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Determination of 2D-Emissivity-Distributions from a Digital 12-bit-CCD-System viewing the Divertor of ASDEX Upgrade tangentially and poloidally

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1 Introduction/Motivation

Understanding the features of plasma wall interaction in the divertor region remains to be a major topic in fusion research. One powerful approach to this is the experimental determination of radiation profiles as provided by the deconvolution of bolometry data [1]. Even more information about the behavior of the plasma is available, if the spatial distribution is not only known for the total radiation, but individually for the main species contributing to it, i. e. hydrogen and bright impurity lines (e. g. from carbon). These two-dimensional profiles can be obtained from the data of a CCD-camera viewing the divertor tangentially together with a mathematical reconstruction algorithm taking into account the geometry of the experiment [2,3].

In this paper, we focus on some experimental and related mathematical improvements of this technique, which have been introduced at ASDEX Upgrade and are necessary in general to minimize artifacts and get reliable emissivity distributions:

Mainly caused by the integration along tangential chords and by large variations of the plasma emission itself, e. g. during density ramps, the intensities to be measured can cover some orders of magnitude. In order to detect the emission patterns as accurately as possible, a digital CCD-camera has recently been installed which provides a dynamic range of 12 bit at a rate of 40 Hz for the full resolution of the chip (1024×1024 pixels) and several binning options.

As for a tangentially viewing camera the number of lines of sight in the lower part of (especially the outer) divertor is low and the crossing angle between them is small [3], all the reconstruction techniques performed so far have the problem of missing vertical resolution in the low-lying strike-point regions. In order to solve this problem, in ASDEX Upgrade Divertor IIb two additional one-dimensional arrays of chords have been installed, which view the lower ranges of the inner and outer divertor poloidally with a resolution of 5 mm (details in Section 2). These additional chords are included into the reconstruction process described in Section 3. In Section 4, we show results of the reconstruction which clearly demonstrate the importance of the improvements decribed here for reliable 2D-profiles.

2 Experimental Setup and Data Acquisition

The principle of the experimental setup is sketched in Fig. 1. In order to reduce the negative effects of neutrons and magnetic fields on the CCD-camera, an image guide (Schott Fiber Optics, IG-567, customized) is used to transfer the image of the tangential view provided by a 7.5 mm-lens mounted outside the vacuum to the detection system. The light collected in front of the outer and inner strikepoint plates by two 7.5 mm-lenses mounted below the roof-baffle (= poloidal views), is relayed to the inside of a vacuum window by two linear arrays, each

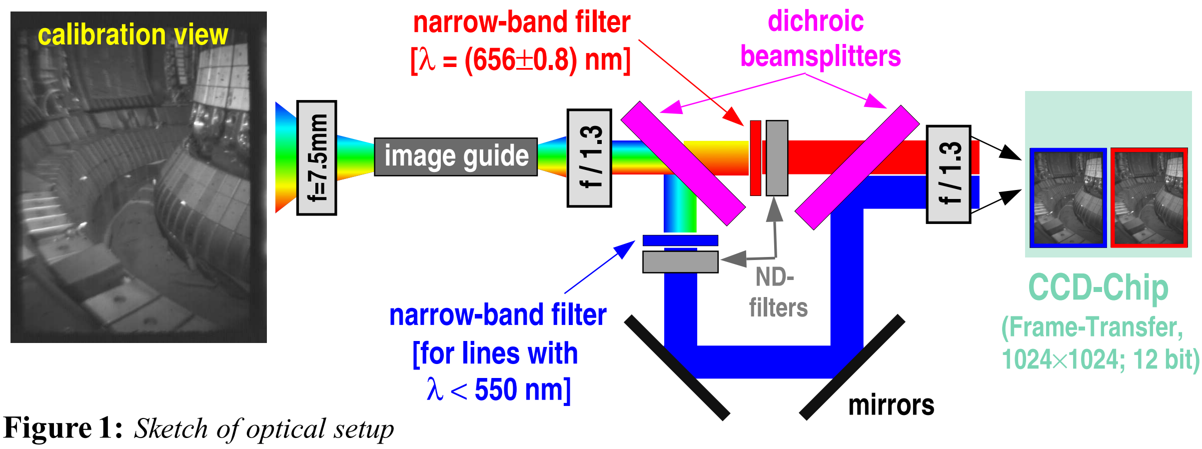

Figure 1: *Sketch of optical setup*

consisting of 70 100-μm-quartz-fibers. The optical setup to record the emission of two lines simultaneously is the same for the tangential and the additional poloidal views: As narrow-band interference filters (FWHM from 1.0 nm to 3.0 nm for different lines) are used, the degree of parallelism of the light has to be as high as possible in order to minimize intensity reductions. Therefore, a high quality lens is used, before the light is divided by a dichroic beamsplitter, reflecting wavelengths below about 550 nm (REFLECT-channel) and transmitting above about 600 nm (TRANSMIT-channel). The filtered (and, where required, attentuated) radiation of both channels is then imaged onto two neighboring areas of the CCD-chip using another dichroic beamsplitter and a lens.

