# Aluminum and tungsten X-pinch experiments on 100 kA, 100 ns linear transformer driver stage

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# Aluminum and tungsten X-pinch experiments on 100 kA, 100 ns linear transformer driver stage

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X-pinch experiments have been carried out on a 100 kA, 100 ns linear transformer driver stage recently built up. The X-pinches exhibited a source size of about 10 $\mu$m, a pulse duration of 3 ns, 3–5 keV radiation energy of 3.9 mJ, and a burst time jitter of tens of nanosecond with the 2-wire 8 $\mu$m W X-pinch load. The generator output current and the X-pinch characteristics depended on the X-pinch wire materials in the tests. X-ray backlighting images from the insects showed the significant phase-contrast effect. © *2011 American Institute of Physics*. [doi:10.1063/1.3587065]

## I. INTRODUCTION

The X-pinch was proposed in 1982 at the P.N. Lebedev Physical Institute.[1] The load configuration is of two (or more) fine metallic wires, which cross and touch at a single point, forming an "X" shape. When a fast rising high current ($dI/dt > 1$ kA/ns)[2] passes through the wires, a localized X-ray source is produced with an X-ray pulse duration less than 1 ns, a spot size of $\sim$1 $\mu$m, and X-ray energies in the 1–10 keV energy range for a 0.2 MA generator.[3] The dynamics of the X-pinch cross section, which are described fully in Ref. 3, could be divided into three stages. First, the wires explode, the core-corona structure forms, and the axial plasma jets appear. Second, a mini-diode structure, composed by two plasma electrodes and a cylindrical plasma column (a mini Z-pinch), forms near the X-pinch crossing point. The mini Z-pinch implodes and one or more fine necks develop and radiate intense X-rays. Finally, the fine necks disappear and the Z-pinch disassembles. At present, there are two directions for X-pinch research. One is megaampere X-pinch experiments and the other is hundreds of kilo-ampere X-pinches driven by a table-top-size generator for backlighting applications. Megaampere X-pinch experiments have been carried on ZEBRA,[4,5] COBRA,[6,7] QiangGuang-1,[8] S-300,[9] and Saturn.[10] The aim of these studies was to explore the X-pinch parameters scaling with the current, to test new X-pinch load configurations, and to achieve more extreme plasma conditions at the bright spots. X-pinches at 100-500 kA pulse generators indicated that the X-pinch typical characteristics of the micron bright soft X-ray source and the nanosecond X-ray pulse could be easily realized with current rise rate of >1 kA/ns. In order to achieve this high current rise rate, the traditional pinch plasma drivers are constructed based on a high voltage pulse sharpening circuits with primary capacitor storage units, intermediate capacitor, high voltage pulse-formed switches, and pulse shaping lines.[11] These accelerators are complex in structure and large in size.

Recently, table-top-size current generators with current rise rate of >1 kA/ns were developed due to the advances of the low inductance capacitors and high voltage spark switches. The X generator, composed by the capacitor bank and multigap spark switches,[12] and the small size pulse-accumulating source (SPAS), composed by capacitor–switch assemblies,[13] were constructed at High Current Electronics, Russian Academy of Sciences for X-pinch experiments. Another type is the fast linear transformer driver (LTD) which is currently being considered as a basis for future ignition-scale pulsed-power devices.[14] A 200 kA, 150 ns LTD stage, GenASIS[15] has been used to test the cylindrical and conical wire-array Z-pinches at University of California, San Diego.

The X pinch performances depend on the facility where the experiments are fielded. Since the LTD technology is developing rapidly,[16] the X-pinch experimental results on LTD would be an essential makeup for this plasma's characteristics besides the shaping line and capacitor-switch assembly based pulsed power generators. We present the experimental investigations of X-pinches on a 100 kA, 100 ns LTD stage, which were recently completed. Two wire X-pinches made from 20 $\mu$m aluminum or 8 $\mu$m tungsten have been tested. The X-pinch radiation, bright spot sizes, X-ray burst time, and phase contrast shadowgraphy have been studied using a set of diagnostics. The experimental descriptions and example data are presented in this paper.

