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Characterization of Size, Composition and Origins of Dust in Fusion Devices

Summary Report of the Second Research Coordination Meeting

IAEA Headquarters, Vienna, Austria

21–23 June 2010

Prepared by

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International Atomic Energy Agency, Vienna, Austria

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Abstract

Eleven experts on processes of dust in fusion experiments met for the 2nd Research Coordination Meeting (RCM) of the Coordinated Research Project (CRP) on "Characterization of size, composition and origins of dust in fusion devices" held at IAEA Headquarters 21–23 June 2010. Participants summarized their studies on dust in fusion experiments and reviewed progress made since the first RCM. Gaps in knowledge were identified and a plan of work for the remainder of the CRP was developed. Presentations, discussions and recommendations of the RCM are summarized in this report.

November 2010

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1. Introduction

Past experience with tokamaks such as TFTR and JET has shown that significant amounts of dust are formed in these machines. In a long-pulse machine such as ITER or a fusion reactor the accumulation of dust presents a combustion hazard in some accident scenarios. Furthermore, dust particles will contain hydrogen isotopes in varying degrees depending on the origin of the dust, and so the production and behaviour of dust is important for tritium inventory assessment. Dust that is contaminated with tritium can become electrically charged from radioactivity, leading to the interaction of the dust with the plasma and electric fields. Taken together, the potential for tritium accumulation and the combustion hazard make dust the principal safety issue for licensing of ITER. Total amount of dust, amount of mobilizable dust, amount of dust on hot surfaces, and amount of tritium accumulated in dust are all subject to strict safety limits that must be verified throughout the operation of the device.

The IAEA Coordinated Research Project (CRP) on "Characterization of size, composition and origin of dust in fusion devices" was formed to improve our knowledge of properties, production mechanisms and dynamics of dust in fusion devices. The CRP held its second Research Coordination Meeting (RCM) 21-23 June 2010 at IAEA Headquarters in Vienna, bringing together 11 experts on processes of dust in fusion experiments. Participants summarized their studies on dust and reviewed progress made since the first RCM that took place in December 2008. Presentations, discussions and recommendations of the meeting are summarized in this report. Participants' presentation materials and additional information about the work of this CRP may be found through the Atomic and Molecular Data Unit web pages under http://www-amdis.iaea.org/.

Section 2 contains summaries of the presentations at the meeting. Section 3 describes remaining gaps in knowledge, R&D needed to address gaps, and specific CRP participant plans to address these gaps during the remainder of the CRP through December 2011. The description is organized under the topics of dust generation, dust mobilization from tiles and codeposited layers, dust particle database development, dust transport to the core plasma, dust contamination of diagnostic mirrors, dust diagnosis on hot surfaces, diagnosis of the total dust inventory, and dust removal technology. Section 4 contains a summary and conclusions. The list of participants is provided in Appendix 1 and the agenda of the meeting in Appendix 2. Appendix 3 provides a list of recent publications by participants in the CRP that are related to the subject matter of the CRP.

2. Presentations and Proceedings

Dr R.A. Forrest, head of the Nuclear Data Section, opened the meeting and welcomed participants to Vienna. He noted the critical issue of verifiable safety limits on total dust (1000 kg) and in-vessel tritium inventory (1 kg) in ITER and expressed confidence that the present meeting would contribute to the knowledge of processes of dust in plasma that is necessary for the development of fusion as an energy source. Dr. B. J. Braams (scientific secretary) extended his welcome and noted the substantial list of publications by participants since the inception of the CRP (at least 27 publications on dust in fusion plasma that carry a date in 2009 or 2010). The prepared agenda was adopted with minor changes: it was agreed to start at 09:00 on the 2nd and 3rd days and it was agreed to split the EFDA presentation by Drs. Zagorski and Malaquias into 2 presentations.

Dr S. Ciattaglia of the ITER Organization reviewed the baseline provisions and the status and plans of R&D for dust inventory control in ITER. The licensing of ITER requires demonstration of the safety of the installation. The licensing process is ongoing; it is hoped to obtain the "acceptability" of the preliminary safety report from the French Nuclear Authority (ASN) after summer, to be followed by the public enquiry and the Group Permanent review in 2011. Confinement of dust and tritium inventory, in particular those in the vacuum vessel, constitutes the main safety issue in ITER; other safety issues, such as decay heat removal and plasma shutdown, are easily met. The key safety limits are 1000 kg dust and 1000 g tritium in the vacuum vessel. Concern over tritium inventory has led to the decision that there will be no carbon in the plasma-facing components in ITER during the nuclear phase. This decision and the approval of few design changes into ITER baseline should provide a viable solution to control dust and tritium with minimum impact on machine availability. However, the ability to measure dust and tritium inventory throughout the operation of ITER remains essential and remains the subject of R&D.

The baseline systems for dust measurements in ITER are erosion measurements by PFC metrology, which provide an upper bound. The erosion measurements employ the in-vessel viewing system (IVVS) [C. Neri, A. Coletti, M. Ferri de Collibus, et al., Fusion Engineering and Design vol. 84 (2009), pp. 224-228]. In addition, near-wall plasma spectroscopy provides a direct measurement of impurity release, which is in turn an upper bound for erosion. The primary erosion measurements are supported by local dust monitors, dust removable samples, a dust production rate model, and by tracking and characterization of removed dust. The baseline systems for measuring tritium inventory in the vacuum vessel are the global balance (difference between tritium injected and tritium burnt in the fusion reaction and tritium recovered from VV) and characterization of material removed from the vacuum vessel, especially Be dust and co-deposited layers where most of the tritium should be. These baseline systems are supported by laser-induced breakdown spectroscopy (LIBS), by models for tritium retention and tritium transport, by removable samples from the VV and by desorption via laser mounted on the in-vessel viewing system (under feasibility study).

The baseline system for dust removal is a remote handling vacuum cleaner mounted on the Multi-Purpose Deployer (MPD) arm; this can only be used during a shutdown when the vessel is exposed to air or nitrogen (at less than atmospheric pressure). The MPD remote handling arm was recently adopted into the ITER baseline in order to cope with several in-vessel tasks including dust and tritium sampling and collection, in-vessel inspection, diagnostics and ELMs coil maintenance. It can be deployed through 4 designated entry equatorial ports and reach over a segment of VV of ±50°. The payload capacity is 2 tons and it has a maximum Point of Reference speed of 100 mm/s and accuracy of ±10 mm. Also the other in-vessel remote handling system (for divertor cassette and blanket removal) can contribute to removal of dust. The baseline systems for tritium removal are divertor baking at 350°C, dust removal, and pulse-width modulation cleaning and conditioning techniques. This is supported by baking of the blanket-first wall at 240°C and vacuum vessel at 200°C, and ultimately by replacement of plasma-facing components. All these systems are included in the Project Requirements (PR) and Plant Design (PD) specifications. (A non-invasive hot dust reactivity measurement is under R&D, but not yet in PR/PD.)

An important broad R&D task is to reduce uncertainties in the dust and tritium inventory measurements, which includes the control of the growth of uncertainties with operation time and number of pulses. A better understanding of the relation between erosion and dust production would be very helpful for reducing the uncertainty in dust inventory. There are several ongoing R&D tasks on dust production and monitoring. Inventory characterization experiments were done at JAEA (V. Alimov) on dust and tritium in relation to W. Tritium desorption from Be co-deposited layers (produced in Romania) is studied at IPP and at PISCES, with further experiments to be launched soon. A dust production rate model is wanted, but development and validation is not progressing well. Development of a dust local monitor is being started by EU-F4E. A dust and tritium removable samples feasibility study is to be launched soon. Also the further potentiality of the IVVS (the only tool available in vacuum) is under study. The definition of detailed MPD task for dust inventory removal is on-going. Design of remote handling End Effectors for dust collection and sampling by the different RH tools is yet to be done. A detailed plan is to be defined to validate the dust and tritium measurement and removal methods during the staged start-up phase of ITER.

Dust/H explosion accident scenario studies are underway. Small to medium scale experiments are completed with H, W and C (EU-F4E) and experiments with Be have been launched (US). These experiments are used for model validation (codes DUST3D and CAST3M). Experiments and model development for mitigation systems are ongoing (EU-F4E) and an integrated large-scale experiment in ITER VV geometry is being defined. ITER plasma heat transient loads experiments are being prepared at QSPA-Be in Russia to qualify ITER Be first-wall. Dust production and characterization will be studied as well.

There are several other major R&D efforts underway that are important for dust and tritium inventory control. The International Tokamak Physics Activity (ITPA) encourages research across machines on plasma-wall interaction issues. The EU (EFDA) has a Plasma-Wall Interaction (PWI) taskforce and an Emerging Materials Technology (EMT) Special Experts Working Group (SEWG). JET has a fusion technology programme and the very important ITER-Like Wall (ILW) project. The IAEA supports a coordinated research program (CRP) on dust in fusion plasma.

An important open issue for ITER is the production of H_2 from the reaction of water vapour with hot dust under accident conditions. Measurements of the dust-vapour reaction are being supported by EU-F4E and measurements and modelling of dust transport is supported by ITPA. The limits on hot dusts are quite low and the uncertainties are high; therefore it is important to have an effective mitigation system, which could place such an accident beyond the design basis. This is an urgent task for the safety review. In parallel there are design requirements to detect and limit, by design, the maximum amount of oxygen entering the VV from each penetration in accident condition.

Dr V. Rohde of the Max-Planck-Institute for Plasma Physics at Garching, Germany, described recent dust investigations in the full-tungsten ASDEX Upgrade (AUG), focussing on the production of dust by arcing and on refined methods for dust collection and analysis. (Work with contributions from Institut Jean Lamour of Nancy University, France.) In AUG dust is observed, but it is not a major feature for operation of the experiment. (It is not known if the dust is a significant impurity source.) The motivation for the studies on AUG is that dust is a safety issue for ITER, and the studies aim to characterize the origins and properties of dust in the machine.

There are several sources of debris and dust in AUG that do not involve plasma; for example human hair, drilling and welding in the vessel, and movement of components as the vacuum or the magnetic field is turned on and off. In addition dust is produced by brittle destruction and by flaking of a:CH layers. The processes of melting and arcing produce dust droplets. Physical and chemical sputtering produces initially just atoms and molecules, but these may condense to form dust directly or to form redeposited surface layers which can then flake off to form dust.

AUG started with carbon plasma facing components. A tungsten divertor was installed in 1995/1996. The formation of thick carbon deposits was observed on the tungsten tiles of the divertor. Over the years 2002-2007 all plasma-facing components were gradually coated with tungsten so that now the entire first wall is tungsten-coated, and the divertor material are tungsten tiles. Carbon deposits are still found, although much reduced; they are presumably due to remaining carbon from preceding campaigns, arcing, damages and chemical erosion at non W-coated locations

Dust is observed during operation of the machine by a fast sensitive CMOS camera looking into the main chamber. Only hot particles can be observed this way. For carbon dust the detection limit in size is about 3 μm. Typical projected velocities are 10-100 m/s. Large uncertainties are introduced when reconstructing the trajectories from images of only a single camera. In normal operation almost no dust is seen, but dust is routinely observed after disruptions. The camera produces about 8 GB of data per discharge and in total almost 8 TB during the 2009 campaign; therefore fast automatic evaluation is needed and this is achieved in cooperation with Nancy University with support from the EFDA Taskforce on PWI. The algorithms are tested on simulated images and on data from a dusty laboratory plasma generator (RF discharge, Ar/C_2H_2 plasma). First applications of the new imaging system and analysis software were presented this year at the EPS and PSI meetings. A dual camera system is being developed now for the next campaign.

