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Alfvén eigenmode structure during off-axis neutral beam injection

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Abstract

The spatial structure of Alfvén eigenmodes on the DIII-D tokamak is compared for contrasting fast ion deposition profiles resulting from on- and off-axis neutral beam injection (NBI). In both cases, poloidal mode rotation and eigenmode twist, or radial phase variation, are correlated with the direction of the normal ion diamagnetic flow and readily inverted with a reversal of toroidal magnetic field, B_T. While off-axis NBI results in weakly driven reversed shear induced Alfvén eigenmodes due to reduced fast ion pressure gradient, $\nabla\beta_{\text{fast}}$, in the region of the mode, these marginally unstable modes exhibit a 2D phase structure that is indistinguishable from that observed during on-axis injection. This result is consistent with recent explorations using the non-perturbative codes Gyro and TAEFL that show a weak dependence of eigenmode structure on drive when fast ion density is uniformly reduced by a scalar multiplier. These codes also obtain unstable, counter-propagating modes with the inverted 2D phase structure when B_T is kept constant and the diamagnetic flow direction is reversed by making $\nabla\beta_{\text{fast}}$ sufficiently positive for an isotropic population of fast ions. While measurements of the spatial profile of fast ion D-α light from the recently upgraded charge exchange recombination diagnostic on DIII-D suggest a strong modification of fast ion pressure towards this limit, no counter-propagating modes have yet been observed in experiment.

(Some figures may appear in colour only in the online journal)

1. Introduction

Alfvén eigenmodes remain a concern for fusion reactor confinement and represent an unknown quantity in performance predictions for ITER and beyond as they are readily destabilized through resonances with energetic ions produced by neutral beam heating [1, 2], predicted to be excited by energetic α particles in burning tokamak plasmas [3, 4], and result in redistribution [5] and coherent losses [6] of fast ions that produce significant deviations from classical predictions of fast ion confinement [7]. Previous experiments on DIII-D have resulted in a successful identification of numerous Alfvénic instabilities [8, 9] arising during current ramp phases of L-mode discharges, where delayed current penetration results in a core-localized reversed magnetic shear and a slowly evolving off-axis minimum in the q profile. Since the installation of a dual-array electron cyclotron emission imaging (ECEI) diagnostic on DIII-D [10], it has been possible to image the 2D structure of Alfvén eigenmodes with high resolution. These data reveal subtle features, such as a variation in eigenmode phase with radius, or an eigenmode twist [11], which represent opportunities for detailed validation of theory.

Significant progress has been made recently in simulating stability and eigenmode structure. A remarkable agreement with experiment [12] has been demonstrated for Gyro [13, 14], GTC [15, 16] and TAEFL [11], which represent both perturbative and non-perturbative methods implementing various aspects of gyrofluid and kinetic theory. In previous comparisons with the predictions of the gyrofluid code TAEFL [11], eigenmode twist was accurately reproduced. It was observed that this non-perturbative attribute is not represented in ideal MHD codes such as NOVA [18] and NOVA-K [19]. It has now been demonstrated that the 2D phase structure, giving rise to a twisted eigenmode, has a well-defined relationship to the direction of the diamagnetic flow and may be inverted in both experiment and simulation by changing the sign of the toroidal magnetic field, B_T, and hence the sign of the fast ion diamagnetic frequency, $\omega_{*i,\mathrm{fast}}$. When fast ion pressure gradients are modified, reducing eigenmode drive, the degree of twist is not affected. Reversal of this twist by local inversion of the fast ion pressure gradient and $\omega_{*i,\mathrm{fast}}$ has not been achieved in experiment.

