Simulating Dust in Magnum-PSI and JET

L. Simons[1,2], J. Holgate[1,2], C.K. Stavrou[3], B. Dudson[4], M. Thomas[4], P. Bryant[5], B. Harris[5], S. Ratynskaia[6], T. Morgan[7], the Magnum-PSI Team[7] & JET Contributors*

[1] *Department of Physics, Imperial College London, SW7 2AZ, London, UK*

[2] *CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*

[3] *Aalto University, P.O.Box 14100, FIN-00076 Aalto, Finland*

[4] *University of York, Heslington, York YO10 5DD, UK*

[5] *Department of Physics, The Oliver Lodge Laboratory, Oxford St. Liverpool L69 7ZE, UK*

[6] *Fusion Plasma Physics, EES, KTH, SE-10044 Stockholm, Sweden*

[7] *FOM Institute DIFFER, Dutch Institute For Fundamental Energy Research, Association EURATOM-FOM, P.O. Box 6336, 5612 AJ Eindhoven, The Netherlands*

Abstract

Dust injection experiments performed at Magnum-PSI are used to benchmark ion drag and heating models used in the dust tracking code DTOKS using Hermes simulated background plasma. Dust particles follow similar trajectories with a period of free-fall under gravity reaching temperatures in excess of $T_d > 2500\ K$ followed by deflection in the ion flow and exiting with a constant velocity of $v = 7.6 \pm 1.4 ms^{-1}$. Utilising this benchmark of the DTOKS code, investigative simulations of breakup events observed in JET. Simulations incorporating this effect reproduce the expected lifetimes and qualitative structures of observed trajectories in JET, providing an attractive technique for mitigating transport of large impurities into the core plasma.

Introduction

Understanding the dynamics of micrometre scale impurities present in magnetic confinement fusion devices is necessary for minimising radiative power losses, increasing operational longevity and, principally, for safety[1, 2]. To investigate the dynamics of intrinsic dust events in the scrape off layer of a tokamak, the initial conditions of the particle must be well known. This is often extremely challenging in tokamaks with the limited diagnostics available from which to reconstruct the initial temperature, velocity and elemental composition, when dust unexpectedly originates from the first wall. Extrinsic dust experiments provide a solution by transforming these parameters into independant variables the experimenter controls.

*See the author list of “X. Litaudon et al. 2017 Nucl. Fusion 57 102001”

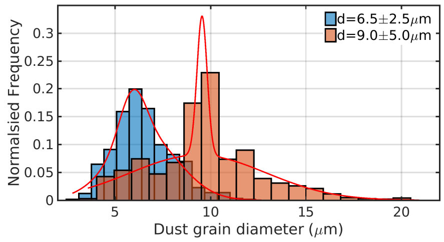


Figure 1: *Distribution of tungsten dust grain diameters fit to double gaussian.*

The Magnum-PSI facility[3] in the Netherlands, part of the EUROfusion consortium, generates magnetised plasmas for tokamak divertor materials testing for ITER. Experiments injecting dust grains under different plasma conditions have been performed on Magnum-PSI and the results have been compared to simulations performed in DTOKS[5]. Calibration of the code in this way provides an independant verification of the equation of motion and heating models and enables investigative simulations of unexplained dust phenomena observed on JET.

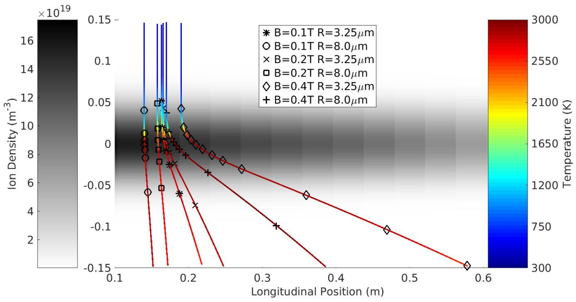
Magnum-PSI

The Magnum-PSI facility achieves plasma conditions relevant to detached divertor operation in ITER using a cascaded arc plasma source impinging on a target guided by a linear superconducting magnet. A Thompson Scattering system was installed to provide measurements of the source electron temperature and density. Two cameras, a Phantom fast imaging visible camera with a maximum framerate of 2000 Hz and an infra red camera, with lines of sight orientated at ± 45 degrees to the injection port, provided a stereoscopic view of the dust. A dust dropper released multiple dust grains simultaneously into the hydrogen plasma column with various magnetic field strengths in the range $0.1-0.4T$. Two samples of tungsten spheres were used, with the distribution of diameters measured using a scanning electron microscope, see figure 1.

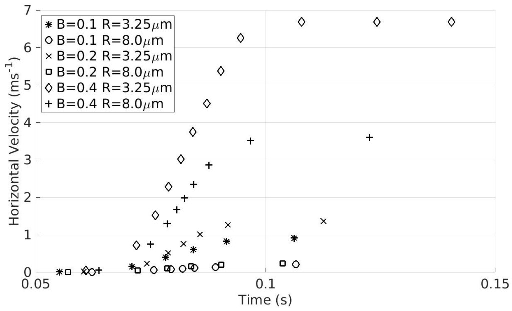
Figure 2: *Phantom camera image of multiple* 3.25 ± 1.0 μm *radius dust grains emitting thermal radiation after exiting the plasma column,* $B=0.4\ T$.

Preliminary results indicate dust grains fell vertically before being deflected by the plasma and exiting with a constant exit velocity estimated as $7.6\pm 1.4\ ms^{-1}$, as seen in figure 2. The visible spectrum suggests a black body radiation profile with a temperature of at least 2500 K.

