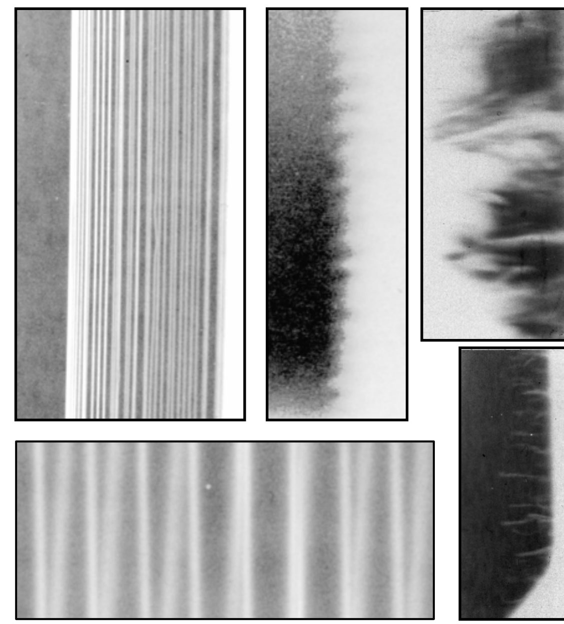
SAND2007-3768C

Energetics of 20-mm diameter tungsten wire arrays on Z

PPPS 2007
Albuquerque, NM

June 18-22, 2007

Daniel B. Sinars
Sandia National Laboratories
PO Box 5800, Albuquerque, NM 87185



Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Collaborators

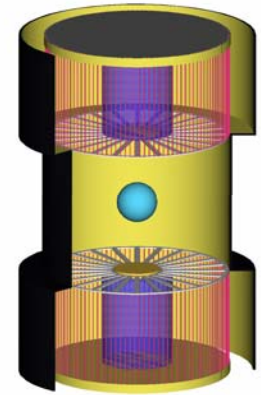
**Michael E. Cuneo, Ray W. Lemke,
Eduardo M. Waisman, William A. Stygar,
Brent Jones, Michael C. Jones, John L. Porter,
David F. Wenger**

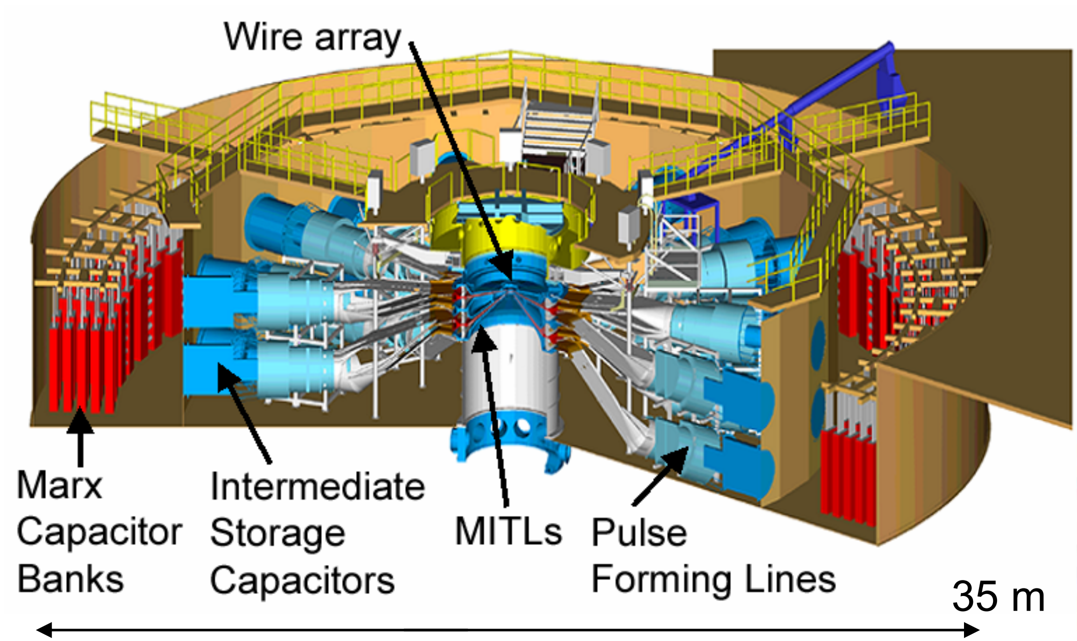
Sandia National Laboratories, Albuquerque, USA

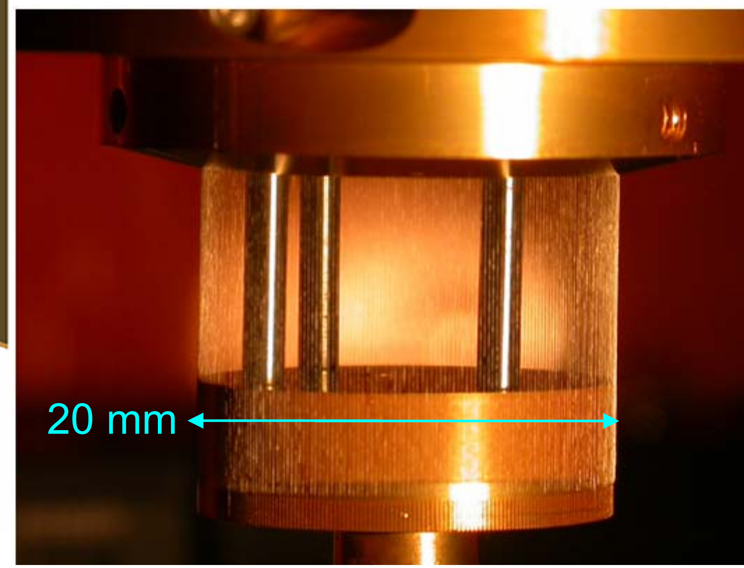
Sergey V. Lebedev

Imperial College, London, United Kingdom

Motivation: Understand behavior of 20-mm diameter tungsten arrays relevant to ICF







The Z facility is a "pulsed power" facility at Sandia National Laboratories, Albuquerque, NM

19 MA peak load current

11.5 MJ stored energy

40 TW electrical power to load

Peak radiation powers have been obtained using annular wire arrays:

1-1.8 MJ x-ray energy yield

(10-15% conversion efficiency)

100-250 TW x-ray power

Radiation after peak power pulse does relatively little to aid capsule compression

