Low-shear configurations to test MHD-stability in Wendelstein 7-X

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Introduction

The magnetic configuration of Wendelstein 7-X (W7-X) was designed for good MHD-stability as one aspect among several optimization criteria. Although the optimization targeted a specific configuration, this property is to some extent present in most configurations. Nevertheless, specific choices of the coil currents can generate magnetic configurations with lower MHD-stability limits. This "tuning" relates to configurations with lower rotational transform ι, increased toroidal mirror field and a horizontal outward-shift of the plasma column. All three changes decrease the shear in the ι-profile and push the values of the vacuum magnetic well towards magnetic hill [1]. Fig. 1 shows a schematic overview of the vacuum magnetic well property in the magnetic configuration-space of W7-X in terms of the toroidal mirror field (Boozer-coordinate Fourier coefficient of |B|, b_{01} ≈ mirror ratio mr), a horizontal shift parameter (imbalance of planar coil currents generating vertical fields) and the ι-value at a minor radius of r_{eff}=0.52m. The values are generated from fit functions to these parameters based on a large number of VMEC-equilibria covering the magnetic configuration space of W7-X. The blue (yellow) plane indicates configurations with standard-ι (low-ι) at the boundary with 5/5 (5/6) islands forming the plasma boundary. For orientation the surface with configurations sharing the same value of the magnetic well property V'' (=d^2V/ds^2, V=plasma volume, s=norm. tor. flux) at r_{eff}=0.2m with that of the so-called low-shear configuration (red bullet, W7-X naming convention ILD) is shown in purple. Configurations above the purple surface have more negative values of V'' and have better Mercier stability properties like the three reference configurations (standard case, high-mirror and low-iota) shown as blue diamonds. The low-shear configuration proves to be marginally stable wrt Mercier modes at low average <β>-values of around 1%. A CAS3D analysis with various profile forms shows a <β>-limit for global modes at about 1.7%. For a test of the MHD-stability-limit at an early stage of the plasma operation, configurations below the purple surface in Fig.1 would be preferred. However, for operation at the nominal field of 2.5T, this part of the configuration space is not fully accessible due to

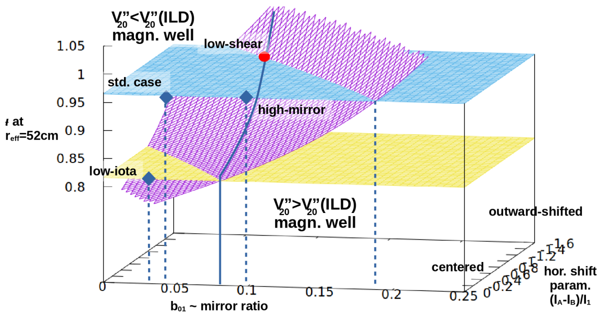

Figure 1: Vacuum magnetic configuration space of W7-X viewed in terms of mirror ratio, horizontal plasma position and ι at r_{eff}=0.52m. Only the outward-shifted region is shown, also the high-iota region is excluded.

various engineering constraints (forces, stresses and movements in the coil system and support structure, limits in power supply and safety systems). This excludes low-iota configurations with large mirror fields, which are Mercier-unstable at low β-values due to a vacuum magnetic hill. Some configurations would be accessible at reduced field strengths for which a viable heating and start-up scenario still needs to be established. The low-shear configuration ILD thus seems to be a good candidate for a first test of MHD-stability in the experiment.

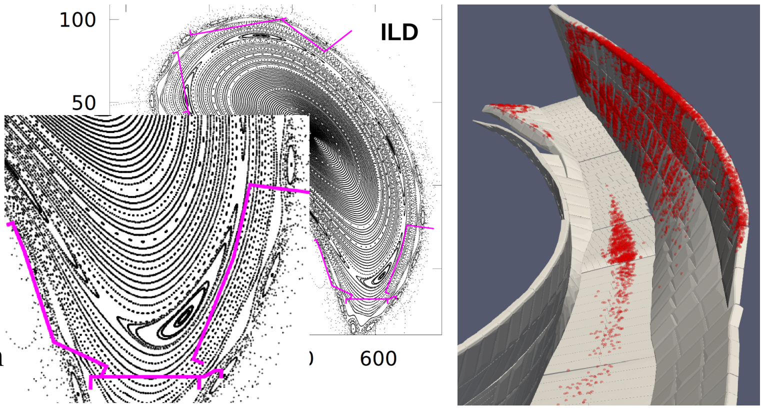

Figure 2: Left: Poincaré plots of vacuum field (ILD) and divertor structures with zoom of lower divertor part (high-iota tail). Right: Hit points on the high-iota tail of the divertor of a field line diffusion calculation for <β>≈0.8%.

