Using rotating current ribbons to model MHD: the EHO

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The QH-mode was originally discovered in DIII-D [1], in strongly pumped plasmas with counter-beam injection. An edge harmonic oscillation (EHO), was identified in these plasmas, usually with an n=1 or n=2 fundamental, and many harmonics, spinning in the NBI direction. Subsequently QH-modes with EHOs were observed with both co, mixed and balanced injection [2]. It has been established that strong rotation, or E×B, shear is necessary for the EHO to be long-lived.

A study of low density, high temperature plasmas at JET, back in 2008 (Beryllium wall and Carbon divertor), showed that under similar conditions (low recycling, but strong co-NBI) a very clear, long-lived, multi-harmonic oscillation is observed near the pedestal region, called the Outer Mode at JET. Similarly to the EHO, its existence was associated with sufficient rotation shear. Since then, we have speculated that the JET Outer Mode is equivalent to the DIII-D EHO. Analysis of the JET multi-harmonic Outer Mode can be found in [3].

Analysis of magnetic signals in JET showed very sudden blips in dB/dt at the Mirnov sensors in the low-field side (LFS). Up to 15 harmonics of the fundamental frequency were observed. A toroidally localised current source spinning in front of the sensors could be responsible for the observed poloidal field perturbations (this MHD model was first proposed in [4]). We successfully modelled the Outer Mode (OM) with a toroidally co-rotating current ribbon, with toroidal width 20-40º, current of 200 A (the total plasma current was 2.5 MA), and parallel to the magnetic field at q=4 (other shots had OMs with other q values). The radial location of the ribbon was found by noticing that the mode frequency matched the toroidal rotation frequency at the pedestal flat top, where grad(T_i) is minimal or zero, so poloidal rotation is expected to be zero (ion temperature and rotation measurements derived from Carbon VI charge exchange spectroscopy). Sufficient toroidal velocity, or its shear, is needed to sustain the OM. We noted in [3] that the frozen-in law of ideal MHD implies that velocity

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shear produces B vorticity, leading to current filament formation: the JET OM is analogous to a smoke ring. Here we investigate if the same model can be applied to the DIII-D EHO.

Because rotation shear appears to be an essential ingredient for both Outer Mode and EHO, we took advantage of DIII-D's recent measurements of main ion rotation [5] to study in detail the time window 1700-1800 ms of the DIII-D shot 169366. This is a QH-mode with 2T, 1.1 MA, 6.7 MW of counter-NBI. Like in the JET case, the pedestal temperatures are high, as well as rotation frequencies, Fig. 1. And, like in the Outer Mode, the toroidal rotation frequency in the flat-top region of the n_e, T_e, T_i, T_C pedestals, R~ 2.25 m, matches the MHD mode frequency, and has shear. Since in that region T_i has negligible gradient, we might be in the same situation as in JET. Another shot, 164900, showed these same features.

