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Array on Array Circuit Studies for ICF Radiation Pulse Tailoring using Z pinches

E.M. Waisman*, M.E. Cuneo, D.B. Sinars, K.W. Struve,

C. Deeney, P.D. LePell

Sandia National Laboratories

Albuquerque, New Mexico 87185, USA

* *Alameda Applied Sciences Corporation, San Leandro, CA94557, USA*

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Outline

- Motivation for these circuit calculations
- Nested array electrical and momentum exchange models
- Comparison with array-on-array data
- Design calculations for ICF pulse tailoring shots
- Conclusions

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Radiation Pulse Shaping

- **A 10-20ns radiation foot, at about 1/14 of power peak, is necessary for optimum ICF capsule implosion** [J.H. Hammer et al, Phys. Plasmas, 6 (1999)]
- **Using two concentric ("nested") wire arrays, we design the arrays so that the outer array arrives on-axis 10-20 ns before the inner array. For this to happen, little or no momentum exchange can occur as the outer array passes through the inner array.**
- **To design the arrays for these tests, a simple 0D circuit model for nested arrays was formulated and employed.**

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0D Circuit model for two nested arrays

- **Inductance and force model [Velikovich et al, Phys. Plasmas 9, 2002], equations of motion, inductances and mutual inductance, and flux equations for 2 arrays**
- **These equations contain the inductive shielding effect, including the perfect shell limit (NR_w=R)**

$$m_1 \frac{d^2 R_1}{dt^2} = \frac{\partial}{\partial R_1} \frac{1}{2} L I^2, \qquad m_2 \frac{d^2 R_2}{dt^2} = \frac{\partial}{\partial R_2} \frac{1}{2} L I^2$$

$$L_1 = \frac{\mu_0 l}{2\pi}\left(\ln \frac{a}{R_1} + \frac{1}{N_1} \ln \frac{R_1}{N_1 R_{w1}} \right), \quad L_2 = \frac{\mu_0 l}{2\pi}\left(\ln \frac{a}{R_2} + \frac{1}{N_2} \ln \frac{R_2}{N_2 R_{w2}} \right), \quad M = \frac{\mu_0 l}{2\pi} \ln \frac{a}{\max(R_1, R_2)}.$$

$$\Phi = L_1 I_1 + M I_2 = L_2 I_2 + M I_1 = L I, \qquad L = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M}. \qquad V = d\Phi / dt$$

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0D Circuit model for two nested arrays

- **Momentum exchange model:**
  - The first time the outer array radius coincides with the inner array radius, the momentum of each array instantaneously changes, conserving total momentum. The amount of the change is varied using an adjustable parameter "f". This is a simplified version of the model used in [R.E. Terry et al, Phys. Rev. Lett. , 83, (1999)]
  - The array momenta are adjusted using the following formula:

$$V_i^a = V_i^b - f(V_i^b - V)$$
$$V = P_{tot} / (m_1 + m_2)$$

  - The subscripts denote each array (i=1,2). The superscripts a and b denote "after" and "before" the one-time collision, respectively. V is the velocity of the total system in the inelastic collision limit, and the adjustable parameter f is allowed to vary from 0 (collisionless) to 1 (inelastic). Ptot is the total momentum, which is conserved by the above equations.

