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ABOUT ONE METHOD OF DETERMINING COIL MISALIGNMENTS IN TOKAMAK

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The paper presents a highly sensitive "e-beam" method of determining misalignments of elements in the ITER-like magnetic system on the base of magnetic measurements. It is suggested to make a "tokamak-stellarator" hybrid by means of addition to the ITER-like magnetic system of a new, not helical Saw Tooth-shaped Coil1 (STC) in order to provide the creation of "resonance" magnetic surfaces with the angles of rotational transform t = n/m = 1/2 or t = 1/3. In one of variants the STC parts can be introduced into the vacuum vessel through the largest port and assembled into a single coil. The calculations of the ITER-like magnetic configuration show that due to the turn of the poloidal field coil PF3 around the axis X direction at an angle $\alpha = 1'$ the resonance structure is formed with t = 1/2 and the maximum island width $\delta_0 \approx 50$ mm. Under this tilt the maximum misalignment of coil elements from the design position $\Delta\alpha$ is only 3.5 mm**.** So, we have found the means for identification of misalignments in the case of magnetic system elements deviation from the design position to the values $\Delta\alpha \approx 1$ mm that leads to the values of perturbing fields $b_j/B_0 \approx 3\ 10^{-6}$.
KEY WORDS: misalignments, magnetic configuration, saw-tooth coils, ITER, magnetic measurements.

ПРО ОДИН МЕТОД ВИЗНАЧЕННЯ НЕТОЧНОСТЕЙ В КОТУШКАХ МАГНІТНОЇ СИСТЕМИ ТОКАМАКА

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Робота представляє високочутливий електронно-пучковий метод визначення неточностей в елементах ІТЕР - подібної магнітної системи за допомогою магнітних вимірів. Це здійснюється шляхом створення гібриду "токамак-стелларатор" за допомогою додаткової негвинтової пилкоподібної котушки(STC), що створює резонансні магнітні поверхні з кутами обертального перетворення t = n/m = 1/2 або t = 1/3. У одному з варіантів STC може розміщуватися усередині вакуумної камери токамаку. Розрахунки ІТЕР-подібної магнітної конфігурації показали, що при повороті котушки полоїдального магнітного поля PF3 навколо осі X на одну кутову хвилину $\alpha = 1'$ утворюється резонансна структура з t = 1/2 і максимальною шириною $\delta_0 \approx 50$ мм. При такому нахилі максимальне зміщення елементу котушки від його проектного положення ($\Delta\alpha$) дорівнює 3,5 мм. Таким чином, був знайдений метод визначення неточностей у виготовленні елементів магнітної системи, що характеризується зміщеннями порядку одного мм і збуреннями поля $b_j/B_0 \approx 3\cdot10^{-6}$.
КЛЮЧОВІ СЛОВА: розрегульовання, магнітні конфігурації, пилкоподібна котушка, ІТЕР, магнітні виміри.

ОБ ОДНОМ МЕТОДЕ ОПРЕДЕЛЕНИЯ НЕТОЧНОСТЕЙ В КАТУШКАХ МАГНИТНОЙ СИСТЕМЫ ТОКАМАКА

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Работа представляет высокочувствительный электронно-пучковый метод определения неточностей в элементах ИТЭР – подобной магнитной системы при помощи магнитных измерений. Это осуществляется путем создания гибрида «токамак-стелларатор» с помощью дополнительной невинтовой пилообразной катушки (STC), создающей резонансные магнитные поверхности с углами вращательного преобразования t = n/m = 1/2 или t = 1/3. В одном из вариантов STC может размещаться внутри вакуумной камера токамака. Расчеты ИТЭР-подобной магнитной конфигурации показали, что при повороте катушки полоидального магнитного поля PF3 вокруг оси X на одну угловую минуту $\alpha = 1'$ образуется резонансная структура с t = 1/2 и максимальной шириной $\delta_0 \approx 50$ мм. При таком наклоне максимальное смещение элемента катушки от его проектного положения ($\Delta\alpha$) равняется 3,5 мм. Таким образом, был найден метод определения неточностей в изготовлении элементов магнитной системы, характеризующихся смещениями порядка одного мм и возмущениями поля $b_j/B_0 \approx 3\ 10^{-6}$.
КЛЮЧЕВЫЕ СЛОВА: разрегулированности, магнитные конфигурации, пилообразная катушка, ИТЭР, магнитные измерения.

