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A Version of Advancement Towards a Commercial Fusion Reactor

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Abstract

In existing fusion reactor designs with magnetic confinement the minor plasma radius r_{pl} is usually comparable with the radius r_w of the first wall, $r_{pl}/r_w \leq 1$. It is well known that the realization of a commercial fusion reactor based on these designs entails a number of unsettled problems, including the first wall problems. In this connection, a research fusion reactor (RFR) with $r_{pl}/r_w << 1$ and with a steady-state self-sustained plasma as a new object of investigations and useful applications can serve as a base for solving these problems. Possibilities of certain stellarator-type magnetic systems are discussed from the standpoint of realization of deep and controllable plasma core detachment from the first wall.

Keywords:

commercial fusion reactor, fusion reactor configuration, steady-state operation, load on the first wall, stellarator-type magnetic system, separatrix edge

1. Introduction

In the past few years considerable progress has been made in the studies on controlled fusion. The magnetic confinement devices have produced a plasma with the parameters approaching the conditions for realization of self-sustained fusion reactions [1,2]. However, the feasibility of a commercial fusion reactor based on these devices still remains an open question. The main reason for this is the interaction of plasma-generated high-intensity energy flows with the 1st wall; this leads, in particular, to a significant reduction in the service life of the 1st wall. In present-day fusion reactor designs, where the plasma radius r_{pl} is generally comparable with the radius of the 1st wall, r_w (see Fig. 1, configuration 1), it appears necessary to replace the 1st wall every 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, 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 of the creation of low-activation materials showing a high resistance to the whole totality of fusion plasma radiations, and also, with due account for the synergy

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effects. This issue has not been resolved so far. 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.

2. The Essence of a Version

The essence of the version consists in an essential reduction of the specific load Γ_w on the 1st wall at the expense of increasing its surface area. At a given fusion plasma radius r_{pl} it means the realization of configuration 2 (see Fig. 1), where $r_{pl}/r_w << 1$ (in toroidal geometry $\Gamma_w = (r_{pl}/r_w)\Gamma_{pl}$, where Γ_{pl} is the energy flow from the unit surface area of the plasma core). 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, meant 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 an effective 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 an associated scientific-technical progress it would be possible to achieve the transition to reactors of considerably smaller sizes (configuration 3, Fig. 1), i.e., to commercial reactors.

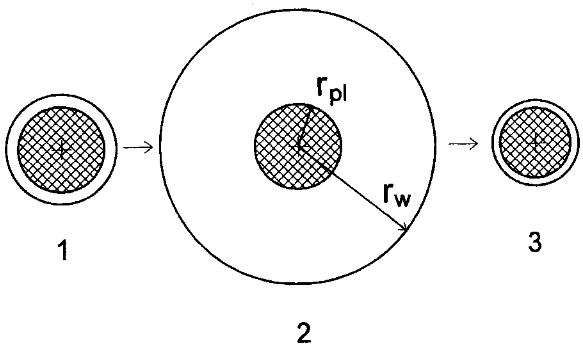

Fig. 1 Fusion reactor configurations: 1 - existing designs; 2 - proposed research fusion reactor; 3 - commercial design.

3. On a Possibility of Deep Plasma Wall Detachment Inherent in Stellarator-type Magnetic Systems

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 with filamentary helical coils an analysis [4] was made to determine the ratio of the radius of separatrix edge to the radius 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. The separatrix edges and the magnetic axes are the singular points of the magnetic surface function $\Psi(r,\theta)$ in the cross-section z = const and are found from the conditions $\partial\Psi/\partial r = 0$, $\partial\Psi/\partial\theta = 0$, where r, φ, z are the cylindrical coordinates, $\theta = \varphi - \varepsilon z/a$, $\varepsilon = 2\pi a/L$, L is the pitch of the helical coil.

