Conceptual analysis of a tokamak-reactor with lithium dust jet

B.V. Kuteev 1), V.Yu. Sergeev 2), S.V. Krylov 1), V.M. Timokhin 2), S.G. Skokov 2)

1) Nuclear Fusion Institute, Russian Research Center "Kurchatov Institute", Moscow, Russia
2) State Polytechnical University, St. Petersburg, Russia

e-mail contact of main author: kuteev@nfi.kiae.ru

Abstract. The steady state operation of tokamak reactors requires re-radiating a substantial part of the fusion energy dissipated in plasma to make the heat loads onto the first wall more uniform and to reduce the erosion of divertor plates. One of the approaches realizing this goal uses injection of lithium dust jet into the scrape-off layer. In this paper a quantitative conceptual analysis of the reactor parameters with lithium dust jet injection is presented. The effects of the lithium on the core and SOL plasma are considered. The first results of developing the lithium jet injection technology and its application on T-10 tokamak are also presented.

1. Introduction

Steady state and long term operation of tokamak reactor requires sufficient reduction and distribution over the first wall the heat loads coming from the core plasma due to heat and particle transport. Usage of impurity injection into the radiative scrape-off layer (SOL) seams a reasonable way to solve the problem. Injection of noble gases and low-Z materials has been thoroughly analyzed in simulations [1] and experiments (see Ref. [2]). Meanwhile the analysis has been restricted by boron. Recently, the interest to lithium injection has started to grow up [3]. This material has the lowest Z and highest acceptable concentration in the plasma core. However, its radiation is rather low, so it was not clear would be or not the reactor regimes in tokamak controlled by lithium injection.

The basic goal of this study is searching for conditions when the major part of the fusion power is radiated by boundary plasma with injected lithium while the reactor core plasma remains low radiating and being clean enough with the effective charge below 1.7. The interest to the dust lithium jet technique is stimulated by necessity to provide wall conditioning in steady state operation and to reduce the total amount of lithium inside the vacuum vessel to a few kilogram level, which better corresponds to reactor safety requirements than the thick lithium wall with capillary porous system containing tons of lithium [4].

2. Layout of heat, particle and radiation flows in a tokamak

A schematic diagram of lithium flows in a divertor tokamak with dust lithium jet injection in vicinity of the stagnation point is shown in Fig.1. Lithium is injected in small droplet form with the characteristic size of 20-30 microns and the velocity lower than 30 m/s [5-7]. The droplets are ablated in SOL [6] and the lithium ionized migrates to divertor plates that determines its density level in SOL.

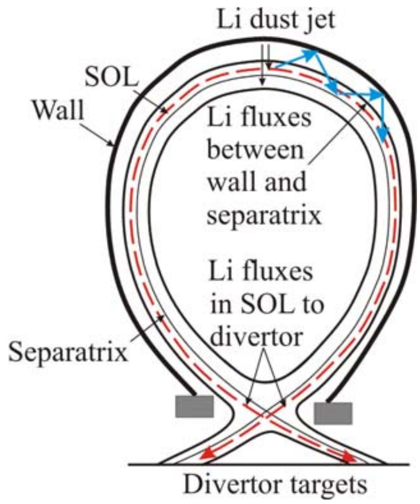


Fig. 1

Four species were considered in steady-state transport analysis: D, T, He and Li. The density and temperature in

SOL were simulated using the simple model of Ref. [8] taking into account different recycling coefficients R on divertor plates for the species. The core density and temperature were calculated using a set of transport equations in assumption of anomalous diffusion D = 0.3 m^2/s, thermal diffusivity χ = (7-9)×D and pinch velocity $V = V(a)\times(r/a)$, Here, $V(a)$ is the velocity at separatrix, a is the separatrix radius and r is the minor radius. Delta function sources were used for accounting fueling rate by gas, pellets and neutral beams as well as helium production and D-T losses due to fusion reactions. The source location was defined by radius $r = b$. The pumping rate for species was equal to (1-R) part of the total corresponding flows into SOL. A similar approach with delta source approximation was applied to the heat transport analysis. The plasma heating source by alpha particles has been simulated by delta source at b = 0.2. Additional heating by neutral beam injection and electron cyclotron radiation were also taken into account at b = 0.5. Bremsstrahlung, He and Li-radiation in coronal approximation were considered similar to Ref. [1] both in the core and SOL plasmas.

