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Review article

Evolution of X-pinch loads for pulsed power generators with current from 50 to 5000 kA

T.A. Shelkovenko [a,b,*], S.A. Pikuz [a,b], I.N. Tilikin [b], M.D. Mitchell [a,d], S.N. Bland [c], D.A. Hammer [a]

[a] *Cornell University, Ithaca, NY, 14850, USA*
[b] *P. N. Lebedev Institute, Moscow, 119991, Russia*
[c] *Blackett Laboratory, Imperial College London, London, SW7 2AZ, UK*
[d] *University of Evansville, Evansville, IN, USA*

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Abstract

A review of X-pinches of various configurations and of different materials as an X-ray source for various applications is presented. The advantages and disadvantages of different designs of X-pinches as a load for generators with a wide range of output parameters and as a source of X-ray radiation for X-ray point-projection imaging were analyzed.

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Keywords: X-pinch; X-ray source; X-ray point-projection imaging

1. Introduction

More than 35 years ago an X-pinch was suggested at the P. N. Lebedev Institute as two or four fine wires arranged so that they crossed and touched at a single point, forming an "X" shape, as the load of the high current pulsed power generator Don (120 kA current amplitude, 40 ns rise time) [1]. The current is divided between the wires except at the cross-point, where all of the current is available to implode the plasma formed there during the current-induced wire explosion [1−12]. In the X-pinch, different types of X-ray sources are formed in different spectral ranges. The radiation source emitting radiation with photon energies of up to ~1 keV is located in the X-pinch minidiode to be defined shortly. It has a size of ≤100 μm and a ~10 ns pulse duration [11]. Radiation with photon energies from 1 to ~10 keV is emitted mainly by X-pinch hot spots with dimensions of ~0.5−5 μm, pulse duration 10−50 ps depending on the radiation energy, wire material, X-pinch configuration, and load current [2−8,10]. Accordingly, the brightness of these sources may vary by several orders of magnitude. Beginning immediately after the soft X-ray burst, higher energy X-ray emission is observed that is attributed to energetic electrons accelerated in the gaps that appear in the X-pinch plasma structure (Fig. 1). The source emitting the harder radiation (mainly electron beam bremsstrahlung) in the photon energy range of >10 keV (up to several hundred keV) has a size from 0.1 to 5 mm and 2−30 ns pulse duration [13−17].

The ability to predetermine the location (within about 200 μm) and the wide energy band of radiation (from infrared to hard X-ray) make X-pinches very useful for wide band spectroscopy [4,6,11−13,15−20] including X-ray absorption spectroscopy [22,23], for studying and testing new diagnostic

* Corresponding author. Cornell University, Ithaca, NY, 14850, USA.
E-mail address: taniashel@yahoo.com (T.A. Shelkovenko).
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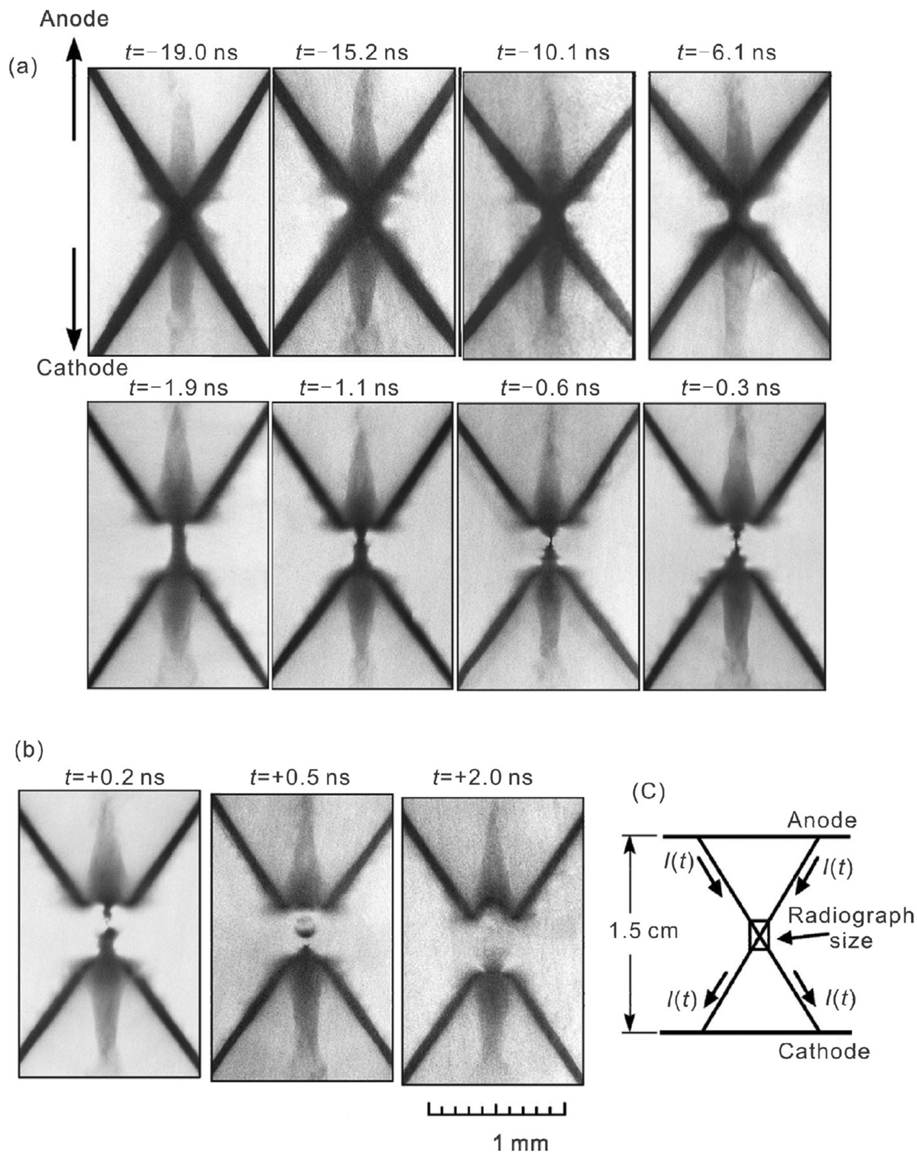