The successful implementation of an off-axis neutral beam injection (NBI) capability at DIII-D [20] provides an opportunity to modify the fast ion pressure profile while maintaining reversed magnetic shear. During the current ramp portion of the discharge, fast ions may be deposited far from the magnetic axis without significantly altering the current profile, which remains dominated by the inductive electric field. During off-axis NBI experiments, some reversed shear induced Alfvén eigenmodes (RSAEs) are observed by ECEI and other diagnostics, but they are very weakly driven. The twist and rotation of these modes remain in the normal sense, indicating that they are destabilized by a region of reduced, but still negative, fast ion pressure gradient. However, the degree of twist is comparable to that observed during on-axis NBI, when modes are strongly driven by steeper fast ion pressure gradients. This is consistent with theory in that Alfvén eigenmodes obtained in TAEFL and Gyro retain a nearly constant 2D phase structure when fast ion pressure is uniformly reduced. This phase structure may yet be indicative of other properties of the plasma, such as the location of rational surfaces within regions of strong mode activity or shear in plasma flows.

Simulations presented in this work further suggest that a region of locally inverted fast ion pressure gradient may destabilize counter-propagating modes that exhibit reversed poloidal mode rotation and inverted eigenmode phase structure. However, although diagnostic data suggest a region of reversed fast ion pressure gradient in these cases, no counter-propagating RSAEs have been observed. This discrepancy motivates further development of simulation codes to include additional details of the experimental conditions, such as the strong anisotropy of co-injected fast ions on DIII-D.

2. Measured changes to fast ion profiles and eigenmode structures

The reference discharge for this work is the well-documented DIII-D discharge #142111 and recent repeats of which are up/down symmetric, inner wall limited, L-mode plasmas with clear evidence of strong Alfvénic activity. Long-lived TAEs are observed at near constant frequency with eigenmodes that are ballooning (i.e. of greater amplitude at outboard radii) and found radially outside the position of $q_{\min}$. RSAEs, in contrast, are highly localized near $q_{\min}$ [21], are initially of constant amplitude on a flux surface, and sweep rapidly from approximately the geodesic acoustic frequency to the TAE frequency where they couple to poloidal sidebands [22] and take on an increasingly TAE-like structure. In the on-axis NBI case, both types of modes are clearly observed throughout the current ramp and disappear completely before the onset of sawteeth. The occurrence of so-called grand cascades at the formation of rational surfaces [23] allows for a confident reconstruction of the temporal evolution of $q_{\min}$, critical to comparison of mode behaviour to theory during off-axis NBI.

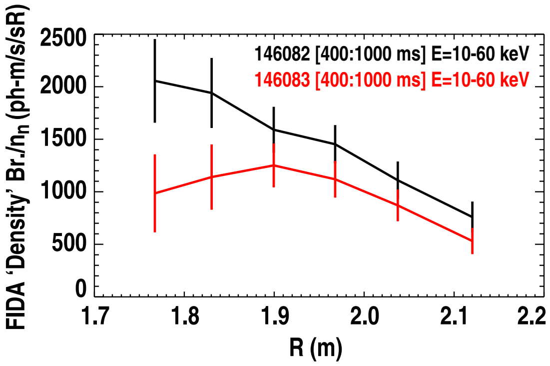

Figure 1. Profiles of FIDA brightness, normalized by dividing into neutral density, are given for typical on (#146082) and off-axis (#146083) NBI dominated discharges. The quantity shown is used as a proxy for the local fast ion density over the range of energies and pitch angles to which the CER spectrometer is sensitive. Integrating from 400 to 1000 ms, there is strong evidence for a region of inverted, or positive, fast ion pressure gradient at small minor radii and flattening of the profile in the region of strong RSAE mode activity.

Two neutral beams, injected at a full tilt angle of 16.5° as described in [24] provide 2 MW of heating each at an injection energy of 76 keV. Safety factor profiles are similar for on- and off-axis NBI discharges, and this is verified by magnetic pitch angle measurements from the motional Stark effect (MSE) diagnostic [25]. Discharges with shapes matched to shot #142111 were carried out, along with circular, inner wall limited discharges. In circular plasmas, reversal of the fast ion pressure gradient in the core is enhanced due to fast ion deposition at a larger plasma minor radius and on a flux surface with a smaller area. The mode activity was found to be similar in these two shapes, with the enhancement of pressure profile inversion in circular discharges having no significant effect.

