High-resolution internal measurements of 3D plasma response for model validation in high-β plasmas

P. Piovesan[1], V. Igochine[2], Y.Q. Liu[3], M. Maraschek[2], L. Marrelli[1], D.A. Ryan[3,4], W. Suttrop[2], M. Weiland[2], D. Yadykin[5], M. Gobbin[1], D. Terranova[1], N.M. Ferraro[6], M.J. Lanctot[6], A. Bogomolov[7], I. Classen[7], M. Dunne[2], A. Gude[2], R. McDermott[2], M. Reich[2], E. Wolfrum[2], the ASDEX Upgrade Team and EUROfusion MST1 Team*

[1]*Consorzio RFX, Padova, Italy;* [2]*MPI für Plasmaphysik, Garching, Germany;* [3]*CCFE, Abingdon, UK;* [4]*University of York, York, UK;* [5]*Chalmers University, Gothenburg, Sweden;* [6]*General Atomics, San Diego, CA, USA;* [7]*DIFFER, Nieuwegein, The Netherlands.*
* See *http://www.euro-fusionscipub.org/mst1*.

The plasma response to external 3D fields, due to error fields or intentionally applied by non-axisymmetric coils, can impact tokamak performance. Helical distortions of flux surfaces can affect heat, particle, momentum, and fast ion transport, as well as tearing, ELM, and Alfvén eigenmode stability. Such effects are usually more prominent at high normalized pressure $\beta_N = \beta_T a B_T / I_P$ approaching the ideal MHD no-wall limit. Here the ideal kink mode is only marginally stable and can largely amplify 3D fields resonant with it. The paper presents an experimental and theoretical investigation of the plasma response to applied 3D fields in ASDEX Upgrade high-β hybrid plasmas [1]. These experiments were made possible by the new availability in 2014 of AC power supplies for the non-axisymmetric B-coils, two rows of 8 internal coils placed above and below the midplane.

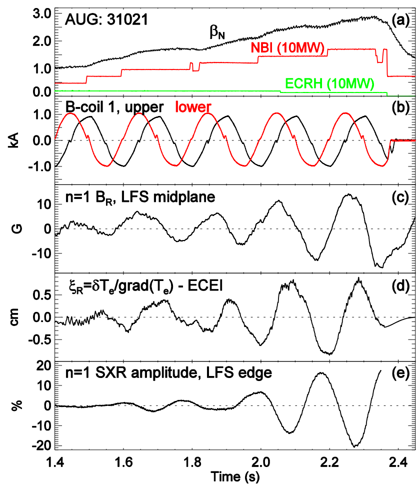

Fig. 1. Perturbation of different edge quantities in response to a rotating n=1 field during a β_N ramp in AUG: (c) total n=1 B_r (vacuum n=1 field ≈2.5G not subtracted), (d) radial displacement from ECE-I at pedestal top, (e) SXR edge channel at LFS.

Previous similar studies in DIII-D [2] focused on advanced tokamak plasmas, which feature lower no-wall limits than hybrids due to elevated safety factor with q_{min}>1.5. The n=1 response in this case is dominated by the external kink and is localized in the outer region of the plasma. On the other hand, the hybrid plasmas investigated here have q_{min}≈1. We find that this has a significant effect on the n=1 response profile, largely increasing the internal kink component with respect to the external one. Helical core displacements of the order of 1cm are observed, which may have consequences on hybrid operation, as discussed below. These measurements also provide an interesting, new test case to validate MHD simulations.

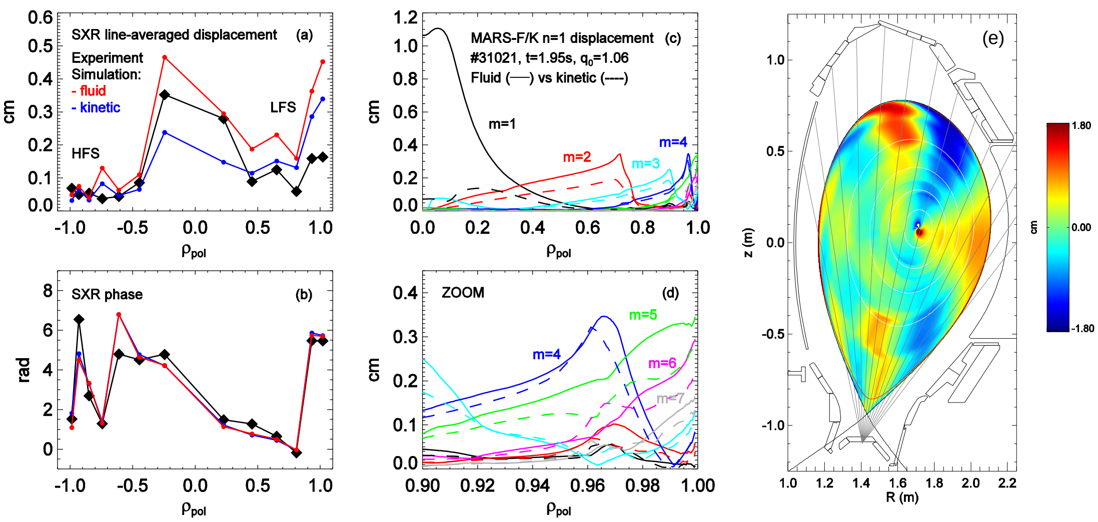

Fig. 2. (a) Amplitude and (b) phase of n=1 SXR line-averaged displacement in experiment (black diamonds) and simulated with MARS-F fluid (red) and MARS-K kinetic eigenfunctions (blue), shown in (c,d) for discharge #31021, t=1.95s. (e) SXR chords used in the analysis and contour of MARS-F n=1 displacement.

