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Rising the Signal-to-Noise Ratio in X-ray Spectra of Femtosecond Laser-Produced Plasmas Using the "Mean–Median" Algorithm

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Abstract—As femtosecond laser pulses increase in intensity and decrease in duration, interaction between the focused laser radiation and a substance is followed by a sharp increase in the intensity of fast-electron, ion, and electromagnetic noise generation. In turn, the noise signals of X-ray detectors grow in amplitude and the signal-to-noise ratio in recording X-ray spectra of multiply charged ions approaches unity. A significant excess of the noise level over the useful signal is observed in plasmas generated by laser pulses with a power density of $\geq 10^{17}$ W/cm^2. The most powerful effect of the above factors is exerted on X-ray spectra recorded by such electromagnetic equipment as CCD-based detectors, photoelectron amplifiers, etc. A new "mean–median" algorithm is described, with which it is possible to considerably increase the signal-to-noise ratio of CCD detectors used to measure X-ray spectra of femtosecond laser-produced plasma.

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INTRODUCTION

Detectors based on charged-coupled devices (CCDs) are widely used in spectroscopy and imaging owing to their high sensitivity and the low noise level. The readout noise, the thermal noise, and the noise due to cosmic rays are usually differentiated [1]. The influence of the readout noise can be reduced by coupling the CCD pixels and averaging the signals and the thermal noise is almost completely eliminated by cooling the detector, whereas suppression of the noise due to cosmic rays is a complicated task: several good algorithms have been proposed, but none of them are versatile. This is particularly the case for the task of eliminating small-amplitude peaks and processing spectra with sharp spectral singularities that are difficult to distinguish from cosmic peaks. (By cosmic or spurious peaks, we mean spectral singularities that exceed the noise level in a spectrum and are not necessarily reproduced in a sequence of spectra recorded under identical conditions.)

Cosmic peaks appear when a CCD array detects high-energy γ-ray photons or cosmic particles capable of penetrating through any shielding material. After a high-energy particle hits a CCD, it is in most cases impossible to read the useful signal acquired in this pixel. The width of these pulses in the resultant spectrum is comparable to the minimum width of a spectral line, and their amplitude varies over wide limits.

Simple methods of analysis (e.g., frequency analysis using Fourier or wavelet transforms and smoothing procedures based on various polynomial filters) make it possible to merely identify and remove peaks with a very large amplitude and small width. In [2], it was shown that none of these algorithms were able to process all types of cosmic peaks. Some methods can lead to a significant distortion of the spectrum or incomplete elimination of cosmic peaks. Even the most advanced and complicated algorithms used in Raman spectroscopy sometimes make mistakes in identifying cosmic peaks and can cause the spectra to be distorted.

The problem of eliminating cosmic peaks is of considerable importance in spectroscopy investigations, since peaks may erroneously be identified as spectral lines or conceal them. Measurements of the cosmic background show that the mean rate with which such peaks appear is ~10^{-7}–10^{-6} peaks/(s pixel). This means that 10–20 peaks can be detected by a CCD array with dimensions of 1000 × 1000 pixels over an integration time of 1 min. In the general case, this value depends on the size of the CCD detector pixel.

