



## REVIEW ARTICLE

IMAGING OF COHERENT PLASMA STRUCTURES, 'BLOBS', CARRYING OUT  
MATTER AND ENERGY FROM BULK PLASMA- A REVIEWG. SAHOO<sup>1\*</sup>, R. PAIKARAY<sup>1</sup> and S. SAMANTARAY<sup>2</sup>

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**Key words:**Edge Transport, Convective  
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Our understanding of edge turbulence and transport in magnetically confined plasma experiments improved considerably in last few decades due to rapidly growing body of theoretical, computational and experimental work. Fast imaging results provide a robust physical picture of the radial convection of coherent plasma structures created due to edge turbulence. These coherent structures, 'blobs', convect matter and energy from bulk plasma towards wall. This paper is a review of said imaging results.

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**INTRODUCTION**

The boundary region of magnetically confined plasmas has fluctuating parameters observed from probe measurements in eighties [1-5]. Fast imaging results confirm fast radial plasma transport in the edge and scrape-off-layer (SOL) of magnetically confined plasma devices [6-7]. Scrape off layer (SOL) is the outer most region of Tokamak like machines where magnetic field lines intersect material walls. The radial transport has not diffusive but convective like features [8]. This fast convective SOL plasma transport is associated with coherent plasma structures, 'blobs' [9-14]. The term blob is a recent terminology used for a number of coherent structures such as plasmoid [15], UFOs [6], intermittent plasma objects (IPOs) [16-17], avaloids [18], quasi-coherent modes [19], zonal flows [20], avalanche [21], filaments [22] and blobs [9-14, 23-28] observed in nature and laboratory. Both experimental observation and theoretical prediction suggests that this fluctuation driven transport across the magnetic field lines is largely dominated by radial motion of filamentary structures which are localized in the drift plane perpendicular to the field and elongated along the field lines [9-14]. In plasmas where external magnetic field is not present the blobs are of spherical or elliptical structures [29-30].

The radial motion of blob-like structures in edge and SOL of magnetically confined plasmas causes cross-field transport of particles as well as thermal energy and strongly influence the properties of the SOL and divertor operation. It is worth noting that the fluctuation-driven blob transport broaden the radial plasma profile and causes erosion of the main chamber walls. This leads to a number of problems like steady operation of a fusion experiment, including main chamber recycling, material mitigation, plasma rotation and density disruption limit [32-36]. The theory and experimental finding basically from probe diagnostics has been the subject of a number of reviews published in the last decade [11-14]. This communication will therefore emphasize on imaging results which has not been given due space in previous review reports, but is very much important since it provides direct evidence of blob formation and propagation. The structure of blobs is better realized from imaging experiments.

## 2. The first observation of blob structure in fast imaging experiment:

D. J. H. Goodall used high speed cine photography (3000-5000 fps) to image plasma in ASDEX (3 s) and DITE (0.2 s) Tokamak [6]. The main disadvantage of the cine film was the delay between exposing and viewing the film. By starting the camera motor 0.5-1 s before the discharge the film got desired time to accelerate to the required speed at the start of the discharge. Bright spots are imaged by Goodall in both DITE and ASDEX tokamak shown in fig 1. Goodall termed the coherent objects as UFO's.

