Faster, 80ns, current scaling experiments yield higher radiated x-ray power and come closer to quadratic dependence

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Michael G. Mazarakis, Mike E. Cuneo, William A. Stygar, Henry C. Harjes, Daniel B. Sinars, Christopher Deeney, Eduardo Waisman, Thomas Nash, Kenneth W. Struve, Dillon H.McDaniel.

Sandia National Laboratories, Albuquerque, NM 87185, USA

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Motivation for this Investigation

- The 20mm, 300 wire W array single or in a nested configuration is widely used with the Z-accelerator for ICF research.
- Arrays of 5.8 mg have been considered in the recent past as the optimum.

  - First Current Scaling Experiments by W.A.Stygar *et al.,* Phys. Rev. E 69,046403 (2004), with 5.8-mg mass which imploded at 95ns, revealed a lesser than a quadratic radiated x-ray power (P) and energy (E) dependence on the peak load current (I). Namely:

    $P \propto I^{1.24}$ and $E \propto I^{1.73}$

    Later T. J. Nash *et al., Phys. Plasmas* 11, 5156 (2004) did current scaling experiments with 40-mm, 4.6-mg wire arrays which imploded at 110 to 115ns. The radiated x-ray power dependence on the peak load current was:

    $P \propto I^{2}$

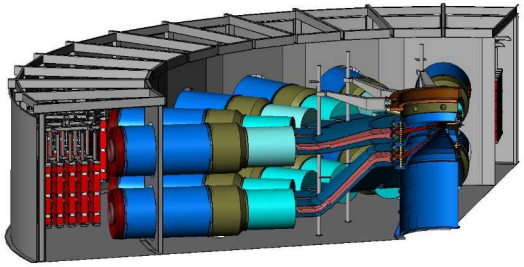
  - In more recent experiments Michael E. Cuneo and Daniel B. Sinars [M. E. Cuneo *et al.,* Phys. Plasmas, 13, 056318 (2006)] discovered that lighter mass loads of 2.5 mg, which give a shorter implosion time of 80 ns, give higher x-ray power pulse than the 5.8-mg loads.

Goal of present experiments

- Perform Current Scaling experiments with lighter masses.
- Establish the power law dependence of x-ray radiated power and energy on the peak load current.
- Compare with previous current scaling results.
- Understand why lighter masses give higher radiated power output.
- Provide guidance for future Z-pinch pulsed power driver designs, power scaling, and provide benchmarks for validations of ICF capsule-x-ray source-accelerator coupled performance.

Implication for ZR

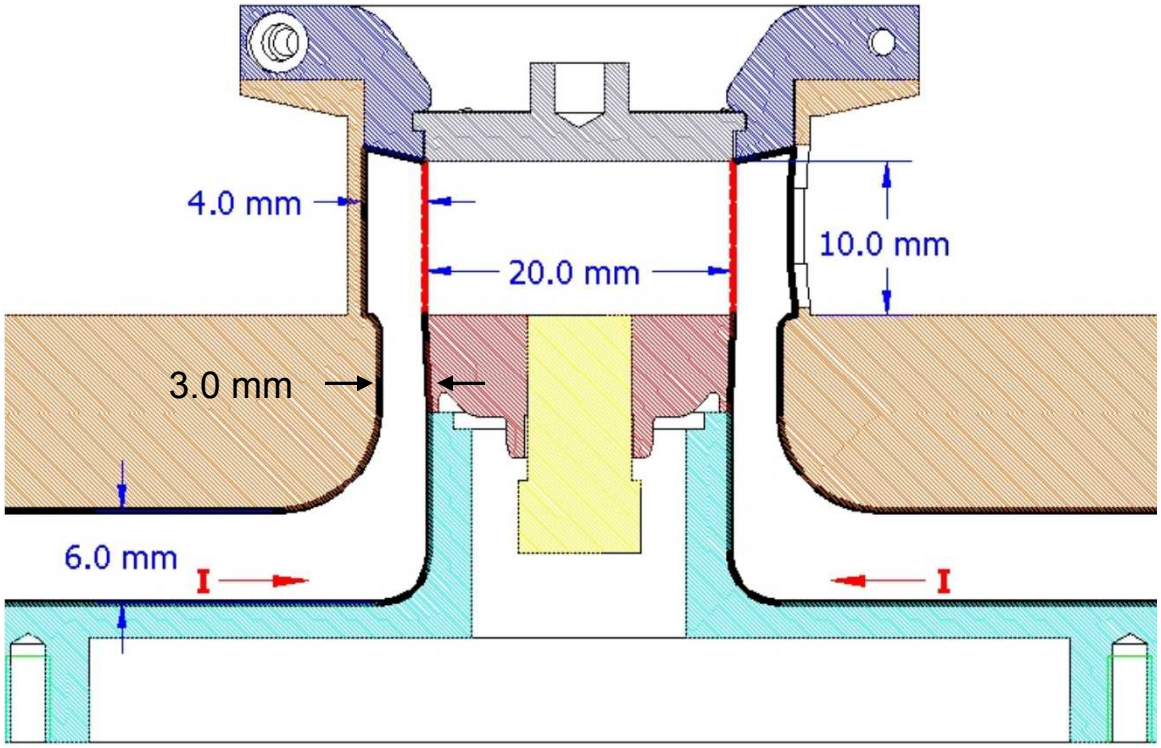
- If ZR could drive 26.5 MA peak current through a 9.5mg, 10cm high, 20mm diameter load, then according to circuit code simulations the implosion time would be 80ns.
- A quadratic current scaling of Z results projects a 440-TW peak radiated x-ray power and 2.8-MJ total radiated x-ray energy.
- A $P \propto I^{1.24}$ and $E \propto I^{1.73}$ current scaling [W.A.Stygar *et al.,* Phys. Rev. E 69,046403 (2004)] gives considerably lower peak power, 300TW, and total energy 2.5 MJ.
- So finding the optimum operating mass (~ 2.4mg for Z) and implosion times that yield highest peak power and close to quadratic current dependence is of great for ZR and for future higher current devices.



