ICRF Operation with Improved Antennas  
in a Full W-wall ASDEX Upgrade, Status and Developments

V. Bobkov\textsuperscript{1,*}, M. Balden\textsuperscript{1}, F. Braun\textsuperscript{1}, R. Dux\textsuperscript{1}, A. Herrmann\textsuperscript{1}, H. Faugel\textsuperscript{1}, H. Füngeldel\textsuperscript{1}, L. Giannone\textsuperscript{1}, A. Kallenbach\textsuperscript{1}, M. Kocan\textsuperscript{1}, H. Maier\textsuperscript{1}, H.W. Müller\textsuperscript{1}, R. Neu\textsuperscript{1}, J.-M. Noterdaeme\textsuperscript{1,2}, Y. Podoba\textsuperscript{1}, K. Polozhiy\textsuperscript{1}, Th. Pütterich\textsuperscript{1}, V. Rohde\textsuperscript{1}, G. Siegl\textsuperscript{1}, F. Zeus\textsuperscript{1}, H. Zohm\textsuperscript{1} and ASDEX Upgrade team

\textsuperscript{1}Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748, Germany  
\textsuperscript{2}EESA Department, Gent University, 9000 Gent, Belgium

\* Email: bobkov@ipp.mpg.de

Abstract. A modified test two-strap ICRF antenna in ASDEX Upgrade with broad limiters and narrow straps has shown an improved operation with full W-wall in 2011 with up to a 40% lower rise of W concentration allowing more stable operation at low deuterium gas injection rate. Local spectroscopic measurements indicate an up to a 40% reduction of the rise of W sputtering yield at the antenna limiters during ICRF power, the improvement being highest at lowest clearance between the plasma and the antenna. Experiments with boron-coated side limiters of two antennas operated together in 2012 showed that the side limiters are responsible to more than half of the increased W content in the plasma. Together with the contribution from the other limiter tiles, not replaced in 2012, the limiters accounts for at least 2/3rds of the W content. The boron limiters on two antennas together with the improved broad-limiter antenna allowed a successful ICRF operation in 2012. As a part of long-term strategy of antenna design development, two three-strap antennas with phase and power balance control for reduction of $E_{\parallel}$ are planned for installation in 2013.

1. Introduction

Operation of ICRF (Ion Cyclotron Range of Frequencies) antennas in magnetic fusion experiments is often accompanied by enhanced plasma-surface interactions. These become more problematic in high-Z machines, such as the full tungsten (W) ASDEX Upgrade (AUG), where the W released from the wall during the ICRF operation contributes to radiation losses from the central plasma. These losses become substantial if the W concentration exceeds $5\cdot10^{-5}$, which is usually the case during ICRF operation in AUG with moderate or low deuterium gas injection rate. A significant part of the ICRF-specific plasma wall interactions in AUG can be attributed to the existence of $E_{\parallel}$, the parallel component of RF electrical field near the antenna [1]. This field contributes to elevated sheath potentials which can directly influence the W sputtering. It can affect as well as depend on the plasma convection in the scrape-off-layer [2]. The resulting effect of the near-field on the W release is difficult to characterize, because the exact conditions, such as small-scale geometry of magnetic field line connections, play a significant role [1, 2], whereas the diagnostic capabilities are limited. In AUG, two strategies on establishing the compatibility of ICRF antennas with the W wall are being pursued.

The first strategy, long-term, is based on reduction of the $E_{\parallel}$ field by following the guidelines on antenna design elaborated with the help of finite-elements EM calculations [1]. Because of the known complexity of the antenna-plasma-wall interactions, an overall reduction $E_{\parallel}$ has been aimed for, rather than only a reduction of the RF voltage on a family of magnetic field lines.
The second, short term strategy on making the ICRF operation compatible with the W wall at the low gas injection rate conditions in AUG, makes use of low-Z materials in the vicinity of ICRF antennas by the implementation of boron coatings on the antenna limiters. This does not solve the general problem of the ICRF-related plasma-wall interaction, but helps AUG to operate with ICRF in a wider range of conditions until the improvements of antenna design prove to be sufficient for the compatibility with W wall.

2. Progress on long term strategy of antenna design development

Considering the finite elements calculations, including codes such as HFSS [4] and TOPICA [5] show that for the original two-strap AUG antenna (see Fig.1a for HFSS case), a reduction of the $E_\parallel$ fields in front of the antenna is achieved mainly by managing the RF image currents on antenna structures.

