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Nested Array Dynamics from Ni-Clad Ti-Al Wire Array Z-pinches

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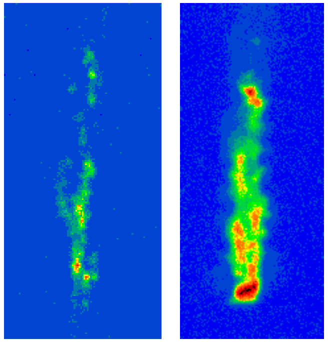
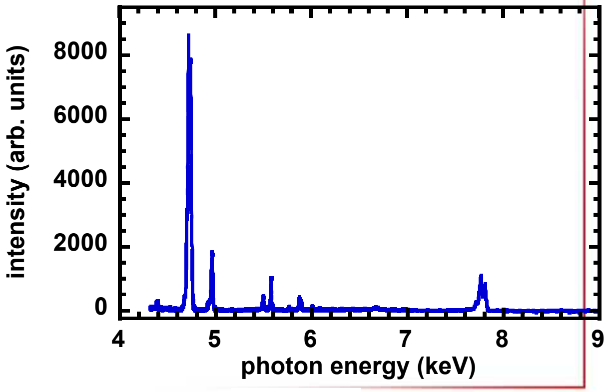
Mixed wire arrays can be used to understand nested array dynamics

- Nested wire arrays have been shown to mitigate the growth of instabilities and provide a more stable implosion
  - This is especially important for K-shell loads, which are large diameter (> 50mm)
- K-shell producing loads provide opportunities to study spectral emissions, which can lead to insight into implosion and stagnation physics
- Previous experiments with dopants have varying results
  - Argon shell-on-shell experiments suggested the inner array dominates the radiated K-shell output
    - This result was also suggested by Ni wire array experiments
  - But aluminum experiments suggested the outer array dominates the hottest portion of the pinch
- Mixed wire arrays provide an opportunity to separate contributions from each array to better understand the composition of the stagnated pinch

55mm dia.



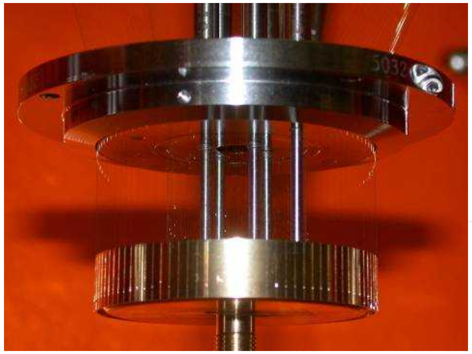
single nested



Various Al/Ni-Ti arrays were fielded

Shot	Load diameter (mm)	Wire Material Outer	Wire Material Inner	Wire dia. (μm) Outer	Wire dia. (μm) Inner	Wire # Outer	Wire # Inner	Total array mass (μg/cm)
Z784, Z1211	50	Ti-Ni	Al	16.2	22.9	96	48	1471
Z796	50	Ti-Ni	Al	16.2	12.7	96	138	1409
Z785, 1209, 1210	50	Al	Ti-Ni	22.9	16.2	96	48	1420
Z795	50	Al	Ti-Ni	12.7	16.2	276	48	1408
Z887	40	Al	Ti-Ni	21.8	16.2	140	70	2104
Z888	40	Ti-Ni	Al	16.2	22.9	140	70	2075
Z889	40	Ti-Ni	Al	16.2	15.3	140	140	2095
Z890	40	Al	Ti-Ni	15.3	16.2	280	70	2095

- Swapped location of different materials
- Two different nested array diameters
- Higher wire number configurations



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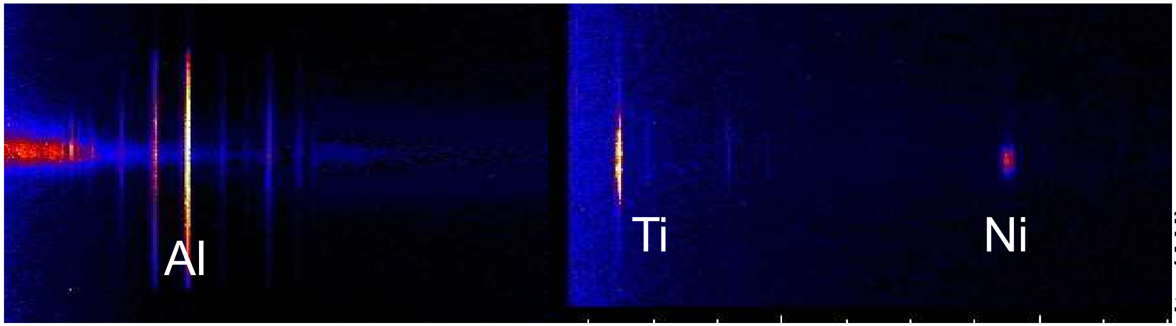
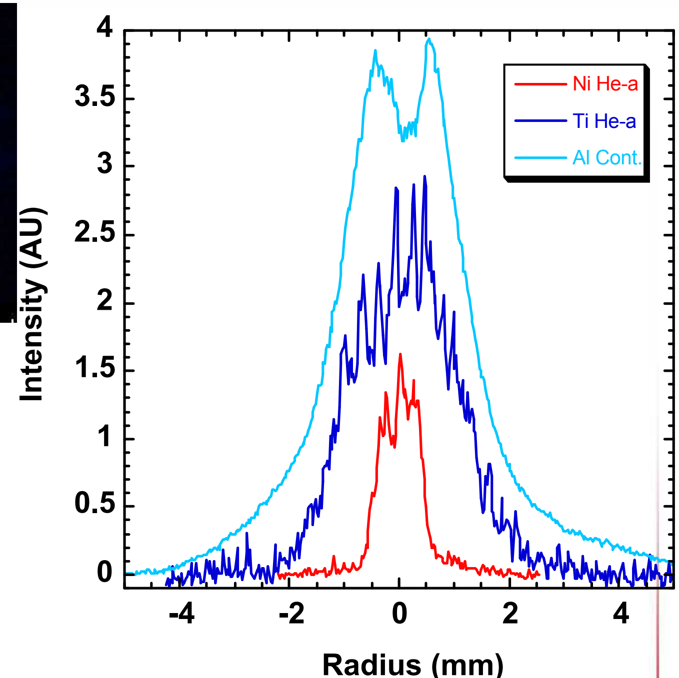
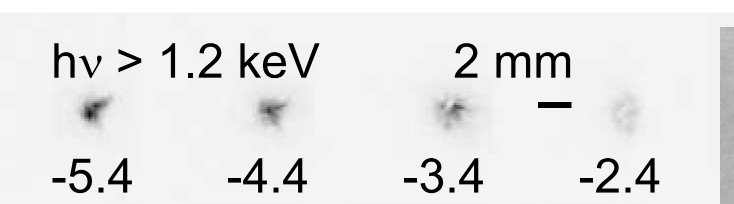
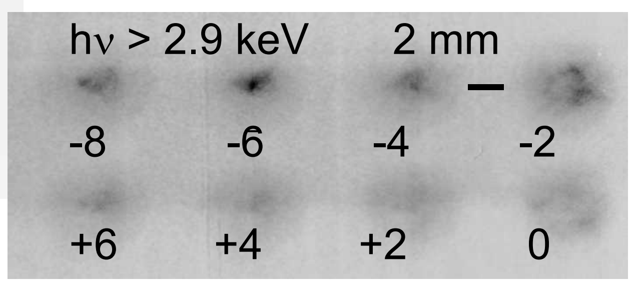
Time-integrated spectra show component-specific spatial variations





