Numerical Modeling of Li limiter Experiments in T-11M tokamak

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Abstract. Numerical study of the SOL in the T-11M with the use of a combination of edge and core plasma codes, SOL-DINA and DINA is carried out. Modeling results are compared with experiment for ohmic heating discharges with Li and Carbon limiter in T-11M tokamak. Temperatures, electron density and lithium distribution in SOL are compared. Values for anomalous radial diffusion coefficients of Li ions and heat conductivity are tested against experiment.

1. Introduction.

The problem of tokamak plasma-facing surfaces protection against erosion caused by interaction with plasma becomes more and more important now. Liquid lithium is one of the candidates of the materials that can be used for making a protective self-recovering surface inside the tokamak vessel. Lithium as a plasma-facing material has attractive features, including a reduction in the recycling of hydrogen species and the potential for withstanding high heat and neutron fluxes in fusion reactors. Excellent effects on plasma performance with lithium-coated plasma-facing components (PFC’s) have been demonstrated on many fusion devices, including TFTR [1], FTU [2] and T-11M [3]. Using a liquid-lithium-filled tray as a limiter, the CDX-U device achieved very significant enhancement in the confinement time of ohmically heating plasmas [4]. The recent NSTX experiments have shown the significant and recurring benefits of lithium PFC coatings on divertor plasma performance in both L- and H- mode regimes heated by neutral beams [5].

This paper presents the results of numerical investigation of the radial and poloidal lithium distribution in the SOL in T-11M tokamak with the lithium limiter. Lithium limiters may help to solve the very demanding heat removal, particle removal, and erosion issues of fusion plasma/surface interactions. Described experiments were performed on T-11M tokamak in an ohmic mode [6, 7]. The intensity of neutral lithium spectral line (Li I =670,8nm) was measured on the lithium and graphite limiters surfaces. The distribution of lithium in a SOL can be obtained by measuring the Li I spectral line intensity on the moving C-limiter surface as a function of its position. A 2D multi-fluid code SOL-DINA [8] has been modified to take into account the T-11M tokamak specific parameters: geometry, magnetic field, transport coefficients and to include Li atomic rates and energy loss parameters. This code was supplemented with Lithium data and applied for computation of Lithium distribution in hydrogen SOL plasma of the T-11M tokamak. Numerical study of the SOL in the T-11M with the use of a combination of edge and core plasma codes, SOL-DINA and DINA [9] is carried out.

2. Li limiter Experiments in T-11M tokamak

Presented work is to study by numerically of the physical processes of Lithium transport in SOL and to develop a quantitative model for determination of fractions circulatory and migratory ions. Presented investigation results correspond the T-11M experiments on determination of the radial distribution fluxes in the SOL in the shade of the limiter [10]. Two limiters were used: lithium, which was used as main limiter, located at the fixed radial position 17.5 cm, and auxiliary graphite limiter, which radial position was varied from 19 to 25 cm. The cross-section of the vacuum vessel containing limiters and diagnostics is presented on Fig. 1. By means of optical diagnostics (Li I spectral line detectors) the intensity of neutral lithium spectral line (Li I λ=670.8 nm) was measured on the lithium and graphite limiters surfaces simultaneously. Since the intensity of neutral atom spectral line is proportional to the flux of neutrals into the plasma, the distribution of lithium in the SOL can be obtained by measuring the Li I spectral line intensity on the C-limiter surface as a function of its position. The radial distribution obtained consists of two parts, which can be fitted by two exponents with different characteristic lengths λ_1=2.2 cm (inner zone) and λ_2=0.7 cm (outer zone) (Fig. 2). During the experiment, the position of Li limiter was fixed (Z_{Li}=17.5 cm), as well as other plasma parameters that can significantly influence the transport of Li (plasma current, density, plasma axis position).

