

# Low Recycling Divertor for JET Burning Plasma Regime ( $P_{DT} > 25$ MW, $Q_{DT} > 5$ ), Insensitive to Plasma Physics

Leonid E. Zakharov<sup>1</sup>, Jean Paul Allain, Samuel X. Bennett, Muhammad A. E. Abdelghany, and Daniel G. Bulgadaryan<sup>2</sup>

**Abstract**—Lasting for already six decades, the current high recycling approach to tokamak fusion is still unable to demonstrate the fusion gain factor  $Q_{DT} = 1$ , which is the minimal milestone on the path to fusion energy. Clearly, an alternative approach is needed. Recently, such an approach was proposed as the low recycling regime with plasma pumping by continuously flowing liquid lithium (24/7-FLiLi) and physics of a burning plasma was described in application to the JET tokamak. This article complements the plasma physics by consideration of feasibility and specifics of the low recycling divertor (LRD). Its significant difference from existing high recycling divertors is in the absence of a sheath potential on the open field lines, resulting in small angle impingement to the target surfaces by high energy plasma particles. For the first time, this article presents the design guidance for LRD suitable for JET-like tokamak. Being the only new element in the machine, the LRD with other existing JET facilities, e.g., neutral beam power (NBI)  $P_{NBI} = 4$  MW,  $E_{NBI} = 120$  keV, opens up the opportunity for demonstration of fusion power  $P_{DT} > 20$  MW,  $Q_{DT} > 5$  and of outstanding tritium burn up, exceeding 7%.

**Index Terms**—Burning plasma, divertor, low recycling, tokamak.

## I. INTRODUCTION

THE first tokamak was built in 1958 in Kurchatov (Moscow) by N. A. Yavlinski and since 1968 it has been accepted worldwide as a leader in plasma confinement for fusion energy development. The fast progress in tokamak

research was culminated in the mid-1990s by deuterium-tritium (DT) experiments on TFTR (PPPL, Princeton, USA) [1] and JET (JET Joint Undertaking, Abingdon, U.K.) [2] where the first appreciable fusion gain factor  $Q_{DT}$  of 0.25 and 0.6, respectively, was obtained. Despite this intermediate success, the tokamak fusion program, already more than 60 years old, remains incapable of demonstrating fusion gain factor  $Q_{DT} = 1$ . The most troublesome concern is the possible shutdown of the JET tokamak without demonstration of  $Q_{DT} = 1$  in the second or potentially third DT experiment. With such a scenario, this fusion milestone would be moved to unpredictable mid- or long-term future.

The main obstacle for high performance tokamak plasma is cooling of the plasma edge by neutral atoms given by the plasma particles escaping from the plasma edge and recycled on the material surfaces. Without particle pumping the recycling is close to 1 and leads to a low edge plasma temperature with peaked profile in the core, turbulence, bad confinement, and need for high external heating power. With high recycling, the path to burning plasma relies exclusively on enhancement of plasma size, magnetic field, plasma current as well as the heating power. Accordingly, the issues, which are tolerable at the present size machines, grow to real problems of plasma control in large machines and require the cutting edge technologies.

The high recycling regime of present tokamaks deviates from the original idea of magnetic fusion of insulating plasma from the walls. It is in good contact with walls. In fact, all the problems of magnetic fusion in demonstrating fusion power gain  $Q_{DT} = 1$  and higher are related to the cold plasma edge. Zakharov [3] explains this in more detail.

The alternative approach to tokamak fusion was prompted by TFTR [4] and T-11M (Troitsk, Russia) [5] experiments with lithium contacting the plasma and emerged as a new concept of tokamak fusion in 1998 when the fundamental role of plasma pumping by lithium was realized [6]. In 2005–2006 both magneto-hydrodynamic stabilization of plasma edge, including edge localized modes (ELMs), and sufficiency of neutral beam injection for fueling were understood. As a result, the plasma physics part of the new concept of tokamak fusion, called lithium wall fusion (LiWF) was completed [7]–[9].

Soon in 2012 the technology of continuously flowing liquid lithium system, or 24/7-FLiLi, was invented as a tool for

Manuscript received July 19, 2019; revised October 21, 2019; accepted November 6, 2019. Date of publication December 6, 2019; date of current version June 10, 2020. This work was supported in part by the Ministry of Education and Science of the Russian Federation under Grant 14.Y26.31.0008, in part by the U.S. Department of Energy under Grant DE-SC0019060, and in part by the Russian Science Foundation under Grant 17-12-01575. The review of this article was arranged by Senior Editor G. H. Neilson. (Corresponding author: Leonid Zakharov.)

L. E. Zakharov is with LiWFusion, Princeton, NJ 08543 USA, with the Department of Physics, University of Helsinki, 00100 Helsinki Finland, and also with the Institute of Laser and Plasma Technology, National Research Nuclear University MEPhI, 115409 Moscow, Russia (e-mail: lezprinceton@gmail.com).

J. P. Allain is with the Ken and Mary Alice Lindquist Department of Nuclear Engineering, Pennsylvania State University, State College, PA 16801 USA.

S. X. Bennett and M. A. E. Abdelghany are with the Department of Nuclear, Plasma and Radiological Engineering, University of Illinois at Urbana-Champaign, Champaign, IL 61820 USA.

D. G. Bulgadaryan is with the Department of Plasma Physics, National Research Nuclear University MEPhI, 115409 Moscow, Russia.

Color versions of one or more of the figures in this article are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TPS.2019.2953591

