SAND2007-2054C

ALEGRA simulations of wire array z-pinch implosions using a mass inflow model of ablation physics

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Workshop on the Physics of Wire Array Z-Pinches

Battle, England, UK

2-5 April, 2007

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

Acknowledgments

- Eduardo Waisman, Edmund Yu (full 2π simulations), and Tom Haill
- Dan Sinars (provided all experimental data).
- Mike Cuneo, Mike Desjarlais, Chris Jennings, and Jerry Chittendon

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Topics / Outline

- Can ALEGRA mass inflow simulations produce Sinars' mass scan data to within the measurement uncertainty?
  - Can this be accomplished using 2D (R-Z) simulations?
  - If 3D is necessary, what fraction of the θ direction suffices?
- Results presented from simulations of 1.15 mg, 2.5 mg, & 6.0 mg tungsten arrays with 0.05 cm radius coaxial aluminum rod.
  - Mass scan data is reviewed.
  - ALEGRA inflow simulation model is summarized.
  - 2D simulations produce trailing mass and current.
  - Simulated currents, radiation power, and density profiles are compared with z1611 measurements.
  - 3D simulation of z1611 in 60 degree wedge produces the same current as 2D problem, but higher power.

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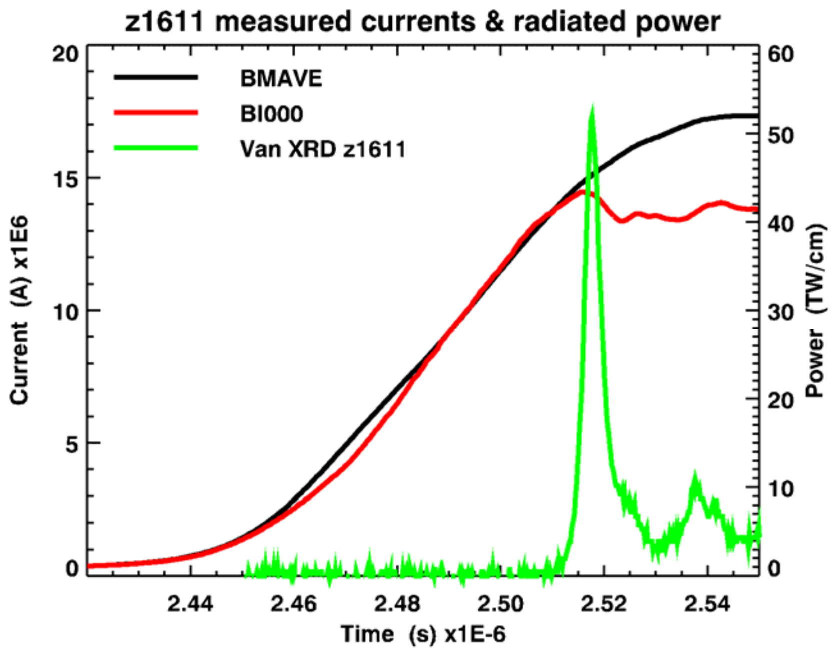
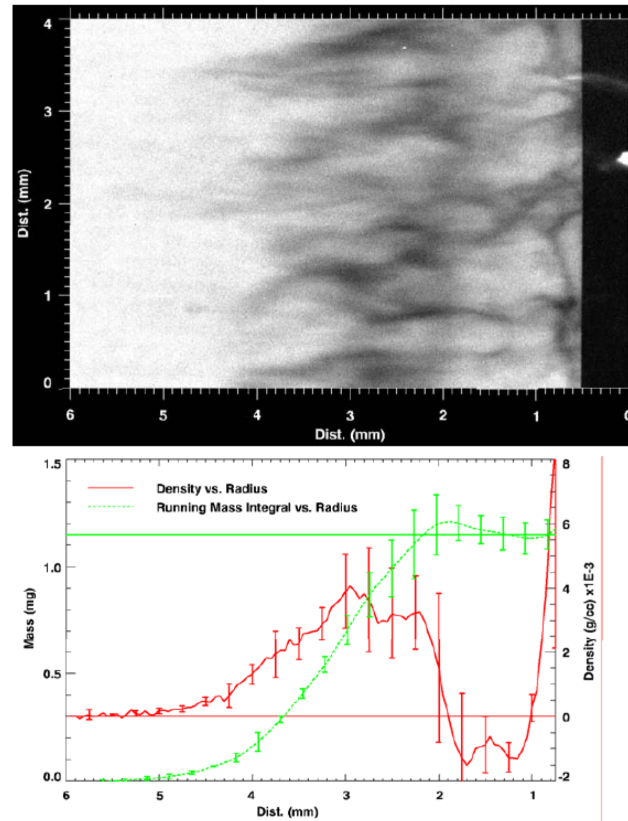
Z1611 measurements provide benchmarks for simulation results: 300 wire (W), R=1 cm, 1.15 mg



z1611 radiograph & density profile @ t = -5.0 ns



100% of array mass at 2 ≤ r ≤ 5 mm ~3.2 ns before peak current; peak power occurs ~1.8 ns after peak current, inductive dip follows 5.7 ns later while mitl current still rising.

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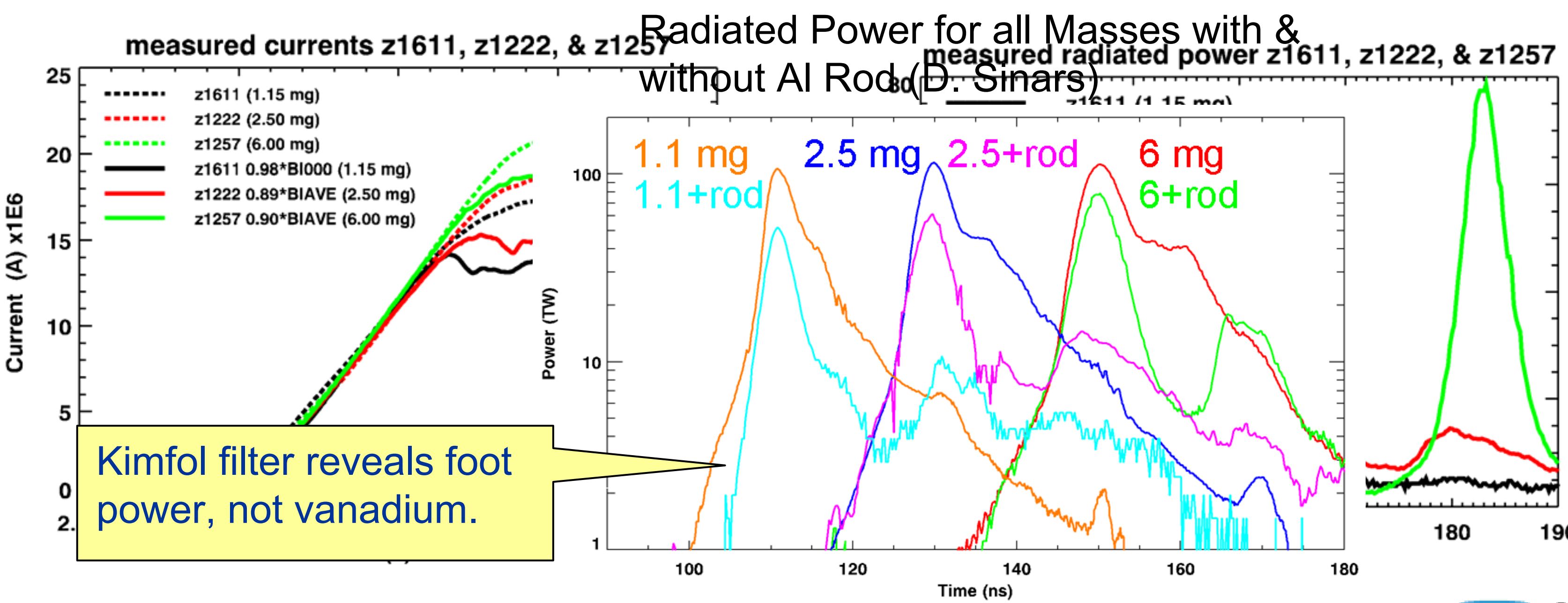
Data from shots with 2.5 mg & 6.0 mg arrays provide additional benchmarks for comparison

- Two sets of shots for each mass, with and without a coaxial aluminum rod.
- We seek a simulation model that produces measured currents & power to within the measurement uncertainty.
- We focus first on shots with the rod, and tune simulation using measurements from 1611, including Abel inverted density profile.



