

Studies of Implosion and Radiative Properties of Tungsten Planar Wire Arrays on Michigan's Linear Transformer Driver Pulsed-Power Generator

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Abstract—Wire arrays were widely studied as loads for Z-pinch generators in order to be used for multiple scientific applications. More recently, tungsten double planar wire arrays (DPWAs), which consist of two parallel planes of wires at a distance of a few millimeters, were suggested and tested for indirect drive inertial confinement fusion. Tungsten DPWAs have previously demonstrated the highest (among planar wire arrays) radiation yield (up to 30 kJ), compact size (few millimeters), and strong electron beam production on university-scale high-impedance Marx bank Zebra generator at University of Nevada, Reno. During the last few years, we have reported on the outcome of the experiments with uniform and mixed Al and stainless steel DPWAs on the low-impedance linear transformer driver (LTD) Michigan accelerator for inductive Z-Pinch experiments (MAIZE) generator at University of Michigan. Here, we present the results of the most recent campaigns with tungsten DPWA

loads, where the successful implosion of W wire arrays on a university-scale LTD MAIZE generator was demonstrated and analyzed. These implosions were recorded using filtered X-ray diodes, X-ray spectrometers, and pinhole cameras, and a 12-frame optical shadowgraphy system. In particular, tungsten DPWAs with a mass up to 87 $\mu\text{g}/\text{cm}$ arranged in various configurations were successfully imploded at a peak current of 0.5 MA during $\sim 190\text{--}215$ ns. The experimentally estimated changes of tungsten DPWA plasma region inductance and total load inductance were correlated qualitatively in time with X-ray bursts. In addition, on shots that demonstrated strong plasma pinching process and Faraday cup signals time were correlated with the appearance of the minimum current-carrying radius of the plasma column. In addition, analysis of soft (4–7 Å) and hard (1–2.4 Å) line radiation indicate keV M-shell tungsten (W) plasma and the presence of electron beams.

Index Terms—Optical imaging, planar arrays, plasma pinch, tungsten, X-ray spectroscopy.

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I. INTRODUCTION

ONE of the primary methods of understanding the nature of high energy density physics (HEDP) is through the radiation emitted. In particular, the radiation from HEDP plasmas produced by pulsed power continues to be a very important topic in experiments on magnetized liner inertial fusion (MagLIF) [1], and with wire array and gas puff plasmas on the largest device, high-current Z-generator at Sandia National Laboratories (SNL). Since the first wire-array tungsten (W) experiments on the Z machine at SNL, where the record X-ray power of 200 TW and X-ray yield of nearly 2 MJ were achieved [2], such arrays were actively studied and considered for various applications including inertial confinement fusion [3]. However, recently the Z-pinch generators of a new architecture started to attract more attention from the pulsed-power community. In particular, a low-impedance linear transformer driver (LTD) allows higher currents and power to be achieved. In addition, LTDs are more efficient than the widely used Marx bank generators and are being con-

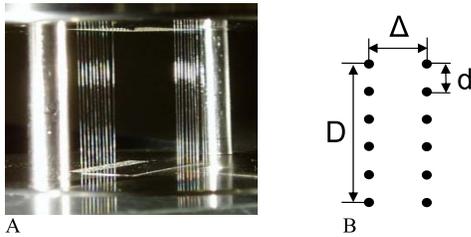


Fig. 1. Tungsten DPWA load. (a) Picture of the load. Supporting rods (at the left and at the right) will be removed before shot. (b) Schematic (axial view) of the load: d is the interwire gap; Δ is the interplanar gap, and D is the wire-array width.

sidered for future petawatt-class Z-pinch generators [4]–[7]. On the other hand, a Z-pinch implosion can produce a large increase in inductance and poor impedance matching to the generator. This is why the study of the radiative performance of Z-pinch driven by LTD modules is very important for the proposed accelerators Z 300 and Z 800, which would use LTD technology at SNL [7].

Experiments with wire arrays on the university-scale LTD generators are very important, because in contrast to large facilities, university-scale generators more readily accommodate research on novel loads, new pulsed-power technology and can be excellent test beds for the development of radiation studies of HEDP plasmas. Such novel Z-pinch loads [8]–[16], planar wire arrays (PWAs), and planar foil liners (PFLs, that might be considered in the future as an alternative load to wire arrays on 40–60 MA pulsed-power generators [10]) were suggested and tested on the high-impedance Marx bank Zebra generator (1.9 Ω , 1–1.7 MA, 100 ns) at University of Nevada, Reno (UNR), during the past decade. In particular, W double PWAs (DPWAs) had previously demonstrated the highest (among PWAs or cylindrical wire arrays) radiation yield (>30 kJ), compact size (few millimeters), and the presence of strong electron beams [8], [9], [13]. Such wire arrays are also very suitable for the new compact multisource hohlraum concept, astrophysical applications, and as an excellent radiation source [10]–[16].

During the past few years, we have reported on the outcome of the experiments with low- and mid-atomic number PWAs (Al and stainless steel, respectively) on the University of Michigan’s (UM) low-impedance LTD Michigan accelerator for inductive Z-Pinch experiments (MAIZE) generator (0.5–1.0 MA) [17]. Because there is almost no data on how wire arrays radiate on LTD-based machines in the USA, it was very important to perform radiation and plasma physics studies on such types of new generators.

Here, we present the results of the most recent campaigns with W DPWA (see Fig. 1). Diagnostics for these campaigns included fast filtered X-ray diodes, X-ray spectrometers, pinhole cameras, and a 12-frame laser shadowgraphy system. Experimental details and diagnostics are presented in Section II, implosion characteristics and radiative properties of W wire arrays on UM-MAIZE are described in Sections III and IV, respectively, and conclusions are summarized in Section V.