Dust and debris is collected immediately after machine opening in AUG. Several observations were made in these dust collection campaigns; e.g. after 7 years of operation without cleaning the port below the divertor looked like an ashtray. The material collected there was mainly mechanical debris from work in the vessel or from movement of components. This kind of debris has to be excluded from analysis as it is not relevant as dust for ITER. Dust had been analysed for carbon PFCs [J. P. Sharpe, V. Rohde, the ASDEX-U experimental team, et al., J. Nucl. Mater. Vols. 313–316 (2003) pp. 455+]. Dust was again recovered and analysed after the 2008 campaign [V. Rohde, M. Balden, T. Lunt and the ASDEX Upgrade Team, Physica Scripta T138 (2009) #014024] and after the 2009 campaign [N. Endstrasser et al., J. Nucl. Mater., submitted]. Carbon is a negligible constituent and it is estimated that about 17% of the W eroded at the divertor winds up in dust; also boron and steel are present in the dust. After the 2008/2009 campaign the total amount of tungsten in dust is estimated at 1210 mg of which 510 mg in particles below 5 μm in diameter. The sub-micron dust is dominated by pure tungsten spheres.

During the campaign 5 silicon wafer dust collectors were installed in the vessel. Particles produced during the plasma operation were trapped on the silicon wafers. After the 2009 campaign the silicon wafer collectors were sealed and unmounted and dust was collected in their close vicinity via carbon pads used as adhesive probes and filtered vacuum sampling. Automated particle analysis was realized using a FEG-SEM FEI Helios Nanolab. The control software identifies, measures and analyses particles; it runs on weekends and has so far inspected 60 mm^2 surface area and classified 50 000 particles including EDX spectra. The classification categories are W-dominated droplets, W-dominated flakes, C-dominated flakes, B crystallites, B flakes, Cu-dominated flakes, Fe-dominated droplets, and contamination (including debris and organic residue). Statistical analysis has started in which the quantity of dust and its classification is correlated with location in the vacuum vessel.

Inspection of the tungsten divertor tiles shows melt damage and also extensive arcing at the inner divertor baffle region. The arc traces are of three kinds: irregular movement associated with glow discharge cleaning, accidental arcs between structures as the Passive Stabilization Loop in AUG in the magnetic field direction, and unipolar arcs on the PFCs that move perpendicular to the field. Tiles are analyzed by a confocal scanning microscope with integrated blue laser profilometer; the spatial resolution is 800 nm and the depth resolution is 6 nm. Two kinds of arc traces are found: long traces (~5 mm by 50 μm, >5 μm deep) and dips (~10 μm by 10 μm, 5 μm deep). Around the arcs one finds tungsten droplets and resolidified molten tungsten splashes, and in some cases the carbon substrate is exposed. Analysis of local erosion shows that at the inner baffle region arcing is the dominant cause of erosion, more important than physical sputtering. Video images of arcing have been made using a fast camera that views the inner baffle with a resolution of 150×150 μm^2 and time resolution 3 μs. The arcing is associated with ELM activity.

Plans for the next two years include video dust trajectory analysis in 3D. The dust collector may be applied also on DIII-D, LHD, and JET. Statistical analysis of data will be pursued, also of other samples (pads, filters) and the studies of arcing will continue.

Dr A. Widdowson of the Culham Centre for Fusion Energy, CCFE, presented an update on dust collection at JET during the 2010 intervention. (Earlier dust collections took place after the various divertor upgrades, most recently in 2004.) The principal source of dust is the spalling of deposited layers once a critical thickness, which depends on the type of deposit, is exceeded. JET has taken its lead from the ITER organisation in identifying dust studies as a principal area of concern for further research and development. With respect to dust production a key question is what fraction of eroded and re-deposited material turns finally to dust. (Present safety assessments rely on the most pessimistic assumption that all co-deposited material is available for dust production.) With respect to dust characterisation the key issues are tritium content, particle size and surface specific area. Dust mobilisation is important for assessing accident scenarios. JET has the opportunity to contribute to all these areas of dust research as was expressed in the 3-year plan for the contributions by JET to this CRP.

The plans for the collection of dust during the present shutdown have been developed over 2009 and early 2010. The divertor is the primary region of interest. In the inner SOL in the divertor Be-rich deposits are found. Underneath the inner and outer louvers (bottom of the divertor) the deposits are rich in carbon. On the divertor floor tiles again Be dominates. There is very little deposited material on the outer SOL, as this is a net erosion zone. The dust collection programme is intended to collect about 100 g of dust from each of these areas. A remote handling cyclone vacuum cleaner has been developed to this end and the detailed planning for the dust collection has been produced. The collection of dust is now underway and the analysis is planned for 2011.

For erosion and deposition studies (related to the production of dust) a set of tiles that have marker coatings are installed on JET, and some of these tiles are to be removed from the vessel during the present shutdown for further analysis. These tiles are in critical areas: the inner and outer divertor target, the inner guard limiter, outer poloidal limiter, and the upper dump plate. Post mortem analysis is planned: nuclear reaction analysis and proton back scattering in order to quantify C, Be and D at the surface; secondary ion mass spectrometry (SIMS) to measure the depth profile of deposits; and cross sectional microscopy to measure the thickness of deposits. The total amount of deposit can be estimated if toroidal symmetry is assumed. Similar studies of tile erosion and of deposits on tiles were carried out after previous campaigns and the properties of the deposits (thickness and composition) vary substantially from case to case.

Other dust studies have been considered for the present shutdown. Dust mobilization studies and smears of the vessel walls (after tile removal) will not be done; it conflicts with the shutdown timescales and the ALARP assessment is prohibitive. The area under the divertor has been inspected again as was last done in 2001. Future ex-vessel dust studies are planned. A representative series of tiles from a poloidal cross section has been identified for these studies. Ex-vessel mobilisation experiments and smears of tile surfaces are possible. The resulting dust samples may be made available to interested Associations for analysis: particle sizes, chemical composition and specific surface area are of interest. It is considered to install a passive dust collector during the next shutdown in 2012. For future erosion studies a tile profiler system has been developed. The system measures profiles of tiles along a sequence of points before and after exposure in JET. Differences in profile above 20 μm can be measured. The first exposed tiles removed from the vessel are ready for analysis. A new enclosure to measure contaminated tiles has been designed and (nearly) commissioned.

The measurements during a shutdown are integrated measurements with respect to the time of a campaign, or several campaigns, and it is difficult to quantify the sources of dust precisely. In addition to plasma-wall interaction processes also mechanical abrasion during maintenance may provide a source of flakes and debris. In conclusion to the presentation, all the activities on JET planned for the CRP are completed or are progressing on schedule with the exception of some in-vessel studies (noted above) that are now judged to be not feasible.

One issue not covered in the presentation, but subsequently added into this meeting report, is contamination and cleaning of diagnostic mirrors. This is a concern for ITER and is related to production and removal of dust. A First Mirrors Test (FMT) for ITER has been carried out at JET with a large number of specimens located in the divertor and on the main chamber wall [M. Rubel, et al., First Mirrors test in JET for ITER: an overview of optical performance and surface morphology, Nucl. Instrum. and Meth. A 623 (2010) pp. 818–822]. Carbon deposits are the most severe problem in the FMT, and are expected to be the most severe issue in ITER if carbon plasma-facing components are used. With caution for extrapolating to ITER the FMT study indicates that in that case some diagnostic mirrors, especially in the divertor region, may be coated with deposits in just tens of discharges. Methods for in-situ cleaning and/or protection of mirrors will be required. Laser cleaning of mirrors exposed to JET plasmas has been performed [A. Widdowson, et al., Poster O-18, 19th PSI, San Diego, 2010], however some damage by the laser of the mirror surface was noted.

Dr C. H. Skinner of Princeton Plasma Physics Laboratory described work on dust detection, mobilization and transport. The presentation described real-time detection of dust on the National Spherical Torus Experiment (NSTX) using an electrostatic dust detector, dust mobilization from ITER-scale castellations, and 3-D dust trajectories in NSTX.

An electrostatic dust detector has been developed [D.P. Boyle, C.H. Skinner, A.L. Roquemore, J. Nucl. Mater. 390-391 (2009) pp. 1086+] and installed on NSTX [C. H. Skinner, B. Rais, A. L. Roquemore, Rev. Sci. Instr. (2010) in press] to provide the first real-time detection of surface dust in a tokamak. The detector is a set of interlocking traces on a circuit board with 25 μm spacing, to which a 50 V bias is applied. An impinging dust particle creates a short circuit and a current pulse that is input to nuclear counting electronics. The number of counts is proportional to the mass of dust. The current also vaporizes or ejects the dust from the circuit board, restoring an open circuit. The device works in air or in vacuum. A first version was developed in 2004 and had a sensitivity in vacuum of about 70 μg/cm^2. This is quite sensitive enough for ITER dust levels, but on NSTX the measured dust production is only about 5.6 ng/cm^2/discharge. The newer (2009) detector has therefore a larger detector area (from 1.2cm×1.2cm to 5cm×5cm), finer grids (30-fold increase in sensitivity), and a much lowered detection threshold in the electronics, and it reached 4000 counts for a dust concentration of 100 ng/cm^2. Due to the lower detection threshold electrical pickup noise was an issue, especially noise from SPAs and the RF antenna on NSTX. A new differential circuit was developed to provide immunity from electrical noise pickup. The detector was calibrated in the laboratory for carbon and lithium particles. The sensitivity to carbon particles is 0.15 ng/cm^2/count and for lithium particles 14.5 ng/cm^2/count [B. Rais, C. H. Skinner, A. L. Roquemore, "Calibration of an electrostatic dust detector", PPPL report in preparation (2010)]

On NSTX the dust detector is shielded by a mesh cover from fibers and large particles that might cause a permanent short. The detector was installed at a lower port and has operated there during July and August 2009. The experiment demonstrated the first real-time detection of dust in contemporary tokamaks. The measurements were validated by (i) comparison of the NSTX signal to the signal from a lab dust source, (ii) by the relative lack of signals on a covered detector that was not sensitive to dust and (iii) by observing the increase in signal upon injection of Li particles. Further development is needed for the ITER environment: the apparatus must be much more rugged, it can be much less sensitive, and must be radiation hardened, among other things.

Experiments were also carried out on dust mobilization from ITER-scale castellations in order to assess if dust between tiles is permanently buried there or if it can be mobilized by a disruption. The experiments involve a castellation mock-up on NSTX with gaps that are the same dimensions as the ITER castellations. The mock-up is made from boron nitride (an insulator) to avoid issues with induced JxB forces. The mock-up was loaded with dust (carbon particles scraped from ATJ tile were used), inserted by a PMI probe, and subject to a plasma disruption. The mock-up was weighed and photographed before and after to assess how much dust is lost. For a single disruption, dust was lost from a gap depth similar to the gap width of 0.5 mm, comprising 12% of the total mass of dust in the castellation gaps.

A third set of studies involved the 3-D reconstruction of incandescent lithium and tungsten dust particle trajectories in NSTX plasmas. This experiment is part of an ITPA DSOL-21 Joint Experiment "Introduction of pre-characterized dust for dust transport studies in the divertor and SOL." The ITPA experiment aims at the characterization of core penetration efficiency and impact of dust of varying size and chemical composition on the core plasma performance in different conditions and geometries, the characterization of dust mobilization from PFCs, and the benchmarking of DustT and DTOKS modeling of dust transport and dynamics. In the NSTX experiment 40 μm diameter Li dust (a proxy for Be dust) and 10 μm diameter tungsten dust were dropped into the scrape-off layer. The particles readily turn incandescent from plasma interaction and were tracked using two visible-range cameras separated in space by ~ 60 degrees. 3-D trajectories suitable for input to the DUSTT/UEDGE code are derived from the two 2-D camera images. For the Li particles 215 trajectories were analysed. Typical particle velocities are some tens m/s in a direction across the magnetic field, but a small fraction of particles travel along field lines; these particles are generally much faster, reaching velocities above 100 m/s. About 1% of the lithium particles are seen to undergo abrupt changes in direction and velocity; this behaviour is not yet understood. The tungsten dust particles are much slower (0.5-1.7 m/s) than the Li. They are closer to and possibly cross the last closed flux surface.

Dr C. Castaldo of ENEA, Frascati, described studies of fast dust particles in tokamaks by aerogel samples and electro-optical probes. The studies concerned dust impact processes, collection of hypervelocity dust in aerogel targets, and development of an electro-optical probe for detection of hypervelocity dust particles.

Hypervelocity impact occurs when the impact velocity exceeds the velocity of compressional waves in both the projectile and the target. The impact pressure can reach 1 TPa and the temperature can be sufficiently high to cause vaporization and ionization of projectile and target material. Impacts can be studied through the associated ionization, through the morphology and geometry of the impact craters, through light emission from the vapour cloud or from the target and solid ejecta, or through microwave emission due to structural changes in the target. A large amount of empirical data is available, in part due to the importance of the subject for space missions.

Evidence of hypervelocity dust in the Frascati Tokamak Upgrade (FTU) is seen in impact craters on electrostatic probes as well as on spikes of the ion saturation current signal vs time [C. Castaldo, S. Ratynskaia, V. Pericoli et al., Nucl. Fusion 47 (2007) pp. L5+; S. Ratynskaia, C. Castaldo, K. Rypdal et al., Nucl. Fusion 48 (2008) #015006]. The latter were detected by two adjacent probes, separated by 6 mm in poloidal direction. The largest spikes (> 5 rms), with typical duration of several tens microseconds, were observed only by one probe at a time, the adjacent one did not show any significant correlated signal. This suggest the occurrence of local ionization events, as larger plasma fluctuations (e.g. the so called 'blobs', filamental structures of dense and hot plasmas elongated in toroidal direction and propagating towards the walls) are expected to have larger poloidal correlation [S. J. Zweben, D. P. Stotler, J. L. Terry et al, Phys. Plasmas 9 (2002) pp. 1981+]. Such local ionization events cannot be due to unipolar arcs, since the maximum current detected by the probes is lower than 50 mA, which is orders of magnitude lower than the threshold current necessary to sustain the arcs. The number of uncorrelated spikes detected by the probes roughly matches the number of the craters detected on the probe tips, confirming the interpretation of the events in terms of dust impact ionization phenomena. The craters are quite different from those produced by arcing; they are missing the rough rims from ejected molten metal that are typical for unipolar spots and they don't have the scratches caused by a migrating arc.

In order to study the high velocity dust more closely very porous silica (SiO_2) aerogel targets are used on FTU. The target material is transparent and has a typical mass density of 0.1 g/cm^3. These collectors have been used in space and they capture compact dust particles with diameter in the range 0.1-100 μm and velocity several km/s without melting or vaporisation. First exposure of aerogel samples on tokamaks was performed in the HT-7 [G. Morfill et al., New Journ. Phys. 11 (2009) #113041] and TEXTOR [S. Ratynskaia, et al., Nucl. Fus. 49 (2009) #122001] tokamaks. The measurements on HT-7 provide evidence of dust particles having velocity of at least several hundreds m/s. On TEXTOR the aerogel targets captured both slow and fast particles with sizes in the range of below 1 μm to about 100 μm. Carbon particles of size up to 100 μm stick to the aerogel surface at a rate of 20–50 cm^{-2}s^{-1} during the flat top phase of the discharge. Tracks were found with captured 10 μm particles for which the impact velocity could be estimated at 2–3 km/s.

On FTU the incidence of high velocity dust impacts is estimated via the cratering to be about 100 cm^{-2}s^{-1}. Craters with typical diameters of 20 μm and depths of 5 μm are produced, causing a wall erosion of about 1 nm/s; therefore these hypervelocity dust impacts are potentially harmful for fusion reactors. An electro-optical (EO) probe for dust detection in the tokamak SOL is being developed at Frascati. In order to discriminate dust impact ionization events from plasma features the probe detects simultaneously the released charge (spikes in ion saturation current) and line emission at a target material wavelength. Hypervelocity dust impact events produce a total charge of 10^{12}–10^{13} e and current spikes of amplitude 20–30 mA. Lower amplitude current spikes due to impacts may be detected by simultaneous light flashes. The interpretation of the measurement relies on modelling and experimental data of the light emission from the expanding vapour cloud produced by the impact, assuming local thermodynamic equilibrium at the target vaporization temperature. For a tungsten probe the 401 nm line is suitable and it is estimated that hypervelocity impacts will produce a signal well above the Bremsstrahlung background on the collecting optics, at least during the first 100 ns after the impact.

Dr P. Humrickhouse of Idaho National Laboratory (replacing Dr P. Sharpe in the CRP) reported on work in the INL Fusion Safety Program on dust resuspension modelling. This work is concerned with accident scenarios and in particular loss of vacuum accidents, so the dust is transported in neutral gas. The INL Fusion Safety Program employs a systems code, MELCOR, that solves thermal hydraulics and other things, including aerosols. MELCOR was developed at Sandia National Laboratory for LWR accident modelling and has been modified at INL for fusion applications. It has been qualified for ITER safety analysis. The direct aim of the present work is to develop and validate a resuspension model and incorporate it into MELCOR. The broader objective is to assess the extent of resuspension and subsequent transport in an accident.

MELCOR will deposit aerosols on surfaces, but has at present no model or mechanism to resuspend them. (This shortcoming is not limited to MELCOR.) Deposition does not really require treatment of particle surface interactions; body forces on particles steer them toward a surface where they are simply assumed to stick. On the other hand, resuspension requires modeling interactions between the particle, the surface, and the boundary layer flow. For adhesion there are two widely used models: the DMT model [B. V. Derjaguin, V. M. Muller and Yu. P. Toporov, J. Colloid and Interface Science 53 (1975) pp. 314+] and the JKR model [K. L. Johnson, K. Kendall and A. D. Roberts, Proc. Roy. Soc. London A 324 (1971), pp. 301+]. Both models assume that particles adhere to surfaces due to van der Waals forces; they differ in their model of the contact region and thus in the precise dependence of the adhesive force on particle shape. Resuspension may then be understood through static force balance; in the simplest picture it occurs when the drag or lift force exceeds the adhesive force. For small particles the drag force depends on the flow in the near-wall viscous sublayer, and so on the viscous shear at the boundary.

The model of resuspension based on static force balance has shortcomings; it predicts either zero resuspension or complete resuspension, whereas partial resuspension is observed in practice. There is no time component to the model and no recognition of effects of fluid turbulence. More recent models for resuspension seek to overcome these shortcomings; these include the VZFG model [P. Vainshtein, G. Ziskind, M. Fichman and C. Gutfinger, Phys. Rev. Lett. 78 (1997) pp. 551+] and the "Rock n' Roll" (RNR) model [M. W. Reeks and D. Hall, J. Aerosol Science 32 (2001) pp. 1+] that is based on the earlier RRH model [M. W. Reeks, J. Reed and D. Hall, J. Phys. D: App. Phys. 21 (1988), pp. 574+]. These are kinetic models of a kind also used to model molecular desorption. The dust particles are viewed as attached to the surface via elastic springs, and the turbulence transfers energy to the oscillating particle. Both models assume that monodisperse particles contact rough surfaces at contact points called asperities, whose radii (and resulting adhesive forces) possess a lognormal distribution. Primary differences between VZFG and RNR models are that RNR considers both drag and lift effects on rolling; it treats contact with multiple asperities; it includes Gaussian distribution of drag forces; and it models spring oscillations as linear in the direction of fluctuating force.

In a numerical implementation of these models (VZFG and RNR) it is necessary to discretize in time and in adhesive force (and particle radius). The force distribution evolves in time as loosely bound particles are resuspended. A Fortran code has now been written to solve the problem and it will be implemented as a MELCOR subroutine. Discretization into nr particle radius intervals, na adhesive force intervals and ns total surfaces for nr×na×ns bins presents significant memory requirements; it may be decided to take all resuspending particles from one bin, rather than calculating a resuspended fraction from each bin. Calculations indicate that this approximation is close to the "exact" solution, though this needs to be verified for a wider range of flow parameters.

Comparisons have been made between the VZFG and RNR models and experimental data for spherical dust particles (Al and C) in well-characterized flow. The results agree well with published calculations. Some key results of the numerical experiments: The RNR model tends to predict more resuspension than the VZFG model for the same material and flow parameters. The spread in adhesive forces and the average adhesive force strongly influence the resuspension behaviour. Both RNR and VZFG models exhibit 1/t dependence of the resuspension rate at long times, which has been previously observed in experiments. Eliminating the Gaussian distribution of drag forces in the RNR model in favour of a simple average has little impact. As expected, larger particles are more easily resuspended than smaller particles. The "geometric factor" characterizing the distance between points of contact (asperities) in the RNR model also significantly influences resuspension, and in practice it will be difficult to measure or estimate.

The models still need to be implemented in MELCOR and verified for a broader range of flow parameters, including comparison to experimental data if available. The relative strengths and weaknesses of competing models need to be assessed. Finally the biggest challenge is to obtain a quantitative result, given the demonstrated importance of parameters such as the mean and spread in the lognormal distribution of surface asperities, and the fact that this surface morphology will be continually evolving for PFCs.

Dr N. Ashikawa of the National Institute for Fusion Studies presented an update since the 1st RCM of work on characterization of dust and on dust dynamics in LHD and JT-60U. One study involved pre-characterized carbon dust in LHD. Another study concerned dust retention in LHD. Plans were presented for study of mixed C-W dust in JT-60U.

The pre-characterized carbon dust experiment in LHD builds upon previous work in which natural dust is studied using a fast infrared video camera [N. Ashikawa, Y. Tomita, S. Masuzaki et al., poster EX/P4-7, 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, 13-18 October 2008]. The camera has a time resolution of 5.3 ms and dust particles are seen for up to about 100 ms as they pass through the field of view. Particles are observed through their radiation, both directly and as a reflected image on the metal wall. In the processing the direct and the reflected image are combined to reconstruct a trajectory in space. The observed velocities span a range of about 1-20 m/s. Size, shape and composition of the natural dust particles seen in the video images are unknown. Analysis of deposited dust shows that the carbon dust particles have normally a diameter below 1 μm while metallic dust particles have diameter in the range 1-10 μm.

For the new experiments a dust holder has been installed in a bottom port. It is filled with well-characterized dust; in this case spherical carbon particles of diameter 8 μm. Some time after the start of the discharge a hot spot forms on the holder and dust is ejected. The dust particles are seen to accelerate in the plasma and to achieve a velocity of up to 40 m/s.

The second topic in the talk of N. Ashikawa is dust retention. In previous related work the D/C ratio in deposited dust was measured on several devices. On TEXTOR one found carbon flakes and a D/C ratio of about 0.08, on TFTR the ratio was reported as 0.007, on JT-60 with open divertor 20 micron flakes were found with H/C=0.04, and JET reported carbon flakes with ratio D/C=0.4. In the new work on LHD dust was collected using a membrane filter and vacuum pump. Mainly large flakes and deposition layers were analyzed by thermal desorption spectroscopy (TDS) and X-ray photoelectron spectroscopy (XPS).

In joint work with N. Asakura and T. Hayashi dust was also collected again on JT-60U in 2010, after the final shut-down of the machine, from ferritic FW tiles and VPS-W divertor tiles that had been exposed over 4 and 6 years of operation respectively. The size of the metallic dust particles is below 100 μm and carbon dusts have size between about 10 and 50 micron. Various shapes of carbon dust are observed: flakes, spheres and conglomerates. Also mixed W-C dust particles are found near the tungsten tiles of the outer divertor.

The ITER Organization and the International Tokamak Physics Association (ITPA) have identified important tasks in the study of dust. High priority is assigned to the characterization of dust production rates (conversion ratio between measured erosion and dust formation), characterization of ejection velocities and the size distribution and morphology of collected dust under high load conditions, and cross-machine studies of dust injection.

Dr C. Grisolia of CEA reported on French research activities on dust in Fusion and (on behalf of Dr J. Winter) on activities at Bochum. Most of this work takes place under the EFDA umbrella and the work is concerned with creation of dust, diagnostics for dust, and methods for dust removal.

A model for dust formation in a DC laboratory discharge was developed at Laboratoire d'Ingénierie des Matériaux et des Hautes Pressions (LIMHP), University of Paris-13 and CNRS [A. Michaud, K. Hassouni and X. Bonnin]. Ingredients of the model are a dust-free DC discharge model, a molecular-level model for particle nucleation, and a growth and transport module for dust particles. Calculations show negative clusters being trapped in the reversed field region where dust growth can occur.

Dust creation is studied in the laboratory of Prof. Winter at Bochum in an RF argon/acetylene discharge. Laser-induced fluorescence is used to measure the Ar^* profile in the plasma. The polymerization of C_2H_2 causes change in plasma properties and this is recognized through the changing Ar^* profile; with C_2H_2 there is a ten-fold increase in the central density of Ar^*, understood to be due to the higher electron energy [I. Stefanović, N. Sadeghi and J. Winter, J. Phys. D: Appl. Phys. Vol. 43 (2010) #152003]. In the dusty plasma afterglow the free electron density is lower than in dust-free plasma due to the presence of negatively charged dust particles that attract electrons. The afterglow has been described by a hydrodynamic model containing densities of electrons, ions and metastables, electron temperature, and dust charge. The model calculations have been compared with experiment [B. Sikimić, I. Stefanović, I. Denysenko, and J. Winter, 37th EPS Conference on Plasma Physics, Dublin, April 2010].

Dust production by lasers is being studied at the CNRS "Laboratoire Lasers, Plasmas et Procédés Photoniques" (LP3) in Marseille. The dust are produced by laser ablation of graphite or W target and are collected on a substrate [A. Vatry, M. N. Habib, P. Delaporte et al., Applied Surface Science, vol. 255 (2009) pp. 5569+]. As seen on photographs in the presentation they are very similar to dusts produced in tokamak discharges.

Erosion monitoring by Speckle interferometry is one of the baseline measurements for ITER. The method, which provides an upper bound for dust production, is being developed in collaboration between CEA Cadarache and FOM (E. Gauthier and H. van der Meiden). Speckle interferometry is based on a Michelson interferometer. One mirror is replaced by the object and the second mirror is mounted on a piezoelectric transducer (PZT). The method was tested on erosion due to laser ablation of a graphite tile by comparing the measurement with a confocal microscopy measurement. About 200 μm was ablated in the test and the erosion is measured with a similar accuracy of 5-7 μm by both methods. Work to integrate this diagnostic in ITER is ongoing; the viewing configurations and optical design need to be optimised with consideration of sensitivity to vibrations and to measurements away from normal incidence.

A direct measurement of macroparticles in plasma is being developed in collaboration between "Institut Universitaire des Systèmes Thermiques Industriels" (IUSTI) at CNRS/Université de Provence (Marseille) and CEPM, Wroclaw University of Technology. The method is based on light extinction spectrometry (LES) and is also used to characterize bubbles in water [F. R. A. Onofri, M. Krzysiek, S. Barbosa, et al, Proc. SPIE, Vol. 7588 (2010), 75880D]. As a dust diagnostic it is sensitive to plasma aggregates (nanoparticles) that are too small to be seen via their light emission. A dust detector employing laser extinction spectroscopy has been built and tested in the laboratory. The diagnostic can be used to measure growth of aggregates, and these laboratory measurements were compared with calculations based on a diffusion-limited aggregation model. Experimental tests were carried out using flowing SiO_2 aggregates.

Dust in plasma is commonly detected by its visible light emission. A system for automatic image analysis has been developed in the MoniTORE project, a collaboration between IRFM Cadarache, INRIA and Institut Jean Lamour at Nancy [http://www-sop.inria.fr/pulsar/projects/monitore/]. MoniTORE supplies automatic routines for robust dust detection and tracking, statistical post-mortem analysis of dust particle trajectories, and stereoscopy for 3D trajectory reconstruction. It has been applied on AUG and TS; for example [N. Endstrasser et al., "Video Tracking and Post-mortem Analysis of Dust Particles from All Tungsten ASDEX Upgrade", 19th PSI, San Diego, 2010].

In collaboration with Princeton Plasma Physics Laboratory an electrostatic dust detector has been installed in Tore Supra. (The diagnostic and its application on NSTX were described at this meeting by C. Skinner.) On Tore Supra the equipment comprises two 12mm-by-12mm detectors (one of them blind) and a single 50mm-by-50mm detector, all with 25 μm grid spacing. The system is placed in the LPT pumping duct. At present there are problems with parasitic signals and the system has not yet been calibrated.

Dust is also studied by mechanical means (impactors) on Tore Supra. The integrated system involves a condensation particle counter (CPC), an engine exhaust particle sizer spectrometer (EEPS) and a particle size distribution analyzer (AEROSIZER). The EEPS has a particle size range 5.6–560 nm and a time resolution of 10 size distributions/sec. The AEROSIZER spans the range 500 nm – 100 μm.

Methods for dust particle removal by photo-cleaning techniques are being developed in collaboration between the LP3 laboratory at Marseille and the Association Euratom/CEA, DRFC/SIPP at St Paul-Lez-Durance with support from EFDA. Deposited layers are ablated by laser irradiation and the produced dust is collected on a substrate. In laboratory tests for C deposits on Si the desorption saturates at a fluence of about 500 mJ/cm^2; the wavelength or pulse duration have little independent influence on the efficiency of desorption. For carbon deposits the ablation products are ejected as vapour and can quickly form aggregates in various shapes and sizes, up to about 1 μm; generally very porous and with amorphous structure. Photocleaning has also been studied for W particles. These form droplets of size 1-5 μm with very smooth surface. For W removal the laser wavelength has influence, with UV light being more efficient than infrared or visible. Also a short pulse duration (e.g., 50 ps) is advantageous. The process is effective in air and in vacuum. The ablation is understood to be caused by electrostatic forces induced by photoelectrons extracted from the deposited particles. Combining the results for W and C some general conclusions are reached: Laser irradiation can easily induce mobilization of carbon and metallic dust. To be efficient for all the kind of dust with a single laser source, the process must use a ns UV laser. (An ultrashort pulse laser can also remove all the dust, but their average power is not compatible with the cleaning of large surface area.) The ablation products are ejected as atoms and nano-aggregates, or are un-modified for the metallic dust. As the mechanisms do not depend of the surface properties, the laser removal does not modify the substrate.

Shock wave methods are another way of photo-cleaning that may be useful for removing C particles from castellations. The process has been studied in a laboratory tile mock-up with castellations 1 mm wide, 10 mm deep and 20 mm long. The shock wave induced by the focalisation of a laser close to the dust leads to the ejection of the dust and the technique appears to be very efficient to move dust from castellations towards cold zones. This method relies on the presence of neutral gas and is sensitive to pressure. At atmospheric pressure the photoelectrons create negative ions by collision with oxygen atoms. For metallic deposits there is very little sensitive to pressure as it is varied between atmospheric pressure and 10^{-3} mbar. For carbon dust a reduction of the gas pressure leads to an increase of the ejection distance of the ablation products. The process is still efficient but the collection system must be set closer to the surface when pressure increases.

Deposit removal and de-tritiation by multi-point plasma discharges is being studied in high-voltage laboratory discharges at LIMHP (Paris-13). The plasma operates in air (N_2/O_2) and an erosion rate of 0.2 mg/h is achieved. Fourier transform infrared (FTIR) spectroscopy shows that carbon is removed as CO and CO_2; also N_2O and O_3 are formed.

Conclusions from the French research activities on dust in fusion: There are many studies of dust creation in SOL plasma and the main mechanism are transient events: ELMs, VDEs and disruptions. The production can be approximated and studied in the laboratory using laser ablation. Dust particle tracking by video is very interesting for fundamental physics. The electrostatic dust detector is helpful, but needs yet to work with W particles and it is difficult to operate it close to the plasma. Mobilisable dust may be measured by laser extinction spectrometry and also by impactors in the gas outflow, but this may not be useful in a tokamak. Speckle laser interferometry is the most suitable for erosion measurement; for dust production it only provides an upper bound. For dust removal laser techniques are suited to ablate particles, especially small ones or welded metal droplets. Other techniques could be used to destroy small particles. Proposed and ongoing activities for the coming years include production of calibrated metallic particles and their treatment using a plasma torch, RF plasma, or other means. Tritium implantation and in vitro/in vivo studies are planned in collaboration with a Romanian team (Dr M. Dinescu, Bucaresti).

Dr S.-H. Hong of the Korean National Fusion Research Institute (NFRI) presented in-vessel dust research on the Korea Superconducting Tokamak Advanced Research (KSTAR) experiment. The

KSTAR vacuum vessel is made of stainless steel (316L) and it has an inboard poloidal graphite limiter. Pulse length is up to 300 s and the plasma fuel can be H or D. The first experimental campaign was held in June 2008 and the second campaign in Fall 2009. Video images show dust creation events during plasma operation.

For the second campaign, 4 pairs of dust collectors were installed. After the second campaign there are arc tracks on the tiles and redeposited graphite is found on the metal wall. The bottom of vacuum vessel was vacuum cleaned and in-vessel dust was collected and analyzed. The dust particles are flakes, metal droplets, and nanoparticles. (Please see the presentation for a photographic inventory of all kinds of dust particles.) Particle diameter ranges from 0.1 μm to 60 μm, with peaks in the distribution around 0.1 μm and 2 μm. In chemical composition, C, Si, Mn, P, S, Ni, Cr and Fe are all found; they would originate from the limiter, vacuum vessel, mirrors, and diagnostic equipment. (316LN steel is about 69% Fe, 16% Cr, 10% Ni, 2% Mo, 2% Mn, and smaller amounts of Si, Co, N, P, S and C.) Metal droplets from the SS vacuum vessel have also been analyzed. Melt droplets range in size from 1 μm to 60 μm, with varying morphology due to differences in crystallization and in plasma-dust interaction. Micro-crystal structures have a size of 1-2 μm.

