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MEASUREMENT OF WALL RADIATION IN THE SOFT X-RAY REGION OF PDX

By

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MEASUREMENT OF WALL RADIATION IN THE SOFT X-RAY REGION OF PDX

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ABSTRACT

A detector setup with three LN-cooled Si(Li) diodes is used to measure soft X-ray spectra (0.8 to 20 keV) emitted from the inside walls of the PDX vessel during the plasma discharge. This setup is part of a pulse-height-analysis system, which is used to measure the plasma and wall radiation simultaneously at five different radial positions. The wall and the plasma radiation are measured under different plasma conditions (e.g., OH and neutral beam heating). The wall radiation is increased very much during the neutral beam heating with an enhancement factor of at least 10 over OH wall radiation. Since we measure the plasma and the wall radiation at the same time, these measurements allow the conclusion that the wall radiation can be attributed essentially to fluorescence (line radiation, e.g., Ti-K α) and scattering (continuum part of the wall radiation spectrum). The fluorescence and the scattering are both caused by soft X-ray radiation flux coming from the plasma. There seems to be no need to invoke other, more exotic causes for the wall radiation (like charge particle bombardment of the wall).

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I. INTRODUCTION

In a fusion reactor a particularly important question is how long the first wall can survive the reactor's hostile environment. For that purpose one must measure in situ the various effects on the first wall caused by the extremely high energy flux. One way to diagnose these effects is to measure directly the wall radiation in various spectral ranges. This paper addresses the problem of wall radiation in the soft X-ray energy region, but under conditions which do not yet approach a severe reactor environment.

Soft X-ray wall radiation can be caused by several primary agents. These can be plasma soft X-ray radiation, energetic electrons, or protons and neutrons coming either from the hot plasma core or from the somewhat cooler edge. A lot of work has been done to understand the interaction physics of each one of these primary quanta. Birks¹ has given experimental values of X-ray fluorescence for X rays, electrons, and protons as primary particles. The fluorescence efficiency for X rays with energies slightly higher than the ionization energy for K, L shells is several orders of magnitude higher than for electrons. But as the electron energy increases above the ionization energy (since X-ray efficiency decreases and electron efficiency increases with primary quantum energy), at some point the electrons become more efficient in creating fluorescence. The protons need very high energy -- a hundred times that of electrons -- in order to be comparably efficient. Garcia et al.² have addressed this problem in a review article on the theory and experiment of K, L shell vacancy production with proton-atom impact.

Fluorescence is not the only process that creates wall radiation. Other processes include inelastic or elastic scattering, which are usually treated either with scalar electromagnetic theory or more appropriately with a vector

theory that takes polarization effects into account.^{3,4} To describe the transmission and scattering of soft X-rays, one usually employs the complex atomic scattering factor, which is equivalent to a complex dielectric constant or complex refractive index.^{5,6} Most of these theoretical models are used to describe X-ray mirrors, multilayer filters, and the surface roughness of highly polished surfaces. In our case, we are dealing with a surface roughness that is many times the wavelength.

In this paper we will not try to explain the observed scattering theoretically, but will rather just summarize the experimental observation. In the first part we describe the experimental method, the multichannel pulse-height-analysis system, used normally for the plasma radiation measurement. In the second part we give the wall radiation results and interpret them in terms of reflectivity and fluorescence efficiency. In summary we offer some suggestions of possible applications of this method in edge plasma studies.

II. EXPERIMENTAL METHOD

The wall radiation measurement is done with an X-ray pulse-height-analysis (PHA) system,⁷ normally used to investigate the temporal and spatial variation of electron temperature and impurities in PDX discharges. The five arms - indicated on Fig. 1 by numbers 1 through 5 -- are used to observe five different lines of sight, passing through different minor radii of the toroidal discharge. The purpose of five arms is to obtain in one or a few discharges the spatial profiles of electron temperature and impurities by Abel inverting the chordal spectra collected by the arms. Each arm consists of three Si(Li) detectors, D, in the same LN Dewar, having different filters and covering different energy regions. The spectra of three detectors in one arm

are combined together to obtain an overlay spectrum extending over a rather large energy range, which is from 1 to 25 keV at best. To cover different energy regions each detector has a set of interchangeable beryllium and/or aluminum filters, F , with increasingly stronger filtering characteristics. To optimize the photon count rate, which should be kept between 10 and 50 kc/s, a set of movable apertures, A , of different sizes is incorporated in each arm and for each detector. The time resolution is given by the time needed to collect a statistically acceptable overlay spectrum. If the photon count rate is between 10 and 50 kc/s, this is typically 50 ms, so that during a single discharge we obtain sixteen consecutive spectra, and hence a time evolution of the discharge.