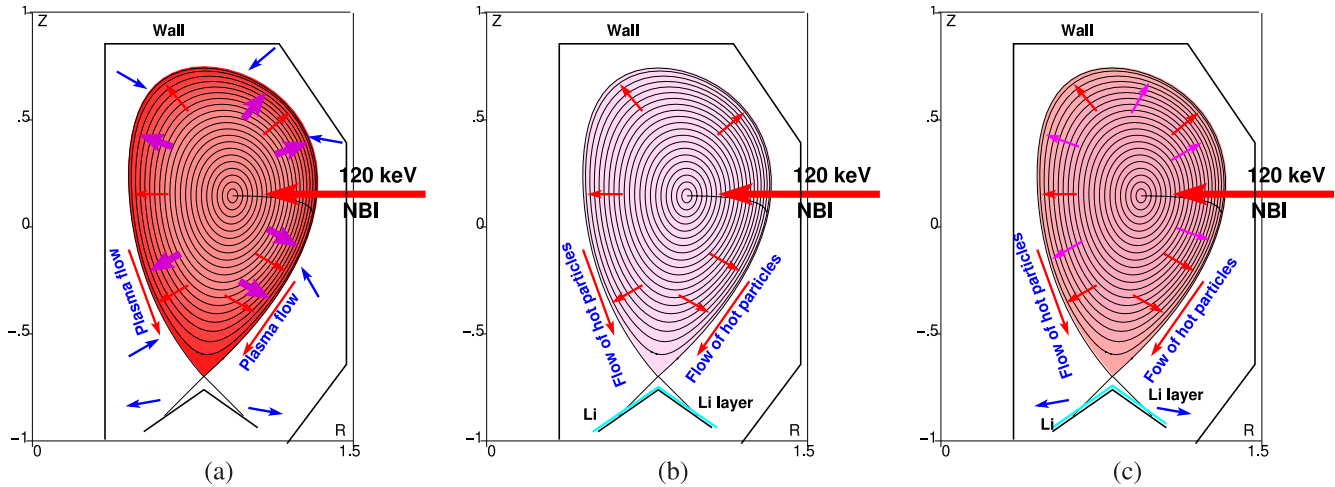


Fig. 1. Three plasma regimes determined by recycling. (a) High recycling regime with complicated plasma core and SoL physics, and typically high-Z plasma-surface interactions: cold plasma edge,  $T^{\text{edge}} \ll T^{\text{core}}$ , large thermal conduction,  $T^{\text{core}}$  is determined by  $P_{\text{NBI}}$ . (b) Idealized case of zero recycling and no plasma cooling with no thermal conduction energy losses or complicated physics of SoL:  $T^{\text{edge}} = E_{\text{NBI}}/5$ , only diffusion matters in zero losses, plasma density  $n^{\text{core}}$  is determined by  $P_{\text{NBI}}$ . (c) Realistic case of low recycling  $R^{\text{recycling}} \simeq 0.5$  with  $T^{\text{edge}} = E_{\text{NBI}}/10$ , negligible thermal conduction losses, and  $n^{\text{core}}$  determined by  $P_{\text{NBI}}$ . Plasma physics plays minor role in performance.

the implementation of the low recycling regime. The first 24/7-FLiLi limiter was installed on the EAST tokamaks [10] in ASIPP (Hefei, China) in 2014 and validated the basic design concept.

Recently, the performance of LiWF regime was analyzed for potential application for deuterium–tritium (DT) experiments on JET tokamak [3]. The results are astonishing:  $Q_{\text{DT}} > 5$ , fusion power  $P_{\text{DT}} > 25$  MW, tritium burn up more than 7% with neutral beam injection (NBI) power of only  $P_{\text{NBI}} = 4$  MW. They can justify the extension of the JET life time for demonstration of the robust burning plasma regime. In contrast to frequent objections to the use of Li in burning plasma because of tritium retention, 24/7-FLiLi is uniquely consistent with requirements of burning plasma and potentially could allow for realization of real-time tritium recycling (RTTR).

The next section of this article outlines the essence of physics of the LiWF regime, which is much simpler and more predictable than that of the present high recycling regime. Then the basic aspects of the 24/7-FLiLi technology are presented. The following section is focused on specifics of low recycling divertor (LRD) with  $R^{\text{recycling}} \simeq 0.5$  and design approaches. The summary emphasizes new strong motivation for about 4 years of extension of JET for demonstration of its not yet revealed burning plasma performance.

## II. BEST POSSIBLE CONFINEMENT REGIME

The present fusion program is guided by the assumption that energy confinement time is determined by the core thermal transport properties. This is valid for high recycling regimes. In fact, the energy confinement is much more sensitive to the level of recycling than to the core thermal transport. Up to now, suppression of plasma cooling by recycling was not utilized for enhancing confinement. Unlike uncontrollable core transport, the low level of recycling can be set up by a proper plasma pumping what leads to a totally different confinement regime.

Three frames in Fig. 1 explain this statement using an example of a tokamak plasma heated by 120 keV NBI.

In the case of high recycling  $R^{\text{recycling}} \simeq 1$ , Fig. 1(a), the NBI serves as a heating source for the plasma core. Most of the particles (blue arrows) are coming to the plasma edge as atoms through the recycling process (edge fueling). The core fueling by NBI is relatively small. Thin red arrows show relatively small diffusion inside and flow outside of plasma particles. Because of the intense plasma cooling the core temperature profile is peaked resulting in anomalously high turbulent thermal conduction and energy losses (illustrated by thick magenta arrows). The level of core temperature is determined by NBI power rather than by beam energy, resulting in high power going to the divertor target plates from the scrape off layer (SoL). The plasma physics of both plasma core and SoL is extremely complicated, thus, making plasma unpredictable and prone to disruptions.

The opposite case with complete pumping of plasma particles and zero recycling  $R^{\text{recycling}} = 0$  is shown in Fig. 1(b). Inside the plasma core the NBI atoms with energy  $E_{\text{NBI}} = 120$  keV are converted into ions and electrons and after their thermal relaxation into the plasma with temperature  $(T_i + T_e)/2 = 24$  keV, which is  $E_{\text{NBI}}/5$ . The temperature profile is automatically flat. The plasma particles diffuse (red arrows) from the confinement zone to the open field lines, cross the separatrix and stream to the target plates where they are consumed by a flowing Li layer. In this case, the NBI current together with the diffusion process determine the level of plasma density, while the temperature is determined exclusively by the  $E_{\text{NBI}}$ .

There are no cold particles in the system. The energy is lost from the plasma exclusively through particle diffusion, which is limited by the best confined component (typically, ions). This regime constitutes the best possible confinement regime.

