Reproducibility conditions for the pulsed X-ray emission in a vacuum spark discharge

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Abstract In our laboratory, a 1 kJ vacuum spark device is developed as a pulsed X-ray source for X-ray detector calibration and applications such as X-ray microscopy and microlithography. After our previous works for the X-ray emission maximization (up to around 10 J per pulse), this paper analyses the influence of four different triggering systems on the X-ray emission reproducibility. The main conclusion is that a high-power, very fast high voltage trigger pulse is required. In order to fulfill these conditions, a pulse transformer and an air spark gap have been added to the initial triggering device (a magnetic pulse compression circuit). With the new trigger pulse (20 J/pulse, 50 ns rise-time, 22 kV amplitude in an open circuit) a reasonable X-ray emission reproducibility is obtained.

Introduction

The X-ray emission from a vacuum spark discharge has been intensely studied for many years. We are developing a vacuum spark device as a pulsed X-ray source for both the calibration of X-ray detectors and a wide range of applications in the field of X-ray microscopy, microlithography and flash radiography.

The experiments showed that the main problem in the vacuum spark device operation was the reproducibility of the X-ray pulses in terms of both the amplitude and the onset moment. From this point of view, we have paid attention to finding favorable conditions to obtain an acceptable reproducibility.

Methods and results

Our vacuum spark device consists of the following parts:

1. The discharge chamber; 2. The main storage capacitor; 3. The high voltage source for the main capacitor charging; 4. The pulsed trigger generator; 5. The high voltage source to charge the pulsed trigger generator; 6. The vacuum system; 7. The diagnostic system.

The discharge chamber configuration is schematically shown in Fig. 1. It was not especially developed for these experiments, and for this reason its dimension (internal diameter = 210 mm, height = 400 mm) are rather big.

A conical anode is electrically connected to the main capacitor. The main discharge is formed between the coni-

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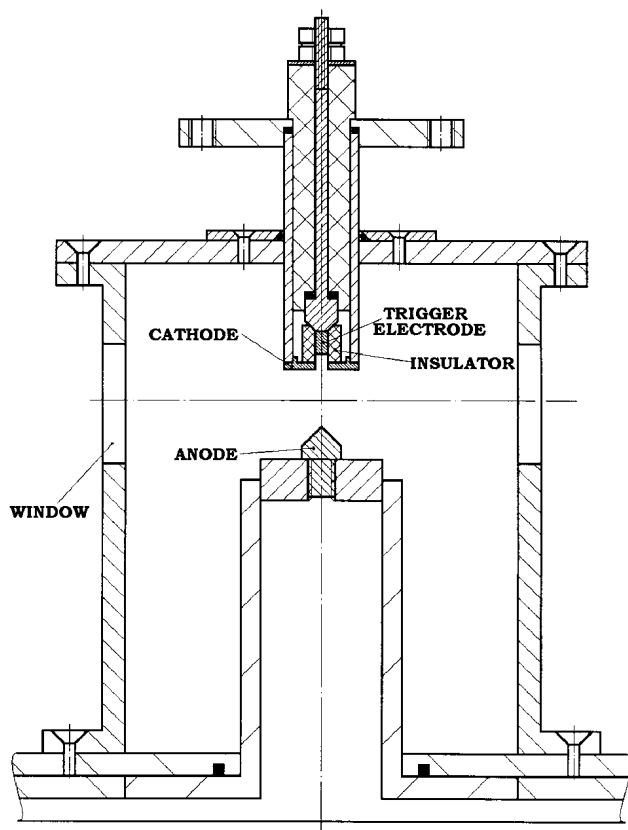e-mail: ciobanes@alpha2.infim.ro

Fig. 1. The discharge chamber configuration.

cal anode and the cathode. In order to initiate the main discharge, it is necessary to form a trigger spark. It is developed on the surface of the insulator between the triggering electrode and the cathode. The anode-cathode distance can be varied from outside without disturbing the chamber vacuum.