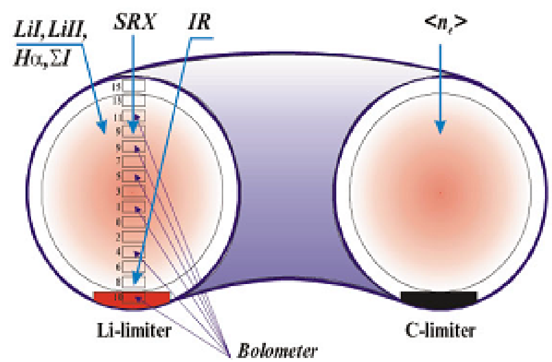

Fig. 1 Location of limiters and diagnostics in T-11M tokamak

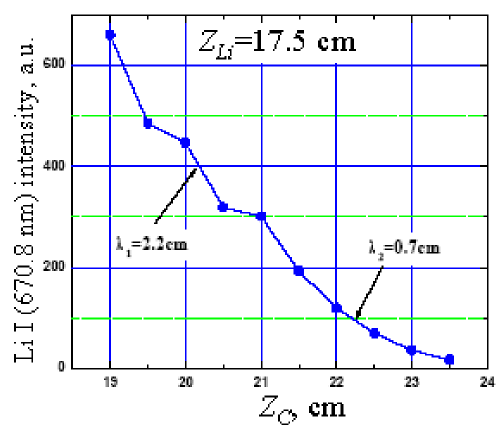

Fig. 2 Lithium flux radial distribution in the SOL plasma of T-11M [10]

3. The model

Geometry

The geometry of the boundary layer of tokamak plasma with toroidal limiter is sketched in Fig. 3. Here the core plasma, transition layer (TL) inside of last close magnetic surface (LCMS) and SOL areas are shown. The coordinates x, y and z correspond to the poloidal, radial and toroidal directions, respectively. The parallel (||) direction is along the total magnetic field, the perpendicular ($\perp$) direction is restricted to be within the magnetic flux surface, such that the (||,$\perp$)-axes are rotated against the (z, x)-axes by a few degrees. In the SOL-DINA code, the self-consistent 2D time-dependant system of equations for conservation of particles and parallel momentum, temperature equations for electrons and ions, and diffusion equations for main and impurity neutrals inside of both SOL and TL areas are solved, which was compared with UEDGE code [11]. System of equations is primarily based on the classical transport equations by Braginskij [12]. The transport along field lines is assumed to be classical, the radial transport is assumed to be anomalous with prescribed radial transport coefficients of the order of Bohm diffusion. The dynamics of neutrals in the SOL is described by 2D diffusion model, which accounts in a self-consistent way for recycling of deuterium ions and for sputtering and self-sputtering of impurity ions at the limiter plates. Hydrogen and impurity atomic rates and energy losses are calculated using ATSV code [13].

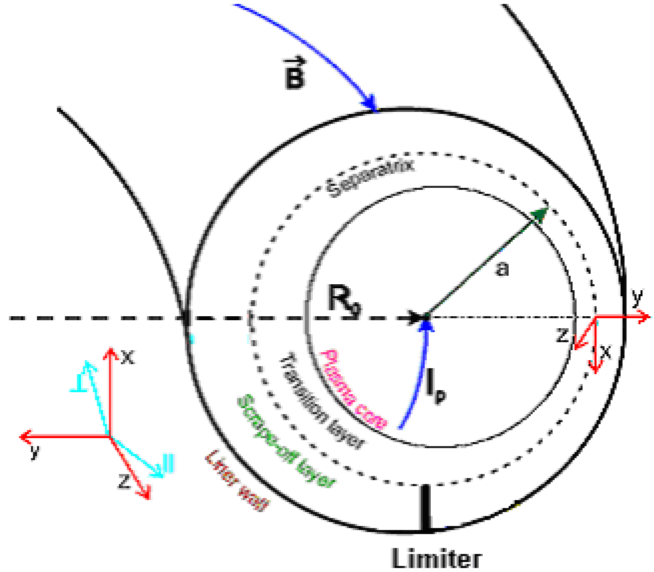

Fig. 3 Boundary layer geometry for tokamak plasma with toroidal limiter

For every ion species *a*=*i*, *j* we solve the continuity, parallel momentum and energy equations. Here *a*=*i* for deuterium ions and *a*=*j* for the different charge states of impurity ions (*j*=1, …, Z_{max}; Z_{max} is the impurity atomic number).

