UDC 533.9

THE CONCEPT OF A RESEARCH FUSION REACTOR

V. G. Kotenko, V. I. Lapshin, G. G. Lesnyakov, S. S. Romanov, E. D. Volkov
Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", Kharkov 61108, Ukraine

In existing magnetic confinement fusion reactor designs the plasma radius r_{pl} is usually comparable with the radius r_W of the 1-st wall, $r_{pl}/r_W \leq 1$. It is well known that the realization of these designs entails a number of unsettled problems, including the 1-st wall problem. According to different kinds of estimates, the interaction of plasma-generated high-intensity energy flows with the 1-st wall leads to a limitation in the service life of the 1st wall to 2-5 years. These estimates should be considered as optimistic, because they rely on taking into account the impact of individual components of the above-mentioned flows. The replacement procedure of the 1st wall, even if it appears technically feasible under conditions of high induced radioactivity, will be extremely expensive and will involve the necessity of disposal of radioactive wastes in great amounts. At a rated 30- to 50-year normal operation of a fusion power plant, the replacement procedure should be repeated no less than 10 times, and the threat for this plant to be transformed into an unprecedented-power factory of radioactive refuse production becomes quite real. To minimize the number of these replacements is the problem, the solution of which is of crucial importance for the commercial fusion reactor. Great hopes for the required increase in the 1st wall service life are pinned on the creation of low activation materials showing a high resistance to the simultaneous and combine (i.e., with due account for the synergy effects) action of the whole totality of fusion plasma radiations . This issue has not been resolved so far by force of disproportion between the reactor conditions and the present-day conditions, taking place in every sort of simulation experiments. Its resolution very much depends on the possibility of conducting long-term materials science experiments at full-scale conditions of self-sustained fusion reactions, i. e., in a fusion reactor now in operation. So, the present-day situation looks like a vicious closed circle, and one should find a way to get out of it.

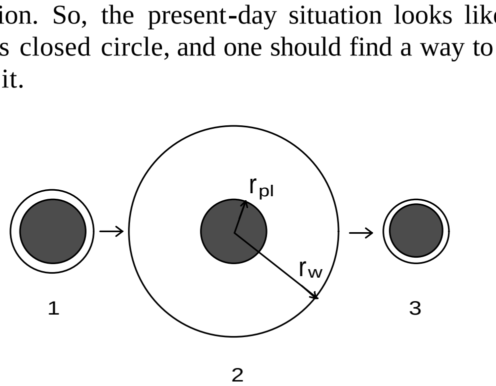

Fig.1 Fusion reactor configuration: 1 - existing designs; 2 – in proposed research fusion reactor (RFR); 3 - future commercial design.

It is evident that at a given fusion plasma radius this way may consist in an essential reduction of specific loads on the 1st wall at the expense of increasing its surface area, i. e., by realizing configuration 2 (see Fig.1), where $r_{pl}/r_W \ll 1$ [1, 2]. As a result, the course of fusion investigations may be as follows:

- at the present stage efforts should go into the design and creation of a steady-state (to prevent a swing in the 1st wall temperature) deuterium-tritium fusion reactor based on configuration 2. This is to be a reactor with all attributes of a fusion power plant operating for long and reliably, because with an appropriate choice of r_W the design loads on the 1st wall, the blanket and on the superconducting magnetic system are reduced to a value providing their long-term normal operation. However, no economic goals can be pursued with this reactor because of an essential reduction in the neutron flow density on the 1st wall. This will be a research fusion reactor (RFR) of independent importance, assigned for the widest range of issues related not only to fusion power engineering. Apart from the mentioned materials science problem, possible RFR applications may also include nuclear fuel production for fission reactors, the transmutation of long-lived radionuclides as a radical means to reduce radioactivity of fusion reactor wastes, production of useful isotopes, etc.;
- at the next stage, with gaining information about the operation of this reactor and with associated scientific-technical progress it would be possible to achieve the transition to reactors of considerably smaller sizes (configuration 3, Fig.1).