The plasma response to slowly rotating (5-27Hz) n=1 magnetic perturbations was measured with a wide set of edge and internal diagnostics during β_N ramps obtained by increasing the NBI power up to 17MW, Fig. 1(a). A benign 3/2 NTM always appears during the β_N-ramp. The poloidal spectrum of the applied n=1 field is determined by the differential phase among upper and lower B-coil rows, $\Delta\phi^{U/L}$. The discharge reported in Figs. 1 to 3 has $\Delta\phi^{U/L}$=315°, corresponding to an almost pitch non-resonant vacuum field. Fig. 1 shows the resulting n=1 perturbation measured by B_r pick-up probes at LFS midplane, Fig. 1(c), n=1 radial displacement from ECE-Imaging channels across the LFS pedestal, Fig. 1(d), and a SXR chord tangent to the separatrix on LFS, Fig. 1(e). In all diagnostics the n=1 perturbation increases with β_N, indicating amplification from a marginally stable, pressure-driven mode.

The entire n=1 response profile was measured from HFS to LFS by two SXR cameras with identical line of sight geometry, toroidally separated by 135°, Fig. 2. The difference between the two cameras allows extracting the n=1 response out of variations due to ELMs that otherwise dominate the signals. This difference may pick-up n≠1 contributions, expected in any case to be small. The amplitude and phase of the n=1 SXR line-averaged displacement are shown in Fig. 2(a,b) for discharge #31021 at t=1.95s, when β_N≈2 is below the no-wall limit, varying in these plasmas among 2.5 and 2.9. The n=1 eigenfunctions calculated by MARS-F fluid and MARS-K [3] kinetic simulations are shown in Fig. 2(c,d). These simulations used experimental profiles of resistivity and toroidal rotation and high-resolution CLISTE [4] equilibria with various constraints (kinetic profiles, fast ion pressure from TRANSP, 3/2 NTM position, SOL currents, no MSE). The SXR measurements perturbed by

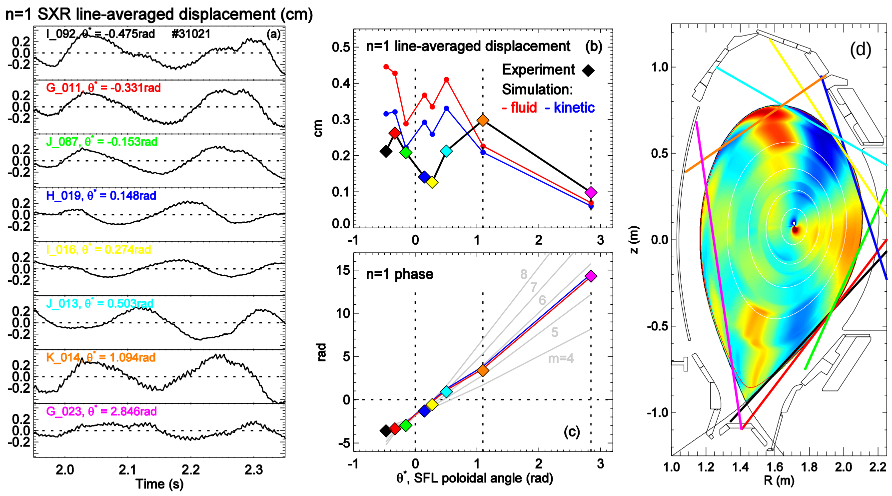

Fig. 3 (a) The n=1 radial displacement from SXR channels almost tangent to the separatrix is in phase with the applied n=1 field. (b) n=1 displacement and (c) phase in experiment (diamonds) and MARS-F/K simulations (red/blue) *vs* SFL poloidal angle. (d) Edge SXR channels used in the analysis and n=1 MARS-F displacement.

MARS-F/K eigenfunctions were simulated taking into account the exact 3D geometry of the SXR volumes of sight [5] and are shown in red/blue in Fig. 2(a,b). MHD predictions are in good agreement with experiment: in both cases a large core displacement is present, mainly due to the m=1 internal kink response, while the edge is dominated by external kink/peeling harmonics with m>nq. MARS-F predicts large sensitivity of the internal kink response with respect to changes in q_0 in the range 1.0-1.1 within the equilibrium reconstruction uncertainty (q_0 scan not shown). The simulation results reported here correspond to q_0=1.06, at which the internal kink response is maximum. On the other hand, drift-kinetic damping can also sensibly change the internal kink response. It must be thus concluded that, to quantitatively validate drift-kinetic effects in the core, internal q profile measurements are necessary.

