LITHIUM EXPERIMENT IN TOKAMAK T-11M AND CONCEPT OF LIMITER TOKAMAK-REACTOR

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The paper suggests the addition or replacement of the magnetic divertor by lithium limiter as producer of irradiated blanket, which should prevent tokamak first wall and divertor plates from local high power loads. The main physical basis of this idea is lithium localization close plasma boundary and poor penetration into plasma center in process of its puffing, as was shown in tokamak experiments. The mushroom tokamak lithium limiter with capillary porous system (CPS) can be used for this aim. The hot part of this limiter can work as lithium emitter to tokamak plasma and cold parts can work as collectors of lithium flowing out of the plasma column. The surface capillary forces of limiter CPS will return the collected liquid lithium from cold to hot parts of limiter again and close the lithium circulation "limiter-plasma-limiter".

The bulk of the power flowing out of the plasma core can be dissipated by non-coronal lithium radiation in the blanket and scrape-off layer. Such scheme was established partly in T-11M experiments with CPS rail limiters. In paper the main results of lithium behavior and its control in T-11M are discussed.

PACS: 52.55.Fa

An application of magnetic divertor to the tokamak configuration is well-known tool for the suppression of impurity efflux from the first wall of vacuum vessel into the plasma core due to the plasma-surface interaction (PSI). The impurity atoms in the scrape-off layer (SOL) are ionized by the electron impact, and move along the destroyed magnetic surface to the wall or diffuse into the plasma column.

The main function of the divertor is to enlarge the SOL thickness for effective capture of the impurity efflux from the wall, and its redirection into the divertor SOL. The "mushroom-type" limiters (Fig.1) also are able to perform the same function. Main advantage of such limiters is ability to catch the impurity flux from wall by "mushroom leg" area. Its disadvantage is an open PSI region at the top ("mushrooms hat") with high power load.

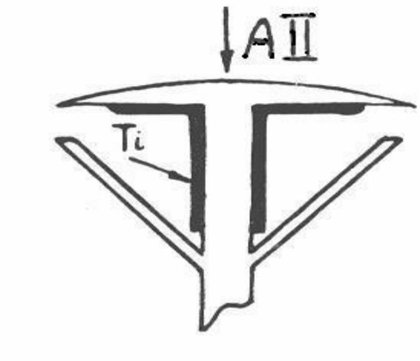

Fig.1. Scheme of "mushroom limiter" [1], AII array is direction to "hat" from hot plasma

The sputtered or evaporated impurity atoms have an opportunity of direct penetration into the plasma. Relatively low ionization potential and recombination rate of multi-ionized atoms in low-density plasma result in their localization at the plasma boundary and subsequent diffusion towards the hot center. The last process is enhanced by neoclassic accumulation phenomena resulted from the "friction" between the hydrogen isotope ions and the impurities with Z>1 (Braginsky's effect). This effect, in particular, explains the increase of Z_{eff} value in the plasma axis region after noble gas puffing (with Z>1) for cooling of the peripheral plasma and reduction of the heat loading of the divertor plates.

Very high second ionization potential (~75.6 eV) and relatively low first one (~5.4 eV) are an outstanding property of lithium in comparison to other impurities. Hence it should have mostly a singly ionized state at the plasma periphery with T_e<15…20 eV, and therefore it is much less subjected to the Braginsky's effect. Perhaps, this lithium property is reason of low lithium penetration into the plasma core after peripheral injection. This fundamental feature of lithium behavior had been noticed in all tokamak experiments with significant lithium injection (TFTR, T-11M, CDX-U, and recently FTU). The concept of decrease of the first wall energy load by uniform Li re-radiation is based upon this Li property.

Lithium impurity accumulated at the plasma periphery provides so-called radiation blanket around the plasma. The configuration with the lithium peripheral plasma layer had been demonstrated in the experiments at the T-11M tokamak with the rail liquid lithium limiter (LLL) with thin (<1 mm) Li-filled capillary-porous structure (CPS) [2,3,4]. The CPS edges are plunged into the liquid Li reservoir for the refilling of evaporated Li in the hot plasma-facing spot (Fig 2). Some fraction of lithium finally returns back to the colder parts of LLL, and another one is absorbed by the first wall and also by the surface of the secondary limiter, which could be used for the variation of Li impurity lifetime. If the average Li ion lifetime τ in this region is much less than the time of transition to ionization equilibrium state (coronal equilibrium) the intensity of lithium radiation (non coronal radiation) could be 100-1000 times higher in comparison to the equilibrium level. The level of the blanket radiation could be controlled by the variation of τ. In T-11M experiment the Li impurity at the plasma periphery provided the re-radiation level up to 80% of total heat power in Ohmic mode (~130 kW for 0.2 s plasma discharge). The typical spatial distributions of plasma radiation for discharges with Li and C limiters are shown in Fig.3. The main radiation power in Li case was localized in thin (5cm) layer close plasma boundary. The lithium spectral line radiation (LiI, LiII, LiIII) and SXR from plasma center showed the quasi steady state character. Very low impurity concentration at the plasma axis ($Z_{eff} \approx 1.1$) had been observed in this phase of T-11M discharges.