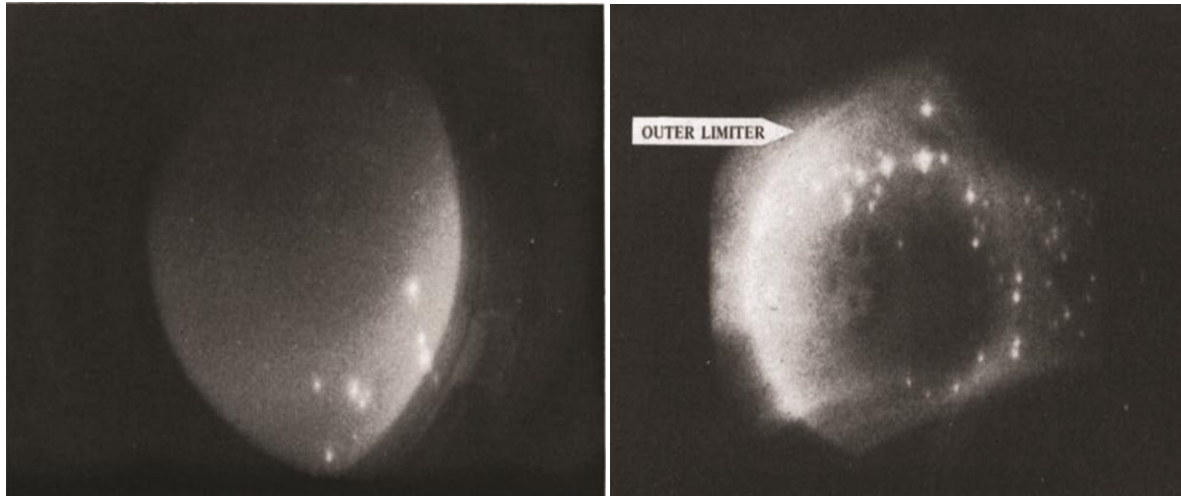


Fig 1: Bright spots (structures) outside main plasma column both in DITE and ASDEX tokamak respectively (Picture Courtesy [6])

## 2. Similar structures observed in other devices:

The very next year S. J. Zweben imaged plasma of Caltech tokamak using a linear array of sixteen photodiodes of the company Fairchild FPT 102[7]. From the data it was observed that the visible light from tokamak was fluctuating in response to the density turbulence in edge plasma and coherent structures were noticed. S. J. Zweben and S. S. Medley imaged edge fluctuation using a rapidly gated, intensified TV camera [31]. They found strong filamentation of the neutral deuterium  $D_{\alpha}$  light, when the camera gating time was  $< 100\mu\text{s}$  during neutral beam heated discharge.

The advanced imaging system came in to picture nearly a decade later when the edge plasma phenomena of TFTR fusion device is imaged using a commercial fast framing visible imaging system [32]. The imaging system was based on a Kodak Ektapro intensified imager coupled to a Kodak Ektapro EM1012 motion analyzer. It was typically operated at 1000 frames/s with exposures as short as  $10\mu\text{s}$ . The intensified imager was sensitive in the 440-700 nm spectral range. It was operated with gates (frame exposures) from  $10\mu\text{s}$  to 5 ms, and with full intensifier gain and 1 ms exposure can detect an illuminance of 1.5 lx. The exposure gates were synchronized with the EM1012 motion analyzer processor. The processor digitized and stored the images in random access memory (RAM) for later download to a computer as binary TIF files or slow analog play-back. Each full image was composed of  $239 \times 192$  pixels and the digitalization is 8 bit deep. The motion analyzer, in conjunction with the intensified imager was able to record full images at frame rates ranging from 50 to 1000 frames/s. The system was also capable of running at up to 6000 Hz by splitting the image and rearranging the multiplexing of the digitizers. The RAM available in the system was able to store up to 1638 full images or the equivalent number of split images, resulting in all cases in a minimum coverage of almost 1.64 s. However, at any given frame rate, the use of a larger split factor allowed more partial images to be stored in memory and in this way increased the total coverage. Analog playback was carried out as slow as 1 frame (or split)/s. The imager itself was mounted on one of the TFTR periscopes beneath the machine, consequently allowing the torus to be viewed from a mid plane viewing port. The camera captured nearly 1600 images in a sequence ( $239 \text{ pixel} \times 192 \text{ pixel} \times 8 \text{ bit}$ ). Plasma disruptions, lithium injection and edge plasma turbulence was imaged using the system. Flying debris (up to 1 cm diameter) coming out from plasma plume with velocity 100 m/s was imaged.

