

## Sensor selection criteria for divertor heat flux feedback control in ASDEX Upgrade

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### Introduction

ITER as well as any future tokamak or stellarator reactor demonstration device will require active control of the divertor heat flux. This will be accomplished by the injection of radiating impurities, where more than one species is required to optimize the radiative power removal in the main plasma and the divertor region [1] [2]. We foresee the combination of a low-Z species for radiation in the divertor and a medium-Z species for radiation in the outer core plasma.

While in ITER the core radiative cooling will be quite limited by the requirement of a separatrix power flux being considerably above the H-L transition power, in a future DEMO the core radiated power will have to be considerably higher to cope with the limited divertor radiative cooling capability. ASDEX Upgrade (AUG) conditions of  $P_{sep}/P_{L-H}$  lie in between the expected ITER and DEMO parameters.

### Sensors for main chamber and divertor radiation feedback

For the realization of a double-radiative feedback a suitable set of sensors is required. The radiation in the main plasma is reliably measured by foil bolometry, here the real time evaluation of the radiated power is the major task. A robust sensor for the divertor heat flux appears more challenging. While a real time measurement of the target heat flux by IR thermography has not been accomplished so far, and may be too complicated to become a standard procedure, a simpler sensor diagnostic appears appropriate. Several different diagnostics have been tested in various tokamaks for target heat flux control by impurity seeding, which can be divided into two major categories: Signals used as a proxy for the heat flux (divertor  $T_e$ , ion saturation current, passive electric current) are converted to an approximated heat load and then directly used to calculate the seeded gas flux. Signals connected to power removal (radiated power, spectral line intensities) are converted into an estimate of the total dissipated power and subtracted from the incoming power flux to construct an approximate divertor power load. While a system using the passive thermoelectric target current measurement as heat flux proxy is routinely used in AUG [3], it may not be applicable in a high heat flux divertor due to technical problems with the installation of the shunt sensors. In

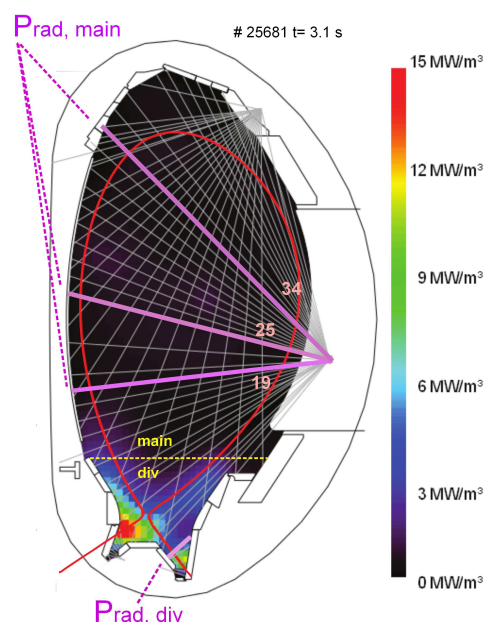


Figure 1: Cross section of AUG, radiated power densities of a high power discharge and bolometer lines setup. Characteristic lines of sight are highlighted: 3 foil bolometer chords are used for main chamber radiation calculation and a diode bolometer chord is used to calculate the effect of divertor radiation on the target power load.

the following, the development of a new double radiative feedback system in AUG is described. Bolometers are used as sensors and argon and nitrogen as seeded species for predominant emission of core and divertor radiation, respectively [1].

### Real-time main chamber radiation

The main chamber radiation can be estimated with sufficient accuracy by the linear combination of 3 representative foil bolometer chords. Weighting coefficients are derived from a fit to a training set of fully deconvoluted AUG radiation profiles. Figure 2a shows a comparison of the total main chamber radiation taken from the 3-chord model with a full deconvolution. Data points represent time-integrated values over typically 0.5 s long intervals with stationary discharge conditions. Mostly high power H-mode discharges are considered with different levels of nitrogen and deuterium puffing. Since the main chamber radiation is only weakly perturbed by ELMs, as seen on corresponding AXUV chords, foil bolometry gives sufficiently accurate results. However, only the total main chamber radiation can be derived, a calculation of its fraction inside the separatrix is not possible by a simple real-time capable model. Deconvolution shows that the major fraction is radiated inside the separatrix. The simple 3-chord model is routinely evaluated in real time using LabView RT and transmitted to the shared memory of the discharge control system [4], where the power flux into the divertor,  $P_{div} = P_{heat} - P_{radmain}$  is calculated.