The X-ray emission is radially measured through a window (Fig. 1), which continues with a cylindrical lateral arm (internal diameter = 50 mm; length = 70 mm). Time resolved measurements of the total X-ray emission (spectrally and spatially integrated) have been made by means of a surface barrier detector (SBD) diode (made in Romania). Very short rise time and the active area dimension (45 mm^2) are just some advantages of this detector. The SBD diode is mounted on the base flange of the lateral arm, and it is at a 175 mm distance from the vacuum spark. With 3 absorption aluminium filters, each of 9 μm, mounted just in the front of SBD diode, an energetic range of 3–40 keV can be detected.

In Fig. 2, the electrical scheme of the diagnostic system is shown. The polarizing voltage is 100 V. For noise minimizing, the electrical signal is transported with a 50 Ω coaxial cable in a Faraday cage. To observe the main discharge current derivative, we used a Rogowski coil, set in the base flange of the discharge chamber. With a 1:100 attenuation, 1 V of the current derivative signal is equivalent to 16 kA/μs.

The use of a digital oscilloscope for observing the X-ray pulses creates some problems, because of the finite number of the sampling points. By using the Tektronix TDS 320 oscilloscope, only the X-ray signals longer than several tens of ns can be quite correctly observed. For shorter X-ray signals, an analog storage oscilloscope with around 500 MHz bandwidth should be necessary. The main dis-

charge circuit consists of a 12.5 μF/20 kV capacitor, in series connected with the anode-cathode discharge space. A short-circuit discharge of the capacitor was made to determine the electrical characteristics. The 232 nH equivalent inductance and the 30 mΩ equivalent resistance have been calculated from the short-circuit discharge waveform. With these electrical parameters, and for a 12–12.5 kV main capacitor charging voltage, 80–100 kA maximum discharge currents can be obtained. Both the anode-cathode separation and the main capacitor charging voltage have an important role to assure X-ray emission reproducibility. In the previous experiments [1, 2, 5, 6], we found that the values of 6–12 mm for the anode-cathode separation and of 12–12.5 kV for the main capacitor voltage have assured a quite satisfactory optimum for the X-ray emission. However, there are strong differences from discharge to discharge in terms of the X-ray pulses amplitude and their onset moments.

In this paper we take into account that after the optimization of both the anode-cathode separation and the main capacitor voltage, the X-ray reproducibility decisively depends on the triggering conditions for the main discharge. Thus, the experimental results are grouped together, taking into consideration the components and methods we used to obtain the trigger pulses. In this way, we have obtained trigger pulses with different amplitudes, rise-times, durations and energies.

The experiments presented here were made with an iron conical anode, with a 60° tip. During the experiments, the pressure was maintained almost constant at the $5 \times 10^{-5} \div 10^{-4}$ mbar value. The anode-cathode separation was 6 or 12 mm. For most of the experiments, the main capacitor charging voltage was 12–12.5 kV.

Trigger pulse provided by a magnetic pulser

In our previous studies [1, 2, 5, 6], in order to obtain the trigger pulses, we used a magnetic pulse compression circuit (magnetic pulser) [3, 4]. The trigger pulse has about 20 J per pulse, 10–11 kV amplitude, and its rise-time is around 100–200 ns. No adequate reproducibility was obtained. Also, the trigger pulse did not assure a reliable triggering discharge. These two disadvantages have required experiments with new triggering methods.

Trigger pulse provided by a coaxial cable pulse generator

To assure the reproducibility of the trigger spark, we tried to use a coaxial cable pulse generator, with a thyratron as the
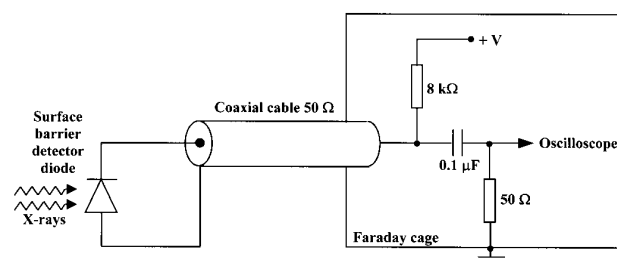

