ADVANCED FUSION CYCLES FOR HIGH-BETA MAGNETIC SYSTEMS

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Power balance analysis of alternative (not D-T) fusion cycles is carried out to find high efficiency and low-radioactivity cycles for fusion reactors based on high-beta magnetic systems, such as field reversed configuration (FRC), spherical tokamak, etc. Cycles based on reactions D-D, D-^{3}He, D-^{6}Li, D-^{7}Be, p-^{6}Li, p-^{9}Be, and p-^{11}B are considered.

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1. INTRODUCTION

We consider fusion cycles based on the following reactions:

$\mathrm{D + D \to n(2.45\ MeV) + {}^3He(0.817\ MeV)}$ (1a)
$\mathrm{D + D \to p(3.02\ MeV) + T(1.01\ MeV)}$ (1b)
$\mathrm{D + T \to n(14.1\ MeV) + {}^4He(3.5\ MeV)}$ (2)
$\mathrm{D + {}^3He \to p(14.68\ MeV) + {}^4He(3.67\ MeV)}$ (3)
$\mathrm{D + {}^6Li \to n(2.958\ MeV) + {}^7Be(0.423\ MeV)}$ (4a)
$\mathrm{D + {}^6Li \to n(\sim 0.66\ MeV) + {}^3He + {}^4He + 1.794\ MeV}$ (4b)
$\mathrm{D + {}^6Li \to p(4.397\ MeV) + {}^7Li(0.628\ MeV)}$ (4c)
$\mathrm{D + {}^6Li \to p + T + {}^4He + 2.257\ MeV}$ (4d)
$\mathrm{D + {}^6Li \to {}^4He + {}^4He + 22.371\ MeV}$ (4e)
$\mathrm{D + {}^7Be \to p + {}^4He + {}^4He + 16.766\ MeV}$ (5)
$\mathrm{p + {}^6Li \to {}^3He(2.3\ MeV) + {}^4He(1.722\ MeV)}$ (6)
$\mathrm{p + {}^9Be \to D + {}^4He + {}^4He + 0.651\ MeV}$ (7a)
$\mathrm{p + {}^9Be \to {}^4He(1.277\ MeV) + {}^6Li(0.851\ MeV)}$ (7b)
$\mathrm{p + {}^{11}B \to 3{}^4He + 8.681\ MeV}$ (8)

In this paper we estimate the potentialities of different cycles using power balance equation. One can characterize the power efficiency by high value of the plasma power gain factor: $Q=P_{\mathrm{fus}}/P_{\mathrm{ext}}>10$ (P_{fus} is the fusion power, P_{ext} is the required power of external heating). In Sec. 2 burning conditions and simple power balance are studied. Most preferable advanced fusion cycles for energy production in the magnetic reactor appear to be D-^{3}He cycles with ^{3}He production. Calculated parameters of low-radioactivity D-^{3}He magnetic fusion reactors are presented in Sec. 3.

2. IGNITION AND POWER BALANCE

Under ideal conditions the burn of the fusion plasma with given Q value is characterised by the criterion

$$n\tau T = \frac{\frac{3}{2}k\left(\sum_i n_i T_i + n_e T_e\right)^2}{\left(1 + Q^{-1}\right)P_{\mathrm{fus}} - P_{\mathrm{br}} - P_{\mathrm{n}}}, \qquad (9)$$

where k is the Boltzmann constant, n is the total density of fusion ions and electrons, τ is the energy confinement time ($\tau=\tau_E$), $T=(n_iT_i+n_eT_e)/n$, T_i is the ion temperature, T_e is the electron temperature, P_{br} is the bremsstrahlung power, and P_{n} in the neutron power. Limit case $Q\to\infty$ corresponds to the ignition regime. In the calculation of $n\tau T$ criterion we assumed, that $T_e=T_i=T$. Reaction rates are taken from Ref. [1]. For bremsstrahlung losses the results of numerical calculations [2, 3] are used, which takes into account of quantum and relativistic effects.

