NUMERICAL MODELING OF PROCESSES OF PLASMA ACCUMULATION, HEATING AND CONFINEMENT IN THERMONUCLEAR REACTOR "ELEMAG" *

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In the article the mathematical model and computer program for numerical modeling of plasma accumulation, heating and confinement processes in thermonuclear reactor "Elemag" is considered. In a basis of model the equations of material and power balance are fixed in view of specific features of multislit electromagnetic traps. The results of a starting mode reactor modeling, the stationary state execution, ways of capacity regulation, results of direct transformation of α - particles kinetic energy in electrical one are offered.

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MATHEMATICAL PROGRAM OF PLASMA PROCESSES NUMERICAL MODELING IN THERMONUCLEAR REACTOR

The equations describe dependence of complete quantity electrons $\mathbf{N_e}$, complete quantity of ions $\mathbf{N_i}$, complete power contents in an electrons component of plasma $\mathbf{W_e = 1.5T_eN_e}$ and complete power contents in a ion component of plasma $\mathbf{W_i = 1.5T_iN_i}$ from time of plasma accumulation

$$dN_e/dt = I_e/e + \Gamma - I_{e\perp} - I_e 1) \qquad {}_{||})$$

$$dN_i/dt = \Gamma - I_i - I_\alpha \qquad (2)$$

$$dW_e/dt = P_{eh} - P_{ek} \qquad (3)$$

$$dW_i/dt = P_{ih} - P_{ik} \qquad (4)$$

Ie, - current of electrons injected in a trap. At an initial stage of plasma accumulation it is limited by formation of the virtual cathode at the center of a trap. The special function, limiting a current of electron injection at approximation of volumetric charge potential to potential of the cathode, is entered at numerical modeling in the program.

$$\Gamma = <\sigma_e v_e> n_{ap} N_e \qquad (5)$$

quantity of electrons and ions pairs formed in plasma volume in time unit (s) as a result of neutral gas ionization, $\mathbf{<\sigma_e v_e>}$ - speed of ionization, $\mathbf{n_{ap}}$ - neutral gas density in plasma. The neutral gas "burns out" and it density in plasma is less than neutral gas density acting in the vacuum chamber

$$n_{ap} = n_{am}/(1 + <\sigma_e v_e> N_e/v_a S_p) \qquad (6)$$

where $\mathbf{v_a} = (8kT_a/\pi m_a)^{1/2}$ - speed of neutral gas molecules, $\mathbf{S_p}$ - area of plasma limiting surface.

Electrons are lost from a trap as a result of cross transfer through a magnetic field with an exit on limiting anode diaphragms and also as a result of longitudinal diffusion in space of speeds with overcoming of an electrostatic barrier $\mathbf{\Phi_e}$ and exit on electrodes of electrostatic magnetic slits lock-out system.

The cross diffusion flow in a multislit electromagnetic trap with axisymmetric geometry of magnetic field in view of electrons mobility in a strong electrical field was calculated in works [1,2]

$$I_{e\perp} = N[D_{ea}(1+\Phi_p/2T_{e0}) + D_{ei}] n_{e0}FR^2 \qquad (7)$$

where **N** – quantity of magnetic slits in a trap, $\mathbf{D_{ea} = T_e \nu_{ea} / m_e \omega_{ce}^2}$, $\mathbf{D_{ei} = T_e \nu_{ei} / m_e \omega_{ce}^2}$ - factors of electrons diffusion on plasma neutral atoms and ions,
$\mathbf{\Phi_p}$ - plasma potential (in power units), $\mathbf{n_{e0}}$, $\mathbf{T_{e0}}$ - plasma density and electrons temperature in the central area of a trap, **F** - factor which is taking into account magnetic field geometry, **R** - radius of a trap on a ring magnetic slit.

