Multiframe point-projection radiography imaging based on hybrid X-pinch.

I.N.Tilikin, T.A.Shelkovenko, S.A.Pikuz,

Lebedev Physical Institute, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 119991 Russia

S.N.Bland

Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom

Corresponding author: Ivan Tilikin, ivan.tilikin@gmail.com

This paper demonstrates the possibility of using a new configuration of the hybrid X-pinch to produce a set of spatially and temporarily separate X-ray bursts that could be used for the radiography of dynamic events. To achieve this a longer than normal wire is placed between the conical electrodes of the hybrid X-pinch, and a set of small spacers (fishing weights) placed along the wire. Each subsection of the wire than acts as a unique X-pinch, producing its own radiation burst from a small (~3 μm) spot. The timing between bursts is 20-50ns, and each is <2ns in duration. For comparison if a longer wire is simply employed without spacers, hot spots of radiation occur in random positions and the time between any 2 bursts does not exceed 20 ns. Examples of two and three frames point projection radiography of solid-state and plasma test objects are given.

I. Introduction

From its creation in 1982, X-pinch plasmas have long been known to provide short, intense bursts of X-ray radiation from a small spatial area [1]. This has led to several applications[2-4], most centered around the use of the X-rays for point projection radiography of other pulsed power driven high energy density plasmas[5-9]. Initially X-pinches were composed of 2 or 4 thin metallic wires twisted into a crossing point and driven by currents ~100-300kA. Experiments with much higher driving currents necessitated an increase in the number of wires [10, 11]; whereas attempts to produce a way of reloading an X-pinch load in vacuum resulted in experiments where the wires were supported by dielectric frames [12]. The most significant development X-pinch research, though, has been the creation of the hybrid X-pinch (HXP)[13-15] which consists of a single thin wire placed between the closely spaced conical electrodes.

This massively simplified load design, and enabled a larger variety of wire materials to be employed , (the product of very thin metallic wires often limiting previously materials that could be employed). Tuning of the parameters of the Hybrid X-pinch has resulted in sources sizes of ~1μm which emits for 100 ps in the soft X-ray region 1-5 keV.

In all development work to date one of the principle aims of X-pinch development has been to create only one point source of X-rays. X-pinches utilizing crossed wires sometimes suffer from secondary pinches, producing another X-ray source spot 100s of microns away from the initial one. This randomly placed spot causes an object being radiographed to be exposed twice, potentially obscuring any data obtained. In recent years better control of the initial conditions of X-pinch's wires - and especially the use of Hybrid X-pinches - has significantly reduced the probability of this occurring. Using X-pinch based radiography to study a large scale, well reproducible experiment then usually relies on the experiment being repeated and the timing of X-ray emission from the X-pinch varied by altering the mass of its wire(s). This has, for instance, enabled the dynamics of wire explosions to be studied [16]. Alternately, to enable small scale, non-reproducible structures - such as the development of instabilities – to be studied, multiple X-pinches can be employed in parallel (providing there is enough current available from the driver). For example on the XP generator at Cornell University two Hybrid X-pinches can be arranged in parallel, and jitter between the X-pinches separated the X-ray bursts by 2-5ns [13-15, 17].

However there are many cases when it could actually be beneficial to obtain multiple X-ray sources from a single X-pinch if the separation and timing of these sources could be controlled. The hardware required to field multiple X-pinches in parallel typically means these would be spaced at least a cm apart. Often there are only limited lines of sight available to an experiment so having sources relatively closer together can be important – especially if they are tracking a single, local, fast moving structure. Fielding multiple X-pinches in a parallel also divides current between the X-pinches. As each X-pinches usually requires a current of at least 50kA with a rise time ~1kA/ns, this starts to place ever greater limitations on the driver.

Given that crossed wire X-pinches can 'suffer' from multiple pinches, we know that multiple X-pinches can be created in series – but in the crossed wire scheme it is impossible to control the timing and location of the X-ray bursts. In this paper we describe a new configuration of Hybrid X-pinch that – for the first time - enables multiple X-pinches to be created in series along the same connecting wire in a controlled fashion. This is accomplished by attaching small spacers along the length of the wire, creating separate lengths that pinch individually.

II. Experiment and diagnostics description.

Experiments were carried out on the BIN generator [18] at the Lebedev Institute, which is driven by up to 300kV, and has a maximum current of 270 kA with a rise time of 100 ns.

The Hybrid X-pinches utilized 95 % Tungsten / 5% Copper Alloy electrodes of 8 mm diameter, 5 mm long. After multiple experiments, best performance was obtained with a single wire of 30µm Mo wire 10mm long was hung between the electrodes. Along the length of the wire two 2mm diameter lead fishing weights were attached creating 3 ~ equal length of wire 2mm long. The fishing weights were used as separators as they were simple to attach to the wire, were highly repeatable, available in a variety of diameters and could be purchased 'off the shelf'. A Rogowski coil monitored current flowing through the X-pinch. Fig.1 shows a photo (Fig.1a) of the experimental load and schematics of the experiments (Fig.1b-c).

Calibrated diamond photo conductive detectors (PCDs) were used to determine the moment of hot spot formation as well as to determine the radiated energy. To measure the emitted energy in the soft X-ray region (2.5<E<5 keV) a 12.5 µm thick Ti filter (the same filter is routinely use for radiography) was used. A pinhole camera with an aperture diameter of ~200 µm was used to obtain a time integrated image of the emission. A Fuji BAS TR imaging plate with 12.5 µm Ti filter was used for image registration.

A specially designed test object was created to separate the images from each hot spot and determine the size of the radiation source: 3 holes of different sizes (1-3 mm) with a wire 10 microns thick on the holes. The holes positioned in a perpendicular direction to the wire in the hybrid X-pinch (see Fig.1b.7), which allows to obtain all images without overlapping from each hot spot formed in different areas of the X-pinch's wire. In later experiments the test object was replaced with a wire installed in the return current circuit (see Fig. 1c. 8). That allows to observe the process of the wire explosion at different moments of time, as well as to determine much more accurately the order of formation of soft X-ray bursts. Magnification for experiments with a solid test object was 1:5, and for experiments with exploding wire – 1:2.5.