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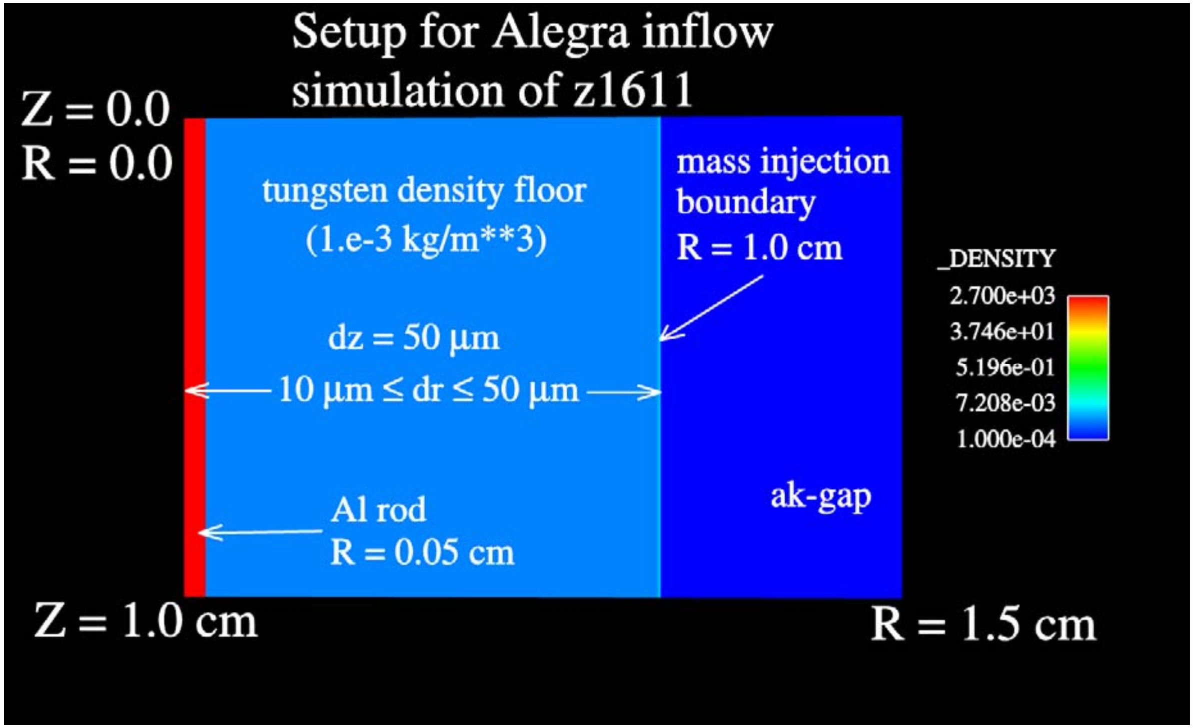
Setup for ALEGRA inflow simulations: density floor provides uniform background for r ≤ 1 cm

- Cells backfilled with tungsten floor material when density $\rho < 1.0e\text{-}3\ kg/m^3$.
- Minimum floor conductivity = void conductivity (1.0e-7 x max Al conductivity).
- Joule heating off if $\rho < 2.0e\text{-}3\ kg/m^3$; artificial viscosity off if $\rho < 2.5e\text{-}2\ kg/m^3$



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Physics models used in ALEGRA inflow simulations of z1611

- Simulations run using 3D ALEGRA. The 2D geometry is a 3D wedge with one cell in theta.
- Radiation MHD with thermal conduction and 2T physics.
- Radiation transport is single group, implicit monte carlo (IMC).
- Sesame 2T EOSs for tungsten and aluminum:
  - The tungsten temperature is limited to 5.e7 K.
  - QLMD conductivity for Al, LMD for tungsten.
  - PROPACEOS tabular opacities for Al and W.
- Thevenin equivalent circuit model of Z accelerator with semi empirical open circuit voltage and time dependent flow impedance.
- Wire array dynamics modeled using mass injection (inflow) algorithm.

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The ALEGRA inflow model of wire array ablation is based on work by E. Waisman, E. Yu, & T. Haill

E. Yu model* is generalized to use local magnetic field rather than global current to inject mass. Conservation of momentum, enthalpy, and mass fluxes produce expressions for velocity & density of injected mass.

$$v(z,R_0,t) = v_n[\frac{B(z,R_0,t)}{B_n}]^{\alpha} \quad \rho(z,R_0,t) = (\frac{1}{2\mu_0})[\frac{B(z,R_0,t)}{v(z,R_0,t)}]^{2.0} \quad dM/dt = 2\pi R_0 \rho v$$

In the Yu model $\alpha = 0.6$, v_n = 2.5e4 m/s, B_n = 60 T (3 MA) as determined by ALEGRA wire array simulations in R-θ geometry.

The parameters v_n and B_n allow considerable flexibility in tuning the z-pinch dynamics. We have explored the range 4.0e3 ≤ v_n ≤ 4.0e5 m/s and 60 T ≤ B_n ≤ 300 T.

***E. P. Yu, et al., "Steady-state radiation ablation in the wire-array Z pinch", Physics of Plasmas 14, 022705 (2007).**