Longitudinal losses according to [3] are determined by speed of particle maxwellization in plasma. All particles which have achieved energy of a potential barrier leave plasma volume at small speed of maxwellization and

$$I2)4 = {}_{||}\pi)^{1/2} e^4 \lambda n^2 V_p m^{-1/2} T^{-3/2} \exp^{-\gamma} \qquad (8)$$

At the large speed of maxwellization the barrier exit of particles is limited by throughput of magnetic slits

$$I2 = {}_{||}(\pi)^{1/2} c r_p n k T (B_0/B_A)^{1/2} \exp^{-\gamma} / e B_A \gamma^{1/2} \qquad (9)$$

$\mathbf{V_p}$ - plasma volume, $\mathbf{\gamma = \Phi/T}$, $\mathbf{r_p}$ - radius of plasma, $\mathbf{B_A}$ - magnetic field in a ring slit, $\mathbf{B_0 = B(r_p)}$. We take the smaller value from these two expressions for longitudinal electron losses $\mathbf{I_{e||}}$ and longitudinal ion losses $\mathbf{I_i}$.

"Depression" of volumetric charge potential $\mathbf{\Delta\Phi}$ is calculated with the help of the A. Kaye theory [4], allowing to find electrons flow, circulating in a magnetic slit

$$\Delta\Phi = 4\pi c n_{e0} k T_e (B_0/B_A)^{1/2} a_0 / v_e B_A \qquad (10)$$

$\mathbf{2a_0}$ - width of a magnetic slit limited by anode diaphragms, v_e - electron speed in a magnetic slit.
α - particles flow from plasma on the first wall of thermonuclear reactor (in recalculation on singly ions)

$$I_\alpha = 0.5 <\sigma_f v_i> n_i^2 V_p \qquad (11)$$

Capacity $\mathbf{P_e = \Phi_a I_e}$ is entered into plasma by electrons injection. It is spent for creation of volumetric charge electrical field, neutral atoms excitation and ionization, electrons and ions heating, covering of energy losses connected with a particles exit from a trap, recharging, bremsstrahlung and betatron radiation. The additional capacity connected with energy recuperation of thermonuclear α-particles $\mathbf{P_\alpha = \Phi_p I_\alpha}$ and hot ions leaving the trap through magnetic slits $P_i = \Phi_i I_i$ overcoming a potential barrier $\mathbf{\Phi_i}$ will be entered through the electron channel in process of plasma accumulation and heating. Thus the following capacity is entered through the electron channel in a trap

$$P_{eh} = P_e + P_\alpha + P_i \qquad (12)$$

Collisional and collisionless energy transfer from electrons to ions is the source of energy for ions heating. Energy, which is transferred by collisional way

$$P_{eq} = 1.5(T_e - T_i)N_e/\tau_{eq} \qquad (13)$$

where $\boldsymbol{\tau_{eq} = 3m_iT_e^{3/2}/8(2\pi m_e)^{1/2}e^4\lambda n_e}$.

The collisionless energy transfer is carried out by ions acceleration formed at neutral atoms ionization in an electrical field of a volumetric charge. The efficiency of heating depends on a place of neutral atom ionization on a slope of a potential well, what, in turn, depends on a ratio of neutral atom, $\boldsymbol{\lambda_l}$ penetration depth to depth of electrical field $\boldsymbol{\lambda_d}$ penetration into plasma. Capacity, which is transferred by collisionless way

$$P_E = \alpha\Phi_p\Gamma \qquad (14)$$

where $\boldsymbol{\alpha}=1/(1+\lambda_l/\lambda_d)$, $\lambda_l=V_a/<\sigma_e v_e>n_a$, $\lambda_d = (\Phi_p/6\pi e^2 n_e)^{1/2}$
Thus capacity of ions heating

$$P_{ih} = P_{eq} + P_E \qquad (15)$$

The expense of capacity through the electrons channel

$$P_{ek} = P_\varepsilon + P_{eq} + P_E + P_{e\perp} + P_{e\|} + P_{br} \qquad (16)$$