Fig. 1. A series of radiographs of two-wire Mo wire X-pinches with two sources and one object X-pinches mounted on the main load electrode (see Fig. 2). (a) A series of 8 radiographs of 23 μm Mo wire X-pinches before the moment of the first X-ray burst. (b) A series of radiographs of 17 μm Mo wire X-pinches after the emission of its X-ray burst. (c) Schematic diagram of an X-pinch in the diode, including a central box which shows the region covered by the radiographs in (a) and (b).

devices [19,21], and other applications [24]. The major application of X-pinches is as a bright point source for X-ray point-projection radiography of plasmas [2–5,9,10,15,25–31,38], biological samples [16,17,27,31,32], and other objects [16,17,33,37–40]. In principle, all three types of radiation sources discussed can be used for radiography, depending on the size, density, and variability of the object under study. However, only hot spot radiation can be used for radiography with high spatial and temporal resolutions, e.g., when studying the X-pinch itself. In the last two decades, interest in the X-pinches for the high energy-density plasma studies and applications has grown rapidly.

For high-resolution X-ray imaging, the most widespread X-pinch application, it is important to obtain a single intense soft X-ray pulse in the desired photon-energy range. As generator currents increase, the X-pinch mass per unit length has to grow and the configuration may have to be modified. To develop a single bright source of soft X-ray, three methods will be reviewed: increasing the X-pinch wire diameter and number of wires in the standard wire X-pinches, modification of the standard X-pinch configurations, and development of new configurations. One more direction of X-pinch modification discussed here is the development of X-pinch configurations that can be reloaded in vacuum.

We want to emphasize that only radiation sources based on X-pinch radiation provide at the same time high brightness of X-rays, comparable to the brightness of synchrotrons of the third generation, high spatial and temporal resolution with almost unlimited field of view. All other X-ray sources (lasers, synchrotrons, and so on) are much more complex than the

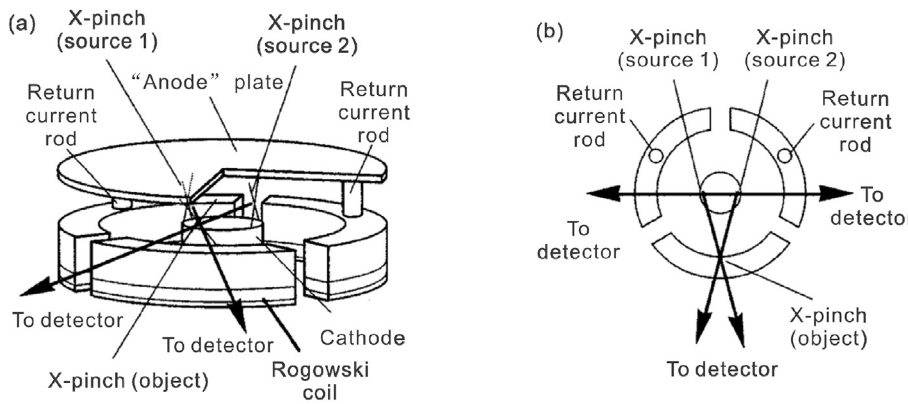

Fig. 2. (a) Configuration for X-ray backlighting experiments involving a total of three X-pinches, two for backlighting (sources 1 and 2) and one (the object) to be imaged on film. (b) Top view of the configuration in the plane of the three X-pinch cross points.

sources based on X-pinches, and cannot provide all these capabilities in a single pulse.

The review of the X-pinch load evolution presented here includes experiments in P. N. Lebedev (Moscow, Russia), Cornell University (Ithaca, N-Y, USA) and Imperial College (London, UK). The most interesting experimental results obtained in other laboratories and available in references are also presented. Experiments reviewed cover generator output current ranging from 50 kA to 5 MA and a variety of load materials from Mg ($Z = 12$) to Au ($Z = 79$) and radiation spectral range of interest is from 200 Å (~60 eV) to 0.1 Å (~100 keV).

2. Standard two- and four-wire X-pinches

Two and four wire X-pinches have been studied on many small- and intermediate-size pulsed-power generators with load current from 80 to 450 kA and with current rise time of 50−100 ns [1−9,13−16,19−23,27,33,34,37,39−42]. In most cases, standard X-pinches with two or four 15−50 μm wires were loaded as the main load of a high current diode with the gap 10−15 mm between electrodes. For X-pinch applications to multi-frame radiography, more complicated schemes with several (2−5) X-pinches were used [2−5,11,12,17,25,28−31]. Fig. 2 illustrates an example of a pulsed power generator load configuration used in such experiments. It involved three two-wire X-pinches, two of which provided backlighting X-ray sources for the third, object X-pinch.

In the beginning all generators used with X-pinch loads were built to achieve a high rate of the current rise (especially through a load like an X-pinch with a high inductance) by including high voltage pulse sharpening circuits with a Marks generator, intermediate capacitor, and a pulse forming line [1−9,19−23,33,34,37]. Many experiments with X-pinches on such generators were done and the results were published in the late 1990 s and early 2000. A short review of a majority of experiments with X-pinches published as of 2005 was presented as a Table in Ref. [9]. This review shows that most of the X-pinch studies were in Russia, USA, UK, France, and Chili.

After 2005, experiments with X-pinches started and were ongoing in China [38]. Started in the review [33], the Table given in Ref. [9] continued and included most papers about the X-pinch experiments up to the year 2015 from all countries presently doing them.

Two- and three-dimensional MHD simulations are used to provide a theoretical description of dynamics of two and four wire X-pinches. Short review of these simulations and a list of references were presented in Ref. [12].

Among recent experiments, of special note are the experiments with two- and four-wire X-pinches performed in the spring of 2017 on the Nene pulsed power generator at Imperial College London [40]. This generator satisfies the rule of a current rise rate of at least 1 kA/ns for X-pinch hot spot formation. This rule was established from the analysis of all available experimental data in 2006 [9]. To produce a soft X-ray pulse duration <0.1 ns and an X-ray spectrum containing bright continuum, the current rise rate of the driving generator must be higher than that value. This rule still does not have any exceptions.

