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A soft X-ray spectrometer with enhanced output count rate

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Abstract. An upgrade of an AMPTEK soft X-ray spectrometer with a silicon drift detector (SDD) to boost the output count rate is presented in the paper. Enhanced count rate is provided by a shaping electronic amplifier which forms pulses with a short rise time from step-wise impulse responses of SDD charge sensitive preamplifier. The rise time of the amplifier pulses is about a half of that used in the AMPTEK amplifier. The output noise of the amplifier equals the noise of the AMPTEK amplifier. The spectrometer is tested with the developed amplifier and amplifier in its digital pulse processing (DPP) unit and SDD radiated by an isotope ^{55}Fe source. The results of the test are compared in terms of the rise time and amplitudes of the response pulses as well as trapezoidal pulses at various peaking and flat top times. The developed amplifier is capable to provide the count rate of output pulses increased by a factor of 1.5 in regards with the standard methods at the same energy resolution.

Keywords: soft X-ray spectrometers, pulse counting, amplitude spectra, digital filters

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Спектрометр мягкого рентгеновского излучения с повышенной скоростью счета фотонов

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Аннотация. В работе представлена модернизация спектрометра мягкого рентгеновского излучения AMPTEK с дрейфовым кремниевым детектором (SSD) с целью повышения его выходной скорости счета квантов. Повышение скорости обеспечивается электронным усилителем-формирователем, который формирует импульсы с коротким фронтом нарастания из ступенчатых импульсов отклика зарядо-чувствительного усилителя сигнала SDD. Время нарастания импульсов усилителя примерно половина времени нарастания выходного импульса усилителя в AMTEK. Выходные шумы этих усилителей одинаковы. Спектрометр испытывался с разработанным усилителем и усилителем в модуле счета квантов (DPP) с использованием источника излучения от изотопа ^{55}Fe. Проводится сравнение тестирования времени нарастания и амплитуды импульсов усилителей, а также трапецеидальных импульсов, полученных цифровой фильтрацией, при их разных длительностях пикирования и плоской вершины. Разработанный усилитель способен обеспечить рост скорости счета в 1.5 раза по сравнению со стандартным методом при сохранении энергетического разрешения спектрометра.

Ключевые слова: спектрометры мягкого рентгеновского излучения, счет импульсов, амплитудные спектры, цифровые фильтры

Финансирование: Проект и изготовление диагностики мягкого рентгеновского излучения на токамаке ФТ-2, описанные в Введении, были поддержаны ФТИ им. А.Ф.Иоффе в рамках Государственного контракта № 0034-2021-0001. Анализ данных в остальных разделах статьи поддержаны ФТИ им. А.Ф.Иоффе в рамках Государственного контракта № 0040-2019-0023.

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Introduction

High count rate spectrometers of soft X-ray emission employ silicon drift detectors (SDD) [1] and digital pulse processors for counting the detected pulses and measurements of their amplitudes [2, 3]. One of the main factors which restrict the output count rate of the spectrometers is the rise time of the impulse response on photons. It is set from a trade-off between the highest count rate and the best energy resolution determined by noise and ballistic effects in the detector [4] as well as pile-up of pulse processing [3]. Advanced modern spectrometers are capable to operate at output count rates up to $4{\cdot}10^5$ 1/s with energy resolution 200 eV [4, 5]. The resolution strongly degrades with increasing the count rate.

A study of fast dynamics of electrons in plasma of the FT-2 tokamak [6] requires measurements of soft X-ray Bremsstrahlung emission at higher count rates and high energy resolution. The enhanced count rate can be achieved with modified algorithms of pulse counting [7, 8] or/and hardware upgrades of spectrometers. The second way is presented in the paper. A commercially available soft X-ray spectrometer of AMPTEK Inc. has been upgraded with a shaping electronic amplifier [9] and a 14 bits digitizer operating at a sampling rate up to 250 MHz [10]. The digitized pulses are shaped to shorter pulses of trapezoidal [11] form which are processed with pulse counting algorithms [3, 12].

