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Z K-shell X-ray Sources Data Review (BJ)

B. Jones, D. J. Ampleford, C. A. Coverdale, C. A. Jennings *et al.*

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Pre-refurb. Z SS inner array variations

TABLE I. Configuration of double-nested stainless steel wire arrays discussed in this work. All were 2 cm tall with a 6 mm anode-cathode power feed gap, and had identical outer wire arrays (55 mm array diameter, 0.71 mg/cm, 104 wires, 10.5 μm wire diameter). The shot labeled "standard" represents a 2:1 mass and radius ratio configuration that was fielded >10 times on Z and which we consider as a baseline for comparison with other variants.

Shot number	Initial R_{inner}/R_{outer}	Initial m_{inner}/m_{outer}	Inner wire number	Inner wire diam (μm)	Total mass (mg/cm)
1084	0.250	1.022	34	18.5	1.44
1308	0.250	0.327	34	10.5	0.95
1386	0.250	0.327	34	10.5	0.95
1306	0.375	0.327	34	10.5	0.95
Standard[a]	0.500	0.500	52	10.5	1.06
1307	0.625	1.308	136	10.5	1.65
1309	0.625	1.308	136	10.5	1.65
1085	0.750	0.308	32	10.5	0.93
1385	0.750	2.444	82	18.5	2.46

[a]Average power and yield discussed later are based on Z shots 578, 840, 841, 847, 974, 975, 976, 977, and 978.

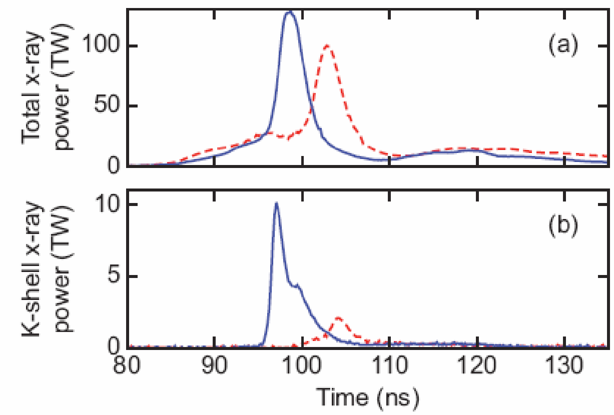


FIG. 10. (Color) (a) Total, and (b) *K*-shell x-ray power for shot Z1084 (red dashed curve) where implosion of outer and inner arrays was not simultaneous, and Z1308 (solid blue curve) which was designed for more nearly simultaneous implosion.

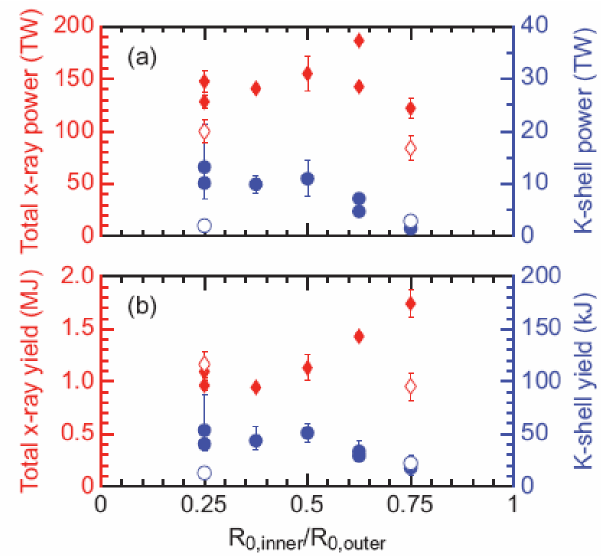
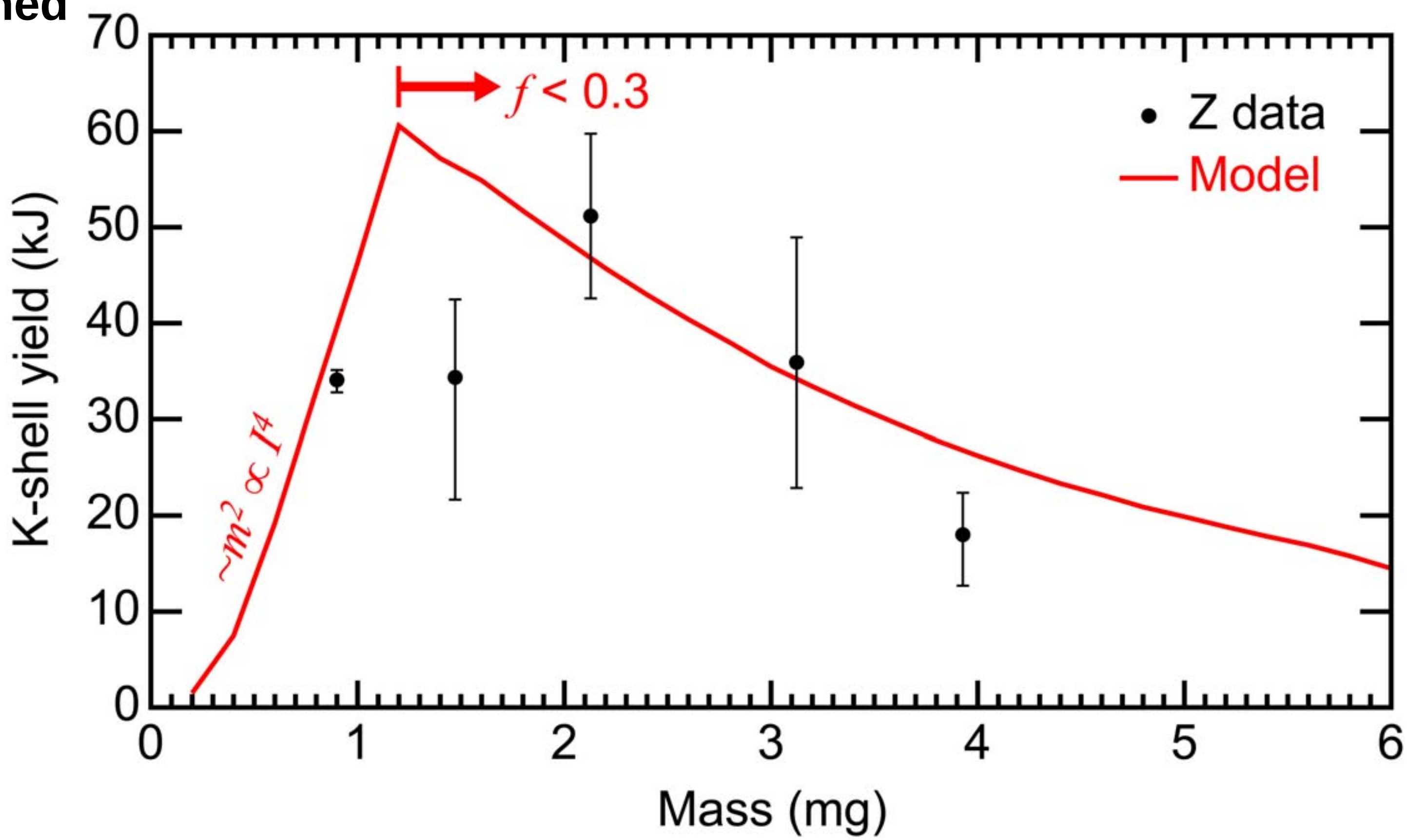


FIG. 13. (Color) Radiated peak power (a) and yield (b) as a function of nested array initial radius ratio for the shots of Table I. Total x-ray outputs are shown with red diamonds, while *K*-shell x-ray outputs are shown with blue circles. Hollow points indicate loads that were not designed for simultaneous implosion of the outer and inner wire arrays.

- B. Jones *et al.*, PoP **15**, 122703 (2008).
- **We argued that the outer and inner array implosions should be simultaneous according to 0D modeling**
- **Nothing worked better than 2:1 mass and radius ratios, so we have largely stuck with that**
- **C.A. Jennings and D.J. Ampleford studied additional nesting variations with 3D MHD and experiment**
- **LOOK HERE FOR HOLLOW FEATURES THAT BAILEY MENTIONED, Z1084-85**

K-shell yield model is reasonably applied to nested stainless steel wire array data on Z

SS mass scan shots, pre-refurb. Z, unpublished



- **Waisman 0D code is used to estimate E_{jxB} and thus η in the NRL scaling model**
  - **Inductive current switch between arrays; 25% momentum transfer**
  - **No ablation model included**
  - **1 mm final radius, motivated by pinhole imaging**

