Impurity accumulation monitoring using multiple diagnostics at ASDEX-Upgrade

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I. Introduction

One of the key requirements for a fusion reactor operation is the existence of a high-performance and at the same time disruption-free operation scenario. To fulfil the latter requirement, an advanced discharge monitoring and disruption avoidance strategy is required. The strategy is based on the division of the plasma operational space into three zones: nominal, recovery, and soft-stop. In each of these zones, a suitable strategy for controlling/soft stopping of the discharge will be used. As the last backup line of defense, present day disruption avoidance strategies will be used.

This contribution will deal with one of the most common causes of disruption on ASDEX-Upgrade (AUG), the impurity accumulation [1]. First of all, we present the design and the first results of a real time (RT) algorithm capable of detection of high core impurity concentration, that has been recently implemented in the Discharge Control System (DCS) at AUG and tested in real plasma operation. Secondly, we will discuss possible future control strategies to reduce the risk of impurity accumulation to appear and strategies that could potentially suppress already detected impurity accumulation and diagnostics improvement to increase the reliability of the impurity detection.

II. Impurity Accumulation detector

The first and the most reliable sign of the core impurity accumulation at AUG is typically the radiation peaking seen on the ratio of the signals on core (R_c) and edge (R_e) bolometry channel. The second sign accompanying impurity accumulation (but not just impurity accumulation) is an increased ratio of the radiated (P_{rad}) to the heating power (P_{he}). We consider the electron heating power as it is more relevant to the impurity accumulation related effects and is computed by RAPTOR [2] (Rapid Plasma Transport Simulator) in real time.

[1] H. Meyer et al., Nuclear Fusion FEC 2016 Special Issue (2017)

Another effect of the impurity accumulation that can be identified in real time using the combination of RAPTOR predictive and RAPTOR observer is the drop of the core electron temperature and flattening of the current profile shape represented by the drop of the internal inductance l_i. RAPTOR predictive solves just a simplified set of transport equations, and RAPTOR observer corrects the temperature profile estimate from the RT ECE diagnostics. Combining all above mentioned quantities, we define an impurity accumulation risk function

$$A = C_1 \frac{R_c}{R_e} + C_2 \frac{P_{rad}}{P_{he}} + C_3 \frac{T_{core}^{obs} - T_{core}^{ECE}}{T_{core}^{obs}} + C_4 \frac{T_{core}^{pred} - T_{core}^{obs}}{T_{core}^{pred}} + C_5\left(l_i^{pred} - l_i^{GS}\right), \qquad (1)$$

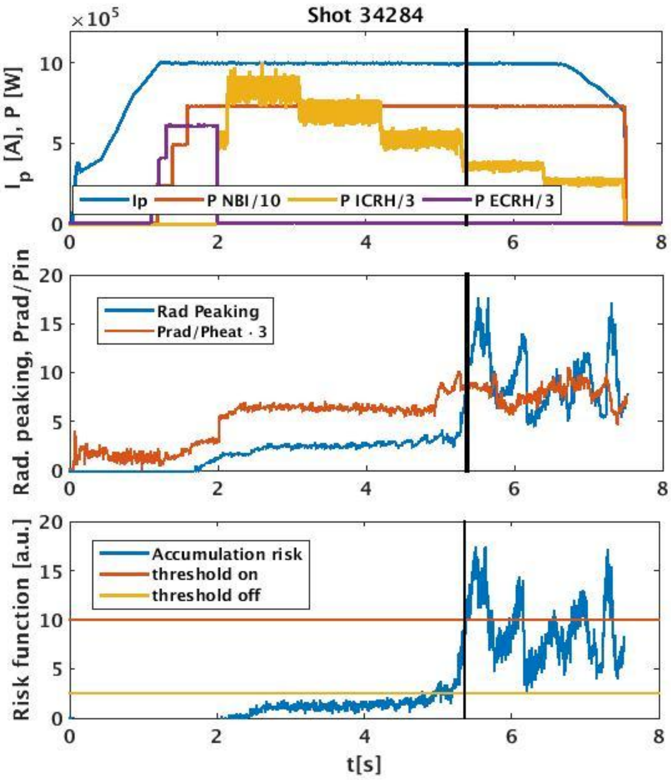

Figure 1: Plasma current, heating actuator trajectories, radiation peaking, the ratio of total radiated power and electron heating power and the accumulation risk function with activation and deactivation thresholds.

where $C_{1\text{-}5}$ are tunable constants, T^*_{core} denotes the temperature between toroidal ρ 0 and 0.2 from the ECE measurement, RAPTOR observer (*obs*) and RAPTOR predictive (*pred*). l_i^{pred} stands for the internal inductance computed by RAPTOR predictive and l_i^{GS} for the internal inductance computed by the JANET (Just ANother Equilibrium reconstruction for Tokamaks) using Shafranov integrals [3]. If the value of A exceeds a threshold, the impurity accumulation alarm is activated. If the value of A gets below switching-off threshold value (lower than switch-on value as shown in Figure 1) and stays there for some time (currently 20 ms), the alarm is switched off. The time derivatives of the above mentioned quantities can be used as well as long as they are not too noisy.

