Available online at www.sciencedirect.com

ScienceDirect

Journal of Nuclear Materials 363–365 (2007) 222–226

journal of nuclear materials

www.elsevier.com/locate/jnucmat

3D measurements of mobile dust particle trajectories in NSTX

A.L. Roquemore [a,*], N. Nishino [b], C.H. Skinner [a,1], C. Bush [c], R. Kaita [a], R. Maqueda [d], W. Davis [a], A.Yu Pigarov [e], S.I. Krasheninnikov [e]

[a] *Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543, USA*
[b] *Hiroshima University, Higashi-Hiroshima 739-8527, Japan*
[c] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[d] *Nova Photonics, Princeton, NJ 08543, USA*
[e] *University of California at San Diego, San Diego, CA 92093, USA*

Abstract

The transport of dust particles in plasmas may play a significant role in the performance of next step fusion devices. Highly mobile incandescent dust particles are observed on NSTX for the majority of the discharges using fast visible cameras. Particles are most often born in the divertor region during events such as ELMs or disruptions. Particles born on the midplane are most often deflected by the plasma boundary and remain outside the scrape off layer. The dynamics of the dust trajectories can be quite complex exhibiting a large variation in both speed (10–200 m/s) and direction. Particles may have constant velocities or exhibit various degrees of acceleration or deceleration. Abrupt reversals in direction are sometimes observed while some of the larger particles are seen to break apart during mid-flight. 3D trajectories of the dust particles have been derived from measurements of dust trajectories taken simultaneously from two observations points with two fast cameras.

PACS: 52.40.Hf; 52.90.+z

Keywords: Dust; Tracking and imaging; ITER; NSTX

---

1. Introduction

In next step devices such as ITER the increase in duty cycle and erosion levels will cause a large scale-up in the amount of dust particles produced [1]. Recent modeling has suggested that dust particles in a tokamak can be very mobile and that during the duration of a discharge, particles can move through the edge plasma over distances that are comparable to the tokamak radii and be an important mechanism of impurity transport into the core plasma [2,3]. An additional safety issue is that large quantities of dust in the vacuum vessel, could be vulnerable to ignition during accidental ingress of air or water [4]. This is an area of high risk/high

---

[*] Corresponding author. Tel.: +1 609 243 3173; fax: +1 609 243 2665.

E-mail addresses: lroquemore@pppl.gov (A.L. Roquemore), cskinner@pppl.gov (C.H. Skinner).

[1] Tel.: +1 609 243 2214; fax: +1 609 243 2665.

0022-3115/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2007.01.065

consequence for ITER and experimental data from contemporary tokamaks is important to challenge models, advance understanding and mitigate the associated risk to ITER's goals.

The National Spherical Torus Experiment (NSTX) is aimed at exploring the physics of high beta and high confinement in a low aspect ratio device [5]. Plasma facing components that are in contact with the plasma are protected by a combination of graphite and carbon fiber composite tiles. The surface temperature of the tiles at the outer divertor strike point can increase to 250–500 °C during a high power discharge [6]. Dust has previously been collected from NSTX during a maintenance period and characterized [7]. This study determined that the average diameter of dust particles in NSTX is 3.27 μm with particle diameters up to 50 μm present. Results from a novel device to detect surface dust in NSTX are presented in Ref. [8]. Incandescent dust particles have been observed by fast cameras in NSTX plasmas showing that dust particles can be highly mobile and often have erratic paths. In this paper we present recent measurements of 3D dust particle trajectories in NSTX plasmas obtained by two overlapping camera views. The aim is to provide an experimental basis for validating predictive models of dust transport in tokamaks. A detailed comparison of these results to models of dust trajectories will be presented in future publications.

