

The X-Point radiating regime at ASDEX Upgrade and TCV

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ABSTRACT

Future fusion reactors require a safe, steady-state divertor operation. With deep divertor detachment, which is typically induced by impurity seeding, the radiation concentrates in a small region at the X-point or on closed flux surfaces above the X-point. This so-called X-point radiator (XPR) moves further inside the confined region with increasing seeding and the location can be actively controlled.

At AUG, the parameter space for operation with an XPR was significantly extended, using active feedback on the XPR location. The XPR is observed in nearly the whole operational space of AUG in the high-densities or high collisionality regime. ELM suppression is consistently observed in all cases where the XPR was moved to a significant height above the X-point.

Direct measurements of density and temperature from the region around the XPR using the new divertor Thomson scattering system at AUG indicate that the temperature at the location of the XPR remains high (> 30 eV) and only the region towards the X-point cools down further. In this cold XPR core, the temperature reduces to about 1 eV.

An XPR is also observed in TCV by the injection of nitrogen as extrinsic impurity. This highlights that the wall material (W for AUG, C for TCV) or machine size does not play a significant role for the existence of the regime. However, the scenario appears to be less stable in TCV. First experiments show the necessity of an active control for the XPR: Depending on the wall conditions and the nitrogen wall storage, the required nitrogen seeding level to achieve an XPR changes.

Both, the low temperatures measured radially outside of the radiation zone at AUG, and the lower stability of the XPR regime at TCV with the presence of carbon are consistent with the predictions of a one-dimensional model of the XPR. However, the model would predict the development of the cold XPR core, and significant radiation at the X-point might already exist before reaching this cold temperature solution.

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Fig. 1. Visible camera image of a discharge with an XPR (AUG #40007, 3.4 s) seen in blue light emitted by nitrogen, dominated by N^{2+} . Magenta is the typical Balmer emission from deuterium in a divertor leg. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1. Introduction

At ASDEX Upgrade (AUG) and JET H-mode discharges, with impurity induced divertor detachment, the radiation concentrates in a small region close to the X-point, inside the confined region. Fig. 1 shows a camera image in the visible range of an AUG discharge with a so-called X-point radiator (XPR). This XPR can be generated with nitrogen or argon seeding at AUG, or also additionally with neon or krypton seeding at JET [1]. The location of the radiator relative to the X-point can actively be influenced and controlled in real-time by impurity seeding [2]. In TCV, an XPR was so far only observed in L-mode [3].

An XPR is very similar or identical to an X-point MARFE [4], however, a MARFE is usually associated with a degradation of confinement or even an H-L back transition and the initialization of a disruption [5]. An X-point MARFE is mainly observed in L-mode discharges in many devices [6–8] and is correlated to the density limit [9]. In order to distinguish the stable radiation at the X-point from the non-stationary evolution of an X-point MARFE, the stable case is named here XPR. This XPR is also observed in H-mode and exists inside the confined region, close to or on the X-point. As soon as this radiation becomes non-stationary and moves up along the high field side, it is named MARFE, following the definition in [10]. An XPR can, however, by definition still be interpreted as an X-point MARFE.

It is possible to reproduce the radiation condensation, which is the thermal instability triggering the XPR or MARFE, with analytic calculations [4] and SOLPS modelling [11–14]. In order to derive the main parameter dependencies for the access and stability conditions for an XPR, a model based on a one-dimensional power balance was recently developed [10]. Following this model, the presence of carbon (intrinsic for a carbon-walled device such as TCV) does not lead to a stable XPR, but would immediately develop into a MARFE, initiating a disruption. The observation of an XPR at TCV is challenging the one-dimensional model. In this work, XPRs in H-mode plasmas in TCV are presented and compared to the model.

In Section 2, the operational range at AUG for the existence of an XPR with ELM suppression is discussed. The local measurements by the divertor Thomson scattering diagnostic will be compared with the 1D model. Section 3 demonstrates the existence of XPRs for H-mode scenarios at TCV, which is then further discussed in Section 4.

2. Operational range and local parameters of an XPR at AUG

At AUG, in H-mode plasmas an XPR can be created by extensive impurity seeding. The standard seed impurity used is nitrogen, but also argon has been demonstrated. Real-time feedback control is implemented to steer the location of the radiator relative to the X-point, using impurity seeding as an actuator [2]. This control scheme was further optimized and is now also set up for argon seeding, where the position of the XPR is much more sensitive on the seeding level due to the high radiation efficiency of argon.