In the classical stellarator, the magnetic-surface function involves the parameter $\eta = 2\pi\varepsilon a B_o/\mu_o I$, where B_o is the longitudinal magnetic field, μ_o is the magnetic constant. The position of singular points depends on η. The character of these dependences is determined by the number $2l$ of helical coils with alternating current directions of I. At $\varepsilon << 1$, the dependences are described by exact analytical expressions. For the $l = 1$ stellarator, the location of both the separatrix edge r_s/a and the spatial magnetic axis r_o/a is found from the condition [5]: $2/((r/a)(1 - (r/a)^2)) = \eta$. Figure 2 (curve 1) shows the graphical solution of this equation. The upper part of curve 1 specifies the position of the separatrix edge, and the lower part gives the position of the magnetic axis. It is seen that with a decreasing $\eta \to 5$ the region of closed magnetic surface existence diminishes $((r_s/a) - (r_o/a) \to 0)$. 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 $\sim r_s/a$. Reasoning from the results of ref. [6] one can suggest that $r_s/a = (1 - 4/\eta)^{1/4}$ can be obtained in the case of the $l = 2$ 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. In $l > 2$ stellarators, the radius of the edge is given by the formula $r_s/a = (\eta/2l)^{1/(l-2)}$. Curves 3,4 in Fig. 2 show the dependences for $l = 3,4$, respectively. The $l = 3$ stellarator is characterized by a linear dependence and the lowest r_s/a values at one and the same η. It should be noted that at a given ε, the η value can be varied within rather wide ranges by changing the B_o/I ratio; that gives an opportunity to control *in situ* the r_s/a value throughout the experiment. This peculiarity of classical stellarator persists with violation of helical symmetry. The calculations of a modular classical-stellarator version with a considerable toroidicity ($a/R_o \approx 0.3$, $l = 3$, a and R_o being, respectively, the minor and major radii of the torus, $\theta = m\varphi$, $m = 3$ is the number of helical pitches) 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 [7].

In the classical torsatron, the longitudinal and helical magnetic-field components are set up by l helical coils, where the currents are coincident in direction. Therefore, the position of separatrix edges in these systems can be controlled by choosing in advance rigorous design parameters ε and l, invariable in the course of experiment. In paper [8], for the $l = 1$ helical coil having a short pitch ($\varepsilon \sim 1$), the following magnetic surface function was obtained by including the first three harmonics in the expressions for magnetic field components:

$\Psi(r,\theta) = (\mu_o I/4\pi a)\{a_1 r\cos\theta + (r^2/2)(\varepsilon d_1 + a^2\cos2\theta) + (r^3/3)[(\varepsilon d_2 + b_1)\cos\theta + a_3\cos3\theta]\}$, $a_1 = \varepsilon^2[K_0(\varepsilon) + K_2(\varepsilon)$, $a_2 = 2\varepsilon^3[K_1(2\varepsilon) + K_3(2\varepsilon)]$, $a_3 = (27\varepsilon^4/8)[K_2(3\varepsilon) + K_4(3\varepsilon)$, $b_1 = \varepsilon^2 a_1/8$, $d_1 = 2\varepsilon$, $d_2 = \varepsilon a_1$.

Here r and z are the dimensionless coordinates (radius a is the unit measure), $\theta = \varphi - \varepsilon z$, $\varepsilon r << 1$, $K_n(x)$ are the Bessel functions. Hence, the radii of the separatrix edge r_s/a and of the spatial magnetic axis r_o/a in the $l = 1$ torsatron can be estimated as: $r/a \sim 0.5(1 \pm (1 - 4/\varepsilon^2)^{0.5})$. Figure 3 (curve 1) shows the corresponding curve. 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 coil. With an appropriately shaped of vacuum chamber, this allows one to move the material wall, being within this sector, away at a distance exceeding the radius a of the cylinder. In torsatrons with $l > 1$, similarly to $l > 1$ stellarators, the radius of the magnetic axis $r_o/a = 0$, the region of closed magnetic surfaces existence is centered, and the