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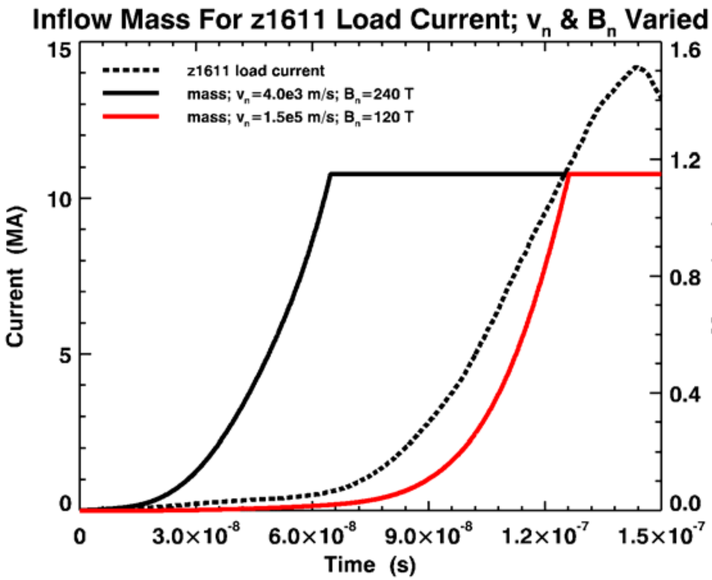
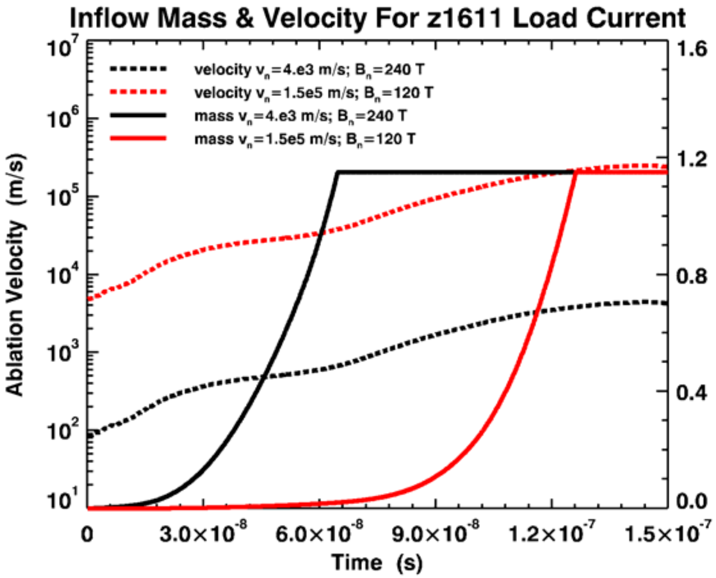
Inflow mass is injected into mesh zones (cells) at $r=R_0$ until the total mass/length/zone is reached

The z-pinch implosion dynamics depends on the values of v_n and B_n: mass injected / time increases as v_n decreases.





Implosion times for these two cases differ by only ~2 ns despite ~60 ns difference in mass saturation time (includes perturbation).

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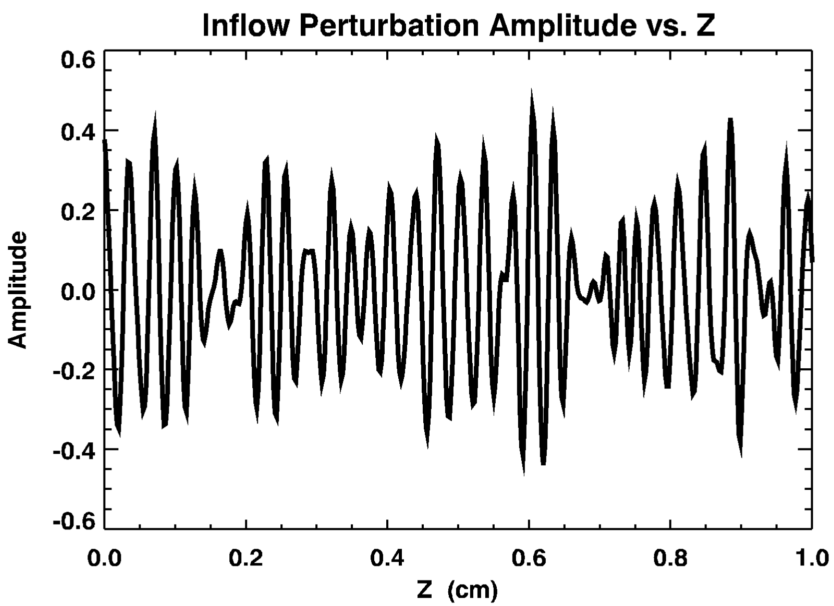
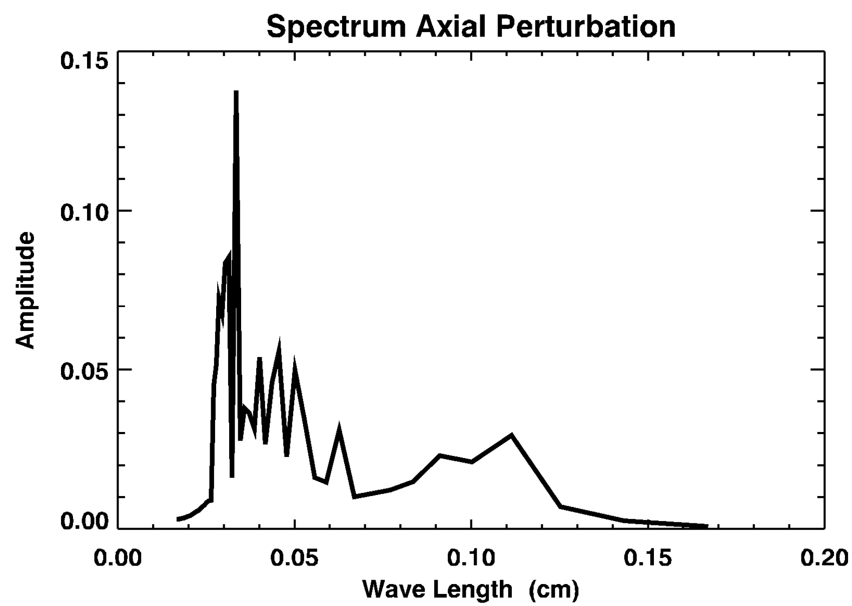
An axial perturbation is applied to the injected mass per zone until the total mass is injected

Perturbation for mass inflow simulations (mathematical form due to E. Waisman).





If cumulative zonal mass < (1. + psf*pertz)*M_{tot} / (N_z*N_θ), then mass is injected (psf = perturbation scale factor).

