was also investigated on the T-11 tokamak. This installation, constructed at the beginning of the 1970s, had a system of neutral atoms injection and the improved configurations of internal copper shell and magnetic fields [21]. Experiments on additional plasma heating by ion-cyclotron, low hybrid and electron-cyclotron resonances were carried out on different tokamaks, large and small. On the small TM-1-VCh tokamak, groundbreaking experiments were conducted on ion-cyclotron plasma heating with the discovery of ion minority heating, ion second harmonic heating, ion–ion hybrid resonance phenomena at comparable amounts of H and D ions and fast wave eigenmodes excitation [22]. These created the basis of the ICRF physics later widely explored on large tokamaks and to be used on ITER for ion heating and plasma stability control.

The T-10 experiments on electron-cyclotron resonance heating showed that the basic problem was to transfer a significant RF power from the RF generator to the plasma core, which at that time was not solved. Using ECR heating to transfer a greater power from a generator seemed obvious, with the beneficial feature of depositing power to a small localized area of plasma minor radius as was indicated by the local dispersion relation analysis at that time. The problem of application of this method rested in many respects on the lack of powerful ECR generators. Such generators—gyrotrons—were being created by the Institute of Applied Physics (Nizhny Novgorod) effort. In 1973, the additional microwave heating of plasma in tokamaks was achieved by ECR waves in pioneer experiments on T-3 tokamak at the frequency of 35 GHz [23]. At least 30 kW RF power from 40 kW full gyrotron capacities was absorbed by the plasma and led to the growth of its electron temperature. On T-10, the experiments on ECR plasma heating were initially carried out at the first harmonic of EC frequency. Heating efficiency in these experiments was 70–80%. The electron temperature in the central areas of target plasma in the Ohmic stage of the discharge was increased by about 0.6–0.9 keV. Creation of a 2-frequency ECH complex of 11 gyrotrons at the frequencies of 81 and 75 GHz with the total planned power of 4.4 MW allowed the investigation of the energy confinement time dependence on additional power, significantly larger than the Ohmic one. The electron temperature obtained in these experiments reached ~10 keV. It is possible to call this value a thermonuclear one. In these experiments no significant deviation from the Maxwellian distribution was observed for the soft x-ray spectrum of



Electron Cyclotron Current Drive in T-10

ECCD efficiency in accordance with linear theory
$\eta_{CD}=0.03\times10^{20}AW^{-1}m^{-2}$- 1st harmonic (1991)
$\eta_{CD}=0.013\times10^{20}AW^{-1}m^{-2}$-2nd harmonic(1994)

Non inductive operation with ECCD
O-mode(1991)

↓

Excellent localization for X-mode w_{ec} ~1/30
High power density up to $25Wcm^{-3}$

Sawtooth suppression by ECCD (1994) for the first time

Figure 5. Electron cyclotron current drive in T-10.

energetic electrons. During these initial ECRH experiments on T-10 at quasi-perpendicular O-mode power launch, the first evidence of sawtooth stabilization/destabilization was reported as well as control of other MHD instabilities [24]. This gave an indication of the importance of the ECR method as an instrument in plasma physics investigations. Good prospects for ECR heating of high density plasma are opened with an opportunity to work on the second harmonic of electron-cyclotron frequency.

