THE THERMONUCLEAR REACTOR CONCEPTUAL PROJECT BASED ON THE MULTISLIT ELECTROMAGNETIC TRAP

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The thermonuclear reactor conceptual design based on the multislit electromagnetic trap with axisymmetric geometry of the magnetic field is developed. Plasma parameters are: density $n_{e,i} = 8{\cdot}10^{19}$ m^{-3}, electron temperature $T_e = 34$ keV, ion temperature $T_i = 38$ keV, plasma volume $V_P = 1140$ m^3. The magnetic, electrostatic, vacuum systems and the blanket of thermonuclear reactor are presented.

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INTRODUCTION

The multislit electromagnetic trap with axisymmetric geometry of magnetic field is the simplest and the best investigated thermonuclear system among electromagnetic traps. Magnetic field in this system is created by coaxial coils with alternating polarity of currents. Magnetic slits between the coils and in axial holes are closed by electrodes at high negative potential. Electrons injected into the trap are accumulated and confined between the magnetic surfaces by an acute-angled magnetic field, and by an external electrical field in the circular magnetic slits and axial holes. The ions are accumulated and confined in the potential well of a volumetric charge of electrons.

In electromagnetic traps the most dangerous plasma instabilities are suppressed. The transport factors of particles and energy are found to be close to the classical values.

The overall reactor dimensions are as follows: the vacuum chamber diameter is D = 10 m, the length is L = 70 m. The magnetic field in the ring slits is B_A=70 kGs, in the axial holes B_{A0}=100 kG, on the boundary magnetic surface, separating plasma from the vacuum magnetic field, B_0=15 kG ($\beta = 1$). The electrostatic potential locking the magnetic slits is Φ_A=700 kV.

The plasma parameters are: density $n_{e,i} = 8{\cdot}10^{19}$ m^{-3}, temperature of electrons $T_e = 34$ keV, temperature of ions $T_i = 38$ keV, plasma volume $V_P = 1140$ m^3.

The total thermonuclear reactor power is $W_f = 4$ GW, the neutron load on the first wall is P_n=2.3 MW/m^2 ($\approx 10^{14}$ n/cm^{2}s). A complete neutrons flow is N_n= $1.42{\cdot}10^{21}$ 1/s, the consumption of thermonuclear fuel (equal-component deuterium and tritium gas mixture) is m_{dt}=$1.2{\cdot}10^{-2}$ g/s.

MAGNETIC SYSTEM

The magnetic system of the thermonuclear reactor consists of coaxial coils with alternating polarity of currents, Fig 1. The magnetic system parameters are: internal radius of coils – 3 m, external radius – 4.2 m, coils width – 0.45 m, length – 75 m, current in coils – 70 kA.

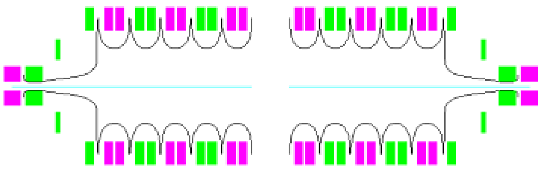

Fig. 1

The magnetic configuration of the reactor is characterized by a deep magnetic well. Figure 2 shows the radial dependence of the magnetic field in the magnetic slit plane, B_r (r, 0) (a), under the coil, B_z (r, 0.84) (b), and on the axis of the system (c), B_z (0, z).

