SAND2015-5027C

Comparative Properties of Ar Z-Pinches Imploded on Z With and Without a Center Jet*

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presented at

Third International Workshop on Radiation from High Energy Density Plasmas
South Lake Tahoe, Nevada
June 9-12, 2015

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*Work supported by DOE/NNSA

Background

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- The advantages of structured gas-puff loads have been investigated for > 20 yrs.
- The most advanced loads consist of 2 shells and a center jet. The inner shell mitigates RT instabilities [1,2] via "snowplow stabilization". The central jet serves as a high-density, shock-and-compression heated radiator [3].
- For currents of 3-4 MA, structured loads have increased Ar K-shell yields by 17-100% [4,5].
- On Z, double-shell Ar loads radiate efficiently without a central jet [6,7]. With a jet, further yield increases were expected and achieved [8]. **Do x-ray spectroscopy and imaging support the above picture?**

1. S. M. Gol'berg and A. L. Velikovich, Phys. Fluids B 5, 1164 (1993).
2. A. L. Velikovich et al., Phys. Rev. Lett. 77, 853 (1996).
3. A. S. Chuvatin et al., IEEE Trans. Plasma Sci. 33, 739 (2005).
4. J. S. Levine et al., Phys. Plasmas 11, 2054 (2004).
5. H. Sze et al., Phys. Rev. Lett. 95, 105001 (2005).
6. H. Sze et al., Phys. Plasmas 8, 3135 (2001).
7. B. Jones et al., Phys. Plasmas 22, 020706 (2015).
8. A. J. Harvey-Thompson et al., preceding talk, this conference

K-shell imaging is qualitatively consistent with the expectation of a better defined and more tightly compressed emitting core when central jet is used.

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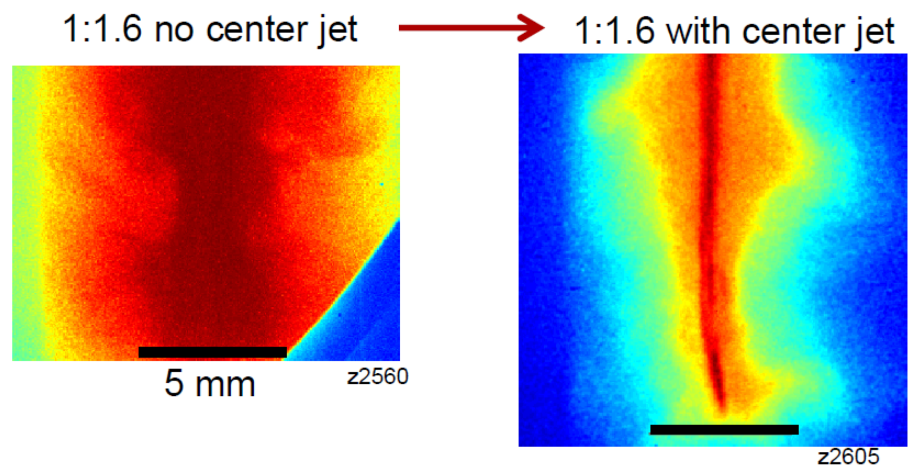