Are there any magnetic systems enabling one to realize configuration 2? Among a great many known magnetic systems of plasma traps, we note the stellarator-type magnetic systems [3], namely, classical stellarators and torsatrons. Using the available literature data for straight stellarators and torsatrons an analysis [4] was made to determine the ratio of the radius of separatrix edge r_S to the radius a of the circular cylinder, where the helical currents I flow, r_S/a (as an analogue of the r_{pl}/r_W ratio). The main results of this analysis are presented below in a graphical form.

For the polarity l=1,2,3,4 straight classical stellarators, Fig.2 presents the ratio r_S/a (and r_0/a - magnetic axis radius in l=1 stellarator) as function of the parameter $h=2peaB_0/m_0I$ [5, 6]. Here B_0 is the longitudinal magnetic field, μ_0 is the magnetic constant, I is the helical current, $e=2\pi a/L \ll 1$, L is the pitch of helical coils. At a given e, the h value can be varied within rather wide ranges by changing the B_0/I ratio; that gives an opportunity to control *in situ* the

r_s/a value throughout the experiment. For the l=1 stellarator the upper part of curve 1 specifies the position of the separatrix edge r_s/a, and the lower part gives the position of the magnetic axis r_o/a. It is seen that with a decreasing $h \rightarrow 5$ the region of closed magnetic surface existence diminishes $((r_s/a)-(r_o/a) \rightarrow 0)$. In spite of this, one fails to significantly move away the separatrix edge from the cylinder surface in the l=1 stellarator (r_s/a cannot be lower than ~0.58). In the l>1 systems, where the magnetic axis radius is r_o/a=0, the region of closed magnetic surface existence is centered, and the maximum dimension of this region is $\sim r_s/a$. In l=2

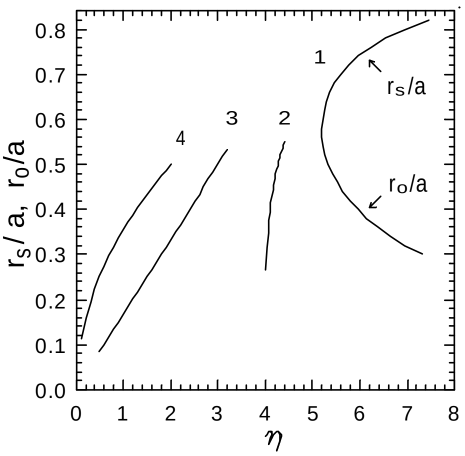

Fig.2 Separatrix edge radius r_s/a (and magnetic axis r_o/a in l=1 stellarator) as function of h in l=1,2,3,4 straight stellarators (curves 1-4, respectively).

stellarator, curve 2 in Fig.2 suggests that at r_s/a<0.5 the radius of the separatrix edge is very sensitive to variations in the parameter h, whose values are close to the critical value. So, the creation of the l=2 magnetic system with r_s/a<0.5 will demand high precision in manufachering and current control system. The l=3 stellarator (curve 3) is characterized by the lowest r_s/a values at one and the same h and a linear dependence. This peculiarity of classical stellarator is not lost in the

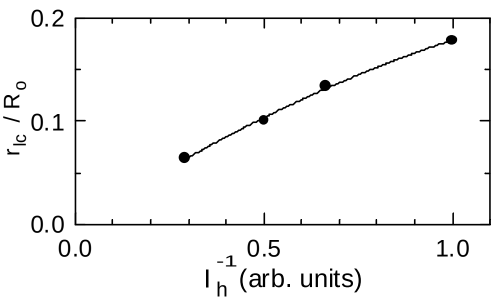

Fig.3 Dependence of the last closed magnetic surface radius r_{cl}/R_o on the helical current I value in the l=3, m=3 stellarator model with a/R_o=0.3 (l is the polarity, m is the number of helical pitches, a is the minor radius of the torus, R_o is the major radius of the torus).

transition to the toroidal case. The calculations of a modular classical-stellarator version [7] with a considerable toroidicity have demonstrated that a three-fold enhancement of current I in helical coils at a constant longitudinal magnetic field value brings about nearly the same decrease in the largest radius of the region of closed magnetic surface existence , see Fig.3.