3. Analytical model and basic equations for conceptual analysis

The set of simplifications made above has allowed us to obtain semi-analytical solutions for the density and temperature profiles in multi-species plasma with different recycling coefficients, realistic source locations for a case of matched core and SOL plasmas.

3.1. Particle balance equations. For the core plasma region the following equation can be applied for each ion specie "*i*"

$$div\Gamma_i = \frac{1}{r}\frac{d}{dr}r\left(-D\frac{dn_i}{dr}+V(a)\frac{r}{a}n_i\right)=\sum_j S_{ij}(r)=\sum_j F_{ij}\delta(r-b_j)=\sum_j\frac{\phi_{i,j}}{V_{bj}}\delta(r-b_j) \quad (1)$$

where S_{ij} are delta-function particle sources for specie "*i*" located at radius b_j, ϕ_{ij} (particles/sec) is the integral flow of i specie into the toroidal volume V_{bj} with radius b_j. Integrating this equation over r gives ion flows

$$\Gamma_i = -D\frac{dn_i}{dr}+V(a)\frac{r}{a}n_i = \frac{1}{r}\int_0^r r\sum_j S_j(r)dr = \frac{\sum_j F_{ij}b_jH(r-b_j)}{r} \quad (2)$$

Here, H is the Heaviside step function. The density profile can be calculated on the basis of the separatrix density $n_i(a)$

$$n_i(r)=n_i(a)e^{\frac{A}{2}\left(1-\frac{r^2}{a^2}\right)}\left(1+\frac{e^{-\frac{A}{2}}a}{Dn_i(a)S_{SOL}}\sum_j\phi_{ij}FH(r,b_j)\right), \text{ where}$$

$$A=\frac{aV(a)}{D},$$

$$FH(r,b_j)=\int_{r/a}^{1}\frac{e^{\frac{Ax^2}{2}}}{x}H(x-b_j/a)dx \quad (3)$$

To evaluate the separatrix density $n_i(a)$ the plasma flow onto the divertor plate with sonic speed V_s of D-T mixture at average temperature T_{av} = 3 eV were assumed:

$$n_i(a) = \frac{\pi R q_{95}}{\Delta_{SOL} S_{SOL}} \sum_j \frac{\phi_{ij}}{V_s(1-R_i)}$$
$$V_s = \sqrt{\frac{5}{3}\frac{T_{av}}{M_{D+T}}} \qquad (4)$$

M_{D+T} = 2.5*amu* is the average mass of the gas flow in the SOL, R_i is the recycling coefficient equal to 0.9 for gases (D, T, He) and equal to 0.1 for lithium, S_{SOL} is SOL area. The SOL width Δ_{SOL} was assumed to be 2 cm. The separatrix density evaluated within these assumptions correlates reasonably with
Empirical scaling presented in Ref. [8].

The set of particle and energy sources included into simulations with their normalized locations b_j/a for all species is given in Table 1.

Table 1.

Source/specie	**deuterium**	**tritium**	**helium**	**lithium**
gas	0.99			
pellet	0.5	0.5		
NBI	0.5			
Fusion (negative)	0.2	0.2	0.2	
lithium dust				0.99

The deuterium sources are produces by gas injection at the border, pellets and NBI at the middle of the minor radius, and the negative loss source near the center due to fusion. For tritium we took into account only the pellet source term and losses due to fusion. The helium source at the center and the border term for lithium dust were taken into account as well.

3.2. Heat balance equations. The heat transport was approximated by anomalous heat conductivity and particle heat transport in the core plasma. The electron and ion temperatures have been assumed equal each other T_e=T_i =T. Bremsstrahlung and mantle radiations were neglected for the temperature evaluations. The heat transport equation (5) took into account the particle transport described in session 3.1. and homogeneous thermal diffusivity coefficient. The fusion heating source Q_{fus}, the neutral beam heating source Q_{NBI} and the ECRH source Q_{ECRH} were approximated by δ-functions at the normalized minor radii b/a = 0.2, 0.3 and 0.6 correspondingly. The Ohmic heating term was neglected.

$$\frac{1}{r}\frac{d}{dr}\left(-n_e\chi\frac{dT}{dr} + 5\Gamma_e T\right) = Q_{fus} + Q_{NBI} + Q_{ECE} \qquad (5)$$