Experience in research of closed magnetic system, intended for confinement of plasma, testifies to their high sensitiveness in relation to different kinds of magnetic field perturbations. Areas with the rational values of angles of rotational transform are especially sensitively to magnetic perturbations. Formation of magnetic islands is thus possible with their ceiling and subsequent stochastisation of force lines [1-4]. Such violations of structure of magnetic field can cause the enhanceable losses of plasma. One of reasons, of magnetic field perturbations there are inaccuracies in making and montage of current-carrying elements of the magnetic system. The aim of the paper was to offer for tokamaks method of exposure of misalignments in the elements of the magnetic system, essence of that consists of creation of stellarator magnetic configuration and measuring of their resonant structures.

The paper presents "e-beam" method of determining misalignments of elements in the ITER-like magnetic system on the base of magnetic measurements (MM). For the period of MM experiments it is suggested to make a "tokamak-stellarator" hybrid (ITER-S) by means of addition to the ITER magnetic system [5] of a new, not helical Saw Tooth-shaped Coil[1] (STC) in order to provide the creation of "resonance" magnetic surfaces with the angles of rotational transform $t = n/m = 1/2$ or $t = 1/3$.

DESCRIPTION OF THE METHOD

The STC has a view of a circular saw with different number of teeth [6]. In one of variants the STC parts can be introduced into the vacuum vessel (VV) through the largest port attached to the inner part of the VV wall and assembled into a single coil (Fig. 1).

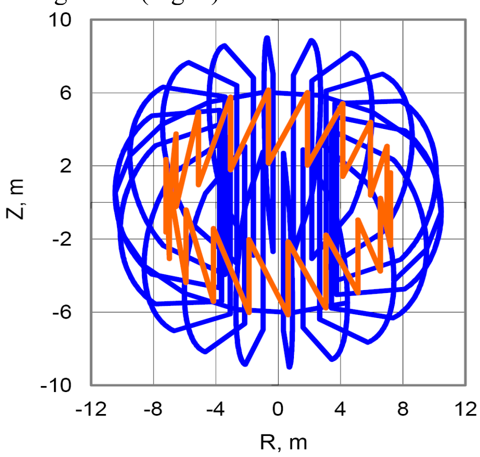

Fig. 1. ITER_S. Toroidal coils system and Saw tooth coil.

At this case the number of "saw teeth" is equal 18. The STC elements have as a straight view, so an arc view repeating the first wall shape. Note three interesting peculiarities of the STC that can be used in equipment design for magnetic measurements:

1. Number of saw tooth like pieces of the STC can be not only 18, but also 9 or 6, or even 3.
2. Tilted pieces of the STC can be lain by a special manner, providing in particular, bending of vacuum ports.
3. There is possibility to create the STC in modular view (Fig. 2). Currents in tilted and vertical pieces of neighbouring STC flow in one direction. Horizontal pieces of the modulus can play role of poloidal field coils. Such STC operates similar to a continuous STC.

Proposed "e-beam" method using the luminescent rod is the fastest and most accurate method giving direct pictures of magnetic surface structure. In the method the basic component of the equipment is a small diameter (∅≈1.5mm) metal rod coated with a thin phosphorus layer. In other poloidal cross-section the electron gun, movable along the minor radius of the torus, is placed. The pictures of many "magnetic surfaces" are obtained by photographing the light emitted by phosphorus due to electrons striking the rod. Experiments on the Uragan-3M torsatron have shown that up to 15 contours of "magnetic surfaces" can be registered. The typical resolution δ_r along the minor radius is of the order of $\delta_r \approx (3 - 5)$ mm [7,8].

