Effect of the phase shift between antennas on W sputtering in ASDEX Upgrade

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The ICRF (Ion Cyclotron Range of Frequencies) systems are successfully used for heating and current drive in fusion experiments. The main problem at ICRF operation is the sputtering of plasma facing material (PFCs) in the antenna vicinity. For future fusion devices, high-Z elements are favorable as materials of the first wall [1, 2, 3]. This initiates a growing interest on the compatibility of ICRF operation in the plasma with high-Z PFCs.

It is believed that an erosion enhancement of PFCs by ICRF systems [4, 5] is due to the generation of strong electric fields ($E_{||}$) along magnetic field lines. This electric field ($E_{||}$) is responsible for the formation of a high RF potential, $V_{||} = \int E_{||}\mathrm{d}l$, which is rectified in the sheath region [6, 7] and accelerates the ions to the limiters. The experiments [8, 9] in 2008-2009 show that the effect of $E_{||}$-field can be partially compensated by choosing an appropriate phase shift $\Delta\phi$ between two neighboring antennas coupled along magnetic field lines. The present analysis continues the early ASDEX Upgrade (AUG) experiments in the years 2008-2011 [8, 9].

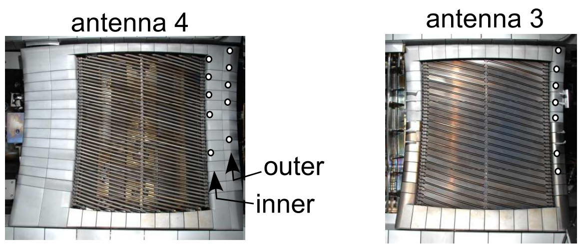

Fig. 1. Antennas 3 and 4 with points of spectroscopic observation

The ICRF system at AUG has 4 two-straps ICRF antennas placed on the low field side. For the standard operation at H-minority resonance heating an antenna's strap current phasing of $(0;\pi)$ is used. Each pair of the neighboring antennas (1-2 and 3-4) is powered through 3 dB-couplers [10] with a phase shift of 90° between two neighboring antennas. At present, the ICRF system can operate in two configurations with independently powered pairs either of neighboring (1-2 and 3-4) or of opposite (1-3 and 2-4) antennas in the torus. In addition, for generation and synchronization of the driven frequencies of all generators a direct digital synthesizer is used to control independently the phases of each antennas pairs.

Tungsten (Γ_{W}) and deuterium (Γ_{D}) fluxes are spectroscopically monitored with seven lines of sight (LOS) for the antenna 3 limiter and with five LOSs on each of the limiter sides (inner and outer) of the antenna 4 (see Fig. 1). The effective sputtering yield of tungsten $Y_{\mathrm{W}} = \Gamma_{\mathrm{W}}/\Gamma_{\mathrm{D}}$

is obtained from a ratio of the tungsten-to-deuterium intensities [11]. The total W content in the discharge is characterized by the tungsten concentration (C_W) measured spectroscopically [12].

The presented results relate to the shot number #27103 (NBI $P = 5$MW, ICRF $P = 3.5$MW at 36.5 MHz from all 4 antennas). The phase shift between antenna pairs 1-3 and 2-4 is scanned in steps of 45^o every 450 ms. During the switching period of the phase, the power of the ICRF generator is turned off. In this experiment [9] the tungsten concentration C_W during the antenna's phase scan in contrast to [8] stays almost independent from the antennas phasing, although Y_W still depends on the antennas phase shift $\Delta\phi$. To understand this phenomena we present a detailed analysis of the local distribution of the observed $\Gamma_{W,D}$ fluxes.

Because of a lack of diagnostics (like RF voltage measurements) in front of the ICRF antennas we have no possibility to make direct measurements of the electrical parameters of the plasma at the limiters. However, some conclusions on the role of the sheath rectification effect can be done from indirect analysis of the $\Gamma_{W,D}$ fluxes and of the sputtering yield Y_W.