The spectrometer is equipped with a 70 mm^2 FASTSDD detector [13] and digital pulse processor (DPP) PX-5 [14]. A charge sensitive preamplifier integrated in the detector delivers step-wise responses on detected photons with sensitivity 3.2 mV per 1 keV of photon energy. The step-wise signals are reshaped in PX-5 to pulses which are digitized by an internal ADC at sampling rate 80 MHz. Further in the paper the pulses from the developed amplifier are referred as A-pulses and pulses from the internal amplifier in PX-5 are referred as P-pulses.

The rise time of the step-wise signals increase with the distance of the photon impact point in the depleted region to the detector anode [15]. This effect results in variations of the rise time of the step-wise signals in AMPTEK charge sensitive preamplifier in the range from 15 ns to 110 ns, see Section 2 of the paper.

Hereafter the rise time of pulses is defined as the time interval between 20% and 80% levels of the pulse amplitude.

The rise time of P-pulses was set about a twice of that of the step signals to optimize the count rate and energy resolution of the spectrometer. This is the rise time which restricts the highest count rate of the spectrometer.

A key unit of the upgraded system is a shaping amplifier which transforms the step-wise signals to A-pulses with shorter rise time and the same noise as in PX-5 unit. The amplifier was described and tested in [9]. The formed pulses are digitized at a sampling rate up to 250 MHz and 14 bits resolution with ADC FM814×250M produced by InSys AO [10]. The recorded signals are numerically shaped to trapezoidal pulses and processed for amplitude measurements. A higher sampling rate and resolution of the employed ADC are advantageous for accurate digitizing short leading edges of the pulses from the amplifier outputs.

The shaping amplifier has been tested with 70 mm^2 FASTSDD AMPTEK detector exposed to photons of 5.9 keV and 6.5 keV energy radiated by an isotope source ^{55}Fe. The developed shaping amplifier and amplifier in PX-5 have been tested for rise times and amplitudes changing with the rise time of the step-wise signals. Changing the amplitudes and rise times of trapezoidal pulses obtained from the amplifier outputs at various peaking times have been tested as well. The amplifier signals were recorded in the test by a digital scope Agilent Technologies MSO9440A with 10 bits resolution and analogue bandwidth 4 GHz at sampling frequency 1 GHz. The recorded signals were smoothed with a digital low pass RC filter with a cut-off frequency 40 MHz.

Rise Time of Reshaped Pulses

Sample pulses measured in the outputs of charge sensitive preamplifier of SDD, external and PX-5 amplifiers are presented in Fig. 1. The amplitudes of five pulses correspond to photon energy 5.9 keV, the second pulse is the response on a photon 6.5 keV and the highest pulse is an overlap of two pulses. The shapes of A-and P-pulses are compared in a larger scale in Fig. 4 in [9]. The rms noises of the signals in terms of photon energy are 300 eV, 44 eV and 46 eV correspondingly.

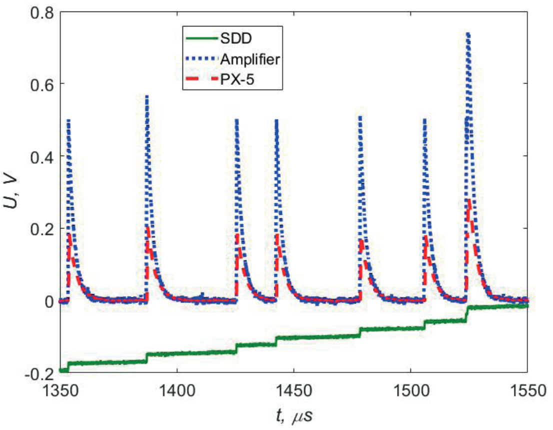

Fig. 1. Impulse responses of amplifies on detected photons

A set of about 1000 pulses measured at the mean input count rate ~ 2·10^4 photons per second were collected and analyzed. Some traces were measured with fully opened 50 mm^2 actual aperture of the detector, the others were recorded with restricted aperture 17 mm^2 collimated by AMPTEK collimator EML-3. The amplitude of a pulse was found from polynomial fitting the measurements around its peak with taking into account the background from preceding pulses. The rise time amounts a time interval between 20% and 80% levels of the amplitudes in the leading edge of the pulse.