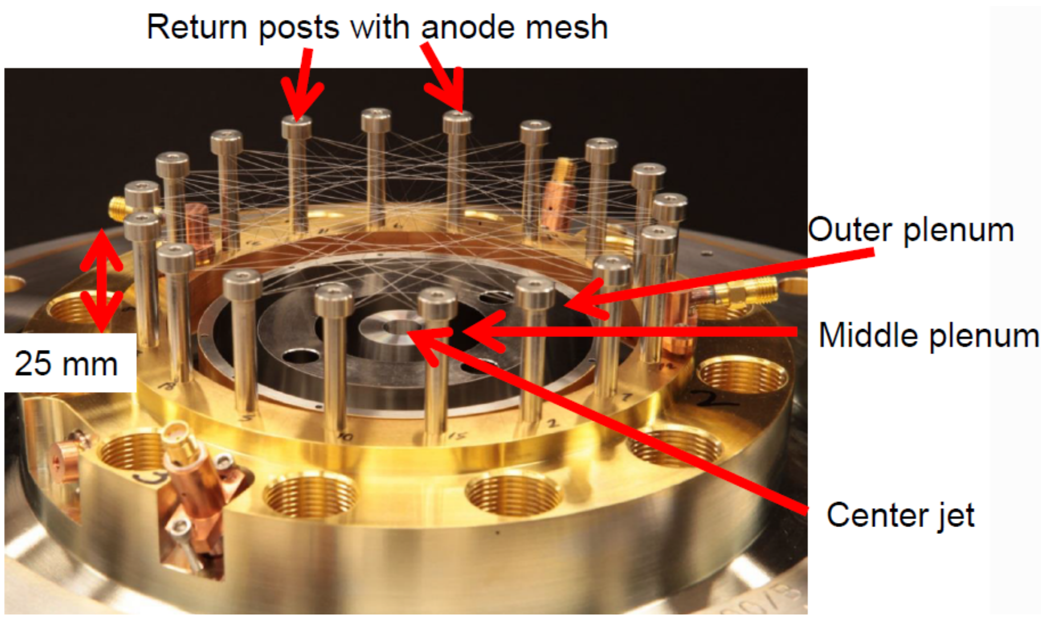

8 cm outer diameter nozzle was developed by Alameda Applied Sciences Corp. [M. Krishnan *et al*., Rev. Sci. Instrum. 84, 063504 (2013).]

Fitting model calculations to x-ray data in order to infer pinch conditions

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- The pinch is assumed to consist of 2 cylindrical zones: a hot K-shell radiating core of the measured diameter surrounded by an 8 mm diameter blanket. There are 5 free parameters: inner and outer ion densities and electron temperatures, and mass load. There are 6 variables to fit: 3 line ratios, the total and K-shell powers, and mass load.

- Preliminary fits from a fast model* were recalculated and fine-tuned using a more detailed, 186-level, 611-line model that transports 15488 photon energies to resolve the line profiles. The best overall fit (minimizing χ^2) is selected. Minimizing χ^2 maximizes the confidence level that the fit is significant.

- The effective ion temperature is often determined by fitting the width of the He-γ line, whose Stark width (< 3 eV) is much less than observed widths. The He-γ width was not measured on all shots.

*J. P. Apruzese, K. G. Whitney, J. Davis, and P. C. Kepple, JQSRT **57**, 41 (1997).

Properties of the shots at peak K-shell power
(numbers alongside in parentheses are from best-fit model)

Property	Z 2560	Z 2605	Z 2603*	Z 2604	Z 2628
mass load (mg/cm)	1.00 ± 10% (1.01)	1.20 ± 10% (1.25)	1.20 ± 10% (1.22)	0.97 ± 10% (0.95)	0.77 ± 10% (0.76)
Outer: inner: jet masses (mg/cm)	**0.385 : 0.615 : 0**	**0.385 : 0.615 : 0.2**	**0.385 : 0.615 : 0.2**	**0.385 : 0.385 : 0.2**	**0.385 : 0.385 : 0**
K-shell diam. (mm)	2.80	**1.20**	**0.62**	1.38	**3.67**
K-shell yield (kJ)	**363 ± 8%**	**373 ± 9%**	**129 ± 9%**	**375 ± 9%**	**143 ± 9%**
peak K-shell power (TW/cm)	11.4 ± 10% (11.5)	11.0 ± 10% (11.0)	2.89 ± 10% (2.93)	13.3 ± 10% (13.2)	2.33 ± 10% (2.31)
total yield (kJ)	1005 ± 20%	1023 ± 17%	1140 ± 17%	894 ± 17%	436 ± 17%
total power at K-shell peak (TW/cm)	16 ± 20% (16)	18.2 ± 20% (16.2)	25.0 ± 20%	17.9 ± 20% (18.5)	4.04 ± 20% (4.24)
Ly-α/(He-α+IC)	2.00 ± 20% (1.54)	1.66 ± 20% (1.57)	0.74 ± 20% (0.58)	1.69 ± 20% (1.55)	2.31 ± 20% (1.67)
Ly-β/He-β	0.85 ± 20% (0.91)	0.77 ± 20% (0.73)	0.19 ± 20% (0.23)	0.78 ± 20% (0.89)	artifacts in data
Ly-γ/He-γ	1.20 ± 20% (1.32)	1.20 ± 20% (1.06)	not measurable	1.16 ± 20% (1.04)	1.40 ± 20% (1.76)
T ion (eff, keV)	50	29	1.1	28	2.8
Te inner (keV)	2.45	**2.00**	**1.10**	2.00	2.80
Ni inner (10^{19} cm^{-3})	6.7	18.	**27.**	17.	**2.2**
Ni outer (10^{19} cm^{-3})	2.5	3.4	3.5	2.4	2.3
χ^2 for fit	1.16	0.71	1.57	0.72	2.47
fit significance confidence level	98%	99%	81%	99%	78%

* 0.8% Xe dopant in center jet for this shot only. All shots contained a 1% Kr dopant in the middle plenum.

The Xe-doped shot Z 2603 showed better compression and achieved 50% higher density than the non-Xe-doped shot Z 2605. These are K-shell images at peak power.