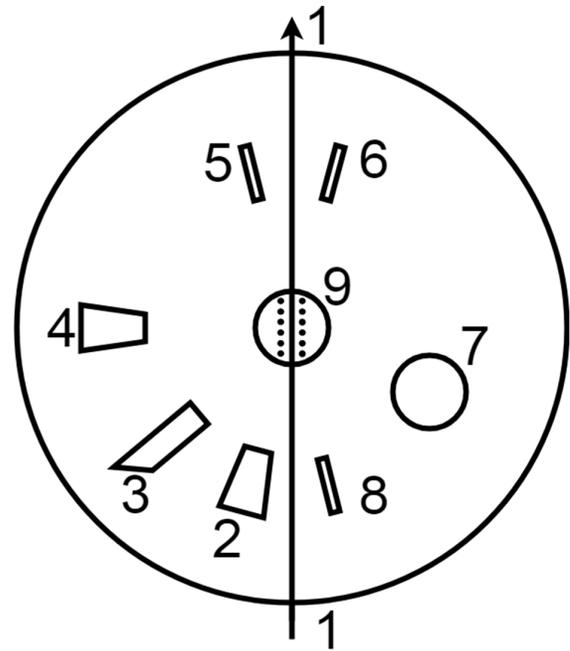


Fig. 2. Schematic (view from the top) of the MAIZE vacuum chamber with the DPWA load and X-ray, electron beam, and laser probing diagnostics. (1) Laser probing beam propagated through the load. (2) and (4) One X-ray pinhole camera placed approximately along load wire planes, and another is near orthogonal to wire planes. (3) Soft X-ray spectrometer with a KAP crystal. (5) and (6) X-ray filtered Si diodes. (7) Hard X-ray spectrometer with an LiF crystal. (8) X-ray filtered PCD detector. (9) DPWA load. The Faraday cup detector is at the top of DPWA load (not shown).

II. EXPERIMENTAL DETAILS AND DIAGNOSTICS

The UM-MAIZE LTD generator is capable of generating about 1-MA current at 100 kV across a low-inductance matched load with 100–120 ns rise time [18]. MAIZE was used as the driver for DPWAs where the array mass was restrained by the changes to wires diameter and PWA configuration: interwire gap (d), interplanar gap (Δ), and array width (D). The previous work showed that DPWA implosion dynamics depend strongly on the aspect ratio (ϕ), defined as the array width (D) divided by the interplanar gap (Δ) [8], [11]. In the experiments considered here, DPWA consisted of 8, 10, or 11 W wires of 5 μm diameter in each plane with $d = 0.7$ or 1 mm and $\Delta = 3$ or 6 mm. The aspect ratio ϕ was varied in a wide range between 0.82 and 3.33. The anode–cathode gap was 1 cm for all wire-array configurations.

The diagnostics fielded were laser shadowgraphy to study the plasma evolution at the early stages of implosion, X-ray devices (0.95–12-keV spectral region) for the investigation of plasma properties near and at the stagnation stage, and Faraday cup detectors for electron beam measurements (see Fig. 2).

The laser shadowgraphy diagnostic consisted of a 12-frame, fast framing camera, with backlighting provided by a frequency doubled Nd:YAG laser (532 nm, with pulse lengths of 2 ns) with a 10-ns interframe spacing [19]. The laser beam propagated through the load parallel to the wire planes (see Fig. 2).

The time history of X-ray yields was investigated using a side-on filtered absolutely calibrated photoconducting

diamond detector (PCD) with the cutoff energy of 2.4 keV and time resolution 0.5 ns, and three side-on filtered Si-diodes AXUV-HS5 (cutoff energies $E1/e1.4$, 3.5, and 9 keV, time resolution 1 ns). The filter cutoff energy $E1/e$ (defined by the $1/e$ transmission of the filter, where e is the base of natural logarithm) denotes a lower boundary of the radiation incident on the filtered detectors. All these detectors, positioned both in front of and behind the target, had lines of sight to the load of 15° or less, with respect to the laser probing beam (see Fig. 2). Two side-on time-integrated X-ray pinhole cameras (spatial resolution of $90 \mu\text{m}$) were employed for plasma X-ray imaging. Each of the X-ray pinhole cameras was working in three spectral bands with the cutoff energies of 1.4, 1.6, and 3.5 keV equipped with a Kodak Biomax MS X-ray film. The axis of one of the pinhole cameras was directed to a center of the load with an angle of less than 15° , again with respect to the laser beam, and another was placed with an angle of less than 100° (see Fig. 2).

Two side-on time-integrated X-ray spectroscopic devices were applied to estimate ionization balance and electron temperature (T_e) of Z-pinch plasmas. The first was the X-ray convex crystal spectrometer with a potassium acid phthalate (KAP) crystal (the double lattice spacing $2d = 26.63 \text{ \AA}$, and a radius of curvature 51 mm) with a low 1-D axial spatial resolution of 4 mm. This device was working in a spectral region between 4 and 13 \AA . Another spectrometer had a lithium fluoride (LiF) convex crystal (the double lattice spacing $2d = 4.027 \text{ \AA}$ and a radius of curvature 25.4 mm) with a low 1-D axial spatial resolution of 4 mm, and registered hard X-ray radiation in a spectral band $1\text{--}2.4 \text{ \AA}$. The protection filter in both spectrometers consisted of a $7.5\text{-}\mu\text{m}$ -thick kapton film together with a $3\text{-}\mu\text{m}$ -thick mylar aluminized from both sides by a $0.15\text{-}\mu\text{m}$ -thick Al layer.

The electron beam-current measurements were performed by a Faraday cup detector placed on axis above the anode and equipped with a $25\text{-}\mu\text{m}$ -thick Cu filter, to filter out electrons with energies less than 94 keV.

During the experiments, the UM-MAIZE was limited to 70% of the maximum charge voltage to prevent damage of the main insulator. In such conditions, the peak current was between 480 and 520 kA, the rise time was between 175 and 240 ns, and the implosion time was 190–215 ns.

III. IMPLOSION CHARACTERISTICS OF TUNGSTEN DPWAS ON THE UM-MAIZE

Tungsten DPWAs with a mass up to $87 \mu\text{g/cm}$ arranged in various configurations were successfully imploded at the current of around 0.5 MA during $\sim 190\text{--}215$ ns on the UM-MAIZE. The aspect ratios that influence the implosion dynamics of DPWAs were changed in a wide range ($\phi = 0.82\text{--}3.33$). In early experiments with Al DPWA on UM-MAIZE, the aspect ratio ϕ was also varied but up to only $\phi = 1.67$ [17]. We illustrate the results using three experiments with W DPWAs of low- and high-aspect ratios.

