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Characterization of dust collected from ASDEX-Upgrade and LHD

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Abstract

Dust has been collected and analyzed from Axial Symmetric Divertor Experiment-Upgrade (ASDEX-Upgrade) and the Large Helical Device (LHD). A total quantity of 984.4 mg of dust was collected from ASDEX-Upgrade, whereas only 17.6 mg was obtained from roughly equal sampling areas in LHD. Particle sizes determined by count-based measurements from all locations in ASDEX-Upgrade averaged 3.33 μm, and LHD dust had an average size of 9.64 μm. Dust from both devices was composed mainly of carbon and constituents of stainless steel, the materials used for most plasma-facing surfaces and the vacuum vessels. Specific surface area (SSA) of the dust from ASDEX-Upgrade ranged between 0.70 and 3.70 m^2/g. LHD samples contained insufficient mass for measuring SSA. Details from the analysis of each dust collection activity in ASDEX-Upgrade and LHD are described in this paper.

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1. Introduction

The behavior of dust produced while operating fusion plasma experiments has been investigated in Germany's Axial Symmetric Divertor Experiment-Upgrade (ASDEX-Upgrade) tokamak and Japan's Large Helical Device (LHD). Each device presents unique configurations for the generation and transport of dust, thereby contributing valuable insight into dust's impact on the safety and operational performance of future fusion reactors. Dust generated in fusion reactors may be abundant, radioactive, chemically reactive, and/or chemically toxic, thereby posing significant safety and environmental hazards were the dust to be mobilized in an accident [1]. Even for normal operation, a dirty, dusty device is undesirable [1]. At each opportunity, dust is collected from current fusion plasma experiments and analyzed to determine physical, chemical, and possibly radiological properties (e.g. dust from machines that use tritium). Identifying locations of relatively large dust deposits within the device chamber is also important because associated areas in larger reactor systems may require periodic cleaning to minimize dust inventories. Dust collected from ASDEX-Upgrade and LHD displayed some intriguing characteristics that are useful in understanding the importance of dust in various fusion reactor configurations.

2. Dust collection in ASDEX-Upgrade

Dust was collected from the ASDEX-Upgrade tokamak during a scheduled maintenance period in July

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2000. Sources of dust generally include erosion of plasma-exposed surfaces, such as plasma-facing components and protective coatings on antennae and diagnostics. Carbon is used as the primary plasma-facing material, although tungsten has also been used in various configurations of tiles protecting the first wall and divertor. The operation campaign of ASDEX-Upgrade prior to this dust collection activity consisted of 620 plasma shots with various discharge types (limited, diverted, and transport barriers). During the campaign, an abnormal event occurred that breached coolant tubes in the upper divertor, resulting in a water shower and some internal washing of dust deposits from component surfaces.

2.1. Collection locations within ASDEX-Upgrade

Sampling locations in the ASDEX-Upgrade vessel were selected from regions expected to have measurable quantities of dust. Twenty-six locations were selected for sampling via the filtered vacuum collection technique [2]. Samples taken at various poloidal locations were classified into three general categories: upper locations with samples taken 0.5 m above the midplane, middle locations with samples taken ±0.5 m of the midplane, and lower locations with samples taken 0.5 m below the midplane. These locations represent regions where differing quantities of dust deposit due to mechanisms such as gravitational settling. Samples were obtained from several toroidal segments; dust deposits are often toroidally uniform. Pumping ducts were also sampled to investigate dust transport in the vacuum system. The total dust mass collected during this campaign was 984.4 mg.