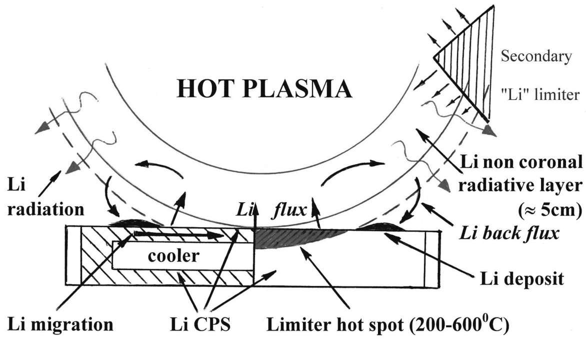

Fig.2. Liquid lithium limiter function diagram [4]

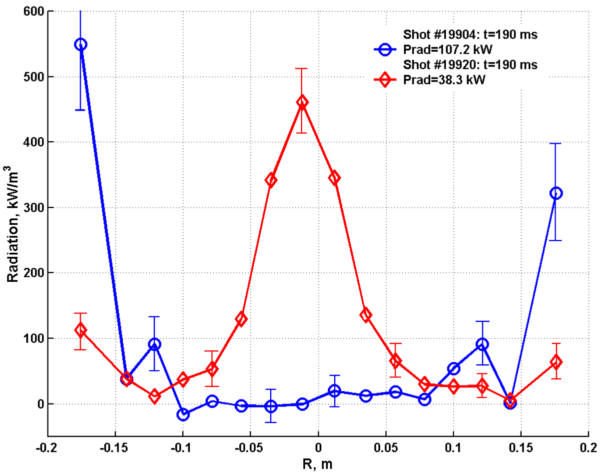

Fig.3. Radiative power profiles at the moment t = 190 ms for two similar C-limiter and Li limiter shots. The average plasma density $<n_e> \sim 2.2 \cdot 10^{19} m^{-3}$ for both cases. Diamond (red) points-C limiter, circle (blue) points -Li limiter [4]

If the limiter temperature was lower than Li melting point (180.6ºC), the visible fraction of lithium impurity was deposited at the cold edges of LLL, while the plasma facing central zone had been depleted revealing the stainless steel mesh in the center of the limiter (Fig.4).

Fig.4. Li limiter surface after the exposition below the melting point

Smooth Li surface had been restored by heating up above the melting point owing to capillary forces resulting in the Li circulation from the colder collector to central hot emitter zone (Fig.5).

This effect might be useful for application in the tokamak-reactor ITER with "mushroom-type" lithium limiters located in the equatorial ports for example [4]. According to the experimental results obtained at the T-11M, an ultimate temperature of the hot Li emitting zone should not exceed 500…600ºC. The colder "legs" of the LLL "mushroom" might be used as a Li collector. The surface tension forces of CPS can return the deposited lithium from "legs" to "hat'.

Fig.5. Li limiter surface after the heating above the melting point

As results we can close the lithium circuit: "hat"-plasma-"leg"-CPS-"hat". The non coronal radiation of lithium ions during its plasma wandering should work as virtual limiter. In condition of intensive plasma boundary cooling by lithium radiation we can hope to decrease the energy flux to "hat" area up to low magnitude, which can be avoided by water cooling. That means that the "hat" area in such conditions can work as lithium emitter to plasma and colder "leg" area as collector of lithium ions out flux to wall.

One of the most critical point of lithium limiter concept is control of Li ion lifetime in irradiative blanket (τ control) for dissipation of the power flowing out of the plasma. The greater is τ the more should be lithium density close a plasma periphery and the increase of lithium influx to plasma core, if the power flow will be constant. The well known method of magnetic field line ergodization [5] as method of τ (and lithium density) decrease can be suggested. The special winding in or close plasma chamber will be needed for its realization. Unfortunately it can't be used really in reactor condition. We suggested the replacement of helical coils by currents, induced in plasma periphery between lithium limiters. Main objection to this suggestion was misgiving of high lithium out flux to plasma during such operation. The test experiment was performed in T-11M (Fig.6).

