PLASMA CONTROL PROBLEMS INVESTIGATION ON GUTTA TOKAMAK

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Abstract— **The problems of design of program control and synthesis of feedback controllers in tokamaks are considered. A dynamical model that describes the current behavior was built for research of dynamical processes in poloidal conducting circuits. The calculated data obtained based on the mathematical model was compared to the electromagnetic measurements that were received during the series of test experiments. The problems of program control of discharge with consideration of engineering features of Gutta tokamak are discussed.**

In order to design the control system for plasma current, shape and position the structural parametric optimization of transient processes is suggested.

The results of the first experiments on the plasma shape control in Gutta tokamak are presented.

I. Introduction

For the past decades a lot of attention is paid to the problems of controlled thermonuclear fusion. A control system is needed in order to conduct experiments with plasma in tokamak. This control system creates special conditions for plasma breakdown and gives further control over its current, shape and location.

A small spherical tokamak Gutta was entered into exploitation at SPbSU in 2005 [1]. It is intended to be used in research work for educational purposes. Present paper is devoted to the control systems building for the Gutta tokamak.

The paper discusses questions of construction of program control for discharge and synthesis of optimal regulators with a feedback. A special feature of program control study, for example in contrast with [2], is construction of a system with a changing structure where the initial values are changing in proper arias. These changes are caused by the nature of the power system and preionization. During the study of optimal regulator synthesis problems, a structural-parametric approach is being developed in distinction from the papers that were presented earlier in [3-6]. The results of experiments on Gutta tokamak are presented.

II. Dynamic model of a poloidal circuit system

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In this paper the problem of Gutta tokamak poloidal electromagnetic system modeling, specifically of poloidal coils and vacuum chamber is studied. An important constructional feature of this device is its power system, built on the base of capacitor banks whose discharge causes a great influence on current dynamics during impulse. The problem of the current dynamics modeling in circuit poloidal system is very important in the sense of the automation of experimental process, experiment data and discharge scenario analysis and calculation and analysis of different control laws.

Poloidal system of conductive coaxial circuits of the device (such as coils of poloidal electromagnetic system and fragmentations of vacuum chamber) are studied. Some of them have their own power sources.

Poloidal circuits currents evolution with consideration to the Gutta tokamak power systems features, could be described with the following system of differential equations

$$\begin{cases} \dfrac{dI(t)}{dt} = L^{-1}U(t) - L^{-1}R(t)I(t) \\ \dfrac{dU(t)}{dt} = C^{-1}I(t) \end{cases}, \qquad (1)$$

where $I(t)$ is the currents vector, L is the matrix of self and mutual inductances of circuits, R is the diagonal matrix of resistances, C is the diagonal matrix of capacities, $U(t)$ is capacity banks voltages. The operation mode of the device is determined by setting the instant the capacitors banks are switched on (switching points) and its initial voltages. The resistances in capacitor circuits can be changed. It is obvious that the system (1) has a changing structure and can have simple discontinuities at switching points in $U(t)$.

It is assumed that parameters such as coils resistance, capacitor values, geometrical parameters of the device do not change during the modeling period.

Elements of capacity and resistance matrices could be changed at switching points depending on the battery circuit scheme.

During the model testing, calculated vacuum chamber current distribution, which corresponds to the variable ohmic field, was reviewed. This distribution corresponds to distribution described in [7-8], which was obtained using another models. The example of such distribution is presented in Fig. 1.

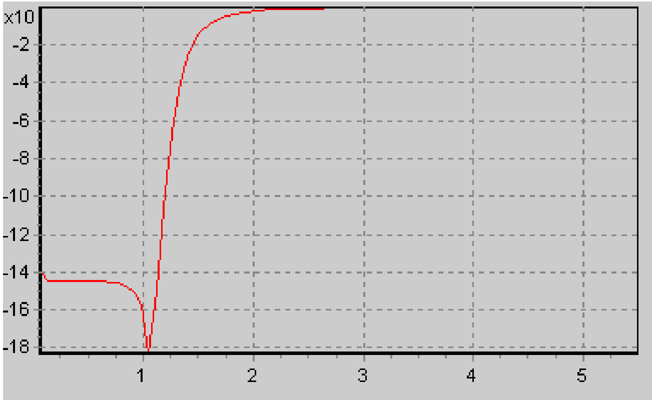

Fig. 1. Example of the current distribution along the vacuum vessel length from the inner point of the midplane to the outer. Horizontal axis — vessel length in conventional units, vertical axis—current amplitude in amperes.

