THERMAL-PHYSICAL ANALYSIS OF LOW-RADIOACTIVE THERMONUCLEAR PLASMA IN THE MAGNETIC FUSION DEVICE

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A field-reversed configuration (FRC) plasma is vortex-like, isolated toroid of plasma with high beta (plasma pressure/magnetic-field pressure). Such a self-organized, stable system is a candidate for the magnetic fusion confinement. The proposal of a compact toroid as fusion reactor together with advanced fuel is based on the low radioactivity of deuterium-helium-3 plasma. Analysis of conceptual parameters of the D-^3He and D-T FRC power plant was carried out. Advantages and disadvantages of the D-^3He reaction, problem of ^3He acquisition and advanced fuels prospects are discussed.

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INTRODUCTION

Main problems in the magnetic confinement include plasma heating, energy and particle confinement, fuel injection, temperature and density profile control, impurities, sustainment and stabilization of the plasmas. Magnetic systems are divided on two classes. The field lines in the first category are closed and plasma confined in this closed-field region. Devices - tokamak, stellarator, spherical tokamak. The second category is magnetic system where field lines continue after confinement region (goes to infinity). Examples of such type devices – FRC (see Fig. 1) [1-3], gas dynamic trap, spheromak, tandem mirror.

The aim of this research is theoretical investigation and analysis of thermal and plasma physics processes in the fusion magnetic devices, namely in a field reversed configuration, in the wide range of the plasma temperature, magnetic field and used fuels. Main goals of the present work are:

- estimation of the controlled D-^3He fusion reaction in a FRC, definition of the most important plasma and power plant parameters;
- research on the increasing of the plasma Q-value (power amplification factor) and system efficiency of the fusion reactor at minimum of neutron wall load.

Biological hazard radiation in fusion reactor is 4-5 times lower than in fission reactors and radioactive materials can be disposed as low-level waste after a full reactor lifetime. The low radiation damage in D-^3He reactors allows permanent (~40 years) first walls to be designed.

The mixture of deuterium and helium-3 has more prospects (high fusion power density, low radioactivity and activation) and it makes this fuel powerful and attractive.

Moreover, D-^3He and ^3He-^3He reactions possess very high efficiency in converting fusion power to electric power (>70%). Electrical conversion efficiency for D-D reaction is 50%. Direct energy conversion for D-T is close to 45%. Fission reactors have 40% and less.

The most important technological advantages (blanket absence and possibility of using of the liquid first wall and direct conversion system) of D-^3He FRC or power plant based on open systems – alternative scheme with low radioactive fuel [4] – in comparison with tokamak and other magnetic systems burning D-T fuel are essential.

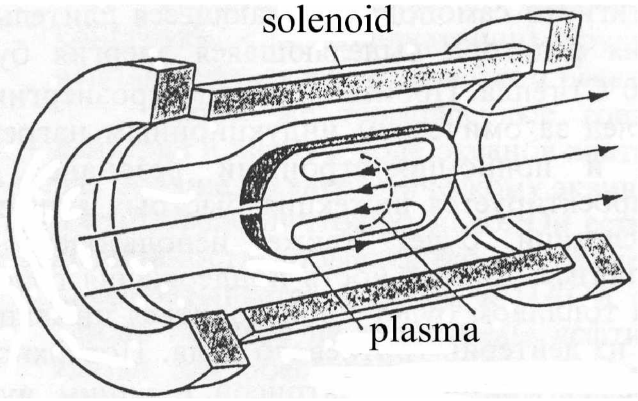

Fig. 1. Field reversed configuration (FRC)

FRC FUSION PARAMETERS

Analysis of D-^3He and D-T plasma taking into account the geometric and engineering parameters of a FRC power plant was carried out.

One of the most important and usefull values is the physical parameter Q (fusion power/ injected power). As you can see from Fig. 2 necessary positive power output for the ignition and sustainment (Q>10) of a D-^3He plasma may be reached at 60-90 keV.

Q-function has unmonotonous character with the maximum at 76 keV. Estimated value (Q=40.1) is enough for the effective work of the FRC reactor. This is result of the correct modelling of thermal and plasma physics processes and optimization of D-^3He plasma parameters and FRC geometric charachteristics. Q-value may be increased using methods of ash removing, one of which (selective ion pumping) is proposed in BMSTU [5].