Experimental Approach

- Vary the pinch peak current by changing the Z - Marx generators' charge voltage.
- Keep the pinch time the same for the different peak pinch currents by adjusting the total wire array mass.
- Keep all the other hardware parameters like wire number, material, height and final transmission line A-K gap the same.
- The results reported here were for two Marx charging voltages; 90 and 60kV.

Load Hardware Design



Load Parameters and results

Shot Number	Wire Number	Wire Diameter (μ)	Total Mass (mg)	Peak Current (MA)	X-ray Power (TW)	X-ray Energy (MJ)
1142	300	7.39	2.48	16.463	170.32	1.084
1143	300	4.79	1.04	11.080	80.04	0.539
1312	300	7.41	2.50	16.715	139.85	0.859
1313	300	4.97	1.12	11.630	88.35	0.517
1387	300	7.41	2.50	17.010	161.86	1.136
1414	300	7.41	2.44	17.241	198.00	1.325
1420	300	7.41	2.48	17.324	172.13	1.340

Load Parameters and results (continued)

Shot Number	Wire Number	Wire Diameter (μ)	Total Mass (mg)	Peak Current (MA)	X-ray Power (TW)	X-ray Energy (MJ)
1605	300	4.80	1.04	11.080	77.64	0.588
1606	300	4.80	1.04	11.129	74.62	0.389
1607	300	4.80	1.04	11.022	84.11	0.543
1608	300	7.41	2.50	17.140	107.93	0.774
1711	300	7.30	2.42	16.705	152.60	1.432
1735	300	7.30	2.42	17.144	159.13	1.168

Ideally the Peak Power and Energy Dependence on Load Current should be Quadratic

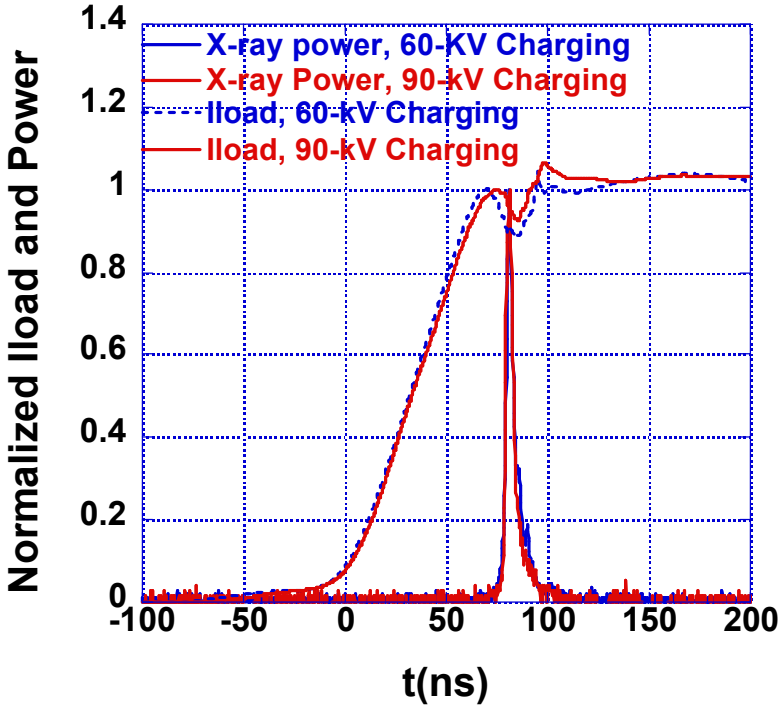
$$\frac{\mu_0 \ell I^2 f^2(t)}{4\pi} = mr(t)\frac{d^2 r}{dt^2}(t)$$