In the classical torsatron, the longitudinal and helical magnetic-field components are generated by helical conductors, where the currents are coincident in direction. Therefore, the position of separatrix edges in these systems can be controlled only by choosing in advance rigorous design parameters ε and the number of helical windings l, invariable in the course of experiments. In the l=1 torsatron, the positions of the separatrix edge and the magnetic axis are determined by the equation [8]: $r/a \approx 0.5(1 \pm (1-4/\varepsilon^2)^{0.5})$. Curve 1 (Fig.4) shows the corresponding dependence. Similarly to the case of l=1 stellarator, r_s/a<0.5 cannot be achieved in this torsatron. However, here the separatrix edge lies in the sector free of the helical conductor. In principle, this allows one to move the material wall being within this sector away at a distance exceeding the radius a of the cylinder. In the l=2 torsatron the sought-for dependence (solid curve 2, Fig.4) has the form [10]: $r_s/a \approx (1-\varepsilon^{-2})^{1/4}$. Similarly to l=2 stellarator, the essential detachment of the separatrix edge (r_s/a<0.5) meets the same technical difficulties. For the torsatrons with l=3,4, where ε<1, one can obtain from [11]: $r_s/a \approx \varepsilon^{2/(l-2)}$ (solid curves 3,4, Fig.4). Some of the numerical calculation results for the low-toroidicity systems are also shown in Fig.4. It is seen that from the standpoint of configuration 2 creation, the torsatrons with l=3,4, where at ε=0.3-0.5 the separatrix edges can be moved far away from the cylinder surface, seem most attractive.

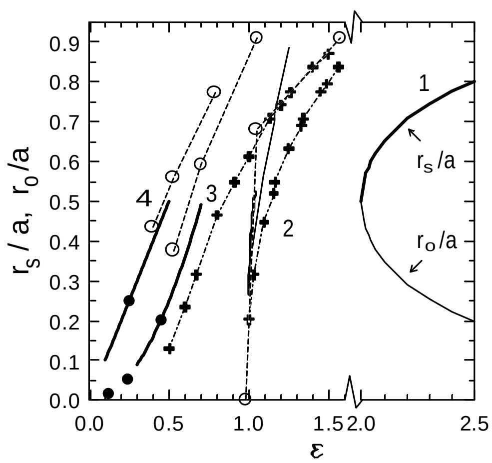

Fig.4 Separatrix edge radius r_s/a (and magnetic axis r_o/a in l=1 torsatron) as function of e in l=1,2,3,4 straight torsatrons (curves 1-4, respectively): solid lines - analytical expressions [4, 10]; (o) [9]; (+) a/R_o=0.0833, numerical calculation [10, 11]; (·) a/R_o=0.03, our numerical calculation.

It should be noted that in toroidal torsatrons the dimensions of the closed magnetic surface existence transverse controlling magnetic field, variation of its distribution, subtraction of the longitudinal magnetic field, etc.).

So, there are a number of magnetic systems which provide a deep detachment (controllable *in situ* in some instances) of the plasma core from the wall, and it is conceivable that this property is inherent not only in stellarators. For example, in local mirror traps of the electric-discharge device-type magnetic system [12, 13] a plasma core with a diameter an order of magnitude smaller than the characteristic size of the system can be realized. In principle, a deep detachment of the plasma core from the wall can be realized in the device with a current-carrying plasma at a steady-state stage of discharge. It remains only to carefully choose the most suitable magnetic system and to determine the r_{pl}/r_W ratio to be close to optimum. There are some reasons to believe that it will not be too small. At r_{pl}/r_W~0.3 the overall dimensions of the reactor will be within the limits of certain known designs [14, 15], and the service life of the first wall made from a common austenitic stainless steel can presumably be increased to a few tens of years [3]. If the service life of the 1st wall is required to be ~10 years and the RFR power value is put minimum then the RFR overall dimensions can appear more acceptable. As a result, the RFR will demonstrate the possibility of long steady-state burning of self-sustained fusion reactions at already existing technological level. The transition to smaller-size reactors, i. e., to commercial reactors, calls for a significant rise of this level, this being perhaps doubtful to fulfill in the absence of RFR.

