Paper P3-38

Estimating the plasma flow in a recombining plasma from the H_α emission

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Abstract

The measurement of the particle flux from a wall is a standard diagnostic method in magnetic fusion devices. A similar procedure can be applied for measuring the plasma flow recombining in front of a wall using H_α. The other Balmer lines are not suited due to the dependence of the atomic physics factor R/YB on the electron density. We apply the method to estimate the recombining plasma flow in the island divertor of the W7-AS stellarator. The maximum plasma flow in the upper divertor is $\Gamma_{rec} = 3.6 \times 10^{22}\mathrm{m}^{-2}\mathrm{s}^{-1}$. The recombination zone extends over the whole target but is not uniform.

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1 Introduction

The measurement of a neutral particle flux emanating from a solid surface is a spectroscopic standard technique in fusion research. It it used to monitor the flux of hydrogen [1, 2] or of impurities ions [3] by measuring the intensity of a suitable spectral line. In order to interprete the measurements in terms of a flux, two conditions have to be fulfilled:

1. The plasma must be ionising
2. The atomic physics factor S/XB (S ionisation rate and X excitation rate) must be independent on electron temperature T_e

To measure the neutral flux the H_α line is well suited for this purpose since S/XB = const for $Te > 10$eV [1]. At lower T_e the temperature must be measured or a corresponding large error interval must be taken into account. Below 1.1 eV, however, the first condition is not fulfilled. Such low temperatures were measured in the edge plasma of tokamaks and stellarators and the volume recombination was detected. We will study the relation between the hydrogen line emission and the recombining plasma flow. The results are applied to estimate the recombining plasma flow in the island divertor of the W7-AS stellarator.

2 Neutral hydrogen flux in an ionising plasma

We consider the one-dimensional case with x as the normal to the surface. Low energy, neutral hydrogen atoms with ground state density n_1 and velocity v penetrate into the edge plasma. The electron density n_e and the electron temperature T_e rises with x. The electron density is low enough that the ionisation from excited states can be neglected in comparison to excitation from ground state. The hydrogen flux $\Gamma_N = n_1 v$ is attenuated by ionisation through electron collisions according to

$$\frac{d(n_1 v)}{dx} = -S(T_e)n_e(x)n_1(x)$$

The n = 3 excited level is populated by electron collisions from the ground state (and from the lower level n=2). It decays by spontaneous emission into the level 2 and 1 (the ground state). The balance for the level n = 3 is given by

$$n_3(A_{31} + A_{32}) = X n_1 n_e + \xi_{ion}$$

The cascade contribution ξ_{ion} is neglected in the following. The H_α volume emission coefficient is given by

$$\epsilon(x) = n_3 * A_{32} = X(x)B * n_1(x)n_e(x)$$

where $B = A_{32}/(A_{32} + A_{31}) = 0.44$ is the branching ratio and A_{31} and A_{32} are the Einstein coefficients for the Ly_α and H_α lines.
Integrating the flux equation and using the balance equation we have

$$\Gamma_N(x) = \int_0^x \epsilon(x)\frac{S(x)}{X(x)B}\; dx$$

If $T_e(x) > 10eV$ for all x, it holds

$$\Gamma_N = S/XB \int_0^\infty \epsilon(x)\; dx = S/XB * I$$

where I is the line integrated (over x) volume emission coefficient of the H_α emission.

3 Plasma flow in a recombining plasma

We consider the analogous case of a recombining plasma. A plasma is recombining for $T_e < 1.1eV$ [4]. The hydrogen plasma flows to a wall, e.g. to divertor target in a stellarator or to a beam dump in a plasma simulator, and is attenuated by recombination. Every recombination act is accompanied by H_α emission. We consider the case of low electron density for which the stationary balance of the population density of the level n = 3 is given by

$$n_3(A_{31} + A_{32}) = Y n_i * n_e + \xi_{rec}$$

The r.h.s. describes the occupation rate of the level n = 3 by radiative recombination with the rate coefficient Y (n_i is the ion density) and the contribution due to cascades, $\xi_r ec$, which is neglected.
The total recombination coefficient of the plasma is given by the sum over the radiative recombination coefficients into the different energy levels of hydrogen $R = \sum_1^\infty Y_i$. The atomic physics coefficient analogous to S/XB is given by R/YB. Assuming that this coefficient does not depend on T_e (see next section), we can write for the recombining plasma flow

$$\Gamma_{rec} = R/YB \ * \ I$$

For an application to the divertor plasma of the W7-AS stellarator we have to extend these considerations to the case of higher electron densities.