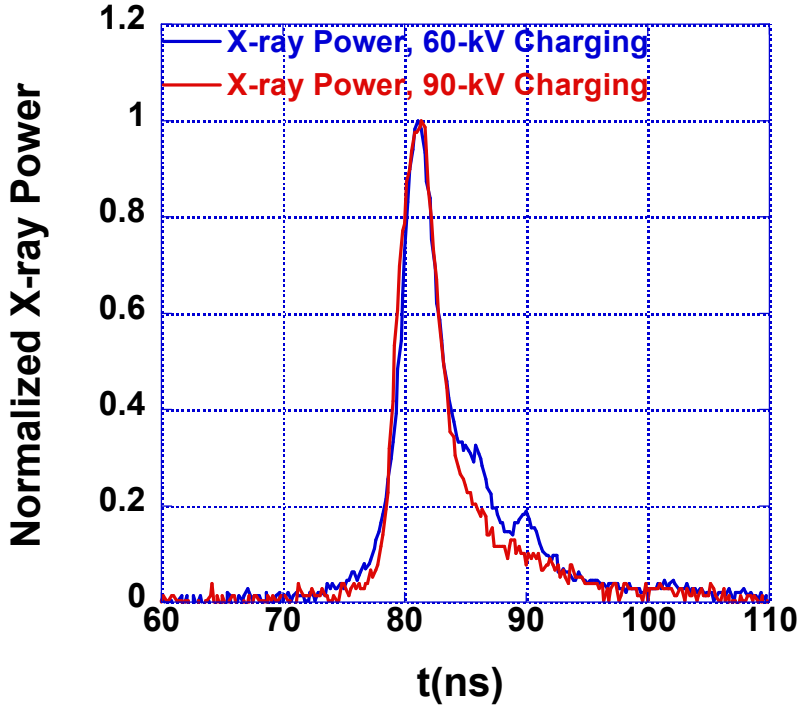
$$\tau_i \equiv \int_b^a \frac{dr}{v(r)}$$

$$E_k(r) \equiv \frac{1}{2} m v^2(r) = \frac{\mu_0 I^2 \ell}{4\pi} \int_b^r \frac{f^2(r)dr}{r}$$

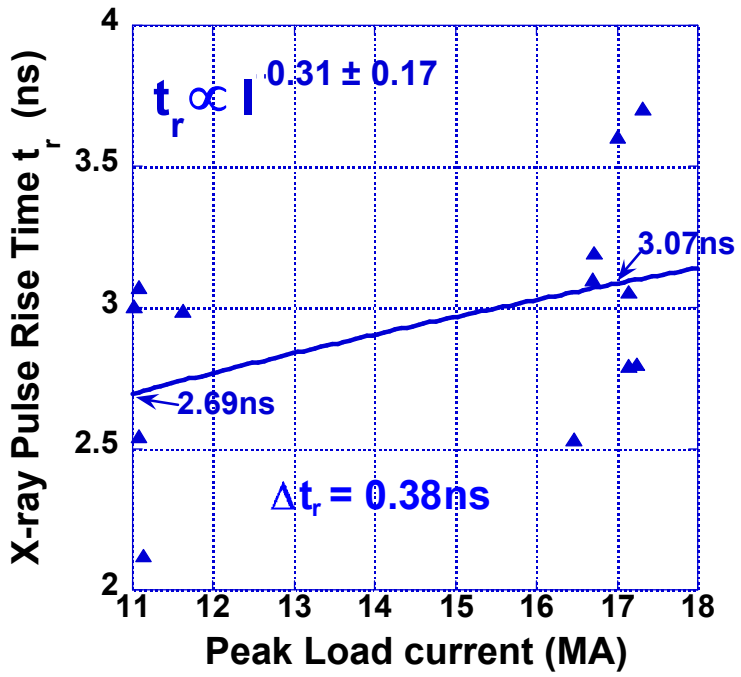
If the fraction of the total K.E radiated as x-ray energy and the thermalization time are independent of I, then both the total radiated x-ray energy E and peak power P are proportional to peak load current square I^2.

