COMPACT STELLARATOR-LIKE CONFIGURATIONS, CREATED BY SYSTEM OF PLANE CIRCULAR CURRENT COILS

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Stellarator magnetic configurations with different combinations of plane circular tilted current coils were studied. Two types of coil combination used for forming of the magnetic configurations: cohesion tilted coils (Villarso coils) and uncoupling tilted coils. As torsatron type, so stellarator type systems with multipolarities l = 2, l = 4 and their combinations were studied. For the first time magnetic configurations with good confinement properties created by system of uncoupling coils stellarator type current combinations were obtained. Splitting of l = 2 coil system allows to obtain l = 4 harmonic, that goes to improvement of confinement properties of the configuration. Variation of value corrective field allowed to obtain quasisymmetric properties of the stellarator configuration.

The prospect for ultimate simple plane circular current coils, being tilted with angle γ_H around the main torus radius R, to create the closed stellarator-like magnetic configuration was shown in paper [1]. The magnetic configurations of such types were investigated in [2, 3] for different number of uncoupled tilted coils N = 2 - 24 and for a wide range of aspect ratio: $A_k = 1\text{-}10$ and practically in every case the closed magnetic configuration with rotational transform ranging from zero to few tenths were found. At a number of cases the D-shape coils were used instead of circular ones with very much similar result, but D-shape allowed to obtain better symmetrisation of closed magnetic configuration. The magnetic configurations of extremely compact $l = 2$, $l = 3$ and $l = 4$ torsatrons with extremely low number of magnetic field periods, i.e., $m_h = 1$ and with "helical" winding were investigated by authors of [4].

In paper [5] the vertically oriented rectangular coil system was combined with circular sawtooth coil placed in external part of a torus to obtain a closed magnetic configuration. This combination was proposed for tokamak PHAEDRUS-T magnetic system with the aim to create the hybrid tokamak - stellarator device for studying plasma confinement. The additional rotational transform allows to operate at lower plasma current and higher beta compare to a standard tokamak. Besides, such system can stabilize the process of current start up in a tokamak configuration.

The present paper is devoted to the stellarator-like magnetic configurations with different combinations of plane circular current coils. Two types of coils used for forming of magnetic configurations are under investigation: the cohesion tilted coils (Villarso coils) and uncoupled tilted coils. The splitting of $l = 2$ coil system allows to obtain $l = 4$ harmonics, that gives an improvement of confinement properties of the magnetic configuration.

The report consists of geometrical description of the tilted coil system and of the part, where properties of magnetic configurations created by different combinations of coils are described.

1. Geometrical description

For the first time a proposition to use the simplest helical system for plasma confinement, based on the Villarso coils, was offered by C. Gourdon et al [6].

The Villarso coils are plane circular coils, that are placed on radius r_{h0} of the major torus axis and tilted to the horizontal plane with angle γ_H. Values of r_{h0} and γ_H have to correspond the condition: $r_{h0} = r_{hc} \cdot \sin\gamma_H$, where r_{hc} is the radius of Villarso coil. Placed around major axis such coils form a toroid with major radius R_o and minor radius r_h, which are: $R_o = r_{hc}$ and $r_h = r_{h0}$ (Fig.1).

A system of number of the Villarso current coils forms the helical magnetic system with equally inclined winding of l periods, where period coincides with the number of the coils. The relation between toroidal and poloidal angles φ and θ, and γ_H is described by the equation

$$\sin\varphi = \cos\gamma_H \cdot \sin\theta / (1 + \sin\gamma_H \cdot \cos\theta). \qquad (1)$$