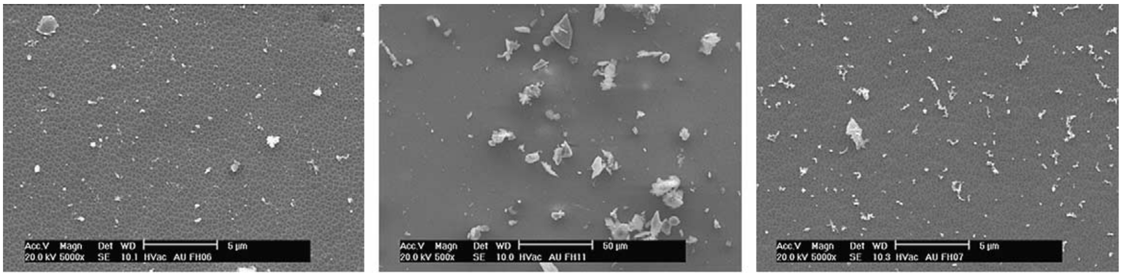
2.2. Particle morphology and size distributions

Scanning electron microscopy (SEM) is used to investigate particulate morphology, and representative images are shown in Fig. 1. The vast majority of particles appeared irregular in shape, and many clusters of very small particles were found. Existence of these small particles and their growth into larger groupings indicates aerosol nucleation from plasma-eroded material may play an important role in dust generation within ASDEX-Upgrade. The particles shown in part b of the figure appear on average larger than those collected from other representative locations. Upon analysis of the count-based particle size distribution for this sample, the larger particles are a small fraction of the overall particle population.

Count-based size distributions were obtained for all dust sampling locations based on optical microscopy imaging and particle counting using the analysis protocol described in [2]. Most locations have distributions that reasonably fit log-normal distributions ($R^2 > 0.95$). Measured count-median diameters (CMDs) ranged from 1.42 to 5.50 μm with an average value 3.33 μm, and the geometric standard deviations (GSDs) ranged from 2.50 to 4.04. There are no significant position-dependent trends of the data moments among all sampled toroidal locations. The average CMD for lower poloidal region samples is small compared those of other poloidal regions (2.21 μm versus 3.6–3.8 μm), even though most of the collected mass came from these positions. A majority of the sample mass is contained in the larger particles of the distribution. Smaller particles, however, significantly outnumber the larger ones, and thereby dominate the count-based distribution.

2.3. Specific surface area

The total effective surface area of dust in a fusion device is an important factor in understanding the consequences of postulated accidents considered in safety analyses. For example, reactive dust with a high surface area may yield explosive concentrations of H_2 when exposed to steam or moist air in postulated loss of vacuum accidents. Specific surface area (SSA) measurements were performed on dust samples taken from two locations in ASDEX-Upgrade from which sufficient dust mass was collected. Material from the structure underneath the inner divertor had an average SSA of



(a) lower (b) middle (c) upper

Fig. 1. Representative SEM photomicrographs of particulate collected from (a) lower, (b) middle, and (c) upper regions of ASDEX-Upgrade.

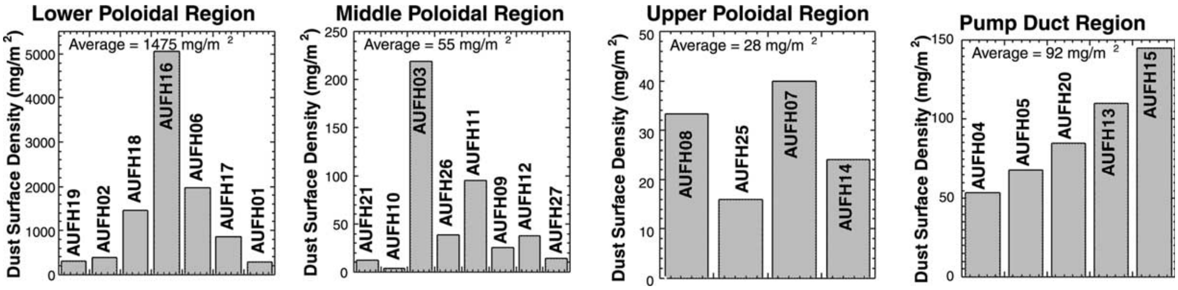


Fig. 2. Distribution of dust surface mass density in ASDEX-Upgrade.

