Intensity calibration including pile-up effect in PHA spectra measurements at W7-X

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ABSTRACT: The pulse-height-analysis (PHA) is a technique used at fusion devices for measurements of content and intensity of the X-ray spectrum. At the stellarator W7-X, this method is applied together with the application of silicon drift detectors for observation of the radiation in the energy range from about 0.5 to 20 keV [1-2]. To receive quantitative information on plasma impurity concentration, several factors should be taken into account. Firstly, the detector response curve which includes the transmission of filters and detector thickness. In this case, the response was determined from the knowledge of the detector's geometry and characteristics of materials used, as calibration measurements with a standard X-ray radiation source were not possible. Secondly, the geometry parameters which define the observation cone of view, and finally, the pile-up effect which is a crucial point in intensity calibration. The pile-up effect can be minimized by settings of the lower values of the digital filter peaking time in X-ray signal processor (DXP), but often it is a compromise between energy resolution and temporal resolution of the time-dependent X-ray intensity signal. The information about the number of lost photons can be derived from the knowledge of the number of photons incoming to the detector and the number of photons observed in a spectrum. For the PHA system dedicated to W7-X, the loss of the pulses which undergo pileup is determined by values of the parameters: input count rate - ICR and output count rate – OCR, both delivered by the DXP. It is always taken into account in the intensity spectra calibration which allows to study the changes in impurity line intensity and hence to determine the impurity concentration.

KEYWORDS: X-ray detectors, nuclear instruments and methods for hot plasma diagnostics, data processing methods.

Contents

1. Introduction

The control of the amount and distribution of impurities in magnetically confined plasmas is one of the big challenges in a magnetic fusion research, in particular, in the research based on stellarator concept, which can relatively easily be operated continuously [1]. Understanding of the transport characteristic of the impurities in stellarator plasmas is crucially important. For this purpose, the proper operation of the diagnostics is significant [2-3].

The stellarator Wendelstein 7-X (W7-X) is the largest and the most advanced type of fusion devices in the world aimed to demonstrate steady-state plasma operation [4].

One of the diagnostics installed on W7-X, dedicated for observation of soft X-ray radiation in broad energy range, is the pulse-height-analysis system (PHA) [5-6]. This spectrometer consists of 3 channels equipped with Silicon Drift Detectors (SDDs) and Beryllium foils of various thicknesses, which allow the observation of spectra from about 0.5 to 20 keV. The detectors are placed at the distance of 8 m from the plasma centre and in the line of sight of each detector, a pinhole consisting of two piezo-slits is located. The change of aperture provides the possibility of regulation of incoming photon flux (input count rate, ICR). It should be noticed that with changing the pinhole size, the volume of plasma changes as well. For the largest aperture, 1.2 mm, the PHA system observes 35 mm in the plasma centre.

The electronics associated with detectors consists of a preamplifier and a multichannel Digital X-ray signal Processor (DXP), in which analogue signals are amplified, digitized, filtered by the use of digital filter (to obtain high signal to noise ratio), processed to remove pile-up, and then routed to a histogramming memory. The DXP needs adjusting (by changing its parameters) to each type of the detector and the preamplifier.

As the physical processes in the stellarator plasma are very fast, the acquisition time of a spectrum must be set possibly short to reveal the detailed time structure of the measured signals. In case of the PHA system, the time is set in the range of 50-100 ms, depending on the plasma conditions. At such a short acquisition time, the PHA system must operate at a possibly high counting rate to obtain reasonable good counting statistics, and on the other hand, to observe spectra with a good energy resolution. In performed W7-X experiments, the FWHM is not worse than 200 eV at the counting rate up to 600 kHz.

2. Detectors and accompanying electronics

In the PHA system dedicated to W7-X, Silicon Drift Detectors (SDD) from PNDetector are applied [7]. In two of three channels, SDDs of round shape and surface area of $10mm^2$ (SDD-10-130 BeWic), covered by 8-um of Be are installed, while in the third channel, SDD with the same surface area but droplet design and filtered by a thin Polymer window (SDD-10-128pnW UTWic), is used. The detectors are equipped with an integrated Field-Effect Transistor (FET) and both elements are cooled. Peltier coolers coupled with the detector chip are responsible for the cooling up to -15°C which reduces the dark current and improves the energy resolution of collected spectra.