First, we will consider the experimental results for the low-aspect-ratio W DPWA in MAIZE shot #1252 (number of wires $N = 8 \times 8$, mass = $63 \mu\text{g/cm}$, $d = 0.7 \text{ mm}$, $\Delta = 6 \text{ mm}$,

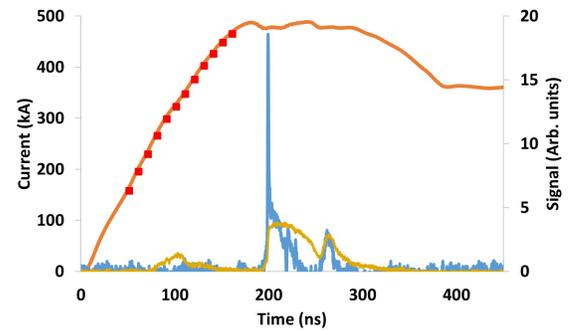


Fig. 3. W DPWA in MAIZE shot #1252 (number of wires $N = 8 \times 8$, mass = $63 \mu\text{g/cm}$, $d = 0.7 \text{ mm}$, $\Delta = 6 \text{ mm}$, and $\phi = 0.82$). Top solid line: current waveform. Middle solid line: 2.4-keV PCD signal. Bottom solid line: 1.4-keV Si-diode signal. 12 squares on current line: shadowgraphy images timing. The Si-diodes signals are not saturated, and show time history of bursts in soft region $> 1.4 \text{ keV}$.

and $\phi = 0.82$). In Fig. 3, the current, PCD, and 1.4-keV Si-diode signals, together with shadowgraphy frame timing are displayed. The peak current was $I = 489 \text{ kA}$, a current rise time was $t = 240 \text{ ns}$, and the implosion time $t_{\text{impl}} = 200 \text{ ns}$. There is the main X-ray peak at 200 ns, and smaller peaks: a 1.4-keV peak at 90–100 ns, and PCD (2.4 keV) and 1.4 keV at 275 ns. The presence of a weak X-ray burst before the main X-ray peak was typical for W DPWA loads with $\phi < 1$, and can be correlated with the beginning of the primary precursor and the standing shock formation [8], [11]. A secondary weak X-ray burst might correspond to later implosions of DPWAs due to the change in load inductance near peak current (see more data in Figs. 4–8 and a discussion as follows).

We applied the wire ablation dynamics model (WADM) [20] to optimize W DPWA loads and to analyze results. This model was successfully used in the previous work to analyze implosion characteristics of various wire loads (including PWAs) on the UNR Zebra generator [9]–[16]. This model uses the equations of motion of thin filaments carrying some current and allows momentum redistribution between the ablating wires and the ablated array plasmas [20]. The WADM does not take the different electrical circuits of each Z-pinch generators into account. Instead, it uses the current pulse measured from the experiment, as an input. For future experiments, we will estimate the max current with a Sin or Sin^2 function. This removes the need for adjustments owing to the different circuitry [20]. The electrical circuits are assumed to be sufficiently distant, such that the magnetic and electric fields are negligible. The other important variables are the load wire configuration and wire materials.

As it was observed before for DPWA loads [8]–[11], [20], each wire plane ablates in a cascade-type manner: the flows of the ablated plasmas from the left and right edges of each wire plane first will merge in front of the centers of the planes and then two resultant plasma jets will merge at the geometric center of the DPWA [11], [20]. These specific features define the implosion characteristics of DPWAs. However, DPWA dynamics also strongly depend on the global magnetic field geometry which is determined by the aspect ratio ϕ . The global magnetic field penetrates to the central axis of symmetry for