- **Al has larger radial extent than Ti, which is larger than Ni**
  - **Hottest portion of the pinch is highly localized**
- **Plasma diameter expands as output increases**
- **Al emits for longer time than Ti, Ni**





50mm diameter
Al on Ni-clad Ti
(96 on 48 wires)

P.D. LePell et al., publication in preparation

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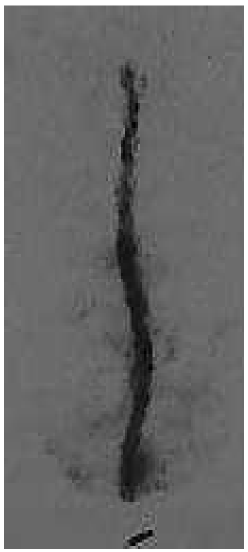
Side-on pinhole images are consistent with radial spectroscopy

Z887
Al-on-Ti



-1.8 ns

Z888
Ti-on-Al

-1.7 ns

E > 2 keV
(Ti, Ni K-shell)

- With Ti-Ni on inner array the brightest emissions for all photon energies are in very narrow regions (~ 0.5mm)
  - Consistent with spectroscopy that shows Ti and Ni K-shell emission are localized
  - Suggests hot, dense core
- With Ti-Ni on outer array, there is more intense emission Ti and Ni K-shell emission over a broader diameter (~ 1mm)
  - Also consistent with the radial spectroscopy, which shows Ti emission over larger diameter than is present when Ti-Ni is on inner array

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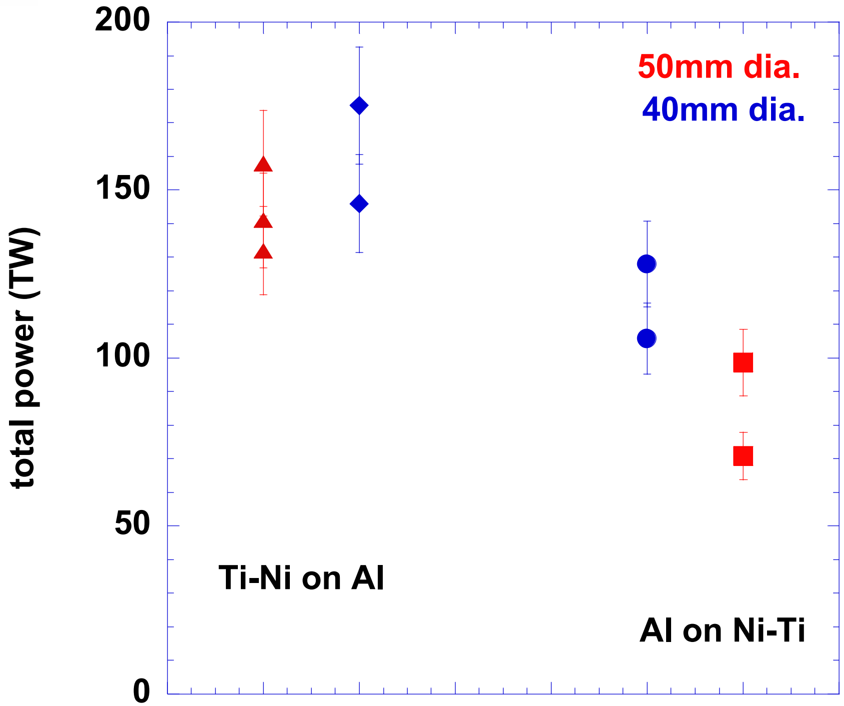
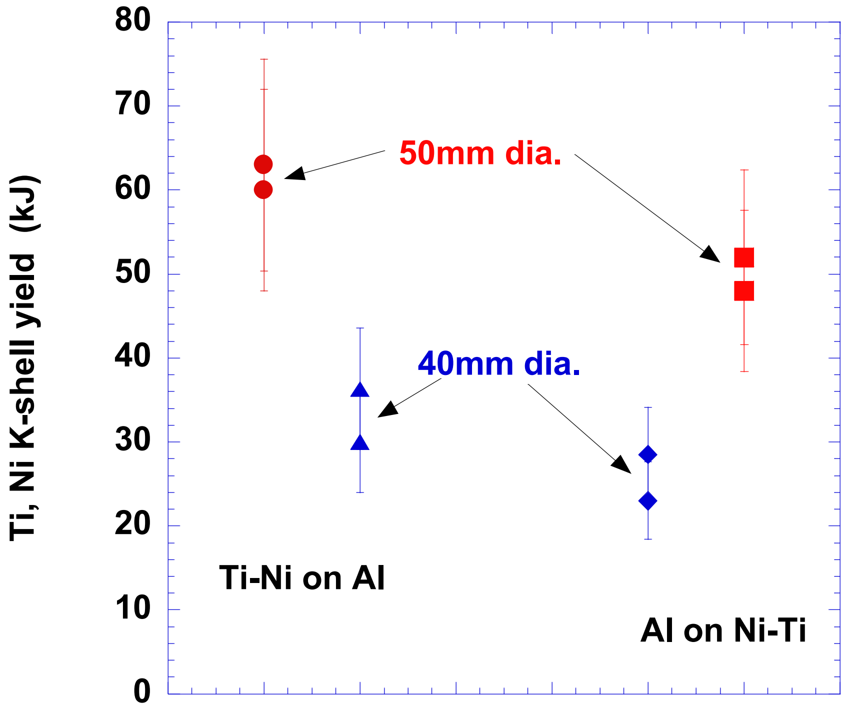
Radiated yields illustrate the contributions of the each array