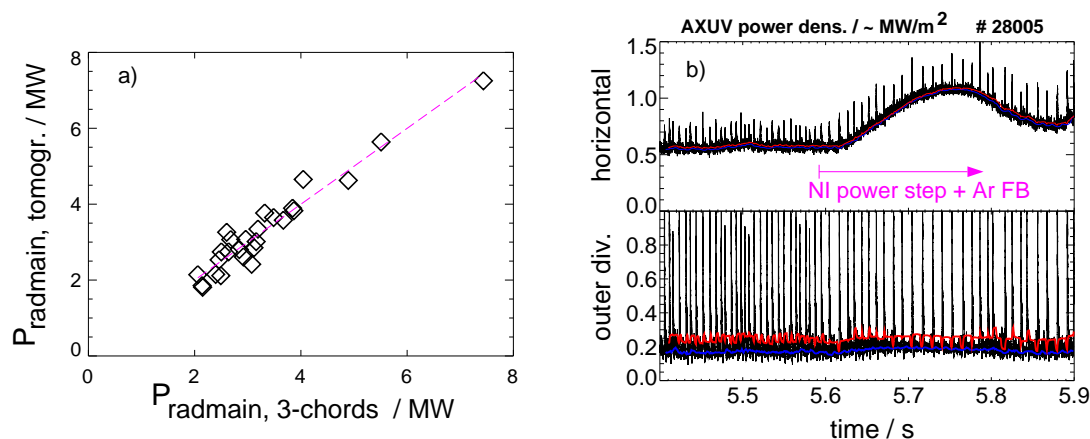


Figure 2: a) Comparison of the total main chamber radiated power from foil bolometer tomography with a simple fit model using line integrated radiation densities [ $W/m^2$ ] from 3 selected chords. The main chamber is defined as the region with  $z > -0.66$  m, so the radiation around the X-point is counted as divertor radiation.  $P_{radmain,3-chords} = 6.12 \cdot F19 + 5.9 \cdot F25 + 0.31 \cdot F34 + 2.23e5$  [W]. b) Fast radiation measurement by AXUV bolometry on a horizontal main chamber chord and in the outer divertor (see fig. 1). Red and blue lines show median and mean filtered divertor radiation. About 30 % of the radiation is emitted during ELMs.

### Real-time divertor radiation and target heat flux evaluation

The implementation of a simple divertor radiation model as described before for the main chamber radiation turns out to be more challenging. This is due to the higher variability of divertor radiation in space (fig. 1) and time (fig. 2). Different combinations of divertor viewing lines of foil bolometers and AXUV diodes were investigated for the possibility to construct

a simple model for the total divertor radiation. The use of a single viewing line in the upper outer divertor revealed the most efficient results. Two simple 1-chord models for the divertor radiation were selected: 1-diode (1d), where a median filter is applied to cut out ELM effects and 1-foil (1f), which is taken just time-averaged. The weighting factor  $w$  for the selected line-integrated measurements was determined by fitting the power balance,  $P_{\text{raddiv-1d/1f}} = w_{1d/1f} I_{1d/1f} = P_{\text{heat}} - P_{\text{radmain-3ch}} - P_{\text{target}}$ , where  $P_{\text{target}}$  is the power load in inner+outer divertor measured by IR thermography. An improved fit is obtained by division of the 1-chord radiation measurement by the plasma current ( $I_p = 0.8\text{--}1.2\text{ MA}$ ). For further application, the 1-diode measurement is normalized by  $I_p/\text{MA}$ , the foil bolometer data are taken just as measured. Finally, a good representation of both the divertor radiation from tomography (fig. 3a) as well as the power balance (fig. 3b) has been obtained. The direct fit of the 1-chord models to obtain power balance is essential, since the fit can partly compensate for systematic experimental errors. These include calibration uncertainties, effects of toroidal asymmetries, unaccounted ELM power losses and radiation power measured by thermography. The use of the power balance for target heat flux control is in fact not well conditioned, since the sensor value  $P_{\text{target,fit}} = P_{\text{heat}} - P_{\text{radmain-3ch}} - P_{\text{raddiv}}$  contains the difference of numbers of similar size. For the real-time application, also the heating power  $P_{\text{heat}}$  must be known in good accuracy by the discharge control system. Figure 3c compares the target heat flux derived from the simple radiation models with the thermography measurement. The agreement is not excellent, but considered sufficient for a feedback application.