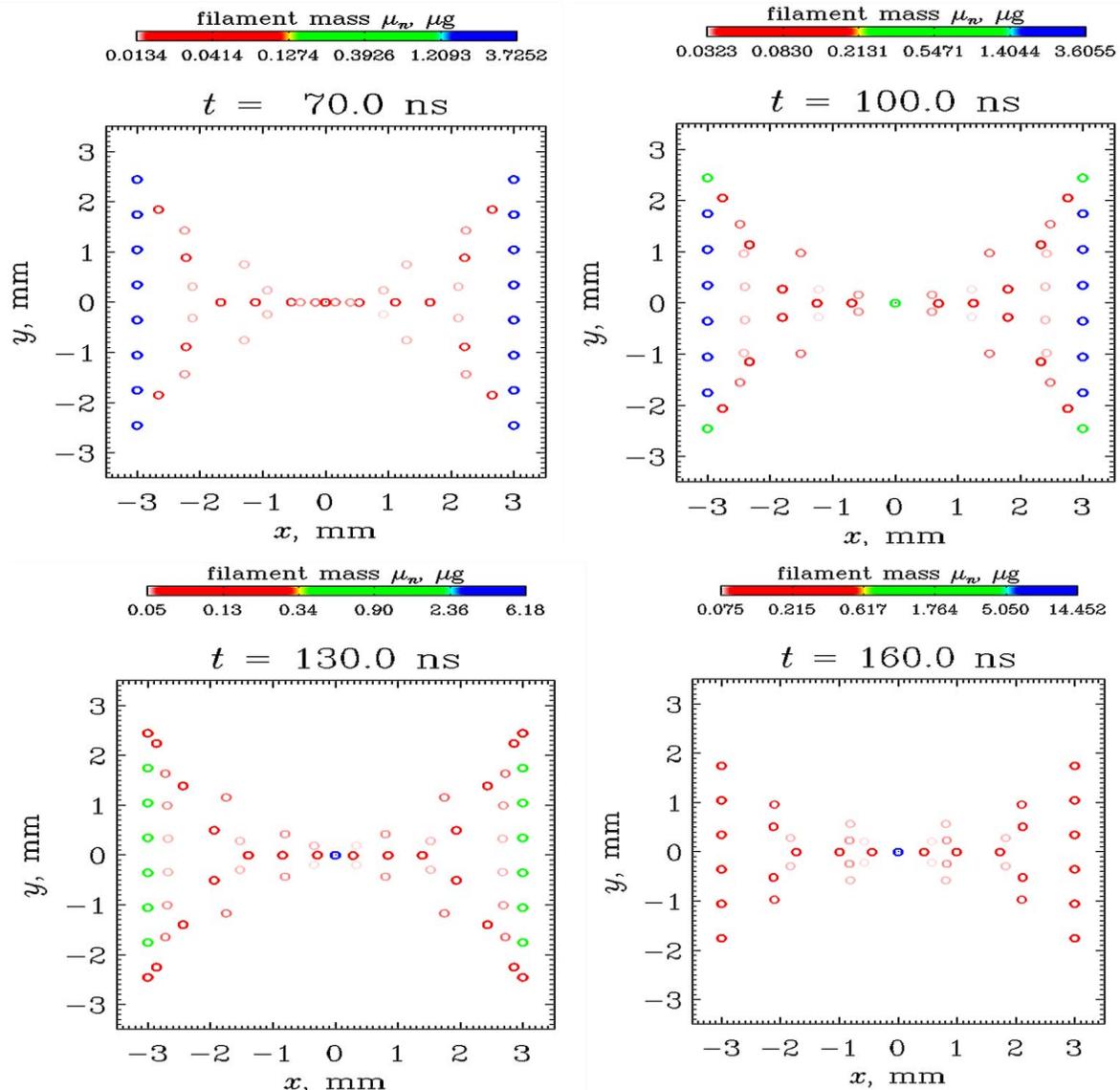


Fig. 4. WADM numerical calculation for the W DPWA shot #1252 (top view): W wire diameter = $5 \mu\text{m}$, number of wires $N = 8 \times 8$, mass = $63 \mu\text{g/cm}$, $d = 0.7 \text{ mm}$, $\Delta = 6 \text{ mm}$, and $\phi = 0.82$.

loads with a low aspect ratio $\phi \leq 0.8\text{--}0.9$. In this case, the DPWA might behave almost as two isolated single PWAs because the DPWA loses inductive coupling. Illustrations using WADM predictions for the MAIZE shot #1252 (with the aspect ratio $\phi = 0.82$) are presented in Fig. 4. The formation of the plasma mass (primary precursor) at central load axis was predicted at 70 ns after current start, and creation of additional mass near precursor (might be the standing shock) in interval 70–100 ns was expected. Interestingly, no precursor was observed for such low aspect ratio ($\phi < 0.8\text{--}0.9$) DPWAs on the high-impedance Z-pinch generator [11], but some precursor formation was seen before in Al DPWAs on UM-MAIZE [17].

The 12 shadowgraphy images (from 50 to 160 ns after current start) are displayed in Fig. 5. The experimental results described in the following show a good match with the WADM predictions. These images correspond to the independent

ablation of each wire plane of the DPWA at an early time between 50 and 100 ns after the current start. Some primary precursors (as in [8] and [11]) were observed and correlated with the appearance of a small 1.4-keV pulse. This phenomenon was not seen in the previous experiments (with similar low ϕ loads) conducted on Zebra at UNR [11]. Later time frames (100–120 ns) continued to display standing shocks and a very nonsymmetrical column of what seems to be a precursor. Frames at 130 ns and later became substantially influenced by self-emission. These pictures resemble the process of an Al DPWA (low $\phi = 0.58$) implosion as seen in the previous campaign [17]. An evidence of the precursor and standing shock formations (as seen before on high-impedance Zebra for DPWAs [11] and more complex PWAs [21]) at/after 100 ns indicates that the implosions of the outmost wires in each wire plane have probably begun, after 130 ns in particular. This agrees with WADM predictions (see Fig. 4, $t = 160 \text{ ns}$).

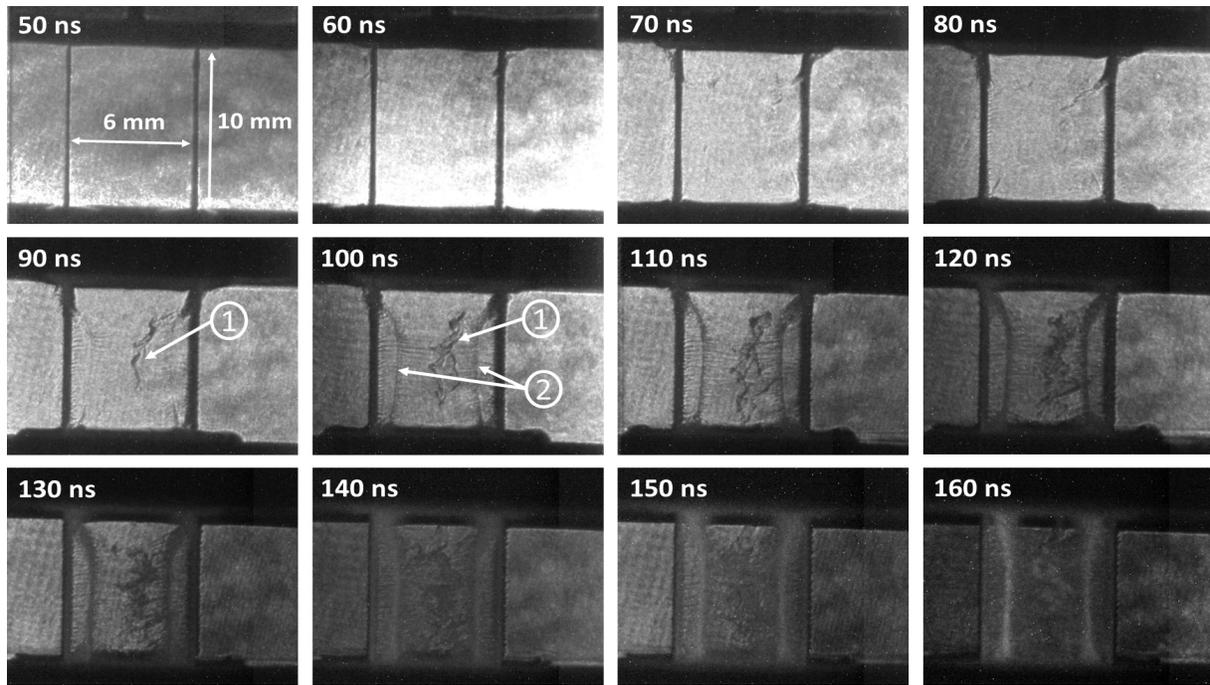


Fig. 5. W DPWA in MAIZE shot #1252. 12 shadowgraphy images for the period from 50 to 160 ns after the current starts. The anode is at the top. The view is along wire planes. The position of the primary precursor is marked by “1,” and the standing shocks are marked by “2.” Number of wires $N = 8 \times 8$. The anode–cathode gap of 1 cm, $d = 0.7$ mm, $\Delta = 6$ mm, and $\varphi = 0.82$.

