Studies of Dust Dynamics in High Temperature Plasmas

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Abstract. The status of research in the field of dust in fusion plasmas that is carried out in Russian and collaborating organizations is outlined. The activity includes studies of dust phenomena in tokamaks, stellarators and Z-pinches, development of monitoring tools, dust generation theory in reactor conditions, technologies of dust evacuation and control of tokamak operation by dust jets. In-situ tunnel microscopy has allowed us to start studying the surface and dust growth at nanometer scales in T-10 and in ELM simulating experiments. The time resolved measurement is the main objective of developing the monitoring tools at present. The surface composition monitoring is worked up on the basis of laser blow-off techniques and laser breakdown spectroscopy of the ablated materials. Hydrogen retention in the carbon containing co-deposited layers on targets retrieved from tokamaks has been studied with the 20% resolution of C/H ratio. In-situ experiments on Globus-M are being prepared. Specific radiation of nanometer clusters of conducting materials lower than black body radiation may be expected on the basis of the theory developed. Generation of dust has been investigated at GW/m^2 range plasma heat loads level in the tokamak/stellarator and the plasma gun QSPA. Brittle destruction of carbon with production of a few micron size particles with 100 m/s velocities was registered when the loads exceed 2-3 GW/m^2. The transition was observed to droplet production regimes for tungsten and lithium. Opportunities of evacuation of radioactive particles from plasma free regions using electric fields have been demonstrated in simulating experiments.

1. Introduction

Dust generation and transport in devices with high temperature plasmas create substantial problems on the way to fusion reactor with magnetic confinement [1]. This is conditioned by chemical and radiation safety, which constrain the total amount of the dust in the reactor at a level of hundred kilograms. Additionally, the dust particles may occur a new plasma component that complements impurities and actively affects the Scrape-off Layer (SOL). The dust may influence operation regimes in the divertor and core plasmas. Accounting for the requirements to tritium losses in fuel cycle, it is desirable to clarify the role of dust in accumulation and transport of tritium in the reactor. In this paper the results of Rosatom program "Dust in high temperature plasmas" are summarized. The program has begun in Russia in 2004 and it has been supported by Kazakhstan activity in 2005. The program has the following goals:

-to clarify the role of dust and atom-molecular clusters in formation of high temperature plasma including effects on the SOL region of tokamaks and MHD-stability of Z-pinches [2];

-to investigate mechanisms of dust generation and transport in high temperature plasmas of fusion devices and facilities simulating reactor heat loads on divertor plates made of different materials;
-to develop and to apply on contemporary machines new approaches of monitoring the first wall surface and detecting particles with 1-1000 nm size.
-to develop an effective technology for dust evacuation from the vessel volume.
-to develop new technologies based on injection of nano and micro particles.

2. Dust monitoring development

Surface and dust structure analysis is extensively developed on the basis of tunneling (STM) and atomic-force microscopy (AFM) [3]. Opportunities of Synchrotron Source of RRC Kurchatov institute are used for analysis of films and dust composition and structure [4]. Now the monitoring of the surfaces in T-10 is possible between shots. Figure 1 shows a photo of the in-situ scanning tunneling microscope and variation of the pyrolytic graphite substrate placed in the limiter shadow region of T-10 after 4 and 10 shots. The developed tools allow us to observe the surface growth and detect dust particles. However, further development providing the temporal resolution better than 1 second is necessary for monitoring of dust behavior during the discharge scenario. Two options are considered to succeed this goal. The first is the STM/AFM device operating during the discharge period, providing data in real time and working in line-by-line regime. The other option will use posteriori scanning of the surface exposed through a moving slit.

Laser ablation techniques for the in-vessel dust diagnostics, including measurement of the deposited film thickness and atomic composition analysis, is developed in Ioffe Institute [5,6]. A feasibility study on hydrogen retention in carbon containing co-deposited layers on targets retrieved from tokamaks has been carried out in development testing. The diagnostic technique is capable of testing the residing layer thicker than 10 nm. The accuracy of the hydrogen/carbon ratio measurement is better than 20%. The technology development level is sufficient for starting the installation of this technique on Globus-M spherical tokamak for testing that is planned in 2007.

