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Three-dimensional Reconstruction of Dust Particle Trajectories in the NSTX

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Three-dimensional reconstruction of dust particle trajectories in the NSTX[a)]

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Highly mobile incandescent dust particles are routinely observed on NSTX using two fast cameras operating in the visible region. An analysis method to reconstruct dust particle trajectories in space using two fast cameras is presented in this paper. Position accuracies of a few millimeters depending on the particle's location have been achieved and particle velocities between 10 and 200 m/s have been observed. [DOI: 10.1063/1.2965001]

I. INTRODUCTION

The existence of large quantities of dust particles inside of a plasma chamber has recently been identified as a serious issue for the development of fusion energy. Dust can contaminate the plasma and the in-vessel dust inventory will need to be controlled for safety reasons.[1] Research into dust behavior in fusion devices includes the formation of dust and its propagation within the vessel, its impact on diagnostic mirrors and windows, as well as the dust inventory accumulation in the lower regions of a fusion device. The transport code, DUSTT[2,3] was developed to study the behavior of dust in a plasma that has been heated to temperatures relevant to a fusion reactor. This code tracks micron-size dust particles from their birth to their eventual destruction. Experimental data are required to validate the DUSTT code. The propagation of dust needs to be measured throughout the entire vessel since any surface that the plasma will contact can produce large amounts of dust.

Highly mobile incandescent dust particles are routinely observed on NSTX using fast cameras operating in the visible and near IR wavelength range. A three-dimensional (3D) tracking code has been developed that uses image sequences obtained from two fast cameras in order to locate particles to within an accuracy of a few millimeters. This is achieved by correlating the pixel position on the images with monuments on the vessel walls and will be described below. From the 3D positions dust particle velocities as a function of position and time can be determined. We found particle velocities ranging from 10 up to 200 m/s.

II. IMAGE PROCESSING

High speed cameras produce a large amount of data during a typical NSTX discharge. The complete determination of dust particle trajectories makes it necessary that each set of frames of each camera is searched for dust particles. For each dust particle candidate its pixel location has to be determined for consecutive frames until the particle has vanished from the image. These pixel locations as a function of time form the raw track data.

To carry out this analysis by hand is very time consuming and error prone. We have therefore developed a set of image processing procedures to make this process semiautomatic. This allows us to efficiently scan an image sequence from an NSTX discharge for dust particle trajectories. The various steps are described in the sections below.

A. Background subtraction

On a fast, well focused camera image, incandescent dust particles produce relatively small spots with a brightness that ranges from barely above the more continuous background up to brightnesses that saturate the camera's dynamic range. In order to determine the particle position on the image accurately the difference of the particle's brightness and the surrounding background light should be as large as possible. To this end a flexible background subtraction algorithm that can be optimized to the various plasma conditions has been developed. To estimate background contributions, for each frame one calculates either the average or the median value of each pixel's brightness value over a series of frames preceding the current frame and a series of frames trailing the current frame. In addition one typically also omits the neighboring frames in this process in order to avoid to cut part of the signal of a slow moving particle. The total number of frames used in each series and the number of frames adjacent to the current frame that are skipped are parameters that can be easily varied for optimization. The estimated background, scaled (enhanced or diminished) by an adjustable parameter, is then subtracted from the current frame. This procedure is illustrated in Fig. 1, together with the expression for the averaging procedure. As an example of the result of this method Fig. 1 shows a side by side comparison of a raw picture frame and the corresponding background subtracted one. Clearly the contrast between the glowing dust particle and the plasma background has been enhanced.

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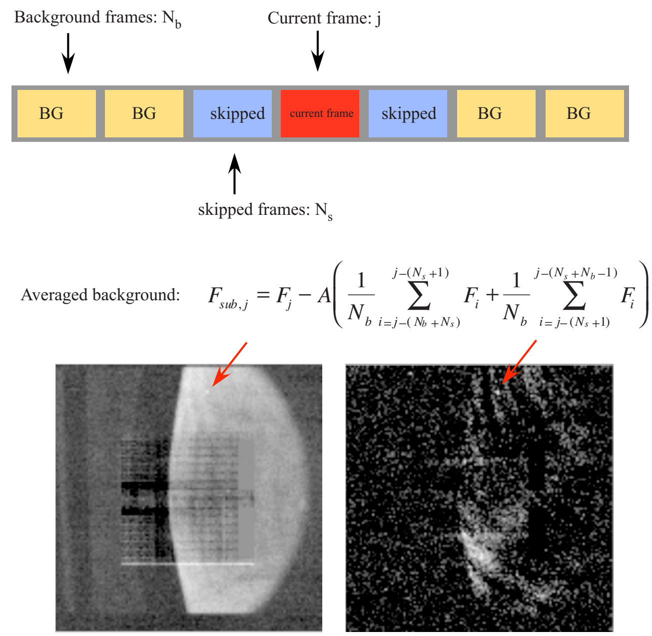

FIG. 1. (Color online) Top: Background subtraction method: the central frame to be corrected is flanked by the frames to be skipped followed by frames (labeled BG) that are used to estimate the background to be subtracted. The variable A is an overall scale factor for the background image. Bottom: raw image (left) and background subtracted image (right); the arrow indicates a dust particle.