Thus, for advancement towards a commercial fusion reactor, we have proposed here as a next step a steady-state operated RFR with an increased plasma-wall detachment so as to further guarantee not only the production but also a long-term (for many years) confinement of a self-sustained plasma at the existing technology level. In such a reactor one can expect some decreasing in plasma contamination, this conclusion being not only from general considerations. For example, the investigations of prompt and non-prompt fluxes of high-energy fusion reaction products at the 1st wall have revealed [16], that a ~20% increases in the 1-st wall radius (plasma radius is fixed) reduces blistering-induced impurities to a permissible level. We consider the primary goal of the RFR is the provision of full-scale conditions for carrying out materials science experiments to create and test 1st wall materials for the commercial fusion reactor. The information level needed for that must be reached before the RFR 1st wall service life comes to an end, because the replacement of the 1st wall is the next problem to be solved. The estimates, resulting from the analysis carried out here point to the existence of a wide variety of magnetic systems which might provide a deep plasma core detachment from the

region within rather moderate ranges can be controlled *in situ* with the help of other means (application of a

wall. For a successful choice of the RFR magnetic system it is necessary that a more extensive and deep analysis of all well known magnetic systems should be carried out from the viewpoint of practical realization of the configuration 2 (Fig.1). The task to optimize the ratio r_{pl}/r_W is of great importance for the reduction of the size and, accordingly, cost of RFR. However, the RFR cost should not be an insurmountable barrier on the way of creating this reactor. An example can be found in the expensive APOLLON Program of landing the man on the Moon, which had not had such a strong motivation as gaining practically an inexhaustible power source by the mankind.

References

1. V. G. Kotenko, G. G. Lesnyakov, S. S. Romanov. *7th Ukraine Conf. on Controlled Nuclear Fusion and Plasma Physics*, Kiev, September 20-21, 1999. Book of abstracts, p. 32 (in Ukraine).
2. V. G. Kotenko, V. I. Lapshin, G. G. Lesnyakov, S. S. Romanov, E. D. Volkov. *10th Intern. Toki Conf. on Plasma Physics and Controlled Nuclear Fusion* (ITC-10), January 18-21, 2000. Abstracts, PII-57, p. 172.
3. E. D. Volkov, V. A. Suprunenko, A. A. Shishkin, *Stellarator*, (Kiev, Naukova Dumka, 1983, in Russian).
4. V. G. Kotenko, S. S. Romanov. Preprint KhFTI 83-8, (Kharkov, 1983, in Russian).
5. V. F. Aleksin, et al. Preprint FTI AN UkrSSR No. 217, (Kharkov, 1968, in Russian).
6. V. F. Aleksin, Zhurn. Tekh. Fiz. **31**, 1284 (1961).
7. V. G. Kotenko. Preprint KhFTI 80-41, (Kharkov, 1980, in Russian).
8. V. V. Demchenko, S. S. Romanov. Preprint KhFTI 76-13, (Kharkov, 1980, in Russian).
9. A. Mohri, J. Phys. Soc. Jpn., **28**, 1549 (1970).
10. D. Marty et al., Nucl. Fus. **12,** 367 (1972).
11. C. Gourdon et al., Nucl. Fus. **11,** 140 (1971).
12. A. I. Bugrova et al., Fiz. Plazmy 19, 972 (1993).
13. V. G. Kotenko, Fiz. Plazmy 25, 972 (1999).
14. F. Tenney and G. Levin. *A Fusion Power Plant*. MATT 1050, (PPPL, 1974).
15. A. Iioshi, K. Uo. *Plasma Physics and Controlled Nuclear Fusion Research* 1974 (Proc. 5th Int. Conf. Tokyo, 1974) Vol. 3, IAEA, Vienna, (1975) 619.
16. L. M. Hively, G. N. Miley. Nucl. Fus. **20**, 969 (1980).