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Parameters of D-T, Catalyzed D-D, and D-^{3}He Tandem Mirror Reactors in Burning Operating

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Abstract

The power balance analysis of D-T, D-^{3}He, and catalyzed D-D fusion fuel cycles in a steady state tandem mirror reactor is carried out. For these cycles possibilities of burning in the tandem mirror reactor with the central cell plasma amplification factor $Q_{pl}>10$ are shown. Parameters of plasma and confinement system are calculated. It is shown that in the tandem mirror reactor it is possible to realize low radioactive fusion cycle on the base of D-^{3}He reaction with production of part or full required value of ^{3}He in D-D reaction.

Keywords:

fusion reactor, deuterium based cycles, tandem mirror, kinetics, power balance

1. Introduction

The problem of searching for new energy sources that will provide the global needs of mankind is becoming acute because of the exhaustion of mineral fuel reserves. The main requirements on such sources are the presence of large fuel resources in nature, ecological cleanliness, and high energy efficiency. One of these promising sources is future fusion reactors. In connection with the results obtained on GAMMA 10 device [1] it is actual to consider the prospects of using the tandem mirror as a base for future concepts of steady state fusion reactor using different fuel cycles.

We analyze D-T, catalyzed D-D and D-^{3}He fusion fuel cycles using previously developed classical kinetic/power balance model for fusion plasma [2-4]. The base of this model is following. Given value of fuel temperature is provided by external heating and fusion products heating. Main losses are following: axial losses with particles leaving plasma due to diffusion into loss region in velocity phase space; radial losses across magnetic field because of radial diffusion induced by microinstabilities; bremsstrahlung and synchrotron radiation. Fusion products parameters (density, pressure, power losses) are calculated on the base of numerical solution of the Fokker-Planck equations. Important general criteria of efficiency of fusion cycles are

$$Q_{pl} = \frac{P_{fus}}{P_{req}} > 10, \tag{1}$$

$$P_{fus} > 2MW/m^3, \tag{2}$$

where Q_{pl} is the plasma amplification factor, P_{fus} is the fusion power, P_{req} is required power of external heating. To satisfy requirement (2) and to suppress synchrotron losses in magnetic reactor high values of β are needed for D-^{3}He and D-D cycles. Among high-beta systems tandem (ambipolar) mirror trap is the most detailed investigated now. Consequently, namely tandem mirror confinement system is considered in this work for analysis and comparisons of different fusion fuel cycles.

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For optimal conditions of the burning with $Q_{pl}>10$ and $P_{fus}>2$ MW/m^3 we estimate the ranges of following main parameters of the plasma and the confining system: plasma temperature T (electron temperature and fuel ions temperature are assumed to be equal $T_e = T_{fuel} = T$); densities of plasma species n_a; ion confining potential φ_i; electron confining potential φ_e; magnetic field of central cell coil B_0; total plasma beta β, taking into account fusion products pressure; neutron power P_n to fusion power P_{fus} ratio ξ_n.

2. Ideal Ignition and Possible Deuterium Based Cycles

Let's consider burning of D-T, D-^{3}He, pure D-D, and catalyzed D-D cycles. In catalyzed cycles lost fusion products of two branches of D-D reaction (T and ^{3}He) are used as a secondary fuel together with a deuterium. Probability of reactions between products and deuterium nuclei during a products slowing down is insignificant due to very short slowing down time. Consequently, to calculate fusion power due to the burning of products in catalyzed D-D cycles secondary fuel can be supposed to be thermalized. Secondary fuel density in the steady state reactor is defined by equality of production and burning reactivity parameters for the products.

Following catalyzed D-D cycles are possible. Full catalyzed cycle, called below as D-D-^{3}He-T, utilizes both secondary tritium and secondary helium-3. In cycle D-D-^{3}He only ^{3}He is burned to obtain higher neutron purity. In this case it is reasonably to store secondary tritium for helium-3 production due to decay process. Cycle D-D-T uses only tritium as secondary fuel.

