DEVELOPMENT OF A CONCEPTION OF THE STELLARATOR BASED ON TORSATRON AND MODULAR SYSTEMS

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The paper presents the historical review of the stellarator conception development on the example of thermonuclear research at the Kharkov Institute of Physics and Technology. The given material covers a period from the time of the large-scale stellarator "Ukraine" offered by I.V.Kurchatov up to the present. The main attention put to torsatron and modular systems.

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In 1960 at the KIPT the academician I.V.Kurchatov initiated the beginning of thermonuclear research. He proposed to construct in Kharkov a large thermonuclear installation – a stellarator which was named "Ukraine". Kurchatov believed that "Ukraina" should be equal to the final installation developed since 1951 in the USA under the project "Sherwood" – the stellarator "D".

A sudden death of I.V.Kurchatov entailed the appreciable correctives in the implementation of this project. As a result, the parameters of "Ukraina" were significantly decreased and it was renamed as "Uragan-1" which approximately corresponded by its characteristics to the stellarator "C" (USA). Thus, in Kharkov, with blessing of the remarkable organizer of the science, the investigations of stellarator systems have been begun. In the 60s there were constructed the stellarator-racetracks "Sirius", "Uragan" (modifications U-1, U-1M and U-2) and their models.

In the late 60s and the early 70s it was recognized as expedient to transfer a main direction of research from the stellarator to the torsatron. During the years which followed at the KIPT one constructed a series of installations of such type: "Saturn": "Vint-20", "Uragan-3M", "Uragan-2M.

A significant contribution to the development of a stellarator system was made by researchers of the USA, Japan, Germany, France, Great Britain, the former USSR and others [1,2]. Experiments on the large heliotron (torsatron) LHD (Japan) are continuing, a largest stellarator based on Modular Coils W-VIIX (Germany) is under construction, a project of a unique compact stellarator NCSX is under development (USA).

In the present paper much consideration is being given to the first torsatrons of the KIPT (Part 1), to compact ring modular systems of a stellarator type (Part 2) and to different scheme and operating conditions of a hypothetical fusion reactor based on the torsatron (Part 3).

1. TORSATRONS OF THE KIPT

Let us note the most important milestones in the origin and development of the idea of a torsatron:

1) In 1961 V.F.Aleksin (KIPT) has found that in a trap composed of a direct solenoid and *l* helical conductors with an unidirectional current, magnetic surfaces (MS) can exist.
2) Later C.Gourdon and collaborators suggested independently a toroidal trap with unidirectional helical current called as a "torsatron" ([3], 1967-1968). During development of the idea C.Gourdon, P.Hubert et al. have offered a torsatron without additional toroidal field winding (TFW); "Ultimate torsatron"; torsatron with plane coils (so-called, "Villarseau Coils" [4], 1967) spatial divertor of the torsatron; first scheme of a torsatron-reactor etc.
3) Due to efforts of Japan scientists (K.Uo et al.) an earlier heliotron conception has come to this direction too ("Helical heliotron")[5].
4) A great contribution into improving the torsatron design was made by researchers of different countries (See, for example, [13, 26]).

Unfortunately, because of limits for this paper, it is not possible even to list the main works on torsatrons. However, there are the references to many of these papers in the book "Stellarator" [1], and in some reviews, see, for example, [2].

At the KIPT the development of first torsatrons [6] begun in 60s on the tide of discontent for a classic scheme of the stellarator-racetrack with a toroidal divertor

While transition to the torsatron modification there was a purpose to simplify ultimately a magnetic system, to create, as a result, a compact torsatron with a spatial divertor. The following torsatrons of different modifications were developed, constructed and investigated (see Table 2).

1.1. <u>The first world's torsatron "Saturn" (experiments started in March, 1970 [7,8]).</u> In its design two modes of operation were provided –"torsatron" and "stellarator". Besides, it was possible to operate with the available toroidal field winding (TFW) and without it. The TFW was made in the form of a continuous winding creating a toroidal field without visible ripples [9].