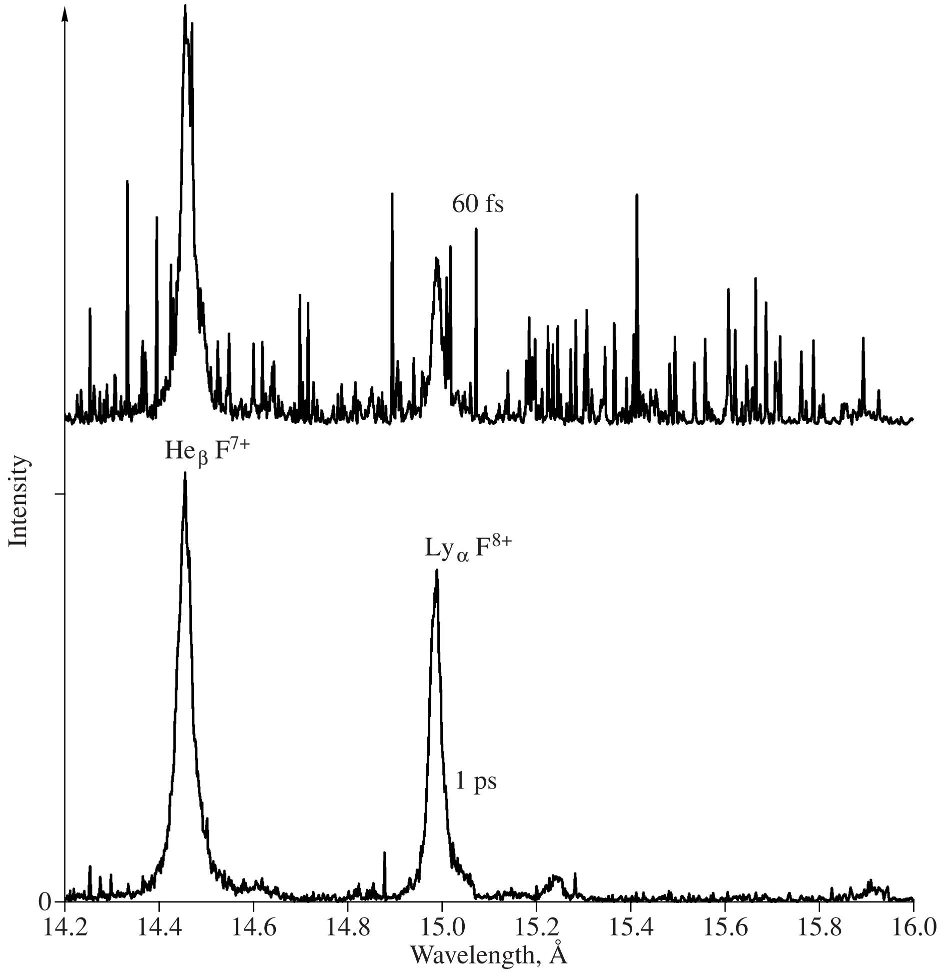

Fig. 1. Increase in the number and intensity of noise pulses in the X-ray spectrum near the He$_\beta$ and Ly$_\alpha$ lines of fluorine after a change from a pulse duration of 1 ps–60 fs.

In X-ray spectroscopy of multiply charged ions produced in a femtosecond laser plasma, the signal under investigation is, as a rule, very high and long integration times are not needed. For this reason, a final spectrum may contain an average of one or two cosmic peaks for each 1000 points. However, experiments show that an increase in the energy of the laser beam focused on the target leads to an increase in the number of spurious peaks.

As the laser pulse power increases, there comes a point where the noise level rises sharply and the signal-to-noise ratio (SNR) in measuring X-ray spectra approximates unity. At power densities of $>10^{17}$–10^{18} W/cm^2, the noise level becomes considerably higher than the signal level.

This is explained by the fact that, when the focused laser beam interacts with a substance, the intensity of generation of fast electrons, high-energy ions [3], and different electromagnetic noises increase sharply. As a result, apart from cosmic rays, there exist interferences caused by laser plasma, which is a source of various powerful high-frequency oscillations and high-energy particles. An additional intense source of noises is characteristic radiation of high-energy electrons and ions produced in the plasma and decelerated in the chamber walls and the components of the experimental setup.

As a result, the CCD detector located near a high-intensity (femtosecond) plasma source detects much more noise than in experiments with nanosecond and picosecond laser pulses. In this case, noises due to the plasma are dominating. Figure 1 presents examples of Teflon spectra, obtained at a fixed laser beam power of 100 mJ and an invariable integration time of 10 s, but at different pulse durations—1 ps and 60 fs.

From Fig. 1, it is apparent that both the amount and intensity of noises increase considerably as the laser pulse becomes shorter. Estimates show that the rate with which spurious peaks are detected (hereinafter, by spurious peaks are meant all peaky noises both of cosmic and plasma origins) is as great as 10^{-2}–10^{-3} peaks/(shot × pixel). As distinct from the cosmic-ray background level, which varies in proportion to time, the amount of noises generated by the plasma is proportional to the number of shots fired at the target over the time of signal integration by the CCD detector.

For the experiment described in this paper (the laser radiation with a pulse repetition rate of 10 Hz interacts with the surface of a solid target), this means that a spurious peak can be detected in every tenth pixel in a spectrum at an integration time of only 2 s. In this case, the signal read out of a fixed pixel of the CCD detector can be distorted in at least two successive spectra. Under these conditions, the methods used to analyze Raman scattering spectra [1, 4–7] are incapable of providing a good result.

Most methods for suppressing cosmic peaks involve a common procedure: (i) smoothing of the original spectrum using a linear or nonlinear filter, (ii) identification of cosmic peaks (but with original and smoothed spectra differing), and (iii) replacement of points containing a spurious peak in accord with the data at adjacent points. In [2], it was shown that such methods provide good results only if spectral lines are significantly smaller in amplitude or much wider than the spurious peaks. If a spectrum contains narrow lines or the amplitude of spurious peaks is comparable to the amplitude of spectral lines, these methods may substantially distort the true spectrum.