Equations for charged particles

Continuity equation (particle balance):

$$\frac{\partial n_a}{\partial t} + div\left(n_a \vec{V}_a\right) = S_a \qquad (1)$$

Here n_a is the density of ions (*a*=*i*, *j*) or electrons (*a*=*e*), $\vec{V}_a = V_{\|}\vec{h} + \vec{V}_{\perp}$ is the velocity of ions or electrons, $V_{\|}$ is the parallel velocity component, $\vec{V}_{\perp}$ is the perpendicular velocity component, $\vec{V}_{\perp} = -D_a \nabla_{\perp} n_a$, where D_a is the anomalous diffusion coefficient, S_a is the source of particles due to ionization, recombination and charge exchange.

Equation of motion (momentum balance):

$$\frac{\partial}{\partial t}\left(m_a n_a V_{\|}\right) + div\left(n_a m_a V_{\|}\vec{V}_a + p_a + \overleftrightarrow{\Pi}_a\right) = R_{\|}^a + \Sigma_{\|} \quad , \qquad (2)$$

Here m_a is the mass of particles, p_a is the pressure, $R_{\|}^a = R_{\|}^V + R_{\|}^T$ is the combination of friction and thermal forces, $\overleftrightarrow{\Pi}_a$ is the viscosity tensor, $\Sigma_{\|}$ is the source of momentum.

All ion species are assumed to have the same common temperature T_i=T_a, which might differ from the electron temperature $T_e \neq T_i$. Consequently only the following two energy equations are considered:

$$\frac{3}{2}\frac{\partial n_e T_e}{\partial t} + div\left(\frac{5}{2}n_e T_e \vec{V}_e + \vec{q}_e\right) = -Q_{ei} - Q_e \tag{3}$$

$$\frac{\partial}{\partial t}\sum_a \left(\frac{3}{2}n_a T_i\right) + div\sum_a\left(\frac{5}{2}n_a T_i \vec{V}_a + \vec{q}_a\right) = Q_{ei} \tag{4}$$

Here Q_{ei} is the collisional energy exchange between electrons and ions, Q_e is the energy losses to the ionization and excitation of deuterium and impurity; $\vec{q}_a = -\left(k_\parallel^a \nabla_\parallel T_a + k_\perp^a \nabla_\perp T_a\right)$, $k_\parallel^a$ is the classical and $k_\perp^a$ is anomalous thermoconductivity coefficients, $\vec{q}_e = \vec{q}_a$, where a=e.

Equations for neutrals

Balance of deuterium neutrals n_i^0 is described by equation:

$$\frac{\partial n_i^0}{\partial t} + div\left(n_i^0 \vec{V}_i^0\right) = n_e\left(n_i R_i - n_i^0 I_i\right) - n_i^0 \sum n_j C_j \text{ , } (i>1) \tag{5}$$

Here R_i is the photo-recombination rate, I_i is the ionization by electron shock rate and C_j is the charge exchange rates, $\vec{V}_i^0$ is the deuterium neutrals velocity, which is equal in diffusion approximation $\vec{V}_i^0 = -T_i \nabla n_i^0 / \left[m_i n_i^0\left(n_i C_i + \sum C_j n_j + n_e I_i\right)\right]$.

Similarly for lithium neutrals n_j^0 the balance equation is:

$$\frac{\partial n_j^0}{\partial t} + div\left(n_j^0 \vec{V}_j^0\right) = n_e\left(n_j^1 R_j^1 - n_j^0 I_j^0\right) \tag{6}$$

where $\vec{V}_j^0 = -T_i \nabla n_j^0 / \left[m_j n_j^0\left(n_e I_j^0 + n_j^1 C_j^0 + \left(n_i^1 + n_i^0\right) I\right)\right]$ is the lithium neutrals velocity and I is the elastic collision rate.

Boundary and initial conditions

Covered transition layer and SOL area grid is shown in Fig. 4, numerical mesh and boundary conditions are pictured in Fig. 5. Here θ is the poloidal angle. The value of θ=π corresponds to the limiter location. Width of transition layer is chosen to be 2 cm. From core plasma the value of heat power Q_{inp}=70 kW is coming to the transition layer. That value is corresponds to the ohmic plasma with $I_p \approx 70$ kA. The value of 70 kW consists of 40 kW in electron channel and 30 kW in ion one.