The two images of the tangential view are recorded with a 12-bit digital camera equipped with a Frame-Transfer-CCD-Chip (Philips FTT 1010; 1024 × 1024 pixels) and offering several binning options which are, at the cost of spatial resolution, useful for increasing the intensity and the frame rate. For the acquisition of the data of the two poloidal views, resulting in four linear arrays of 70 spots behind the beam splitting system, another fast camera system with a sensitive CCD-Chip (SONY ICX249, 752 × 290 pixels) was installed. Making use of the advantages of this Interline-Transfer-Chip and the especially enhanced binning options, the minimum cycle time needed for recording the data of the four arrays — with an effective dynamics of about 11.5 bit — is as low as 3 ms. Therefore, this system provides, in addition to supporting the 2D-reconstruction, the emission profiles of two lines with a considerable time resolution for each AUG-discharge.

3 Preprocessing of the CCD-Camera Data and Reconstruction of 2D-Profiles

As a result of the optical setup described above it is important to perform some steps of preprocessing of the CCD-data before feeding them into the reconstruction routine. First, the fibers of an image guide only have an acceptance angle of about 30 degrees, which is smaller than the maximum field of view provided by the lens viewing the plasma (about 50 degrees). Despite the restriction of the effective field of view by coupling the light into the image guide, this leads to an intensity decrease towards the edges of the transmitted image. As the interference filter optics further influences the spatial distribution of the intensity imaged onto the CCD-chip, the best way to correct these intensity reductions is to make use of a calibration measurement, where a white area was illuminated homogeneously. Another effect which, if it were not corrected, would lead to false information in the reconstructed emissivity distri-

bution, is the (barrel-shaped) distortion of the image caused by the rather small lens viewing the plasma. The comparison of the original CCD-image of a test pattern with the corrected one shows that these corrections for intensity distribution and lens distortion are really necessary.
As the reconstruction routine strongly depends on the accurate position of all the Lines Of Sight of the camera relative to the plasma, i. e. the vessel, great care has to be taken in determining the correlation between the coordinates of the CCD-chip (x, y) and the ones in 3D-space (R, z, ϕ). In order to check and ensure the quality of the data reflecting the relationship between (x, y) and (R, z, ϕ), prominent points (R, z) in the divertor have been projected into 3D-space using this geometry data and overlayed onto a (corrected) calibration image showing the ASDEX Upgrade Divertor IIb without plasma.
The mathematical evaluation technique applied is based on general tomographic concepts as used e. g. in the reconstruction of the radiation distribution from bolometry data [1]. In order to include the additional information from the poloidal views into the reconstruction process, only one relative calibration factor for each of the one-dimensional arrays has to be determined and applied to the poloidal data.

4 Results: Improved Resolution of reconstructed 2D-Profiles by additional Poloidal Views

The main focus of this paper is to demonstrate the enhanced quality of the reconstructed 2D-emission profiles brought about by the improvements described above, in particular by the added poloidal views. Therefore, we directly compared the 2D-profiles obtained with and without including the poloidal data. As an example, the corresponding CIII-data from a discharge, where the strike-points were shifted (AUG#14375), are shown in Fig. 2: Taking the preprocessed CCD-data of the tangential view (upper left) as input the 2D-profile in the *upper* row was reconstructed without the information from the poloidal views. In contrast, the 2D-