Table 1

Parameter range of AUG, where the XPR is observed with N_2 seeding and where the ELM suppression was achieved.

Parameter	XPR existence	ELM suppression
I_p	0.8 – 1.2 MA	0.8 – 1.2 MA
B_t	1.8 & 2.5 T	1.8 & 2.5 T
q_{95}	3.7 – 6	3.7 – 6
P_{heat}	1.7 – 26 MW	1.7 – 17.5 MW
H_{98}	0.8 – 1.1	0.7 – 1
f_{GW}	0.7 – 0.95	0.7 – 0.8

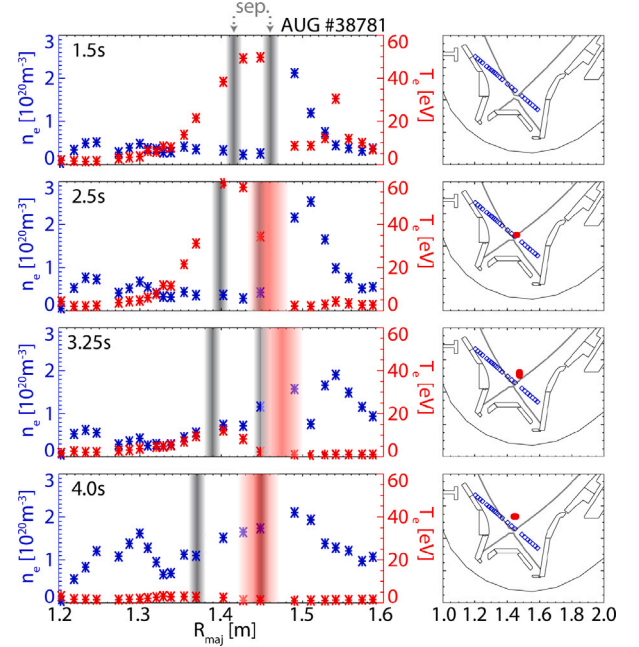


Fig. 2. T_e and n_e from DTS at different time points in AUG #38781. The grey shaded areas indicate intersection of the DTS beam path with the separatrix, the red shaded area the radial location and width of the XPR (note: the XPR might be vertically higher than the DTS measurement location, thus, these measurements are located between the XPR and the separatrix). Right: Location and extend (FWHM) of the XPR (red) and the location of the DTS measurements (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The operational range at AUG, where an XPR is observed with nitrogen seeding, was significantly extended in terms of I_p , B_t , q_{95} and P_{heat} compared to previous publications [2]. Table 1 lists the parameter range, where the XPR scenario was tested and accessed. In almost the complete operational range of AUG at high density or high collisionality the XPR was observed after the injection of a sufficient amount of nitrogen. The nitrogen concentration inside the confined plasma, measured by CXRS [15], is for such scenarios typically around 2–3%. ELM suppression is accessed when the XPR is significantly above the X-point (typically above 7 cm). Only at the highest heating powers it was not attempted to achieve the ELM suppression, therefore, the existence of this regime is only tested for up to 17.5 MW.

With the ELM suppression, the line averaged electron density and energy confinement decrease. The pedestal gradients are reduced, leading to lower pedestal top values. Since the electron temperature gradient further inwards is increased, the overall reduction in energy confinement is not very strong (about 10%–15%), while the reduction of the line averaged density is of the order of 20%. The influence on the pedestal is discussed more in [2].

The divertor Thomson scattering system (DTS, [16]) allows direct measurements of electron density (n_e) and temperature (T_e) in the X-point region. Fig. 2 shows the measurement location of DTS and the location of the XPR as identified by the AXUV diagnostic. The