2. Experiment configuration

The open geometry of a low aspect ratio tokamak makes NSTX ideally suited to view and measure dust trajectories. Two fast cameras view the same plasma region in the visible and into the near-infrared wavelengths. A detailed description of the fast camera view ports used in dust measurements in NSTX is provided in Ref. [9] and will only be summarized here. There are 6 view ports available at the midplane to view dust in the main chamber. These are displaced by 60–90° allowing the location of the dust particle within the vessel to be obtained by triangulation using background objects with known locations as markers. Additionally, there are two special views of the lower divertor region: a tangential view at about the height of the X-point and a vertical view of the same toroidal region of the divertor from above. Each of the divertor view ports has a sapphire window that transmits the near-infrared wavelengths.

Fast cameras have been used on NSTX to view fast transient plasma phenomena such as ELMs [10] and MARFEs [11]. Incandescent dust particles have always been observed in the background while viewing these phenomena and have only recently been applied directly to the recording of dust particle trajectories. The three cameras applied to the dust measurements presented here are the Phantom 7 made by Vision Research [12], the Photron Ultima SE [13] and the Kodak Motion Corder [14] The Phantom 7 was routinely operated at 68 000 frames per second (fps) using a 128×128 pixel array. For these measurements, the Photron camera was operated at between 2000 and 9000 fps, respectively, with corresponding pixel arrays of 256×256 and 256×128 pixels. The Kodak was operated between 250–500 fps with a 512×240 pixel array. Only 2–5 frames of data were obtained with the Kodak when tracking even the slowest particles, making it marginal for tracking dust. Both of the faster cameras have used near-infrared and neutral carbon filters to reduce the background light and enhance the visibility of the incandescent dust particle.

3. Experimental observations

3.1. Plasma conditions

In the 2006 run period the cameras were only available to record dust particle trajectories for a restricted set of plasma conditions. Most of the plasmas were neutral beam heated discharges with at least 4 MW of beam heating. However, incandescent dust was often seen in both the divertor and main chamber region in the ohmic phase of the discharge before the strike points were established. Only data taken during the flat top portion of beam heated discharges is reported below.

3.2. Divertor dust particles

The tangential divertor camera (Phantom 7) views the particles in the area from the outer diameter of the center stack at major radius, $R = 28$ cm out to $R = 75$ cm, while the vertical camera (Photron Ultima) has recently had its view extended from $R = 28$ cm outward to $R = 105$ cm. The first divertor particles to be tracked with two cameras were viewed during high elongation double null discharges with the inner strike point on the center stack and the outer strike point on the flat plate of the inner divertor floor. This is the so-called center stack limited configuration. The inner and outer strike points from a representative discharge in this configuration are shown in Fig. 1 using the equilibrium reconstruction code EFIT 02 [15]. The dotted lines show the field of view (FOV) for the two divertor cameras. In this case, both cameras view regions outboard of the outer strike point. A second configuration has the X-point at a larger major radius, the two strike points are on the divertor floor and straddle the gap between the inner and out divertor. In this case, the tangential camera views particles inboard of the outer strike point and the vertical camera views both inboard and outboard particles. As predicted in [2,3] and confirmed by the present observations, dust particles outboard of the outer strike point move toroidially in a clockwise direction and particles inboard of the outer strike point move in the opposite direction.

