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Investigating the momentum balance of a plasma pinch: An air-side stereoscopic imaging system for locating probes

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The momentum balance of a plasma pinch in the Reconnection Scaling Experiment (RSX) is examined in three dimensions using several repositionable, insertable probes. A new camera-based system described here triangulates the locations of the probe tips so that their measurements are spatially registered. The optical system locates probes to within ±1.5 mm of their absolute 3D position in the vessel and to within ±0.7 mm relative to other probes, on the order of the electron inertial length (1–2 mm). © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4898176]

I. INTRODUCTION

A plasma pinch of length l is kink unstable when magnetic pressure from axial current density, \( J_z \), exceeds the tension of the longitudinal field, \( B_z \), or, \( J_z > J_{\text{crit}} = 4\pi B_z/\mu_0 l \) (Shafranov, 1956). The pinch generated in the Reconnection Scaling Experiment (RSX) (length \( l = 480 \text{ mm} \), effective radius \( a = 20 \text{ mm} \), \( B_z = 110 \text{ G} \), axial current \( I_z = 270 \text{ A} \) additionally exhibits a metastable state near \( J_{\text{crit}} \) in which the kink amplitude remains indefinitely constant while the phase structure gyrates (Furno et al., 2006). This saturated behavior may be due to the sheath conditions at the axial boundaries which resist lateral motion of the plasma, a theory previously analyzed by Lanski (Lanski and Shchetnikov, 1990).

To investigate the internal momentum balance (\( \mathbf{J} \times \mathbf{B} - \nabla p = \rho \mathbf{v} \times \mathbf{B}/dt \)) that supports the metastable state, RSX is fitted with multiple diagnostic ports that allow probes to be introduced into the plasma and manually translated in three dimensions between discharges (Intrator et al., 2008). 3D profiles of the force densities are assembled over many repeated shots (Sears et al., 2014). The full momentum balance requires measurement of vector magnetic field to calculate the magnetic force density, plasma density and temperature to calculate pressure gradient, and velocity to calculate acceleration, necessitating three types of probes (magnetic, triple Langmuir, and Mach, respectively). Whether the probes are used simultaneously from separate ports or in turn from a single port, the absolute position of their sensing tips must be known in order to spatially register the three terms of the momentum balance. As is common in plasma experiments, measurement of the position of the probe tips is confounded by the inherent flexibility of the long, slender probes, the low dimensional tolerance of the vacuum seals that hold the probes, and the complicated geometry of the vacuum vessel and magnet system. Accuracy of absolute probe tip position in RSX has been previously limited to >10 mm, inadequate compared to the 20 mm radial plasma density scale length. (Relative resolution has been 0.9-3 mm for a single probe moved from shot to shot, but in the present investigation we are comparing multiple probes.)

Here we present measurements of plasma pressure and magnetic field that are registered to within ±0.7 mm using a new camera-based system to locate the probe tips. Two calibrated cameras image the vacuum vessel interior through window ports, and a software module triangulates the probe tip positions. The simple optics require none of the moving parts usually associated with precision probe motion, such as micropositioners. By dropping the requirement that probes be precisely positioned, but merely that their locations be precisely known, this camera system allows us to acquire and accurately register the terms of the momentum balance using our existing probe-positioning hardware.

The structure of the paper is as follows: Sec. II describes the plasma physics experiment where we implemented the camera-based techniques; Sec. III describes the hardware and operating procedures; Sec. IV describes the software developed; Sec. V assesses the precision of both the optical and direct methods, and Sec. VI gives an example of the impact of optical-based corrections on measurements of plasma pressure and magnetic field. Conclusions are summarized in Sec. VII.