In the wall the recycling of deuterium is assumed to be 50% and recycling of Li is equal 0. In the limiter the recycling of

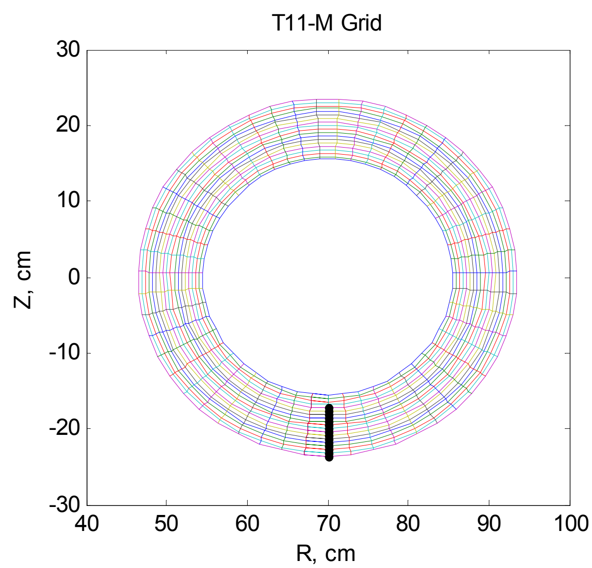

Fig. 4 Grid of transition layer and SOL area

deuterium is assumed to be 100%. Spattering coefficient of Li in the limiter is assumed to be 25%. Both electron and ion temperatures in the wall are assumed to be 1 eV. Values of $\lambda_n=\lambda_T$ are assumed to be equal 1 cm, δ_e=5 и δ_a=2.5. Values of n_i in the boundary between the core plasma and transition layer is taken $0.6\cdot10^{13}$ cm^{-3}, $\Gamma_j = \Gamma_a^0 = 0$. Because of consideration of the stationary solution in the paper we are using the arbitrary initial conditions.

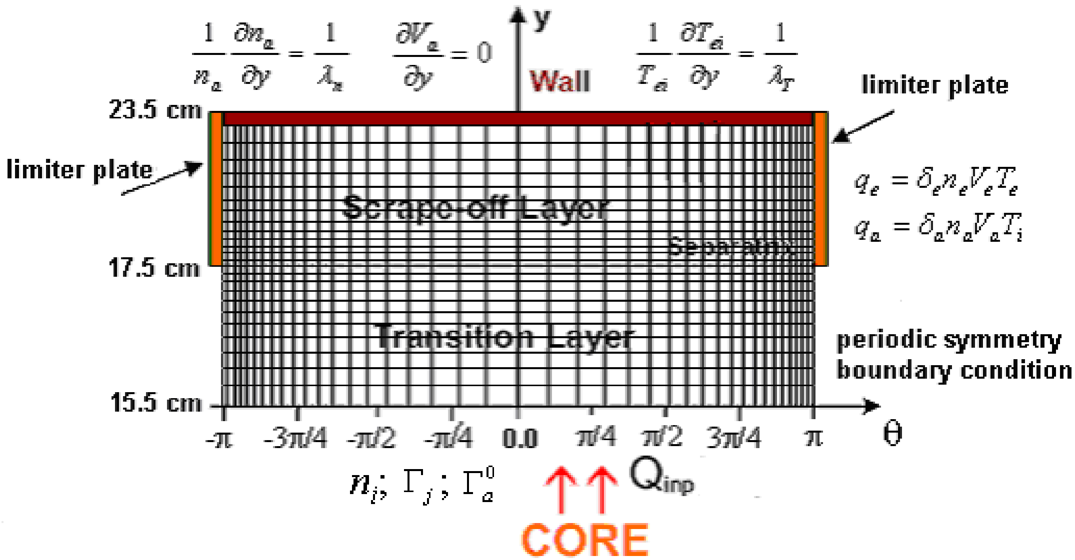

Fig. 5 Numerical mesh and boundary conditions

4. Results and comparison with experiment

Simulation results are performed for T-11M [3] tokamak, which has the plasma major and minor radii 0.7 m and 0.175 m, respectively. Toroidal field in the plasma axis is 1.2 T and plasma current is 70 kA. Simulations have carried out with the value of $k_\perp^a$, which to be around 0.7 m^2/s, and corresponds to the Bohm level. Simulation results include the two kinds of the plasma temperatures and particle densities data. Firstly we present their stationary profiles along