Measurement of fast ion D-α (FIDA) light [26] at spatially resolved locations provides a diagnosis of the radial fast ion density profile within a range of energies and pitch angles defined primarily by the viewing angle of the spectrometer. The FIDA brightness, as measured by the recently upgraded DIII-D charge exchange recombination (CER) diagnostic [27] is divided by beam neutral density in order to obtain a measurement of fast ion density over the designated period of integration and for the region of particle phase space to which the diagnostic system is sensitive. This quantity is plotted for on- and off-axis NBI discharges in figure 1. For the off-axis case, there is an inversion of the fast ion density gradient at inner radii, leading to positive values of $\nabla\beta_{\mathrm{fast}}$ in this region. At radii near the location of RSAEs in these discharges, the fast ion pressure gradient appears to remain negative, but is significantly reduced, resulting in a reduced drive for these modes. The RSAEs that are identified during off-axis NBI are weakly driven and have amplitudes near the threshold of detection for ECEI.

The direction and degree of eigenmode twist appear to be insensitive to fast ion drive in excess of the stability threshold. Even very weakly driven modes exhibit a strong

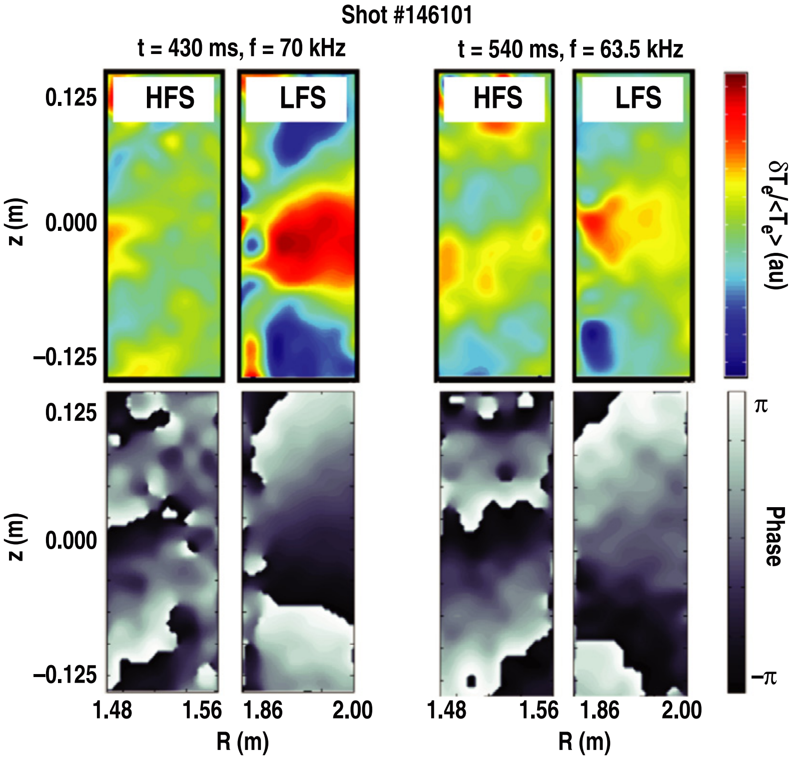

Figure 2. Measured eigenmode amplitude (top) and 2D phase structure (bottom) are shown for weakly driven modes imaged during off-axis NBI in discharge #146101. Absolute mode amplitude is comparable to sources of diagnostic noise for these measurements and cannot be resolved precisely. However, 2D phase information is preserved, and a curvature in lines of constant phase reveals that a poloidal twist of the eigenmode structure, correlated with the direction of mode rotation, remains a ubiquitous feature.

