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Imaging of high-speed dust particle trajectories on NSTX

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Imaging of high-speed incandescent dust particle trajectories in a tokamak plasma has been accomplished on NSTX using up to three high-speed cameras each viewing the same plasma volume from different locations and operating at speeds up to 68 000 frames/s with exposure times varying from 2 to 300 μs. The dynamics of the dust trajectories can be quite complex exhibiting a large variation in both speed (10–200 m/s) and direction. Simulations of these trajectories will be utilized to ascertain the role dust may play in future machines such as ITER where significant dust production from wall erosion is expected. NSTX has numerous view ports including both tangential as well as radial views in both the midplane and lower divertors. Several vertical ports are also available so that a few specific regions in NSTX may be viewed simultaneously from several different camera positions. The cameras can be operated in the full visible spectrum but near-infrared filters can be utilized to enhance the observation of incandescent particles against a bright background. A description of the cameras and required optics is presented. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2347696]

I. INTRODUCTION

Incandescent dust has been routinely observed on NSTX by visible fast cameras that were originally used to study specific plasma processes. Only recently have fast cameras been employed with the specific purpose of characterizing the dynamics of dust particles in tokamak plasmas. This new interest is in response to the need to understand and predict the consequences that large amounts of dust generated by wall erosion will have on next-step machines.[1] On NSTX, research into measurement and control of dust is underway[2] with the goal of projecting the results to ITER. The present study is aimed at providing data on the dynamics of dust particles inside of a plasma to further understand dust generation and mobility. The data will be used as input to codes such as DUSTT,[3] a dust transport code developed at UCSD. To provide data for these models, visible cameras have been employed to observe incandescent dust particles during their creation and to track their trajectories inside the plasma. At least two fast cameras are required to accurately track a particle and provide reliable data to fit into predictive codes. A description of the cameras is presented and the various views are shown. Example trajectory data recently obtained with two cameras simultaneously in the divertor region of NSTX are presented.

II. FAST CAMERA CAPABILITIES

Dust particle trajectories can be quite complex. Some particles have very high velocities, while others are literally suspended in one location for long durations. Particles have been observed to make abrupt 180° changes in direction, others may initially have a constant velocity and suddenly accelerate rapidly out of the field of view. Individual particles are often seen to break apart in midflight resulting in from two to ten new particles. Each of these effects is being modeled by the DUSTT code. However, these extreme behaviors are more of an abnormality constituting about 10% of the observed particles. The majority of particles have a more benign behavior in that they move in either straight lines with constant medium velocities or have some constant curvature. Tracking these particles can be demanding, and pinpointing their location requires a camera with high sensitivity, and fast frame rates.

Three cameras have been routinely employed to study dust behavior in NSTX. The two fastest cameras are based on complementary metal-oxide semiconductor (CMOS) technology, which is known to be more resistant to radiation damage than the more common charge-coupled device (CCD) cameras.

The camera having the greatest sensitivity as well as the highest framing rate that is used for dust measurements on NSTX is the Phantom 7 manufactured by Vision Research[4] and provided as part of a collaboration between NSTX and Nova Photonics. The camera's primary mission is to measure fast phenomena such as turbulence and multifaceted asymmetric radiation from the edge (MARFE).[5] This camera is state of the art in technology in that it has 12 bit monochrome bit depth, the best on the commercial market. It provides frame rates of up to 120 000 frames/s, though it is typically operated at 68 000 frames/s with corresponding 128 × 128 pixel array and has enough onboard memory to capture a full discharge on NSTX. Even at these fast frame rates, the images are bright and small dust particles are easily visible.

A second camera, the Photron Ultima SE,[6] is provided as part of a collaboration between the US and Japan. This camera has been used extensively on NSTX as a divertor diagnostic to study ELMs.[7] The camera has the capability of operating at up to 40 500 frames/s but for tracking dust, it is typically operated from 2000 to 13 500 frames/s. Particles in the main chamber with speeds of 100 m/s will only travel of the order of 1.5 cm per frame over a path length of the order of 1–3 m. The slower particles in the divertor are typically tracked at 2250 frames/s where 1–2 cm steps per frame are more than adequate to determine particle velocities. This camera is immune to the ambient magnetic fields on NSTX and can be mounted directly on a view port.