Under ideal conditions, one can characterize the burning with the given value of the plasma amplification factor Q_{pl} by criterion

$$\Lambda \equiv n_\Sigma \tau_E T = \frac{\frac{3}{2} k n_\Sigma^2 T^2}{P_{fus}\left(1 + Q_{pl}^{-1} - \xi_v\right) - P_{br}}, \qquad (3)$$

where k is the Boltzmann constant, τ_E is an energy confinement time, n_Σ is a total density of fuel ions and electrons, P_{br} is a power of bremsstrahlung, $\xi_n=P_n/P_{fus}$ is the neutron power ratio. Electron temperature is assumed to be equal to fuel temperature $T_e = T_{fuel} = T$. To calculate P_{fus} fusion reactions cross sections are taken from database [6].

In working temperature range of D-^{3}He and D-D cycles T = 60..80 keV characteristic kinetic energy of electrons kTe is not small in comparison with the rest

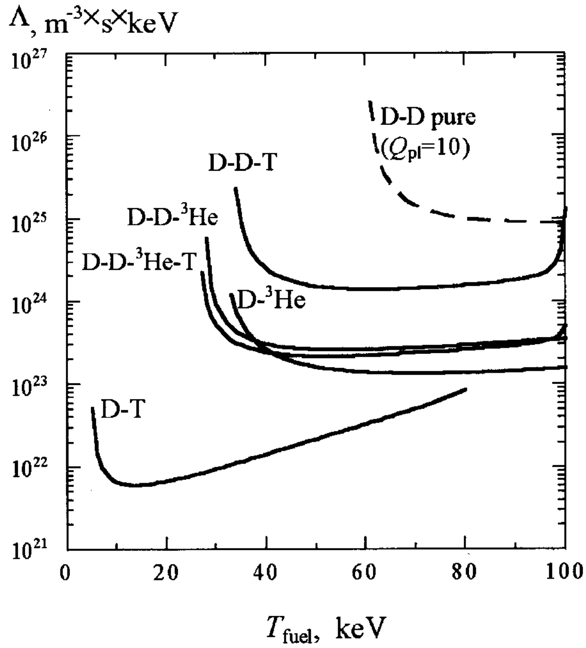

Fig. 1 Ignition criteria for D-T, D-^{3}He, and catalyzed D-D cycles (solid lines); criterion for burning with Q_{pl} = 10 for pure D-D fuel (dashed line). For D-T cycle $n_D = n_T$, for D-^{3}He — $n_D = n_{3He}$.

electron energy $m_e c^2$ = 511 keV, and it is necessary to consider both electron-ion P_{br}^{e-i} and electron-electron P_{br}^{e-e} bremsstrahlung losses using relativistic electron distribution function and formulas of quantum electrodynamics for bremsstrahlung cross sections. Results of numerical calculations of bremsstrahlung can be approximated with error less then 2 % by following fits [4,5]

$$P_{br}^{e-i} = \frac{32}{3}\sqrt{\frac{2}{\pi}}\,\alpha r_e^2 m c^3 Z_{eff}^2 n_e^2 \sqrt{\tau} \times \left\{\frac{9}{8}\sqrt{\frac{\pi}{2}}\sqrt{\tau}\left[\ln\left(2\tau + \frac{1}{2}\right) + \frac{3}{2} - C\right] + \exp\left(-2\tau\right)\right\}, \qquad (4)$$

$$P_{br}^{e-e} = \frac{4C_F}{\sqrt{\pi}}\alpha r_e^2 m c^3 n_e^2 \tau^{3/2} \times \left(1 + 1.17\tau + 0{,}28\tau^2 - 0.6\tau^3\right), \tau < 1, \qquad (5)$$

$$P_{br}^{e-e} = 24\alpha r_e^2 m c^3 n_e^2 \tau\left[\ln(2\tau) + \frac{5}{4} - C\right], \tau \ge 1, \qquad (6)$$

where α is the fine structure constant, r_e is the classical radius of the electron, C = 0.5772... is the Euler constant, $C_F = (5/9)(44-3\pi^2) \approx 8$,

$$\tau = \frac{kT_e}{mc^2}, \quad Z_{\text{eff}}^2 = \sum_i \frac{Z_i^2 n_i}{n_e}$$