In contrast to the “plasma physics driven fusion” of Fig. 1(a), in the zero recycling regime of Fig. 1(b) two most

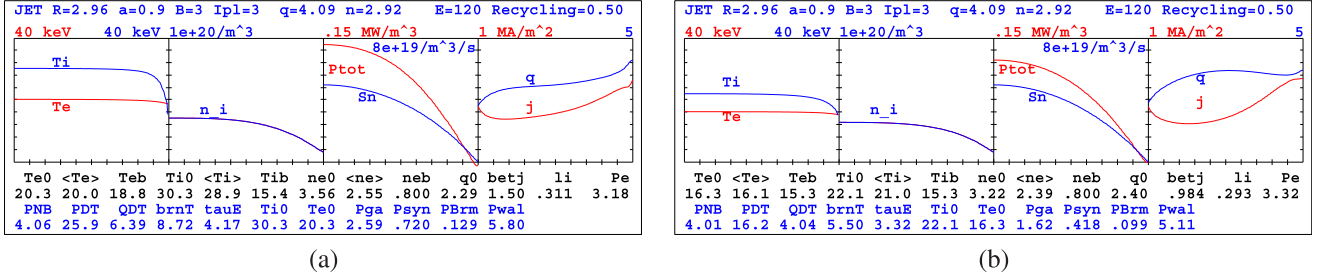


Fig. 2. Stationary radial profiles of burning plasma for low 0.5-recycling regime and the JET-like tokamak parameters. The horizontal axis in all frames is the normalized minor radius. The pairs of plots in each frame represent ion  $T_{i}$ , and electron  $T_{e}$  temperatures, densities  $n_{i}$ ,  $n_{e}$  (coinciding due to neglected He accumulation), deposition of total power  $P_{tot}$  and particle source  $S_n$  from NBI, and the central density  $j$  and the current safety factor  $q$ . (a) Reference case with diffusion and ion thermal conduction equal to ion neo-classical thermal conduction, the electron thermal conduction assumed 100 times larger. (b) Same with tenfold enhanced ion thermal conduction with only modest effect on performance potential.

controversial parts of tokamak plasma physics are absent: thermal transport in the core, and SoL plasma physics, which make the tokamak plasma unpredictable. The entire plasma, including the core and the edge, is well controlled by NBI and equilibrium system. Such a predictability represents the necessary condition for disruption avoidance. The absence of this property in the high recycling regime makes plasma prone to disruptions.

The third frame Fig. 1(c) illustrates the realistic low recycling situation with  $R^{\text{recycling}} \simeq 0.5$ . Regarding all properties, this regime is much closer to the zero recycling case than to high recycling. As will be shown later the important parameter is  $1 - R^{\text{recycling}}$ . The only difference with the idealized case is that the edge temperature is reduced by this factor and with the same 120 keV NBI energy it will be  $(1 - R^{\text{recycling}}) \cdot E_{\text{NBI}}/5 = 12$  keV.

The physics of the low recycling regime is pretty simple. The mean free path of plasma electrons  $\lambda_e$  and D-ions  $\lambda_i$  along the field line is given by

$$\lambda_{e,m} = 93 \cdot \frac{T_{e,\text{keV}}^2}{n_{20}} \quad \lambda_{i,m} = 125 \cdot \frac{T_{i,\text{keV}}^2}{n_{20}} \quad (1)$$

where  $n_{20}$  is plasma density in units  $10^{20} \text{ m}^{-3}$ . For edge temperatures exceeding 1 keV the mean free path becomes larger than the length of the open field lines in SoL. As a result, the particles escaping from the confinement zone deliver energy to the target plates without collisions, i.e., convectively. As a result, the plasma edge temperature is determined by the heating power and particle flux to the plates as

$$\frac{5}{2} (T_i^{\text{edge}} + T_e^{\text{edge}}) \cdot \frac{\Gamma_{\text{NBI}} + \Gamma_{\text{gas puff}}}{1 - R^{\text{recycling}}} = P_{\text{NBI}} + P_{\alpha\text{-rad}} \quad (2)$$

where  $\Gamma_{\text{NBI}}$ ,  $\Gamma_{\text{gas puff}}$  are the external particle sources of NBI and gas puff, and the heating power  $P_{\text{NBI}}$ ,  $P_{\alpha\text{-rad}}$  includes the contribution from NBI, fusion  $\alpha$ -particles and the losses due to synchrotron and bremsstrahlung radiation. Owing to finite recycling the total particle flux to the wall is enhanced by  $1 - R^{\text{recycling}}$  in the denominator. For the plasma controlled by NBI the same formula gives the expression for the edge temperature

$$\frac{T_i^{\text{edge}} + T_e^{\text{edge}}}{2} = \frac{1 - R^{\text{recycling}}}{1 + \frac{\Gamma_{\text{gas puff}}}{\Gamma_{\text{NBI}}}} \cdot \frac{E_{\text{NBI}}}{5} \cdot \frac{P_{\text{NBI}} + P_{\alpha\text{-rad}}}{P_{\text{NBI}}} \quad (3)$$

For plasma simulations these equations serve as boundary conditions for plasma temperature.

Above expressions (2, 3) for the edge temperature are the essence of the low recycling LiWF regime showing its insensitivity to the core plasma physics. Its role is limited to affecting the fraction of the plasma temperature profile on the top of a very large pedestal, which is fully controlled externally. We drop here the discussion of the boundary conditions for the plasma density, which is low due to pumping by flowing lithium. Unlike the edge temperature, the edge density is sensitive to enhanced diffusion due to, e.g., trapped electron modes or externally imposed resonant magnetic perturbations.

In application for JET-like tokamak parameters (major radius  $R = 2.96$  m, minor radius  $a = 0.9$  m, plasma current  $I_{pl} = 3$  MA, and toroidal field  $B_{\text{tor}} = 3$  T) the results of burning plasma simulations are described in [3]. Two frames in Fig. 2 show the core plasma profiles and key plasma parameters from transport simulations by the ASTRA code [11]. In all cases of [3] the diffusion coefficient is taken equal to the neoclassical ion thermal conduction (i.e., essentially magnetically unconfined electrons), while electron thermal conduction is assumed 100 times larger than ion neoclassical value, i.e., essentially infinite as the worst thinkable case.

The ion thermal conduction for Fig. 2(a) is assumed neoclassical. It is enhanced by factor 10 for the case shown in Fig. 2(b). Even such an order of magnitude enhancement of ion thermal conduction results only in 37% reduction of fusion power from 25.9 MW to 16.2 MW and reduction in  $Q_{DT}$  from 6.39 to 4.04. This illustrates insensitivity of the low recycling regime to the core thermal conduction. In comparison, simple doubling of thermal conduction would be lethal for the conventional plasma.

Table I, taken from [3], gives the burning plasma parameters for different energies of NBI and its particle deposition profiles.

