Fast 2-D camera control, data acquisition, and database techniques for edge studies on NSTX

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Abstract

Fast 2-D cameras examine a variety of important aspects of the plasma edge and in-vessel components on the National Spherical Torus Experiment (NSTX). Four Phantom and two Miro visible-light cameras manufactured by Vision Research are used on NSTX for edge studies. Each camera can take several gigabytes (GBs) of data during each plasma pulse. Timely access to this amount of data can itself be a challenge, but analysing all this data using manual frame-by-frame examination is not practical. This paper describes image analysis, database techniques, and visualization methods used to organize the fast camera data and to facilitate physics insights from it. An example is presented of analysing and characterizing the size, movement and dynamics of coherent plasma structures (typically referred to as "blobs") near the plasma edge. Software tools that generate statistics of blob speed, shape, amplitude, size, and orientation are described. The characteristics of emitted blobs affect plasma confinement and heat loads on plasma facing components, and are thus of particular interest to future machines like ITER.

Keywords: Fast Cameras, NSTX, Blobs

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1. Introduction

The National Spherical Torus Experiment (NSTX) [1] is a medium-sized, magnetically-confined, fusion experiment (plasma major radius up to 85 cm, minor radius up to 68 cm) at the Princeton Plasma Physics Laboratory (PPPL). NSTX is undergoing an upgrade, to be completed in 2014, which will double the toroidal magnetic field, the plasma current, and the neutral beam heating power and increase the pulse length from 1 second to 5 seconds. NSTX is particularly well suited to studying plasma edge turbulence and plasma facing component (PFC) conditions due in large part to the open geometry of NSTX which allows good diagnostic access. Fast 2-D cameras play important roles in these studies on NSTX.

2. Overview of fast 2-D cameras used for edge studies on NSTX

Camera type	Typical MB/shot	Max MB/shot	GigaPix /sec	Max Resol.	Max Rate (KHz)	Max Rate Resol.	Bits
Phantom 7.3 (2@)	350	3500	3.0	800x600	500	32x8	14
Phantom 710 (2@)	350	3500	7.0	1280x800	680	128x32	12
Miro 4	350	3500	0.6	800x600	111	32x16	10
Miro 2 (color)	50	2000	0.3	640x480	105	32x16	10

Table 1. Characteristics of fast 2-D camera data for NSTX edge studies.

Fast 2-D cameras (see Table 1) are used to study a variety of different phenomena inside the vacuum vessel of NSTX, including plasma-wall interactions, impurity production and transport, divertor performance, etc. A Phantom 710 and a Phantom 7.3 [4] are used for looking down on the Liquid Lithium Divertor and custom software was written to visualize non-axisymmetric strike points in the divertor region [5]. The Miro 2 is a color camera and is used with a wide-angle view to see most of the vessel interior. A second Phantom 7.3 camera was moved around for various views, e.g. at the Beam Emission Spectroscopy (BES) optics and the RF antenna, and a second Phantom 710 is used in the Gas Puff Imaging (GPI) system [6]. The Miro 4 also gets moved around for various applications. A color Miro camera can be used as a good indicator of the dominant line emission at the edge, e.g. green for lithium. 3D particle trajectories of macroscopic incandescent dust particles have been obtained for NSTX plasmas by using two Phantom cameras with overlapping fields of view [5,6]. Precursors to type III Edge Localized Modes (ELMs) have been seen in NSTX by using Phantom and Miro cameras to observe increases in primary filaments globally and relative fluctuation levels at the plasma edge [9].

Setup parameters and summary waveforms for the fast cameras are kept in MDSplus [8-10], but the raw camera data is not (though may be in the future). Some fast cameras have a filter wheel in front of them which is controlled by a Visual Basic program. Users specify trigger times, frame rates, and resolution, as well as configuration comments, using IDL [13] widgets, which write into MDSplus. Just before the plasma pulse, this information is read from MDSplus and the hardware configured. The “Cine” files native to Phantom cameras are first stored on a file server connected directly to the camera PCs, and copied overnight to a compressible ZFS [2] storage array on our Storage Area Network (SAN) [3]. One advantage of making the raw Cine files widely accessible is their use in the Phantom Cine Viewer from the camera vendor, Vision Research [4]. IDL, C and C# code are also available for random-access reading of frames in the Cine files. Reading frames directly from the Cine files is 2-3 times faster than reading the data from MDSplus segmented records.