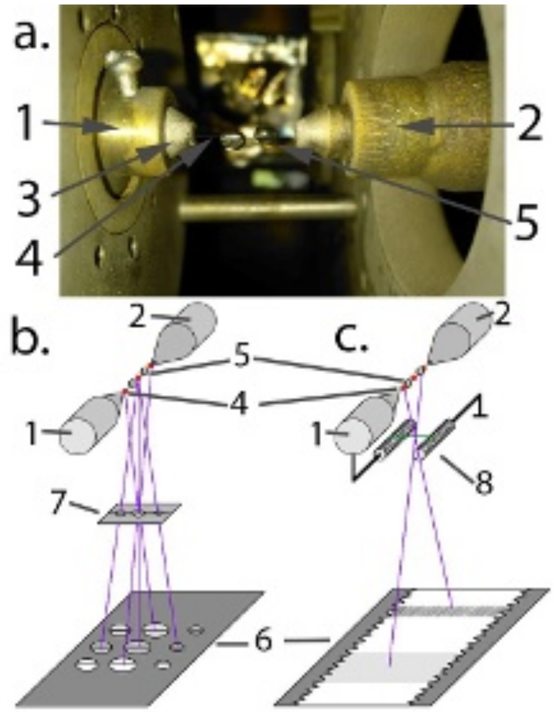


Fig.1. Photo (a) and schemes (b, c) of the load in the experiments. 1 – anode, 2 – cathode, 3 – conical electrodes (W95%Cu5%) of a HXP, 4 – 30 μm Mo wire, 5 – spacers (fishing weights), 6 – Fuji BAS TR imagine plate, 7 – test object, 8 – exploding wire in the return current circuit.

III. Experimental results.

In all experiments, the current through the X-pinch with two spacers between electrodes and the signal from the PCD were measured. This allows registering the moment and the power of radiation. Experimental signals are shown in Fig. 2. Three bright bursts were recorded by the PCD at times 95, 105, and 125 ns after current start. The duration of the X-ray burst did not exceed 2 ns, which corresponds to the resolution of the recording system. The radiated energy, measured by PCD in the range of photon energies 2.5-5 keV, was: 220, 70 and 350 mJ, respectively each burst by time.

Pinhole images of the HXP and the images of the test object from this shot are shown in Figure 3. The pinhole image shows that such loading gives x-ray bursts from 3 different areas. At the same time, these 3 areas are quite strongly separated in space. The PCD recorded three bursts that were 15 and 20 nanoseconds apart in time, with the last one consisting of two bright bursts close to each other in time (see Fig. 2).

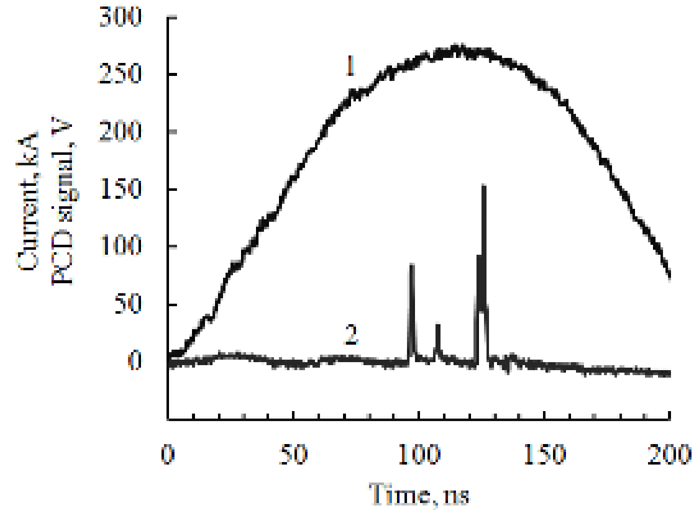


Fig.2. Current (1) and PCD signal (2) in the experiment with a test object.

The last two bursts overlapped in Fig 2 correspond to 2 bursts of X-rays from the same segment of wire. This corresponds to the image seen in fig.3.c where 2 images of the W wire are observed – hence whilst 2 segments of the hybrid pinch produced a single X-ray pulse, it appears one part produced 2 closely spaced/timed pulses (in a similar way to how some crossed wire X-pinches can produce 2 pulses). The left point on Fig.3.a corresponds to the last burst in time. The enlarged part of the image (Fig.3.c) shows three images of the test object from the three main bursts, which can be considered as three HXPs loaded in a circuit in series. The left image has two images of the wire, which means doubled burst of soft X-ray (SXR), which is seen on the last peak in the PCD signal. The pinhole image shows that the middle point has the lowest intensity, which corresponds to the average moment in time. So, radiograph images of the test object can be separated by time. Estimation of the radiation source size was made by measuring the blur of the shadow edge for each of the three brightest soft X-ray bursts and it gives 3-5 µm. After selecting the wire length in each part of X-pinch, it was possible to achieve stable timing of two HXPs formation, the third one often did not produce a hot spot resulting in a poor image. This may be due to maximum output current and its rise time of the BIN generator. Therefore, only a couple of the HXPs were further considered as a good radiation source.

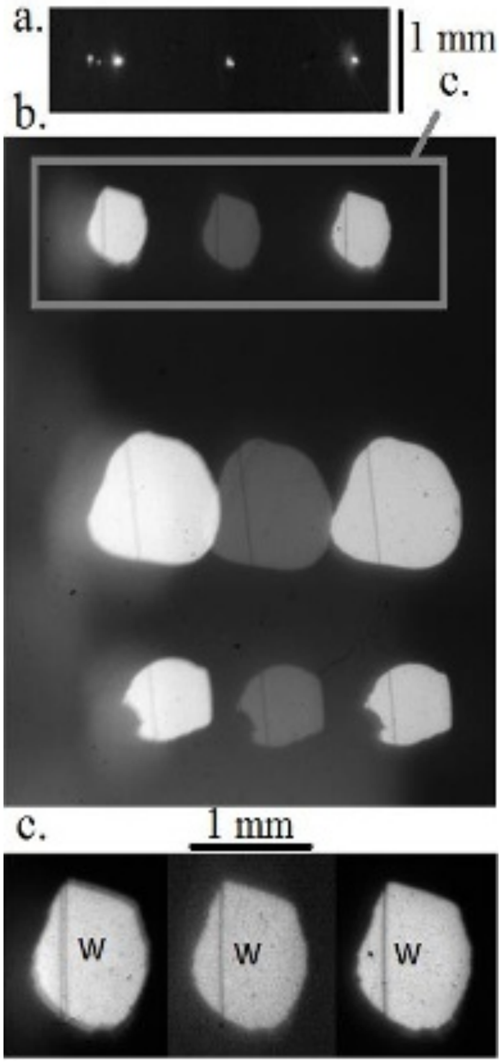


Fig.3. Pinhole image of the HXPs (a); radiograph images (b) of the test object (10 μm W wire - w); enlarged part of the image in a gray frame (c).