Complex investigations to compare the torsatron with the classic stellarator [8] in general confirmed the identity of MS on these systems, and, at the same time, revealed some distinctions. This has opened the way for the further improvement of torsatrons.

1.2. <u>The first *l*=1 ultimate torsatron "Vint-20'</u> (Fig. 1*) with a helical winding law providing the compensation of a vertical magnetic field (start in 1972, experiments since 1973 [10,11]). The torsatron comprises a sole winding – a toroidal helix placed in the vacuum volume. It is partially discharged from the action of ponderomotive forces. An ultimate level of a toroidal magnetic field Bo equals to 1.8 T.

A partial compensation of forces F_R and the decrease of the aspect ratio (Ap) by a factor of 4.5 leaded to a significant decrease in the specific metal amount and in

* All Figures and Tables are presented in Figures Section

the energy capacitance of the toroidal magnetic system (TMS) of the torsatron "Vint-20" as compared to "U-2". Disadvantages of this installation include a very large helical rippling (ε_h) of MS.

1.3. In 1973-1980s a torsatron with superconducting windings "Crystal-2" and its model "Crystal-1" were developed ([12]).

1.4. The first torsatron with a spatial divertor providing the removal of a diffused plasma without contacts with construction elements and with a quasi-force free magnetic system – l=3 torsatron "Uragan-3" (See Fig. 2) [14,15,16] (start in 1981). Development of the divertor of torsatron was preceded by the comprehensive analysis of many divertor systems. As a result, at the KIPT one concluded that a natural (without special divertor current coils) spatial divertor is the best choice for the torsatron. (The divertor of such type is used now in LHD). In "U-3", to realize ideas of a spatial divertor, it was necessary to dispose TMS in vacuum and to create a system of HW fastening being discharged from the action of ponderomotive forces and "transparent" to divertor fluxes.

At the KIPT the detailed investigations of toroidal "force-free" magnetic systems (FFMS) [17,18,19,20) and experiments on small-scale models "Micro" and "Vint-100" (l=3 torsatron [18], start in 1973) were performed. They showed that the idea of FFMS may be applied also for TMS of torsatrons and for tokamaks with a multipolar ($l \geq 8$) HW [19,21,22]. Using the "force-free" model "Vint-100" a field Bo=7.5 T being record for stellarator magnetic systems was reached [18].

So, the idea of "force-free" systems was used for the first time in two cases: for constructing the l=1 ultimate torsatron "Vint-20" and (in full measure) for creation the large l=3 torsatron "U-3".

Comparison between TMS of the stellarator-racetrack (with a toroidal divertor) and the torsatron (with a spatial divertor) has showed that TMS of the torsatron is characterized by a specific metal amount being less by a factor of 4, and an energy capacitance being less by a factor of 2.

On the torsatron "U-3" thorough magnetic measurements have been performed [21]. As a result, a conclusion was made about an insufficient accuracy of HW manufacturing. Therefore, it was decided to develop a new HW with the best accuracy. A new modification was called "Uragan-3M". Magnetic measurements on U-3M [22, 23] have showed a significant improvement of the MS quality. Up to now "U-3M" is used for carrying out the plasma experiments related in main with the divertor investigation.

1.5. The model of the modular l=3 torsatron "MMT" (A.C.1001186, priority in 1981, [24], magnetic measurements since 1986[25]) (seeTable 1). Researchers of the KIPT proposed [24]. An updated modular torsatron MMT with a modular compensation winding (CW) used as a reverse current lead for joining the HW parts in a single module. The order of multipolarity (p) of CW was higher than the number of helical conductors (l) of HW: $p > l$. The first module torsatron with p=l (see Table 1) was proposed by J.Shohet in 1980 [26]. As a disadvantage of MMT one can consider a complicated manufacturing of the module, and as advantages - a possibility to create the torsatron on the base of one-type modules and minimum distinctions of the magnetic configuration from the torsatron configuration with a continuous HW [25]. MMT with $p>l$ has a number of advantages over MMT with $p= l$.