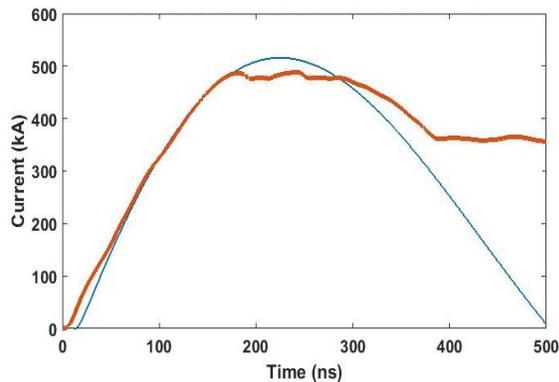


Fig. 6. W DPWA, shot #1252. Simulated current (thin line) versus measured by B-dots (thick line). The aspect ratio $\varphi = 0.82$.

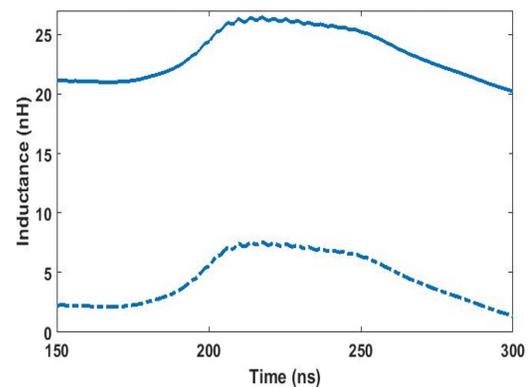


Fig. 7. Time dependences of plasma region inductance (dotted line) and total load inductance (solid line) for W DPWA shot #1252. The aspect ratio $\varphi = 0.82$.

A low-impedance pulsed-power driver, such as an LTD, delivers a current pulse that strongly depends on the load inductance [22]. Combined with a proper understanding of the total machine impedance, this dependence allows us to extract information about the time evolution of the inductance of a load from a measurement of current [22]. Understanding the behavior of the inductance will help us to better optimize future loads as well as measure the strength of the pinching. The general procedure for calculating inductance requires a suitable, time-averaged load inductance and resistance along with a full circuit model of MAIZE. (See [22] for the full MAIZE circuit model, including the equivalent inductance, resistance, and capacitance of the generator, and transmission line sections.) The change in load inductance at the time of the pinch was treated as a small perturbation in the total device

impedance, approximating the energy stored in the magnetic field due to load current as constant over the relatively short pinch timescales. Previously, time-averaged circuit parameters were determined by locating the intersection of peak current and rise time contours in an inductance–resistance phase space. This process required that peak current occurred prior to the pinch, such that the current pulse up to peak current was unperturbed by prompt changes in load impedance. Because the wire implosions presented in this paper exhibit pinching prior to reaching peak current, alternative means of estimating the unperturbed, time-averaged load parameters were employed.

The initial equivalent partial inductance of each load was calculated from the partial self-inductance of each wire, the partial mutual inductance between wires, and the partial

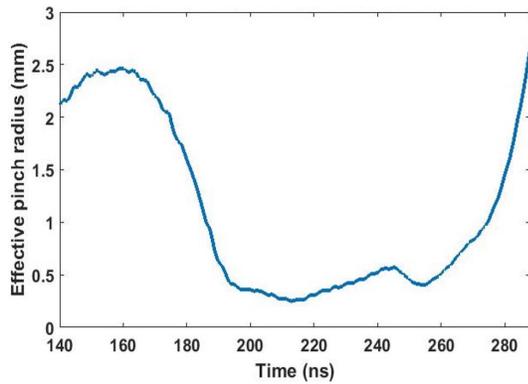


Fig. 8. Time dependences of estimated plasma effective radius for W DPWA shot #1252. The aspect ratio $\phi = 0.82$.

mutual inductance between each wire and the six axial return posts of the load hardware. Other stray partial mutual inductances vary negligibly from shot-to-shot and are absorbed into the partial inductance of the transmission line section in the circuit model. Increasing the wire radius in these calculations by as much as two orders of magnitude changed the equivalent load inductance by only a few percent (changing the total machine inductance by less than 0.3% in all cases). It was, therefore, assumed that wire explosion had a negligible effect on inductance, and that all observable inductance changes were due to the motion of wire cores (i.e., the pinch process). The calculated initial inductance was, therefore, used as the unperturbed (prepinch) load inductance in a simulated current pulse, which is compared to the experimental measurement (Fig. 6). The time-averaged load resistance for the simulated current is chosen to match the slope of the measured current early in time and provide the best possible agreement with the measured current pulse during the portion of the rise time when the load is in the plasma phase but has not yet begun to pinch (roughly 50–150 ns for most shots) [22]. The moment the wires enter, the plasma phase appears on the measured current as a “notch” roughly 30–50 ns into the shot (Fig. 6).

As in [22], the characteristic load inductance and resistance are used to establish a predicted current from simulation in the absence of a pinch. Time-dependent inductance can be computed from $L(t) = L(0) \cdot (I_{\text{predicted}})^2 / (I_{\text{measured}})^2$ assuming the pinch occurs on a timescale that is fast enough that the energy stored in the magnetic field of the load current is roughly constant. Fig. 7 shows the sample inductance calculations using this method. This inductance is then used to estimate an effective current-carrying radius (Fig. 8), i.e., the radius of a single, uniform plasma column with the same inductance as the calculated inductance of the load [22]. This effective radius is a qualitative estimation of pinching intensity that provides a characteristic length scale describing the average radial location of current over the course of the plasma pinching [22]. The experimentally estimated changes of W DPWA plasma region inductance and total load inductance were correlated qualitatively in time with the main (at ~200–225 ns) and secondary (at ~255–275 ns) X-ray bursts (both for >1.4 keV and >2.4 keV regions) on shot that demonstrated strong plasma pinching process (Figs. 3 and 7).