twist. Two examples of weakly driven RSAEs excited during a period of exclusively off-axis NBI in discharge #146101 are shown in figure 2. Careful application of windowed Fourier transforms and singular value decomposition [28, 29] enhances the resolution of coherent mode activity in ECEI signals above uncorrelated thermal noise and diagnostic artefacts. Within a single Fourier window, the mode structure is acquired as a complex quantity, allowing 2D phase information to be extracted for oscillations whose amplitude eigenmodes may be unacceptably noisy or ambiguous, allowing for a comparison of RSAE eigenmode phase with previous experiments. Although off-axis injection has resulted in mode amplitudes of less than 0.2% in normalized electron temperature fluctuation (approximately a factor of 5 less than the strongest RSAEs observed on DIII-D), the 2D phase is remarkably similar to that observed in the RSAEs of discharge #142111 [11] and other repeats thereof with exclusively on-axis NBI and strong mode activity. As expected, toroidicity-induced Alfvén eigenmode (TAE) frequency and mode structure were very similar to on-axis injection cases since the change in $\nabla\beta_{\mathrm{fast}}$ outside the radius of q_{min} is not significant in these discharges.

3. Comparisons to simulated Alfvén eigenmode structure

TAEFL and Gyro simulations produce a robust 2D eigenmode phase under fixed thermal plasma equilibrium conditions, predicting little change in the phase structure as drive is reduced. Figure 3 quantifies changes in eigenmode frequency and radial phase variation as fast ion pressure gradients are reduced to the stability threshold by everywhere decreasing the fast particle density. The phase difference between two fixed points on a radial chord through the eigenmode varies slowly, though mode amplitude and frequency increase significantly with increased drive. Because there are few RSAEs excited during off-axis injection, and only brief portions of their frequency sweep are accessible, this trending in mode frequency is difficult to validate and will require further study. However, only a very weak dependence, if any, of eigenmode twist with a variation of mode drive is observed in experiment.

For the toroidal mode numbers observed, mode rotation in the laboratory frame is dominated by wave propagation in the plasma frame, as the RSAE and TAE frequencies are both much larger than the associated Doppler shift, and the direction of mode propagation is readily determined by the observed poloidal rotation of the mode and the direction of plasma current, I_{P}. Radial phase variation in RSAEs and TAEs and the corresponding twist in 2D eigenmode structure are correlated with the direction of the fast ion diamagnetic flow and mode propagation. As shown in figure 4, a clockwise diamagnetic flow produces a twist in lines of constant phase such that there exists a region near the peak in mode amplitude that lags in phase both poloidally and toroidally. This is equally well described as a phase velocity that is directed outwards at small minor radii, but is reversed at larger minor radii. In the case of RSAEs, this has been measured simultaneously at both sides of the magnetic axis and the position of reversal in the radial phase velocity is consistently outside the peak in mode amplitude. Gyro simulations suggest a correspondence of this location to the first rational surface beyond the peak in mode amplitude.