Early experiments showed that, for the same driver conditions, symmetric X-pinches worked more stable. For example, 4-wire X-pinches work better than two-wire X-pinches [15,33]. This was found to be clear in the experiments on the Nene pulsed power generator. It is a very small generator but made according to the standard approach of a portable Marx bank and a pulse-forming line. This generator gives only 50 kA current in a pulse duration of about 50 ns, with the output voltage about 250 kV. In the Nene experiments, four-wire X-pinches (four 5 μm W wires) produced a single X-ray burst in 80% of the shots, while in the two-wire X-pinches with similar linear mass (two 7.5 μm W wires) did this only in 30% of the shots. Evidently 50 kA current is close to the lower limit of current sufficient to drive X-pinch loads.

For high-resolution X-ray imaging, the most interesting X-pinch application, it is important to obtain a single intense soft X-ray pulse in the desired photon-energy range ($E \approx 1{-}10$ keV). It seems energetically advantageous to have the X-pinch emitting X-ray burst near the peak current. In reality the best results (single bright hot spot) were achieved when the X-ray burst occurred in the time interval between the maximum of the current derivative and the current maximum. Analysis of the results of our experiments carried out on different facilities [9,11,15,31,36] shows that optimal mass for "good" X-pinch work depends not only on current (according to Bennet equation $m \sim I^2$ [35]), but also on wire material [15,36]. In Ref. [36] a more general scaling for the optimal X-pinch linear mass m_l was presented as

$$I_{max}^2 t_{max}^2 \rho / m_l^2 = \text{const} \quad (1)$$

where I_{max} is the current amplitude, t_{max} is the time of current maximum and $\boldsymbol{\rho}$ is a parameter dependent on the load material. The parameter $\boldsymbol{\rho}$ is a density of expanded wire core in the maximum of expansion. An example of the core density together with description of the method of the density estimation was presented in Ref. [4].

At present, four wire X-pinches are typically used as sources of radiation for radiography of different solid, plasma and biological objects when 2–5 X-pinches are placed in a return current circuit [2–5,7–11,13,14,39,40,41,15,23] or one or two X-pinches are used as the main load in the high current diode [2,4,15,34,36,37,39,48,52,53]. Such configurations enable taking several images in the same pulse of the generator, however, the X-ray burst timings are dependent on many factors and it is difficult to have the desired time for imaging for all images.

In some cases, two or even three generators were synchronized and used to create the object under study, using X-pinches separately [41,42]. A particularly interesting scheme was realized when the small SXPD (400 kA, 150–200 ns rise time) generator was synchronized with ANGARA-5 generator and images of exploding Ni wires were obtained using X-pinches made from four 25.4 μm diameter molybdenum wires [42]. Using synchronized generators enables choosing any desired time for imaging.

3. Multi-wire X-pinches for generators with current 1 MA and higher

The first 1-MA-current X-pinch experiments that were discussed in publications conducted in the 1990 s and early 2000 s on generators Gamble II [43] and ZEBRA [44,45] using low wire-number (2–4) loads. X-pinches produced multiple bursts of X-rays and a high level of hard radiation. As was understood later, the load mass in these experiments was far from optimal, which led to multiple early pinching and intense electron beam generation. Extensive studies of 1-MA X-pinches were conducted on the COBRA pulsed-power generator starting in 2005 at Cornell University. COBRA has an extended range of the current pulse parameters, namely the current rise time can be varied in the range 95–200 ns, and was used with wide variety of X-pinch loads [9,47]. It was shown that only multiwire (6–32) X-pinches can produce a single hot spot. For example, the optimal linear mass of a W X-pinch on COBRA in the regime with 100 ns current rise time was 3 mg/cm (eight 50 μm W wires). X-ray images of the eight 75 μm W-wire X-pinch are presented in Fig. 3 and show the process of neck formation versus time. Images were obtained in the radiation of two X-pinches placed in return current circuit, as shown in Fig. 3(a). All three X-pinches shown in Fig. 3(a) produced single hot spots. Fig. 3(c) shows that the X-pinch neck has a diameter about 300 μm. To form a ~1 μm diameter hot spot the neck had to be compressed about 300 times in the 44 ns before the X-ray burst.

With a stable current pulse, the mass of the X-pinches can be adjusted to radiate only one soft X-ray burst with an energy yield estimated to be 1–2 J [9]. Multiburst X-pinches can radiate up to 10–12 J in all bursts [47]. Summarizing the experiments on the measurement of energy yield on all used pulsed power generators with currents from 250 to 1000 kA, it can be concluded that the radiation yield depended on many factors but in average increased with the current growing [9,15,31,39].

The multiburst structure of the X-pinches in the previous 1 MA experiments can be understood now as improperly chosen load mass. For example, in the ZEBRA experiments

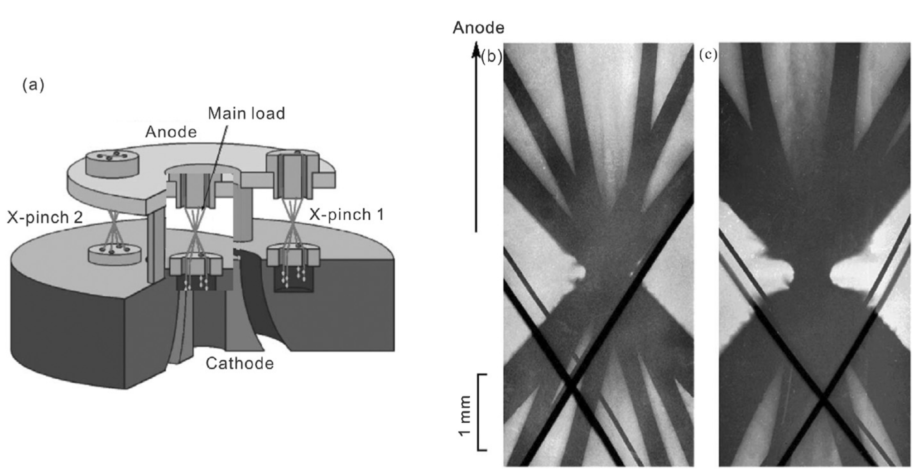

Fig. 3. (a) Cutaway view of an X-pinch load showing the two-frame X-ray backlighting setup, which includes two backlighter X-pinches and two other return current posts. X-ray images of an eight 75 μm W-wire X-pinch obtained in radiation from four 12.5 μm and four 20 μm Mo X-pinches, at times of (b) 72 ns and (c) 44 ns, respectively, before the W X-pinch emitted its soft X-ray burst. The backlighter X-pinch timings were 88 and 116 ns, respectively, after the start of the current pulse. The images of crossed 240 μm Cu wires that did not carry current in the lower part of each image give information about the spatial resolution provided by the backlighter X-pinch (the upper one of the two images) and the load X-pinch.