4 The atomic physics factor for high densities

For arbitrary densities we have to consider the collisional-radiative model of Hydrogen. Its solution, the population density n(p) ($p \geq 2$), is expressed as sum of two terms

$$n(p) = R_o(p) n_e n_i + R_1(p) n_e n_1 \tag{1}$$

R_o and R_1 are called population coefficients. They are tabulated as a function of T_e and n_e, e.g. in [1]. The particle balance equation for the ground state density n_1 and for the ion density n_i can be written as follows

$$\frac{dn(1)}{dt} = -S_{CR} n_e n_1 + \alpha_{CR} n_e n_i \tag{2}$$

where S_{CR} and α_{CR} are the effective rate coefficients for ionisation and recombination, respectively, defined by the collisional-radiative model.

[Figure 1 about here.]

We define photon emission rate coefficients for H_α $\epsilon_o(3,2) = A_{32}R_o(3)$ and $\epsilon_1(3,2) = A_{32}R_1(3)$ (see [5]). They have the same dimension as the effective ionisation and recombination rate coefficients. The ratio S/XB is equal to the ratio $S_{CR}/\epsilon_1(3,2)$ and the ratio R/YB is equal to the ratio $\alpha_{CR}/\epsilon_0(3,2)$. Fig. 1 shows these ratios as a function of the electron density [5].

[Figure 2 about here.]

S/XB is about 10 at low density and $T_e > 10\ eV$. It increases for densities $n_e > 10^{19} m^{-3}$. In this case the occupation of the level n = 3 by excitation from the level n = 2 dominates over excitation from ground state and the collisional excitation to the upper levels $n > 3$ dominates over the radiative decay (ladder like excitation-ionisation process).

For H_α, R/YB is about 10 and varies only little (within a factor of 2) up to densities of $n_e = 10^{21} m^{-3}$. Furthermore, there is only little dependence of R/YB on electron temperature. In the divertor plasma of the W7-AS stellarator densities up to $7 * 10^{20} m^{-3}$ were measured [6]. Consequently, the H_α line is well suited to measure the plasma flow.

Fig. 2 shows the factor R/YB for the Balmer lines with n=3,4,5,7 and 10. The electron temperature was set to 0.3 eV in the calculation. The R/YB values for n=4,5,7 and 10 strongly increase in the density range of interest. Thus, the use of other lines of the Balmer series has to be excluded in our case.

5 Plasma flow in the island divertor of the W7-AS stellarator

5.1 Identification of the recombining plasma

At high density we observe volume recombination in the divertor plasma on top of W7-AS. A direct experimental indication is the detection of the high-n Balmer spectrum [6]. We present here another experimental fact based on the comparison of the flux measurements by Langmuir probes and the H_α diagnostic. Some target plates of the island divertor in the W7-AS stellarator were equipped with Langmuir probes to measure the particle flux and observed by a set of CCD cameras with H_α filters. The line-of-sight of a CCD camera is approximately normal to the target so that neutral fluxes can be evaluated as described in Sec. 1. In the case a recombining plasma the plasma flow is also related to the target normal. The flow parallel to the magnetic field lines j is given by $\Gamma_N = j * sin(\phi)$ where ϕ is the angle between the target and the field lines. The parallel flow is not discussed here.
In Fig. 3 we compare the ion saturation current of the probes to the H_α emission (at the probe position) in a discharge with a density ramp (discharge #50732). Both signals are from a strike line at target tile 13 on top (strike line at probe #5) and at bottom (strike line at probe #4).

[Figure 3 about here.]

The H_α signals and the ion saturation currents are proportional to each other up to 0.36 s (attached divertor phase). Both diagnostics are suitable to measure the particle flux to the divertor under these conditions. At high densities after 0.36 s, the H_α emission increases while the ion saturation current continues to decrease (detached divertor phase). The ratio H_α/I_s is 5 in the lower divertor and 26 in the upper divertor (in Fig. 3 the data were scaled that this ratio is one in the attached phase). The deviation in the detached phase is a temperature effect and can be understood in the following way.

[Figure 4 about here.]