![HFSS E_\parallel calculations normalized to the total power of 1 MW crossing the antenna plane. a) original AUG ICRF antenna; b) broad-limiter antenna; c) three-strap antenna.](image)

The first, low-cost step of the strategy was the modification of one two-strap antenna by installing narrower straps and broader limiters, referred to as “broad-limiter” antenna (see Fig.1b for corresponding HFSS model and Fig. 2 for the photo of the real antenna), prior to the 2011 experimental campaign. The aim was to study whether it behaves better than the original antenna, and if so, progress with more aggressive antenna changes (see section 2.3). It should be noted that the broad antenna limiters increase the area of the plasma-facing components coated by W in the very vicinity of the antenna. This is a drawback of such antenna design,
to some extent compensated by the fact the broad limiters provide a better “shadow” inside the antenna from the long magnetic field line connections and the parallel plasma flows coming from the outside of the antenna.

As in the previous campaigns, the $H$ minority scheme with $(0 \pi)$ strap phasing was utilized in 2011 with 4 two-strap antennas ($a1\ldots a4$) in pairs connected via 3dB hybrids. Antennas $a1$ and $a3$ ($a2$ and $a4$) located opposite to each other (see Fig. 3) formed antenna pair(s) throughout the 2011 campaign to allow independent feeding of neighboring antennas. As only antenna $a4$ has been modified, for some of the experiments $a1$ and $a2$ were mismatched to allow direct comparison between $a3$ (original) and $a4$ (broad-limiter). However, this limited the available ICRF power to only about 500 kW per antenna, because of the issues with reflected power at the RF generators, due to the low efficiency of the 3dB hybrid insulation scheme at strongly misbalanced reflections from the antennas.

2.1. Equality of conditions for operation of original and broad-limiter antennas

To ensure the equality of conditions for operation of the original and the broad-limiter, a number of parameters need to be controlled.

Radial coordinates of several poloidal locations of one poloidal side limiter per antenna have been measured before the experimental campaign. These were found to be equal within the accuracy of the measurements of 2 mm for both $a3$ and $a4$ antennas, which are used for the comparison. The configuration of antenna and guard limiters in AUG provides a similar profile of the connection lengths outside the original and the broad-limiter antennas.

With central temperature and density profiles fixed, the location of the gas injection plays a significant role for $W$ sputtering, as is shown in Fig. 4 for the experiment conducted in 2009 [6]. Both $W$ influx $I_W$ and the effective $W$ sputtering yield $Y_W$, measured spectroscopically at the poloidal side antenna limiter, are reduced significantly (especially at vertical position $z>0.1$), when $D_2$ working gas injection local to the antenna is used, compared to the gas injected with the same rate remotely (see [6] for details of gas injection). Thus, the remote $D_2$ gas injection was chosen for the antenna comparison.

To minimize influences of boron layers on the limiters deposited during boronizations in AUG on the characterization of $W$ release during ICRF, experiments were conducted at least 100 plasma shots after the boronizations.
2.2. Comparison of original and broad-limiter antenna in operation

To test the antennas, an H-mode scenario with $P_{\text{NBI}}=5\text{MW}$ at a magnetic field $B_t = -2\text{T}$ and plasma current $I_p = 0.8\text{MA}$ with constantly decreasing $D_2$ gas injection rate $\Gamma_{D2}$ was used with ICRF power at 30 MHz for central heating. In H-modes in the full-W AUG under such conditions, a lower threshold of $\Gamma_{D2}$ exists, from which on the W accumulation in the plasma develops. The point of the accumulation can be easily determined by observing the central and the edge lines of sight of the bolometers (see lower two graphs of Fig. 5). In Fig. 5, vertical dashed lines show the W accumulation thresholds for the shot where only the broad-limiter antenna was used (red) and for the shot where only one original antenna was powered (blue). The broad-limiter antenna allows operation at lower $\Gamma_{D2}$ without the W accumulation, with other parameters fixed.

Interestingly, a comparison with pure NBI heated discharges in the same scenario shows that the application of ICRF power using the broad-limiter antenna prolongs the phase without W accumulation to lower $\Gamma_{D2}$ for this scenario, as is expected from the application of central RF heating without the detrimental effect of the W source. At the same conditions, the ICRF power from the original antennas does not affect the duration of the W-accumulation-free phase, exposing the negative influence of the W source associated with ICRF.

The antenna comparison was successfully reproduced several times during the 2011 experimental campaign. The data from this series of discharges are summarized in Fig. 6, where the change of W concentration $\Delta C_W$ due to ICRF is shown with respect to $\Gamma_{D2}$. The latter is normalized to allow the use of the data taken at different machine conditions during the 2011 campaign. Value of $\Gamma_{D2}^\text{norm}=0$ corresponds to the W accumulation threshold, whereas $\Gamma_{D2}^\text{norm}=1$ corresponds to the maximum value of $\Gamma_{D2}$ at the beginning of ramp-down of the gas injection rate. The data plotted is limited to $\Gamma_{D2}^\text{norm}>0.1$ to show stationary conditions only. It can be seen that $\Delta C_W$ is lower for the broad-limiter antenna than for the original antenna, being about 40% lower than that for the original antenna at the low gas injection rates.