[44,45], with almost the same current and dI/dt as in the COBRA experiments, the linear mass of the X-pinches (0.1–0.25 mg/cm for Ti, Fe, Mo, W, and Pt two-wire X-pinches) were more than an order less than the optimal linear mass of X-pinches studied on the COBRA generator.

Experiments with multiwire X-pinches used as loads for the S-300 high-current generator ($I = 2.3$ MA, rise time 150 ns, Moscow, Russia) were carried out in 2008. The X-pinches consisted of different numbers of wires ($N = 2-20$) made of tungsten, molybdenum, nichrome, and stainless steel having lengths of 10–12 mm and various diameters ($d = 55-300$ μm) and crossed at an angle of 60°. A wide range of linear masses ($m = 3.6-40$ mg/cm) was investigated. At 2.3 MA, the power of the soft X-ray radiation with photon energy from 1 to 2 keV increased to 120 GW, and, the size of the hot spots were less than 20 μm. The energy recorded in lines of neon-like molybdenum (in the range of 2.5–3 keV) was more than 10 J [46].

At the same time, experiments with multiwire X-pinches were carried out on the SATURN generator (SNL, $I = 5-6$ MA, rise time 70 ns). According to Eq. (1), the linear mass of the X-pinch wires in those experiments was 108 mg/cm and large wire-number cylindrical wire arrays (~100 wires, 108 mg/cm) were twisted into an X-pinch and tested. Those experiments were not very successful at producing hot spots as a bright source of soft X-ray. Other configurations of X-pinches, the description of which is given below, were developed and used in the experiments.

4. Nested X-pinches

Experiments (see Refs. [9,46,47]) have shown that, although the correct choice of the wire mass decreases the number of hot spots and the hard X-ray intensity, the soft X-ray yield at currents of >1 MA remains not very stable. In practice, the required increase in the X-pinch linear mass can be achieved by increasing either the initial diameter of the wires (while keeping constant the number of wires) or their number (while keeping constant the wire diameter). In both cases, there will be an increase in the size of the X-pinch crossing region which complicates its topology.

Experiments performed in the COBRA facility [9,47] show that the soft X-ray yield from X-pinches made of a large number of fine wires is much higher than that from X-pinches made of a small number of thicker wires having the same total linear mass. Most likely, this is because, in the latter, the azimuthal asymmetry of the crossing region is stronger. As the wire diameter is decreased, while the number of wires is increased accordingly, the asymmetry of the crossing region becomes less pronounced even for an arbitrary arrangement of wires. In this case, the packing density of wires in the crossing region also increases.

To make the structure of the crossing region more compact and symmetric, an X-pinch configuration with a regular arrangement of wires (see Fig. 4) was proposed in Refs. [34,49]. Such a configuration, based on natural hexagonal symmetry, allows one to manufacture multilayer (nested) X-pinch loads. Several X-pinch configurations with a regular arrangement of wires in the crossing region were investigated [34,49].

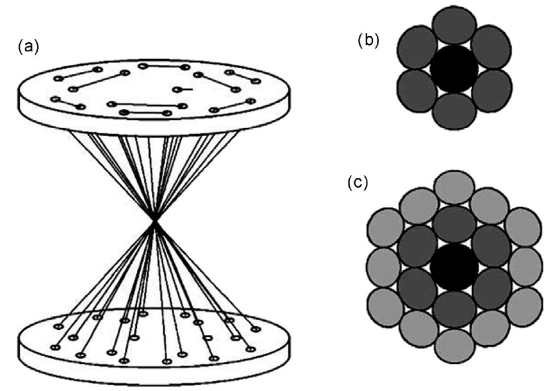

Fig. 4. (a) Schematic diagram of wire arrangement in a nested X-pinch; (b) and (c) show possible arrangements of wires in the plane through the crossing regions of two- and three-layer nested X-pinches, respectively.

The nested multilayer X-pinches with higher Z material wires in the outer layer show a smaller, simpler source structure than the standard X-pinches. Examples of the results obtained in the best configurations of the standard and nested X-pinches in the COBRA experiments are presented in Figs. 5 and 6. XUV ($\lambda = 20-500$ Å) images of the X-pinch were recorded using a four-frame microchannel-plate (MCP) camera with a 5-ns time resolution and an about 100 μm spatial resolution. Analysis of such images can provide information on the processes accompanying plasma compression in the X-pinch neck. In particular, the plasma jets observed just after the first X-ray burst indicate breaking of the compression symmetry in standard X-pinches (Fig. 5(a)). In a three-layer nested X-pinch, the process of compression is more stable (see Fig. 5(b)). In the case of the (1NiCr(25 μm) + 6Mo (25 μm) + 12 W (25 μm)) X-pinch, the PCD signal shows single hot spot burst and a single burst of radiation from energetic electron beam (Figs. 5(d) and 6(d)-(f)). Standard X-pinch has two hot spots is apparent in Figs. 5(c) and 6(a-c).

Only the nested X-pinches developed a single intense hot spot, as shown in the enlarged images in Fig. 6(b) and (e) and the pinhole picture shown in Fig. 6(c) and (f) for photon energy above 3 keV. Even the best of the standard X-pinches tested on COBRA have complicated radiation source structure [9,49]. As was shown in Ref. [34], the nested X-pinches work quite reproducible. The X-ray bursts intensities are almost the same on most shots with the same nested X-pinch configurations. The only disadvantage of this load is the complicated structure consisting of two or three layers of wires with different diameters and materials. Also for each generator, it would be necessary to find the right configuration to match the generator parameters. For example, in the experiments on the S-300 and SATURN generators such configurations were not found in a limited number of shots.

The best results in experiments on the SATURN generator were obtained with solid X-pinches made from tungsten [48]. The X-pinches consist of two massive conical electrodes

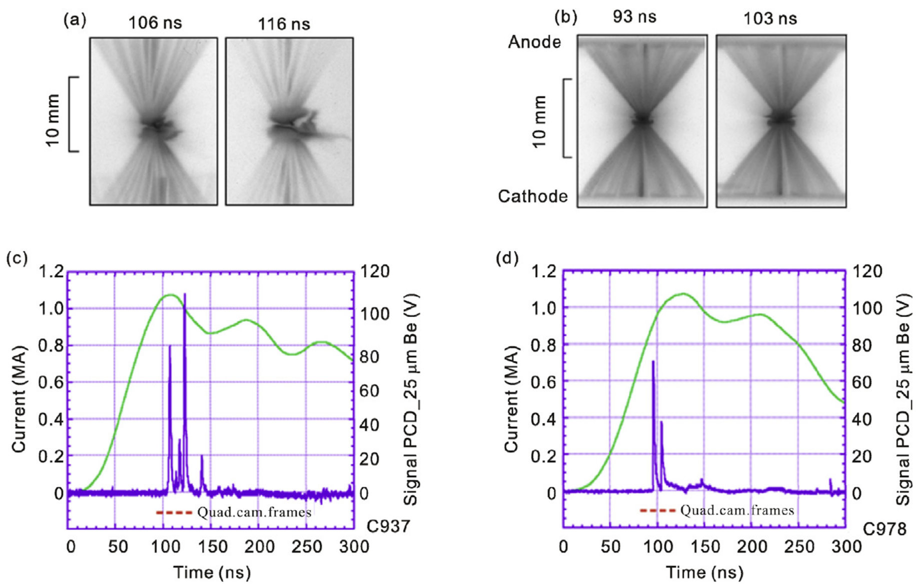

Fig. 5. (a) XUV images of a standard X-pinch made of thirty-two 25 μm diameter W wires and (b) a three-layer nested X-pinch made of 19 wires (1NiCr(25 μm) + 6Mo (25 μm) + 12 W (25 μm)). The images were taken using a four-frame microchannel plate camera with magnification 1:1.2. (c) and (d) show waveforms of the currents and PCD signals recorded through a 12.7 μm thick Ti foil for the standard W wire and nested X-pinch, respectively.

connected with a neck that was several hundred microns in diameter. The electrodes and the neck were a single machined piece of metal, so the neck could be broken when the vacuum chamber was evacuated. Solid X-pinches were a prototype for hybrid X-pinches, which will be discussed below.

5. Hybrid X-pinches

As has been shown in research on standard X-pinches (see Fig. 1), the most important processes leading to the unique behavior of X-pinches occur in a small region (less than 1 mm in length) in the vicinity of the wire cross point [4,25]. In the early stages of X-pinch development, a minidiode was formed in this region from the dense wire core material and developed in the initial wire explosion (Fig. 1(a)). In the stage of X-pinch dynamics prior to the final implosion and X-ray burst emission, the “electrodes” of the minidiode were connected by a plasma column created in the processes of exploding wire plasma merging followed by pinching of the plasmas outside the dense cores due to the X-pinch current [4,25,50]. In fact, the creation of the micron-scale hot dense plasma that proceeded unstable magnetic implosion in a cascading process [50], which led to the emission of the characteristic X-ray burst of an X-pinch, seemed completely independent of the behavior of any part of the X-pinch structure other than the central plasma column, including the minidiode “electrode” structures and behavior. However, important feature of a standard X-pinch is thought to be the absence of material on the axis in the initial wire configuration just above and below the wire cross point. That allows axial motion of the matter and appears to help an X-pinch adjust its linear mass in the crossing area to fit the current.

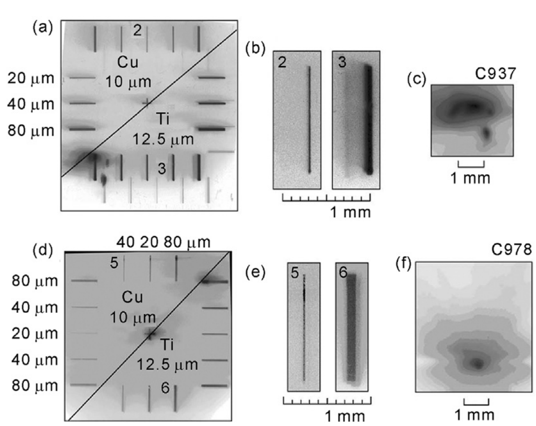

Fig. 6. Point-projection X-ray images of the slit patterns obtained with the X-pinches imaged in Fig. 5 (a) thirty-two 25 μm diameter W wires and (d) three-layer nested X-pinch made of 19 wires (1NiCr(25 μm) + 6Mo (25 μm) + 12 W (25 μm)), (b) and (e) are enlarged parts of the slit patterns from images (a) and (d) showing the hot spots structure. The images were obtained with magnification 1:9.67. Time integrated pinhole images obtained with 50 μm hole diameter and magnification 1:1 in radiation with $E > 3$ keV are shown in (c) and (f) for these X-pinch configurations, respectively.

To simplify X-pinch loading and still retain the structure of the minidiode in Fig. 1(a), conical solid electrodes connected by a single wire with appropriate linear mass was suggested and tested in 2010 (Fig. 7(a)) [51].

To reduce the formation of the electrode plasma, the electrodes were made from tungsten alloy (95% W+5% Cu) with a cone angle of 60° and an axial hole with 1 mm diameter. The hole diameter was much bigger than all wire diameters. The electrodes did not prevent axial motion of the wire material. X-pinches with conical tungsten alloy electrodes were named hybrid X-pinches (HXPs).

