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The Z Accelerator as a Source of >100 kJ of X-Rays above 4.8 keV

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Recent K-shell scaling experiments on the 20 MA Z accelerator at Sandia National Laboratories have shown that large diameter (40 and 55 mm) arrays can be imploded with 80 to 210 wires of titanium or stainless steel. These implosions have produced up to 150 kJ of >4.5 keV x-rays and 65 kJ of >6.0 keV x-rays in 7 to 18 ns FWHM pulses. This is a major advance in plasma radiation source (PRS) capability since there is presently limited test capability above 3 keV. In fact, Z produces more >4.5 keV x-rays than previous aboveground simulators produced at 1.5 keV. Z also produces some 200 kJ of x-rays between 1 and 3 keV in a continuous spectrum for these loads. The measured spectra and yields are consistent with 1-dimensional MHD calculations performed by NRL. Thermoelastic calorimeters, PVDF gauges, and optical impulse guages have been successfully fielded with these sources.

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Introduction

Pulsed power driven Z-pinches have been used for many years to measure material properties and to test optical components.[1,2] These sources are promising for this application because of their high efficiencies. For example, the Saturn accelerator produces 75 kJ of 1.8 keV x-rays and up to 40 kJ of 3 keV x-rays [3] from a stored electrical energy of 5 MJ. Saturn typically delivers about 8 MA to loads with masses up to 500 μg/cm. Despite good pinch quality and high x-ray powers over a range of load parameters, z-pinches on machines like Saturn have not been able to produce significant yield above 3 keV, however, due to the limited masses that can be imploded.

There is a need for high photon energy sources (above 3 keV) not only for materials, thermostructural response, and optics testing, but also for helping to benchmark calculations necessary for improving load design and scaling relevant to DECADE and other future high current simulators. The loss of the energy rich underground testing capacity left a gap for several experimental environments, including the ability to produce high fluences (> 5 cal/cm^2) of x-rays over reasonable areas (tens to thousands of cm^2) with photon energies of 5-80 keV. Production efficiencies in this photon regime from two of the common physical processes used to produce intense x-ray sources in the lab (thermal plasma radiation and Bremstrahlung) are very low. While high yield ICF sources hold promise for filling this testing gap, non-ignition sources that produce adequate environments will still be preferred in many cases for several reasons, including the lack of concurrent neutron fluxes and lesser facility damage.

Sandia National Laboratories have constructed a 20 MA Z-pinch driver, called Z, as a modification of the existing PBFA II accelerator. Z offers the opportunity to significantly advance the x-ray capabilities in the 4 - 10 keV regime. One of the limits in producing higher energy photons has been that even at 8 MA, large enough masses could not be imploded to produce high enough densities to get > 3 keV sources to radiate efficiently. With Z, masses of greater than 1 mg/cm can implode at velocities greater than 70 cm/μs. Based on K-shell scaling laws [4,5], these conditions will achieve densities and temperatures that could produce in excess of 200 kJ of titanium K-shell x-rays. This would result in fluences of 1 - 15 cal/cm^2 that could be used for various applications.

In this paper, initial data on the titanium and stainless steel wire array loads showing the optimization of the energy by varying the implosion velocities and wire number will be presented. Calculations by NRL will be presented to determine the pinched plasma parameters and the measured data will be compared to NRL scaling calculations.

The Z Generator

Z, as the PBFA II modification is known, is a 36 module machine based on classical water-dielectric pulse-forming technology that routinely delivers 20 MA and 3 MJ into the vacuum insulator stack. [6] A schematic of Z is shown in figure 1. Load current monitors show that 15-18 MA are delivered to various imploding Z-pinch x-ray sources with a time to peak current of 105 ns. Source diagnostics available on Z include photoconducting detectors (PCD's), which can measure 1-10 keV radiation; XRD's, which can measure 180 - 1500 eV; nickel bolometers for total x-ray yield; time-resolved pinhole images; and time-integrated and time-resolved crystal spectrometers.