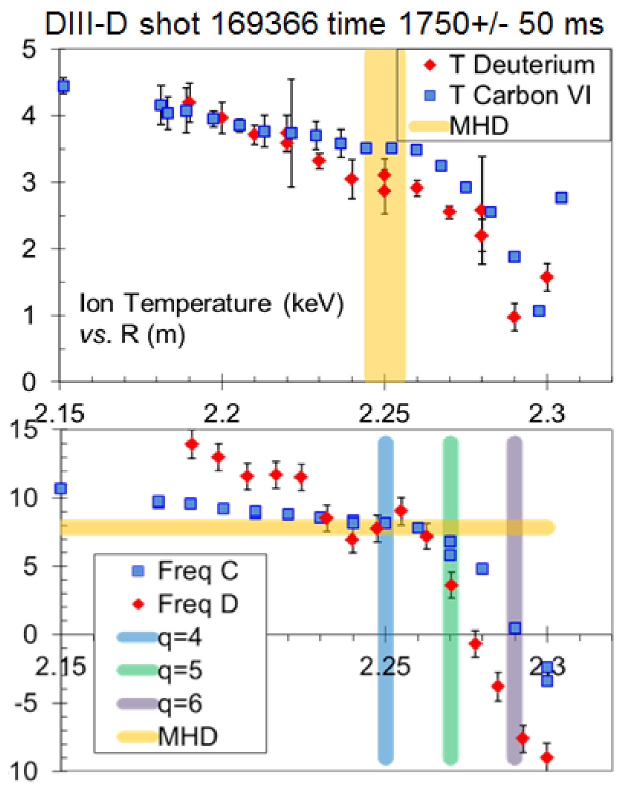

Fig. 1: Top: Deuterium and Carbon temperature profiles, in keV, vertical bar marks approximate location where MHD and rotation frequencies match. Bottom: toroidal rotation frequencies, in kHz, with location of rational q surfaces marked with vertical bars and mode frequency with horizontal yellow bar.

With carefully validated data (electron density and temperature from Thomson Scattering, Carbon VI temperature, density and rotation from CER, and core MSE) and with the PyD3D tool set and prescriptions [6], we produced a kinetic equilibrium reconstruction for 169366 at 1750 ms. A simple ONETWO model was used to account for considerable fast ion pressure, typical of the QH-mode. The resulting location of the rational surfaces is depicted in Fig.1. We see that mode and toroidal rotation frequencies would match at q=4, and not at $q \geq 5$. Uncertainties remain in the equilibrium reconstruction, in part because we used T_C as a proxy for T_i in the construction of the total pressure profile. T_i and main ion rotation measurements are still somewhat uncertain, possibly due to high Z_{eff} and large fast ion pressure, and difficult to implement in PyD3D. Whether the various uncertainties might

