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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT.
To supplement existing metrology techniques EFDA-JET has been investigating non-contact surface scanning of plasma facing components during shutdown periods. Research has been focusing on commercially available technologies capable of remote handling, assessing their abilities against common artefacts with features and surface representative of new first wall protection tiles.

1. INTRODUCTION

In the engineering field traditional feature based dimensional inspection tools are fast becoming supplemented by non-contact target-less measurement using clouds of points. New point cloud measurement devices can collect hundreds of thousands of points per second and allow detailed inspection of complex surfaces. The improvements in technology and the increased complexity of EFDA-JET plasma-facing surfaces for the ITER-Like wall project created a renewed interest in investigating the capabilities of commercially available non-contact surface measurement technologies for remote in-vessel measurement during shutdown periods.

Current inspection techniques verify the dimensional accuracy of components at the manufacturer and then during assembly on site, final installation in vessel is confirmed by photogrammetry which is a well established technology using a metric camera and retro-reflective targets. Once installed in-vessel the surface of components can be inspected visually by means of high resolution imagery and where damage is suspected, removed for physical inspection. It is the in-vessel non-contact measurement of surfaces during shutdown periods which is being investigated, during this time the machine will be at ambient temperature and pressure with no active magnetic fields.

The measurement surfaces on which we focus are the limiter protection tiles which would be susceptible to damage during an off-normal event. The tile assemblies are made of a series of tile blocks to reduce electromagnetic forces and each is castellated (~12×12mm) to allow for thermal expansion. In order to prevent exposed edges each block shadows the next through an angled surface which protects the adjacent block from damage. The protection tile surface is beryllium, due to its toxicity these tiles are not suitable for use as measurement objects therefore measurement artefacts have been created which simulate the surface finish and features present on the protective tiles, it is these we will use to evaluate the measurement systems.

2. BACKGROUND

The concept of an In-Vessel Viewing System (IVVS) for EFDA-JET has been studied before by the Italian National Agency for New Technologies, Energy and Environment (ENEA). The proposal was for a probe to be inserted vertically into the machine while at vacuum carrying a laser along optical fiber, the probe would rotate axially whilst a moving prism at the end reflected the laser beam to the surface. Range measurements would be performed by calculating the phase difference of amplitude modulated laser and would simultaneously collect intensity measurements of the returned laser for visualization purposes [1]. The IVVS system proposed for EFDA-JET was not commissioned but the principle has been taken forward to the ITER device. Other institutions involved in IVVS research were the Oak Ridge National Laboratory in USA who proposed the use of a frequency modulated laser for ITER also inserted into the tokamak during periods of high gamma radiation, high vacuum, elevated temperature and magnetic field [2]. This principle was demonstrated at the TFTR and NSTX fusion devices by Menon et al. [3, 4]. A Finnish consortium under the Finnish Fusion Energy Research Programme (FFUSION) developed a prototype of a viewing system conceived at JET using linear arrays of optical fibers to deliver images to remote CCD sensors [5]. The systems mentioned are not designed to operate during fusion experiments when plasma is present but the levels of residual radiation to be found in the ITER device will still be above those found in the EFDA-JET machine.

The systems discussed broadly meet the requirements laid out by a 2001 report into viewing and inspection in tokamak machines [6], being designed for a very challenging environment, operating at vacuum and elevated temperature amongst other factors. This research is not investigating operating in such an environment, instead investigating the performance of technologies for measurement during a shutdown period in which the machine would be returned to ambient temperate and pressure with no active magnetic fields. In this environment the entry of remote handling equipment would be possible and therefore this research is not limited to custom equipment entering the vessel through a small port, instead we are able to investigate commercially available systems which could be delivered into the vessel by remote handling. The dimensions of the EFDA-JET vessel and the new plasma facing surface set it apart from other fusion devices but the authors would be interested in discussing the approach of other fusion institutions to dimensional metrology of in vessel components. Recent work at EFDA-JET has developed a remotely operated stereo-photogrammetry setup to supplement existing target based photogrammetry by providing high quality images which can be used for feature based measurement i.e. corners. The technology currently requires manual selection of features for measurement but is still undergoing development. Several fusion machines including ASDEX Upgrade, W7X and MAST are using coordinate measurement arms which consist of a series of thermally stable bars connected by angle encoders to measure components both inside and outside the vessel. These manual arms feature touch probes and triangulation laser scanners to perform measurements but offer a limited working volume due to uncertainty increasing as arm length increases. Operating current manual coordinate measurement arms requires a level of dexterity not currently seen in remote handling equipment.