3. Image analysis software

One challenge with thousands of frames of data over hundreds of potentially interesting shots is to be able to quickly narrow in on possibly important features or patterns. GPIthumbnails.pro, an IDL program, creates web pages of a series of shots with thumbnails of Gas Puff Imaging (GPI) images from 7 times throughout the gas puffing period, along with a summary plot of plasma parameters vs. time (plasma current, D-alpha light, injected power by type, and stored energy). This allows a user to browse easily through many shots, even though the resolution is so coarse, interesting features can easily be missed. Once a likely shot and time range have been identified, the user may wish to get thumbnails at smaller time intervals, using FCthumbnails.html, as shown in Fig. 1.

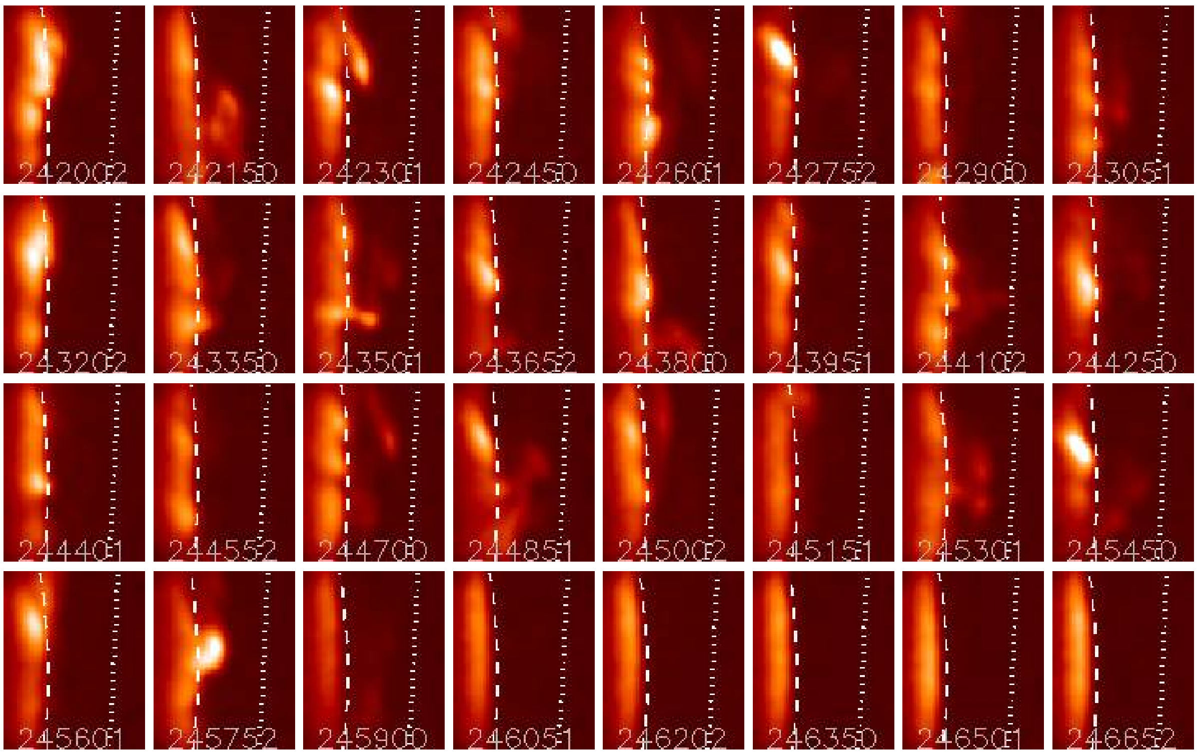

Fig. 1. Example output from FCthumbnails.html, used for browsing through raw camera data at specified intervals. The shot time in microseconds is listed. The separatrix (dashed lines) and limiter shadows (dotted lines) are indicated. Such output can be used to find interesting features, such as the L-H transition indicated by the suddenly stable edge at 245900 µs.

Next, the user can play through the Cine file data with VCR-like software, FCplayer.pro, which has many image enhancement and output capabilities. For example, it can create an AVI movie from 2 Cine files, synchronized in time.