During the series of test experiments on Gutta tokamak the comparison of the calculated data and the measured with various electromagnetic diagnostics data was performed.

As an example of such a comparison the calculated (See Fig. 2.) and measured (See Fig. 3.) loop voltage on the outer loop during vertical magnetic field evolution can be examined.

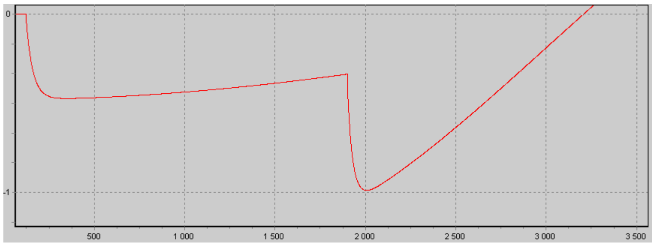

Fig. 2. Calculated outer loop voltage. Horizontal axis – time in microseconds, vertical axis – voltage, 1V in point. Red line - Loop voltage on outer loop.

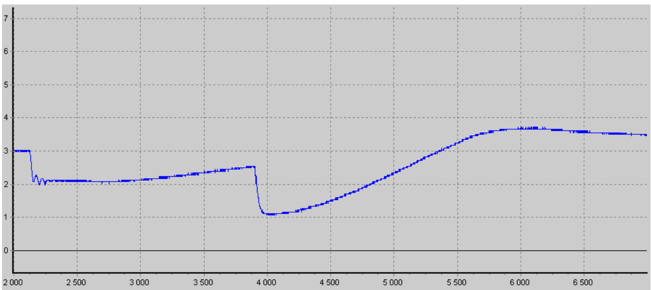

Fig . 3. Measured outer loop voltage. Horizontal axis - time in microseconds, vertical axis – voltage, 0.5V in point. Red line - Loop voltage on outer loop of vacuum vessel.

We should mention that the origin of the plot in Fig. 3. has a displacement about 2000 μs in comparison with the Fig .3.

The comparison discovered that calculated results have a good correspondence to the actual data with 50 or more vacuum camera divisions.

This model was adapted for ITER tokamak. Its power system differs from Gutta tokamak energetic system, but the suggested model implementation allows to consider systems of this type. With the given mode of operation, the simulation of currents, fluxes and field dynamics in breakdown region was performed. Calculated data was compared with data obtained with TRANSMAK code. The graphs that describe the deviations of similar parameters were obtained. As an example, the deviations of currents in coils are shown in Figures 4 and 5.

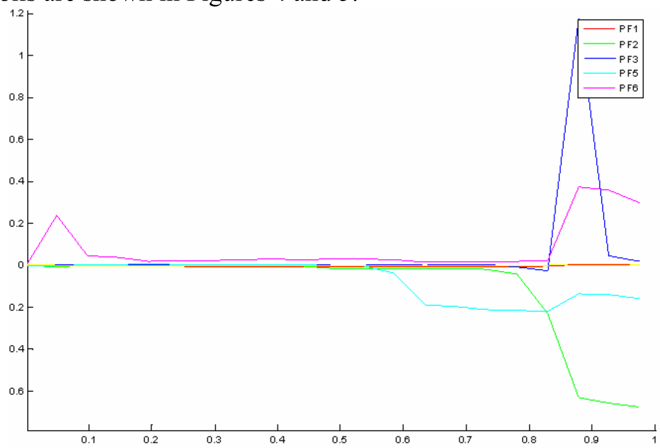

Fig. 4. Errors in poiloidal coils (PF1, PF2, PF3, PF4 ,PF5) currents. Horizontal axis— time in seconds. Vertiacal axis — deviation in percents.

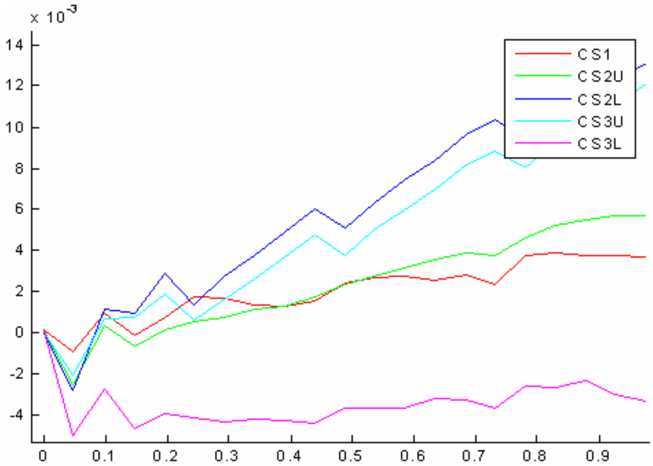

Fig. 5. Errors in central solenoid coils (CS1, CS2U,CS2L, CS3U, CS3L) currents. Horizontal axis— time in seconds. Vertiacal axis — deviation in percents.