In all cases here, except 9, only 50% of  $\alpha$ -particle energy was assumed to heat the plasma. In addition to the large value of  $Q_{DT}$ , the burned up fraction of tritium is unprecedentedly high. In the case 9 it is 75% (out of potentially 85% confined  $\alpha$ -particles). With a better realization of  $\alpha$ -heating the same parameters as in reference case 1 with  $P_{\text{NBI}} = 4$  MW are achieved with only 3.5 MW. More cases are presented in [3].

Note that all calculations of the burning plasma were performed under very conservative assumptions about heating

TABLE I  
BURNING PLASMA PARAMETERS FOR JET-LIKE DEVICE IN LiWF REGIME AS PREDICTED BY ASTRA CODE [11] SIMULATIONS

JET Fusion performance, $B=3$ T, $I_{pl}=3$ MA							Recycling 0.50
#	$P_{NBI}$ MW	$E_{NBI}$ keV	$P_{DT}$ MW	$Q_{DT}$	$f_{T-burnup}$	NBI deposition profile	Heating by $\alpha$ -particles
1	4.06	120	26.0	6.4	8.73 %	parabolic	50 %
2	2.98	120	17.4	5.84	7.96 %	parabolic	50 %
3	3.99	120	23.0	5.76	7.85 %	hollow	50 %
4	3.06	120	15.5	5.08	6.93 %	hollow	50 %
5	4.03	100	21.2	5.25	5.97 %	parabolic	50 %
6	3.01	100	15.6	5.19	5.90 %	parabolic	50 %
7	4.01	100	19.0	4.73	5.38 %	hollow	50 %
8	3.00	100	13.6	4.53	5.15 %	hollow	50 %
9	3.52	120	25.5	7.25	9.89 %	parabolic	75 % (85 % expected)

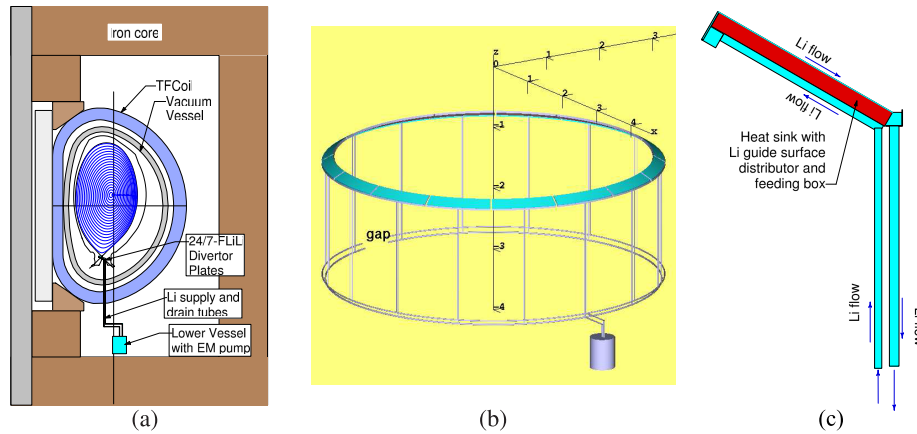


Fig. 3. (a) Possible position of 24/7-FLiLi “lithium Plumbing” manifold for JET geometry of toroidal field coils, vacuum vessel, and iron core. (b) 3-D view of 24/7-FLiLi with a single lower vessel with electro-magnetic (EM) pump, controlling the flow, and horizontal drain/supply pipe rings with a toroidal gap. Vertical feed-through tubes connect in-vessel plates with the outside manifold, e.g., through the vertical ports. (c) Cross section of the 24/7-FLiLi target plate with lithium supply and drain pipes.

by  $\alpha$ -particles and about the behavior of electrons, which are assumed magnetically not confined and having extremely large thermal conduction. Also the diffusion coefficient, which is critical for the energy confinement, is taken 60 times larger than the theoretical level. Accumulation of helium in plasma was neglected expecting a short DT phase. Because of the tendency to have flattened or reversed safety factor profile  $q$ , the turbulence is excluded from the reversed  $q$  area. This can reduce the diffusion coefficient and further enhance the performance of the burning plasma.

One of the critical aspect of LiWF regime is strongly reduced power directed to the divertor. Because of exceptionally good confinement, the external heating power is reduced by an order of magnitude relative to any estimates for the high recycling regimes in present-day scenarios. At the same time, the plasma performance is unreachable for high recycling. The high temperature of the core plasma  $\approx 30$  keV promises to irradiate the significant part of  $\alpha$  heating of electrons to the side walls, rather to the divertor target plates. This represents a totally new approach for the problem of power extraction from the plasma, which cannot be solved for the high recycling regime by material improvements given strong coupling of the edge with plasma stability and triggering disruptions.

### III. BASICS OF 24/7-FLiLi DIVERTOR

The key number, which makes utilization of pumping properties of liquid lithium practically feasible, is very low liquid lithium flow rate of 1 g/s in order to pump out  $10^{21} - 10^{22}$  hydrogen isotope plasma particles per second with 1–10% of atomic concentration of D + T in Li exiting the plasma contact zone. A 50-100  $\mu\text{m}$  thick film creeping under gravity along the plasma facing surface of the divertor target plates would be sufficient for pumping.

The system of tubes (with internal cartridge heaters), shown in Fig. 3, connects such divertor plates with the exterior of the vacuum vessel and a lower liquid lithium vessel with an EM pump inside. Half of the tubes supply liquid lithium from the lower vessel to the plates, whereas the other half drains lithium from the vacuum chamber to the lower liquid vessel. Fig. 3(a) shows the position of horizontal supply and drain tubes together with the lower vessel underneath the JET toroidal field coils. The vertical feed-through sections penetrate the vacuum vessel through the vertical ports. A 3-D sketch of the lithium manifold with 16 target plates is shown in Fig. 3(b). The gap in the horizontal parts of the manifold prevents excitation of a toroidal current along the pipes as well as allows for the use of reliable single wire heaters inside the