Line filters and near IR filters have also been used with some success in reducing background light. However, this method can still be applied when filters are used to enhance the image.

B. Track visualization

After background subtraction, the next step in the analysis process is the creation of a composite image from each camera in which possible particle tracks are displayed as white lines of various thicknesses related to the brightness of the particles (Fig. 2).

For each (background subtracted) frame a "binary" image (consisting only of completely white or completely back pixels) will be created by setting all pixels with a value smaller than a certain adjustable threshold value to zero (black). One has to consider that particles with a brightness that is smaller than the threshold will be lost.

Those pixels that have a brightness equal or larger than the threshold value are set to 255 (white). The composite image is subsequently formed by adding the pixel intensity values for corresponding pixels in the sequence of frames. Any pixel value in the summed image equal or larger than 255 is reset to 255.

FIG. 2. Binary composite image showing the various tracks of dust particles for a sequence of frames. On the left hand side one track has been marked by a polygon for automatic track finding.

C. Automatic track finding

Each track candidate is marked in the composite image by an enclosing polygon circumscribed by the use of a mouse. This polygon is then converted to a mask. The automatic track-finding algorithm applies this polygon mask to each binary image frame, isolating the area of the image corresponding to the current track. If no pixel value larger than 0 is found in the currently analyzed frame after the polygon mask has been applied, the frame is skipped. In contrast, a pixel value larger than 1 indicates the presence of a dust particle belonging to the track candidate. At this point it is necessary to block out all pixels that are not part of the dust particle. Therefore the binary image combined with the polygon mask is converted to a new combined mask and applied to the background subtracted frame image. The final pixel position of the dust particle is obtained from the weighted average (the weight is the pixel intensity value) of all the pixels located in a predefined area surrounding the pixel with the highest intensity in the masked frame image. The position values are stored in new files for each polygon mask.

This procedure is repeated for all track candidates identified in the binary composite image. The final result is a set of files containing the location of possible dust particles belonging to the corresponding track.

III. CAMERA CALIBRATION

For the analysis presented here a simplified camera optics model is used where each pixel location corresponds to a

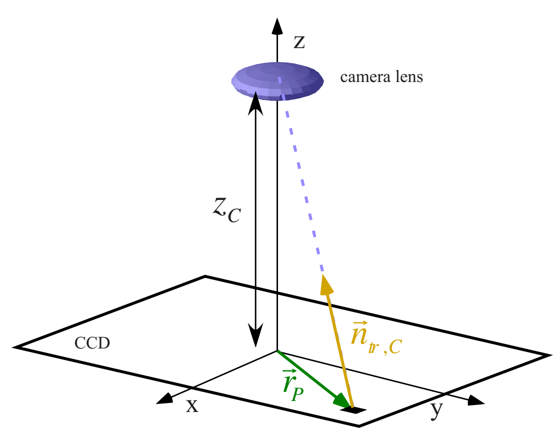

FIG. 3. (Color online) The camera coordinate system used to determine the sight line for each individual pixel. Vector $\vec{r}_P$ is the pixel position vector and the vector $\vec{n}_{tr,C}$ is the unit vector of the sight line in the camera system. The variable z_C, corresponding to the image distance of the lens, is one of the calibration parameters.

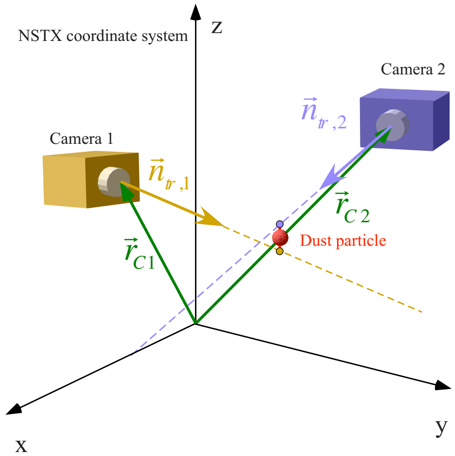

FIG. 4. (Color online) Geometry used in the NSTX coordinate system to reconstruct the location of a dust particle. The vectors $\vec{r}_i$ are the position vectors of the camera and the vectors $\vec{n}_{\mathrm{tr},i}$ are the unit vectors for the direction of the line of sights.

light ray (or line of sight) that would illuminate the pixel. To determine the line of sight in space for a given pixel location a transformation function needs to be determined. We assign each camera a coordinate system as shown in Fig. 3 and we treat the camera as a pinhole camera. The origin of the camera coordinate system is defined at the intersection of the optical axis with the complementary metal-oxide semiconductor (CMOS) sensor. The direction of the line of sight is then given by the unit vector $\vec{n}_{\mathrm{tr},C}$ pointing from the pixel to the center of the camera lens. The distance z_C of the lens from the CMOS sensor is treated as a parameter to be determined in the calibration procedure. A transformation matrix has to be determined to transform the unit vector $\vec{n}_{\mathrm{tr},C}$ from the camera system to the NSTX coordinate system.