In this paper, we propose an easily applicable algorithm with the name of "mean–median" (MM), which allows spurious peaks to be efficiently distinguished and eliminated even in heavily contaminated spectra obtained with a powerful influence of noise on the useful signal. The MM method was tested on model spectra with a predetermined level of different noises. In practice, the MM algorithm was used to purify experimental X-ray spectra of Ne-like ions of Fe produced by interaction of intense femtosecond laser radiation with solid targets.

MEAN–MEDIAN ALGORITHM FOR ELIMINATING NOISED FROM X-RAY SPECTRA OF PLASMAS

In this paper, we propose a peak identification procedure based on the assumption that the mean value of a normally distributed physical quantity obtained in a set of measurements lies in the vicinity of the median; i.e., the numbers of measurements with values greater and smaller than the mean are virtually identical. The intensity value in any pixel of the CCD detector in a set of sequentially recorded spectra falls into the category of these quantities.

Measurements distorted by a spurious photon will be characterized by a greater deviation from the median than the other points and will thereby shift the mean from its true value (i.e., from the mean value for a set of measurements in the absence of distortions). Rejecting such points until the distribution of the measured pixel signal intensity becomes close to the normal distribution, we determine the number of measurements distorted by a spurious photon for each pixel of the CCD array.

The pixel signal intensity in a set of ten measurements is plotted in Fig. 2a; the second measurement is considered to be distorted. The original distribution of the pixel signal intensity is asymmetrical (Fig. 2b); whereas the distribution of the pixel signal intensity with the second measurement rejected has a shape close to the normal distribution (Fig. 2c).

For each pixel in the spectrum, measurements in which a spurious photon hit this pixel are determined thereby. Then, spurious peaks are successively eliminated from all recorded spectra. The intensities of all recognized spurious peaks are replaced by intensities obtained by linear interpolation between the signal intensities of two pixels adjacent (on the right and on the left) to the pixel under investigation, in which the signals satisfy the statistical condition described above.

In other words, to correct the distorted portion of a spectrum, we use information from adjacent pixels that have not been damaged by a spurious photon and, therefore, can eliminate peaks with a width of more than one or two pixels. Figure 3 presents the fragment of an actual spectrum in the spectral line region (*1*) before and (*2*) after the peaks were removed. The figure demonstrates the feasibility of eliminating a low-intensity peak with a width of two pixels (spectral pixels 3 and 4) and a high-intensity narrow peak in pixel 13. (The procedure for determining the number of measurement containing this peak was used to illustrate the performance of the MM algorithm and was shown in Fig. 2.)

It should be noted that many methods for eliminating peaks based on analysis of reproducibility of these peaks from spectrum to spectrum (e.g., a rigorous summation algorithm [6]) propose replacing spurious peaks by values from the other recorded spectra in which this pixel has not been damaged. This is acceptable only if the signal is fully stable and global variations in the spectrum intensity are absent. In our experiments, the intensities of lines varied from spectrum to spectrum over wide limits and substitution of spurious peaks by values from the other spectra could lead to significant distortions.

Let us assume that N (an odd number) sequentially recorded spectra contain one measurement with a spurious peak and that the mean intensity of the pixel signals is S. The other measurements are distributed so that one-half of them lies at distance $-\sqrt{S}$ from the true intensity value, while the other half lies at $+\sqrt{S}$. Under these conditions, the algorithm fails to recognize a spurious peak smaller than