A large number of features in camera data, like blobs (see next section), can be handled well with database software. The IDL program LoadBlobs.pro identifies blobs in individual frames, then computes velocities between frames, and then loads a database with the results. Other plasma characteristics, like heating type, amount of lithium deposition, and separatrix location, can be added to the database, as well, or joins can be made with other databases. A typical shot on NSTX will have thousands of blobs identified within the camera viewport for a 10 ms period. General database tools, or customized ones, such as the IDL program DbAccess.pro [14], can be used to set constraints and explore relationships among parameters and between different types of shots.

4. Example: Blob Tracking

Turbulence at the plasma edge affects plasma confinement and heat loads on plasma facing components, the understanding of which is critical for designing future tokamaks. The complex, highly-varying nature of turbulent structures in plasmas, such as blob filaments (sometimes simply known as blobs), make their characterization and correlation with other plasma properties challenging [15]. Examples in this section illustrate automatic analysis and database techniques to facilitate looking for patterns and correlations.

For the Gas Puff Imaging system [6] a lens and fiber bundle were oriented on NSTX so a Phantom 710 fast camera could look approximately along the field lines near the outer midplane. These Gas Puff Images were recorded at 391,000 frames per second, with an exposure time of ~2.1 μs/frame. The intensity of light from the puffed Helium emission is a function of the temperature and density of the plasma. The cases presented below were from fairly stable times in the shots, and did not have events such as L-H transitions, ELMs, and variations in heating. The structure of the turbulence was analyzed by first normalizing (i.e. dividing) each 64x80 pixel frame by an average frame, created from 1-5 ms (400-2000 frames) around the frame's time, and then smoothing the results for each frame over 3x3 pixels in space (~1 square cm) to reduce the random noise level. Resulting images were then contoured at 1% intervals, and the closed contours which fit certain size constraints (< 30 pixels, or 10 cm) were considered to be blobs. The contour midway between the lowest level contours (dashed lines in Fig. 2) and the peak was fit with an ellipse (solid lines in Fig. 2).

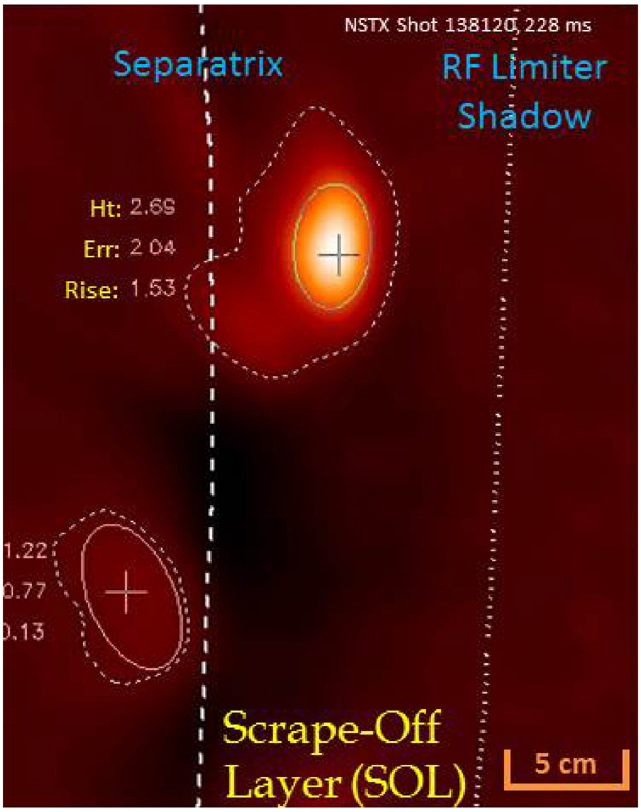

Fig. 2. An example of a analyzed blobs from a false-color image from the GPI camera. The separatrix position, taken from EFIT equilibrium reconstructions, is shown by a dashed line

and the limiter shadow is shown by a dotted line. The solid ellipses indicate a fit to a contour line midway between the base and top of the blob region.

The ellipticity, size, tilt angle, amplitude and location of the peak of these blobs were recorded for each frame. The blobs were then tracked from frame-to-frame to obtain their speeds in 2D vs. time. A blob was tracked from one frame to the next if its area did not change by more than 20 cm^2, and if its peak location did not change by more than 3 cm, which corresponds to a maximum speed of 12 km/sec. The blob speeds and lifetimes were added to the data set, which was then recorded in an SQL database.

Once in the database, blob speed, tilt and ellipticity for many blobs can be examined in relation to the separatrix, as with BlobTrails.html, e.g., as shown in Fig. 3. This lets the user notice turbulence flow patterns and shear more easily than by stepping through the images a frame at a time.

