Primary topic B: Plasma boundary
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Plasma-wall interactions can turn magnetic fusion to dust

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Industrial scale magnetic fusion energy generation would require producing burning D-T plasma discharges for time duration much exceeding all present and near future fusion experiments. While achieving burning plasma conditions with net positive fusion energy production for intervals of several minutes is within reach of modern fusion technologies and is projected to be demonstrated on ITER tokamak [1], much more progress is needed for transition from large scale fusion experiments to fusion reactors, such as DEMO. Among major issues that need to be resolved is sustainment of burning plasma and reactor vessel operability for periods of time sufficient for fusion reaction to be economical, which can be of order of a year. For such an extended plasma operation, the issues related to degradation of reactor plasma-facing components (PFCs) due to large variety of plasma-surface interaction processes become of crucial importance. The plasma-wall material interactions are multifaceted. Deposition of large particle and energy fluxes from plasma to wall material causes its structural damage leading to modification of physical properties, loss of PFCs material into plasma, and conversely implantation and deposition of plasma and plasma contaminant components onto the wall. These considerations have led to change of initial ITER divertor design from carbon composite to tungsten PFCs due to tungsten's lower sputtering yield and tritium retention. However, despite these advantages, it was demonstrated experimentally that tungsten under high heat fluxes, relevant to unmitigated steady-state and transient plasma events in next generation tokamaks, can develop surface cracks and even melt, producing fine dust particles and droplets [2]. Moreover, growth, cracking and pealing-off of deposited layers also known to be a source of dust in fusion devices. The produced dust can be a very significant if not major source of impurities in fusion plasmas, as the 1 to 100 μm dust grains contain large amount of material and are not confined by the magnetic field due to extremely small charge-to-mass ratio. Unlike wall material sputtering by plasma particles, dust production induced by a variety of cumulative processes is rather difficult to predict and quantify. Recent experimental campaigns on Large Helical Device (LHD) with 1-3 MW heating power L-mode plasma discharges, each exceeding 1000s in duration, demonstrated that accidental release of dust into the plasma was a main cause of discharge termination, preventing achieving an hour mark. The sources of dust in LHD varied and included pealing of deposited layers from ICRF antenna shield and divertor surfaces, melting of in-vessel components, and wall damage by unipolar arcs. These processes are very likely to exacerbate with increased power and operational time of PFCs in fusion reactors.

Given the long history of magnetic fusion development, studies of dust related phenomena in fusion devices just recently attracted substantial attention and are still in their early stages. Although dust was collected and analyzed *post mortem* in current major tokamaks,

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very little is known about quantities of dust to be produced in long discharge operation reactors. Experiments with tungsten exposure to plasma pulses on QSPA Kh-50 accelerator yield dust production rates, extrapolated to ITER conditions, of order of 1 g/s, which significantly exceed dust production rates in present tokamaks. At the same time computer simulations of dust transport in ITER-like edge plasma show that tungsten dust injections with rates as low as a few mg/s can already significantly impact ITER plasma performance [3]. The existing experimental observations of dust in fusion discharges also provide inconclusive results – JET and some other present tokamaks reported decreasing frequency of dust observations in plasma with number of plasma discharges after beginning of a campaign, while LHD having much longer plasma discharges sees opposite trend. A significant effort is necessary to understand and quantify dust sources in future fusion reactors, in particular, for long burning plasma operation. Progress in this direction would require combined advanced experimental, computational and theoretical studies of plasma-material interactions at high plasma fluxes and long durations.

Another aspect critically important for understanding the dust impact on performance of fusion reactors is transport and interactions of formed dust with plasma. Substantial work has been done recently on development of dust transport models and codes, such as DUSTT, DTOKS, and MIGRAINE, for simulation of dust dynamics in fusion plasmas. However, experimental validation of the models and modeling results remains scarce. Also large diversity of fusion plasma conditions and dust characteristics requires development of different models to be applied in different situations. Among complexities arising in description of dust-plasma interactions are plasma transport processes in dust material ablation cloud, poorly known dust material properties, irregular dust shapes, and magnetic field effects. All of these require extensive theoretical and experimental investigations. Furthermore, dust transport modeling should be coupled with modeling of plasma transport in fusion devices. First steps were done recently in this direction with the quasi-stationary coupling of DUSTT code with edge plasma transport code UEDGE. More needs to be done to couple dust and plasma transport simulations in self consistent and time-dependent manner. This requires careful consideration of difficulties arising from strong localization of impurity source provided by ablation of a large dust grain in fusion plasma. Also to evaluate full impact of dust on fusion plasma performance coupling with core plasma transport is necessary. The sophisticated simulations can provide predictive capabilities for assessment of plasma operational conditions and their response to possible dust sources in fusion reactors.

In conclusion, in view of plasma-material interaction challenges presented for future fusion reactors the dust related issues cannot be ignored or side-stepped. The potential of dust to become a major cause preventing achievement of economical long burning plasma discharges should be considered with utmost seriousness.

[1] ITER Physics Basis Editors, et al., *Nucl. Fusion* **39** (1999) 2137.
[2] S. Pestchanyi, et al., *Phys. Scr.* **T145** (2011) 014062.
[3] R.D. Smirnov, et al., *Phys. Plasmas* **22** (2015) 012506.