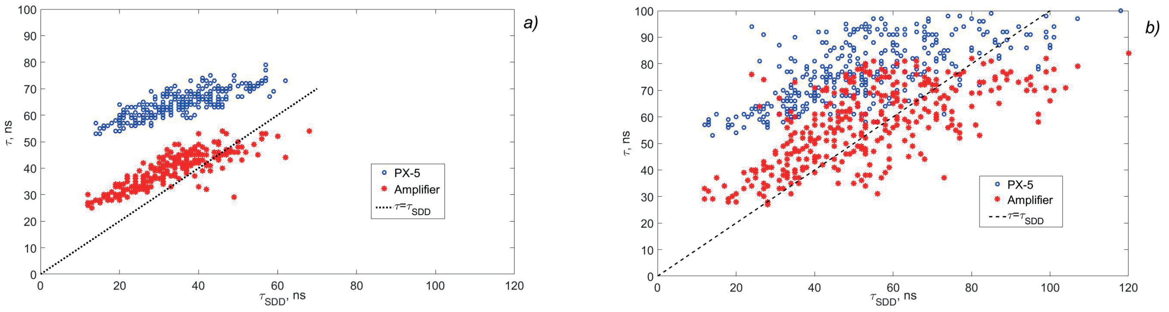

Fig . 2. Rise times of PX-5 and amplifier pulses with (*a*) and without (*b*) collimator

Fig. 2 shows the rise times of pulses from both amplifiers measured with collimated (*a*) and not collimated (*b*) detectors at various rise times of the step-wise pulses. One can see that the developed amplifier provides considerable shortening the front edges of A-pulses which amount 0.5–0.8 of that of P-pulses in the range from the shortest to longest fronts of the step-wise detector responses.

The pulse amplitudes versus their rise times are presented in figure 3 for collimated (*a*) and open aperture (*b*) detector. The spectral peaks of the ^{55}Fe radiation source at 5.9 keV and 6.5 keV are clearly resolved in the plots. The energy resolutions of the Kα peak measured from the amplitude distribution of A- and P-pulses are 255 eV and 315 eV at FWHM correspondingly. The amplitude resolution of A-pulses is close to the specified resolution of SuperSDD 25 mm^2 AMPTEK detector measured for trapezoidal pulses at peaking time 200 ns [5]. Resolution of P-pulses used in the PX-5 unit is 20% worse. Digital trapezoidal shaping is normally used to improve energy resolution and count rate of spectrometers. Trapezoidal shaping of A- and P-pulses is considered in the next section in terms of distortion of their trapezoidal form and variation of their amplitudes with the rise time.

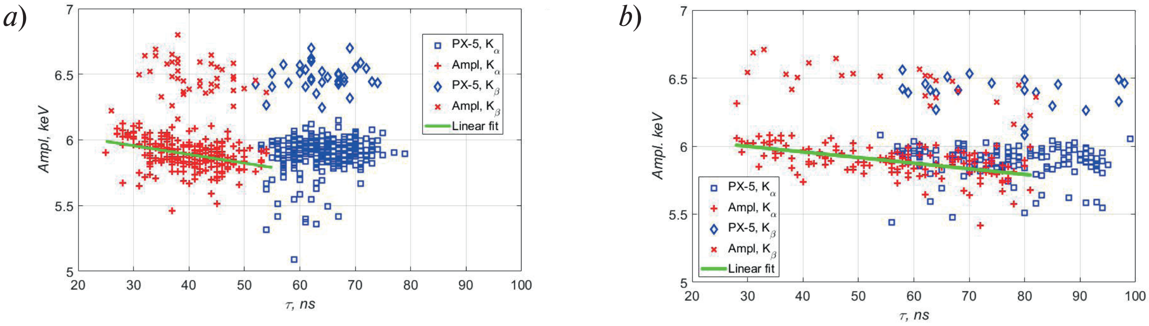

Fig. 3. Amplitudes of reshaped pulses with collimated (*a*) and open area (*b*) detectors