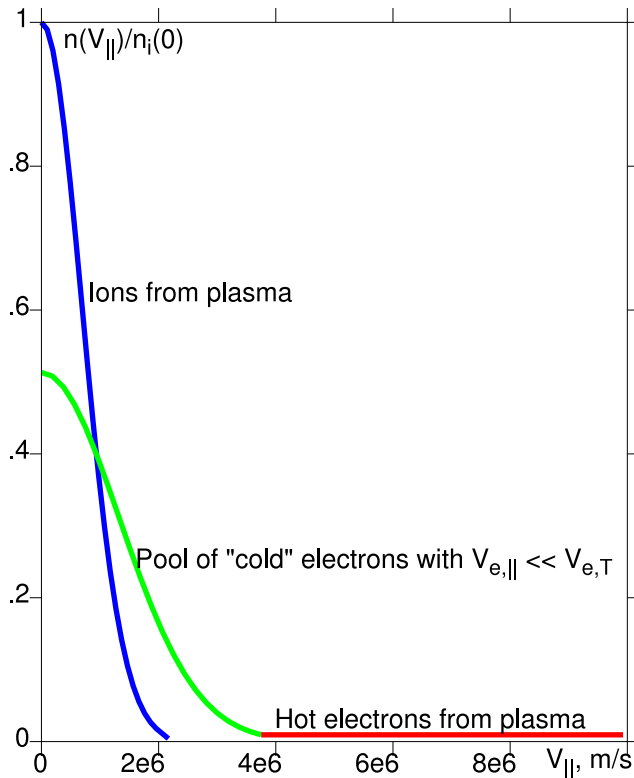


Fig. 4. Sketch of distribution functions of parallel to magnetic field velocities inside the SoL of hot ions (blue curve) and hot electrons (red) from the plasma, and of a pool of “cold” electrons (green).

horizontal sections. Fig. 3(c) shows a simplified cross section of the target plate with Li supplied to the top of the plate and drained from a collector at the bottom of the plate. Li slowly ( $\approx 1$  cm/s) flows along the plasma facing guide surface.

The critical requirement is wetting of the guide surface by lithium, which makes the film insensitive to any possible forces, e.g.,  $(\mathbf{j} \times \mathbf{B})$ -force. Wetting also holds Li attached to the surface regardless of its orientation, even upside-down. At the moment the best arrangement is a copper plate of 0.8–1 thickness with 0.1 mm thick stainless steel (SS) foil attached to the copper surface with no voids and good thermal contact. High temperature  $\approx 400^\circ$ – $500^\circ$  C lithium can wet SS foil, which protects copper from contact with lithium. The copper plate serves as a heat sink with the highest metal thermal conduction. It also matches the SS foil in thermal expansion coefficient. It has its own internal structure with channels for active cooling and, if necessary, heaters. After wetting, the temperature of the entire sandwich can be dropped to the operational temperature  $\approx 200^\circ$  C.

Another important requirement is continuity of flow with time. Once launched liquid lithium flow should not be stopped. Otherwise residual outgasing from the vacuum vessel wall could create a crust on the lithium surface and the flow may not be restarted. At the same time the 24/7 flow is highly useful even between discharges, serving as the “garbage collector” of impurities from the wall.

The small velocity of liquid lithium makes the analysis, design and control of its flow, essentially laminar, straight-forward. For the first time, it was done for FLiLi limiter of the EAST tokamak, which operates in accordance with the

design [10]. The details for the case of JET can be found in [3] and do not represent a significant challenge.

Some complications do exist due to need of  $200^\circ$  C for all tubes with LiLi and the divertor plate. Because of this, the thermal regime of the divertor plate is a challenge to keep the surface of lithium in the range of  $200^\circ < T_{\text{LiLi}} < 400^\circ$ .

We drop here a deeper consideration of lithium flow issues.

#### IV. DESIGN GUIDANCE FOR THE LOW RECYCLING DIVERTOR

The physics of the low recycling regime is essentially general, rather than plasma, physics. It is simple and reliable as soon as it would be possible to implement the 0.5 level of recycling. Besides low recycling, the approach relies on existing facilities, some, like NBI, used in a relaxed mode. The technology of flowing lithium for pumping plasma was invented, although still requires full scale implementation. The new critical element, which determines the feasibility of the new approach to tokamak fusion is the interaction of the plasma facing Li surface with the stream of energetic particles from the plasma.

The following specifics of SoL in the LiWF regime determine the needs for a new approach to the divertor plate design.

- 1) A minuscule  $10^{16} \text{ m}^{-3}$  level of density in the “SoL” and no collisions.
- 2) Accumulation of a pool of “cold” electrons with low parallel velocity  $V_{\parallel}$  and the density close to the ion density as shown in Fig.4, thus, establishing quasi-neutrality.
- 3) Small value of electric potential, which may trap “cold” electrons [12].
- 4) High Electron Emission from bombardment of Li by high energy ions, but playing no role due to low ion density.
- 5) Free flow of independent 10–20 keV plasma particles to Li [Fig. 1(b) and (c)] with equal fluxes of electron and ions.

As a result, the only option for the low recycling divertor is the utilization of grazing impact angle for SoL particles. The first modeling of such an impact for the reference case of 20 keV D atoms have been performed using the SCATTER code [13]–[15] (MEPhi, Moscow, RF) and for 16 keV D with DYNAMIX code [16] (University of Illinois at Urbana-Champaign, USA). For  $10^\circ$  degree particle velocity angle to the plate the sputtering results from all codes are consistent and near 0.1 as is shown in Fig. 5(a) and (b). Fig. 5(a) also gives the fraction of reflected particles as a function of the angle and their energy relative to initial incident energy. Both of them, as well as sputtering, increase for smaller impingement angle. For the case of  $10^\circ$  degree, the DYNAMIX code gives approximately twice larger fraction of reflected particles and their energy than the SCATTER code.

The angular distributions of sputtered Li and reflected D atoms from the DUNAMIX code are shown in Fig. 6(a) and (b). The sputtered Li is directed in a wide space angle around the normal to the target surface. The reflected D atoms have a preferable direction around mirror reflection.