3. Dust generation experiments

Experiments aimed at studying the dust generation in conditions corresponding to ELM and disruptions had been started using the plasma gun QSPA and electron beam-plasma discharges [1,7]. For investigated materials (C, W, Li) the regimes with dust production are realized when heat load thresholds are exceeded. Brittle destruction of carbon and liquid droplet ejection are the basic mechanisms. Significant growth of the erosion rate has been detected after the transition. Typical picture of the tungsten surface erosion in a dust producing regime of QSPA is shown in Fig. 2.

Lithium erosion was studied in T-10. Pellets with the size of 0.7 mm and the velocity of 300 m/s penetrated into plasmas, which provided heat loads higher than 10 GW/m^2. The transition from atomic to cluster/droplet ablation has been observed on the pellet track photos. A typical photo is shown in Fig. 3. The pellet moves from top to bottom and is accelerated in toroidal direction by rocket effect due to the plasma current. The fracture of the pellet track before the transition is characterized by symmetric structure of the pellet cloud in the toroidal direction. After the transition the cloud is asymmetric in toroidal direction and the longer wing corresponds to pellet acceleration. Such data may be interpreted as appearance of clusters/droplets in the pellet cloud. Those droplets are affected to the rocket effect similar to that accelerating the major pellet, and to which cloud atoms are insensitive. This hypothesis reasonably explains the phenomena observed.

A new ablation regime characterized by generation of dust particles was observed in graphite pellet experiments on W7-AS stellarator [8]. The following analysis of these data has shown that typical size of the particles is about 10 microns and the velocity is above 200 m/s. These observations agree with the brittle destruction mechanism of dust production and models predicting an average graphite grain size for the ejected dust and velocities above 100 m/s.

4. Dust survival and migration in T-10 tokamak

Results of film/dust studies on T-10 tokamak were presented in Ref. [9,10]. Our assessments of the dust particles survival in high temperature plasmas were made in assumption that plasma energy flows onto the particle (evaluated using probe theory) balance cooling its surface by black body radiation at the temperature corresponding to a substantial vapor pressure of dust material (mbars). This analysis predicts rather wide survival domain for T-10 operation conditions (see Fig. 4).

The recent experiments with carbon dust injection showed that 2-10 micron dust at 300 m/s velocity penetrates into the tokamak plasmas 3-5 cm beyond the last closed magnetic surface. In Fig. 5 the dust cloud is shown which thickness was used for evaluation of the penetration lengths. The dust particles reach plasma with the electron temperature up to 100 eV and the density about 10^{13} cm^{-3}. The data obtained denote significant influence of radiative cooling on dust survival. Carbon and tungsten dust penetration beyond the separatrix in reactor conditions seems possible.

5. Dust evacuation

The technology of dust evacuation from eradiating media is developing by the Institute of High Energy Density [11,12]. Dynamics of dust flows was investigated in simulating experiments at accelerator and radioactive source cells. It was shown that the surface charge generated by eradiation of dust may be sufficient for the dust collection by electrodes, which produce electric fields in the volume (see Fig. 6). Formation of static and dynamic dust structures- crystals, helical vortexes and tore was observed at the gas pressure lower than 20 Torr.

6. Dust jet technologies for tokamak

Development of innovative technologies, which use injection of high speed dust jets into tokamak plasmas for emergency tokamak discharge quench and for the first wall conditioning and SOL plasma control, are in progress in RRC Kurchatov Institute.

Fast quenching the tokamak discharges in the case of expected major disruption or other emergency situations is realized now using killer pellets [1-3] and intensive gas jets [4]. Both technologies provide delivery of cold gas (hydrogen or noble gases in gas or solid state phases) with the total weight comparable or even exceeding that of the plasma particles. After making the decision to quench discharge it is desirable to inject the pellet or gas into plasma in a few milliseconds, which requires km/sec or higher velocities for both. For killer pellets the main technological problem is rather complicated technique and a substantial delay time necessary for the pellet acceleration. The lack of appropriate high-pressure (>100 bar) fast valves with large throughput (>10^{24} atom/shot) and low sonic speeds of heavy gases create problems with application of gas jets technology.

Since the quenching substance should be delivered into the periphery plasma and it penetrates then into the plasma core due to stimulated MHD-events the integrity of pellets providing deep pellet penetration is not essential for the quench technology. This means that delivery of the same amount of quenching gas in dust form will produce the effects on plasma discharge similar to those from gas jets. Meanwhile, formation of dust jets in sprits-like piston injectors may allow reaching the necessary parameters (amount, speed, low delay time) by even simpler and more efficient technology.

