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Confinement and Equilibrium with Internal Islands in a Configuration Scan with respect to Iota in W7-X

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Wendelstein 7-X (W7-X) is an advanced stellarator [1] designed to explore the reactor viability of optimized stellarators. The device started operation in December 2015 with a simple uncooled limiter for an integral commissioning phase of about three months. In 2016/17 an uncooled divertor, the so-called test-divertor-unit (TDU), was installed which has the same geometry as the water-cooled high-heat-flux (HHF) divertor (currently undergoing installation). Two campaigns lasting about 3 months each in 2017 and 2018 were performed for a first exploration of divertor plasmas [2], for initial testing of the optimization goals in various magnetic configurations, as far as plasma parameters allowed, and for addressing a wider range of physics questions like heating schemes, current drive or turbulence investigations.
In a dedicated series of experimental programs the space of magnetic configurations has been explored in a scan [3] varying the vacuum rotational transform iota between two main configurations used for divertor operation. In these two main configurations naturally occurring island chains define the plasma boundary for proper plasma-divertor interaction. The first is the so-called high-iota configuration with an axis-iota just above 1 rising towards the boundary which is formed by the 5/4-island chain, and the second is the so-called standard configuration with a boundary-iota of 1 (=5/5) and a central iota-value of just above 5/6. Such a scan is of interest with respect to plasma confinement, equilibrium and stability as the position of the iota=1-resonance is shifted radially through the confinement volume in the scan with different higher-order resonances appearing at the plasma boundary, e.g. 10/9, 15/13 and 15/14. In particular, it is known that rational values of iota appearing at the edge can lead to changes in the confinement behaviour of magnetic configurations of which one example is the appearance of the so-called iota-windows of the H-mode in devices like W7-AS [4] or Heliotron-J [5]. The appearance of rational values of iota within the plasma can trigger MHD-modes but has also been observed in connection with internal transport barriers.
The experiments were performed with 2MW of ECR-heating power (140GHz, X2-mode) at a field strength of 2.52T on axis in the ECRH-launching plane. The line density was targeted at $3.5 \cdot 10^{19} m^{-2}$ but a constant line density during the 4s-discharges was not fully achieved. The experimental results can be summarized as follows:
From the view point of confinement an improvement in confinement was observed as iota was lowered in the iota-range where good flux surfaces limited the plasma. The confinement in this range is somewhat better than the expectation from the dependencies in the ISS04-scaling on density and volume. The major part of the volume effect arises from the altered magnetic field topology at the boundary when the separatrix-bounded configuration changes to the larger-volume, limiter configurations. In the range in between the two main separatrix-configurations, where good flux surfaces limit the plasma, the volume only changes slightly and can not explain the improvement.
Connected to MHD-stability, the configurations in the lower half of the scanned iota-range, where the 5/5 resonance is in the outer half of the plasma and moving towards the plasma boundary once iota is reduced, burst-like MHD-events were observed in the fluctuation diagnostics (Mirnov, ECE, soft-X ray camera system) but also in the equilibrium diagnostics (diamagnetic signal) and in the Rogowski-coil signal measuring the plasma current [6]. The modes could be shown to be located at the position of the 5/5-islands of the vacuum magnetic field, the average beta values of the discharges being small (in the range of 0.2 to 0.4%) such that the vacuum field seems to be a viable first approximation. It should be noted that similar burst-like modes are also observed when the 5/4- or the 5/6-island chain is present in the outer regions of the plasma depending on the specific configuration.
Up to now, to include finite beta-effects in the evaluation, the VMEC-code was used which rests on the assumption that the equilibrium consists of nested flux surfaces, thus excluding a major characteristic of the experimental situation with islands in the confinement region. With the so-called VMEC/EXTENDER-approach [7,8] this can be corrected to a certain extent, but the resulting fields are not true MHD-equilibrium fields and do not include the plasma response to the changed internal magnetic topology. Therefore, the HINT-code [9] which can treat islands and stochastic regions in the MHD-equilibrium (amongst other codes like PIES, SIESTA and SPEC) is used for equilibrium calculations.
This contribution shows the experimental results of the configuration scan with respect to confinement and mode-activity. It also presents HINT-calculations for various configurations in the iota-scan and compares them with the results of the VMEC/EXTENDER-approach. The pressure profiles used for the calculations are modelled so as to reproduce the measured energy content and are derived from Thomson scattering data for electron temperature and density and from ion temperature profile data gained from the XICS-diagnostic. A major concern in the comparison is the location and width of the 5/5-islands and the possible appearance of

stochasticity around the islands or at the plasma edge. Also the small but finite beta-values are considered in the volume effect in the confinement investigation.

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