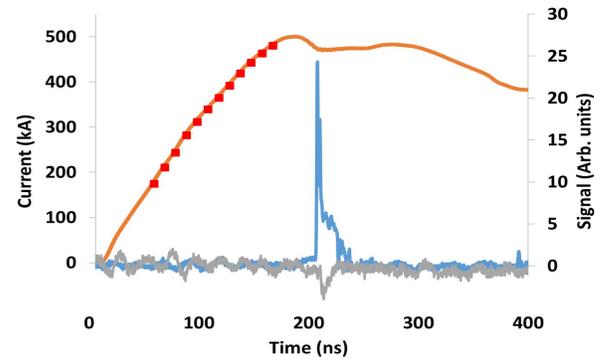


Fig. 9. W DPWA in MAIZE shot #1246. Top solid line: current waveform. Middle solid line: 2.4-keV PCD signal. Bottom line: Faraday cup signal. 12 squares on current line: shadowgraphy images timing. The aspect ratio $\phi = 3$.

The magnitude of inductance change was correlated with amplitude of X-ray detector signals (1.4 and 2.4 keV) at ~200–225 ns and 255–275 ns. Also, the moments of the appearance of a minimum current-carrying radius (~0.25 mm at 215 ns and ~0.35 mm at 255 ns) agreed qualitatively with the time of the main and secondary X-ray bursts (Figs. 3 and 8). It represents another proof of conclusion from [22] that the inductance change magnitude can likely be used as a figure of merit describing the intensity of a pinching of DPWA plasmas.

For DPWA loads with a high aspect ratio ϕ , the global magnetic field is effectively excluded from the interior of a load and the precursor is formed, which is illustrated here using the MAIZE shot #1246 (mass = 79 $\mu\text{g}/\text{cm}$, $d = 1$ mm, $\Delta = 3$ mm, wires number $N = 10 \times 10$, and $\phi = 3$). In Fig. 9, the experimental results for MAIZE shot #1246 are shown: current and PCD (>2.4 keV) signals, and Faraday cup burst (electrons with energy > 94 keV) together with shadowgraphy timing. Maximum of the current was $I = 500$ kA, the current rise time was $t = 185$ ns, and the implosion time $t_{\text{impl}} = 205$ ns corresponding to the main X-ray peak (>2.4 keV). The Faraday cup peak burst was at 205–210 ns which correlated well with the main X-ray burst.

The 12 shadowgraphy images (from 53 to 163 ns after the current start) are displayed in Fig. 10. These images correspond to ablation of both planes of the W DPWA at the early time (53–93 ns) with observable mass accumulation on axis and beginning of the precursor formation (see Fig. 10). Indeed, shadowgraphy recorded the precursor formation between 93 and 163 ns with the observation of the disturbance zone near the anode that occurs in most DPWA loads with high ϕ [17]. In the interval 153–163 ns, frames displayed synchronized implosion of two wire planes slowly moving to the center axis and started to connect in the center with formation later plasma column at stagnation stage (not seen for this shot). Basically, these frames resemble the process of stainless steel DPWA (high $\phi = 1.67$) implosion at the early LTD MAIZE experiments [17].

The experimentally estimated changes of W DPWA plasma region inductance and total load inductance were correlated qualitatively in time with X-ray burst (at ~205–230 ns) for

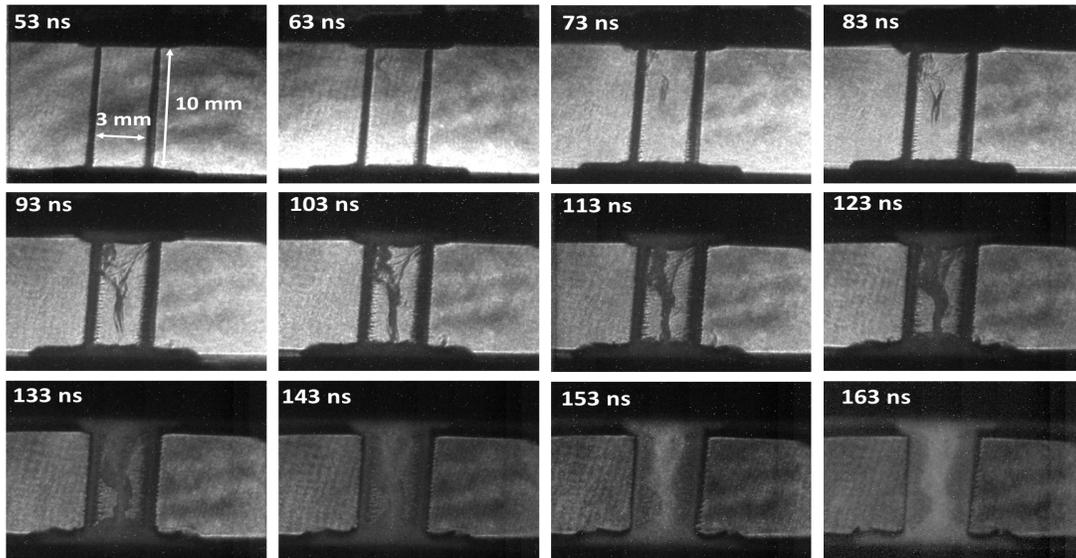


Fig. 10. W DPWA in MAIZE shot #1246. 12 shadowgraphy images for the period from 53 to 163 ns after the current starts. The anode is at the top. The view is along wire planes. Number of wires $N = 10 \times 10$. The anode-cathode gap is 1 cm, $d = 1$ mm, $\Delta = 3$ mm, and $\phi = 3$.

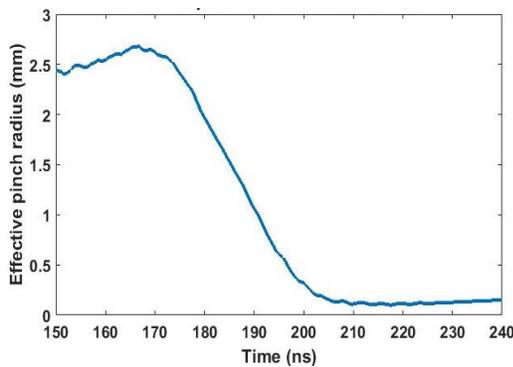


Fig. 11. Experimentally estimated time dependences of plasma effective radius for W DPWA shot #1246. The aspect ratio $\phi = 3$.