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In the Z-accessible regime, K-shell scaling for Fe reduces to a simple expression

$$Y_K = f\ S\ E_{\mathbf{j}\times\mathbf{B}}$$

$$S = \min\left(1, m/m_{BP}(Z,\eta)\right) \longrightarrow m/m_{BP}(Z,\eta=4)$$

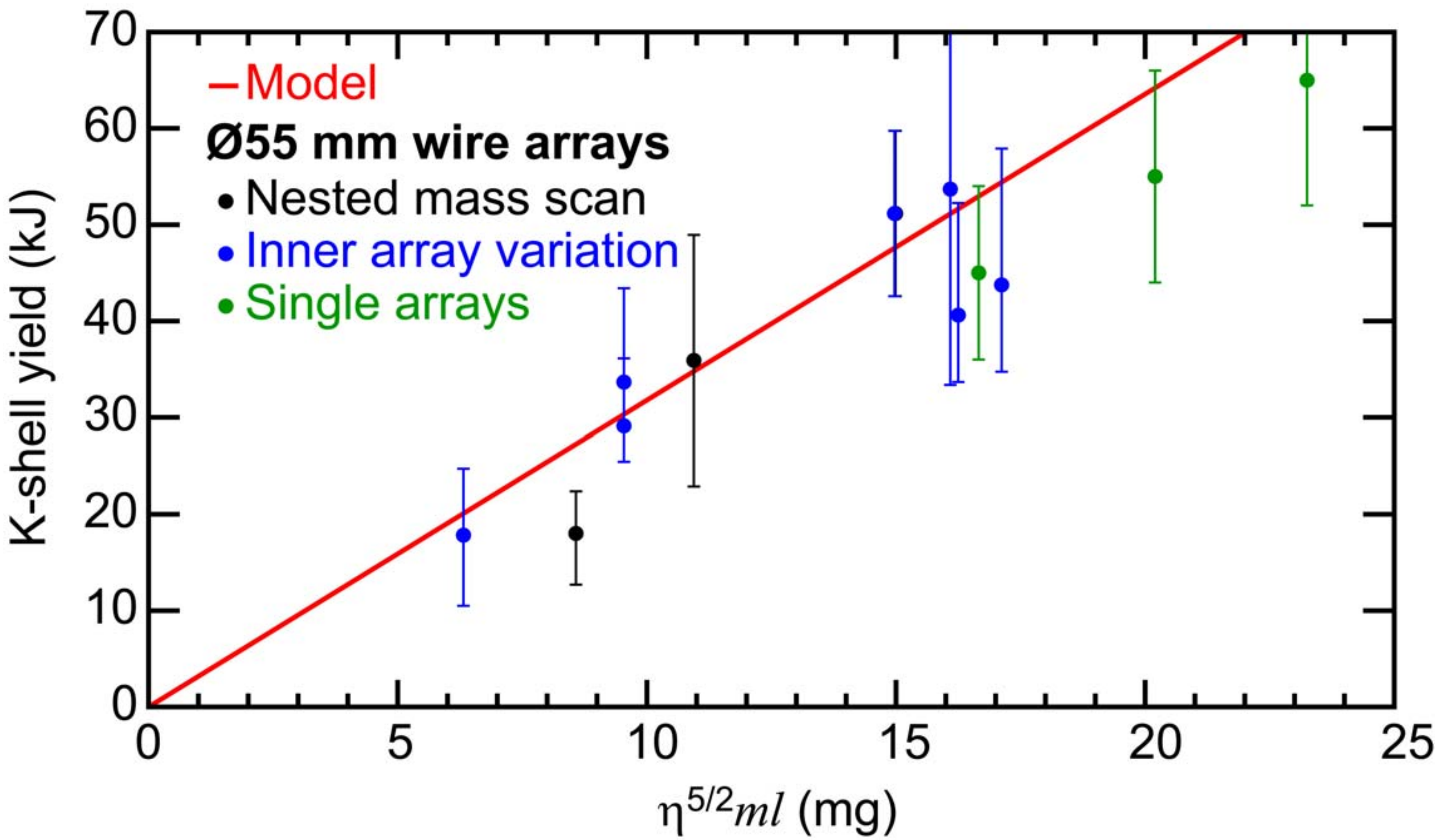
$$f = \min\left(0.3,\ c(Z,\text{load})\,Z^{1.2}E_{\mathbf{j}\times\mathbf{B}}^{3/2}/m^{5/2}\right) \longrightarrow c(Z,\text{load})\,Z^{1.2}E_{\mathbf{j}\times\mathbf{B}}^{3/2}/m^{5/2}$$

$$\eta = \frac{E_{\mathbf{j}\times\mathbf{B}}/(ml/Am_p)}{E_{min}(Z)}$$

$$\boxed{Y_K = c(Z,\text{load})\,F(Z)\,\eta^{5/2}ml}$$

- J. W. Thornhill *et al.*, IEEE T. Plasma Sci. **34**, 2377 (2006).

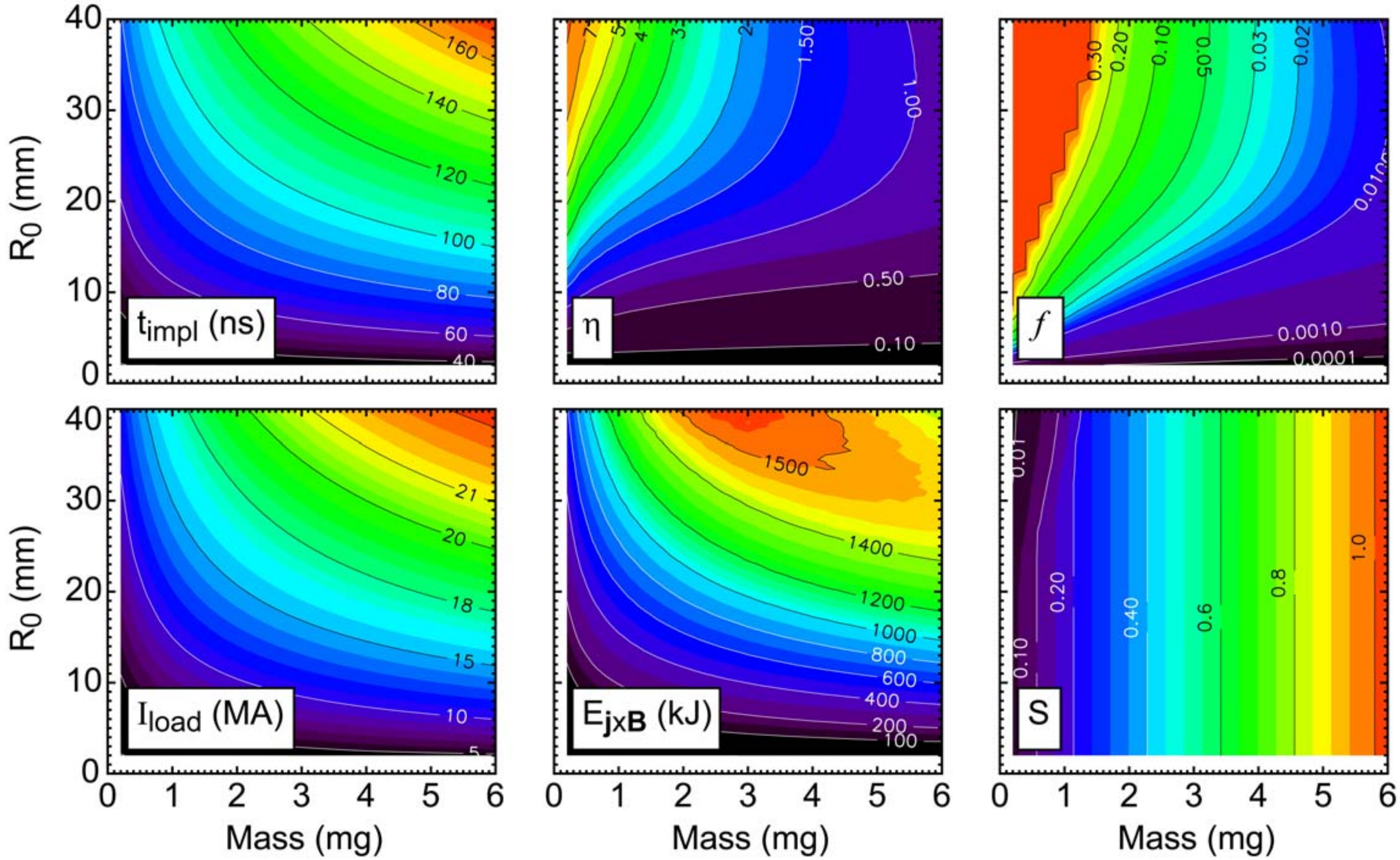
K-shell yield model benchmarked to nested stainless steel wire array data on Z



- **0D implosion model is used to estimate E_{jxB} and thus η in the NRL scaling model**
  - **Inductive current switch between arrays; 25% momentum transfer**
  - **No ablation model included**
  - **1 mm final radius, motivated by pinhole imaging**

SS K-shell scaling

K-shell yield model coupled with 0D implosion simulation guides shot design on the new Z



- **Waisman 0D model (older version, constant Zflow) was used to estimate E_{jxB} and thus η in the NRL scaling model**
- **Lemke V_{OC} waveform rescaled for 82 kV Marx charge**