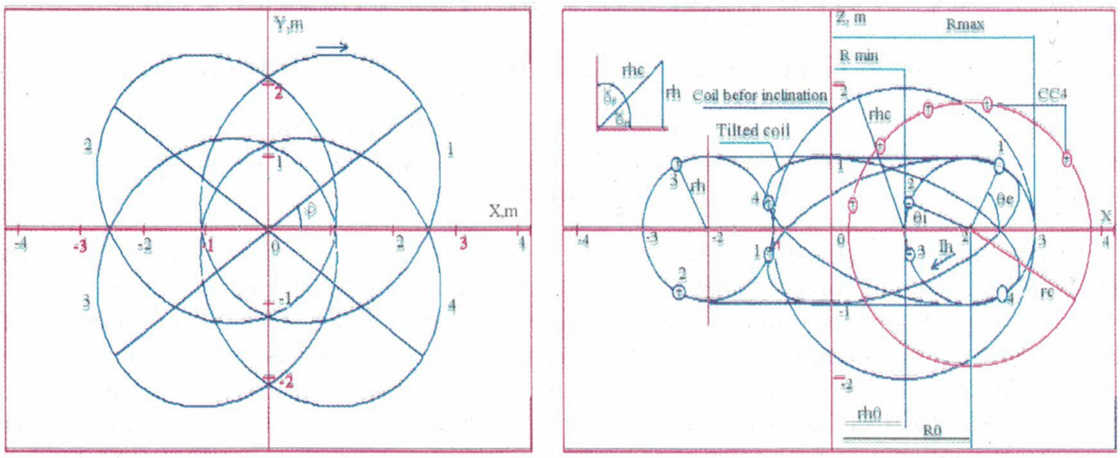

Fig. 1. Torsatron with Villarso coils (combination *(l = 2) + (l = 4)*), *a* - top view, *b* - side view, Ro = 2.0 m, rhc = 2.0, rh = 1, rho = 1, θe = 57°, θI = 19.5°, $\gamma_p = 60°$, $\Delta\varphi = 34.8°$, rc = 1.8 m (CC - 4), Ah = Ro/rh = 2.0

As known, the equally inclined helical windings give magnetic configurations with better properties for confinement of plasma, namely - larger confinement volumes and higher rotational transforms. The main course of Villarso coil use is the possibility to obtain good parameters of magnetic configuration for a low aspect ratio system. In our case the number of magnetic field periods is equal to the number of helical coils.

The systems with multipolarities *l = 2* and *l = 4* and their combinations where used for the study, because each of them has advantages and disadvantages supplementing each other. The *l = 2* system gives big rotational transform and large confinement volume, but the disadvantages of the system are large ripples and low shear of the rotational transform. The *l* = 4 system gives a good confinement volume and high rotational transform at the edge of plasma confinement volume, but the shear is so high, that any small distortion of the last closed flux surface can destroy the magnetic configuration.

So, the combination of both types of coils allows to preserve the advantages and to avoid disadvantages. As an example, the helical poles of the Kharkov *l = 2* stellarator Uragan-2M were bifurcated with this purpose [7]. Each of the two helical poles of Uragan-2M device was splitted into two 33°-poloidal sectors with a 18-degree poloidal gap between them. The angular width of gap does not change along the winding.

In the present study we bifurcated the *l = 2* poles by displacement of the separate helical parts along the φ direction. Fig. 1 shows a torsatron combination *(l = 2) + (l = 4)* with Villarso coils: Fig. 1*a* is for a top view and Fig. 1*b* for a side view. In our case the angular gap between bifurcated coils in θ direction depends on a pole position, as it can be seen in Fig. 1*b*. There is condensation of coils at the inner part of the torus what is typical for the equally inclined windings.

For calculations we usually used a system with $R_o = 2$ m, $B_o = 2$ T of either as a torsatron or as a stellarator helical current combination. Confinement magnetic field was produced by currents in tilted coils in a torsatron case and the additional toroidal magnetic field was used in a stellarator case. In some cases, when the K_φ value differs from unit, an additional field was applied to a torsatron configuration also. For compensation of the vertical field component we used several combinations of poloidal coils with one, two and five pairs of poloidal currents (case CC4, in Fig. 1b). There is a significant condensation of poloidal coils' positions at the inner side of the torus for the five pair coils variant. The different inclination angles for Villarso coil system were analyzed to vary the aspect rations inside the γ_H interval between 25° and 50°.