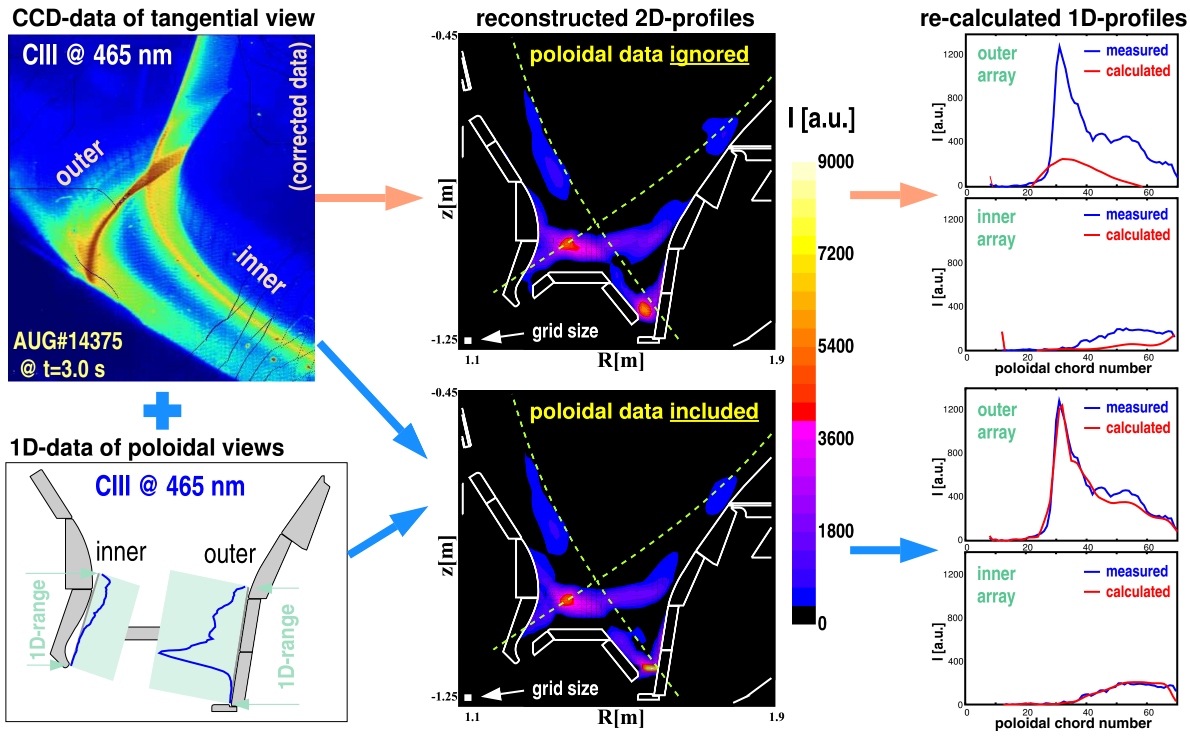

Figure 2: *2D-reconstruction with and without including profile information from poloidal views*

profile in the *lower row* was obtained by including the poloidal data which are sketched in the lower left corner.
Usually, a CCD-image which has been re-calculated from the reconstructed 2D-profile is shown to compare it with the original one. As, however, in our case, these re-calculated tangential views are not only very similar to the measured CCD-data, but also for the cases with and without inclusion of the poloidal data, they are not shown here. We just state that this extreme similarity is a main reason for the missing z-resolution of the 2D-profile without additional z-resolved data. Instead of the re-calculated tangential data, much more significant data for characterizing the quality of the reconstruction are included in the right column of Fig. 2: Here, the measured one-dimensional poloidal data are compared with the corresponding data which were re-calculated from the reconstructed 2D-profiles without (upper row) and with (lower row) additional poloidal information.
Obviously, in the case where the poloidal data have been ignored in the reconstruction, the re-calculated profile disagrees completely with the experimental data. In contrast, the agreement is very good for the case with consideration of the poloidal data.
Having a closer look to the reconstructed 2D-profiles, two main improvements are brought about by adding the additional z-resolved data: First, the CIII-emission in the vicinity of the outer strike-point is much more localized and the maximum value is considerably higher. The same behavior is seen, only less pronounced, for CIII between X-point and roof-baffle in the inner divertor. As the poloidal array only measures a very low amount of CIII in front of the strike-point plates, this restricts the reconstruction and, therefore, the emission is more localized and peaked at the place where it really comes from.
Assuming that the CIII- and D_α-emission in the visible is proportional to that in the VUV for typical SOL-parameters [4], and comparing the spectrally resolved data with the corresponding bolometry data, which sum up the radiation below about 200 nm, we find a good agreement of the spatial distributions.

Conclusions and Future Work

In conclusion, owing to several improvements, the reconstruction of 2D-emission distributions from CCD-camera data works reliably in ASDEX Upgrade. Based on the significantly enhanced resolution in vertical direction, we would suggest to equip other devices as well with this kind of additional poloidal lines of sight. As the hard- and software of the camera system are now ready for routine operation, it can be used to investigate open questions in divertor physics experimentally. Topics to be addressed are e g. the reduction of the power load onto the target plates by enhanced radiation or the redistribution of radiation in the X-point region during the H-Mode density limit.

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