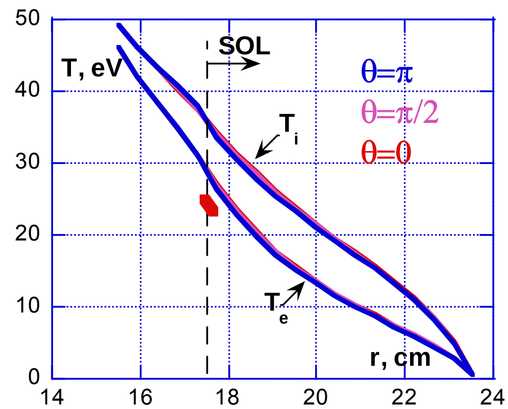

Fig. 6 T_e and T_i profiles

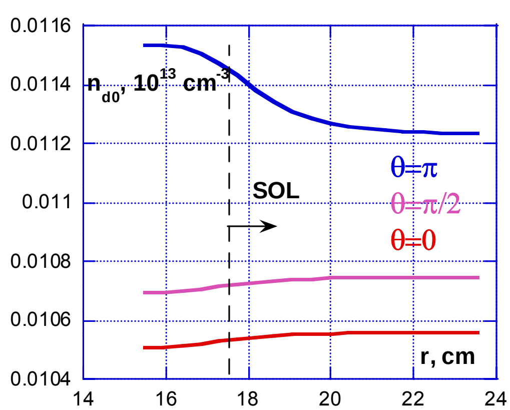

Fig. 7 Profiles of deuterium neutrals

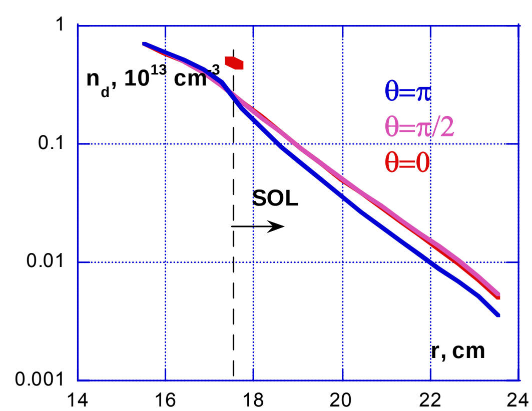

Fig. 8 Profiles of deuterium ions

the minor radius r for the three values of the poloidal angle θ. Secondly we present the time evolutions of the volume averaged plasma temperatures and particle densities. In the Fig. 6 the profiles of electron and ion temperatures are presented. The Figs. 7 and 8 show the profiles of neutral and ion deuterium densities. The Figs. 9 and 10 present the profiles of neutral and ion Lithium densities. Dotted line in the pictures shows the minor radius of separatrix (r=17.5 cm).