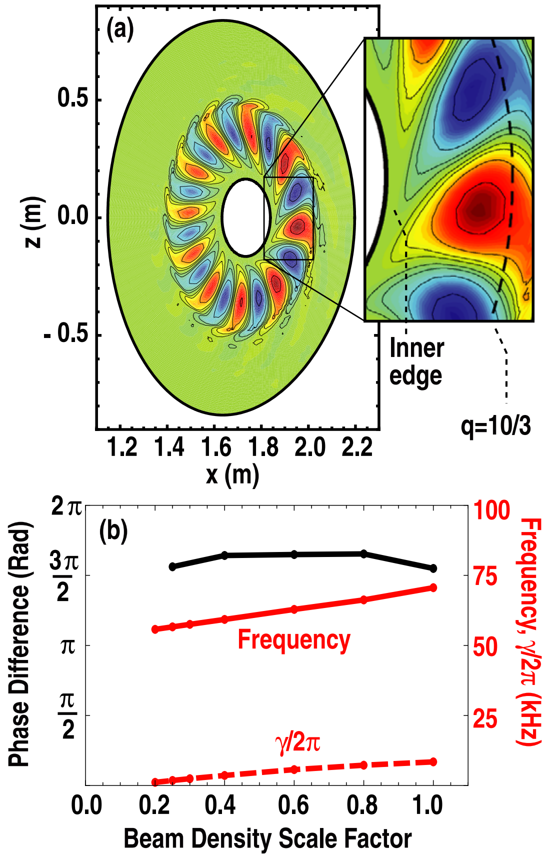

Figure 3. A weak dependence of modelled RSAE mode structure on fast ion drive is demonstrated in Gyro simulations. The density of fast ions from NBI is varied uniformly from 20% (representing the marginal stability limit) to 100% of the fast ion pressure as estimated from experimental data. The relative phase of the modelled eigenmode is compared at the inner simulation boundary and the 10/3 rational surface, as illustrated in (*a*). In (*b*), this value remains near $3\pi/2$ throughout the scan, though mode frequency and growth rate increase with drive. This result is corroborated by similar scans performed in TAEFL.

When the direction of toroidal magnetic field (and hence the diamagnetic flow) is reversed in experiment (independent of plasma current), the direction of mode propagation and the orientation of eigenmode twist are also reversed for all RSAEs and TAEs. TAEFL, Gyro, GTC, M3D-k [30] and fully nonlinear simulations using GEM [31] reproduce this correlation. In experiment, it is a robust feature with no recorded counter examples.

The direction of the diamagnetic flow may also be reversed locally by an inversion of fast ion pressure gradient, such as in the off-axis NBI case in figure 1. When a spatial profile consistent with FIDA measurements and having a localized inversion of the fast ion pressure gradient at small minor radii is applied in the TAEFL and Gyro codes, modes propagating in the counter-current direction are predicted to become unstable. In these simulations, the fast particle population is represented by an isotropic, the Maxwellian distribution at the injection energy. Eigenmode amplitude is peaked inside q_{min}, the direction of Alfvén wave propagation in the lab frame is reversed, and the twist of the eigenmode (2D phase variation) is inverted with respect to the forward propagating RSAE. The 2D eigenmode of a typical example is presented in figure 5, along with the plasma profiles used for this specific case, and is contrasted to the co-propagating mode that resembles those observed in experiments on DIII-D.

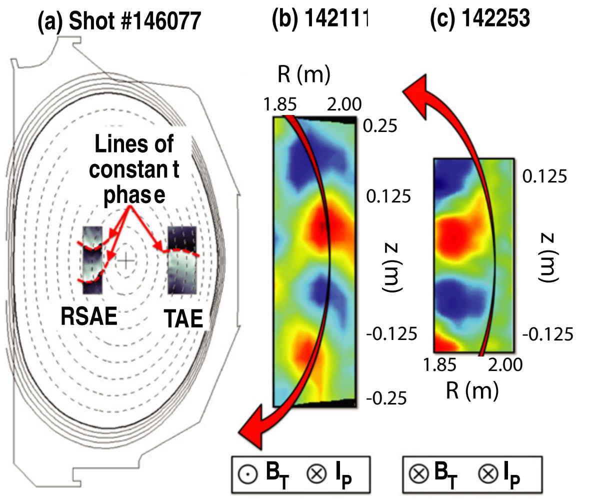

Figure 4. A twisting of RSAEs and TAEs is evident in 2D phase plots obtained via ECEI and has a fixed relationship to the direction of the normal ion diamagnetic flow (red arrows). Measured mode structures from shot #146077 (*a*) have been imaged simultaneously using the dual-array capability available on DIII-D and are typical of those destabilized during standard operation $(+I_\mathrm{P}, -B_\mathrm{T})$, including shot #142111 (*b*). Measured mode structure during reversed magnetic field operation $(+B_\mathrm{T})$ is shown for shot #144256 (*c*). In this case, data show that twisting is inverted for both types of modes.

At no time were the predicted counter-propagating modes observed in experiment. Mode rotation in the laboratory frame unambiguously determines the direction of mode propagation, and this has been independently verified by beam emission spectroscopy (BES) measurements of fluctuating density [32]. Furthermore, a reversal of eigenmode twist is repudiated by ECEI data. An absence of counter-propagating RSAEs indicates that the conditions for mode excitation encapsulated in TAEFL and Gyro are not satisfied in experiment and underscores the need for ongoing research in this area. In particular, improved diagnosis of the slowing down distribution of beam injected fast ions and analysis for these particular experiments is the subject of W.W. Heidbrink (this issue) and ongoing work.