In subsequent experiments, the test object was replaced by an exploding 25 μm Ag wire 20 mm long in a return current (see Fig.1c). Fig.4 shows the oscillogram signals of this experiment. The current through the HXPs and the exploding wire is given, as well as the SXR bursts can be seen on PCD signal.

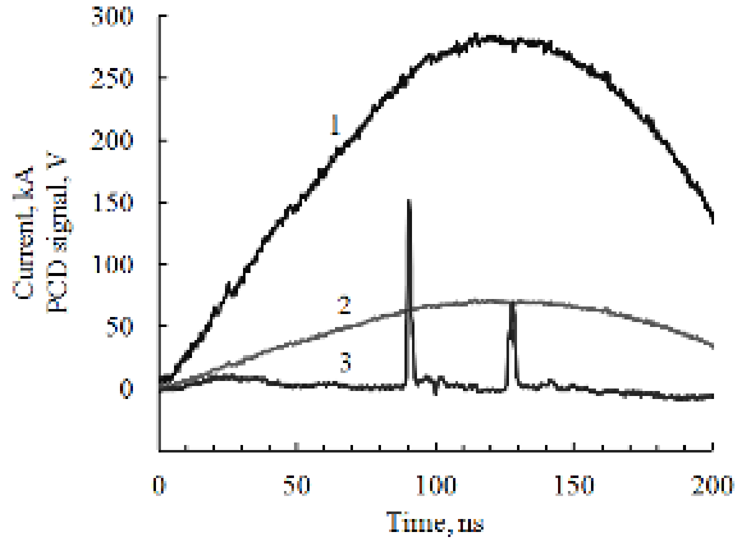


Fig.4 Current of the HXP (1) and wire (2) in return current circuit and PCD (3) signal in the experiment with exploding 25 μm Ag wire as a test object.

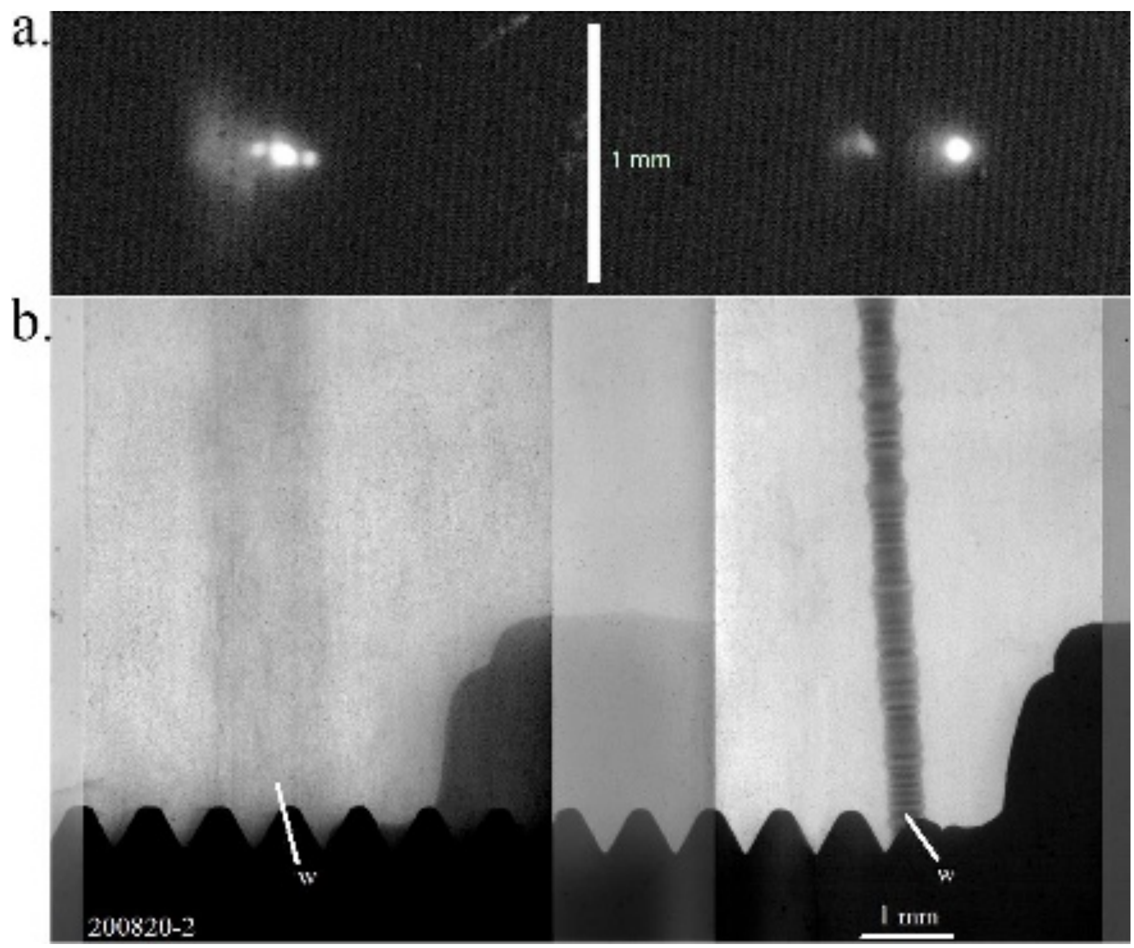


Fig.5. Pinhole image of the HXPs (a) and radiograph images (b) of the exploding 25 μm Ag wire in two moments of time: 90 ns (right) and 125 ns (left).

