The spectrum simulation of the soft X-ray for vacuum spark with laser initiation

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Abstract. The spectra recovery technique based on measurement of soft X-ray radiation in a low-energy vacuum spark (discharge energy $E_c \leq 20$ J) with using of pair of pin-diodes and a set of removable K-edge filters is presented. The numerical model of soft x-ray spectrum and algorithm of selection of spectral distributions for coordination with experimental data are offered. Results of processing are presented in the form of the simulation spectra.

1. Introduction
Studying of temporary and spectral characteristics of the soft x-ray radiation of a vacuum spark plasma with laser initiation gives important and useful information on the processes proceeding in such hot plasma [1-5]. This information allows to create sources of the soft x-ray radiation with necessary spectral characteristics.

A simple technique of recovery of soft x-ray spectrum region for the low-inductive vacuum spark with small energy of discharge ($\leq 20$ J) is reported in this article. As input data for simulation of spectrum, we use measurements of soft x-ray in the pairs of matched pin-diodes with the removable K-edge filters corresponding to different regions of spectrum [6]. The offered algorithm we developed for rapid analysis of the experimental data obtained using X-ray pin-diodes and representation of result in the form of the simulated spectra.

2. Experimental setup
The scheme of the experimental setup is described in our articles [5,6]. The experimental setup consists of a vacuum interaction chamber (the residual pressure $P \approx 10^{-5}$ Torr), a high-voltage discharge system, initiating Nd:YAG laser ($\lambda = 1.06$ µm, the pulse energy $E_{laser} = 30-60$ mJ and pulse duration $\tau \approx 15$ ns) and the diagnostic system. In turn, the high-voltage discharge system consists of conical electrodes, low inductance capacitor bank (capacitance $C = 0.22$ uF), high voltage DC ($U = 10-15$ kV). The cathode is made from brass and anode is made from iron. The gap between the electrodes is $d_{nc} \approx 5.3$ mm. In our experiments the laser radiation was focused on the anode.

Two matched pin-diodes in combination with three pairs of K-edge filters (Al(9 µm) and Mg(17 µm), Ti(5 µm) and Al(36 µm), Fe(10 µm) and V(20 µm)) for the registration of soft x-ray radiation were applied. The pin-diodes were placed inside the vacuum chamber at the distance of 20 cm from the discharge area. With each pair of filters was done the individual series of measurements.

3. Experimental results
Figure 1 shows typical recorded waveforms of signals from x-ray pin-diodes for the two pairs of K-edge filters produced under the same conditions. It also shows synchronous signals of the discharge current from Rogowski coil.
Figure 2 shows recorded waveforms of soft x-ray signals for Fe (10 um) and V (20 um) K-edge filters and signals from the Rogowski coil for different discharges in the same series of measurements.

Figure 2. Waveforms of soft x-ray signals for Fe (10 um) and V (20 um) K-edge filters and signals from the Rogowski coil: as named a long pulse of emission of soft x-ray(a) and as named a short pulse of soft x-ray emission(b). Shown pulses of soft x-ray were obtained under identical conditions in a series of measurements. The energy stored in the discharge capacitor $E_c = 16.33$ J.

As it can be seen from Figures 1a,b and 2a there is a significant delay duration of the start of the discharge and much longer duration of time of forming of the discharge than in the case of focusing of laser beam on the cathode [5]. In some cases the discharge with a small delay duration and with as named a short pulse of emission of soft x-rays as on figure 2b is possible. The proportion of such pulses can reach 20% in the series of measurements and they are not considered.