For boundary conditions we assumed that the separatrix temperature at the stagnation point T_s was determined by longitudinal electron heat transport [8]. The effect of the plasma radiation on the T_s has been neglected and the following equation (6) has determined the T_s at the stagnation point:

$$T_s = \left(\frac{7 \cdot q95 \cdot \pi \cdot R \cdot \left(P_{fus} + P_{NBI} + P_{ECE} - I^{br} - I^{mtl} \right)}{2 \cdot S_{SOL\perp} \ \chi_{\|}} \right)^{\frac{2}{7}} \tag{6}$$

Here, $\chi_{\|}$ is the longitudinal heat conductivity coefficient [1], $S_{SOL\perp}$ is SOL cross-section area at the separatrix, R_c is the plasma major radius, I^{br}, I^{mtl} are radiation terms and P are power source (see below). The temperature profile in the core plasma $T(r)$ was calculated using the set of equations

$$\begin{aligned} T(r) &= e^{-F_1(r/a)} \left(T_s + a \int_1^{r/a} g(z) e^{F_1(z)} dz \right) \\ F_1(z) &= -\frac{5a}{\chi} \int_1^z \frac{\Gamma_e(x)}{n_e(x)} dx \\ g(z) &= -\left[\frac{1}{z \, S_{SOL} n_e(z) \chi} \left(P_{fus} H(z - b_{fus}/a) + P_{NBI} H(z - b_{NBI}/a) + P_{ECE} H(z - b_{ECE}/a) \right) \right] \end{aligned} \tag{7}$$

3.3. Radiation model. Bremsstrahlung radiation in the core plasma was evaluated using the density and temperature profiles as well as the effective plasma charge profile Z_{eff}.

$$\frac{dI^{br}}{dV} = 5.35 \cdot 10^{-37} Z_{eff} n_e^2 T^{1/2}, W/m^3 \tag{8}$$

For the mantle I^{mtl} and SOL I^{SOL} radiations we used the model of Ref. [1]:

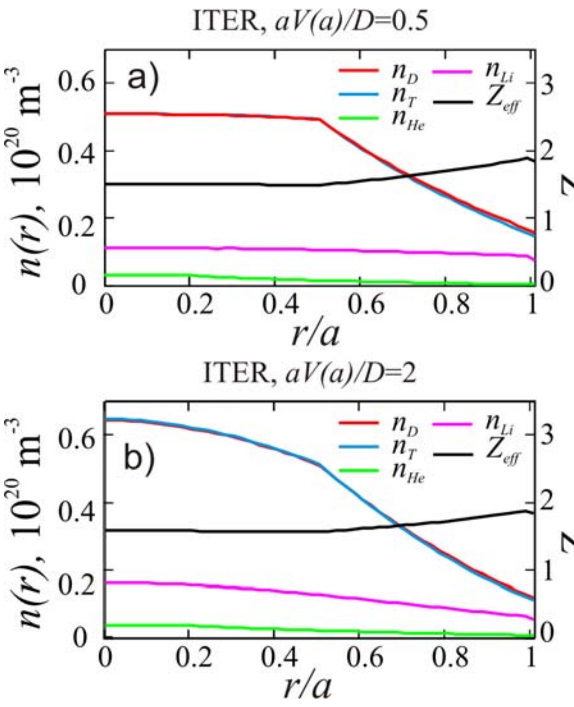
$$I_i^{mtl} = 2\chi \, n_e^2(a) \, S_{SOL} n_i(a) \int_{T_s}^{T_0} L_i(T) \, dT \tag{9}$$

$$I_i^{SOL} = 2 \cdot S_{SOL\perp} \sqrt{2\chi_{\|} n_e(a) n_i(a) T_s^2 \int_0^{T_s} L_i(T) T^{0.5} dT} \tag{10}$$

Here, $L_i(T)$ is the specific radiation of lithium or helium in coronal approximation [1].

4. The results of simulations

The results of calculating the plasma parameters in ITER&DEMO-like conditions for $aV(a)/D = 0.5$ and 2 are given in Table 2 and Fig.2-4. Values of flows and power sources for different regimes are presented in Table 2. The lithium density profile is formed by the border source and looks most flat. The internal source at $0.5r/a$ for D and T produces a clear nipping effect on these profiles. The internal fusion source for He makes the corresponding profile mostly sharp. A strong effect of fusion reactions is seen in Fig.3 where the central densities of deuterium and tritium are obviously hollow in the case of $aV(a)/D = 0.5$. Although that Z_{eff} grows towards plasma periphery due to lithium injection, the volume averaged value does not exceed the 1.6-1.7 acceptable level. The temperature profiles (Fig.4a,b) give reasonable central values and demonstrate source location effects. Higher temperatures correspond to higher values of $aV(a)/D$.



