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A Pulsed, High-Intensity Source of XUV Radiation Based on Ferrite Surface Breakdown at High Current

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***Abstract*—High-current discharges along a ferrite surface have been studied on BIN pulsed power facility (270-kA current amplitude, 80-ns rise time, and 300-kV output voltage). The samples of the ferrite were placed in the vacuum diode as the main load of the pulser. It was found that the initial discharge pattern could be predefined by drawing on the surface with a graphite pencil. Each discharge generated an intense, reproducible pulse of optical and XUV radiation, with time-integrated optical and XUV images being similar to ∼5 consecutive shots; thereafter, the discharge channel would start to follow the shortest path between the electrodes, and continue with similar characteristics for at least the next 10 pulses. The transverse size of the emitting region did not exceed 200 μm in the 150 < E < 280 eV spectral band, probably due to plasma pinching. No soft X-ray (>0.8 keV) radiation was registered using photoconducting detectors.**

***Index Terms*—Ferrite, pulsed power, XUV imaging, XUV radiation source.**

I. Introduction

INVESTIGATIONS of the breakdown of a ferrite surface have demonstrated that à discharge can be made to propagate along a predefined channel, and that as it propagates, the conductivity of this channel becomes 10^4 times higher than that of surrounding ferrite [1], [2]. In later experiments, it was found that such channel, including the one of an arbitrary shape, was made when the current passed through a graphite line drawn along the surface of the ferrite [3]. These experiments were performed with moderate discharge parameters (current amplitude <50 kA, current rise time ∼3 μs, and voltage applied to the load 25 kV), but showed principal possibility to generate relatively intense and stable pulses of visible and XUV radiation.

In this paper, we report the first experiments with similar loads but with much more powerful electrical discharge. We show that despite the much higher voltages and currents, a stable discharge channel is still formed, and that repeatable XUV pulses (here defined as in [4] as <500 eV) are produced on repetitive shots.

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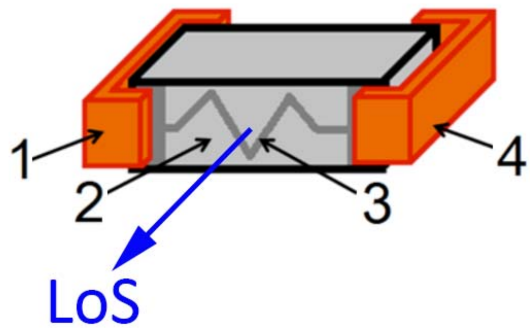

Fig. 1. Scheme of the load: 1—cathode, 2—ferrite, 3—pencil-marked line, 4—anode, and LoS—line of sight.

II. Experimental Setup

The discharge along a surface of the ferrite was studied using the BIN facility [3], with peak current 270 kA, rise time 80 ns, and the drive voltages up to 300 kV. The total stored energy of the generator is 3 kJ. The load used was Ni–Zn Fe_2O_4 ferrite of M400 HH type and had dimensions $10 \times 10 \times (5 - 30)$ mm. Fig. 1 shows a diagram and a photograph of the generator load. The path of the current flow along the ferrite surface was preset by a graphite pencil (Koh-I-Noor HB) with a 0.5-mm width and “natural” pencil line thickness about 5–10 μm. The pressure in the vacuum chamber did not exceed 10^{-4} torr.

III. Diagnostics and Experimental Results

Fig. 2 presents a series of images obtained upon the sequential passing of the current through the ferrite surface. The images were recorded by the photocamera Canon EOS 600D. Camera shutter was opened during the entire time of the current pulse, and the camera was focused on the ferrite surface. The first image of the discharge channel in visible light shown in Fig. 2 was taken before current pulse, and the next photograph was taken in the first discharge pulse (#1). The first shot image was taken without any filter in front of the camera lens and was completely overexposed. In subsequent shots, the neutral filter with optical density $D = 2$ (100 times attenuation) was placed in front of the lens. One can see that during five discharge pulses (from shot #2 to shot #5),