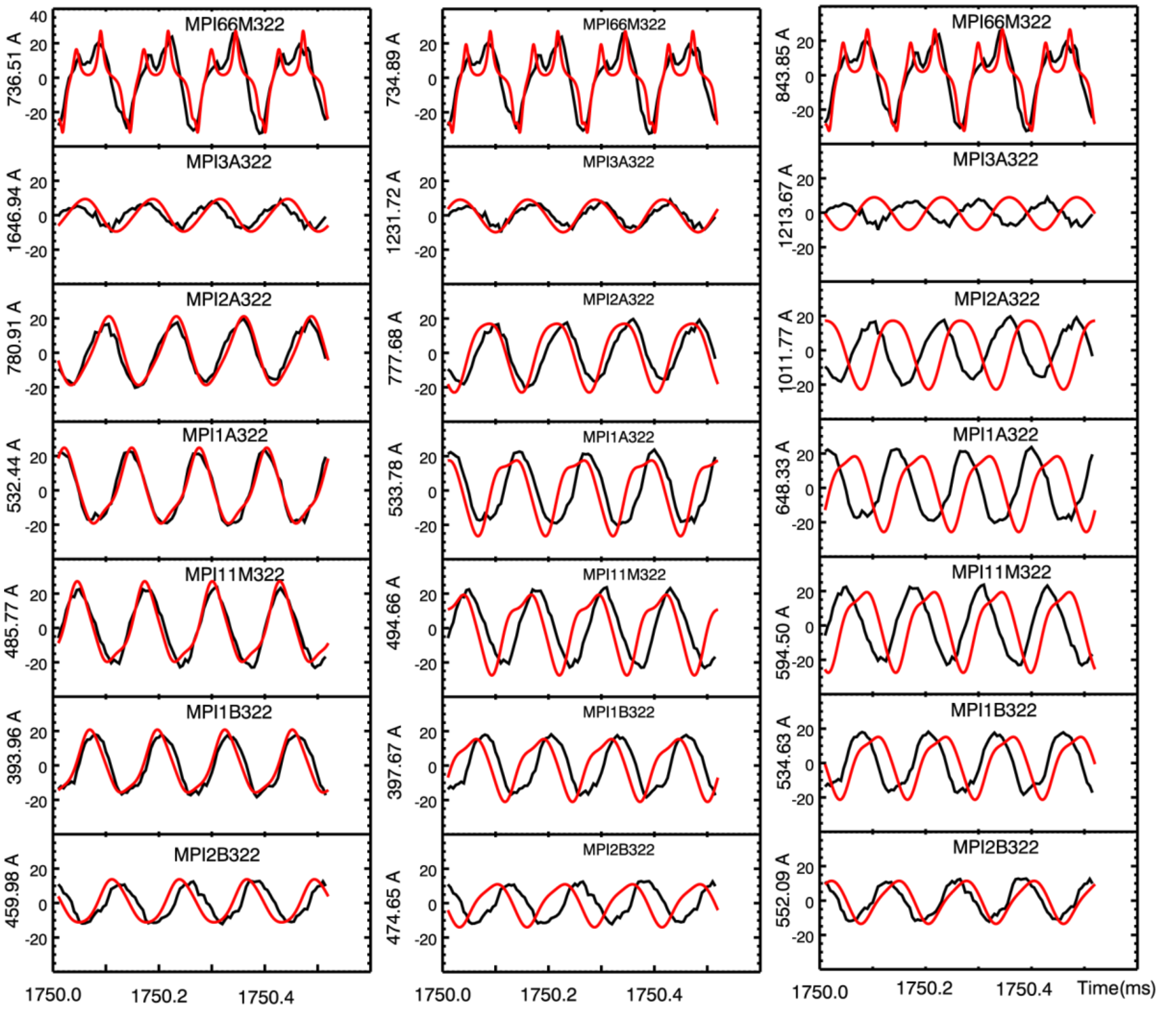

Fig. 2: Model signals (red) compared with data (black): the top row is an outer midplane Mirnov, the following ones are in the HFS, from above to below the equator. The 1st column shows the best match to the data , with a q=5 ribbon, 100º wide, and a q=4 ribbon, 50º wide, with 1/3 of the total ribbon current. Shown in the 2nd column are two q=5 ribbons, 3rd column, two q=4 ribbons, with same widths and current ratios but different currents. The y axis label of each plot indicates the total current in the ribbons needed to match the experimental signal.

allow us to shift the q=4 and/or q=5 surfaces inward 1 cm, so that both would correspond to matching main ion rotation and mode frequencies, is not known at this point.

From the reconstructed equilibrium we traced closed field lines in rational surfaces with q=4,5,6,7, using trip3d [8]. Wide current ribbons are constructed by adding the field produced by parallel current filaments, toroidally displaced from the original. Finally, we computed the dB/dt signals that would be produced at the sensors if the ribbons were to be spun toroidally with the mode frequency. We did not find a good match for any single q value, and they were especially poor for q>5. Using two ribbons, to account for the double bump structure in the LFS coils, we found a better match with a combination of a q=4 and a q=5 ribbons, than with either q=4 or q=5 structures alone, see Fig. 2. We found very poor match for q=6, 7.

We also used the DIII-D MHD analysis Fourier code modespec [9] to identify the magnetic mode by fitting the measured mode phase to a function of the poloidal angle θ. Modespec correctly recognizes the m=5 structure of synthetic data from a current filament at q=5. In the experimental data, modespec identifies the n=2 harmonic as consistent with m=10, matching q=5, but the n=1 harmonic is identified as having m=6, or maybe m=7. In this analysis, neither m=4 nor m=5 provides a good fit to the HFS measurements of the n=1 harmonic. An alternate SVD analysis technique [10] created principal axes vectors from q=4,5,6,7 filaments and identified q=4 and q=5 as dominant components of the data, with likelihood 0.6 and 0.73 respectively, and q=6 and 7 below 0.3. The SVD method fits the data to a model of the field from helical currents in the magnetic geometry of the discharge, but does not include the response of the plasma to those currents. In contrast, the modespec algorithm identifies the spatial distribution of the measured magnetic perturbation outside the plasma, but without reference to a specific model of the plasma geometry. The plasma response remains a source of uncertainty, since a current source with a q=5 structure might possibly drive a kink-type plasma response near the plasma edge with higher m numbers.

In summary: we find a representation of this EHO with a combination of q=4 and q=5 spinning current ribbons. So, is the EHO, like the OM, made of smoke rings? Alas, too much uncertainty remains to exclude a kink in the gradient region [11, 12] as EHO model.

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