The edge poloidal structure of the n=1 response predicted by MARS-F/K agrees with edge measurements at different toroidal/poloidal angles, including eight SXR channels almost tangent to the separatrix, Fig. 3(d), ECE-Imaging and Lithium beam. A poloidally propagating structure at the n=1 field frequency is evident when comparing the SXR displacement at different poloidal angles, Fig. 3(a). The phase of these oscillations has a linear dependence on the straight field line poloidal angle, θ*, a linear fit giving m=5.5±0.2. The n=1 displacement is larger at LFS than HFS, confirming the ballooning nature of the n=1 response. In this case, adding kinetic effects really improves agreement with experiment, since the edge q profile has much lower uncertainty than in the core. All these evidences confirm that the edge n=1 response is mainly due to the ideal external kink/peeling mode. No evidence of magnetic islands was found, though this may be due to diagnostic limits, e.g. line integration in SXR, low optical thickness for ECE-Imaging channels near the separatrix.

To probe the kink-resonant nature of the n=1 response, the m-spectrum of the applied n=1 field was scanned by varying the differential phase $\Delta\phi^{U/L}$ at constant β_N. Fig. 4 shows the

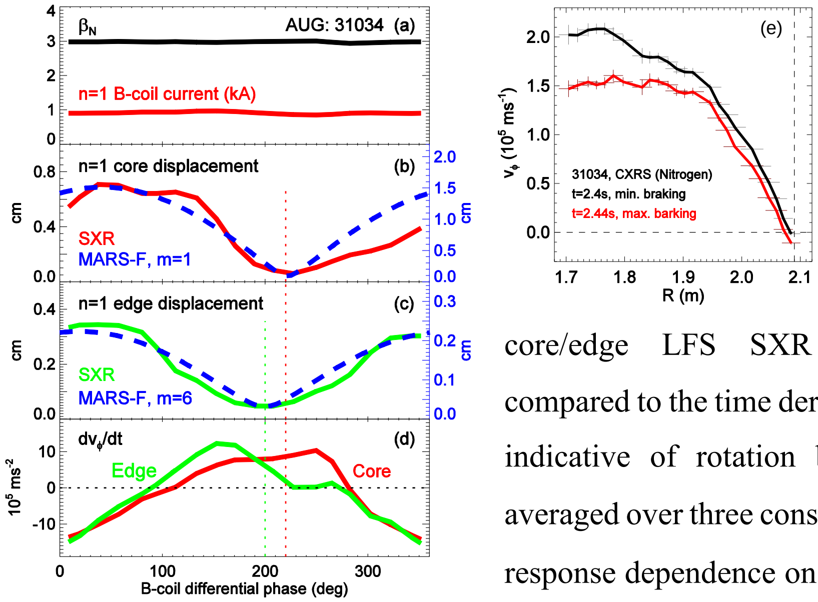

Fig. 4. (a) β_N and n=1 B-coil current, (b) n=1 SXR core and (c) edge displacement *vs* MARS-K displacement, (d) time derivative of core/edge rotation averaged over three $\Delta\phi^{U/L}$ scans. (e) Toroidal rotation profiles at minimum and maximum n=1 response.

core/edge LFS SXR displacement *vs* $\Delta\phi^{U/L}$, compared to the time derivative of core/edge rotation, indicative of rotation braking. All quantities are averaged over three consecutive $\Delta\phi^{U/L}$ scans. The n=1 response dependence on $\Delta\phi^{U/L}$ agrees with MARS-K (dashed blue lines). The core/edge responses are minimum at different $\Delta\phi^{U/L}$ in agreement with MARS-K. The n=1 response causes global rotation braking largest in the core, where the response also peaks, as shown by the rotation profiles in Fig. 4(e) at minimum (black) and maximum (red) n=1 response. Edge rotation reverses to counter-I_P, a small but robust effect confirmed by accurate error estimates. Evaluation of the torques due to the n=1 displacement, i.e. NTV, e.m., and changes in NBI torque due to fast-ion transport, is ongoing.

The internal response measurements reported here provide an excellent basis to validate MHD codes. More experiments are needed to fully validate kinetic effects, in particular knowledge of core q is necessary. Work is ongoing to extend code validation to M3D-C^1 with 2-fluid effects [6] and the free-boundary 3D equilibrium code V3FIT [7].

This work has shown that hybrid plasmas are highly sensitive to 3D fields as the no-wall limit is approached. Their distinctive feature is an n=1 response peaking in the core due to $q_{min}\approx 1$. This causes significant rotation braking and may also increase core thermal and fast ion transport, with possible consequences on hybrid discharge performance. Such effects may become an issue in presence of error fields or 3D fields for ELM mitigation and should be carefully evaluated. In future experiments it will be also interesting to extend these studies to lower rotation, where 3D field penetration is easier. Work is ongoing to compare these results to other tokamaks equipped with non axi-symmetric coils such as DIII-D.

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