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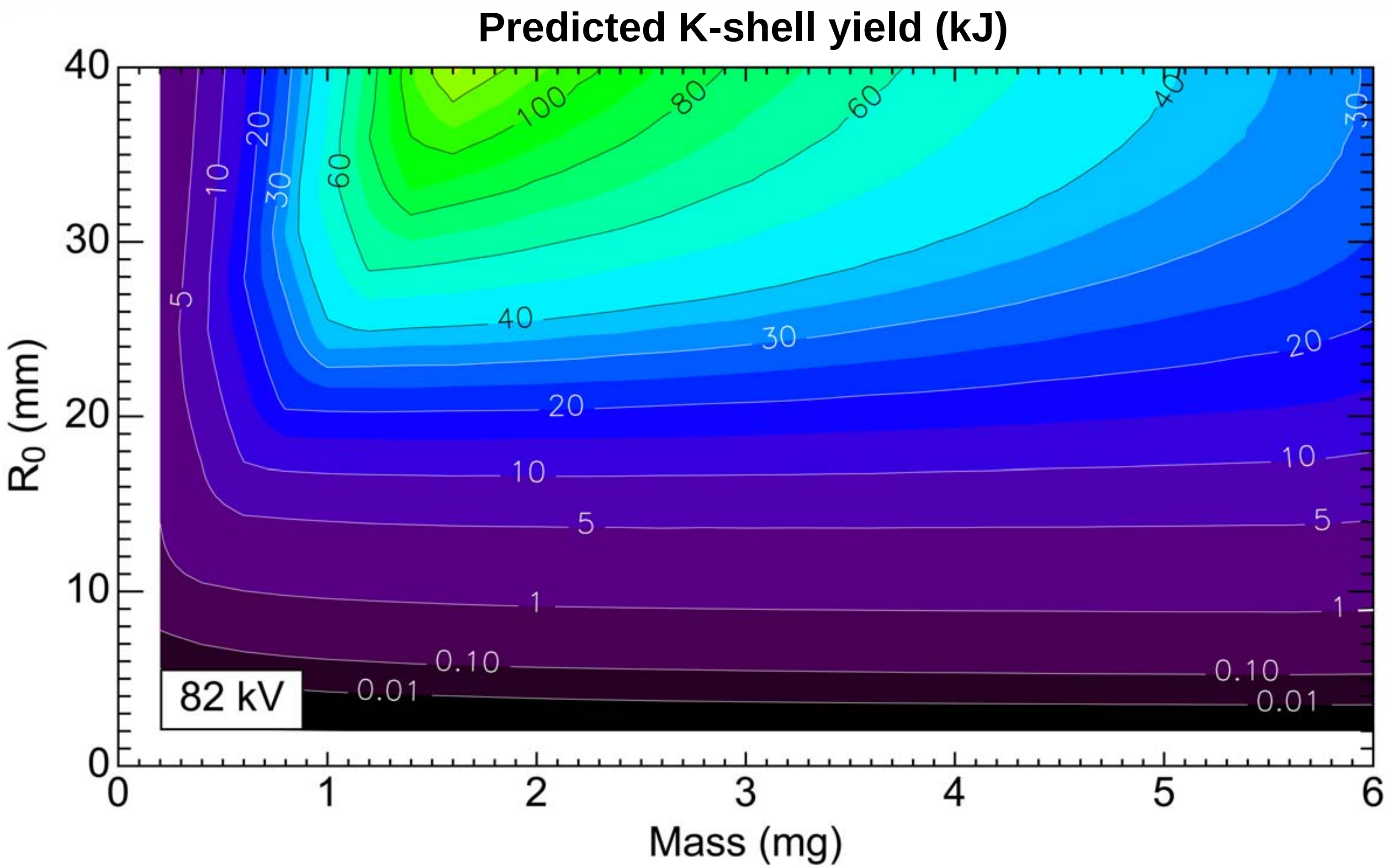
SS K-shell scaling

K-shell yield predicted with scaling model and 0D simulation over m,R_0 parameter space



- **Waisman 0D model (older version, constant Zflow) was used to estimate E_{jxB} and thus η in the NRL scaling model**
- **Lemke V_{OC} waveform rescaled for 82 kV Marx charge**

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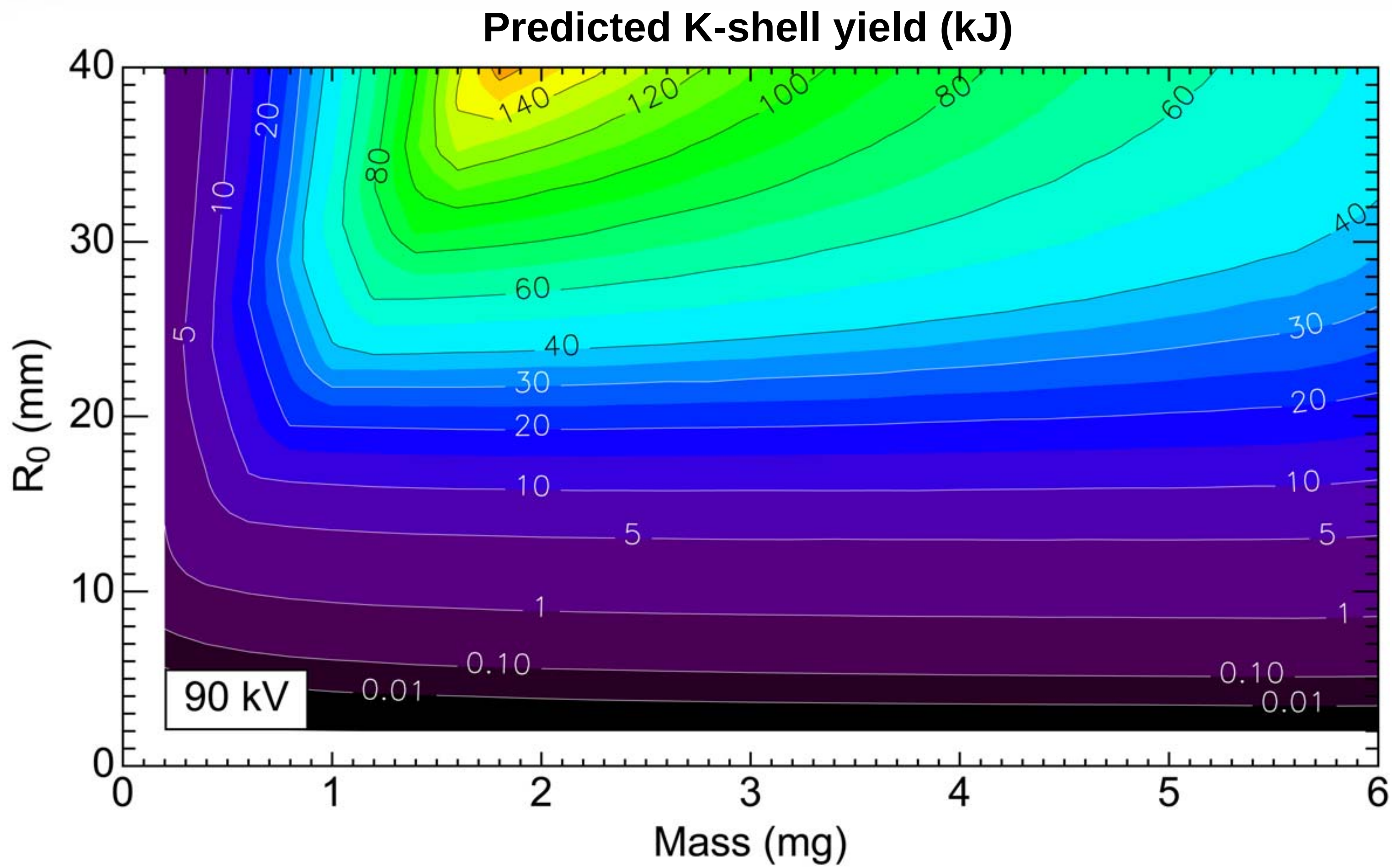
SS K-shell scaling

K-shell yield predicted with scaling model and 0D simulation over m,R_0 parameter space



- Waisman 0D model (older version, constant Zflow) was used to estimate E_{jxB} and thus η in the NRL scaling model
- Lemke V_{OC} waveform rescaled for 90 kV Marx charge

