Calculation of the equilibrium plasma configurations with high elongation and triangularity for the T-15 Upgrade tokamak

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1. Introduction

In this work, the problem of optimisation of the equilibrium plasma configuration for the T-15 Upgrade tokamak is considered. The possibility of creating plasma with maximum values of the elongation and triangularity within the framework of the specified poloidal field coil system is investigated.

The main parameters of the T-15 Upgrade tokamak are given in the Table 1.

		T-15	AUG	DIII-D	EAST	WEST	KSTAR	ITER
I_p, MA		**2**	1.6	3.5-5	0.5	1	2	15
A		**2.2**	3.3	2.5	4.1	5-6	3.6	3.1
R_o, m		**1.48**	1.65	1.67	1.75	2.5	1.8	6.2
a, m		**0.67**	0.5	0.67	0.43	0.5	0.5	2
k_{95}		**1.7-1.9**	1.8	<=2	1.6-2	1.3-1.8	2	1.85
δ_{95}		**0.3-0.4**	0.4	<=0.6	0.6-0.8	0.5-0.6	0.8	0.48
$B_{t\|Ro}$, T		**2.0**	3.1	2.2	3.5	3.7	3.5	5.3
t_{pulse},s		**10**	10	10	1000	1000	300	400
P_{AUX}, MW	ECRH	**6**	4	5	0.5	0.6	7.5	20-40
	NBI	**9**	20	17			20	33-50
	ICRH	**6**	6	5	3	3-9	6	20-40
	LH	**4**			4	6-7	5	0-40

Table 1. The main parameters of the T-15 Upgrade tokamak in comparison with the other installations.

Optimisation of the divertor magnetic configuration needs the numerical analysis which allows us to determine the divertor geometry, coordinates of the X-points, length of the separatrix legs and their slope to the divertor plates and other parameters. Calculations were performed using the TOKAMEQ code designed to solve the problem of MHD equilibrium in tokamaks [1].

2. Statement of the problem

The statement of the problem includes the two-dimensional Grad-Shafranov equation with regularity conditions on the main axis of the torus and at infinity.

$$-\frac{1}{r}\Delta^*\psi = \gamma\cdot\begin{cases} j_\varphi(\psi, r), \ \ \psi > \psi_p (inside\ the\ plasma) \\ \sum_{k=1}^{N} I_k\delta(r - r_{k,}\, z - z_k), \ \ \psi < \psi_p\ (outside\ the\ plasma)\end{cases}$$

$$\psi(0, z) = 0$$

$$\lim_{r,z\to\infty}\psi(r, z) = 0$$

Here $\Delta^* \equiv r\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial\psi}{\partial r}\right] + \frac{\partial^2\psi}{\partial z^2}; \gamma = 0.8\pi^2;$

r_k, z_k, I_k are coordinates of the poloidal field coils and poloidal currents respectively, ψ_p is magnetic flux at the plasma boundary. The plasma boundary is initially unknown and defined during the calculations.

Distribution function of the plasma current is given as follows

$$j_\varphi(r, \psi - \psi_p) = r\frac{dp}{d\psi} + I(\psi - \psi_p)I'(\psi - \psi_p)/r \equiv$$

$$\equiv \lambda\left\{\beta r(\psi - \psi_p)^{\gamma_1} + (1 - \beta)\frac{\hat{R}^2}{r}(\psi - \psi_p)^{\gamma_2}\right\} \equiv \lambda f(r, \psi - \psi_p)$$

Here γ_1 and γ_2 are parameters of the plasma current density distribution;

$\hat{R}^2 = \frac{\iint_{\Omega_p} r dr dz}{\iint_{\Omega_p}\frac{dr dz}{r}}$ is average value of the r^2 over the plasma column;

Coefficient λ is calculated by reference to the value of the total plasma current I_{pl}:

$$\lambda\iint_{\Omega_p} f(r, \psi - \psi_p) dr dz = I_{pl}$$

It is possible to state two different types of problems:

1) The direct problem

It is necessary to find the distribution of the magnetic surfaces of the plasma for given values of r_k, z_k, I_k, ψ_p and parameters describing the plasma current profile j_φ. Obviously, solution exists not for all given parameters.