## II. EXPERIMENTAL SETUP

The 100 kA, 100 ns linear transformer driver was composed of 12 capacitor-switch bricks and four DG6 silicon steel magnetic cores embedded in a disk with 1.5 m in diameter and 0.21 m in height (see Fig. 1(a)). Each brick was composed of two 20 nF low inductance capacitors charged in opposite polarity ($\pm$70 kV), a multigap gas switch, and electrical buses connections. The discharging inductance of one brick was 260 nH, and the output pulse rise time was $\sim$100 ns.[17] The X-pinches were installed in a vacuum chamber at the end of the transformer secondary line and tested under a pressure below $2.0 \times 10^{-2}$ Pa. The current was monitored by two integrating Rogowski coils with one located immediately following the current-return rod (R1) and the other on the bottom plate of the generator (R2). The

 

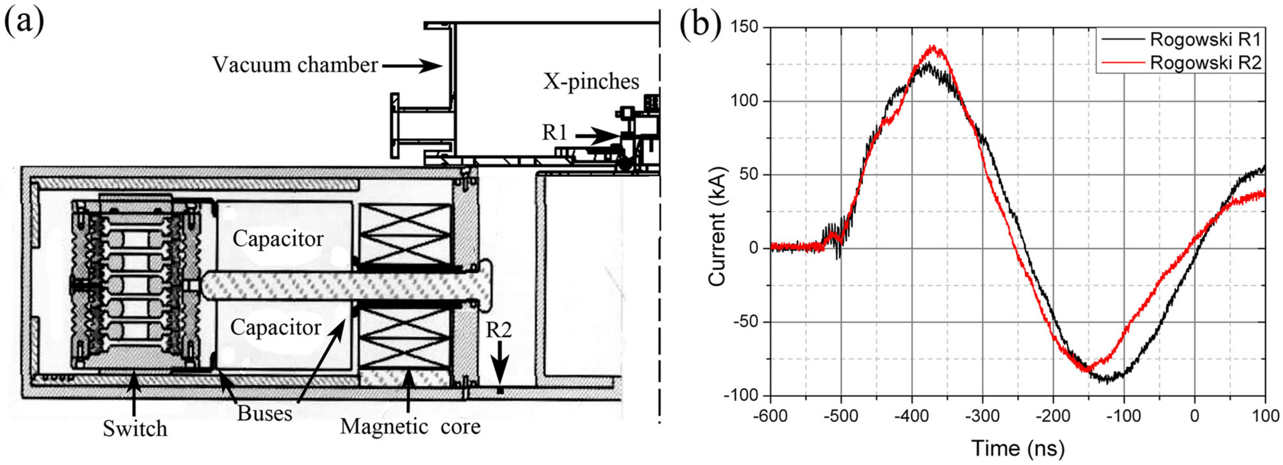


FIG. 1. (Color online) (a) Schematic of the generator. (b) Typical current waveforms with short circuit at the X-pinch place.

short current, tested by replacing the X-pinches with a copper rod in 23.5 mm diameter, reached its peak value of 132 kA with a 10%-90% rise time of 85 ns (Fig. 1(b)).

The extreme ultraviolet (XUV) and the soft X-ray powers (160-280 eV, >650 eV) were recorded by an X-ray vacuum diode (XRD) with a 2.5 $\mu$m terephthalate (Mylar) filter, see Fig. 2(a). The XRD was calibrated before the experiment in 2010 at Beijing Synchrotron Radiation Facility in energy ranges of 0.1-1.4 keV and 2.1-5.0 keV. The spectral responses of the detector with and without the filter are shown in Fig. 2(b). Two types of Si-pin detectors filtered by 12.5 $\mu$m Ti were used to measure X-rays in 3-5 keV energy band. One is the standard product AXUV-HS5 from the International Radiation Detector company (IRD), USA with a sensitivity area of 1 mm $\times$ 1 mm and a thickness of 100 $\mu$m. A sensitivity value of 0.273 A/W was used to estimate the X-ray radiation power. The other is self-developed with a sensitivity diameter of 22 mm and a thin Au foil deposited (Si-pin #1). An oscilloscope, Tektronix DPO 4104, with a sampling rate of 2.5 GS/s and passband of 500 MHz recorded the current and the detector signals, with $\sim$7 m shielded SYV-50-7 cables.