We analyzed also the system with winding law which is often called as an equally inclined one:

$$\varphi = \theta - \alpha\sin\theta - \beta\sin 2\theta, \tag{2}$$

where $\alpha = rh/R_o, \beta = -\alpha^2/4$ to compare it with the Villarso coils' system. There are differences between values of the φ angular coil displacements for given θ angle splitted coil position in these cases. The Table illustrates these differences. Note, the equation 1 gives an exact equally inclined low, but equation (2) is an approximate expression.

Table

Table of splitted angles for two types of winding law

No.	γ_H°	θe/θi °	Δφ° plane coils	Δφ° equal incline	α	β	Comments
1	30	26/8.8	15.17	16.27	0.5	-0.0625	
2	30	38	22.9	23.83	0.5	-0.0625	
3	30	42	25	26.39	0.5	-0.0625	
4	42	38	17.45	20.6	0.669	-0.112	
5	42	45	20.9	24.29	0.669	-0.112	
6	30	60.1	36.9	38.36	0.5	-0.112	
7	30	45	26.9	28.2	0.5	-0.112	
8	30	57/19.5	34.8	36.5	0.5	-0.112	See Fig.1
9	30	71.3	45	48	0.5	-0.112	*l*=4
10	30	80	51.75	53.97	0.5	-0.112	

2. Results of calculation

The magnetic configurations with different coils' inclinations γ_H in region 25 - 50 degrees were investigated that provided to study systems with different aspect rations from 2.37 to 1.3. These were systems with multipolarities $l = 2$, $l = 4$ and their combinations. The $l = 3$ system was studied too, but the results will be a subject of another paper.

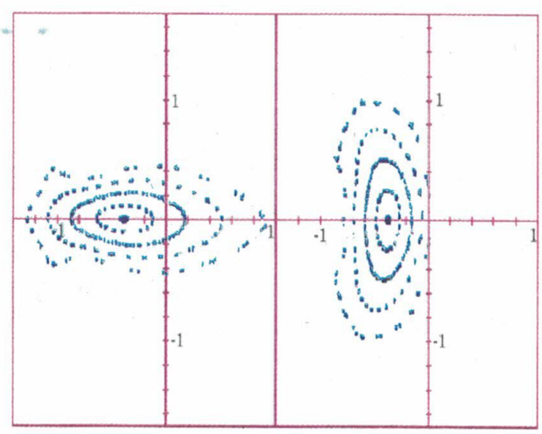

Fig. 2. $l = 2$ torsatron, (Ro = 2 m, rhc = 2, γ_H = 30°, rh = 1, Kφ = 0.28), CC4, rc = 1.8 m, bz(0)=0, Bo = 2T, Ih = 2800 kA, rp = 0.707 m, tmax = 0.264, to = 0.48

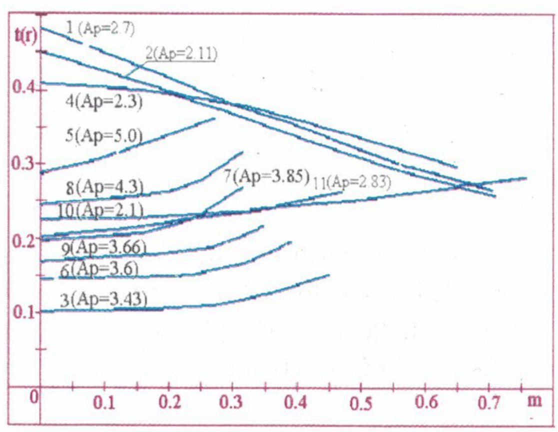

Fig. 3. Rotational transform dependencies for $l = 2$ stellarator and torsatron, stellarator field case (lines 3,5 - 9,11), torsatron case (lines 1, 2, 4, 10), γ_H = 35° (1, 2, 3); γ_H = 42°(4 - 8), 45° (9), 50°(10,11).

