THE ASPECT RATIO AND PLASMA ELONGATION DEPENDENCIES OF TOKAMAK-REACTOR PARAMETERS

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Abstract

In this paper it is shown that the Tokamak-Based Demonstration Reactor - DEMO with large aspect ratio (LAR) has more available parameters than tokamaks with intermediate (ITER) and small (ST) aspect ratios.

1. INTRODUCTION

The major goal of the Tokamak Physics Programs is to obtain the necessary information for the design of a Tokamak-Based Demonstration Reactor - DEMO.

During DEMO designing the problems, connected with the cost of installation and with the high availability of operation will arise. From this point of view it is interesting to analyze the possibilities of tokamak-reactor with low (A<1.5) and with high (A>4), in comparison to ITER, aspect ratios [1-4].

In this paper for obtaining the dependencies of the main plasma parameters for DEMO on aspect ratio and plasma elongation we used method, described in [5].

2. CALCULATION METHOD AND RESULTS.

The status of a facility (facility with ignition, burn ets.) is determined by the so-called triple product, $\boldsymbol{F_p}$

$$\boldsymbol{F_p = n\tau T}\ , \tag{1}$$

where n and T are the density and the temperature of a plasma, τ is the energy confinement time.

The thermal/magnetic energy ratio (β) is limited by the possibility of developing of ballooning instability in the plasma :

$$\boldsymbol{\beta = 10^{-2}\beta_N \frac{I}{aB}}\ , \tag{2}$$

where I is the plasma current, a is the minor plasma column radius, B is the magnetic field value.

For the plasma energy confinement time the ITER-scaling law [6] for H-mode has been chosen:

$$\boldsymbol{\tau = 0.028 I^{0.9} B^{0.2} P_\alpha^{-0.66} n_{19}^{0.4} M^{0.2} R^{2.03} \varepsilon^{0.19} k^{0.91}}\ . \tag{3}$$

Here, $\boldsymbol{M}$ is the mass-number of plasma ions, $\boldsymbol{P_\alpha}$ is the plasma heating power (for reactor with self-sustaining reactions it is the power confined in the α -particles), $\boldsymbol{\varepsilon = A^{-1} = a/R}$ is the inverse aspect ratio $\boldsymbol{A}$, $\boldsymbol{R}$ is the major plasma column radius, $\boldsymbol{k}$ is the plasma column elongation. For the further analyses let us assume that $\boldsymbol{\tau = 0.5\tau_{ITER}}$.

For density limit we used the Greenwald value

$$n_{20} = \frac{IA^2}{\pi R^2}. \tag{4}$$

For plasma current we used

$$I = \frac{5BR}{2qA^2}(1+k^2), \tag{5}$$

where $q = q_\psi (A-1)/A$ [3].

The value of magnetic field in the toroidal center is equal

$$B = \frac{B_c[A-(1+\Delta)]}{A}, \tag{6}$$

where B_c is the maximal permissible magnetic field value and Δa is the distance from the plasma internal boundary to the points, where the magnetic field is maximal.

In the analyses we will take into account the specific energy flux transferred by neutrons through the plasma column edge, P_n.

From expressions (1)-(6) one can obtain formulas for the dependencies of main plasma parameters on the aspect ratio and plasma elongations. For example we have:

a) $R,\ m$

$$R = 55\frac{q_\psi^{1.9}}{\beta_N^{0.83}} \cdot \frac{P_n^{0.55}F_p^{0.83}}{M^{0.17}B_c^{2.89}} \cdot \frac{[3/2(1+k)-\sqrt{k})]^{0.55}}{k^{0.75}(1+k^2)^{1.9}} \cdot \frac{A^{2.93}(A-1)^{1.9}}{[A-(1+\Delta)]^{2.89}}, \tag{7}$$

b) $I,\ MA$

$$I = 138\frac{q_\psi^{0.9}}{\beta_N^{0.83}} \cdot \frac{P_n^{0.55}F_p^{0.83}}{M^{0.17}B_c^{1.89}} \cdot \frac{[3/2(1+k)-\sqrt{k})]^{0.55}}{k^{0.75}(1+k^2)^{0.9}} \cdot \frac{A^{0.93}(A-1)^{0.9}}{[A-(1+\Delta)]^{1.89}}, \tag{8}$$