0.684 ± 0.007 m^2/g. Dust found on the vacuum vessel below the inner divertor had an average SSA of 3.681 ± 0.017 m^2/g. Dust composition of the samples from these locations included carbon and metal with unknown weight proportions, thereby rendering unknown the components' relative contribution to surface area. The SSA measurements for dust in ASDEX-Upgrade are consistent in magnitude with the average SSA values obtained from other fusion experiments [3,4]: 2.44 m^2/g in DIII-D, 0.77 m^2/g in Alcator C-Mod, 0.82 m^2/g in TFTR, and 0.3–1.4 m^2/g in Tore Supra.

2.4. Dust composition

Qualitative elemental composition of dust collected from ASDEX-Upgrade was obtained from energy dispersive X-ray (EDX) analysis. Nearly all particles investigated contain some amount of C, Fe, Cr, and Mn. These are the components of most structural (stainless steel) and plasma-facing (carbon) materials in ASDEX-Upgrade. Several particles are mixtures of these components, indicating a formation mechanism that involves mixed-materials.

A complementary composition analysis was attempted on ASDEX-Upgrade dust. Induction coupled plasma atomic emission spectroscopy (ICP-AES) analysis is a measure of the relative intensities of optical and near UV emissions from a sample of material injected into plasma. Typical measurements require a sample mass of at least 1–2 g. To perform this measurement on ASDEX-Upgrade dust, locations that provided large mass collections were added together. These samples were collected from the lower vessel regions below the divertor structure: AUFH16 (404.8 mg), AUFH18 (87.8 mg), and AUFH06 (316.8 mg), for a total mass of 0.81 g. This quantity is barely sufficient for measurement in the ICP-AES used at the INEEL. Materials from these sample locations were found to have the following composition: 67.6 wt% Cu, 23.7 wt% Fe, 5.1 wt% Cr, and 3.6 wt% Ni. Copper is the largest contributor to the composition of this sample, and components of stainless steel are also present. The range of sensitivity of the ICP-AES precludes detection of C, especially for a sample with insufficient mass.

2.5. Distribution of surface mass density

The total mass of dust collected by each filter divided by the sampled area gives the surface mass density at each sampling location. Fig. 2 shows the distribution of surface mass density for all poloidal regions of the ASDEX-Upgrade vessel. Surface mass density is largest in the lower poloidal regions, and in fact is highest at the very bottom of the vessel below the roof baffle (AUFH16). A significant quantity of the dust's mass inventory resides on the vessel bottom; of the total mass collected (984.4 mg), 95% (931.1 mg) was obtained from the lower regions. Upper poloidal regions display much lower surface mass densities, whereas the middle regions display moderate values. The middle region collection location near the ICRH antenna (AUFH03) likely has greater surface mass density than other middle regions locations because of greater erosion rates from this structure. Pump duct locations show increasing mass density at distances farther from the vessel connection port.

3. Dust collection in LHD

In March 2001, scheduled completion of the third experiment campaign provided an opportunity to examine dust in LHD, a heliotron fusion device that addresses the unique plasma physics and engineering issues of an advanced concept alternative to the tokamak. The helical-wound, superconducting coils contribute to LHD's capability to operate with a steady-state currentless plasma. Plasma-facing materials for LHD are predominately stainless steel and carbon. The inner surface of the stainless steel (SS316L) vacuum vessel adjacent to the helical coil is covered with stainless steel plates that serve as coil armor. The vacuum vessel is also protected at the helical divertor strike points by actively cooled carbon tiles.

3.1. Collection locations within LHD

Locations for dust sampling in the LHD vessel were selected from regions expected to have sufficient quantities of dust. Twenty-two locations were selected for sampling via the filtered vacuum collection technique. A group of measurements were obtained from three planes of orientation of the vacuum vessel near module 4. General positions that were sampled include inner and outer port surfaces, top surface of the coil armor, on top (plasma-exposed) and underneath (shielded from plasma) divertor target plates, and vacuum vessel surfaces. The ICH antenna structure was also sampled. Surface orientation of sampled locations varied and is classified as horizontal (surface normal within 30° of vertical), intermediate (surface normal between 30° and 60° of vertical), or vertical (surface normal greater than 60° of vertical). The total dust mass collected during this campaign was 17.6 mg.