The magnetic configuration of a $l = 2$ torsatron without additional toroidal field possesses of large confinement volume and high rotational transform, if a pitch angle between helical conductor and the horizontal torus generating line is in the region 40 - 50 degrees. The disadvantages of this simple scheme are the large enough ripples of magnetic field and rather low shear. The ripples are possible to diminish by adding a subsidiary toroidal field and by using small pitch angles. Fig. 2 shows the $l = 2$ torsatron flux surfaces with $\gamma_H = 30°$ and $K_\varphi = 0.28$ (K_φ is the ratio of toroidal field created by the helical winding to the total toroidal field). There are high enough rotational angles in the system, but $\iota(r)/2\pi$ dependence is not good ($\iota(0)/2\pi = 0.48$, $\iota(r_{max})/2\pi = 0.264$).

A torsatron type helical winding allows to work without additional toroidal field. The principal technological difference between torsatron and stellarator diappears if a subsidiary magnetic field is added. A difference relates to the values of helical winding currents only. However there are essential differences in the properties of magnetic configuration. Fig. 3 illustrates the radial dependences of rotational transform: it increases in the stellarator (see lines 3,5 - 9,11) and decreases in the torsatron. At the same time, confinement volumes are essentially larger in torsatron cases (lines 1, 2, 4). An increasing dependence for torsatron takes place for one case only, namely when $\gamma_H = 40°$ (line 10). This is probably connected with correcting field value b_z. It equals + 3.2 % for this case in comparison to other cases with $b_z = 0$.

The $l = 4$ torsatron with Villarso coils has a good magnetic configuration (e.g., Figs. 4, 5), and rotational transform dependences (Fig. 5, 7 - 9) correspond to the $l = 4$ torsatron. Both configurations are characterized by the high shear values but an external part of flux surfaces is unstable. As for the magnetic axis position, it can be displaced essentially even by a small vertical field. In Fig. 5 the rotational angles for torsatron configurations $l = 2$ and $(l = 2) + (l = 4)$ ($\gamma_H = 30°$) are shown where the lines 4, 6 correspond to *(l= 2) + (l = 4)* combination. The angle increasing is smoother for these cases. The flux surfaces for $(l = 2) + (l = 4)$, $\gamma_H = 30°$ and at the angle splitting $\Delta\theta_e = 80°$ are shown in Fig. 6. Here we have more stable configuration with smooth rotational transform dependence.

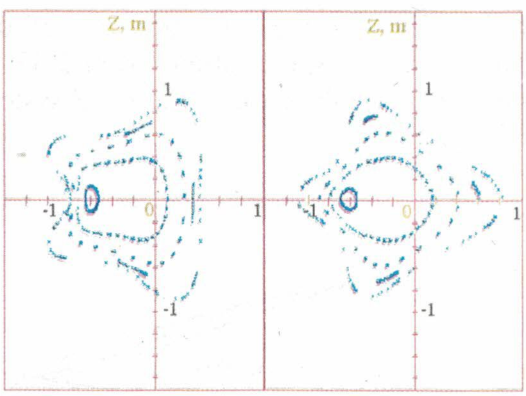

Fig. 4. $l = 4$ torsatron, (Ro = 2m, rhc = 2, γ_H=30°, rh = 1, Kφ = 0.36), CC4, rc = 1.8, m, bz(0) = 0 %, Bo = 2 T, Ih1,4 = 1800 kA, Δφ = 45°, rp = 0.76, tmax = 0.385, to = 0.069

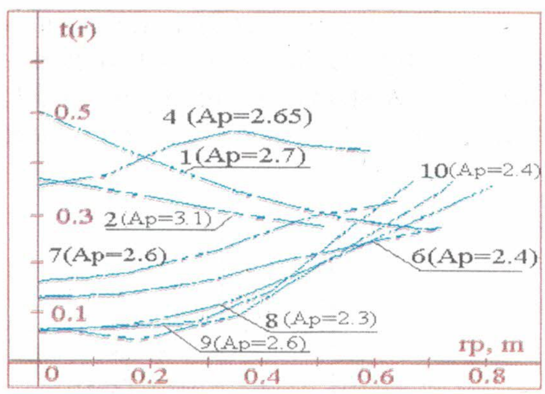

Fig. 5. Rotational transform dependencies for $l = 2$, $(l = 2) + (l = 4)$ and $l = 4$ torsatrons, γ_H=30°, CC4, bz(0) = 0 %; 1,2 – $l = 2$; 4,6-$(l=2)+(l=4)$; 7 - 9 – $l = 4$ torsatron