However, investigations of ILD wrt heat-loads on the divertor structure (targets and baffles) showed unexpectedly high loads at the outboard-side baffle of the so-called high-iota tail of the divertor resulting from the strong outward-shift of this configuration shown in Fig. 2. In particular, one of the x-points is very close to the outboard-side baffle moving further outward with increasing β which leads to undesirable heat deposition on the baffle edges (see Fig.2 right).

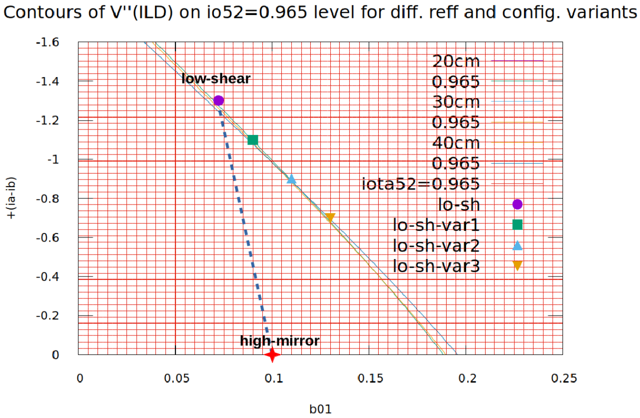

Figure 3: Variations of ILD (low-shear) in the space of planar field coil asymmetry and mirror ratio keeping the boundary iota value constant (blue plane in Fig.1).

Extension of configuration space for experiments

To mitigate the baffle heat-load problem in ILD, configurations were explored with reduced outward-shift at constant boundary-iota but increased mirror ratio as suggested by the results in Fig.1. Fig.3 shows a sequence of less outward-shifted configurations at constant ι designed to keep the vacuum magnetic well and ι-profiles constant by increasing the mirror ratio. The final choice is a modification of the “lo-sh-var2” of Fig.3 which has the W7-X designation MMG. This eliminates the high baffle loads (see Fig.4) while leaving the MHD-stability-properties largely unaffected (see Fig.5). The seven coil currents of this configuration for $B_{ax}(\varphi=0°)$ =

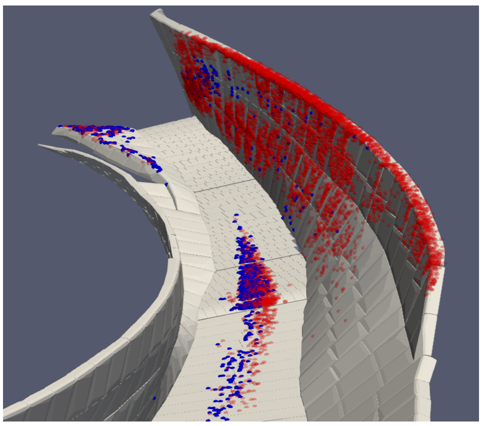

Figure 4: Overlay of hit-points of field line diffusion calculation for ILD (red) and MMG (blue) configuration. Compare right frame in Fig.3.