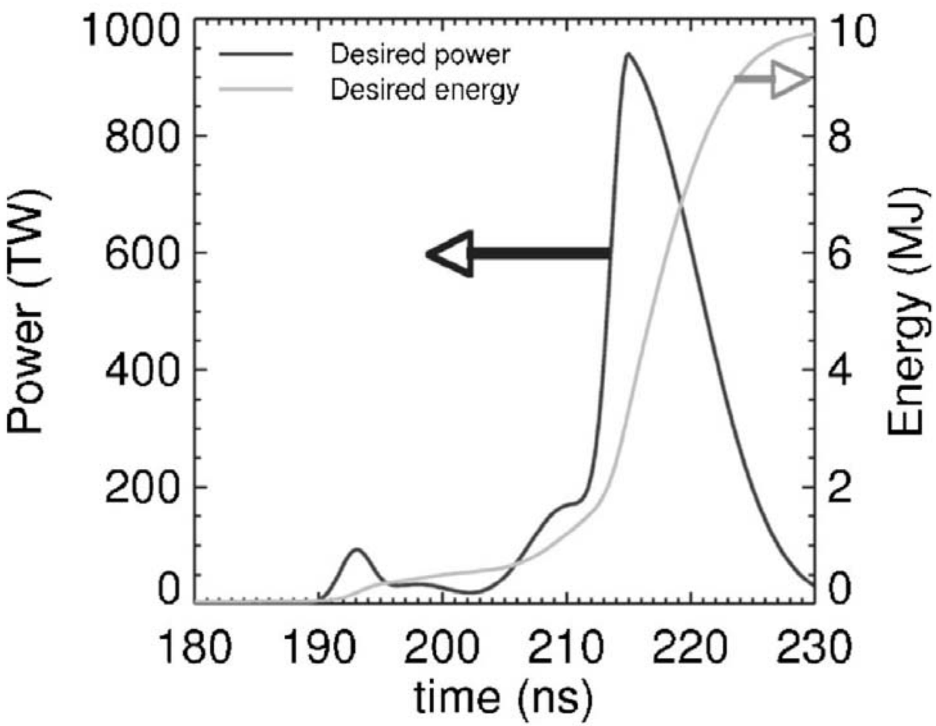
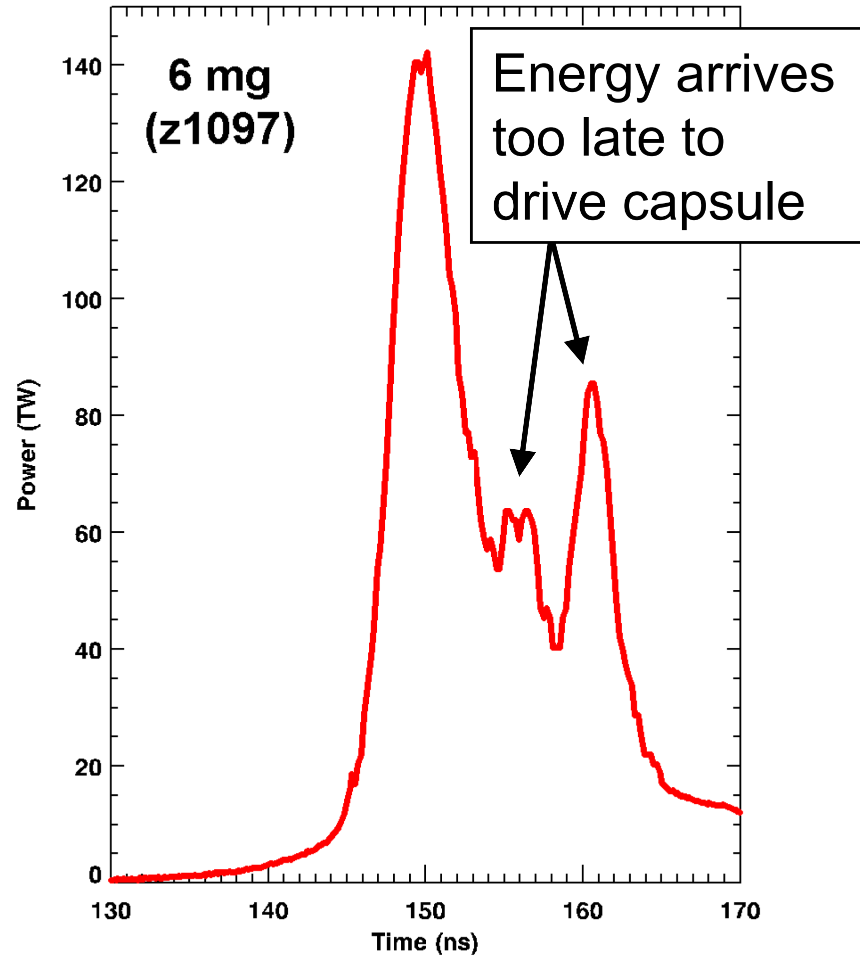


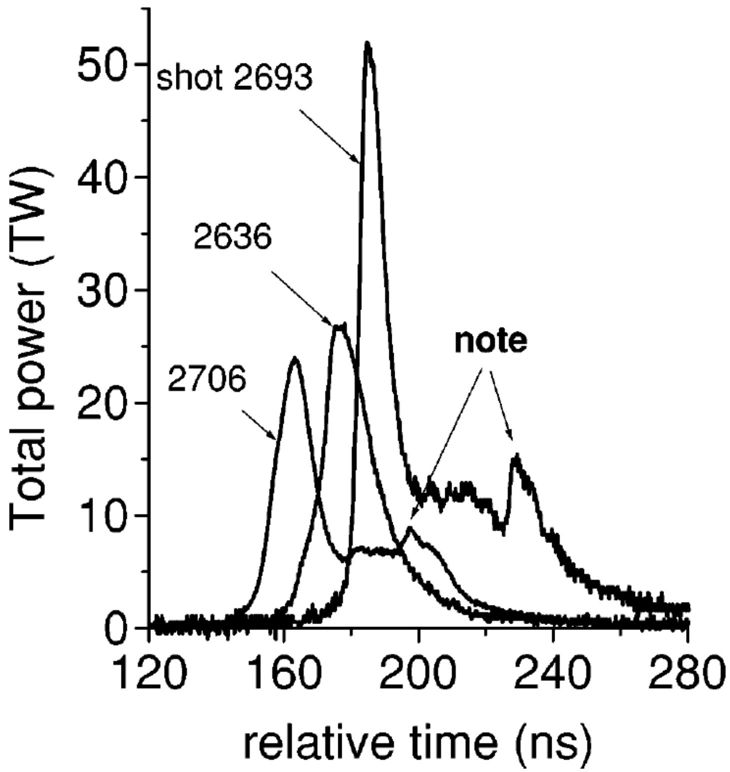
FIG. 7. Ideal Z-pinch x-ray power history and the running integral of the radiated energy for required three-step pulse.

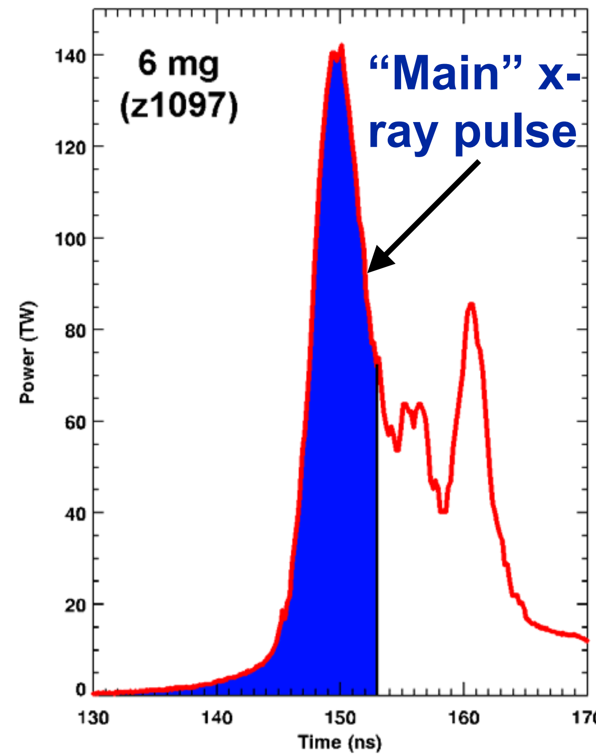
R.A. Vesey *et al.*, Phys. Plasmas 14, 056302 (2007).



Sandia National Laboratories

Question: Can we explain the main radiation pulse solely on basis of JxB implosion kinetic energy?





Previous work with Al arrays on SATURN claimed that the total radiation was 2-4x kinetic energy.

