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Low radioactive and hybrid fusion – A path to clean energy

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ABSTRACT

Aneutronic/low radioactive fuel is the way to clean and cheap energy of the future. An alternative scheme using compact toroids – field-reversed configuration or spheromak – may be applied for the reactor based on any magnetic confinement system. Even more, any fusion concept, including hybrid magneto-inertial fusion might use advantages of D–^{3}He fuel. Advanced fuel, including helium-3 – based fusion plasma and alternative systems are reviewed. Different schemes of reactors, near-term technology and non-electric applications are discussed.

1. Introduction

Prospective high energy density systems such as different sources of neutrons and protons will be used in the near future to perform cutting-edge materials research, non-destructive analysis, medical isotope production, chemical waste disposal, personnel training, etc. (Ryzhkov, 2008; Santarius, Kulcinski, El-Guebaly, & Khater, 1998). The goal of the investigation is complex numerical research and optimization of the pulsed high-temperature processes in a dense magnetized plasma (target), e.g. compact torus. An embedded magnetic field is compressed along with the target plasma to achieve magnetic insulation.

This research is aimed at the evaluation of open magnetic systems attractiveness both magnetic confinement fusion and magneto-inertial fusion. A nuclear fusion power plant might, therefore, possess sufficient commercial attractiveness to break into the energy. This advanced direction for world energy production would be capable of replacing depleted resources of fossil fuels.

Today quasi-stationary systems are investigated in more detail, so we propose to consider both quasi-stationary and pulsed installations. Advantages of such power systems are compactness, low losses and the fact that instabilities have little time to develop. Hydrodynamic instabilities are determined by the heterogeneity of flows. Plasma-wall interaction is a less critical problem than in tokamaks. Impurities could be a problem, but probably not as big as in systems with metal and fluid liners. In comparison with inertial fusion methods pulse duration and confinement are greater. Other advantages of such systems and configurations are high frequency of fuel feed, quasi-stationary operation (which is provided with lasers or additional heating systems), and high burnup level which reduces the necessary amount of fuel and increases the amount of energy released.

2. Magneto-inertial fusion

This research is aimed at the evaluation of hybrid fusion attractiveness, namely magneto-inertial fusion (Chirkov & Ryzhkov, 2012; Kostyukov & Ryzhkov, 2011). Evolution of traditional inertial and magnetic confinement fusion is the concept with high density plasma in strong magnetic fields. Magneto-inertial approach to a fusion combines the advantages of magnetic and inertial confinement and provides low-cost simple fusion schemes. Interest in magneto-inertial fusion research has recently been stimulated by (a) laser-driven magnetic flux compression experiments, (b) approximation to a high β (beta is the ratio of plasma pressure to external magnetic pressure) magnetic systems, and (c) advantages of plasma guns and liners. Schematic of spherical implosion of the magnetized target during its uniform compression with plasma jets and laser beams is shown in Fig. 1.

A Magnetic System (MS), such as gas-dynamic trap (Ryzhkov & Anikeev, 2010), field-reversed configuration (Ryzhkov, 2011), mirror-based source (Chirkov, Ryzhkov, Bagryansky, & Anikeev, 2011) is one of the most promising magnetic confinement systems, and it might be also used for magneto-inertial fusion. In contrast to tokamaks, the presented systems have no toroidal magnetic field. This allows the attainment of high beta (plasma pressure/magnetic field pressure) values, and, consequently, higher fusion specific power. The latter parameter in tokamaks will be 3 times less than in fission reactors, while another MS may exceed this limit. Moreover, the MS has linear cylindrical geometry with a natural divertor, thus providing intrinsic engineering advantages. It appears feasible