Verification did not discovered big deviation in data calculated with suggested model and reference data. Current deviations do not exceed 1.2 %.

Testing process allows to make the decision about model adequacy in describing current dynamics and it's aptitude to be used for building program control laws for the different types of tokamaks.

III. Program control

The beginning of the plasma discharge start is considered to be one of the most important stages of plasma column formation in tokamak, as the plasma evolution dynamics at a later time depends on it. It is necessary to guarantee given loop voltage in the center of the breakdown zone and low magnetic fields amplitudes in this zone to provide plasma breakdown. Electron cyclotron resonance preioization is used on Gutta tokamak to assist breakdown. It is necessary to provide optimal conditions for preionization because of rather short and low-powered SHF pulse. These conditions differ current plasma breakdown[9].

In the general form the control problem for system (1) could be considered as a control problem for system with variable structure. This form is given follows:

$$\begin{cases} \dfrac{dx(t,x,y,u)}{dt} = f_1(t,y) + f_2(t,x,u) \\ \dfrac{dy(t,x)}{dx} = f_3(t,x) \end{cases} . \quad (2)$$

The coefficients of system (2) remain constant on half-intervals $[t_k, t_{k+1}), k = 0,..., p-1$, $0 \le t_0 \le t_1 \le ... \le t_p \le T$. The parameters of optimization are: half-interval boundaries t_k, initial conditions $y(t_k) = y_k$ at the beginning of the half intervals and the step function $u(t)$.

Let us define $tk = (t_0, t_1,...t_p)$, $yk = (y_0, y_1,...y_p)$.

Let us define functional on the trajectories of system (2), which describes electromagnetic conditions for the pre-ionization and breakdown in the general form,. It will be as follows:

$$I(tk, yk, u) = g_1(x(t_m)) + g_2(x(t_p), y(t_p)), \quad (3)$$

where t_m corresponds to the beginning of the ECR pre-ionization and corresponds to the breakdown beginning.

Different optimization methods were considered and implemented for this task.

As a result, tokamak regime that provides pre-ionization and plasma breakdown at the given time with given loop voltage was calculated. Further the discharge parameters, which corresponds to the such mode of operation, measured using the control and diagnostic complex of Gutta tokamak will be illustrated.

In Fig .6 the plot, that illustrates visible plasma light dynamics that illustrates the plasma discharge evolution with optimal pre-ionization conditions is presented in the graph. Here t_m for (3) is 3600 µs, t_p for (3) is 3800 µs. Pre-ionization begins at 3600 µs. At 3800 µs optimal breakdown conditions was created. Further, the plasma visible light amplitude increases, what corresponds to breakdown and plasma current rising, is observing.

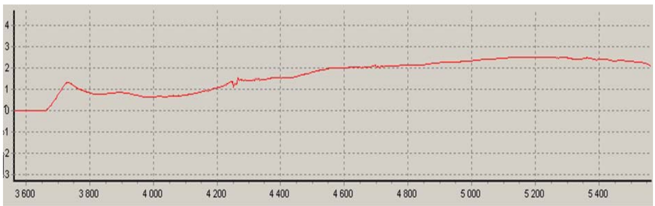

Fig. 6. Plasma visible light. Horizontal axis – time in microseconds, red line – plasma visible light amplitude in conventional units.

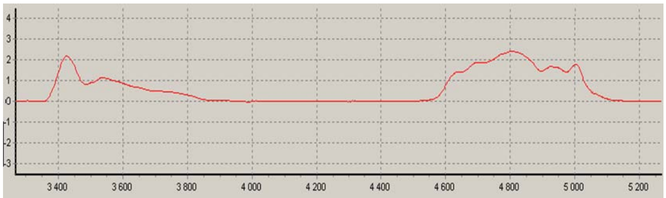

Fig. 7. Plasma visible light. Horizontal axis – time in microseconds, red line – plasma visible light amplitude in conventional units.