where: $\boldsymbol{P_\varepsilon = \varepsilon\Gamma}$ - losses on neutral atoms excitation and ionization, $\boldsymbol{\varepsilon = 70}$ **eV** - the energy is spent on the ionization act and accompanying excitation of neutral gas atoms, $\boldsymbol{P_{eq}}$ and $\boldsymbol{P_E}$ - capacity on collisional and collisionles ions heating, $\boldsymbol{P_{e\perp} = 1.3T_eI_{e\perp}}$, $\boldsymbol{P_{e\|} = \Phi_aI_{e\|}}$ - losses connected with electrons transfer across a magnetic field on anode diaphragms and along a magnetic field on electrostatic system electrodes, $\boldsymbol{P_{br}}$ - losses on bremsstrahlung. The losses on betatron radiation are not taken into account, as the plasma in basic volume is outside of a magnetic field.

The expense of capacity through ions channel

$$P_{ik} = P_i \_+P_p +P_r \qquad (17)$$

where: $\boldsymbol{P_i = \Phi_iI_i}$ - losses connected with ions exit, $\boldsymbol{P_p = 1.5T_iI_\alpha}$ - losses connected to ions removal from plasma in result of thermonuclear reaction, $\boldsymbol{P_r = T_i<\sigma_{10}v_i>n_{ap}v_i}$ – losses on recharge.

STARTING MODE MODELING

Thermonuclear reactor «Elemag» represents a multislit electromagnetic trap with axisymmetric magnetic field geometry. Quantity of magnetic slits is **N** = 40. Radius on a ring magnetic slit 3.6 m, length between axial apertures - 90 m. Width of a magnetic slit limited by anode diaphragms is $\boldsymbol{2a_0}$ = 0.5 cm. Plasma volume - 1140 m^3, area of a surface limiting plasma - 1140 m^2. A magnetic field in a ring magnetic slit – $\boldsymbol{B_A}$ = 70 kGs, in axial apertures $\boldsymbol{B_{A0}}$ = 140 kGs. Electrostatic potential closing magnetic slits -700 kV.

The modeling of plasma accumulation and heating in a starting mode was carried out in real time. Plasma density $n_{e,i}$ electrons and ions temperature $\boldsymbol{T_e}$ and $\boldsymbol{T_i}$, plasma potential $\boldsymbol{\Phi_p}$ and potential "depression" in a magnetic slit $\boldsymbol{\Delta\Phi}$, neutral gas density in plasma $\boldsymbol{n_{ap}}$, current of electrons injection $\boldsymbol{I_e}$, current of cross $\boldsymbol{I_{e\perp}}$ and longitudinal $\boldsymbol{I_{e\|}}$ electrons transfer, current of ions in magnetic slits $\boldsymbol{I_i}$, current of α-particles $\boldsymbol{I_\alpha}$ and capacities which are entered in reactor and spent there were display on the screen of the monitor. The results of modeling are submitted in the figure.