The HXPs were first tested on the XP-generator with 450 kA current and rise time 45 ns. The short rise time prevented the minidiode being shortened by the electrode plasma. The experiments on XP were very successful and a small hot

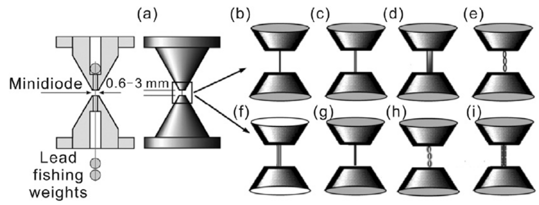

Fig. 7. (a) Illustration of replacing the X-pinch wires with solid conical electrodes with a wire in between and cross-sectional view of the "hybrid X-pinch" (HXP) with conical electrodes. Different configurations of HXPs: (b) with single wire, (c) several wires, (d) metal tube, (e) braided wires, (f) metal tube with wire inside, (g) plastic tube with melted powder, (h) braided wires covered by melted powder, (i) wire covered by glue with powder of salt.

spot radiating an intense burst of soft X-rays was recorded in HXPs with a wide range of the wire materials, diameters and length [51]. Radiographs showed the soft X-ray source size to be about 1.5 μm and SXR power from 1 to 1.7 GW. As was shown in Ref. [52], the source size is smaller in the radial direction than in axial direction.

The HXPs were then studied as the main load using three generators with a relatively long current rise time and a large range of parameters: COBRA, BIN, and MINI [51,52,53,54]. In Table 1, the main results of the experiments are presented.

Experiments on XP and COBRA generators were very successful. Practically all wire materials, fine tubes, several wires and wires with coating (glue and any powder) produced an intense burst of soft X-rays [52,53,54]. In Fig. 7 several possible versions of HXPs are shown. Sometimes the source size was not small enough to use for point-projection radiography with high spatial resolution, but was useful for other applications such as X-ray spectroscopy. In Refs. [53,54] it was shown that in the same HXP experiment, the line radiation of different materials, including gases could be recorded.

Experiments on BIN and MINI generators were not so successful. It was found that on the BIN generator, only wire materials with medium *Z* and medium conductivity (Ni, Nb, Mo) could be used to generate a single burst of soft X-rays [52,53]. The results of the experiments carried out at the XP, COBRA, and BIN facilities, possessing different parameters, allow us to conclude that hybrid X-pinches are efficient at facilities with the current of 0.25−1 MA and current rise time from 45 to 100 ns and they can be used as point sources of soft X-rays for projection X-ray imaging and other applications.

In accordance with the experimental results shown in Table 1, it could have been expected that the problems in designing a soft X-ray point source based on the hybrid X-pinches would increase with an increase in the current rise time. Given the current rise time at the MINI generator and estimates of the diode closure time, we had very little hope for success. Actually, all resistive wires traditionally used in X-pinches (Mo, W, Ni, NiCr, and Ti) did not operate in this configuration. However, the application of highly conducting wires, in particular, those made from Al, Cu, and Ag, turned out to be surprisingly efficient. As was shown in Refs. [55,56], the dense cores of such wires possess high expansion rates during the explosion. With a current rise time of 170 ns, the core can be expanded by a factor of ten as compared to the initial wire diameter. It is likely to be explained by the fact that the diode gap of the hybrid X-pinch is being filled in this case with a poorly conducting expanding material of the wire core that hinders the gap closure of the plasma generated at the electrodes.

The energy yield of hybrid X-pinches at the MINI generator was substantially lower than that of standard four-wire X-pinches [36]. However, even 10 mJ of the soft X-ray energy emitted by an HXP is sufficient for getting an image of a test object with a 33: 1 magnification (Fig. 8). The source size estimated based on the image edge blurring is 2.8 μm, and the calculated size of the HS is 1.1 μm [10].

On the KING generator (see Table 1) we had even less hope than on the MINI generator for success in experiments with standard and especially with hybrid X-pinches. But in 50% of shots with standard four 25 μm Mo X-pinches, and with HXPs using 25 μm Ag wire (2 mm gap), hot spots were formed, and the bursts of soft X-rays were radiated (Fig. 9).

In Fig. 9 examples of oscilloscope signals recorded with a standard four 25 μm Mo X-pinches and with an HXP with a 25 μm Ag wire on the KING generator are presented. One can see that current signals have a part with higher d*I*/d*t* than average. These parts are marked on the figures and have d*I*/d*t* about 2 kA/ns. Whenever the current signal had this 2 kA/ns part, the X-pinches formed intense burst of soft X-rays (curve 2 in Fig. 9).

Recent experiments with HXP loads were performed on the Nene pulsed power generator at Imperial College London. In these experiments HXPs with 13 μm Mo wire and 1 mm interelectrode gap formed a single hot spot in all shots.

Table.1
Generator used in experiments with HXPs and results of the experiments.

Generator and its parameters (peak current, rise time)	Institution	Wire materials	Minidiode gap (mm)	Hot spot size *a* (μm)	Hot spot size *b* (μm)	Radiated energy (J) ($E > 1$ keV)
XP (450 kA, 45 ns)	Cornell University (Ithaca, N-Y)	All wire materials, dielectrics, any coating	0.5−0.8	4	0,7−2.6	~0.2−1
COBRA (1 MA, 100 ns)	Cornell University (Ithaca, N-Y)	All wire mate-rials, any coating	1.5−2.5	6	1.4	1−3
BIN (270 kA, 100 ns)	P.N. Lebedev Institute (Moscow, Russia)	Ni, Nb, Mo	1.8−2.2	4	1.5	0.1−0.15
MINI (260 kA, 170 ns)	P.N. Lebedev Institute (Moscow, Russia)	Cu, Ag	2−3	2.8	1.1	~0.01
KING (200 kA, 200−220 ns)	P.N. Lebedev Institute (Moscow, Russia)	Cu, Ag	2−3	5	<5	~0.02
Nene (50 kA, 50 ns)	Imperial College (London, UK)	Mo	~1	7	<7	~0.005

Note: Hot spot size *a* was measured based on the image edge blurring and hot spot size *b* was calculated according the procedure presented in Ref. [10].