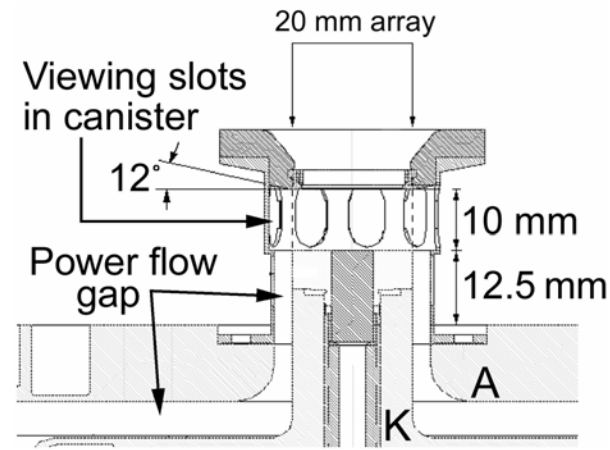
For 20 mm tungsten arrays on Z, the main radiation pulse typically contains ~50% of the total energy

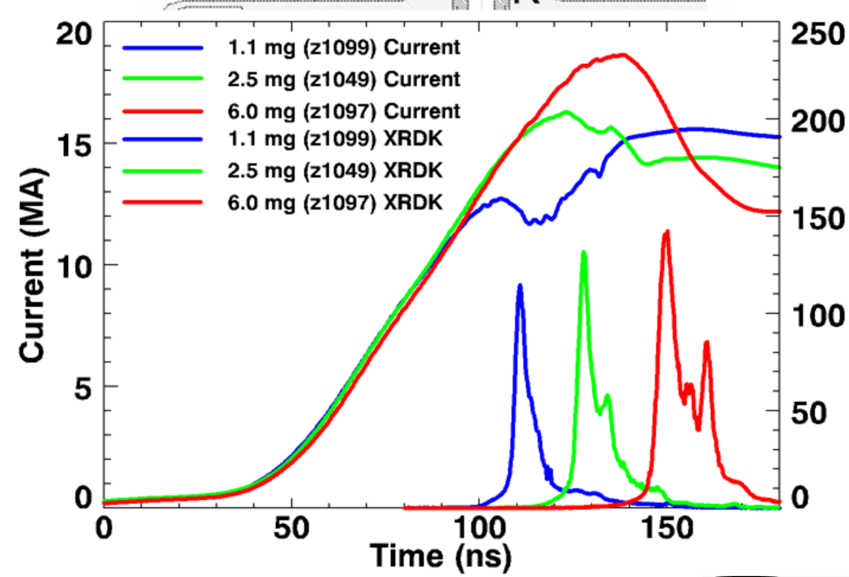
K.G. Whitney *et al.*, Phys. Plasmas 11, 3701 (2004).

Sandia National Laboratories

I will discuss single-array data from three different mass arrays

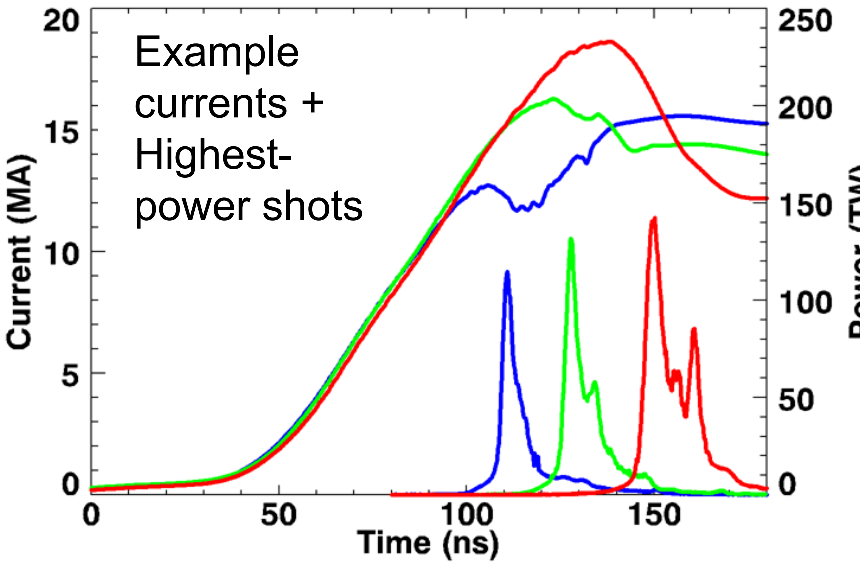
- Studied 3 20-mm diameter, 10-mm tall, 300-wire W arrays:
  - 6.0 mg (11.5 μm wires, 100 ns implosion)
  - 2.5 mg (7.4 μm wires, 81 ns implosion)
  - 1.1 mg (5.0 μm wires, 66 ns implosion)
- Identical hardware used each test
- Implosion time variation also changed the peak current
- Goals:
  - Study ablation dynamics[†]
  - Study radiation scaling[††]





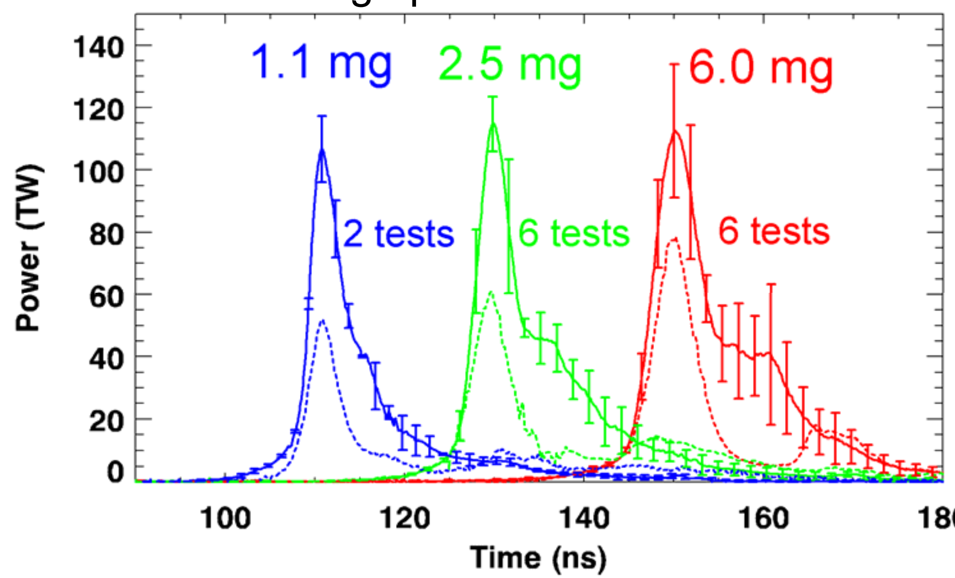
† D.B. Sinars *et al.*, Phys. Plasmas 13, 042704 (2006).
†† D.B. Sinars *et al.*, this talk.

As array mass decreased, so did FWHM of main pulse, keeping powers relatively high



The change in radiation pulse shape with implosion time kept the powers high even as the radiated energy dropped

Average power + std. deviation



Average radiated powers were comparable for the three arrays (Dashed lines correspond to array-on-rod tests to be discussed later).

Array	E_{main} (kJ)	E_{total} (kJ)	E^{rod}_{main} (kJ)	E^{rod}_{total} (kJ)	τ_{imp} (ns)	τ_{rise} (ns)	E/I^2_{max} (kJ/MA^2)	P/I^2_{max} (TW/MA^2)
1.1 mg	440±28	832±21	240	488	66	3.1	2.50±0.16	0.62±0.13
2.5 mg	532±46	1106±106	306	667	81	3.6	2.08±0.25	0.47±0.06
6.0 mg	692±66	1278±239	428	804	100	4.3	1.85±0.27	0.31±0.07

The kinetic energy is usually estimated using the peak current and the current convergence ratio

From Ryutov, Derzon, & Matzen, Rev. Mod. Phys. 72, 167 (2000).

