Structure of island localized modes in Wendelstein 7-X

G. A. Wurden[1], T. Andreeva[2], S. Ballinger[3], S. Bozhenkov[2], C. Brandt[2], B. Buttenschoen[2], H. Damm[2], M. Endler[2], S. Freundt[2], J. Geiger[2], K. Hammond[2], M. Hirsch[2], U. Höfel[2], C. Killer[2], G. Kocsis[4], P. Kornejew[2], A. Krämer-Flecken[5], M. Krychowiak[2], S. Lazerson[6], K. Rahbarnia[2], J. Schilling[2], T. Szepesi[4], H. Thomsen[2], V. Winters[7], S. Zoletnik[4], and the W7-X Team

[1] *Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87545 USA*

[2] *Max-Planck-Institut für Plasmaphysik, Wendelsteinstrasse 1, 17491 Greifswald*

[3] *Massachusetts Institute of Technology, Cambridge, MA, 02139 USA*

[4] *Wigner Research Centre for Physics, Budapest, Hungary*

[5] *Institute for Climate and Energy Research – Plasma Physics, Forschungszentrum Jülich, Germany*

[6] *Princeton Plasma Physics Laboratory, PO. Box 451, Princeton, NJ 08540 USA*

[7] *University of Wisconsin, Madison, WI 58706 USA*

Introduction: Low frequency edge fluctuations (150-1200 Hz) localized near the last closed flux surface, showing discrete losses of stored energy with each event, are seen during an iota scan of the magnetic configurations in Wendelstein 7-X. The nature of the fluctuations change from quasi-continuous[1,2], to bursty (sawtooth crashes), and back to quasi-continuous, as the 5/5 island chain appears in the plasma core and then moves outwards in radius, during progressive discharges as iota is scanned (lowered). Typically, 1-4% of the diamagnetic stored energy is lost per event, which when summed up over time accounts for ~10-15% of the overall plasma losses. The amplitude of the fluctuations increase with increasing ECRH input power, and also with the application of positive control coil currents (which causes widening of magnetic islands). Bursts of energy and particles are picked up on the divertor. We see toroidal current fluctuations at the edge of the plasma (using 8 partial Rogowski sensors), with polarities dependent on magnetic island positions. With the 360 chord soft X-ray diagnostic [3], consisting of 20 cameras (each with 18 chords) located poloidally around one of the triangular planes of the W7-X vacuum vessel, we can determine the radial location of the sawtooth crashes, using the intersection of sight-lines which show inversion. The intersections of the inversion chords correspond well to magnetic flux surface Poincaré plots, revealing the 5/5 island chain. The crashes, which we name "island localized modes" (ILM's) are found to originate at the 5/5 magnetic island positions. Fine structure can be seen during the 1-3 millisecond time of the crash, which has phase variations from island to island, within the same crash event. Complex magnetic perturbation signatures are seen in the Mirnov coils.

Experimental Setup: During the most recent operating campaign (OP1.2b), we scanned iota in a series of discharges (see paper T. Andreeva, et al., P2.1063 this conference), from the "high-iota" magnetic configuration, with iota just above unity (5/5) on axis, rising to iota < 5/4 at the plasma edge, down to "standard iota", which has iota in the plasma boundary just less than 5/5. This scan resulted in an interesting change in the low frequency fluctuations. First, at high iota, there is the quasi-continuous "ELM-like" 170 Hz fluctuation (reported last year [1]). Then, we lowered the iota profile by reducing the planar coil current settings, in a series of steps. The 5/4 island chain at the plasma edge moves all the way out past the divertor plates, and the 5/5 island chain appears in the core, and "marches" outwards, to larger radii.