Some research has already been performed into the performance and capabilities of non-contact measurement equipment with applicability to EFDA-JET [7] focusing on early information about the EFDA-JET ITER-Like wall limiter tiles. This work indicated the need for measurement test artefacts which closely simulated the surface finish and features of the measurement surface and also measurements in a volume representative of the actual measurement volume. Recent work has involved testing new technologies for their suitability against a previously used test artefact, some newly developed pieces and a trial in a volume representative of the EFDA-JET vessel.

3. FURTHER TESTING

We selected the equipment most suitable for measuring the given volume which performed the best in previous tests. This was a hand-held laser scanner using the principle of laser triangulation. The scanner unit has a laser source and optical sensor mounted with fixed distance and angle between them. The source projects a moving laser spot or laser line onto the surface which is captured by the sensor; the deviation of the line on the sensor provides three dimensional surface data as the distance and angle between source and sensor is known. This hand held unit captures a single line of data at a time and must be moved over the surface to capture the complete scene maintaining a mean stand-off distance of 85mm ±20mm. To position the collected data in a single coordinate system the scanner is tracked by an external unit, in previous tests a linear array of cameras was used which tracked the hand held scanner by photogrammetry. Previous work showed a small number of scan lines fitted incorrectly Fig.1 against the majority of data which has been attributed to infrared LED photogrammetry targets on the scanner being occluded by the user; to minimize the possibility of this happening for these tests we replaced the photogrammetry bar with an alternative tracking solution, a laser tracker. A laser tracker is a polar measurement device which measures distance using an interferometer along with the horizontal and vertical angle at which the laser beam was transmitted and received. The complete six degrees of freedom of the hand held laser triangulation scanner must be known so the laser tracker is supplemented by an infrared camera mounted to the top which ‘sees’ IR LEDs on the scanner, this combination provides a spherical range of up to 30m diameter with only two conical lines of sight required to the target in comparison with the three required for the photogrammetry solution.

The other equipment involved in the trial is an amplitude modulated laser scanner similar to those suggested for an IVVS solution which creates a hemi-spherical cloud of data points from a single location. Range data is collected by analyzing the phase shift of a received signal against a reference wave and intensity data simultaneously collected for visualization purposes. Data collected from multiple locations can be registered by common geometric features in the collected data.

Measurement of a section of the In Vessel Test Facility (IVTF) at EFDA-JET Fig .2 was performed using the phase based measurement device and a section of the resultant point cloud shown Fig.3. The data was collected from a single position and because of this there are occlusions in the data where objects were not visible to the scanner though high surface curvature or another in-vessel component being along the same line of sight as the occluded object but closer to the scanner. An example of this effect can be seen behind the lamp circled in the images (position is different in the scan and photograph) and pipes in the scan. This effect can be minimized by multiple scanner locations but the higher the level of radial change in surface, the more scanner locations will be required and uncertainty is introduced as data from multiple viewpoints must be combined into the same coordinate system in a process known as registration.

A problem affecting laser scanning systems is the partial reflectance of the beam from two or more surfaces which creates phantom points along the line of sight of the beam Fig .4. For phase measurement systems the errors are caused by a portion of the signal returned with one phase angle and another portion returned with a different phase due to the extra distance it has travelled to be returned by another surface. The mean of the calculated distance produces a point on neither surface. These points can be removed through software processing where the error is large but where the distance between the surfaces is smaller the result is smoothing and lack of definition on sharp edges. These effects are minimized where the laser spot has a smaller diameter but the laser cannot remain focused to its smallest diameter throughout the operating range.