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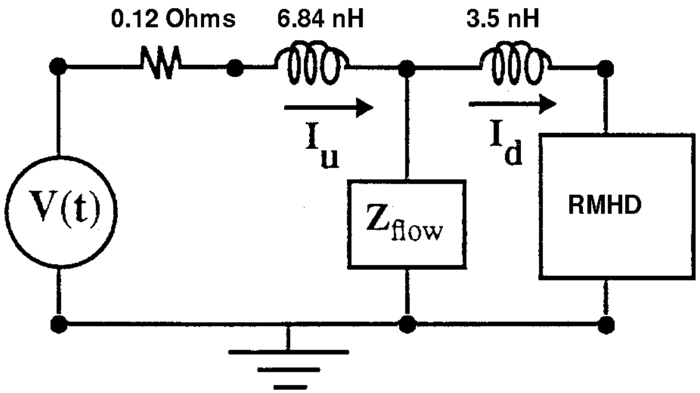
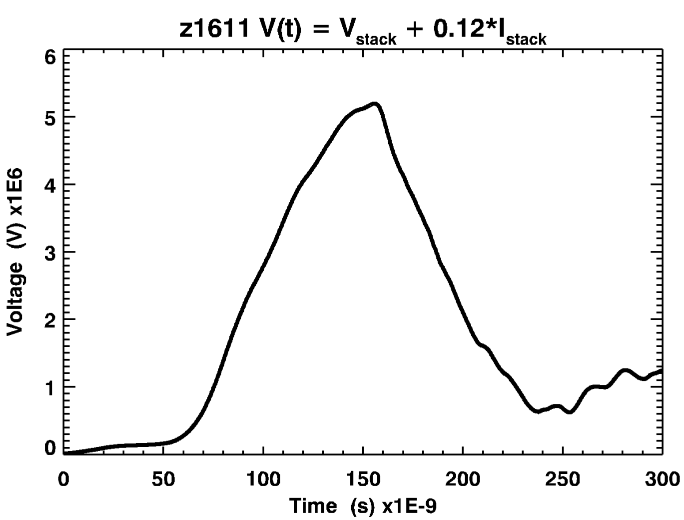
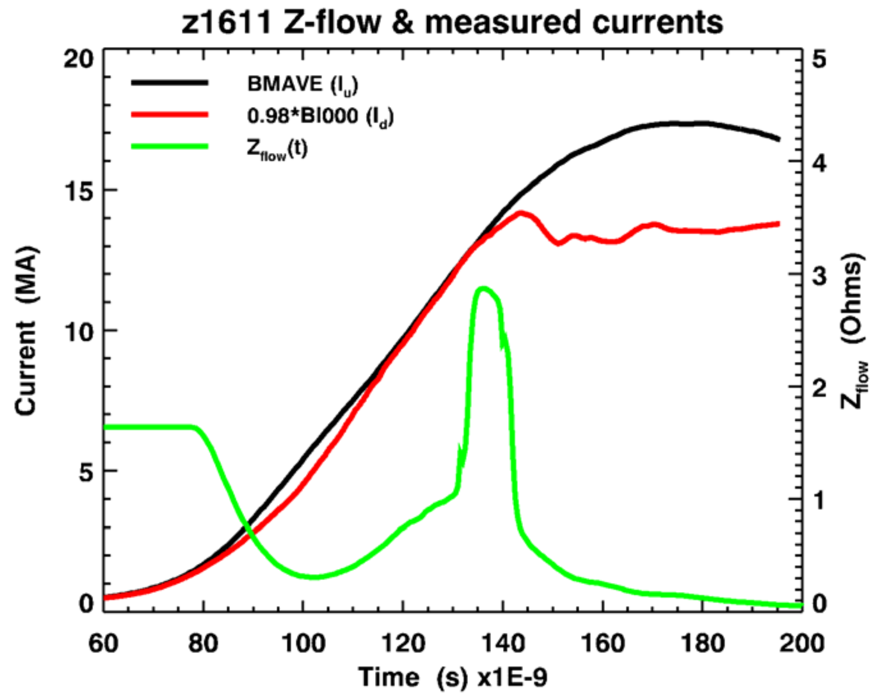
Z1611 stack voltage & current, mitl & load B-dots used to obtain V(t) & Z_{flow}(t) for simulation







$$Z_{flow}(t) = \Delta V / \sqrt{I_u^2 - I_d^2}$$

See Z circuit analysis in E. M. Waisman, et al., Physics of Plasmas 11(5), 2009-2013 (2004), in which the 4 mitl levels are accounted for.

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Movie generated from z1611 simulation results

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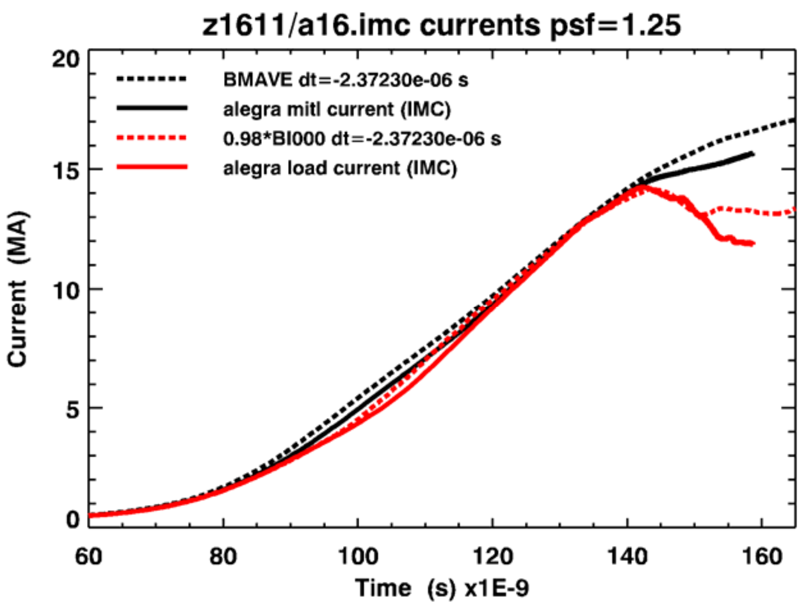
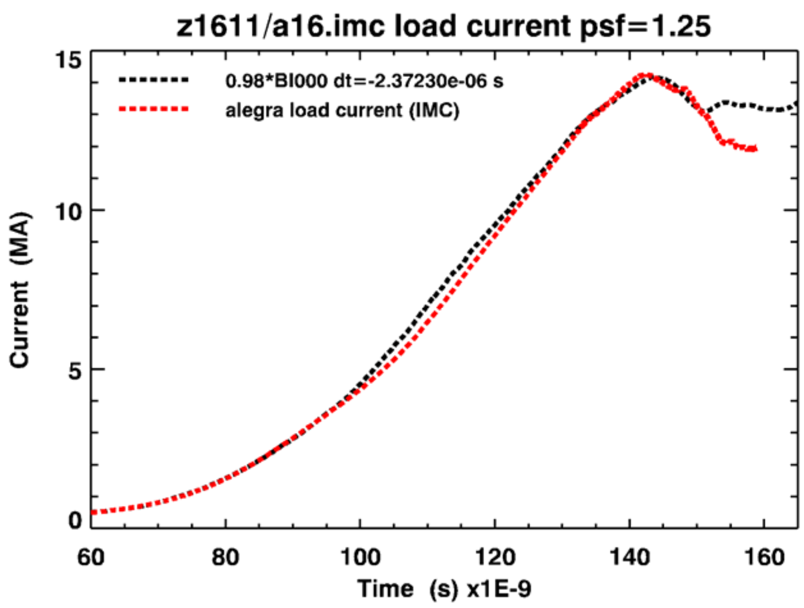
Time dependent Z-flow & tuned flow parameters produces load current in good agreement with inner mitl B-dot

z1611 simulation, low flow velocity result: v_n = 4.e3 m/s; B_n = 240 T (I_n = 12 MA).