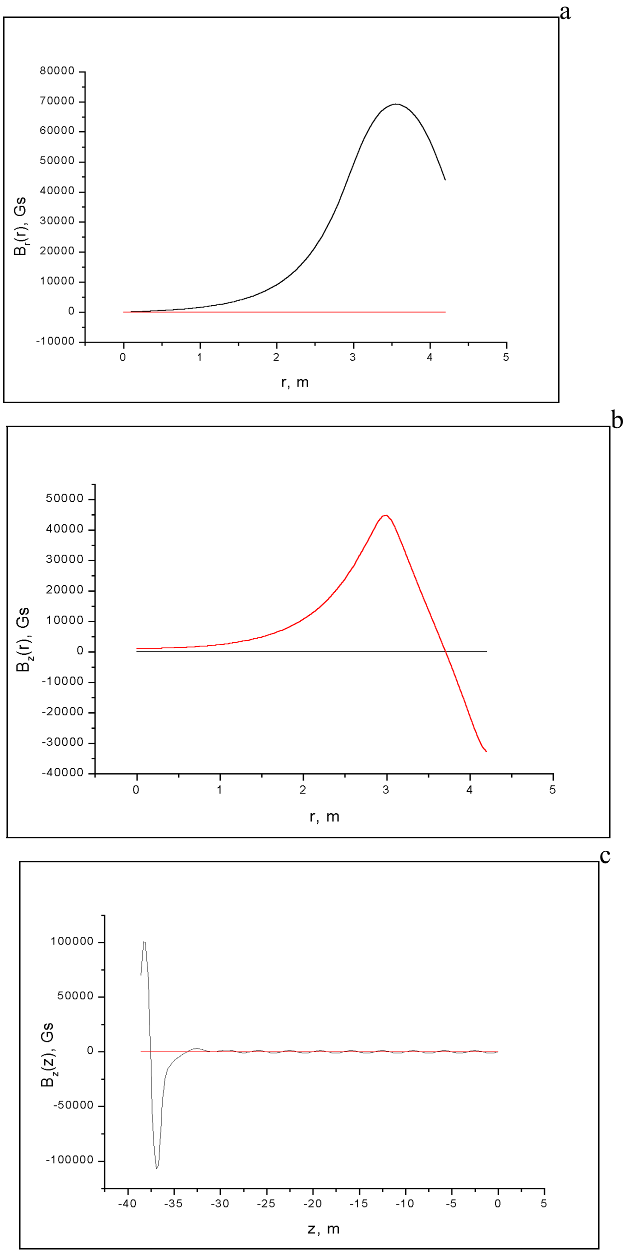

Fig. 2

The plasma displaces a weak magnetic field from the central area of reactor up to the boundary magnetic surface $B_0 = [8\pi n_e k(T_e + T_i)]^{1/2} \approx 15$ kG, being at a distance of 0.9 m from the coil surface. The radius of plasma under the coil is a_p=2.1 m (in the ITER project a = 2 m). The nonmagnetized plasma volume with due regard for the ripple of magnetic field is V_p=1140 m^3.

Ponderomotive forces in the operating thermonuclear reactor are mutually balanced except for the extreme coils, i.e., the last sections of the central part of the magnetic system, interface coils and coils of axial holes. In event of emergency switching of one or several coils the balance of forces is broken. The analysis of various emergencies suggests the conclusion, that the maximum force of repulsion between the coils does not exceed $1.49 \cdot 10^5$ T. Specific load on the coil from this force (548.9 kg/cm^2) is within the limits of elastic deformations of materials, of which the coils and power skeleton will be made. The successful solution of ponderomotive forces problem lies in the application of unified blocks.

The unified block consists of two single-sectional coils of the magnetic system. A corrosion-resisting steel ring with an outer diameter 10 m, width 1.66 m and thickness 0.3 m serves simultaneously as a power skeleton and a vacuum chamber. Steel rims of the coil are closely connected to the ring. The electrostatic system of magnetic slit locking is placed between the coils. The uniform block also includes the blanket, radiation protection of the coil, heat carrier pipelines, branch pipes of external pumping system, inputs of power and cooling supplies for the magnetic field coils, high-voltage inputs.

Made of a superpurity aluminium wire, the coil windings are cooled with liquid hydrogen. The advantages of such windings in comparison with superconducting ones are the absence of restrictions on magnetic field and current density values, a low sensitivity to radiation damages, possibility of damage "annealing" at normal temperature. The technology of manufacturing the wire from an industrially produced raw material is mastered. The cost of the superpurity aluminium wire is approximately 120 times lower than that of a superconductor.

For estimations of the magnetic system parameters the data from [1] have been taken. The resistance of 99.999% pure aluminium at liquid hydrogen temperature of 20K is taken to be $\rho = 2.7 \cdot 10^{-11}$ Ω/m, the power consumption of refrigerator is 30 W/W. The aluminium wire section 5x6 cm (in view of channels for liquid hydrogen pumping S = 27 cm^2). The number of turns in two sections n = 288, the total length of the wire L = 6508 m, resistance R= $6.51 \cdot 10^{-5}$ Ω. The magnetic field in a ring slit achieves 70 kG at a current I=10^5 A. The Joule losses in the windings and the power consumed by the refrigerators make P = 19.5 MW, the thermonuclear power on the unified block is equal to 100 MW.

In the thermonuclear reactor, ceramic oxide materials cooled by the gaseous coolant are supposed to be used as a blanket. The tritium breeding ratio K_T in this blanket attains saturation at blanket thickness D = 50 cm. For lithium oxide Li_2O K_T=1.2. The K_T value can increase up to 1.5 in the circuit with neutron multiplication in (n, 2n) reaction on lead or beryllium [2]. Structurally, the blanket consists of beryllium elements with built-in oxide ceramic tubes having gas cooling channels.

ELECTROSTATIC SYSTEM

The electrostatic magnetic slits "locking" system consists of ring electrodes located by pairs on each side of the plane of symmetry of the magnetic field in the magnetic slit. The electrodes are mounted either on insulators, or on two ceramic ring plates, fixed on a common skeleton, and are inserted as a unit between the magnetic field coils. The internal electrodes - anode diaphragms - and external electrodes – ion collectors - are at zero potential. A high negative potential is applied to the middle electrodes. This potential is shared equally among intermediate electrodes that provide a uniform distribution of the potential. For oxide-coated polished aluminium electrodes, the breakdown voltage for a vacuum gap of 50 mm is equal to 540 kV [3, p. 173]. The breakdown voltage across the surface of electrical porcelain insulator of 50 mm in length, exceeds 200 kV. For six vacuum igaps, of the thermonuclear reactor electrostatic system, each being 50 mm wide, the breakdown voltage exceeds 1200 kV.