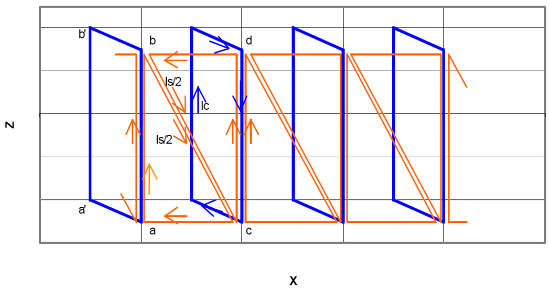

Fig. 2. Modular view of Saw-tooth coil (three angular contours) and toroidal field coil.
Pieces *ac* and *bd* are parts of poloidal field currents (PFC).
Arrows show current directions.

In the course of calculations we have considered a resonance case of ITER-S with the angle of rotational transform t=1/2. The basic configuration in two cross-sections is shown in Fig. 3. In the figure we used the next designations: R_{ST} – radial position of STC, R_0- main radius of torus, b/B_0 – ratio between amplitude of perturbation field b and toroidal field B_0, N_{ST} – saw teeth quantity, N_T –number of toroidal field coils (TFC}, Z_{ST} – half altitude of STC, Z_{TC} – half altitude of TFC, I_{TC} =1- current in TFC, I_{ST} – current in STC with respect to I_{TC}; IPO1, IPO2, IPO6 – currents in poloidal field coils, t_0, t_{max} – rotational transform angles in the center and in the edge of the configuration.

The stellarator configuration is created with the use of STC with 18 teeth. As a result of the tilt of the upper poloidal field coil (PF-3) with angle α° per one minute (Δα=3.5mm, the turn around the direction of X- axis) there appears an island structure n=1, m=2 (2 islands) with a maximum value of the island width $\delta_0 \approx 5.1$ cm (Fig. 4). The coil parameters are: R= 12.1 m, Z = 3.06 m, Ic = 4530 kA.

Direct calculations have shown that the maximum values of the horizontal and vertical magnetic field components of this coil b_R and b_z corresponds to the position of the toroidal angle $\varphi = \pi/3$. In the point R=6.7 m, Z = 0, that approximately corresponds to the centre of the resonance structure, the relative values of the radial (B_R) and horizontal (B_z) magnetic field components were the following:

$$B_z/ B_0 = 0.054259664,\ B_R /B_0 = -0.\ 0156872567, \text{ where } B_0 = 4.63 \text{ T (case } \alpha=0)$$

$B_z/ B_0 = 0.0542706062$, $B_R / B_0 = -0.\ 0156741147$ (case α=1′).

The differences in components before and after the coil inclination ($\Delta b_j/ B_0 = (b_{j1} – b_{j2})/ B_0$) are equal:

[1] The STC winding was proposed and investigated for the first time by A.V.Georgiyevskiy and V.A.Rudakov together with the scientists of Wisconsin University in 1995 [6].

$$\Delta B_Z/ B_0 = 1.094\cdot 10^{-5}, \text{ hence } \Delta B_Z = -1.094\ 10^{-5}\cdot 4.63\cdot 10^{4} = -0.5066 \text{ G}.$$

$$\Delta B_R / B_0 = 1.314\cdot 10^{-5}, \text{ hence } \Delta B_R = +\ 1.314\ 10^{-5}\cdot 4.63\cdot 10^{4} = 0.6085 \text{ G}.$$