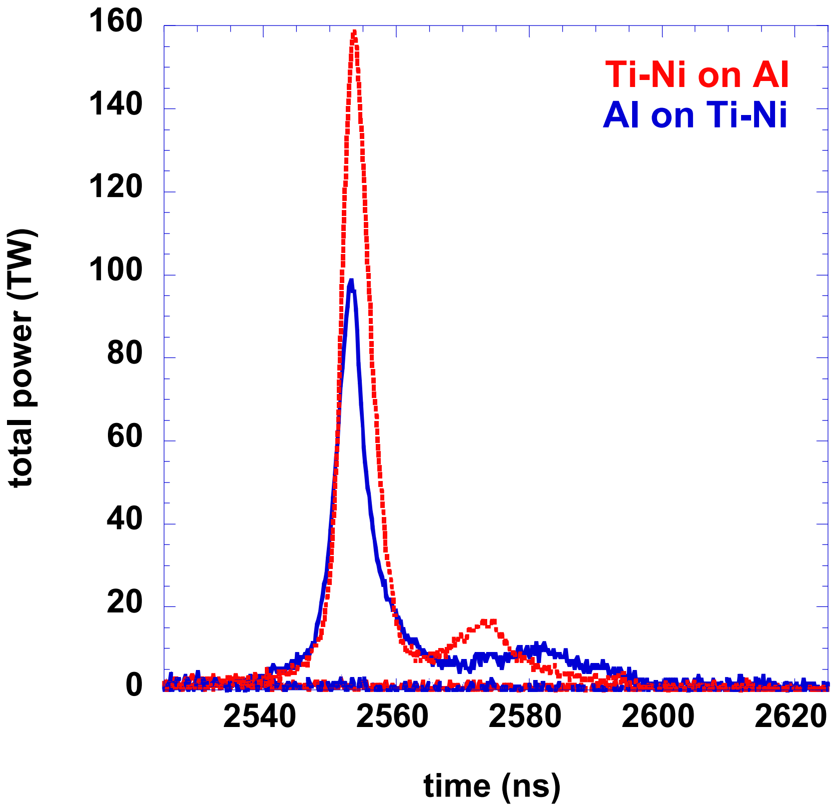


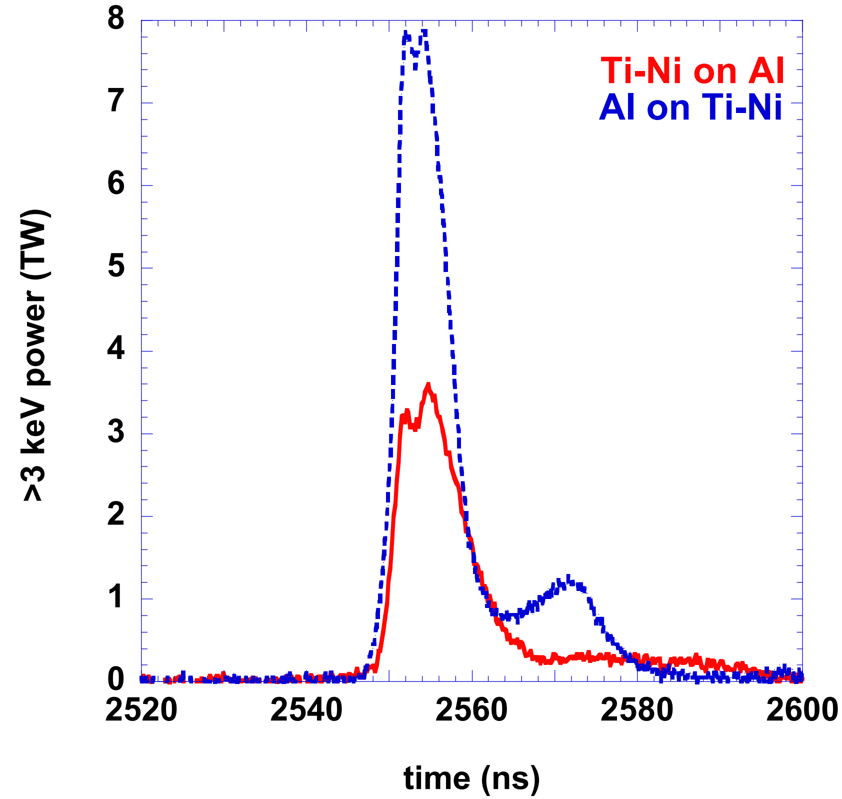


- Total power is lower when Ti-Ni is on inner array
- Ti-Ni on outer array emits similarly to Ti-Ni on both arrays
  - 60-70 kJ in K-shell for 50mm nested
- Ti-Ni on inner array shows a drop in higher energy emissions, but not commensurate with reduction in available Ti-Ni mass
  - Suggests inner array predominantly in hottest, densest portion of pinch