Besides loose dust and metal droplets a large amount of amorphous C:H nanoparticles of size about 100 nm in diameter is identified, and also a large amount at size about 1 μm. These particles are stuck to the surface and pose a serious problem for tritium inventory control; the tritium in these a-C:H layers can not be recovered unless the entire layer is removed. On KSTAR these deposits are studied with use of 18 (8 toroidal, 10 poloidal) specially designed coupons: box enclosures with a small slit on the plasma side and in which the graphite deposits are analyzed. The deposition profile within the enclosure provides information about the sticking fraction and reflection [A. von Keudell, Nucl. Fusion 39 (1999), pp. 1451+]. The deposition in the coupons was studied at the end of the campaign (395000 s of plasma operation including glow discharge cleaning). The variable angle spectroscopic ellipsometry (VASE) shows that the film has optical properties n=2.34 and k=0.25. The optical properties of a-C:H thin film are interpreted as measurements of the H/(H+C) ratio and of their material density [T. Schwarz-Selinger et al., J. Appl. Phys. 86 (1999), pp 3988+]. XPS measurement of the deposition in the cavity shows a small fraction (~3%) of boron in the layer, thus it can be considered as a-C:H. The H/(H+C) ratio is determined as 20-25% and the material density as ~2.1 g/cm3. Using this information the average flux of deposited material is estimated to be $\sim 8.94\times10^{12}\ cm^{-2}s^{-1}$ at the midplane. The carbon flux is strongly dependent on the poloidal position. Due to the high internal stress, the films near the mid-plane are converted into flakes while the film at the bottom of the vacuum vessel is stable.

A dedicated small plasma Transport and Removal Experiment of Dust (TRED) device is being built this summer for operation in September (2010). The experiment is based on the Japanese ITER Home Team's electric curtain concept. One objective of the experiment is to study high frequency glow discharge wall conditioning in a laboratory experiment before installing an HF GDWC system on KSTAR. TRED is a box-shaped device (120 cm longest dimension) that has a 3 kW ion-cyclotron plasma source, a dust dispenser at one end, a dust collector at the other end, an electrostatic grid to trap and move the dust particles, and diagnostics including a CCD camera, various probes, and visible spectroscopy. An HF GDWC system will be installed on TRED and the dust transport and removal efficiency will be studied with various shapes and configurations of electrodes.

Dr A. Malaquias of the European Fusion Development Association (EFDA) described activities sponsored by EFDA in the associations concerning in-vessel dust and tritium management. These activities are implemented by means of two Task Agreements (TA): one on tritium inventory and removal and one on dust inventory and removal. Each of the two TA is supported by EFDA to the level of about 6 professional staff per year, plus some equipment support. Each TA is composed of individual Work Packages (WP) addressing specific studies or system development. The presentation provides an overview of the results achieved under the different work packages related to dust and tritium.

It is expected that dust inventory will have to be measured via net erosion. An EFDA task, WP1.1, has been established "to perform a review of possible laser-based techniques which could be employed together with a detailed feasibility study for the possible integration on ITER." Several methods are being evaluated under this task. Field imaging LIDAR through Fourier Transform heterodyne is one such system. Drawback is that it is a single-point measurement and is sensitive to vibration masking of the measurements. Laser-induced breakdown spectroscopy (LIBS) timing is another option. It is predicted to be capable of 1 mm resolution, but the method is in an early phase of development and there are no documented results yet on fusion experiments. A third proposed system, Speckle interferometry, relies on multi-wavelength interferometry. This is also not straightforward to apply and may require consideration of vibration information obtained by other systems (by external sensors, or by Fourier transform processing of the signals).

A second EFDA task on net erosion measurements is WP1.2, "to perform a feasibility study in order to check a potential port-plug application of the Speckle interferometry on ITER." (See also the presentation by C. Grisolia.) Integration studies for ITER show that the method is capable to cover erosion measurements on the inner wall, the upper limiter (Be melting), and the inner and outer divertor targets. Each separate system could have a spatial coverage of about 700 mm and spatial resolution of about 1 mm. The depth resolution is in the order of few micrometer and the effect of vibrations can be removed if a dual wave length setup is used. It is planned to start tests on the Magnum-PSI divertor target simulator in 2011.

A third EFDA task on erosion measurements is WP1.3, "to review the spectroscopy diagnostics foreseen on ITER to check their adequacy for erosion measurements." Using the measurement capability of the impurity monitor (VUV system of ITER) some individual lines are proposed to perform wall influx measurements: 400.9 nm for a WI line, 514.3 nm for a CII line, and 351.6 nm for a BeI line. The results show that the measurements are feasible in terms of S/N and coverage; however, a problem with these spectroscopic measurements, especially the neutral lines, is that they can at the best measure only gross erosion as they do not recognize prompt redeposition (requiring measurements of higher states of ionization) making the net erosion measurements unpractical. Furthermore, melt layer erosion due to arcs will not be measured, molten droplets are not visible (no line radiation and it is not possible to differentiate between radiation from hot surface and droplets), and spectroscopy will be unable to quantify melt layer erosion during ELMs. The estimated uncertainties are largest for the case of tungsten erosion and it would be very valuable to have suitable ionic W lines.

On the issue of dust removal EFDA has a task WP2.1, "to assess the possibility (including integration issues) of using a photocleaning method for removing the dusts deposited on the divertor surfaces." Laboratory experiments are performed on dusts produced by laser ablation of graphite or W target and are collected on a substrate. These laser-produced dusts have similar morphologies and nature to tokamak ones. Studies on dust displacement under direct laser radiation have been done for C, W and Al (substitute for Be) on Si substrate, looking for the dependence of the displaced fraction on laser wavelength and pulse duration. A laser shock wave method was studied for the removal of C particles from castellation between tungsten tiles. (See also the presentation of C. Grisolia.) With respect to application to the ITER port-plugs it must be noted that direct irradiation requires local dust collectors. The shock wave could be used to mobilise dust but requires integration on 8 ports for complete divertor coverage.

For measurement of tritium inventory EFDA has the task WP3.1, "to perform a feasibility study on non-invasive methods: Port-plug based scanning laser system, preferably with parallel light collection optics (LIDS, LIAS and LIBS)." The acronyms represent laser-induced desorption, ablation, and breakdown spectroscopy. LIDS has been tested on thick a-C:H layers in TEXTOR (2.5-3 μm a-C:H layer on tungsten). It has been established for reliable in situ fuel retention detection. The lower detection limit depends on the natural Hα signal fluctuations. B2-Eirene modelling was carried out in a feasibility study for LIAS and LIBS on ITER. The code is used to predict the background Hα signal intensity in ITER shots; it suggests that the diagnostic signal is good enough for inner wall measurements but for some divertor locations (viewed from the top port of ITER) it is only marginally measurable relative to the background.

A second EFDA task for tritium inventory measurement is WP3.2, "to perform a feasibility study on VV remote handling method: Remote Handling based scanning laser system (adaptation of the IVVS* system and/or plugged in the IVVS carrier or on a dedicated carrier)." Laboratory studies were performed to define the properties of the laser and of the optical setup. LIBS spectra were recorded with the Echelle spectrometer during laser ablation of CFC in argon; the results are in excellent agreement with simulations, but gas pressure and accuracy are still to be optimized. Implementation on a robotic arm was assessed and several optical arrangements were analyzed in terms of avoidance of contamination of optics and operation efficiency.

Another EFDA task for tritium inventory is WP4.4, "to perform a feasibility study envisaging a possible implementation of a photonic heating technique on the IVVS carrier or a robotic arm system." A heating model was validated against experimental data for laser irradiation of a tungsten layer (60-80 nm) and a DLC+H layer (4 μm) on a graphite substrate. For the application of the system on a robot arm the effect of laser deposition is studied for different angles and under vibrations. The deposition of laser energy is heterogeneous (varying by about 2 J/cm^2) for practical values of incidence angles.

EFDA task WP4.5 is "to proceed with a feasibility study on a potential remote handled application of a photonic ablation technique on ITER, emphasising the need to guarantee an efficient collection of the wastes." This method can be used at atmospheric pressure and also at very low pressure (between shots) for removing layers from top of the vessel and divertor. Under vacuum ablation wastes are ejected by the laser and deposited on a collector plate. Under atmospheric pressure the ejected dust may be collected by a vacuum cleaning system. Different concepts of nozzle shape have been studied for best access and in order to maximize dust collection.

The final EFDA project reported by Dr Malaquias concerned arc-discharge cleaning of plasma-facing Components (no WP number). This is successful for Al (substitute for Be) but required much longer times to remove W layer. Improvements on the scanning approach (XY moving arc) will allow 5-10 times faster removal times. The system works under vacuum but tests under atmospheric pressure will be started soon. The average roughness is marginally increased (from 1.25 μm to 3.36 μm in one set of experiments) so that the method can be used to remove deposit layers from the inner wall of the vessel without damage to the surface.

EFDA plans for 2011 are focussed on the following areas: (1) End effectors for use on the Multiple Purpose Deployer arm (MPD). This includes development of effectors to work simultaneously with or to support remote vacuum cleaning (ITER base line). The technology shall be tested on other devices in the associations. It also includes to develop at ITER integration level laser-based, arc-based, or other techniques for layer cleaning with collection of wastes with capability to measure and control locally the tritium inventory on places of higher retention, in particular at the top of the vessel. (2) Port plug based systems. This includes proof of principle of LIAS, LIDS and LIBS in an ITER-relevant set-up in a tokamak or other experiment, and it includes erosion monitors: integration into ITER and modelling of Speckle interferometry. (3) Coordination of all activities involving laser based techniques.

Dr R. Zagorski of the European Fusion Development Association (EFDA) presented recent achievements and future plans of the EU plasma-wall interaction (PWI) task force. EFDA exists parallel to the Joint Undertaking for ITER "Fusion for Energy" (F4E), located in Barcelona, which acts as the Domestic Agency to provide and manage the EU contribution to ITER and the EU Contribution to the Broader Approach (JT-60SA). Under EFDA, two main task forces and several topical groups have been formed in order to coordinate the fusion R&D. The PWI task force is headed by R. Neu (IPP) and the Integrated Tokamak Modelling task force is headed by P. Strand and R. Coelho. Topical Groups have been established for Materials, Diagnostics, MHD, Transport, and Heating and Current Drive.

The ITER high priority research needs are strongly related to PWI; they include [D. Campbell, ITPA CC meeting, June 2008] disruption and runaway mitigation, ELM control and mitigation, plasma facing materials (reference scenarios with W and Be PFCs, C removal), scenario development, and diagnostics R&D (dust and hot dust, divertor erosion, mirrors, H/D/T inventory). The aim of the PWI Task Force is to concentrate European research on the most urgent problems in the field of PWI for ITER and future devices and to propose scientific and technological concepts to overcome these problems.

The work of the EU PWI task force is targeted at ITER through 7 Special Expert Working Groups (SEWGs) on: Fuel Removal, Dust, Material Migration, Mixed Materials, Fuel Retention, High-Z Materials and Liquid Metals, and Transients. The SEWGs each have an annual meeting some time in the summer and a general annual meeting of the PWI TF is held near the end of the calendar year. The PWI task force cooperates and coordinates with the International Tokamak Physics Activity (ITPA) Div/SOL group and with other EFDA structures (TG's ITKM TF, JET TF's and EFDA Emerging Technologies). Different from ITPA, EFDA supports work performed in the associations through funded Task Agreements.