4. Processing of the experimental data

The algorithm of the processing of experimental results is constructed as follows. We find the amount of soft x-ray emission $Nm$ during the pulse of soft x-ray for each of three pairs of K-edge filters. It is the time integral within the vertical dotted red lines shown in Figures 1-2a. Table 1 shows the values of $Nm_{1}$ and $Nm_{m}$ for five combinations of filters. Thus two pairs of filters Al (9 um) + Al (36 um) and Fe (10 um) + Al (36 um) were add to the pairs of filters, which had been listed above. In the fourth column of Table 1 the experimental values $\eta_{m,n} = Nm_{n}/Nm_{m}$ are shown and physically similar calculated value of $\delta_{n,m} = Nm_{n}/Nm_{m}^{5}$ is shown in the fifth column (explanation is below).
Table 1. Quantitative soft x-ray evaluations for different filters.

| Pairs of Filters | Amount of soft x-ray emission \( N_{m,n} \) in 1÷5 eV | Amount of soft x-ray emission \( N_{m,n} \) in 6÷10 eV | \( \eta_{n,m} \pm \Delta \eta_{n,m} \) (experiments) | \( \delta_{n,m} = N_{m,n}^s / N_{m,n}^s \) (evaluations) |
|------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Al(9 um), Mg(17) | 1201                            | 291                             | 4.1±1.0                         | 3.3                             |
| Ti(5 um), Al(36 um) | 809                             | 159                             | 5.1±1.3                         | 3.3                             |
| Fe(10 um), V(20 um) | 297                             | 252                             | 1.2±0.3                         | 1.5                             |
| Al(9 um), Al(36 um) | 1201                            | 159                             | 7.6±2.0                         | 6.8                             |
| Fe(10 um), Al(36 um) | 297                             | 159                             | 1.9±0.5                         | 0.5                             |

Full spectrum of soft x-rays emission \( S_{full} \) can be represented as follows:

\[
S_{full} = P(T_e) \cdot p + S_\_L(Fe) + S_\_L(brass) + S_\_K(Fe) + S_\_K(brass),
\]

where \( P(T_e) \) is bremsstrahlung spectrum, \( p \) is the varied parameter, \( T_e \) is the electron temperature of plasma[6]. Other components in equation (1) determine the contribution of \( K, L\)-recombination radiation series for anode (Fe) and cathode (brass) materials. For example we write the contribution to the full spectrum of \( K\)-series of recombination radiation for cathode (brass) in the following form:

\[
S_\_K(brass)_i = A_{K(brass)} \cdot \exp \left( \frac{-(\epsilon_i - \bar{\epsilon}_{K(brass)})^2}{\Delta \epsilon_{K(brass)}^2} \right),
\]

where \( S_\_K(brass) \) is the form of the function which can be used to describe of \( K\)-series of recombination radiation for Cu and Zn ions, \( \epsilon_i = i \cdot 20 \) eV (\( i = 0 \div 500 \)) is value of quantum energy of soft x-rays, \( \bar{\epsilon}_{K(brass)} \) is most probable energy and \( \Delta \epsilon_{K(brass)} \) is deviation from this energy (their selection is based on physical considerations), \( A_{K(brass)} \) is varied parameter. For example \( \bar{\epsilon}_{K(brass)} = 8400 \div 8600 \) eV and \( \Delta \epsilon_{K(brass)} = 500 \div 700 \) eV, that corresponds to the area of location and width of \( K\)-series of ions Cu and Zn (brass). Other components of \( S_{full} \) are formed in the same manner.

We introduce the quantity \( N_{m,n}^s \) as the sum over the range of energies of the simulated spectrum of soft x-rays \( S_{full} \) for the \( k\)-th filter (\( k=n,m \)) and taking into account the sensitivity of the pin- diode:

\[
N_{m,n}^s = \sum_i S_{full,i} \cdot F_{i,k} \cdot S_{d_i},
\]

where \( F_{i,k} \) is the spectrum transmission of the \( k\)-th filter, \( S_{d_i} \) is the spectral sensitivity of pin- diodes. We see that the calculated value \( N_{m,n}^s \) is physically similar to the experimental value \( N_{m,n} \). If our the simulated spectrum \( S_{full} \) is close to the real spectrum of soft x-rays in the investigated energy range \( \epsilon_{x-ray} = 0.5 \div 10 \) keV then the value \( \delta_{n,m} = N_{m,n}^s / N_{m,n} \) can be correctly compared with the experimental value \( \eta_{n,m} \) for the corresponding filters from the Table 1.