The detector converts each photon into photoelectron which later produces a cloud of electron-hole pairs. Thanks to the applied field gradient, the electrons and holes are then drifted towards electrodes. The accumulated charge is converted to a voltage signal by the FET preamplifier. The produced charge is proportional to the energy carried by incoming photons. The signal from the preamplifier is digitized in A/D converter at the input of the pulse processor while the digital filtering is responsible for shaping and noise reduction. The preamplifier is connected to the digital pulse processor (DPP) and data acquisition electronics. The PHA system works in the multi-channel analyzer (MCA) mode. The spectrum from each detector is measured usually in 1024 energy channels with the MCA bin width set to 10 - 30 eV.

There are several parameters which must be set by the operator in the acquisition software for the PHA spectra collection. Besides the MCA channel number and bin width which in combination with chosen thickness of Be filter define the observed energy range, the value of peaking time must be also specified. This parameter, which is related to the number of points which are averaged by the digital filter, can be set in the range from 0.1 up to 164 μs. For longer values, better energy resolution can be obtained but at the cost of increased dead time and thus lower output count rate (OCR) (worse statistics). To increase data throughput as much as possible, the peaking time during the first W7-X campaign (OP1) was set to 1μs which allowed for observation of the PHA spectra with resolution sufficient to resolve spectral lines. Fig. 1 presents an example of collected spectra for two chosen peaking times, for 0.3 μs and for 1 μs. It is clearly seen that for lower peaking time value (0.3μs) resolution is worse than the one for higher peaking time (1 μs) which prevents resolving Ar XVII and Ar XVIII lines. Table 1 presents the list of spectral lines presented in fig.1 with corresponding wavelength and transitions. It should be noted that only dominant lines have been identified.

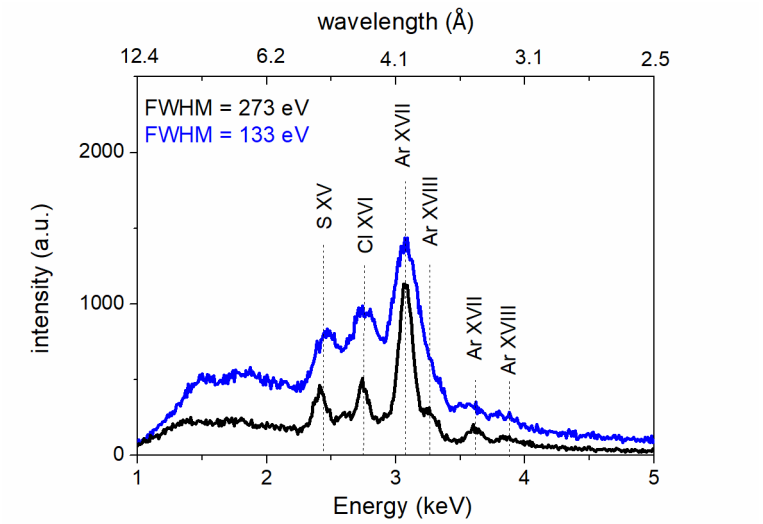

Fig. 1. Example PHA spectra collected for peaking time equal to 1 µs (——) and 0.3 µs (——).

Table 1. Identified spectral lines presented in fig.1 with corresponding wavelength and transitions.

