

CURRENT SCALING OF OPTIMUM K-SHELL X-RAY YIELD AND LOAD MASS APPLIED TO ARGON GAS-PUFF Z-PINCHES*

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Abstract

A simple two-level radiation-scaling model has previously been shown to agree with 0.7-MA neon gas-puff and 7-MA aluminum wire-array experiments. Here, the scalings of optimum load mass and peak K-shell yield with current for argon gas puffs are compared with data over an order-of-magnitude current variation. Optimum load conditions are determined by maximizing K-shell yield subject to fixed implosion energy, resulting in peak yield and optimum mass as functions of implosion energy and stagnation radius. The scalings with current result from implosion-energy and implosion-time relations that fit Double Eagle nested-shell argon gas-puff results. Both the maximum-yield and optimum-mass scalings provide good absolute-value fits to the data, including the variation with implosion time.

I. BACKGROUND AND MODEL REVIEW

A simple radiation-scaling model based on two-level atomic physics and plasma energy balance [1] was developed to guide selection of plasma-radiation-source (PRS) load parameters and estimate K-shell x-ray yields for z-pinch drivers. The model has been shown to agree in detail with neon gas-puff experiments [2] at 0.7 MA and aluminum wire-array experiments [3] at 7 MA. Here, it is used to predict the current scaling of peak K-shell yield from optimum load parameters for argon gas-puffs. Results are compared with data from a variety of generators and load conditions spanning an order-of-magnitude current variation, including recent results on the Sandia National Laboratories Z generator at 15 MA [4]. In light of the variety of driver and load configurations represented by the data, it is noteworthy that both the maximum-yield and optimum-mass scalings provide good absolute-value fits to the data, including the implosion-time variation.

Optimum temperature and mass are determined by maximizing K-shell yield subject to energy balance with fixed implosion energy, resulting in peak yield and optimum mass as functions of implosion energy and stagnation radius.

The current scalings result from the implosion energy vs current, implosion-time scaling, and compression ratio that fit Double Eagle (DE) nested-shell argon results. [5]

The two-level model is a simple, first-principle treatment useful for estimating how K-shell x-radiation from the PRS scales with plasma, pulsed-power, and imploding-load parameters. [1] Input parameters for the model are the implosion energy $E_W(J/cm)$, load mass $m(g/cm)$, stagnation radius $R_f(cm)$ of the radiating plasma, and atomic number Z_A . The only radiation considered is the line associated with the principal 2-to-1 transition of a single, K-shell ionization state, calculated for uniform density and stagnated-plasma temperature $T(eV)$ within R_f . The temperature derives from a simple energy-balance equation. For gas-puff z-pinches, the implosion energy is calculated from local snow-plow implosions in measured gas-density distributions and contains both radial kinetic energy and internal energy due to shock heating. [6]

Energy balance takes the form [1]

$$E_W = E_I + Y + E_p \quad (1)$$

with all quantities in J/cm of load length. In Eq. (1), E_W is the implosion energy, E_I is the stagnated-plasma internal energy, Y is the K-shell radiated energy, and E_p contains energy losses in neglected processes such as radiation from other excitations and residual energy in the plasma rebound following peak compression. The internal energy in the K-shell regime can be written

$$E_I = 1.8 \times 10^5 m T / Z_A^{0.28} \quad (2)$$

The radiation term in Eq. (1) is given by $Y = S Y_t$, where the optically-thin radiation rate is given by

$$Y_t = \frac{3.9 \times 10^{16} m^2}{R_f T Z_A^{1.2}} \exp\left(-\frac{10.2 Z_A^2}{T}\right) \quad (3)$$

and S is the radiation escape fraction. For the conditions of this study, $S = 1$ for plasma parameters that maximize the yield. [1] The model is in good agreement with neon

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and aluminum experimental yields when E_p is taken to be $E_w/2$, so that energy balance becomes

$$E_w / 2 = E_t + Y_t \quad (4)$$

It is convenient to normalize the load mass and stagnation temperature according to

$$y = T / T^* \quad ; \quad n = m / m^* \quad (5)$$

where

$$T^* = 3.4 Z_A^2 \quad (6)$$

$$m^* = 8.3 \times 10^{-7} E_w / Z_A^{1.72} \quad (7)$$

so that Eqs (2) and (3) take the form

$$1 = ny + 2Y_t / E_w \quad (8)$$

$$\frac{Y_t}{E_w} = \frac{E_w}{K_b} \frac{n^2}{y} \exp\left(3 - \frac{3}{y}\right) \quad (9)$$

where

$$K_b (J/cm) = R_f Z_A^{6.64} / 390 \quad (10)$$

characterizes the transition energy centered between the asymptotic I^4 and I^2 regimes. [1]