3.2. Particle morphology and size distributions

SEM and optical microscopy were used to investigate the details of particulate morphology. The vast majority of particles from LHD appeared somewhat irregular in shape, although a very small population of spherical particles was observed. Sharp surfaces associated with cleaved edges of particles also were not present to any great extent. There were very few noticeable agglomerates or clusters of particles. Detailed views of typical dust particles indicated the presence of surface porosity.

Measured CMDs ranged from 3.00 to 14.39 μm with an average value of 9.68 μm, and the GSDs ranged from 1.75 to 4.07. Few sample locations contained sufficient numbers of particles to give log-normal distributions, and the median particle diameter is larger for LHD when compared to other fusion devices in which dust has been investigated [1]. There are no identifiable position-dependent trends of the particle size data among all sampled locations. Average sizes of particles from plasma-exposed and non-plasma-exposed surfaces vary no more than 5 μm, and surface orientation does not appear to effect particle size.

3.3. Dust composition

Qualitative elemental composition analysis of dust collected from LHD was obtained with EDX analysis. Fig. 3 shows the composition of representative dust particles. An accompanying X-ray spectrum indicates the detected elements. The presence of gold in all samples results from sputter coating a layer of gold atoms at least 10 nm thick. This step during sample preparation is required to avoid charging effects on the non-conductive filter substrate. Nearly all particles investigated contained some amount of C, Fe, Cr, and Mn. These are the primary components of LHD structural (stainless steel vacuum vessel) and plasma-facing (carbon divertor tile) materials in LHD. Copper particulate was also detected, indicating erosion of articles containing copper conductors. Titanium was also detected at a few locations, likely originating from the titanium getter used to remove oxygen from the LHD vacuum. Several particles are mixtures of these components, suggesting co-deposition or some other mechanism of mixing materials.

3.4. Distribution of surface mass density

Fig. 4 shows the distribution of surface mass density for the three planes sampled in LHD (data from ports are not shown). The data are classified by the orientation of the surface and if the surface was exposed to plasma. As indicated in the figure, intermediate and vertical surface locations without plasma exposure appear to hold greater dust mass than positions exposed to plasma. Given these data, it is possible to estimate of the dust inventory (total mass) in the LHD vacuum vessel. Assuming uniform surface mass density derived from the

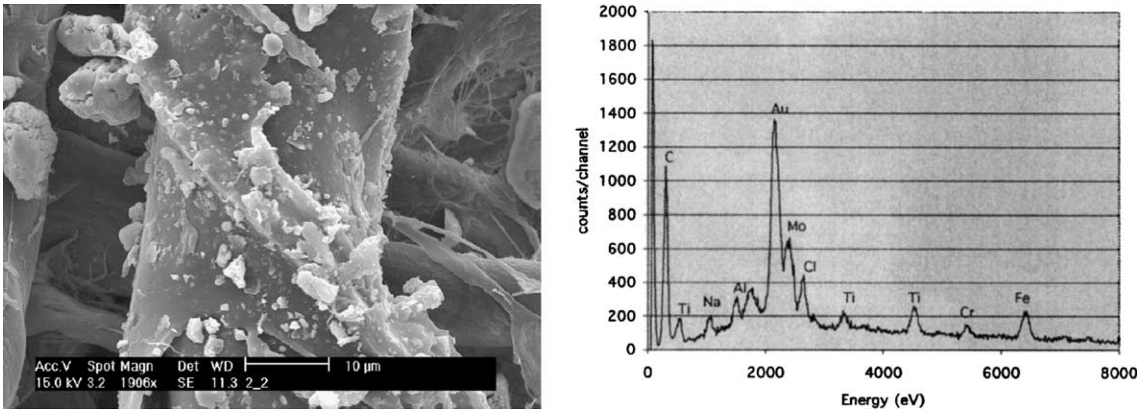


Fig. 3. Carbon, steel, and titanium particles collected from LHD coil armor.