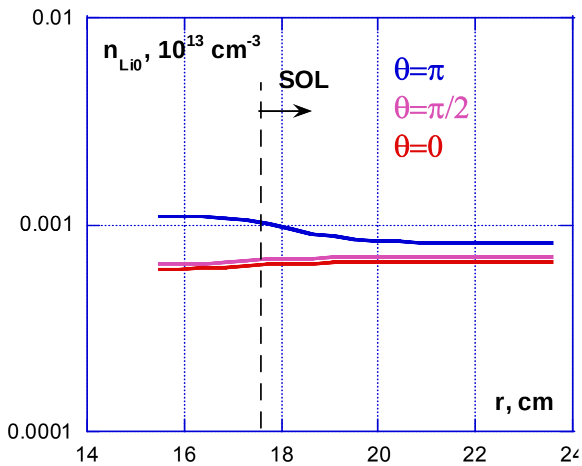

Fig. 9 Profiles of Lithium neutrals

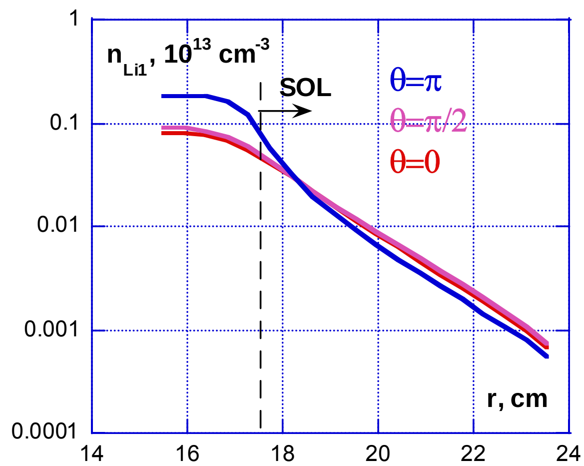

Fig. 10 Profiles of Lithium ions

One can see that the ion density distributions together with the both electron and ion temperature distributions do not depend strongly on poloidal angle θ whereas there is the irregularity of neutral distributions along the angle: the maximum of both deuterium and Lithium neutrals is located nearby limiter.

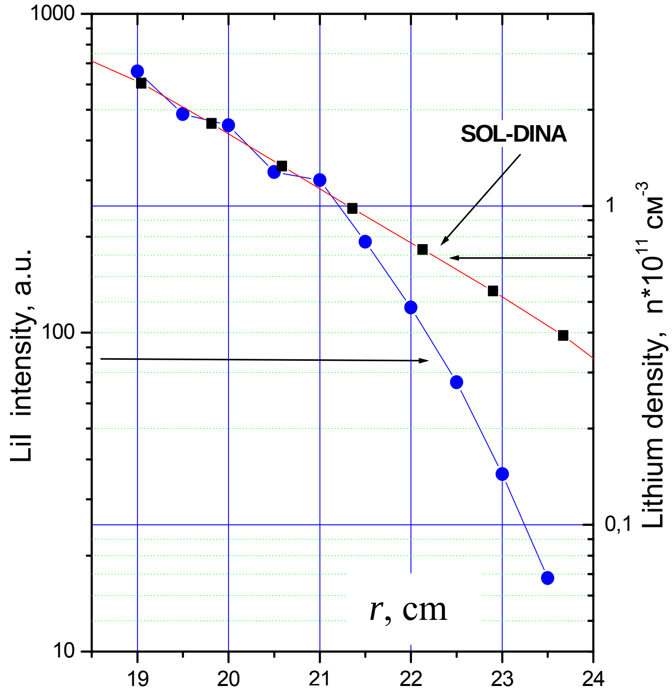

Fig. 11 Comparison between the experimental and simulated Lithium ion distributions in SOL

Red points in the Fig. 6 and 8 denotes the measurement data in the boundary between plasma and SOL – the electron temperature is measured to be around 25 eV and electron density (it is close to deuterium ion density) is measured to be around $0.4 \cdot 10^{13}$ cm^{-3}. These results were turned out from the volt-ampere characteristic measurements of special discharges between the lithium limiter and vacuum vessel. One can see that they are close to the simulated values.

Fig.11 demonstrates the appropriate accordance between experimental and modeled distribution of the Lithium ions inside of SOL area for $r \leq 21$ cm. Steeper decrease of the Lithium ion density in the experiment is explained by location of the ICRH antenna 22 cm apart from plasma column axis [10], which was not taken into account in the SOL-DINA modeling.

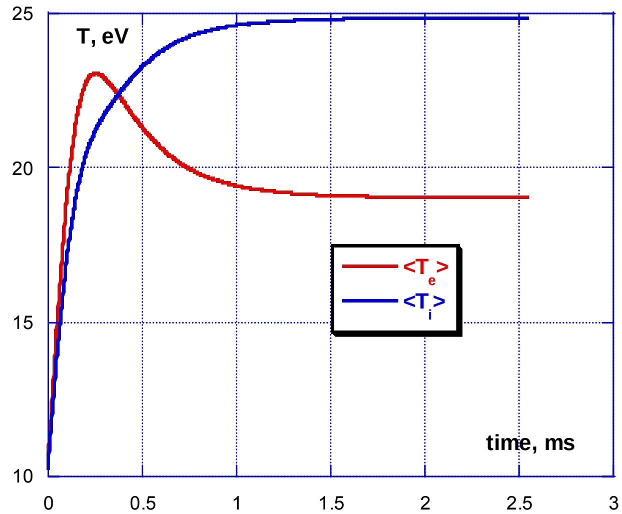

Fig. 12 Time traces of $<T_e>$ and $<T_i>$

In Figs. 12-14 the time traces of the volume averaged plasma temperatures and particle densities are presented.