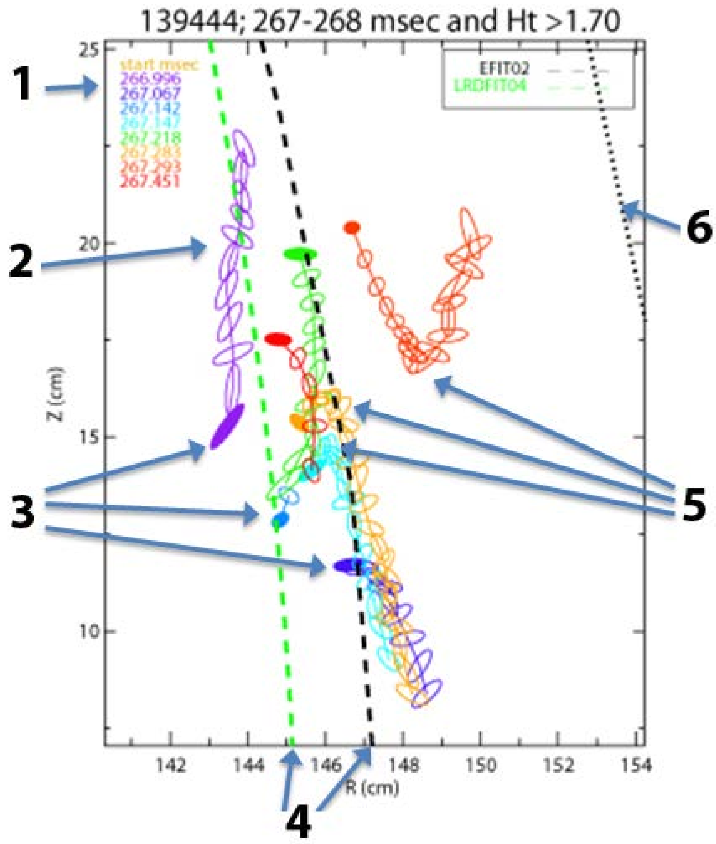

Fig. 3. Output from BlobTrails.html showing blob history for 1 ms on NSTX shot 139444. Indicated are 1) the starting times of the blobs tracked, 2) the tilt and elongation from fitting an ellipse (relative size can be shown, but is not in this example), 3) the starting location of blob trails are indicated by a filled ellipses, 4) the location of the separatrix predicted by LRDfit (green), and EFIT (black), 5) sheared flow indicated by changes in direction, and 6) the location of the limiter shadow. “Ht > 1.70” means that only blobs with a normalized intensity 70% higher than the average are shown.

When velocity distributions are compared for a series of shots that systematically varied the amount of lithium deposited [16] e.g., differences in blob frequency and poloidal motion are evident. In a 3 ms window on a shot with 314 mg. of lithium injected (141324) only a few blobs were ejected through the separatrix, while one with 151 mg of lithium (shot 141322), had 15 ejected, and one with 22 mg. of lithium (shot 141397) had 20 ejected.

Output from DbAccess in Fig. 4 shows the poloidal speed of larger and smaller blobs as a function of their distance from the separatrix. The poloidal speed of smaller blobs looks pretty random, but larger blobs show evidence of shear as they mostly move upward inside the separatrix, downward a few centimeters around the separatrix, more upward from 2-4 cm outside, and then somewhat downward again, on average.