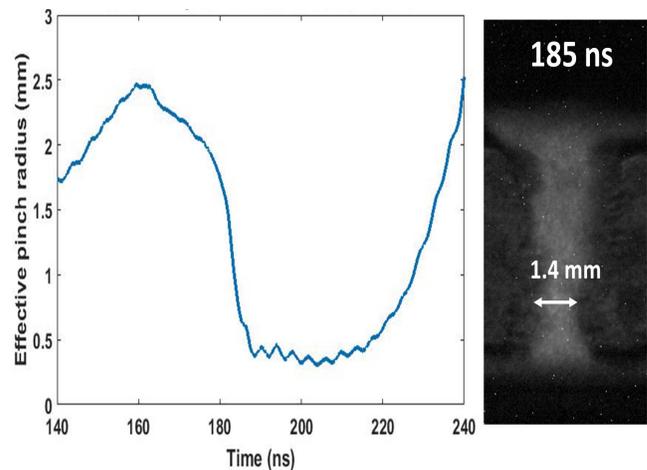


Fig. 12. Experimentally estimated time dependences of plasma effective radius for W DPWA shot #1244 (left), and direct measurement of a minimum diameter of plasma column at a time just 5 ns before main X-ray burst (right). The aspect ratio $\phi = 2.33$.

>2.4 keV region, and Faraday cup signal (>94 -keV electrons energy) on shot that demonstrated strong plasma pinching process (Figs. 9 and 11). Also, the moment of appearance of a minimum current-carrying radius of plasma column (~ 0.12 mm at 210–215 ns) was also correlated qualitatively with the time of main X-ray burst (Figs. 9 and 13).

A direct measurement of the minimum radius of the plasma column was performed using shadowgraphy images for W DPWA for MAIZE shot #1244 with a high aspect ratio $\phi = 2.33$ (mass = $63 \mu\text{g/cm}$, $d = 1$ mm, $\Delta = 3$ mm, wires number $N = 8 \times 8$), whereas the last image frame (185 ns after current start) occurred closest to the main X-ray burst. The experimental results for this high-aspect-ratio MAIZE shot #1244 were: the peak current was $I = 482$ kA, the current rise time was $t = 175$ ns, and the implosion time was $t_{\text{impl}} = 190$ ns. The main X-ray burst in a spectral region > 2.4 keV occurred at 190 ns. The 12 shadowgraphy images were obtained from 75 to 185 ns after the current start. Because the dynamics of the plasma implosion of shot #1244 closely resembled that of MAIZE shot #1246 with similar high aspect ratio, we are showing only the

last image frame at 185 ns after current start, which was used for the measurements of the Z-pinch size and which shows good reproducibility of results for W DPWAs of the same geometry (Fig. 12). The experimentally estimated changes of W DPWA plasma region inductance and total load inductance were correlated qualitatively in time with the main X-ray burst (at ~ 185 – 195 ns) for >2.4 keV region, on shot #1244 that demonstrated strong plasma pinching process (Fig. 12). The moment of appearance of a minimum diameter of the plasma column was correlated qualitatively with the main X-ray burst [Fig. 12 (right)]. Direct measurement indicates that this diameter was from 1.4 to 2.8 mm (radius 0.7–1.4 mm), that corresponds qualitatively to estimated time dependences of plasma effective radius [Fig. 12 (left)] about 0.5–0.6 mm at 185 ± 2 ns.

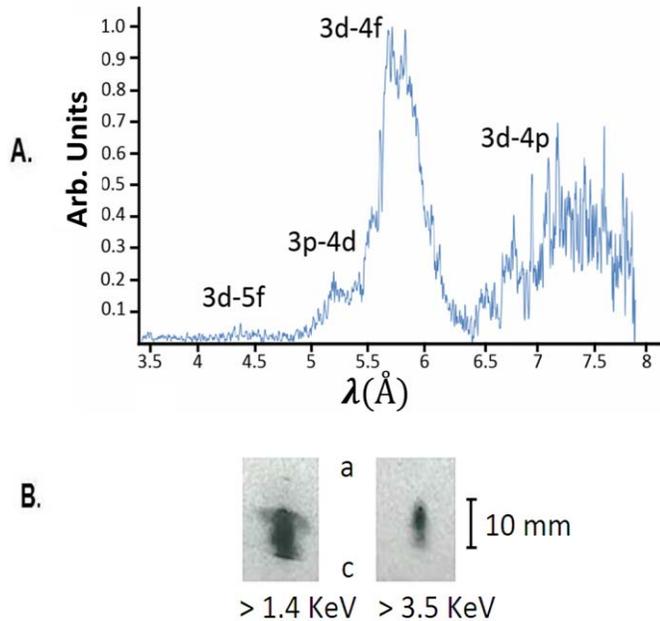


Fig. 13. (a) Time-integrated X-ray M-shell spectrum of W DPWA (shot #1252, $N = 8 \times 8$, $\phi = 0.82$, mass $63 \mu\text{g}/\text{cm}$) from the MAIZE LTD. (b) Time-integrated pinhole images from W DPWA experiment (shot #1252). Anode is at the top.

Also, we can conclude that the dynamics of W DPWA implosions with high $\phi \sim 2-3$ on a low-impedance LTD generator are different from results obtained for $\phi < 1$.

IV. RADIATIVE CHARACTERISTICS OF TUNGSTEN DPWAS ON THE UM-MAIZE

The shape of X-ray radiation signals from PCD and Si detectors (Figs. 3 and 9) in the experiments on the UM-MAIZE LTD generator indicated good implosion of W DPWAs and resembles signals obtained early on the Marx bank Zebra machine.

During the W DPWA experiments on the UM-MAIZE generator, the X-ray spatially resolved time-integrated (SRTI) spectra in the spectral region of $4-7 \text{ \AA}$ [Fig. 13(a)], and X-ray time-integrated pinhole images (the cutoff energies: 1.4 and 3.5 keV that correspond wavelength $3.5-8.9 \text{ \AA}$, [Fig. 13(b)]) were collected. Though implosion characteristics of low- and high-aspect-ratio W DPWAs are different as discussed in Section III, M-shell W spectra look very similar. In particular, the M-shell W spectral features are dominated by Ni-like W ions due to 3d-4f, 3d-4p, 3p-4d, and 3d-5f transitions and include higher than Ni-like ionization stages, which indicate keV W plasma [16], [23]–[25] that seems to be of a high electron temperature for such a university-scale LTD generator. Similar M-shell W spectrum was observed for shot #1246 of different load parameters: $N = 10 \times 10$, $\phi = 3$, mass $79 \mu\text{g}/\text{cm}$ (not shown here).