c) $P,\ GW$

$$P = 7.5 \cdot 10^4\frac{q_\psi^{3.8}}{\beta_N^{1.66}} \cdot \frac{P_n^{2.1}F_p^{1.66}}{M^{0.34}B_c^{5.78}} \cdot \frac{[3/2(1+k)-\sqrt{k})]^{2.1}}{k^{1.5}(1+k^2)^{3.8}} \cdot \frac{A^{4.86}(A-1)^{3.8}}{[A-(1+\Delta)]^{5.78}}, \tag{9}$$

From the relations (7)-(9) one can see that all parameters can be represents as a product of the constant coefficient determined by chosen physical quantities, function of plasma column elongation, and function of the aspect ratio, $f_\gamma(A)$, where γ is *R,I,P, ets.*

The ratio of bootstrap current to full plasma current for circular tokamaks may be found from formula [7]

$$\frac{I_{boot}}{I} = 1.17\bar{\beta}_p A^{-0.61}\left[1-0.62\left(1-\frac{q_0}{q_a}\right)\right], \tag{10}$$

where $\bar{\beta}_p$ is the ratio of thermal energy to the energy of poloidal magnetic field, q_0 and q_a are the safety factor values at the center and near the periphery of plasma column.

The dependencies of f_γ for ***I, R,*** and ***P*** on ***A*** are given in Fig.1 (Δ=0.3). In Fig.2 one can see the dependencies of full plasma and bootstrap currents on ***A***. We can see that the functions f_R and f_P have minimum at some optimal value of A_{opt}. In Ref. [5] it was been shown that $A_{opt} \sim 1+\Delta$. The plasma current decrease with increasing the aspect ratio.

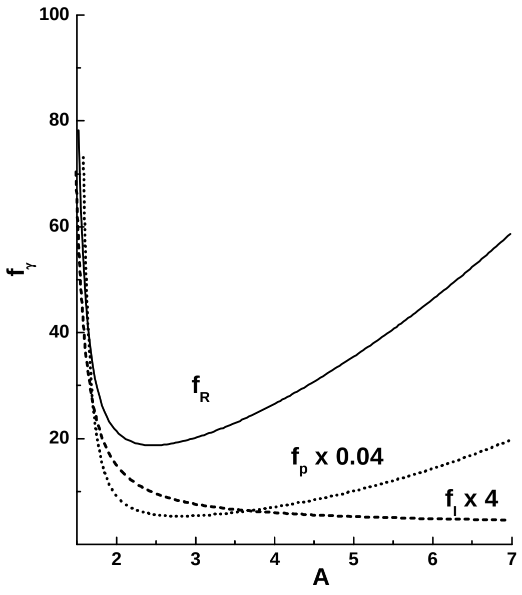

Fig.1. Dependencies of f_R , f_P and f_I on aspect ratio.

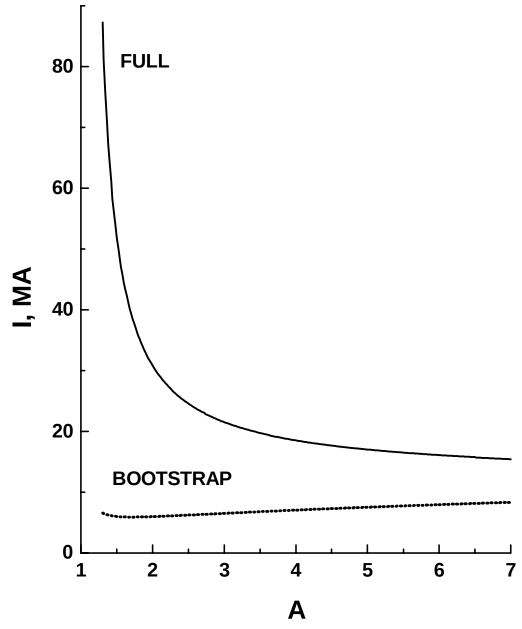

Fig.2. Full and bootstrap currents as aspect ratio function.