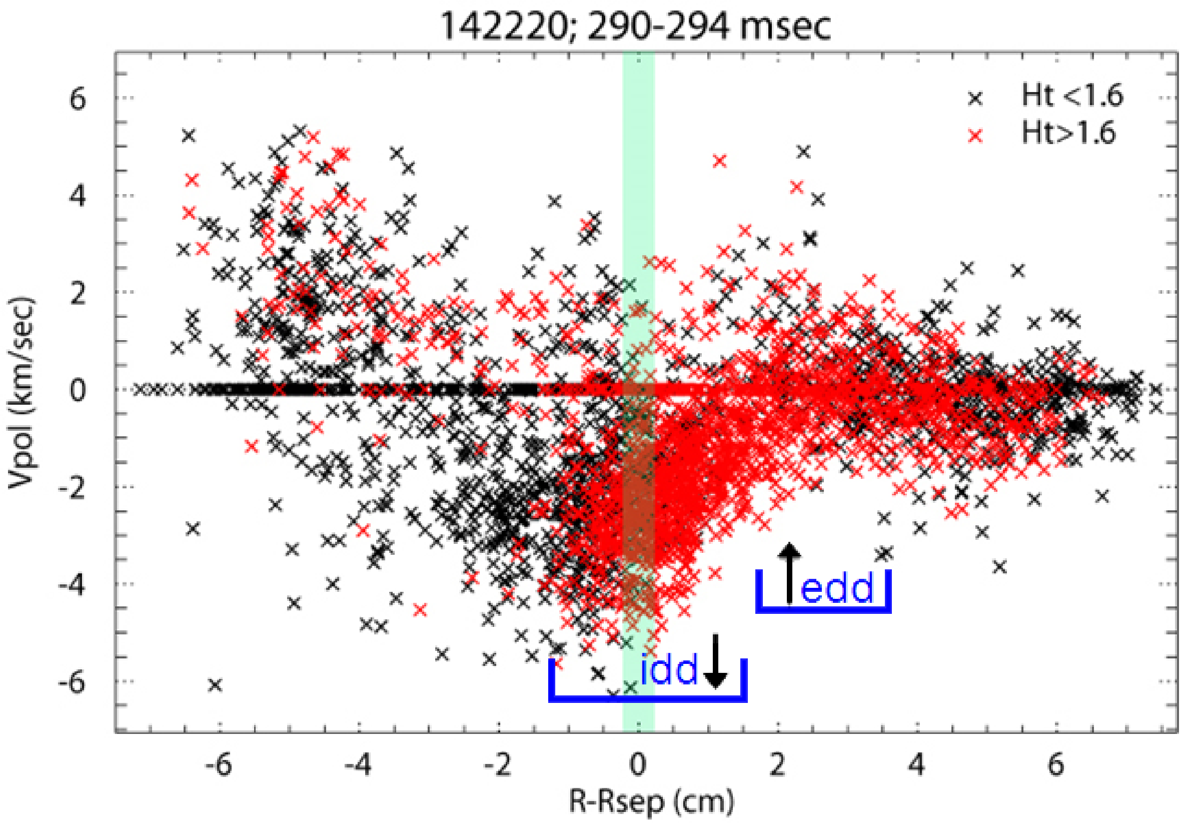

Fig. 4. Poloidal velocity vs. distance from the separatrix plotted for all blobs detected over 4 ms for NSTX shot 142220. Larger than average blobs are in red, smaller ones in black. Blue lines indicate the ion drift direction (idd) and electron drift direction (edd) to show how the shear reverses from the -1 cm to 2 cm region and between 2 & 4 cm. Note that there are many more large blobs outside the separatrix. The green area indicates the separatrix region.

Fast camera measurements of the 2D motion of blobs in the Scrape-Off Layer (SOL) of other tokamaks have been made using GPI at Alcator C-Mod [17], EAST[18], and TEXTOR [19]. In these devices the observed blob structure and motion is at least qualitatively similar to that shown for NSTX in Figs. 3 and 4. The most detailed 2D blob tracking analysis algorithm (outside of NSTX) has been done for the GPI data in Alcator C-Mod [20]. Similar 2D imaging of blobs has also been done on other plasma devices such as the RFX-Mod reversed field pinch [21], the simple magnetized torus device TORPEX [22], and the linear device QUEST [23].

5. Future Possibilities

The existing NSTX GPI database from 2010 (the most recent year of operation) contains over 300 shots of 30,000 frames each, of which only a small fraction (<10%) has yet been analyzed. Movies of some of this data can be seen at [http://w3.pppl.gov/~szweben/NSTX2013/NSTX2013.html]. There are surely many undiscovered phenomena within this database. The analysis is presently limited by the time it takes to create a blob database for a shot, and the manual effort required to make sure the data is not biased by phenomena such as like L-H transitions, large ELMs, different heating methods, lithium deposition, etc. Additional intelligent searching and "filtering" techniques will aid this effort. Automatic ways to constrain a shot list to certain characteristics, or times within a shot to certain features, such as near the L-H transition, would help users sift through the data. Refinements can be made to the blob tracking algorithms, including automatic aides in shear identification. Because of the volume of camera data, timely access after the shot is limited by a 1 Gigabit network pipe, which will eventually be replaced by 10 Gigabit.