Important parameters of fusion cycle are neutron yield $\xi_{\mathrm{n}}=P_{\mathrm{n}}/P_{\mathrm{fus}}$, and relative bremsstrahlung losses $\xi_{\mathrm{br}}=P_{\mathrm{br}}/P_{\mathrm{fus}}$. Results of calculation of the main parameters of different fusion cycles are presented in Table 1. The first two elements in the cycle designations indicate the main reaction, then, the main reaction products used as the secondary fuel within the catalysed cycles are shown. For example, D-D means that the reactions (1), (2) only are taken into account; D-D-T, the reactions (1)-(3); D-D-^{3}He-T, the reactions (1)-(4) etc.

The analysis of the power efficiency of fuel cycles for the magnetic fusion reactor is based on the local power balance equation

$$P_{\mathrm{fus}} + P_{\mathrm{ext}} = P_{\mathrm{n}} + P_{\mathrm{br}} + P_{\mathrm{s}} + \frac{3}{2}\frac{\sum n_i kT_i + n_e kT_e}{\tau_E} + P_a \qquad (10)$$

averaged over the plasma volume. In Eq. (10), P_{s} is the synchrotron loss power (calculated from the Trubnikov formula [4]), P_a is the loss power of fusion products.

Note that advanced fusion cycles in magnetic reactor require high value of $\beta = 2\mu_0 p / B_0^2$ (μ_0 is diamagnetic constant, p is the plasma pressure, B_0 is external confining field) to achieve high power efficiency.

Proton reactions p-^{6}Li, p-^{9}Be, and p-^{11}B, where neutrons are not born, at all, are of a definite interest. Results of the calculation of the most promising proton cycle p-^{11}B are presented in Table 2 for the following ideal conditions: zero densities of ashes (fusion products), $P_{\mathrm{s}}=0$, $P_a=0$, all fusion power and external heating power transferred to ions. For this analysis we use recently obtained p-^{11}B reactivity parameter values [5]. Power flow from ions to electrons calculated using Spitzer's formula, that allows calculate T_e for given T_i. In Table 2, B_0 corresponds to fusion power value $P_{\mathrm{fus}}=5$ MW/m^3 at $\beta=1$. According our calculations maximal Q value for p-^{11}B cycle is $Q_{\mathrm{max}}\approx3.7$ at $n_{11\mathrm{B}}/n_{\mathrm{p}}=0.1$. Under the same ideal conditions in p-^{6}Li and p-^{9}Be cycles $Q_{\mathrm{max}}\approx0.33$ (at $n_{\mathrm{p}}/n_{6\mathrm{Li}}$, $T_i=500$ keV, $T_e=225$ keV) and $Q_{\mathrm{max}}\approx0.23$ (at $n_{\mathrm{p}}/n_{9\mathrm{Be}}$, $T_i=200$ keV, $T_e=130$ keV), respectively. For these cycles $B_0\approx14$ T for $P_{\mathrm{fus}}=5$ MW/m^3 and $\beta=1$.

The highest energy efficiency over all considered advanced cycles can be obtained in D-^{3}He and catalysed

D-D cycles.

Table 1. Main parameters of different cycles at $T_e=T_i=T$: D-T ($n_D=n_T$), D-^{3}He ($n_D=n_{3He}$), D-^{6}Li-… ($n_{6Li}/n_D=0.3$), D-^{7}Be-… ($n_{7Be}/n_D=0.3$), p-^{6}Li ($n_{6Li}/n_p=0.2$), p-^{9}Be ($n_{9Be}/n_p=0.1$), p-^{11}B ($n_{11B}/n_p=0.1$).