1.6. The torsatron with a helical compensation winding (CW) (see Table 1 and [28], A.C.433908, priority in 1972). This torsatron is close to the idea of an "ultimate stellarator" ([29], 1980). The torsatron with a helical CW creates a more uniform magnetic field as compared to the traditional torsatron. (Experimental testing was not carried out).

1.7. The large-scale $l=2$ torsatron "Uragan-2M" (Bo=2.4T, Ro=1.7 m, ε_h =0.44m, ε_p = 0.2 m) with an additional toroidal field winding (TFW) [30]. (Magnetic measurement in 1996). A magnetic configuration of the torsatron U-2M is specified by a low value of helical ripples (εh ≈ 6%). This result was obtained by optimization of helical winding parameters.

2. COMPACT MODULAR RING MAGNETIC SYSTEMS

During fifty-years of developing the stellarator one suggested tens of types of modular magnetic systems (MMS) (see, for example, Table 1 and [31]). Development of MMS was based on the aim to simplify the stellarator construction with a complex HW and to make easier disassembling of the reactor-stellarator. Investigations at the KIPT came to search the most simple and compact MMS based on one-type plane current circular coils.

2.1. In 1969 one proposed a MMS "Vintopol" [32] with a plane geometric and space magnetic axes composed of tilted and turned, by the helical law plane current circular coils ([31], Table 1). The studying of this MMS, including experiments on the direct model [32], allowed passing to the development of even simpler ring systems. The modular system composed of elliptic coils turned relatively to each other was proposed in 1966 [32].

2.2.1. In 1988 a modular system "Vintopol-II" ("Tilted Coils") was proposed [33] (A.C. SU 1562957) (Table 1). This MMS comprises a compensation poloidal field winding **(**CPFW) and l plane current circular coils uniformly placed along the circular tore axis and turned (tilted) at an equal angle ϒ around a major tore radius Ro. Note, that a few years later P.Moroz also came to this way of investigations (see, for example, [36]). In this system the rings are not mechanically coupled with each other (a_c< Ro) (a_c is the ring radius, t(a) and t(o) are the angles at the boundary MS and on the magnetic axis). One studied the influence of the aspect ratio of rings Ac (Ac ≈ 1.04÷4.3), their numbers (l=3÷16) and the angle of tilt γ(γ =20º÷50º) on the MS parameters [33]. (In the system TC it is possible to control the parameters of MS by changing angles ϒ.) Characteristic values of MS parameters are: t(a)=(0.4÷0.6, a/ac=0.3. It was shown, that there are MS with values of angle t ≈ (02÷0.4) in the maximally compact variant (l=3, Ac≈1.04). Disadvantage of "Vintopol-II" are large helical ripples (εh>0.2) at values l<8.

2.2.2. One of the peculiarities of MS in this system is decreasing (as in the tokamak) function t=f(r), i.e.

t(0)>t(a). The system "Tilted Coils" can be used as a TFW winding in the tokamak for the purpose to create a hybrid "Tokamak-Stellarator" ("T-S"). Therefore, investigations of MS of "Vintopol-II" with D-shape rings were carried out ([34], 1993). By selection of ring parameters one succeeded to find the variants "T-S" with angles t(a) ≤ 0.15 and with $\varepsilon_h \leq 0.15$.

2.2.3. Besides D-shape Tilted Coils one studied TFW composed of rectangular TC [35]. The works on TC, STC and "S-T" hybrid were conducted in the framework of the Raytheon Company (USA) under interaction with the Wisconsin University [35]. It was shown that MS are formed only at large angles of tilt of TC ($\gamma \geq 25^o$).

2.3. In tokamaks so large angles γ were difficult to realize, and at small γ MS were shifted to the external parts of coils. For symmetrization of MS and improving their quality one suggested (see, for example [35]) a relatively simple additional winding of the poloidal field in the form of a closed ring saw - "Saw-Tooth Coils" (STC). It was shown [35] that with the use of STC it is possible to create MS with parameters required for the STC hybrid. STC can be used also as an addition to TFW coils of the existing tokamak in order to create the T-S hybrid.