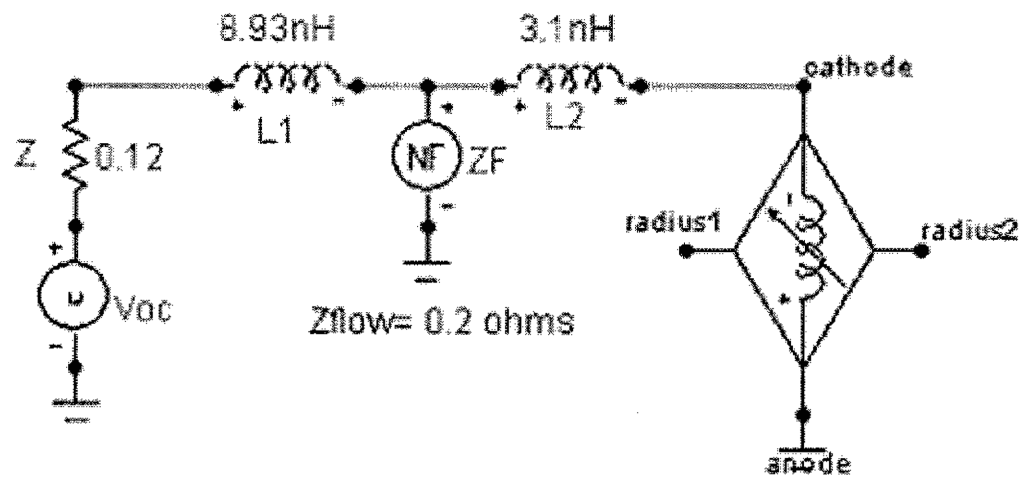
0D Circuit model for two nested arrays

- **A Thevenin equivalent is used to drive the circuit either using MCAP or IDL:**

Z VOC DRIVER ARRAY ON ARRAY

Includes momemtum exchange (W-MEC shots June 2002)

Magnetic shielding and forces: Sasha Velikovich model



PRS2B(1.5,0.6,1.,20,1,5.e-3,5.e-3,16.6e-4,30,5.2e-4,300,1)

(ranode,rad1,rad2,compress,length,m1,m2,rw1,n1,rw2,n2,fmom)

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Comparison with previous Z shot data

- The model was compared with data from Z shots 745 and 746
- The wire array configuration in these shots was as follows:
  - Outer array: 40 13.1 μm Ti wires at a 2.5 cm radius (0.987 mg/cm)
  - Inner array: 20 13.1 μm Ti wires at a 1.25 cm radius (0.494 mg/cm)
  - 2 cm array height, 3.1 cm return-current can radius
- Calculation results:
  - Collisionless limit (*f=0*) yields the maximum time separation between the arrival times of the outer an inner array, 6 ns.
  - For *f=0.2*, the arrival time difference changes to 3 ns.
- Calculations for other arrays (Z793, Z795, and Z796) found a maximum time separation of 4 ns. These shots also used a 2:1 $mass_{outer}/mass_{inner}$ ratio
- None of the Z shots had a significant radiation foot. Under our hypothesis, a radiation foot occurs only if the arrival times differ significantly. Since the maximum time separation was about 5 ns for these shots, we did not expect to see a radiation foot preceding the main radiation pulse.