Analysis of the aneutronic fuels (D-^3He, p-^{11}B, p-^6Li, etc) shows that Q-value has strong dependence on bremsstrahlung, because at certain conditions in such fuels bremsstrahlung gets over 50% of the total fusion power.

In this work, we have used improved analytic equilibria for a FRC which span parameter space from elliptical (elongated Hill's vortex) to "racetrack"-like separatrix shapes.

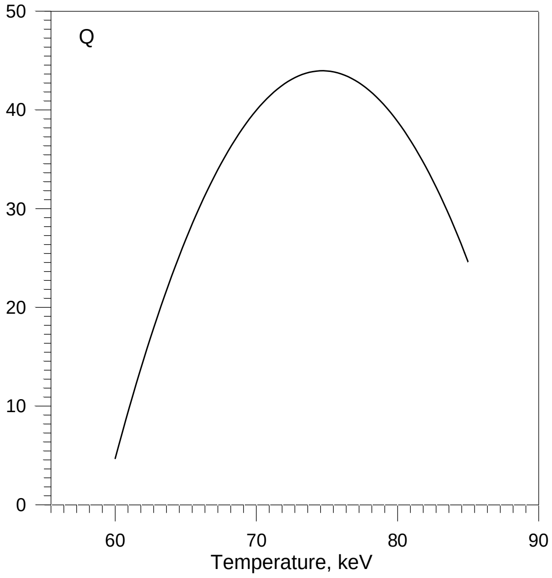

Fig. 2. Plasma Q-value dependence on ion temperature for a D-^{3}He FRC power plant

Principal parameters [4,6] of the *D-^{3}He* and *D-T* plasma and FRC fusion power plant are shown in the Table.

Principal parameters of the D-^{3}He and D-T plasma and FRC fusion power plant

	D-^{3}He	D-T
Plasma		
Separatrix radius, r_s	1.25 m	1.87 m
Separatrix length, l_s	30.75 m	20 m
Elongation, k	12.26	10.7
First wall radius, r_w	1.77 m	2 m
Plasma volume, V_p	121.5 m^3	220 m^3
External B-field, B_e	6.39 T	2.4 T
Averaged beta, $<\beta>$	75 %	56 %
Ion temperature, T_i	72 keV	24 keV
Electron temperature, T_e	71.85 keV	25 keV
Ion density, n_i [m^{-3}]	3.25x10^{20}	1.5x10^{20}
Electron density, n_e [m^{-3}]	5.07x10^{20}	1.7x10^{20}
Energy confinement time, τ_e	1.46 s	1.1 s
Reactor		
Fusion power, P_f [MW]	1937	1785
Charged particles, P_q [MW]	1192	367
Neutron, P_n [MW]	49	1427
Radiation, $P_{brems}+P_{syn}$ [MW]	745	31
Electrical power, P_{enet} [MW]	1000	1000
Plasma Q-value, Q	40.1	44.6
Injected power, P_{inj} [MW]	49.5	40
System efficiency, Ef_{sys} [%]	49.8	45
Chamber volume, V [m^3]	301	440
Surface heat load, P_t [MW/m^2]	2.18	0.12
Neutron wall load, P_{nwall}	0.14	5.7
Thermal conversion efficiency	0.6	0.52

Calculation of physical parameters including the density of all species and all power characteristics by integration over the respective profiles for the plasma density, the magnetic field and the plasma temperature is performed.

Parameters which provides positive power output in the plasma and maximum of system efficiency are found. FRC using advanced fuel in comparison with the same *D-T* power plant has the higher fusion power density (15.5 and 5.5 MW/m^3). Plasma parameters providing positive power output and most effective reactor regimes are obtained. Possibility of controlled fusion in a FRC using *D-^{3}He* fuel is evident.

^{3}He PROBLEM AND D-^{3}He APPLICATION

From the beginning of consideration *D-^{3}He* fuel as source of energy in thermonuclear power plants scientific world seriously discussed the question about the helium-3 getting. The fact is that very small amount of this isotope may be found on the Earth and such resource is not enough for commercial reactor. From this point of view the most attractive and optimistic is an idea of *^{3}He* extraction on the Moon [7].