$$\Delta = (N + 1)\sqrt{S + S}. \quad (1)$$

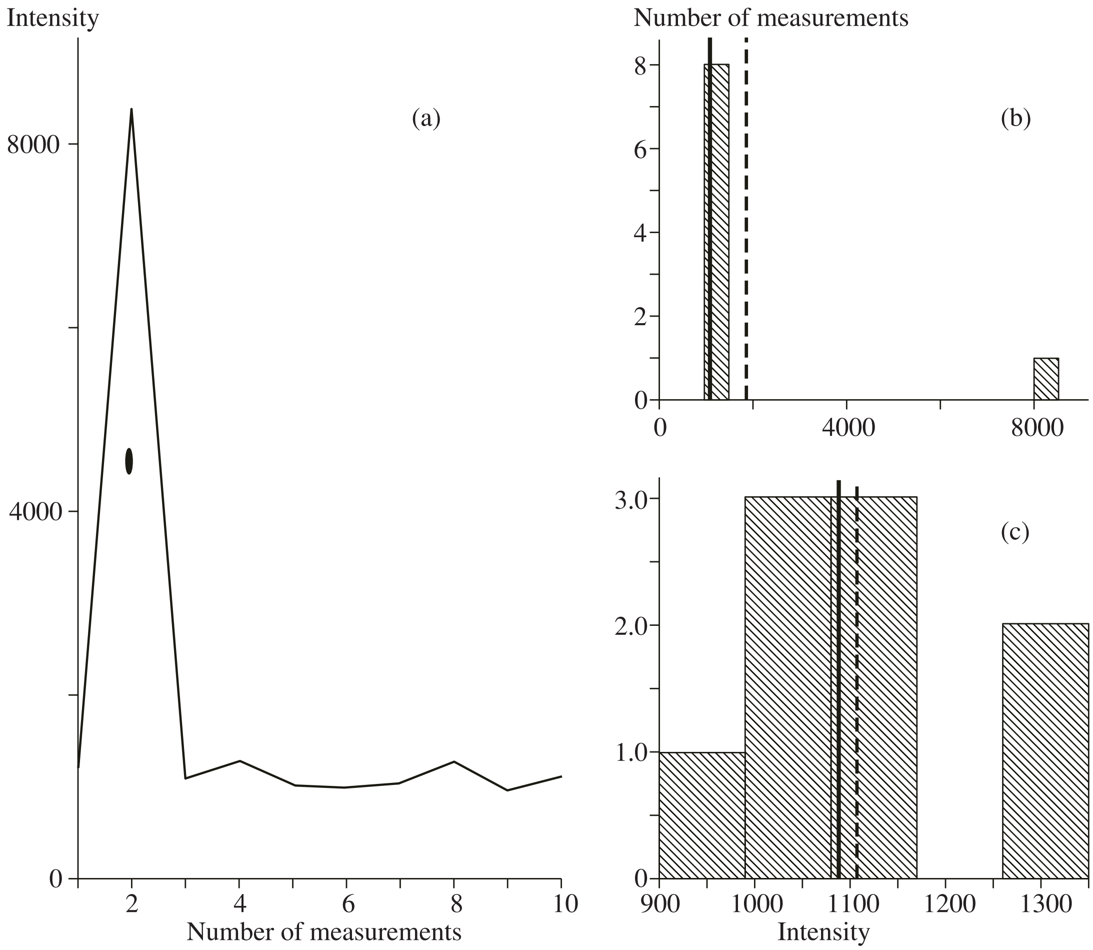

Fig. 2. Determining the numbers of measurements in which the values for a unit pixel of the CCD array considerably exceed the mean signal level: (a) the measured signal intensity for a unit pixel of the CCD detector vs. the recorded spectrum number and distributions of measurements in the intensity (b) for the whole set of measurements and (c) for the set without a suspicious (in this case, the second) measurement. The median for a set of measurements is shown with a solid vertical line, and the mean intensity in this cell is shown with a dashed line.

In addition, when a spurious peak is superimposed on a very narrow (five or six pixels) spectral line, elimination of a peak may slightly distort the spectral line.

From the above examples demonstrating the features of the MM algorithm, three conclusions can be drawn.

(1) The integration time must be limited to avoid broadening of spurious peaks produced by cosmic particles or photons that hit adjacent pixels. Spectra were acquired over an exposure time of 2 s, which corresponded to 20 laser pulses.

(2) To enhance the reliability of identification of small-amplitude spurious peaks, the signal stability must be improved to a maximum degree. In the ideal case, only the Poisson noise must be responsible for variations in the intensity. In addition, according to Eq. (1), it is desirable that short (about eight to ten spectra) sets of measurements be selected.

(3) To reduce possible distortions of spectral lines after elimination of a peak, the final spectrum may be

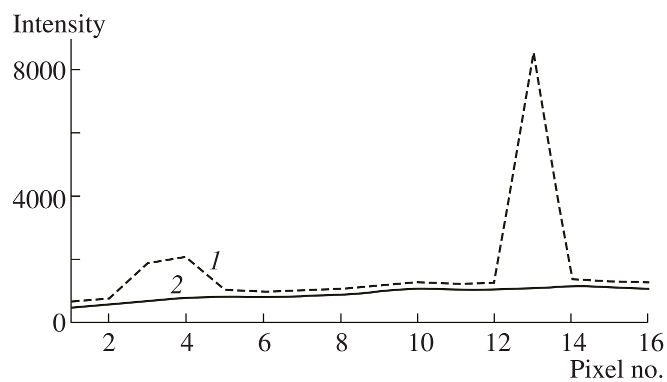

Fig. 3. Measured partial spectrum (*1*) before and (*2*) after application of the algorithm. The peaks were found and eliminated in pixels 3, 4, and 13. The procedure for finding a peak in pixel 13 is illustrated in Fig. 2a; the spectrum is shifted by 200 units along the intensity axis.