In Fig.3. one can see the dependencies of plasma current, tokamak major radius and plasma reactor power on plasma elongation when the another parameters are *const*.

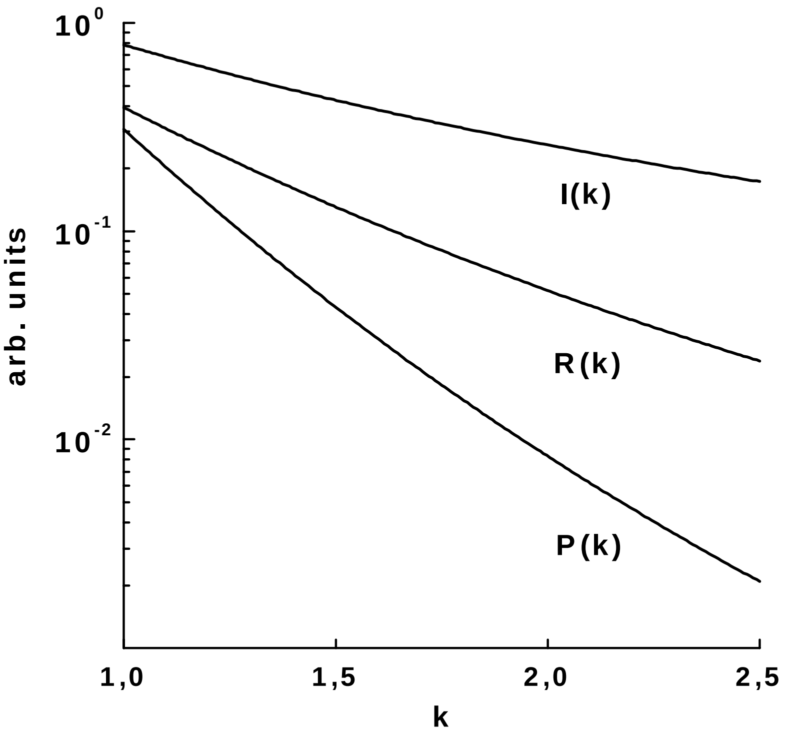

Fig.3. Dependencies of plasma current, tokamak major radius and reactor power on plasma elongation.

One can see that as the ellipticity increases the tokamak radius, plasma current and reactor power decrease.

Let us consider for example the dependencies of some tokamak -reactor parameters on aspect ratio when the major tokamak radius is *const*. Another parameters were taken the same as in ITER. The results of such calculations are presented in the Table.

TABLE

	ST	ITER	LAR	LAM	HAM	HAM1	HAM2
A	1.3	2.9	6	2.5	3.5	4.5	6
Δ	0	0.3	0.3	0.3	0.3	0.3	0.3
R, *m*	8	8	8	6	6	6	6
I, *MA*	128	22	5.6	19.6	11.5	7.3	4.1
P, *GW*	19.4	1.5	0.15	0.6	0.3	0.14	0.05
P_n, MW/m^2	6.3	1	0.2	0.6	0.4	0.26	0.12

From the Table one can see that when the aspect ratio increases such plasma parameters as current, full reactor power and wall loading decrease.

3. Conclusion.

So from our point of view the reactor DEMO must be based on the tokamak with high aspect ratio:

- The *plasma current* which is necessary for reactor operation drops when the aspect ratio rise, and so the problem of plasma current maintaining is simpler.
- The *bootstrap current* is rise when the aspect ratio rises. In this case the design of the steady-state tokamak-reactor is simpler.
- The *neutron wall loading* is less in LAR than in ST.
- The aspect ratio rise gives us the possibility to rise the magnetic field value at the plasma center, with the same value of the critical magnetic field at the inner toroidal field coil leg. The conditions for obtaining the high plasma parameters are better for higher magnetic field.
- The installation with high aspect ratio has high availability of operation.

The rise of the plasma elongation results in the better reactor parameters obtaining. For example, the change of the plasma elongation from 1 up to 3 results in the major plasma radius reduction about one order of value.

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