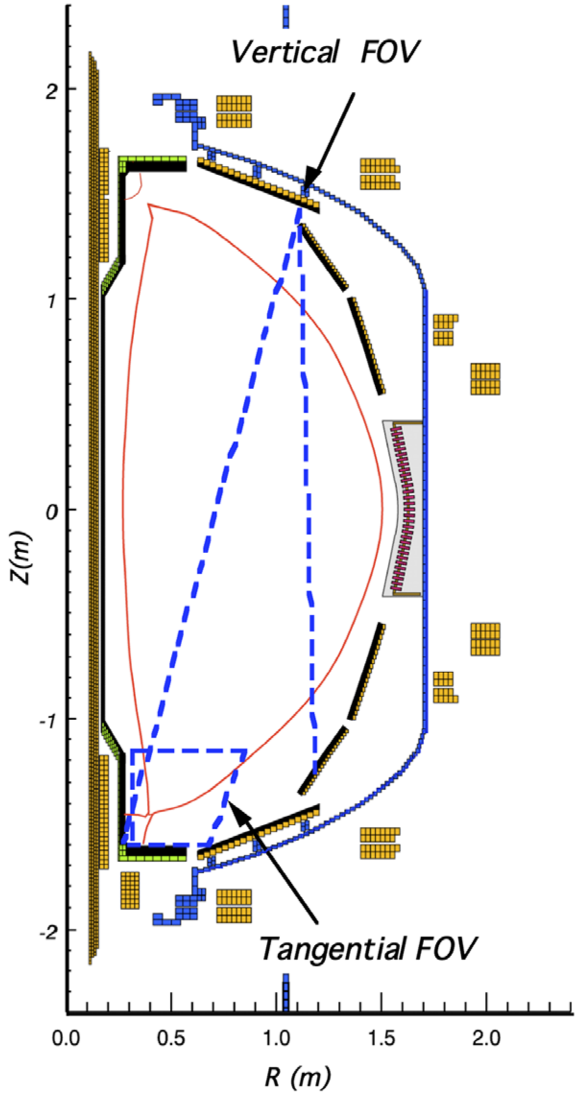

Fig. 1. Equilibrium reconstruction of centerstack limited discharges from EFIT 02. The dotted lines are the outline of the two divertor camera views at the point where the field of view (FOV) of the tangential divertor camera is tangent to the center stack.

A large toroidal component in dust particle trajectories was typically observed in most discharges and in particular was observed for both of the above plasma configurations. An example is shown in the 3-D plot in Fig. 2(a) [9]. The toroidal angle is in NSTX machine coordinates where clockwise (counter to the plasma current) motion is in the direction of increasing angle. The radial coordinate starts at the center of the center column and for the vertical component, $Z = 0$ is at the level of the lower divertor plate. The majority of divertor dust particles closely hug the divertor plates staying within approximately 5 cm of the surface throughout the extent of the camera's FOV. For this reason, the Z-component in Fig. 2(a) is artificially displaced in 2 cm increments for clarity. Divertor particles that have significant vertical components tend to also have much higher velocities, well above the average of 20–60 m/s [9], but represent less than 10% of divertor particles for the plasma conditions observed to date. These particles are often observed in the main chamber views.

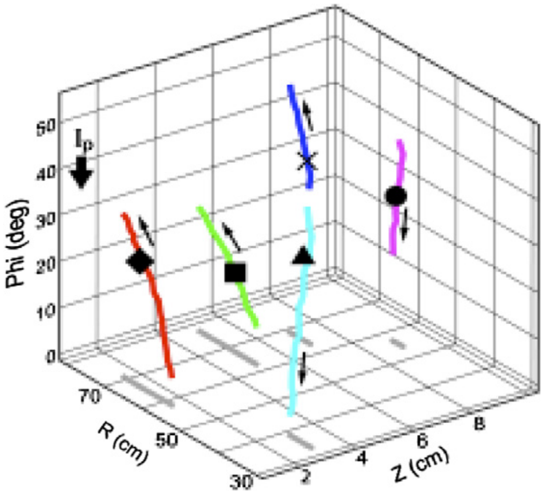

Fig. 2(a). Particle trajectories in the lower divertor as observed from the vertical camera view. The particles outside of the outer strike point (diamond, square and X) have a clockwise toroidal component. When the two strike points straddle the gap, particles inboard of the outer strike point (triangle and circle) travel in the counter clockwise direction. The arrows point in the direction of motion.

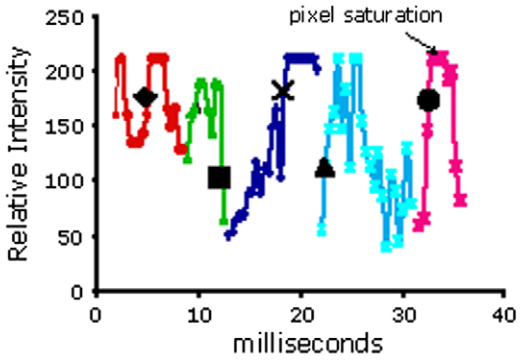

Fig. 2(b). Variation in the light intensity during the period of emission of each dust particle. The camera exposure was 0.44 ms duration showing rapid changes in intensity.