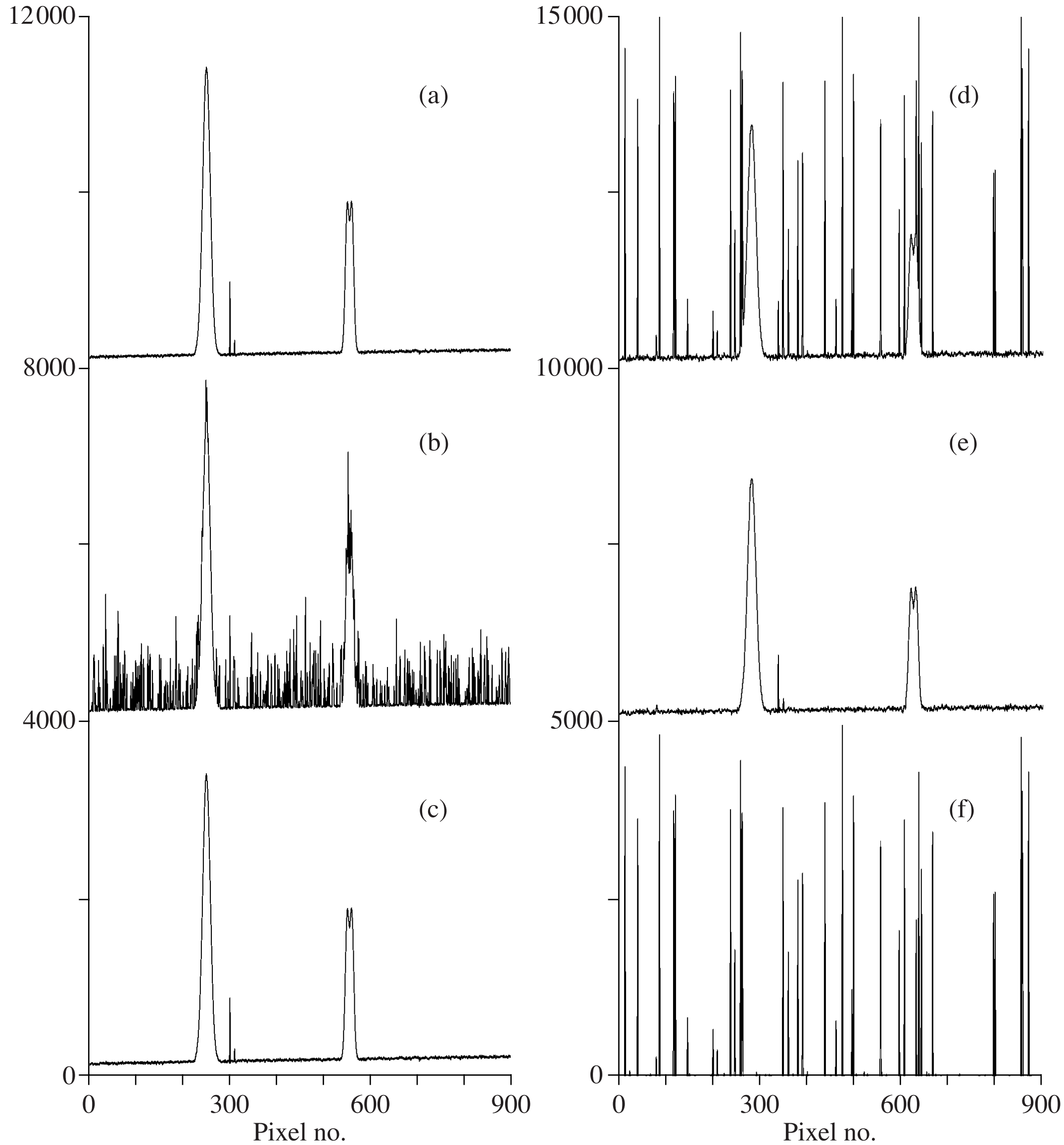

Fig. 4. (a) Net model spectrum averaged over eight spectra; (b) the model spectrum with peaks added, (c) the same spectrum after processing according to the algorithm for eliminating spurious peaks, one of the eight model spectra (d) before and (e) after the purification, and (f) the difference spectrum (f) = (d) – (e), which contains recognized and eliminated peaks.

constructed by averaging all purified spectra. In this case, interferences due to the readout noise are also suppressed.

TESTING THE MM ALGORITHM ON A MODEL SPECTRUM

For initial testing of the MM algorithm, a series of model spectra was generated in the Matlab programming environment according to the following rules.