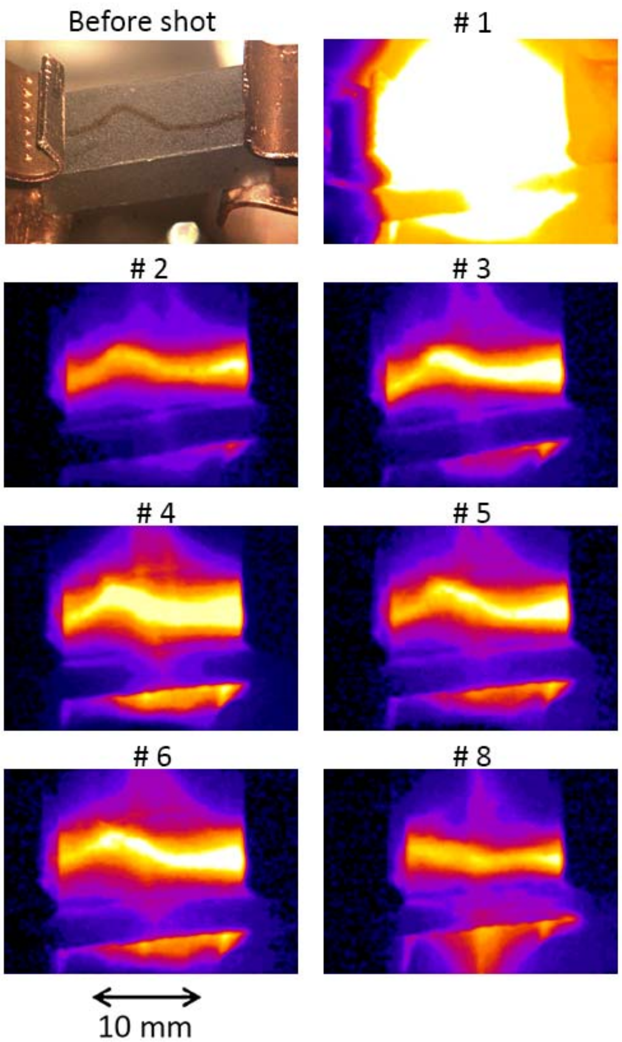

Fig. 2. Time-integrated optical images of the ferrite surface discharge. The frames before shot and shot #1 were taken without the filter, frames #2–#8 with the use of 100-fold gray filter in front of the photocamera lens.

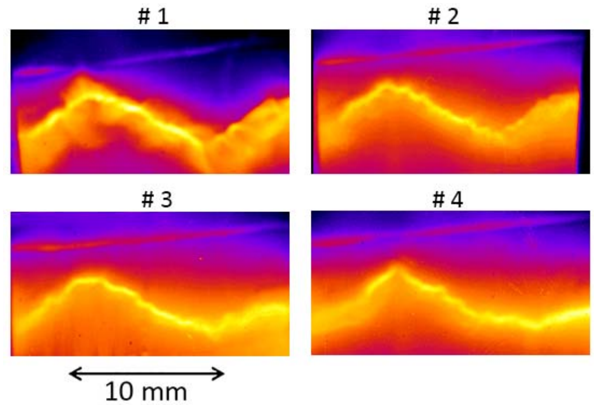

Fig. 3. Time-integrated images of the discharge channel in subsequent shots obtained with the open pinhole camera on the Kodak DR-50 film.