The first camera to detect incandescent dust on NSTX is the Kodak Motion Corder,[8] an early model high-speed camera. This camera can operate at up to 10 000 frames/s but in practice it is limited to much slower rates. As the frame rate is increased to 1000 frames/s, the image is transferred to the upper left hand corner of the pixel array requiring a wide-angle lens to achieve a useful field of view. This limits the resolution and distorts the edge of the image severely. This camera is most useful when mounted on a midplane port and operated at 500 frames/s.

III. VIEWING ACCESS TO NSTX

Six view ports provide access to the midplane of NSTX. The toroidal location of each midplane view port is shown in Fig. 1(a). The arrows in the figure point in the direction of the axis of the port. The field of view (FOV) of the two most utilized ports is shown in the figure and the shaded region is the area of overlap between the two views. Some portion of a tangential cross section is obtained in each of the six views. As can be seen, the coverage is greater than 50% of the machine volume.

Development of a reentrant tangential view port in the divertor region of NSTX was first proposed by one of the authors (Nishino) for ELM and turbulence studies using the Photron camera described above. The implementation of this view port is described in Ref. 9. A complementary reentrant view port looks vertically downward on the divertor from the top of the machine. Its view is somewhat occluded because it looks through long radially oriented gap in the tile support structure that is just 5 cm wide. Its viewing region on the divertor is about 1 m on each side and is centered on the tangency radius of the view from the tangential divertor window. The FOV of the tangential divertor port at its tangency radius with the center column is outlined in the poloidal cross section of NSTX in Fig. 1(b). The radial extent of the FOV from the vertical port is also shown at the same tangency radius. Trajectories taken from the vertical camera during a single discharge are displayed in Fig. 2 showing the general trend of particle motion in the toroidal and radial directions. Each of the particles had almost no vertical component staying approximately 5 cm above the divertor so their trajectories have been artificially displaced by 2 cm in the figure for clarity. The dust particles located outside of the outer strike point generally have a clockwise toroidal component that is in the direction of parallel flow in the outer divertor. Particles inboard of the outer strike point tend to travel in the opposite toroidal direction. For this figure, the clockwise direction is in the direction of increasing angle and the radial direction starts at the center of the central column. Also, the vertical (Z) component is zero at the level of the lower divertor plate.

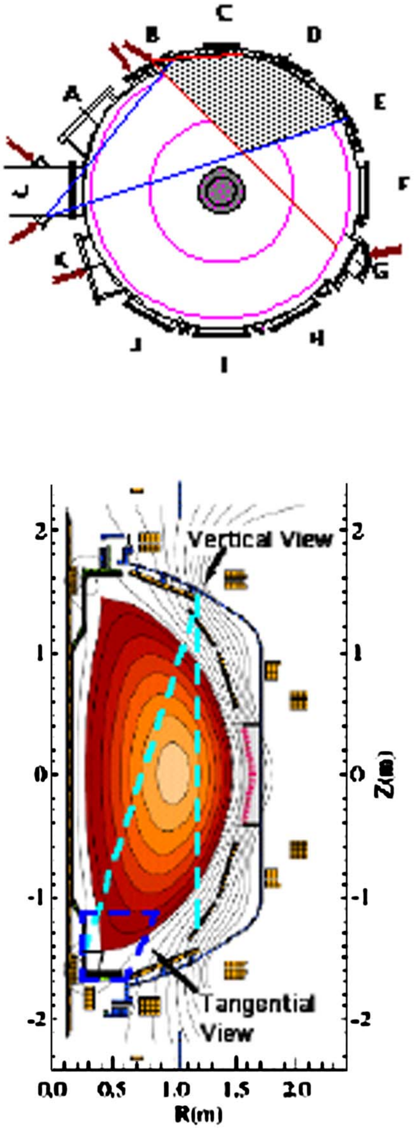

FIG. 1. (a) Plan view of NSTX showing the camera view port locations. The arrows indicate the direction of the view port axis and the shaded region is the area of overlap of the views for the two most widely utilized ports. (b) Poloidal cross section of NSTX. The dotted polygon is the outline of the viewing region for the tangential divertor port at the point of tangency with the center stack. The dotted cords from above outline the radial extent of the field of view from the vertical port at the same point of tangency.