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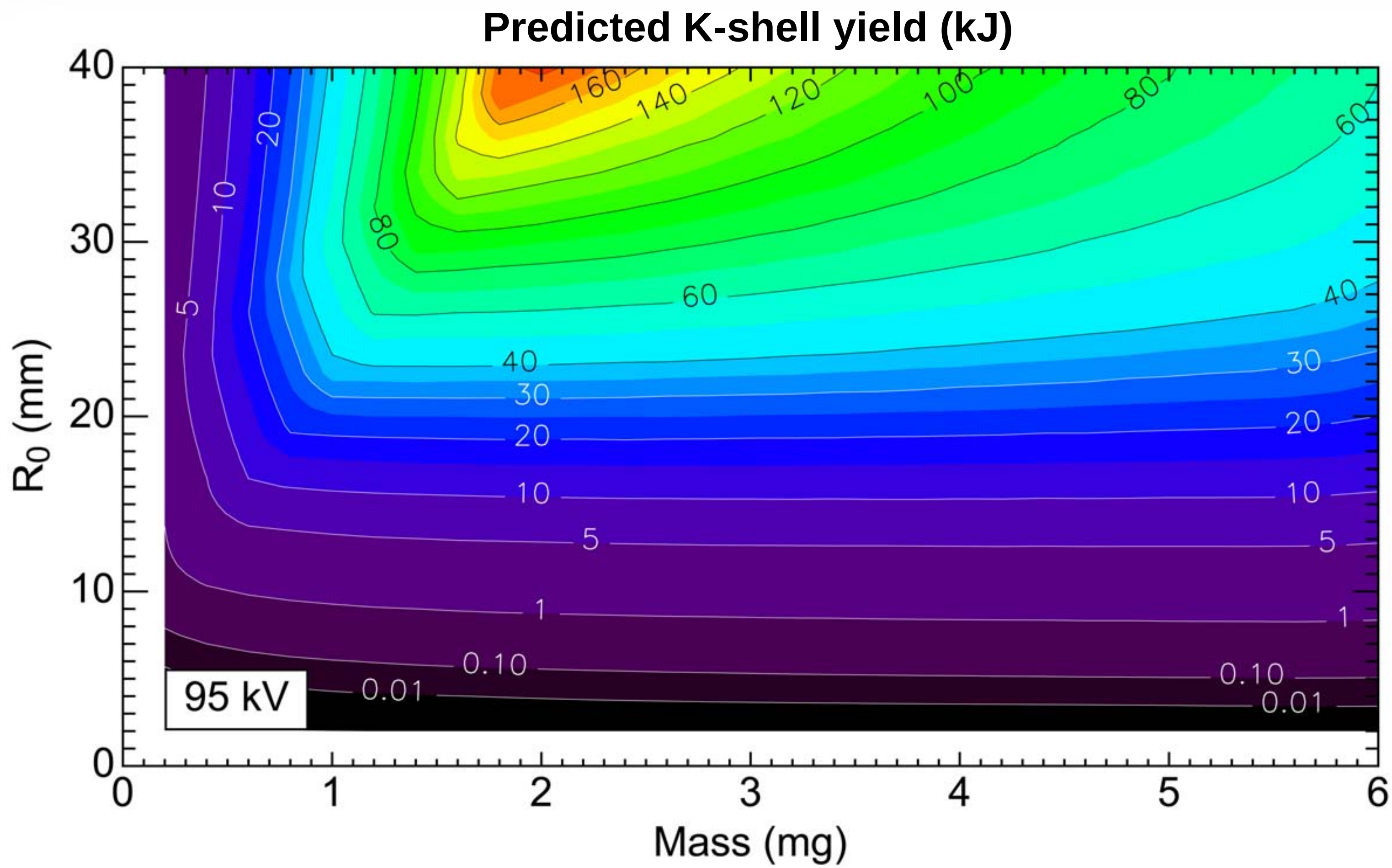
K-shell yield predicted with scaling model and 0D simulation over m,R_0 parameter space



- **Waisman 0D model (older version, constant Zflow) was used to estimate E_{jxB} and thus η in the NRL scaling model**
- **Lemke V_{OC} waveform rescaled for 95 kV Marx charge**

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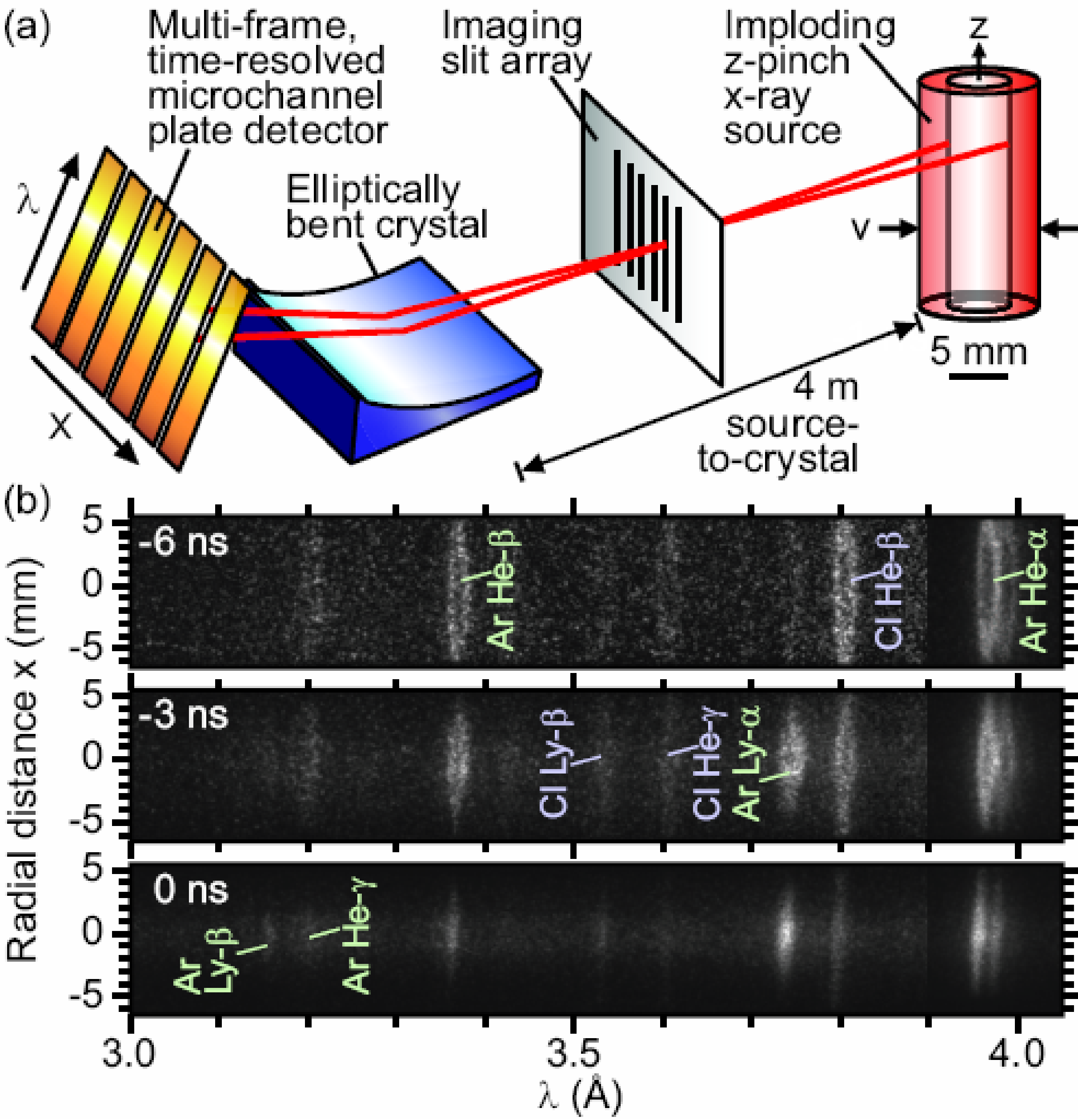
Z1422, Coverdale D_2 gas puff with Doppler split dopant lines

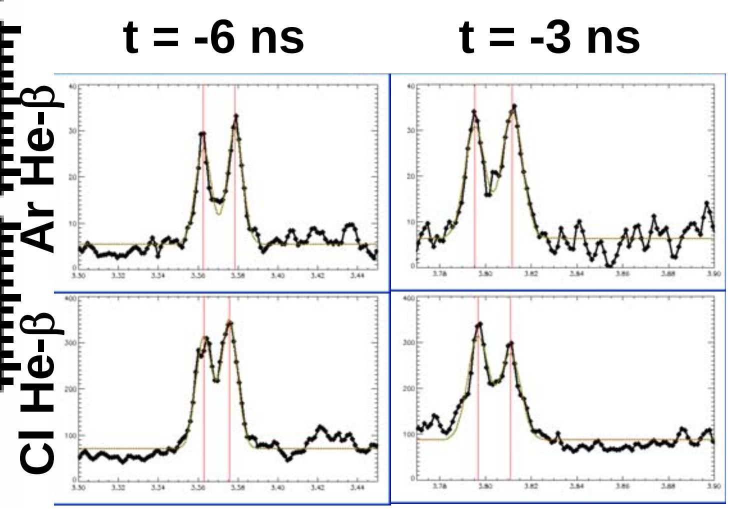


- **D_2 gas puffs discussed in:**
  C.A. Coverdale *et al.*, PoP **14**, 022706 (2007).
  C.A. Coverdale *et al.*, PoP **14**, 056309 (2007).
  A.L. Velikovich *et al.*, PoP **14**, 022701 (2007).