Fig. 2. The electrical scheme of the diagnostics system. The polarizing voltage is 100 V. For noise minimizing, the electrical signal is transported with a 50 Ω coaxial cable in a Faraday cage.
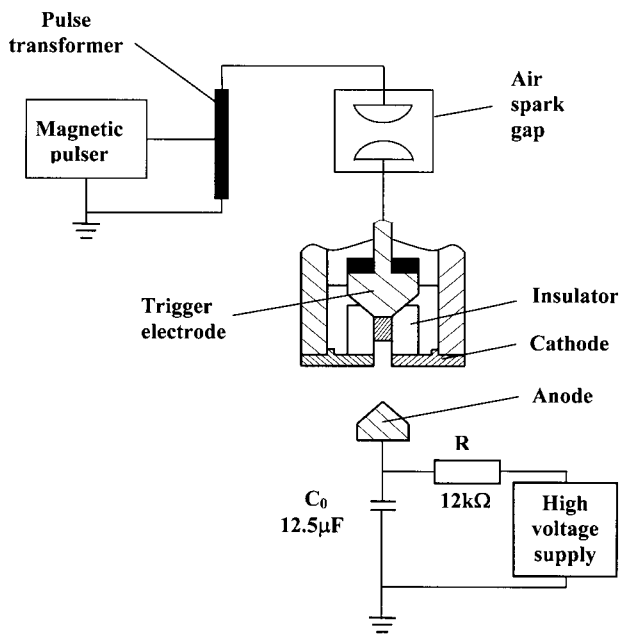
Fig. 3. The final electrical scheme of the vacuum spark device. To force the trigger spark forming only at high voltages, an air spark gap was introduced between the pulse transformer (1:2 ratio) and the triggering electrode.

switch. We hoped that the high voltage pulse, with a much shorter rise-time as well as the three times greater amplitude, might provide both a reliable trigger spark and X-ray emission reproducibility. The energy of the pulse provided by the coaxial cable is much lower (about hundreds of mJ) than the energy of the pulse provided by the magnetic pulser (20 J).

The tests, performed only with the trigger pulse, demonstrated that the trigger spark was always obtained, even in a high vacuum. Also, the visually observed trigger spark was at the right spatial position. But, although 50 discharges have been performed, the results showed that the X-ray emission came from the trigger spark only, in spite of several discontinuities on the discharge current derivative. We believe that due to the low energy of the trigger pulse, the main discharge was not sufficiently spatially focused between the two electrodes, stopping the X-ray emitting micropinches to appear.

Trigger pulse provided by a magnetic pulser and a final pulse transformer

We went back to the experiments with the magnetic pulser in order to benefit of its high energy trigger pulse. By using a final pulse transformer with 1:2 ratio, pulses with 22 kV amplitude and a 250 ns rise time have been obtained in an open circuit.

With this system, the trigger spark reproducibility problems were eliminated. Thus, we have paid attention to the X-ray emission reproducibility. The experimental results were contradictory: very good discharges with strong X-ray pulses, synchronized with the di/dt discontinuities, followed by discharges without X-ray emission. Later on, the following behavior became systematic in a working session: intense X-ray pulses from the first discharges, and afterwards the

discharges were without X-ray emission. To explain this behavior, the trigger pulse was observed. For the first experiments of the working day, this pulse was about 15–20 kV, and later the trigger spark was formed at much lower voltages (3–4 kV). Our explanation is that in the clean vacuum at the beginning, higher breakdown voltages are necessary to initiate the discharge. After several discharges, the appearance of the metal microtips, together with the impurities formed inside the chamber, lead to very low trigger spark voltages. The electrons provided by these trigger sparks have not enough energy to initiate discharges with X-ray emission.