Thus, despite the increased area of the antenna plasma facing components coated by W, and even at relatively low RF power of $\sim 500\text{ kW}$ used per antenna, the modified antenna behaves consistently better in terms of the balance between the central heating and the source of W.
released during its operation. This does not explain, however, whether the W sputtering has decreased or the heating efficiency has increased. The $k_{||}$-spectrum peaks at slightly higher $k_{||}$ of 9.5 m$^{-1}$ for the broad-limiter antenna compared to the corresponding peak at $k_{||} = 8.5$ m$^{-1}$ for the original antenna. The results presented above could thus also be consistent with a slightly more efficient heating for the broad-limiter antenna at the same level of W sputtering, although this difference in $k_{||}$ can be considered small. To shed more light on separation of the effects of the W sputtering and the heating efficiency, the local measurements of W sputtering patterns at $a3$ and $a4$ are presented below.

2.3. Local measurements at original and broad-limiter antenna

In [2], the measurements from 2009 were presented, taken at about the same conditions as for the experiments described below, showing practically equal measured values of W influx $\Gamma_W$ and W sputtering yield $Y_W$ for $a3$ and $a4$, both being original antennas at that time.

For 2011, the lines of sight for the local spectroscopic measurements of $\Gamma_D$, $\Gamma_W$ and $Y_W$ at the broad-limiter antenna were chosen to match approximately the same poloidal locations as in [2]. However the observation spots cover the different profiles of the broad and the original limiters and thus are not any longer equivalent. The different limiter shapes result in significantly higher absolute values of particle flux of impinging deuterons $\Gamma_D$ measured at the outer row of measurements of the broad-limiter (see the spots on dashed line in Fig. 2 and dashed line in Fig.3) than at the inner row of $a4$ and the row at $a3$. These high $\Gamma_D$ measurements could be explained by a combination of factors: a) the “shadowing” effect by the broad limiters is present due to the longer connection lengths of magnetic field lines at the outer row of $a4$ than at the inner row of $a4$ and due to the upstream parallel plasma flows; b) the limiter shape yields smaller averaged clearance between the plasma and the surface of the $a4$ broad limiter covered by an observation spot than at the row at $a3$. To be less prone to the variations in the diagnostics geometry during the antenna comparison, we limit ourselves to considering $Y_W$, in particular its changes due to ICRF ($\Delta Y_W$). The measure of the effective sputtering yield $Y_W$ is the most relevant for the characterization of the changes in sputtering, because $Y_W$ is a priori normalized to the particle flux and sets a boundary condition for the W concentration near the W source.

Figure 7 shows comparison of $\Delta Y_W$ at $a3$ (original) and $a4$ (broad-limiter), averaged over the time of operation of either $a3$ or $a4$, and over the same range of the vertical positions of the measurements, depending on the plasma outermost position $R_{out}$. It can be seen that the broad-limiter $a4$ is characterized by lower $\Delta Y_W$, both for the inside and the outside rows of the lines of sight, and especially so at higher $R_{out}$ when the plasma is closest to the antenna. Thus at $R_{out} \approx 2.165$m, $\Delta Y_W$ measured at $a4$ is about 40% lower than at $a3$. It is therefore likely that the improved operation of the broad-limiter antenna is related to the reduced W sputtering, rather than to the changes in the heating efficiency.

![FIG. 7. $\Delta Y_W$ comparison for $a3$ and $a4$ depending on the plasma outermost position $R_{out}$ using data from ##26541-26544.](image-url)
The “shadow” effect of the broad limiters mentioned above seems to be limited to the flux of the impinging particles $I_D$ only and is not present for $\Delta Y_W$.

It has to be noted that diagnostic capabilities which existed so far in AUG did not allow to confirm that the reduction of $\Delta Y_W$ is caused by the reduced $E_{||}$. In order to help resolving this, a new retarding field analyser which connects along magnetic field lines to $a4$ has been introduced and tested in the summer of 2012. Simultaneous characterization of the profiles of plasma potentials for $a4$ and $a2$ (the latter characterized by the same type of probe from the midplane manipulator) are planned for the end of 2012.

2.4. Three-strap antenna design and plans

Two completely new three-strap antennas are planned for installation in 2013. Figure 1c shows the calculations of the near fields for the antenna which shows a significant reduction of $E_{||}$. Figure 8 presents a front view of the antenna CAD model. The principle of the design is based on finding a minimization of image currents by balancing between the $(0 \pi)$-phased image current contributions. This is done by controlling the phase and the power distribution between the outer straps and the inner strap. The issues connected to the different shapes of the side limiters will be eliminated, because the same shape of the side limiters as that for the original antenna will be used for the three-strap antennas. To monitor the balance of the RF currents, an array of RF and DC antenna shunts [2] will be mounted on the antennas limiters.