Fig.5b shows images of the exploding wire in the radiation of the multiframe HXP. The pinhole image (Fig.5a) shows two bursts, which corresponds to the PCD signals in Fig.4. The images of the exploding wire are obtained at 90 and 125 ns, so the dynamics of the wire explosion can be seen. The wire core structure is still visible at an early point in time on the right part of the Fig.5b, then at a later time the wire is significantly expanded and does not show a pronounced structure, that is seen on the left part of the Fig.5b. Repeated experiments in a similar configuration have shown that the time between flashes can vary from 30 to 50 ns using the same wire lengths between the X-pinches.

In some cases, it is necessary to obtain images with a smaller time difference. For this purpose, a longer wire can be used without spacers on it. Fig.6.a shows the oscillogram of the current and signal from the PCD. There are two close peaks at 95 and 100 ns on the signal. It was possible to register images of the exploding Ag wire from the radiation of multiple hot spots from one HXP. The images are presented in Fig.6b. It can be seen that the images are very close in time. So, to get images with time difference not more than 20 ns, HXP with a longer wire can be used. Note, that in this scheme, neither the number of radiating hot spots nor the time between them is controlled.

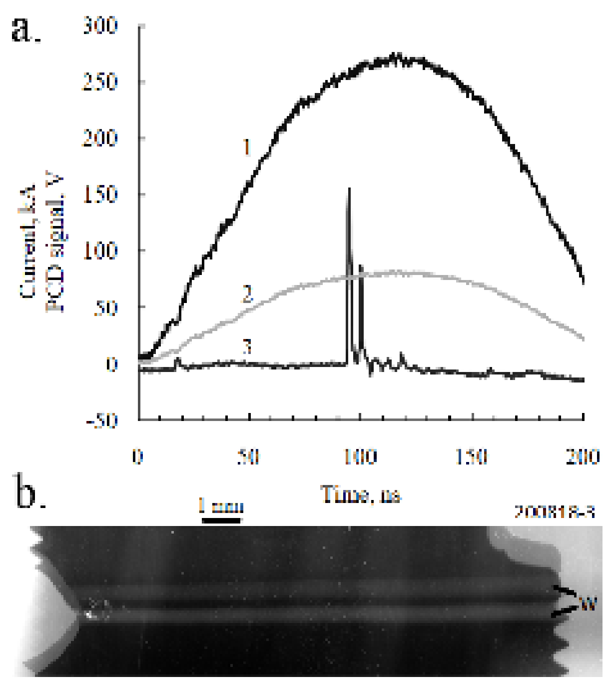


Fig.6. Scope signals (a; 1-current through the HXPs, 2- current through wire in return current circuit, 3-PCD signal) and the radiograph images at 95 ns and 100 ns in experiments with longer 25 μm Ar wire in the HXP without spacers (b).

IV. Conclusions

This paper demonstrates the possibility of using an HXP with a longer wire and/or a longer wire with spacers to obtain multiple HXPs in series. The length of the wires or the number of spacers can be changed, thereby adjusting the number of radiation bursts as well as the time difference between them depending on the output parameters of generators and geometry of high voltage diodes. At the same time, the higher and longer the generator current, the more hybrid X-pinches can work in a series. If use a longer wire is used without spacers it is possible to produce multiple bursts with a time difference of less than 20 ns. With spacers several wire parts are used, the time difference between bursts is between 30 and 50 ns. Thus, it is possible to study static objects or use multiframe hybrid X-pinch to study the dynamics of any object in synchronous mode with the generator.

Although this research is still in the early stages of development, the possibilities are none-the-less exciting for probing dynamic experiments. Presently radiography of such experiments requires either multiple spatially separate sources or potentially transport of the experiment to a 3rd generation Synchrotron/XFEL facility which can produce multiple closely timed X-ray pulses. Coupling the techniques described in this paper with new driver technology that is enabling X-pinches to become far more portable and user friendly may result in multi pulse radiography becoming more common place in universities and smaller research laboratories. Here it could be used to test new ideas and diagnostics and compliment experiments at larger facilities. First though methods to precisely alter the timing of the different wire segments in the new Hybrid X-pinch configuration need to be further explored, as do the limitations on its use – for instance could it be expanded to 4 or more pulses with the right electrode design and driver.

Acknowledgments

This work was supported by the National Nuclear Security Administration Stewardship Sciences Academic Programs through the Department of Energy under Grant No. DE-NA0003764.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. S. M. Zakharov, G. V. Ivanenkov, A. A. Kolomenskii, S. A. Pikuz, A. I. Samokhin, and J. Ulshmid, «Wire X-Pinch in a High Current Diode», Soviet Technical Physics Letters, 8, 456-457 (1982).

2. S. A. Pikuz, T. A. Shelkovenko, V. M. Romanova, D. A. Hammer, A. Ya. Faenov, V. A. Dyakin, and T. A. Pikuz, «High-luminosity monochromatic x-ray backlighting using an incoherent plasma source to study extremely dense plasmas», Rev. Sci. Instrum. 68, 740–744 (1997).

3. A. G. Tailor, M. C. Goffinet, S. A. Pikuz, T. A. Shelkovenko, M. D. Mitchell, K. M. Chandler, and D. A. Hammer, «Physico-chemical factors influence beet (Beta vulgris L.) seed germination», The Biology of Seeds: Recent Research Advances, CAB International (2003).

4. T. A. Shelkovenko, S. A. Pikuz, D. A. Hammer, Y. S. Dimant, and A. R. Mingaleev, «Evolution of the structure of the dense plasma near the cross point in exploding wire X pinches», Phys. Plasmas 6, 2840–2846 (1999).

5. J. D. Douglass, S. A. Pikuz, T. A. Shelkovenko, D. A. Hammer, S. N. Bland, S. C. Bott, and R. D. McBride, «Structure of the dense cores and ablation plasmas in the initiation phase of tungsten wire-array Z pinches», Phys. Plasmas 14, 012704 (2007).

6. T. A. Shelkovenko, S. A. Pikuz, D. B. Sinars, K. M. Chandler, and D. A. Hammer, «X pinch plasma development as a function of wire material and current pulse parameters», IEEE Trans. Plasma Sci. 30, 567–576 (2002).

7. J. Wu, L. P. Wang, J. J. Han, M. Li, L. Sheng, Y. Li, M. Zhang, N. Guo, T. S. Lei, A. C. Qiu, and M. Lv, «X-pinch radiography for the radiation suppressed tungsten and aluminum planar wire array», Phys. Plasmas 19, 022702 (2012).