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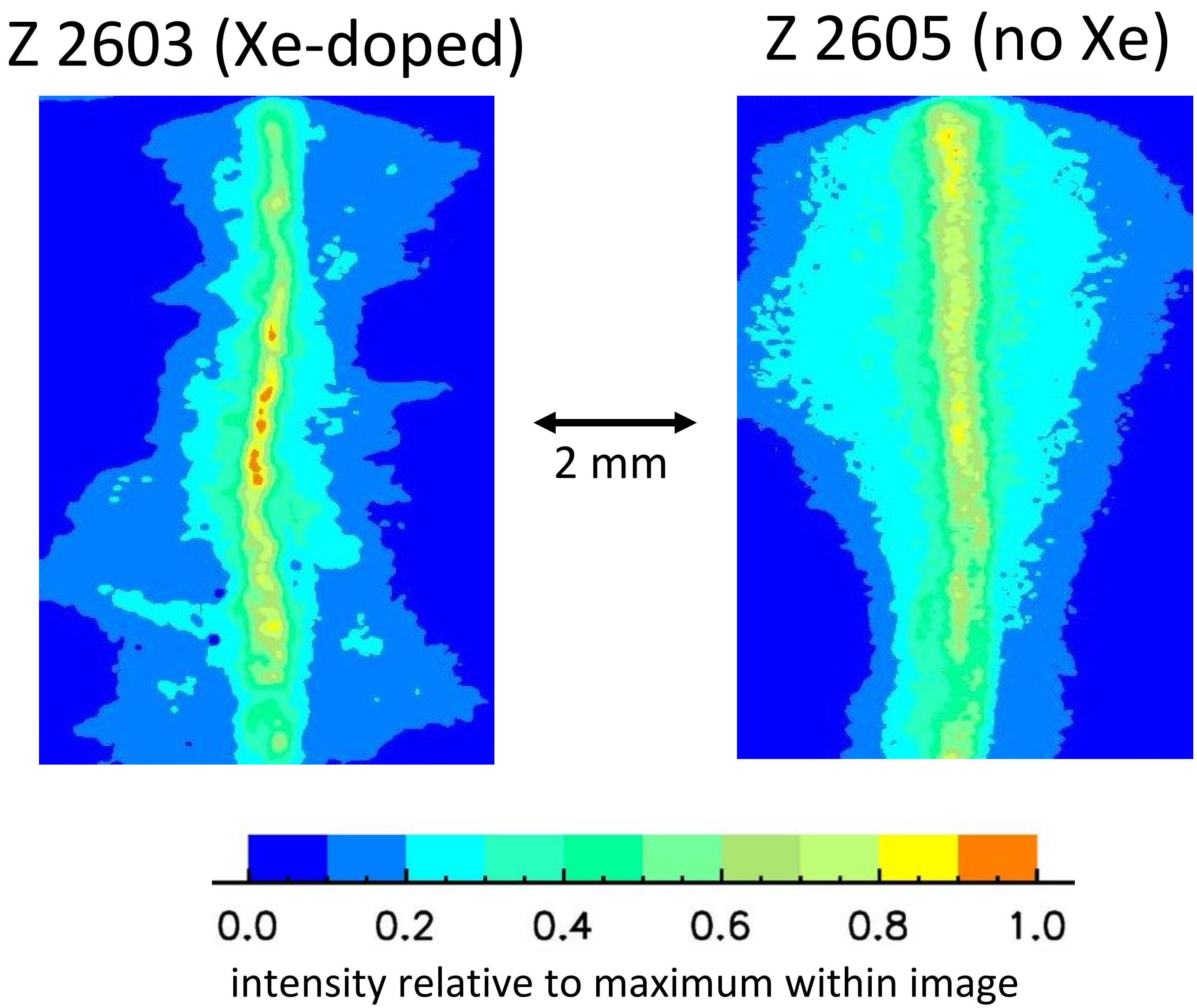


Radiative cooling by 0.8% Xe in the center jet appears to be consistent with the lower temperature and internal energy of Z 2603 compared to its non-Xe counterpart Z 2605. The Xe-doped shot also radiated the highest total x-ray power and yield.

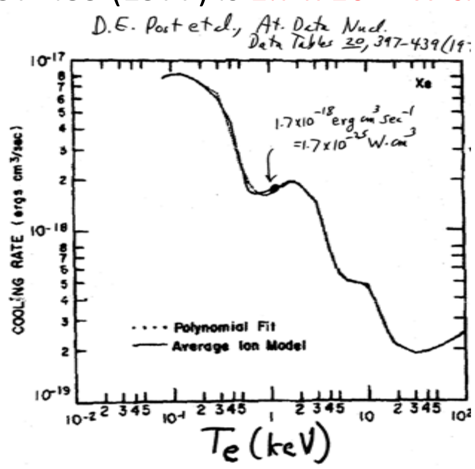
Z 2603 (Xe doped)