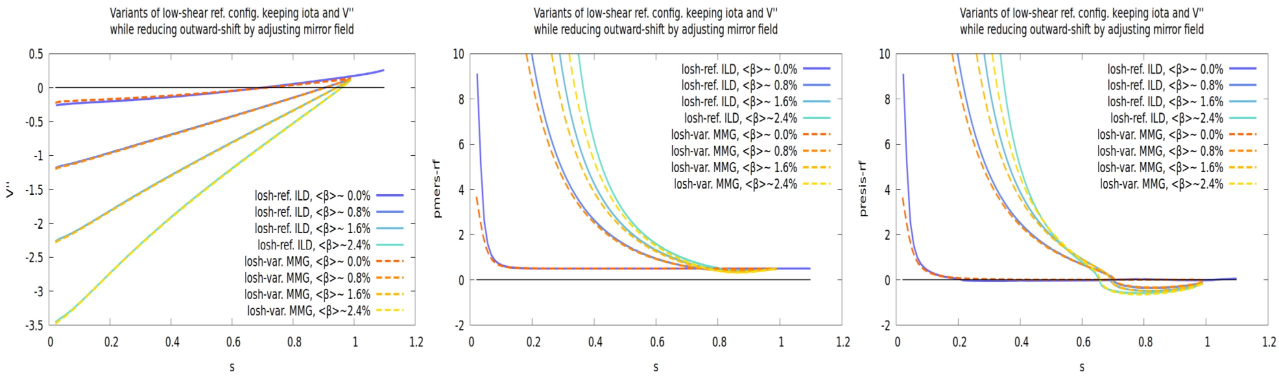

Figure 5: V'' (left), ideal (middle) and resistive (right) interchange criteria for ILD and MMG for different beta-values with pressure profiles ~(1-s)^2. The effect of low-order resonances is omitted.

2.52T are given as (I_1,…, I_5, I_A, I_B)=(14232A, 13549A, 12595A, 10033A, 9820A, -7087A, 5764A) and the toroidal mirror field is about 12% . An investigation with CAS3D for pressure profiles ~ (1-s)^2 (peaking factor of about 3) shows that the stability limit for the appearance of global modes is similar to ILD (see Fig. 6) although the predicted β-limit is increased from 1.7% (ILD) to about 1.9% (MMG). An additional configuration considered in the study with a mirror ratio of ca 13% (NNG) shows, as expected from the mirror ratio dependence, a lower critical β-value of about 1.8%.

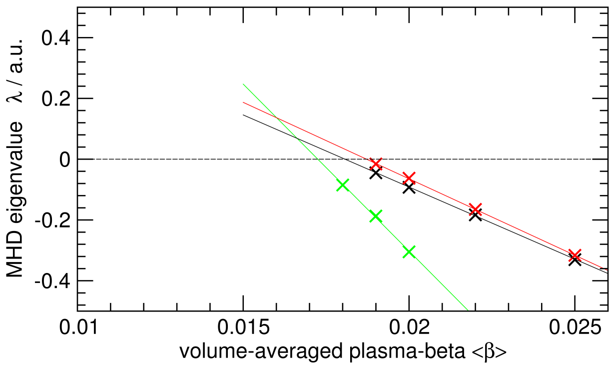

Figure 6: Eigenvalues of the most unstable ideal MHD-perturbations for the low-shear reference configuration (ILD, green) and two alternatives MMG (red) and NNG (black). The stability limits are for pressure profiles with peaking factor 3 at <β>-values of about 1.7% (ILD), 1.8% (NNG) and about 1.9% (MMG).

First experiments in low-shear configurations

During the last experimental campaign OP2.1 (Sep. 2022 to March 2023) first experiments have been performed in both configurations to test at low heating power the predicted heat-load distributions and to start with tests of the stability limit. A direct comparison of the heat deposition on the divertor components is shown in Fig.7 for experiments with $P_{ECRH} \approx 3.7$MW and line densities with $5{\cdot}10^{19}m^{-2}$ in ILD and $4{\cdot}10^{19}m^{-2}$ in MMG. The heat-loads seen in ILD are clearly mitigated in the less outward-shifted MMG, consistent with the predictions.