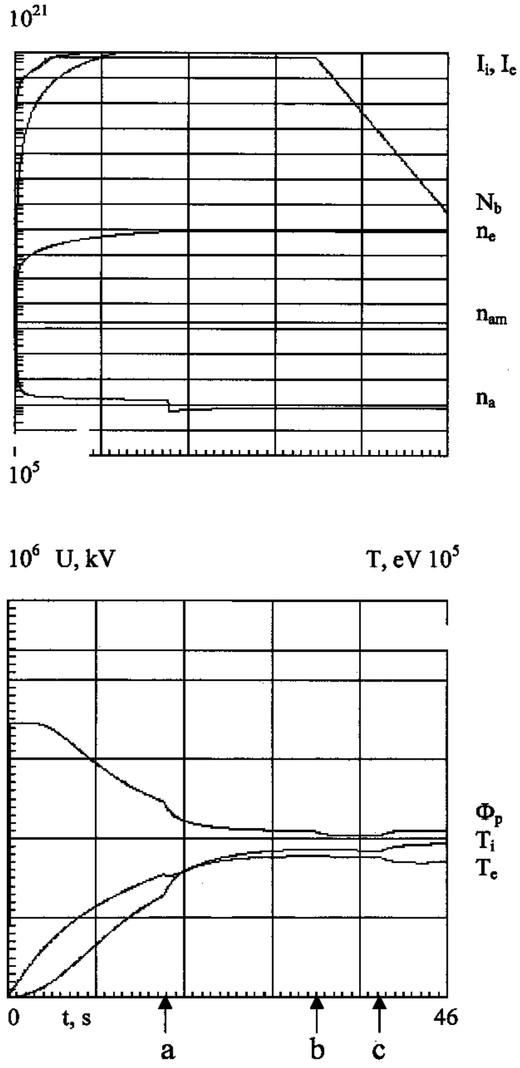

Fig.

Plasma parameters achievable in a starting mode depend on capacity of electron injection, and the growth rate is determined by quantity of entered neutral gas. Electrons temperature is less than ions temperature, which is connected with proceeding plasma accumulation and expense of electrons channel energy on entered neutral gas ionization and heating. Besides the electrons channel spends energy for bremsstrahlung and indemnification of electrons losses on cross and longitudinal transfer.

STATIONARY MODE

In a starting mode the achievement of calculated plasma parameters does not stop further plasma accumulation and heating process. The stationary mode is achieved when the conditions of material and power balance will be executed. Accumulated plasma density is regulated by neutral gas submission. In a stationary mode the quantity of gas, acting in plasma, Γ should correspond to quantity of substance leaving a trap α-particles and ions of deuterium and tritium $\boldsymbol{I_\alpha + I_i}$. Plasma density will remain constant during all operating time of thermonuclear reactor at performance of neutral gas balance $\boldsymbol{\Gamma = I_\alpha + I_i}$, see figure, point “a”. Increase of gas submission, $\boldsymbol{\Gamma > I_\alpha + I_i}$ or reduction of gas submission $\boldsymbol{\Gamma < I_\alpha + I_i}$ leads to plasma density increase or reduction with exit on a new stationary level $\boldsymbol{\Gamma = I_\alpha + I_i}$. Other plasma parameters are arranged under a new stationary condition.

The mechanism of thermonuclear reaction α-particles energy recuperation and connected with it energy recuperation of fast electrons in an external electrical field is included with growth of density and temperature of plasma ions. When the capacity of recuperated energy $\mathbf{P}_{e\|}$ becomes equal to capacity of electron injection $\mathbf{P}_e$, feeding of electrons injectors can be switched to a source of recuperated energy. At the further increase of plasma parameters the external electron injection is switched off and work of reactor proceeds in an independent mode. Thermonuclear fuel (as equal component of a mix deuterium and tritium) is entered in plasma, there is an ionization of neutral gas, having heated electrons and ions in a potential well volumetric charge, thermonuclear reaction between ions, energy recuperation α-particles and energy recuperation fast electrons, restoring power balance, see figure, point “b”. The de-energizing of electrons injection does not render essential influence on process of plasma accumulation, the accumulation proceeds for the account of α-particles energy recuperation. The adjustment of ions temperature is achieved by change of factor of collisionless energy transfer from electrons to ions, α. At reduction of neutral gas temperature up to temperature of liquid nitrogen α is increased in $(300/77.2)^{1/2}$ times, see figure, the point "c". The ion temperature is grows, electron temperature, accordingly, falls.