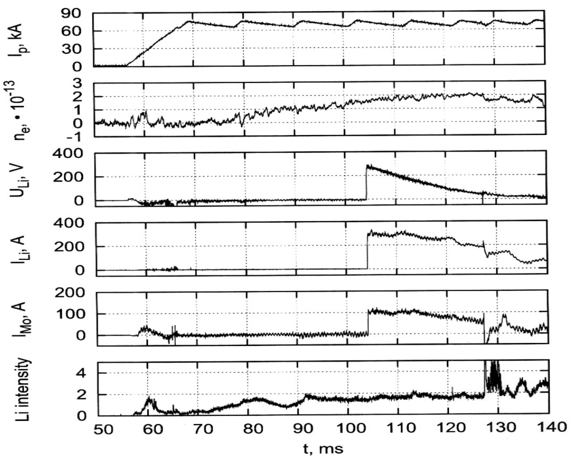

Fig. 6. Lithium limiter biasing in T-11M: Total current I_p, density, voltage spike U_{Li} (positive), I_{Li} and I_{Mo} and Li(I) intensity

The positive bias voltage U_{Li} (≤300V) was applied between Li limiter and plasma chamber. The similar Mo rail limiter (d=0.2m) was situated in opposite ports of T-11M ($\Delta\varphi=180^0,\Delta\theta=180^0$) and was connected by small resistor ($1.5 \times 10^{-2}\ \Omega$) with plasma chamber. The saturation type electrical current (I_{Mo}) equal 100 A was measured between both rail limiters during voltage puls. As we can see, the indicator of lithium emission from limiter - Li(I) intensity – was almost non sensitive to current pulse. The alteration of applied voltage polarity does not change remarkably the lithium emission. That means the electrical biasing of lithium limiters can be used for current generation in tokamak boundary plasma and excitation of magnetic perturbation in chamber without the visible increase of lithium emission. The length of magnetic line connected both limiter was equal 6m.

This lithium limiter concept has also an additional advantage. That is the possible separation of He atoms from the mixture with hydrogen isotopes. Of course, the details of LLL design for this purpose are to be developed more definitely after getting more relevant experience at the large tokamaks.

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ЭКСПЕРИМЕНТЫ С ЛИТИЕМ В ТОКАМАКЕ Т-11М И КОНЦЕПЦИЯ ЛИМИТЕРНОГО ТОКАМАКА-РЕАКТОРА

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Предлагается замена или дополнение магнитного дивертора литиевым лимитером, создающим излучающий бланкет, который должен разгрузить первую стенку и диверторные пластины реактора от чрезмерных тепловых нагрузок. В основе этой идеи лежат две обнаруженные экспериментальные особенности поведения лития: локализация лития вблизи границы шнура при его инжекции с периферии и его сравнительно незначительное проникновение в центр шнура. Технически для замены предлагается использовать «грибковый» лимитер с капиллярной пористой структурой (КПС), заполненной литием. Горячая часть такого лимитера («шляпка») может работать как инжектор лития, а холодная («ножка») как коллектор. Силы поверхностного натяжения должны возвращать жидкий литий с холодной части лимитера на горячую, замыкая тем самым контур циркуляции лития «лимитер – плазма – лимитер». При этом основной поток тепла, выходящего из плазмы, должен трансформироваться в некорональное излучение лития и передаваться равномерно на первую стенку реактора. Такая схема была реализована частично в опытах на токамаке Т-3М. Обсуждается поведение лития, обнаруженное в этих экспериментах и возможный способ его контроля.

ЕКСПЕРИМЕНТИ З ЛІТІЄМ У ТОКАМАЦІ Т-11М І КОНЦЕПЦІЯ ЛІМІТЕРНОГО ТОКАМАКА-РЕАКТОРА

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Пропонується заміна або доповнення магнітного дивертора літієвим лімітером, що створює випромінюючий бланкет, який повинний розвантажити першу стінку і диверторні пластини реактора від надмірних теплових навантажень. В основі цієї ідеї лежать дві виявлені експериментальні особливості поводження літію: локалізація літію поблизу межи шнура при його інжекції з периферії і його порівняно незначне проникнення в центр шнура. Технічно для заміни пропонується використовувати «грибковий» лімітер з капілярною пористою структурою (КПС), заповненою літієм. Гаряча частина такого лімітера («капелюшок») може працювати як інжектор літію, а холодна («ніжка») як колектор. Сили поверхневого натягу повинні повертати рідкий літій з холодної частини лімітера на гарячу, замикаючи тим самим контур циркуляції літію «лімітер – плазма – лімітер». При цьому основний потік тепла, що виходить із плазми, повинний трансформуватися в некорональне випромінювання літію і передаватися рівномірно на першу стінку реактора. Така схема була реалізована частково в досвідах на токамаці Т-3М. Обговорюється поводження літію, виявлене в цих експериментах і можливий спосіб його контролю.