(1) A "net" spectrum free from noise and spurious peaks was generated. In this spectrum, there were two principal and intense Gaussian peaks, one of which (near pixel 600) was a doublet with a spacing between the components of ten pixels. To simulate sharp low-intensity spectral singularities (such as dielectronic satellites), two very narrow peaks with a low intensity (pixels 300 and 310) were added. The total length of the spectrum was 1000 points.

(2) To take into account global variations in the intensity due to either fluctuations of the laser radiation intensity from pulse to pulse or changes in the position of the laser beam focusing on the moving target, the peak intensity was multiplied by an arbitrary value, so that the peak intensity had a relative standard deviation of 20% from the mean value. Then, the Poisson noise was added to each spectrum (equal to the square root of counts in each pixel). The Gaussian white noise was

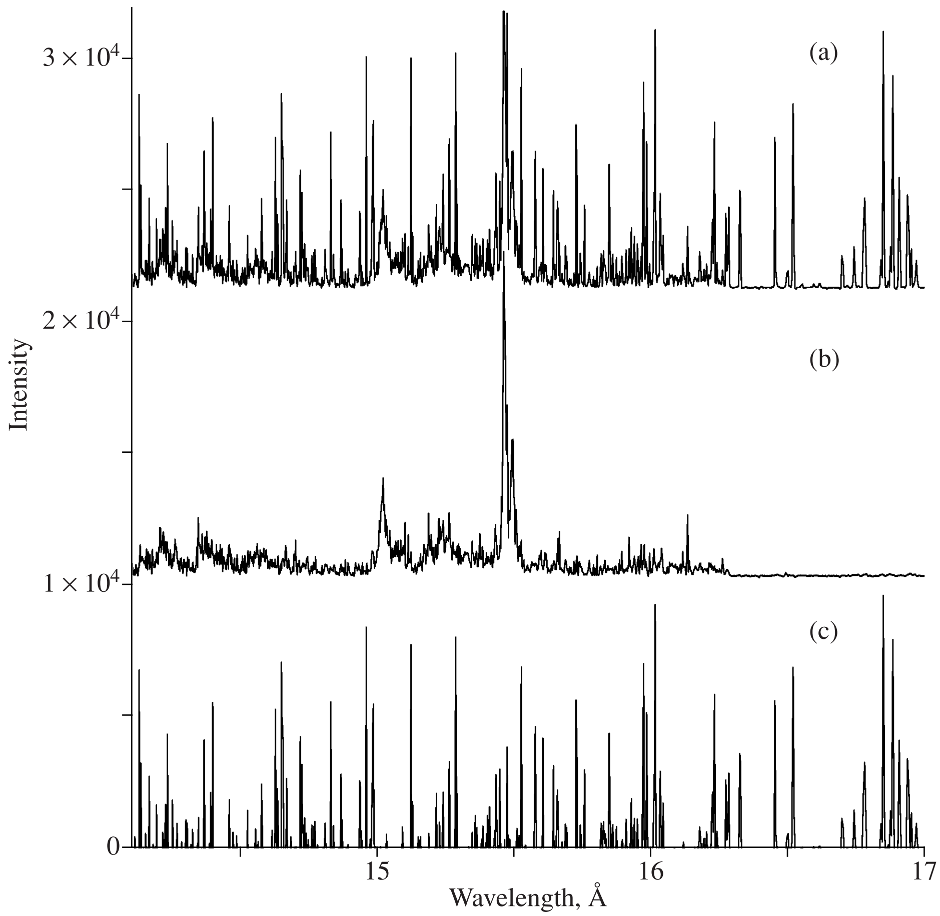

Fig. 5. Spectrum of Fe ions in the region of 14.2–17.0 Å, measured at a laser pulse duration of 60 fs and a pulse power of 100 mJ over an exposure time of 2 s: (a) recorded spectrum, (b) purified spectrum, and (c) removed peaks.

also added to the signal to take into account the readout noise.

(3) Each spectrum was complemented by 50 spurious peaks uniformly distributed over 1000 spectrum points. The peak intensities were selected as an arbitrary number of from 0 to 5000, which is comparable to the useful signal value. The width of each spurious peak was one pixel.

Figure 4a presents the initial "net" spectrum averaged over eight model spectra. The averaged model spectrum with noises and additional peaks included is shown in Fig. 4b. This spectrum, processed according to the described algorithm for eliminating spurious peaks, is displayed in Fig. 4c. One of the eight model spectra before and after the purification is shown in Figs. 4d and 4e, respectively, and the difference spectrum (Figs. 4d and 4e), which contains recognized and eliminated peaks, is presented in Fig. 4f. Both in the averaged and single spectra, it is clearly seen that all spurious peaks have been found and removed. A fine structure of the spectral line near pixel 600 is easily discernible, and narrow spectral lines in the regions of pixels 300 and 310 are seen to remain virtually unaltered. None of the known methods that use only one recorded spectrum to eliminate spurious peaks are able to distinguish such narrow spectral singularities from spurious peaks.