Complete thermal capacity of thermonuclear reactor $\mathbf{P}_f$ = 4. 01 GWt, capacity of α- particles recuperated energy, $\mathbf{P}_\alpha$ = 192 MWt, $\mathbf{P}_E$ = 127 MWt is allocated directly as electrical capacity (in a high-voltage electrical circuit). $\mathbf{P}_\alpha - \mathbf{P}_E$ = 65 MWt - internal energy expense in thermonuclear reactor on ionization and heating of entered fuel and covering of power losses from plasma. A complete flow of thermonuclear neutrons from plasma $\mathbf{N}_n = 1.43*10^{21}$ n/s, density of neutrons flow on the first wall $\mathbf{n}_n = 1.24*10^{14}$ n/cm^{2}s. The expense of thermonuclear fuel (equal component of gases deuterium and tritium mix) $\mathbf{m}_{D,T} = 1.22*10^{-2}$ g/s.

REGULATION OF THERMONUCLEAR REACTOR CAPACITY

The most simple and convenient way of capacity adjustment consists in regulation of fuel submission into reactor as well as in any electrical generator working on liquid or gaseous fuel. The complete stop of reactor occurs in time t ≈5s at the de-energizing of fuel supply (Γ = 0).

From other possible ways of thermonuclear reactor capacity adjustment it is possible to apply change of a magnetic field $\mathbf{B}_A$ or change of electrostatic potential $\mathbf{\Phi}_A$. In the first case energy losses on the cross electrons transfer increase with appropriate decrease of plasma temperature and density. In the second case electrostatic barriers $\mathbf{\Phi}_e$ and $\mathbf{\Phi}_i$ decrease with the appropriate increase of particles and energy losses on diffusion in space of speeds. These ways of capacity adjustment are inertialless and should be applied to fast changes of thermonuclear reactor capacity or its stop in an emergency.

CONCLUSION

The main result of work is plasma parameters theoretical account and modeling in thermonuclear reactor «Elemag». Reactor comes on calculated plasma parameters for t ≈ 30 sec in a starting mode at a current of electrons injection 100 A and consumption of the equal component of gases deuterium and tritium mix $4.63*10^{-2}$ g/s. Energy recuperation of thermonuclear α-particles in an electrical field of electron volumetric charge with subsequent energy recuperation of electrons in an external electrical field allows to disconnect electron injection. The stationary condition with plasma parameters $n_{e,i} = 8*10^{13}$ cm^{-3}, T_e = 33.9 keV, T_i = 38.7 keV is achieved by reduction of neutral gas submission up to $1.21*10^{-2}$ g/s. The complete thermal capacity of thermonuclear reactor P_f = 4.01 GWt, P_{net} = 127 MWt transforms directly in electrical energy (electrical current of a high voltage). Plasma parameters of a stationary mode are confirmed by theoretical accounts of the thermonuclear reactor basic characteristics.

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ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ НАКОПИЧЕННЯ НАГРІВУ ТА УТРИМАННЯ ПЛАЗМИ В ТЕРМОЯДЕРНОМУ РЕАКТОРІ “ЕЛЕМАГ”

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В роботі розглядається математична модель та комп’ютерна програма для чисельного моделювання накопичення нагріву та утримання плазми в термоядерному реакторі “Елемаг”. В основу програми покладено рівняння матеріального та енергетичного балансу з урахуванням специфічних особливостей багатощілинних електромагнітних пасток. Представлені результати моделювання стартового режиму, стаціонарного стану, методи регулювання потужності, результати прямого перетворення кінетичної енергії α-часток в електричну.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ НАКОПЛЕНИЯ, НАГРЕВА И УДЕРЖАНИЯ ПЛАЗМЫ В ТЕРМОЯДЕРНОМ РЕАКТОРЕ «ЭЛЕМАГ»

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В работе рассматривается математическая модель и компьютерная программа для численного моделирования накопления, нагрева и удержания плазмы в термоядерном реакторе «Элемаг». В основу модели положены уравнения материального и энергетического баланса с учетом специфических особенностей многощелевых электромагнитных

ловушек. Представлены результаты моделирования стартового режима, стационарного состояния, методы регулирования мощности, результаты прямого преобразования кинетической энергии α-частиц в электрическую.