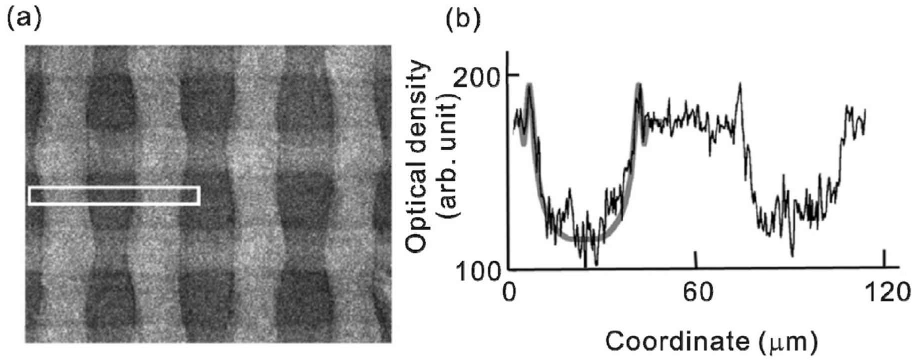

Fig. 8. (a) X-ray image of a mylar mesh obtained in the emission of an HXP with a 2 mm long 25 μm diameter copper wire at the MINI facility and (b) optimal density profile of the image, together with a calculated optimal density profile (black solid curve) corresponding to a 1.1 μm source.

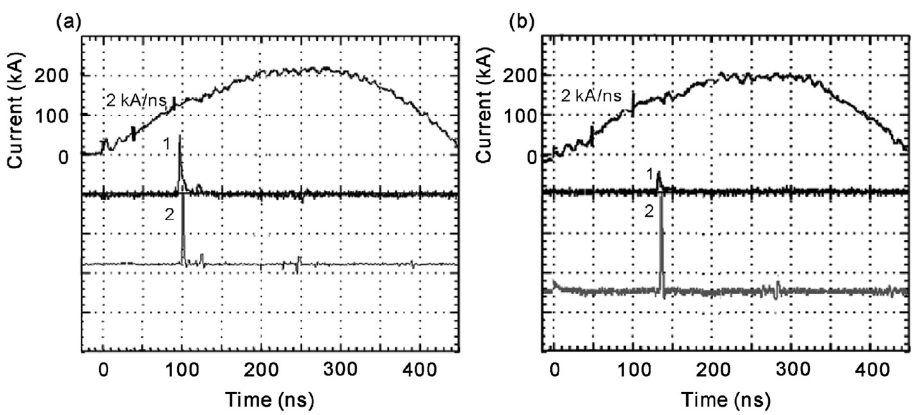

Fig. 9. (a) Examples of oscilloscope signals recorded with standard four 25 μm Mo X-pinches and (b) HXPs with a 25 μm Ag wire on the KING generator, curve 1 for $E_\gamma > 9$ keV (Si-diode signal, 240 μm Al filter), and curve 2 for $E_\gamma > 1.5$ keV (PCD signal, 18 μm mylar filter).

Our experiments showed the HXPs results to be very sensitive to the generator prepulse [53]. Small (~5 kA) and relatively short current pulses (~50 ns) are enough for wire explosion and can disturb the HXP dynamics.

X-pinches are well known to produce very small, dense plasma pinches ("hot spots") that emit subnanosecond bursts of 1–8 keV radiation. Hard X-ray radiation in the range from 8 to 300 keV or more is also emitted, and only a small portion of which is associated with the X-pinch hot spot [13,14,16,17,44,46]. The electron beams and hard X-ray radiation are the sources of debris and background radiation. This is a hindrance in the use of the radiation from X-pinches for some applications.

The investigations reviewed in this paper showed that energetic electrons are also generated in HXPs and that these electrons are intimately connected with the soft X-ray bursts. HXPs produce smaller sources of hard X-ray radiation with shorter pulse duration of the pulse than standard X-pinches, as well as lower maximum photon energy than standard X-pinches, which produce some X-rays with energy of up to the generator voltage [17,18,44,46]. Even on the low-voltage generators like MINI or KING electron beam and hard X-ray radiation were recorded using Si-diodes and pinholes with thick filters [36]. In Fig. 9, the pulse of soft X-ray is about 25% more intense in the case of HXP, while the pulse of hard X-ray radiation is 4 times stronger in the case of standard Mo X-pinch. Such signals are quite standard for those 50% of shots when hot spots are formed in the X-pinches.

We conclude that the intensity of hard X-ray strongly depends on the X-pinch configuration. The practical result of the low intensity of electron beams in HXPs allows use of the same conical electrodes in many shots.

Very recent experiments have also shown that the HXPs can be used as the sources of bright UV radiation (>5 J radiated energy in 1–3 ns pulse) with a much lower level of hard X-ray radiation than in standard X-pinches [57].

Because the HXP configuration is compatible with simple loading methods, it is one of the main candidates for creating a reloading system for X-pinches with the possibility of repeated use without breaking the vacuum. These experiments are now being prepared, but other possible candidates were examined in the experiments presented below.

6. Candidate X-pinch configurations for the creation of an in-vacuum reloading system

Another X-pinch configuration tested on the XP and BIN generators was X-pinches in dielectric frames. This configuration was intended to test X-pinch wire-loading configurations using a simple plastic frame that might enable the X-pinch wire loads to be prepared in advance, later – loaded into the vacuum chamber, and changed under vacuum after a pulse. Several frame configurations and materials were tested, some of which suffered from early surface flashover and current shunting away from the X-pinch. Fiberglass frames have been proved to be successful both in minimizing the current shunting up to the time of the X-pinch X-ray burst and, in most tests, in substantially reducing X-ray emission from energetic electrons and secondary soft X-ray bursts following the first X-ray burst. Both of these features are beneficial for using X-pinches for point-projection radiography as well as for recording X-ray spectra from the X-pinches.

This configuration was successfully tested on the XP generator with very short rise-time and not so successful on the BIN generator. On the XP generator several different configuration of the loads were tested [58]. Up to 6 X-pinches were placed in the frame. The smallest anode–cathode gap for hot spot formation was 5 mm. The experiments showed the current through the load to be much less than the generator current because of high load inductance or leak of current. In Fig. 10, results of experiments with four two-wire X-pinches placed in a frame in series are presented. Fig. 10 shows that all four X-pinches radiated single bursts of soft X-rays with intensity high enough for point-projection imaging with 4 times magnification.