2.4. In conclusion of this section let us dwell on different modifications of ultimately compact torsatron (CT) with a one-period (m_h=1) HW that is composed of *l* deformed rings (see Table 1 and [37, 38, 39, 40]) disposed on the toroidal surface ("coupled rings" – as a bunch of keys). The coefficients of HW modulation α and β can be varied in a wide range. MS were studied for CT with *l*=2,3 and 4 at Ah near the unit (Ah=1.02÷2.0). (Ah is the aspect ratio of HW (of rings), Ah-Ro/ah). Two variants of CT, with the presence of TFW and without this winding, were studied.

It was shown that for CT without TFW (the simplest variant) one can reach radii ao/ah ≈ (0.4 ÷ 0.5) and angles t(a) ≈ (0.1÷ 0.3). In one of variants of CT without TFW one obtained MS with a minimum aspect ratio Ap ≈ 1.2. The "helical winding" of CT can be presented also in the form of plane coupled *l* rings (so-called "Villarseau Coils"[4]). Recently (2001) the system of *l*=4 Villarseau Coils was used as one of elements of TMS in the calculated model of the compact stellarator [41].

3. DEVELOPING THE CONCEPTION OF A REACTOR-TORSATRON

By the beginning of 70s the experiments on plasma confinement confirmed the supposition about a diffusion character of losses in stellarators. It implied that there were not obstacles in principle to create a fusion reactor on the base of a stellarator system. Therefore, the engineering and technical problems and the tasks of optimizing reactor parameters for the purpose to decrease the overall dimensions and the cost, to simplify the design etc., were first and foremost.

At the KIPT a cycle of works on development of a reactor on the base of stellarator systems has been carried out. Investigation of TMS of the stellarator-reactor was conducted in 1971 [43]. The paper [44] demonstrated a possibility for development of the stellarator-reactor operating in a plateau regime of neoclassical dependence of transition coefficients. A possibility for creation of a thermonuclear neutron source was studied and the parameters of a demonstration facility with a superconducting TMS based on the torsatron "Uragan-7" were proposed [45,46].

In the team with researchers of LPI and NIIEFA a series of works on developing and optimizing parameters of a modular reactor-torsatron were carried out [47, 48]. A design of a reactor module [AC N 1050419, priority in 1982] was developed (see Fig.3) including all reactor systems. Repairing works on this reactor comes to changing a defective module with a module in good repair that essentially reduces the duration of a nonproductive idle time of the reactor. Engineering development and optimization made it possible to conclude that a thermonuclear power plant based on the reactor-torsatron may be commercially efficient [48].

A scheme of the reactor-stellarator with an additional TF has been developed [49]. A possibility to construct a reactor with a hyperconducting magnetic system that significantly simplifies its design as compared to the superconducting variant was shown [50].

Taking into account of the spatial distribution of plasma parameters [51] confirmed the assumption that the maximum of energy release in the reactor corresponds to the maximum of a density and temperature at the core of a plasma**.** In this case the total energy release exceeds in several times the value that follows from estimations over averaged values of plasma parameters. Besides, the estimations of the energy lifetime with the use of mean values of parameters are under-estimated too.

A possibility of a stable self-sustaining fusion reaction in the reactor-stellarator is shown in paper [52]. Note, that the traps of a tokamak type do not possess this property.

The disadvantages of reactors based on DT mixture fusion are a necessity of working with tritium and high fluxes of thermonuclear neutrons (14 MeV). Reactors operating with the D-3He mixture are significantly safer. Development of a torsatron design operating with the D-3He was performed in papers [50, 53].

The development of a conception of the modular reactor-torsatron is presented most fully in review [54]. The projects of reactors based on stellarator systems fulfilled in laboratories of other countries are considered in review [55].

The use of the TC system allows an idea of combining the properties of stellarators (stationarity and MHD stability) and of tokamaks (compactness, MS simplicity). This work has been done on the example of the ITER project. Thus, it has been shown that the opportunity to create the tokamak-reactor with a vacuum transformation angle t(a) ~ 0.1 exists that simplifies the problems of providing the start and stable thermonuclear fusion.