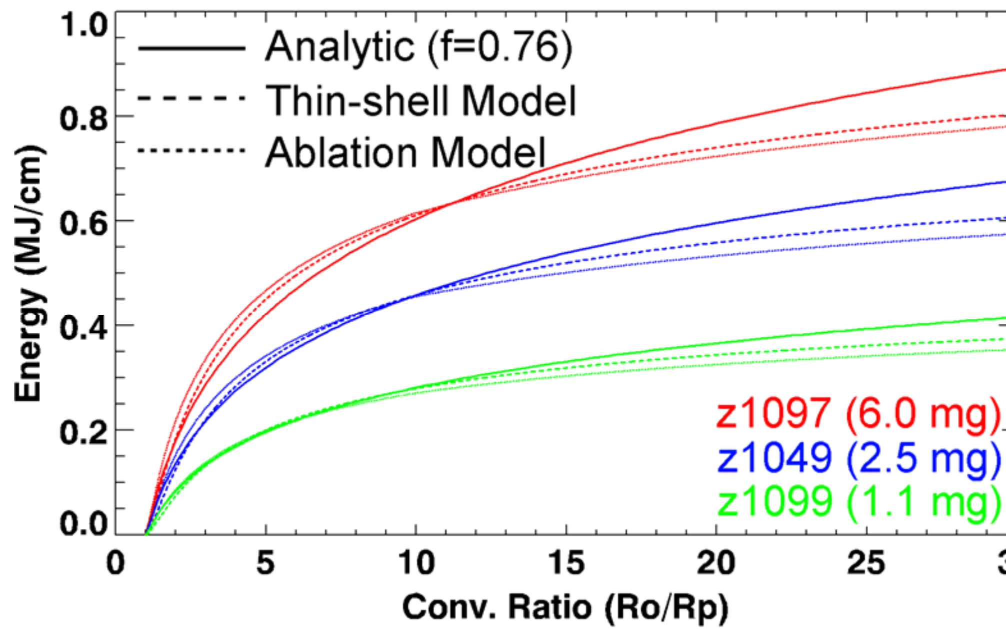
$$W_{kin} = \frac{\mu_0}{4\pi} \int_0^{t_p} \frac{dI^2}{dt} \ln\left(\frac{r}{R_p}\right) dt$$

For thin shells driven by a long pulse, this can be approximated by:

$$W_{kin} = \frac{f \mu_0}{4\pi} I_{max}^2 \ln\left(\frac{R_0}{R_p}\right)$$

(f is a form factor incorporating the current shape and circuit)

Since our E/I_{max}^2 ratio varies, we need to assess whether it is due to a variance in the convergence ratio or if some other physics is at play

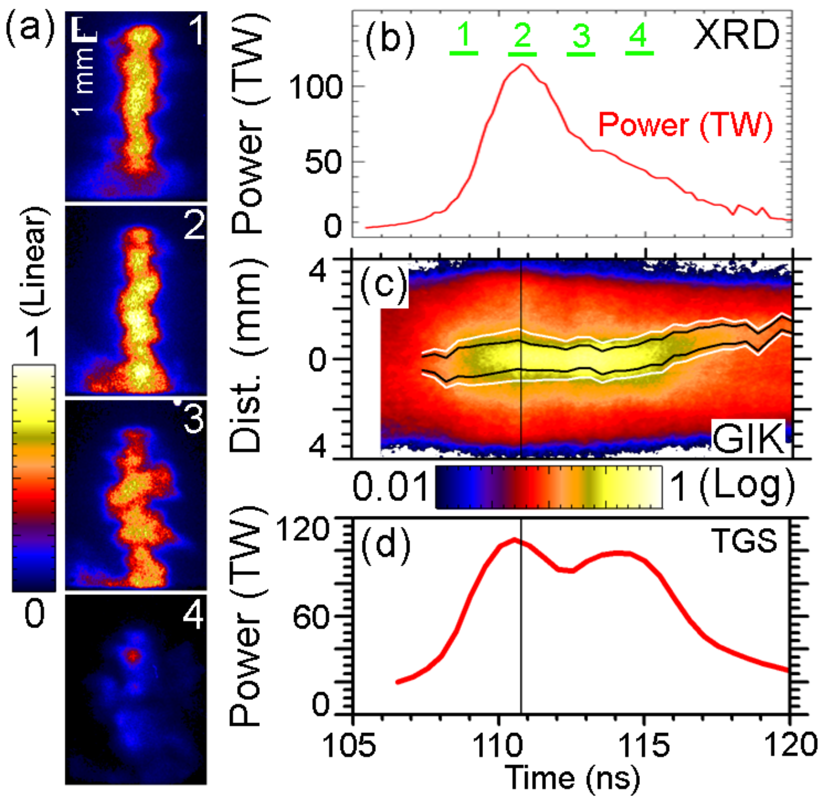


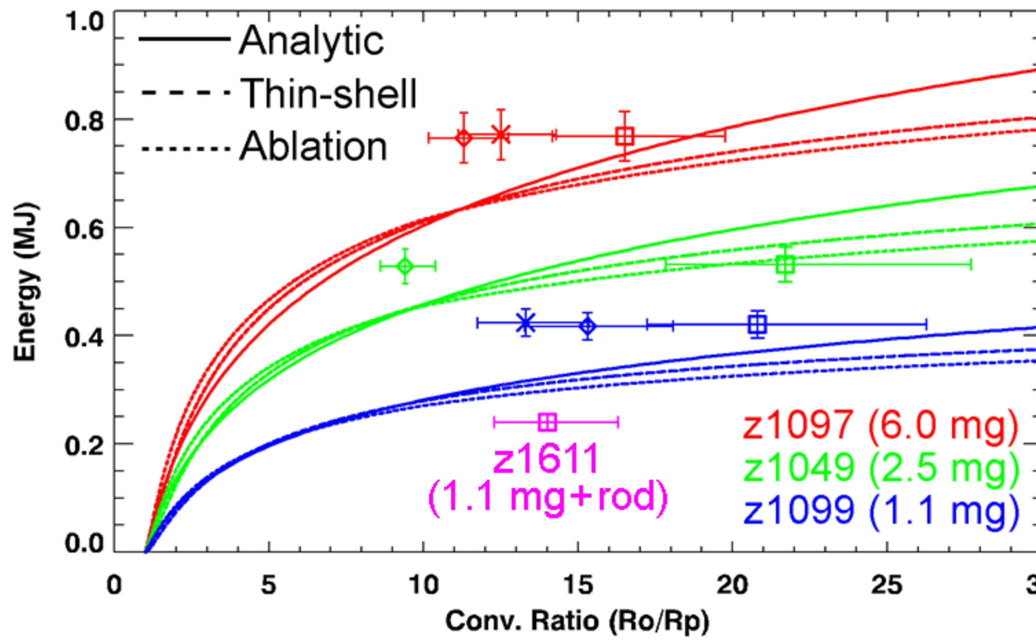
Comparison among a 0-D thin-shell calculation, a rocket model calculation†, and the analytic expression for the kinetic energy shows agreement if f~0.76 is used for all three masses

† D.B. Sinars *et al.*, Phys. Plasmas 13, 042704 (2006).