As particles traverse regions of higher temperature plasma they can rapidly heat up. Ablation and thermal sublimation are also occurring. These factors cause variation in the particle emission. When viewed with a near-infrared filter this variation is readily detected. A display of the emission intensity in the near-infrared throughout the particles emission period is displayed in Fig. 2(b) with each trace representing one of the particles in Fig. 2(a). The step size is the camera exposure time of 0.44 ms, showing that large changes in the emission can occur in a short period. When using other filters such as C II, the variation in intensity is much less pronounced, however, the filter reduces the background light to the level that relatively dim incandescent particles can be observed.

3.3. Main chamber

Tracking of particles in the midplane of NSTX has only recently started. The Phantom 7 camera has been required for ELM and MARFE studies so the Kodak and Photron cameras have been employed. The Photron camera is the principal camera while the Kodak is used mainly to verify coordinates. With this arrangement, general trends have been observed. The majority of particles seen in the midplane views are mostly confined to the cooler regions near the scrape off layer (SOL) but exceptions are often observed. Particles born at the vessel walls will generally drift toroidally along the outer wall of the chamber in the direction of the plasma current. A particle generated from the vessel wall near the midplane, will initially have an inward radial motion until it encounters the plasma boundary where it will either be deflected outward and drift in the direction of the plasma current, or it will suddenly vanish, most likely from being be rapidly vaporized. Particles inboard of the SOL usually have an initial vertical component indicating that they were generated in the upper or lower divertor region. Their trajectories become more toroidal with time and also move in the direction of the plasma current. Particles both inboard and outboard of the SOL will be gradually deflected vertically downward in a direction perpendicular to the magnetic field lines on NSTX. This motion is being actively investigated. The particles that are inside the SOL, typically have a larger velocity than those outside the SOL. An example of particle trajectories illustrating the trends mentioned above is shown in Fig. 3. The coordinate system is similar to the one used in Fig. 2 except that $Z = 0$ is located at the midplane. Note the separatrix is located at $R = 148$ cm for this discharge where two of the particles vanish. The accuracy of the particle position is compromised because of the relatively fewer recorded frames of the Kodak and is estimated to be within ±4 cm.

Very high velocity particles are often seen in the main chamber resulting from events such as Type I ELMs or disruptions. Fig. 4 shows the aftermath of a disruption on NSTX showing hundreds of glowing dust particles distributed throughout the

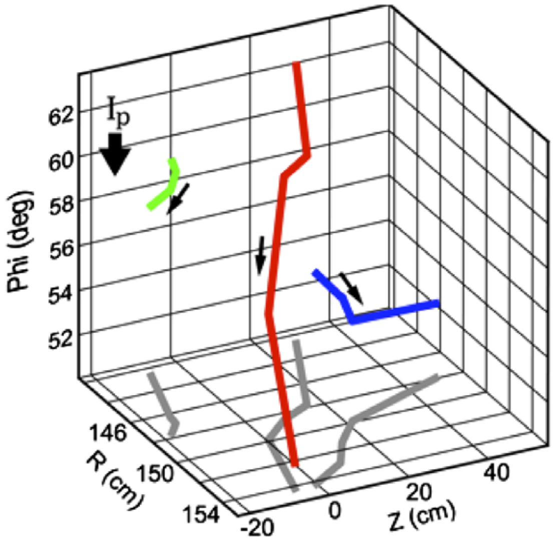

Fig. 3. Example trajectories for particles near the midplane of NSTX. The separatrix is located at $R = 148$ cm for this discharge. Two of the particles vanish at the separatrix and one crosses to the outboard side. An arrow points in the direction of motion showing a drift in the direction of the plasma current.