II. YIELD OPTIMIZATION

The objective is to maximize Y_t constrained by energy balance for fixed implosion energy E_w . The implosion energy depends on the load-current history (and therefore the implosion time) and the ratio R_0/R_f , where R_0 is a measure of the outer radius of the gas distribution. The implosion time is proportional to mR_0^2 , so that constant E_w requires $R_0 \sim m^{-1/2}$, and fixed compression ratio requires $R_f \sim R_0$. For fixed E_w , the radiation term takes the form

$$\frac{Y_t}{E_w} = \frac{E_w}{K_{b1}} \frac{n^{5/2}}{y} \exp\left(3 - \frac{3}{y}\right) \quad (11)$$

where K_{b1} is for $R_f = R_{f1}$ corresponding to $n = 1$.

Maximizing Eq. (11) subject to Eq. (8) results in the optimal stagnation temperature given by $y_{op} = 6/7$ and load mass n_{op} given by

$$\frac{E_w}{K_{b1}} = \frac{0.71(1 - 6n_{op}/7)}{n_{op}^{5/2}} \quad (12)$$

for which the maximum K-shell yield is

$$\frac{Y_{max}}{E_w} = \frac{1}{2} (1 - 6n_{op}/7) \quad (13)$$

The variations of n_{op} and Y_{max}/E_w with E_w/K_{b1} are shown in Fig. 1. The asymptotic behaviors in the weak-emission (I^4) and strong-emission (I^2) regimes are indicated.

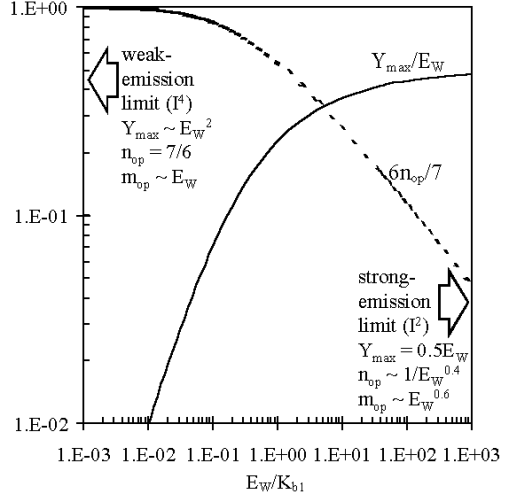


Figure 1. Variations of normalized load mass and K-shell efficiency with implosion energy.

The model variables are next related to implosion time t_{imp} and E_w in order to recover the scalings with current from the general results of Eqs. (11) - (13). Electrical-energy balance and the equation of motion provides the following. [1]

$$E_w (J/cm) = 10^3 \gamma I_0^2 (MA) \cdot \ln\left(\frac{R_0}{R_f}\right) \quad (14)$$

$$t_{imp} (s) = 10^{-6} C_t \frac{m^{1/2} (g/cm) R_0 (cm)}{I_0 (MA)} \quad (15)$$

The three constants $\gamma = 0.7$, $R_0/R_f = 14$, and $C_t = 17$ are chosen to fit DE argon nested-shell experiments, where K-shell yield vs implosion-time was obtained by varying the nozzle pressure (load mass) [5]. The data are seen in Fig. 2 to compare well with the model when the mass and peak current of each shot were used to compute individual model yields. Two radiation calculations are performed: one using the full implosion energy (kinetic + shock heating) that agrees with the data, and a second using only the kinetic portion that gives about half the measured yields. The results demonstrate that shock heating should be included in radiation modeling to predict the performance of a gas-puff or nested-wire PRS.

Substituting the three constants into Eqs. (14) and (15) leads to

$$E_w (J/cm) = 1850 \cdot I_0^2 (MA) \quad (16)$$

$$\frac{R_{0op} (cm)}{t_{imp} (s)} = \frac{1.8 \times 10^7}{n_{op}^{1/2}} \quad (17)$$

An outer radius, determined from Eq. (17) with $n = 1$, is used to determine R_{f1} from the compression ratio, which is then used to calculate K_{b1} from Eq. (10). The variation of

peak argon K-shell yield with current and implosion time, is then determined from Eqs. (12), (13) and (16).