The installation of two antennas will allow the use of the full 3dB insulation scheme without jeopardizing ICRF power and ELM tolerance. The upgrade includes also additional transmission lines and phase control hardware. A prototype of the new digital-based phase control system, described in [7], has been tested during experiments in 2011, by making a variation of phase between two neighboring antennas $a3$ and $a4$ during a plasma discharge.

FIG.8. Front view of the three-strap antenna from CAD.

FIG.9. In-shot phase control between $a3$ and $a4$ and effect on W source at one of the locations.
The results are presented in Fig. 9, where ICRF power, phase difference $\Delta \Phi$ between $a3$ and $a4$, and $I_W$ at one of the outer lines of sight at $a4$ are shown. The value of $I_W$ on the single line of sight reacts sensitively on the changes of $\Delta \Phi$. A more detailed analysis [8] shows that the integral behavior of the W sources at $a3$ and $a4$ is less sensitive to the phase between the antennas, because the reaction is location dependent. A significantly more sensitive behavior is expected for the new three-strap antennas during variation of phase between the straps. The phase will need to be actively controlled, ultimately together with the power balance in real time, to minimize the total W source. Because of the expected strong load dependence on the changes of the strap phasing, the load tolerance of the 3dB hybrid system will be crucial for the operation.

3. **Short-term strategy: boron coated antenna limiters**

Previous studies [2] have shown that the antenna limiters play a dominant role as a W source during application of ICRF power. To increase the operational window for the ICRF system in AUG, the side limiters of $a1$ and $a2$ (see Fig. 10) were coated by a 50 $\mu$m thick layer of boron prior to the installation in the vessel. Boron is used in AUG during boronizations, therefore no new material was introduced into the machine.

For the whole 2012 experimental campaign, both antennas $a1$ and $a2$ with the boron-coated limiters were connected as a pair within the 3dB hybrid connection scheme, whereas $a3$ and $a4$ were connected as the other pair. This allowed a discrete operation of the antennas with the boron-coated limiters and of the antennas with the W-coated limiters.

The difference in production of W between the two antenna pairs was clearly visible in the experiment. Figure 11 shows the comparison of the two antenna pairs in terms of W concentration for the case of the scenario with $I_p=1$MA, $B_t=-2.5$T, $P_{NBI}=7.5$MW, $P_{ECRH}=2.5$MW, $P_{ICRF}=1.5$ MW per antenna pair at the frequency of 36.5 MHz. A very similar picture is observed with $B_t=-2.0$T at 30 MHz. The side W limiters account for more than half of the increase of W concentration. Based on the local spectroscopic observations on the upper row of the limiters at $a3$, the contribution of the upper and the lower rows of the limiters, not replaced by the boron-coated limiters at $a1$ and $a2$, can be roughly estimated to be 1/4 to 1/3 of that from the side limiters. The total effect of the antenna limiters on the W source is thus even stronger, even more so considering the fact that the $a4$ broad-limiter antenna, one of the two antennas with the W limiters, has previously shown the reduced W release (subsections 2.3 and 2.4). Therefore the
observations confirm the dominant role of the antenna limiters in the W source associated with the ICRF power in AUG.

The improved ICRF operation of the antennas \textit{a1} and \textit{a2} with the boron-coated limiters allowed multiple ITER-relevant experiments using the ICRF power [9-11] during the 2012 experimental campaign. 

The boron coatings have shown good durability during the high-power AUG experiments. Surfaces of all limiter tiles, except the leading edges of tiles at the upper corners where the heat loads were the highest, showed almost no changes. The surface of the upper corner tiles was modified, forming crystals of boron in several locations. Nevertheless this did not jeopardize the machine operation nor the improved ICRF operation.

4. Conclusions and outlook

The experiments with a single modified two-strap ICRF antenna with broad-limiters and narrow straps in ASDEX Upgrade have shown improvements in compatibility with the full W-wall for the antenna compared to the antennas of the original design. A more stable operation at low deuterium rate has been observed, as well as a lower change of W concentration in the plasma and a lower change of sputtering yield measured at the antenna limiters. This antenna has successfully tested the long-term strategy of the antenna design development. A completely new antenna design with two antennas three straps each is planned for 2013 with the aim to minimize the antenna near fields to improve the W compatibility further. As a short-term solution, the boron-coated antenna side limiters have been tested in 2012. The experiments with the boron-coated limiters confirmed the dominant role of the limiters as W sources as well as provided a good possibility to conduct multiple ITER-relevant experiments with ICRF power in ASDEX Upgrade with W wall.

References

[9] Stober J. et al., Dominant ECR heating of H-mode plasmas on ASDEX Upgrade using the upgraded ECRH system and comparison to dominant NBI or ICR heating, this conference, EX/1-4.