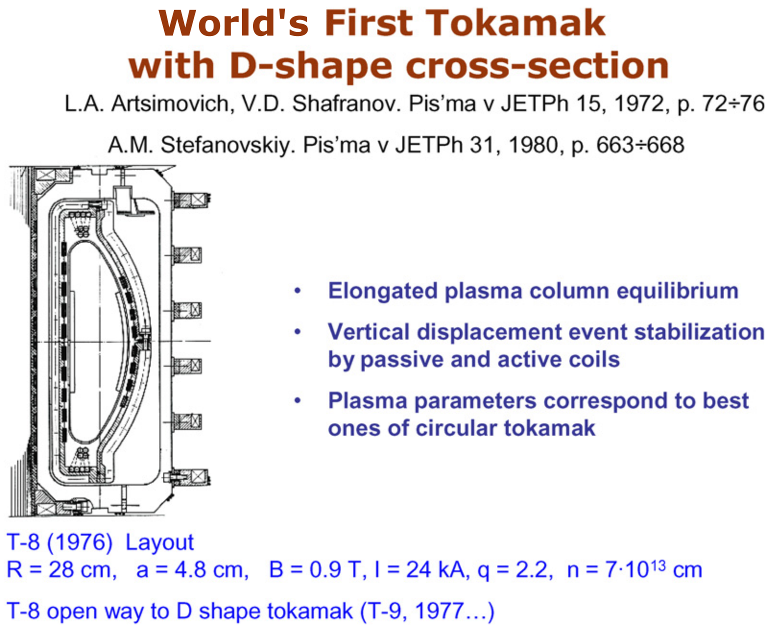
Respective experiments at a frequency of 140 GHz have shown an opportunity of effective plasma heating up to the level of line average plasma density of $6\times10^{19}\,m^{-3}$. Experimentally, the efficiency of ECH driven current generation was determined [25]. Full stabilization of internal local plasma instability and an opportunity of a strong stabilizing influence on MHD behaviour developing on the periphery of the plasma were again shown and to a greater extent (figure 5). One of the real ITER problems today is to minimize the volume of volt–seconds needed for a discharge start. T-10 experiments on non-inductive initiation of plasma start-up are currently directed towards this task [26].

Estimates of the size of a thermonuclear tokamak reactor, obtained on the basis of various plasma energy confinement scalings, gave metre values for the small radius of a plasma core and, hence, a great volume of magnetic field which should be stationary in time. These two circumstances forced researchers to think of a way of using superconducting windings in tokamak magnetic systems. The T-7 tokamak (1978) was the first-ever large tokamak with superconducting coils of a toroidal field [27]. The basic direction of research on T-7 was additional plasma heating and maintenance of non-inductive current by lower hybrid (LH) waves. Upon completing the set of studies this machine was transferred to China.

In the middle of the 1960s, experiments on tokamaks started at the Ioffe Institute. The first small toroidal device—TUMAN-1—was put into operation in1964. The main aim was to study adiabatic compression. The chamber was made of glass with a thin metallic liner. The chamber had two straight parts where compressing coils were arranged.

In 1970, the FT-1 tokamak, constructed with the help of the Kurchatov Institute, began operation. The chamber, coils and transformer were sourced from the T-2 tokamak ($R=62$ cm, $a=22$ cm, $B_o=1$ T, $I_p=40$ kA). Tokamak TUMAN-2, constructed in 1971, had a porcelain toroidal chamber with a thin metal liner. Adiabatic compression research was undertaken at this facility as well as on its upgraded version, TUMAN-2a, with a fully toroidal metal chamber. The largest tokamak at the Ioffe Institute—TUMAN-3—began operation in 1977 and is still in use. Its parameters are $R=55$ cm, $a=23$ cm, $B_o=1$–3 T, $I_p=130$–180 kA. The main topics of research have been adiabatic compression, RF heating, H-mode investigation, NB heating and parametric instability [28]. Many interesting and important results were obtained during research at the Ioffe Institute with the FT-2 tokamak ($R=55$ cm, $a=8$ cm, $B_o=3$ T, $I=50$ kA, 1980), in particular, in H-mode physics, LH heating and current drive and parametric instability.