A test artefact from previous work was present in the IVTF and highlighted a significant problem for metallic surfaces with internal corners Fig.5; a 90^{o} corner was imaged as a curve intersecting the true corner point. The deviation of these areas to nominal CAD when their effect was removed from the registration process was greater than 2mm. To ensure this effect was not an error with the measurement device, environment or test artefact a similar trial was held using new artefacts and equipment from an alternative manufacturer at the United Kingdom National Physical Laboratory in a highly controlled environment, the same effect was seen.

These tests have highlighted the need for a series of test artefacts with known geometry traceable to a national length standard with which to assess non-contact metrology technology. The National Physical Laboratories [8] and National Research Council of Canada [9] amongst other national measurement centers have been working to develop artefacts for free-form surface measurement. This project has been developing similar artefacts targeted towards the needs of the fusion community, the need to assess and qualify equipment performance before use is particularly important as access to equipment may be restricted after use in vessel. This area is discussed in Ongoing Work
The laser tracked hand held laser scanner was not trialed in the IVTF but the same measurement artefact was used and several interesting effects noted, the most relevant of these being the smoothing of edges Fig.6. As the EFDA-JET ITER-Like wall protective tiles feature a large number of such features. The complexity of diagnosing the exact cause of this error is that the scanner can capture the part from multiple positions and it is therefore likely the smoothing is caused by more than one of the errors identified by Curless & Levoy [10].

A second problem which affects the hand held laser scanners is the ability to measure highly reflective surfaces without overexposing their sensor. When the sensor becomes overexposed the position of the laser spot centre on the sensor cannot be correctly determined, resulting in no data being collected, or it is created in the wrong position. During testing stainless steel spheres were scanned using the hand held triangulation laser scanner and a series of phantom data points were collected in lines away from the sphere. It should be noted that the system was able to scan the majority of the sphere without problem, being able to do this by using a feedback loop from the sensor which altered the intensity of the laser dependent on the intensity detected by the sensor. Many other non contact measurement technologies would require highly reflective surfaces such as these to be coated before scanning to prevent specular reflection. The phase-based technologies also suffer from this problem where a large percentage of the beam is reflected away from the unit minimizing the return to the sensor affecting the range measurement, also affecting the intensity measurement and therefore the visualization. The measurement of very dark surfaces caused problems for both phase-based and hand held laser scanners as the reflectance from the surface is very low, in this situation the laser power can by dynamically increased as occurs in the hand held laser scanners. For phase-based systems if the sensor does not receive a sufficient level of reflected laser power no point will be created, alternatively the range may be incorrectly estimated. Both measurement technologies may incorrectly measure range when crossing from an area of high reflectance to an area of low reflectance and vice-versa [10].

CONCLUSIONS

Based on the work performed so far we will make some general observations about the suitability of the two technologies tested. The first observation is that phase-based laser scanners are ideal for non-contact measurement of large areas without sharp curvature or small features. The rationale for this is their ability to cover large areas and ranges quickly collecting last numbers of points, in the order of >100,000 points per second. For measurement of the EFDA-JET ITER-Like wall tiles the diameter of the laser beam does not allow for detection of small features in the sub millimeter level, if this can be reduced improvements in the minimum resolvable size could be achieved

Hand held triangulation laser scanners have shown themselves very useful where significant detail of an object is required as they are capable of reaching most surface areas of objects being measured, this ability has a price however in terms of scanning time. Where a phase-based scanner was capable of collecting data across an area of the in vessel test facility in a matter of minutes a hand held laser scanner would likely require hours to cover the same area. With relation to the ITER-Like wall tiles on which this work is focusing the phase-based laser scanner could quickly confirm the presence of a tile assembly and its position in the vessel but would be unable to provide a detailed image of the surface to assess damage, for this a triangulation scanner could be appropriate.