Type of line	Energy (eV)	Wavelength (Å)	Transition
He-like S (S^{+14})	2460.6255	5.038	$(1s2p)^1P_1 \rightarrow (1s^2)^1S_0$
He-like Cl (Cl^{+15})	2789.808	4.444	$(1s2p)^1P_1 \rightarrow (1s^2)^1S_0$
He-like Ar (Ar^{+16})	3139.5515	3.949	$(1s2p)^1P_1 \rightarrow (1s^2)^1S_0$
H-like Ar (Ar^{+17})	3321.4	3.731	$(2p)^2P_{3/2} \rightarrow (1s)^2S_{1/2}$
He-like Ar (Ar^{+16})	3683.8429	3.365	$(1s3p)^1P_1 \rightarrow (1s^2)^1S_0$
H-like Ar (Ar^{+17})	3935.3	3.150	$(3p)^2P_{3/2} \rightarrow (1s)^2S_{1/2}$

The second also important parameter is a trigger threshold which is responsible for the low-energy limit for the fast filter, which is used primarily for pileup inspection. Depending on the PHA energy channel, it was set to 1000 eV for the 1st and 2nd energy channel, and 360 eV for the low energy channel.

3. Calibration of the spectra

The PHA system at the W7-X has a dedicated for energy calibration port which is equipped with the mini X-ray tube. The radiation of this lamp excite the spectra of elements located inside the PHA port (stainless steel and Cu plates). Thanks to the observed fluorescence spectra and later, identification of well-known spectral lines, it is possible to complete the energy calibration curve [8]. To perform the intensity spectra calibration, an X-ray source of known intensity is needed. The precise calibration of the efficiency of detectors themselves is performed on the synchrotron Bessy [9], lately with the use of an absolute cryogenic thermal detector [10], but in case of the PHA system dedicated to W7-X, it was not possible to calibrate the whole spectrometer (including electronics) this way. Also, a calibrated X-ray lamp or a standard radioactive source of intensity high enough, which would simulate plasma emission were not used as they were not available. Instead of direct calibration, self-calibration [11] of detectors and filters is performed based on known material characteristics and geometrical parameter. The detectors response curves have been calculated based on the transmission of the Be window (with additional 30-nm Aluminum

on the detector surface) and additional filters, as well as absorption of the active detector depth (450-μm of Si) [12]. Figure 2 presents the detector response curves of each of the PHA channel including extra Be filters.

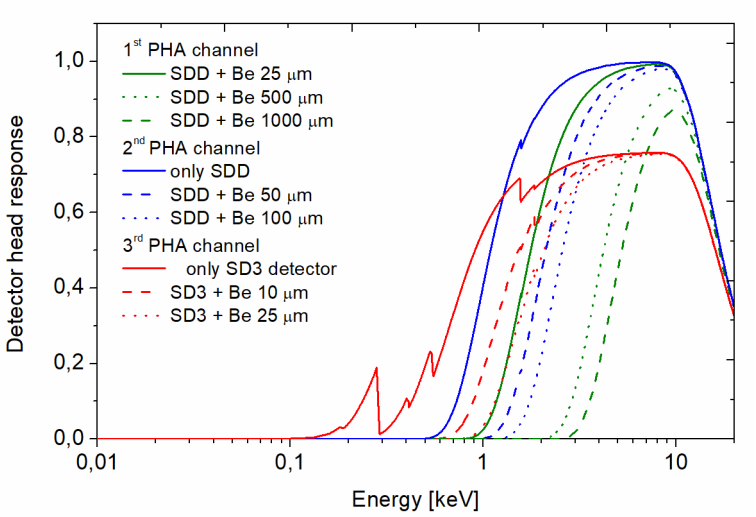

Fig. 2. Detector response curves for each of the PHA channels with accompanying filters.

To calculate the measured spectra emissivity ε (W·eV^{-1}·m^{-3}), geometrical factor is needed to be known. This parameter depends on the pinhole size, distance between plasma-pinhole and detector surface S_D. It is defined as:

$$A = \frac{4\pi}{\sum_i S_D \cdot cos(\alpha_i) \cdot \Delta V_i / R_i^2} \qquad (1)$$

where α is an angle between the connecting line for each plasma point i and the vector perpendicular to the detector surface S_D, R_i is the distance between plasma and detector surface, while ΔV_i is a volume of the plasma element i. The detailed description can be found in [8].