The total concentration of the tungsten (C_W) is proportional to the total influx of tungsten. If the main source of Γ_W is physical sputtering, the used normalization of Γ_W/Γ_D gives us a normalized sputtering yield or in the case of $\Gamma_D \gg \Gamma_\alpha$ an average sputtering coefficient:

$$\Gamma_W = \Gamma_D \cdot \gamma_W^D + \sum_\alpha \Gamma_\alpha \cdot \gamma_W^\alpha = \Gamma_D \cdot \left(\gamma_W^D + \sum_\alpha \gamma_W^\alpha \cdot c_\alpha\right) = Y_W \cdot \Gamma_D$$

where α denotes the impurity ion species in the flux to the wall, the $\gamma_W^{\alpha,D}$ are the sputtering coefficients of tungsten by ions of species of α and D $c_\alpha = \Gamma_\alpha/\Gamma_D$ is a concentration of the impurity α in the ion flux.

The sputtering coefficients γ_W^α are functions of ion energy and of the surface conditions like contamination and modification of thin surface layer. Due to the sheath rectification effect, the ions obtain an additional energy in the RF sheath. Thus, at fixed impurity concentrations c_α and at a fixed surface state, a variation of the sputtering yield Y_W could characterize the variation of the DC self-bias in the RF sheath, which is proportional to the RF component of the voltage/current in the plasmas in front of the ICRF antennas.

A reduction or an increase of the tungsten influx and respectively of the tungsten concentration C_W could be due to a variation of the sputtering yield Y_W or due to a change of the sputtering ion flux. Thus, the tungsten flux should be monitored together with the deuterium flux to distinguish a change of Γ_W due to Y_W or Γ_D.

In Fig. 2-4 the Γ_W and Γ_D fluxes at the LOSs are shown. The Y_W, Γ_D, correspond to the time average values over 60% of the phase scan to avoid a distortion due to a phase step switch. In the figures it is given the LOS coordinates Z and the phase shift $\Delta\phi$ between antennas for each step of $\Delta\phi$.

The deuterium fluxes Γ_D at all LOSs of limiters have different magnitudes but the evaluations of Γ_D during the discharge stay in proportion. The same behavior is observed even without the ICRF heating at the beginning of the discharge. Obviously there is an effect of the phase shift $\Delta\phi$ on the deuterium fluxes Γ_D. However, the changes of Γ_D are not caused by partial compensation of $E_{||}$, because in such case with a change of $\Delta\phi$ we would expect strong spatial redistribution (along Z-axis) of the Γ_D fluxes. But we observe a change of the Γ_D fluxes in proportion at all LOSs during the phase scan.

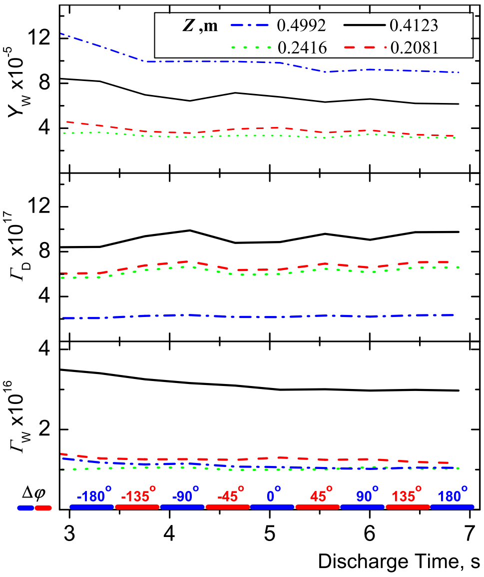

Fig. 2. Fluxes and sputtering yield on the antenna 3 limiters. For simplicity only half of the LOS is shown

At the LOSs of the antenna 3 limiter the tungsten flux reduces from the upper LOS to the central part of the limiter together with Γ_D. The bottom Γ_W points have small oscillations which are not identical to Γ_D signals. These oscillation are obviously caused by the change of sputtering coefficients γ_W^{α}. Thus at these LOSs we have a change of the sheath voltage due to the partial compensation of $E_{||}$ during the antennas phase scan. The calculated sputtering yield is maximal at the lower LOS and respectively we have a maximal increase of the sheath voltage in the central part of the antenna 3 limiter. However, absolute value of the Γ_W at the central part of the limiter has much lower magnitude comparing to Γ_W at the upper part of the limiter (black solid line in Fig. 2), where a change of Γ_D due to $\Delta\Phi$ is not observed.