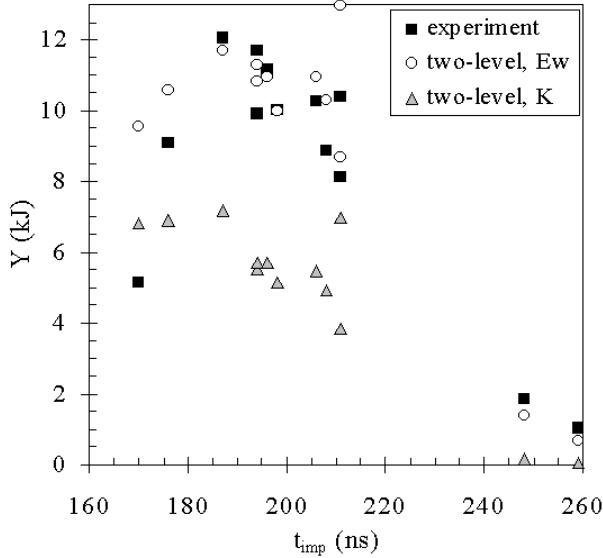


Figure 2. K-shell yield vs implosion time for DE argon nested-shell loads compared with the model.

III. RESULTS

The variation of predicted maximum argon K-shell yield with current is shown in Fig. 3 for 100-ns and 300-ns implosion times. The yield smoothly varies from the expected I^4 to I^2 dependence as the current increases, with the center of the transition at about 8 MA for argon. For other atomic numbers, the definition of K_b provides a transition current that varies like $Z_A^{3.3}$. In the I^4 regime,

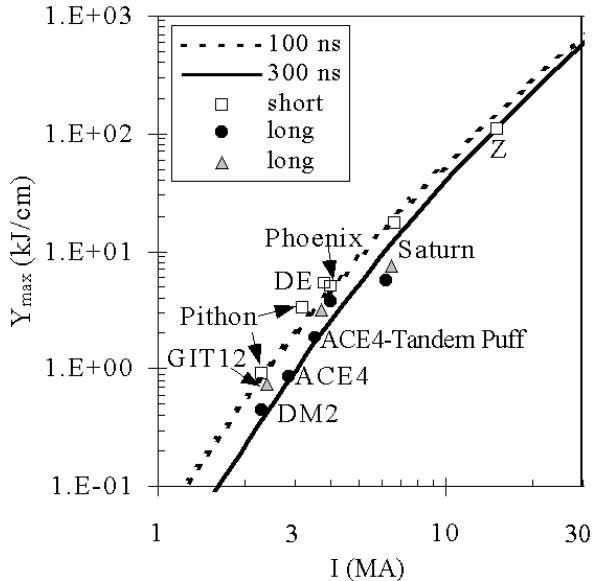


Figure 3. Maximum argon K-shell yield vs peak current for various generators and loads compared to the model for $t_{\text{imp}} = 100$ and 300 ns.

the model yield varies inversely with implosion time. At higher currents, this long-implosion-time yield penalty is reduced, suggesting that high-current, long-implosion-time drivers may achieve yields approaching those of 100-ns drivers.

Also plotted in Fig. 3 are the maximum argon K-shell yields achieved with various generators and loads. The labels “short” and “long” correspond respectively to implosion times in the 70- to 110-ns and 190- to 300-ns regimes. Circles and triangles correspond respectively to uniform-fill and nested-shell nozzles.

The variation of predicted optimum argon mass with current is compared to various measurements in Fig. 4.

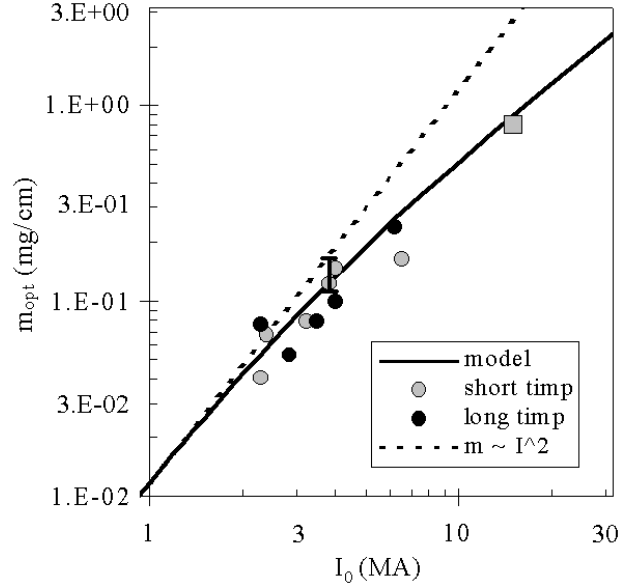


Figure 4. Optimum argon load mass vs peak current for various loads compared to the model.