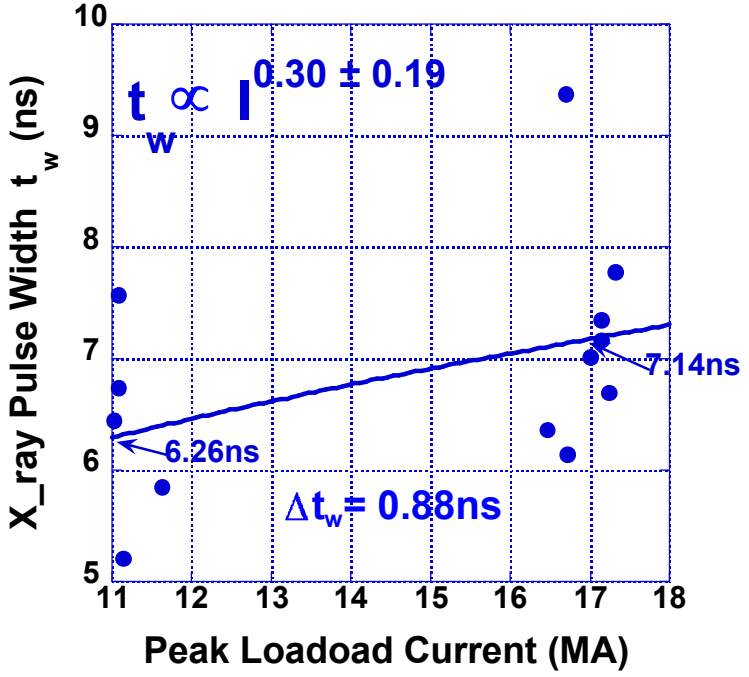
The Load current and x-ray Power profile are similar for both High and Low Current shots



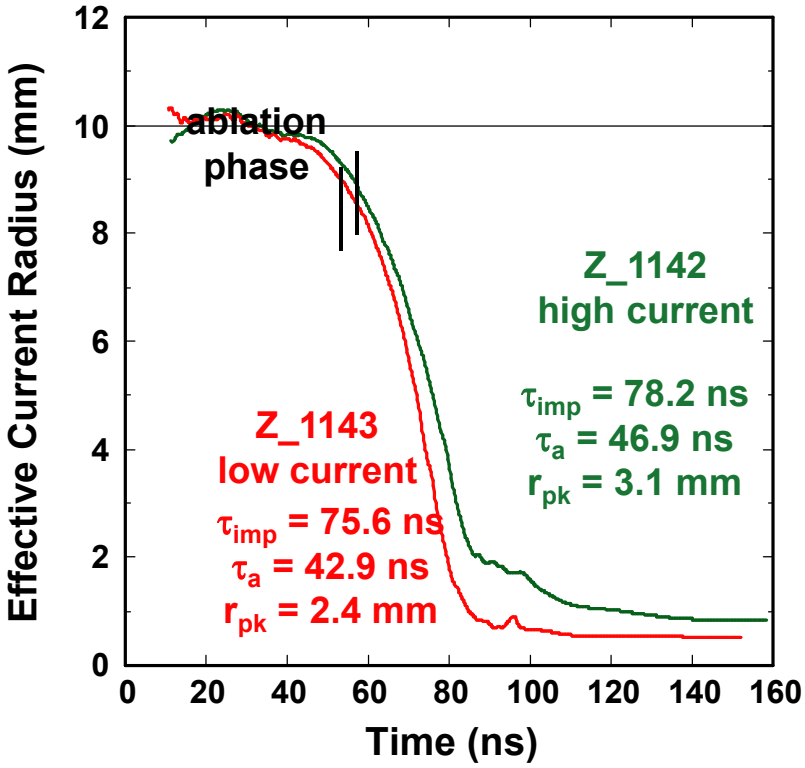


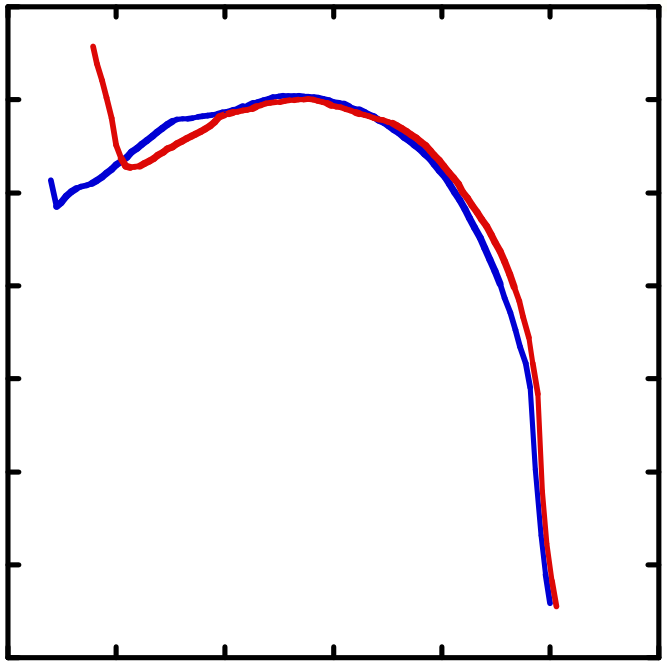
The t_r and t_w slightly increase with the load current





