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LOCATING RATIONAL SURFACES FROM REFLECTOMETER FLUCTUATIONS

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1. Introduction

One issue for advanced tokamak operation, e.g internal transport barriers, is the measurement and control of the current density and associated $q = d\Phi/d\Psi$ profiles (toroidal to poloidal flux derivative). 2-D equilibrium codes with magnetic measurements from flux loops and coil arrays are normally used to reconstruct the plasma boundary and internal flux surface geometry. However, magnetic measurements alone are insufficient for an accurate reconstruction of the core flux surfaces, so additional diagnostic information (e.g. MSE or polarimetry) is necessary to constrain the code solutions. For ITER, MSE and polarimetry will be technically challenging, however, if the radial locations of one or two rational surfaces ($q = m/n$) in the core can be measured via other means then these can also act as code constraints. Presented here is a proof-of-principle demonstration of the use of fluctuation reflectometry to locate low order rational surfaces.

2. Technique

Large amplitude MHD modes can generate substantial magnetic islands - seen as flat regions in the electron temperature (T_e) profile near rational q values. High resolution ECE and Thomson scattering (TS) - together with SXR tomography - commonly measure such islands. But as q-profile diagnostics each has limitations (i.e. flux surface data required for the positional mapping of line-of-sight measurements, or knowledge of internal $|B|$ field). MHD can also produce, to a lesser degree, a localised flattening or deformation of the density gradient across the island. TS and profile reflectometry [1,2] have observed such island structures, but generally have problems of sensitivity or resolution. An alternative technique is to monitor the level of microwave reflectometer phase fluctuations $\tilde{\phi}$ as a cutoff layer moves across a rational surface. If an island is present then even a small deformation of the density gradient ∇n will lead to an enhancement in the reflectometer's sensitivity to plasma fluctuations $\tilde{n}$ via: $\tilde{\phi} \propto (4\pi/\lambda)\, \tilde{n}\, \nabla n^{-1}$. This technique combines the advantages of reflectometry: limited access requirements, simple experimental setup, inexpensive - with high sensitivity. Of course, independent knowledge of the reflectometer cutoff layer position is still required, which could be provided by a fast frequency swept profile reflectometer while a slow frequency ramped reflectometer (<GHz/ms required to capture the full bandwidth of the plasma turbulence) provides the fluctuation information. These can be separate diagnostics, or one system with interleaved slow and fast frequency sweeps. For the demonstration here, a simple fixed frequency O-mode homodyne reflectometer operating on the ASDEX Upgrade tokamak is sufficient. The cutoff layer movement is generated by inherent density variations and is measured by a separate broadband swept profile reflectometer [3].

3. Results

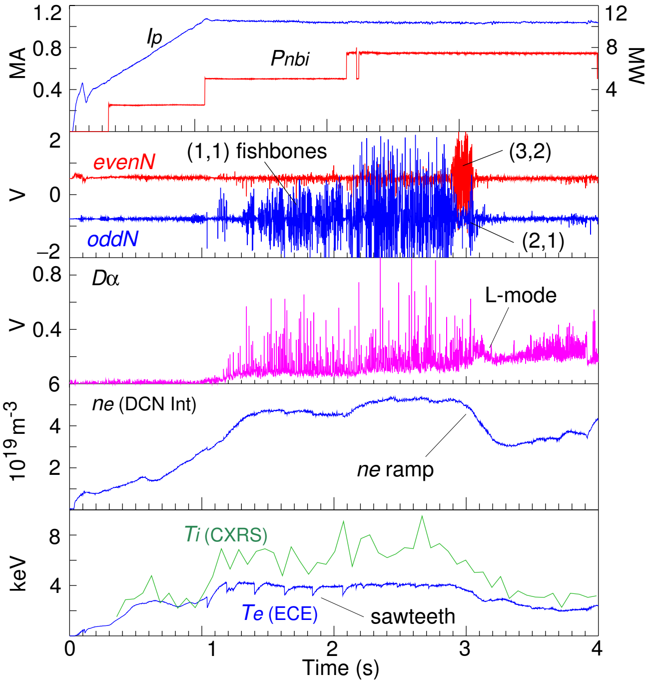

Figure 1: Plasma parameter time traces for 1.0MA/2.1T AUG shot #15025.