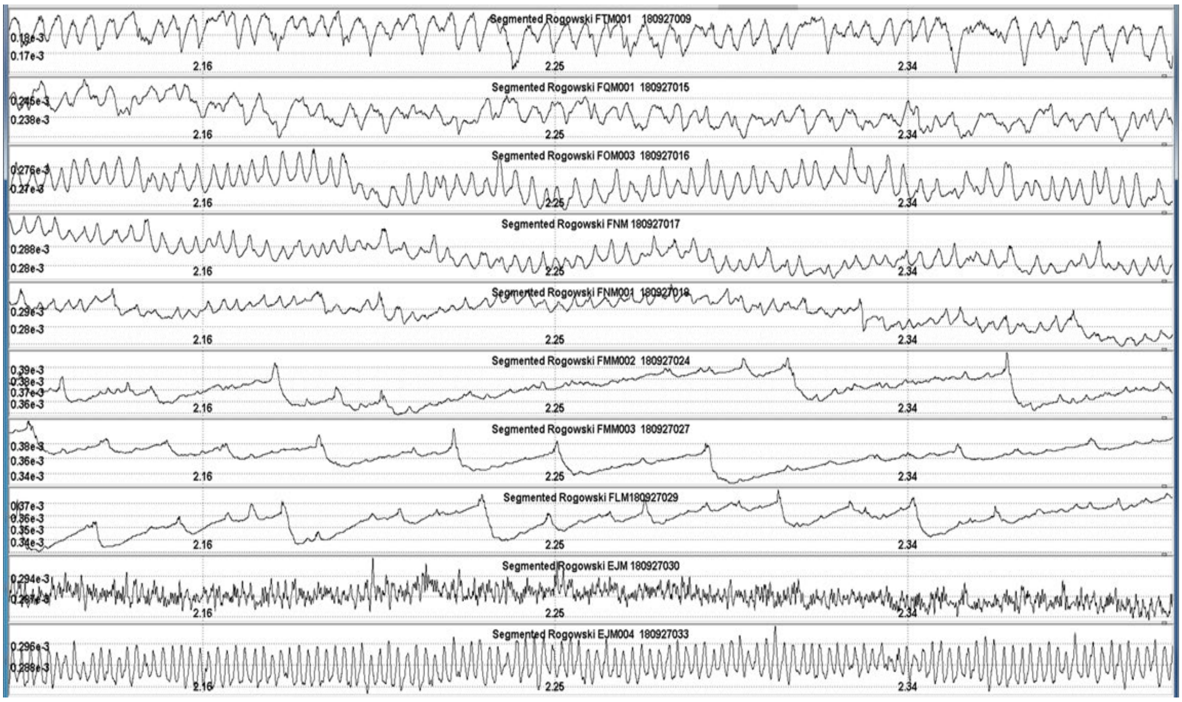

Figure 1: Time traces (in seconds) from one segmented Rogowski coil for different shots, showing the change in the nature of the fluctuations (in this case, in edge plasma currents), during a shot-by-shot iota scan from high iota (top, FTM) down to standard iota (bottom, EJM) magnetic configuration.

In Figure 1, the dominant fluctuation frequency changes from 170 Hz to as high as 1200 Hz, but more interestingly, there are four configurations (with the 5/5 islands at ~ 70-90% or the minor radius) where, in addition, "crashing" or sawtoothing behavior occurs. We name these fluctuations as Island Localized Modes (ILMs), and in this paper we further focus on them using the W7-X soft X-ray diagnostic tomographic system. We have multiple diagnostics to look at the edge sawtoothing activity, which involves transport of energy, particles, and currents, past the last closed flux surface into the very edge of the plasma. The crash time duration is 1-3 milliseconds. The time behavior of several diagnostics during sawtoothing is shown below in Figure 2 for an FMM002 discharge, shot 20180927.022.

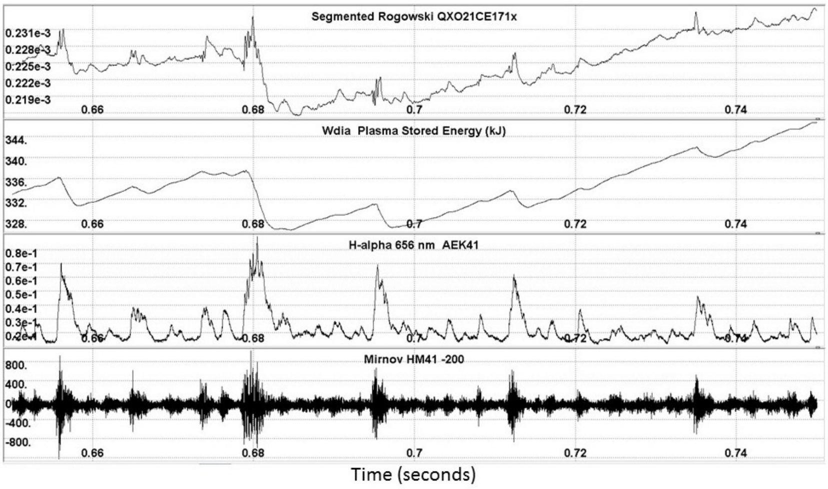

Figure 2 Sawtoothing activity, time traces of segmented Rogowski, diamagnetic energy, H-alpha, and one Mirnov coil. The FMM002 configuration has a noticeably higher energy confinement time, by ~50%, than standard or high iota configurations.

In Figure 3, we first indicate all 360 soft X-ray sightlines in red, outside of the blue last closed flux surface (LCFS), overlaid on a Poincare plot corresponding to the FMM magnetic configuration. Chords which show fully inverted behavior are green, and the 11 transition chords between inverted, and non-inverted sawteeth, are shown in red inside the LCFS.