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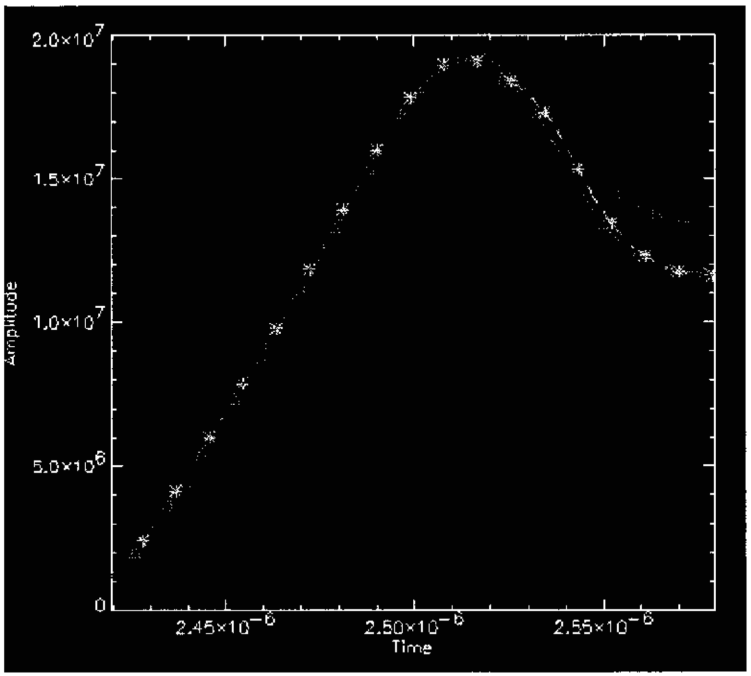
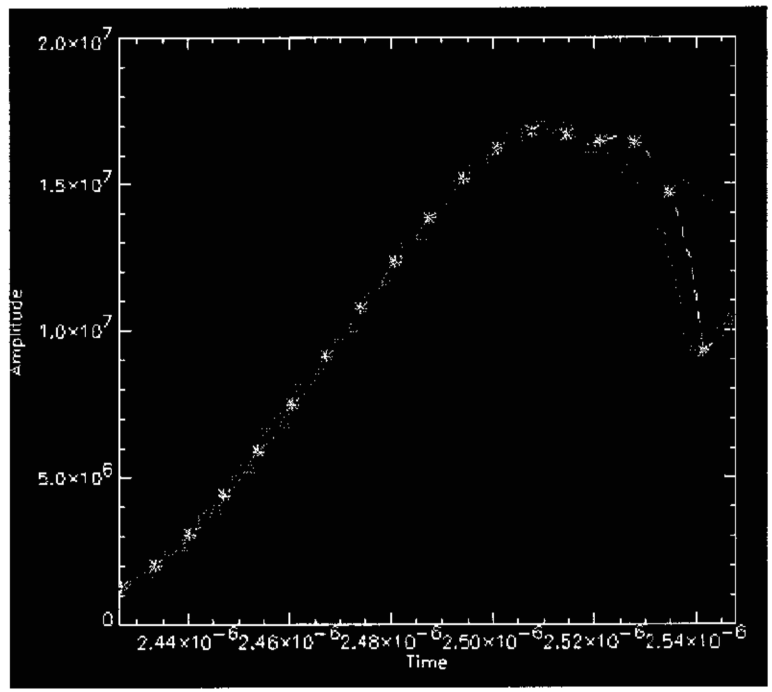
Detailed Comparison with shot 745

- **Model was run with cold value of wire radius for the inner array and 10 times the cold value for the outer array for *f=0,0.2 and 1.0* and the resulting pre and post convolute currents were compared with experimental traces**





Shot 745. Experimental pre-convolute and load currents (red crosses) and the calculated values for fmom=0 (green asterisks), fmom=0.2 (blue) and fmom=1 (magenta triangles). All of the calculated curves fit reasonably well, with a hint that transparent is perhaps the best fit after current peak.

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Sandia Z-machine Experiments to Test Concept

- In June 2002, 7 shots on the Sandia Z-machine will evaluate this technique
  - 5 nested arrays: 1 cm radius on 0.6 cm radius; 1 cm height; 1.5 cm return-current can radius
    - 1 shot with 300 on 30 wires, 2:1 mass ratio (6 mg/cm on 3 mg/cm)
    - 2 shots with 300 on 180 wires, 1:3 mass ratio (2.5 mg/cm on 7.5 mg/cm)
    - 2 shots with 300 on 30 wires, 1:3 mass ratio (2.5 mg/cm on 7.5 mg/cm)
  - 2 single arrays: 1 cm radius; 1 cm height; 1.5 cm return-current can radius
    - 1 shot with 300 wires, 2.5 mg/cm for comparison with 1:3 mass ratio nested shots
    - 1 shot with 300 wires, 6 mg/cm for comparison with 2:1 mass ratio nested shots
- The arrays in the 2:1 mass ratio tests are expected to arrive nearly simultaneously on-axis; even with $f = 0$ the time separation is only 2.1 ns.
- The arrays in the 1:3 mass ratio tests are designed to arrive on-axis 10-20 ns apart. For this to occur, $f \leq 0.2$, so the arrays must be nearly transparent (i.e., nearly collisionless). To help achieve this, two shots will use only 30 wires in the inner array.