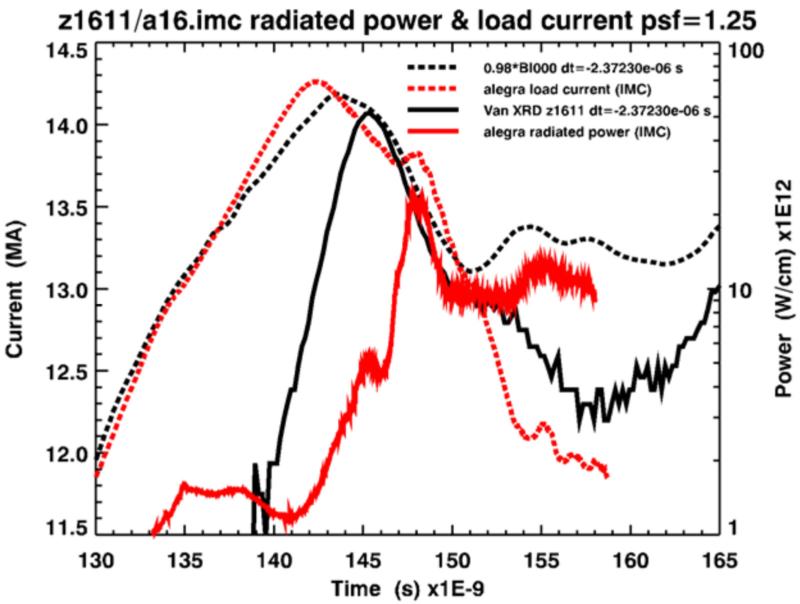


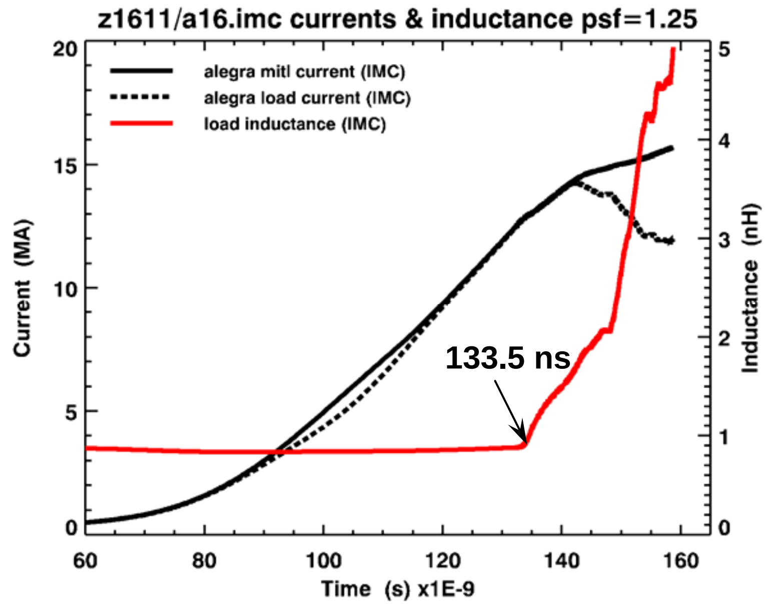


Relative error (ε) simulated current 60 ≤ t ≤ 150 ns: ε < 8.0% load; ε < 9.5% mitl.

Simulated power 3 ns later and 2x lower relative to measured: inductance indicates implosion is late

z1611 simulation: currents, radiated power, & inductance.





M. Cuneo analysis of 1611 shows significant change in current radius (inductance) not later than 130.9 ns (or earlier than 116.3 ns).

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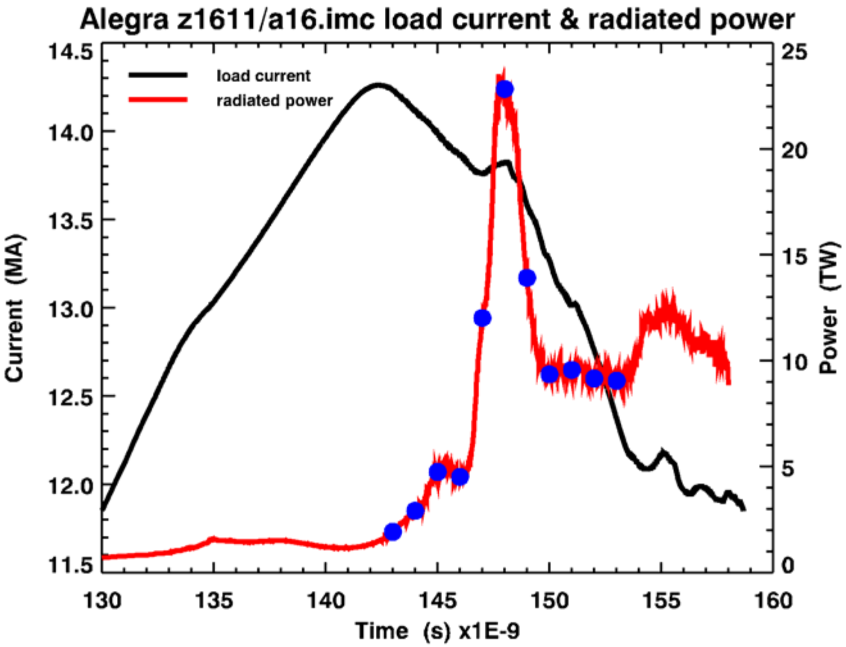
Simulated density vs. r, averaged over z at various times is compared to Abel inverted profile for 1611

Density averaged over axial distance z defined as:

$$< \rho(r,t) >= \frac{1}{H}\int_0^H \rho(r,z,t)dz$$

Cumulative current averaged over z defined as:

$$< I(r,t) >= \frac{2\pi r}{\mu_0 H}\int_0^H B_\theta(r,z,t)dz$$



A sequence of density and cumulative current profiles will be shown at various times thru the power pulse (blue dots in the figure).

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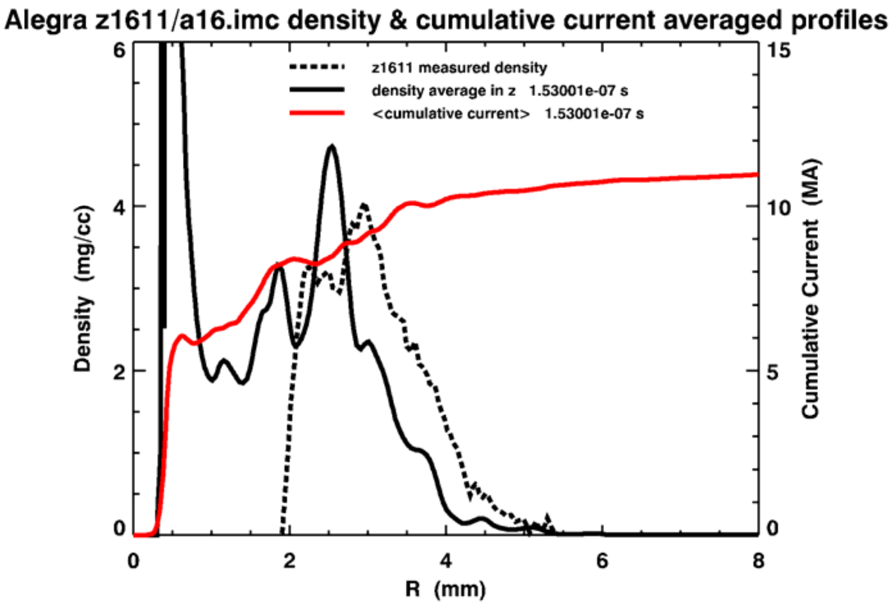
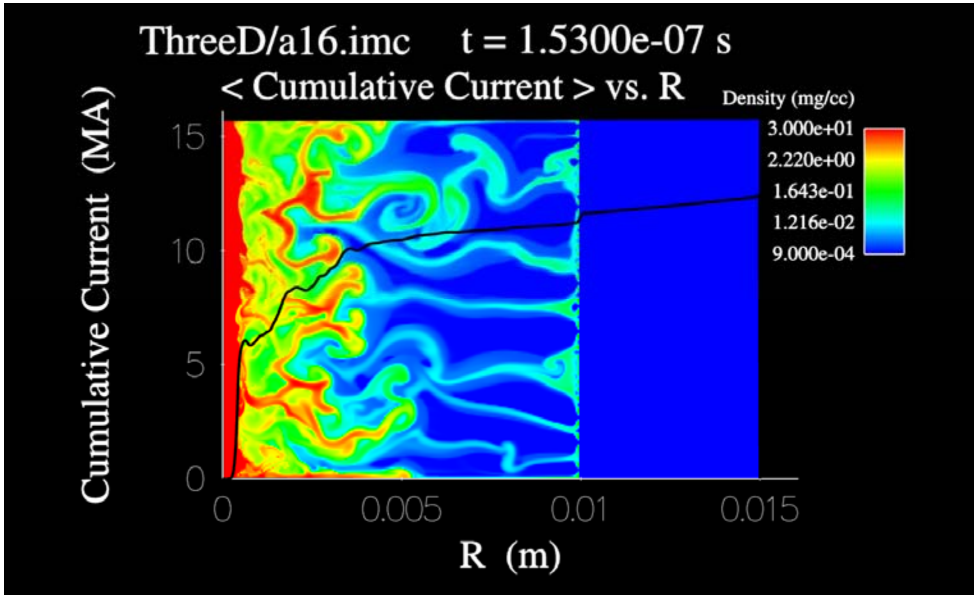
Simulated trailing mass produces density profile in agreement with Abel inversion, but 9 ns later

t = [illegible] ns relative to peak power (z1611 simulation):