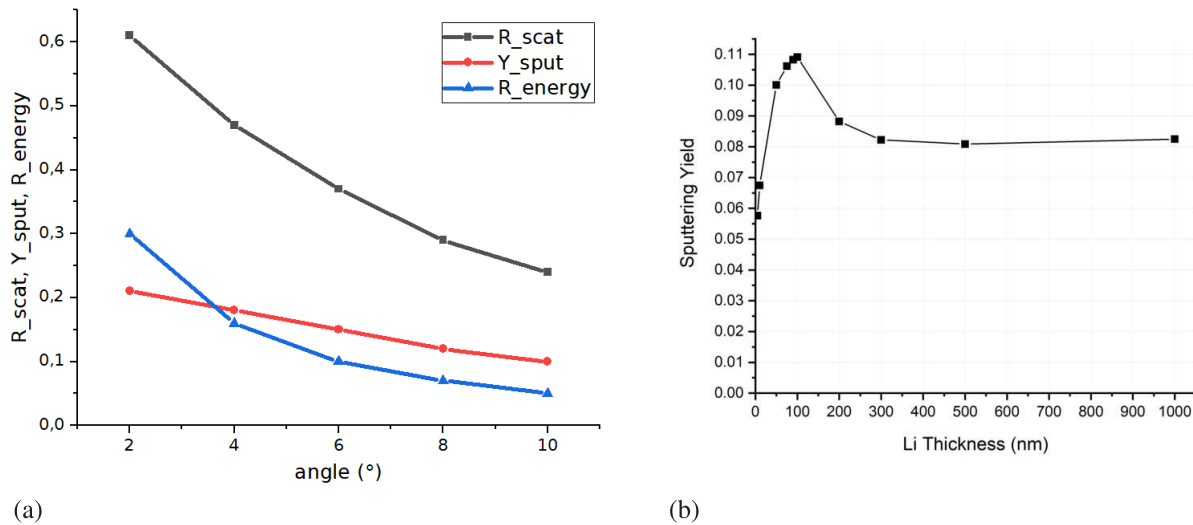


Fig. 5. Sputtering and reflection results for grazing angles of impingement. (a) SCATTER code results on sputtering of Li (red), the fraction of reflected D-particles (black), and the fraction of the total energy (blue) in reflected particles as a function of impingement angle. (b) Sputtering yield from the DYNAMIX code for  $10^\circ$  impingement angle as function of the thickness of Li layer on a tungsten surface. For the LRD, the relevant case is the asymptotic value at 1000 nm.

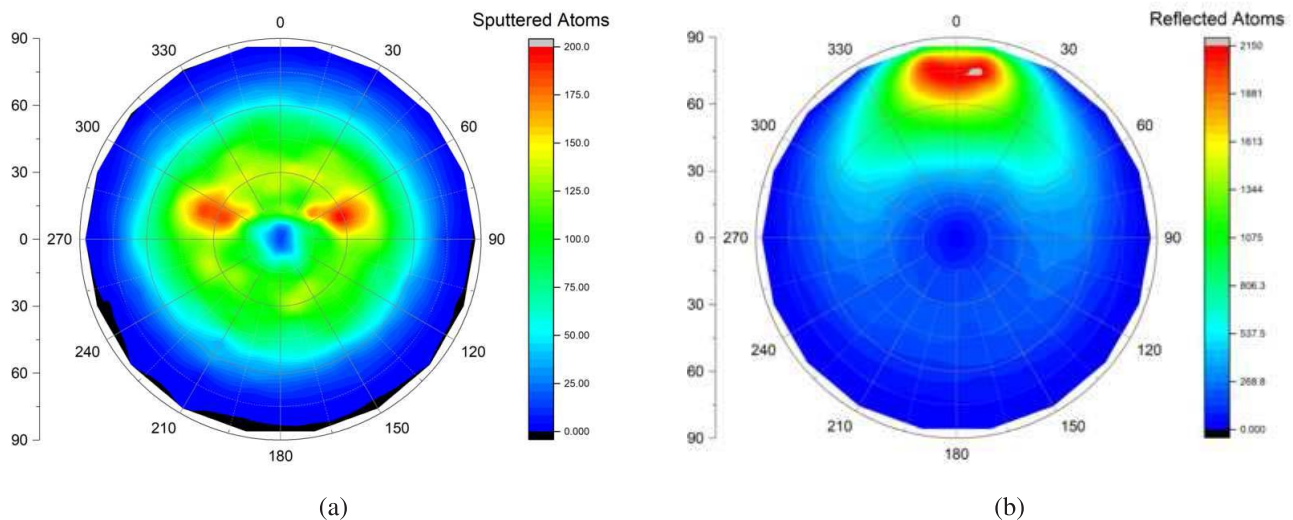


Fig. 6. Angular distribution of (a) Li sputtering yield and (b) reflected D particles as calculated by the DYNAMIX code for  $10^\circ$  degree of impingement.

The SCATTER calculations were made for a set of impingement angles. The particle reflection for two of them for  $4^\circ$  and  $10^\circ$  is shown in Fig. 7(a) and (b). Significant reduction of scattering in the reflection angle is noticeable for a smaller angle. Some numerical discrepancy with DYNAMIX results is noticeable on the angular distribution at  $10^\circ$  in Fig. 7(b). For now, this is not a very important discrepancy in independent calculations given the same sputtering yield and good general tendencies. We leave the resolution for the future.

The main result of numerical simulation is the acceptably low Li sputtering by high energy plasma particles. Another important result is well-directed reflected D atoms and the energy in them. They give the basic guidance for the divertor design.

We postpone for the future the consideration of evaporation of Li by the heat flux. This would require better understanding

of the thickness of the energy deposition related to the thickness of SoL. All of this will take more time for research. Nevertheless, the advantage of the small impingement angles is evident although it would require good plasma control.

One of the consequence of the computational results is the necessity of interception of reflected particles, which would require a secondary plate for every target plate of the divertor.

Fig. 8 illustrates two versions of LRD. The first one has a single target surface situated near the X-point of magnetic configuration. The impingement angle there is automatically very small  $\ll 10^\circ$ . In this case the reflected particles will be well directed along the target surface and can be intercepted by another Li surface (FLiLi or passively coated by Li, not shown). Also, at small impingement angle these particles carry a significant energy, thus, reducing the heat flux on the target surface.