Sandia National Laboratories

Traditionally the convergence ratio is estimated using x-ray self-emission imaging





We estimated the CR using:
(a) X-ray pinhole camera (>1 keV)
(b) Grazing-incidence streak (375-450 eV)
(c) Trans. Grating Spectrometer (~450 eV)

The soft x-ray emission characteristic of the peak of the radiation spectrum is consistent with CRs of 9-15.

The pinhole images (>1 keV) are consistent with CRs of 16-22.

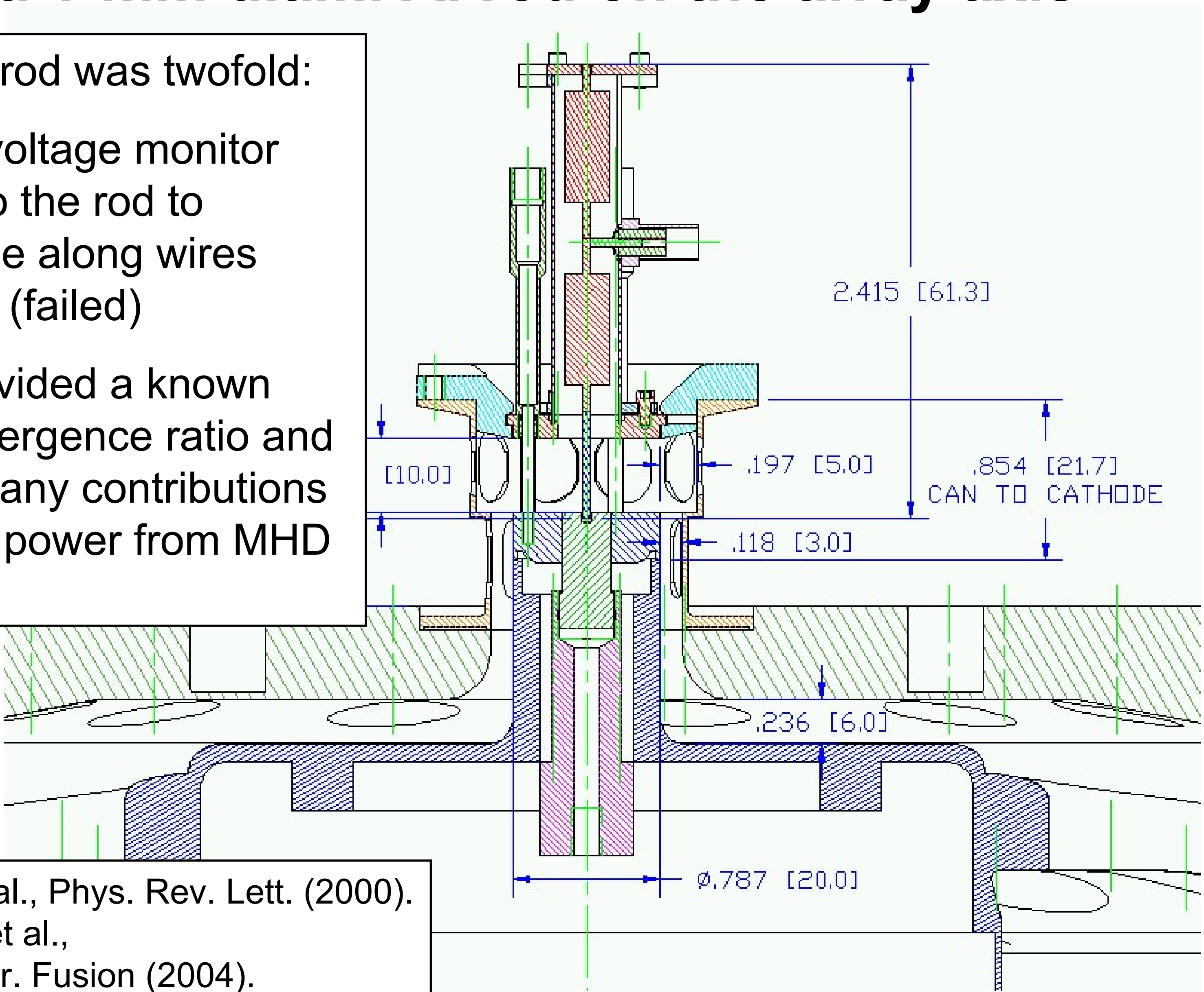
To get 421 kJ on z1099 requires a CR>30!

On three shots (1 per each mass), we used a 1-mm diam. Al rod on the array axis

Purpose of the rod was twofold:

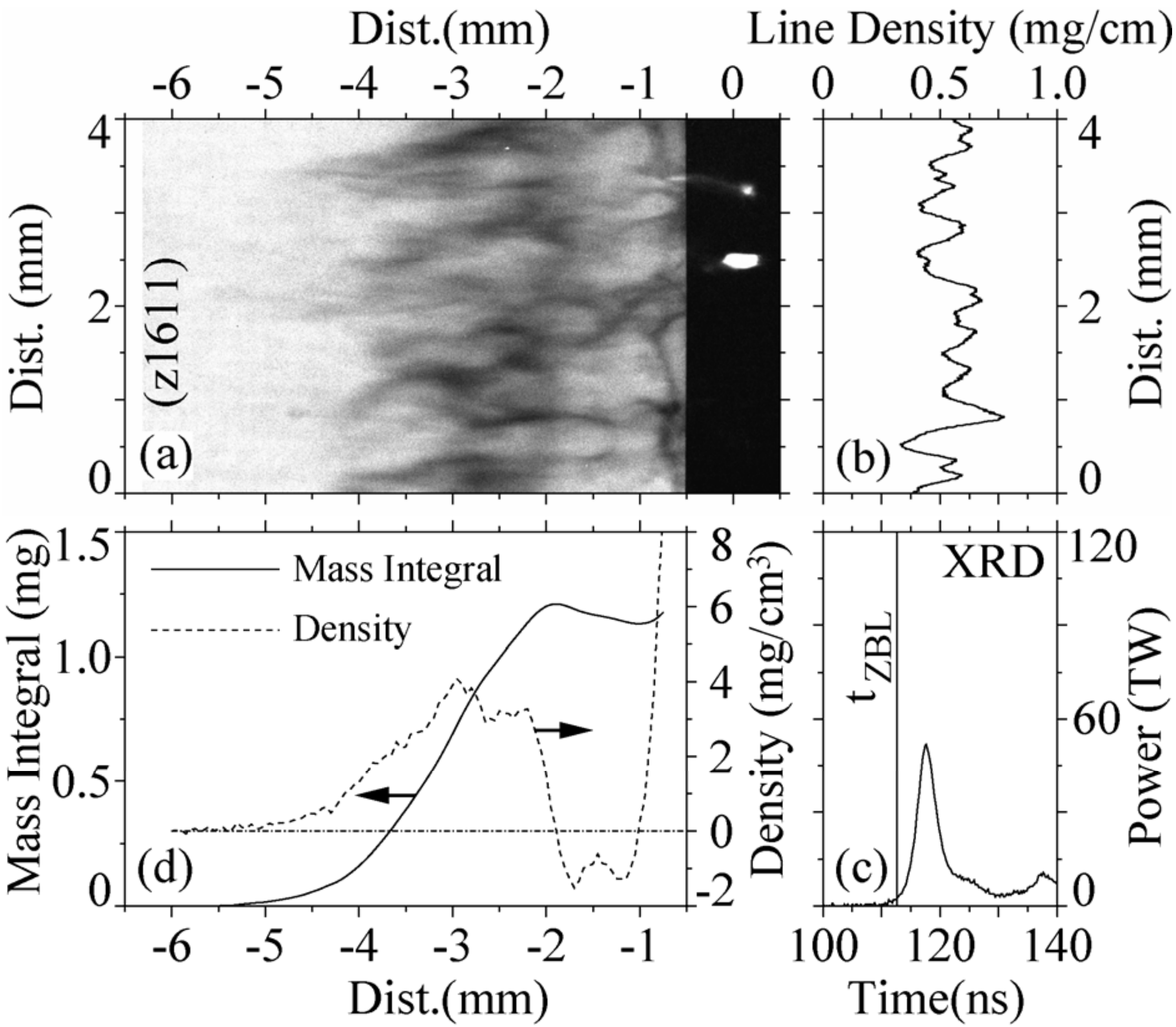
(1) A resistive voltage monitor was attached to the rod to measure voltage along wires during initiation (failed)

(2) The rod provided a known maximum convergence ratio and would dampen any contributions to the radiation power from MHD instabilities†



†m=0: Rudakov et al., Phys. Rev. Lett. (2000).
†m=1: Chittenden et al.,
Plasma Phys. Contr. Fusion (2004).