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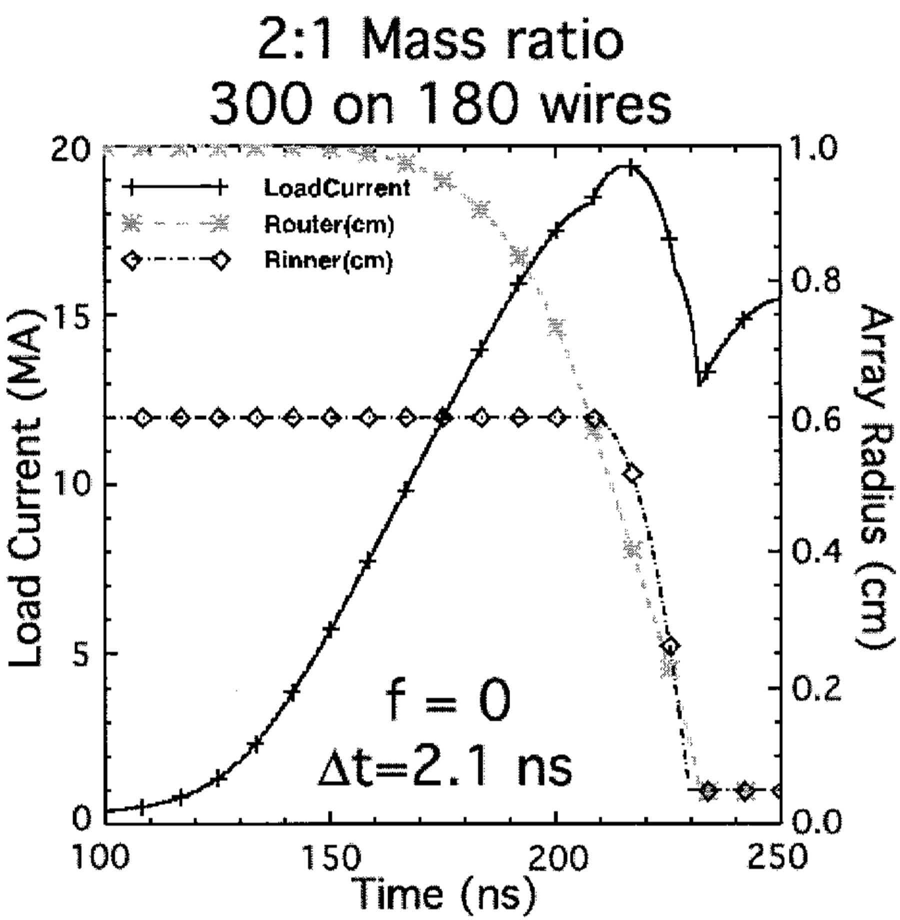
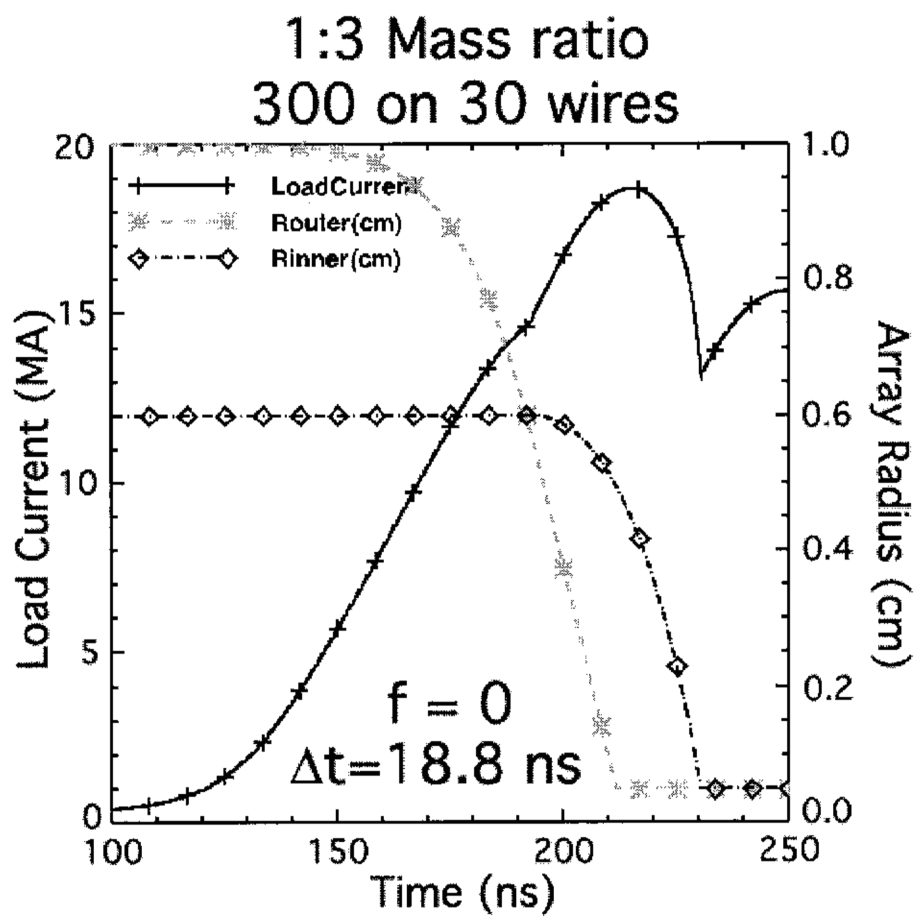
Effect of varying mass ratios on implosion time





