FORMATION OF A HIGH ENERGY DENSITY FIELD REVERSED CONFIGURATION FOR COMPACT TOROID APPLICATIONS

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Formation of a compact toroid (CT) or field reversed configuration (FRC) with a maximum input of energy and the capture of the magnetic field into plasma is an important scientific and technical challenge. The new method of CT formation is proposed and applications of CT/FRC are presented.

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INTRODUCTION

Compact torus (CT) – spheromak and field reversed configuration (FRC) is the so-called alternative fusion scheme [1-3]. CT has several features that make perspective its application for the space propulsion. CT is a closed magnetic trap, with all the advantages in relation to open systems. The CT has high value of beta (beta is the ratio of plasma pressure to external magnetic field pressure). Therefore, the energy of the plasma in the CT is 70…80 % of the total energy.

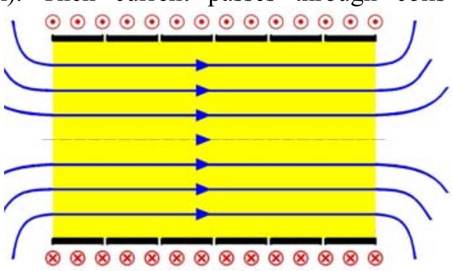
1. FORMATION SCHEME

Formation of a CT or FRC [1-3] with a maximum input of energy and the capture of the magnetic field into plasma is an important scientific and technical challenge. The proposed method of formation is similar to the formation of FRC based on θ-pinch [1], but has some differences, which will be described below. One of the main CT formation problems is the low level of the captured magnetic flux.

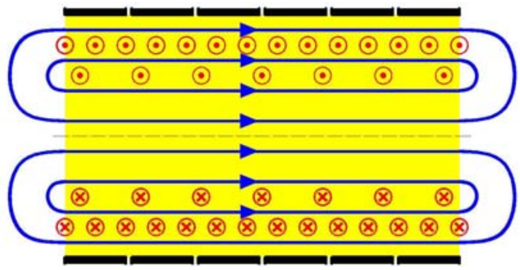
The general formation scheme is shown in Fig. 1. Chamber is filled with working fluid (hydrogen or deuterium). Then current passes through coils and creates a poloidal magnetic field (Fig. 1,a). Current is cut off at the time of the maximum current that is creating a circular current into the plasma. Plasma current is directed in a way to support the decaying field (Fig. 1,b). Poloidal current is passed through the plasma to maintain this field. This is a circular field, decreasing with the radius. The result is a helical magnetic field, which supports the resulting current in the plasma and increases the captured flow. Then solenoid of reversed field is turned on (Fig. 1,c), an elongated configuration with a circular magnetic field is a result. Configuration is compressed in the longitudinal direction and goes to equilibrium (Fig. 1,d).

Level of trapped magnetic flux does not exceed 20…30 % in experiments. In our experiment a level of longitudinal magnetic field is captured by the plasma reached at least 60 % (in experiments with a quartz chamber up to 90 %). These results show that this formation method is perspective.

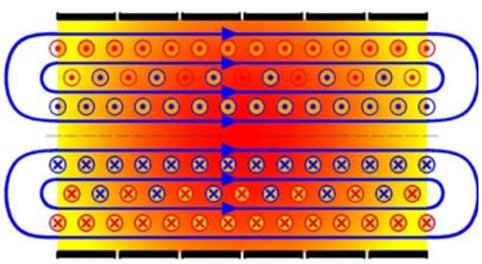
A study of compact torus formation with a longitudinal current was done [4]. This method of formation has not been used before, and was tested for the first time. Experiments showed that this method can significantly increase the energy input into plasma.



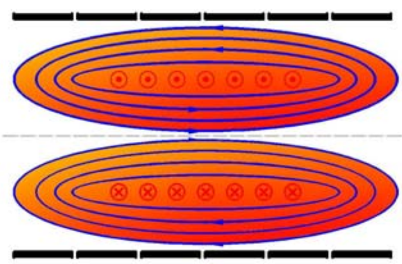
a - *generation of poloidal magnetic field*



b - *flow capture*



c - *compression and elongation*



d - *equilibrium*

Fig. 1. Compact torus formation: B_p is the poloidal magnetic field, I_p is the poloidal current, B_t is the toroidal magnetic field, and I_t is the toroidal current

A theoretical study of possibility to use that configuration as a plasma rocket engine was done [5-7]. During experiments two cameras of dielectric materials with different diameters were used.. Larger diameter chamber gave the expected increase in the lifetime of the configuration. Experiments with a small camera gave an increase in the value of the captured magnetic flux because of better material quality (quartz). Diagnostic system was developed using the B-probe to determine the magnetic flux.

2. FRC APPLICATIONS

The main losses from plasma are bremsstrahlung radiation, charged particles transport and neutrons.

The global plasma power balance is given by:

$$P_f + P_i = P_n + P_{brem} + P_{tran} + P_s + P_t.$$

Where P_f is the fusion power, P_i is the injection power, P_n is the neutron power, P_{brem} is the bremsstrahlung power, P_{tran} is the charged-particle transport power, P_s is the synchrotron radiation power, P_t is the thrust power.

Ratio of the fusion power to the total power of losses for reactors (all radiation and particle losses) for D-T and D-^{3}He reactors are shown in Fig. 2 and Fig. 3 respectively.

Results of solution of the power balance for the D-T and D-^{3}He reactors are shown in Table 1. Parameters of a FRC power plant are presented for comparison. As seen D-T reactor is more powerful then D-^{3}He and therein more the power of loss. This is due to that on D-^{3}He reaction has less neutron yield.