In cases where higher time resolution is needed (for pellet injection - to observe sudden changes in electron temperature, Z_{eff} , and impurities; for neutral beam injection heating; for adiabatic compression heating; for ECRH heating, etc.), it is possible to increase the time resolution by going to spectrum collection times as low as 5 ms. In this case, however, one needs to add up to ten reproducible discharges.

The energy resolution is ~ 240 eV at 5.9 keV and can be improved slightly by increasing the shaping amplifier time constant. This increase in time constant would, however, result in a lowering of the maximum allowed count rate.

To observe the wall radiation, the arms 1 and 5 have to be swung up or down so that the lines of sight do not pass through the plasma, but sample only the radiation coming from a particular part of the wall.

III. EXPERIMENTAL RESULTS

The more important issues concerning wall radiation are to identify the primary quanta (X-ray photons, electrons, or protons) and then to find the fluorescence efficiency and reflectivity of the wall. As pointed out earlier, the protons, or any heavy particles, can be excluded at the outset, because their minimum energy for fluorescence lies in the 1 MeV range. The electron energies have to be 10 keV and higher. These electrons should come from the plasma edge, which has a temperature of the order of some 10 eV. In the case of a Maxwellian distribution very few electrons will have the needed energies, so one would have to invoke either a non-Maxwellian distribution function or a strong diffusion of more energetic electrons from the hotter plasma region. An additional difficulty with the electron as the primary quantum is to visualize how these electrons avoid striking the limiter yet continue to travel toward the wall, which lies deeply in the shadow of the limiter. For these reasons, if we could show that the plasma soft X-ray radiation could by itself explain the observed wall radiation, then we should consider it an adequate and most probable explanation.

In Fig. 2, the time evolution of various plasma parameters is shown. This discharge is an ohmically heated discharge with no neutral beam heating. The minor and major radii are 40 and 143 cm, respectively. Maximum plasma current is 290 kA and the toroidal field is 1.4 T. Most of the wall radiation studies were done with this low toroidal field. The strong bursts of soft X-ray radiation shown in Fig. 2f at 0.35, 0.4, and 0.48 s represent an involuntary injection of titanium into the discharge (titanium is coming from the wall, being deposited there during titanium gettering of the vacuum vessel).

The uncorrected raw wall radiation spectra for the same discharge are shown in Figs. 3a and 3b. The very low energy part of the spectrum (0.6 - 1.2 keV) is strongly attenuated due to a 12.5- μ m beryllium window in front of the detectors. The measured wall radiation is not constant during the discharge and its spectrum varies strongly in time, too. During the plasma build-up phase, we typically see a low energy (0.6-1.2 keV) background radiation which dies out very soon after 100 ms. The low energy fluorescent lines are seen early in the discharge with high energy lines coming later. Near the end of the discharge, in the plasma current decreasing phase, these fluorescent lines weaken considerably and the continuum comes up strongly.

The line between 3.2 and 3.7 keV, in Fig. 36 and observed after 0.39 s in the discharge, is not a true line, and most probably is pulse pile-up convolution of the Si-K α line with itself. One can show, that in case of a single line pile-up (convolution of a line with itself), the convoluted pulse pile-up "line" at twice the energy of the original line has a strength of $\tilde{R} = R^2 \tau_{pp} / 4$, where $\tilde{R}$ is the count rate of the convoluted pulse pile-up "line," R is the count rate of the original line, and τ_{pp} is pulse pair resolution time. The Si-K α line count rate at 0.51 s in the discharge is $R = 36$ kc/s, τ_{pp} is ~ 3 μ s, so that the pulse pile-up line count rate should be $\tilde{R} = 972$ c/s. From Fig. 3 we observe $\tilde{R} \sim 1.3$ kc/s, which is very nearly the theoretical pulse pile-up rate.

As mentioned earlier, the five arms look at five different minor radii. In Fig. 4 the raw spectra from four arms (arm number 2 was not operating) and for each one of the three detectors in each arm are shown 0.39 s into the discharge. Arm 3 monitors the central radiation, arms 4 and 5 the respective tangency radii (minor radii) of 10 and 30 cm, and arm 1 the wall radiation.

There are also long-term variations in continuum and fluorescent line wall radiation. Sometimes the Ti-K_α line is especially prominent, and at other times the whole discharge is characterized by very weak fluorescent lines and a strong continuum. An example of a long-term variation in the wall radiation is displayed in Fig. 5. In this case the titanium K_α lines are not observed, but a strong background radiation is prominent.