Inductance Unfolds show similar trajectory for Low current and High current shots

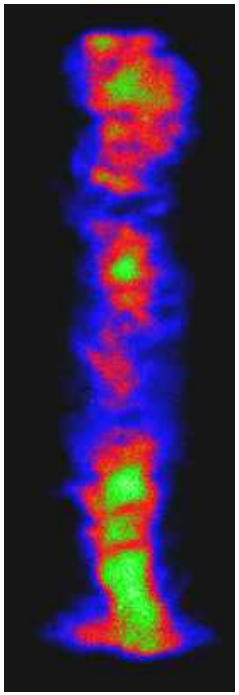




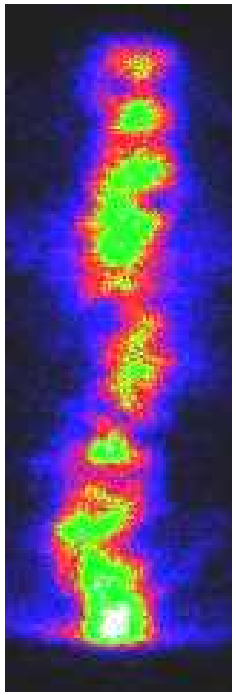
Waisman, Cuneo, et al.,
Phys. Plasmas, 11, 2009 (2004)

Cuneo, Waisman, et al.,
Phys. Rev. E 71,046406 (2005)

The diameter of the pinch at stagnation is larger for the higher current by 0.29mm.