Waveforms show distinct differences when the Al is on the outer array

50mm nested





- Total power was lower for Ni-Ti on the inner array
  - Pulseshape was narrower, faster risetime
- > 3 keV power was higher for Ni-Ti on the inner array
  - Pulseshape was wider, longer risetime

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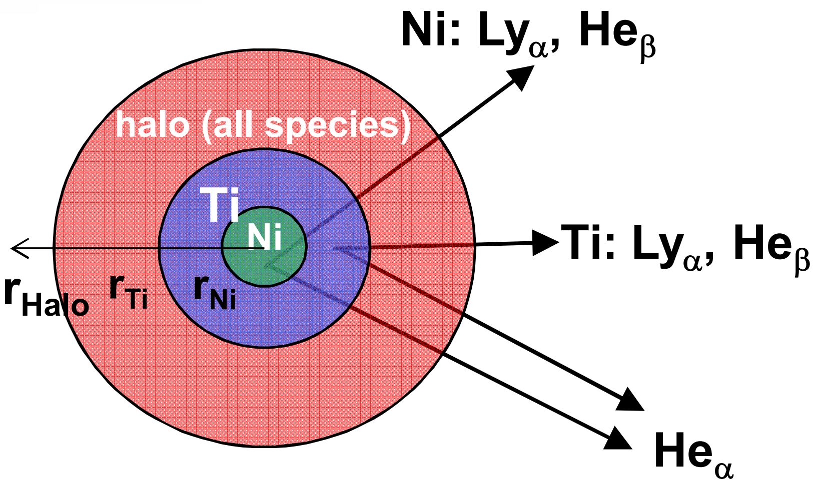
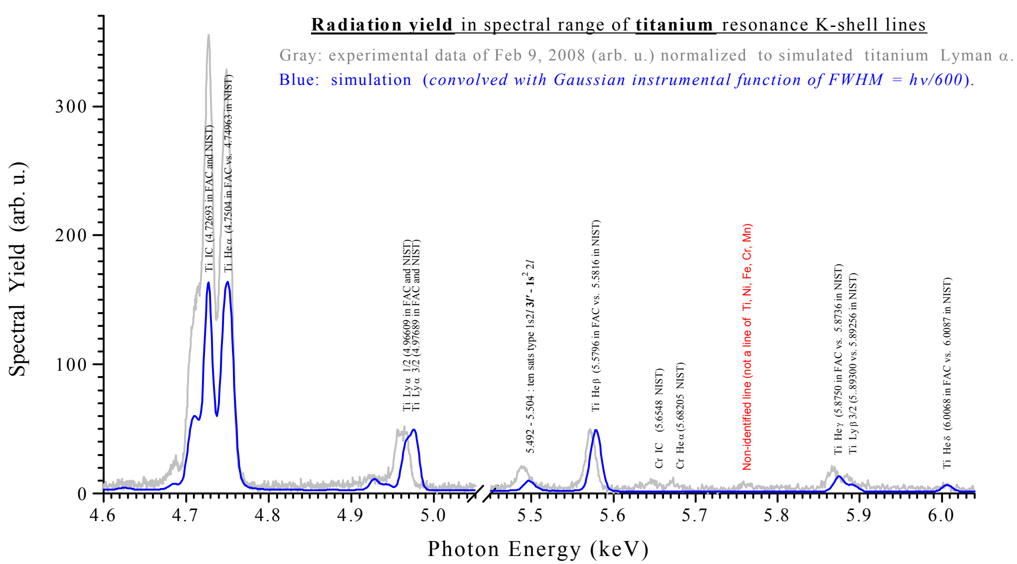
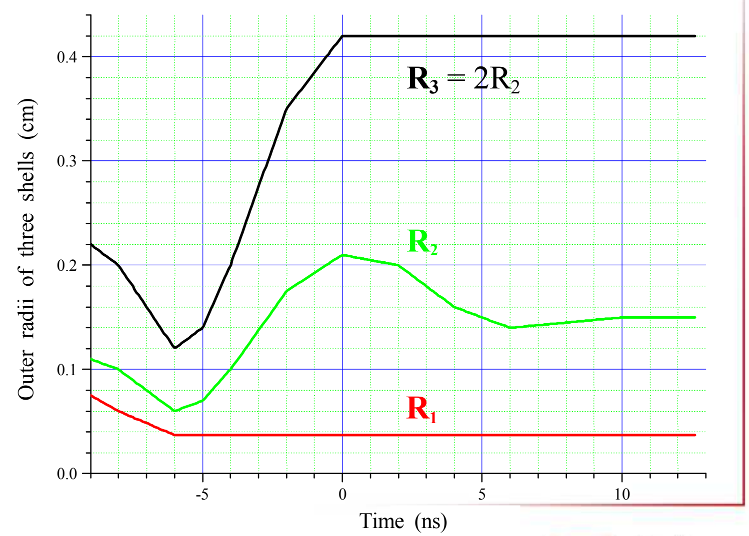
Detailed spectroscopic analysis also suggests that the inner array dominates



- Ly_α, He_β lines optically thin, give T_e for Ni and Ti
- He_α lines not optically thin and used to make sure halo did not impact result
- Model matched measured pinch size, radiative characteristics, and spectrum