Initial radiation experiments have focused on the production of intense, near-Planckian emissions from tungsten wire arrays [7] for driving vacuum and dynamic hohlraums for ICF physics. Using 40 mm tungsten arrays with 120 and 240 wires, Z has produced 160 TW and 1.8 MJ of total radiation. Time-integrated and time-resolved spectra combined with PCD's and bolometers have shown emission > 100 kJ above 1 keV. These emissions are continuous with an exponential fall-off.

Optimization of high Z radiators on the Z accelerator could give significant yields at higher photon energies with good spectral fidelity, in part due to the L-shell and M-shell radiation spectra which lie in the 1 - 5 keV range. This would provide an alternate path to the already successful use of mixed K-shell and L-shell radiators on Double-EAGLE [8], Phoenix [9,10], and Saturn [11].

Scaling of Z-pinch K-shell radiators

Z-pinch scaling theories developed by the Naval Research Laboratory[4,5,12] predict that the Z accelerator, with optimum load designs, can generate significant yields (hundreds of kilojoules) above 3 keV photon energy, as depicted in figure 2. This simple scaling theory is based on phenomenological fits to a series of detailed one-dimensional radiation-magnetohydrodynamic calculations where the conversion of only implosion kinetic energy into x-rays was studied for different implosion velocities and masses. For reference, the scaling predictions for the 8-MA Saturn accelerator are shown in Figure 2, as are the measured yields at different photon energies. The measured yields agree well with the scaling theories. The scaling curve for Z indicates an improvement of more than an order of magnitude over the Saturn predictions for photon energies greater than 3 keV.

Based on the availability of wires, in combination with the understanding of Z-pinch implosion and yield scalings, titanium (Ti) and stainless steel (SS) wire array loads were used for the initial scaling experiments. As listed in Table 1, the array diameters were 40 mm for Ti and 55 mm for SS. These array diameters were chosen to achieve implosion velocities high enough that the kinetic energies per ion were at least twice the minimum energy per ion required to ionize to the K-shell.

Table 1. The Z titanium and stainless steel shot parameters and yields.

Material	Array Diameter (mm)	Wire Number	Wire Diameter (μm)	Array Mass (μg/cm)	K-shell Yield (kJ)	K-shell FWHM (ns)	Shot Number
Ti	40	80	25.4	1839	90±15	18	67
Ti	40	140	20.3	2060	110±20	10	87
Ti	40	110	20.3	1619	120±20	10	88
Ti	40	90	20.3	1324	150±25	11	119
S.S.	55	210	10.0	1302	47±10	9	89
S.S.	55	170	10.0	1054	55±10	7	121
S.S.	55	140	10.0	868	65±10	8	122

Titanium and Stainless Steel Wire Array Results

In Table 1, the measured yields and pulsewidths for all the titanium and stainless steel shots are summarized. The first titanium wire array imploded on Z (Z shot 67) was composed of 80, 25.4-μm diameter wires on a 40 mm diameter array. (see figure 3) Based on calibrated PCD arrays, 3.5 ± 0.5 TW of titanium K-shell x-rays were measured with an 18 ns FWHM. The corresponding Ti K-shell yield (4.9 ± 0.1 keV) was 90 ± 15 kJ. The yield from the titanium K-shell source was further optimized by using thinner (20.3-μm dia.) wires to allow an increase in the wire number. This led to yields of 110 to 125 kJ, although with shorter pulsewidths. The highest yield of 150 kJ was achieved by reducing the array mass to increase the implosion velocity. The measured K-shell power pulse for the highest yields shot (Z119) is shown in Figure 4(a) and the broadband spectrum is shown in Figure4(b).

The titanium spectrum shows that these higher atomic number sources have both significant K-shell components and significant L-shell components above 1 keV. Due to the energy ranges of the L-shell of titanium, the above 1 keV x-rays are dominated by the recombination continuum, which still contains some 150 kJ. The combination of the Land K-shell radiation may provide interesting spectral fidelity opportunities. Figure 4(b) suggests that the temporal fidelity of these sources is also good. This is a major advantage of conventional Z-pinch implosions that the pulsewidths are usually broad enough for fidelity, whereas, ignition-type pellets will tend to have pulsewidths that are too short.

