B-field dependency of high-β plasmas at Wendelstein 7-X stellarator: first analysis of the observed W_{dia} crashes and impurity signals

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One scenario to achieve high beta plasmas in Wendelstein 7-X stellarator, developed in the 2025 experimental campaign, consists of rising the plasma density with a sequence of pellets in ECR-heated plasmas with a heating power of 2 MW (cf. Fig. 1). A steepening of the core density gradient has been observed in Thomson-data [1] in similar scenarios. In the second phase, the plasma is heated by a combined NBI/ECRH phase, which increases the peak density and keeps the steep density gradient. The density rise is stabilized by increasing the O2-ECR heating, after 6 s. Due to the high density of $n_e > 8*10^{19}$ m^{-3}, O2-polarization of the ECRH is used to improve the absorption [2].

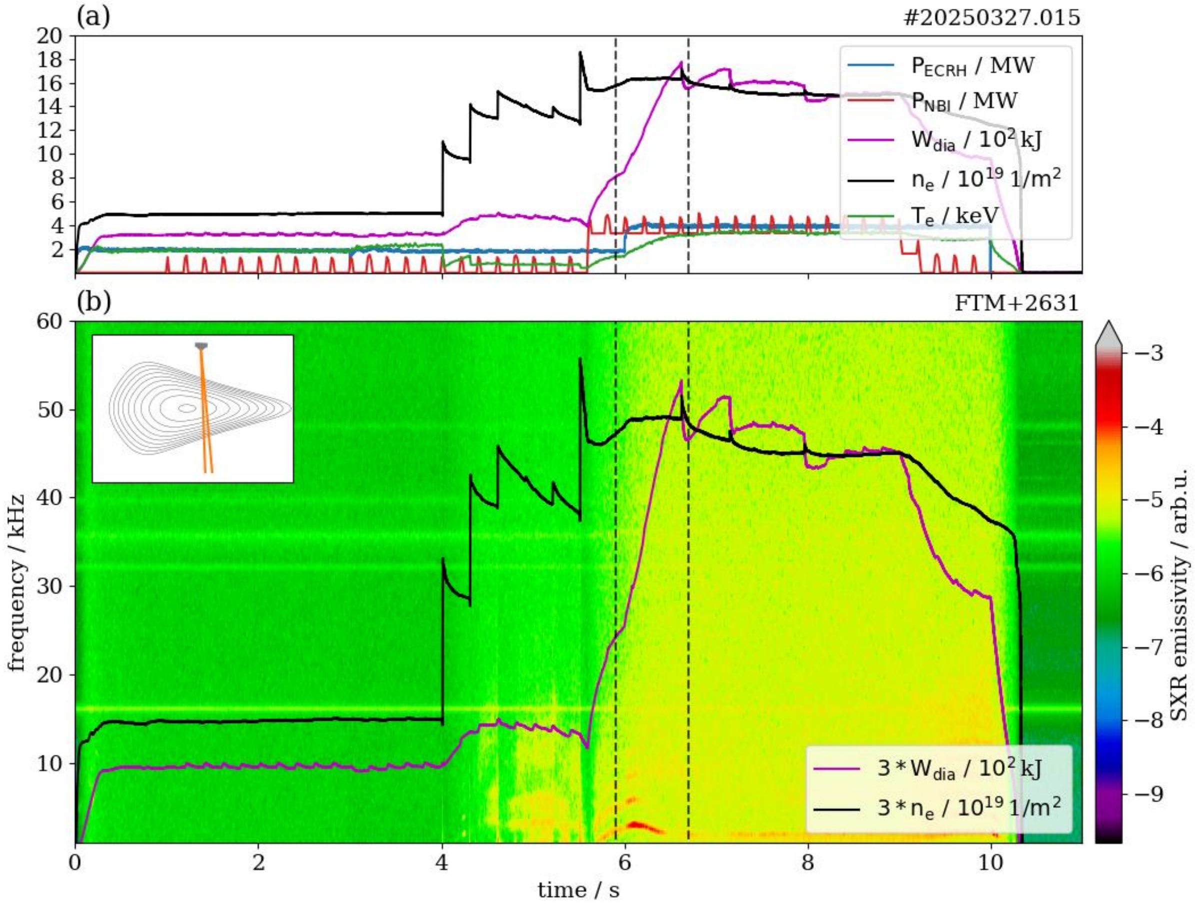

Fig. 1 Top: time traces of heating powers and plasma parameters for W7-X experimental program 20250327.015. Bottom: spectrum calculated from one SX-ray diode signal with an overlay of time traces of the diamagnetic energy and line-integrated density from interferometer.