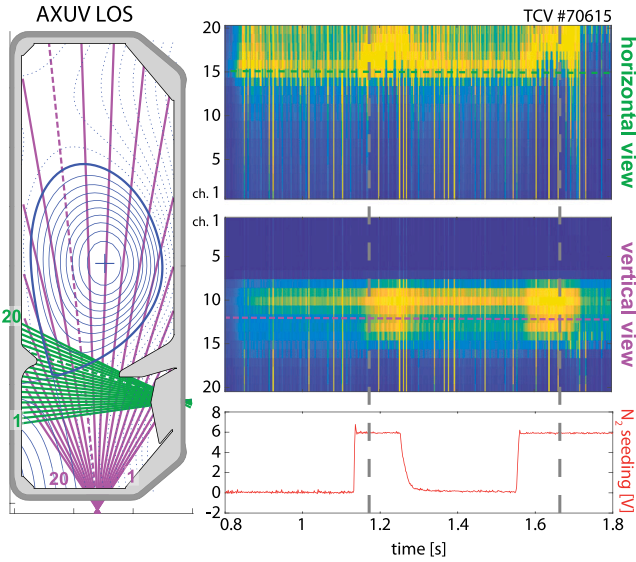


Fig. 3. Left: LOS location of AXUV channels. Right: Contour plot of the measured intensity of the AXUV cameras from the side (top) and from below (middle), showing the shift of radiation depending on the nitrogen seeding rate (bottom). The most significant LOS are indicated by the dashed lines, the vertical grey lines indicate time points shown in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature at the location of the XPR remains high (> 30 eV) at 2.5 s and only cools down in the region between the XPR and the X-point (see 3.25 s & 4.0 s). In this cold XPR core, the temperature reduces to the range of about 1 eV, below which the deuterium 3-body recombination rate strongly increases [17]. The strong density increase indicates that the pressure conservation along the flux surface is maintained [18].

These findings are consistent with recent SOLPS-ITER simulations [14] which show that a fully developed XPR consists of a cold core close to the X-point surrounded by a radiating mantle. The spatial coverage and resolution of the DTS does not allow to identify if a (small) cold XPR core exists always as soon as the radiator is present.

3. XPRs in H-mode at TCV

In TCV, XPRs have, until this study, only been determined to exist in L-mode plasmas [3]. In the following evidence is shown that the XPR also forms in TCV H-mode plasmas. The characteristics of those discharges is the following: $I_p = -210$ kA, $B_t = -1.4$ T, $P_{heat} = 1.3$ MW (NBH) in a conventional divertor configuration with nitrogen seeding ramps.

3.1. XPR observation in TCV

Fig. 3 shows the shift of radiation with two pulses of nitrogen seeding, as observed by the AXUV cameras. Fig. 4 shows that this shift is from the scrape-off layer (SOL), close to the X-point and inner baffle, to inside the confined region, indicating that an XPR was formed and moved for a few cm inside the confined region.

This concentration of the radiation inside the confined region can also be observed using the multi-spectral imaging diagnostic MANTIS [19], see Fig. 5. The NII emission is first distributed in the SOL, but later concentrates at the X-point. The emission of NII spectral lines is an indication of electron temperatures below 10 eV (e.g. 6.5 eV at the emission front [20]) in this region.

The shift of radiation inside the confined region, and with this the existence of the XPR, was observed in several discharges with different seeding trajectories. Fig. 6 gives an overview of different trajectories applied. The location of the NII emission ($\lambda = 399.0$ nm) peak is tracked using the MANTIS system, given in the coordinate L_{pol} (poloidal length

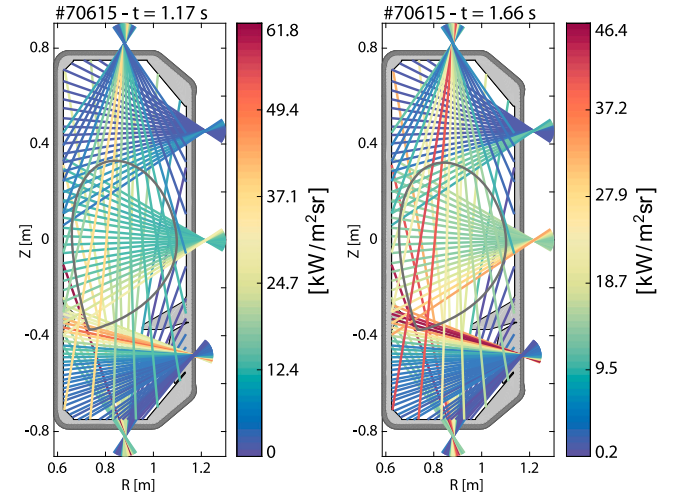


Fig. 4. Bolometry line of sight intensity before and after creation of XPR in TCV #70615. The peak of radiation moves from outside (left) to inside the confined region (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