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1) A.C. - *Authors Certificate SU, BI - Bulleten Inventions*
2) *VANT, Ser. Termonuclear Fusion, M., ZNIIAtominform*

SUPPLEMENT

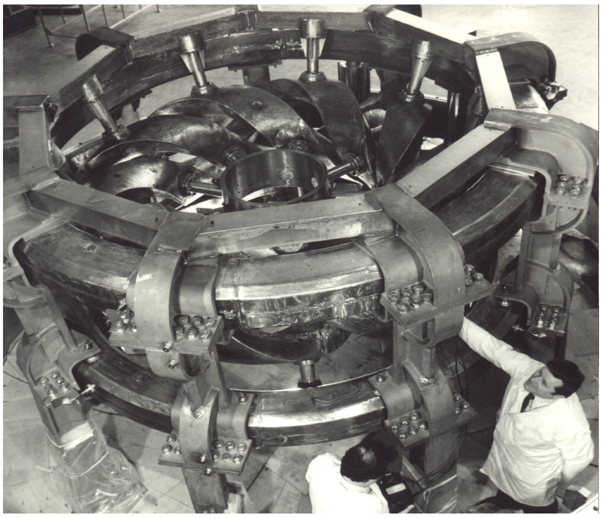


Fig. 1 Magnetic system of Uragan-3M Device

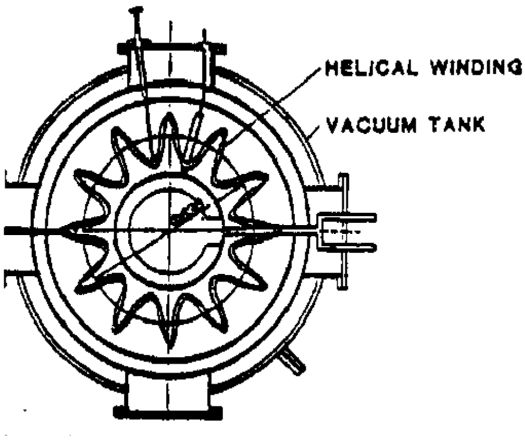
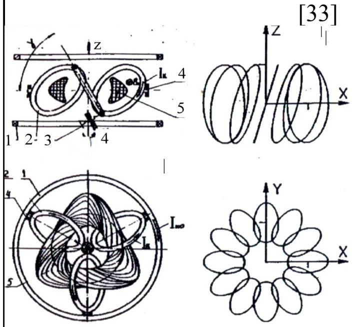
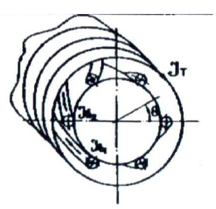
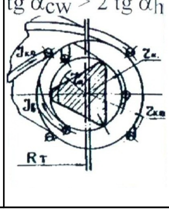
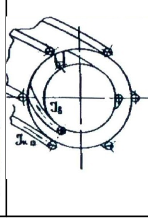
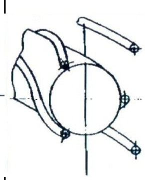
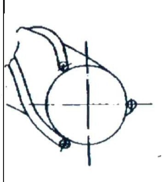


Fig.2 Vint-20 Device scheme

Fig.3 Reactor modulus: 1- plasma, 2- HW, 3 - CW, 4-force construction, 5- blanket, 6-cryostat, 7-radiation defense, 8- divertor

Table 1. Different kinds of stellarator modular systems (More full information see in [31])

[33]	CLASSICAL STELLARATOR	[28]	TORSATRON [3]		
		With helical CW	With multipolar CW		Without CW (p=0)- ultimate torsatron
			P=(2+5)l	P≤l	
		$tg\ \alpha_{cw} > 2\ tg\ \alpha_h$ 			