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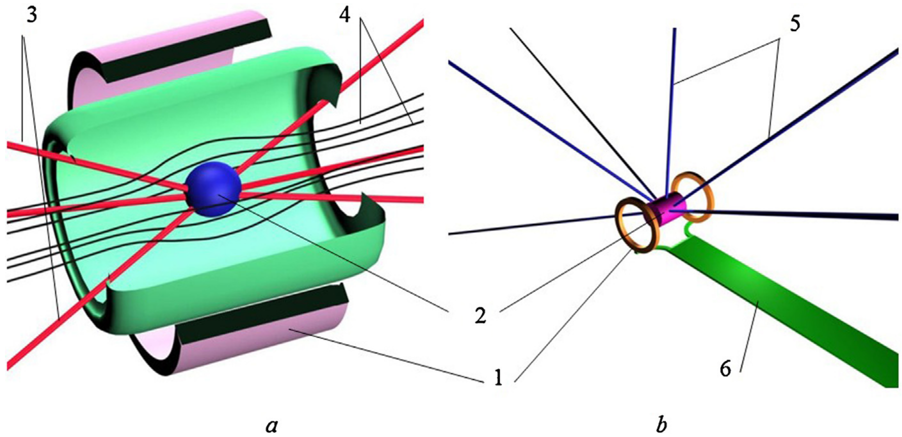

Fig. 1. Options for magnetized target implosion – compression by powerful plasma (*a*) and laser pulses (*b*): 1 – magnetic coils, 2 – plasma target, 3 – plasma jets, 4 – magnetic field lines, 5 – laser beams, 6 – system of current supply.

to build a relatively compact Demonstration Fusion Reactor on the basis of an MS.

3. D–^{3}He fuel

High-power density magnetic fusion systems are attractive for advanced fuel cycles, such as D–^{3}He, p-^{11}B, p-^{6}Li, and for both magnetic confinement fusion and magneto-inertial fusion to get clean (low radioactivity) energy, i.e. fusion scheme. Lower neutron wall load, higher power density, and absence of a tritium-breeding blanket make the engineering development of an alternate concept fusion reactor burning an advanced fuel easier compared to D–T fusion power plants. The open field lines in the edge region of many alternate configurations also allow the possibility of using direct conversion of charged-particle fusion power to electricity at high efficiency. A D–^{3}He power plant might, therefore, possess sufficient commercial attractiveness to break into the energy marketplace. This advanced direction for world energy production would be capable of replacing depleted resources of fossil fuels. Even now, when the fusion reactor ITER is under construction, the search for simpler devices with easier construction and engineering characteristics, assuming more effective work cycles and higher efficiency of the thermal power conversion to electric energy continues. Much of the research, however, with modifications to the magnetic-field configuration, could also be used for the traditional fusion concepts.

The FRC plasma is a compact toroid confined by an exclusively poloidal magnetic field, and the open field line geometry facilitates direct energy conversion of the charged-particle flow. High beta (ratio of plasma pressure to magnetic field pressure) makes the FRC a prime candidate for magnetic and magneto-inertial fusion, and its applications because of: (a) higher power density than other magnetic fusion concepts (order of magnitude at the same temperature); (b) a compact device due to high β; (c) lower capital cost; (d) only such systems may be used to design low-neutron thermonuclear fusion power plants, based on a D–^{3}He or p-^{11}B mixture instead of D–T fuel, that leads to neutron wall load decreasing; (e) excellent vacuum pumping of impurities by the edge plasma, which both carries away fusion ash to the plasma core boundary. Self-organized configurations together with advanced fuels satisfy: (a) production of tritium only from low reactivity D–D reactions, (b) minimal tritium inventory or no tritium, (c) a small fraction (1–5%) of the fusion power produced as neutrons, (d) low activation, and (e) high overall energy conversion efficiency (Table 1).

Energy balance calculation methods were used to analyze D–^{3}He magnetic reactors (Chirkov, 2013; Khvesyuk & Chirkov, 2002; Khvesyuk, Ryzhkov, & Santarius, 2001). Basic reactor parameters are given in Table 2. D–^{3}He cycles with different helium-3/deuterium ratio $x_{3\mathrm{He}} = n_{3\mathrm{He}}/n_\mathrm{D}$ are considered. For example, $x_{3\mathrm{He}} \approx 0.3$ corresponds to the maximum capability of use of helium-3 in the reactor. In the case of $n_{3\mathrm{He}} = n_\mathrm{D}$ typical value of the neutron flux on the first wall is $q_n \approx 0.15$ MW/m^2.