The circles are kinetic masses based on matching snow-plow implosions to observed implosion times. The error bar, masses determined by interferometry for the DE nested-shell experiments [6], agree with the kinetic values. The square is an estimate of mass for the highest K-shell yield Z shot. [4] The data show that the optimum mass does not depend on implosion time, in agreement with modeling. The dashed line extends the weak-emission scaling to higher current. The optimum mass is proportional to I^2 for low currents and transitions to $I^{1.2}$, in agreement with the higher-current data.

The weaker current scaling of mass for strong radiators should be considered in the design of high-current loads, though the predicted yield reduction for non-optimal load masses is weaker than for low currents. If so, the mass at high current may be increased (initial radius decreased) for mediation of the Raleigh-Taylor (RT) instability with a minor K-shell yield penalty. This possibility is illustrated in Fig. 5, where the relative yield vs. load mass is plotted for argon at low and high current, corresponding to $E_w/K_{b1} = 0.1$ and 3.6. At high current, load masses a factor-of-two greater than optimum are predicted to reduce K-shell yield

by about 10%. For aluminum loads, the corresponding low and high currents in Fig. 5 are reduced to 0.85 and 5.1 MA, and the weak high-current dependence of yield on masses above optimum has been demonstrated [1, 3]. Based on a single non-optimum argon shot, Fig. 5 shows that this trend has not yet been observed on Z. [4]

The possibility of using masses more massive than optimum with minor yield penalty may be most useful for high-current, long-implosion-time drivers such as the Decade Quad and Dual Quad, where $t_{\text{imp}} = 300$ ns for argon leads to an optimum load-radius of about 6 cm. Load-performance risk reduction may be achieved by decreasing $R_{0\text{opt}}$ to about 4 cm by a factor-of-two increase in load mass above optimum.

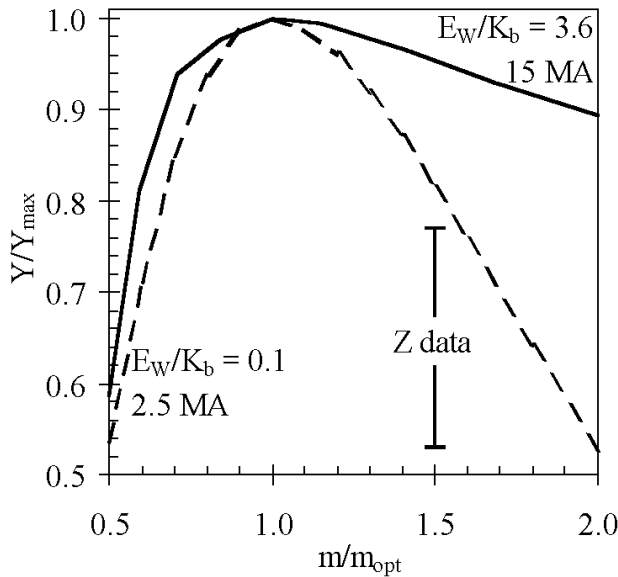


Figure 5. Variation of argon K-shell yield with load mass for currents in the weak- and strong-emission regimes.

IV. CONCLUSIONS

A simple radiation-scaling model based on two-level atomic physics and plasma energy balance has been used to determine the current scalings of optimum load mass and peak K-shell yield for Ar gas puffs. Results of the model were compared with data over an order-of-magnitude current variation. In light of the wide variety of driver and load configurations sampled, it is noteworthy that both the maximum-yield and optimum-mass scalings provide good absolute-value fits to the data, including the implosion-time dependence. Agreement with the data depends on the use of the full implosion energy (kinetic + shock-heated internal) of distributed-mass loads.

In addition to extending validity to atomic number 18 from previous neon and aluminum benchmarks, agreement of argon data with the zero-dimensional radiation-

scaling model also suggests that gas puff performance is not greatly degraded by instability effects. This observation supports the snowplow mechanism proposed for suppression of RT modes in distributed-mass loads. [7]

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