F:/ ...785 / Complete .... Dec 2010 / **60 DEMO**



F:/ ...785 / Complete .... Dec 2010 / **60 DEMO**

Analysis of Z785, Al on Ni-Ti

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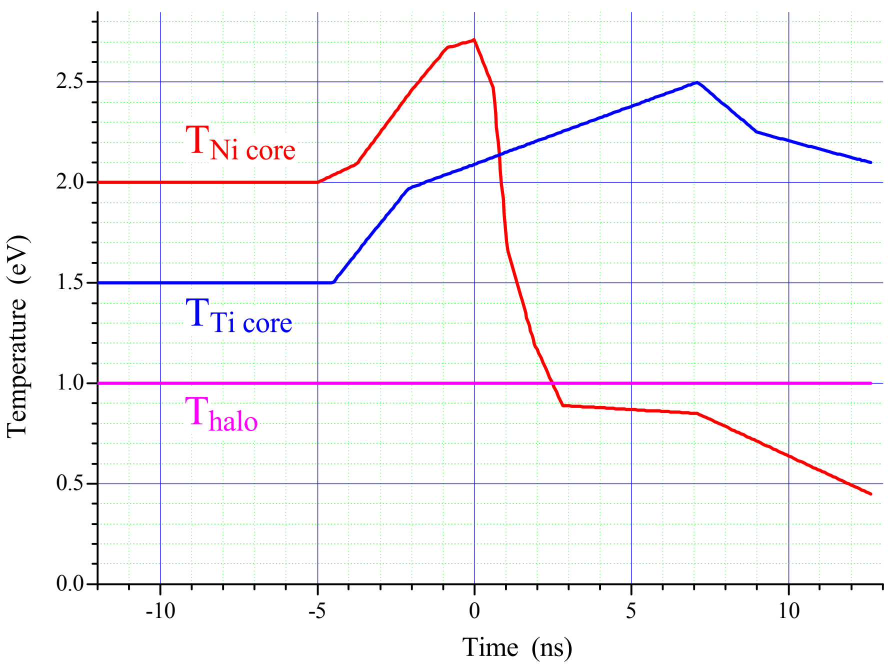
Modeling shows that the inner core cools early and is dominated by the Ni cladding from the inner array

	Inner core	Outer core
T_e (keV)	2.7 – 3.1	2.3 – 2.7
Total n_i (cm^{-3})	(3.2 – 5.5) x 10^{19}	3.5 x 10^{19}
% Ni mass	6 – 9	0.3 – 0.5
% Ti mass	< 0.5	6 – 13
% Al mass	< 0.5	12 - 18

Note:
% mass is fraction of the initial mass of each species
T_e = electron temperature
n_i = ion density



- **High Ni concentration in inner core suggests that cladding material dominates hottest portion of pinch**
- **Ti dominates the outer core region**
- **Al (initially on outer array) contributes to outer core, but is primarily in halo**

- **Inner core temperature peaks and then cools while outer core temperature continues to increase**

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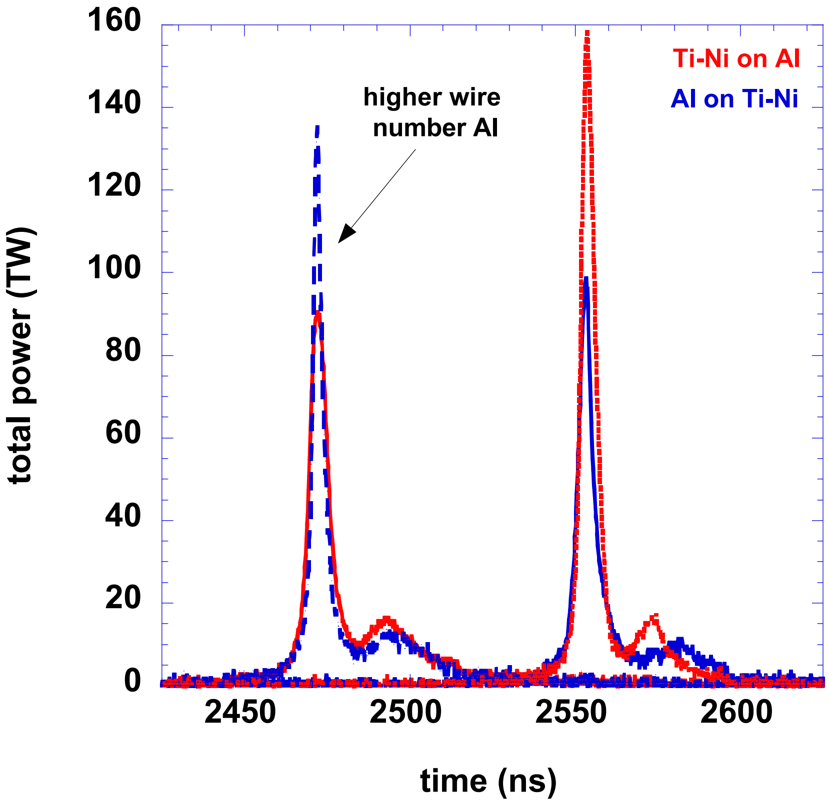
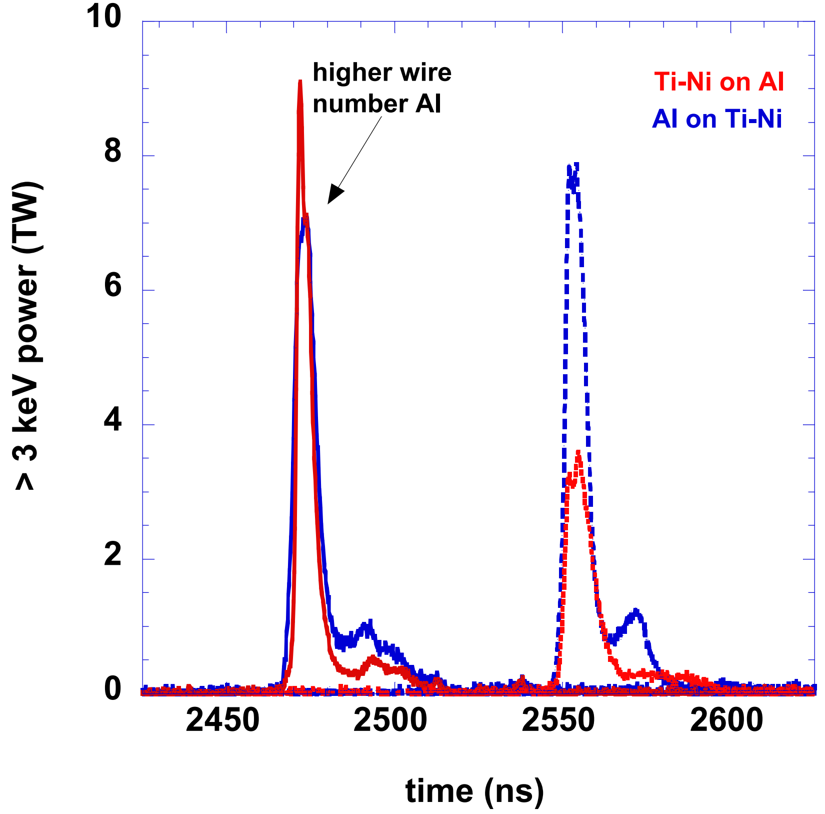
The higher Al wire number arrays provide additional insight into the dynamics of the implosion