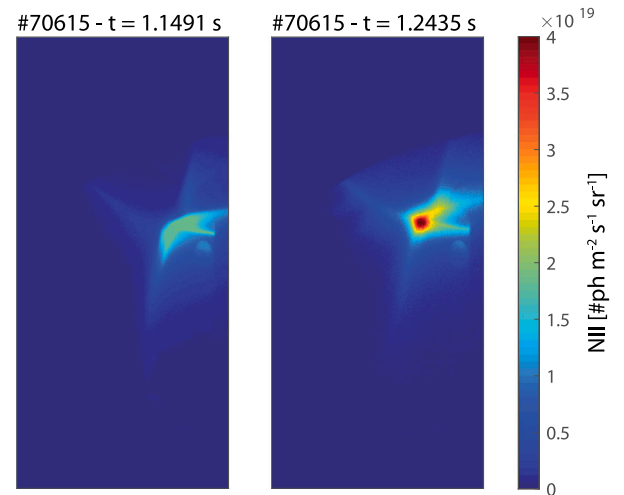


Fig. 5. Filtered camera image of an NII spectral line (399.0 nm) by MANTIS before (left) and after (right) development of XPR in TCV #70615. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

along the divertor leg, 0 m at the divertor target and 0.4 m at the X-point). The range of the XPR regime in this measurement can be identified in accordance with other diagnostics and is colour coded in the figure. Below 40 cm, the radiation is in the SOL, for 40 – 43 cm, the XPR is present. If the emission peak is detected higher, the plasma transits into L-mode and, if no fast countermeasure is taken, a radiative collapse and disruption follows.

The observations, e.g. in Fig. 6, indicate that the operational window for a stable XPR is much smaller for TCV than for AUG. Over-seeding can easily occur at TCV and the plasma tends to transit to L-mode and disrupt. Whether the higher sensitivity to seeding leading to the H-L transition and disruption in TCV compared to AUG is due to the differences in machine size, available heating power or the carbon wall cannot be concluded.

The 1D-model [10] predicts a lower stability for TCV: An XPR will convert to a non-stationary MARFE when the dominant radiating impurity is carbon, as it is intrinsic for TCV. However, seeing the existence of an XPR at TCV contradicts this prediction. But the model is not fully applicable if the XPR consists only of the radiating front but did not yet develop the cold core.

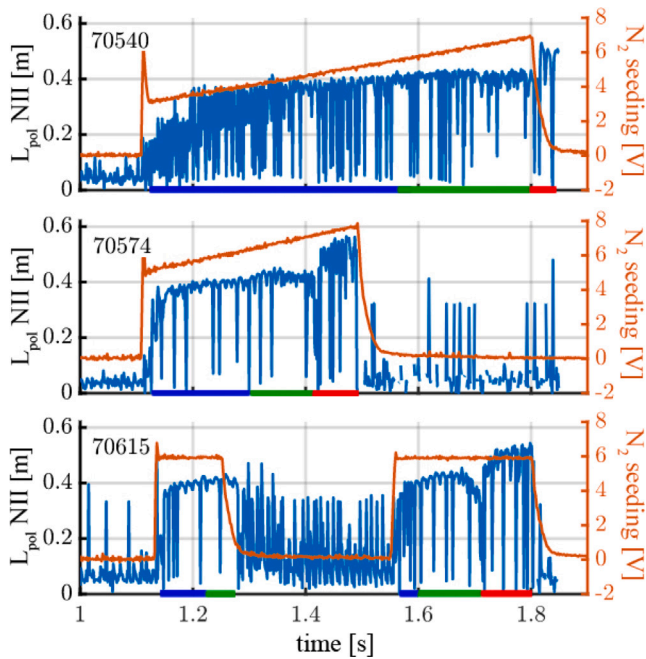


Fig. 6. Nitrogen seeding level and NII emission peak position (vertical distance along the divertor leg, 0 m at the target, 0.4 m at the X-point) as tracked by the MANTIS system for three discharges at TCV. The large spikes are dominantly caused by ELMs. The coloured bars along the time axes correspond to when the radiation is below the X-point (blue), the XPR exists (green) and the plasma transits back to L-mode (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

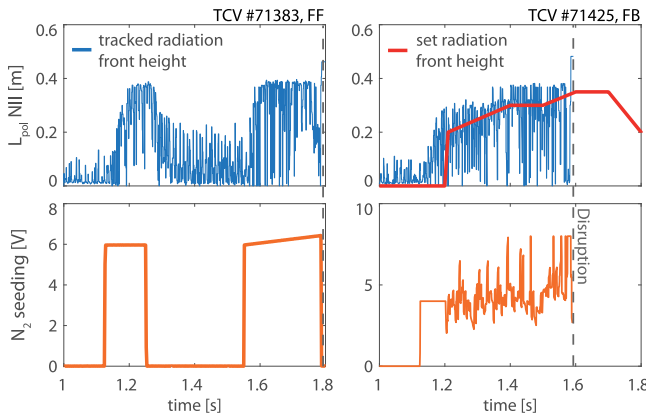


Fig. 7. Tracked radiation peak height and nitrogen gas puff for a discharge with feed forward seeding (left) and with feedback on the radiation location (right). Note: Due to the operation in another campaign than Fig. 6, the range of the XPR regime in terms of L_{pol} is between 30 – 35 cm.