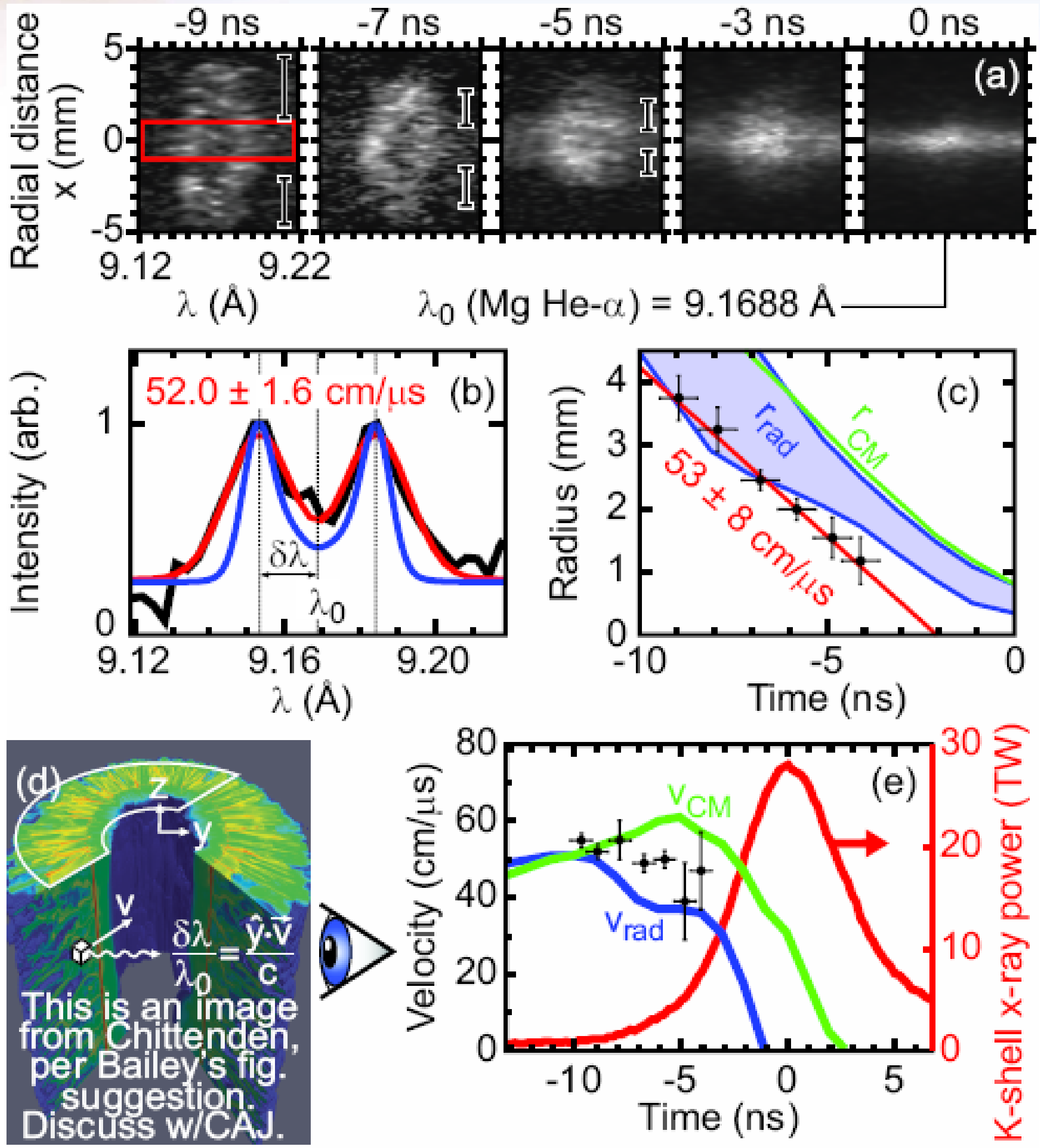
- **Time- and space-resolved spectral measurements with TREX instruments**
- **Doppler splitting analysis in preparation (B. Jones *et al.*)**
- **Doppler splitting fit results for emissivity-weighted average velocity (2-3 cm/μs errors):**

	Velocity (cm/μs)	
Line	**t=-6 ns**	**t=-3 ns**
Ar He-β	**71**	**58**
Cl He-β	**66**	**55**
Ar He-α	**68**	**56**

- **Plasma decelerates as it stagnates, also seen in Chittenden 3D MHD**
- **Doppler splitting vanishes by time of peak x-ray power (t=0)**



Z1520, Coverdale Al shot shows Doppler split in Mg dopant



- C.A. Coverdale *et al.*, HEDP **6**, 143 (2010) **discusses Apruzese (NRL) analysis of z1520 gated, spatially-integrated spectra (LePell TREX?)**
- **Maron *et al.* (Weizmann) analyzing spectral data with 3-zone model**
- **C.A. Jennings has performed 3D MHD modeling—interesting to compare**

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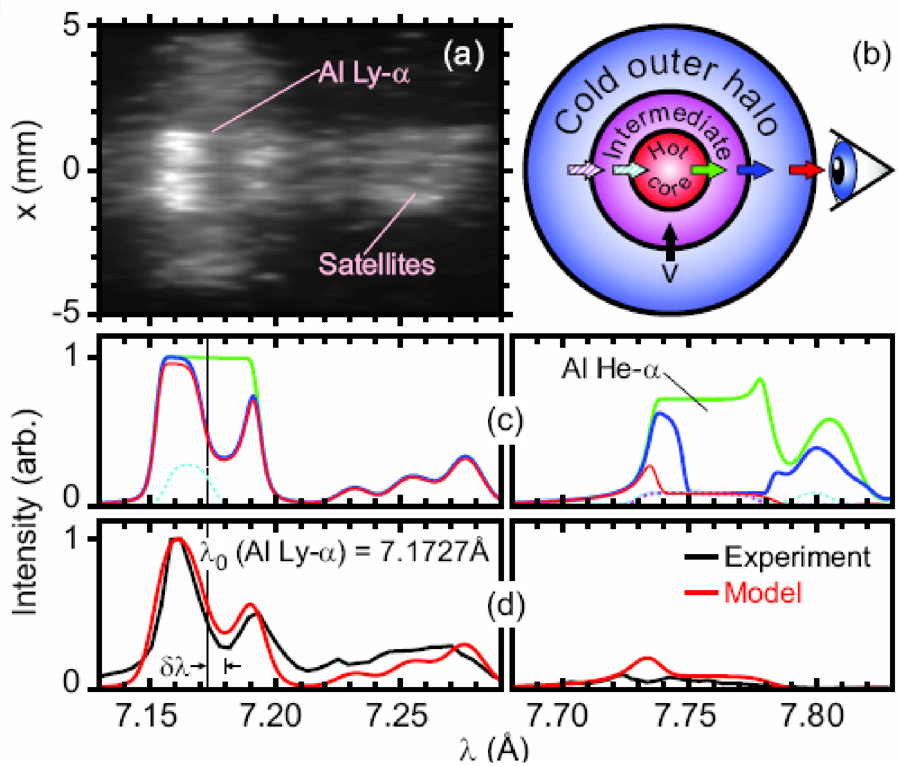
Z1518, ~6 mg, 20 mm Al single array with good TREX data



t = -13 ns

Zone	R (mm)	T_e (eV)	n_i (cm^{-3})
Core	1.5	300	7e19
Interm.	4.5	150	4e19
Halo	10	50	4e19

- **Doppler shifted absorption at foot of x-ray pulse reveals 30± 10 cm/µs velocity in trailing mass (B. Jones *et al.*, in preparation)**
- **Maron *et al.* (Weizmann) analyzing spectral data with 3-zone model, determining plasma conditions in each zone (verify these numbers)**
- **C.A. Jennings (Gorgon) and E.P. Yu (ALEGRA) performing 3D MHD modeling—interesting to compare**
- **Also compare to S.B. Hansen line shape modeling?**

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11/18/08-12/12/08, Z1857-1866, A0012, A0037 shot overview

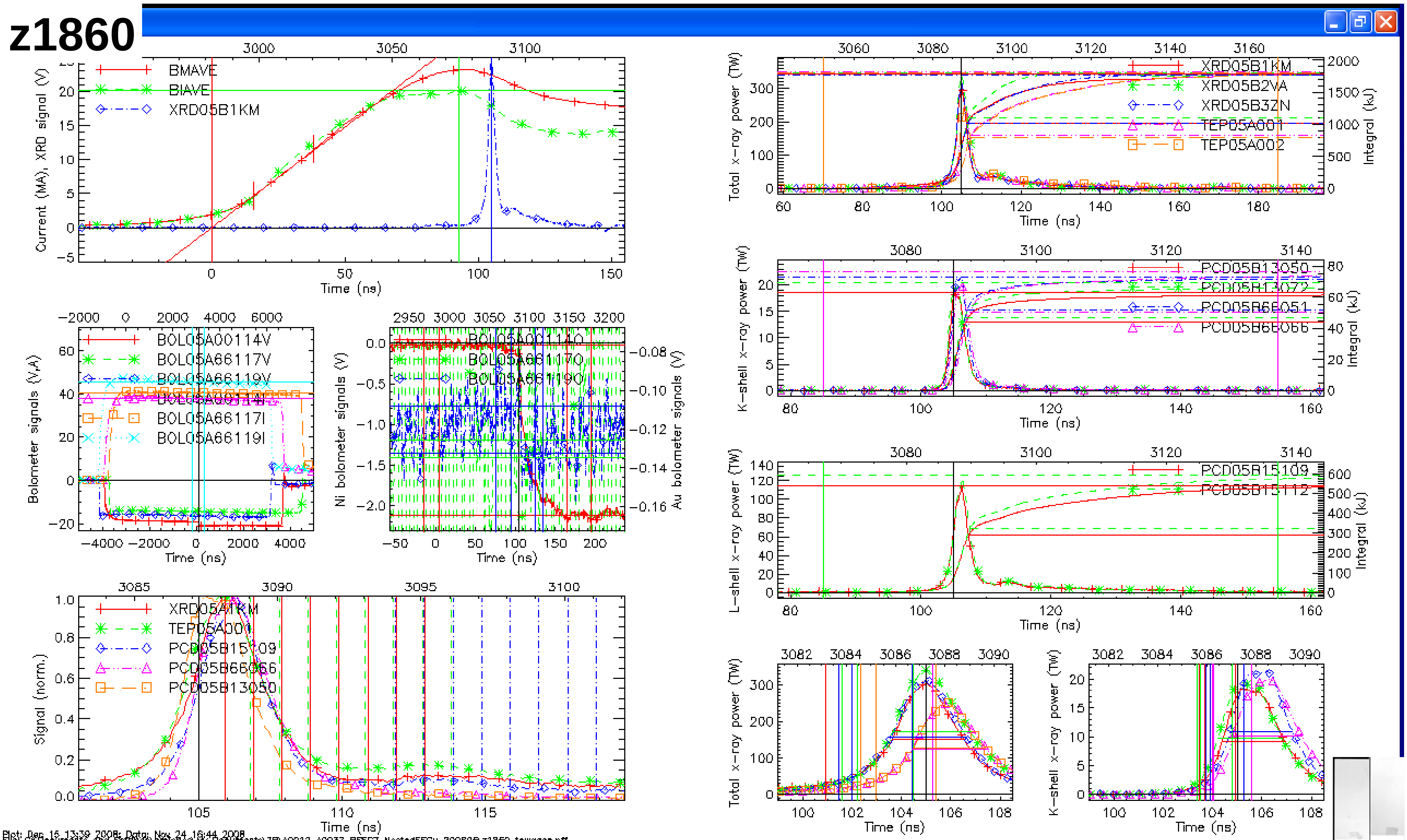
Shot	A #	Wire mater-ial	Array dia. (mm)	Wire #	Wire dia. (um)	Array mass (mg/cm)	Cath. Step (mm)	Total yield (MJ)	K yield (kJ)	K-shell 10-90% rise (ns)
z1857	A0012-1	SS304	65/32.5	200/100	8.15	1.24	None	2.0	48±6	2.34±0.07
z1858	A0012-5	SS304	65/32.5	200/100	8.15	1.24	2x2	1.2	30±3	2.9±0.1
z1859	A0012-3	SS304	65/32.5	400/200	8.15	2.48	None	2.3	18±2	2.1±1.3
z1860	A0012-6	SS304	65/32.5	200/100	8.15	1.24	2x2	1.8	61±5	1.51±0.09
z1861	A0012-2	SS304	65/32.5	200/100	8.15	1.24	None	1.8	65±4	1.95±0.09
z1862	A0012-4 /A0037-EXTRA	Cu	65/32.5	112/56	10.35	1.26	2x2	2.0	25*±5	3.7±0.2
z1863†	A0037-1	Cu	65/32.5	112/56	10.35	1.26	2x2	1.5	20±3	2.32±0.09
z1866†	A0037-2	Cu	80/40	112/56	10.35	1.26	2x2	2.0	10±2	2.5±0.1