The two ingredients needed to demonstrate the technique, strong core MHD and substantial plasma density variation, are provided by a series of 1.0 MA/2.1 T H-mode discharge with a lower single null configuration of the type shown in fig. 1 (#15025). With the H-mode formation (NBI power step-up to 4 MW), m/n = (1,1) and (2,1) fishbones (odd N magnetic signal) plus sawteeth activity (central T_e ECE trace) are observed, indicating central $q_o < 1$. There is also intermittent (3,2) Neoclassical Tearing Mode (NTM) activity throughout the discharge (even N magnetic signal), but after $t \approx 2.865$ s the mode amplitude rises rapidly and the fishbones diminish, to be replaced later by a strong (2,1) mode after $t \approx 2.96$ s. As the (2,1) mode grows and its rotation slows down (there is intermittent locking and unlocking between 3.08 and 4 s) there is a loss in confinement and the density gently ramps down from a line average of 5 to 3×10^{19} m^{-3}. Fig. 2 shows the cutoff layer radius and rms fluctuation level from a 49 GHz O-mode reflectometer channel between 2.9 and 3.3 seconds. Prior to $t \approx 3.08$ s the discharge is in H-mode and the cutoff layer is close to the edge. The large fluctuation spikes are due to the ELMs. As the discharge drops back into L-mode the cutoff moves inward by about 20 cm, crossing the $q = 2$ and $q = 1.5$ rational surfaces. The fluctuation level falls by almost 2 orders of magnitude, followed by a distinct blip around $t \approx 3.19$ s. The cutoff layer position is calculated from smoothed multi-channel O-mode fast-swept reflectometer density profiles, validated against slower sampled Thomson scattering density data. Mapping the temporal behaviour of the rms fluctuation level against the cutoff layer evolution gives the radial profile shown in fig. 3. It is not so important that the confinement and profiles are changing during the radial sweep since it is not the purpose to measure the precise density fluctuation profile but simply locate distinct identifying markers associated with the rational surfaces.

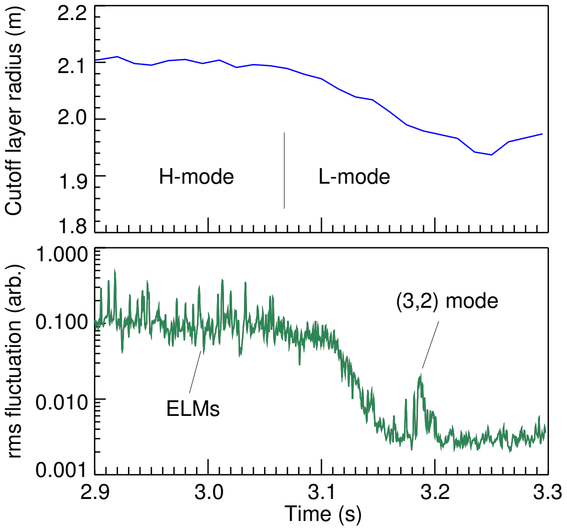

Figure 2: 49GHz O-mode reflectometer cutoff layer position (from profile refl.) plus rms fluctuation level for #15025.

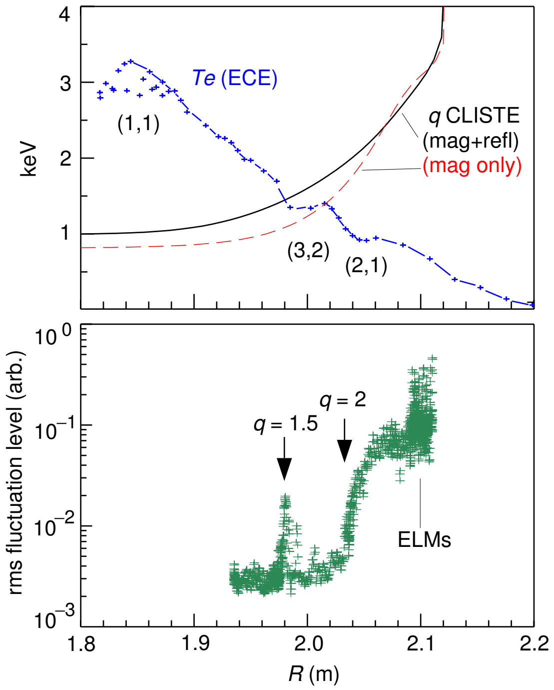

Figure 3: T_e *(ECE),* q *(*CLISTE*) profiles at* $t = 3.2s$*, plus refl. rms fluctuation profile - mapped from fig. 2*

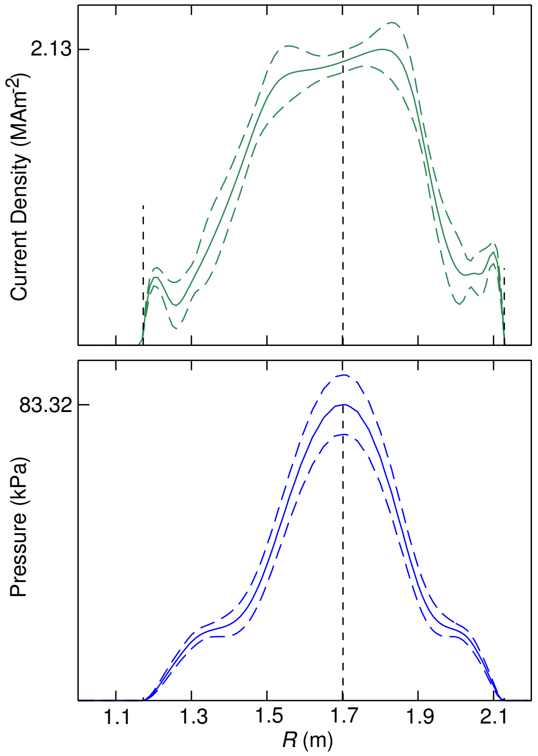

Figure 4: Current density and plasma pressure profiles from CLISTE *for fig. 3 constraints at* $t = 3.2s$*, shot #15025.*

Fig. 3 also shows the T_e profile (ECE) at $t = 3.2$ s. There are two islands at 1.99 m and 2.05 m which are identified from mode analysis of magnetic and SXR camera data as (3,2) and (2,1) modes respectively. The rms fluctuation profile shows enhanced signal fluctuation levels coinciding with both island locations. Outside the (2,1) mode the fluctuation level remains high due ELM effects and higher order coupled modes at the edge. Note, due to the reflectometer's sensitivity to the density gradient, the fluctuation peaks do not necessarily imply that plasma turbulence actually increases at the rational surfaces.