With the stainless steel arrays, a similar mass scan was performed by decreasing the number of 10-μm diam. wires in the array from 210 to 170 to 140. Similar to the titanium results, the yields increased as the implosion velocity increased. These implosion velocities are high, typically approaching 100 cm/μs. The highest yield was 65 kJ with a 8 ns FWHM. We are performing one- and two-dimensional radiation-magnetohydrodynamic calculations to assess the stability and radiation dynamics of these implosions. In Figure 5, the K-shell power pulse (a) and the K-shell spectrum (b) from the highest yielding shot are plotted. The K-shell spectrum is dominated by the two helium-alpha transitions from chromium and iron. The L-shell emissions above 1 keV (not shown) exceed 200 kJ since there are strong L-shell transitions in nickel and iron above 1 keV. The 9 ns FWHM of the K-shell emissions has adequate fidelity for effects tests.

By analyzing the spectra, x-ray pinhole images and PCD data, following the techniques discussed in reference 13, the fraction of the initial array mass which is ionized to the K-shell was deduced to be less than 12% for all the arrays. Since such a small fraction of the initial mass was radiating the K-shell x-rays, it is not surprising that such an interesting spectrum is present; the cooler regions will radiate L-shell emissions at the same time as the hot core radiates K-shell lines. This low mass fraction is also consistent with the observation of poor quality pinches, for eaxample, the implosions discussed here had final plasma diameters of 4 mm whereas higher wire number tungsten wire arrays produced 2 mm diameter pinches. The poor pinch quality, however, implies that the imploded plasma is not heated as efficiently as would be predicted by the 1D scaling radiation-MHD calculations. To improve this heating, future experiments will employ increased numbers of smaller diameter wires to improve the uniformity of the implosion. The spectral analyses did indicate that high temperatures (2.8 to 3.7 keV) were being reached in the K-shell emitting regions, which offers potential to obtain even higher energy x-ray sources. Electron densities for these shots are estimated to be > 6×10^{20} cm^{-3}. Again, this is too low for efficient higher energy x-ray production but the increased wire number in future shots should rectify the low densities.

The best results from these initial scaling experiments are shown in figure 2. They are within a factor of 2-3 of the ideal scaling, as predicted by NRL. Future experiments with these loads are intended to further optimize the loads and it is expected that the experimental results will agree better to the ideal scaling predictions, as the Saturn results do, when this optimization is complete.

NWET testing capabilities

The yields and spectra generated from these titanium and stainless steel loads on Z are useful for weapons effects testing, as shown in figure 6. Comparison to an envelope of fluences and photon energies previously identified by C. P. Knowles as important for weapons effects testing indicates that the fluences obtained for these loads are substantial, and fall into the envelope in a region where satellite optics and material response testing can be performed. Previous results on Z using aluminum also fall into this same envelope. It is worth noting that for these high photon energy, K-shell sources, there is a benefit beyond just high fluence: a broader spectrum as discussed above.

KTECH Corporation fielded impulse gauges, PVDF stress guages and thermoelastic calorimeters on these Ti and SS Z shots at possible sample locations. Low noise levels were measured and the impulse gauges demonstrated the existence of a 3 ms window in which impulse measurements can be made. In fact, the titanium source, in its non-optimized form, has already been used in support of the neutron generator program at SNL, see figure 7.

As new components are needed for the stockpile, high fidelity, high fluence sources will become more important. Materials testing is necessary to help validate the codes that will be used to model components. Computer models are being used more and more for certification of components through the ASCI program and accurate material property values are crucial for improved accuracy in the models. Since there is no guarantee that new components will use only materials for which appropriate testing has already been done, continued development and use of advanced x-ray sources is important. The development of appropriate test environments is also important for this testing capability, and debris mitigation techniques are currently under investigation. [14,15]

Conclusions

In conclusion, large diameter, high wire number titanium and stainless steel wire arrays were imploded on the Z generator, producing yields of 150 ± 15 kJ of > 4.8 keV x-rays and 65 ± 15 kJ of > 6.0 keV x-rays. Plasma electron temperatures of 2.8 to 3.7 keV and electron densities of $> 6 \times 10^{20}$ cm^{-3} were measured. To put these results in perspective, in comparison to the previous best PRS yield of 40 kJ of argon K-shell x-rays from the Sandia National Laboratory's Saturn generator, the measured yield above 4.8 keV on Z is 15 times greater than that achieved on Saturn, and 30 times greater than Saturn for > 6 keV. These initial high atomic number K-shell scaling results are not yet fully optimized, but are already within a factor of 2-3 of the ideal scaling. Future experiments on these types of loads will employ higher wire number arrays to improve the quality of the Z-pinch and optimize the radiation output. The use of nested wire array configurations will further optimize the yields.

These experiments have provided excellent data above 3 keV which can be used by the Z-pinch physics community to benchmark calculations that can be utilized in designing high fidelity loads for DECADE and other future high current pulsed power machines. The comprehensive data sets will also help assess the ability of the available codes to accurately model Z-pinches and predict outputs. They also represent a significant enhancement in the above ground testing soft x-ray capability. Early indications are that some NWET missions can be addressed on Z even at the higher current and energy levels. Additional work will address 7 - 10 keV scaling, enhanced fidelity sources, and the development of usable test environments.

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Figure Captions

Figure 1. A cross-section of the Z generator. The marx banks store 11.5 MJ of electrical energy. The marxes and waterline sections produce a 3 MJ, 50 TW electrical pulse at the insulator between the water and vacuum. This electrical pulse drives 18 MA through an imploding load with a 100 ns time to peak.

Figure 2. Z-pinch scaling theory predictions for the Saturn and Z generators. The circles represent actual data obtained on Saturn and Z.

Figure 3. A photograph of a 40 mm diameter titanium wire array composed of 80, 25.4-μm-diam. wires

Figure 4. Z119 – the highest yield titanium shot on Z to date. The power pulse for this shot is shown in (a), and the time-integrated spectrum is shown in (b).

Figure 5. Z122 – the highest yield stainless steel shot on Z to date. The power pulse is shown in (a), and the time-integrated K-shell spectrum is shown in (b).

Figure 6. The "need" envelope for weapons effects testing courtesy of C.P. Knowles overlayed with the measured Z data.

Figure 7. A photgraph of impulse guages being fielded on Z accelerator shots, employing the titanium K-shell loads discussed in this paper.

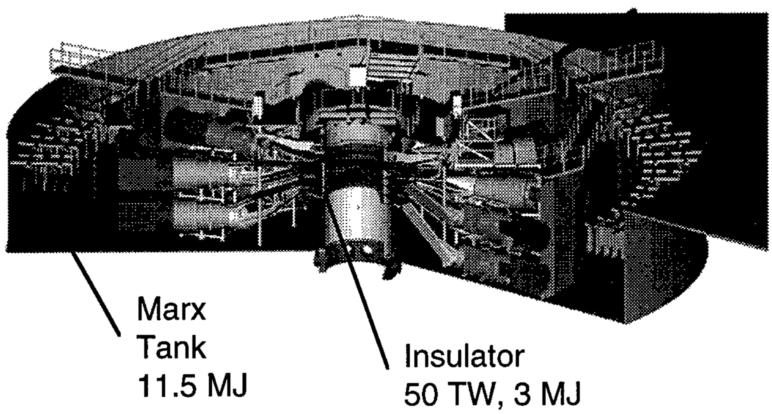
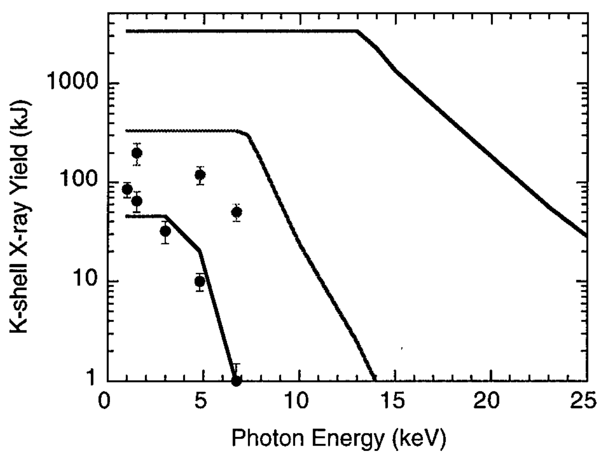


Figure 1.



K-shell X-ray Yield (kJ)
1000
100
10
1
0
5
10
15
20
25
Photon Energy (keV)

Figure 2.

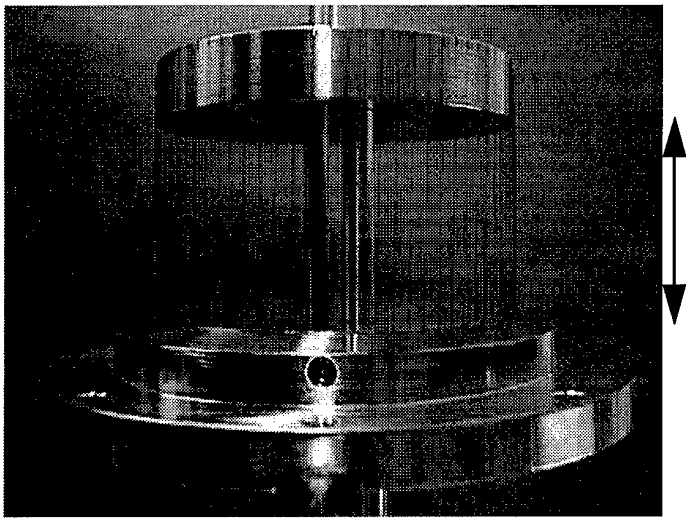


Figure 3.

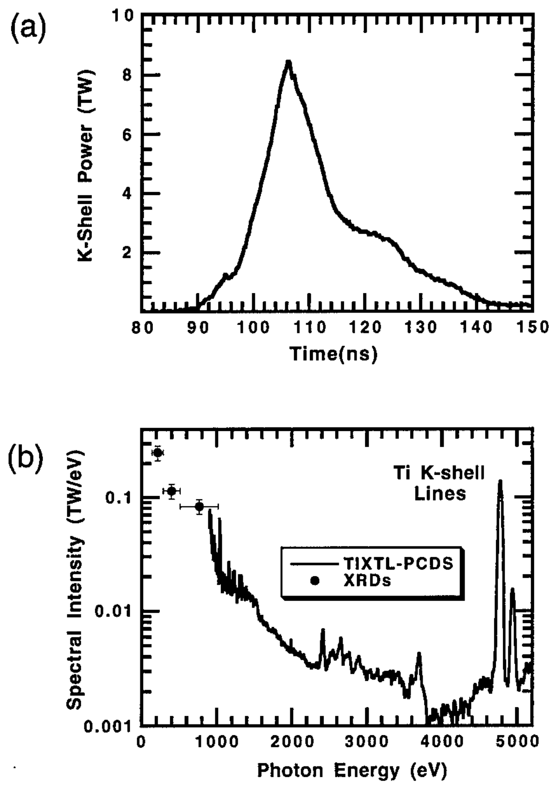

(a)
K-Shell Power (TW)
Time(ns)
(b)
Spectral Intensity (TW/eV)
Ti K-shell
Lines
TIXTL-PCDS
XRDs
Photon Energy (eV)

Figure 4.