Highlights of the PWI scientific work during 2009 include the following:

- First evidence for a threshold in chemical erosion for detached plasmas at very low temperatures (1-2 eV); further development of the local and global transport codes (ELMs and gaps in ERO, grid extension to the wall ongoing in SOLPS).
- Retention in W further explored (impact of bombardment with He, simulation of neutron damage) and confirmed to be low; porosity network in CFC characterized by high resolution tomography.
- First attempts to characterize runaway electrons in Tore Supra and Textor, as well as in JET; similar valves now implemented in MAST, Textor and JET for massive gas injection (MGI) studies; modelling effort started for runaways and MGI (FZ Karlsruhe).
- Performance of nitrogen seeding scenarios well established in full-W AUG and first trial of a liquid lithium limiter in FTU.
- Coordinated experiments on ICRF cleaning in Textor, Tore Supra, as well as in JET under TFE/H.
- Dust trajectories investigated in several devices using fast cameras.
- Further exploration of ternary systems (Be-C-W but also including oxygen, Be-O-W) in lab experiments (IPP, MedC); benchmarking of ERO-TRIDYN ongoing in collaboration with the PISCES facility.

A few highlights were discussed in more detail. The deposition inside a poloidal gap of a castellated limiter was studied on TEXTOR and compared with PIC simulations. Laboratory experiments in Garching show that fuel retention in W is reduced by simultaneous exposure to He bombardment, but is somewhat enhanced by neutron damage. Laboratory experiments, also in Garching, of N-W interaction show that wall storage of nitrogen saturates at a level that depends on injection energy. The deposition depth remains below 2 nm, implying negligible diffusion, and the saturation density points to the formation of WN. Due to the dilution effect the tungsten sputtering yield is reduced in N saturated samples.

The special expert working group on Fuel Removal has focussed on optimization of ion-cyclotron wall conditioning (ICWC), with first trials on gaps. Chemical methods of fuel removal are based on O_2, N_2, and NH_3, the latter being most favourable for ITER. The fuel removal efficiency of ICWC was explored in coordinated experiments on TEXTOR, Tore Supra, and AUG; optimisation is ongoing. For fuel removal in gaps thermo-oxydation is explored at CIEMAT, ECR or GDC at IPP and FZJ, laser methods at CEA, and a plasma torch at MedC. Dust production during cleaning processes is being studied for laser cleaning at CEA, IPPLM, VR; this work shows dust and flake production with significant fuel content.

The work of special expert working group on Dust has focussed on dust measurements during plasma operation and on dust injection experiments. Dust measurements during plasma operation were carried out using CCD (TS, AUG), fast IR (AUG), electrostatic detector (TS), and Thomson scattering (FTU). Dust collection is ongoing at JET, AUG, TEXTOR and Tore Supra. Carbon dust tends to have a complex structure whereas tungsten dust appears to be mainly spherical droplets, perhaps due to transients. Tore Supra finds a conversion factor of 5-8% from erosion to dust. In preliminary dust injection experiments in TEXTOR the edge C content is increased with no effect on the core plasma.

The main orientations for 2010/2011 take into account: (1) Bilateral collaborations; on mixed materials with PISCES and modelling of material damage with plasma gun experiments (in collaboration with the RF). (2) Focus on recent ITER requests; related to disruptions and runaways, to R&D for tungsten, to divertor re-attachment heat loads, and to ion-cyclotron wall conditioning. (3) Integrated plasma operation; the impact of impurity seeding on erosion, mixed materials, fuel retention, etc. (4) (Very important:) Strengthening of the modelling for extrapolation to ITER and DEMO. The focus is on interpretative modelling for benchmarking tools that are used for ITER simulations (SOLPS, ERO, DIVIMP, …), all carried out in close connection with the Integrated Tokamak Modelling task force (code development). Seven task agreements have been implemented for 2010: on fuel retention, fuel removal, dust, material migration, high-Z materials, mixed materials, and transients.

The work programme for 2011 has been established and the call is in preparation. In the area of fuel removal the key activities are wall conditioning and discharge tailoring, investigations of chemical cleaning methods, further development of photonic cleaning methods, and fuel removal in gaps. In the area of dust generation the key tasks are to assess dust generation (in particular conversion factor from material erosion to dust) and dust properties in tokamaks, and to improve detection of dust in the plasma and understanding of the impact of dust formation on plasma performance and operation.

Dr H.-K. Chung of the Atomic and Molecular Data Unit, IAEA, reviewed database and knowledge base developments in the AMD Unit. Broadly the Unit activities are divided into data generation and data exchange. For the purpose of data generation the unit organizes coordinated research projects (CRPs) and other meetings; the fruits of these activities appear in several IAEA serial publications. For the purpose of data exchange the unit coordinates the Data Centre Network and the Code Centre Network and has started to create a Knowledge Base on A+M and PMI data for fusion. (Detailed information supplementing this presentation may be found via the links at the top and in the left side-bar of the AMD Unit home page, http://www-amdis.iaea.org/.)

The CRPs are the main mechanism by which the unit encourages new research. A CRP involves representatives from 10 to 15 institutes world-wide for synergistic collaboration on a topic in A+M/PMI data for fusion. The duration is 3-4 years during which 3 Research Coordination Meetings are held. Objectives are the generation, compilation and evaluation of data, the establishment of databases, and the development of new techniques. The output of a CRP are publications, meeting presentations and reports, a final report in “Atomic and Plasma-Material Interaction Data for Fusion” (APID), and data and results in the ALADDIN numerical database and in the future also in the Knowledge Base. Recent CRPs closest in interest to the present one on Dust are one on “Data for Surface Composition Dynamics Relevant to Erosion Processes” (2007-2011) and one on “Tritium Inventory in Fusion reactors” (2002-2006). It is planned to start new CRPs on “Erosion and Tritium Retention for Beryllium Plasma-Facing Materials” (2012-2016) and on “Plasma-Wall Interaction of Tungsten and its Alloys in Fusion Devices” (2013-2017), besides other ones on atomic and molecular processes.

In 2010 the unit organizes research coordination meetings for 3 ongoing CRPs; also a meeting of the International Fusion Advisory Council Subcommittee on Atomic and Molecular Data, a meeting of the Code Centres Network and two meetings of the project “XML Schema for Atoms, Molecules and Solids (XSAMS)”. INDC reports (yellow report series) are published for each meeting. Once per year the unit publishes the International Bulletin on Atomic and Molecular Data for Fusion, which contains new data that has been entered into the on-line AMBDAS bibliographical database for A+M and PMI articles. An issue of Atomic and Plasma-Material Interaction Data for Fusion (APID Series) is published at the conclusion of each CRP and occasionally after Consultants Meetings.

Database and data transfer activities of the AMD Unit are carried out in cooperation or coordination with the Data Centre Network (DCN). The partners in the DCN are all engaged in atomic and molecular (A+M) and particle-surface/plasma-material (PSI/PMI) data for fusion and other applications through programs on the collection, dissemination, evaluation and generation of A+M/PSI/PMI data. Data is exchanged through the ALADDIN numerical database, the AMBDAS bibliographic database, also the OPEN-ADAS numerical database, and the GENIE multi-database search engine. ALADDIN has two sections, one on atomic and molecular collisions and one on plasma surface interaction. The data in ALADDIN are generally the result of CRPs or other meetings organized by the AMD Unit. AMBDAS contains spectroscopic data supplied by NIST (A. Kramida and J. Fuhr) and collision data supplied by the Oak Ridge Controlled Fusion Atomic Data Center (CFADC). One can search by reactants, process, authors, keywords, or year. Since version 3.1 (April 2010) results are supplied with a Digital Object Identifier (DOI) link if that is available. Out of 46878 reference data, 34420 data are linked to the full text of the electronic journal article and 5115 data are linked to an abstract by DOI.

OPEN-ADAS (http://open.adas.ac.uk/) is a joint development between the Atomic Data and Analysis Structure (ADAS) project and the IAEA to provide access to fundamental and derived atomic data from ADAS and its related databases. ADAS provides computer codes and data collections for modelling radiating properties of ions and atoms in plasmas for fusion and astrophysical application. ADAS use a subscription model and the OPEN-ADAS makes the low-level data publicly available; subscription is still needed to use the higher level analysis codes.

The GENIE search engine provides a unified interface to 8 separate databases around the world for level structure and radiative properties of atoms and 4 separate databases for collisional properties: cross sections and rate coefficients for excitation, ionization and recombination (electron impact collisions only at this time).

The Code Centre Network (CCN) is a joint effort to provide access to codes that are relevant for modellers in fusion plasma science, either through on-line compute capability, via download of the code, or through direct contact with the CCN member for their expertise. The network codes include online codes for heavy particles collision cross-sections (A. Dubois, J. P. Hansen and P. Vainstein), online codes based on the Average Approximation for electron impact excitation cross sections (due to J. Peek), online codes for radiative rate coefficients, an interface to the Los Alamos atomic physics codes to calculate atomic structure and electron impact excitation and ionization cross sections, results from the Los Alamos codes for selected elements, an interface to the FLYCHK code at NIST to calculate ionization distributions and spectral properties of atoms, and results from FLYCHK for the average charge state of elements from hydrogen to gold for plasma conditions 0.5 eV $\leq$ Te $\leq$ 100 keV and $10^{12}/cm^3 \leq Ne \leq 10^{24}/cm^3$.

Recently the AMD Unit has started to develop a Knowledge Base for A+M/PSI data for fusion (http://www-amdis.iaea.org/w/). The Knowledge Base relies on Wiki pages. It is hoped that these will be developed through voluntary content contributions and peer review by the A+M/PSI community with the AMD Unit in a coordinating role. The Knowledge Base is inspired by goals of Web 2.0 technology: to facilitate interactive information sharing, interoperability, user-centred design and collaboration on the web. The present content draws almost exclusively on past APID volumes, INDC(NDS) reports and presentations at CRP Research Coordination Meetings, but as new contributors participate in the development the sources can also become more wide-ranging. Major headings in the present design of the Knowledge Base include Data Needs (sections on magnetic confinement fusion, inertial confinement fusion, atomic data, molecular data, and plasma-material interaction data) and Data Sources (sections on online databases, data centres and code centres). There are also sections on special topics including the CRPs of the AMD Unit. The section on the CRP on Dust is quite well populated already based on the contributions at the first (and as this meeting report is being written also the second) RCM. Further contributions are very much invited.

The Knowledge Base is still in an early stage; many pages are just empty placeholders at this time, citations and references are often lacking, and much more integration and cross-linking is to be done. In a technical development that took place during the RCM the Knowledge Base is now maintained under MySQL and (different from before) the pages are found quite prominently by Google. Contributions to the Knowledge Base are invited basically from anyone active in the area of A+M/PMI data for fusion. Registration is required for contributors (in order to edit pages one needs a password), but it is hoped that many of our CRP participants, consultants and other contacts and their colleagues too will eventually be interested to contribute.

3. R&D Needs and Work Plan

This section describes remaining gaps in knowledge, R&D needed to address these gaps and participants' work plans for the remainder of the CRP through the end of 2011. The description is organized under the topics of dust generation, dust mobilization from tiles and codeposited layers, dust particle database development, dust transport to the core plasma, dust contamination of diagnostic mirrors, dust diagnosis on hot surfaces, diagnosis of the total dust inventory, and dust removal technology.