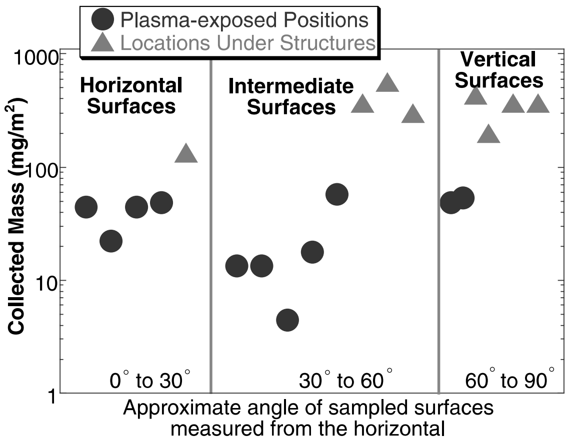


Fig. 4. Distribution of surface mass density of dust collected from LHD.

total mass collected and total area sampled (17.6 mg/4345 $cm^2 = 40.5$ mg/m^2), and estimating the inner surface area of the LHD chamber as 400 m^2, the total dust inventory may be on the order of 16.2 g. The accuracy of this estimate is unknown. This estimate and the experience of attempting to collect dust provides evidence that LHD is very clean and has very little dust at this early point of its operational history.

4. Conclusions

Dust was collected from ASDEX-Upgrade during an outage in July 2000. The predominant particle size determined by count-based measurements from all locations averaged 3.33 μm. Particles of this size are of considerable importance for safety analysis because they are transportable and respirable (i.e. efficiently deposit in the lungs). The total mass collected in this campaign was 984.4 mg, and nearly all the mass was found at the very bottom of the chamber. Specific surface area of the dust ranged between 0.70 and 3.70 m^2/g. The dust was composed mainly of carbon and constituents of stainless steel, the materials used for PFC and structure of the divertor.

In March 2001 dust was collected and examined from LHD, a fusion experiment with an alternative plasma configuration. Dust was collected in three different planes of rotation, typically at the vacuum vessel wall, on top and behind the divertor plates, and from the top of coil armor. The total amount of dust collected (16.5 mg) over roughly equivalent areas is much less than amounts collected from tokamaks – LHD is comparatively very clean. This small quantity precludes many of the standard analysis techniques used to study fusion dust (e.g. BET SSA measurements, ICP spectroscopy for composition, and laser diffraction measurements for volume-based particle size distributions). Dust particles analyzed with SEM/EDX were found to contain materials of structures in LHD, such as steel constituents from the vacuum vessel wall and carbon from the divertor plates. The average surface mass density was 40.5 mg/m^2 for all surface types; a value comparable to middle and upper locations in other fusion research devices (compare to ASDEX-Upgrade at 55 and 28 mg/m^2, respectively). Average count-based particle size from all locations is 9.64 μm, and few sample locations contained sufficient numbers of particles to give log-normal distributions, and the median particle diameter is larger for LHD when compared to other fusion devices in which dust has been investigated. Continued collection and analysis of dust will aid in understanding the role of LHD's operation history on dust production and behavior.

References

[1] J.P. Sharpe, D.A. Petti, H.-W. Bartels, 6th International Symposium on Fusion Nuclear Technology, San Diego, 7–12 April 2002.

[2] W.J. Carmack, M.E. Engelhardt, P.B. Hembree, K.A. McCarthy, D.A. Petti, DIII-D Particulate Characterization, INEEL External Report INEEL/EXT-97-00702, November 1997.

[3] J.P. Sharpe, Ph. Chappuis, D.A. Petti, Fus. Technol. 39 (2001) 1061.

[4] R.A. Anderl et al., BET Surface Area Measurements of Materials for Fusion Safety Studies, ITER Engineering Design File, ITER/US/97/TE/SA-20, January 1998.