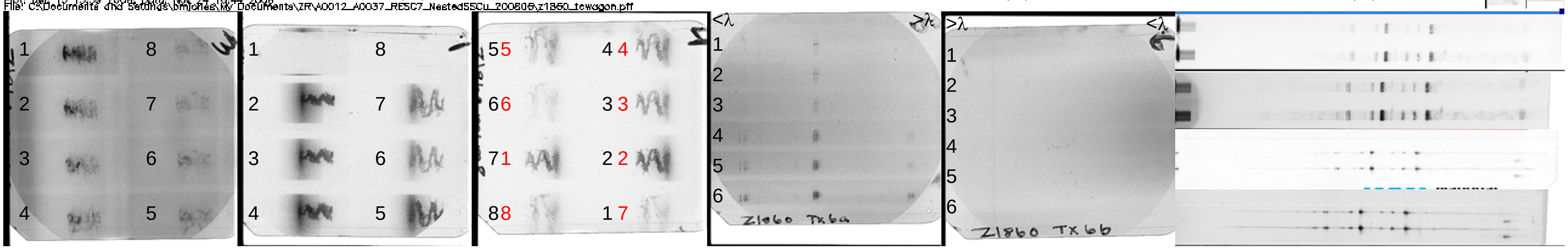
* Includes reduction from 28.5 kJ for axial length variation from TIXTL

† 9 post convolute

- **Goals:**
  - **First shots since Z refurbishment to study K-shell wire array sources**
  - **Begin to study SS and Cu wire arrays on the new machine (SS mass scan at 65 mm dia., Cu large dia.**
  - **Study z-pinch stagnation with x-ray spectroscopy (TIXTL, TREX)**
  - **Assess cathode bubble (not really seen in most ZR shots)**
- **All loads 20 mm tall, 82 kV Marx charge, pre-pulse suppression, older feed**
- **Cu had ~4% Ni dopant**
- **TIXTL filter transmission correction assuming all photons at: Fe He-α 6.7 keV (SS), or Cu He-α 8.4 keV (Cu)**

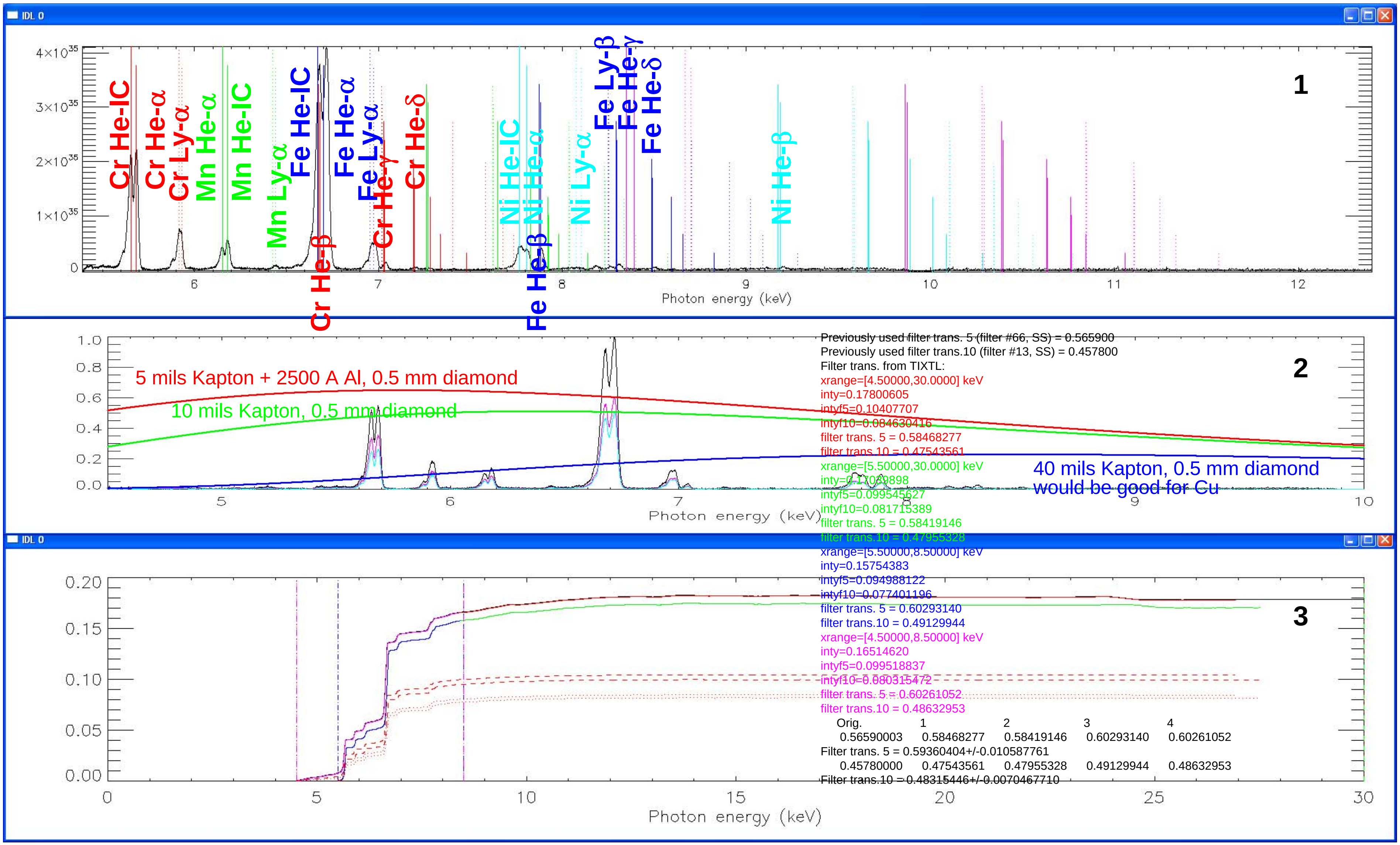
z1860


BMAVE
BIAVE
XRD05B1KM
Current (MA), XRD signal (V)
Time (ns)
XRD05B1KM
XRD05B2VA
XRD05B3ZN
TEP05A001
TEP05A002
Total x-ray power (TW)
Integral (kJ)
BOL05A00114V
BOL05A66117V
BOL05A66119V
BOL05A66117I
BOL05A66119I
Bolometer signals (V,A)
Ni bolometer signals (V)
Au bolometer signals (V)
PCD05B13050
PCD05B13072
PCD05B66051
PCD05B66066
K-shell x-ray power (TW)
PCD05B15109
PCD05B15112
L-shell x-ray power (TW)
XRD05A1KM
TEP05A001
PCD05B15109
PCD05B66066
PCD05B13050
Signal (norm.)
Plot: Dec 15 13:39 2008; Data: Nov 24 16:44 2008