II. EXPERIMENT DESCRIPTION

The main RSX vacuum vessel is an octagonal cylinder 800 mm long and 325 mm wide, depicted in Figures 1 and 2. It is equipped with twenty-two ports, six of which provide three-dimensional probe positioning along cartesian axes, described in prototype form in (Intrator et al., 2008). Each of the six ports consists of a rectangular opening in the vessel measuring 150 mm to 230 mm long and 100 mm wide, rimmed by a double O-ring seal. A smooth plate, considerably larger than the opening, presses against the O-rings from outside the vessel, but is otherwise free to slide in two dimensions parallel to the vessel surface; a gang of adjustable threaded rods holds the plate in place but allows its repositioning. Finally, the center of the plate is bored through and welded to a KF25 vacuum flange to which a gate valve and a probe housing can be attached. The probe housing allows the probes (items 1, 3, 6, and 8 in Figures 1 and 2) to be inserted and withdrawn from the vessel in the third dimension of positionability. The sliding

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plates are manipulated in the thin region between the vessel and the surrounding electromagnets, with only millimeters of clearance to the magnet bore at the limits of their range.

During a scientific campaign, probes remain stationary during the shot, which lasts about 1 ms. Then the probes are moved by hand to the next station in the transect, their new position is confirmed, and the shot is repeated. The distance between sequential probe positions is typically 3 mm.

An existing method to locate the probe tips is based on measuring the position of their air-side stalks. Then, knowing the length of the probes’ stalks, and judging them to be fairly straight, we infer the position of the probe tips by a simple cartesian translation. The probe stalk positions are directly indicated in each of three dimensions by reticles passing over scales affixed to the vessel. Thus, between shots, the operator translates each probe while watching the reticles to achieve the next desired position. We call this system using reticles the direct method for probe location, in contrast to the optical method that is the subject of this paper.

The experiment has already produced new and detailed results for flux ropes, plasma columns threaded with magnetic field. In experiments with a single flux rope, a radial profile of ion viscosity in agreement with Braginskii’s theory of collisions is developed from measurements of the axial velocity shear and the radial pressure balance (Dorf et al., 2010). When the kink is metastable, force densities are measured in three dimensions and a complementary image current is discovered near one end (Sears et al., 2014). Experiments of two colliding flux ropes display reconnection between the coalescing ropes, and the current sheet is observed to be thinner than the ion inertial length (Intrator et al., 2009). As the inflow of antiparallel field from the colliding flux ropes exceeds the Sweet-Parker threshold, magnetic pressure piles up outside the current sheet and reconnection stagnates. The flux ropes can also bounce (Sun et al., 2010).

Distributed measurements at many locations along the length of the pinch have also led to important observations. In experiments of the current-driven kink mode with one end of the column free to move, the stability threshold is below the classical Kruskal-Shafranov limit (Furno et al., 2006), but the kink amplitude quickly saturates and remains steady for long times (Furno et al., 2007). Plasma flow also lowers the instability threshold (Intrator et al., 2007). The periodicity of the gyration allows accurate and repeatable time alignment of many similar (but not identical) shots using conditional triggering (Labit et al., 2007); (Pécseli and Trulsen, 1989).

III. HARDWARE

Here we describe an optical method of assessing the probes’ positions. The tool consists of two cameras viewing the collection of probes through windows at the end of the vessel. Digital photographs are recorded after the probes have been repositioned for each shot. Then the location of each probe tip, identified separately in each photograph, is transformed to vessel coordinates. The technique locates probe tips to within 1.5 mm of their 3D position relative to the vessel and to within 0.7 mm relative to other probes.

Two cameras arranged at the end of the vessel form the core of the optical system, as shown in Figure 1. Each camera is a Logitech webcam model C615 with 1920 × 1080 resolution, retrofit with a 16 mm lens. In this combination, the field

![FIG. 1. Cross section of the vacuum vessel, viewed from above. A plasma column is formed between the gun (5) and the anode (2). Only the inner edges of the annular magnets are shown. Section A is detailed in Figure 2; the vessel at section B serves only to distance the end wall from the plasma, and has been truncated in this drawing. The components are (1) magnetic field probe, (2) anode, (3) magnetic field probe, (4) fiducial magnetic probe, (5) plasma gun, (6) triple plasma probe, (7) fiducial magnetic probe, (8) triple plasma probe, (9) left camera assembly, and (10) right camera assembly.](image-url)
of view is narrowed to 36° to dedicate more pixels to the objects of interest: the pixel resolution at a distance of 1730 mm from the camera, in the region of the probes, is 0.33 mm.