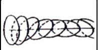
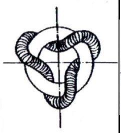
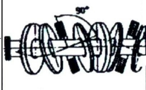
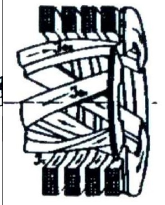
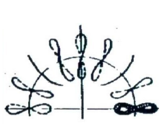
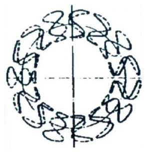
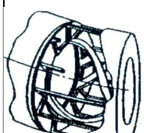
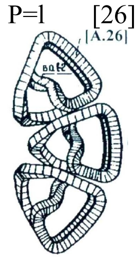
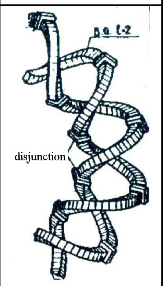
STELLARATOR TYPE DISCRETE SISTEMS			MODULAR CLASSICAL STELLARATOR	TWISTED COILS SYSTEMS [27]	MODULAR TORSATRON			
Plane elliptical three angular coils [42]	Spatial axis systems (l=1)	Spatial magnetic and plane geometric axes [32]		l=2	CW WITH OPPOZITE DIRECTED CURRENT PARTS			With disjunctions
					l=3 [27]	P>l [24]	P=l [26]	
								

Table 2. Parameters of the first torsatrons and their models

No	Name	a_p/a_h	a_h, cm	R, cm	A_h	Bo, T	*l*	m_h	*t*	*to*	S	Start time	Position	Comments
1	Devices Saturn	5/8.0	10	35.6	3.56	1.0	3	8	0.5	<0.4	<0.2	1970	Kharkov Ukraine	Torsatron-stellarator
2	Spac-1	4/6	8.4	40	4.77	0.18	2	21	0.15	-	-	1971	Nagoya Japan	Helical Heliotron
3	Heliotron D	10/30	13	108.5	8.55	0.3	2	25	3	0.27	3.0	1971	Kyoto Japan	
4	Vint-20	7.5/-	7.25	31.5	4.34	2.0	1	13	1.5	<0.75	1.5	1972	Kharkov Ukraine	Ultimate torsatron
5	Torso	6.5/-	10	40	4.0	2.0	3	12	0.8	0.3	0.15	1974	Calem UK	Ultimate torsatron
6	Proto-Cleo	5/-	9.5	40	4.21	0.3	3	13	0.6	-	-	1976	Wisconsin USA	
7	Heliotron DM	4/-	6	45	7.5	1.0	2	21	1.5	-	0.6	1976	Kyoto Japan	
8	Heliotron E	20/ 41x21	30.0	220	7.33	2.0	2	21	2.5	0.5	<1.0	1980	Kyoto Japan	
9	Crystall -2	6/-	9.5	60	6.32	2.0	3	15	0.5	-	0.2	1980	Kharkov Ukraine	Supercon-ductive MS
10	Uragan-3	13.5/-	27	100	3.7	2.5	3	9	0.6	0.25	0.25	1980	Kharkov Ukraine	Divertor Force-free MS

РОЗВИТОК КОНЦЕПЦІЇ СТЕЛАРАТОРА НА ПІДСТАВІ ТОРСАТРОННИХ ТА МОДУЛЬНИХ СИСТЕМ

О.В. Георгієвский, В.А. Рудаков

У роботі представлено історичний огляд розвитку концепції стеларатора на прикладі термоядерних досліджень у ННЦ ХФТІ. Даний матеріал покриває період з часу, коли І.В. Курчатов пропонував збудувати у Харкові великомасштабний стеларатор "Україна", по теперішній час. Головна увага надана торсатронним та модульним системам.

РАЗВИТИЕ КОНЦЕПЦИИ СТЕЛЛАРАТОРА НА ОСНОВЕ ТОРСАТРОННЫХ И МОДУЛЬНЫХ СИСТЕМ

А.В. Георгиевский, В.А. Рудаков

В работе представлен исторический обзор развития концепции стелларатора на примере термоядерных исследований в ННЦ ХФТИ. Данный материал покрывает период с момента, когда И.В. Курчатов предложил построить в Харькове крупномасштабный стелларатор "Украина", по настоящее время. Главное внимание уделено торсатронным и модульным системам.