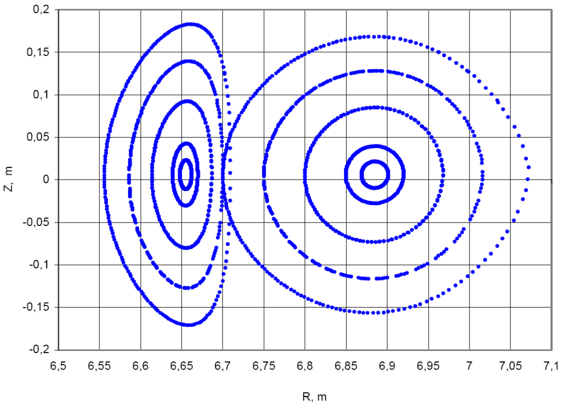

Fig. 3. Base configuration without misalignments. Field period cross-section (right), half field period (left). R_{ST}=7.3, R_0=6.3 m., N_{ST}=18, N_T=18, Z_{TC}=5.14, Z_{ST} =2 m, B_0(6.3)=5.3 T, ($B_{zpfc}+B_{zST}$ =+0.53% at R=6.0m). I_{TC}=1(9275 kA), I_{ST}=-0.5, t_{max}=0.493, IPO1=IPO6=-0.305.

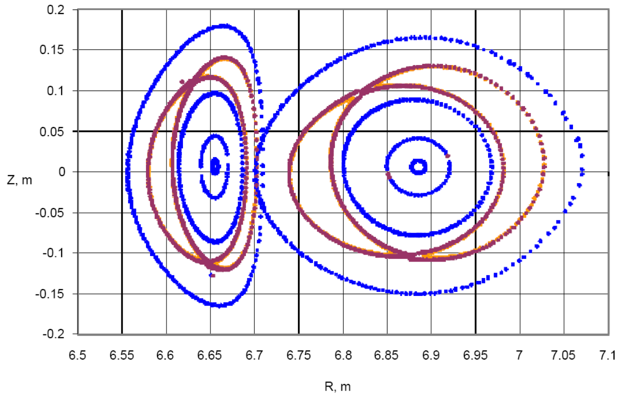

Fig. 4. Magnetic configuration with two islands at resonance n/m =1/2. PF-3 coil tilted by angle 1′.

If we use the formula of [5]:

$$\delta_0 = 4\ (b_{mn}\ Ro/\ m\ B_0\ t')^{1/2},$$

then we obtain for δ_0 =5.1 cm, R_0 = 6.7 m, m=2, t' = 1.4 10^{-3}, B_0= 4.63 *T,* b_{mn} = 0. 314 G**.** Here $t' = \partial t/\partial r$ *is* shear. Substituting as b_{mn} the quantity ΔB_Z =0.5066 G, we obtain:

$$\delta_0 = 4\ (0.5066\ \cdot 670/\ 2\cdot 46300\cdot 0.0014')^{1/2} = 6.5 \text{ cm}.$$

The analogous estimation with $b_{mn} = \Delta B_R$ = 0.6085 G give gives the value δ_0 =7.1 cm.

So, the perturbing action of poloidal field coil (PF-3) misalignment in the form of the angle of tilt α=1′ leads to the perturbing field of the order $b_{mn}/ B_0 \approx 10^{-5}$ and provokes forming of the resonance structure in the form of two island n=1, m=2 with the maximum width of the island $\delta_0 \approx$ 5.1 cm. Taking into account the degree of approximation of the island structure size estimation, it can be said that the observed scale of the island structure does not contradict to the values of the perturbing field arising as a result of the coil tilt.

We would remind, that at the above-mentioned tilt of PF-3 (α=1′) the maximum coil misalignment Δα=3.5mm, and $\delta_0 \approx$ 51 mm. As a result, the perturbation $b_{mn}/ B_0 \approx 1\cdot 10^{-5}$ creates the islands with the maximum width $\delta_0 \approx$ 51 mm that exceeds by an order of magnitude the above-mentioned value of the resolution of the proposed method ($\delta_r \approx$ 3 - 5 mm).[2] Therefore, we can assert that the minimum misalignment can be fixed at a level Δα ≈ 1 mm, $b_{mn}/B_0 \sim 3\cdot 10^{-6}$. This is confirmed by the below-given results of the calculations at the angle of tilt α=1/4′.