Radiography offers a second, independent method for estimating the convergence



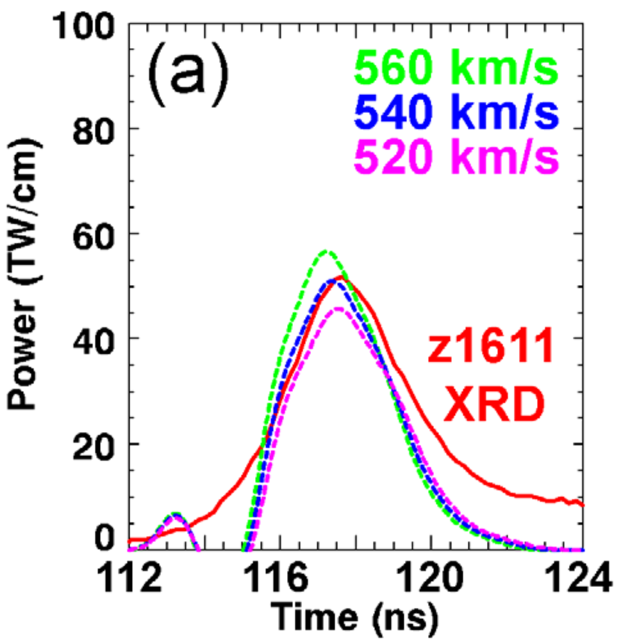
Obtained a beautiful radiograph on a 1.1 mg + rod shot (z1611)

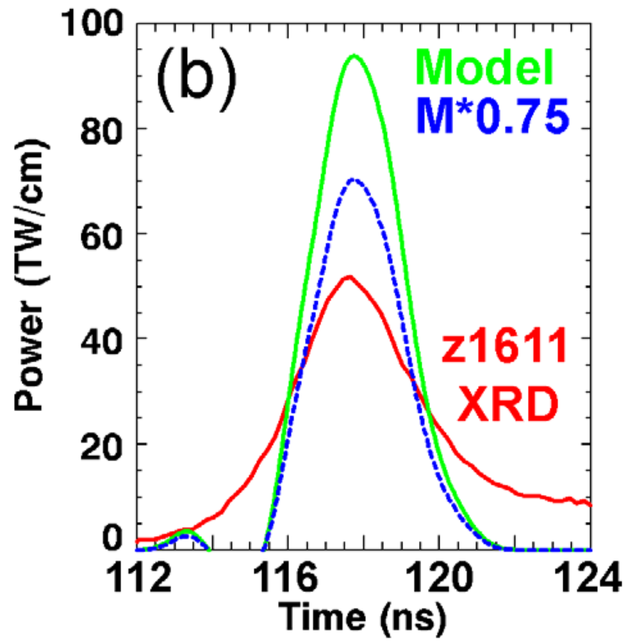
The mass density profile was obtained using an Abel inversion

The timing of the radiograph relative to the x-ray pulse is known (5 ns), and so estimates can be made of the kinetic power using simple assumptions

Sandia National Laboratories

It is plausible that the array+rod main radiation pulse is solely due to implosion kinetic energy





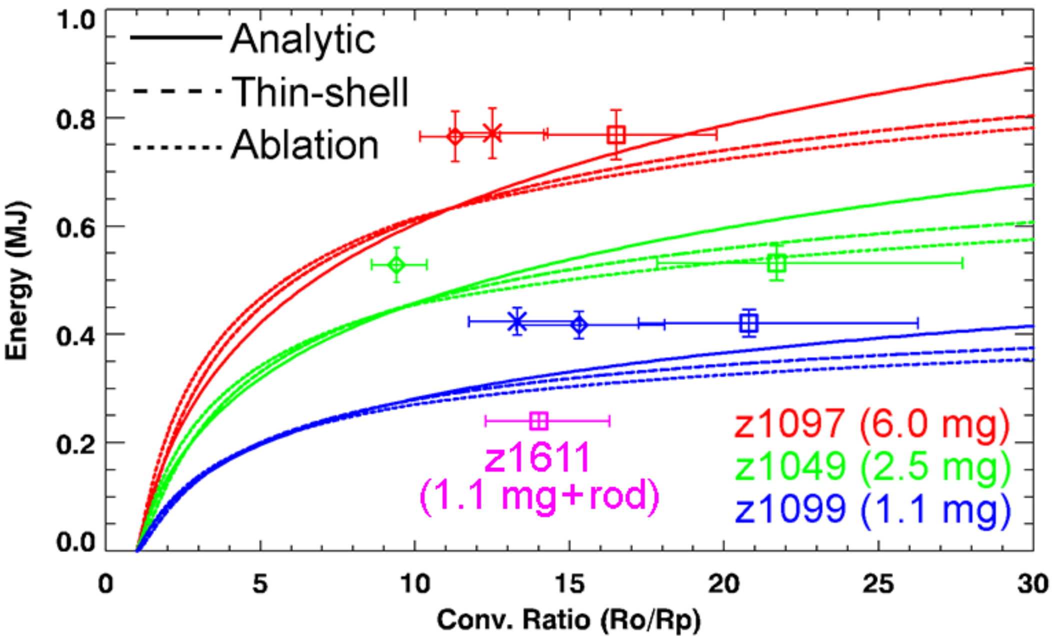
E_{main}=240 kJ
E_{vcon}=160 kJ
E_{Acon}=273 kJ

Conclusion:
It is plausible that the main x-ray pulse on the rod shot was due solely to implosion KE

(a) The kinetic energy flux through r=0.7 mm (the radius of the soft x-ray emission), calculated assuming constant velocities for the density profile from z1611, compared with the x-ray power measured on that test.
(b) The same calculations but now assuming an initial velocity of 400 km/s and a constant acceleration of 60 μm/ns^2 (equivalent to 14.1 MA at 3 mm radius). ALEGRA calculations suggest that about 25% of the kinetic energy is lost to the rod as shocks and internal heating.