At the beginning of the 1970s, Artsimovich and Shafranov proposed the idea of a tokamak with an elongated plasma cross section to improve its stability [29]. The experiments led to a series of tokamaks with non-circular cross sections: T-9, T-8, T-12, TBD (figure 6). These showed the possibilities for plasma equilibrium formation of a non-circular form, the growth of efficiency of using a magnetic field volume and the creation of a poloidal divertor configuration. The subsequent step was the large T-15 tokamak project which included the experience and results of operation of various installations. The system of additional heating in T-15 provides heating and maintenance of a current both by injection of neutral atoms (9 MW) and ECR and ICR waves (6 MW each). The T-15 diagnostic complex is based on the experience of many installations worldwide and the toroidal magnetic field is created by a system of coils made from Nb_3Sn superconductor. The basic work on T-15 construction was completed in 1988. During the commissioning of T-15, the steady state regime of T-15 superconducting magnetic system operation with a field at a plasma axis of 3.6 T was demonstrated (design value 3.5 T). About one hundred impulses in an Ohmic mode at a plasma current of 0.4–1.0 MA were carried out (figure 7). Currently, experiments on T-15 are suspended due to economic difficulties. Since the early tokamak investigations, large-scale plasma stability was the one of the main topics of theoretical and experimental activity at the Kurchatov Institute. The year 1963 was the first time when the major disruptions were observed on the TM-2 tokamak [30]. The tokamak density



World's First Tokamak with D-shape cross-section

L.A. Artsimovich, V.D. Shafranov. Pis'ma v JETPh 15, 1972, p. 72÷76

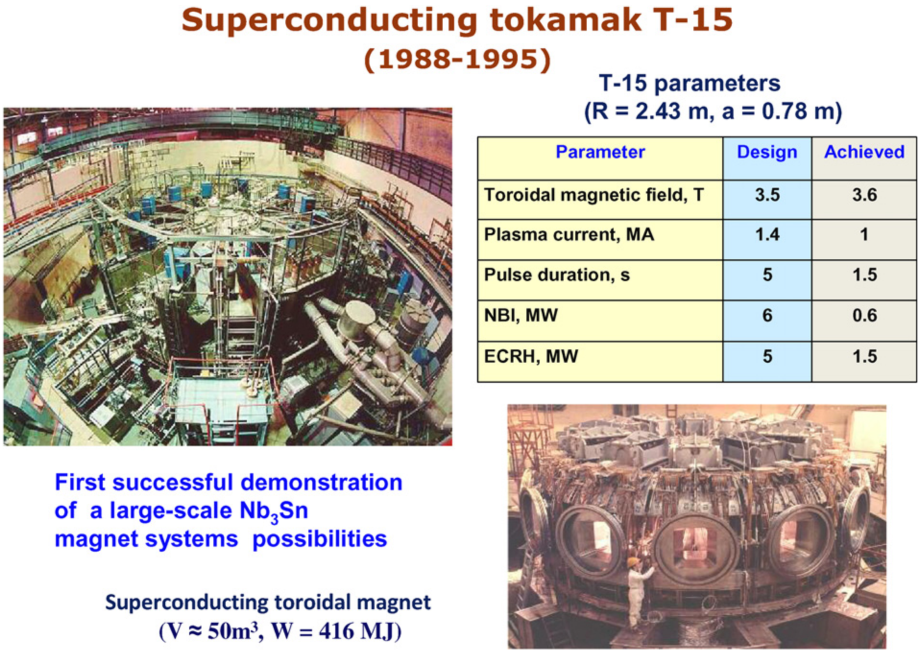
A.M. Stefanovskiy. Pis'ma v JETPh 31, 1980, p. 663÷668

- Elongated plasma column equilibrium
- Vertical displacement event stabilization by passive and active coils
- Plasma parameters correspond to best ones of circular tokamak

T-8 (1976) Layout
R = 28 cm, a = 4.8 cm, B = 0.9 T, I = 24 kA, q = 2.2, n = $7\cdot10^{13}$ cm

T-8 open way to D shape tokamak (T-9, 1977…)

Figure 6. The T-8 tokamak, with D-shape cross-section.