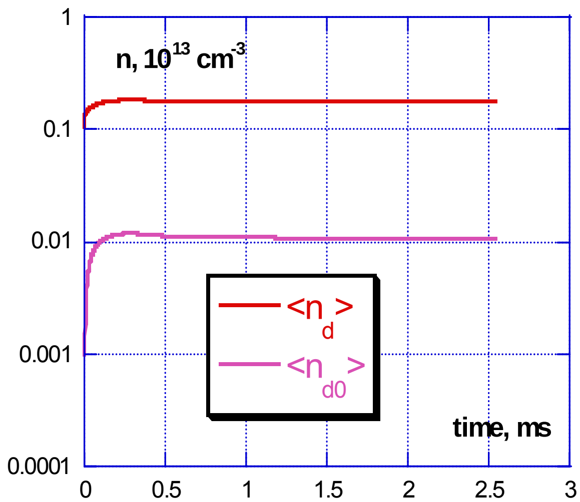

Fig. 13 Time traces of ions and neutral density of deuterium

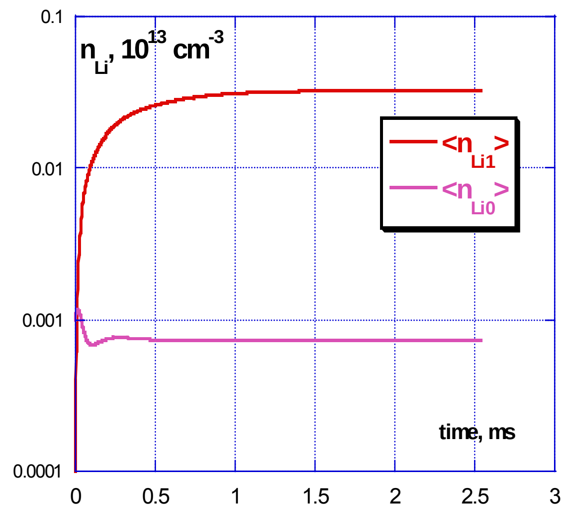

Fig. 14 Time traces of ions and neutral density of Lithium

From the time evolution results one can see that the characteristic time of unsteady process is about 1 ms.

5. Conclusions

The new 2D code SOL-DINA was modified for studying of physical processes in SOL area of tokamak with lithium limiter. Updating of SOL-DINA code is performed by inclusion of the part of area of edge plasma with the closed magnetic surfaces. The test calculations are showing the good consent of the some modeling results with experimental data. It concerns the values of electron temperature and electron density in the boundary between the plasma and SOL, which are 25 eV and $0.4\cdot10^{13}$ cm^{-3} correspondingly.

On Fig.11 two curves are presented: density of lithium in absolute units and intensity of lithium line in relative units, which is approximately proportional to lithium density. The inclination of curves on a partially coincides (for $r \leq 21$cm) and misses on radiuses more 22cm. This divergence is caused by that the simplified model does not consider yet the influence of HF antenna as the second limiter. Thus, the obtained data shows, that the process of lithium transport in a scrap-of-layer is caused basically by abnormal transport of lithium ions with factor close to Bohm level (~1 m^2/s).

It is shown that the ion density distributions and both electron and ion temperature distributions do not depend strongly on poloidal angle θ whereas there is the irregularity of neutral distributions along the angle: the maximum of both deuterium and Lithium neutrals is located nearby limiter. Beside the characteristic time of unsteady process is found out about 1 ms.

Because the T-11M lithium limiter is located in the single toroidal angle the distribution of the density plasma particles around the limiter area have to have a three-dimensional view. In future the three-dimensional non-stationary code for modeling of the limiter dispersion and behavior of atoms and ions of lithium near the limiter is supposed to be created. Results of such three-dimensional simulations can be used as boundary conditions for SOL-DINA code.

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