Fig .7 illustrates, that deviation from the optimal parameters leads to breakdown absence. Here t_m for (3) is 3300 µs, t_p for (3) is 3500 µs. During the pulse shown in Fig. 7, optimal conditions for the ECR pre-ionizations was created, but by the 3500 µs the breakdown conditions was not optimal. Breakdown occurs at 4580 µs, when the necessary magnetic field configuration was generated. This situation is inadmissible because of idle consumption of the central solenoid magnetic flux. It leads to the plasma discharge shortening.

It case of the pre-ionization optimal condition absence, plasma discharge on Gutta tokamak is often impossible.

IV. The structural parametric optimization of transient processes

The control system with a feedback that is needed to gain the control over the current, plasma shape and its position is necessary for conducting experiments with plasma in tokamak. Due to this fact, the problems of analysis and synthesis of stabilizing regulators of current and plasma shape gain a great value. Linear systems are widely used in problems of construction of control systems for complex objects. The synthesis of regulator that stabilizes plasma shape in tokamak is done on a basis of linearization of differential equations that define the plasma behavior. The procedure of reduction and LQG-algorithms of analytical regulator construction are applied to the LTI-object [3-5]. The equations of the control object in the state space are the following

$$\dot{x} = Ax + Bu$$
$$y = Cx, \tag{4}$$

where $x \in E^n$ is the vector of state space $u \in E^r$ is the control vector, $y \in E^k$ is the measurement vector and A, B and C are known matrices. The control object is completed with a regulator of a decreased dimension with the following structure :

$$\dot{z} = A_c z + B_c y$$
$$u = C_c z, \tag{5}$$

where matrices A_c, B_c, C_c can be obtained using the reduction procedure and the LQG-optimal synthesis. The control object closure by the gained regulator is done in accordance to the scheme in Fig. 8

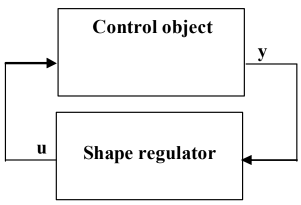

Fig. 8. The control object closure by the gained regulator.

When we say "regulator synthesis" we mean such a choice of parameters of the regulator of LTI-object component that gives us a closed object that is stable and a quadratic quality functional (6) can be minimized on the given trajectory of a closed system

$$\int_o^T \left(y^*(t) R\, y(t) + c_0 \cdot u^*(t) Q u(t)\right) dt, \tag{6}$$

where R and Q are positively defined, symmetrical weight matrices. But due to a large dimension and a complexity of the control object model structure, the LQG-approach is used for its reduction and also the number of assumptions is added, such as the influence of the control object «l_i, β – drops» impact to the dynamics is considered indirectly.

A mathematical model of a structural parametric optimization of the dynamics of a set of trajectories that are perturbed at initial points and external disturbance is given. Within this approach, the optimization of transient processes of the full-sized control object that is closed by a regulator of a decreased dimension is conducted. It is suggested to use an integral performance criterion as a functional that allows optimizing the transient process, perturbed by ensemble of initial data and ensemble of external influences. Let us investigate the equation of control object (4) that is completed by the regulator of decreased dimension (5) with presence of a constantly applied disturbance

$$\begin{bmatrix} \dot{x} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} A & BC_c \\ B_c C & C_c \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix} + M\, f(t)$$
$$y = C\, x \tag{7}$$
$$u = C_c z$$

where M is the known matrix of dimension $m \times s$, where m is the is a dimension of vector $[x\ z]^*$; $f(t)$ is an s-dimension vector that is known and can be integrated in $[t_0\ t_1]$. Let's assume that the perturbation region at the moment t is

$$x_0^* G_1 x_0 + \int_{t_0}^{t} f^*(\tau) G_2(\tau) f(\tau)\, d\tau \le 1. \tag{8}$$

where $G_1, G_2(\tau)$ are positively defined matrices. Let us symbolize this region as S_t in the space value x_0, f_t. Further, the matrices A_c, B_c, C_c of a dynamic regulator (5) will be taken as parameters that are to be optimized. Let's unite the elements of these matrices into a vector of parameters $p = \{p_i\}$, where each parameter has its own index. Let's assume that P is a matrix of a linear part of the system (7). By labeling it as P(p) we emphasize that it is depended of the parameters that are being optimized. The symbol $x(t)$ from this point on will stand for an augmented vector of state $[x \quad z]^*$ of a dimension m. Then the equation of the control object with presence of constantly applied perturbations can be written as

$$\dot{x} = P(p)x + M\, f(t)$$
$$y = L\, x \tag{9}$$
$$u = Kx\,.$$

Where, if we take into account the fact that x is an augment vector of state, $L = [C \quad 0]$, $K = [0 \quad C_c]$.