Furthermore, the operation at TCV is complicated by the unknown wall storage of nitrogen. Depending on the previous discharges and the discharge history, the same nitrogen seeding level might not be sufficient to create an XPR, or can lead to an over-seeding. In order to compensate for the unknown wall storage, an active control of the nitrogen seeding level is necessary.

3.2. XPR controllability and active control at TCV

If the existence of radiation at the X-point immediately leads to a disruptive MARFE, the scenario would not be controllable. However, the plasma can recover from an XPR state, as seen in Figs. 3, 6 or 7,

where the NII emission peak goes back to the target after switching off the seeding. Therefore, an active control might be possible.

The real-time front detection algorithm of [21] is adjusted to track the NII emission peak (location of the maximum emission) instead of the emission front (location where 50% of the peak signal are reached towards the target), once the NII emission front moves close to the X-point. This signal is used by a real-time controller in order to adjust the nitrogen seeding level to match the requested location of the emission peak. Fig. 7 shows the comparison of a discharge with a feed forward programmed nitrogen seeding rate and one with successful active feedback.

In between ELMs, the noise of the peak tracking is within the camera resolution, in the range of 1 cm. The large peaks in the tracking signal are caused by ELMs, which lead to a strong emission at the divertor target, detected close to $L_{pol} = 0$ cm. The disturbance of the real-time signal by the ELMs provokes a too high seeding rate (see Fig. 7) and then causes a radiative collapse. In order to avoid such errors, an ELM filter has to be applied to the real-time signal. This is yet to be done, as well as to extend the control to a broader range of scenarios.

4. Conclusion

Observing an X-point radiator at ASDEX Upgrade and TCV together with the observation at other devices (Alcator C-mod [6], JT-60U [7], JET [1]) shows that this feature is independent of the wall material or device size. For AUG, the operational range with an XPR is currently much broader than for TCV, covering almost the full available range of B_t , I_p and P_{heat} , while in TCV for now it is only tested in one specific scenario. For AUG, using the divertor Thomson scattering system one can observe a cold XPR core developing with a radiating mantle.

The one-dimensional model predicts that the plasma at the X-point transits from a high temperature ($T_{e,X} > 25$ eV) to a low temperature solution ($T_{e,X} \leq 2$ eV), which in the presence of carbon would be unstable [10]. These predictions appear to be in variance with the observation of an XPR at TCV. However, the model potentially only applies to the cold XPR core solution while in the case of TCV, the observed XPR might only be present by the radiation front, but did not yet develop the cold core. However, soon after the XPR develops into a non-stationary MARFE and disrupts. Therefore, the model might not be applicable for the onset of the radiation, but could well explain why the XPR cannot easily be maintained at TCV. Whereas at AUG, where carbon is not significantly present, the XPR is maintained also with the cold core and can be sustained for several seconds.

While X-point radiation is not the foreseen operational regime for the ITER divertor, the observation at multiple devices indicate that the XPR is a universal feature of tokamak plasmas and makes it a promising regime, which might also occur in future devices. In order to predict the access conditions and stability of an XPR for a reactor scale device, further experiments for a size scaling as well as significant modelling efforts are still required.

CRedit authorship contribution statement

M. Bernert: Writing – original draft, Conceptualization, Investigation. **S. Wiesen:** Conceptualization, Investigation. **O. Février:** Conceptualization, Investigation. **A. Kallenbach:** Conceptualization, Investigation. **J.T.W. Koenders:** Software, Investigation, Conceptualization. **B. Sieglin:** Software, Investigation. **U. Stroth:** Conceptualization, Investigation, Writing – review & editing. **T.O.S.J. Bosman:** Software, Investigation. **D. Brida:** Investigation. **M. Cavedon:** Investigation. **P. David:** Investigation. **M.G. Dunne:** Investigation. **S. Henderson:** Investigation. **B. Kool:** Software, Investigation. **T. Lunt:** Investigation. **R.M. McDermott:** Investigation. **O. Pan:** Investigation. **A. Persek:** Investigation. **H. Reimerdes:** Investigation. **U. Sheikh:** Investigation. **C. Theiler:** Investigation. **M. van Berkel:** Conceptualization. **T. Wijkamp:** Investigation. **M. Wischmeier:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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