Two examples of synthesized spectra for the central plasma radiation and the wall and plasma radiation are shown in Figs. 6 and 7. The spectra are synthesized by overlaying the corrected and normalized spectra of three detectors in the same arm. The central plasma radiation is characterized by a continuum radiation, from which the electron temperature of 0.96 keV is obtained, and by a set of strong K_α lines emitted by various impurities in the plasma: sulphur, chlorine, titanium, chromium, etc. From the intensity of the K_α line radiation, the absolute density of each respective impurity is calculated. In Fig. 7, the radiation spectrum at the tangency radius of 32 cm is shown. This represents the plasma radiation 8 cm from the edge of the plasma, but still inside the plasma. Two regions in the spectrum are observed. The region up to ~ 2.3 keV represents the plasma radiation. It is a continuum radiation, and from the slope of the spectrum the electron temperature of 260 eV can be inferred. Above ~ 2.3 keV, the spectrum is dominated by wall radiation. This part of the spectrum contains a strong background radiation with a prominent Ti-K_α line.

In Fig. 8, the time evolution of the central plasma radiation in several photon energy regions and in Fig. 9, the evolution of the wall radiation in the same energy regions are shown. The two figures represent the same plasma discharge. In both cases the radiation in the ohmic part increases with time,

because the plasma current and electron temperature increase. The discharge is heated with neutral beams from 0.5 to 0.7 s. During this time, because of strong heating, the high energy radiation is raised more strongly. The wall radiation follows closely the plasma radiation.

The spatial distribution of both the plasma and wall radiation and for different times in the discharge is shown in Figs. 10 to 14. The plasma minor radius is 40 cm, so points beyond 40 cm (or $\theta \geq 29^\circ$) represent wall radiation. The wiggles in the data for the wall radiation are caused by the shot-to-shot variation: several shots are needed to scan the region from $\theta = 29^\circ$ to 35° with arm 5. These wall radiation wiggles are especially strong during neutral beam injection. Shot-to-shot variation in beam power seems to have a stronger effect on the wall radiation than on the plasma radiation. The neutron noise -- neutrons are created in a D^0-D^+ (beam-plasma) reaction -- makes the determination of the wall reflectivity and fluorescence rather unreliable. Nevertheless, a part of the nonlinearly increased wall radiation during the beam injection is probably due to the increased reflectivity, which might be caused by the downward (in energy) inelastic scattering of an increased high energy population of the primary photons.

From these profile data (Figs. 10 to 14) we conclude that the wall radiation is fairly homogeneous. No enhancement of the wall radiation was observed at the position of cover plates, which are nearest to the plasma and which shield the divertor coils from the plasma, and are indicated in Figs. 10 to 14 as small hatched areas. This again supports the hypothesis that the primary agent for the wall radiation is the plasma X-ray radiation and not the charged particles. This is because the charged particle bombardment of these protective plates would result in an enhanced wall radiation, since these

plates are very near the plasma.

From the data as represented by Figs. 8 to 14, one can obtain quantitative information on reflectivity and fluorescence.

A. Reflectivity

Let us assume that we have two detectors: one looking through the center of the plasma and the other directly at the wall. The first detector will register the direct plasma radiation in addition to the radiation from the opposite wall: $N_{DP} = N_P + N_W$ (photons.cm⁻².sterad⁻¹.s⁻¹), where N_P is the central plasma radiation and N_W is the radiation from the opposite wall. The other detector will register only the wall radiation: $N_{DW} = N_W$. We assume here, that the radiation falling on the wall and the radiation leaving the wall are uniform and homogeneous over the whole surface of the wall. This we can do because the plasma as viewed from the wall is subtending a rather large solid angle. In that case we can define the wall reflectivity as $R = N_W/N_P$, where N_W is measured directly and N_P indirectly through N_{DP} . Normally $N_{DP} \gg N_W$, so that we can approximate $R \sim N_{DW}/N_{DP}$. N_{DP} is measured with arms 2, 3, 4, and 5 and N_{DW} with arms 1 and 5.

Table I shows measured reflectivity defined in units of 10⁻³ as a function of time and energy for the discharge shown in Figs. 8 and 9. The neutral beam heating values, typically a factor of 3 (at low energies) to 40 (at high energies) higher, are not included. For energies larger than 1.3 keV the reflectivity seems to increase with time or electron temperature. The reason for this could be that at higher electron temperatures more photons are inelastically scattered from the higher energy to the lower energy part of the spectrum. The reflectivity seems also to depend on photon energy: it

decreases with energy. The reason might be the same as mentioned above.