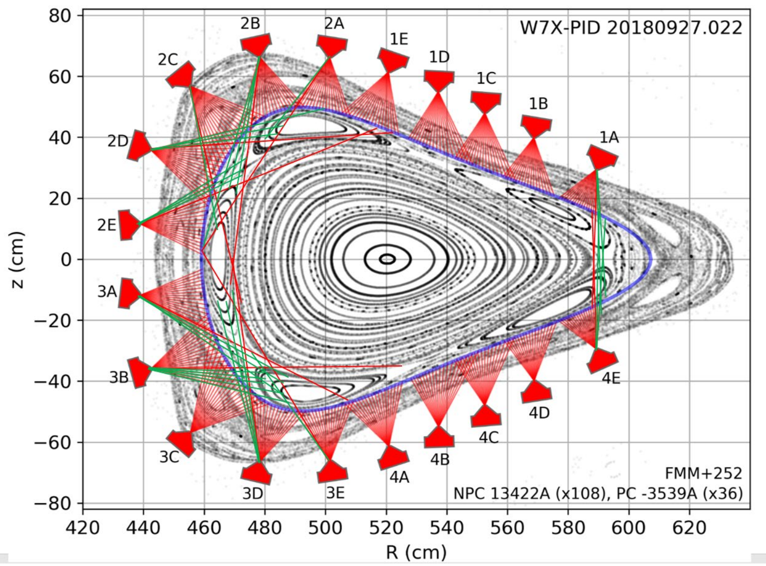

Figure 3. X-ray sight lines overlaid on Poincaré plot for this magnetic configuration. Blue line represents the last closed flux surface. Red lines inside it are X-ray chords which transition from crashing to pulsing "upwards". Green lines are fully inverted (upwards pulse of x-rays at the sawtooth crash).

Furthermore, when the island is shifted radially during the magnetic field scan, the transition lines shift radially as well, consistent with Poincaré plot predictions of island positions.

Discussion:

Two types of low-frequency fluctuation behavior, oscillatory and sawtooth crashing, vary as the magnetic geometry (iota) and therefore island positions in the plasma are scanned. Using Poincaré plot information, we infer that when the large island chain near the plasma edge (either 5/4 or 5/5) is being "cut" by the divertor plates, we see saturated oscillatory behavior.

But when the island chain is located further inside the plasma (e.g., the 5/5), we see sawtooth crashes, which accompany step-like drops in the diamagnetic stored energy, and associated changes (either crash or pulse upwards) in soft X-ray emissivity, depending on whether the X-ray chord tangency point is inside or outside of the magnetic island position. We speculate that when the islands are positioned so they are no longer being “cut”, an additional loss channel …sawtooth crashing…comes into play. For certain magnetic configurations, we even see a mixture, where both oscillatory and sawtoothing behavior exist together. Edge plasma current fluctuations seen on the partial Rogowskis are large, and due to the fast timescales, must be localized (edge or surface) toroidal plasma currents. Electron temperatures (ECE channel 1) are in the 300-400 eV range at the island inversion radius locations. The application of control controls can enhance or suppress sawtoothing activity, in accordance with expected increases (or decreases) in island size. The sodium beam and microwave Doppler backscatter reflectometer show accompanying density fluctuations which are propagating poloidally inside/at the island locations, consistent with ExB rotation around the island. One possible explanation for the frequency of the quasi-continuous oscillations is that it is inversely related to the island size….it takes longer to ExB rotate around a big island, than a small one. We speculate that the instability which leads to sawtoothing, is due to drift-zonal flows in the magnetic island [4], which are unstable as the toroidal plasma current evolves within the islands. In the future, we will look for time evolution and flattening of the electron temperature profile at island locations, seen by the Thomson scattering diagnostic, with boxcar averaging techniques to improve the signal to noise ratio. We also will be investigating the fine structure of the crashes, which may have specific island X-point structural behavior, using full soft x-ray tomographic reconstructions.

Acknowledgements: Supported by the US-DOE/IPP collaboration under DOE LANS Contract DE-AC52-06NA25396. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References:

[1] G. A. Wurden, S. Ballinger, Bozhenkov, et al, “Quasi-continuous low frequency edge fluctuations in the W7-X stellarator”, P5.1077, 45th EPS Conference on Plasma Physics, Prague, 2018.

[2] M. Hirsch et al, “Major Results from the stellarator Wendelstein 7-AS”, PPCF 50, 053001 (2008).

[3] C. Brandt et al, "Installation of the soft X-ray multi-camera tomography system (XMCTS) in the Wendelstein 7-X stellarator“. Fusion. Eng. Design 123, 887–891 (2017).

[4] D. Grasso, L. Margheriti, F. Porcelli and C. Tebaldi, “Magnetic Islands and spontaneous generation of zonal flows”, Plasma Physics and Controlled Fusion, 48(9) L87, 2006.