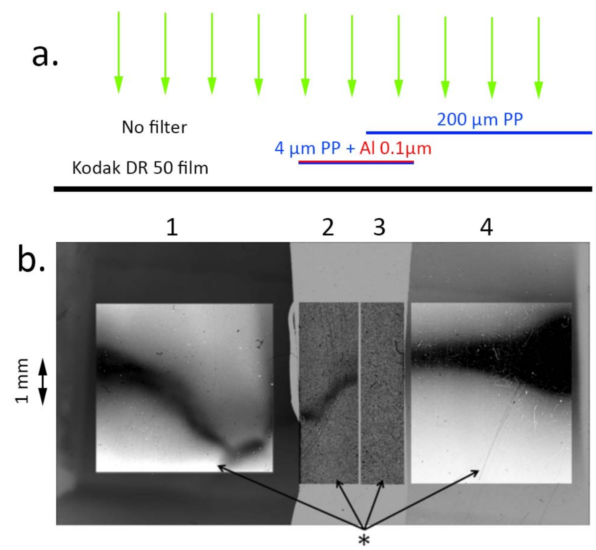

Fig. 4. (a) Arrangement of the filters placed in front of the film in the pinhole camera. (b) Images obtained with the pinhole camera in different spectral bands: 1—entire spectrum, 2—XUV (200 eV $< E <$ 285 eV) and SXR_1 ($E >$ 500 eV), 3—SXR_2 ($E >$ 2 keV), and 4—SXR_2 and visible light. The image segments were adjusted in the Adobe Photoshop software. The film was carefully shielded to avoid side scattered light.

the breakdown path is generally preserved, and it repeats the line initially drawn on the ferrite sample with a pencil before the first discharge. However, it is seen that in subsequent discharge pulses after pulse #5, the breakdown path starts to straighten. This finally leads to the breakdown occurring along the shortest path (shot #8). In the following shots (up to 15th), the discharge path remains unchanged. Without the drawn line, a discharge occurs anyway, and simply followed the shortest path between electrodes and also remains unchanged in subsequent shots. In all cases, there was some indication that a fraction of the current also flowed along the back surface of the ferrite, which might be expected as there was nothing to prevent the formation of a secondary discharge over this surface (not seen by the camera).

The next series of experiments was directed to study the breakdown channel radiation in the XUV spectral band. To visualize the breakdown path, a pinhole camera without filter (open pinhole) with 200-μm aperture was placed at a distance 30 cm from the ferrite surface. Kodak DR-50 film was used to record images. The magnification of the imaging system was about one-to-one, and diffraction cutoff energy [4] was ≈200 eV. For radiation with lower photon energy, diffraction broadening of the images was significantly larger than pinhole aperture and reached value in the order of 1 mm for visible light. Time-integrated images of the discharge channel in the series of subsequent shots are presented in Fig. 3. In the first shots, images are very well reproducible even in fine details, but after 5–7 shots, the channel starts to straighten as it was seen on the images taken in visible light (Fig. 2).

To get the information about the spectral composition of the radiation generated in the discharge, a set of filters was placed in the pinhole camera in front of the film [Fig. 4(a)]. Transmission curves of the filters are shown in Fig. 5. Unfortunately, the exact sensitivity curve of the DR film for the XUV radiation is unknown, but it generally follows the transmission curve of the plastic coating layer with characteristic k-window (such as the curve shown in Fig. 5 and sensitivity curves of Kodak RAR2497 [5]). Also, this film is sensitive to the visible light.

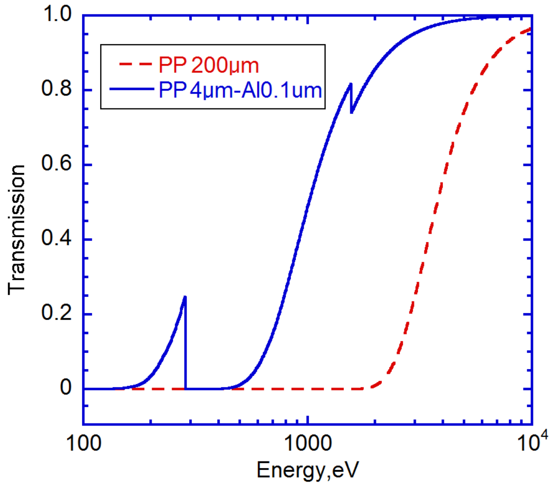

Fig. 5. Transmission curves of 200-μm polypropylene and 0.1-μm Al-coated, 4-μm polypropylene filters.