Trapezoidal Shaping of Output Amplifier Pulses

The digitized signals are digitally shaped to trapezoidal pulses which are used in processing algorithms for counting and measuring pulse amplitudes. The algorithms are most efficient with trapezoidal pulses of ideal symmetrical forms. Real pulses tend to this form when their width is much larger than the rise time of input pulses. Wide symmetrical trapezoidal pulses may be not consistent with high count rate measurements because a large rise time of digitized pulses. Distortion of short trapezoidal pulses weaken detection of overlapped pulses [8, 9]. The external amplifier with shorter rise time output addressed to these problems.

Fig. 4 represents digitized normalized P- and A-pulses responded on a step voltage in the output of the charge sensitive preamplifier of 17 ns (Fig. 4, *a*) and 107 ns (Fig. 4, *b*) rise time. They are plotted in the figure with dashed-dotted and solid black curves indicated by letters P and A. The other curves in the figure are trapezoidal pulses shaped from the P- and A-pulse. They

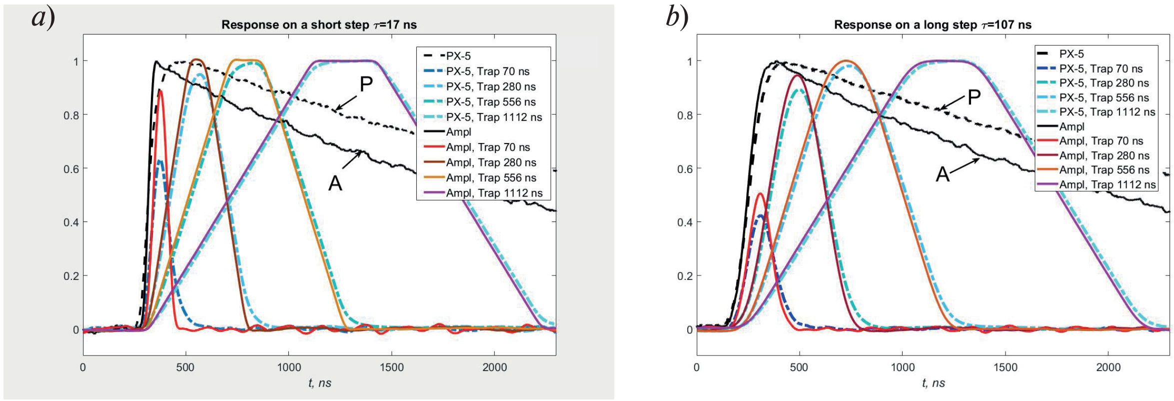

Fig. 4. Shapes of trapezoidal pulses responding short (*a*) and long (*b*) step input pulses

are plotted with colour dashed-dotted and solid curves correspondingly. The trapezoidal pulses have Gaussian-like form [7], [8], i.e. their width and slope at FWHM equal the width and slope of a Gaussian pulse of the same amplitude. The widths of the trapezoidal pulses at FWHM shown in legends correspond to their peaking times 50, 200, 400 and 800 ns. The trapezoidal pulses are calculated using [11] and then divided by the set peaking time and normalized to the amplitude of the longest trapezoidal pulse.

One can see that the longest trapezoidal pulses shaped from the A-pulse exhibit the best form in Fig. 4, *a*. Trapezoidal A-pulses calculated at smaller peaking time have smoothed but symmetrical form within 0.5% of their amplitude. Trapezoidal pulses shaped from the P-pulse are far from the ideal trapezoidal form at all peaking times. The biggest asymmetrical distortions at the tail of short trapezoidal pulses restrict detection of overlapped pulses and, hence, limit the count rate of the spectrometer, see example in [9].