The size of the X-pinch bright spot was measured by a slit array camera with a magnification of $\sim$3.8 and a direction perpendicular to the X-pinch axis. The width of the slit was about 40 $\mu$m and the membrane material was 40 $\mu$m SUS304 steel. The slit array camera and the biological phase contrast shadowgraphs were covered by a 12.5 $\mu$m Ti filter with the X-ray pass band in the 3-5 keV. The X-ray images were recorded by Kodak Biomax-MS X-ray films and scanned into a computer for further analysis with a 4000 dpi Agfa Duoscan scanner.

## III. EXPERIMENTAL RESULTS

Fig. 3 shows the X-pinch load currents (Rogowski R1) and detector signals from shot 10014 (2-wire 20 $\mu$m Al) and shot 10017 (2-wire 8 $\mu$m W). The load currents exhibited the oscillation feature in all shots, which indicated that the current path reconnected immediately after the mini-diode broke up and X-rays burst. X-ray bursts have not been observed on the negative half-period. At the beginning of the load currents, the waveforms from these two X-pinch wire materials were nearly overlaid, but they separated at $\sim$50 ns after the current start with a slower current rise rate for the W X-pinches. A plausible explanation is that plasma impedances were quite different at the time when the mini-diode was formed. The aluminum X-pinches had a bigger initial

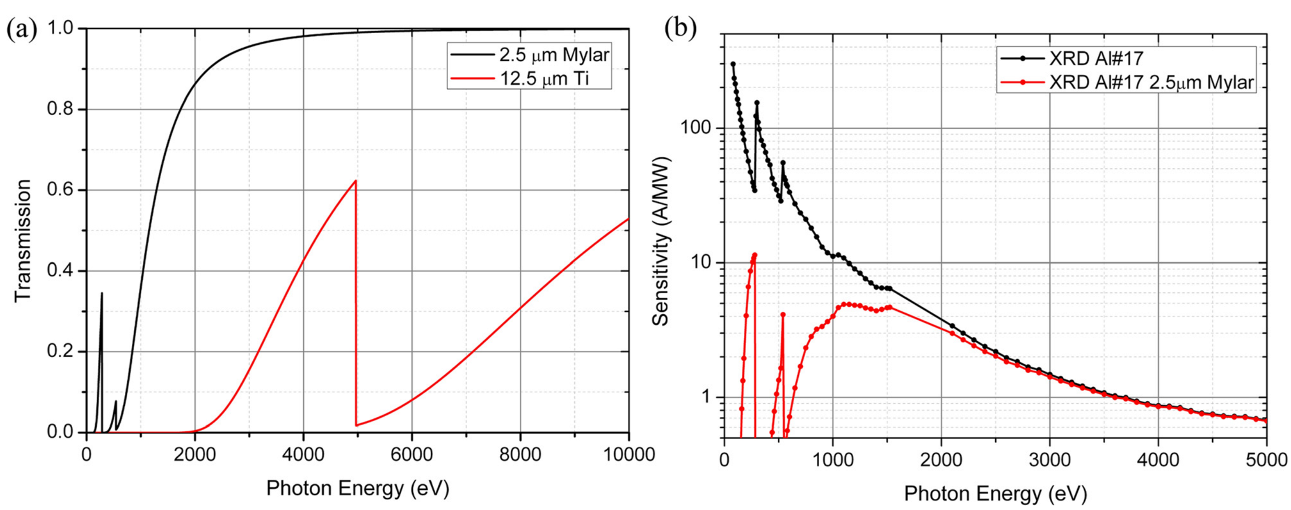


FIG. 2. (Color online) (a) Filter transmissions. (b) The XRD sensitivities with and without filters.