The general scheme of magnetic engine RACETA (Rocket As Compact Elongated Toroid Advanced project) is shown in Fig. 4. In the reactor chamber, the plasma configuration 7 confined in quasi-equilibrium that is sustained by fuel injection 8. Charged particles and neutrons are results of a fusion reaction occurring in the reactors chamber. Neutrons and the radiation go to the chamber walls and heat it.

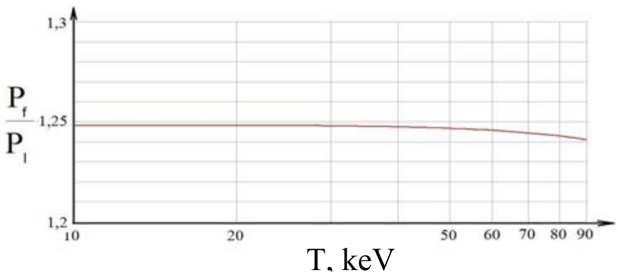


Fig. 2. Ratio of the fusion power to total loss power for D-T reactor

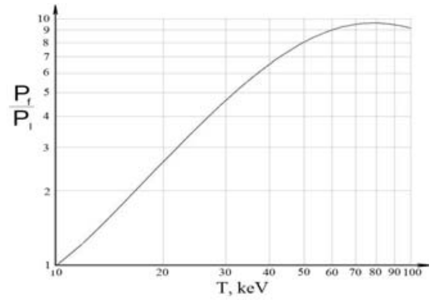


Fig. 3. Ratio of the fusion power to total loss power for D-^{3}He reactor

Charged particles (reaction products and fuel) are translated into the mixing chamber 2 with hydrogen (H) injectors 3. Propellant 4 is heated by the reaction products and going through the nozzle 5 and creating thrust. Part of hydrogen is cooling the reactor's chamber. After reactor chamber, hydrogen goes to the turbine and produces electricity. Parameters of fusion jet were calculated for each fuel type. The results are shown in Table 2. Advantages of D-^{3}He fuel [11, 12] are the highest thrust and specific impulse.

Table 1

Comparison of calculated parameters of reactors and conceptual designs of power plants

Parameters	D-T reactor	D-^{3}He reactor	Artemis [8]	FRC Wisc [9,10]
Fuel	D-T	D-^{3}He	D-^{3}He	D-T
Specific fusion power P_{fusion}, W/m^3	14,9	12,3	24	8,11
Specific power of loss P_{loss}, W/m^3	11,9	1,55	6,47	6,63
Fuel density n, m^{-3}	$1{,}39\cdot10^{21}$	$8\cdot10^{20}$	$5\cdot10^{20}$	$3\cdot10^{20}$
Temperature T, keV	20	7	87.5	24
Fusion gain factor	1,248	9,7	7	1,3
Electric power P_{net}, MW	417	670	1000	1000
Magnetic field B, T	5	7	7	2,4
Beta	0,9	0,9	0,9	0,8

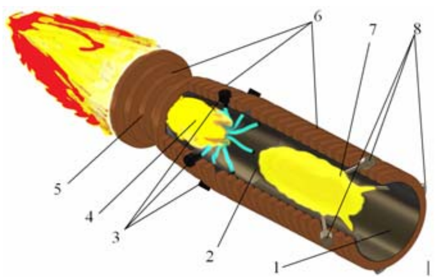


Fig. 4. Magnetic fusion engine RACETA (Rocket As Compact Elongated Toroid Advanced project): 1 – reactor chamber; 2 – mixing chamber; 3 – H injectors; 4 – propellant; 5 – nozzle; 6 – magnets; 7 – plasma; 8 – fuel injector

Table 2

Fusion jet main parameters

Parameter / Fuel	D-T	D–^{3}He
Fuel density n, m^{-3}	10^{21}	$3\cdot10^{20}$
Temperature T, keV	20	70
Hydrogen flow, kg/s	0,4	0,5
Specific impulse, m/s	22800	48120
Thrust, N	9120	24060

CONCLUSIONS

In this paper, we consider the field-reversed configuration (FRC) formation and its applications as a reactor and magnetic fusion engine for rocket vehicle.

Power balance of the FRC reactor was calculated. The advantages of the proposed system based on D-^{3}He fueled compact toroid are high thrust and open magnetic field lines that enables the direct energy conversion.

The main characteristics of the reactor and plasma thruster based on FRC were obtained. Comparison of suggested D-T and D-^{3}He FRC systems is presented. The results showed the prospect of using this high beta system for interplanetary flights.

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ПРИНЦИП СОЗДАНИЯ УЛУЧШЕННОЙ СИСТЕМЫ УДЕРЖАНИЯ ПЛАЗМЫ НА ОСНОВЕ КОМПАКТНОГО ТОРА

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Рассмотрен новый принцип создания системы удержания плазмы высокой плотности на основе обращенной магнитной конфигурации (FRC), как наиболее перспективной для малорадиоактивных/безнейтронных реакций синтеза. Рассчитан баланс мощностей реактора на основе D-T и D-^{3}He топлива. Обсуждается применение D-^{3}He топлива в качестве источника энергии для перспективных двигательных установок, представлены основные параметры (тяга, импульс) для такой системы.

ПРИНЦИП СТВОРЕННЯ ПОКРАЩЕНОЇ СИСТЕМИ УТРИМАННЯ ПЛАЗМИ НА ОСНОВІ КОМПАКТНОГО ТОРА

І.В. Ромаданов

Розглянуто новий принцип створення системи утримання плазми високої густини на основі зверненої магнітної конфігурації (FRC), як найбільш перспективної для малорадіоактивних/безнейтронних реакцій синтезу. Розраховано баланс потужностей реактора на основі D-T і D-^{3}He палива. Обговорюється застосування D-^{3}He палива в якості джерела енергії для перспективних двигунових установок, представлені основні параметри (тяга, імпульс) для такої системи.