Also, SRTI spectra were registered in the spectral region $1-2.4 \text{ \AA}$ (Fig. 14). These data show intense characteristic “cold” L-shell lines of W, which is evidence of strong electron beam in W plasma. For W DPWAs, most of the intense W L-shell lines were localized near the cathode, however,

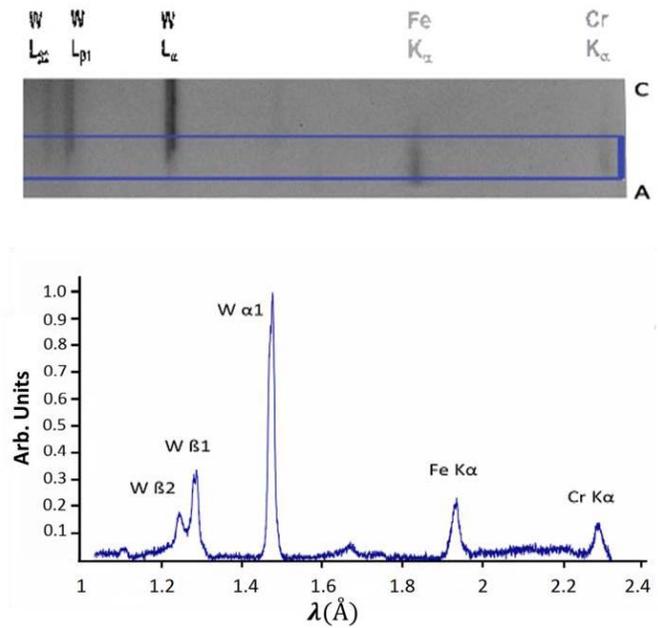


Fig. 14. Time-integrated, spatially resolved-hard X-ray W DPWA spectrum (top) (shot #1246, $N = 10 \times 10$, $\phi = 2.33$, and mass $79 \mu\text{g}/\text{cm}$ at the MAIZE LTD generator). The lineout taken closer to the anode (location is indicated by the blue box at the top) with strong “cold” spectral lines of W material and “cold” Fe and Cr lines of stainless steel anode (bottom). The anode is at the bottom.

the intense beam-excited “cold” Fe and Cr K-shell lines near the anode are also present. The measured electron beam current (with electron energies $> 94 \text{ keV}$) was of 10.9 kA for MAIZE shot #1246. Average electron beam current (with high electron energies $> 94 \text{ keV}$) for W DPWAs with $\phi > 1$ was 13 kA, and for W DPWAs with $\phi < 1$ was 15 kA (approximately 3% of the total MAIZE current for W DPWA shots). The experimental error was 35%. For comparison, the electron beam current in experiments with W DPWA on the Marx bank generator Zebra was 20–35 kA [26], which is approximately up to 4% of the total Zebra current.

V. CONCLUSION

For the first time, the implosion of a tungsten (W) double planar wire array (DPWA) on Michigan’s LTD generator was demonstrated in reproducible shots and analyzed. As it was found in our early LTD research with Al and stainless steel DPWAs, the experiments with W DPWA were characterized by longer current rise time compared to similar loads on high-impedance Z-pinch generator. In particular, W DPWAs with a mass up to $87 \mu\text{g}/\text{cm}$ arranged in various configurations were successfully imploded at the current of 0.5 MA during $\sim 190-215 \text{ ns}$.

The diagnostics package consisted of laser shadowgraphy setup for monitoring plasma evolution at early stages of its implosion, X-ray devices ($0.95-12\text{-keV}$ spectral region) for investigation of plasma radiative properties near and at the stagnation plasma stage, and Faraday cup detectors for plasma electron beam measurements. The experimentally estimated changes of W DPWA plasma region inductance and total load

inductance were correlated qualitatively in time with X-ray bursts, Faraday cup signals, and appearance of a minimum current-carrying radius of plasma column on shots that demonstrated strong plasma pinching process. It was observed that the implosion dynamics of a W DPWA with low aspect ratio $\phi < 1$ (array width to interplanar gap Δ) was very different from that of W DPWA with $\phi > 1$. In particular, for the low-aspect-ratio W DPWAs, the 12-frame system shows the ablation of both wire-array planes and formation of nonintense precursor and standing shocks 90–100 ns after the current start. The presence of a preliminary weak X-ray burst (~ 100 ns after current start) before the main peak was typical for all W DPWA loads with $\phi \leq 1$. For most of high-aspect-ratio W DPWAs with $\phi > 1$, laser shadowgraphy images correspond to ablations of both planes of W DPWA at the early time (50–90 ns) with observable mass accumulation on an axis, and beginning of a strong precursor formation. After ~ 90 ns, the shadowgraphy recorded precursor images (93–163 ns) with the observation of a disturbance zone near the anode. Between 153 and 163 ns frames displayed what seems to be a synchronized implosion of two wire planes slowly moving to the center load axis, which started to connect in the center with the later plasma column formation at stagnation stage (at approximately 205–215 ns) with generation of 2–3 closely placed X-ray bursts. Also, the moment of appearance of a minimum radius of the plasma column was correlated qualitatively well with the time of the main X-ray burst. Direct measurement using shadowgraphy images show that the minimum diameter was 1.4 mm, which corresponds well to estimated time dependences of plasma effective radius about 0.5–0.6 mm at 185 ± 2 ns.

Soft X-ray spectroscopy in the spectral region of 4–7 Å and X-ray images in region 3.5–8.9 Å highlight intense M-shell W spectral features that indicate the existence of keV “hot” W plasmas. Hard X-ray spectroscopy in the spectral region of 1–2.4 Å demonstrates intense characteristic “cold” W L-shell lines localized near the cathode and Fe and Cr K-shell lines near the anode, and hence the presence of the strong electron beam with average electron beam current around 15 kA (for electron energies > 94 keV).

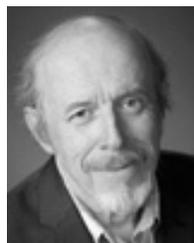
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