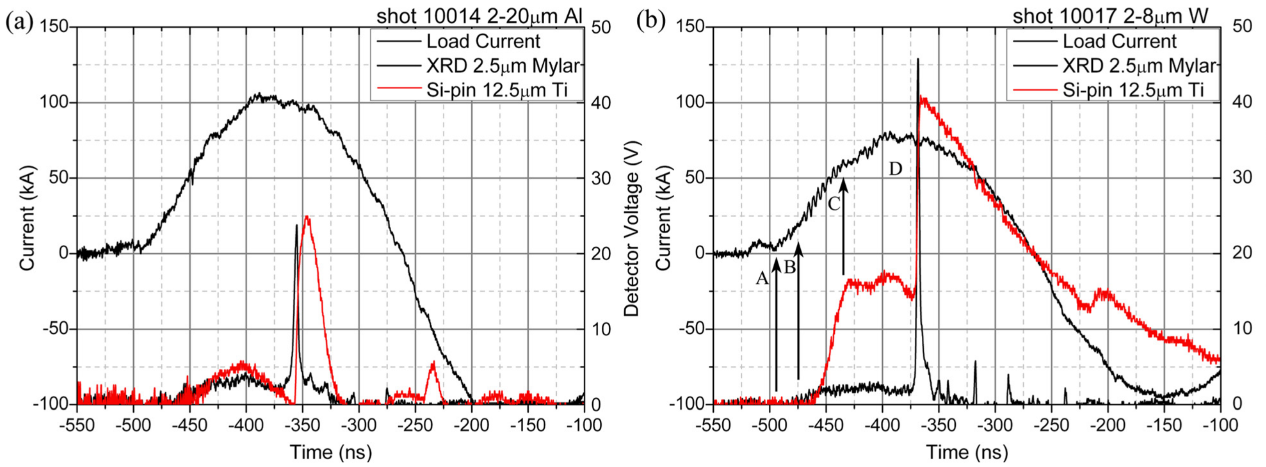


FIG. 3. (Color online) (a) The X-pinch load currents and detector signals from shot 10014 (2-wire 20 $\mu$m Al), (b) w 10017 (2-wire 8 $\mu$m).

wire diameter and a larger expanding rate than the tungsten wires. This would result in a larger diode diameter and thus smaller load impedance. The XRD detector signals began $\sim$20 ns after the current start and sustained till the bursts. The Si-pin had a poor time response and was saturated under the main X-ray bursts due to a large sensitive area of the detector. But the prepulse signal indicated that the X-ray radiation in the energy band of 3-5 keV existed before the main pulse with a larger radiation power for the tungsten wire than the aluminum. The X-pinch development stages could be identified from synthesizing the current and radiation waveforms (see Fig. 3) discussed above. The surface of the wires began to turn to plasmas at the time B when the XUV radiations started. The time C probably corresponded to the time when the mini Z-pinch plasmas and the axial jet formed.

The X-ray radiation power and energy could be estimated by taking account of the detector sensitivities and filter transmissions. The current waveform and detector signals from shot10040 (2-wire 8 $\mu$m W) are shown in Fig. 4. The signal recorded by the XRD detector gave the X-ray peak power of $\sim$175 MW, a burst full-width at half-maximum (FWHM) of 3 ns, and X-ray energy of $\sim$1.5 J. The main X-ray burst in the 3-5 keV from the AXUV-HS-5 had an X-ray peak power of $\sim$0.48 MW, a FWHM of 6 ns, and

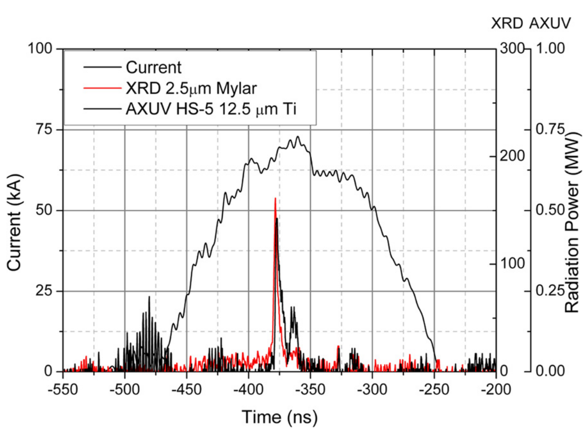


FIG. 4. (Color online) The X-pinch load currents and detector signals from shot 10040 (2-wire 8 $\mu$m W).

X-ray energy of $\sim$3.9 mJ. Another X-ray burst appeared $\sim$10 ns after the first main pulse in the AXUV-HS-5 trace but not significantly observed in the XRD signal. According to spectral responses of the detectors, we estimated that the burst was probably composed by harder X-rays (>6 keV) due to bremsstrahlung mechanism, which will be discussed below.