Amplitude of Trapezoidal Pulses

Fig. 4 shows that the normalized amplitude of trapezoidal pulses strongly depends on the rise time of step-wise signals at small peaking time of trapezoidal filter. Thus, the amplitude of trapezoidal pulses should depend on the rise time of trapezoidal pulses. Note that the rise time of an ideal trapezoidal is 60% of its peaking time, but it does not hold for actual trapezoidal pulses. Fig. 5 presents the dependence of amplitudes on the rise time of trapezoidal pulses determined with an accuracy of 1 ns. The mean amplitudes versus the rise times for trapezoidal pulses shaped from P- and A-pulses are plotted in the figure 5 for peaking times 50 ns, 100 ns, 200 ns and 400 ns. The error bars are the standard deviation of the amplitude measured at the corresponding rise times of trapezoidal pulses. The amplitude of trapezoidal pulses decreases linearly with the rise time (Fig. 5, *a*, *b*). The measured amplitudes scan in the range which is consistent with a model developed in [7] for KETEK H7 SDD of 7 mm^2 sensitive area [16].

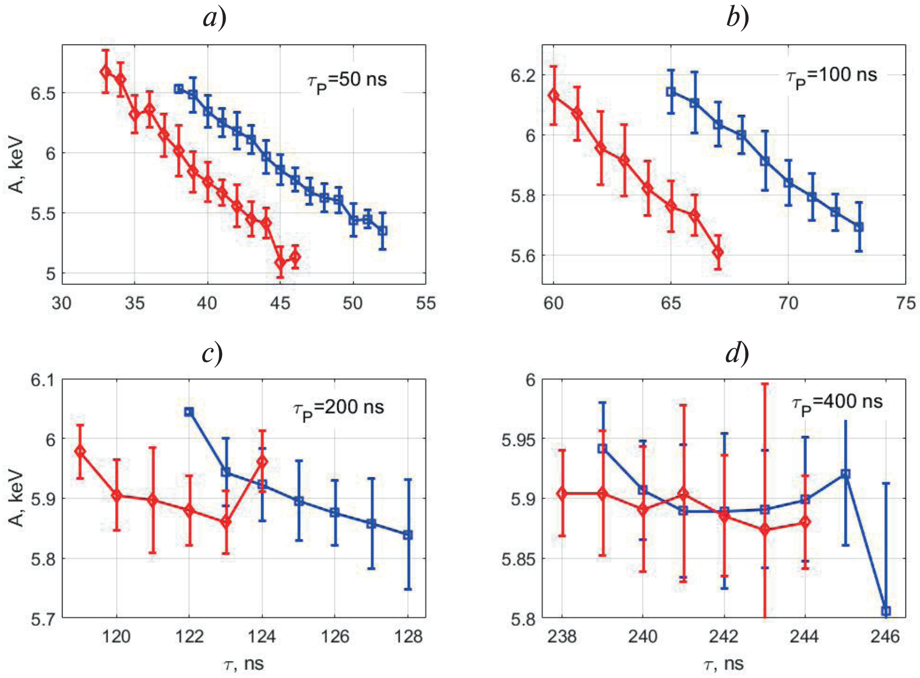
a) *b*) *c*) *d*)

Fig. 5. Amplitude versus rise time of trapezoidal pulses at peaking times τ_p of 50 (*a*), 100 (*b*), 200 (*c*), and 400 (*d*) ns

Thus, the inferred amplitudes were corrected for measured rise time of pulses for better amplitude spectral resolution. The effect of the correction on the spectral resolution is presented in Fig. 6.

The spectral width of Kα peaks at FWHM in various measurements with collimated detector and the technical specifications of the spectrometer are plotted versus the peaking time of trapezoidal pulses. The range of the peaking times is separated in two plots for better reading.