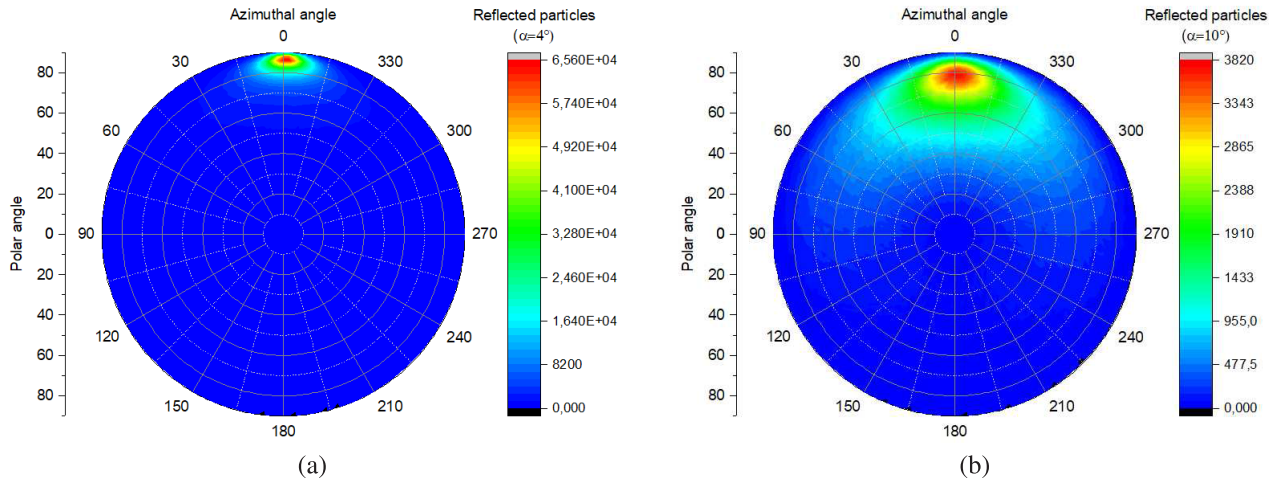


Fig. 7. Angular distribution of reflected D atoms from SCATTER code for (a) 4° and (b) 10° degrees of impingement.

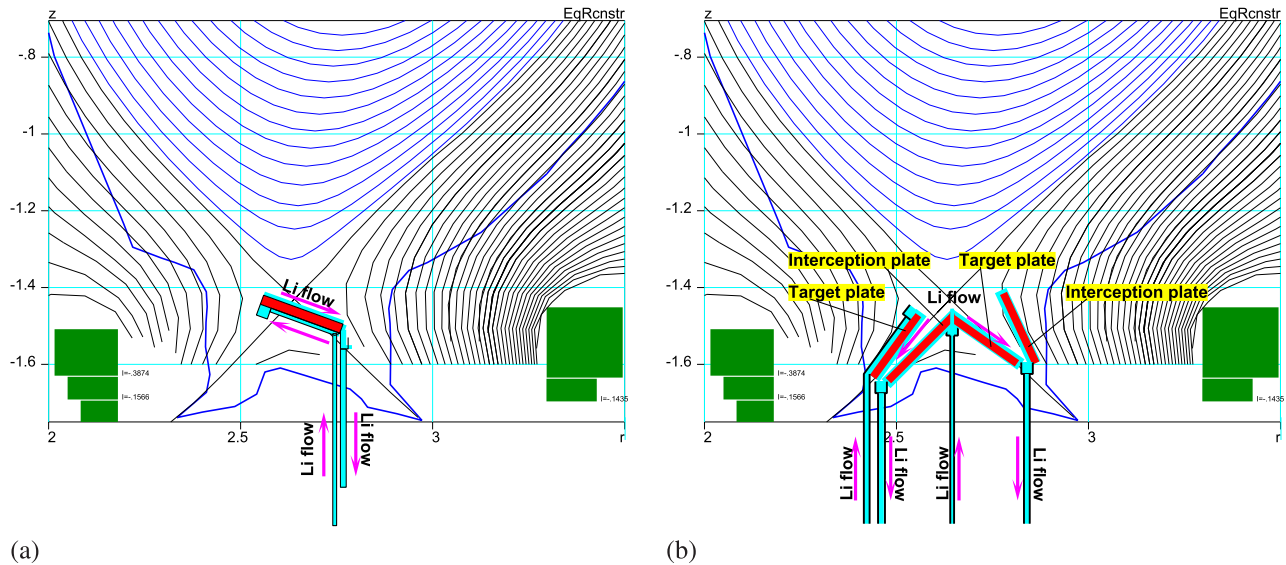


Fig. 8. Two versions of LRD with (a) single target surface (the interception plate not shown) and (b) two target surfaces with two interception plates. (Liquid lithium can flow along a SS surface even with its upside-down orientation. Weak Raileigh–Taylor instability, if any, does not affect the Li film flow.)

The disadvantage of this version is that both the significant fraction of evaporation and sputtering of Li is directed toward the plasma.

The second version contains two FLiLi target and two interception surfaces. The right interception surface is passive (with Li supplied externally), the left one has a FLiLi film similar to the target surfaces). More challenging for design and implementation, this version directs particles out of plasma to the intercepting surfaces, while a significant fraction of sputtering and evaporation yields can be also intercepted with the proper localization of the strike area.

V. CONCLUSION

The possible end of the JET facility, the best in the fusion program and the only one capable of performing DT fusion operation, motivated consideration and development of an alternative utilization of its capacity for DT plasma.

With this idea in mind, the low recycling approach, based on reliable general physics, rather than on plasma physics,

was analyzed in detail being much better predictable than the plasma physics of high recycling with its never properly understood confinement, plasma edge and such a crucial phenomenon as disruption.

The physics studies of the low recycling regime, performed for the JET-like tokamak parameters, have demonstrated the astonishing performance with reliably obtainable  $Q_{DT} > 5$  in well controllable and predictable plasma, which is crucial for disruption avoidance. This quality is beyond the horizon for the present high recycling plasma.

The 24/7-FLiLi technology means for plasma pumping by flowing lithium already passed the technology tests and are well understood. New fabrication technique for the heat sink with the SS foil guide surface is under development in MEPhi (Moscow). Finally, the critical initial simulation of interaction of the energetic particles with the pumping Li surface was performed in two research centers and reported in this article. They convincingly show the feasibility of a divertor with recycling suppressed to the 0.5 level.