With increasing density the divertor plasma cools down. For $T_e < 10eV$ S/XB depends on the electron temperature. This effect explains the rise of the H_α emission at t = 0.36 s. The observed ratio $H_\alpha/I_s = 5$ requires $T_e = 2..3eV$ (see Fig. 1: S/XB = 2.8 for 3 eV). In the upper divertor the ratio $H_\alpha/I_s = 5$ is larger than at bottom and the temperature must be lower than 1.1 eV. Under such conditions the divertor plasma is recombining and the pre-condition for the flux interpretation of the H_α signal is not fulfilled.

5.2 Estimation of the plasma flow

In order to locate the recombining plasma more accurately we study the H_α emission in the divertor plasma on top in more detail. Fig. 4 shows the temporal evolution of the spatial profiles from target tile 13 (see Fig. 5 for the geometry) of the density ramp-up discharge #55254. In the attached phase up to t=0.36 s the H_α signals show the strike lines at the target tiles. We observe a pattern with four strike lines: A, B, C and D. The H_α intensity and thus the neutral flux varies only little with increasing density. At t = 0.36 s the H_α emission from the strike lines A and B increases by a factor of 3. The increase can be understood as a temperature effect as explained above. A rough estimation from the temperature dependence of S/XB gives T_e about 3 eV, i.e. the plasma is still ionizing. The strike lines C and D are unchanged at this time point. In the next time scan at t = 0.381 s we find the maximum H_α emission between the strike lines B and C. The H_α intensity increases by a factor of 8 at this position (after background subtraction), i.e the plasma is recombining as explained above. The zone extends over the pixel range 110-160. From Fig. 4 we find the maximum H_α intensity

$I_{max} = 0.06\mathrm{Wcm}^{-2}$. With R/YB = 10 we arrive at the maximum plasma flow of $\Gamma_{rec} = 1.8 \times 10^{22}\mathrm{m}^{-2}\mathrm{s}^{-1}$ at tile 13.

[Figure 5 about here.]

The toroidal distribution of the recombining plasma zone (in discharge #55254) is shown in Fig. 5 by the black contour. The width of the recombining zone at tile 13 is indicated by the black section of the cut. In the same way as described above the H_α profiles of target tile 5 was analyzed. The recombination zone was defined by an H_α emission above a threshold value ($I_{thr} = 0.045\mathrm{Wcm}^{-2}$). All pixels above the threshold were counted to the recombination zone. These pixels were enclosed by the black contour in Fig. 5. The maximum H_α intensity at target tile 5 $I_{max} = 0.11\mathrm{Wcm}^{-2}$ is about twice as high as at tile 13, i.e the maximum plasma flow $\Gamma_{rec} = 3.6 \times 10^{22}\mathrm{m}^{-2}\mathrm{s}^{-1}$.

6 Summary

The H_α diagnostic can be used also in a recombining plasma to estimate the plasma flow but not the neutral particle flux. The other Balmer lines are not suited due to the dependence of the atomic physics factor R/YB on the electron density. We estimated the maximum plasma flow in the upper divertor of the W7-AS stellarator to $\Gamma_{rec} = 3.6 \times 10^{22}\mathrm{m}^{-2}\mathrm{s}^{-1}$. The recombination zone extends over the whole target but is not uniform. To apply this method, the existence of the recombining plasma must be verified by an independent experimental method.

7 Figure Captions

Fig. 1 The atomic physics factors S/XB and R/YB as a function of electron density and temperature. Note that $S/XB = S_{CR}/\epsilon_1(3,2)$ and $R/YB = \alpha_{CR}/\epsilon_0(3,2)$.

Fig. 2 The atomic physics factor R/YB for different Balmer lines as a function of the electron density. The electron temperature was set to 0.3 eV.
Fig. 3 Comparison of H_α and Langmuir probe signals at selected positions in the upper and lower divertor. The signals from the divertor at bottom are shifted by 2 units. Both diagnostics give consistent results when the divertor plasma is attached (ionising plasma up to 0.36 s). At high densities the H_α signal is not proportional to the ion flux as measured by the Langmuir probes. The H_α emission increases due to the low electron temperature of the divertor plasma.
Fig. 4 The temporal evolution of the H_α emission profiles in front of the upper divertor plates (target tile 13). The four strike lines are A, B, C and D. The volume recombination zone lies between the strike lines B and C (pixel range 110-160).
Fig. 5 Two-dimensional distribution of the recombining divertor plasma in discharge 55254 at 0.4 s as indicated by the black contour.