This transformation can be described by an Euler rotation matrix. The three Euler angles and the variable z_C are the parameters that are determined by fitting the reconstructed directions to the known directions from the camera location to a set of monuments in the vessel. Using these transformation matrices in combination with the known camera locations one can now reconstruct the sight line corresponding to each camera pixel in the NSTX coordinate system.

IV. TRACK RECONSTRUCTION

Figure 4 illustrates the transformed sight lines in the NSTX coordinate system necessary to reconstruct the location of the dust particle.

Corresponding two-dimensional tracks from the two camera views are initially identified by comparing the frame times associated with each track. However, this provides only a necessary condition for assuring that the two data sets describe the same particle track. In a second step the shortest distance between the sight lines belonging to each view are determined for all possible combinations of track data files with matching frame times. This distance is used as a criterion on whether the two data files belong to the same dust particle track. Typically a distance value of 5 cm has been used as a cut-off value. In addition these distances are a measure of the accuracy with which the location of a dust particle can be determined. The average of the positions along the two sight lines is finally used as the 3D location of the dust particle.

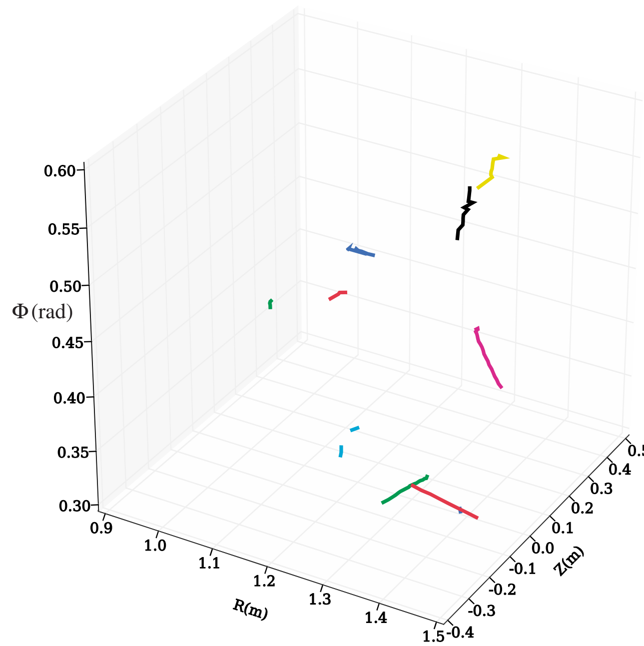

FIG. 5. (Color online) Reconstructed tracks for NSTX shot 121052 in a (R,z, θ) coordinate system.

V. RESULTS

Figure 5 shows a set of reconstructed tracks in the main chamber of NSTX for shot 121052. The position uncertainties have been estimated from the distance of the two sight lines and range from ±3 mm up to ±2 cm. The upper limit depends on the criterion that is applied for matching tracks. A more detailed error analysis will be carried out in the future.

From the reconstructed particle tracks it also possible to

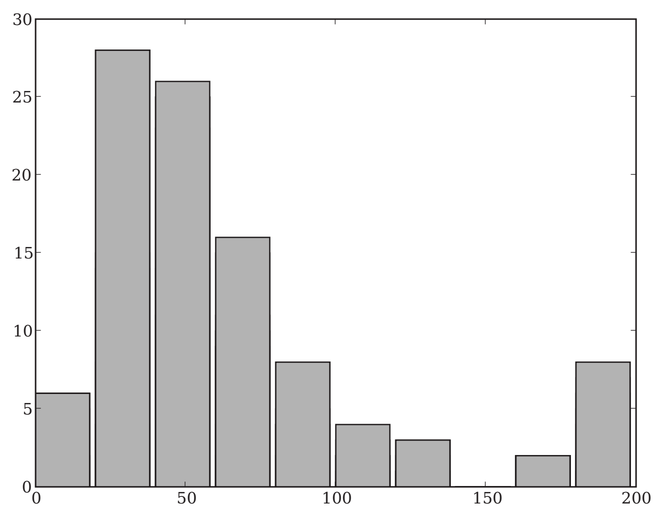

FIG. 6. Histogram of instantaneous velocities (in m/s) determined from the tracks shown in Fig. 5. A total of 11 particle tracks have been used.

determine particle velocities. A histogram of instantaneous velocities observed for all tracks in this shot is presented in Fig. 6.

A similar set of tracks and velocity measurements has been obtained for dust particles in the lower divertor region of NSTX.

In general, this method can be used to determine 3D trajectories of incandescent particles in any region of the vessel that can be viewed simultaneously by two synchronized cameras. The accuracy of the reconstruction depends on the relative angle of the two camera views, on the total number of pixels, on the speed of the camera, and on the quality of the calibration image including the number of measured positions on the vessel wall. This method has already significantly reduced the error in the particle position by more than a factor of 2 as compared to previous works.[4] The addition of a third camera is expected to further significantly reduce the overall position error bars. High precision dust particle position measurements could lead to new diagnostic tools for high temperature plasmas.[5]

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