Cycle	Reactions	T, keV	$n\tau T$, m$^{-3}\times$s$\times$keV	$\xi_n=P_n/P_{fus}$	$\xi_{br}=P_n/P_{fus}$	Q_{max} *
D-T	1	14	6.14×10^{21}	0.80	0.013	
D-^{3}He	3, 2, 1	70	1.36×10^{23}	0.01..0.06	0.3	
D-D	2	100	8.84×10^{24}**	0.38	0.65	
D-D-^{3}He-T	2, 3, 1	52	2.17×10^{23}	0.36	0.22	
D-D-T	2, 1	61	1.4×10^{24}	0.67	0.23	
D-D-^{3}He	2, 3	55	2.58×10^{23}	0.1	0.33	
D-D-^{3}He-^{3}He	2, 3	56	1.72×10^{23}	0.06	0.28	
D-^{6}Li	4, 2	170***	–	0.21	2.3	0.66
D-^{6}Li-^{3}He-^{7}Be-T	4, 2, 3, 5, 1	130	1.10×10^{24}	0.26	0.51	
D-^{6}Li-^{3}He-^{7}Be	4, 2, 3, 5	140	3.01×10^{24}	0.074	0.79	
D-^{7}Be	5, 2	500***	–	0.04	1.27	3.22
D-^{7}Be-^{3}He-T	5, 2, 3, 1	375	2.53×10^{25}	0.18	0.79	
D-^{7}Be-^{3}He	5, 2, 3	375	1.03×10^{25}**	0.04	0.97	
p-^{6}Li	6	210***	–	0	15.6	0.07
p-^{9}Be	7	155***	–	0	8.28	0.14
p-^{11}B	8	200***	–	0	3.56	0.39

* For anburning fuels ($Q<10$)

** Corresponds to $Q=10$. (No ignition at $T_e=T_i$)

*** Corresponds to Q_{max} at $T_e=T_i$.

Table 2. Main parameters of p-^{11}B cycle under ideal conditions. $n_{11B}/n_p=0.1$, $P_{fus}=5$ MW/m^3, $\beta=1$.

T_i, keV	100	200	250	275	300	350	400	500
T_e, keV	78	127	147	155	164	178	192	216
n_p, 10^{20} m^{-3}	7.17	3.79	3.46	3.25	3.21	3.16	3.12	3.10
n_e, 10^{20} m^{-3}	10.8	5.69	5.19	4.88	4.81	4.74	4.68	4.65
B_0, T	8.09	7.91	8.31	8.37	8.62	9.11	9.56	10.43
ξ_{br}	3.29	1.41	1.36	1.27	1.31	1.40	1.48	1.68
Q	0.44	2.44	2.77	3.71	3.22	2.53	2.08	1.47

An attractive feature of D-^{3}He fusion fuel cycle is the possibility of creating low neutron yield fusion reactor with a first wall lifetime 30-40 years, which is due to a low neutron flux to the wall. A serious problem encountered in realisation of the equicomponent D-^{3}He fuel fusion cycle is related to the fact that no commercially significant source of ^{3}He isotope is available on the Earth. One of the possible solutions is the delivery of ^{3}He from the Moon [6].

To solve the problem of ^{3}He supply low-radioactivity cycles with ^{3}He production can be realised [7, 8]. The light helium to deuterium ratio about 0.1–0.3 can be obtained in the cycles with complete ^{3}He self-supply. In Refs. [7, 8] conditions corresponding the low level of a relative neutron power (5% of a total fusion power) where obtained.

3. D-^{3}He CYCLES WITH ^{3}He SELF-SUPPLY IN MAGNETIC REACTORS

In cycles with ^{3}He self supply light helium obtained any way is stored and than, together with deuterium, is injected into the plasma, where the neutronless reaction (3) is used for energy production.