B. Fluorescence

The most apparent features in the wall radiation spectra have been a strong background and several bright fluorescent lines. The fluorescent lines, observed in PDX discharges, are Si-K $_{\alpha}$, Cl-K $_{\alpha}$, Ti-K $_{\alpha}$, and one unidentified line near the position of the K-K $_{\alpha}$ and Ca-K $_{\alpha}$ lines (3.5 keV). The "unidentified" line is most probably the pulse pile-up auto convolution of the Si-K $_{\alpha}$ line. The strength of these lines changes over time: usually the Si-K $_{\alpha}$ line appears immediately at the beginning of the discharge as a strong line and in later times it can be, relative to the background, weakened. On the other hand, Ti-K $_{\alpha}$ usually appears late in the discharge. During some PDX runs Ti-K $_{\alpha}$ was unusually strong, mostly correlated with a longer period of a strong Ti-gettering, which coated all inner surfaces of the PDX vacuum vessel with titanium. Strong Cl-K $_{\alpha}$ lines seem to be correlated with the more recent PDX openings, where the vessel surfaces were exposed to air and then later cleaned with a cleaning liquid, which might have contained chlorine.

As in the case of the reflectivity, we can define the fluorescence efficiency as a ratio of the intensity of the given fluorescent line radiation coming from the wall to the central plasma chord radiation with appropriate lower and higher energy brackets. The lower bracket should be the ionization energy of the given atom and shell. In the case of Ti-K $_{\alpha}$ fluorescence, we choose $5 \leq h\nu \leq 6.1$ keV. A typical central chord radiation in these brackets is $N_p \sim 10^{10}$ [photons.cm $^{-2}$.ster $^{-1}$.s $^{-1}$] with, at the same time, the Ti-K $_{\alpha}$ wall radiation being $N_w \sim 2 \times 10^8$. If we assume that the central chord soft X-ray flux is causing the Ti-K $_{\alpha}$ wall radiation, then the fluorescence efficiency is

approximately $\eta_F = \dots / N_p = 2 \times 10^{-2}$. Similar values were obtained in other discharges under different conditions.

IV. SUMMARY AND CONCLUSIONS

The continuum and fluorescent line radiation from the inner walls of the PDX tokamak were investigated. The measured continuum reflectivity, obtained by assuming the plasma soft X-ray radiation as the primary quanta of 0.3 to 4×10^{-3} agrees well with the soft X-ray elastic reflectivity of 10^{-4} to 10^{-3} , quoted in the literature.⁸ The fluorescence efficiency for Ti-K α - again with soft X rays as a primary agent -- also agrees well with the values found in Ref. 1, i.e., $\sim 10^{-2}$. Therefore, we can state in conclusion, that the wall radiation observed in PLX can be explained by the wall material fluorescence and elastic (and, maybe, to some degree inelastic) scattering of the soft X-ray plasma radiation. Though we cannot exclude this possibility completely, the charged particles striking the wall seem not to contribute to the wall radiation except, only possibly, in the initial short plasma build-up phase of the discharge.

This method can be easily adopted for the studying of both short-term (during a single discharge) and long-term (changing plasma and wall conditions) temporal evolution of the medium-Z materials recycling at the limiter. Another application is to investigate the flux, direction, energy, and the temporal evolution of the electrons bombarding the limiter by observing the soft X-ray radiation from the limiter. In both cases one would have to measure, for comparison, the central soft X-ray radiation, the radiation from the wall in the shadow of the limiter, and the radiation from the limiter itself.

A better way of studying the electrons at the edge is to have a special radially movable probe, made from an appropriate material, to observe the soft X-ray radiation coming from that probe. In this case one would, e.g., observe the radiation from two opposite sides of the probe. The side of the probe, which is slanted toward the electron flux so that it is intercepting more electrons, would show the radiation due to the plasma electrons impinging on the probe, superimposed on the secondary radiation caused by the primary soft X-ray flux coming from the plasma. The side of the probe, slanted toward the ion flux, would show more strongly the radiation caused by the primary soft X-ray flux. Subtracting the two spectra coming from the two sides of the probe should give us information on the total flux and the energy distribution of the drift electrons in the vicinity of the probe. A better setup would be to have two probes: one far from the plasma with only plasma soft X-rays as the primary agent and the other movable and intercepting the electron flux. The comparison of the movable probe and the fixed probe would allow mapping of the electron flux as a function of minor radius.

Utilizing a similar probe measurement, one can also study the medium-Z impurity recycling and transport during a single discharge or in a discharge series. This is done by examining the time evolution of the fluorescent K_{α} line of these medium-Z impurities coming either from the wall, limiter, or having been earlier injected into the discharge.