Edge fluctuation of TEXTOR-94 was investigated by A. Huber *et al.* using photomultiplier array and 2D-camera [33]. Two thermal lithium beams was also used for spectroscopic observations. Outside the last closed flux surface (LCFS) the drift velocity of fluctuation, or blobs were found to be propagating poloidally with velocity  $\sim 1$  km/s and radial velocity was  $\sim 0.14$  km/s.

Two years later the turbulent blob structures (filaments) in National Spherical Torus Experiments (NSTX) was imaged using a fast framing, intensified, digital visible camera [34]. Two beautiful images obtained in NSTX with a  $20 \mu\text{s}$  exposure time and 1 ms time gap. The structure disappears at exposure time above  $100 \mu\text{s}$  and no repeated spatial structure is observed from one frame to next. By introducing controlled edge gas puff, the brightness and contrast was increased in the fluctuation images. The turbulent structures were also measured independently. A set of discrete fiber optically coupled sight-lines were also used to measure the frequency spectra of these light fluctuations with a 200 kHz bandwidth. This gas puff imaging data was supplemented by Thomson scattering put light on blob birth and transport in tokamak edge plasma in the device. The need of theoretical and experimental research to find out possible effect of electron temperature and large neutral gas puff on edge turbulence was suggested in that paper.

Same year J. L. Terry *et al.* imaged turbulence in SOL of Alcator C-Mod [35]. They have used a gated ( $0.5$ - $10 \mu\text{s}$ ) fast-framing camera and measured poloidal size of SOL fluctuation, which was  $\sim 0.01$ - $0.03$  m. They found  $D_{\alpha}$  emission with exposures  $2$ - $10 \mu\text{s}$ . They have reported that the fluctuations found in the C-Mod SOL was not different from other tokamaks, stellarators and spherical torus, although fluctuation life time was comparatively longer. The propagation velocity of blob was  $\sim 10^2$ - $10^3$  m/s for different operating conditions.

Two year later an ultra-high speed CCD camera was used by E. S. Marmor *et al.* to image bursty turbulence in the SOL plasma of Alcator C-Mod tokamak [36]. The time resolution was  $\sim 2 \mu\text{s}$ . Individual density structures were seen to grow, move and then disappear on the time scale of microseconds. The plasma blob was of typical spatial scales  $\sim 1$  cm in radial and poloidal directions. They suggested that this bursty turbulence is responsible for much of the transport in SOL.

High-speed video image of the plasma of MAST device is obtained at the start of an ELM and reported by A. Kirk *et al.* [37]. They found the spatial and temporal structure of periodic eruptions observed in magnetically confined laboratory fusion plasmas, called edge-localized modes (ELMs) are similar with those structures during solar eruptions, blob-filaments. They reported that ELMs were associated with a filament like structure. The filaments were extended along a field line and are generated on a  $100 \mu\text{s}$  time scale. They erupted from the outboard side and connected back into the plasma. The filament was observed on several diagnostics to extend beyond the separatrix and ELM effluxes were observed radially up to 20 cm from the plasma edge. They demanded that this was the first time; a high-speed picture of an ELM was obtained showing this filament like structure.

The two-dimensional radial vs poloidal structure and motion of edge turbulence in the National Spherical Torus Experiment (NSTX) were measured by S. J. Zweben *et al.* using high-speed imaging of the visible light emission from a localized neutral gas puff [38]. In the experiment the image of the gas cloud was transferred to a Princeton Scientific Instruments Inc. PSI-4 camera using a lens and mirror inside the re-entrant port and a  $400 \times 400$  coherent fiber optic bundle. The PSI-4 camera used for the experiments had a specialized CCD that continuously stored the preceding 28 frames on the chip itself. The framing rate in NSTX was typically set at  $10 \mu\text{s frame}^{-1}$  to capture turbulent motion with a typical autocorrelation time of  $\sim 40 \pm 20 \mu\text{s}$ . The two-dimensional picture reported by them revealed regions of strong localized light emission known as 'blobs', which move both poloidally and radially at a typical speed of  $\approx 10^3$  m/s. Sometimes it did have spatially periodic features. The generic feature of edge turbulence i.e. intermittency was briefly described in that communication. They reported that the average blob area found by them was  $10$ - $15 \text{ cm}^2$  and average life time of the blob was  $\sim 60$ - $70 \mu\text{s}$ . The poloidal velocity was found to be  $\sim 1.2 \times 10^3$  m/s and radial velocity  $\sim 0.5 \times 10^3$  m/s. S. J. Zweben *et al.* got all these results in He I light emission, where electron temperature is  $\sim 5$ - $50$  eV.

J. L. Terry *et al.* imaged velocity field of edge/SOL turbulence in Alcator C-Mod using gas puff imaging diagnostics [39]. Using high speed movies of edge/Scrape-Off-Layer emission, they measured velocity fields of the turbulent fluctuations. They found that the velocities inside the separatrix were almost purely poloidal. In the SOL

the radial velocity component was outward and significant radial acceleration was observed by them. They found that poloidal and radial components of the SOL velocities vary with the discharge conditions. The magnitudes of all the velocity components measured were ranging from 0 to ~1000 m/s. They did not find well defined blobs inside separatrix. Outside separatrix they found downward poloidal propagation of blobs.

J. A. Alonso *et al.* [40] reported the impact of different confinement regimes on the 2-D structure of edge turbulence. They compared the results of NSTX tokamak and TJ-II stellarator. They reported radially propagating structures (blobs) in the SOL of TJ-II with radial velocities ~ 1000 m/s and with a poloidally asymmetric spatial distribution. The poloidal velocity was found to be ~ 1-5 km/s.

S. J. Zweben *et al.* in 2006 compared the main imaging results for L-mode plasmas in NSTX with Alcator C-Mod imaging results [41]. They reported that at the measurement locations which were near or just outside the magnetic separatrix, there was a qualitative decrease in the turbulence at the L-H transition. But, the radial and poloidal correlation lengths of the turbulence were not significantly different between the L-mode and the H-mode. The average radial gradient of the poloidal velocity of the turbulence was smaller in the H-mode than in the L-mode plasmas. They found most significant change from in the turbulence from the L-mode to the H-mode was a decrease in the fluctuations in the poloidal velocity of the turbulence, as if the flow was more frozen in the H-mode. Poloidal velocity of blobs in NSTX was ~5 km/s, five times more than that of blobs in Alcator C-Mod. Radial velocity was, however, ~ 1-2 km/s for blobs in NSTX and ~ 1.5 km/s for blobs in Alcator C-Mod.

J. R. Myra *et al.*, imaged NSTX plasma with gas puff imaging (GPI) supplemented by Thomson scattering (TS) technique and put light on blob birth and transport in tokamak edge plasma [42]. The camera used in those experiments was able to produce a time sequence of two dimensional images (movie). For these experiments a camera framing rate of 4  $\mu$ s was employed. For a total of 300 frames the camera resolution of 64 X 64 pixels covered approximately 23 cm in the radial and poloidal directions. When viewed along the magnetic field lines the emission pattern revealed blob formation and motion phenomena in SOL region. The GPI camera was fitted with a He I filter at 587.6 nm. This allowed quantitative interpretation of the intensity in terms of plasma parameters. The velocity of blobs near the wall was ~ 300 m/s, where as at separatrix it was ~ 2500 m/s.

M. Agostini *et al.* reported the statistical properties of edge turbulence in NSTX with the GPI diagnostics [43]. The line emission from plasma was measured with a charge couple device (CCD) camera (PSI-5 fast camera, 250 000 frames/ s, for 1.2 ms). A 2D imaging of the turbulence in NSTX (64 X 64 pixels that cover 230 X 230 mm<sup>2</sup>) was captured by them. 2-D motion of the structures (blobs) was also reported by them. The probability distribution function of the probe data obtained simultaneously was non-Gaussian, with high exponential tail. Those tails increased with increasing minor radius from inside the separatrix into the SOL of plasma. Again, the intermittent behavior of the edge fluctuations was pointed out which was inconsistent with imaging results.

G. Y. Antar *et al.* investigated the origin of convective structures in the scrape-off-layer of linear magnetic fusion devices CSDX using fast imaging technique [44]. They found that the life time of intermittent or semi-periodic events depends on the source not only in early phase but also throughout their existence [44].

S. H. Muller *et al.* studies of blob formation, propagation and transport mechanisms in basic experimental plasmas (TORPEX and CSDX) using the results obtained from fast camera imaging [45]. They found that although blobs are having 3-D structures, which are disconnected from the plasma sheath, they exhibit similar statistical properties as the sheath connected blobs in the interchange regime.

M. Schwabe *et al.* imaged formation of many coherent structures like blobs, bubbles and cusps, which convects matter and energy from plasma surface to outer region in dusty plasma [29]. It is worth noting that no external magnetic field applied in the experiment. Rather formation of micro-particle bubbles, blobs, and spraying cusps were observed and their activity can be turned on and off by changing control parameters, such as the rf power and the gas pressure.

M. Xu *et al.* imaged blob structures in a linear helicon plasma device using an advanced fast framing camera (100000 fps) [46]. A 24 cm diameter telescope (f/10) was coupled with the camera. They found coherent structures (blobs) in the central plasma pressure gradient region. The structures followed an outward directed spiral-

shape trajectory in  $(r, \theta)$  plane and are azimuthally stretched developing an anisotropy as they approach an axisymmetric radially sheared azimuthal flow.

J. R. Myra *et al.* used GPI diagnostics to analyze edge turbulence structures in NSTX, Alcator C-Mod device in the year 2013 [47]. The camera they used was capable of capture image in every  $2.5 \mu\text{s}$  for a total interval of 20 ms. They used both He and D gas puff. They reported the blob-filament interaction with sheared flows and put light on L-H transition physics.

A. Niemczewski *et al.* studied neutral particle dynamics over a wide range of operating conditions in the Alcator C Mod tokamak using special purpose pressure gauge [48]. They found that there was a strong dependence on neutral pressure both in the main plasma chamber and in the divertor on the SOL conditions. They found as detachment progresses the neutral pressure increases where as the ion flux to the target below the divertor nose had dropped by a factor of 4. D. A. D'Ippolito and J. R. Myra reported the influence of ion-neutral interactions such as charge exchange and elastic scattering on SOL stability [14]. They also proposed that plasma near the plates would be dominated by recombination. They put light on the effect of neutrals on SOL and divertor stability in tokamaks and proposed that neutrals must have important role on matter and energy transport in edge/SOL of a tokamak. G. Sahoo *et al.* reported pressure dependence on blob formation and transport [30]. At higher base pressure i.e. pressure corresponding to minima of Paschen curve or more convective transport of matter and energy in form of blob was reported.

### 3. Dimension and velocity of blobs:

Irrespective of the plasma device, it is observed that the typical diameter of the blob  $D_{\text{blob}}$  obeys the inequality

$$0.1 D_{\text{bulk}} < D_{\text{blob}} < D_{\text{bulk}} \quad (1)$$

Where  $D_{\text{bulk}}$ ,  $D_{\text{blob}}$  are the diameters of bulk plasma structure and plasma blob respectively. A wide variety of blob shape like sphere, ellipsoid, dumbbell, mushroom shape, filament shape and finger shape were observed in these results. The typical velocity of blob is  $\sim 10^2 - 10^3$  m/s. The blob velocity has scaling with poloidal blob size [14]. The stability of smaller blobs is determined by Kelvin-Helmholtz instability due to vorticity advection term and that of large blobs are determined by curvature driven instability due to sheath conductivity and curvature terms [14].

### 4. Summary and Overview:

The fast imaging results in different plasma devices confirmed the transport of matter and thermal energy from bulk plasma in form of coherent structures, blobs, predicted from probe measurements. The blobs can be basically observed in edge and SOL of the magnetically confined plasmas and between the bulk plasma boundary and wall of the other devices. The size of the blob depends upon the size of bulk plasma and structure of blob depends up on the instability responsible for blob formation. The typical velocity with which blob propagates is  $10^2 - 10^3$  m/s. The life span of blobs are  $\sim$  microseconds, hence high speed imaging devices are necessary for imaging diagnostics.

### References:

- [1] C. Surko and R. E. Slusher, *Science*, **221**, 817 (1983).
- [2] A. V. Nedospasov, *J. Nucl. Mater.*, **196-198**, 90 (1982).
- [3] P. C. Liewer, *Nucl. Fusion*, **25**, 543 (1985).
- [4] A. J. Wootton, B. A. Carreras, H. Matsumoto, K. McGuire, W. A. Peebles, Ch. P. Ritz, P. W. Terry and S. J. Zweben, *Phys. Fluids B* **2**, 2879 (1990).
- [5] F. Wagner and U. Stroth, *Plasma Phys. Controlled Fusion* **35**, 1321 (1993).
- [6] D. H. J. Goodall, *J. Nucl. Mater.*, **111-112**, 11 (1982).
- [7] S. J. Zweben, J. McChesney and R. W. Gould, *Nucl. Fusion*, **23(6)**, 825 (1983).
- [8] S. J. Zweben, *Phys. Fluids*, **28**, 974 (1985).
- [9] M. Endler, *J. Nucl. Mater.*, **266-269**, 84 (1999).
- [10] S. J. Zweben, J. A. Boedo, O. Grulke, C. Hidalgo, B. LaBombard, R. J. Maqueda, P. Scarin and J. L. Terry, *Plasma Phys. Controlled Fusion*, **49**, S1 (2007).

- [11] V. Naulin, *J. Nucl. Mater.*, **363–365**, 24 (2007).
- [12] B. Lipschultz *et al.*, *Nucl. Fusion*, **47**, 1189 (2007).
- [13] O. E. Garcia, *Plasma and Fusion Research: Review Articles*, **4(019)**, 1 (2009).
- [14] D. A. D'Ippolito, J. R. Myra and S. J. Zweben, *Phys. Plasmas*, **18** 060501, (2011).
- [15] W. H. Bostick, *Phys. Rev.*, **104(2)**, 292 (1956).
- [16] J. A. Boedo *et al.*, *Phys. Plasmas*, **10**, 1670 (2003).
- [17] J. A. Boedo *et al.*, *Phys. Plasmas*, **8**, 4826 (2001).
- [18] G. Y. Antar, H. Yu and G. Tynan, *Phys. Rev. Lett.*, **87 (6)**, 065001 (2001).
- [19] A. Mazurenko, M. Porkolab, D. Mossessian, J. A. Snipes, X. Q. Xu and W. M. Nevins, *Phys. Rev. Lett.*, **89(22)**, 22504 (2002).
- [20] M. Jakubowski, R. J. Fonk and G. R. McKee, *Phys. Rev. Lett.*, **89(22)**, 225004 (2002).
- [21] P. A. Politzer *et al.*, *Phys. Plasma*, **9**, 1962 (2002).
- [22] N. Katz, J. Egedal, W. Fox, A. Le and M. Porkolab, *Phys. Rev. Lett.*, **101**, 015003 (2008).
- [23] G. P. Zank and H. R. Muller, *Phys. Plasmas*, **8(5)**, 2385 (2001).
- [24] R. T. Tsunoda, *Reviews of Geophysics*, **26(4)**, 719 (1988).
- [25] J. J. Sojka, M. D. Bowline, R. W. Schunk, D. T. Decker, C. E. Valladares, R. Sheehan, D. N. Anderson and R. A. Heelis, *Geophys. Res. Lett.*, **20(17)**, 1783 (1993).
- [26] B. Basu, *Geophys. Res. Lett.*, **15(5)**, 417 (1988).
- [27] M. C. Kelly and S. Fukao, *J. Geophys. Res.*, **96(A3)**, 3747 (1991).
- [28] N. A. Godarenko and P. N. Guzdar, *J. Geophys. Res.*, **106(A11)**, 24611 (2001).
- [29] M. Schwabe, M. Rubin-Zuzic, S. Zhadanov, A. V. Ivley, H. M. Thomas and G. E. Morfill, *Phys. Rev. Lett.*, **102**, 255005 (2009).
- [30] G. Sahoo, Ph. D. thesis submitted to Ravenshaw University, May 2014.
- [31] S. J. Zweben and S. S. Medley, *Phys. Fluids B*, **1**, 2058 (1989).
- [32] R. J. Maqueda and G. A. Wurden, *Nucl. Fusion*, **39(5)**, 629 (1999).
- [33] A. Huber, A. V. Nedospasov, U. Samm and B. Schweer, *J. Nucl. Mater.*, **266-269**, 546 (1999).
- [34] R. J. Maqueda *et al.*, *Rev. Sci. Instrum.*, **72(1)**, 931 (2001).
- [35] J.L. Terry *et al.*, *J. Nucl. Mater.*, **290-293**, 757 (2001).
- [36] E. S. Marmor *et al.*, *Nucl. Fusion* **43**, 1610 (2003).
- [37] A. Kirk *et al.* *Phys. Rev. Lett.*, **92(24)**, 245002(2004).
- [38] S. J. Zweben *et al.*, *Nucl. Fusion*, **44**, 134 (2004).
- [39] J. L. Terry, S. J. Zweben, O. Grulke, M. J. Greenwald and B. LaBombard, *J. Nucl. Mater.* **322-326**, 322 (2005).
- [40] J. A. Alonso *et al.*, *Plasma Phys. Controlled Fusion*, **48**, B465 (2006).
- [41] S. J. Zweben *et al.*, *Phys. Plasmas*, **13**, 56114(2006).
- [42] J. R. Myra, D. A. D'Ippolito, D. P. Stotler, S. J. Zweben, B. P. LeBlanc, J. E. Menard, R. J. Maqueda and J. Boedo, *Phys. Plasmas*, **13**, 092509 (2006).
- [43] M. Agostini, S. J. Zweben, R. Cavazzana, P. Scarin, G. Serianni, R. J. Maqueda and D. P. Stotler, *Phys. Plasmas*, **14**, 102305 (2007).
- [44] G. Y. Antar, J. H. Yu and G. Tynan, *Phys. Plasmas*, **14**, 022301 (2007).
- [45] S. H. Muller, C. Theiler, A. Fasoli, I. Furno, B. Labit, G. R. Tynan, M. Xu, Z. Yan and J. H. Yu, *Plasma Phys. Controlled Fusion* **51**, 055020 (2009).
- [46] M. Xu, G. R. Tynan, P. H. Diamond, C. Holland, J. H. Yu and Z. Yan, *Phys. Rev. Lett.*, **107**, 0550031 (2011).
- [47] J. R. Myra, W. M. Davis, D. A. D'Ippolito, B. LaBombard, D. A. Russell, J. L. Terry and S. J. Zweben, *Nucl. Fusion*, **53**, 073013 (2013).
- [48] A. Niemczewski *et al.*, *Nucl. Fusion*, **37(2)**, 151 (1997).