Sandia National Laboratories

Assuming z1099 has a similar mass profile, it remains difficult to explain 421 kJ in the main pulse



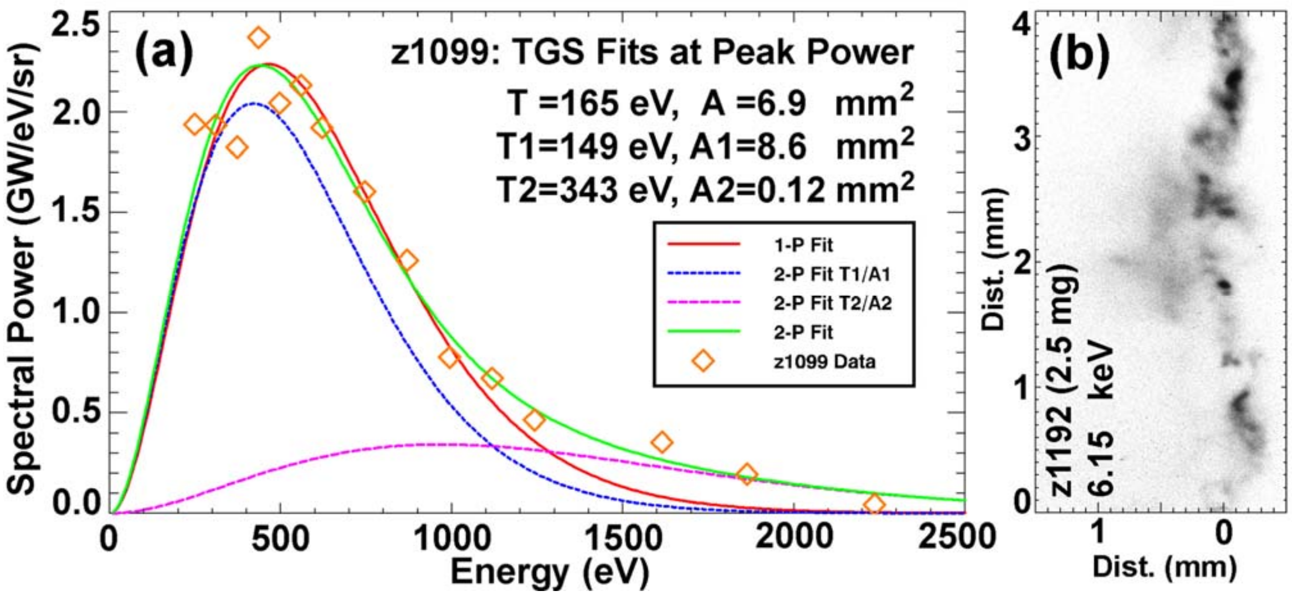
One is still forced into the conclusion that high current convergence ratios are necessary (due to MHD instabilities?†). Is there evidence to support this?

†m=0: Rudakov et al., Phys. Rev. Lett. (2000).
†m=1: Chittenden et al., Plasma Phys. Contr. Fusion (2004).

Array	E_{main} (kJ)	E_{total} (kJ)	E^{rod}_{main} (kJ)	E^{rod}_{total} (kJ)	τ_{imp} (ns)	τ_{rise} (ns)	E/I^2_{max} (kJ/MA^2)	P/I^2_{max} (TW/MA^2)
1.1 mg	440±28	832±21	240	488	66	3.1	2.50±0.16	0.62±0.13
2.5 mg	532±46	1106±106	306	667	81	3.6	2.08±0.25	0.47±0.06
6.0 mg	692±66	1278±239	428	804	100	4.3	1.85±0.27	0.31±0.07

Sandia National Laboratories

TGS data and self-emission at 6151 eV are consistent with small-area, high-temperature blackbody



Diameter of time-integrated emission is ~0.4-0.5 mm (CR 40-50!)

Pinches consistently have a high-energy tail well above that expected from a single-planckian fit to the peak of the spectrum.

A two-planckian fit suggests that the tail could be from a small-area, high-temperature blackbody radiating ~50% of total power.

Time-integrated self-emission at 6151 eV has an area and brightness comparable to what is expected from such a blackbody

Sandia National Laboratories

Summary

- **Light (short τ_{imp}) arrays produced high powers given reduced I_{max}. The radiation pulse rise times are proportional to τ_{imp}, and the powers could be consistent with $I_{max}^2/\tau_{imp}^{1.5}$ scaling [as in Stygar *et al*., Phys. Rev. E (2004).].**
- **The CR of the self-emission varies with photon energy:**
  - **~450 eV emission has CRs of 9-15**
  - **>1 keV emission has CRs of 16-22**
  - **6.15 keV emission (time-integrated!) has CRs ~40-50**
  - **1.1 mg bare-axis array requires CRs >30 to explain the energy in the main pulse.**
  - **Total energy radiated is another ~2x higher.**
- **Array-on-rod shot main radiation pulse can be explained solely in terms of JxB energy of implosion (self-emission, radiography). Bare-axis shots appear to require average CRs >20 for the current to explain the main radiation pulse. The total radiation emission certainly requires a non-kinetic source to explain.**
- **Electrical circuit analysis† (not discussed) suggests average current radius is very large (CR=6.7 at end of main radiation pulse for 1.1 mg array). But problems there, e.g., current at R=6.6 mm on z1611 when mass is 2-4 mm.**

† E. Waisman *et al.*, Phys. Plasmas (2004).

Backup Slides

Lighter masses are more efficient at extracting the available energy!

- **The 1.1 mg arrays are 50% more efficient at extracting energy and 100% more efficient at extracting power from the available current pulse than 6 mg arrays**
- **Ratio of rad. energy to I_{max}^2**
  - **1.85±0.27 kJ/MA² (6 mg)**
  - **2.08±0.25 kJ/MA² (2.5 mg)**
  - **2.50±0.16 kJ/MA² (1.15 mg)**
- **Ratio of peak power to I_{max}^2**
  - **0.31±0.07 TW/MA² (6 mg)**
  - **0.47±0.06 TW/MA² (2.5 mg)**
  - **0.62±0.13 TW/MA² (1.15 mg)**

$$\Pi = \frac{\mu I_{\max}^2 \tau^2}{4\pi \hat{m} r_0^2}$$

Two implosions with the same functional dependence of current with time (i.e., similar normalized currents) should occur in a similar fashion if π is the same. [Ryutov, Derzon, & Matzen (2000).]

$\pi_6 = 6.47$; $\pi_{2.5} = 6.85$; $\pi_{1.1} = 6.84$

By this metric, each of these arrays should have behaved similarly. Why didn't they?

Sandia National Laboratories

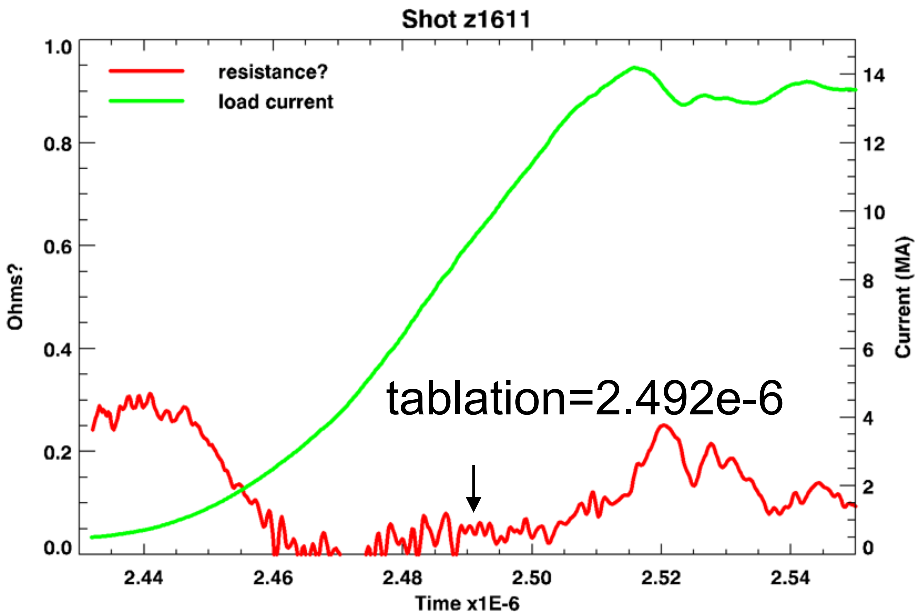
Scaling of τ_{rad} with τ_{imp} suggests power has a τ_{imp} dependence. Is this $P \alpha I_{max}^2/\tau^{1.5}$, or $\alpha (I_{max}/\tau)^{1.5}$, or ??