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List of Figures

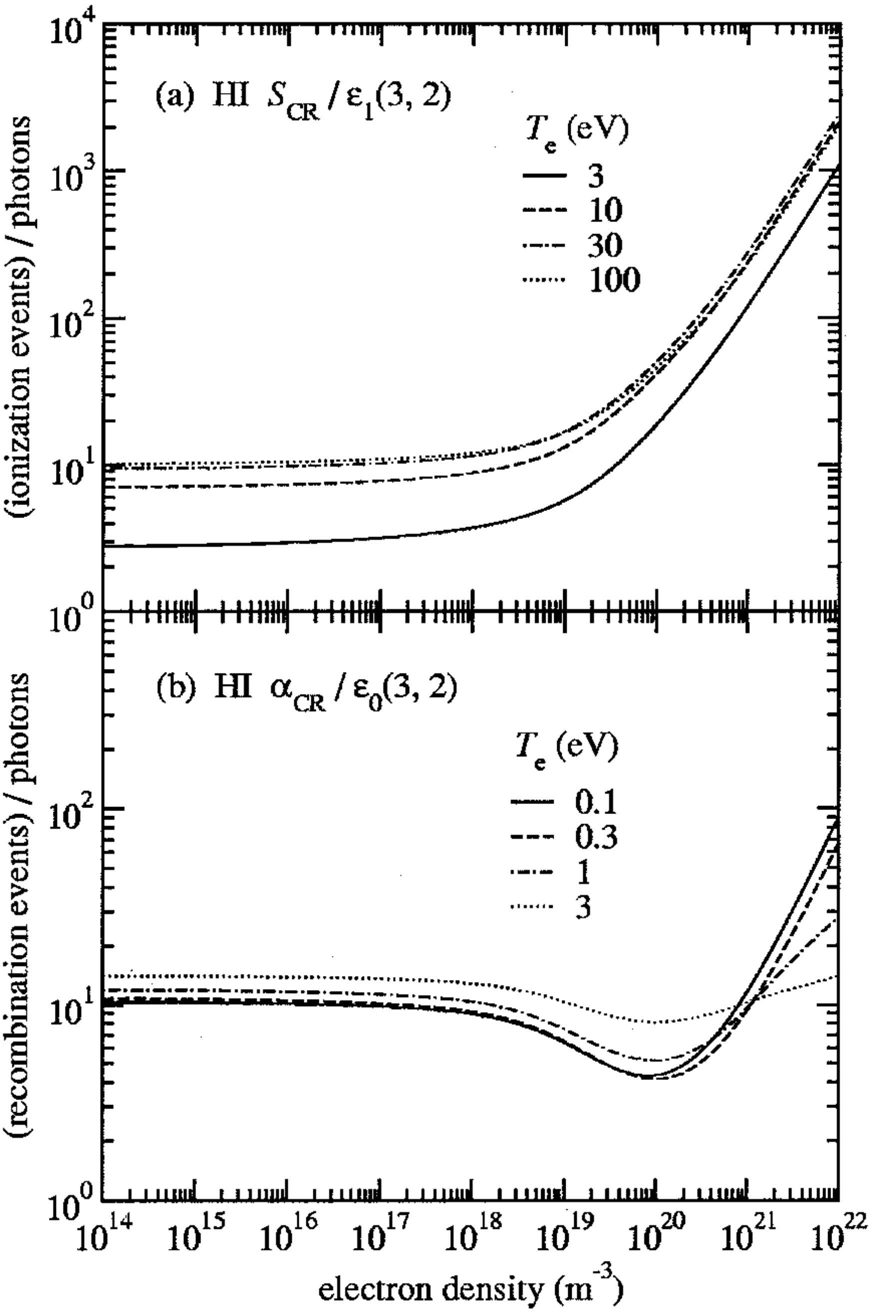

(a) HI $S_{CR} / \varepsilon_1(3, 2)$
T_e (eV)
3
10
30
100
(ionization events) / photons
(b) HI $\alpha_{CR} / \varepsilon_0(3, 2)$
T_e (eV)
0.1
0.3
1
3
(recombination events) / photons
10^0
10^1
10^2
10^3
10^4
10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22}
electron density (m^{-3})