Fig. 4(b) shows an example of the pinhole image obtained using this filter set. For clarity, the image segment behind each filter was adjusted using the Adobe Photoshop software to clearly show the presence or absence of radiation behind this filter. There is an intense emission in the visible light, recorded both on the film without filters [Fig. 4(b), segment 1] and behind 200-μm polypropylene [Fig. 4(b), segment 4]. Also, there is an image behind 4-μm polypropylene film with 0.1-μm Al coating which was completely opaque for a visible light [Fig. 4(b), segment 2]. This filter transmitted radiation in XUV ($E = 200-280$ eV) and soft X-ray ($E > 500$ eV) energy bands. However, there is no image on the film behind the two filters when they overlapped [Fig. 4(b), segment 3]. Here, the visible light is blocked, and a photon energy of ∼2.5 keV would be needed for the exposure of the film.

The preliminary analysis of the pinhole images allows us to estimate the transverse size of the discharge channel emitting visible light and XUV radiation in the spectral band 200–280 eV. Typical transversal size defined from the pinhole images for the visible radiation is ∼3 mm and for the XUV ∼200–400 μm. The more detailed analysis will be described elsewhere.

Analogous experiments were performed using the same pinhole camera (diameter 200 μm) and the image recording on the Fuji BAS TR image plate (IP). This plate does not have a protective coating and is sensitive to XUV and X-ray radiation but is not sensitive to the visible light [6]. IPs were scanned by the DURR HD-CR35 NDT scanner with the hardware resolution about 50 μm. The examples of the discharge channel images obtained using this technique are presented in Fig. 6. The IP is sensitive to the XUV radiation in much wider spectral band than the DR50 film. The IP sensitivity curve extends at least up to 100 eV and does not have K-shell absorption dip in the range of 280–500 eV [7]. This leads to higher sensitivity of the system and allows seeing more details in recorded images. Discharge channels, visible in the IP images, were wider than the channels recorded on the film. This fact is, probably, connected with different spectral sensitivities of recording media, but to date, it is not well understood. The adequate interpretation of the results requires more experiments and analysis.

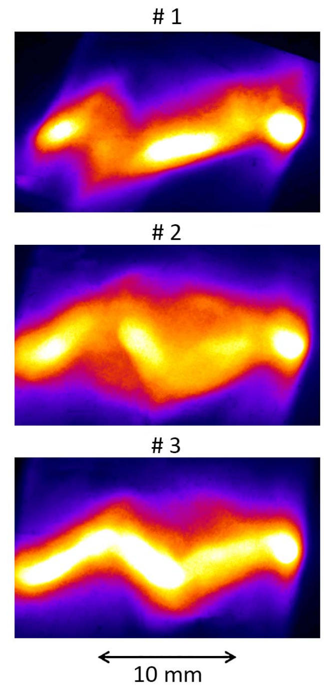

Fig. 6. Pinhole images of the discharge channel recorded on the IP Fuji BAS TR IP in subsequent shots. The images were cleaned using the Adobe Photoshop software.

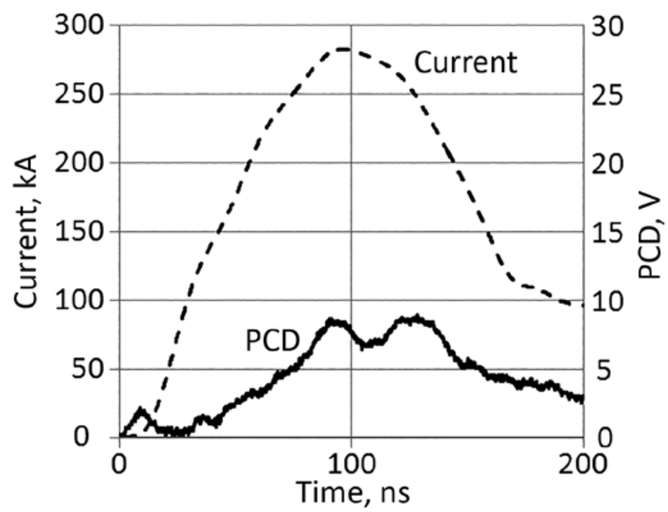

Fig. 7. Oscillograms of the discharge current and the PCD signal without filter upon the breakdown on the ferrite surface.