### Double radiative feedback

The 3-chord main chamber radiation model and the Praddiv-1f model have been implemented in the AUG discharge control system for simultaneous control of the power flux into the divertor and to the targets. The main chamber radiation is controlled by argon injection through a midplane valve, while nitrogen injected through toroidally distributed valves in the divertor private flux region is used to control the divertor radiation and thus  $P_{\text{target}}$ . Figure 4a shows time traces of a discharge with simultaneous double feedback. Both radiation control schemes use proportional and integral parts (PI) and cooperate smoothly, no instabilities have been observed so far during parameter variations. The  $P_{\text{div}}$  controller achieves very fast reactions since the radiation build-up by Ar in the core is more effective than the divertor cooling by nitrogen, despite the more than an

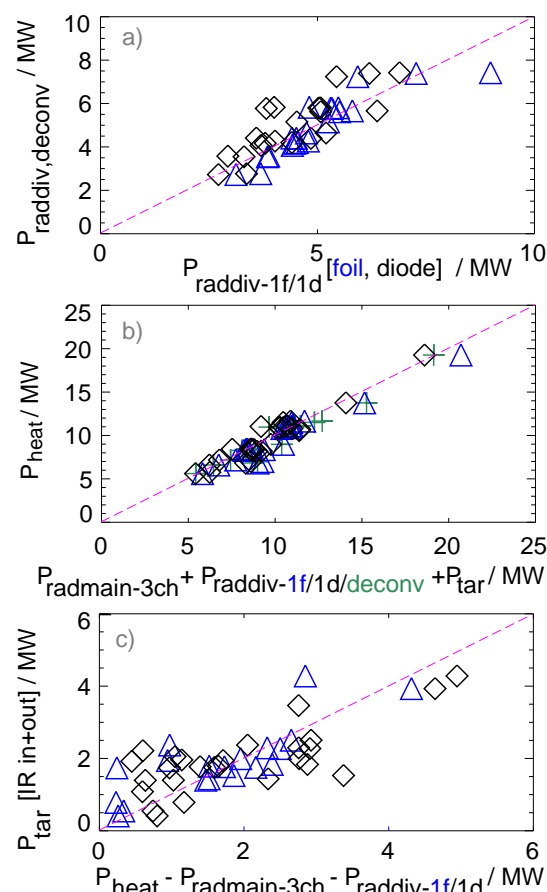


Figure 3: a) Fit of the divertor radiated power from tomography versus extrapolation model from 1 foil (triangles) and 1 AXUX diode (diamonds) chord. b) Power balance for the two 1-chord divertor radiation models and the tomographic reconstruction (+). c) Target heat flux from the simple real-time capable radiation models.

order of magnitude higher N<sub>2</sub> valve flux. Instead of using divertor radiation for power balance, the Pdiv controller can also be used together with the AUG standard target heat flux controller [3]. Figure 4b shows 3 example discharges using this mode to exemplify the quality of the power balance model based on the simple divertor radiation model. The deviations appear acceptable.