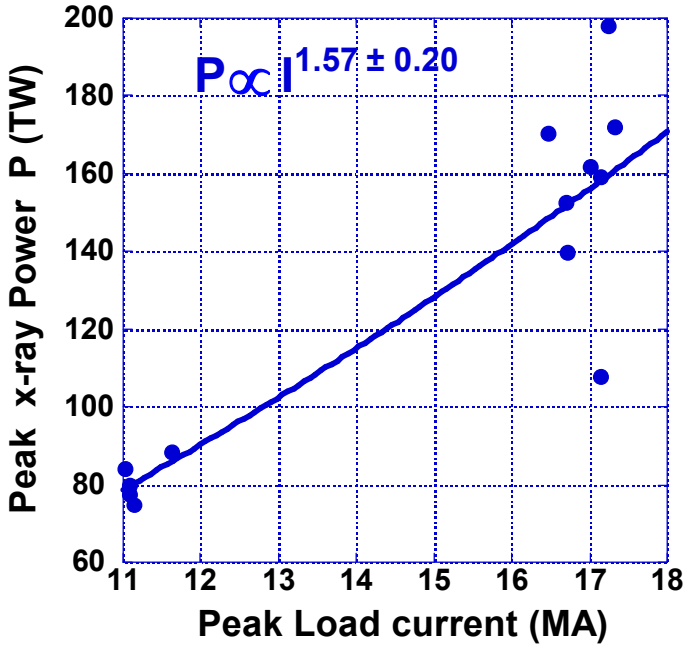


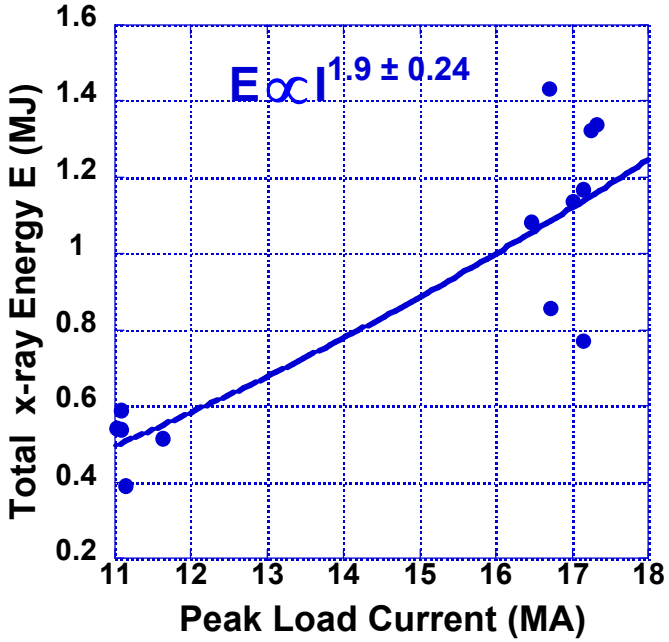
0.96mm
60-kV
88.3TW



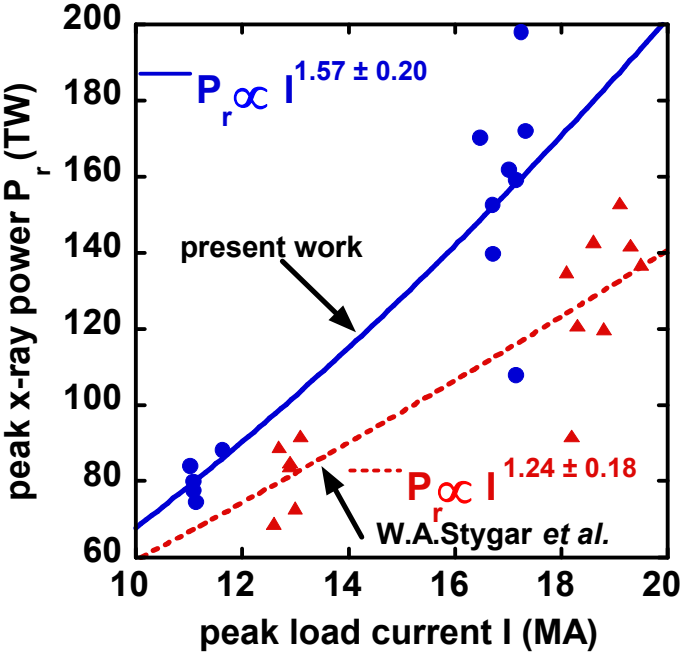
1.25mm
90-kV
170.3TW

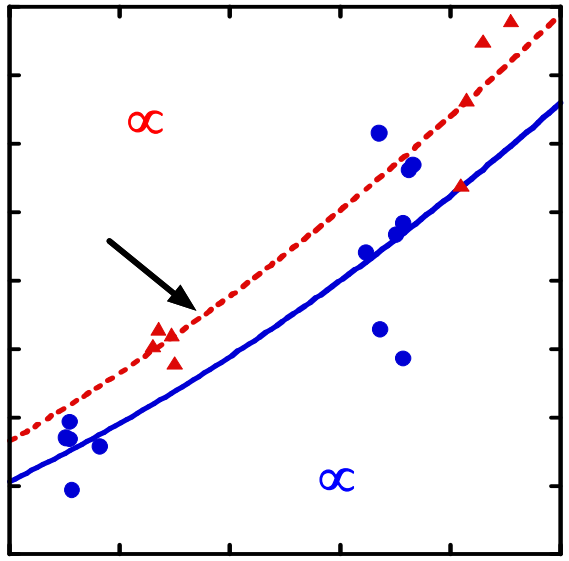
Present Work Results, Total X-ray Radiated Energy and Power