The high-beta phase can be kept for several seconds during the combined NBI & ECRH phase. In this phase, we observe three fast crashes of the diamagnetic energy W_{dia}. These crashes are visible in many diagnostic systems. In the soft-X ray data (XMCTS [3]) the duration of such a crash is estimated to be of the order of 500 µs (cf. Fig. 2) and it is core-localized (inversion radius is at $s=r^2/a^2 < 0.3$; r: minor plasma radius, a: radius of LCFS). In the Mirnov diagnostic, visible activity is starting approx. 200 µs before the activity is seen in XMCTS and lasts for 1 ms.

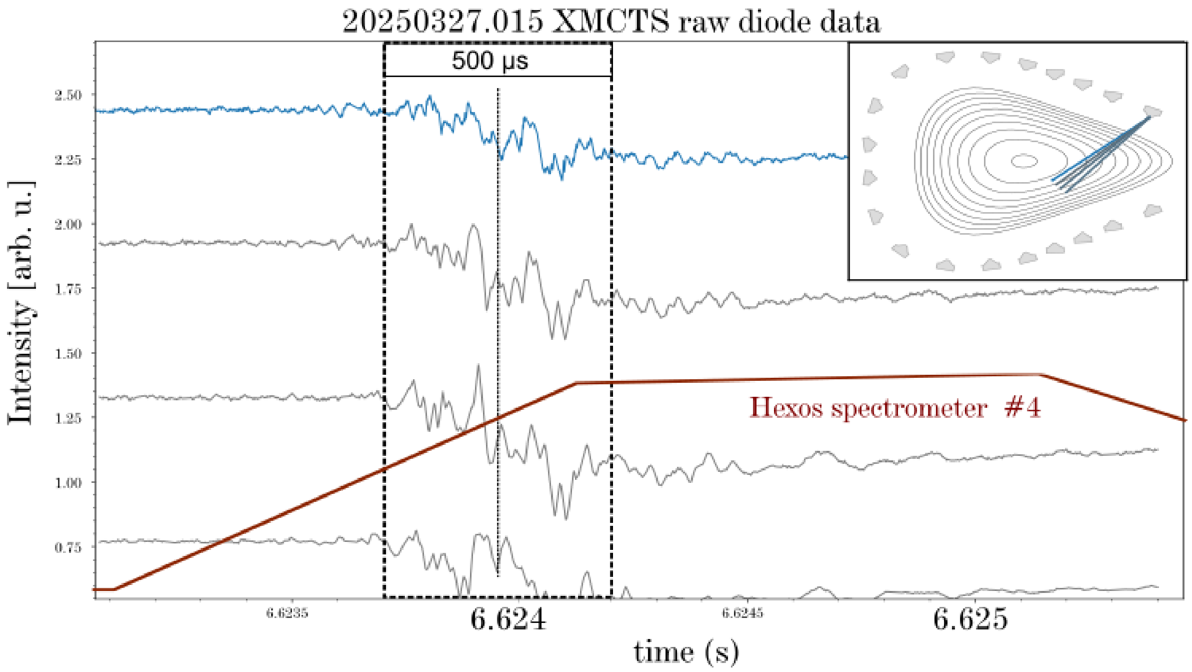

Fig. 2 Time traces of XMCTS diode data in blue and grey (the inset indicates the respective view lines in the triangular plane) and in red an HEXOS intensity signal integrated over the spectral range from 60 to 160 nm.

The VUV/XUV spectrometer diagnostic HEXOS [4] measures a fast rise of light impurity radiation (B, O, C), within the time resolution of 1 ms at the same time as in the XMCTS data (which is recorded with a time resolution of 1 µs), cf. Fig. 3. The synchronization between different diagnostics is assured by centrally distributed time stamps [5]. The synchronization has been checked before the experimental campaign in 2024 for a set of diagnostics, including both XMCTS and HEXOS.

The origin of these crashes is not yet established, but we like to point out the resemblance of the general characteristics with core density crashes (CDCs) observed in LHD super dense core plasmas [6]. Their explanation is a non-ideal ballooning mode instability, which is also for the Wendelstein 7-X plasmas under investigation (kinetic ballooning modes [7]).