A black dashed line shows the spectral width of Kα measured with DPP PX-5 which collected more than 10^6 photons. The measurements are conducted at four peaking times and count rate $2 \cdot 10^4$ 1/s. Blue diamonds and red crosses represent the widths of the Kα peak calculated from the amplitude distribution of about 250 P- and A-pulses correspondingly. Some difference between the distributions measured by PX-5 and from P-pulses is accounted for a small statistic of P-pulses.

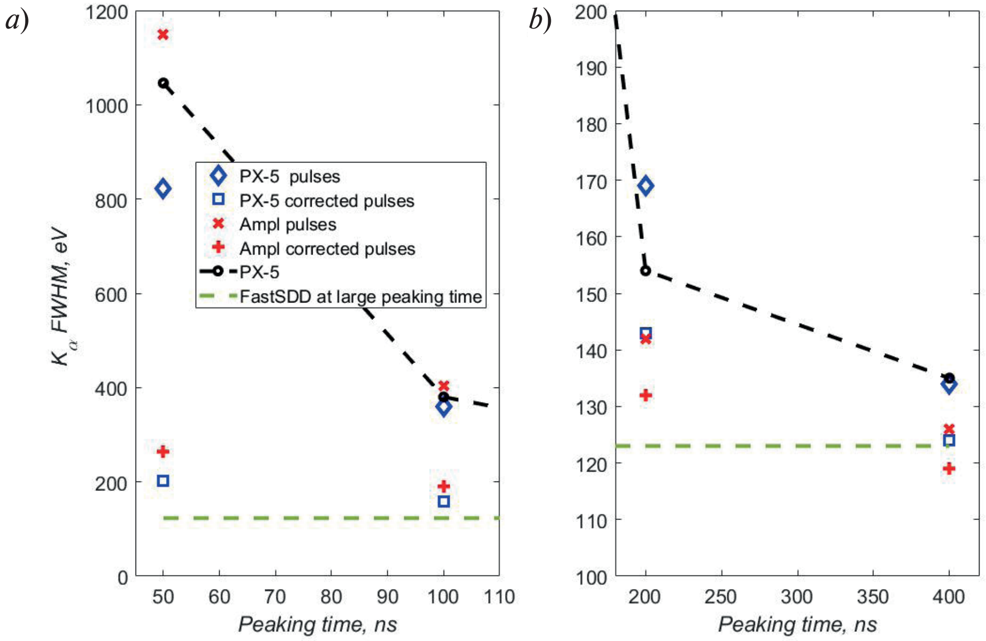

Fig. 6. The width of Kα peak measured at short (*a*) and long (*b*) peaking times

Blue squares and red pluses represent the peak width of P- and A-pulse amplitudes corrected for their rise time. The correction is most pronounced at small rise times - spectral resolution improves by factors of 5 and 2 for 50 ns and 100 ns peaking times. The spectral resolution considerably improves at larger peaking times and achieves the specification of the AMPTEK spectrometer 123 eV. This level is actually available with DPP PX-5 at peaking times of a few microseconds, see [5].

Conclusion

Shaping step-wise signals from a charge sensitive preamplifier of AMPTEK FASTSDD and recording the shaped pulses at a high sampling rate allows more accurate measurements of their amplitude at shorter rise times. The shorter rise time provides better resolution of amplitudes of strongly overlapped pulses and reduction of the dead and resolving time of spectrometers [8]. A two-fold reduction of the rise time of shaped pulses should increase the count rate of the spectrometer at least by a factor 1.5–2. Algorithms for counting and amplitude measurements of recorded pulses with taking into account their rise time are under development.

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The design and construction of the soft X-ray diagnostic system in the FT-2 tokamak described in the Introduction were supported by Ioffe Institute under State Contract No. 0034-2021-0001. Data analysis in other sections was supported by Ioffe Institute under State Contract No. 0040-2019-0023.

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