To measure the radiated energy yield, calibrated diamond photoconducting detectors (PCDs) were used with and without different filters. According to [8], the PCD spectral sensitivity without filter is almost constant from 10 eV to 6 keV. The acceptance angle of the detector was big enough to measure the intensity of the emitting radiation from the entire surface of the ferrite sample. Fig. 7 shows the characteristic emission of a discharge channel from a PCD without a filter. Behind the 10-μm Be filter, transmitting photons with the photon energy $E > 800$ eV, no detectable signals were recorded. XUV radiation passed through the 4-μm polypropylene filter

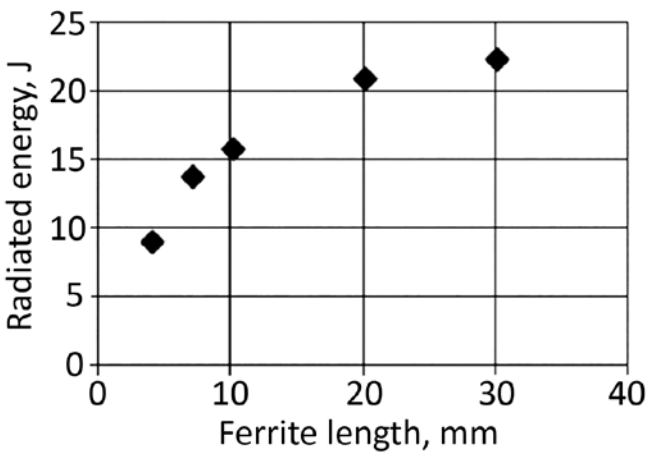

Fig. 8. Radiated energy versus a ferrite length over the whole range of PCD sensitivity (10–800 eV).

was detectable, and the signals' shape was generally the same as shown in Fig. 7, but the signals' amplitude was too low for the analysis.

The duration of the XUV radiation pulse (full-width at half-maximum) in the energy band above 10 eV and below 800 eV is $\sim$80 ns. The energy yield was measured in three directions in the equatorial plane (0° and $\pm$45° from perpendicular to the ferrite surface) and two additional directions in the meridian plane (+30° and +60° from perpendicular to the ferrite surface toward anode). The difference in the measurements was not significant. Assuming that the isotopic distribution of the radiation the energy yield of 20-mm ferrite was estimated $\sim$20–25 J and this corresponds to the average XUV power $\sim$0.3 GW into one semisphere. Almost the same yield was measured from the opposite side of the ferrite sample. No radiation was detected from two other ferrite surfaces where was no direct connections with the pulser output electrodes.

Dependence of the radiated energy yield on the length of the ferrite sample was also studied, and the results obtained in the experiments are shown in Fig. 8. The radiated energy yield increases when the sample length increases, but the growth rate decreases noticeably. This could be connected with increasing the inductance of the load when the discharge channel length increases and starts to make the coupling with the pulser output impedance. The highest radiated energy yield appeared to saturate at the ferrite sample lengths from 20 to 30 mm. The ferrites with the length more than 30 mm were not tested due to the geometry of the output electrodes of the pulser.

IV. Conclusion

The investigations showed that a high-current discharge in the surface breakdown of ferrite is a stable source of the intense XUV radiation. The initial form of the discharge channel can be predefined and reproduced in a series of discharges.

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Authors' photographs and biographies not available at the time of publication.