The example film images of the slit array from W and Al X-pinches are shown in Fig. 5. In shot 10019 (2-wire 8 $\mu$m W), the X-pinch produced three distinct bright radiation sources located within an axial distance of $\sim$300 $\mu$m. The intensity of the brightest one (Fig. 5(a), A) was much greater than the other two (Figs. 5(a), B and 5(a), C). Supposed that the source intensity had a Gaussian distribution, the FWHM of the source equaled to the distance between the 12.5% and 87.5% peak intensity points.[6] That was $\sim$11 $\mu$m for the brightest spot. Multispots were also observed at shot 10016 (2-wire 20 $\mu$m Al) of varying intensity and the source size from the brightest one was $\sim$15 $\mu$m.

There was a pattern (Fig. 5(a), C) with a width of more than 100 $\mu$m at the anode side in W X-pinch images. Since the pattern width was much larger than the slit, it was the X-ray source slit image rather than the slit backlighting shadow. From the slit pattern's location, width, and brightness, we assumed that the X-ray source is not one of the X-pinch brightspots but the anode of the mini-diode. The mini-diode structure formed about tens of nanoseconds before the bright spots appeared and radiated. After each pinching, an intense induced electric field was established with its peak value on the axis and rapidly decreases as the radial coordinate increases. Electrons were accelerated under this electric field to high kinetic energies, collided with the anode of the mini-diode, and radiated X-rays by the bremsstrahlung mechanism. This phenomenon was not been observed for X-pinches made from the light material Al in our experiments.

The first X-ray burst time as a function of the load linear mass and the crossing angle from all shots is shown in Fig. 6. The trend that the first X-ray burst time increased with the load linear mass and decreased with the load crossing angle was observed under the configurations tested. The

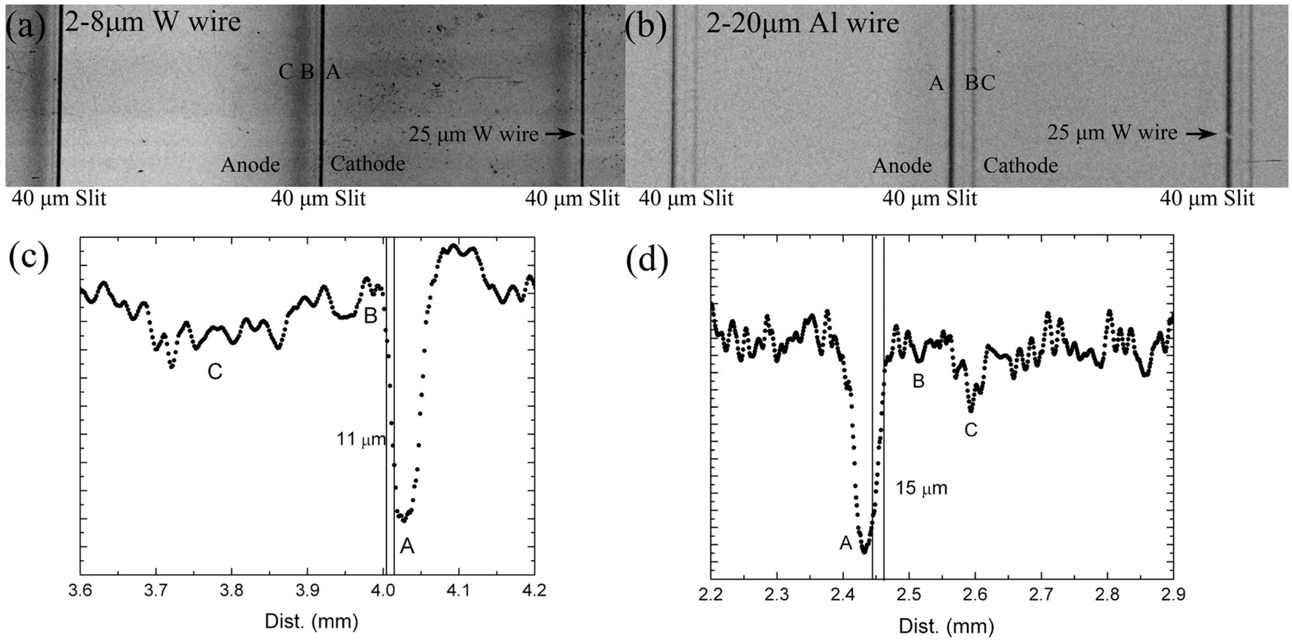


FIG. 5. (a) and (b) Example film images of the slit patterns from X-pinch of W and Al. (c) and (d) Line outs through the 40 $\mu$m slit images from parts (a) and (d). The vertical bars indicating the 12.5% and 87.5% peak intensity points.