The temperature-related terms suffer from the density cutoff on the ECE diagnostics that often appears alongside the impurity accumulation. In other words, if the density is too high, we can not rely on the temperature drop information. Therefore two accumulation risk functions are computed: a “no cutoff”, and the other a “cutoff”. Depending on the electron density from the density observer [4], the decision on which alarm function will be used is made.

Presently, only the radiation peaking ($C_1 = 1$) and the ratio between the radiated and heating power ($C_2 = 0.7$) is used. The other terms provide additional information about impurity accumulation risk, but as RAPTOR is still in a development stage, they can often cause a false alarm or delay the alarm activation. However, a substantial improvement is expected in this area as new physics and new transport models are being included in RAPTOR [5] and the impurity accumulation detection tool is ready to take the temperature related terms into account.

III. Experimental results

The detector has been implemented in the DCS system and has worked since discharge 34284. An example from discharge 34284 is shown in Figure 1. In this discharge, the IC power was reduced in steps until the impurity accumulation appeared at $t = 5.36$ *s*, when the impurity accumulation alarm was activated. The impurity concentration remained high until the end of the discharge as one can see on high radiation peaking, but it did not cause a disruption. Such a situation is relatively common, therefore the impurity accumulation alarm should not be interpreted as a precursor of disruption that stops the discharge, but rather as a flag tagging “ill” plasma that can be “healed” in several ways discussed in section IV.

The detection algorithm has been active in 66 discharges: 6 L-mode, 2 I-mode 4 discharges studying impurity accumulation (as the one shown in Figure 1) and other H-mode discharges. The impurity accumulation was detected in all 11 cases when it appeared, out of which 3 ended by disruption. The alarm was activated 200 ms before in two cases and 600 ms in the third one. In 5 cases, the fake alarm appeared due to the diagnostic noise.

IV. Outlook: Avoidance strategies and diagnostics upgrades

The development of the detection algorithm is the first step in the development of a complex impurity accumulation avoidance strategy. First, it will be necessary to improve the detection algorithm and if feasible to detect some warning signs that appear before the accumulation starts. It will require some upgrades on the side of the real time diagnostics available at AUG. First of all, the detection algorithm would benefit greatly from more bolometry channels to measure the radiation profile. The impurity accumulation is mostly preceded by electron density peaking around the magnetic axis. As the peaking appears just in a small region of the plasma, it cannot be detected early enough by the interferometric measurements available in real time. A real time Thomson scattering diagnostics (work in progress) with sufficient spatial and temporal resolution could be useful for the detection of density peaking early enough and suitable strategies could be developed to avoid the appearance of impurity accumulation.

The baseline impurity accumulation avoidance strategy routinely used on AUG is the application of EC heating at a fixed position close to the core. Central electron heating is always helpful in impurity accumulation avoidance, however it is optimal to deposit the EC power as close to the magnetic axis as possible. Therefore, a new feedback mode to track the magnetic axis with the EC power using movable mirrors has been developed, though not yet tested in real time, and is expected to become routinely available within a few months. If the impurity accumulation already appears, the most convenient way to remove it is to apply additional central electron heating- either EC or IC that deposits a significant part of its energy to electrons. Another possibility is to change NBI sources from tangential to more radial injectors. EC heating is generally the most efficient method, but suffers from the density cutoff appearing alongside the impurity accumulation. The intended impurity accumulation avoidance strategy is following:

- Track the magnetic axis with the EC power.
- If accumulation is detected, add more heating power from convenient actuator.
- If possible, switch from tangential to more radial NBI sources [6]. However, the exact role of the NBI and its relevance to various scenarios are still under investigation.

Details about the underlying principles of this strategy are discussed in [6]. This strategy is going to be tested and optimized on AUG in the coming years. In addition, an attempt will be made at developing a real time separation of the discharges that can be saved from those that should be terminated.

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