Experiments on the BIN generator produced from only single X-pinches in long frames (~5–6 cm) radiated weak soft X-ray bursts. Most X-pinches on the BIN produced only an intense burst of XUV radiation with 4–6 ns duration. No harder radiation was recorded. Therefore, we conclude that on generators with about 100 ns rise time X-pinches in frames can be good sources of XUV radiation.

Changing the length of the frame, X-pinch, the wire size, and the wire material all made it possible to vary the timing, intensity, and hardness of radiation from X - pinches in frames in a succession of tests. Much less hard X-ray radiation was observed in the experiments than with standard X-pinches. Our experiments demonstrated X-ray imaging (1–3 keV) of the object in a single pulse with <0.1 ns pulse duration and <5 μm spatial resolution on XP but not on BIN [58].

The idea to make X-pinch configurations changeable in vacuum has been tested in different laboratories in the world with very different X-pinch like load configurations. Most successful experiments are presented below.

The idea to prepare X-pinch loads before experiments was carried out at the University of California, San-Diego (USA) using laser-cut X-shaped foils (10 μm Ta and Cu with 30 μm cross point diameter) driven by the 250 kA, 150 ns rise time GenASIS Linear Transformer Driver [59,60]. The foil X-pinches were manufactured at General Atomics' Laser Micro-Machining (LMM) Center, which provided two different laser-machining platforms to cut the foil targets. In Refs. [59,60] the

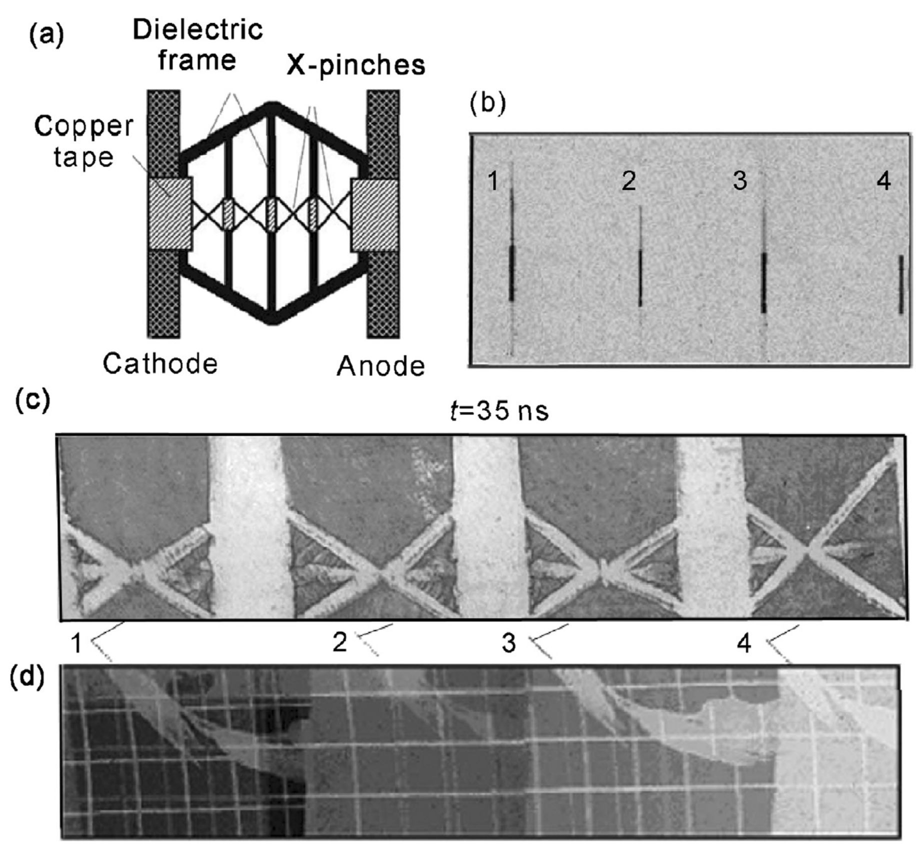

Fig. 10. (a) Four X-pinches in series in a frame, (b) SSW-camera images, (c) laser shadow images, (d) four images of a test object with a 50 μm wire mesh.

authors said that in the experiments, a single source of radiation with 3 ns duration was observed. The source size was <7 μm.

Simpler loads were tested in experiments at the Institute of High Current Electronics (Tomsk, Russia). Plasma jets from an arc discharge were used as a load for a high-current generator with an interelectrode gap of 1.3–1.5 mm. A single bright source was formed [61]. The size of the emitting region in the range of energies from 1.5 to 3.0 keV was about 13 μm in diameter and about 24 μm in height with an aluminum jet, and about 7 μm in diameter and about 17 μm in height for a tin jet. The burst of X-ray radiation lasted 2–3 ns. The total radiation yield per pulse in the spectral range 1.56–1.90 keV reached 50 mJ into 4π solid angle. With this load, there was no need to disassemble the vacuum chamber after each shot. The service life of an arc discharge can be about 50 shots.

7. Conclusions

Different configurations of the X-pinches were discussed in this review in terms of requirements to have sources for point-projection imaging. These requirements are the most stringent from the points of view of the size of the source, field of view, intensity, energy and duration of the radiation burst. All other applications of the X-pinches, excluding X-ray absorption spectroscopy [62], do not have such stringent requirements. For application of the X-pinches for X-ray absorption spectroscopy, the X-ray source must meet the same requirements as the source for point-projection imaging. From this we conclude that if a radiation source satisfies the requirements discussed in the paper, it can be used for most of X-pinch applications.

We want to emphasize that only radiation sources based on X-pinch radiation provide at the same time high brightness of X-rays, comparable to the brightness of synchrotrons of the third generation, high spatial and temporal resolution with almost unlimited field of view. All other X-ray sources (lasers, synchrotrons, and so on) are much more complex than the sources based on X-pinches, and cannot provide all these capabilities in a single pulse.

Conflict of interest

There is no conflict of interest.

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