With the decorative shroud removed, the cameras consist of a single circuit board with all components including the sensor chip soldered in place. For this work the boards have been stripped of their autofocus servomechanisms to prevent the lens parameters from changing; instead, new, longer focal-length lenses are positioned in front of the sensors, and adjusted for focus, with miniature optical stages. Frames are recorded using the Logitech software on a PC with the cameras attached via USB. An aluminum bracket holds each camera circuit board, lens, and optical stage together as one assembly, as shown in Figure 3. This unit can then be alternately calibrated on a bench or fixed to the vacuum vessel without altering its focus.

The coordinate transformation from the object plane to the sensor is established by calibrating the camera assembly. We use a third party procedure (Strobl et al., 2014) that implements the Brown-Conrady model of lens distortion (Brown, 1966), discussed further below.

Once calibrated, the camera assemblies are attached to the vessel by way of threaded studs, using spherical washers for fine angle adjustment. Each camera views through a 3.375′′ conflat window. Next, the coordinate transformation from the vessel space to the camera sensor is established using our own iterative optimization algorithm. This is done by selecting three or more non-colinear points or fiducials, whose coordinates in the vessel are very accurately known (Figure 4(c)), and identifying them in an image recorded by the camera. Then the transformation operator (consisting of a rotation matrix and a translation vector) is the unique one that carries the fiducial coordinates to the corresponding pixels.

At this point the optical system is ready to begin a data campaign. Once the probes have been positioned before a shot, the vessel interior is illuminated and images are recorded from each camera, such as those in Figures 4(a) and 4(b). The computer cursor is used to manually select the pixels that represent the probe tips. Templates like Figure 5 are used to prescribe what should be considered the tip of the probe, to help with repeatability. Now the coordinate transformation from the vessel frame to the camera sensor is essentially inverted and applied to the probe tip pixels. The result is the three-dimensional location of the probe tip with respect to the vessel. There are two ways that this inversion can be carried out to restore depth information that is lost in the 2D record of a camera.

The first way is to use the concept of stereo vision to combine the information from both cameras. Each camera alone projects the pixel of interest along a ray in the vessel frame. The probe tip coordinate in the vessel frame is then simply the intersection (or point of minimum approach) of the two rays. While this is an elegant solution, the cameras have fairly small parallax and the two rays are nearly parallel, so small errors in each camera projection lead to errors ten times larger in the depth estimate.

The second way incorporates our knowledge of the probe depth (the z-axis depicted in Figure 1 or equivalently the length $d$ in Figure 6) obtained from the direct method (based on reticles) of locating probes. Here we constrain the z-coordinate and then find the x and y coordinates for each camera view independently. This gives a more accurate depth estimate due to the $10 \times$ factor inherent in the stereo concept, and it is necessary in locations where the plasma gun blocks one camera’s view of a probe tip.

It is clear that the optical method improves our knowledge of probe location only in the lateral direction (in the x-y plane). But the gradient scale length of RSX plasmas is also much shorter in the lateral direction than it is axially, so lateral resolution must be proportionally finer.
FIG. 4. Simultaneous camera images from (a) left and (b) right cameras; (c) a diagram of the components in the vessel as seen by the right camera, including an x-y plane at the depth of the probes to illustrate the axes used in the plots of this paper. The x-y plane is detailed in the inset to show scale, and the x axis increases to the left since the cameras view the vessel from behind. Fiducial points (starred) are distinct features with well-known locations that are used to calculate the transformation from vessel space to pixel space.