The second important parameter which must be taken into account is the pile-up effect which always creates losses in the observed number of photons.

3.1. Calculation of the pile-up effect

The measured spectrum will only be a valid measure of number of photons and their associated X-ray energy provided that the filtered pulse is sufficiently well separated in time from its preceding and succeeding neighbor pulses so that its peak amplitude is not distorted by overlapping. In the case of overlapping, one deals with the pile-up effect, which manifests itself in production of multiple amplitude peaks in addition to the main peak. In the spectrometers based on the digital techniques (with digital filters) all pile-up peaks are removed, but due to the process of cleaning, some input pulses are lost from the final statistics. Output count rate (OCR) of pulses is then always lower than the input count rate (ICR) of X-ray quanta interacting in the SDD detector according to statistical formula (2) [13]. Assuming that dead time τ_d for the slow channel of the measuring system is known, one can apply the following formula to calculate the real ICR_r which refers to OCR:

$$OCR = ICR_r \times \exp(- ICR_r \cdot \tau_d) \qquad (2)$$

In the case of the DXP Mercury-4 from XIA [14] used in the PHA spectrometer for W7-X, for the first approximation, τ_d is expressed by $2(t_p+t_g)$, where t_p and t_g are the parameters of the trapezoidal digital filter known as peaking time and gap time, correspondingly. The t_p is rising

and falling time, and the t_g duration of the flat top of the filter. The gap t_g is introduced to remove the effect of fluctuation in rise time of output pulses, which arise from the irregularity of charge collection in a detector and as a result improves energy resolution. The gap should be optimized to obtain the highest energy resolution. The relations OCR – ICR for different values of peaking time t_p are shown in fig. 3.

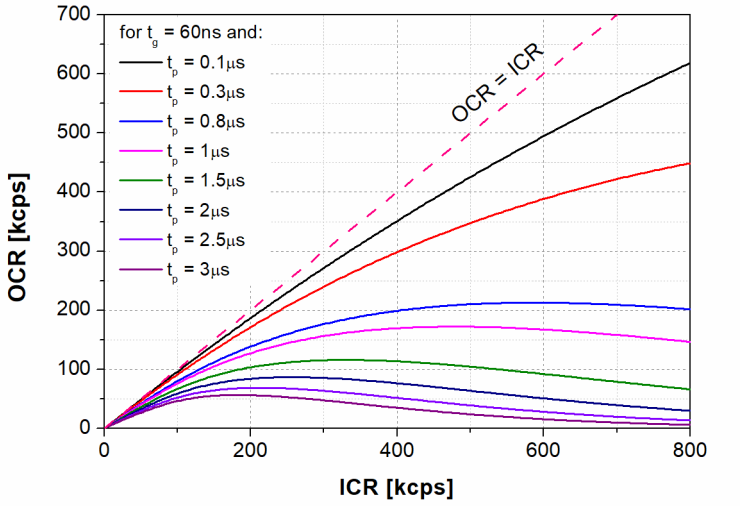

Fig.3. Theoretical curves of incident count rate (ICR) and output count rate (OCR) for various peaking times, t_p.

The DXP Mercury-4 delivers the value of input count rate taken from the output of fast channel, but it is somewhat lower than the real frequency of coming quanta because fast channel has its own dead time τ_{df}. To obtain the real input count rate ICR_r of quanta having measured input count rate from the fast channel (ICM_m) the following formula is used:

$$ICR_m = ICR_r \times \exp(- ICR_r \cdot \tau_{df}) \qquad (3)$$

The equation (2) should be inverted to obtain ICR_r.

Usually, during the last W7-X experimental campaigns, the pile-up effect was oscillating in the range from 15% to 35 % depending on plasma conditions and pinhole size (photon flux).

3.2. Removal of the pile-up events in DXP

Two parallel processings of signals from incident photons are applied in the PHA system based on Mercury-4, one in the fast channel which is used especially for the pile-up inspection and the second one in the slow channel which is used for determination of amplitude of pulses. Such separation of both functions is especially useful in the case of a strong photon flux.