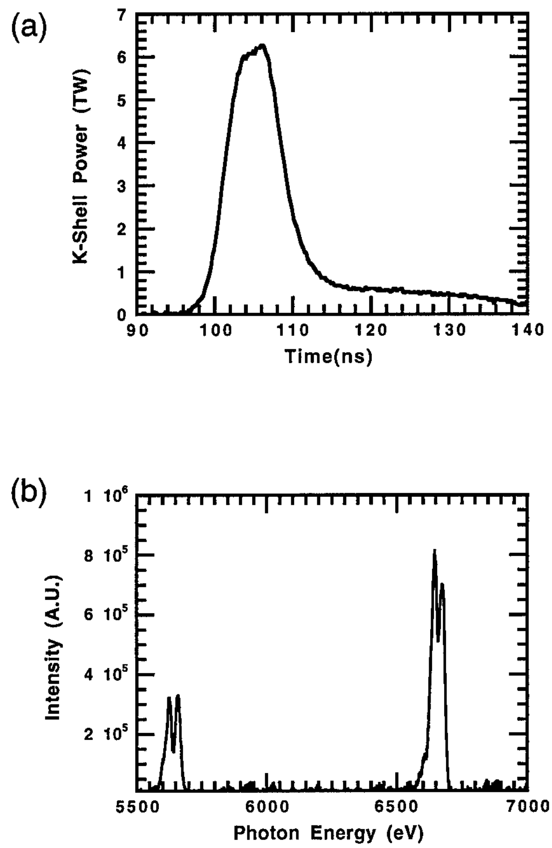
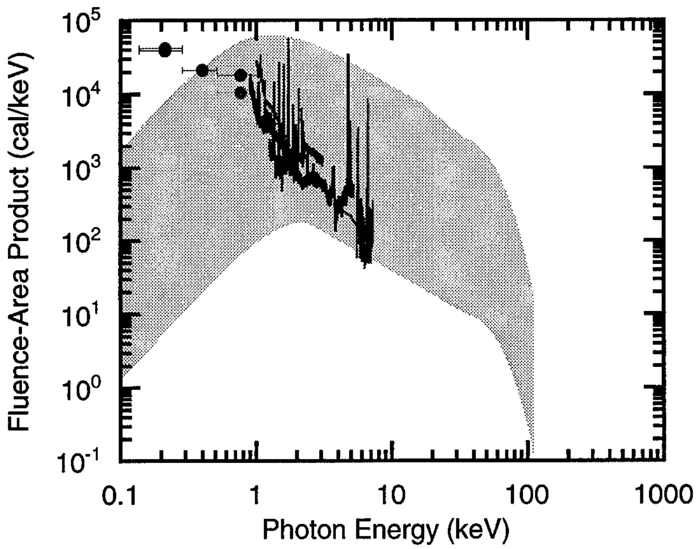

(a)
K-Shell Power (TW)
Time(ns)
0
1
2
3
4
5
6
7
90
100
110
120
130
140
(b)
Intensity (A.U.)
Photon Energy (eV)
$1\ 10^6$
$8\ 10^5$
$6\ 10^5$
$4\ 10^5$
$2\ 10^5$
5500
6000
6500
7000

Figure 5.



Fluence-Area Product (cal/keV)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
0.1
1
10
100
1000
Photon Energy (keV)

Figure 6.

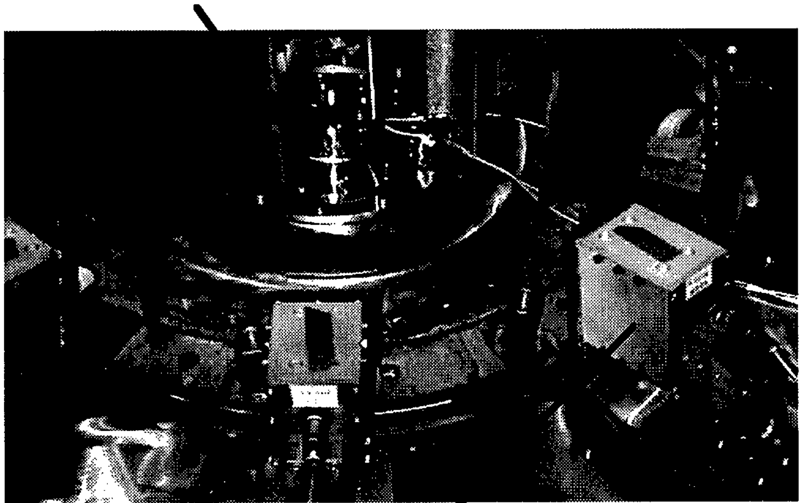


Figure 7.

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