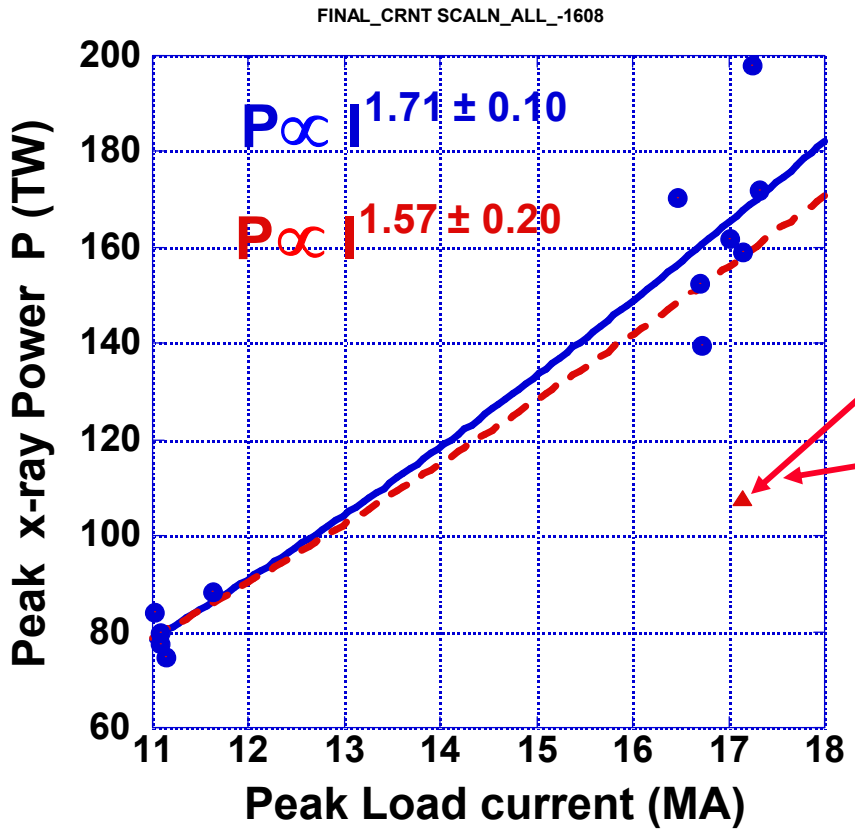


Our data come closer to quadratic dependence than W. A. Stygar *et al.*





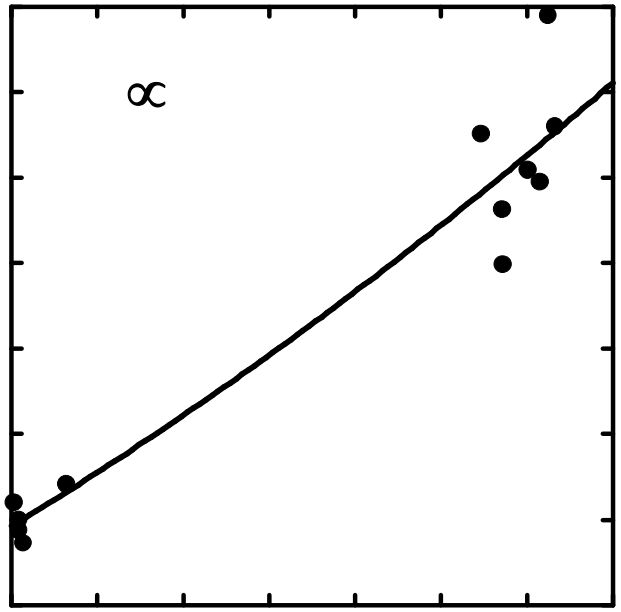
Present Work Results, Total X-ray Radiated Power

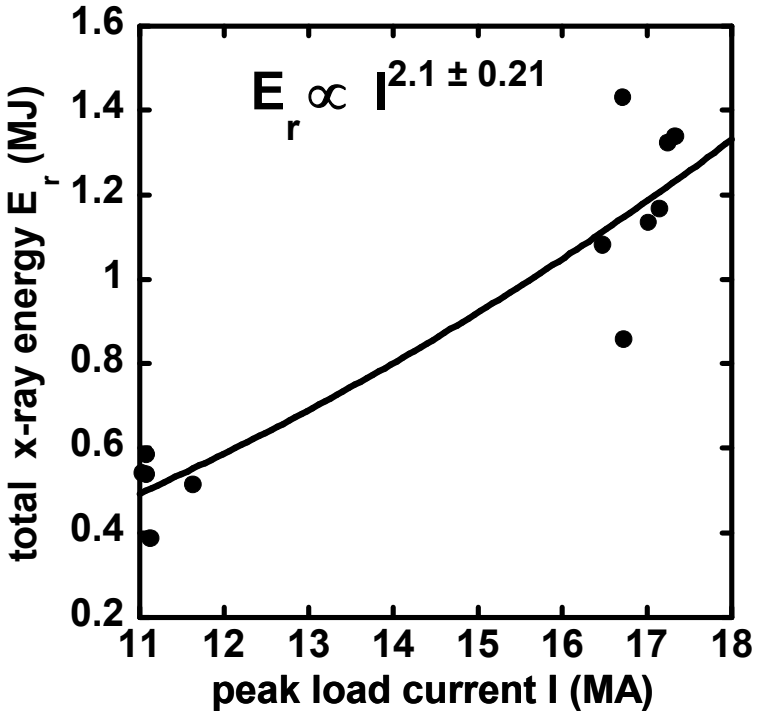


One shot Z_1608 (load instal-led at midnight) gave very low power for no apparent reason. However it substantially affected the power scaling by more than 1σ.

According to Chauvenet criterion this shot should be discarded since the expected number of such deviant (1.893 σ) shots in a 8-high current shot sable is less than 0.5.

Scaling without shot 1608 comes closer to Quadratic





Summary

- We have fired a total of 13 shots; eight at high current and five at low current.
- The peak x-ray energy output appears to have practically quadratic (1.9 ± 0.24) dependence relative to the peak load current. However the peak x-ray power follows closer the 3/2 power law (1.57± 20) and approaches quadratic dependence if we discard shot 1608 (1.71± 10).
- Ablation seems to be the dominant pinch mechanism. However the total radiated energy scales as if RT dominated.
- Although the fast pinches do not use all the available driver energy, they yield more radiated power and tighter stagnations than the slower, higher mass pinches.

Presentation Outline.

- We report the results of a new series of current scaling experiments with the Z accelerator.

- The novelty of this work is the shorter implosion times of 80 ns as compared with the 95 ns and 110ns of a number of previously reported works.