We have considered the following ^{3}He sources:

a) the light helium produced in the reaction (1a) and, than, released from the gaseous mixture evacuated by vacuum system;

b) the tritium produced in the reaction (1b), which is also released from the gaseous mixture and, than, retained for converting into ^{3}He, as a result of the decay: $T\rightarrow{}^{3}He+e^{-}+0.018$ MeV;

c) the decay of the tritium produced in the blanket as a result of the reaction of the type: $n+{}^{6}Li\rightarrow T+{}^{4}He+4.8$ MeV, and $n+{}^{7}Li\rightarrow T+{}^{4}He+n-2.47$ MeV.

Thus the ^{3}He production is possible due to reaction (1a) and (1b) in the plasma and neutron-lithium reactions in the blanket.

To increase obtainable ^{3}He value in the cycle so-called selective drift pumping [9, 10] of the fusion products due to induced weak magnetic field oscillations can be applied.

In cycles with the selective removal of fusion products, all charged fusion products, ^{3}He and T included, are moderated in the plasma releasing their energy to it, than, attaining the energy ε*, their forced removal from the plasma is expected.

Table 3. Parameters of D-^{3}He reactors with ^{3}He self-supply.

Parameters	D-^{3}He reactors with ^{3}He self-supply			
	Tandem mirror	FRC	Spherical tokamak	Classical tokamak
Plasma temperature T, keV	65	70	40..50	40..50
Vacuum magnetic field B_0, T	5..17	8	5	11
Plasma beta β	0.7	0.5..1	0.4..0.6	0.09..0.15
Synchrotron wall reflectivity Γ_s	0.65	–	0.65	0.92
Required confinement time $\tau_\perp$, s	14	2	5	14
Plasma radius a, m	1	2	2	2
Plasma length L, m	40..60	5	–	–
Big toroidal radius R, m	–	–	3	6
Plasma elongation κ	–	2.5	3.7	2.5
Plasma current I_p, MA	–	–	87	38
Total fusion power P_{fus}, MW	650..900	950	1500	2500
Power gain factor Q	10	20	20	20
Relative bremsstrahlung losses ξ_{br}	0.25	0.21..0.25	0.4	0.4
Relative synchrotron losses ξ_s	0.1	~0	0.06	0.33
Neutron yield ξ_n:				
with selective pumping system	0.05	0.04..0.06	–	0.12
with no pumping	0.15	0.12..0.21	0.13	–
First wall neutron flux q_n, MW/m^2:				
with pumping	~0.13	~0.5	–	0.14
with no pumping	~0.4	~1.5	~0.4	–

Selective drift pumping can be used for the forced selective removal of the charged products moderated to the energy ε*~200-400 keV. Such a process does not affect the fuel confinement time. The removed ^{3}He and T are stored and the obtained ^{3}He is used as one of the D-^{3}He fuel component. A given cycle has some important advantages. First, the major part of tritium has no time for the interaction with deuterium in the reaction (2) that allows one to obtain a great amount of ^{3}He than that in the first variant. Second, since the reaction (2) is negligible, the neutron flux to the first wall is essentially reduced in comparison with cases with no selective removal. Here, it is important that the reduction occurs due to the most dangerous high energy neutrons with the birth energy ε_0=14.1 MeV.

In this work we consider the possibility of high efficiency operating of D-^{3}He reactors based on different magnetic systems: tandem mirror, field reversed configuration (FRC), classical and spherical tokamaks. Parameters of magnetic reactors using D-^{3}He cycles with ^{3}He self-supply are presented in Table 3. Parameters of a tandem mirror system we calculate according the model developed in Refs. [2, 3]. For the FRC power balance model [11] is used, and for classical and spherical tokamaks calculation model of Ref. [12] is used.

4. CONCLUSIONS

In the framework of presented study the most optimal low-radioactivity fusion cycle appears to be D-^{3}He cycle. Problem of ^{3}He supply for D-^{3}He reactors can be solved by the use of D-^{3}He cycles with ^{3}He self-supply.

According to carried out calculations highest power efficiency of magnetic fusion reactors with D-^{3}He cycles corresponds the high-beta confinement systems such as FRC and spherical tokamak.

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