Two groups in the International Tokamak Physics Activity (ITPA) organization organize R&D to assist ITER in dust issues. The ITPA Divertor and Scrape-Off Layer topical group has a Joint Experimental Proposal DSOL-21 on the "Introduction of pre-characterized dust for dust transport studies in the divertor and SOL." The ITPA Diagnostics group has Joint Experiment #4 on a dust microbalance diagnostic. Dust is also a topic for the ITPA Diagnostics Special Working Group on First Wall Diagnostics (http://firstwall.pppl.gov/). Within EFDA the main goal of the 2011 Plasma Wall Interaction Task Force activities in this area is to improve the knowledge on dust generation and its characterization in different tokamaks. It also includes the development of dust generation and transport models in order to provide better predictions for ITER. Specific activities are foreseen to investigate the appearance of dust in plasma discharges and on the post mortem investigation of the dust morphology. The EFDA activities on dust and tritium management under the Emerging Technologies programme aim to support feasibility studies on a selection of laser/photonic based techniques with potential for integration in ITER that are not being covered under other programmes. Under the dust topic there are two main areas being addressed, dust inventory and dust removal. The Fusion for Energy organization (F4E) has called for proposals for the development of in-vessel dust measurement techniques (F4E -2010-GRT-050 (ES-SF)). Activities in Japan are coordinated between LHD, JT60-U and Japanese Universities. In Korea a dust test facility is being constructed.

The ITER perspective and needs were presented at this meeting by S. Ciattaglia and the ongoing work of EFDA on dust and tritium management and plasma-wall interaction was presented by A. Malaquias and R. Zagorski. In this Section, ITER and EFDA activities are only briefly noted as a reminder, and we refer back to the presentations in Section 2 for a more detailed description. Mainly this Section serves to record the specific work plans of the participants in the CRP.

Dust creation

Dust in tokamaks can be produced during plasma operation by the disassembly of plasma facing tile surfaces or of plasma-grown co-deposited layers under the impact of ELMs or disruptions, by the chemical agglomeration of sputtered C_n clusters, and by arcing on metal surfaces. In ITER, additionally, some photonic and oxidative methods for tritium removal can produce in-vessel dust.

The primary measure of the dust inventory on ITER will be the amount of material eroded from the divertor with the conservative assumption that all of this turns to dust. This is clearly an overestimate and more experimental data on the ratio of erosion to dust from present tokamaks and from ELM and disruption simulators would be very helpful. Information on dust generation by severe off-normal events such as runaway electrons, dust and aerosol production from Be and W melt layers or from Be-T, W-Be-C and a:C-T codeposits is needed. It needs to be established whether or not significant quantities of dust will be produced by ITER's wall conditioning techniques.

Within EFDA an initiative, WP11-PWI-03-01, is dedicated to investigation of dust generation in present devices. The formation of metallic dust (W and Be) and the identification of dust generation mechanisms, in particular the impact of transients events such as ELMs and disruptions, will be studied. The plan is to validate modelling for dust creation, transport and suspension and assess the implications for a standard ITER scenario. Dust generation in Tore Supra, TEXTOR, AUG and possibly other relevant devices will be characterized in comparison to JET with respect to its location in the vacuum vessel, generation rates, and physical and chemical properties. The emphasis will be on the fuel content, size distribution, surface specific area and reactivity. A second initiative (WP11-PWI-03-02) is aimed at the conversion of co-deposits to dust. The dust conversion factor (gross erosion to dust production) will be assessed for different EU devices. The generation of carbon and metallic dust due to various techniques for fuel and co-deposit removal such as photonic and oxidative methods (see also SEWG on fuel removal) will be studied. Dust properties (e.g. composition, size distribution) and surface state of PFC after mechanical removal of co-deposits will be characterized. The uptake (re-take) of deuterium by layers previously depleted by oxidative or photonic (laser heating, flash-light) methods will be determined. 2011 EFDA Plasma Wall Interaction Task Force activities include the investigation of mechanisms for dust generation during plasma operation and during the maintenance phase including conditioning.

Tungsten melting experiments are planned in AUG. In Japan surface analysis of JT-60 tiles is planned. The H/C ratio in LHD tiles will be measured. D retention in carbon and metallic dust will be studied in collaboration with EAST. Tile analysis and dust collection is planned for KSTAR. On JET a comparison of actual dust quantities collected with deposits and erosion from specified tile surfaces will be completed in 2011.

Dust mobilization from codeposited layers

Modeling by the DUSTT code has shown that impurity influx via dust can be more effective in contaminating the core plasma than influx of gaseous impurities. The first step in this process, the mobilization of dust from surfaces to the edge plasma, is poorly understood and hence the tolerable amount of surface dust compatible with a high purity burning plasma is not known. Dust mobilization can be measured by Thomson scattering (D-IIID) or by video cameras (all devices); however, dust is only visible to a camera if it is heated up and larger than 3-5 microns.

Laboratory investigations have begun at IPP on droplet production by arcing for the coatings used in AUG. In AUG many W droplets are found that appear to be too small for video observation. The droplets are produced by arcing at some PFCs.

On JET the removal of tiles from JET vessel for both analysis of deposits and surface erosion is in progress and the amount of dust collected from the JET vessel will be quantified. Deposits on tile surfaces will be analysed in 2011. Dust sampling by other techniques may be performed.

The INL resuspension code (for dust in neutral gas) will be incorporated into MELCOR for safety analysis of events such as air ingress. Resuspension theory indicates that particle adhesive forces, and thus resuspension, depend on the nature of particle-surface contact, which depends not only on the particle size but also on the surface morphology. It is usually assumed that the latter gives rise to a lognormal distribution of adhesive forces even for a single particle size. The characteristics of this distribution are difficult to determine in practice, and remain a source of considerable uncertainty in predicting dust resuspension. Any experiment for the purposes of benchmarking should therefore provide (i) the adhesive force distribution for the particles and surfaces of interest, (ii) sufficient description of the flow and geometry to allow determination of the friction velocity and (iii) the resulting resuspended fraction as a function of time.

Dust particle database

During the meeting a database of dust particles was proposed that would compare properties of dusts collected in different plasma devices or in the same device in different locations or at different times.

The Garching group (primarily V. Rohde and post-doc N. Endstrasser) will take the initiative for a database of dust particles. Equipment developed in the electronics industry and in space science makes it possible to measure geometric, spectral and composition parameters of thousands of dust particles in an automated manner, and the particles can also be classified into broad categories such as flake, droplet or agglomerate. The core of the planned database will be the measurements and classification of tens of thousands of individual dust particles obtained in distinct "experiments": instances in which dust is collected from a particular location in some fusion experiment or laboratory plasma device. The A+M Unit at IAEA desire to host the database and contribute to its specification. The geometric and other parameters that characterize an individual dust particle need to be defined in a manner that is useful across fusion experiments. J. Winter will be asked to extend the classification to the kinds of dusts observed in his hydrocarbon dust laboratory plasma experiments. The intent of the Garching group, with contributions from others, is to create a pilot database during the remainder of the CRP that can accommodate data from any fusion experiment. In addition to data on individual dusts collected in experiments the database would contain descriptions of properties (mobility, safety issues) of the various categories of dusts.

INL has characterized dust from many operating machines. This data will be compiled and included in the database. While no collections are currently planned, the equipment and facilities to perform sampling and characterization are still in place at INL, and this analysis can be done for any machine if desired. This may prove useful for identifying whether observed variations in size distribution are primarily due to different creation mechanisms and constituent materials, or to the method of analysis.

Dust transport to the core plasma

Substantial progress has been made in the measurement of dust trajectories in fusion devices such as AUG, NSTX, DIII-D, LHD, and Tore Supra (see the presentations here by V. Rohde, C. H. Skinner, N. Ashikawa and C. Grisolia). The main features of the dust motion are reproduced by simulations using the DUSTT code (Smirnov). However some non-reproducible dust dynamics features need further investigation. The motion of dust particles below about 5 micron, which are not incandescent, is difficult to diagnose. The measurements at FTU of hypervelocity dust by images of their impact on PFCs (presentation of C. Castaldo) also need to be better understood.

EFDA initiative WP11-PWI-03-03 aims at improving the detection of dust in the plasma and relating the dust generation to discharge conditions. It is hoped to improve the understanding of the impact of dust formation and mobilization on plasma performance and machine operation. It is also planned to characterise dust collected during plasma operation.

Dust mobilization after a disruption and the potential acceleration to hypervelocities will be studied at FTU in collaboration with the University of Naples. Dust tracking code development is underway in AUG, LHD and Tore Supra. A video evaluation code is developed and tested at the University Nancy. It is to be adapted to measurement with fast cameras in AUG. For validation of the code, dust will be artificially injected to AUG. On NSTX lithium and tungsten particles will continue to be imaged with fast cameras and 3D trajectories reconstructed and compared to the DUSTT model in collaboration with UCSD.

Dust contamination of diagnostic mirrors

ITER relies on diagnostic information to guide plasma control and many diagnostics use in-vessel mirrors. Thus obscuration of diagnostic mirrors with dust not only reduces the information on the plasma but could threaten machine operations. This area is little studied, and gaps in knowledge include the adhesion of dust to mirror surfaces, the relative fraction of nano-scale (sticky) dust to micron scale dust, nano-scale dust production from crumbling of codeposits, and the transport of dust to mirrors. Technology to clean dusty mirrors has not yet been developed for the ITER environment.

The ITPA has recognized R&D on first mirrors as a high-priority task. ITPA work on erosion of mirror surfaces and deposition of impurities on these surfaces is coordinated by the Specialist Working

Group on first mirrors of the Topical Group on diagnostics. Dust deposition and the erosion associated with dust removal is a part of their concern. An overview of recent work in the field of first mirrors encouraged by ITPA is available [A. Litnovsky, et al., Progress in research and development of mirrors for ITER diagnostics, Nucl. Fusion 49 (2009) #075014 (8pp)]. The work plan of the SWG on first mirrors consists of six essential areas including (III.) mitigation of particle deposition onto mirror surfaces, and (IV.) cleaning diagnostic mirrors from deposits. The removal of nanoscale deposits is most challenging, as the damage threshold for the film and the substrate is nearly the same. In order to reduce damage to the mirror surface laser-based methods are favoured for removal of deposits.

Laser-based techniques for mirror cleaning are an area of active interest at JET (see presentation by A. Widdowson) and at CEA and PPPL. At PPPL a Nd laser will be used to clean the Be coatings on Mo mirror substrates that are anticipated in ITER.

Diagnosis of dust on hot surfaces

A potential accident scenario considered for ITER involves a coolant leak and simultaneous air ingress. In this situation there is the potential for hydrogen to be generated by chemical reactions between dust on hot surfaces and steam or water. To limit the potential associated explosion hazard the quantity of dust on hot surfaces must be maintained below 6 kg of C and 6 kg of Be, or if C is absent, 11 kg of Be and 230 kg of W. Potential diagnostic techniques for dust on hot surfaces are described in a presentation by Junghee Kim at the ITPA Diagnostics meeting at Oak Ridge, 11-14 May 2010 (ITER IDM report ITER_D_34DQM6) and at PSI-19 [Junghee Kim, et al., Overview of diagnostic methods for hot-dust measurement in ITER, Poster P2-91, 19th PSI, San Diego, 2010]. This is a needed but difficult measurement and validation of potential diagnostic techniques is required. At present this is not part of the CRP plans.