- In the present study we utilized lighter weight tungsten wire arrays, which had 300 wires, 20-mm diameter and 10-mm height and imploded at 80ns.

- We measured the z-pinch radiated x-ray power and energy as a function of the peak current.

- Our power scaling results are 2σ shy from quadratic.

There is Some Difference in X-ray Pulse Shape from Shot to Shot and for Low and High Currents. All Variations within Error Bars.

High Current

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Low Current

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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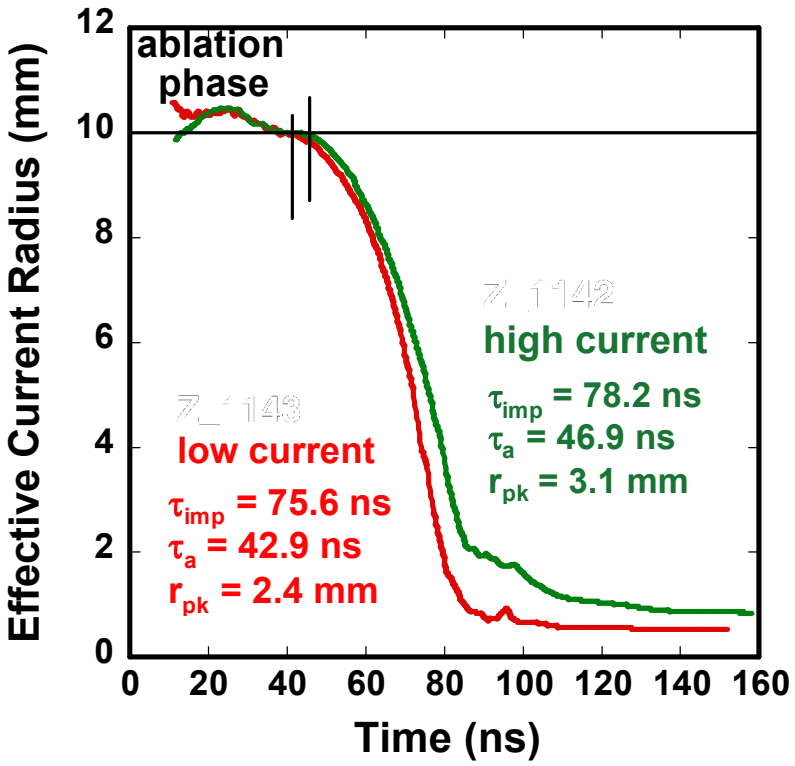
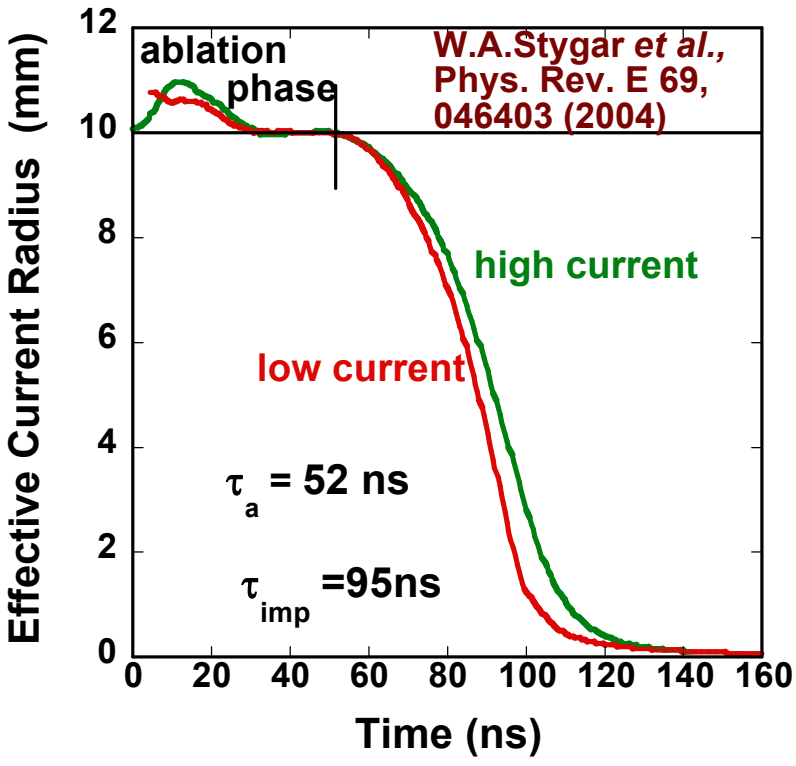
Low and high Current Averages

Inductance Unfolds show similar trajectory for Low current and High current shots





Cuneo, Waisman, et al., Phys. Rev. E 71,046406 (2005)

Waisman, Cuneo, et al., Phys. Plasmas, 11, 2009 (2004)