8. R. B. Baksht, A. G. Rousskikh, A. S. Zhigalin, V. I. Oreshkin, and A. P. Artyomov, «Stratification in Al and Cu foils exploded in vacuum», Phys. Plasmas 22, 103521 (2015).

9. T. A. Shelkovenko, S. A. Pikuz, and D. A. Hammer, «A review of projection radiography of plasma and biological objects in X-Pinch radiation», Plasma Phys. Rep. 42, 226 (2016).

10. T. A. Shelkovenko, S. A. Pikuz, J. D. Douglass, R. D. McBride, J. B. Greenly, and D. A. Hammer, «Multiwire X-pinches at 1-MA current on the COBRA pulsed-power generator», IEEE Trans. Plasma Sci. 34, 2336 (2006).

11. T. A. Shelkovenko, S. A. Pikuz, I. N. Tilikin, M. D. Mitchell, S. N. Bland, and D. A. Hammer, «Evolution of X-pinch loads for pulsed power generators with current from 50 to 5000 kA», Matter and Radiation at Extremes 3, 267 (2018).

12. M. D. Mitchell, S. A. Pikuz, T. A. Shelkovenko, D. A. Hammer, K. M. Chandler, «X-Pinches in Dielectric Frames», IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 34, NO. 5 (2006).

13. T. A. Shelkovenko, S. A. Pikuz, S. N. Mishin, A. R. Mingaleev, I. N. Tilikin, P. F. Knapp, A. D. Cahill, C. L. Hoyt, and D. A. Hammer, «Hybrid X-pinches», Plasma Phys. Rep. 38, 359 (2012).

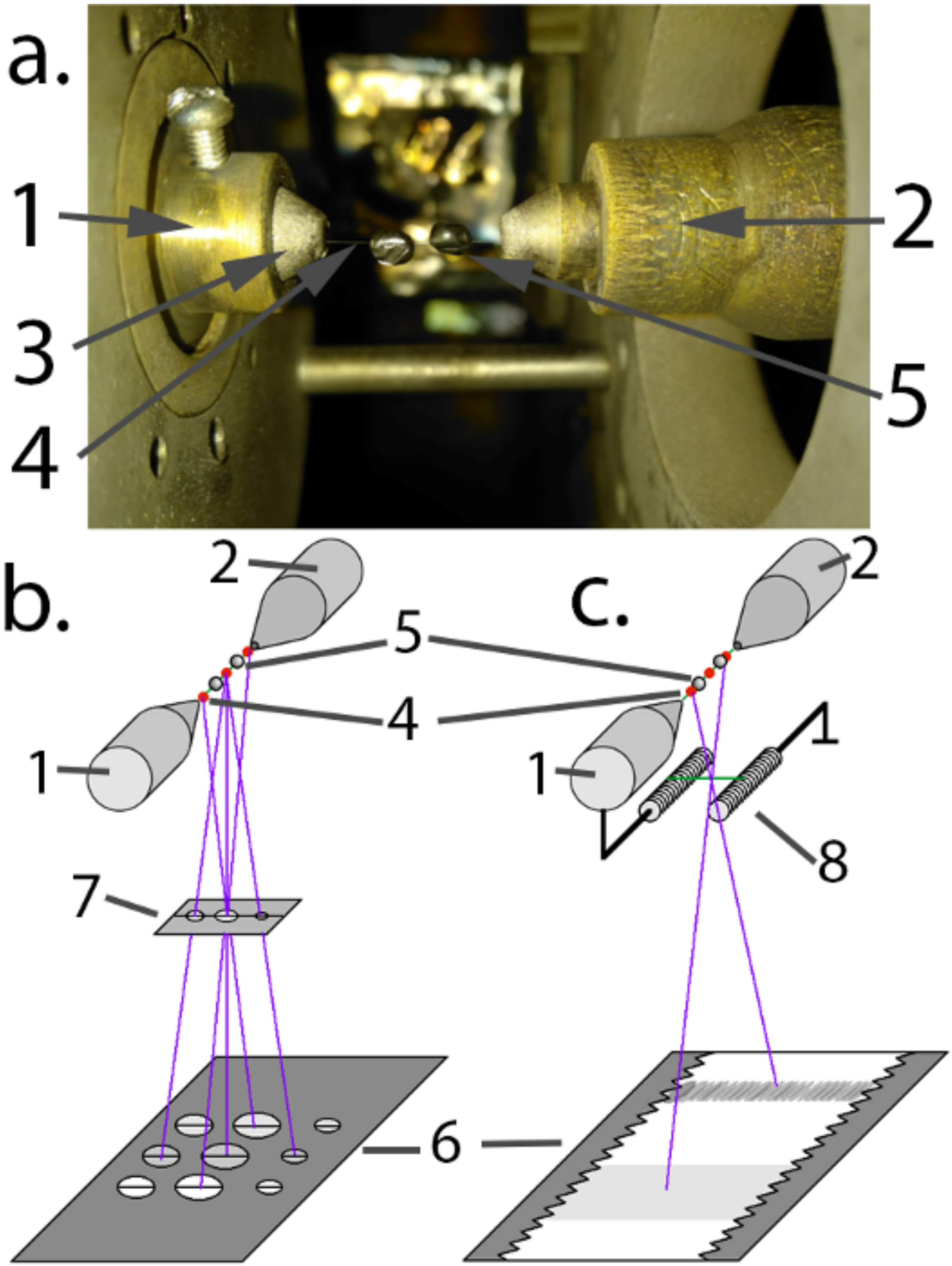
14. T. A. Shelkovenko ,S. A. Pikuz, A. D. Cahill, P. F. Knapp, D. A. Hammer, D. B. Sinars, I. N. Tilikin, S. N. Mishin, «Hybrid X-pinch with conical electrodes», Phys. Of Plasmas, 17, 112707 (2010).