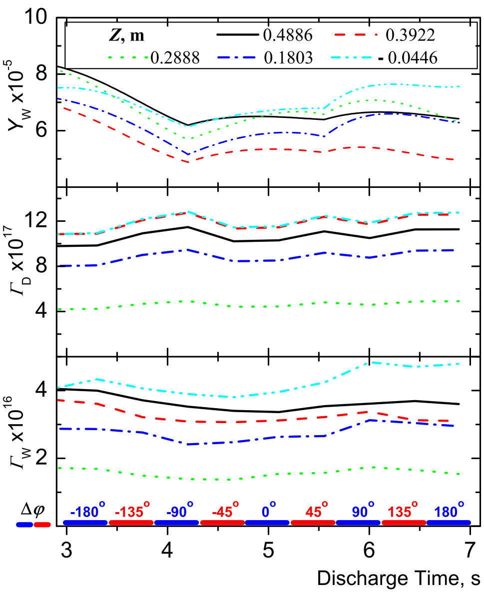

Fig. 3. Fluxes and sputtering yield at the LOS of antenna 4 limiters (outer).

At the outer (Fig. 3) and inner (Fig. 4) sides of the antenna 4 limiter, the Γ_D signals vary in proportion like in the case of the antenna 3 limiter. The sputtering yield Y_W at the beginning of the phase scan reduces with discharge time t at all LOSs (3 s $< t <$ 4.2 s, $-180^o < \Delta\phi < -90^o$). Such decrease is explained by growth of deuterium fluxes Γ_D but not by a change of Γ_W. The sputtering yield Y_W and fluxes $\Gamma_{W,D}$ are also identical between inner and outer parts of the antenna 4 limiter. This means that the limiter do not strongly suppress the coupling of $E_{||}$

between antenna 4 and 3 along magnetic field lines.

At some LOSs an anomalous behavior of the tungsten fluxes is observed (see black solid lines in Fig. 2 and in Fig. 3). These Γ_W fluxes stay almost constant, in contrast to the Γ_D fluxes. As it is mentioned above, when impurity concentrations c_α and the sputtering coefficients γ_W^α are constant then $\Gamma_W \sim \Gamma_D$. Obviously such behavior means that the absolute magnitude of the impurity fluxes Γ_α are not changing together with a change of Γ_D or that the sputtering coefficients γ_W^α are inverse proportional to the Γ_D. In last case it could mean that with an increase of the deuterium flux the RF voltage in the sheath is reduced. Such behavior of $\Gamma_{W,D}$ could be also explained by presence of any sputtering process independent from Γ_D like arc, hot spot and other.

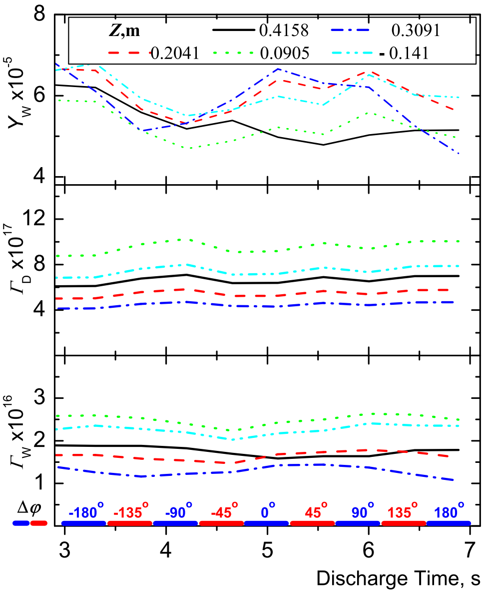

Fig. 4. Fluxes and sputtering yield at the LOS of antenna 4 limiters (inner).

The analysis of the $\Gamma_{W,D}$ fluxes can clarify the independence of C_W on the phase scan. The detectable distortions of the Γ_W fluxes due to a change of $\Delta\phi$ are observed at the LOSs with minimal magnitudes of Γ_W. Thus, the phase-depending component of Γ_W has a small impact on the resulting flux of tungsten into the plasmas. It is why we do not observe a change of C_W during the antennas phase scan.

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