X-ray burst jitter, which is defined as $[\sum (t - t_{av})^2/n]^{1/2}$, where $t$ is the time of the first X-ray burst and $t_{av}$ is the average time of the first X-ray burst for $n$ tests under the same conditions,[18] was ~18 ns with 2–wire 8 $\mu$m W (about 45°). The X-ray jitter was less than 5 ns on XP (400 kA, 40 ns),[18] less than 10 ns on X (260 kA, 120 ns),[12] and about 100 ns on a (320 kA, 1.2 $\mu$s) capacitor bank.[19] Our results fit the trend that the X-ray jitter probably increased with the current rise rate.

Finally, the backlighting image from shot 10014 (2-wire 20 $\mu$m Al) for a mosquito with 25 $\mu$m crossed tungsten wires installed as a spatial mark is shown in Fig. 7(a). Although the mosquito without hard bone inside has a very small absorption cross section, the legs, the body, and the structures inside were clearly visible, and some parts had comparable contrasts to the 25 $\mu$m tungsten wires. In the enlarged portions of the legs (Fig. 7(b)), we can see the sharpening edges and the apophysis on the legs. Fig. 7(c) shows the backlighting image for a heavier object, spider from shot 10037 (2-wire 20 $\mu$m Al). In the figure, only the spider profile could be observed. These results indicate that phase contrasts are much greater than the absorption contrasts in the X-pinch backlightings for the soft biological objects.

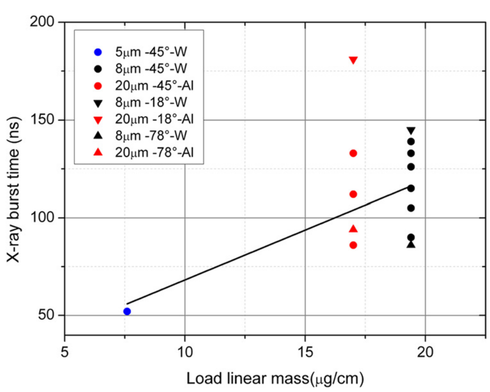


FIG. 6. (Color online) Time of the first X-ray burst as a function of the linear mass and the crossing angle.

## IV. CONCLUSIONS

Our work on a 100 kA, 100 ns linear transformer driver stage recently built up showed that the X-pinches exhibited common characteristics with the line and capacitor-bank based driver, with a source size of about 10 $\mu$m, a pulse duration of 3 ns, 3-5 keV radiation energy of 3.9 mJ, a burst time jitter of tens of nanosecond, and hard X-ray radiations caused by the bremsstrahlung mechanism using 2-wire 8 $\mu$m W X-pinches.

The results behaved a strong coupling of the load and the linear transformer driver. First, oscillating current waveforms were observed in all shots with comparable amplitude of the positive and the negative half-period. The reverse current was harmful for the capacitors. Second, the generator

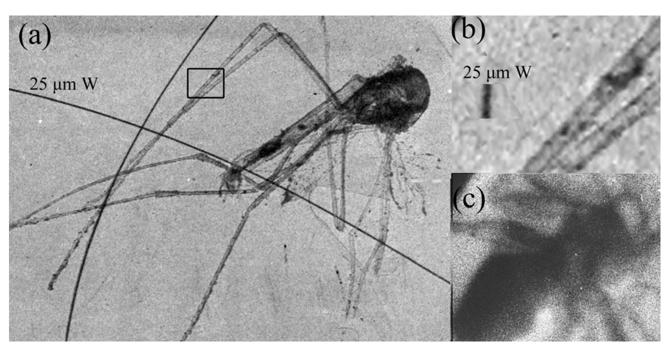


FIG. 7. The X-ray radiographs of insects taken by X-pinch X-ray sources. (a) A mosquito from shot 10014 (2-wire 20 $\mu$m Al). (c) A spider from shot 10037 (2-wire 20 $\mu$m Al). The areal density is thick for this source spectral.

output current and the X-pinch characteristics depended on the X-pinch wire materials in the tests.

## ACKNOWLEDGMENTS

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