A cryogenic dust injector (hydrogen, deuterium or neon) is designed for T-10 tokamak experiments with fast discharge shutdown. In case of success the technology may be implemented on large tokamaks like JET and ITER. The advantages of the technology are as follows:
-the technique may be reliable and efficient in production of gas in solid state in amounts (~cubic cm per shot) sufficient for large tokamaks and;
-high speed of dust jet in km/s range and low delay time, which allow realization of the injection into plasma in a few milliseconds after the decision-making;
-low pressure of the hydrogen gas (~1 bar) forming solid phase, which is significant for hydrogen as an explosive gas.

Maintenance of the first wall by evaporation of lithium limiters, laser blow-off technique and pellet injection has been already tested in several tokamaks. The lithium technology has demonstrated reduced recycling regimes for hydrogen atoms and low values of effective plasma charge.

The dust jet technology applied for injection of lithium into a tokamak may be very effective for boundary and divertor plasma control and the first wall conditioning. Ablation of the lithium dust cloud in the scrape-off layer or divertor region of the tokamak reduces the temperature in the edge plasma and changes greatly the basic mechanisms of the plasma-wall interaction reducing the amount of heavy mass impurities. Rather small dust particles with the size of a few tens microns and a low velocity about 10 m/s are needed for full ablation inside the SOL plasma. The ablated atoms provide then a thin renewable layer over the full first wall and divertor elements. Injection of ten-micron dust lithium jets may be realized using piston spray injectors.

Modelling has been performed by the transport code B2SOPLS5.0 without drifts for the ASDEX Upgrade configuration. A typical shot has been chosen for simulation: $T_e = T_i = 100eV$,

$n = 4 \cdot 10^{19} m^{-3}$ at the inner core boundary, anomalous diffusion coefficient $D = 0.5 m^2 / s$. The source of neutral Li with half width 1 *cm* was located at the *X*-point. The recycling of Li was neglected. In Fig. 7 the density of Li+1 is shown for the source intensity $\dot{N} = 10^{22} s^{-1}$. The same density but at lower density levels is shown in Fig.7 (here the isodensities with large values are not shown). Note that the Li-source intensity is comparable with the total particle flux of main ions to the plates and outer wall, being the order of the total ionization source for the main ions. In spite of this fact the density of Li+1 at the separatrix is three orders of magnitude smaller than the density of main ions.

Resulting Li density at the separatrix and at the core side of the simulation domain is rather small. The density perturbation is large only in the vicinity of the Li source. The Li flux to the core is also small compared to $\dot{N} = 10^{22} s^{-1}$: about $10^{18} s^{-1}$. The electron temperature at the separatrix and in the core remains almost unperturbed by lithium injection, see Fig. 7. The electron temperature in the absence of Li injection is shown for comparison. On the other hand the electron temperature at the plates and in the divertor region is reduced significantly. The reason for such behavior is 2D character of the Li motion at the edge plasma of a tokamak. After the first ionization Li ions start to diffuse away from the source. Perpendicular to the flux surfaces they have the same diffusion coefficient *D* as the main ions. Outside of the separatix Li ions start to move with large velocity towards the plates along the magnetic field and hence poloidally due to the strong drag of the main ions. As a result the poloidal location of Li ions at the separatrix is the order of a few cm and most of them flow to the divertor plates.

First simulating experiments have been performed on T-10 using carbon dust jet formed of 2-10 micron particles accelerated by helium gas flow to the velocity about 300 m/s. Figure 5 shows a photo of the tokamak port from low field side while the jet comes from the top. The region of high radiation in the injection area is seen. The jet penetration 3-5 cm beyond the tokamak limiter is detected that exceeds the single dust penetration length. Formation of the virtual limiter by the dust jet can be seen at the top.

References

[1] FEDERICI G., SKINNER C. H., BROOKS J. N., et al., Nucl. Fusion, **41** (2001) 1967.
[2] VINOGRADOV V.P., KARAKIN M.A., KRAUZ V.I., et al., Plasma Physics Reports **32** (2006) 642.
[3] KHIMCHENKO L.N., BUDAEV V.P., GUSEVA M.I., et al., EPS2004, London, UK, Paper P4-146.
[4] STANKEVICH V., SVECHNIKOV N.Yu., LEBEDEV A.M., et al., 23rd Symposium on Fusion Technology, (20-24.09. 2004), Venice, Italy, P4C-F-27.
[5] RAZDOBARIN G.T., FEDERICI, G., KOZHEVIN V.M., et al., Fusion Sci. Technol. **32-43** (2002) 41.
[6] MUKHIN E.E., KUTEEV B.V., RAZDOBARIN G.T., et al., Devices and Techniques of Experiment (in Russian) (2006) 1.
[7] ZHITLUKHIN A., FEDERICI G., GINIYATULIN R., et al. Proc. 20 IAEA Conf. on Fusion Energy, Vilamoura, Portugal, 1-6 November, 2004, Paper IT/P3-30.
[8] KUTEEV B.V., MARTYNENKO Yu.V., SERGEEV V.Yu., et al., EPS2004, London, Paper P1-205.

[9] GUSEVA M.I., GUREEV V.M., KOLBASOV B.N., et al., Fusion Engineering and Design, **66-68** (2003) 389.
[10] KUTEEV B.V., in Dust in Fusion Plasmas, Napa, California, April 5, 2005. <http://maemail.ucsd.edu/~dust/>
[11] FORTOV V.E., RYKOV V.A., FILINOV V.S., et al., Plasma Physics Reports **31** (2005) No 12, p. 7.
[12] VAULINA O. S., SAMARIAN A. A., PETROV O. F., et al., Plasma Physics Reports, **30** (2004) 918 .

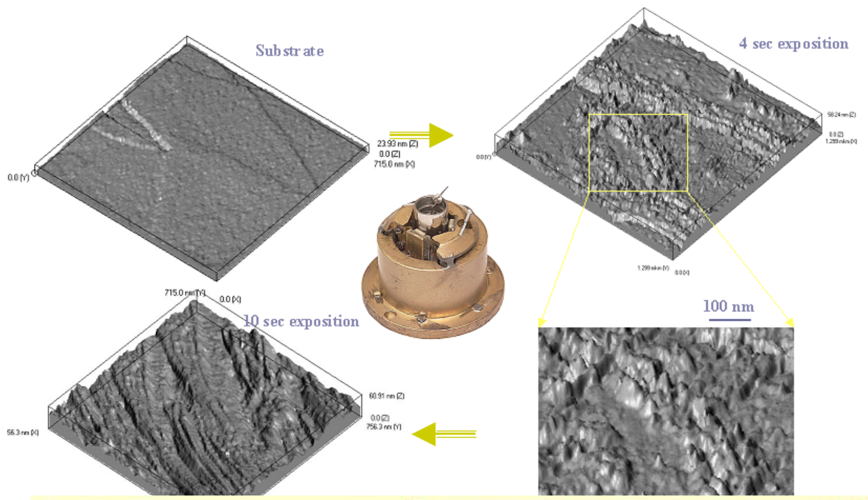

Fig. 1. View of the in-situ STM and surface evolution after exposure in T-10.

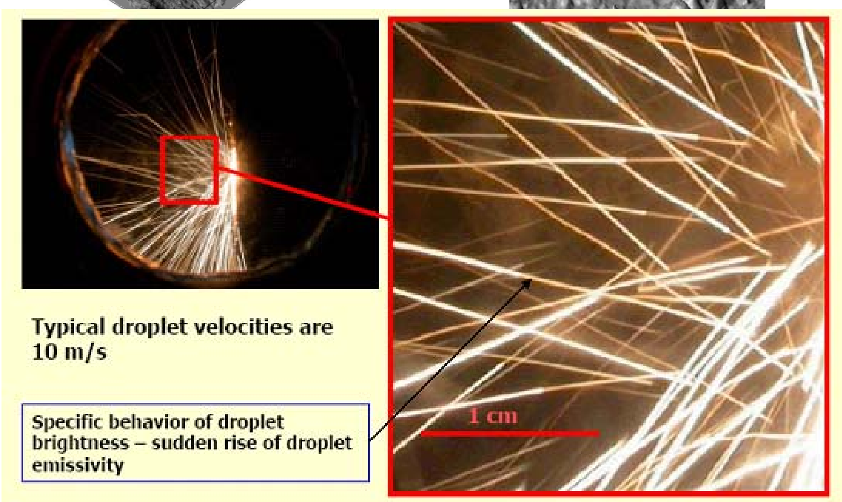

Fig. 2. Photo of tungsten surface erosion in dust producing regime in QSPA.

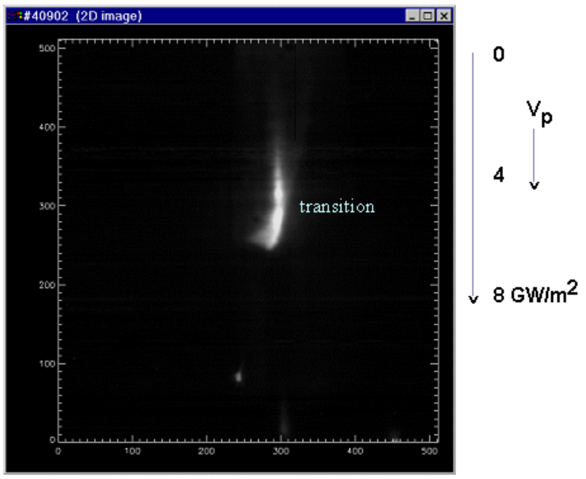

Fig.3. Track of lithium pellet showing the transition from atomic to cluster/droplet erosion.

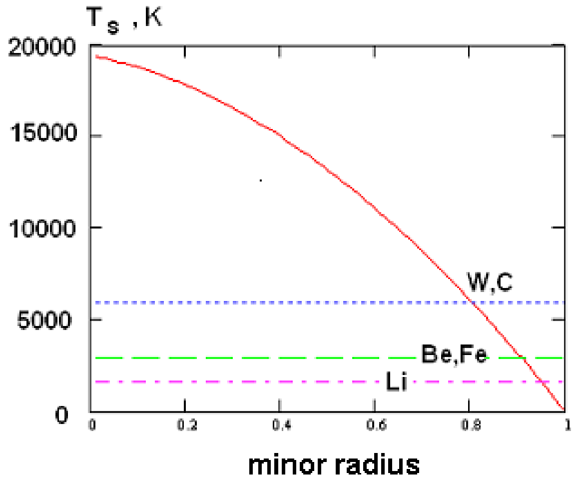

Fig 4. Profiles of the plasma parameters in T-10 and survival domains for Li, Be, Fe, W, C.

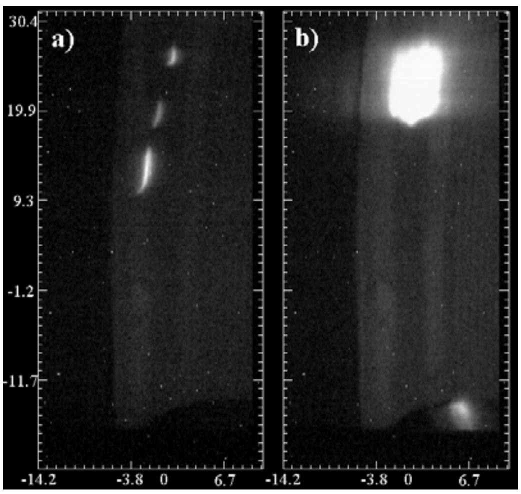

Fig. 5. Photo of carbon dust cloud forming virtual limiter in T-10.

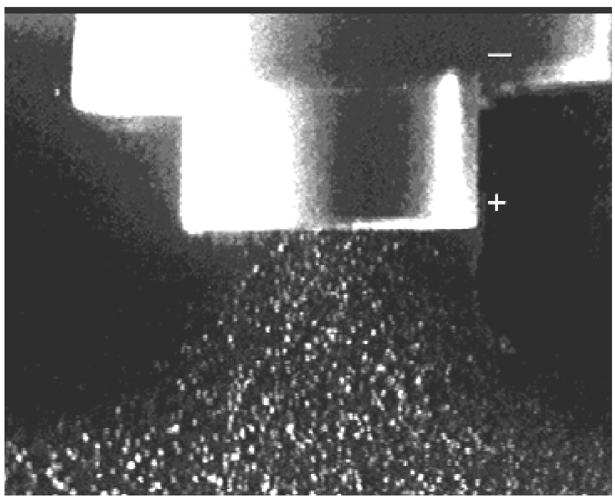

Fig.6. Photo of radioactive dust evacuation by means of electric fields.

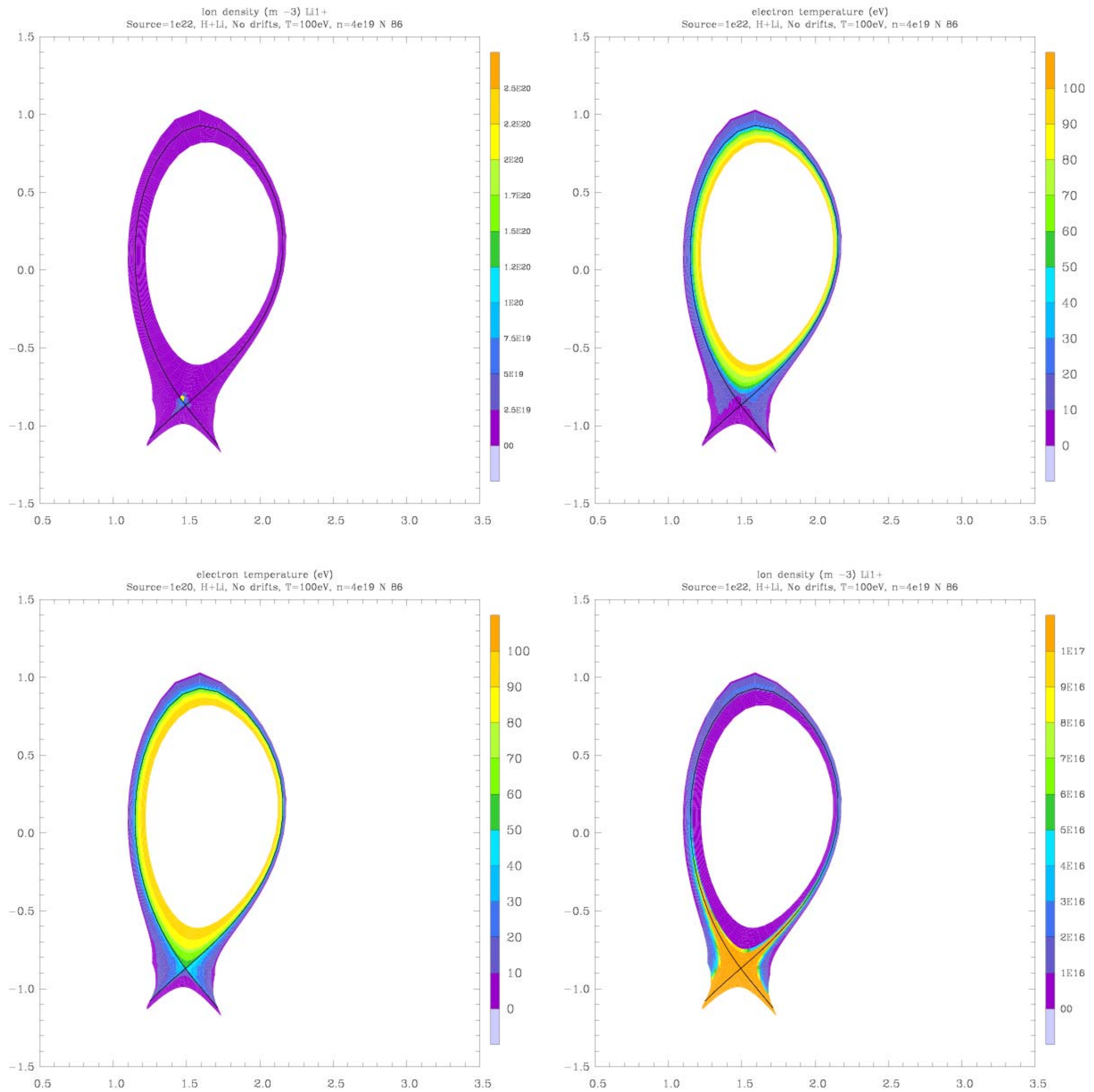

Fig. 7. Code simulations of lithium dust jet source in the ASDEX Upgrade configuration.