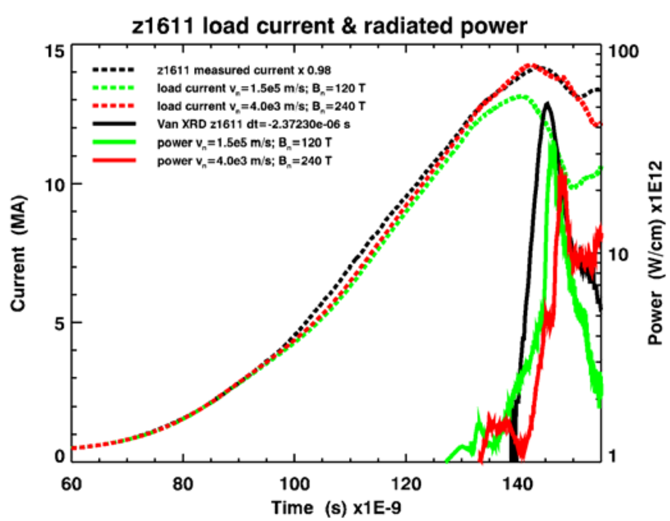


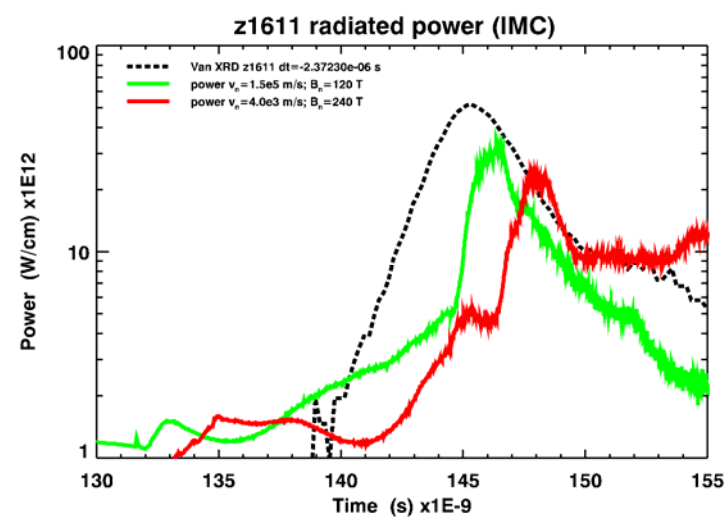


The simulated power thru peak is due to ~12% of the mass, with 88% trailing mass. In contrast, z1611 measurements suggest that power thru peak is produced by ~100% of the mass.

Large increase in flow velocity improves timing of power & density, but produces massive precursor

- Normalizing flow velocity (v_n) increases by x37.5 to 1.5e5 m/s.
- Normalizing magnetic field (B_n) decreases by x0.4 to 120 T (6 MA).
- Added flow velocity perturbation of 1.5 about average using same waveform as mass perturbation (in phase).





More mass in precursor at high velocity produces foot in power pulse, less mass later results in faster implosion time and higher power.

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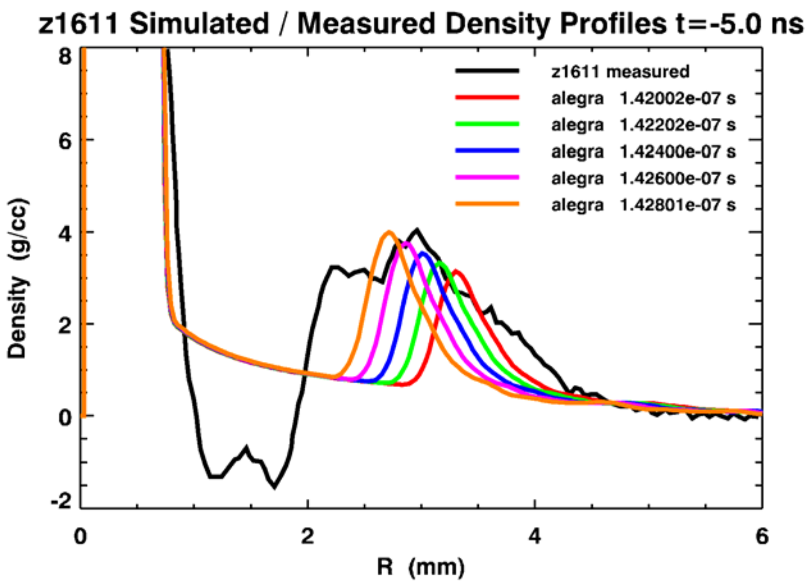
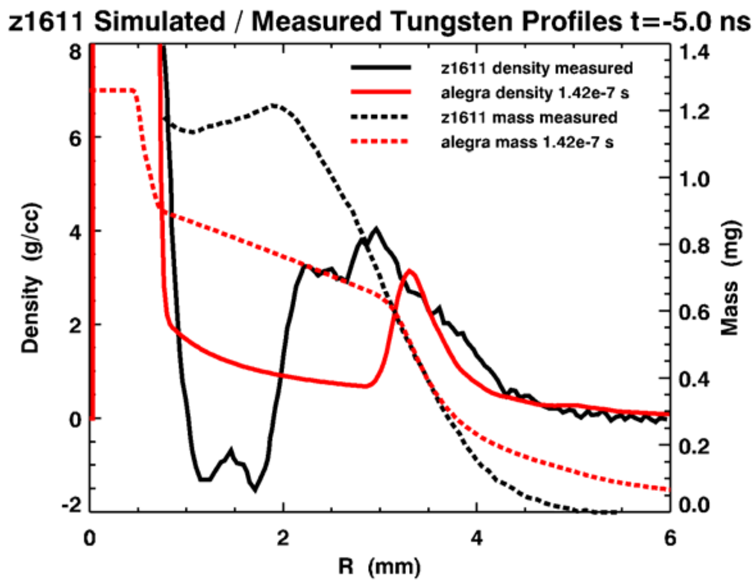
Timing difference between simulated & measured density profile ~2 ns: peak power due to 43% of array mass

Simulated & measured density & mass profiles for shot 1611 (1.15 mg): B_n = 120 T (6 MA), v_n = 1.5e5 m/s.





In contrast to low flow velocity problem, implosion is less shell like with significant mass in precursor that is swept up by magnetic field to produce final density profile.