Superconducting tokamak T-15 (1988-1995)

T-15 parameters (R = 2.43 m, a = 0.78 m)

Parameter	Design	Achieved
Toroidal magnetic field, T	3.5	3.6
Plasma current, MA	1.4	1
Pulse duration, s	5	1.5
NBI, MW	6	0.6
ECRH, MW	5	1.5

First successful demonstration of a large-scale Nb$_3$Sn magnet systems possibilities

Superconducting toroidal magnet ($V \approx 50\,\mathrm{m}^3$, W = 416 MJ)

Figure 7. The T-15 superconducting tokamak.

limit was observed on T-3 in 1964 [31]. This 'Kurchatov' density level has, in recent years, been remarkably overcome by world community activity on chamber wall cleaning by lower temperature discharges. Later, there was found to be a causal connection between the tokamak plasma confinement, plasma current distribution (l_i) and the development of large-scale fluctuations of the poloidal magnetic field measured by magnetic probes. The investigations of tokamak external perturbation were performed by magnetic probes in 1970 [32] and earlier by visible plasma radiation (1966). Both methods showed the helical structure, predicted earlier by Morozov and Solovjev (1960) [33], as a common feature of all tokamak perturbations. The MHD origin of the measured perturbations as any mixing of ideal kink and resistive tearing modes was explained by V. Shafranov (1970) and H. Furth, P. Rutherford, H. Selberg (1973). The multi-channel SXR measurements, which were performed for the first time on T-4 (1971) and then on the ST tokamak (1974), gave important information about features of internal MHD activity. The most significant result of SXR measurements on T-4 was the observation of a very short (10–50 μs) drop in the central electron temperature (fast thermal quench), which preceded the major disruption development (1976) [34]. This has subsequently been confirmed on many tokamaks. The fast flattening of plasma temperature and density during the fast thermal quench permits the supposition of the simultaneous loss of magnetic shear at the plasma centre as a result, for example, of any internal disruption ($m = 1/n = 1$). This should excite the development of large-scale ideal kink instability ($m = 2/n = 1$) across the whole hot region of the plasma column, which seems to be a main mechanism of major disruption ('vacuum bubble', Kadomtsev-Pogutse model, 1973, R. Kleve, J. Drake, D. Boyd 1985, ITER Physics Basis, 1999). The history of tokamak MHD investigations in the 60–80 years of the previous century, which completed the picture of large-scale tokamak stability, is a shining example of successful international scientific cooperation.

It is important to emphasize that during the 1960s, 1970s and 1980s, parallel to experimental tokamak investigations at the Kurchatov Institute, there was strong theoretical activity on plasma physics and tokamak theory foundation led by B. Kadomtzev, V. Shafranov, R. Sagdeev, A. Mikhailovskii and many others. This work was summarized in the 'Voprosy Teorii Plasmy' (Problems in Plasma Theory) books initially edited by M. Leontovich. This work on 2D–3D plasma equilibrium, linear and non-linear instabilities, on plasma heating and non-inductive current drive created the foundation for magnetic confinement of hot plasmas including tokamaks. Semi-qualitative analysis of numerical drift type turbulent plasma, similarity laws, experimental energy confinement time scalings from tokamaks worldwide allowed Kadomtsev to conclude that the creation of the D–T tokamak reactor with reasonable size, magnetic field and plasma parameters was possible. After some years, this conclusion was considerably strengthened by the important discovery of H-mode regimes in tokamaks with divertors (ASDEX & F. Wagner, 1982). E. Velikhov proposed having this as a base for a conceptual study of a tokamak reactor named INTOR for the international community. In the INTOR project, 1979–1987, there was participation by the EU, Japan, USSR and USA and it was an important step for the ITER project which now has seven regions as lead participants.

Conclusion

The success of the tokamak concept has been proved by the work of the whole international community that joined the concept development after 1970. It was at this time that a wide international cooperation started and made a great contribution to tokamak-reactor physics and technology development. Although, as mentioned above, the level of physics comprehension did not allow the construction of a reliable tokamak design, the accumulated experimental data and developed codes are a serious basis to expect success at a final stage of physical studies to be performed on the ITER tokamak. Major challenges remain in tokamak physics studies, reactor technology and radiation resistive material development. However, expert estimations indicate no insurmountable problems among these. Mastering thermonuclear energy would provide mankind with an inexhaustible, safe and ecologically acceptable energy source. In conclusion the author would like to thank his Russian colleagues who participated in preparing materials for this paper thus making possible its creation.

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