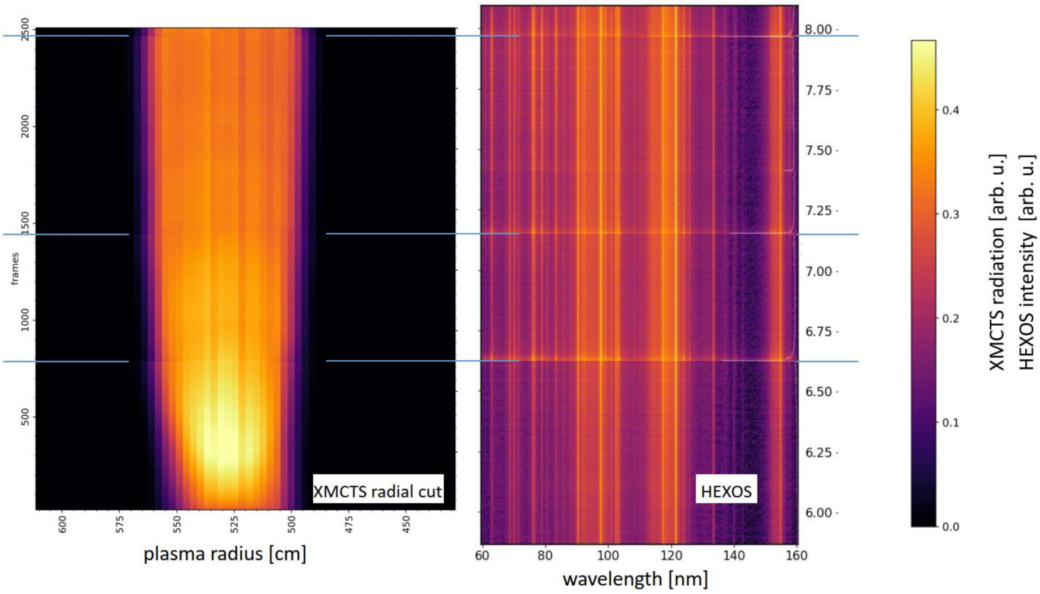

Fig. 3 Left: time resolved XMCTS tomography data, represented as a radial profile along the symmetry plane (color coded: amplitude, vertical axis: time). Right: the VUV spectrum recorded by HEXOS. Horizontal blue lines indicate the times of W_{dia} crashes.

The change of the iota profile has been reconstructed by the STELLOPT equilibrium code (using data from magnetic coil measurements, Thomson scattering, XICS and XMCTS line integrated signals) for two time points before and after the crash [8]. A reduction of the edge iota profile and an increase of the toroidal current is observed. Moreover, the pressure profile gradient flattens mostly due to the density decrease and the maximum beta is reduced.

Considering the timing of the events (cf. Fig. 2), we discuss two possible causality scenarios in the following:

1) The Shafranov shift and potentially beginning ergodization of the edge plasma caused by the increased beta [9] leads to a wetting of previously unexposed plasma facing components. Impurities are released into the plasma core and cause a sudden relaxation of the steep density gradient.
   A) These impurities reach the hot core plasma and radiate a large amount of energy, leading to a local cooling. As a result, the decrease in plasma pressure (by the temperature decrease), the density peaking cannot be sustained. This is the time, when XMCTS shows the crash in the SX-radiation.
   B) An edge temperature decrease related to the impurity influx creates a cold pulse, which is propagating towards the plasma core on a fast time scale of less than 1 ms and then causes the crash of the steep plasma density gradient located further inward.

2) The density gradient reaches a high steepness, which may trigger a ballooning-type instability leading to the fast collapse. The observed increase in SX radiation stems from:
   A) plasma surface interaction from the density pulse running radially outward and reaching the divertor/PFC leading to sputtering and increase in plasma radiation.
   B) the local density increase by the radially outward propagating density pulse. Since the bremsstrahlung and line radiation increase with density, the effect is an increase of the observed radiation at further outward locations. The increase of effective volume additionally adds to the sudden increase of impurity radiation.

Sequence 1A) would require, that the released impurities affecting the plasma gradient enter the plasma edge/core region either very fast (or unnoticed by the HEXOS diagnostic).

Since the timing of the increase in HEXOS and XMCTS data is within the same millisecond, the causality sequence 2A) is very unlikely, since the impurities would need time to propagate from the PFC towards the core plasma, where the crash is localized.

Scenarios 1B) and 2B) are the most likely candidates at the present stage of data analysis. Concerning 2B) we note that the observed core localization of the crash suggests that ideal or kinetic ballooning modes may play a role. Further analysis is required to identify the dominant mechanism. Especially, the newly developed advanced tomographic inversion methods [10] will become important for the experimental estimation of the expected high mode numbers.

Unfortunately, other impurity diagnostics like the bolometer system are recording on a yet slower time scale than HEXOS, so that this data does not provide further insight without additional impurity transport modelling, which is outside the scope of this contribution.

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