There are two tests for inspection of pile-up events, both performed in the fast channel. The first test is based on measuring the distance between two subsequent (triangular) pulses in the fast channel. They must be separated far enough to avoid the pile-up in the slow channel and the distance is related to the peaking time of the slow channel. The pile-up in the slow channel occurs always when pulses are so close that the rising (or falling) edge of one pulse lies under the peak of its neighbor pulse. Overlapped pulses in the slow channel are then removed.

The second test is based on measuring the width of pulses in the fast channel. If a pulse is found to exceed certain fixed value (related to the peaking time of the fast channel), the fast - channel pile-up takes place, and it leads to pile-up in the slow channel as well. The corresponding cluster of pulses in the slow channel, which is of abnormally high amplitude, is then removed.

4. Summary

The PHA spectra can deliver information about the kind of impurities in the W7-X plasma but only calibrated one can reveal information about the physical processes like impurity transport. Typical PHA spectrum, measured during the W7-X campaign, is presented in fig. 4a. Around 1.2keV increase of radiation is visible, which results from the applied filter (50µm of Be), for which the transmission rapidly increases from 1 keV. For the same reason, the sharp increase in calibrated spectra (fig. 4b) is observed.

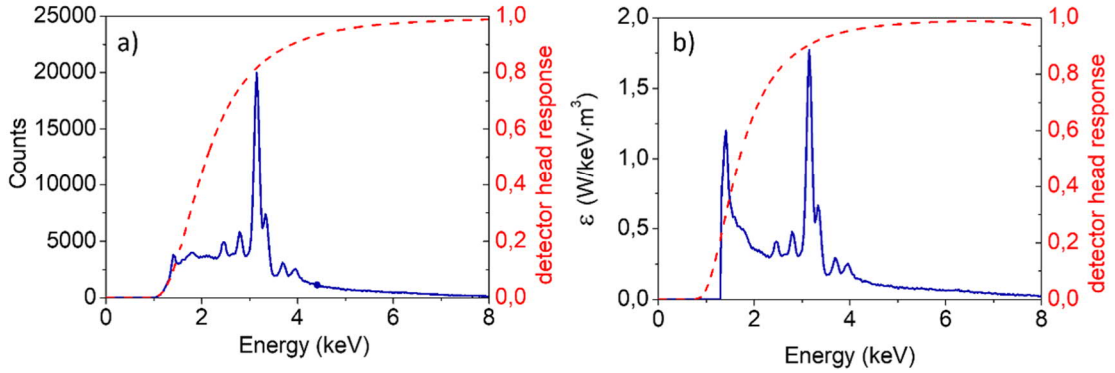

Fig.4. Example of measured PHA spectrum (a) and corresponding calibrated spectrum (b) including filter transmission and pile-up losses. The spectrum was collected by the 2nd PHA channel with 50µm of Be filter.

It is clearly visible that calibrated spectrum (fig. 4b) exhibits different features than the measured one. The change in the shape of the spectrum is determined by the transmission of the filter and absorption of the detector. The correction for pile-up is made by multiplication of the spectrum by a constant value determined with reference to the theoretical curve presented in Fig. 3, which shows relation between input and output count rate and according to the formula (3). Additionally, the geometrical factor is also included in the calibration process according to the equation (1). The part of the spectrum below about 1.5 keV is not reliable because of high error in determination of transmission efficiency, which is smaller than 5%.

Proper calibration of the PHA spectra enables to deliver qualitative and quantitative information regarding radiation from the W7-X plasmas for different impurities. Determination of line intensities allows to estimate contribution of each impurity with respect to average plasma density and, in consequence, predict the plasma evolution and better understand the possible radiation collapse, due to both intrinsic and external impurities.

Moreover, the proposed method of PHA spectra calibration allows the cross-calibration with other diagnostic like XICS spectrometer (X-ray imaging crystal spectrometer) which delivers plasma flow profiles by measuring the Doppler shift of X-ray line emission from various impurities [15-16].

Acknowledgments

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