IV. SOFTWARE DESCRIPTION

Data processing tasks are divided among three software modules. The first module, available from (Strobl et al., 2014), computes the mapping of objects onto the 2D sensor, including distortions from the lens. The second module obtains the transformation that locates the camera within the vessel frame. The third module applies this transformation to the probe tips to calculate their positions. While the first module is available from a third party, we have developed the second and third modules specifically for this work.

The first module (Strobl et al., 2014) implements the Brown-Conrady model of lens distortion (Brown, 1966). It assesses the parameters of the lens by performing a least-squares fit on a number of images of a calibration target which is placed in various orientations relative to the camera. The calibration target consists of a checkerboard pattern of specific dimensions which the software is programmed to recognize and process automatically. The lens distortion model allows for astigmatism as well as radial and tangential distortion, and the coefficients represent the focal length in two axes; the principal point in two axes; the angle between the two axes; the radial distortion to sixth order; and the tangential distortions (those distortions that are not azimuthally symmetric) to second order.

The second software module is responsible for obtaining the transformation from camera frame to vessel frame. In the field of robot vision this is called the Perspective...
Three-Point Problem, and a handful of techniques exist for its solution (DeMenthon and Davis, 1992). The transformation is depicted as the rotation \( \hat{R} \) and the translation \( \hat{T} \) in Figure 6. The module needs to be run only once after the cameras have been installed, because thereafter the cameras are not moved nor are their focii adjusted. The module first requests the user to select (by way of the mouse cursor) the fiducial points in an image (i.e., the starred points in Figure 4(c)), and to enter their known coordinates in the vessel frame at the command line. Then the crux of the second module is to find the coordinates of the fiducial points in the camera frame. Working on sets of three fiducial points at a time, the geometric problem is reduced to an eighth-order polynomial in \( n \), the distance from the camera origin to one of the fiducial points. The polynomial is presented as Eq. (A1) in the Appendix. We solve Eq. (A1) with an iterative root-finding method, since the analytic solution, having large exponents, can be sensitive to errors from numerical precision. Once \( [\hat{r}_j] \) is obtained it is a matter of simple geometry to find the positions \( \hat{r}_j \) and \( \hat{r}_k \) of the other two fiducial points. Then we can define the linearly independent set \( \hat{U} = (\hat{l}_j, \hat{l}_j, \hat{l}_j \times \hat{l}_j) \) in the vessel frame, and similarly \( \hat{U}' = (\hat{l}_j, \hat{l}_j, \hat{l}_j \times \hat{l}_j) \) in the camera frame. Finally the rotation from camera frame to vessel frame can be written down as \( \hat{R} = \hat{U} \cdot \hat{U}^{-1} \), and the translation as \( \hat{T} = \hat{r}_i - \hat{r}_i \cdot \hat{R} \).

When more than three fiducial points are provided, we average the results from all permutations.

The third module applies the transformations \( \hat{R} \) and \( \hat{T} \) to probe tips in the camera images to obtain the probe tip positions in the vessel frame, namely, \( \hat{r}_n = \hat{r}_n \cdot \hat{R} + \hat{T} \). First it requests the user to select the tip of probe \( n \) in an image using the cursor. Since the camera image is two dimensional, the position \( \hat{r}_n \) of probe tip \( n \) is known only up to a scalar factor, \( \alpha_n \), such that \( \hat{r}_n = \alpha_n \hat{r}_n \). There are two ways to find the scalar, \( \alpha_n \). In the solution that does not rely on stereo principles, the depth \( d_n \) (z-coordinate in the vessel frame) is supplied from the direct method and the scalar multiple is \( \alpha_n = (d_n - \hat{z} \cdot \hat{T})/(\hat{z} \cdot \hat{r}_n \cdot \hat{R}) \). In the stereo method, images from the two cameras mutually constrain the depth, and the scalars \( \alpha_{n,1} \) and \( \alpha_{n,2} \) minimize the difference between the positions obtained from each camera, \( |\hat{r}_{n,1} - \hat{r}_{n,2}| \).

V. PERFORMANCE

We evaluate the performance of the optical method for three use cases: resolving the relative translation of a single probe from shot to shot; resolving the relative position of one probe with respect to another; and resolving the absolute position of a probe with respect to the vessel. We emphasize the non-stereo method since, in contrast to the stereo method, it works in the regions where the gun hides a probe from one of the cameras.

In the first case, resolving the relative translation of a single probe from shot to shot, the factors that contribute to uncertainty are the repeatability of identifying the probe tip in successive images, and any remaining distortion of the lens not compensated by the calibration. To measure these factors, the optical method was applied to a data campaign in which a triple probe was scanned over a 2D transect in a series of 521 shots covering an area in the x-y plane of roughly 60 mm × 100 mm. The repeatability of identifying the probe tip was evaluated by selecting the tip of a stationary probe in a series of images and finding the standard deviation of the resulting positions, which is 0.30 mm. The lens calibration error was estimated by submitting the camera to a number of calibrations (without adjusting its focus) and finding the standard deviation in the resulting positions for a stationary probe, arriving at 0.32 mm. These two factors are listed in Table II for comparison to the plasma scale length parameters listed in Table I. Since these are independent factors, their sum contribution (added in quadrature) is 0.44 mm. This and the remaining instrument performance values are listed in Table III.

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We can check this sum contribution by comparing the measurements of the left and the right cameras. In Figure 7 the probe positions as determined by the left camera for a sample subset of shots are plotted as filled circles, and using the right camera, as open circles. The relative error when translating a single probe from shot to shot is represented here by the standard deviation of \( b \), and is 0.4 mm, in agreement with the quadrature sum of the two independent factors. The error based on the stereo method is also 0.4 mm, as expected since it uses the same information.

In the second use case, resolving the relative position of one probe with respect to another, we must add to 0.44 mm the error of 0.5 mm introduced by constraining the z-coordinate of each probe based on measurements with the direct method. The quadrature sum, 0.7 mm, gives the accuracy to which multiple probes can be spatially registered. The stereo method does not use the constraint in the z-coordinate and so remains

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**Table I. Plasma parameters for comparison to instrument performance, calculated assuming \( n = 3 \times 10^9 \text{m}^{-3}, T_e = 3 \text{eV}, n_i = 3 \times 10^9 \text{m}^{-3}, T_i = 3 \text{eV}, B = 0.01 \text{T} \) and that the primary species is hydrogen.**

<table>
<thead>
<tr>
<th>Feature length [mm]</th>
<th>Plasma parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td>ion inertial length</td>
</tr>
<tr>
<td>30</td>
<td>density gradient scale length</td>
</tr>
<tr>
<td>18</td>
<td>ion gyroradius</td>
</tr>
<tr>
<td>2.7</td>
<td>electron mean free path</td>
</tr>
<tr>
<td>1.0</td>
<td>skin depth</td>
</tr>
<tr>
<td>0.4</td>
<td>electron gyroradius</td>
</tr>
</tbody>
</table>

---

**Table II. Parameters of the instrument and their associated uncertainties contributed to the position of a probe. Values have all been converted to their equivalent lengths in mm at the plane of the probes (the object plane). For example, pixel resolution is given as the distance between adjacent pixels mapped onto the object plane. Complete descriptions of each parameter are given in the text.**

<table>
<thead>
<tr>
<th>Uncertainty [mm]</th>
<th>Instrument parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>lens distortion</td>
</tr>
<tr>
<td>1.1</td>
<td>error from fiducial points</td>
</tr>
<tr>
<td>0.5</td>
<td>depth assumption</td>
</tr>
<tr>
<td>0.32</td>
<td>lens calibration error</td>
</tr>
<tr>
<td>0.30</td>
<td>pixel resolution at 1.73 m</td>
</tr>
<tr>
<td>0.30</td>
<td>manual point identification</td>
</tr>
</tbody>
</table>
TABLE III. Lateral and axial resolution of the various probe locating methods. The effective resolution of the optical system is the relative optical performance, 0.4 mm, which holds as long as a camera is not adjusted. If the camera must be adjusted during a campaign, then the resolution increases to the absolute optical performance, 1.5 mm. Descriptions of each performance metric are given in the text.

<table>
<thead>
<tr>
<th>Instrument resolution [mm]</th>
<th>Direct</th>
<th>Non-stereo</th>
<th>Stereo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral single probe, relative</td>
<td>0.9$^a$</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Lateral multi probe, relative</td>
<td>10</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Lateral absolute</td>
<td>10</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Axial absolute</td>
<td>10</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

$^a$The value listed for the uncertainty in relative position of a single probe using the direct method applies to linear translations. For rotations, such as with Mach and magnetic probes, the uncertainty increases to 3 mm. It is larger than the linear measure because any bend in the probe stalk displaces the probe tip away from the axis of rotation.

at 0.4 mm. This is the relevant metric when it comes to comparing the terms of the momentum balance.

Finally, for the third case, the resolution in absolute position is represented by the mean of $b$ in Figure 7, an average measure of how well two independent cameras agree on the absolute position of a probe. For the non-stereo method it is 1.5 mm. Using the stereo method, which does not couple the error in depth assumption to the lateral position, the uncertainty is 1.4 mm.

Figure 7 also shows the position measurements using the direct method, plotted as diamonds. The difference between these points and the average of the camera-based measurements, $a$, is taken to be the accuracy of the direct method with respect to the vessel, roughly 10 mm. The standard deviation among locations of $a$ roughly gives the relative single-probe accuracy of the direct method. It is 0.9 mm when a probe is moved linearly, and 3.0 mm when a probe is rotated.

All quantities that contribute to resolution are listed in Table II for comparison to the relevant physical length scales of the plasma. They are typical values, obtained by averaging over all four probes and over several trials of lens calibration and fiducial point selection, and have all been converted to their equivalent lengths in mm at the plane of the probes (the object plane). For example, pixel resolution is given as the distance between adjacent pixels mapped onto the object plane. Each row in the system performance Table II is described below:

- **Lens distortion** is the change in probe positions when the distortion parameters of the lens are set to zero.
- **Error from fiducial points** is the deviation of probe positions when the set of fiducial points is varied.
- **Depth assumption** is the error contributed by the uncertainty in the $z$-coordinate of the probe when applied to the non-stereo optical method.
- **Lens calibration error** is the standard deviation in a probe’s position when the set of lens calibration photographs is varied.
- **Pixel resolution** is the distance between pixels mapped onto the object plane.
- **Manual point identification** refers to the precision of marking a probe tip with the cursor, measured as the standard deviation over many attempts on a probe tip that was not moved.

Further descriptions of the instrument performance values listed in Table III are given below:

- **Lateral single probe, relative** is the uncertainty in the displacement of a single probe as it is moved from shot to shot.
- **Lateral multi probe, relative** is the resolution in the distance between two probes.
- **Lateral absolute** is the resolution in the position of a probe with respect to the vacuum vessel.
- **Axial absolute** is the resolution in the $z$-coordinate. For the stereo version of the optical method we see that it is larger than for the direct method.

In summary we see that the relative accuracy of the optical method (0.4 mm) is smaller than the skin depth (1.0 mm) for some plasmas of interest, so in theory it should resolve the dynamics of the electron fluid. The accuracy when comparing the relative position of multiple probes is 0.7 mm, still adequately small compared to all length scales of the plasma. Finally, we see that the absolute error of the direct method can be large (10 mm), which is a concern when we overlay data from multiple probes, or reposition a probe at the end of a campaign to repeat several shots. The optical method will be a good improvement in these situations, having an absolute error of only 1.5 mm.

The direct method allows nearly as much precision as the optical method when moving a probe from one station to the next in its transect, resolving translations as large as 10 cm to an accuracy of 0.9 mm. When compositing data from thousands of probe locations, however, the optical system offers several advantages. First, its relative accuracy of at least

![FIG. 7. Comparison of probe position measurements. This plot in the x-y plane at the z coordinate of the horizontal triple plasma probe shows four nominal positions of the probe tip as measured using the direct method (diamonds); the positions as obtained by the optical method with the left camera (filled circles); and obtained using the right camera (open circles). The accuracy of the direct method is estimated as the mean value of $a$. The accuracy of the optical method with respect to the vessel is taken as the mean of $b$, and relative to other probes, as the standard deviation of $b$. Means and standard deviations are calculated over all probe positions, all calibration trials, and all permutations of fiducial points. Plotted here is only a representative sample of the probe tip positions, for visual clarity.](ps)
0.7 mm applies not only to sequential translations of a single probe but to the relative distance between all probes over all shots. This means that data from probes of several types, each operating from a different port and scanning the same volume in turn, can be spatially registered to within 0.7 mm. Second, the optical system is mechanically simpler than the direct method; its few moving parts (the optical stages) are locked down after installation; it is not physically connected to the probes so it is not affected by their temporary removal for repair; it has no components inside the vessel nor any vacuum seals; and it makes no assumptions about the lengths or straightness of probe stalks. Third, the optical system decreases the shot cycle. Probes need not be positioned so carefully, and the digital images can be analyzed from the safety of a desk, in parallel with the capacitor energization for the next shot. Finally, it creates a digital timestamped record of probe positions that can be compared against the logbook.

This is a unique approach to locating probe tips in plasma experiments. Contrasting strategies have been adopted in other plasma machines. In the Large Plasma Device, for example, an in-vacuum ceramic motor is used to precisely position a magnetic field probe to 100 μm accuracy (Collette and Gekelman, 2008) in a 6 cm × 6 cm sampling area. An earlier system on LaPD, which is 12 m long, had external motors but internal gear drives that could deliver a probe to any location in the vessel (Pfister et al., 1991). A more recent positioning device on LaPD was based on rotation of a ball joint, which then requires an angular scale in two coordinates to locate the probe (Leneman and Gekelman, 2001). In the present system described here, by dropping the requirement that probes be precisely positioned (but merely that their location be precisely known), we relax the requirements for precision on the components that position the probes. This makes for a simple and robust probe positioning system.

VI. APPLICATION OF THE OPTICAL METHOD

Figure 8 shows data from a triple probe and a magnetic field probe that have been scanned over the same x-y plane. Here we plot quantities related to the radial pressure balance: contours of the pressure gradient, and the centroid of the axial current density. The pressure is obtained from the triple probe as a product of electron density and electron temperature (for this analysis we assume \( T_e = T_i \)), and the current density is obtained from the magnetic field. If there are anisotropic pressure components, out-of-plane curvatures or electric fields that play a role in the momentum equation, we might expect a finite misalignment between the plasma pressure and the magnetic surfaces, reminiscent of the Shafranov shift in tokamaks. Therefore we must not rely on concentricity of quantities to judge whether two probes are mutually registered.

In Figure 8(a), pressure gradient contours and the current density centroid are plotted using the probe positions from the direct method. The centroid of the current density falls roughly 10 mm away from the apparent peak in pressure. In Figure 8(b), probe positions from the optical method are used, and the centroid of the current density falls a couple of millimeters away from the pressure peak. Further analysis will show whether the remaining misalignment is significant, but it is clear that the correction from the optical method of probe location is important.

VII. CONCLUSION

We have found that an optical approach to probe location with inexpensive hardware can resolve probe positions relative to other probes to 0.7 mm, and to 1.5 mm with respect to the vacuum vessel. Using this tool, we have shown that the direct method of locating the probes, in which their motion
is measured using scales attached to the outside of the vessel, also provides accurate positions to within 0.9 mm when a single probe is scanned, but that the error from one probe to another, and to the vessel, can be as great as 10 mm. The correction due to the optical method is significant when aligning quantities measured by multiple probes. Installing the optical system, which is entirely outside the vessel, did not require breaking vacuum.

The limiting factor on resolution is now the reproducibility of plasmas from shot to shot. But the precise location of probes provided by the optical system should allow us to investigate shot-to-shot variability and turbulence with cross-correlation techniques.

The peaks in current density and plasma pressure, acquired by separate probes, are found to coincide within error bars when this system is used to locate the probe tips. This makes possible an investigation of the momentum balance that supports the metastable kink, with further analysis presented in (Sears et al., 2014) and reserved for a later paper.

The optical system could be improved by inscribing precise and visually contrasting fiducial marks in the vessel and on the probe tips. This would make automated image processing (i.e., computer vision) easier to implement. The parallax could be greatly increased by installing a third camera on a side port much nearer to the probes, with the new difficulty then being the operation of the camera in regions of high electric and magnetic fields.

In summary, this stereo camera method is a general and easily implemented technique that addresses the difficulty in measuring the exact locations of insertable probes inside a vacuum vessel. It significantly improves the mutual spatial registration of measurements from separate probes, as when computing the terms of the momentum balance. The method obviates complications from vessel geometry and is mechanically simple.

ACKNOWLEDGMENTS


APPENDIX: CALCULATING THE DISTANCE, $r_p$ TO A FIDUCIAL POINT

One root of the polynomial (A1) below gives the distance from the camera frame origin to the $i$th fiducial point. Typically it is easy to identify the physically meaningful root and discard the others. The coefficients of the polynomial are:

$$a_2 = 64L_kL_j(c_i c_j - c_i)^2 + 16c_i^2 M^2 (c_j - 1)(c_i^2 - 1) + 64c_i M(c_i c_j - c_i)(L_k(c_j - 1) + L_j(c_i^2 - 1)) - N^2 - 2Q(M^2 + 4c_i^2 L_k L_j),$$

$$a_1 = 64c_i M L_k L_j(c_i c_j - c_i) + 16c_i^2 M^2 (L_k(c_j - 1) + L_j(c_i^2 - 1)) - 2N(M^2 + 4c_i^2 l + k^2 L_j),$$

$$a_0 = 16L_k L_j c_i^2 M^2 (M^2 + 4c_i^2 L_k L_j)^2,$$

where variables $\Theta$ and $l$ are defined in Figure 6 and,

$$c_i = \cos(\Theta_i),$$

$$c_j = \cos(\Theta_j),$$

$$c_k = \cos(\Theta_k),$$

$$L_i = |\bar{l}_i|^2,$$

$$L_j = |\bar{l}_j|^2,$$

$$L_k = |\bar{l}_k|^2,$$

$$M = L_j + L_k - L_i,$$

$$N = 4(L_i(c_i c_j c_k - c_j^2 - c_k^2 + 1) + L_j(c_i c_j c_k + c_j^2 - c_i^2 - 1) + L_k(c_i c_j c_k + c_i^2 - c_j^2 - 1)), $$

$$Q = 4(1 + c_i^2 - c_j^2 - c_k^2 + 2c_i^2 c_k^2 - 2c_i c_j c_k).$$

so that finally the polynomial to solve is,

$$a_4|\bar{r}_i|^8 + a_3|\bar{r}_i|^6 + a_2|\bar{r}_i|^4 + a_1|\bar{r}_i|^2 + a_0 = 0. \quad (A1)$$


Strobl, K. H., Sepp, W., Fuchs, S., Paredes, C., Smisek, M., and Arbter, K., DLR CalDe and DLR CalLab (2014), see http://www.robotoe.dlr.de/callab/.