Diagnosis of total dust inventory

The ITER plans for dust management [S. Rosanvallon, et al., Dust limit management strategy in tokamaks, J. Nucl. Mater. 390-391 (2009) 57] include indirect measurement of dust generation via measurements of the erosion of plasma facing components. Initially 100% of the erosion products will be conservatively assumed to be dust. Direct local measurements of dust are envisioned to provide information on dust generation on a pulse-by-pulse basis with a measurement requirement of 20% relative and 50% absolute accuracy. Operation of in-vessel dust diagnostics in the harsh ITER environment remains a huge challenge. The Fusion for Energy organization (F4E) has called for proposals for the development of in-vessel dust measurement techniques (F4E -2010-GRT-050 (ES-SF)) and tenders by JET and AUG are under consideration.

The EFDA Emerging Technologies programme has launched three tasks on the subject of erosion measurements: (i) a review of the existing laser techniques with potential application for erosion measurements; (ii) a study for the integration of speckle interferometry in ITER and (iii) evaluation of the capability of using the spectroscopic diagnostics already foreseen for ITER to perform erosion measurements. (See the presentation by A. Malaquias.)

At PPPL real-time measurements of surface dust have been pioneered by electrostatic dust detectors on NSTX (see presentation by C. H. Skinner). This technology is being enhanced with the addition of a helium puffer system to clear low levels of residual dust remaining on the detector after measurement. Collaborations to extend this diagnostic to LHD and Tore Supra are underway.

Dust collection by a Si wafer in a box is planned for AUG, DIII-D, FTU, JET, and KSTAR followed by an inter-machine comparison. Automated analysis by Energy Dispersive X-ray analysis (EDX) is envisioned. On FTU deposition on a Si wafer exposed with a reciprocating probe will be compared to an aerogel to distinguish vacuum vent effects and see damage from hypervelocity particles in different plasma conditions. On AUG work will continue with marker probes and spectroscopic studies of the contribution of arcs to dust generation on W coated carbon tiles. On KSTAR a reciprocating probe with a Si wafer will be used to collect dust during a vent to test for dust deposition.

Dust release and removal technology

Once the ITER mobilizable dust level approaches the 670 kg limit dust removal will be necessary to permit continued plasma operations. The relative abundance of very small particles will determine the need for sophisticated removal techniques.

EFDA activities on dust removal under the Emerging Technologies programme are aimed at techniques based on laser and electric arc layer cleaning. These techniques are needed to access the areas on the top of the vessel and in the divertor where sticking layers cannot be removed by the baseline vacuum cleaning method.

A new laboratory experiment Transport and Removal Experiment of Dust (TRED) is being built at the Korean National Fusion Research Institute (NFRI). Electrostatic dust removal techniques originally developed in Japan in the ITER EDA will be tested in this facility.

PPPL is testing an electrostatic dust conveyor originally developed by NASA for planetary missions where planetary dust obscured solar cells and electric power generation. The conveyors are being tested for both conductive (carbon, tungsten) and non-conductive dust. A precharge cycle is aimed dielectrophoretic triboelectrification that facilitates the transport of nonconductive dust.

The mobilization of dust trapped in castellation gaps by laser will continue to be studied at CEA.

At INL modelling studies are being carried out to assess the dependence of dust mobilization efficiency on particle size, surface morphology, and flow characteristics.

4. Recommendations and Conclusions

The Coordinated Research Project (CRP) on "Characterization of Size, Composition and Origins of Dust in Fusion Devices" was established in order to address the possible extremely important impacts of dust particles in fusion devices such as ITER. At present ITER is in the process of nuclear licensing and the accumulation of dust and of tritium in dust is the most critical safety issue. It is essential for ITER to demonstrate that it can satisfy safety limits on dust and on tritium and that this can be verified throughout the operation of the machine.

At the 2nd Research Coordination Meeting (RCM) of the CRP participants summarized their studies on dust in fusion plasma experiments and reviewed progress made since the first RCM. Clearly the study of properties of dust remains of high interest at all major fusion experiments. Much progress was reported on video imaging of dust particle trajectories, on the collection and analysis of dust in specially designed receptacles and in electrostatic dust detectors, and on the study of dust mobilization from the vacuum vessel during disruptions and other extreme events. The production of dust by melting and flaking and the associated damage to the vacuum vessel are also studied on all devices. In addition the mobilization and transport of dust in plasma is studied in dedicated laboratory experiments.

Representatives from ITER and from EFDA at the meeting described the further needs for ITER for research on dust, and participants described their research plans including development and installation of new equipment. A dust particles database is foreseen that relies on automated analysis of dust collected at different occasions from different experiments. It is desired to have a pilot of this database in place by the time of the 3rd and final research coordination meeting of the CRP, near the end of 2011.

Appendix 1

IAEA second Research Coordination Meeting on Characterization of Size, Composition and Origins of Dust in Fusion Devices

21–23 June 2010, IAEA Headquarters, Vienna, Austria

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Appendix 2

IAEA second Research Coordination Meeting on Characterization of Size, Composition and Origins of Dust in Fusion Devices

21–23 June 2010, IAEA Headquarters, Vienna, Austria

Agenda

Monday, 21 June **Meeting Room A-07-42**

09:30 – 10:00 Opening, Adoption of Agenda, *R.A. Forrest, B.J. Braams*

Session 1: Reports I

Chaiperson: C. Grisolia

10:00 – 10:45 S. Ciattaglia (ITER): Dust inventory control status in ITER: baseline provisions, R&D plan and first results

10:45 – 11:15 *Coffee Break*

11:15 – 12:00 V. Rohde: Recent dust investigations in full tungsten ASDEX Upgrade: dust production by arcing, refined dust collection and analysis

12:00 – 14:00 *Lunch*

Session 2: Reports II

Chairperson: V. Rohde

14:00 – 14:45 A. Widdowson (CCFE): Update on dust collection at JET during 2010 intervention

14:45 – 15:30 C. Skinner (PPPL): First real-time detection of surface dust in a tokamak

15:30 – 16:00 *Coffee Break*

16:00 – 16:45 C. Castaldo (ENEA): Detection of fast dust particles in tokamaks by aerogel samples and electro-optical probes

Tuesday, 22 June **Meeting Room A-07-42**

Session 3: Reports III

Chairperson: C. Castaldo

09:00 – 09:45 P. Humrickhouse (INL): Dust resuspension and transport modeling

09:45 – 10:30 N. Ashikawa (NIFS): Update on characterization of dust and its dynamics in LHD and JT-60U

10:30 – 11:00 *Coffee Break*

11:00 – 11:45 C. Grisolia (CEA): Overview of French contribution to dust open issues

11:45 – 13:15 *Lunch*

Session 4: Reports IV

Chairperson: N. Ashikawa

13:15 – 14:00 R. Zagorski (EFDA): The EU plasma wall interaction task force: recent achievements and plans

14:00 – 14:45 A. Malaquias: In-vessell dust & tritium management

14:45 – 15:15 *Coffee Break*

15:15 – 16:00 H. Chung: Database and knowledge base developments at IAEA

16:00 – 16:45 S.-H. Hong: In-vessel dust research in KSTAR: preliminary results on flakes, metal droplets, and nanoparticles

Wednesday 23 June **Meeting Room A-07-42**

Session 5: Review

Chairperson: C. Skinner

09:00 – 12:00 All
Comprehensive review and summary of progress made

12:00 – 14:00 *Lunch*

Session 6: Update of Work Plan

Chairperson: P. Humrickhouse

14:00 – 17:00 All
Development of work plan

17:00 – *Adjourn*

List of Publications

(Articles authored or co-authored by CRP participants that were published in 2009 or 2010 and that are related to the subject matter of the CRP.)

J. Berndt, E. Kovazević, I. Stefanović, O. Stepanović, S. H. Hong, L. Boufendi, and J. Winter, "Some Aspects of Reactive Complex Plasmas," *Contrib. Plasma Phys.*, vol. 49, no. 3, pp. 107–133, 2009. http://dx.doi.org/10.1002/ctpp.200910016

D. P. Boyle, C. H. Skinner, and A. L. Roquemore, "Electrostatic dust detector for fusion devices with improved sensitivity," *Journal of Nuclear Materials*, vol. 390-391, pp. 1086–1089, June 2009. http://dx.doi.org/10.1016/j.jnucmat.2009.01.295

A. Campos and C.H. Skinner, "Advances in Dust Detection and Removal for Tokamaks", *Journal of Undergraduate Research* vol. IX (2009) 30.
http://www.scied.science.doe.gov/scied/JUR_v9/default.htm

C. Castaldo, S. Ratynskaia, M. De Angeli, and U. de Angelis, "On the feasibility of electro-optical detection of dust-impact ionization in tokamaks," *Plasma Physics and Controlled Fusion*, vol. 52, no. 10, pp. 105 003+, October 2010. http://dx.doi.org/10.1088/0741-3335/52/10/105003

J. W. Davis, B. W. N. Fitzpatrick, J. P. Sharpe, and A. A. Haasz, "Thermo-oxidation of tokamak carbon dust," *Journal of Nuclear Materials*, vol. 386-388, pp. 764–767, April 2009. http://dx.doi.org/10.1016/j.jnucmat.2008.12.212

N. Endstrasser, F. Brochard, V. Rohde, M. Balden, T. Lunt, S. Bardin, J. L. Briançon, and R. Neu, "Video tracking and post-mortem analysis of dust particles from all tungsten ASDEX-Upgrade," *Journal of Nuclear Materials*, August 2010. http://dx.doi.org/10.1016/j.jnucmat.2010.07.045

C. Grisolia, S. Rosanvallon, P. Sharpe, and J. Winter, "Micro-particles in ITER: A comprehensive review," *Journal of Nuclear Materials*, vol. 386-388, pp. 871–873, April 2009. http://dx.doi.org/10.1016/j.jnucmat.2008.12.192

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C. Hernandez, H. Roche, C. Pocheau, C. Grisolia, L. Gargiulo, A. Semerok, A. Vatry, P. Delaporte, and L. Mercadier, "Development of a Laser Ablation System Kit (LASK) for Tokamak in vessel tritium and dust inventory control," *Fusion Engineering and Design*, vol. 84, no. 2-6, pp. 939–942, June 2009. http://dx.doi.org/10.1016/j.fusengdes.2008.12.033

C. Hernandez, H. Roche, C. Pocheau, M. Naiim-Habib, J. C. Patterlini, R. Sibois, M. Lapeyre, C. Grisolia, and L. Doceul, "Integration of Laser Techniques in a Remote-Handled System for Tokamak Using and Dust Management," *IEEE Transactions on Plasma Science*, vol. 38, no. 3, pp. 237–241, March 2010. http://dx.doi.org/10.1109/TPS.2009.2035503

C. Hernandez, H. Roche, C. Pocheau, M. Naiim-Habib, J. C. Patterlini, R. Sibois, M. Lapeyre, A. Semerok, L. Doceul, and C. Grisolia, "Integration of laser techniques in a remote handled compact system for tokamak in vessel tritium and dust inventory, control and removal," June 2009, pp. 1–4. http://dx.doi.org/10.1109/FUSION.2009.5226378

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B. Rais, C.H. Skinner, A.L. Roquemore, "*He puff system for dust detector upgrade*," PPPL report PPPL-4563, Oct 2010, Submitted to Review of Scientific Instruments. Available online at www.osti.gov/servlets/purl/990740-q2oaPj/

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