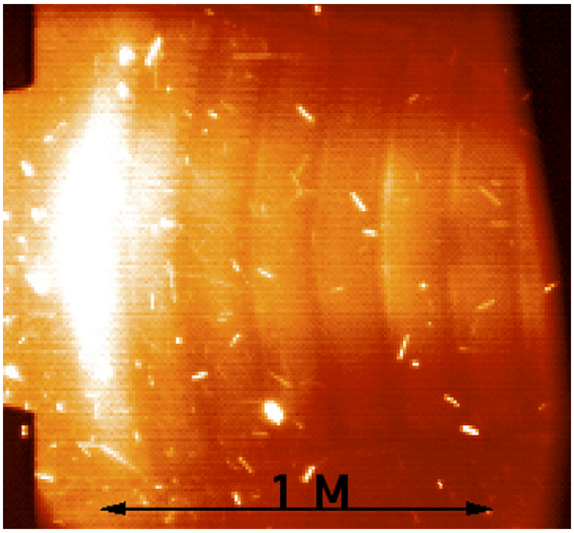

Fig. 4. Tangential midplane view of NSTX with the High Harmonic Fast Wave antenna in the background. A single frame displays dust generated during a disruption. For this case, dust particles are generated for a ~30 ms duration with most of the dust originating from the lower divertor region. The camera was unfiltered for this image.

chamber volume during a disruption. In this discharge, the dust production continued for ~30 ms. This reinforces the need for ELM and disruption mitigation. When ELMs and disruptions are avoided, the amount of visible dust decreases in both the main chamber and divertor regions throughout a run day as long as the same plasma configuration is maintained. Any change in operating scenario will generally create a new crop of dust particles.

4. Summary

Incandescent dust particles have been tracked in NSTX using two cameras simultaneously at two different locations with each displaced by approximately 90°. 3D trajectory information including velocity information has been derived with sufficient accuracy to be utilized to benchmark dust transport models that can then be applied to predicting dust behavior in future devices. Future work includes adding an additional view port on the midplane and purchasing a new high speed camera to replace the outdated Kodak.

Acknowledgements

The authors would like to thank T. Holoman for fabricating the camera mounts and fiber optic holders as well as the reentrant view port configuration. This work is supported by the US DOE Contract No. DE-AC02-76CH03073.

References

[1] G. Federici, C.H. Skinner, J.N. Brooks, et al., Nucl. Fusion 41 (1967) 2001.
[2] S.I. Krasheninnikov, Y. Tomita, R.D. Smirnov, R.K. Janev, Phys. Plasmas 11 (2004) 3141.
[3] A.Yu. Pigarov, S.I. Krasheninnikov, T.K. Soboleva, T.D. Rognlien, Phys. Plasmas 12 (2005) 1.
[4] ITER Technical Basis, ITER EDA Documentation Series No. 24, IAEA, Vienna, 2002 (Chapter 5.3), p. 13.
[5] S.M. Kaye et al., Nucl. Fusion 45 (2005) 168.
[6] D.A. Mastrovito et al., Rev. Sci. Instrum. 74 (2003) 5090.
[7] J.P. Sharpe et al., J. Nucl. Mater. 337–339 (2005) 1000.
[8] C.V. Parker, C.H. Skinner, A.L. Roquemore, J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.01.209.
[9] A.L. Roquemore, W. Davis, R. Kaita, C.H. Skinner, R. Maqueda, N. Nishino, Rev. Sci. Instrum. 77 (2006) 10E526.
[10] N. Nishino et al., Proceedings of the 21st IEEE Symposium on Fusion Engineering, (SOFE), Knoxville, TN, IEEE Cat. No. 05CH37764C, September 2005.
[11] R. Maqueda, J. Nucl. Mater., these Proceedings, doi:10.1016/j.jnucmat.2007.01.166.
[12] Vision Research Inc., 100 Dey Road, Wayne, NJ 07470.
[13] Photron Ltd., Fujimi-cho 1-1-8, Chiyoda-ku, Tokyo 102-0071.
[14] Eastman Kodak Company Motion Analysis division, 11633 Sorrento Valley Rd., San Diego, CA 92121-1097.
[15] S.A. Sabbagh et al., Nucl. Fusion 41 (2001) 1601.