Let's research a performance functional for the system (9) with the made structural choice of parameters $p = \{p_i\}$ that are to be optimized

$$I(p) = \int_{t_0}^{t} \left\{ \sum_{i=1}^{N} \sup_{(x_0, f_f) \in S_t} (l_i^* x(t))^2 + \sum_{i=1}^{r} \sup_{(x_0, f_f) \in S_t} u_i^2(t) \right\} dt, \tag{10}$$

where l_i - m-dimensional column-vector of some give matrix

$$\widetilde{L} = [l_1 \ldots l_N]. \qquad (11)$$

Taking into account (8) and (11) the functional (10) can be written as [11]

$$I(p) = \int_{t_0}^{t_1} \left\{ tr[\widetilde{L}^* D(t) \widetilde{L}] + tr[K\, D(t) K^*] \right\} dt, \qquad (12)$$

where $D(t)$ - is a solution of the matrix differential equation

$$\dot{D} = P(p)D + DP^*(p) + MG_2^{-1}M^*$$
$$D(t_0) = G_1^{-1}. \qquad (13)$$

Where $tr[A]$ is the spur of matrix A. After reconstitution of the functional in a standard way [10] we will get a representation (14) for the variation of functional (12) and gradient of the functional by parameters $p = \{p_i\}$ (17):

$$\delta I = -\int_0^T tr[D(t)\Theta(t)\Delta_p P(p) + \Theta(t)D(t)\Delta_p P^*(p)]\, dt, \qquad (14)$$

Where

$$\Delta_p P = P(p + \Delta p) - P(p) \qquad (15)$$

$$\dot{\Theta} = -\Theta P - P^*\Theta - (\widetilde{L}\widetilde{L}^* + K^*K), \ \Theta(T) = 0 \qquad (16)$$

Expression (17) gives us a gradient of the studied functional by the parameters

$$\frac{\partial I}{\partial p_i} = -\int_0^T 2\, tr\left(\Theta D \frac{\partial P^*}{\partial p_i} \right) dt. \qquad (17)$$

On the basis of the analytical expressions (12)-(17) a gradient method of optimization of the functional (12) by the parameters $p = \{p_i\}$ can be performed.

IX. The Results of the First Experiments on the Plasma Shape Control in Gutta Tokamak

During the conduction of many experiments in the Gutta tokamak, it is necessary to have a digital control system that allows different control models, it is respectively easy to adjust the parameters of the system and to interact with the digital system of the data collection [12,13]. The construction of such control system is difficult due to the fact that the characteristic time of the process is very short because of small size of the plant. There were developed different versions of the control system in real-time for horizontal position of plasma with the use of feedback. The system is constructed on the bases of the power transistor switch, PC, special software and hardware, elements of electromagnetic diagnostics. The results of the testing experiments series for plasma shape control are given further. In a number of cases we managed to rich a higher level of discharge duration and the value of plasma current. We take an error signal as an input signal. This error signal is a magnetic flux that goes through the equatorial plane of the vacuum vessel that characterizes the horizontal shift of plasma column. Signals of executing system are used as control signals. This executing system is a bank of capacitors with a power transistor switch that is connected to a chain of coils of transversal current. The goal of control system is to provide the restrictions on the error signal that were set by the user with the use of executing system and a chosen control law. A special software for doing the control process is installed on the PC. This program measures the error signal each 2.5 microseconds and forms a control command for the switch depending on the values, entered by the user, each 5 microseconds. The period of control mode can be set and lies between 1.5 and 4 ms. By the end of the discharge, the program prints out information on the discharge in the form of graphs and tables. Figure 9 presents graphs of an error signal that characterizes the horizontal shift of plasma column when the discharge control absent (a) and present (b).

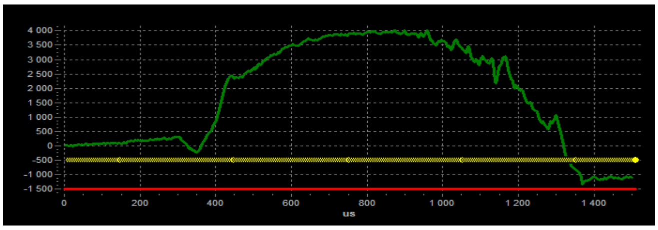

Fig. 9. a. Testing experiments without controls. Horizontal axis – time in microseconds, Vertical axis – vertical magnetic flux in conventional units.