Inner zone (K-shell) measured radius: 0.31 mm
Inner zone electron temperature: 1.1 keV
Inner zone ion temperature: 1.1 keV
Inner zone Ar density: 2.7 x 10^{20} cm^{-3}
Inner zone Xe density: 2.2 x 10^{18} cm^{-3}
Inner zone electron density: 4.5 x 10^{21} cm^{-3}
Total inner zone internal energy: 4.8 kJ/cm

Z 2605 (no Xe)

Inner zone (K-shell) measured radius: 0.60 mm
Inner zone electron temperature: 2.0 keV
Inner zone ion temperature: 29 keV
Inner zone Ar density: 1.8 x 10^{20} cm^{-3}
Inner zone Xe density: 0.
Inner zone electron density: 3.1 x 10^{21} cm^{-3}
Total inner zone internal energy: 34.2 kJ/cm

Radiative cooling coefficient for Xe from Post et al., At. Data Nucl. Data Tables 20, 397-439 (1977) is 1.7 x 10^{-25} W cm^3.



Difference in internal energy: 34.2-4.8 = 29.4 kJ/cm
Difference in total power at K peak: 25-18.2 = 6.8 TW/cm
Volume of 1 cm length of the Z 2603 K-shell zone is 0.003 cm^3
Radiative cooling due to Xe is estimated as:
(0.003 cm^3)(1.7 x 10^{-25} W cm^3)(2.2 x 10^{18} Xe cm^{-3})
(4.5 x 10^{21} electrons cm^{-3}) = 5.0 TW/cm.

At 5 TW/cm, 6 ns is needed to radiate the internal energy difference of 29.4 kJ/cm between the Xe and non-Xe shots

Summary of Main Results

- Adding a central jet to the 2 shells of an Ar gas-puff load on Z increased the K-shell yield (by ~ 13%) by creating a denser, but still-hot stagnated core. However, adding the jet also increased the overall mass load which may have contributed to the observed effects. Use of a Cl-bearing tracer might be able to resolve this. (Sze et al., Ref. 5).
- A cooler, sub-keV outer zone contained 73-96 % of the load mass. This region reduces the K-shell yield by only a few percent by inner-shell absorption of β and higher-order lines. But, the higher-order line powers and ratios are often significantly affected.
- Adding a Xe dopant (0.8% by number) to the central jet resulted in greater compression of the core, likely by radiative cooling. But the cooling halved the electron temperature and reduced the K-shell yield by ~ 66%.

Supplementary viewgraphs

The best fit minimizes χ^2, which also minimizes the chance that random excursions of the data are creating a coincidental but meaningless fit.

$$\chi^2 = \sum_n \frac{[measured(n) - predicted(n)]^2}{\sigma^2(n)}$$

The sum is over the variables measured (line ratios, powers, etc).

In the present work, σ is the estimated experimental uncertainty.

Note that if each measurement is within one standard deviation of the model prediction, χ^2 will be ≤ the number of data points.

χ^2 tables based on standard statistics give the confidence interval referred to above.

Determining confidence level from χ^2

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Degrees of Freedom (*df*)	Probability (*p*)										
	0.95	0.90	0.80	0.70	0.50	0.30	0.20	0.10	0.05	0.01	0.001
1	0.004	0.02	0.06	0.15	0.46	1.07	1.64	2.71	3.84	6.64	10.83
2	0.10	0.21	0.45	0.71	1.39	2.41	3.22	4.60	5.99	9.21	13.82
3	0.35	0.58	1.01	1.42	2.37	3.66	4.64	6.25	7.82	11.34	16.27
4	0.71	1.06	1.65	2.20	3.36	4.88	5.99	7.78	9.49	13.28	18.47
5	1.14	1.61	2.34	3.00	4.35	6.06	7.29	9.24	11.07	15.09	20.52
6	1.63	2.20	3.07	3.83	5.35	7.23	8.56	10.64	12.59	16.81	22.46
7	2.17	2.83	3.82	4.67	6.35	8.38	9.80	12.02	14.07	18.48	24.32
8	2.73	3.49	4.59	5.53	7.34	9.52	11.03	13.36	15.51	20.09	26.12
9	3.32	4.17	5.38	6.39	8.34	10.66	12.24	14.68	16.92	21.67	27.88
10	3.94	4.86	6.18	7.27	9.34	11.78	13.44	15.99	18.31	23.21	29.59

χ^2

In most of the present work, 6 variables (K-shell and total power, mass load, and 3 line ratios) are measured. A best fit is found by varying 5 free parameters in the model. Those parameters are inner and outer zone electron temperatures and ion densities, and the mass load. If a given best-fit yields a χ^2 of 2.20, the probability that the fit is not due to a coincidental random excursion of the data is 90%.