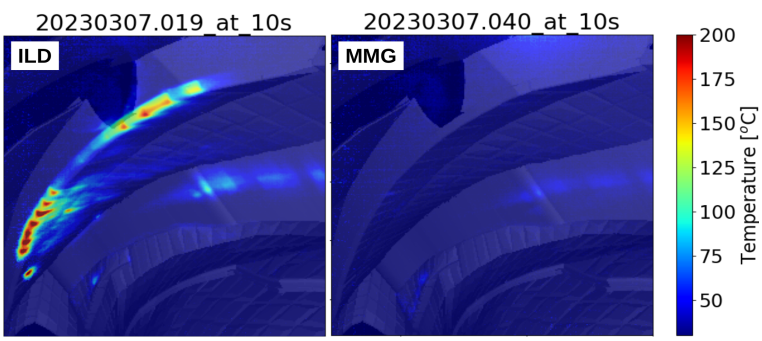

Figure 7: Divertor thermography observation of the high-iota tail of the divertor. Left: heat-loads on outboard-side baffle in ILD. Right: No heat-loads in MMG.

Experiments in new magnetic field configurations in W7-X require a careful energy and power extension procedure distinguishing between different heating methods and accounting for different density levels. Most of these experiments

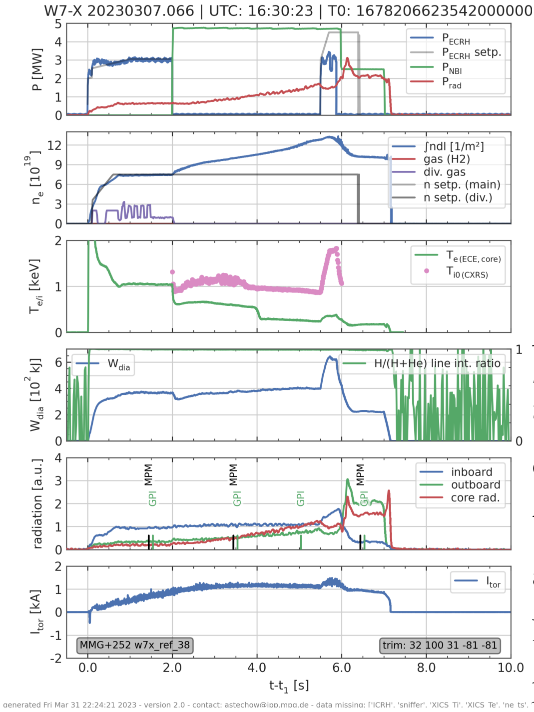

Figure 8: XP20230307.066: time traces from top to bottom of: plasma heating and radiation; line-integrated electron density; electron and ion temperatures; diamagnetic energy; plasma radiation; plasma current.

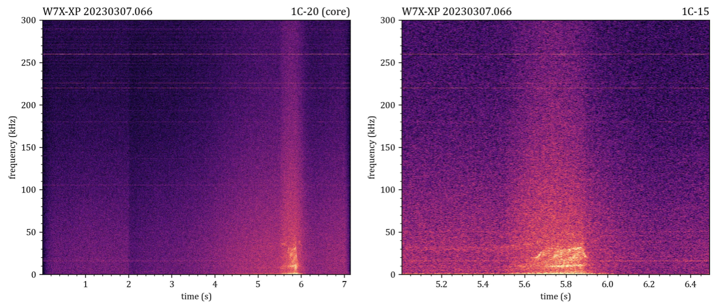

Figure 9: Spectrogram of two core channels of the soft X-ray multi-camera system. Left: entire experiment. Right: time region around NBI-O2-combined heating phase.

did not show much MHD-activity or measureable fluctuations. However, the analysis is still in progress. Also, only a first experiment with a combined heating phase (5.4MW NBI + 3MW ECRH-O2) aiming at high-β-values has been possible (see Fig.8). During the combined heating phase plasma energy and ion temperature were considerably increased (see Fig.8, 4th and 3rd time trace from top), but the corresponding <β>-value corresponds to only about 0.8% which is too small to test the stability-limit. Nevertheless, the core channels of the Soft-Xray multi-camera system detected low-frequency activity in the range of 10 and 30kHz during the phase of applied O2-heating which is still investigated. In the Mirnov-coils these modes have not been detected so far. The analysis of the experiments is ongoing.

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References

[1] Geiger, J et al., *Investigation of Wendelstein 7-X Configurations with Increased Toroidal Mirror*, 35th EPS Plasma Physics Conference, Hersonissos, Crete, 2008, http://ocs.ciemat.es/EPS2008/pdf/P2_062.pdf