For the case α=1/4′ the magnetic field components have the values:

$$b_Z/ B_0 = 0.05422573762,\ b_R / B_0 = -0.\ 0156839726,$$

that gives the following values of their differences:

$$\Delta Bz/ B_0 = -2.88\cdot 10^{-6}, \text{ hence } \Delta Bz = -2.88\ 10^{-6}\cdot 4.63\cdot 10^{4} = -0.133 \text{ G.}\ \cdot$$

$$\Delta B_R / B_0 = 3.28\cdot 10^{-6}, \text{ hence } \Delta B_R = +\ 3.28\ 10^{-6}\cdot 4.63\cdot 10^{4} = 0.151 \text{ G.}$$

The calculations of the magnetic configuration for this case enabled to obtain the resonance structure m=2, n=1 with $\delta_0 \approx$ 25 mm (Fig. 5), that does not contradict to the above given root dependence δo on the amplitude of resonance magnetic field amplitude b_{mn}. The value of the resolution (δ_r) of the proposed MM method is (3 – 5) mm, i.e. $\delta_r \ll \delta_0$. Thus, a possibility was found for identification of misalignments in the case of deviation of the position of magnetic system elements from the design position by the value Δα ~ 1 mm. Besides, it is possible to observe the influence of coil misalignments leading to the relative values of perturbing fields of $b_{mn} / B_0 \approx 3\cdot 10^{-6}$.

The results of calculations of toroidal field coil misalignment influence on the formation of resonance structure are presented in Table. In particular, inclination of the plane of the toroidal field coil #10 at the angle 1/4′ (maximal displacement of the coil part is 0.4mm) leads to forming of two-island resonance structure with $\delta_0 \approx$ 22 mm. In this case the perturbation field value equals to $b_{mn} / B_0 \approx 2.6\cdot 10^{-6}$**.**

Thus, it is possible to do the main conclusion, that proposed for ITER tokamak (with additional, rather simple - non helical winding STC) method, of vacuum “resonance” magnetic measurements using the luminescent rod, allows to

[2] Note, that a similar result is obtained in the calculations of the magnetic configuration for the case of misalignment of the same winding by 3mm along the Y axis direction (see Table 1 - 05061001, 05061002) (dy_{P03}=0.003)

identify error magnetic fields up to $b_{mn}/B_0 \approx 3\cdot10^{-6}$, caused by PFC or TFC misalignments with value ≈ 0.4 – 1 mm. All results presented above calculated at resonance ι = n/m = 1/2. There is resonant structure obtained at the case ι = n/m = 1/3 (Table, 6 position). For these case three-island structure obtained as a result of the PF-3 coil inclination by the angle 1′.

Table

The misalignments in ITER-S coils

N	Files	Coil	α°	Δα mm	δ_0 mm	b/B_0
1	05041301 05041302	PF-3	1′	3.5	51	$\sim1\ 10^{-5}$
2	05051301 05051302	PF-3	1/4′	~1	25	$\sim3\ 10^{-6}$
3	05062701 05062702	TF-10	1′	1.6	30	$\sim1.04\ 10^{-5}$
4	05063001 05063002	TF-10	1/4′	0.4	22	$\sim2.6\ 10^{-6}$
5	05061001 05061002	PF-3	0**	3	52	$6\ 10^{-6}$
6	05040502* 05040503	PF-3	1′	3.5	16	$\sim1\ 10^{-5}$

*) resonance ι =1/3.
**) displacement along Y axis.