The problem of lunar helium-3 mining is not fantastic as 10-20 years ago. In addition to tritium decay and *^{3}He* production in the catalyzed cycles and additional modules-reactors (e.g. *D-^{3}He-^{6}Li* fusion cycle) [8] other proposals exist. Isotopic-geochemical investigation [9] of deep rock of the hydrocarbon in the Niigata basin are shown that gases with light-isotopic values of ^{13}C methane (biochemical range) are accompanied by hyper mantle relationship helium isotopes *^{3}He/^{4}He*, that opens the opportunity for extraction helium-3 on the Earth in large quantities. Ignition of p-^{11}B will require non-Maxwellian fusion concepts (e.g., inertial electrostatic confinement or colliding beam fusion).

However, this is tentative data and necessity of lunar *^{3}He* remains at the same time dominant version and essential problem of low-radioactive *D-^{3}He* reactor designing. Helium-3 breeding (e.g. proposal with additional p-^{6}Li fuel reactor is considered early) or lunar mining must be investigated more carefully.

Helium-3 supply on the Earth is just for one year energy at full *^{3}He* extraction from the atmosphere and underground gas. Lunar soil, which contained desired isotope, covers the Moon (sea richer of helium, than highlands).

In future, at intensification of research and extension of commercial power plants, technology will be much cheaper, what we have with computer systems right now.

Applications of alternative systems and advanced fuels: Near term – medical isotope production, cancer therapy, detection of explosives and chemical wastes. Mid term – destruction of fissile material and radioactive wastes. Long range – small electrical power plants, use of advanced fuels (helium-3), space propulsion, base load electrical power plants, hydrogen and synthetic fuel production.

CONCLUSIONS

The main result of the work is the part of the system analysis of *D-^{3}He* and *D-T* FRC power plant. Theta-pinch, spheromaks merging and rotating magnetic field formation of FRCs has been used successfully in previous experiments, but it extrapolates poorly to the fusion regime. Viable FRC startup and sustainment methods with reasonable input powers are being sought. Improvement of transport and thermal physical properties for the less collisional plasmas of the fusion regime is expected. So far we have studied the thermal physical characteristics of a low radioactive FRC. The present state of art has demonstrated how fusion research can achieve advantages from comparative studies performed in different configurations. Fortunately, in the magnetic systems with open-filed lines almost all of the charged particle transport losses will flow out the ends of the device. Thus, systems of direct and thermal energy conversion may be easily used. Furthermore, magnetic fusion systems are more convenient for using liquid first wall, have proved technology and easy in maintenance. The feasibility of using helium-3 from the Moon to supply energy on Earth very important and timely issue [10].

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ТЕПЛОФИЗИЧЕСКИЙ АНАЛИЗ МАЛОРАДИОАКТИВНОЙ ТЕРМОЯДЕРНОЙ ПЛАЗМЫ В МАГНИТНЫХ КОНФИГУРАЦИЯХ

С.В. Рыжков

Плазма обращенной магнитной конфигурации (FRC) – это изолированный тороид плазмы с высоким бета (давление плазмы/магнитное давление). Такая самоорганизованная, устойчивая система - один из кандидатов для магнитного удержания термоядерной плазмы. Проведено исследование компактного тора в качестве термоядерного реактора вместе с малорадиоактивным топливом – дейтерий-гелий-3 плазмой. Представлен анализ концептуальных проектов $D\text{-}^3He$ и $D\text{-}T$ FRC коммерческой электростанции. Обсуждены преимущества и недостатки $D\text{-}^3He$ реакции и проблема добычи ^3He, а также перспективы улучшенных топливных циклов.

ТЕПЛОФІЗИЧНИЙ АНАЛІЗ МАЛОРАДІОАКТИВНОЇ ТЕРМОЯДЕРНОЇ ПЛАЗМИ В МАГНІТНИХ КОНФІГУРАЦІЯХ

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Плазма зверненої магнітної конфігурації (FRC) – це ізольований тороїд плазми з високим бета (тиск плазми/магнітний тиск). Така самоорганізована, стійка система - один з кандидатів для магнітного утримання термоядерної плазми. Проведено дослідження компактного тора в ролі термоядерного реактора разом з малорадіоактивним паливом – дейтерій-гелій-3 плазмою. Представлено аналіз концептуальних проектів $D\text{-}^3He$ і $D\text{-}T$ FRC комерційної електростанції. Обговорено переваги і недоліки $D\text{-}^3He$ реакції і проблема видобутку ^3He, а також перспективи поліпшених паливних циклів.