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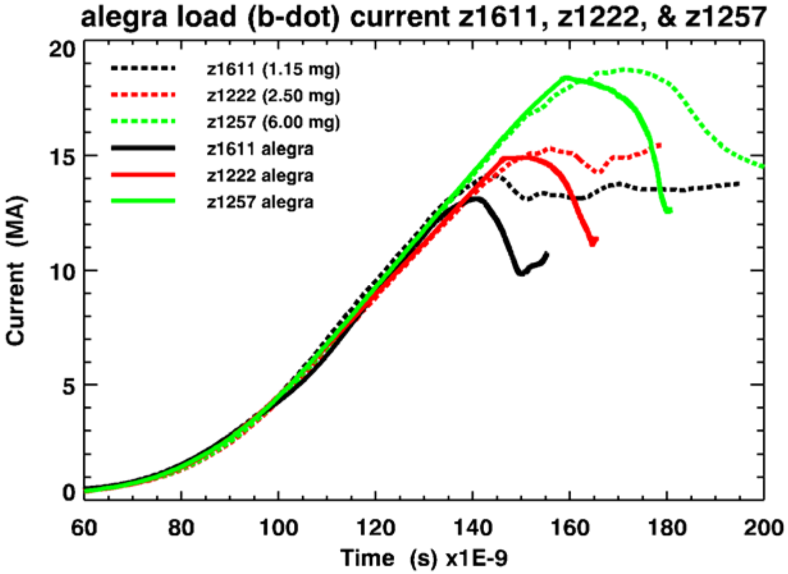
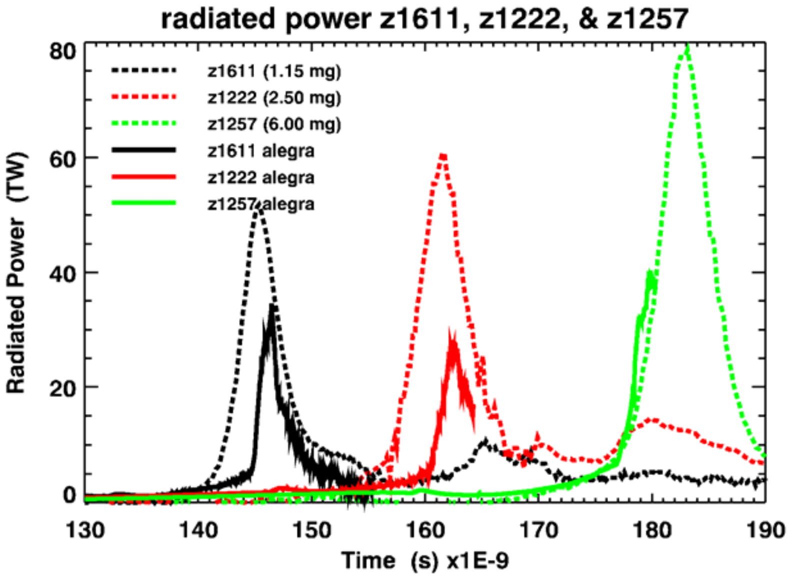
Simulations of 1.15 mg, 2.5 mg, & 6.0 mg shots with Al rod require high flow velocity for timing: radiated power is low

Simulated currents & radiated power shots 1611 (1.15 mg), 1222 (2.5 mg), 1257 (6.0 mg): B_n = 120 T (6 MA), v_n = 1.5e5 m/s (1611), 1.2e5 m/s (1222), 0.8e5 m/s (1257).





Abrupt change in dI/dt coincident with onset of implosion (100% depletion of mass) at array radius. Results for 2.5 mg & 6.0 mg array indicates mass depletion too uniform.

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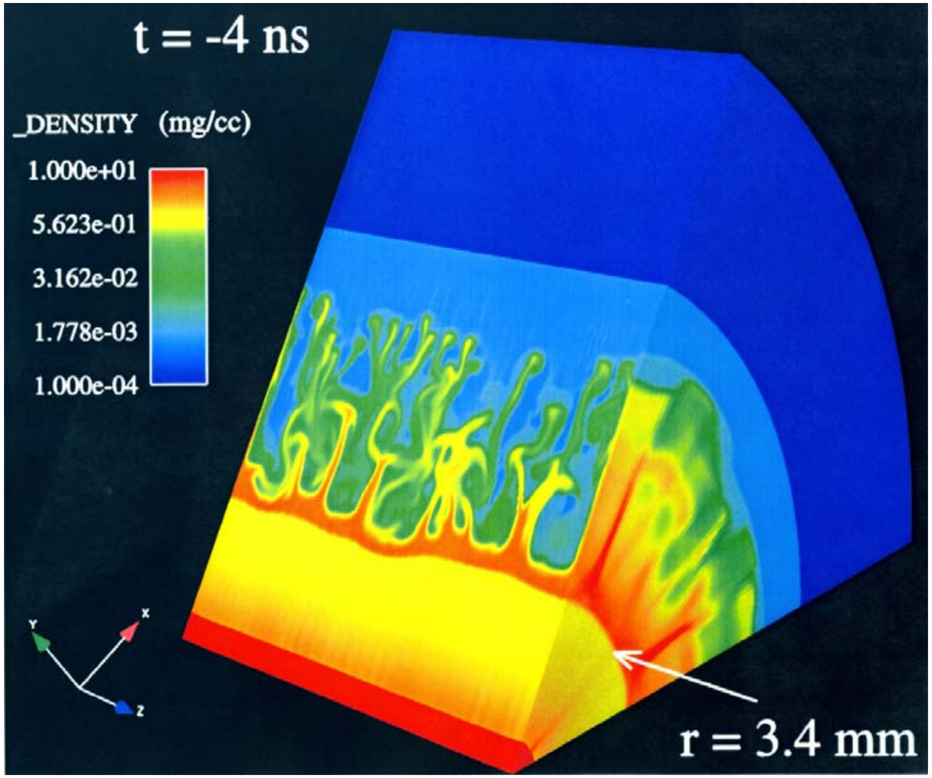
The high flow velocity z1611 simulation is repeated in a 60 degree wedge with uncorrelated perturbation in z & θ

- v_n=1.5e5 m/s; B_n=120 T.
- 60 azimuthal cells.
- Radiation diffusion.
- Perturbation with different phase is applied to groups of 10 azimuthal cells.
- Perturbation is correlated in a given azimuthal group, and uncorrelated from group to group.
- Snowplow stabilization by precursor plasma precludes growth of large bubbles.