In Fig. 1 dependencies of criterion L on plasma temperature for ignition regime ($Q_{\text{pl}}^{-1} = 0$) are plotted for different cycles. Accordance to the calculation, ignition of pure D-D cycle is impossible under considered conditions. For this fuel the criterion corresponding to $Q_{\text{pl}} = 10$ is plotted. Requirements of cycle D-D-T are essentially harder in comparison with other catalyzed cycles. Consequently, we will not consider this cycle as pure D-D cycle.

Following cycles are analyzed below on the base of classical kinetic model: cycle D-T with $n_D = n_T$, numbered as No 1; D-^{3}He with $n_D = n_{3He}$ (No 2), and with $n_D = 5n_{3He}$ (No 3); D-D-^{3}He-T (No 4); and D-D-^{3}He (No 5).

3. Power Balance and Kinetic Analysis of the Tandem Mirror Fusion Plasma

Simple geometry of the mirror trap, steady state operating and possibility of using direct energy conversion systems are attractive from viewpoint of creating tandem mirror based fusion reactor. Anomalous radial transport can be suppressed [7], and problem of MHD-stabilization of high-beta plasma has principle solution [8]. As experiments [9,10] on GAMMA-10 tandem mirror have showed, axial confinement agrees with Pastukhov model [11]. Measurements of spectra of microinstabilities in the central cell of GAMMA-10 [12,13] have sowed that radial transport is induced by low-frequency drift oscillations, and possibility of control of radial confinement time by externally applied radial electrostatic field was shown [7].

According to the classical kinetic-balance model of multicomponent plasma, analysis of efficiency of fusion fuel cycles is based on specific power balance equation

$$P_{\text{fus}} + P_{\text{req}} = P_{\parallel} + P_{\text{R}} + P_{\text{n}} + P_0 + P_{\text{L}} + P_{\text{rad}}, \qquad (7)$$

where $P_{\parallel}$ and P_{R} are axial and radial power losses of fuel ions and electrons, P_{n} is the neutron power (neutrons instantly leave plasma), P_0 and P_{L} are power losses of charged fusion products correspondingly due to appearing in loss region and scattering (both Coulomb and nuclear) during slowing down and diffusion into loss region, P_{rad} is the radiation losses power (bremsstrahlung P_{br} and synchrotron radiation P_{s}). Axial losses are calculated according Pastukhov model [11]. Synchrotron losses are calculated by Trubnikov formula [14]. Power of radial losses is

$$P_{\text{R}} = \sum_{a=\text{fuel,e}} \frac{\frac{3}{2} n_a k T_a}{\tau_{\text{R}}}. \qquad (8)$$

Power losses P_0 and P_{L} are calculated as energy fluxes into loss region in velocity phase space using distribution functions of the charged products. The appropriate Fokker-Planck kinetic equations [4,5] are solved to calculate the kinetics of fusion products, as their distribution functions are substantially different from Maxwellian. Distribution functions of the fuel ions and the electrons can be with good accuracy supposed to be Maxwellian, and balance equations based on the corresponding Spitzer and Pastukhov formulas can be used for the fuel ions and the electrons. The kinetic equations we solve using the assumption that plasma in the central cell of the tandem mirror is homogeneous. A feature of the model under consideration is that for fusion products with energy more than 1 MeV it allows for nuclear elastic scattering by including corresponding terms into the Fokker-Planck collision operator. Taking into account nuclear elastic scattering is connected with the fact that cross sections of Coulomb and nuclear elastic scattering are comparable at the energy of about 5 MeV, and nuclear elastic scattering cross section becomes greater at larger energy [15], and nuclear elastic scattering affects the sharing of fast fusion particles energy between fuel ions and electrons.