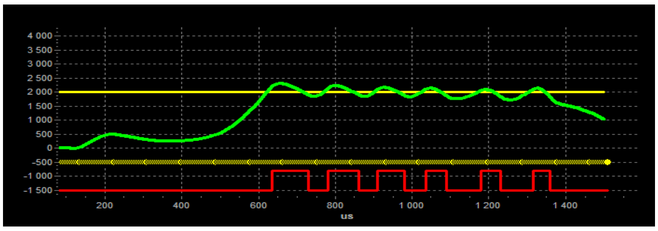

Fig. 9. a. Testing experiments with controls. Horizontal axis – time in microseconds, Vertical axis – vertical magnetic flux in conventional units.

IX. Conclusions

In this paper poloidal circuits currents dynamics simulation was presented. Testing of model shows it's adequacy concerning the results of electro-magnetic measurements on Gutta tokamak and regimes of operation of ITER tokamak. Discharge start on Gutta tokamak program control problem is reviewed and results of optimization are presented.

Structural-parametric approach for optimization of linear stabilizing regulators of current and plasma shape are discussed and the results of first experiments on plasma position feedback control are presented.

References

[1] D.A. Ovsyannikov, A.D. Ovsyannikov, A.P. Zhabko, E.I. Veremey, G.M. Vorobyov, V.M. Zavadskij, Program for scientific and educational investigations on the base of small spherical tokamak Gutta, International Conference Physics and Control, August 24-26, 2005, Saint-Petersburg.

[2] Kuznectov A.V., Ovsyannikov D.A. Program control optimization by the plasma break down condition and its evolution under given scenario in tokamak with iron core. –M., 1990, Preprint Efremov Institute

[3] Ovsyannikov D. A., Veremey E. I., Zhabko A. P. et al. Mathematical methods of plasma vertical stabilization in modern tokamaks // Nuclear Fusion. 2006. Vol 46. P. 652-657.

[4] Ovsyannikov D. A., Zhabko A. P., Veremey E. I. et al. Plasma current and shape stabilization with control power reducing // Proc. of the 5th Intern. workshop: "Beam Dynamic & Optimization". St.-Petersburg, 1998. P. 103-111.

[5] Misenov B.A., Ovsyannikov A.D., Ovsyannikov D.A. et al. Non-linear model of tokamak plasma shape stabilization // Intern. conf. on Informatics and Control (ICI&C'97). St.-Petersburg, 1997.

[6] V. Belyakov, A. Kavin, E. Lamzin, D. Ovsyannikov, S. Sytchevsky, V. Vasiliev, Plasma control in tokamaks, International Conference Physics and Control, August 24-26, 2005, Saint-Petersburg.

[7] Aristov Yu.A., Vorobyov G.M., Kuznectov A. V. The inductors coil positions optimization in tokamak. M., 1992, Preprint Efremov Institute.

[8] Vorobyov G.M., Kuznectov A. V. The equilibrium system coil positions optimization in tokamak. M., 1992, Preprint Efremov Institute.

[9] G.M. Vorobyov, D.A. Ovsyannikov, A.D. Ovsyannikov, E.V. Suhov, E. I. Veremey, V. M. Zavadsky, A. P. Zhabko. The The Experiments of the small Spherical Tokamak Gutta. Proceedings of thr 16th IAEA Technical Meeting on Research using Small Fusion Devices. Mexico City, Mexico, 30 november-3 December 2005. P. 53-56.

[10] D.A. Ovsyannikov, N.V. Egorov, Mathematical modeling of ion and electron beams formation systems. Saint-Petersburg, 1998.

[11] Kirichenko N.F. Introduction to the motion stabilization theory. Kiev, 1978.

[12] V.M. Zavadsky, G.M. Vorobjov, S.V. Zavadsky. The Gutta tokamak acquisition and control system. // Intern. conf. on stability and control processes. Vol. 3. St.-Petersburg, 2005.

[13] L.A. Esipov, V.M. Zavadsky, S.V. Zavadsky, I.E. Saharov, S.V. Shatalin. Plasma column equilibrium control system of FT-2 tokamak // Thesis of proceeding XXVI Zvenigorod conference on plasma physic and CTS. Zvenigorod. 1999.