Z1860 TX6a
Z1860 TX6b

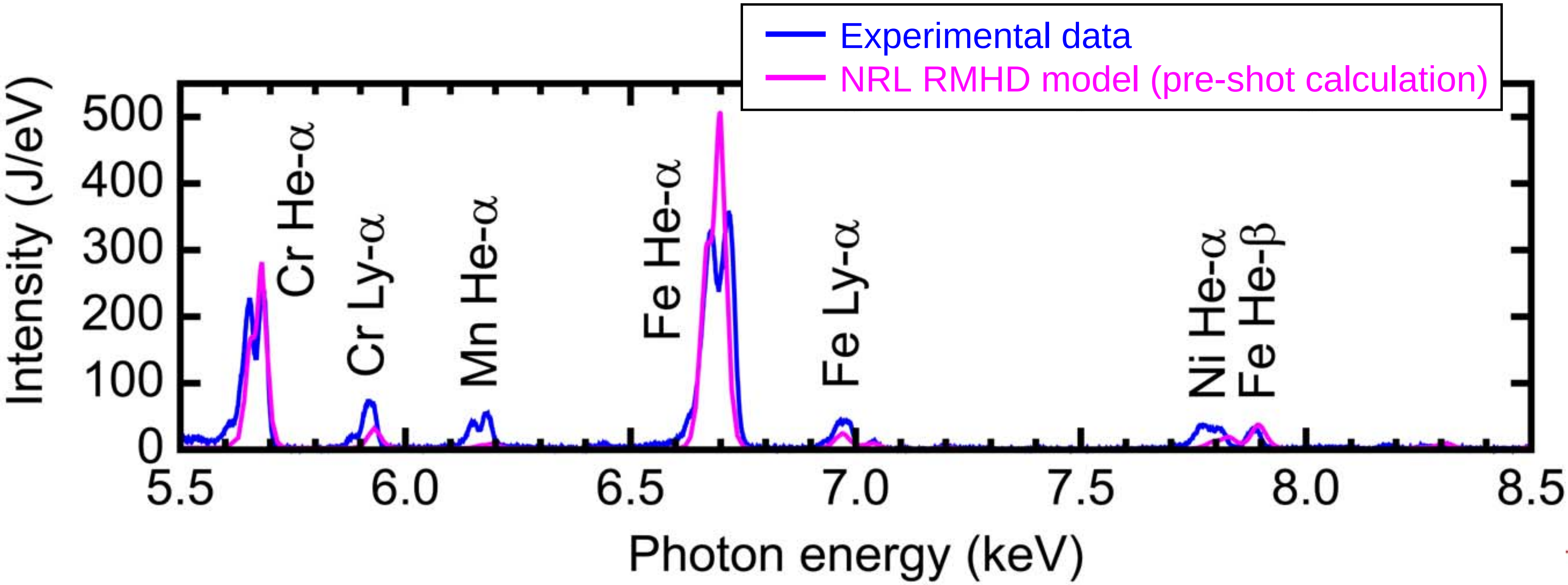
z1860 TIXTL processing – filter transmission factors

- Plot 1: TIXTL K-shell spectrum vs. photon energy.
- Plot 2: Filter transmission x diamond absorption curves, also multiplied by spectrum
- Plot 3: Integrated: spectrum (solid), spectrum x filter #66 transmission x diamond absorption (dashed), spectrum x filter #13 transmission x diamond absorption (dotted). Colors correspond to integration over ranges shown below.
- Average filter transmission values are shown in text below. Original value assumed Fe He-a only. Corrections not too big.



NRL benchmarked 1D RMHD calculation can do a reasonable job of estimating the K spectrum

- Reasonable to use simulated spectrum if it is experimentally demonstrated that the calculated spectrum is reliable
- Measured K-shell spectra agree well with pre-shot simulation; energy in the main lines and net K-shell yield are correct
- More physical line shapes with multi-frequency post-processing
- Experimental data used in post-shot RES testing analysis



z1860

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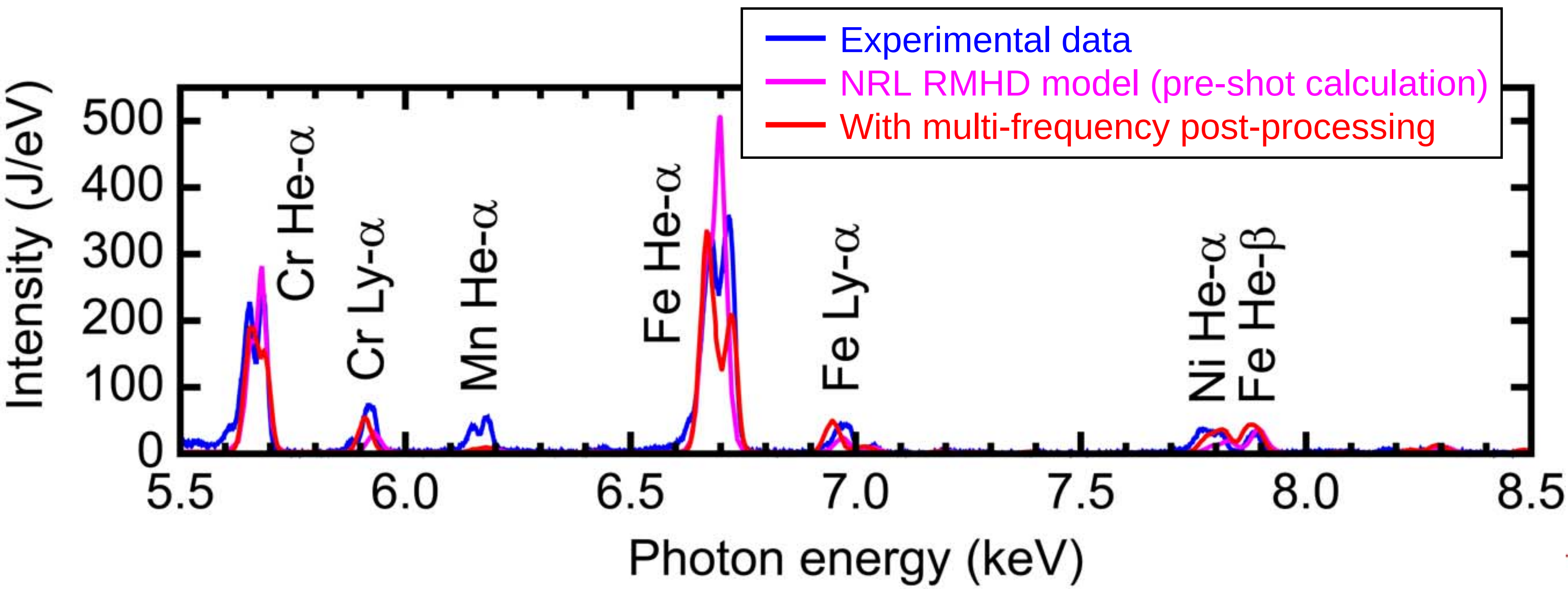

z1860

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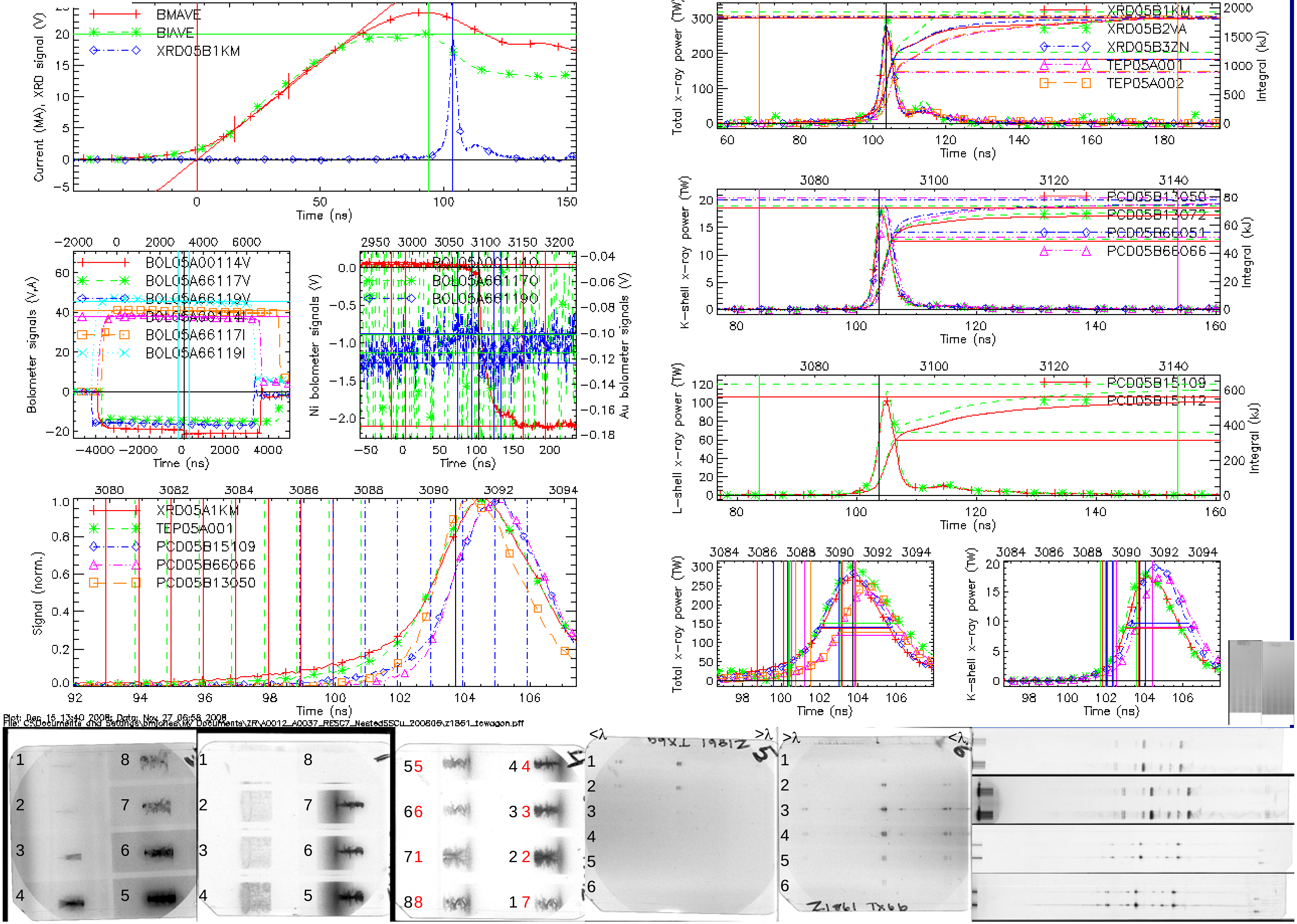
z1861