USE OF THE MM METHOD FOR RAISING THE SIGNAL-TO-NOISE RATIO IN RECORDING X-RAY SPECTRA OF FEMTOSECOND LASER PLASMA

Description of the Experiment

The MM method was used to process spectra recorded on the ULTRAS facility of the National Laboratory for Ultrafast and Ultraintense Optical Science, Polytechnic University of Milan (Italy) [8].

A Ti:Sa laser generating 60-fs pulses with a peak power of as great as 2 TW and a repetition frequency of 10 Hz was used in these experiments. An off-axis parabolic mirror focused the laser radiation into a 15-μm-diameter spot at a solid target housed in a vacuum chamber. The solid target was shaped as a cylinder that rotated and moved translationally so that the laser radiation was incident on a pure surface each time.

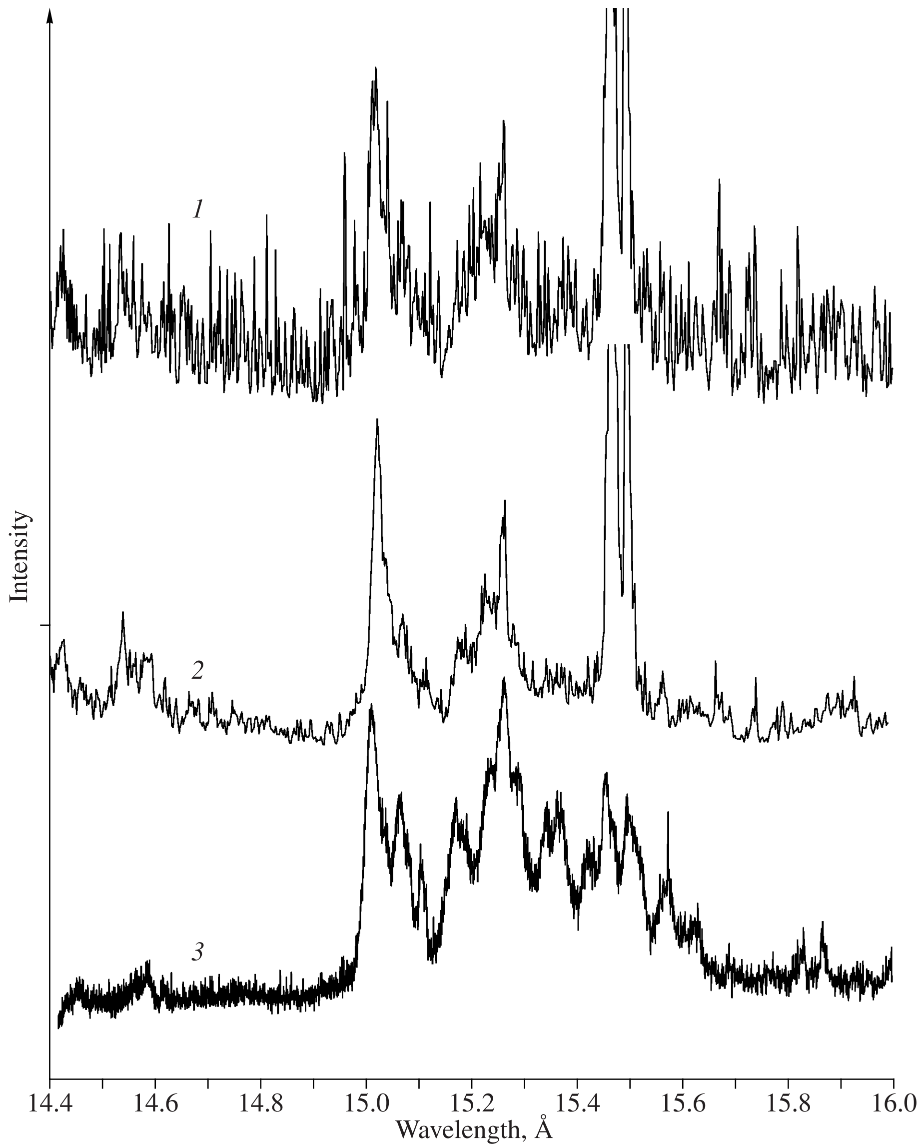

Fig. 6. Fe spectra obtained at (*3*) nanosecond and femtosecond durations of the laser pulse (*1*) before and (*2*) after the application of the MM algorithm (only a part of the *K* line of Fe is shown).