2) The "quasiinverse" problem

Let the equilibrium state of the plasma be described by major radius R_{pl}, minor radius a_{pl}, z-coordinate of the magnetic axis z_{pl} and elongation k. It is necessary to find the poloidal currents I_k for given coordinates r_k, z_k and parameters describing the plasma current profile j_φ so that the plasma has needed values of R_{pl}, a_{pl}, z_{pl}, k.

3. Results of the calculations

Calculations were performed for the ohmic plasma parameter with $\beta_p \approx 0.18$ and $l_i \approx 0.7$. The possibility of producing single-null (SN) and double-null (DN) plasma configurations with maximum values of the elongation (k_{95}~2) and triangularity (δ_{95}~0.4), different positions of the X-points is considered. The dependences of the plasma elongation and triangularity on coordinates of upper and lower X-points were found.

The results of the calculations show that the poloidal field coil system of the T-15 Upgrade tokamak allows to produce both single-null (SN) equilibrium magnetic configurations (with upper and lower x-points) and double-null (DN) configurations of the plasma. Within the limits for poloidal currents it is possible to displace the lower x-point over the range $\Delta R \approx 25$ cm and $\Delta z \approx 30$ cm and the upper x-point over the range $\Delta R \approx 15$ cm and $\Delta z \approx 12$ cm. The maximum values of the elongation and the triangularity were determined for each type of the equilibrium magnetic configuration of the plasma.

It has been found that the maximum value of the elongation is $k_{95}=2$ and the maximum value of the triangularity is $\delta_{95}=0.4$ for each type of the magnetic configuration. Equilibrium magnetic configurations with maximum elongation can be obtained within the wide range of the x-point radial position (ΔR = 20-25 cm for lower x-point and ΔR = 10-15 cm for upper x-point).

Figure 1 shows the single-null equilibrium plasma configurations with lower x-point (LN) (fig. 1a) and with upper x-point (UN) (fig. 1b) and double-null (fig. 1c) magnetic configuration with maximum elongation at different x-point positions. For single-null configurations the elongation is $k_{95} = 2.01$ (LN) and $k_{95} = 1.97$ (UN) and the triangularity is $\delta_{95} = 0.26$ (LN) and $\delta_{95} = 0.32$ (UN). For double-null configuration the values of the elongation and triangularity equal to $k_{95}= 2.01$ and $\delta_{95} = 0.31$ respectively.

Figure 2 represents the single-null (fig. 2a, fig 2b) and double-null (fig. 2c) magnetic configurations with maximum value of triangularity. For single-null configurations the triangularity is $\delta_{95} = 0.41$ (LN) and $\delta_{95} = 0.4$ (UN) and the elongation is $k_{95} = 1.71$ (LN) and $k_{95} = 1.69$ (UN). For double-null configurations the values of the triangularity and elongation equal to $\delta_{95} = 0.4$ and $k_{95} = 1.72$ respectively.