z1611 (1.15 mg array) in 60 degree wedge



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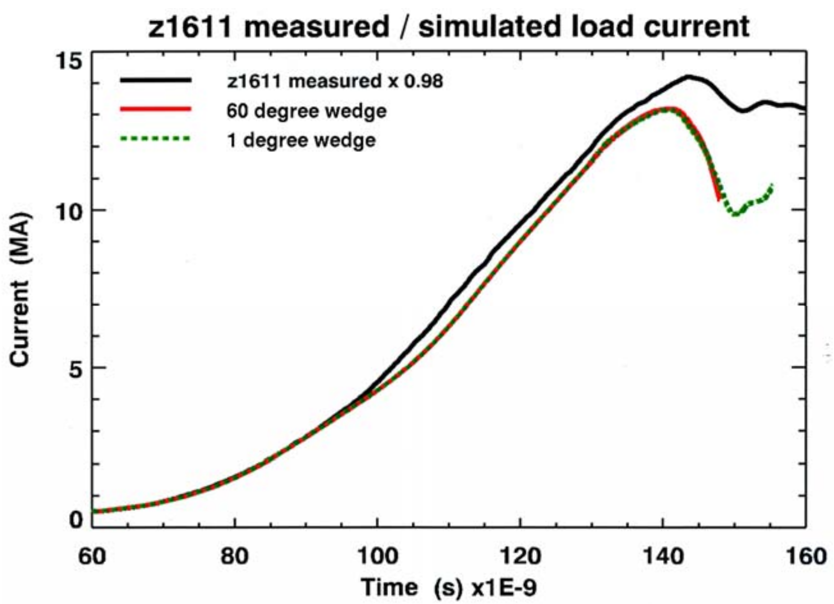
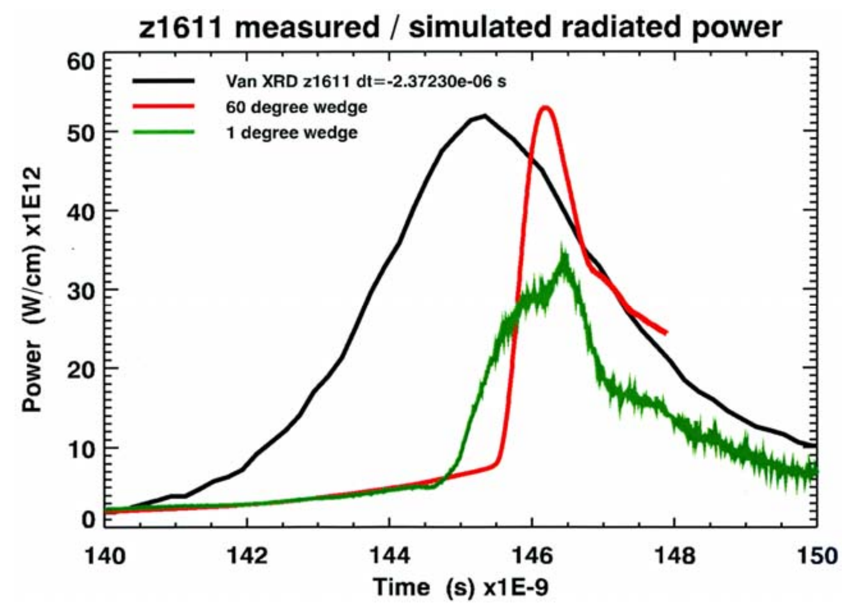
The 60 degree (3D) and 1 degree (2D) wedge simulations of z1611 produce the same current, but different power

Simulated & measured currents & radiated power for shot 1611 (1.15 mg):
B_n = 120 T (6 MA), v_n = 1.5e5 m/s.





Radiated energy about the same (~85 KJ) thru peak power in both cases. Final imploding plasma mass is more shell-like in 60 degree wedge simulation.

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Conclusions

- 2D ALEGRA inflow simulations of z1611 with high flow velocity (1.5e5 m/s) have produced best agreement with measurements to-date.
  - Timing of peak power & density profile are within 1-2 ns of measured.
  - Timing of peak power for 2.5 mg (z1222) & 6.0 mg (z1257) arrays also in good agreement (1-3 ns).
  - Simulated radiated power and energy are consistently low (~50% for power) for all array masses.
  - Precursor mass accumulating on Al rod may soften the stagnation event, which reduces radiation output.
  - 3D, 60 degree wedge simulations produce same current as 2D problem, but more power.
- Abel inverted density profile for z1611 does not show significant mass accumulated on Al rod, as in simulations.

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Conclusions

- At 5 ns before peak power, total array mass in z1611 must be more shell-like and with higher kinetic energy than in simulations to account for differences in simulated & measured powers.
- 3D and 2D simulations of z1611 produce similar currents but different radiated powers.
  - 3D simulations with some fraction of 2π may be required to produce an accurate power pulse.
- If ~100% of the z1611 array mass is involved in power production ~1 ns after peak current, where is the trailing current flowing?

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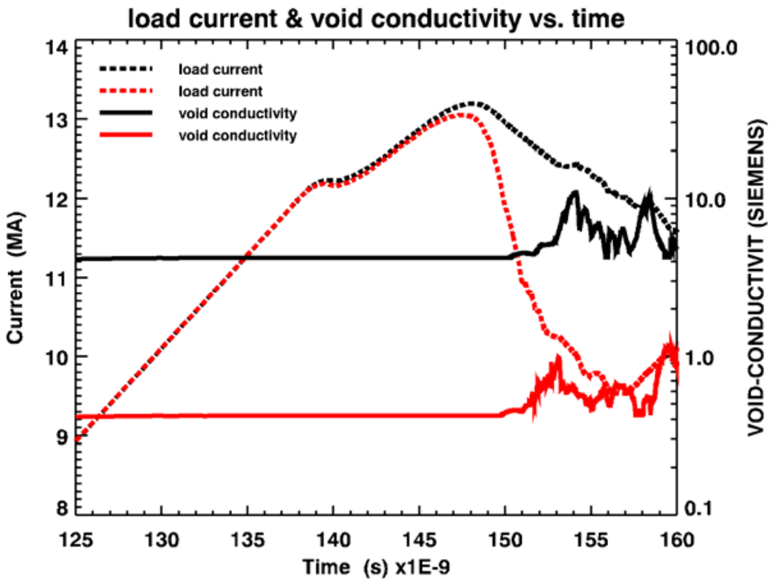
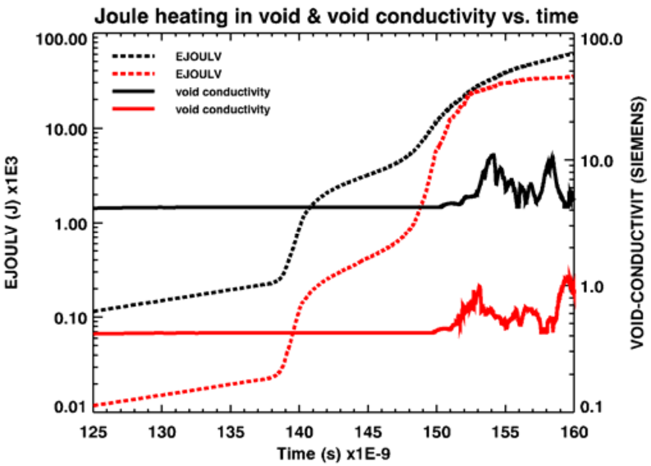
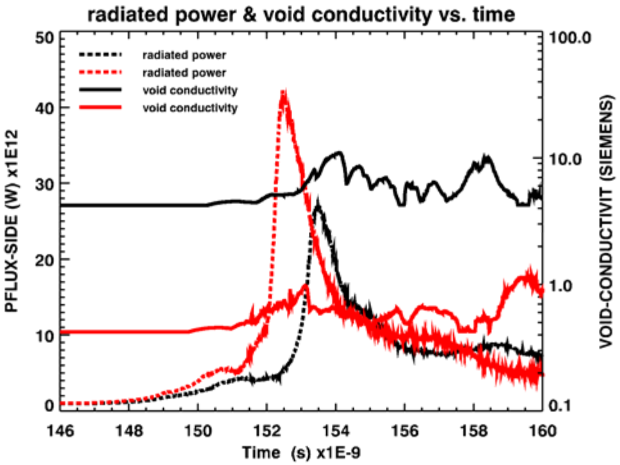
Reducing void conductivity by x10 reduces current in trailing mass (spikes)





At t=-1.0 ns before peak power current in void is 0.09 MA (**low void con**) and 0.65 MA (**high void con**). In case with lower void con there is less energy in void (~10 KJ). More current in leading shell produces higher power.



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