IV. VIEWING OPTICS

Dust particles are visible while they are heated to incandescent temperatures but their detection can be hampered by large amounts of background light such as is always present around the strike points in the divertor or around the rf lim-

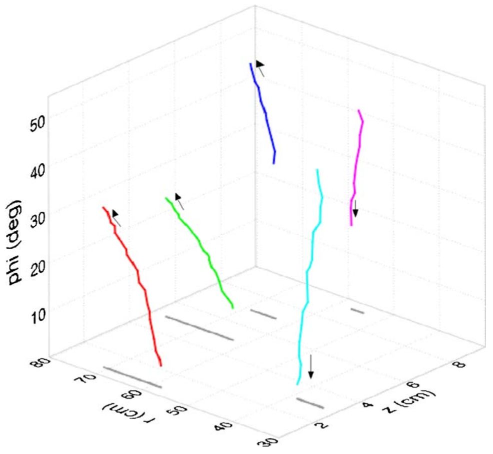

FIG. 2. Example trajectories of particles in the lower divertor region. Particle trajectories moving in the clockwise direction (increasing PHI) are from particles outboard of the outer strike point while particles with counterclockwise motion are from particles inboard of the outer strike point.

iters. It is helpful in some cases to use a near-infrared filter (for instance, Tiffen 87) to reduce the background light. Both cameras make use of the near-infrared filter to obtain the divertor data presented in this article. Three of the viewing windows have reentrant designs that dictate the use of fiber optic bundles. The bundles range from 1.3 to 4 m in length, are very flexible, and have an 8 × 10 mm cross section. The fiber element size is 10 μm so that the bundle is made of 800 × 1000 individual elements configured to make a coherent bundle. The large cross section of the bundle provides for full illumination of each of the camera sensors. The exit lens at the end of the fiber bundle is closely coupled to the lens on the camera with up to a 2 cm gap between the lenses to accommodate a filter wheel if desired. Both lenses are usually telephoto lenses with the focus set to infinity. If a narrow band interference filter (or filter wheel) is used, placing it between two lenses focused at infinity has the advantage that near-parallel rays of light are transmitted through the filter. Since a narrow band interference filter has a small angle of acceptance, a darkened ring around the outside of the image can be formed if a filter is placed directly on the end of a moderately wide-angle camera lens without the use of the fiber bundle. Full image capability is obtained when placing the filter between the fiber bundle and the camera.

When the Kodak and Photron cameras are mounted directly on midplane view ports, filters are generally not used and the view is selected where the background light is low.

V. 3D RECONSTRUCTION OF THE TRAJECTORIES

By having two images displaced by nearly 90°, a good measure of the trajectories in three dimensions can be obtained. NSTX utilizes a measuring arm inside the vessel during outages, and many hundreds of measurements have been taken of the absolute location of objects on the vessel walls. By knowing the spatial coordinates of the camera's view port and of several objects on the far wall in the camera's FOV, it becomes a geometry problem to pinpoint the coordinates of a particle at a given time. An IDL program has been written to enhance particle images and convert camera pixels to an X, Y, Z coordinate system. Coordinates from the two cameras pinpoint the particle location and can be combined to yield standard tokamak coordinates of R, $\varnothing$, and Z. Velocities are then obtained from the distances the particles travel combined with the framing rates of the cameras. Figure 3 shows averaged velocities of particles in the lower divertor obtained using this method. The data were obtained on two consecutive discharges. The tangential view was used to identify particles that had little or no vertical velocity component, at least in the region of overlapping views. Figure 3 shows that the majority of particles in the lower divertor have velocities between 20 and 60 m/s with some slower and some faster particles observed. Tracking of dust particles in the main chamber simultaneously with two cameras has recently been achieved and is presently being analyzed.

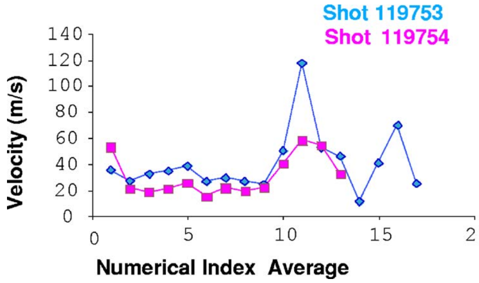

FIG. 3. Averaged velocity of dust particles in the lower divertor from two sequential discharges.

The IDL tracking program locates the centroid of the brightest pixels in a user-selected square around the particle and assigns a coordinate to the particle. The very dim particles are naturally difficult to observe especially in the bright region of the divertor. In addition to the use of filters to reduce the background light, the IDL program enhances the particle visibility by subtracting out the median value of the light level from the overall frame allowing small or dim particles to be observed that went previously undetected.

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