D–^{3}He conceptual power plant designs – Apollo (Kulcinski, Emmert, & Blanchard, 1992), ARIES-III tokamak (Bathke et al., 1997) and Artemis (Momota, Ishida, & Kohzaki, 1992), CT RV FRC (Ryzhkov, 2007) are summarized in Table 2. The main advantages of a D–^{3}He fusion reactor in comparison with a D–T power plant

Table 1
Parameters of D–^{3}He reactor based on different magnetic systems.

Parameter	Tokamak	Spherical tokamak	Stellarator	FRC
Plasma radius a, m	2	3	2	1.25
Plasma length L, m	–	–	–	30.75
Aspect ratio	3	1.5	20	1
Plasma elongation E	2.5	3.8	1	12.3
External magnetic field B_0, T	11.3	3.2	8.2	6.4
Plasma current I, MA	38	200	–	299
Average beta β	0.09	0.54	0.1	0.75
Fuel $x_{3\mathrm{He}} = n_{3\mathrm{He}}/n_\mathrm{D}$	0.2	0.36	1	1
Plasma temperature T, keV	50	60	70	72
Wall reflectivity Γ_s	0.92	0.65	0.95	0.99
Confinement time τ, s	14	16	30	1.46
Fusion power P_{fus}, MW	2500	1500	1500	1937
Bremsstrahlung P_{br}/P_{fus}	0.40	0.60	0.15	0.38
Synchrotron power P_s/P_{fus}	0.33	0.023	0.25	0.005
Neutron power P_n/P_{fus}	0.12	0.15	0.02	0.025
Fusion energy gain $Q = P_{fus}/P_{ext}$	20	20	∞	40

Table 2
Comparison of the main parameters of D–^{3}He tokamak and FRC power plants (conceptual design).

Parameter	Apollo	ARIES-III	Artemis	CT RV
Net electric power, MW	1000	1000	1000	1000
Fusion power, MW	2144	2682	1610	1962
Bremsstrahlung, MW	652	Radiation fraction 0.72	Radiation 357	776
Synchrotron radiation power, MW	1027			8.7
Transport power, MW	456		1181	1188
Neutron power, MW	147	110	77	51.7
Injected power, MW	(138)	(172)	5	62.6
Net efficiency	0.43	Recirculation 0.24	0.36–0.62	0.49
Neutron wall load peak, MW/m^2	Ave. 0.1	Average 0.08	0.27	0.15
Fuel ^{3}He/D	0.63	~1	0.5	1
Big radius (Separatrix length), m	7.89	7.5	(17)	(30.75)
Small radius (Separatrix radius), m	2.5	2.5	(1.12)	(1.23)
Ion temperature, keV	57	55	87.5	68.5
Electron temperature, keV	51	53	87.5	68.5
Electron density, m^{-3}	1.9×10^{20}	3.3×10^{20}	6.6×10^{20}	5.4×10^{20}
Ion density, m^{-3}	1.3×10^{20}	2.1×10^{20}		3.46×10^{20}
Plasma current, MA	53	30	160	298.8
External B-field, T	10.9 (19.3)	7.6	(6.7)	(6.38)
Average beta, %	6.7	Toroidal 24	90	74.8
Energy confinement time, s	16	11.8, $\tau_p^{ash}/\tau_E = 2$	2.1, $\tau_p/\tau_E = 2$	1.44

are low radioactivity, low cost and short-lived radioactive inventory. The neutron wall load and temperature in Reference Variant (RV) are minimal compared with other reactors.