ONGOING WORK

To provide a more quantitative assessment of the performance of measurement systems a series of new test artefacts have been manufactured which simulate the finish and features of an ITER-Like wall limiter tile assembly along with pieces to determine acceptable working angles to assist remote handling. The pieces are being measured by the National Physical Laboratory (NPL) who are the UKs National Measurement Institute and can provide traceable measurement of the dimensions of the pieces produced. These traceable measurements provide our best knowledge about the actual dimensions of the pieces and allow data from various measurement systems to be compared to this as-built data. A series of state of the art technologies have measured the artefacts in controlled conditions at NPL and will allow direct comparison of measurement technologies; these technologies include the principles covered in this paper along with white-light projection. The parts will be mounted to a frame with volume representative of a vacuum vessel octant to ensure results are scalable to that of a complete machine.

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Figure 1: Fitting of scan lines to a sphere.

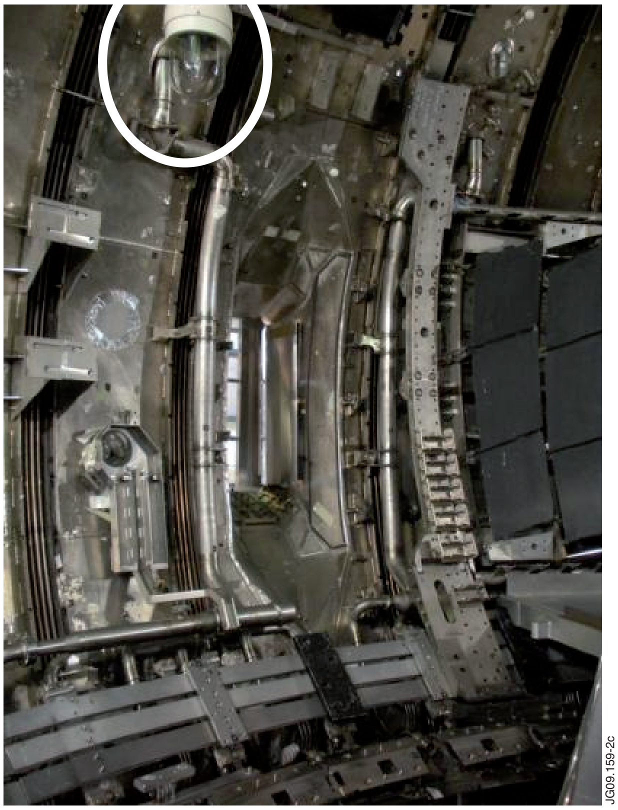

Figure 2: Inside of the IVTF at EFDA-JET.

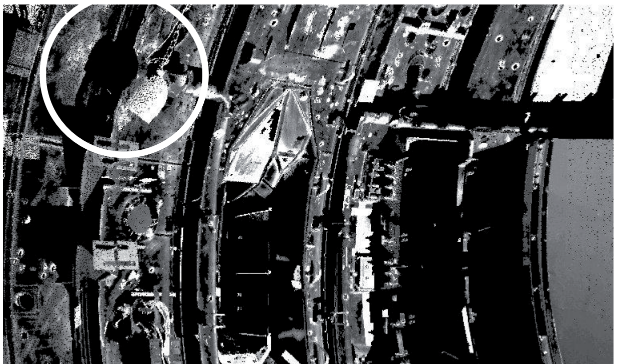

Figure 3: Intensity image of data collected by phase-based laser scanner.

Figure 4: Partial beam reflection off a corner.

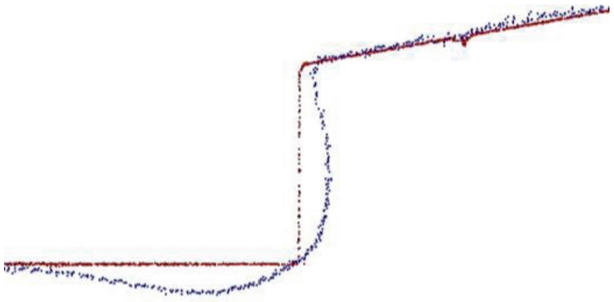

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Figure 5: Corner imaged as a curve.

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Figure 6: Smoothing of sharp edges.