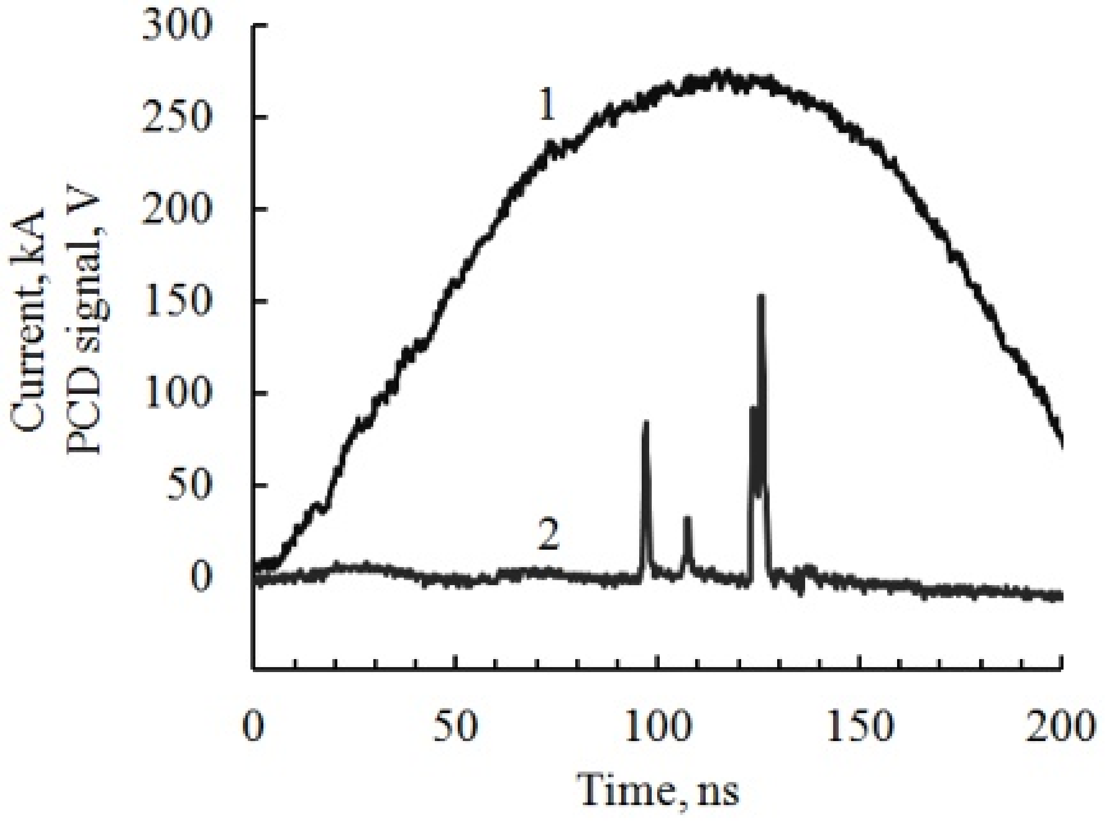
15. T. A. Shelkovenko, I. N. Tilikin, G. V. Ivanenkov, W. Stepniewski, A. R. Mingaleev, V. M. Romanova, A. V. Agafonov, A. D. Cahill, C. L. Hoyt, P. A. Gourdain, D. A. Hammer, and S. A. Pikuz, «Dynamics of hybrid X-pinches», Plasma Physics Reports, Vol. 41, No. 1, pp. 52–70 (2015).

16. V. M. Romanova, G. V. Ivanenkov, A. R. Mingaleev, A. E. Ter-Oganesyan, T. A. Shelkovenko, and S. A. Pikuz, «Electric explosion of fine wires: Three groups of materials», Plasma Phys. Rep.,vol. 41, no. 8, pp. 617–636 (2015).

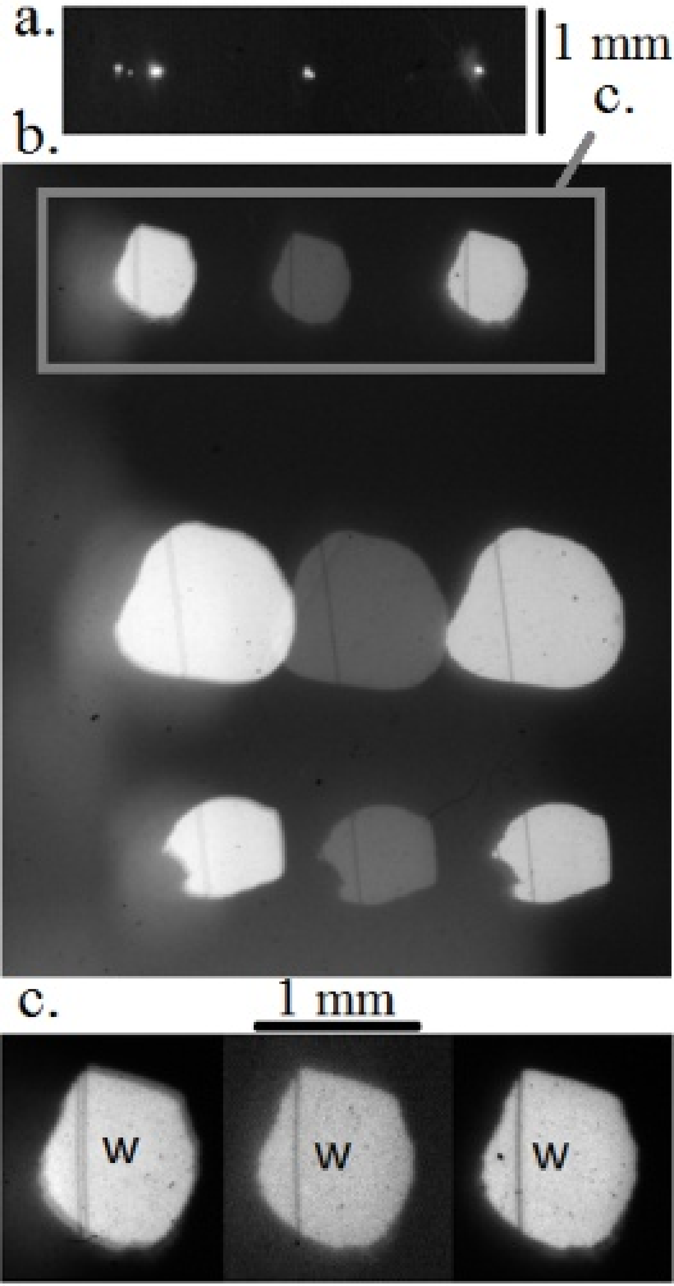
17. T. A. Shelkovenko, S. A. Pikuz, and D. A. Hammer, «A review of projection radiography of plasma and biological objects in X-Pinch radiation», Plasma Phys. Rep. 42, No. 3, pp. 226–268 (2016).

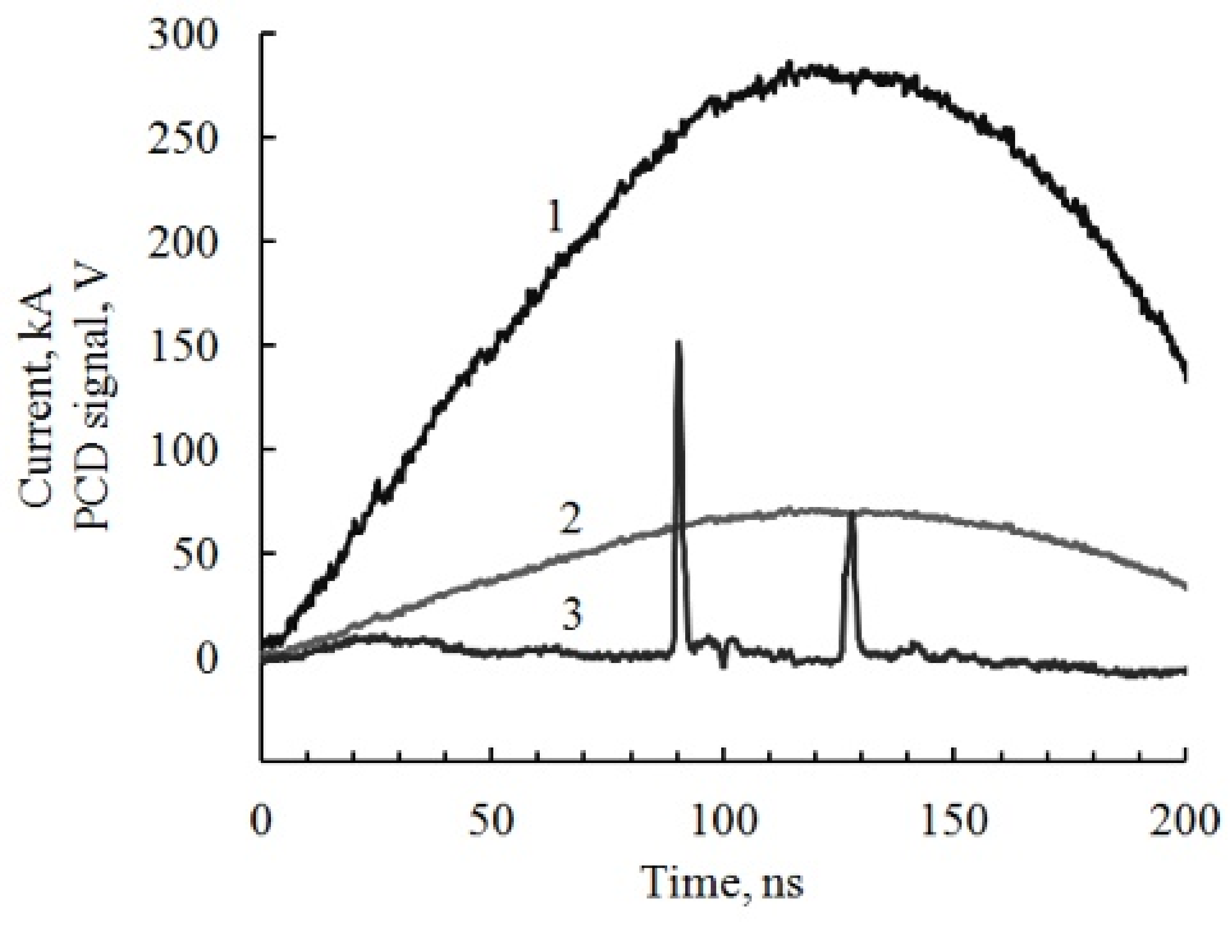
18. S. A. Pikuz, T. A. Shelkovenko, and D. A. Hammer, «X-pinch. Part II», Plasma Phys. Rep. 41, 445 (2015).