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TABLE I

Time evolution of the wall reflectivity in units of 10^{-3}

and at several different energies

(The subscript in R denotes the lower and upper photon energy limits in keV.)

Time[s]	0.09	0.15	0.21	0.27	0.33	0.39	0.45	0.75	0.81	0.87
$R_{0.6-1.2}$	5.1	8.1	6.9	5.1	3.7	3.6	4.0	3.3	1.9	2.7
$R_{1.3-2.0}$	1.2	2.8	2.6	2.8	1.9	2.2	3.6	2.6	1.0	2.0
$R_{2.0-2.5}$	2.3	1.0	1.9	1.4	1.3	1.3	2.6	2.5	0.7	2.0
$R_{2.6-3.0}$		0.3	0.7	0.4	0.5	1.1	1.2	1.6	0.3	1.3
$R_{4.2-4.9}$			1.3		0.5	0.3	0.5	0.9	1.1	

FIGURE CAPTIONS

FIG. 1 Cross section of PDX vacuum vessel indicating five PHA arms (1 to 5). Each arm samples soft X-ray radiation from a different plasma region (minor radius). The arms 1 and 5 can also sample the wall radiation.

FIG. 2 Time evolution of the plasma parameters, typical for these wall radiation studies. The time is given in ms. In 2a, the plasma current I and the loop voltage V in units of [10 kA] and [V], respectively, is represented, in 2b the line integrated electron density $\langle n_e l \rangle$ in units of [10^{15} cm^{-2}], in 2d the major radius R , in 2e electron cyclotron emission, and in 2f soft X-ray radiation from the center of the discharge as observed by a surface barrier diode.

FIG. 3a Time evolution of the wall radiation spectrum from 0.06 to 0.36 s. Time resolution is 60 ns. $\dot{N}_{ph}$ is the photon count rate in photons in energy bin of 100 eV, BG denotes background (continuum) radiation. The arrows point to K_{α} line energies of silicon, chlorine, and titanium.

FIG. 3b Time evolution of the wall radiation spectrum from 0.36 to 0.78 s.

FIG. 4 Example of the raw spectra for arms 1, 3, 4, and 5 at 0.39 s in the discharge. The arms 3, 4, and 5 are observing the plasma radiation at different minor radii and arm 1 the wall radiation. Arm 2 was not working. The ordinate is in units of number of photons in energy bin of 100 eV.

FIG. 5 Long-term changes in wall radiation. Discharge time is 0.39 s. Ti-K α lines almost disappeared, but the background radiation is strong. The figure shows raw data from three detectors of arm 1. The ordinate is in units of number of photons in energy bin of 100 eV.

FIG. 6 Synthesized spectrum for the central chord ($r = 0$) radiation. The electron temperature is 960 eV at $t = 0.27$ s in the discharge. The prominent K α lines are due to sulphur, chlorine, titanium, and chromium.

FIG. 7 Synthesized spectrum for the combined plasma and wall radiation at the edge of the plasma ($r = 32$ cm) and at $t = 0.27$ s. The electron temperature is 260 eV. The spectrum for energies above ~ 2.3 keV is mostly the wall radiation.

FIG. 8 Temporal evolution of the central plasma radiation ($r = 0$ cm) for different parts of the spectrum. BG denotes background. The PDX discharge has the following parameters: $R = 143$ cm, $a = 40$ cm, $B = 1.4$ T, $I_p = 290$ kA.

FIG. 9 Temporal evolution of the wall radiation.

FIG. 10 Radial profile of the plasma and wall radiation for different parts of the spectrum. It is for ohmic heating only and at 0.15 s, early in the discharge. θ is the angle between the arm 5 and the horizontal plane.

FIG. 11 Radiation profile for ohmic phase at 0.33 s in the discharge.

FIG. 12 Radiation profile for ohmic phase at 0.45 s in the discharge, immediately before the neutral beam injection.

FIG. 13 Radiation profile for neutral beam injection phase at 0.57 s in the discharge. The strong oscillations in the profile reflect the shot to shot variation, caused by a change in neutral beam injection power and by different noise contributions coming from the neutron flux and disturbing the Si(Li) detectors.

FIG. 14 Radiation profile for neutral beam injection phase at 0.69 s. The neutron induced noise here is even stronger.

Fig. 1

Fig. 2

Fig. 3(a)

Fig. 3(b)

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

82X0977

Fig. 10

#82X0973

Fig. 11

#B4X2373

Fig. 12

82X0974

Fig. 13

#82X0975

Fig. 14

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