4. Discussion

FIDA diagnostic measurements suggest a strong modification of the fast ion pressure profile during off-axis NBI experiments. However, the readily identifiable features of counter-propagating RSAEs have not been observed on DIII-D. It remains to be determined as to whether additional damping terms that are omitted in the model contribute to the stability of these modes, or if a more complete description of the distribution of energetic ions in these cases is required. Diagnostic tools, such as FIDA, inherently integrate over finite regions of particle phase space. Therefore, self-consistent modelling of the spontaneous charge exchange spectra is essential and requires sophisticated methods for iterating the full 5D energetic particle distribution, including non-isotropy in velocity space.

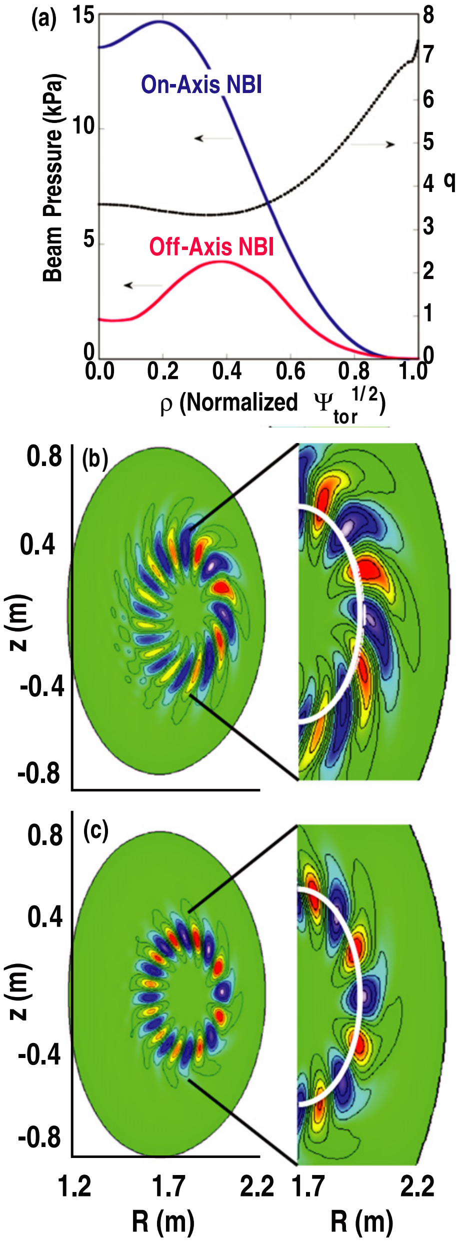

Figure 5. Profiles of safety factor and fast ion pressure for DIII-D discharge #142111 at $t = 725$ ms are shown in (*a*), along with an estimate of the fast ion pressure profile in a generalized off-axis NBI case. The estimate reflects the classical slowing down distribution, is within the error bars of relevant FIDA measurements, and is applied in the code as an isotropic, Maxwellian fast particle distribution. The simulated mode in (*b*) is similar to the experimentally observed eigenmodes of discharge #142111, from which estimates of the thermal and fast ion plasma profiles are taken. The simulated mode in (*c*) exhibits inverted phase structure and reversed mode propagation, rotating poloidally counter-clockwise in the laboratory frame. The radius of $q_{\rm min}$ is indicated in (*b*) and (*c*) by a solid white line.

These experiments confirm that RSAEs, composed of a dominant poloidal mode number and having time averaged mode amplitude that is nearly constant on a magnetic surface, are characterized by a twisting that is correlated with the direction of the fast ion diamagnetic flow and mode propagation. This twisting results in a region of strong mode amplitude that lags in phase with respect to the mode periphery. This has been confirmed in discharges where the magnetic field is reversed and both mode rotation and the normal ion diamagnetic flow are in the opposite sense. While the dependence of the 2D phase structure on the direction of toroidal magnetic field is reproduced in many predictive codes, Gyro and TAEFL have further demonstrated a robustness of the eigenmode phase with respect to mode drive. However, a quantitative description of how this readily diagnosed quantity reflects properties of the tokamak plasma, and how it may be applied as a more rigorous tool for code validation, remains elusive.

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References

[1] King-Lap W. 1999 *Plasma Phys. Control. Fusion* **41** R1
[2] Heidbrink W.W. 2008 *Phys. Plasmas* **15** 055501
[3] Fasoli A. *et al* 2007 Progress in the ITER Physics Basis: Chapter 5. Physics of energetic icons *Nucl. Fusion* **47** S264
[4] Nazikian R. *et al* 1997 *Phys. Rev. Lett.* **78** 2976
[5] Heidbrink W. *et al* 2007 *Phys. Rev. Lett.* **99** 245002
[6] Van Zeeland M. *et al* 2011 *Phys. Plasmas* **18** 056114
[7] The D.-D.T. *et al* 2007 *Phys. Rev. Lett.* **99** 245002
[8] Van Zeeland M. *et al* 2006 *Nucl. Fusion* **46** S880
[9] Heidbrink W. *et al* 1991 *Nucl. Fusion* **31** 1635
[10] Tobias B.J. *et al* 2010 *Rev. Sci. Instrum.* **81** 10D928
[11] Tobias B.J. *et al* 2011 *Phys. Rev. Lett.* **106** 075003
[12] Deng W., Lin Z., Holod I., Wang Z., Xiao Y. and Zhang H. 2012 *Nucl. Fusion* **52** 043006
[13] Candy J. and Waltz R.E. 2003 *J. Comput. Phys.* **186** 545–81
[14] Bass E. and Waltz R. 2010 *Phys. Plasmas* **17** 112319
[15] Lin Z. *et al* 1998 *Science* **281** 1835
[16] Deng W., Lin Z., Holod I., Wang X., Xiao Y. and Zhang W. 2010 *Phys. Plasmas* **17** 112504
[17] Spong D.A. *et al* 1992 *Phys. Scr.* **45** 159
[18] Cheng C.Z. and Chance M.S. 1987 *J. Comput. Phys.* **71** 124–46
[19] Cheng C.Z. 1992 *Phys. Rep.* **211** 1
[20] Murakami M. *et al* 2009 *Nucl. Fusion* **49** 065031
[21] Van Zeeland M. *et al* 2006 *Phys. Rev. Lett.* **97** 135001
[22] Van Zeeland M. *et al* 2007 *Phys. Plasmas* **14** 056102
[23] Sharapov S.E. *et al* 2001 *Phys. Lett.* A **289** 127–34
[24] Heidbrink W.W., Van Zeeland M.A., Grierson B.A., Muscatello C.M., Park J.M., Petty C.C., Prater R. and Zhu Y.B. 2012 *Nucl. Fusion* **52** 094005
[25] Holcomb C.T., Makowski M.A., Allen S.L., Meyer W.H. and Zeeland M.A.V. 2008 *Rev. Sci. Instrum.* **79** 10F518
[26] Heidbrink W. 2010 *Rev. Sci. Instrum.* **81** 10D727
[27] Grierson B.A. *et al* 2012 *Phys. Plasmas* submitted
[28] Nardone C. 1992 *Plasma Phys. Control. Fusion* **34** 1447
[29] Classen I. *et al* 2010 *Rev. Sci. Instrum.* **81** 10D929
[30] Fu G.Y., Park W., Strauss H.R., Breslau J., Chen J., Jardin S. and Sugiyama L.E. 2006 *Phys. Plasmas* **13** 052517
[31] Chen Y. and Parker S.E. 2003 *J. Comput. Phys.* **189** 463
[32] McKee G. *et al* 1999 *Rev. Sci. Instrum.* **70** 913