6. Summary

Fast 2-D cameras are excellent sources of information for operating a fusion experiment and for understanding important internal processes in plasmas. Browsing methods and statistics from databases are needed to digest this vast amount of information and to understand the physics being revealed. Some examples used to better understand NSTX GPI fast camera data were presented here.

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References

[1] S. Kaye, M. Ono, Y.-K.M.Peng, D.B. Batchelor, M.D. Carter, W. Choe, et al., "The Physics Design of the National Spherical Torus Experiment.", *Fusion Technology* **36**, July 1999, p. 16, or http://nstx.pppl.gov/

[2] http://en.wikipedia.org/wiki/ZFS accessed 15-Jul-2013

[3] http://en.wikipedia.org/wiki/Storage_area_network accessed 15-Jul-2013

[4] Phantom cameras, http://www.visionresearch.com/, accessed 1-Apr-2013

[5] F. Scotti,, *et al.*, "Full toroidal imaging of non-axisymmetric plasma material interaction in the NSTX divertor", *Rev. Sci. Instrum.* **83** (2012).

[6] S.J. Zweben, et al,, "Structure and motion of edge turbulence in the National Spherical Torus Experiment and Alcator C-Mod", *Phys. Plasmas* **13**, 056114 (2006).

[7] A.L. Roquemore, N. Nishino, C.H. Skinner, C. Bush, R. Kaita, R. Maqueda, W. Davis, A.Yu Pigarov, S.I. Krasheninnikov, "3D measurements of mobile dust particle trajectories in NSTX", *J. Nucl. Materials*, Volumes **363-365**, 15 June 2007, p. 222-226.

[8] W.M. Davis, R.I. Patel, W.U. Boeglin, A.L. Roquemore, R.J. Maqueda, S.J. Zweben, "Advances in fast 2D camera data handling and analysis on NSTX", *Fusion Eng. Des*. **85** (2010), p. 325-327.

[9] R.J. Maqueda, R. Maingi, and the NSTX team, “Primary edge localized mode filament structure in NSTX” *Phys. Plasmas* **16**, 056117 (2009)

[10] MDSplus, http://www.mdsplus.org/, accessed 1-Apr-2013

[11] J.A. Stillerman, T.W. Fredian, K.A. Klare, G. Manduchi, “MDSplus Data Acquisition System”, *Rev. of Sci. Instrum.* **68** (1) January 1997, p. 939.

[12] W. Davis, P. Roney, T. Carroll, T. Gibney, D. Mastrovito, “The use of MDSplus on NSTX at PPPL”, *Fusion Eng. Des*. **60** (2002), p.247-251.

[13] IDL (Interactive Data Language)**,** Data Visualization Software, http://www.exelisvis.com/ProductsServices/IDL.aspx, accessed 1-Apr-2013

[14] W. Davis, D. Mastrovito, “DbAccess: interactive statistics and graphics for plasma physics databases”, *Fusion Eng. Des*. **71** (2004), p. 183-188.

[15] J.R. Myra, W.M. Davis, D.A. D'Ippolito, B. LaBombard, D.A. Russell, J.L. Terry, and S.J. Zweben “Edge sheared flows and the dynamics of blob-filaments”, presented at the 24th IAEA Fusion Energy Conference, San Diego, USA, October 8 - 13, 2012, paper IAEA-CN-197/TH/P4-23.

[16] B. Cao, S.J. Zweben, D.P. Stotler, M. Bell, A. Diallo, S.M. Kaye, B. LeBlanc, “Edge turbulence velocity changes with lithium coating on NSTX”, *Plasma Phys. Control. Fusion* **54** (2012).

[17] J.L. Terry et al, *Phys. Plasmas* **10**, 1739 (2003)

[18] S.C. Liu et al, *Rev. Sci. Inst.* **83**, 123506 (2012)

[19] I. Shesterikov et al, *Rev. Sci. Inst*. **84**, 053501 (2012)

[20] R. Kube et al, *J. Nucl. Materials* **438** (2013), p. S505-S508

[21] M. Agostini et al, *Plasma Phys. Cont. Fusion* **54**, 065003 (2012)

[22] A. Fasoli et al, *Nucl. Fusion* **53**, 063013 (2013)

[23] S. Banerjee et al, *Nucl. Fusion* **52**, 123016 (2012)