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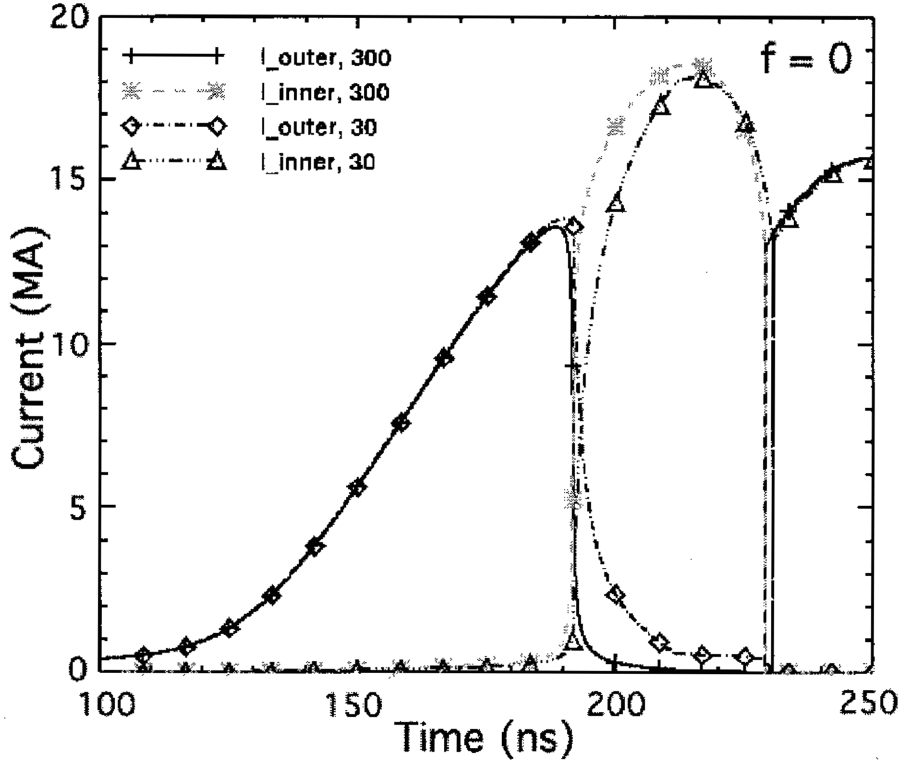
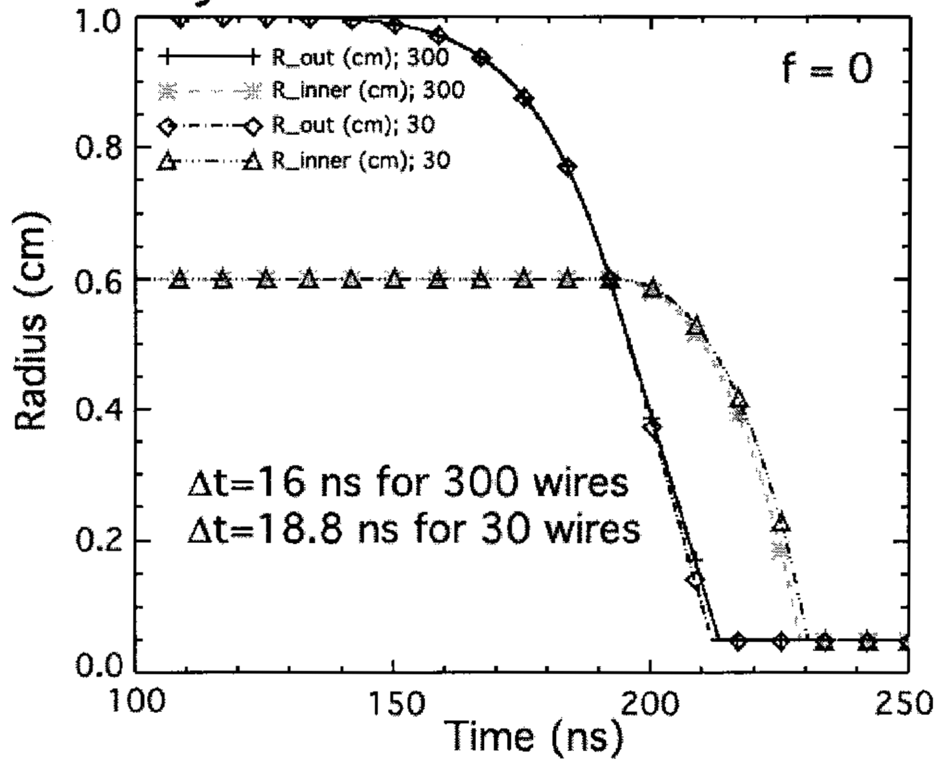
Effect of varying inner array wire number