Plasma was generated by pulses with durations of 60 fs–1 ps and a power of 10^{16}–10^{18} W/cm^2. The X-ray spectra in the range of 1.41–1.62 nm were recorded by a spectrograph [9] with a spherically curved mica crystal. A CCD array (Roper Scientific, 1300 × 1300 cells) with 20-μm cells was used to detect X rays. The dispersion circuit of the spectrograph was adjusted to the first order of reflection, which allowed us to observe resonance lines of the target materials and their dielectronic satellites with spectral resolution $\lambda/\delta\lambda$ ~5000.

As a rule, from two to four sets of measurements containing 100–200 recorded spectra were made during the experiment. Generally speaking, at a sufficient stability of the signal, any sequentially recorded eight to ten spectra can be used to clear the experimental results of spurious peaks. However, to improve the quality of analysis, one may preliminarily examine the modulations of the spectrum intensity, which are permanently present in the experiment. This can be done with ease by analyzing the frequency characteristic of the signal in a set of successive measurements for any fixed spectral point.

Since the signal duration is small (i.e., recorded spectra are few in number), to reveal the time dependences of the spectrum intensity, we used a modified covariant method (which belongs to the class of parametric methods) for determining the spectral density of the signal power. For the described layout of measurements, a distinct harmonic dependence was observed in the total spectrum intensity, which could be attributed to the target motion. According to the rate of change of the signal, we could select either from eight to ten sequential spectra or a discrete set of spectra recorded under the most similar conditions.

RESULTS AND DISCUSSION

The developed algorithm was used to process spectra of Fe ions in the plasma produced by focusing a laser pulse with a duration of 60 fs and a power of 100 mJ onto the target. The exposure time for recording each spectrum was selected to be 2 s, and nine spectra were used in the analysis. One of the recorded spectra before noise elimination is plotted in Fig. 5a. It is apparent that the signal is rather noisy, the noise intensity is very high, and the SNR approaches unity. It is impossible to extract information on the shape and amplitude of lines without preliminary processing. The same spectrum is plotted in Fig. 5b after the application of the MM algorithm to the series under investigation. In spite that one spurious peak at 16.1 Å has not been eliminated, the spectrum is seen to become considerably purer.

Spurious peaks in a few spectral pixels could remain in the case where a spurious photon was detected in at least one-half of all the recorded spectra. It is important that none of the spectral lines or no part of a line are identified as a spurious peak, which is demonstrated by Fig. 5c, in which the difference spectrum containing eliminated peaks in plotted. A few missed peaks will disappear after averaging over all the recorded spectra.

A portion of the spectrum in the region of >16.2 Å does not contain a useful signal, since it lies beyond the operating range of the spectrograph. Application of the algorithm results in complete purification of this part of the spectrum (Fig. 5b), and the remaining signal (a straight line) is a dark signal of the CCD detector, i.e., its readout and thermal noises.

It is evident that the spectrum purified using the proposed method is easier to analyze. In the case of an extremely noisy signal or in the presence of significant variations of the intensity in a series of spectra (i.e., the intensities of lines in the recorded spectra differ twofold and more), the algorithm can miss a spurious peak or erroneously identify a portion of the spectrum as a spurious peak. In this case, it is possible to use the averaged spectrum, in which these features virtually disappear.

The averaged Fe spectra obtained at a laser pulse duration of 60 fs and a pulse power of 100 mJ in the range of 14.4–16.0 Å are plotted in Fig. 6. As noted in the Introduction, standard averaging (*1*) merely lowers the noise amplitude, but the structure of the spectrum fails to be clarified. On the other hand, after preliminary elimination of spurious peaks in the spectra and subsequent averaging (*2*), one can easily discern separate spectral lines and estimate their widths and amplitudes. For comparison, Fig. 6 also shows the Fe spectrum (*3*) obtained at nanosecond durations of the laser pulse [10]. The satellite structures of Na-like ions near the resonance lines of Ne-like Fe ions are clearly resolved in spectra *2* and *3*.

CONCLUSIONS

The MM method for eliminating peaklike noises from radiation spectra of femtosecond laser-produced plasmas has been tested both on model and actual spectra. Using this method, one can eliminate spurious peaks of any amplitude and width; in this case, narrow spectral lines and lines comparable in amplitude with the noise level remain unaltered. Spurious peaks can also be identified under conditions of global fluctuations of the plasma radiation intensity; nevertheless, to obtain the best results, it is recommended that a set of the most stable measurements be used in analysis. The method dispenses with preliminary estimation of any threshold values. Owing to simplicity and clearness, the MM method can be employed both to increase the SNR in spectra of femtosecond laser plasmas and to investigate other processes in which a CCD detector is used for signal recording.

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