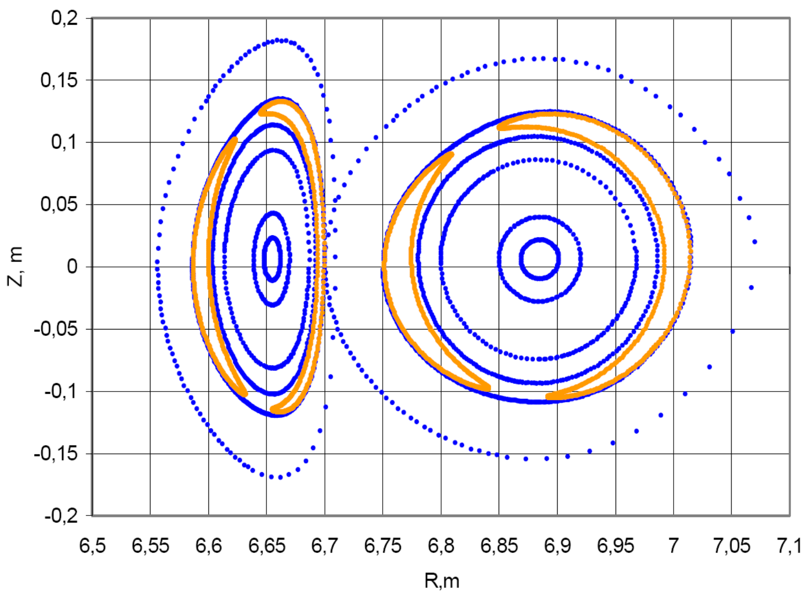

Fig. 5. Magnetic configuration with two islands at resonance n/m =1/2. PF-3 coil tilted by angle 1/4′.
Turn around of the X-axis direction

There is problem to make TF and PF systems symmetric with respect to the toroidal axis (elimination of the main n=1 component). Recommended level of compensation is 10^{-5}. Remind for comparison, that the achieved level of toroidal error field compensation by a saddle loop method is of about $3\cdot10^{-4}$ (that is not enough) and for the poloidal field coils 10^{-5} [10]. But before compensation there is necessity to identify the error field. Proposed method of MM gives reliable means to solving this problem.

Thus, it is possible to do the main conclusion, that proposed for ITER tokamak (with additional, rather simple - non helical winding STC) method, of vacuum "resonance" magnetic measurements using the luminescent rod, allows to identify error magnetic fields up to $b_{mn}/B_0 \approx 3\cdot10^{-6}$, caused by PFC or TFC misalignments with value ≈ 0.4 – 1 mm. All results presented above calculated at resonance ι = n/m = 1/2. There is resonant structure obtained at the case ι = n/m = 1/3 (Table, 6 position). For these case three-island structure obtained as a result of the PF-3 coil inclination by the angle 1′.

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CONCLUSION

So, the paper presents a highly sensitive "e-beam" method of determining misalignments of elements in a tokamak magnetic system on the base of magnetic measurements. Note that using the proposed resonance MM methods one can determine, with a high accuracy, other magnetic field errors too. For example, at the first stage of MM it is possible to find, and, in a great measure, to compensate the averaged, by φ, summary (nonlocal) additional magnetic field components ΔB_Z and

ΔB_R. Their sources can be, in particular, a value of magnetic permeability (μ) of metalwork not taken into account. The proposed MM makes it possible to detect "surprises" which cannot be foreseen by any calculations. As a rule (not as an exception) different "surprises" took place in many cases when starting large-scale installations. Let us show, also, other (potential) possibilities of the suggested MM method (see, also, [11]).

There is an opportunity to perform a highly sensitive control of the accuracy by retaining the currents in PFC and TFC coils according to the rearrangement of the "resonance" island structure related with the change of these currents ($\Delta I/I \leq 0.38\%$, the estimation was shown in calculations for NCSX magnetic system [11]). The offered method of measuring of inaccuracies in the elements of the magnetic system has higher exactness as compared to the known methods of the magnetic measuring in tokamaks.

Proposed is the method for detecting the errors of the average vertical (ΔB_z) and radial (ΔB_R) magnetic fields. Note that potential possibilities of the proposed MM method are not limited by the above list. Future work will be focused on developing the methods applied to identify specific types of coil misalignments.

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