Fig. 7 demonstrates the rotational transform dependences for case $\gamma_H = 50°$ with an angle splitting $\Delta\varphi = 28.6°$ (lines 3 - 7) and $l = 2$ case (line 2). $\Delta\varphi$ is the half of a coil splitting in φ direction. The lines 6, 7 correspond to $K_\varphi = 1$, lines 3, 4 relate to $K_\varphi = 0.68$. Their behavior allows to conclude that the *(l = 2) + (l = 4)* combination gives higher slope rise of rotational angles without additional field. This is connected with higher value of the helical component in this case. Note, an increase of the splitting angle φ gives a decrease of the $l = 2$ harmonic and rise of the l=4 harmonic. The splitting angle $\Delta\varphi = 45°$ gives the $l = 4$ torsatron.

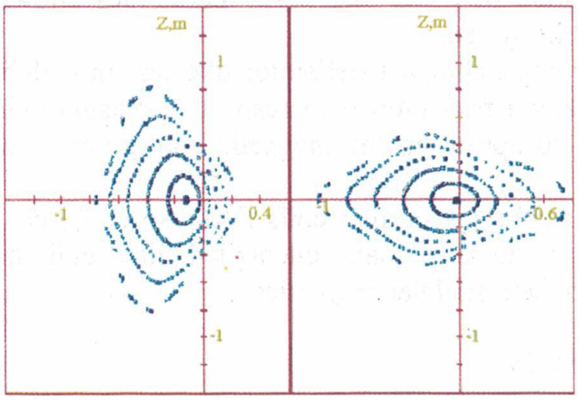

Fig. 6. $(l = 2) + (l = 4)$ torsatron, Ro = 2 m, rhc = 2, $\gamma_H = 30°$, rh = 1, Kφ = 0.4), CC4, rc = 1.8, bz(0) = +1 %, Bo = 2 T, Ih = 2000 kA, Δθe = 80°, rp = 0.58 m, tmax = 0.3, to = 0.08

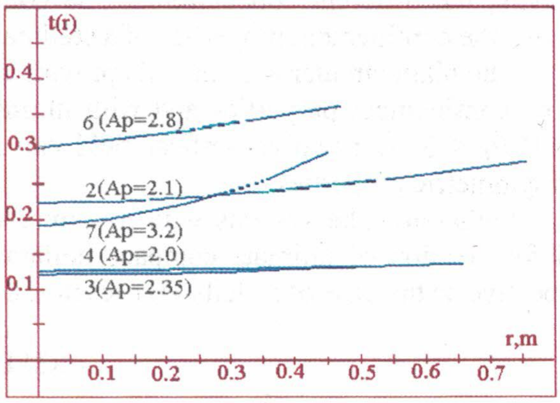

Fig 7. Rotational transform dependencies for $l = 2$ and $(l = 2) + (l = 4)$ torsatrons, $\gamma_H = 50°$; 2 – $l = 2$, Kφ = 1; 3 - 7 - $(l = 2) + (l = 4)$, $\Delta\varphi = 28.6°$; 3, 4 - Kφ = 0.68; 6, 7 - Kφ = 1

There is a possibility to obtain the harmonic combination $(l = 2) + (l = 4)$, similar to the coil splitting case, by applying different currents in each pair of helical coils in $l = 4$ torsatron. Calculations have confirmed this supposition. In calculations we varied the difference in the pair currents up to three times leaving the total current fixed. The much smoother rotational angle behavior was obtained for this case too.