4. Conclusion

Alternative energy development is the way to clean and inexpensive energy, and alternative applications of advanced fusion cycles at high temperature in low radioactivity plasmas may lead to alternative technologies in energy and also to medical radioisotope production, neutron/proton sources, fusion jets, space propulsion, etc. (Ryzhkov, 2005). This paper reports on a comparative analysis of the magnetic fusion energy systems based on aneutronic D–^{3}He fuel. The power balance for a reactor is described for plasma confinement inside closed field lines (region called separatrix). The conceptual designs use a D–^{3}He fuel cycle and require advances in technology and physics for economical attractiveness. Results from the systems analyses are summarized, and a comparison with the D–T-fueled tokamaks is included. The applications of plasma and engineering physics to the D–^{3}He fuel cycle, however, are expected to produce a design that is competitive with fissile and fossil power plants. This advanced direction of world energy production development may be capable of replacing the rapidly depleting resources of fossil fuels more economically and safely.

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References

Bathke, C. G., & the ARIES team. (1997). Systems analysis in support of the selection of the ARIES-RS design point. *Fusion Engineering and Design*, *38*, 59–74.
Chirkov, A. Yu. (2013). Low radioactivity fusion reactor based on the spherical tokamak with a strong magnetic field. *Journal of Fusion Energy*, *32*, 208–214.
Chirkov, A. Yu., & Ryzhkov, S. V. (2012). The plasma jet/laser driven compression of compact plasmoids to fusion conditions. *Journal of Fusion Energy*, *31*(1), 7–12.
Chirkov, A. Yu., Ryzhkov, S. V., Bagryansky, P. A., & Anikeev, A. V. (2011). Plasma kinetics models for fusion systems based on the axially-symmetric mirror devices. *Fusion Science and Technology*, *59*(1T), 39–42.
ITER, http://www.iter.org/
Khvesyuk, V. I., & Chirkov, A. Yu. (2002). Low-radioactivity D–He-3 fusion fuel cycles with He-3 production. *Plasma Physics and Controlled Fusion*, *44*, 253–260.
Khvesyuk, V. I., Ryzhkov, S. V., Santarius, J. F., Emmert, G. A., Nguyen, C. N., & Steinhauer, L. C. (2001). D–^{3}He field reversed configuration fusion power plant. *Fusion Technology*, *39*(1T), 410–413.
Kostyukov, I. Yu., & Ryzhkov, S. V. (2011). Magneto-inertial fusion with laser compression of a magnetized spherical target. *Plasma Physics Reports*, *37*, 1092–1098.
Kulcinski, G. L., Emmert, G. A., Blanchard, J. P., Emmert, G. A., Khater, H. Y., Maynard, C. W., et al. (1992). Summary of APOLLO, a D–^{3}He tokamak reactor design. *Fusion Technology*, *21*, 2292–2315.
Momota, H., Ishida, A., Kohzaki, Y., Miley, G., Ohi, S., Ohnishi, M., et al. (1992). Conceptual design of D–^{3}He FRC reactor ARTEMIS. *Fusion Technology*, *21*, 2307–2323.
Ryzhkov, S. V. (2005). Compact toroid and advanced fuel – together to the Moon? *Fusion Science and Technology*, *47*(1T), 342–344.
Ryzhkov, S. V. (2007). Comparison of a deuterium – helium-3 FRC and mirror trap for plasma confinement. *Fusion Science and Technology*, *51*(1T), 190–192.
Ryzhkov, S. V. (2008). Modeling and engineering applications for weakly turbulent plasma. In *35th EPS Conf. on Plasma Physics and Contr. Fusion. Europhysics Conference Abstracts, ECA 32D (1)* (pp. 561–564).
Ryzhkov, S. V. (2011). A field-reversed magnetic configuration and applications of high-temperature FRC plasma. *Plasma Physics Reports*, *37*, 1075–1081.
Ryzhkov, S. V., & Anikeev, A. V. (2010). Improved regimes in high pressure magnetic discharges. In *Proc. of the 14th International Heat Transfer Conference* Washington D.C., IHTC14-22212,
Santarius, J. F., Kulcinski, G. L., El-Guebaly, L. A., & Khater, H. Y. (1998). Could advanced fusion fuels be used with today's technology? *Journal of Fusion Energy*, *17*, 33–40.