Measurements of plasma electron temperature, density and flow rate at the injection plane informed simulations of the plasma generated using the Hermes fluid code[6]. These provided the geometry and plasma parameters to DTOKS used in solving the coupled dust equations. The simulations of the plasma spanned a radial distance of 0.15 m which is 0.1 m smaller than the radial dimensions of the chamber. For this reason, particles in DTOKS were injected uniformly over a circular area of diamter $7cm$ (equal to the port size) centered on



(a) *Trajectories of dust grains coloured by dust temperature with ion density*



(b) *Velocities of dust grains shown in figure 3a*

Figure 3: *Example trajectories of dust grains (a) of various sizes in different plasma conditions as simulated by DTOKS shown with their horizontal velocity (b).*

$(r,\theta,z) = (0.147, 0.01, 0.1575)$. The initial dust velocity of $v_r = -1.4\ ms^{-1}$ was calculated from gravitational free fall over $0.1\ m$ which is justified given the relatively low neutral density and temperature in the device.

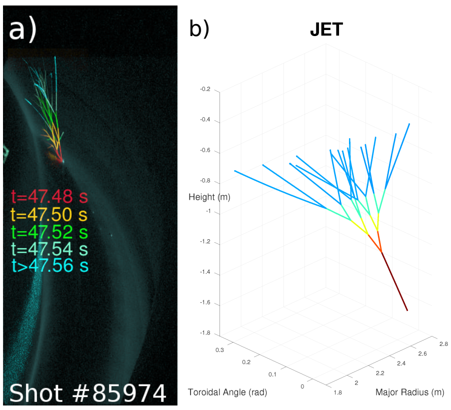


Figure 4: *(a) example of branched tracks colour coded to indicate the time of frame after pulse started (b) DTOKS simulation of shot #85974.*

Examples of the motion of several dust grains with radii of $3.25\ \mu m$ and $8.0\ \mu m$ released over this area in plasmas of different magnetic field strengths is shown in figure 3. The dust grains initially free-fall under gravity until they reach the central plasma, where they experience a strong ion drag force which deflects their motion in the direction of the ion flow, parallel to the magnetic field. At this time, strong heating due to ion collection increases their temperature until at $T = 2800\ K$ it is matched by heat loss due to thermionic emission of electrons. The exit velocity is of order $\sim 6.8\ m/s$.

Dust Trajectories and Breakup in JET

The benchmarking of DTOKS simulations against experimental measurements of the motion of pre-characterised dust grains in various well diagnosed tokamak edge like plasmas permits confidence in an in-depth interpretive analysis of dust in JET. Breakup of dust in DIII-D has previously been reported[7] though no explanation for the breakup mechanism had been suggested. Similar phenomena have been seen by the near IR divertor view camera on JET as shown in figure 4(a). A possible explanation for these forking tracks is the rotational breakup of liquids[8].

A comparison of this theory to experiment is made by incorporating this process into DTOKS and conducting simulations of liquid tungsten droplets (T=3500 K) with initial radii of 50 μm with plasma background generated by EDGE2D/EIRENE, see figure 4(b). When rotational breakup occurs, particles are assumed to be ejected with a relative velocity of $v_r = a\omega_d$ in the plane $\underline{B} \times \underline{v_d}$ where ω_d is the angular velocity of the dust. The key characterstics of the breakup dynamics are recovered by the DTOKS simulation; a forking structure with a mean breakup timescale of $\langle t^* \rangle = 4.8\ ms$.

Conclusion

A verification of the force and heating models emplyed by DTOKS was done through a comparison of simulations to dust injection experiments performed at Magnum-PSI. Tungsten spheres of radii $3.25 \pm 1.3\ \mu m$ and $4.5 \pm 2.5\ \mu m$ were dropped into a magnetised plasma under various conditions and recorded using stereoscopic visual and infra-red cameras. Estimates of the experimental exit velocity of $7.6 \pm 1.4\ ms^{-1}$ and temperature $T_d \geq 2500\ K$ agree well with those of DTOKS $\sim 6.8\ ms^{-1}$, $T_d \geq 2800\ K$ though further processing of the data is required to make a quantitative conclusion.

Modelling and simulation of rotational breakup of liquids in JET reproduce the time-scales and qualitative branching features observed. Full reconstruction of observations in Magnum-PSI will allow for a detailed comparison and validation of ion drag model predictions. Planned work involves analysis of experimental results from different tokamaks (DIII-D, MAST & JET) to create predictive models and better understand dust breakup.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] S. I. Krasheninnikov, R. D. Smirnov, and D. L. Rudakov, Plasma Phys. Control. Fusion **53**, 083001 (2011).

[2] R. C. Isler, R. V. Neidigh, and R. D. Cowan, Phys. Lett. A **63**, 295 (1977).

[3] J. Scholten, et al., Fusion Eng. Des. **88**, 1785 (2013).

[4] A. First, B.C. Second and D. Third, Journal of interesting papers **10**, 10 (2004)

[5] J.D. Martin, M. Coppins, and G.F. Counsell, J. Nucl. Mater. **337-339**, 114 (2005)

[6] B. D. Dudson and J. Leddy, Plasma Phys. Control. Fusion **59**, 054010 (2017).

[7] D. L. Rudakov, et al. Rev. Sci. Instrum. 79, (2008)

[8] J. T. Holgate, L. Simons, Y. Andrew, C. K. Stavrou, and JET contributors, (submitted to PRL, 2018)