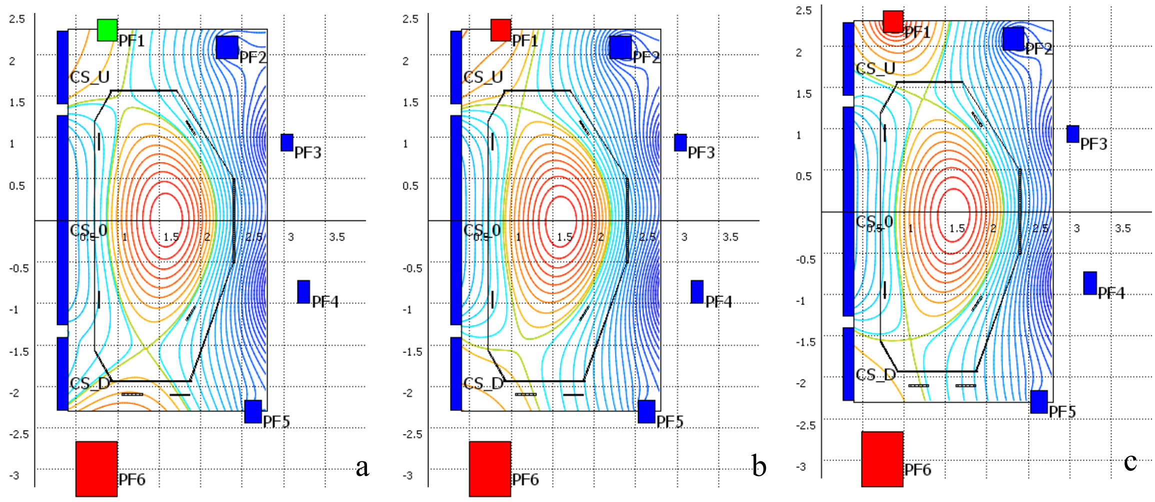

Fig1. Contour plots of poloidal magnetic flux ψ for single-null (a, b) and double-null (c) equilibrium plasma configurations with maximum value of the elongation k_{95}=2 at different positions of x-points. Plasma current is I_p =1.85 MA. Colour marks the coil current direction: blue – along the plasma current, red – opposite current, green – zero current. The bold black lines represent the vacuum chamber, two pairs of the passive stabilizers and conducting elements of the load-bearing structure under the bottom of the vacuum chamber.

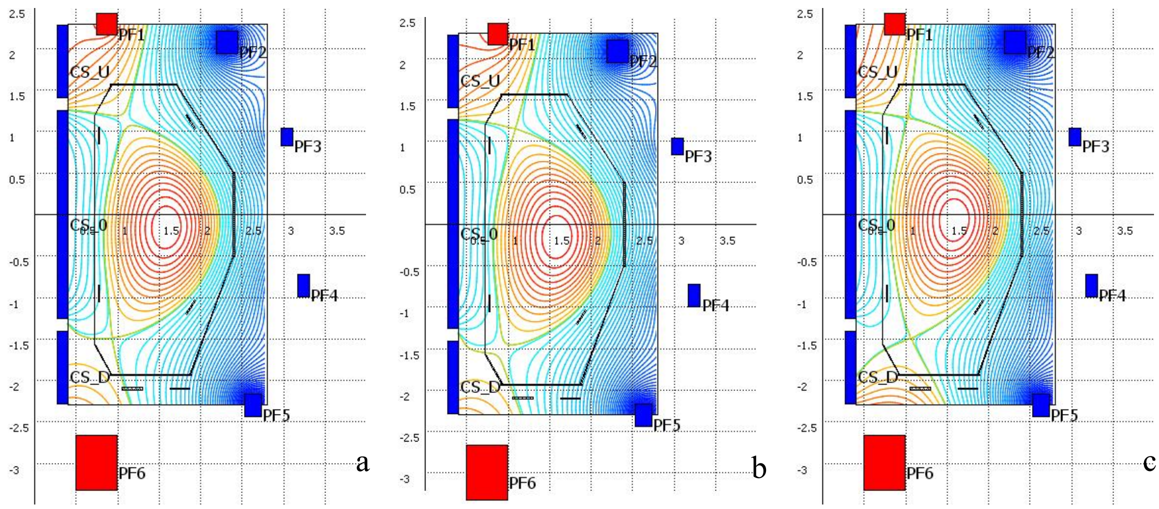

Fig2. Contour plots of poloidal magnetic flux ψ for single-null (a, b) and double-null (c) equilibrium plasma configurations with maximum value of the triangularity δ_{95}=0.4. Plasma current is I_p =1.85 MA.

The calculations have shown that it is possible to control the equilibrium magnetic configuration of plasma over a wide range. It creates favourable conditions for regimes with high plasma performance in the T-15 Upgrade tokamak.

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Reference

[1] D. Yu. Sychugov, Problems of Atomic Science and Tech., Ser. Thermonuclear Fusion, 2008, issue 4, pp. 84-88