Figure 1:

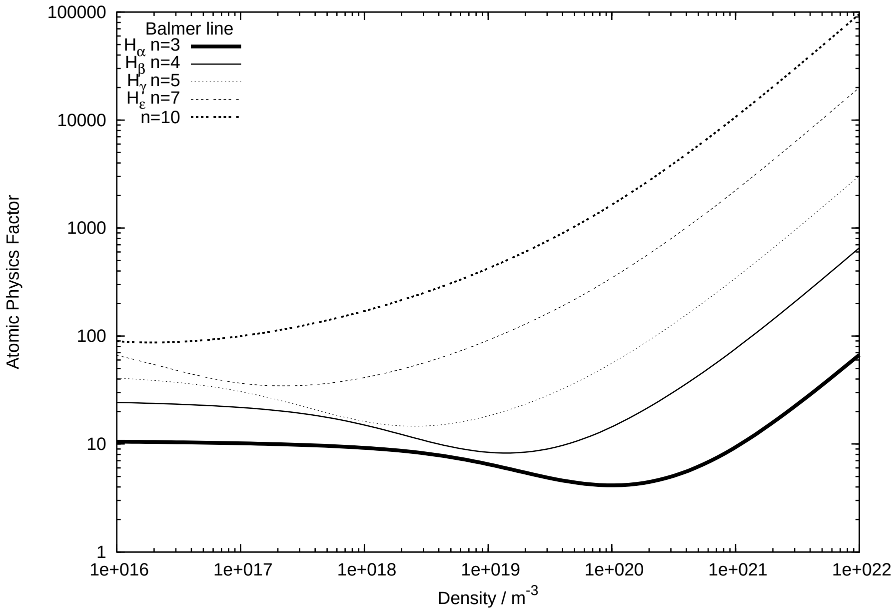
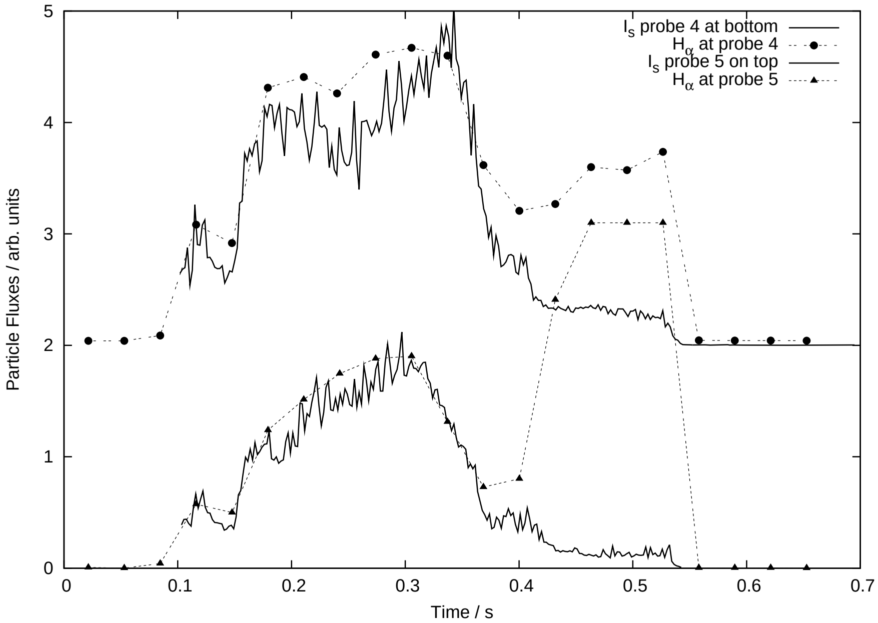

Balmer line
H_α n=3
H_β n=4
H_γ n=5
H_ε n=7
n=10
Atomic Physics Factor
100000
10000
1000
100
10
1
1e+016
1e+017
1e+018
1e+019
1e+020
1e+021
1e+022
Density / m^{-3}

Figure 2:



Particle Fluxes / arb. units
Time / s
I_s probe 4 at bottom
H_α at probe 4
I_s probe 5 on top
H_α at probe 5
0
1
2
3
4
5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Figure 3:

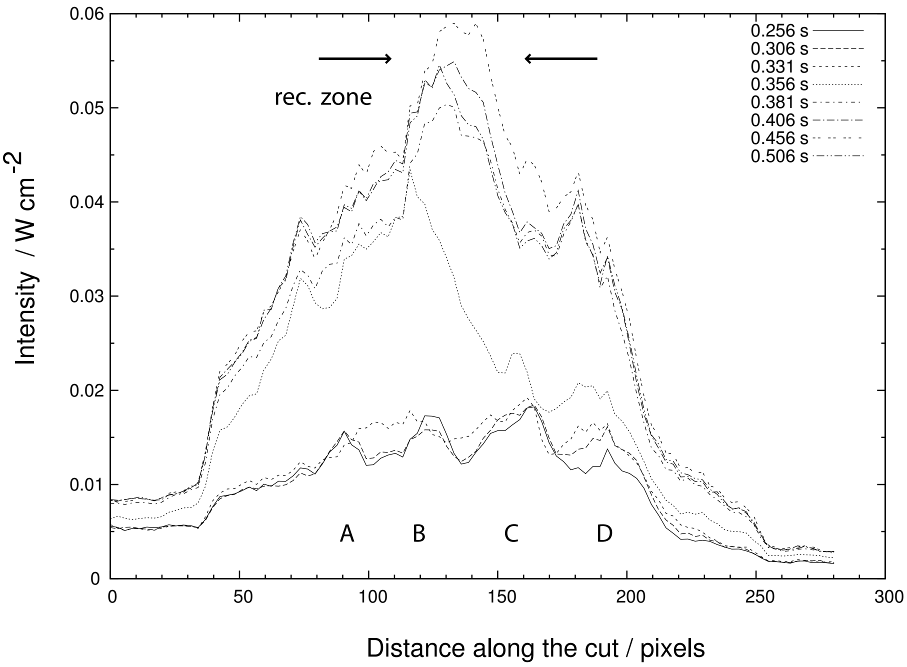

0.256 s
0.306 s
0.331 s
0.356 s
0.381 s
0.406 s
0.456 s
0.506 s
rec. zone
A
B
C
D
Intensity / W cm-2
Distance along the cut / pixels
0
0.01
0.02
0.03
0.04
0.05
0.06
0
50
100
150
200
250
300

Figure 4:

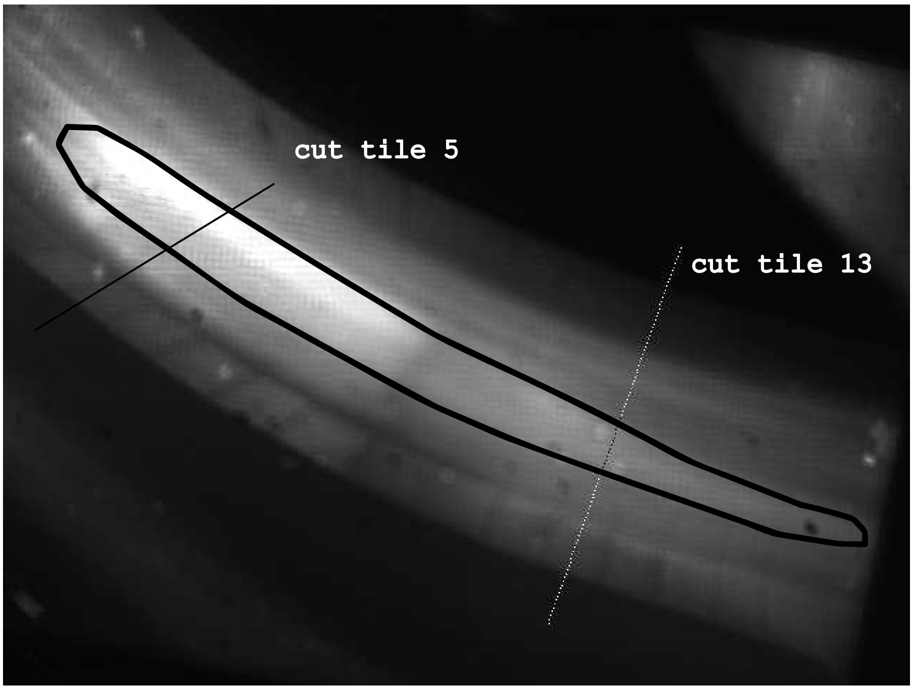


Figure 5: