Plasma perturbation by electrically biased probes in Wendelstein 7-X

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Electric (Langmuir) probes are a common diagnostic tool for the investigation of plasma edge physics in magnetized fusion plasmas. They offer several advantages, such as highly localized measurements, flexible operation schemes and geometries, and typically good temporal resolution (particularly for fluctuations). However, they have the inherent drawback of being an invasive diagnostic, potentially perturbing the plasma they are set to measure. The effect of such probes on the plasma can consist of (i) the pure presence of the probe, acting as a plasma limiter, and (ii) perturbation of the electric potential by electrically biased probes. The latter effect has also been used on purpose to alter the electric field in the plasma edge [1].

In the Wendelstein 7-X stellarator, electrically biased reciprocating probes were routinely employed during the test divertor operation phase (2017-2018) [2]. It was observed that positively biased probes, collecting electron currents, can significantly affect the plasma in their local vicinity, as seen by other probes on the same reciprocating probe head and in magnetically connected target Langmuir probes [2]. Here, the nature and propagation of these perturbations is explored in more detail for the first time, discussing the mitigation in future experiments as well as the possible exploitation for field line mapping. Further, we report on the particular effect of inserting a probe head as a limiter object into a magnetic island, causing changes in heat fluxes and plasma conditions in the island.

The key diagnostic setup is presented in Figure 1. The Multi-Purpose Manipulator (MPM) hosting the reciprocating electric probes is installed at the outboard side of W7-X. The electric probes in the upper divertor module of the neighboring W7-X segments are placed at a distance of 10m along the magnetic field such that field lines from the divertor probes pass close by the MPM path in most magnetic configurations [3].

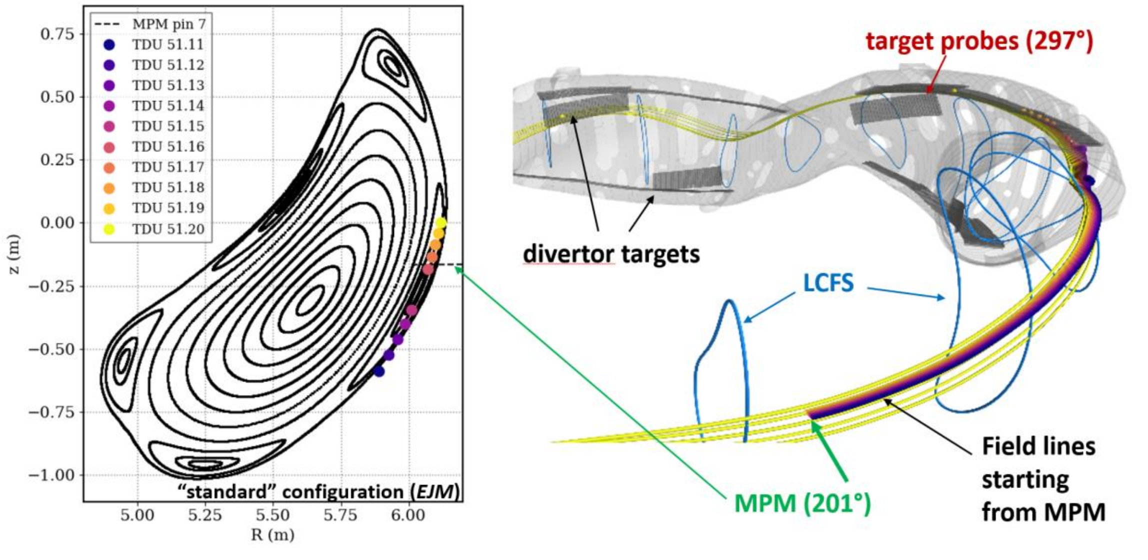

Figure 1: Left: Poincare cross section of W7-X in the plane of the MPM (dashed line). The colored circles correspond to the intersection of field lines starting at the target (*TDU*) probes with the MPM plane. Right: 3D sketch of some W7-X components visualizing the magnetic field lines between MPM and target probes

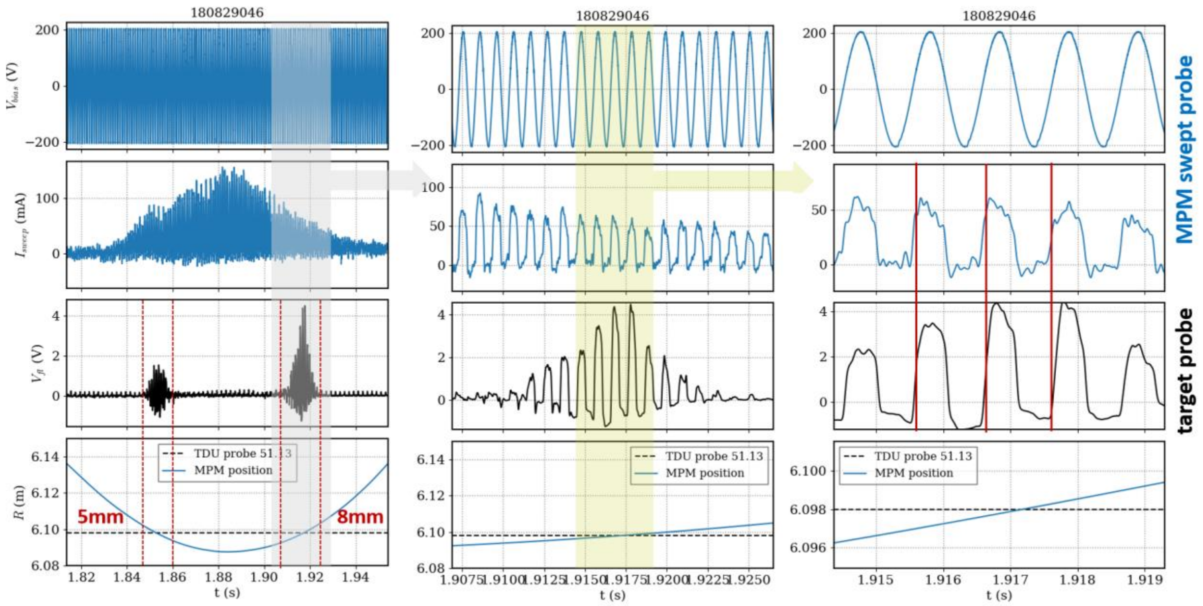

Figure 2: Time traces during an MPM insertion including a swept Langmuir probe: a) bias voltage of swept probe, b) current of swept probe, c) floating potential at target probe 51.13, d) position of MPM probe and position of field line starting from target probe 51.13, intersecting the MPM path. The center and right column are increasingly zooming into a narrower time range, as indicated by the grey / lime shaded bars.

First, we test this magnetic connection between both diagnostics that is expected from field line tracing. In a plasma close to radiation collapse, which features rather low SOL temperature and densities as well as low fluctuation levels, the effect of electrically biased probes on the MPM are investigated. In the experiment presented in Figure 2, the MPM probe carrying a swept Langmuir probe pin was plunged into the SOL. The bias voltage of the probe pin is sinusoidal at a frequency of ~1kHz with an amplitude of 200V. The envelope of the probe current correlates with the probe insertion, with the highest currents (positive currents denoting electron collection currents) at the deepest probe insertion at ~t=1.88s. Due to the low density and temperature plasma, the ion saturation current of the MPM probe and the floating potential V_{fl} at the target probe are very small. However, V_{fl} of the target probe is modulated by the swept probe signal exactly when the MPM probe passes the flux tube connecting both diagnostics. The time instant of the peak of V_{fl} at the target probe agrees with the swept probe passing the connecting the magnetic field line within 1mm, as calculated using vacuum field line tracing. Relating the temporal duration of the signal at the target probe and the MPM movement, the effective width of the flux tube is 5mm (MPM moving in) / 8mm (MPM moving out). In comparison, the diameter of the swept probe pin is 2mm.

Zooming closer into the time series (center and right column in Figure 2), it becomes clear that the shape of the signal at the target V_{fl} probe resembles the current drawn by the swept probe, not the bias voltage. This indicates that the current drawn by the probe is the key to the perturbation, as it drains the flux tube of ions / electrons, which have to be resupplied by perpendicular transport into the flux tube. In addition, the signal at the target probe exhibits a delay of about 20µs compared to the source signal at the swept probe, as visually indicated by the red vertical lines in Figure 2 (right) for electron collection. This delay is presumably a combination of the parallel propagation across L=10m (e.g. at electron thermal velocity $v_{th,e}$=5e5m/s for T_e=1eV in a very cold collapsing plasma) and a poloidal propagation as the

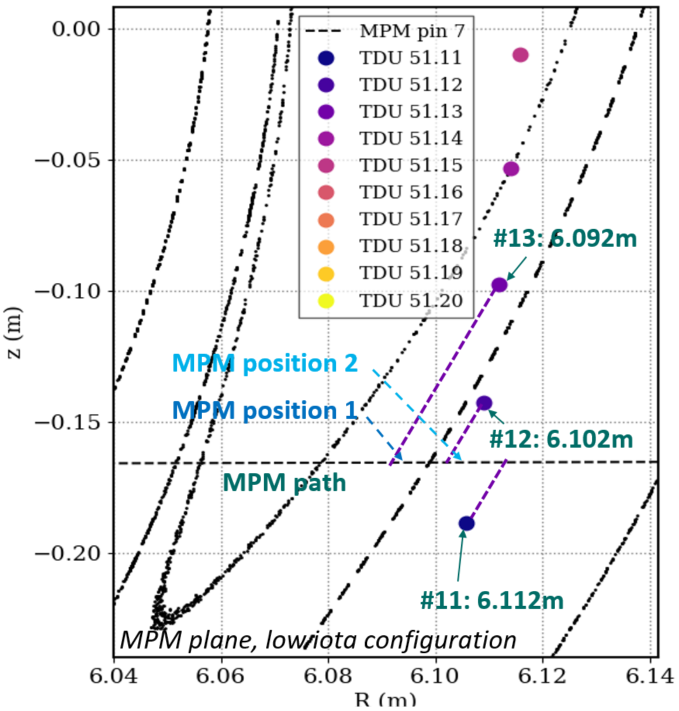

Figure 3: Poincare cross section of MPM vicinity in Low Iota configuration. Colored circles refer to mapped target probe positions. Blue MPM position labels refer to Fig 4.

target probe field line has a small poloidal distance of 10mm to the MPM path (e.g. v_{pol}=500m/s for 10mm results in 20µms delay) [4]. However, the individual contributions of parallel and poloidal propagation cannot be disentangled here.

In the next step, a similar experiment is performed in a more regular plasma in the "low iota" configuration, where field lines from multiple target probe field lines pass close by the MPM path, see Figure 3. Here, the MPM probe was positioned for 500ms each at two constant positions in the SOL to improve statistics, allowing to average over 500 sweep cycles, resulting in the smooth time traces of the MPM swept probe (Figure 4 a,b) and target probes (Fig 4 c,d). The current of the swept probe clearly reflects the different probe positions, with the deeper insertion (dark lines) showing higher ion and electron currents. The plasma perturbation from the swept probe is picked up by target probes #12 ($I_{i,sat}$ mode) and #13, #14 (V_{fl} mode), i.e. up to a poloidal distance of ~10 cm from the MPM in E_rxB direction, but not by target probe #11 (V_{fl} mode) which is close to the MPM path but opposite to E_rxB direction, incidcating a possible role of poloidal E_rxB convection. Further, the data shows indications for the radial propagation of the perturbation: Considering target probe #12, the perturbation signal arrives earlier for the lightly colored data, which corresponds to a MPM position very close to the position of probe #12. Moving the MPM 1cm further inside the plasma (dark colors), the perturbations arrive slightly later.

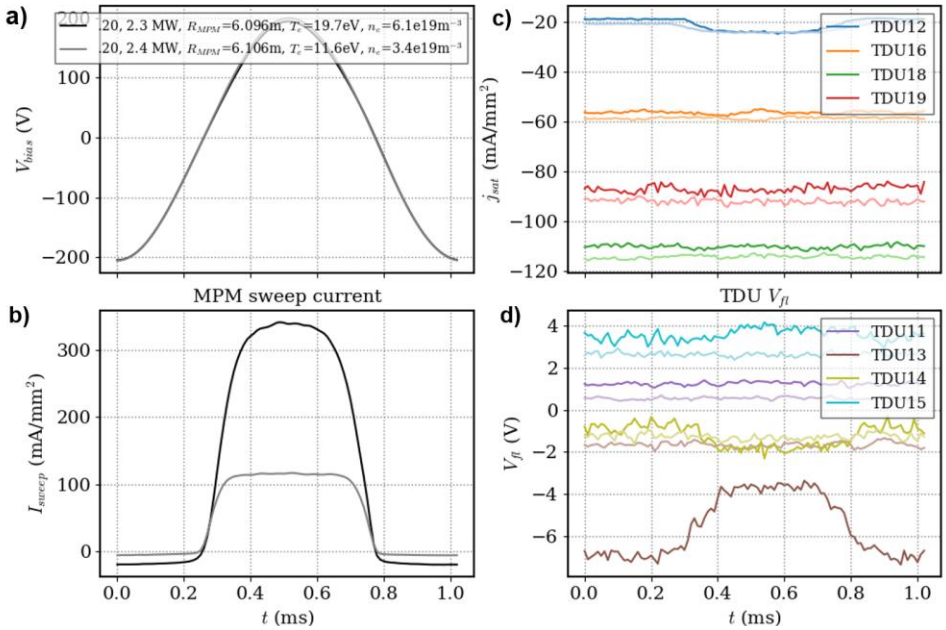

Figure 4: Averaged time traces over 500 sweep cycles at constant MPM position.

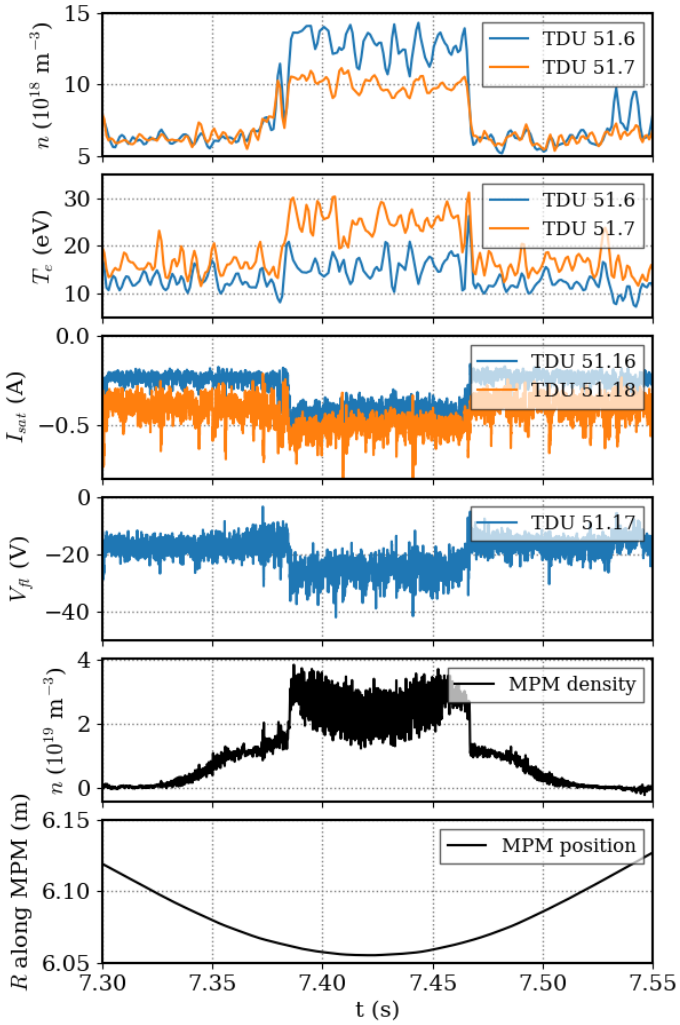

Figure 5: Modification of plasma conditions in target probes (blue/orange) due to MPM probe (black) insertion.

Finally, we consider the effect of inserting the MPM as field line limiting object in the edge island in the magnetic standard configuration, see Figure 1. During the probe insertion presented in Figure 5, the density measured by the MPM probe (black) appears to instantaneously jump to a higher level (when moving in) and back down when moving out. This is observed in several such experiments but not in the majority - no clear relation to external parameters was identified so far. This density jump leads to a very steep localized density gradient when considering the profile from the reciprocating probe. Interestingly, several target probes show the same kind of quick transition behavor in n_e, T_e, V_{fl}, $I_{i,sat}$. In this situation, the swept probe on the MPM does not play a role. This observation implies that the insertion of a probe into a magnetic island plasma can significantly affet plasma conditions, possibly due to the limiting effect of the probe and the subsequent re-distribution of heat fluxes in the magnetic island.

Summarizing, the operation of electrically biased reciprocating probes significantly affects the SOL plasma in cases of electron current collection and by limiting field lines inside a magnetic island. To mitigate both issues, swept probes should not go too far into the electron collection branch, and probe heads should be kept as small as possible. However, as an upside, the initially unintended phenomena described here allow to validate magnetic field mapping and investigate the parallel, poloidal, and radial propagation of plasma perturbations.

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