4. Results and Conclusions

To compare different fuels in calculation for all cycles common values of following parameters are taken: $P_{\text{fus}} = 4$ MW/m^3; $\tau_{\text{R}} = 20$ s; the plasma radius is rp = 1 m; the coefficient of reflection of synchrotron radiation is $\rho_s = 0.65$; mirror ratios are $R_p = B_m/B_c = 5$, and $R_1 = B_m / B_1 = 2$, where B_c is magnetic field in the central cell plasma, B_m is magnetic field in the plugs, B_1 is magnetic field in the medium sections of the plasma of the plugging cells. Total beta of plasma β, taking into account fusion products pressure, the fuel ions temperature T_{fuel}, and the ion confining potential φ_i were varying in calculations. The electron confining potential is calculated according to the Pastukhov model [11] using system of balance equations for the number of particles and the charge density. Densities of plasma species, central cell vacuum magnetic field B_0, and central cell plasma amplification factor Q_{pl} were defined from calculations.

Calculations showed high efficiency of D-T cycle can be achieved if $\tau_{\text{R}} \sim 1$ s unlike other cycles require

Table 1. Parameters of D-T, D-3He, and catalyzed D-D cycles in the central cell of tandem mirror reactor. P_{fus} = 4 MW/m^3, R_p = 5, r_p = 1 m, r_s = 0.65, t_R = 20 s.

Cycle No	1	2	3	4	5
Fuel	D-T	D-^{3}He	D-^{3}He	D-D-^{3}He-T	D-D-^{3}He
n_D, 10^{20} m^{-3}	0.73	1.2	2.2	2.6	3.2
T_{fuel}, keV	15	65	80	75	75
φ_i, keV	48.8	228	320	375	400
β	0.1	0.6	0.85	0.85	0.9
B_0, T	4.4	5.7	5.4	4.9	5.3
P_n/P_{fus}	0.8	0.02	0.05	0.35	0.1
P_{rad}/P_{fus}	0.02	0.44	0.32	0.23	0.34
P_{ch}/P_{fus}	0.23	0.59	0.68	0.48	0.66
Q_{pl}	20	20	20	16	11

τ_R~10..20 s, that is the main reason for assuming low level of radial transport (τ_R = 20 s). On the other hand, one can suppose the method of radial losses suppression, developed in experiments [7,12,13], can be used to achieve required radial transport level.

Results of calculations are presented in Table 1. There value of T_{fuel} corresponds to maximum of Q_{pl} at given values of other parameters. At T_{fuel} = 75 keV in catalyzed cycles No 4 and No 5 $n_D : n_{3He}$ = 1 : 0.084, and in D-D-^{3}He-T cycle $n_D : n_T$ = 1 : 0.013. In Table 1 P_{ch} is total power losses with charged particles.

From the presented results one can see that D-^{3}He and catalyzed D-D cycles have hard requirements to the parameters of the plasma and the tandem mirror confinement system in comparison with D-T cycle, but they have lower neutron output. The lowest neutron ratio of D-^{3}He cycles No 2 and No 3 is very attractive for future prospects of low radioactive fusion reactor. Besides, in cycle No 3 problem of supplying by ^{3}He is partially solved because of about 40 % of ^{3}He fuel is produced in D-D reaction. Catalyzed cycle D-D-^{3}He use only deuterium as a primarily fuel, and this cycle in principle can be realized in tandem mirror based reactor, but requirements to confinement system are too hard: β = 0.9, φ_i = 400 keV, very low radial transport level (τ_R ~ 20 s). Consequently, detailed investigation of possible limit parameters of tandem mirror system is needed for prospects of this cycle. Another direction is searching and analysis of other high-beta confinement systems such as for example field reversed configuration.

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