Temporal offset to illustrate power differences



50mm dia. arrays



- **Higher wire number Al on outer array showed higher total power, but comparable >3 keV power**
- **Higher wire number Al on the inner array showed a decrease in the total power radiated, but an increase in the >3 keV power**

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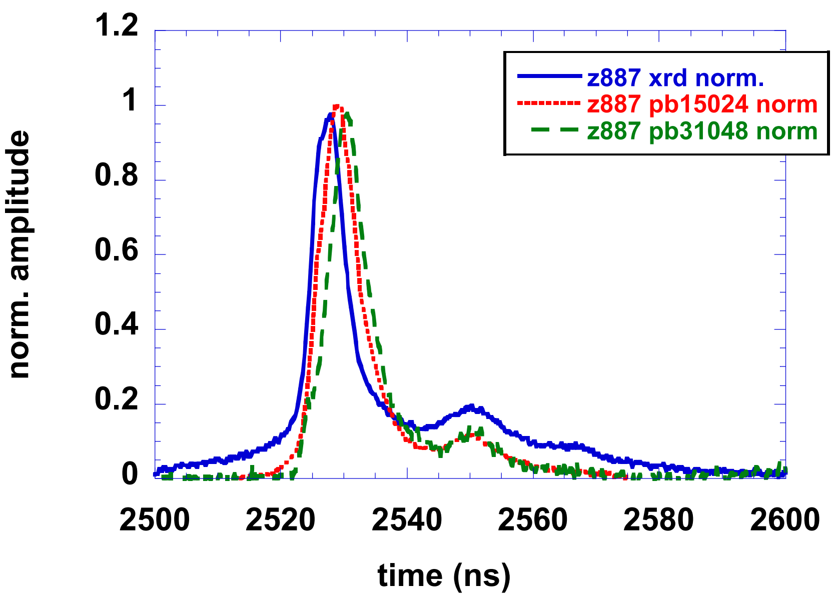
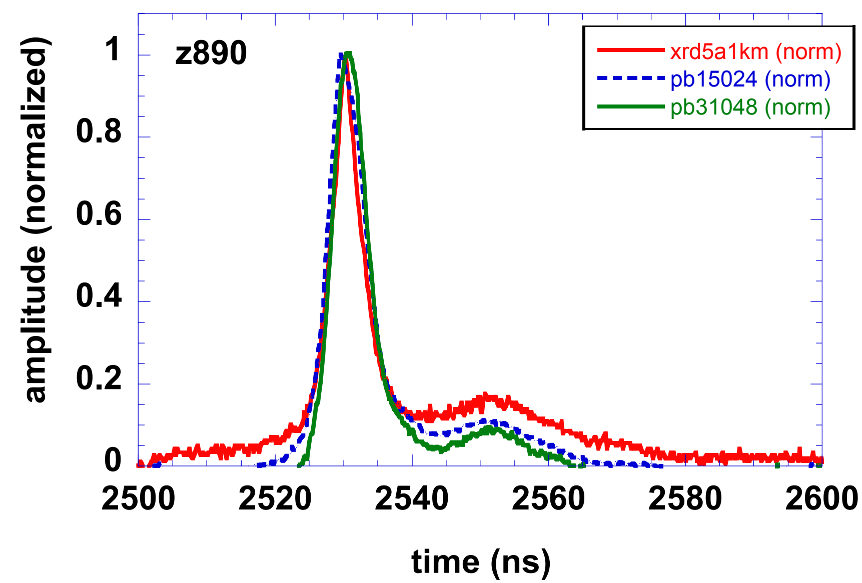
For the 40mm arrays, the higher wire number outer array shows more uniform radiation in all spectral bins





- For the typical wire number on the outer array, the time history suggests that higher energy emissions (Ti, Ni) start at time similar to softer emission (Al), but peak later

- For the higher wire number outer Al array, the pulseshapes in all energy bins were similar, and the delayed peak in higher energy emissions was less pronounced

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The power variations with Al on the outer array are due to pulseshape changes

50mm and 40mm nested wire arrays
2:1 mass & diameter ratios

shot	Al outer wire #	Ni-Ti inner wire #	total rise (ns)	total FWHM (ns)	total yield (kJ)	total power (TW)	> 3 keV rise (ns)	> 3 keV FWHM (ns)	> 3 keV yield (kJ)	> 3 keV power (TW)
785	96	48	4.8	4.4	1131	107.2	5	9.4	44	3.20
795	276	48	3.8	3.6	1111	140	1.6	5	53	7.91
887	140	70	6.2	6.6	1210	81.35	5.8	7	16.7	1.64
890	280	70	5.8	5.6	1169	92.27	4.2	6.4	24.3	2.50

- **Faster risetimes, narrow FWHM for higher wire number outer configurations in all energy bins**
  - **Consistent with previous wire number trends observed on single and nested wire arrays**
  - ***Faster risetime suggests reduction in instability growth***
- **Higher radiated yield for > 3 keV photons with higher wire number outer arrays**
  - **Same effect previously seen with stainless steel wire number variations, although in that case, inner and outer wire number was increased**

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Different behavior is observed when the higher wire number is on the inner array

50mm and 40mm nested wire arrays
2:1 mass & diameter ratios

shot	Ni-Ti outer wire #	Al inner wire #	total rise (ns)	total FWHM (ns)	total yield (kJ)	total power (TW)	> 3 keV rise (ns)	> 3 keV FWHM (ns)	> 3 keV yield (kJ)	> 3 keV power (TW)
784	96	48	5	5.4	1427	161	3.2	5.9	60	7.4
796	96	138	6	6.8	1231	102	3.4	7.2	63	6.3
888	140	70	5.6	7.2	1435	118	6.2	4	30.3	4
889	140	140	4.6	5.8	1394	141	7	8.6	36.6	3.4

- **Lower total power, lower > 3 keV power**
  - **Slower risetimes, wider FWHM for higher wire number inner configurations**

- **If inner array produces hottest portion, with Al on the inner array, and higher wire number, slight enhancement of > 3 keV yield likely due to Al free-bound continuum increases**

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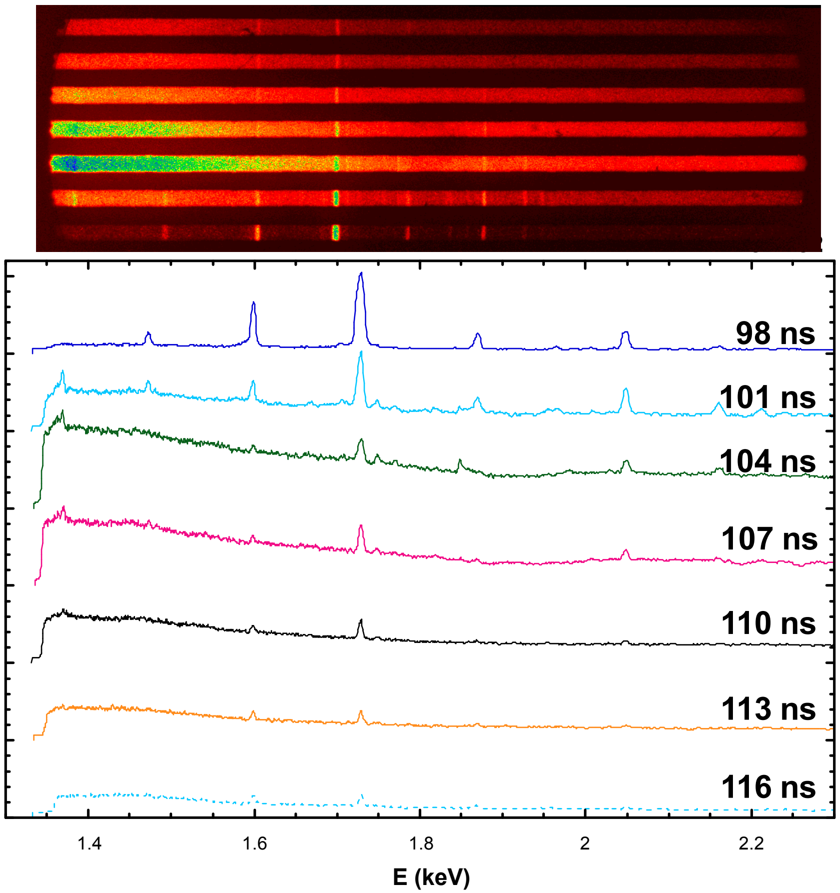
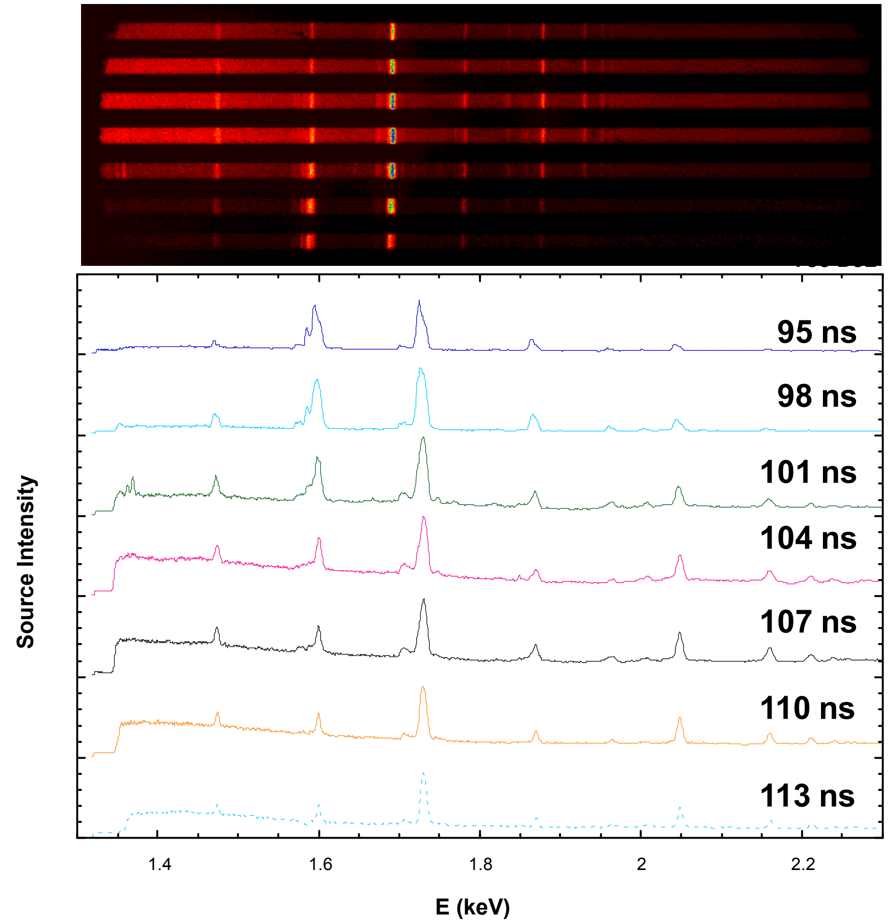
Time-resolved spectroscopy shows enhanced Al free-bound continuum with Al inner array