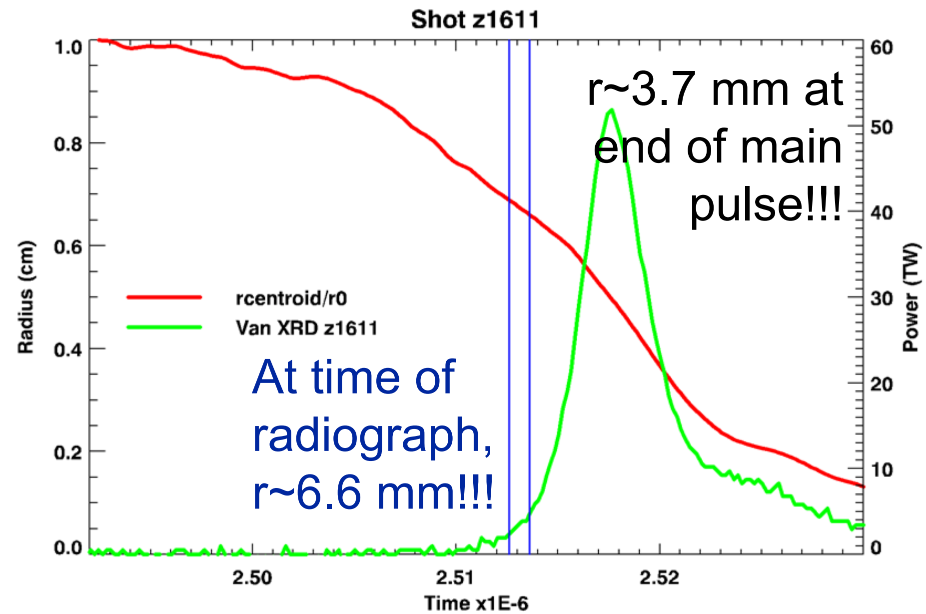
- For these three highest-power shots, there remain strong differences in their radiation power efficiencies
- Ratio of rad. energy to I_{max}^2
  - 2.22 kJ/MA^2 (z1097)
  - 2.03 kJ/MA^2 (z1049)
  - 2.61 kJ/MA^2 (z1099)
- Ratio of peak power to I_{max}^2
  - 0.41 TW/MA^2 (z1097)
  - 0.50 TW/MA^2 (z1049)
  - 0.71 TW/MA^2 (z1099)
- Let's ask the question: What if we normalize the powers to $I_{max}^2/\tau^{1.5}$?
- Ratio of peak power to $I_{max}^2/\tau^{1.5}$
  - 388 TW-ns$^{1.5}$/MA^2 (z1097)
  - 376 TW-ns$^{1.5}$/MA^2 (z1049)
  - 379 TW-ns$^{1.5}$/MA^2 (z1099)
  - Coincidence?
- Ratio of peak power to $I_{max}^2/\tau^{1.5}$
  - Here τ is from Cuneo method
  - 315±68 TW-ns$^{1.5}$/MA^2 (6 mg)
  - 342±47 TW-ns$^{1.5}$/MA^2 (2.5 mg)
  - 336±62 TW-ns$^{1.5}$/MA^2 (1.1 mg)

Cuneo noted last year that low-inductance mass scan data consistent with $P \alpha (I_{max}/\tau)^{1.5}$. Here 1395±280 (6 mg); 1356±249 (2.5); 1407±374 (1.1)

Sandia National Laboratories

Example Circuit Analysis: z1611 (1.1 mg array + rod)





After an initial resistance phase, "resistance" has settled down. Assume everything after tablation is due to array motion.

Inductance inferred from changes in load inductance implies that current stays out at very large radius.

If resistance is also present, the inductive radius goes farther out!

Sandia National Laboratories

Summary of single-array "mass scan" tests

TABLE I: Summary of the tests described in the manuscript. All tests used 300-wire, 20-mm diameter, 10-mm tall tungsten wire arrays inside identical raised, 30-mm diameter, 9-slotted return-current canisters with 8.0-mm wide slots (except for z0987 and z0988 which used 7.5-mm wide slots). A 1-mm diameter Al 5056 rod was placed on axis during tests z1222 and z1257. The peak load current prior to stagnation and the value at the time of peak x rays are listed. Parameters for the radiation pulses measured with 4-μm Kimfol(polyimide)-filtered XRDs or 1-μm Vanadium(V)-filtered XRDs are listed. The energy up to the peak radiation power (as measured by the Kimfol-filtered XRD) is listed along with the energy within and prior to the FWHM of the KimXRD signal.

Test No.	Array Mass (mg)	Wire (μm)	τ_{imp} (ns)	I_{max} (MA)	I_{peak} (MA)	XRD Power Kim/V (TW)	XRD rise Kim/V (ns)	XRD fwhm Kim/V (ns)	E_{peak} (kJ)	E_{main} (kJ)	E_{total} (kJ)
z0987	6.0	11.5	103.9	17.7	14.6	92/87	3.8/3.8	7.1/8.1	285	589	863
z1097	6.1	11.6	100.3	18.6	16.3	142/120	3.8/3.9	5.7/6.9	453	769	1556
z1098	6.1	11.6	99.3	19.1	17.6	107/92	4.5/4.1	6.9/8.1	353	725	1396
z1175	5.9	11.4	99.6	19.9	17.6	124/109	4.1/3.9	6.0/7.4	382	709	1330
z1176	5.9	11.4	99.3	20.3	18.1	140/121	4.5/4.5	5.1/6.5	450	724	1359
z1195	6.0	11.5	101.3	20.6	17.8	94/85	4.4/4.1	7.4/13.2	384	637	1165
z1257*	6.0	11.5	96.1	20.8	19.0	79/73	5.1/5.3	5.3/6.6	275	428	804
z1055	3.4	8.7	86.3	17.7	17.0	101/98	4.1/3.9	8.4/8.8	378	725	1072
z0988	2.5	7.4	81.1	–	–	114/100	3.1/3.1	4.3/5.3	286	481	1054
z1049	2.6	7.5	80.5	16.2	15.6	131/115	3.3/3.8	4.2/5.1	287	532	1056
z1051	2.6	7.5	80.8	14.7	13.0	123/113	3.4/3.4	4.4/5.1	287	536	1104
z1054	2.6	7.5	80.8	16.4	15.5	118/108	3.5/3.4	4.4/5.0	255	479	968
z1192	2.5	7.4	82.7	16.8	15.2	122/99	4.1/3.6	5.1/6.1	409	589	1190
z1194	2.5	7.4	78.6	16.9	16.1	119/96	4.1/3.6	4.9/6.0	347	573	1263
z1222*	2.5	7.4	76.7	17.2	16.5	65/57	4.0/4.1	4.7/5.9	197	306	667
z1099	1.1	5.0	65.7	12.7	12.2	115/87	2.9/4.6	4.3/6.7	224	421	846
z1177	1.2	5.1	67.4	13.9	13.2	102/85	3.2/3.3	4.7/7.6	199	460	817
z1611*	1.2	5.1	??.?	14.4	13.9	???/52	?.?/3.3	?.?/3.9	108	240	488