4. q-profile reconstruction

Included in fig. 3 are two q-profiles computed using the CLISTE equilibrium code [4] (without kinetic data). The dashed curve is with standard magnetic measurements alone, while the solid curve is with reflectometer constrains applied; namely the radial positions of the $q = 1.5$ and $q = 2$ values. The corresponding (constrained) current density j_{tor} and pressure profiles p are shown in fig. 4. The constraints raise the core q and give a better fit to the experimental data resulting in a broader j_{tor} profile and a more peaked core p profile with flat regions around the islands in agreement with experimental pressure profiles.

5. Mode sensitivity

The mode sensitivity is illustrated by another similar AUG shot, #13356 in fig. 5. Here, two rms fluctuation profiles are shown, first during a density ramp-up at the start of the discharge with no pronounced MHD activity, and secondly during a (2,1) mode induced density collapse. For this shot, the temporal behaviour of the 49 GHz fluctuation channel is mapped using (compensated) Thomson scattering density data. The non-MHD profile is smooth and monotonically increases with radius. During the sweep the cutoff layer crosses rational surfaces, but there are no obvious indicators in the fluctuation level. With MHD, the profile displays clear rational surface peaks correlating with the (3,2) and (2,1) islands in the T_e profile and SXR data. A spectral analysis of reflectometer signal reveals a clear set of spectral peaks for both modes, from which it is possible to perform the harmonic amplitude analysis (based on Bessel function decomposition) [5]. For example, as the cutoff moves towards the (3,2) mode centre (i.e. rational layer) the ratio of 1st to 3rd harmonic amplitudes reverses, consistent with the increasing phase $\tilde{\phi}$ perturbation.

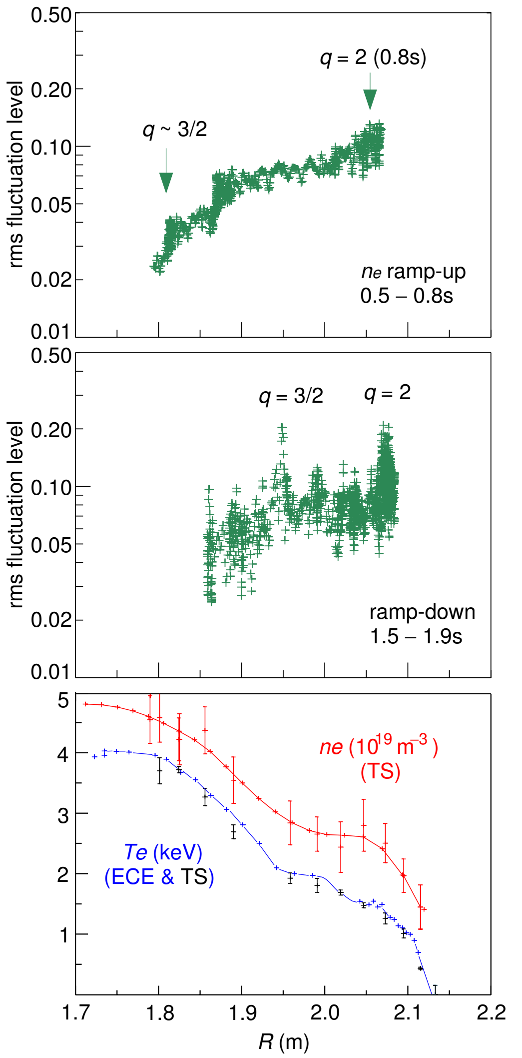

Figure 5: 49GHz O-mode refl. rms fluctuation profile during density ramp-up and ramp-down with strong MHD, plus T_e (ECE) and n_e (TS) profiles for shot #13356.

6. Radial errors

The fluctuation peaks appear at the island inner edges, perhaps due to density gradient or island width effects in the cutoff layer location from the profile reflectometer. MSE data is available for shot #13356, but it results in a much flatter and lower q-profile with rational q-positions at the island outer edges. This discrepancy is still to be resolved.

7. Discussion and conclusions

Like ECE and SXR this technique needs MHD modes to locate the rational layers, which is perhaps its main drawback - since MHD is generally undesirable in tokamak plasmas. Nevertheless, the technique does not require a pronounced flat spot in the density profile (as is the case for profile or mean phase shift detection, c.f. [3]) - just enough deformation to produce a reliable and significant indication of rational surface position above the statistical background fluctuations/diagnostic noise floor. However, further experimental study and simulation modelling are required to determine the minimum detectable mode amplitude or degree of density profile flattening and island width.

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