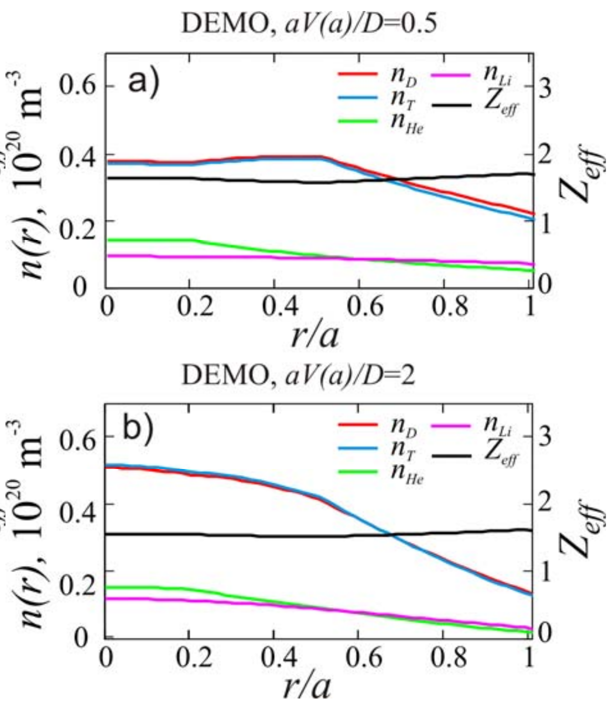
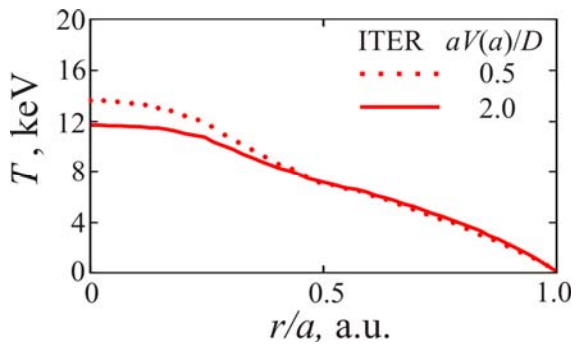


Fig. 2. *Fig*. 3.



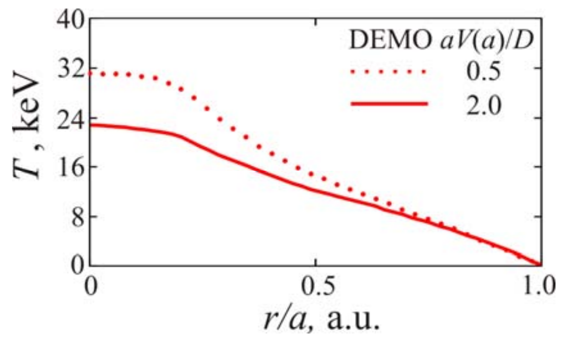


Fig. 4a. *Fig.* 4b.

The bremsstrahlung radiation is not very sensitive to the $aV(a)/D$ ratio and grows by a factor of 2 from ITER to DEMO conditions. The mantle Li and He radiations are a significant part of the power balance and exceed by a factor of 2-3 the corresponding SOL radiation of these impurities. Both mantle and SOL radiations values grow up for flatter plasma profiles with higher edge lithium density. The power to divertor plates reaches 0.4-0.5 of the total power both for ITER and DEMO.

Table 2.