## REFERENCES

- [1] K. M. McGuire *et al.*, "Review of deuterium–tritium results from the Tokamak Fusion Test Reactor," *Phys. Plasmas*, vol. 2, no. 6, pp. 2176–2188, 1995, doi: [10.1063/1.871303](https://doi.org/10.1063/1.871303).
- [2] M. Keilhacker, "JET deuterium: Tritium results and their implications," *Nucl. Fusion*, vol. 39, pp. 34–209, Mar. 1999.
- [3] L. E. Zakharov, "On a burning plasma low recycling regime with  $P_{DT}=23\text{--}26$  MW,  $Q_{DT}=5\text{--}7$  in a JET-like tokamak," *Nucl. Fusion*, vol. 59, no. 9, 2019, Art. no. 096008, doi: [10.1088/1741-4326/ab246b](https://doi.org/10.1088/1741-4326/ab246b).
- [4] J. D. Strachan *et al.*, "Fusion power production from TFTR plasmas fueled with deuterium and tritium," *Phys. Rev. Lett.*, vol. 72, no. 22, pp. 3526–3529, 1994.
- [5] V. A. Evtikhin, I. E. Lyubinski, A. V. Vertkov, S. V. Mirnov, and V. B. Lazarev, "Technological aspects of lithium capillary-pore systems application in tokamak device," *Fusion Eng. Des.*, vols. 56–57, pp. 363–367, Oct. 2001.
- [6] S. I. Krashennnikov, L. E. Zakharov, and G. V. Pereverzev, "On lithium walls and the performance of magnetic fusion devices," *Phys. Plasmas*, vol. 10, no. 5, pp. 1678–1682, 2003.
- [7] L. E. Zakharov, W. Blanchard, R. Kaita, H. Kugel, R. Majeski, and J. Timberlake, "Low recycling regime in ITER and the LiWall concept for its divertor," *J. Nucl. Materials*, vols. 363–365, pp. 453–457, Jun. 2007.
- [8] L. E. Zakharov, J. Li, and Y. Wu, "Fusion-fission research facility (FFRF) as a practical step toward hybrids," *VANT*, vol. 34, no. 3, p. 27, 2011. [Online]. Available: <http://vant.iterru.ru>
- [9] L. E. Zakharov, "Basics Of fusion-fission research facility (FFRF) as a fusion neutron source," *Fusion Sci. Technol.*, vol. 61, no. 1, pp. 237–242, 2012.
- [10] J. S. Hu *et al.*, "First results of the use of a continuously flowing lithium limiter in high performance discharges in the EAST device," *Nucl. Fusion*, vol. 56, no. 4, 2016, Art. no. 046011.
- [11] G. V. Pereverzev and P. N. Yushmanov, "ASTRA: Automated system for TRansport analysis," Max Planck Inst. Plasma Phys., Garching bei München, Germany, Tech. Rep. IPP 5/98, 2002.
- [12] E. M. Granstedt, "The low-recycling lithium boundary and implications for plasma transport," Ph.D. dissertation, Dept. Astrophysical Sci., Princeton Univ., Princeton, NJ, USA, 2013. [Online]. Available: <https://search.proquest.com/pqdtdlocal/1005735/docview/1466568643/fulltextPDF/480C0BEA3EF7434EPQ/1?accountid=13314>
- [13] N. N. Koborov, A. I. Kuzovlev, V. A. Kurnaev, V. S. Remizovich, and N. N. Trifonov, "Energy distributions of particles transmitted through free foils at oblique incidence," *Nucl. Instrum. Methods Phys. Res., B, Beam Interact. Mater. At.*, vol. 129, no. 1, pp. 5–10, 1997.
- [14] V. A. Kurnaev, N. N. Trifonov, and V. A. Urusov, "Ion reflection from solids at sliding incidence—Computer simulations versus analytical theories and experiment," *Nucl. Instrum. Methods Phys. Res. B, Beam Interact. Mater. At.*, vol. 212, pp. 270–273, Dec. 2003.
- [15] D. Bulgadaryan, D. Kolodko, V. Kurnaev, and D. Sinelnikov, "Facility and the method for MEIS analysis of layers redeposited in plasma devices," *J. Phys., Conf. Ser.*, vol. 748, no. 1, 2016, Art. no. 012016.
- [16] G. Hou, "The development of a dynamic radiation-surface interaction simulation code," M.S. thesis, Purdue Univ., West Lafayette, IN, USA, 2010. [Online]. Available: <https://search.proquest.com/docview/858604061?pq-origsite=gscholar>



**Leonid E. Zakharov** was with Kurchatov Institute, Moscow, Russia, MIT, Cambridge, MA, USA, PPPL, Princeton, NJ, USA. He is currently the President of LiWFusion, consulting company on magnetic fusion, Princeton, NJ, USA. He has coauthored (with S. I. Krashennnikov) LiWF concept of tokamak fusion, the inventor of flowing lithium technology for tokamaks.



**Jean Paul Allain** was a Professor and the Associate Head of Graduate Programs with the Department of Nuclear, Plasma and Radiological Engineering, University of Illinois at Urbana-Champaign (UIUC), IL, USA, and with Nuclear Engineering Department, Purdue University, West Lafayette, IN, USA, from 2007 to 2013. He is currently the Inaugural Head of the Ken and Mary Alice Lindquist Department of Nuclear Engineering, Pennsylvania State University (PSU), State College, PA, USA. He holds the Lloyd and Dorothy Foehr Huck Chair in Plasma Medicine with the Huck Institutes for Life Sciences, University Park, PA, USA. He is also a Faculty Co-Hire of the Institute for Computational and Data Sciences, PSU, and also a Professor of biomedical engineering. His group's research areas include advanced functional biointerfaces, advanced nuclear fusion interfaces, multi-scale computational irradiation surface science, nanostructured functional materials, adaptive and self-healing interfaces, sustainable nanomanufacturing, and *in situ*, in-operando material surface diagnostics.



**Samuel X. Bennett** was born in Boynton Beach, FL, USA. He received the B.S. degree in physics from the University of Illinois at Urbana-Champaign, IL, USA, in 2016, where he is currently pursuing the Ph.D. degree in nuclear, plasma, and radiological engineering.

His current research interests include plasma–surface interactions, atomistic simulations, and high-performance computing.



**Muhammad A. E. Abdelghany** received the B.S. degree in nuclear engineering from Alexandria University, Alexandria, Egypt. He is currently pursuing the Ph.D. degree with the University of Illinois at Urbana-Champaign, IL, USA.

His current research interest includes nanopatterning under surface irradiation.

Mr. Abdelghany is the Co-Founder of the IEEE Nuclear and Plasma Sciences Society student chapter.



**Daniel G. Bulgadaryan** received the B.Sc. degree from the Department of Radiophysics, Donetsk National University, Donetsk, Ukraine, in 2014. He is currently pursuing the Ph.D. degree with NRNU MEPhI, Moscow, Russia.

His current research interests include ion–surface interaction, surface analysis, and emission properties of plasma-facing materials.