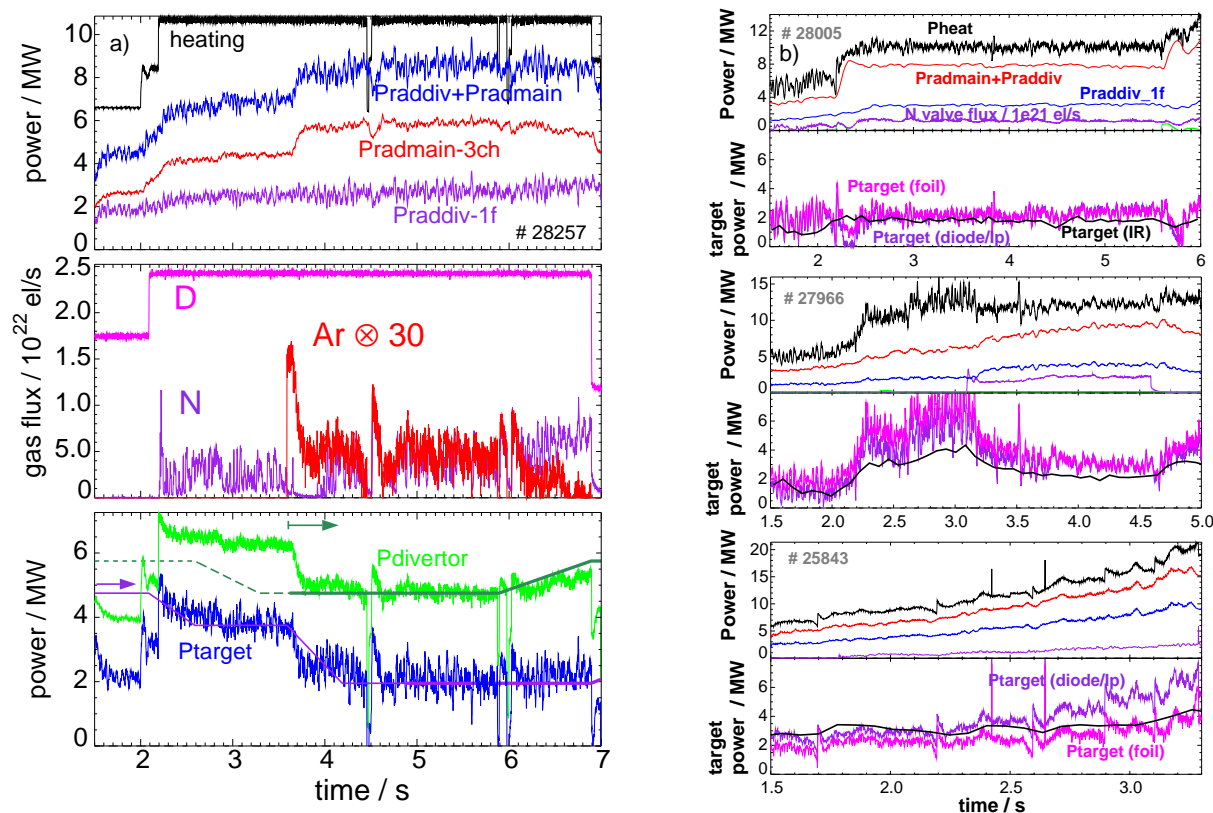


Figure 4: a) Time traces of a discharge with double-feedback of power to the divertor using Ar as main chamber radiator and simultaneous target power control using nitrogen injection in the divertor private flux region. The Ptarget control is on early in the discharge, the additional Pdiv control is activated at  $t=3.6$  s b) Comparison of the target power loads from simple 1-foil and 1-diode/ $I_p$  models with IR thermography for a double (N, Ar) and two N-seeded discharges.

## Conclusions

A double radiation feedback system for simultaneous control of the power flux into the divertor by Ar seeding and of the target heat load by N seeding has been implemented in ASDEX Upgrade. The use of few and simple sensors ensures the required reliability of the system. So far, only foil bolometers have been used which are not fast enough for removal of ELMs from the signals. The alternative use of fast AXUV diodes is foreseen for the future, however issues of long term stability of their calibration may arise. This double feedback will allow the further enhancement of the power dissipation capability in tokamaks with a closed, vertical target divertor.

## References

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