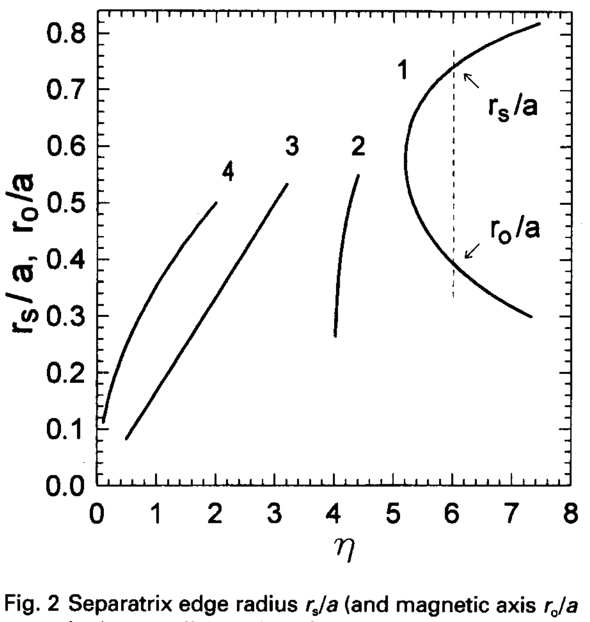

Fig. 2 Separatrix edge radius r_s/a (and magnetic axis r_o/a in $l = 1$ stellarator) as function of η in l =1,2,3,4 straight stellarators (curves 1–4, respectively).

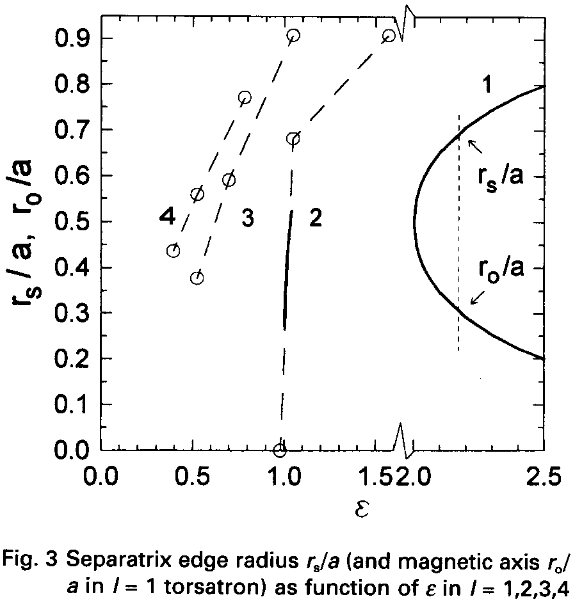

Fig. 3 Separatrix edge radius r_s/a (and magnetic axis r_o/a in $l = 1$ torsatron) as function of ε in l = 1,2,3,4 straight torsatrons (curves 1–4, respectively).

maximum dimension of this region is $\sim r_s/a$. For the l = 2 torsatron, the dashed curve 2 (Fig. 3) was obtained from the treatment of the data presented in [9-11]. In the $r_s/a < 0.5$ region, this dependence can be described by an approximate expression: $r_s/a \sim (1 - \varepsilon^2)^{1/4}$ (solid part of curve 2). For l = 3,4 torsatrons, the dashed curves 3,4 (Fig. 3) were obtained as result of data [9] treatment. It is seen that in these torsatrons one can expect a further decrease in the radius of separatrix edge at $\varepsilon < 0.5$. It should be noted that in toroidal torsatrons the dimensions of the closed magnetic surface existence region within rather moderate ranges can be controlled *in situ* with the help of other means (application of the transverse controlling magnetic field, variation of its distribution, subtraction of the longitudinal magnetic field, etc.).

4. Discussion

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] the 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 $r_{pl}/r_w \sim 0.3$ 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 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.

5. Summary and Further Activities

For advancement towards a commercial fusion reactor, we have proposed here as a next step a steady-state operated research fusion reactor with an increased plasma-wall detachment so as to further guarantee not only production but also a long-term (for many years) confinement of a self-sustained plasma at the existing technological level. As we consider, the primary goal of RFR is to obtain 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, as replacement of the 1st wall is the next unsettled problem. 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 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). Of great importance for the restriction of both the size and cost of RFR is the task to optimize the ratio r_{pl}/r_w.

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