Aluminum Inner



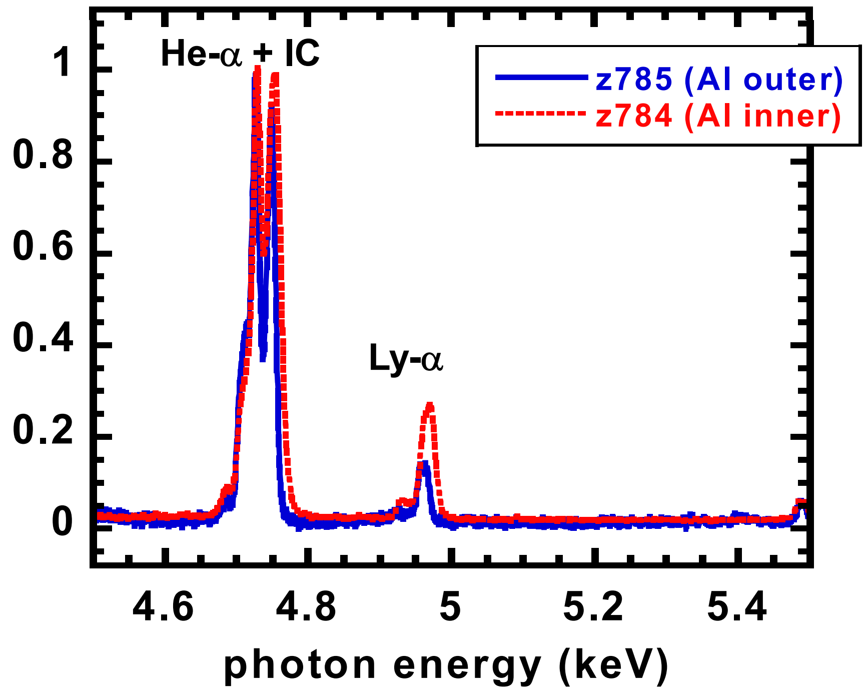
- Dominated by continuum at stagnation
- Al He-α nearly consumed by continuum at stagnation

Aluminum Outer



- Dominated by Al Ly-α line through stagnation
- Al He-α still prominent through stagnation

Plasma conditions can be estimated from the He Ly-α/(He-α + IC) ratio



- Line ratios, CRE analysis
  (J. P. Apruzese et al., J. Quant. Spectrosc. Radiat. Transf. **57, 41 1997)**
- T_e and n_i somewhat higher for Ni-Ti on outer array
  - Consistent with observed higher yield
  - T_e similar for all cases
- Highest density for high wire # Al
  - Consistent with outer array pushing mass from inner array

	Ni-Ti outer (784)	Ni-Ti outer, high # Al inner (796)	Ni-Ti inner (785)	Ni-Ti inner, high # Al outer (795)
T_e (keV)	3.2	3.05	2.8	2.9
n_i (10^{19} cm^{-3})	5.3	4.8	4	6

Plasma conditions for the 40mm arrays show….

	Ni-Ti outer (888)	Ni-Ti outer, high # Al inner (889)	Ni-Ti inner (887)	Ni-Ti inner, high # Al outer (890)
T_e (keV)				
n_i (10^{19} cm^{-3})				

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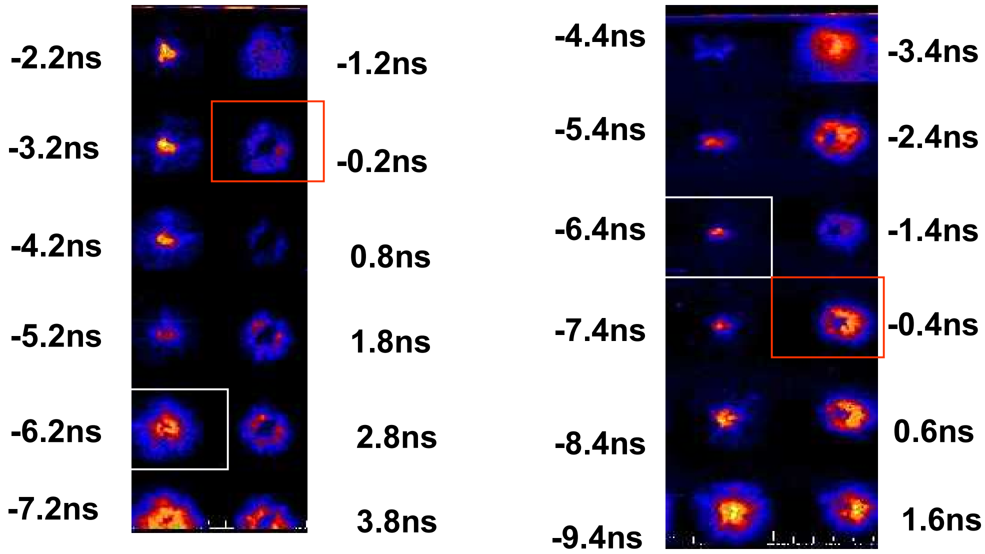
These results generally suggest that outer wire array drives the inner array

- Analysis of measured radiated output and modeling all suggest the inner dominates the core regions of the radiating plasma
  - Significantly more output than expected from inner materials
- The higher wire number on the outer array appears to reduce instability growth, resulting in higher output from inner array

End-on pinhole images, > 3 keV



Z887

Z890
(high # outer)

- *Earlier compression of inner material*
- *Larger radiating region*

Similar mechanism as the pusher-stabilizer-radiator model from gas puffs?
(H. Sze, PRL 95, 105001 (2005))

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Summary

- Ti-Ni on outer array
  - Intense emission Ti and Ni K-shell emission over ~1 mm diameter
  - Radiated yield >3 keV is similar to that observed when Ti-Ni on both arrays
    - Consistent with typical thinking for higher velocity needed for higher energy photon emission

- Ti-Ni on inner array
  - Brightest emissions >3 keV are in very narrow regions (~ 0.4mm)
    - Consistent with spectroscopy that shows Ti and Ni K-shell emission are localized
    - Suggests hot, dense core
  - Radiated yields > 3 keV is lower, but not commensurate with reduction in mass

- Higher wire number on outer wire array improved pulseshape, resulted in higher powers, and also higher yields from inner array material
  - Outer acting as “pusher”