a.
1
2
3
4
5
b.
c.
1
2
4
5
6
7
8

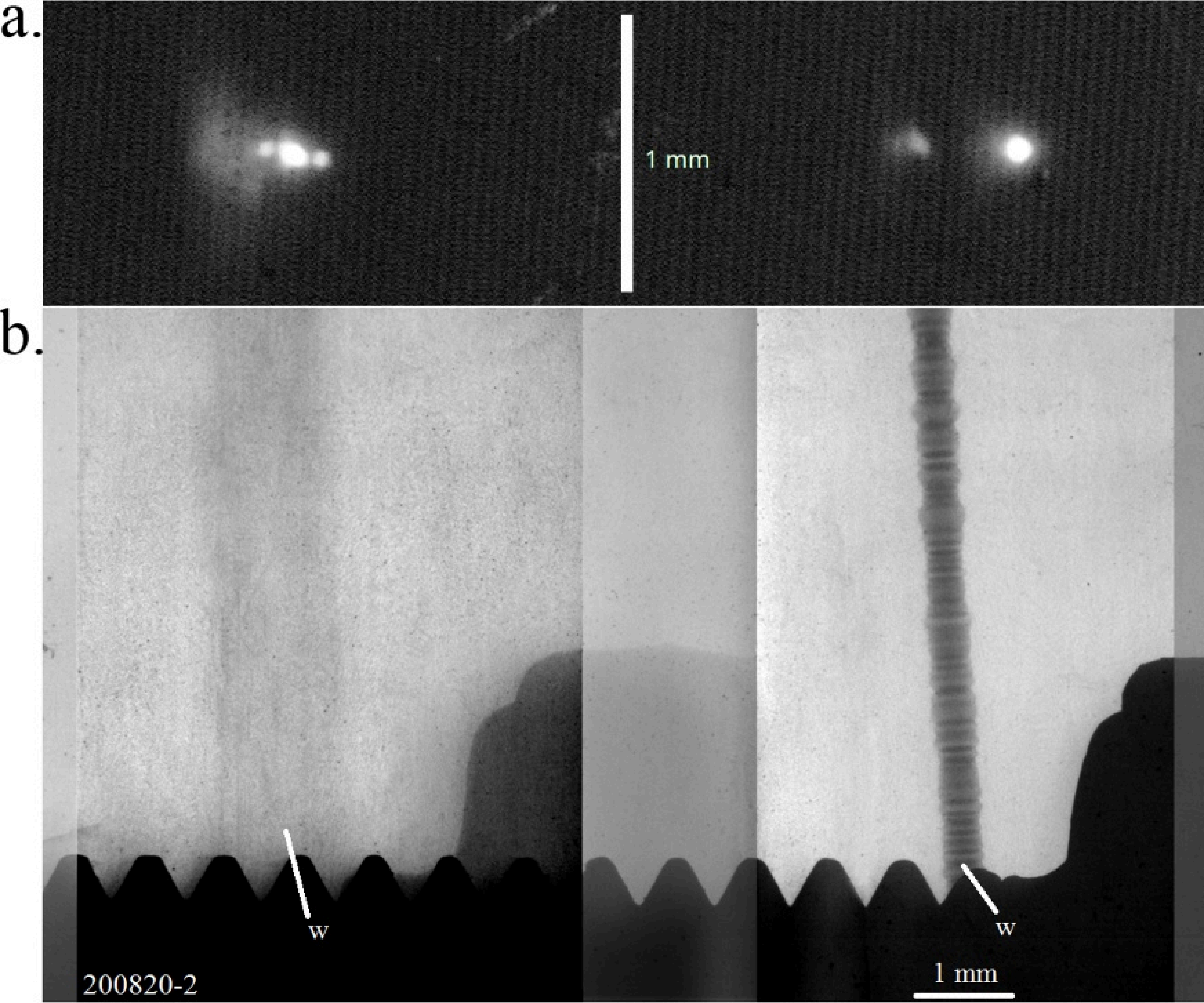


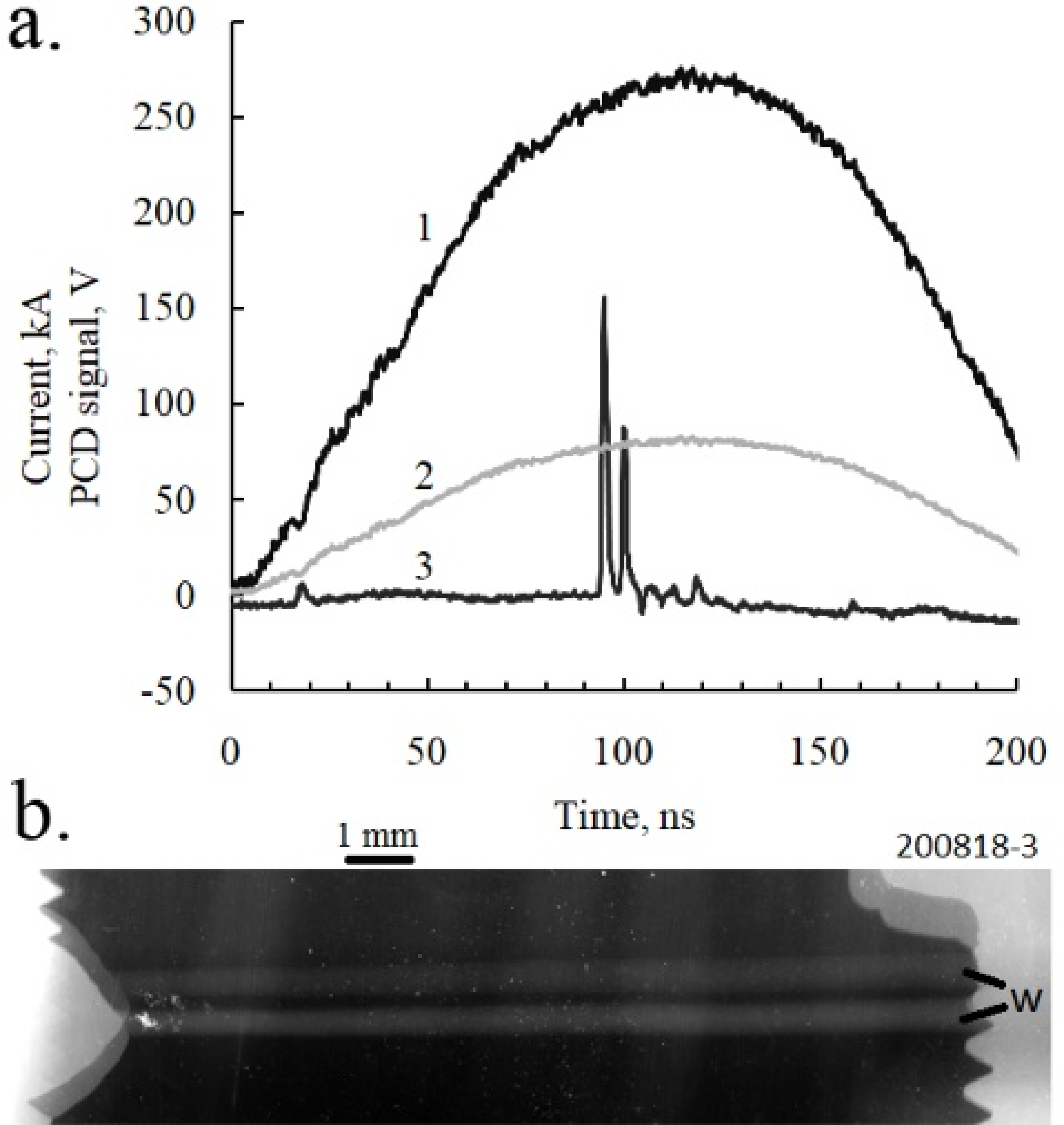
Current, kA
PCD signal, V
300
250
200
150
100
50
0
1
2
0
50
100
150
200
Time, ns


a.
1 mm
c.
b.
c.
1 mm
W
W
W



Current, kA
PCD signal, V
300
250
200
150
100
50
0
0
50
100
150
200
Time, ns
1
2
3


a.
1 mm
b.
w
w
200820-2
1 mm



a.
300
250
200
150
100
50
0
-50
Current, kA
PCD signal, V
1
2
3
0
50
100
150
200
Time, ns
b.
1 mm
200818-3
w