We can write the following inequalities using data from the fourth and fifth columns of Table 1:

\[
|\delta_{n,m} - \eta_{n,m}| \leq \Delta \eta_{n,m}, \ (n=1 \div 5, \ m=6 \div 10),
\]
where $\Delta \eta_{n,m}$ is the experimental variation of the $\eta_{n,m}$ (see Table 1). For three pairs of filters there are five independent inequalities (4) which can be written in the form of system. We assume that the system is compatible.

After that we achieve the fulfillment of all the inequalities of system (4) by varying the parameters $p, A_{K(Fe)}, A_{L(Fe)}, A_{K(brass)}, A_{L(brass)}$ and adjusting the power parameters in (2) and electron temperature $T_e$. In the future this procedure can be automated.

As the system (4) can have more than one solution we introduce the criterion of optimization for solution found in system of inequalities (4). The idea of this criterion is to determine the proportion of soft x-rays with the energy of a photon $\varepsilon_{x-ray} \leq 2$ keV and to compare it with a similar calculated value. We introduce the parameter $Cor$ which is calculated as follows:

$$Cor = \frac{\mu^s - \mu}{\mu},$$

where values $\mu^s = \frac{N_{m1} - N_{m6}}{N_{m1}}$ and $\mu = \frac{(N_{m1} - N_{m6})}{N_{m1}}$ are calculated for Al and Mg K-edge filters (indexes 1 and 6 respectively). The value of $\mu = 0.758$.

Let us explain. For example, we found two different sets of coefficients $p, A_{K(Fe)}, A_{L(Fe)}, A_{K(Cu)}, A_{L(Cu)}, A_{K(Zn)}, A_{L(Zn)}$ (et al.), which are solutions of the system (4). Then the best set of parameters is that one for which the value $Cor$ is less. In our case the value $Cor = 0.085$.

5. Simulation of spectrum

As a result of this simulation we obtain the soft x-ray spectrum of vacuum spark for the range of photon energies $\varepsilon_{x-ray} = 0.5$÷10 keV. Parameters $\delta_{n,m}$ which were calculated to this spectrum are listed in the right column of Table 1. We optimized the values $\delta_{n,m}$ only for 4 pairs of filters. The value $\delta_{5,10}$ (pair of filters Fe (10 um) and Al (36 um)) is significantly less than the range of allowable values for $\eta_{5,10}$ that indicates the energy imbalance for this pair of filters. It can be explained by different conditions of the laser initiation of vacuum spark in experiments with different filters. Figure 3 shows the synthesized soft x-ray spectrum of vacuum spark which was simulated for the electron temperature of the plasma $T_e < 1000$ eV [4].

![Figure 3](image_url)

Figure 3. Detailed synthesized soft x-ray spectrum of vacuum spark and transmission spectra of used K-edge filters [7] (a). Full synthesized soft x-ray spectrum and transmission spectra of used K-edge filters (b). The value of discharge energy $Ec = 16.8 \pm 0.5$ J.
In Figure 3 we can see the emergence of strong peaks, presumably recombination $L$-series of ions Cu and Zn (brass) in the range $\varepsilon_{x-ray}=1200\sim1800$ eV. Soft x-rays $L$-series of ions Fe on the low-energy edge of energy range is absent. This is because the sensitivity of used pin-diodes and the transmittance of Al and Mg filters in the range of quanta's energy $\varepsilon_{x-ray}\leq1000$ eV are small.

**Conclusions**

This work presents the algorithm and the results of recovery of soft x-rays spectrum of vacuum spark with focusing of laser initiated beam on the anode of the discharge system. Perhaps due to the instability of the laser radiation the vacuum spark has not stable dynamics of plasma formation. Similarly unstable is a spectrum of soft x-ray.

When calculations are automated, the proposed method will allow to produce express-analyze of the spectral structure of x-ray pulse at the time of experiment. It is convenient and essential for understanding the physics of the processes occurring in the vacuum spark discharge.

**References**

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