Trigger pulse provided by a magnetic pulser, in series connected with a pulse transformer and an air spark gap

To force the trigger spark forming only at high voltages, an air spark gap was introduced between the pulse transformer and the triggering electrode (Fig. 3). The air spark gap has copper semispherical electrodes (25 mm diameter) and works at atmospheric pressure. It is placed inside a Plexiglas cylindrical chamber and the inter-electrode separation can be modified from the outside. The self-breakdown voltage is 3.6 kV/mm, for a short-circuit load. But our conditions are more complex, because the air spark gap is connected at the triggering electrode of the vacuum spark device. For this reason, a number of tests are required to establish an optimum inter-electrode separation. This new triggering system has also the advantage of a shorter rise-time of the trigger pulse (around 50 ns).

All the experiments made with this new triggering system were observed with a 500 ns time base of the TDS320 oscilloscope. In this way, the sampling distance was 10 ns. Thus,
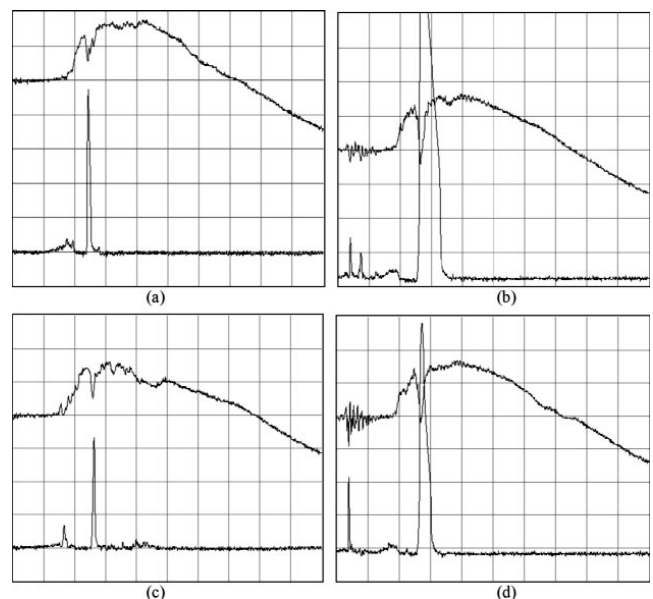

Fig. 4. Four successive vacuum spark discharges with the trigger pulse provided by a magnetic pulser, in series connected with a pulse transformer and an air spark gap. The lower traces show a reasonable reproducibility – both in amplitude and onset moment – of the X-ray emission. Experimental conditions: iron conical anode, 60° tip angle; anode-cathode separation = 12 mm; main capacitor charging voltage = 12.5 kV; time base = 500 ns/div. Upper traces: Current derivative: 1 V/div (1 V = 16 kA/μs). Lower traces: X ray pulses: (a), (b): 2 V/div; (c), (d): 3 V/div.

the X-ray pulses with more than tens of ns duration are possible to be quite correctly measured.

After the optimization of the air spark gap inter-electrode separation, the best results were obtained for a 12 mm anode-cathode separation, and a main capacitor charging voltage of 12.5 kV. In Fig. 4, the four successive discharges show a reasonable reproducibility.

In order to estimate the soft-X-ray energy emitted per pulse, the used formula is:

$$\text{Energy/Pulse} = \frac{\int i\,dt}{d}\frac{4\pi D^2}{a} = \frac{\int u\,dt}{Rd}\frac{4\pi D^2}{a}$$

where: $\int i\,dt$ is the electrical charge generated inside the X-ray detector (SBD diode); detectivity $d = 10^{-5}$ C/J; discharge – detector distance $D = 175$ mm; detector active area $a = 45$ mm^2; "u" is the electrical signal provided by the detector in a resistance $R = 50\ \Omega$. In Fig. 4d, the electrical signal is approximated as a triangle with 20 V amplitude, and 400 ns base width. With these data, around 30 J soft-X-ray pulse energy results.

Discussion

In order to have a reasonable X-ray emission reproducibility, an initial optimization of the main experimental parameters (the main discharge energy, the electrode geometry, the anode material, and the trigger pulse ampli-

tude) is required. More than this, the X-ray emission reproducibility is favored by a trigger pulse with high energy, high amplitude and short rise-time. These last conditions were achieved by using a magnetic pulser, in series connected with a final pulse transformer (1:2 ratio) and an air spark gap at atmospheric pressure.

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