Parameter, bpuff/a=bLijet/a=0.99 bpell/a=0.5, bfusion/a=0.2	**ITER *aV/D*=2**	**ITER *aV/D*=0.5**	**DEMO *aV/D*=2**	**DEMO *aV/D*=0.5**
Flux D puffing (10^{21} [1/sec])	1.19	1.65	1.08	1.61
Flux D pellet (10^{21} [1/sec])	3.06	4.25	2.78	4.15
Flux T pellet (10^{21} [1/sec])	3.28	4.46	3.16	4.56
Flux Li dust jet (10^{21} [1/sec])	8.75	13.02	5.00	7.65
Volume-averaged Zeff	1.69	1.69	1.69	1.69
Volume-averaged n_e (10^{20} [m-3])	1.02	1.02	1.08	1.08
P_{NBI} (MW)	32	32	32	32
P_{ECRH} (MW)	20	20	20	20
P_{fus} (MW)	100.0	86.4	372	423
T_0 (keV)	11.6	13.4	23.2	31.6
T_s (keV)	0.14	0.13	0.23	0.23
Bremstrahlung radiation (MW)	22.8	19.5	37.7	33.9
Mantle radiation (MW)	25.5	41.5	88.5	211.9
SOL radiation (MW)	16.2	21.3	43.7	63.5
Power to divertor plates (MW)	87.5	56.1	254.1	165.7
Enhancement factor of Li recycling to re-radiate 80% of total power, 20% power goes to divertor plates	4.5	2.3	4.9	2.1

5. T-10 experiments with lithium dust jet injection

Experiments with Li jet injection have been performed on the T-10 tokamak. The piston type injector produced the jet using 70-micron diameter orifice and providing the velocity of 20 m/s [7]. The injection rate of 100 mg/s in the first experiments was too large and initiated the discharge shut down similar to the massive gas puffing and killer pellet injection. The evolution of discharge parameters in Li-injection experiment is shown in Fig. 5. The plasma termination occurred 30 ms after the jet injection start and indicated the runaway electrons production (SXR and HXR bursts, residual current). No negative or positive effects of the Li jet injection and initiated disruptions were detected on sequential plasma discharges without injection.

6. Discussion

The calculations show that lithium injection provides substantial increase of the radiation in the core and SOL plasma. Both for ITER&DEMO-like plasmas the Li and He radiations onto the divertor plates evaluated in coronal approximation reduce the heat flow onto divertor plates by a factor of 2. However, the divertor heat loads are still high. From the thermal stability conditions of tokamak discharge it is possible to reduce the divertor heat loads upon to 0.2 of the total heat flow through separatrix [8,9]. To realize this condition it is necessary to enhance the impurity radiation by a factor of 2-5 as follows from the Table 2.