Other problem of magnetic slits locking system consists in accuracy positioning, namely - superposition of a geometrical plane of electrodes symmetry with a plane of the magnetic field symmetry. It concerns only the anode diaphragm, which are at zero potential, and can be rigidly related to the coils of the magnetic system. The anodic slit limited by anodic diaphragm, should have the size $2a_0$=5 mm. The centre of a slit should coincide with a plane of magnetic symmetry with an accuracy of 0,1 mm. Positioning of the electrostatic locking system of the multislit electromagnetic trap "Jupiter 2M" has given excellent results in understanding of increase of plasma confinement efficiency [4]. The positioning of each unified block of the thermonuclear reactor can be carried out on the stand. The important condition of the successful work is a rigid fastening of the electrostatic system after positioning has been carried out. Another approach is also possible, i.e., to set the electrostatic system on server-based devices and to carry out additional tuning at preventive works on the reactor

The other electrodes of electrostatic system do not require such an exact positioning. It is important that they should be "in the shadow" of the anodic diaphragm, away from plasma radiation. This is achieved by increasing the interelectrode gap and by placing an additional entrance diaphragm, which limits the radiation flow from plasma.

In experimental studies of the multislit electromagnetic trap "Jupiter 2M", electron injection through axial holes was used for creation and heating of plasma [5]. The same technique can be used in the thermonuclear reactor, too. The only difference is in the values of injected current and accelerating potential. The Paton Institute has developed high-emissive cathode units meant for a current up to 100 A/cm^2 of the emitter surface. In CERN, a feed through insulator for input of high voltage up to 660 kV in the vacuum container has been developed [3, p. 199]. These developments can be used for electron injection through the axial holes in the thermonuclear reactor.

Another variant of electron injection lies in the use of small annular slits in cork coils. The advantage of this method consists in the absence of direct optical contact with radiation from the reactor zone plasma.

VACUUM SYSTEM

The vacuum system of the thermonuclear reactor consists of a vacuum chamber and vacuum pumping means. The vacuum chamber, 10 m in diameter and 70 m in length, is assemble from unified blocks. Each block has an independent vacuum pumping system, or is connected to a common high-vacuum collector. The high-vacuum collector represents a large-section pipe located along the vacuum chamber of the reactor.

Helium cryogetter, turbo-molecular, ion transfer and diffusion pumps can be used as high-vacuum system pumps. Cryogetter pumps can provide extremely pure vacuum conditions for reactor operation, and also, make it possible to extract deuterium and tritium from the exhaust gas. The extreme pressure attainable by cryogetter pumps is below 10^{-10} Torr, the pumping rate is 10^5 l/s per m^2 of the cryochannel, the electric energy consumption for pumping rate of 10^6 l/s at pressure 10^{-4} Torr is 20 kW. The turbo-molecular and diffusion pumps consume the electric power energy for pumping approximately by order of magnitude more. The ion pumps show the lowest energy consumption for pumping, but they poorly pump out inert gases. The roughing-down pumping is performed by mechanical pumps with the use of liquid-nitrogen traps for oil vapor recovery.

The pumping rate of the reactor vacuum system is determined by the balance of gases incoming to the reactor and pumped out from it. At a consumption of fuel $1.21 \cdot 10^{-2}$ g/s introduced into the reactor as an equal-component gas mixture of deuterium and tritium, the rate of pumping to remove gaseous products of disintegration is equal to $6.2 \cdot 10^7$ l/s. Here it is also necessary to consider the inleakage and gassing from the reactor walls. In any case, taking into account a continuous operation of the reactor, the vacuum system should be designed with a double stock of "durability". High-efficiency cryogenic pumps are developed at the B. Verkin Institute for Low Temperature Physics and Engineering in Kharkov.

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КОНЦЕПТУАЛЬНЫЙ ПРОЕКТ ТЕРМОЯДЕРНОГО РЕАКТОРА НА ОСНОВЕ МНОГОЩЕЛЕВОЙ ЭЛЕКТРОМАГНИТНОЙ ЛОВУШКИ

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Разработан концептуальный проект термоядерного реактора на основе многощелевой электромагнитной ловушки с осесимметричной геометрией магнитного поля. Параметры плазмы: плотность $n_{e,i} = 8 \cdot 10^{19}$ $м^{-3}$, температура электронов $T_e = 34$ keV, температура ионов $T_i = 38$ keV, объём плазмы $V_P = 1140$ $м^3$. Представлены магнитная, электростатическая, вакуумная системы и бланкет термоядерного реактора.

КОНЦЕПТУАЛЬНІЙ ПРОЕКТ ТЕРМОЯДЕРНОГО РЕАКТОРА НА ОСНОВІ БАГАТОЩІЛИННОЇ ЕЛЕКТРОМАГНІТНОЇ ПАСТКИ

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Розроблено концептуальний проект термоядерного реактора на основі багатощілинної електромагнітної пастки з вісесиметричною геометрією магнітного поля. Параметри плазми: густина $n_{e,i} = 8 \cdot 10^{19}$ $м^{-3}$, температура электронів $T_e = 34$ keV, температура іонів $T_i = 38$ keV, об'єм плазми $V_P = 1140$ $м^3$. Представлено магнітну, електростатичну, вакуумну системи та бланкет термоядерного реактора.