Comparison of 1:3 mass ratio cases illustrating the effect of reducing the number of wires in the inner array from 180 to 30 wires





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Model Predictions for June Z shots

Summary of predicted on-axis arrival time differences for June shots:

- 2:1 mass ratio (6 mg/cm on 3 mg/cm), 300 wires on 180 wires
  - $f = 0.0$: 2.1 ns difference
  - $f = 0.2$: 2.1 ns difference
  - $f = 0.5$: 0.3 ns difference
- 1:3 mass ratio (2.5 mg/cm on 7.5 mg/cm), 300 wires on 180 wires
  - $f = 0.0$: 16.0 ns difference
  - $f = 0.2$: 10.4 ns difference
  - $f = 0.5$: 0.0 ns difference
- 1:3 mass ratio (2.5 mg/cm on 7.5 mg/cm), 300 wires on 30 wires
  - $f = 0.0$: 18.8 ns difference
  - $f = 0.2$: 14.4 ns difference
  - $f = 0.5$: 7.0 ns difference

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Conclusions

- A 0D circuit model was formulated for nested arrays containing inductive shielding effects and momentum exchange as the arrays pass each other.
- Assuming that each array will radiate when it reaches the axis, the 0D model can be used to tailor the total radiation pulse by varying the arrival times of the two arrays in a nested array configuration.
- The model was used to simulate nested array shots in Z. It predicts <5 ns between the arrival times of the two arrays on-axis. This is consistent with the lack of a significant radiation foot preceding the main pulse in these shots
- The 0D model was used to design a set of arrays which will be fielded during shots on the Sandia Z-machine. The shots will test a range of cases.
- Model predicts that the inner array mass has to be a factor of 2 or larger for the implosions to be separated by 10-20 ns. Also the momentum exchange has to be less than about 0.2. As a result, the experiments will attempt to increase the transparency of the inner array by increasing the interwire gaps in the inner array.

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