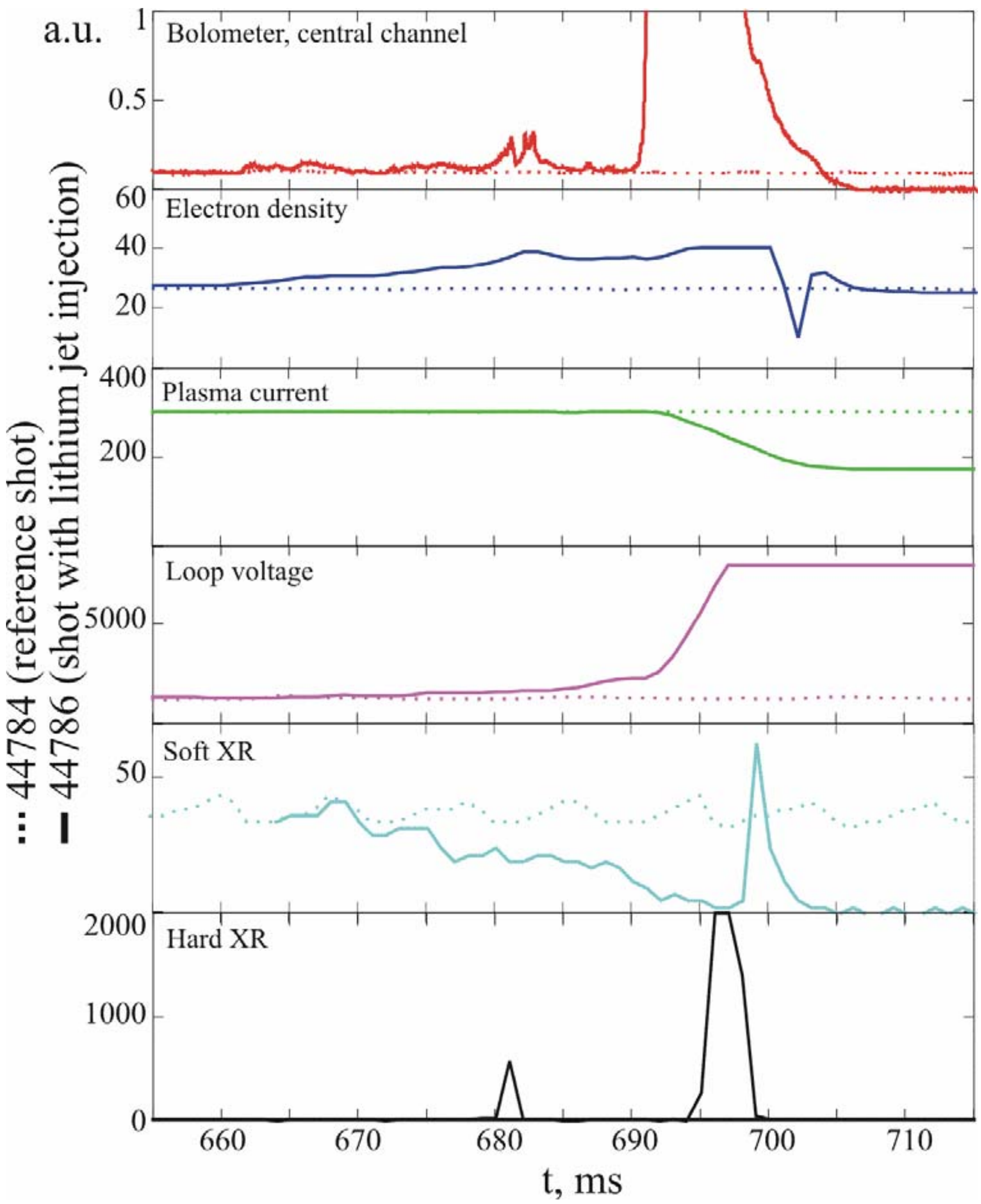


Fig. 5.

Actually, a very significant effect was not taken into account in this modeling. It is the growth of lithium radiation due to interaction of lithium ions with wall and neutrals during its travel from the stagnation point to the divertor region. Such effect is well known for impurities and it may increase the peripheral radiation by a factor of 100 (see Ref. [1] where calculations for C and O impurities have been made). For the problem of lithium injection the effect also must be valuable. However, the quantitative estimations of the effect are difficult and this requires more experimental studies of lithium – plasma interaction.

One may expect that the wall temperature will be most significant factor for the effect control. In the case of the temperature is higher than 350 C the lithium will not store at the wall due to evaporation. However at the temperature close to 700 C one may expect effective lithium hydrides formation. The optimal temperature condition should be searched in this range.

Conclusions:

1. In accordance with the analysis presented the lithium jet injection technique might have good perspectives for tokamak-reactor performance. For ITER and DEMO conditions the mantle and SOL might re-radiate more than a half of the total power with ~ 0.1 g/s lithium injection even in coronal approximation.
2. Stimulating the lithium recycling in the SOL volume by charge exchange and recombination processes may improve the situation significantly.
3. Although that Z_{eff} grows towards plasma periphery due to lithium injection, the volume averaged value does not exceed the 1.7 acceptable level under assumption of the 0.1 Li recycling coefficient. This assumption should be checked experimentally, which is planned in T-10 tokamak experiments.
4. The analytic solutions for the density and temperature profiles of different components demonstrate a variety of shapes and significance of simultaneous accounting the terms responsible for particle diffusion, anomalous pinch and sources.
5. First experiments with Li jet on T-10 have been performed at 100 mg/s injection rate and have demonstrated opportunities of the technology for emergency shutdown.

References

[1] POST, D., et al., Journal of Nuclear Materials, **220-222** (1995) 1014-1018.
[2] Progress in the ITER Physics Basis, Nucl. Fusion **47** (2007) S45.
[3] ZAKHAROV, L., “Magnetic DEMO, CTF fusion reactors and their strategy”, http://w3.pppl.gov/~zakharov/030106DEMO.pdf
[4] EVTIKHIN, V.A., et al., PPCF **44** (2002) 955-977.
[5] KUTEEV, B.V., et al., (Proc. 21st Int. Conf. Chengdu, 2006), CD-ROM file EX/P4-13.
[6] TIMOKHIN, V., et al., 33nd EPS Conference on Plasma Phys., Roma, 19 - 23 June 2006, P-4.092.
[7] TIMOKHIN, V., et al., 34th EPS Conference on Plasma Phys., Warsaw, July 2-6 2007, Paper P1-205.
[8] WESSON J., Tokamaks, Clarendon Press, Oxford (2004).
[9] REBUT, P., 33nd EPS Conference on Plasma Phys., Roma, 19 - 23 June 2006.