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CHARACTERISTIC EFFECTS OF PULSED POWER GENERATORS OF DIFFERENT ARCHITECTURE ON THE IMPLOSION DYNAMICS OF MID-Z_a DOUBLE PLANAR WIRE ARRAYS

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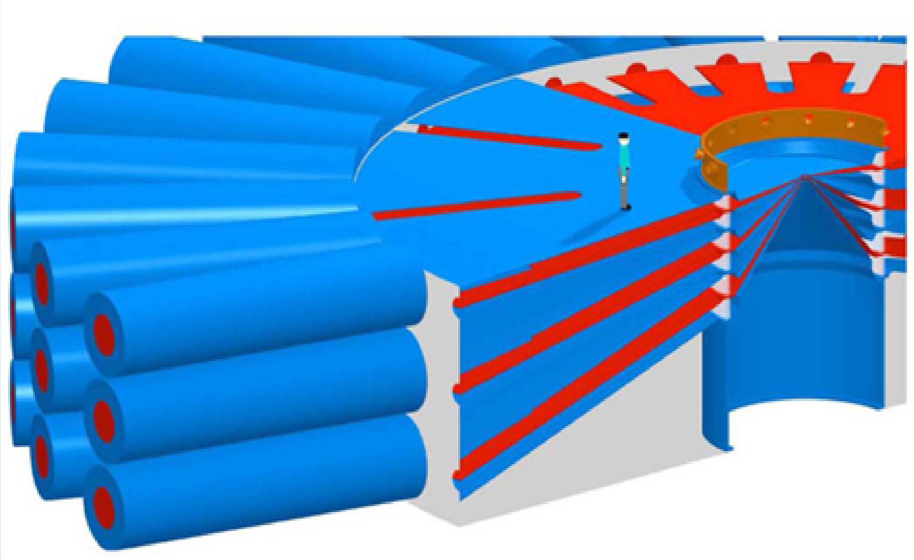
Introduction and Motivation

- The linear transformer driver (LTD) is a modular induction cavity that can be configured to produce a high voltage pulse of 70 to 300 ns length, with at least twice the efficiency of the conventional Marx bank machines.

- Because there is very limited data on how wire arrays and foil liners radiate on LTD-based machines in the USA, it is very important to perform radiation and plasma physics studies on these new type of generators.



As an example of the potential of this LTD technology, this figure from Stygar *et al** is a conceptual design for Z-300, a proposed machine based on the LTD architecture. The Marx's bank Z facility is a 26 MA, 22 MJ, 80 TW driver in a 33-m diameter. The conceptual Z-300 LTD would be a 50 MA, 50 MJ, 300 TW driver in a 35-m diameter.

*W. A. Stygar, T.J. Awe, J.E. Bailey et al, Phys. Rev. ST Accel. Beams 18, 110401 (2015)

M. G. Mazarakis, W. E. Fowler, K. L. LeChien et al, IEEE Trans. Plasma Sci. 38, 704 (2010)

M. G. Mazarakis, W. E. Fowler, A. A. Kim et al, Phys. Rev. ST Accel. Beams 12, 050401 (2009)

A. A. Kim, M. G. Mazarakis, V. A. Sinebryukhov et al, Phys. Rev. ST Accel. Beams 12, 050402, (2009)

Introduction and Motivation (cont.)

- Brass Double Planar Wire Arrays (DPWAs) on the University of Nevada, Reno's (UNR) high-impedance Zebra Marx bank generator (1.9 Ω, 1 MA, 100 ns) were published earlier, and showed them to be excellent radiators on the Zebra generator. Likewise, DPWA's of other materials on 1-MA university scale Z-pinch generators have also shown them to be great x-ray radiators.

- In addition to being excellent radiators of x rays, PWA sources have applications in inertial confinement fusion (including the new compact multisource hohlraum design), astrophysical studies, and lasing research.

V. L. Kantsyrev, L. I. Rudakov, A. S. Safronova *et al*, Phys. Plasmas 15, 030704 (2008).
B. Jones, D. J. Ampleford, R. A. Vesey *et al*, Phys. Rev. Lett. 104, 125001 (2010).
V. L. Kantsyrev, A. S. Chuvatin, L. I. Rudakov *et al*, Phys. Rev. E 90, 063101 (2014).
A. S. Safronova, V. L. Kantsyrev, A. A. Esaulov *et al*, J. Phys.: Conf. Ser. 244, 032031 (2010).
M. E. Weller, A. S. Safronova, V. L. Kantsyrev *et al*, Phys. Plasmas 21, 031206 (2014).

Experimental Description

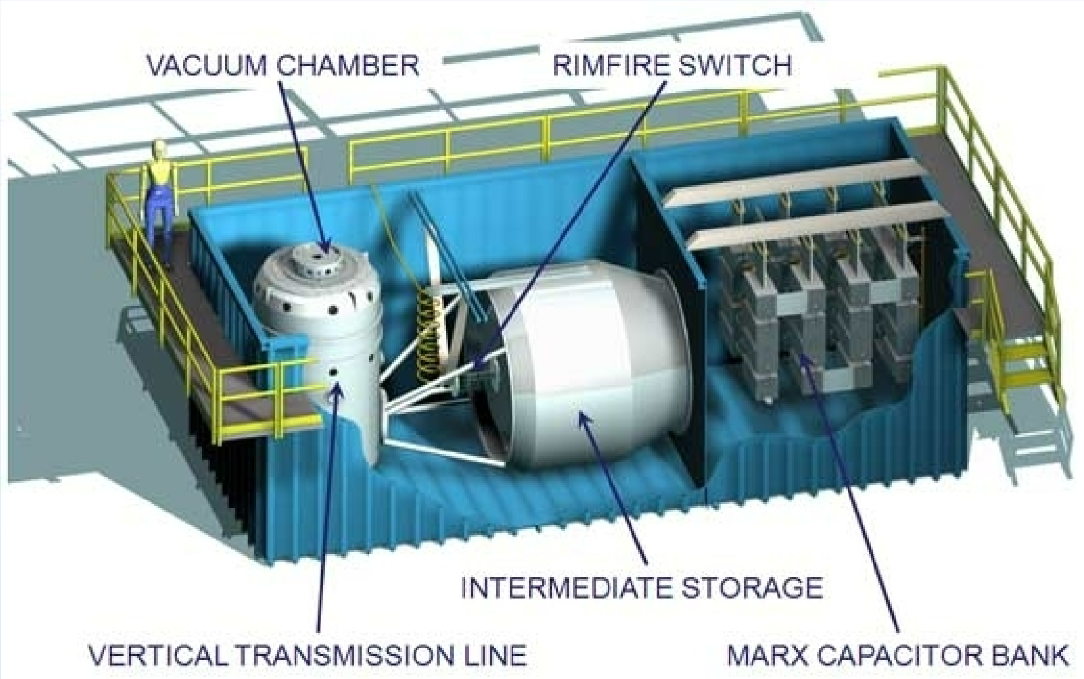
- Experiments were performed with DPWA loads on the University of Michigan's (UM) low-impedance Linear Transformer Driver (LTD) MAIZE generator (0.1 Ω , 0.5-1 MA, and 100-250 ns).

- Recently, results of the implosion dynamics and radiative characteristics with high-Z_a Tungsten (W) and low-Z_a Aluminum (Al) DPWAs on the MAIZE generator have been published. Brass [an alloy of mid-Z_a elements Copper (Cu) and Zinc (Zn)] was also studied on the MAIZE generator to fully understand the implosion dynamics of low- to mid- to high-Z_a elements, which is a main topic of this talk.

N. D. Ouart, A. S. Safronova, V. L. Kantsyrev *et al*, IEEE Trans. Plasma Sci. 38 (4), 631 (2010).
A. S. Safronova, V. L. Kantsyrev, M. E. Weller *et al*, IEEE Trans. Plasma Sci. 44 (4), 432 (2016).
V. L. Kantsyrev, A. S. Safronova, V. V. Shlyaptseva *et al*, IEEE Trans. Plasma Sci. 46 (11), 3778 (2018).
C. J. Butcher, V. L. Kantsyrev, A. S. Safronova *et al*, Phys. Plasmas 28, 082702 (2021).

Two University Scale Z-pinch Generators of Different Architecture

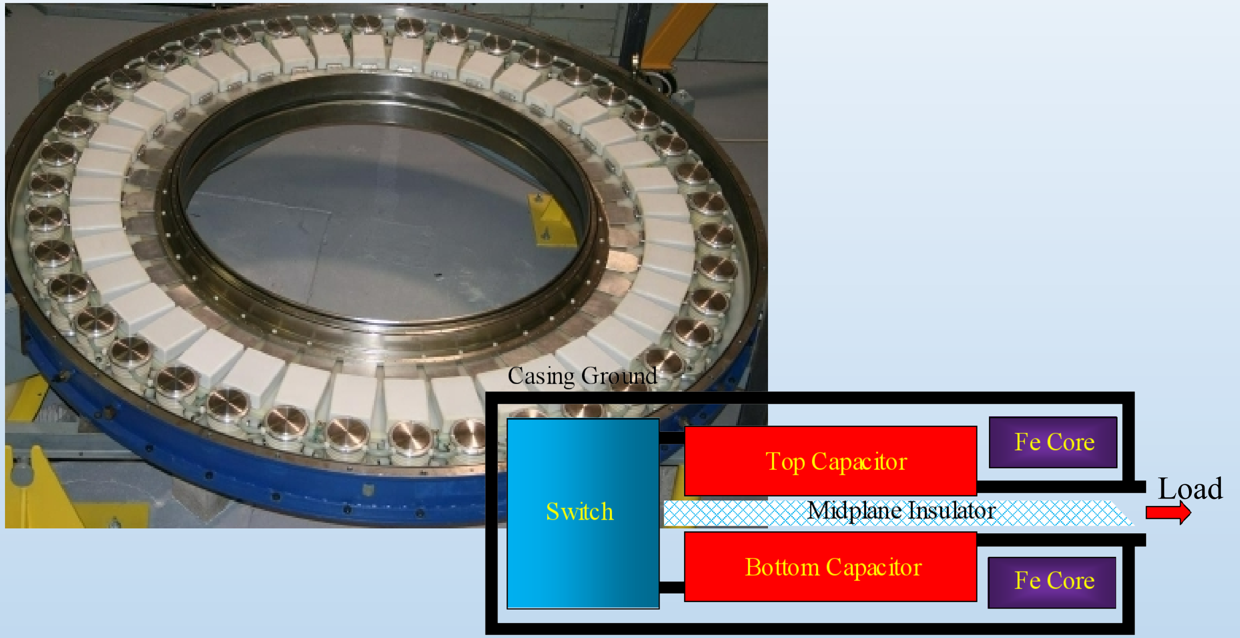
UNR Zebra Marx bank Generator



Zebra has a high impedance of 1.9 Ω, 1 MA of current (1.7 MA with Load Current Multiplier), up to 150 kJ of stored energy, and a fast rise-time of 100 ns.

Image Credit: Nevada Terawatt Facility [Cut away view of the Zebra generator]. Retrieved from https://www.unr.edu/ntf/facility/zebra

UM MAIZE Linear Transformer Driver



MAIZE has a low impedance of 0.1 Ω, 0.5–1 MA of current, 7.9 kJ of stored energy, and a rise time of 100–250 ns.

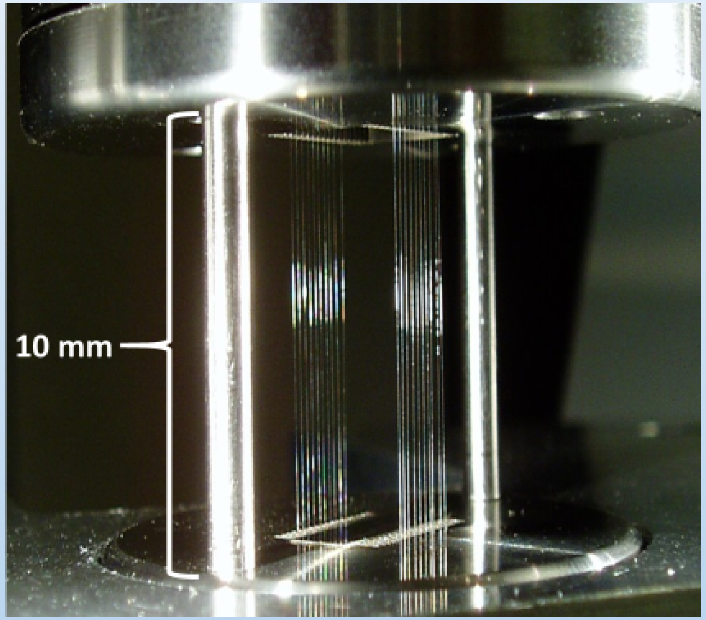
Image Credit: University of Michigan Plasma, Pulsed Power, and Microwave Laboratory. Retrieved from https://plasmabay.engin.umich.edu/research/michigan-accelerator-for-inductive-z-pinch-experiments-maize/

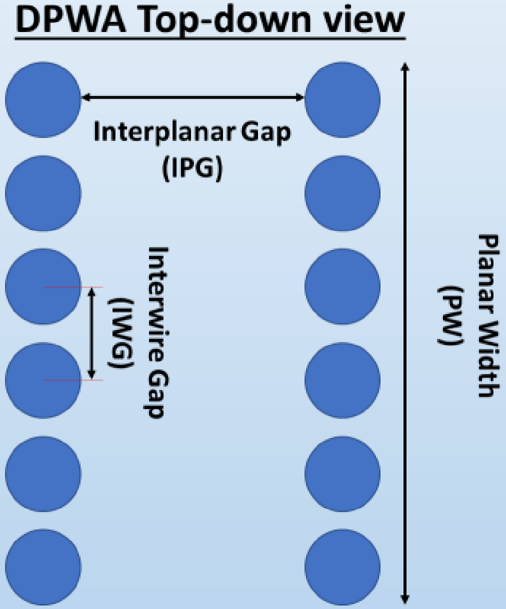
R.M. Gilgenbach, M.R. Gomez, J.C. Zier, "MAIZE: a 1 MA LTD-driven Z-pinch at the University of Michigan". AIP Conference Proceedings (Dense Z Pinches 2008) 1088, pp. 259-262 (2009)

LOADS: Double Planar Wire Arrays

- The Double Planar Wire Arrays (DPWAs) consisted of two wire planes of micron-scale diameter Brass wires, with an anode-cathode gap of 10 mm.

- Two main factors that influence the implosion of these types of loads are the array mass and the aspect ratio (ϕ), defined as the ratio of the planar width to inter planar gap.

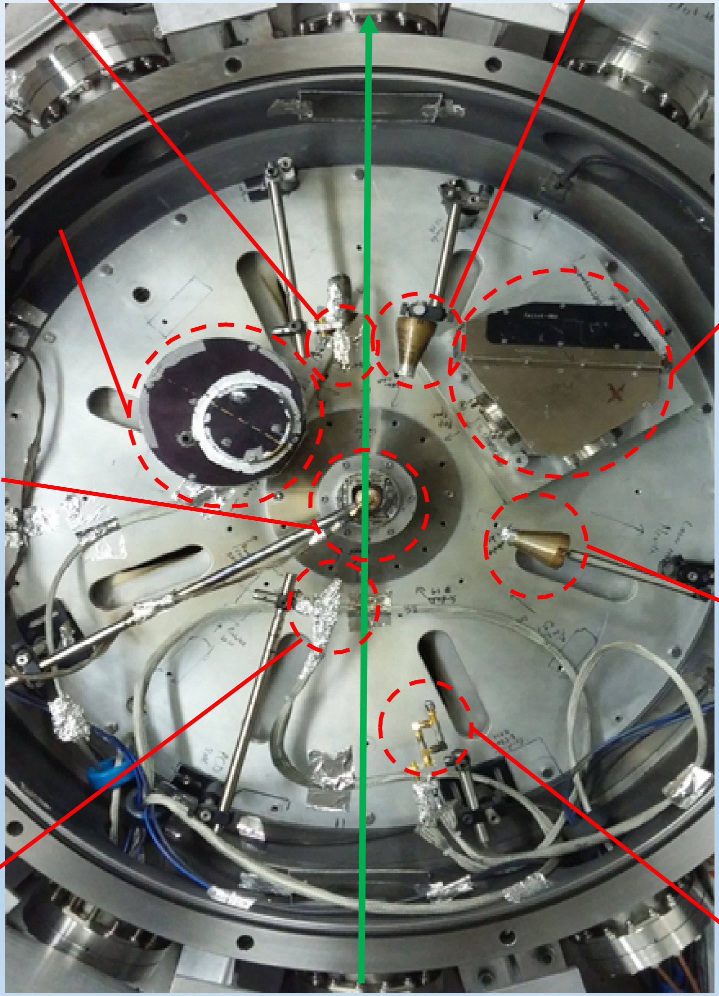


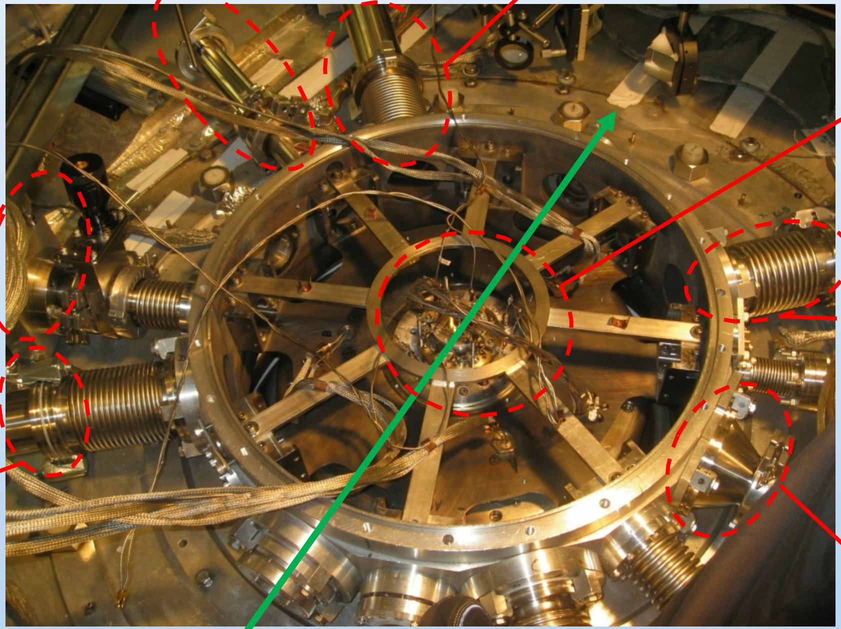


Example of a Double Planar Wire Array (above, left), and a top-down diagram of a DPWA (above, right). Note: the structural rods are removed prior to the shot.

K. M. Williamson, V. L. Kantsyrev, A. A. Esaulov *et al*, Phys. Plasmas 17, 112705 (2010).
V. L. Kantsyrev, L. I. Rudakov, A. S. Safronova *et al*, Phys. Plasmas 15, 030704 (2008).

MAIZE and Zebra Diagnostic Chambers



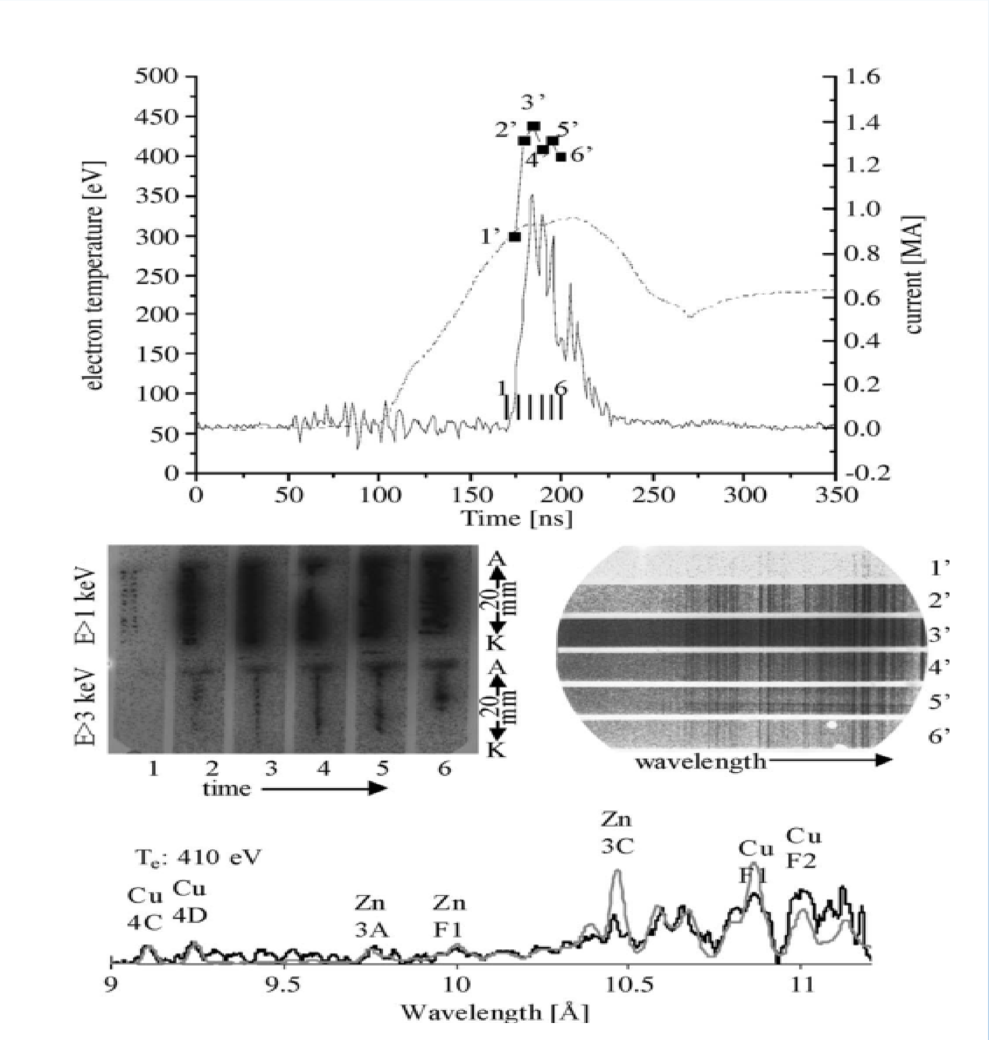


- MAIZE diagnostic chamber (left) and Zebra diagnostic chamber with LCM (above).
- Many of the same diagnostics were shared between the MAIZE and Zebra experiments.
- However, experiments on MAIZE featured an ultra-fast, intensified, 12-frame camera for use in shadowgraphy, while Zebra featured a Time-gated KAP x-ray spectrometer.

Brass DPWAs on the Zebra generator

- In Ouart *et al* (2010)*, the implosion dynamics and radiative characteristics of Brass DPWAs on the Zebra generator were measured and described. The experiments tested two Brass (70% Cu, 30% Zn) DPWAs (Zebra Shot# 1036 and 1257) both with 8/8 arrays, ϕ=1.63, 124 µg mass, and a 20 mm anode-cathode gap.

- Zebra Shot# 1036 is shown on the right*. Time gated spectroscopy analysis (black squares) showed good correlation in time with the PCD signal (black line, arb. units), reaching a maximum electron temperature of 410-450 eV. Emission time lasted approximately 80 ns, as measured by the PCD.



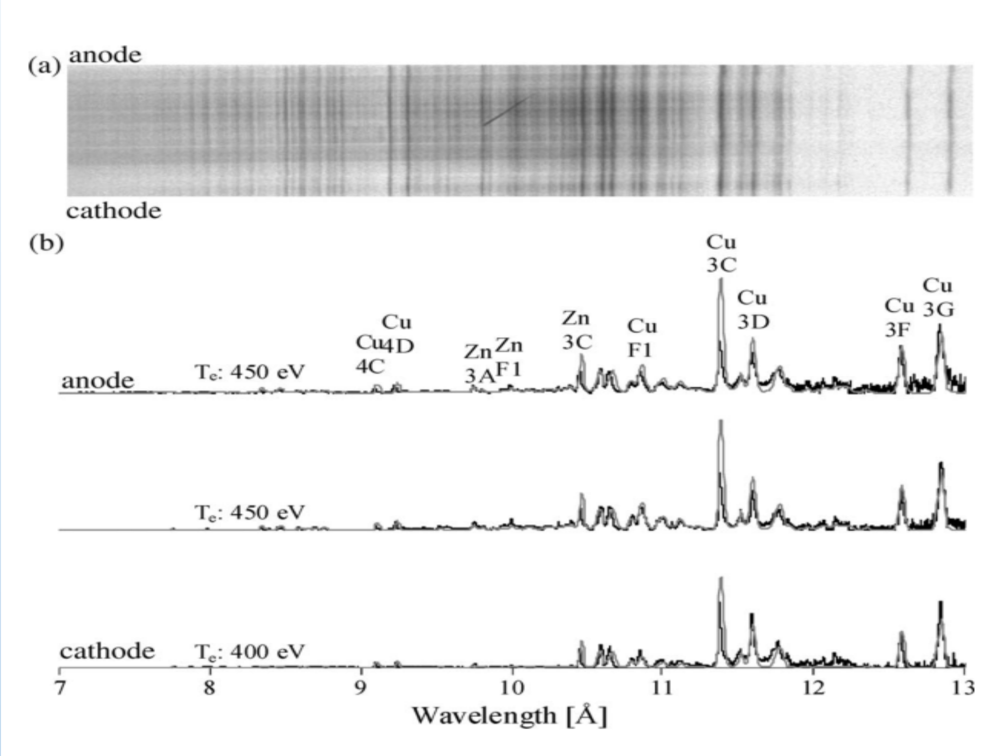
Implosion of a DPWA (Zebra Shot# 1036). Shown are current and PCD signals, as well as time-gated spectra and T_e (black squares) and time-gated pinhole images (black lines). Image from Ouart *et al* (2010)*.

***N. D. Ouart, A. S. Safronova, V. L. Kantsyrev *et al*, IEEE Trans. Plasma Sci. 38 (4), 631 (2010).**

Brass DPWAs on the Zebra generator (cont.)

Label		Upper transition Lower transition	Cu/Zn Wavelength [Å]	Cu/Zn A_{rad} [10^{12} s^{-1}]
F-like	F1	$1s^22s^22p^43d$ J=5/2 $1s^22s^22p^5$ J=3/2	[Cu] 10.857 [Zn] 9.998	[Cu] 33.0 [Zn] 38.0
		$1s^22s^22p^43d$ J=3/2 $1s^22s^22p^5$ J=3/2	[Cu] 10.867 [Zn] 10.008	[Cu] 31.5 [Zn] 36.1
	F2	$1s^22s^22p^43d$ J=5/2 $1s^22s^22p^5$ J=3/2	[Cu] 10.976 [Zn] 10.103	[Cu] 11.5 [Zn] 13.4
	F3	$1s^22s^22p^43d$ J=5/2 $1s^22s^22p^5$ J=3/2	[Cu] 11.123 [Zn] 10.248	[Cu] 10.9 [Zn] 13.9
Ne-like	4C	$1s^22s^22p^54d$ $^1P_1$ $1s^22s^22p^6$ $^1S_0$	[Cu] 9.115 [Zn] 8.353	[Cu] 10.1 [Zn] 11.7
	4D	$1s^22s^22p^54d$ $^3D_1$ $1s^22s^22p^6$ $^1S_0$	[Cu] 9.245 [Zn] 8.481	[Cu] 10.9 [Zn] 13.3
	3A	$1s^22s^12p^63p$ $^1P_1$ $1s^22s^22p^6$ $^1S_0$	[Cu] 10.580 [Zn] 9.752	[Cu] 5.65 [Zn] 6.81
	3C	$1s^22s^22p^53d$ $^1P_1$ $1s^22s^22p^6$ $^1S_0$	[Cu] 11.390 [Zn] 10.466	[Cu] 39.7 [Zn] 45.8
	3D	$1s^22s^22p^53d$ $^3D_1$ $1s^22s^22p^6$ $^1S_0$	[Cu] 11.608 [Zn] 10.676	[Cu] 15.0 [Zn] 19.7
	3F	$1s^22s^22p^53s$ $^1P_1$ $1s^22s^22p^6$ $^1S_0$	[Cu] 12.591 [Zn] 11.532	[Cu] 1.33 [Zn] 1.55
	3G	$1s^22s^22p^53s$ $^3P_1$ $1s^22s^22p^6$ $^1S_0$	[Cu] 12.849 [Zn] 11.786	[Cu] 1.69 [Zn] 2.04
Na-like	Na1	$1s^22s^22p^53s3d$ J=1/2 $1s^22s^22p^63s$ J=1/2	[Cu] 11.514 [Zn] 10.576	[Cu] 40.4 [Zn] 46.5
	Na2	$1s^22s^22p^53s3d$ J=1/2 $1s^22s^22p^63s$ J=1/2	[Cu] 11.737 [Zn] 10.785	[Cu] 8.55 [Zn] 11.0

Atomic data for the important Cu and Zn L-Shell lines. (Table from Ouart *et al*, 2010*)



- Spatially resolved spectra from Zebra Shot# 1257 showed that the plasma was hotter near the anode (450 eV) and cooler near the cathode (400 eV).*
- The table (left) shows diagnostically important L-shell spectral lines from Brass DPWAs.

*N. D. Ouart, A. S. Safronova, V. L. Kantsyrev *et al*, IEEE Trans. Plasma Sci. 38 (4), 631 (2010).

Present Work: Brass DPWA experiments on MAIZE

MAIZE Shot	Material	Load	Aspect Ratio	Mass (µg/cm)	Current Max (kA)	Current Risetime (ns)	Implosion Time (ns)
1315	Al	DPWA	0.58	41	585	260	220
1320	Al	DPFL	1.17	340	565	215	140
1334	W	DPWA	1.05	76	475	200	245

(Table from Butcher *et al*, 2021*)

MAIZE Shot	Material	Load	Aspect Ratio	Mass (µg/cm)	Current Max (kA)	Current Risetime (ns)	Implosion Time (ns)
1249	Brass	DPWA	1.67	57	462	315	224
1250	Brass	DPWA	2.33	76	475	210	230

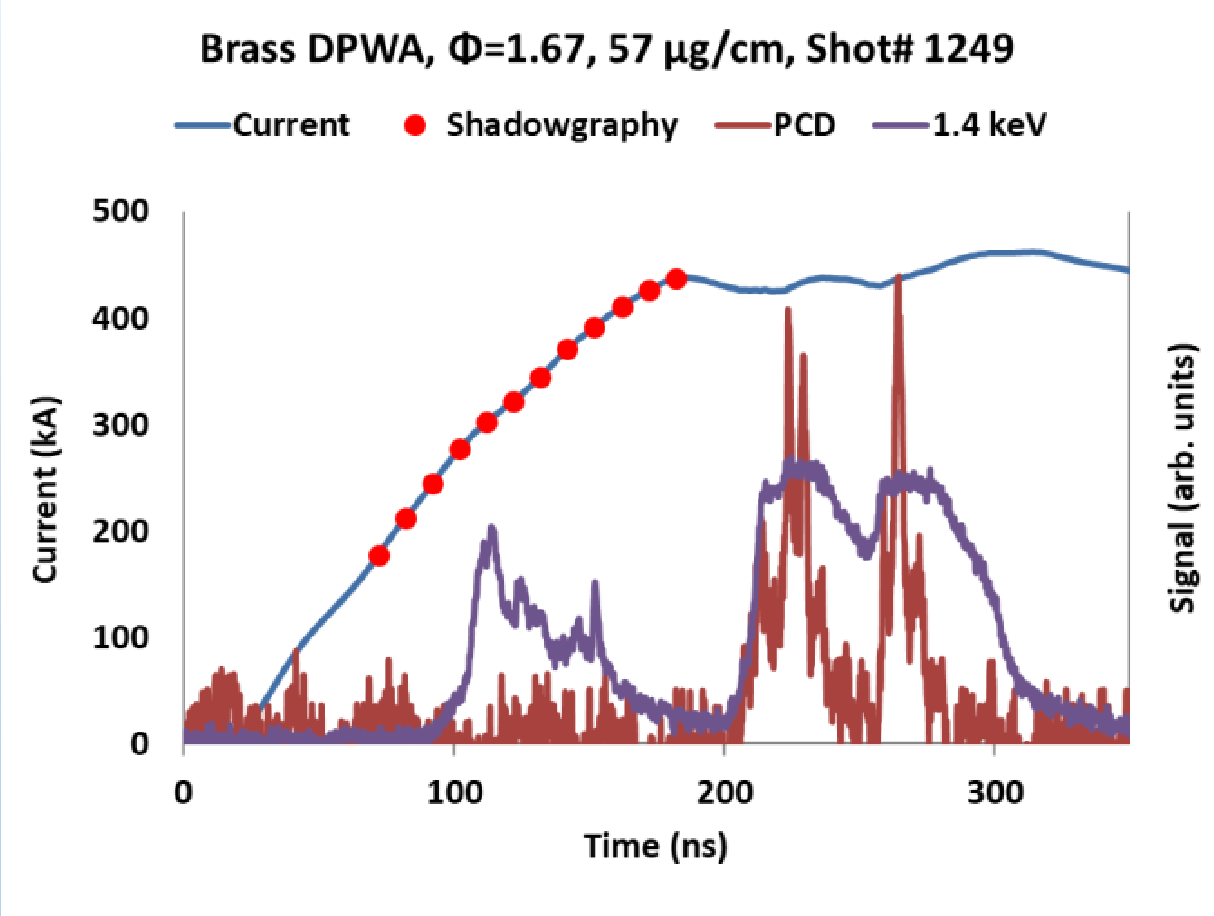
- Present work on the MAIZE LTD includes implosions of DPWAs of various metals. While the focus of this presentation is on Brass, both Al and W DPWAs have been previously imploded on MAIZE.

***C. J. Butcher, V. L. Kantsyrev, A. S. Safronova *et al*, Phys. Plasmas 28, 082702 (2021).**

MAIZE Shot 1249, X-ray Diode Signals

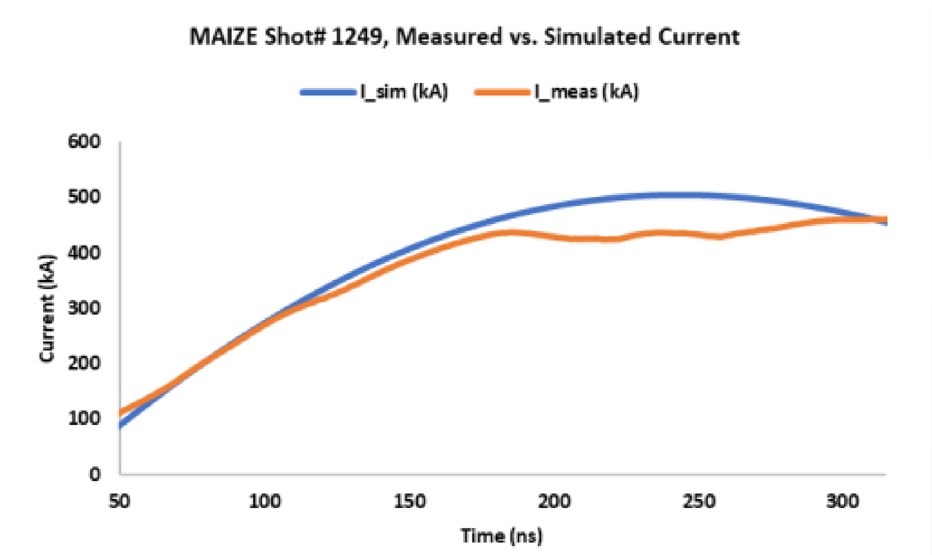
- MAIZE Shot# 1249 diode signals (right) featured a current rise-time of approximately 180 ns, with two distinct radiation bursts recorded by the PCD (>2.4 keV) after 200 ns. The total emission time of the main radiation burst was approximately 80 ns.

- The >1.4 keV diode recorded radiation bursts that correlated well in time with the most intense PCD signals. In addition, it shows lower-intensity bursts beginning at approximately 100 ns, when the two plasma planes began to form a precursor column.

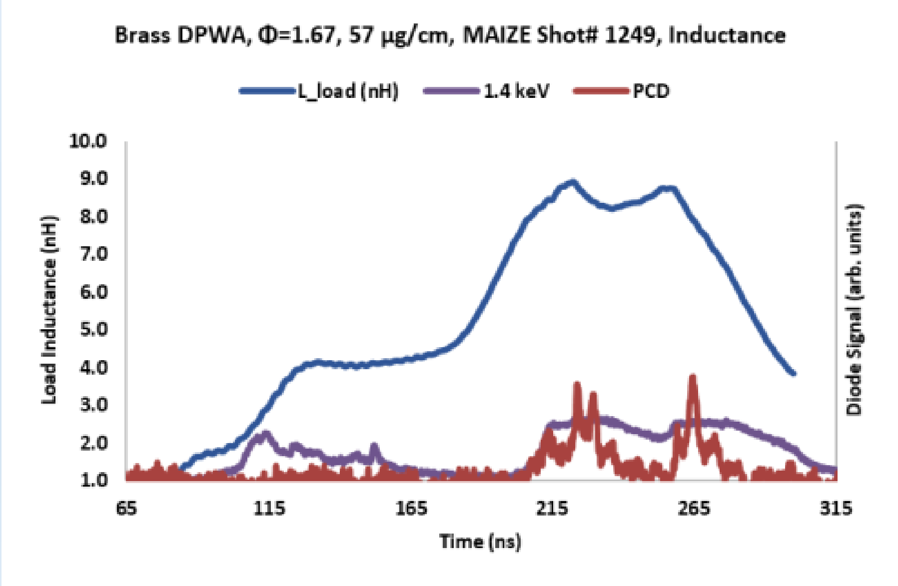


MAIZE Shot 1249, Inductance

- As the MAIZE LTD driver is a low-impedance (0.1 Ω) machine, the current trace throughout the implosion is strongly dependent upon the load inductance. This dependence allows us to extract information about the time evolution of the inductance of a load from a measurement of current.



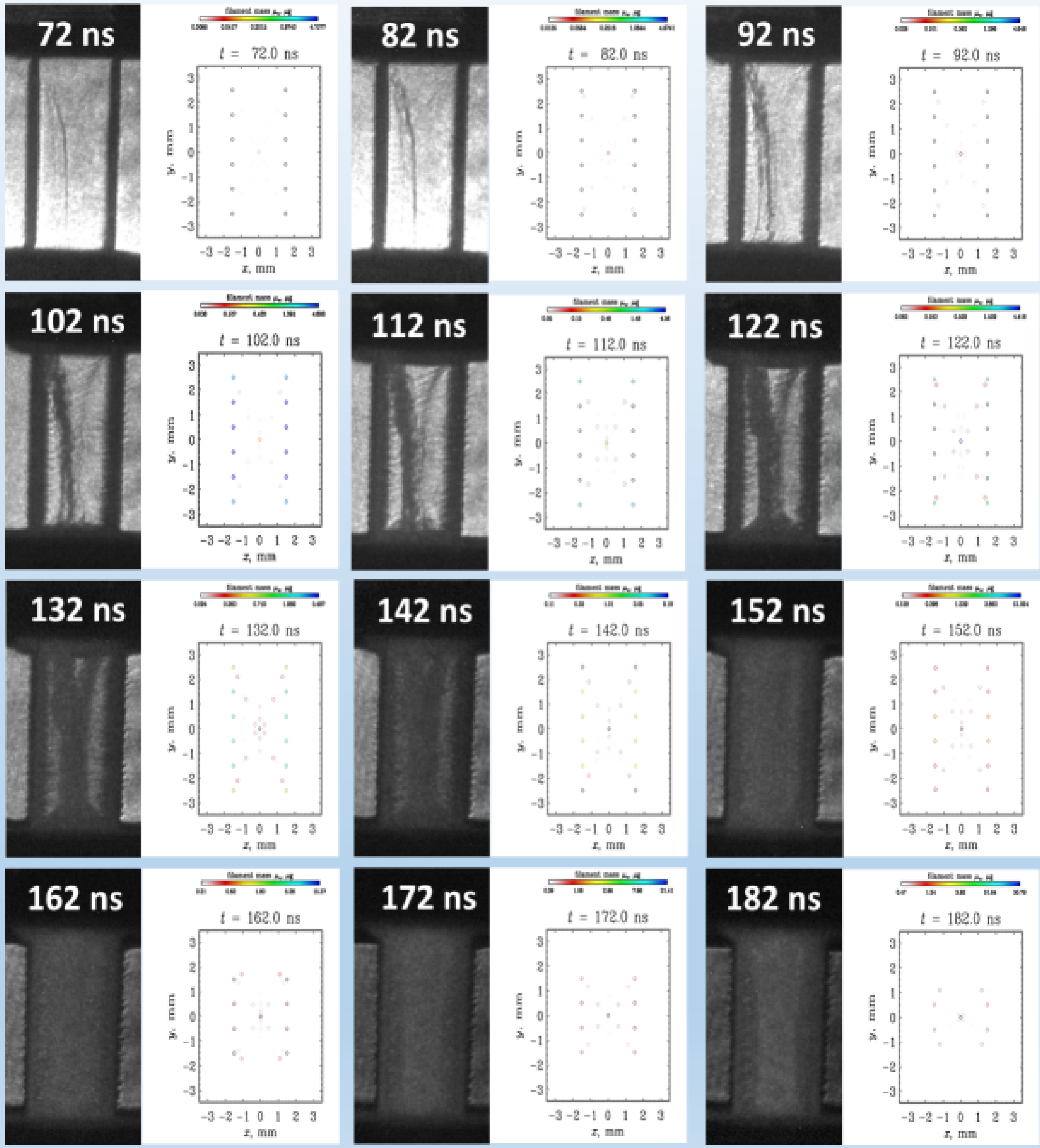
- The inductance peaks correlated well in time with the x-ray bursts, reaching a relative maxima of 4 nH at 125 ns, corresponding with the first bursts in the >1.4 keV signal, and reaching its total maximum of 8.9 nH at 215 ns, corresponding to the first peak of main burst, and another relative maxima of 8.7 nH at 255 ns, corresponding to the second main burst.



A. M. Steiner, D. A. Yager-Elorriaga, S. G. Patel *et al*, Phys. Plasmas 23, 101206 (2016).
C. J. Butcher, V. L. Kantsyrev, A. S. Safronova *et al*, Phys. Plasmas 28, 082702 (2021).

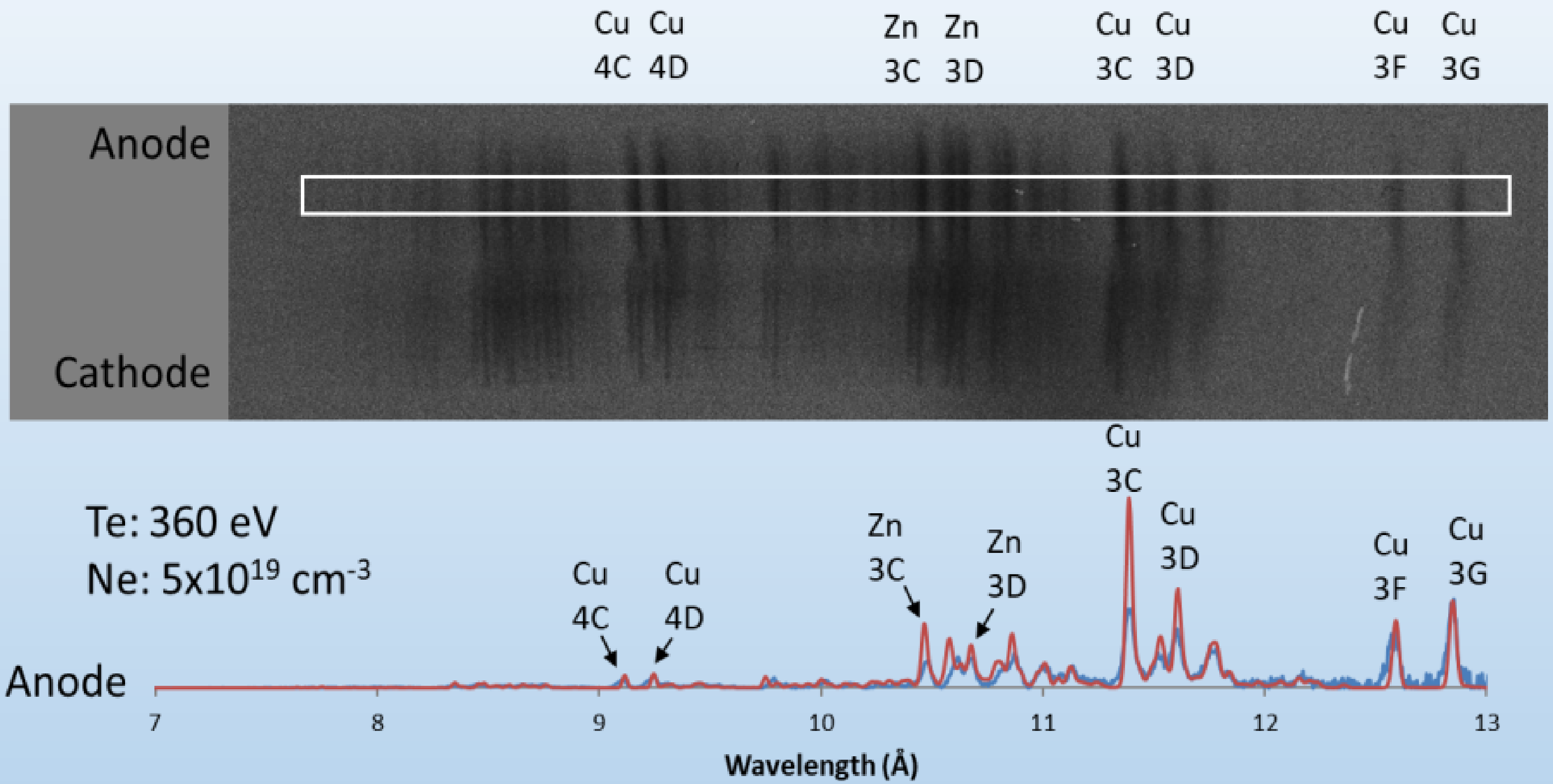
MAIZE Shot 1249, WADM and Shadowgraphy

- The Wire Ablation Dynamics Model (WADM)* showed good correlation with shadowgraphy imaging early on in the pinching process.
- Shadowgraphy images reveal that standing shocks begin forming around 72-92 ns.
- Both WADM and shadowgraphy show the precursor formation beginning around 112-132 ns after the start of current, which corresponds to a small burst in the >1.4 keV signal.
- Note: Shadowgraphy images are viewed looking through the space between the planes, while WADM modelling is viewed from above the load.



***A. A. Esaulov, V. L. Kantsyrev, A. S. Safronova *et al*, Phys. Rev. E 86, 046404 (2012).**
C. J. Butcher, V. L. Kantsyrev, A. S. Safronova *et al*, Phys. Plasmas 28, 082702 (2021).

MAIZE Shot 1249, Spectroscopic Analysis

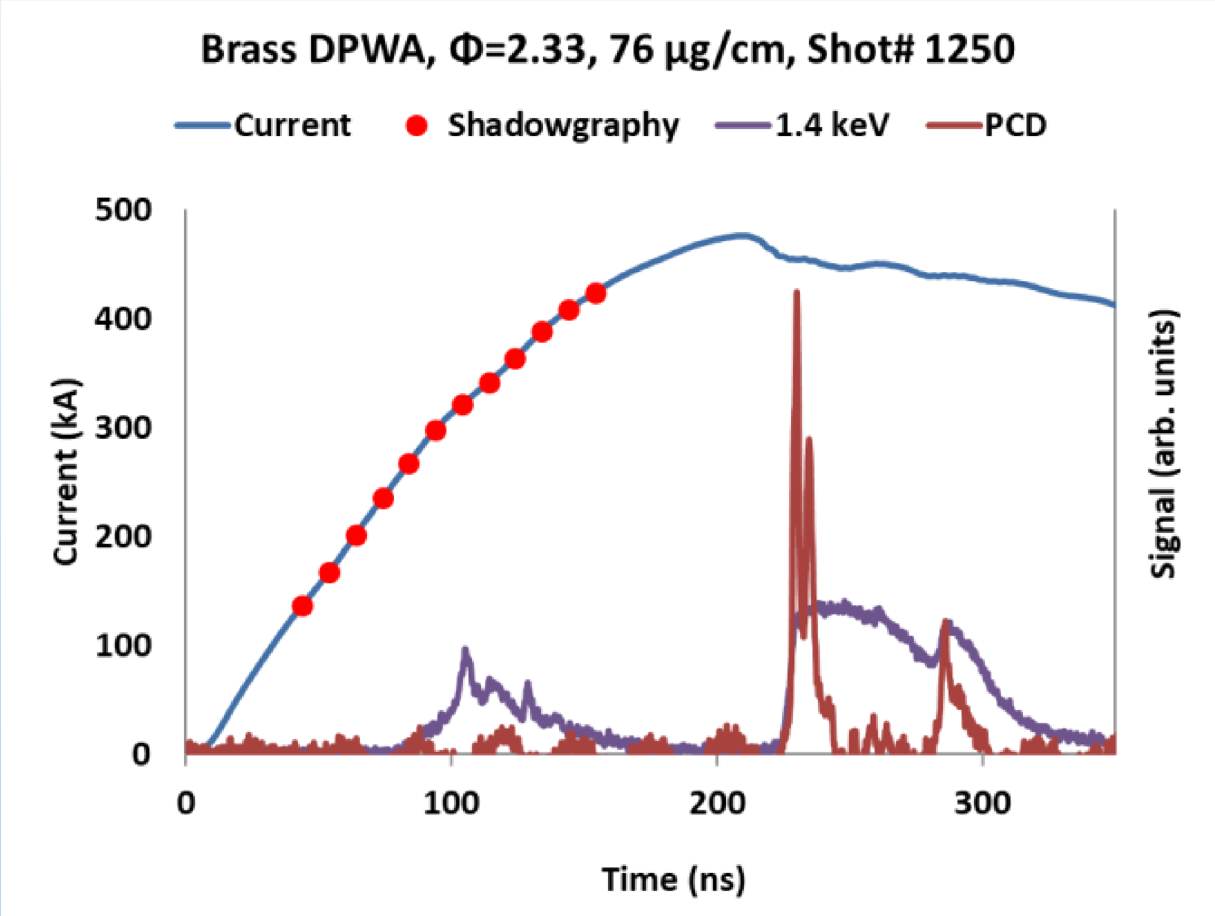


- The spectral analysis from MAIZE Shot# 1249 (above) showed an electron temperature of 360 eV and density of 5×10^{9} cm^{-3} near the anode, and demonstrates the evidence of optically thick Cu 3C and Zn 3C Ne-like lines.

MAIZE Shot 1250, X-ray Diode Signals

- MAIZE Shot# 1250 diode signals featured a current rise-time of approximately 200 ns, with two distinct radiation bursts recorded by the PCD after 200 ns. The total emission time of the main radiation burst was approximately 25 ns for the first burst, and 20 ns for second, less-intense burst.

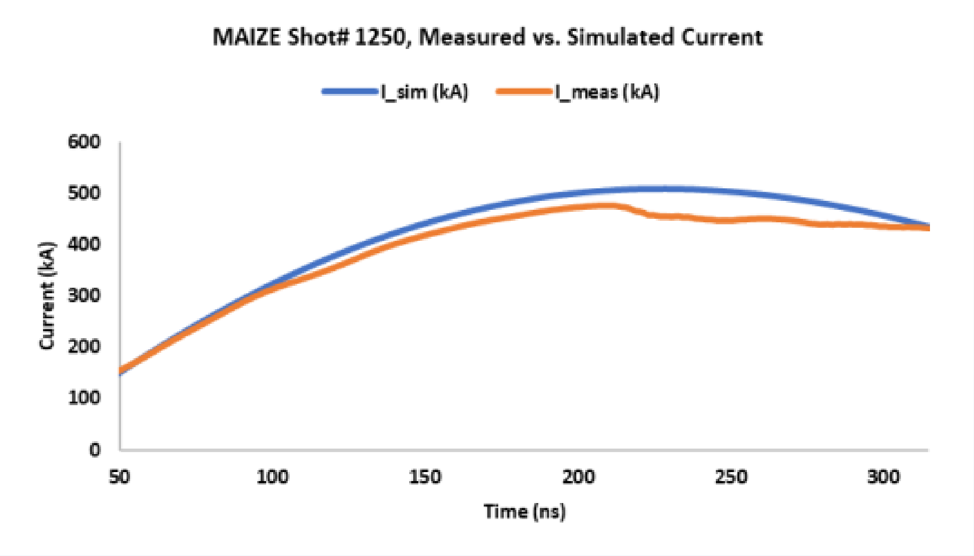
- The >1.4 keV diode recorded radiation bursts that correlated well in time with the PCD signals, as well as a lower emission burst beginning at approx. 100 ns, when the two plasma planes began to form a precursor.

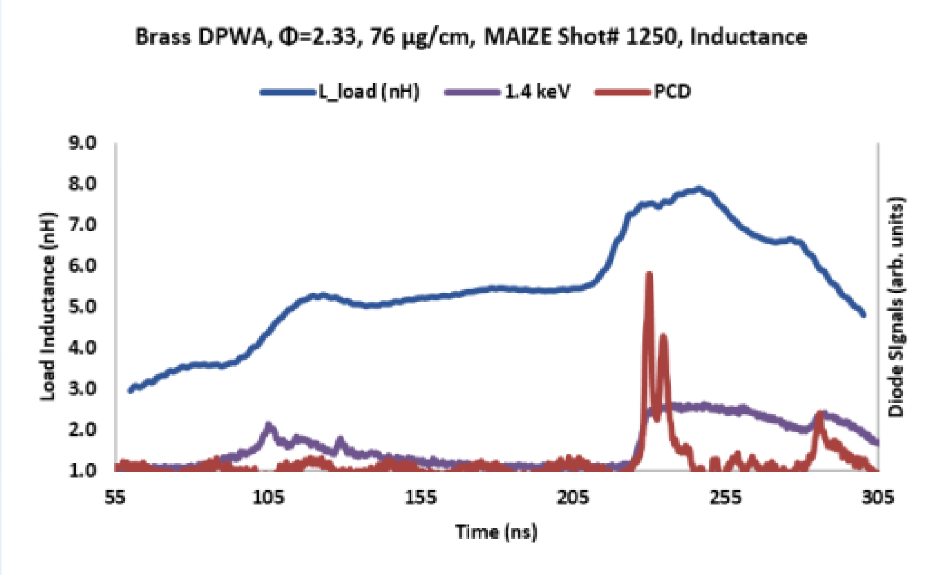


MAIZE Shot 1250, Inductance

- The inductance peaks correlated well in time with the x-ray bursts, reaching a relative maxima of 5.3 nH at 120 ns, corresponding with bursts in the >1.4 keV signal, and reaching its total maximum of 7.8 nH at 245 ns, corresponding to the main burst, and another relative maxima 6.6 nH at 275 ns, corresponding to the final burst.

- It is interesting that the higher aspect ratio DPWA (MAIZE Shot# 1250, Φ=2.33) reached a lower maximum inductance (7.8 nH) than the lower aspect ratio DPWA (MAIZE Shot# 1249, Φ=1.67) at 8.9 nH, despite having a higher-intensity PCD signal.



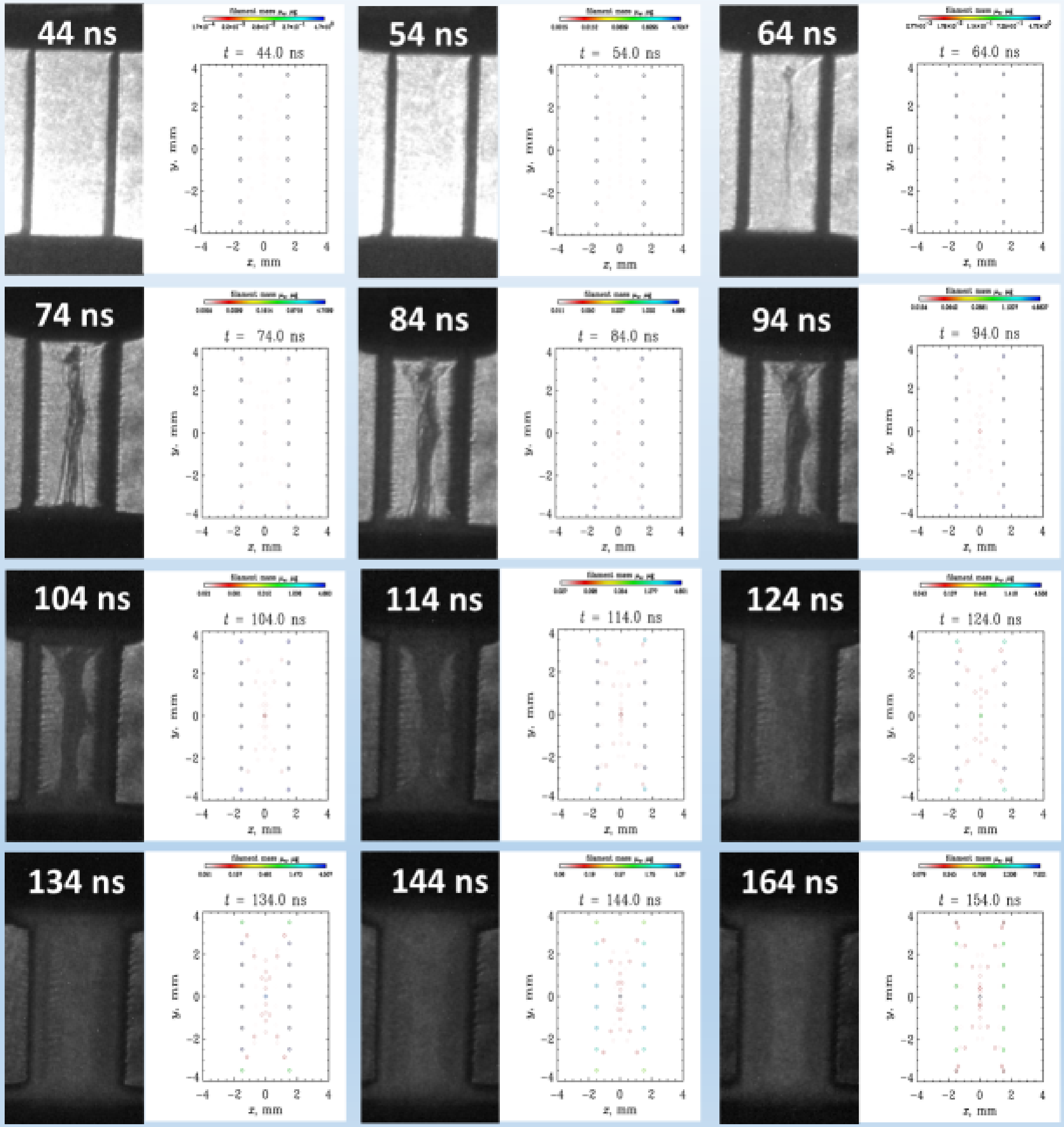


A. M. Steiner, D. A. Yager-Elorriaga, S. G. Patel *et al*, Phys. Plasmas 23, 101206 (2016).
C. J. Butcher, V. L. Kantsyrev, A. S. Safronova *et al*, Phys. Plasmas 28, 082702 (2021).

MAIZE Shot 1250, WADM and Shadowgraphy

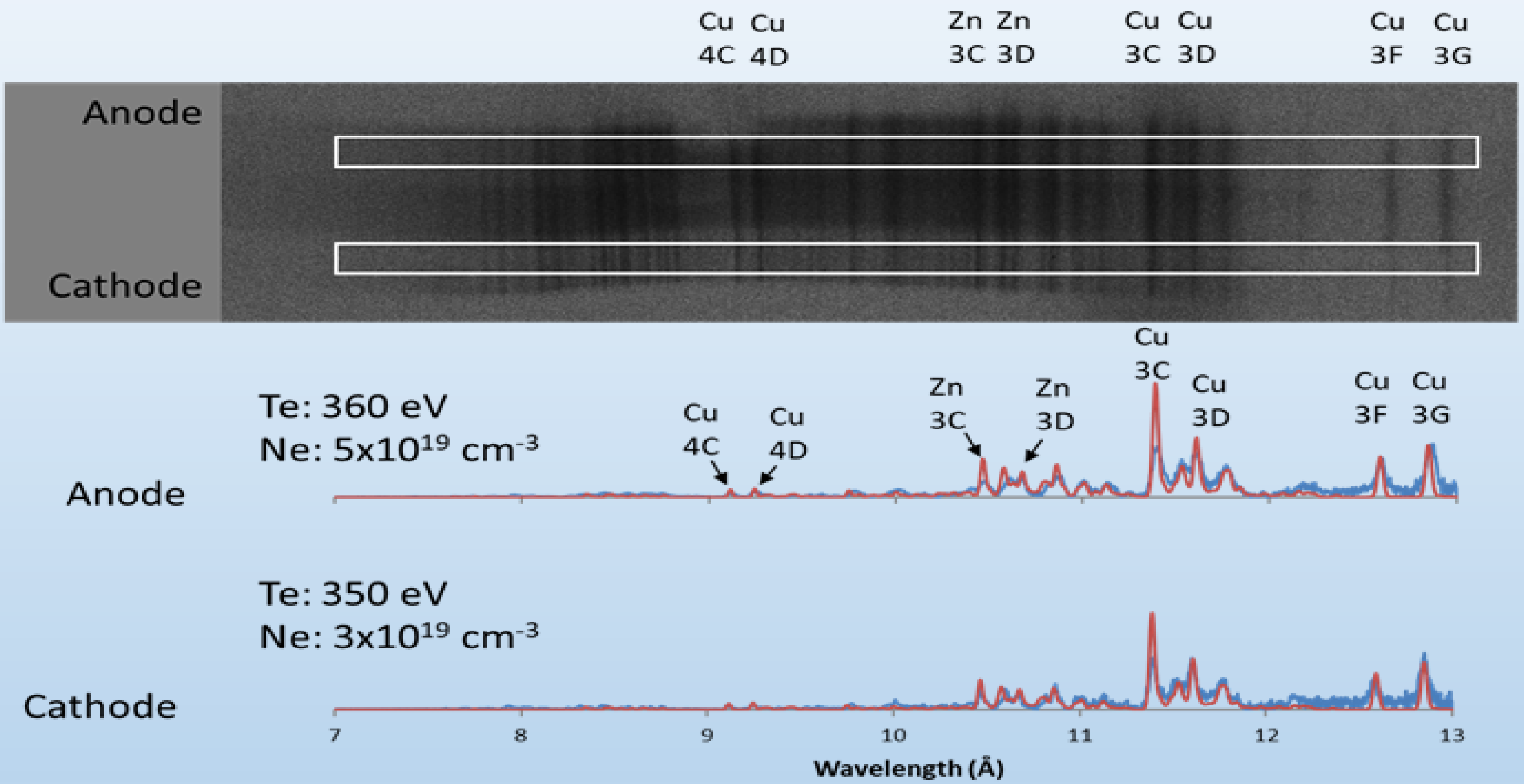
- The WADM* modelling corresponded well in time with the shadowgraphy imaging.

- Shadowgraphy images show that standing shocks form around 64-74 ns, and the precursor column began forming at around 94-124 ns after the start of current, which agrees with the WADM modelling that shows the central accumulation of mass occurring at the same time.



*A. A. Esaulov, V. L. Kantsyrev, A. S. Safronova *et al*, Phys. Rev. E 86, 046404 (2012).

MAIZE Shot 1250, Spectroscopic Analysis



- The spectral analysis from MAIZE Shot# 1250 revealed an electron temperature of 360 eV and density of $5x10^9$ cm^{-3}, and evidence of optically thick Cu 3C and Zn 3C Ne-like lines near the anode.
- Similar parameters (T_e = 350 eV and N_e = $3x10^9$ cm^{-3}) and a less optically thick Cu 3C line near the cathode.

Energy Output of DPWAs on MAIZE

MAIZE Shot	Material	Load	Aspect Ratio	Mass (μg/cm)	Current Max (kA)	Current Risetime (ns)	Implosion Time (ns)	Energy over 4π (J)
1315	Al	DPWA	0.58	41	585	260	220	6.7E-02
1320	Al	DPFL	1.17	340	565	215	140	3.3E-02
1334	W	DPWA	1.05	76	475	200	245	1.6E+00

(Table from Butcher *et al*, 2021*)

MAIZE Shot	Material	Load	Aspect Ratio	Mass (μg/cm)	Current Max (kA)	Current Risetime (ns)	Implosion Time (ns)	Energy over 4π (J)
1249	Brass	DPWA	1.67	57	462	315	224	5.3E-01
1250	Brass	DPWA	2.33	76	475	210	230	7.7E-01

- When compared to low-Z_a Aluminum (Al) and high-Z_a Tungsten (W) DPWAs imploded on the MAIZE generator, the mid-Z_a Brass DPWAs proved to be the second highest radiators in the >2.4 keV band (measurement with absolutely calibrated filtered PCD), with Al the lowest and W the highest.

***C. J. Butcher, V. L. Kantsyrev, A. S. Safronova *et al*, Phys. Plasmas 28, 082702 (2021).**

Conclusions

- To expand upon previous work with low-Z_a Al and high-Z_a W DPWAs on the MAIZE generator, mid-Z_a Brass DPWAs were imploded in order to get a more full understanding of the radiative properties of low- to mid- to high-Z_a elements imploded on the low-impedance MAIZE LTD, in which it was found that the energy radiated in the >2.4 keV band was proportional to Z_a.

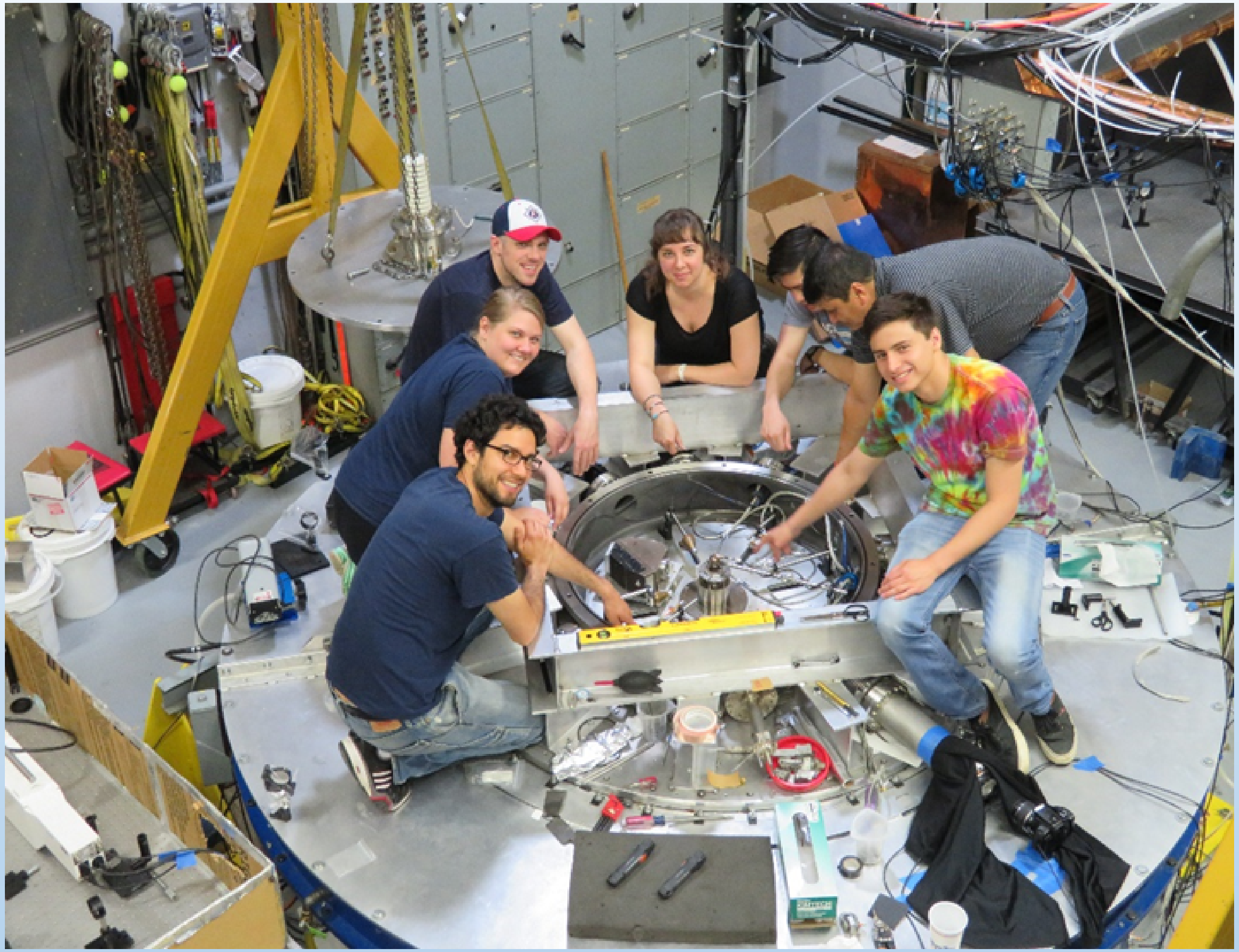
- Two Brass DPWAs of different aspect ratios (Φ=1.67 and Φ=2.33) were imploded on the MAIZE LTD generator; both began radiating in the >1.4 keV band around 105-115 ns, when the precursor formed, and both demonstrated two distinct radiation bursts in both the >1.4 keV band and the PCD (>2.4 keV) at the time of implosion, and featured an approximately 200 ns current risetime prior to implosion. Similar loads imploded earlier on the high-impedance Zebra Marx bank generator demonstrated one main burst lasting approximately 60 ns, immediately proceeding the current peat at about 90 ns from the start of current. The slower current rise-time and "bursty" x-ray behavior on the MAIZE LTD is attributed to the low-impedance of the machine, while the high-impedance Zebra Marx bank has a much faster rise-time and well defined main x-ray burst.

- Due to the low-impedance of the MAIZE LTD generator, the change in inductance of the load throughout the implosion had a significant effect on the current trace throughout the implosion. This effect was exploited to estimate the time-dependent inductance of the load through the implosion, which correlated well in time with the radiation bursts. Implementation of this technique on the Zebra generator is in development, though the Zebra machine is a high-impedance machine and thus the current trace is less effected by changes in load inductance.

- WADM modeling on the Brass DPWAs on MAIZE showed good correlation with shadowgraphy images and radiation bursts, as did previous WADM modelling on Brass DPWAs on the Zebra machine.

- Spectral modelling of the Brass DPWAs on MAIZE revealed a relatively uniform plasma, with electron temperatures on the order of 360 eV and density of 5×10^{9} cm^{-3}, which is cooler than similar loads on the Zebra generator which ranged from 450 eV to 400 eV. This cooler plasma temperature on MAIZE is due to the lower maximum current (approximately 500 kA on MAIZE vs. approximately 1 MA on Zebra). However, the most intense L-shell Cu and Zn lines were optically thick in experiments on both Zebra and MAIZE.

Acknowledgments



University of Nevada, Reno (UNR) and University of Michigan (UM) teams during the collaborative campaign on the MAIZE Linear Transformer Driver (LTD) at UM.

This research was supported by NNSA under DOE grants DE-NA0003047 and DE-NA0003877.