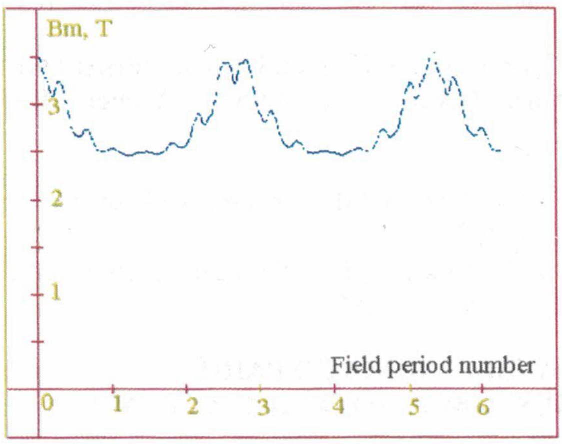

Fig. 8. Bm dependence, $(l = 2) + (l = 4)$ torsatron, Ro = 2 m, rhc = 2, $\gamma_H = 30°$, rh = 1, Kφ = 0.4), CC4, rc = 1.8, bz(0) = -3 %, Bo = 2 T, Ih1,4 = 2000 kA, Δθe = 80°, rp = 0.3 m, r = rp, $\varepsilon h_{max} = 0.03$.

The confinement properties of magnetic configuration depend on behavior along a magnetic field line of the magnetic field modulus. Large ripples in a stellarator system are responsible for high plasma loses. In tokamaks the field line smoothing provides a suppression of plasma losses connected with helical ripples. The highest effect of field ripples takes place at the outer part of flux surfaces. One of the main purposes of noway stellarator configuration study is to find a quasisymmetric behavior of field lines. In paper [8] it was shown that in torsatron with $\alpha < 0$ and negative vertical field the ripples in the outer part of flux surfaces became small. The very similar field behavior was found for the Villarso coil system. Fig. 8 shows the modulus B dependence in the $(l = 2) + (l = 4)$ torsatron configuration with a negative vertical field ($b_z(0) = -3$ %).

The phenomena can be explained as folows. The negative vertical field displaces a magnetic configuration inward of torus. The outer part of the flux surface becomes to be placed near the minor geometrical axis of the torus, where poloidal components of magnetic field are small and because of this the ripples are small there.

3. Conclusion

Stellarator-like magnetic systems with ultimate simple current coils for helical field creation were studied. Magnetic configurations with different combination of plane circular tilted coils with currents both of torsatron and stellarator types were analyzed. Splitting of the coils in the $l = 2$ coils' system gives the $l = 4$ harmonic of a poloidal field. A similar result was obtained by supplying the different coil currents. The combination of $l = 2$ and $l = 4$ harmonics allows to improve the confinement properties of a stellarator-like system.

The plain circular current coils provide obtaining a compact stellarator-like system with high plasma confinement properties and with ultimate low aspect ratio with respect to plasma radius: $A_p = R_o/r_p < 3$. A negative vertical field can lead to appearing the magnetic configuration with quasisymmetric properties.

Stellarator-like systems with low number of cohesion current coils (Villarso coils) can be used for creation of ultimate compact stellarators. Systems of many uncoupled tilted coils have prospective as the base of a stellarator reactor, due to their modular properties.

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КОМПАКТНІ СТЕЛАРАТОРО-ПОДІБНІ КОНФІГУРАЦІЇ, СТВОРЕНІ СИСТЕМОЮ ПЛОСКИХ КРУГОВИХ КОТУШОК СТРУМУ

А. В. Георгієвський, В. Т. Реірсен, В. А. Рудаков

Досліджено стелараторні магнітні конфігурації з різними комбінаціями плоских кругових нахилених котушок струму. Було використано два види комбінацій котушок для створення магнітних конфігурацій: зчеплені нахилені котушки (котушки Віларсо) та розчеплені нахилені котушки. Були вивчені системи як торсатронного, так і стелараторного типу з мультипольністю l = 2, l = 4 та їх комбінації. Вперше отримано магнітні конфігурації, створені системою розчеплених котушок струму комбінацій стелараторного типу, що забезпечують добре утримання плазми. Розщеплення котушкової системи з l = 2 дозволяє отримати гармоніку l = 4, що приводить до покращення характеристик утримання конфігурації. Зміни величини корегуючого поля дозволили отримати квазі-симетричні властивості конфігурації стеларатора.