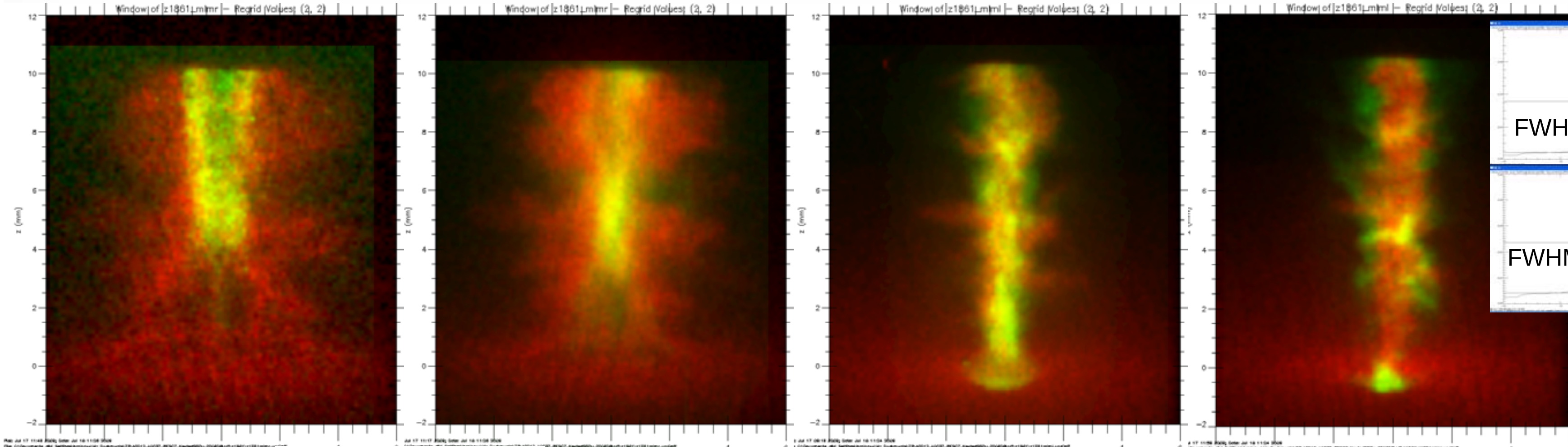


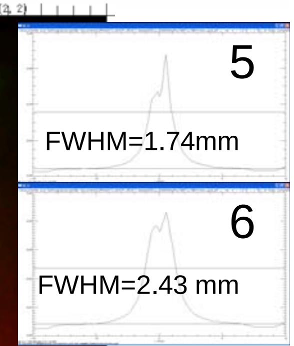
BMAVE
BIAVE
XRD05B1KM
Current (MA), XRD signal (V)
Time (ns)
XRD05B1KM
XRD05B2VA
XRD05B3ZN
TEP05A001
TEP05A002
Total x-ray power (TW)
Integral (kJ)
PCD05B13050
PCD05B13072
PCD05B66051
PCD05B66066
K-shell x-ray power (TW)
PCD05B15109
PCD05B15112
L-shell x-ray power (TW)
BOL05A00114V
BOL05A66117V
BOL05A66119V
BOL05A66117I
BOL05A66119I
Bolometer signals (V,A)
BOL05A66117O
BOL05A66119O
Ni bolometer signals (V)
Au bolometer signals (V)
XRD05A1KM
TEP05A001
PCD05B15109
PCD05B66066
PCD05B13050
Signal (norm.)
Total x-ray power (TW)
K-shell x-ray power (TW)
Z1861 TX66

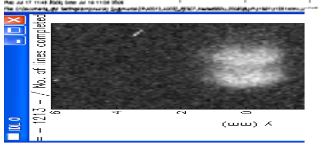
277 eV
~7 keV

Z1861 pinhole camera image overlay

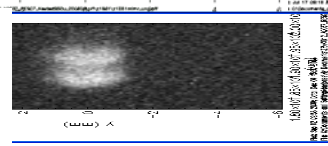
1	2	3	4
z1861MLMRf7MLMCf3.psd	z1861MLMRf2MLMCf4.psd	z1861MLMLf6MLMCf5.psd	z1861MLMLf7MLMCf6.psd
MLMCf3 -4.93 ns	MLMCf4 -2.96 ns	MLMCf5 -0.80 ns	MLMCf6 +1.03 ns
MLMRf7 -3.62 ns	MLMRf2 -2.80 ns	MLMLf6 -0.62 ns	MLMLf7 +0.38 ns

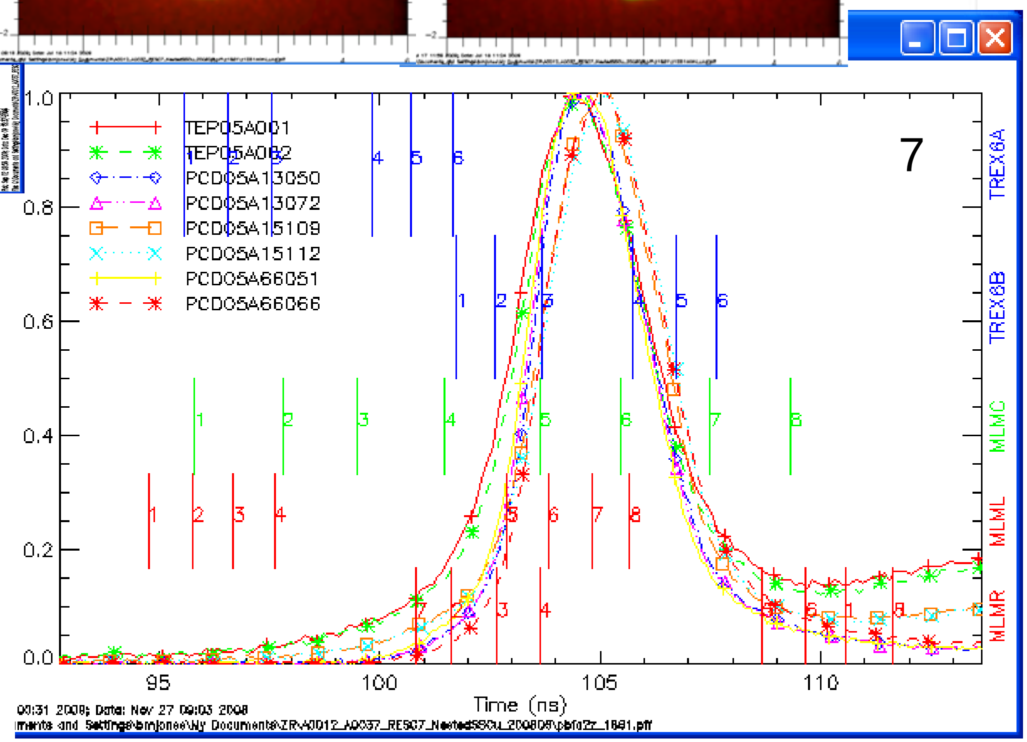






TREX 6A f6
Fe He-a





- **Plot 1: Hollow shell seen during final implosion. Frame times are mismatched by 1.3 ns, but still looks ok. Note that hollow K-shell images suggests that we should be able to see Doppler splitting at this time. TREX 6A f 5-6 maybe has c-shaped lines with red side attenuated. Might have to have much larger gain to see it.**
- **Plot 2: Very good match of 277 eV and K-shell frame timing, Still see hollowness in region nearer anode on both images. Below that, a region with little trailing mass has hit the axis and is generating stronger K-shell emission there. Note cathode zipper too.**
- **Plot 3: Good timing match just before peak x-ray power. There still are some fingers of imploding cooler material; peak x-ray power seems to correspond to when all material has reached the axis. TREX 6B frame 3 should be at this same time. Compare K-shell FWHM to check for timing consistency. No hollowness observed in either TREX or PHC at this time.**
- **Plot 4: K-shell image has similar time to TREX 6B frame 4, which starts to see hollowness. Lineout of K-shell image suggests hollowness (plot 5, 6mm; plot 6, 5 mm above brightest spot) though there is clearly a lot of 3D structure. Apparently larger diameter of K-shell emission than 277 eV may be due to timing mismatch.**
- **Plot 7: Shows timing of MLM and TREX frames relative to x-ray pulse. Could delayed L-shell be real?**

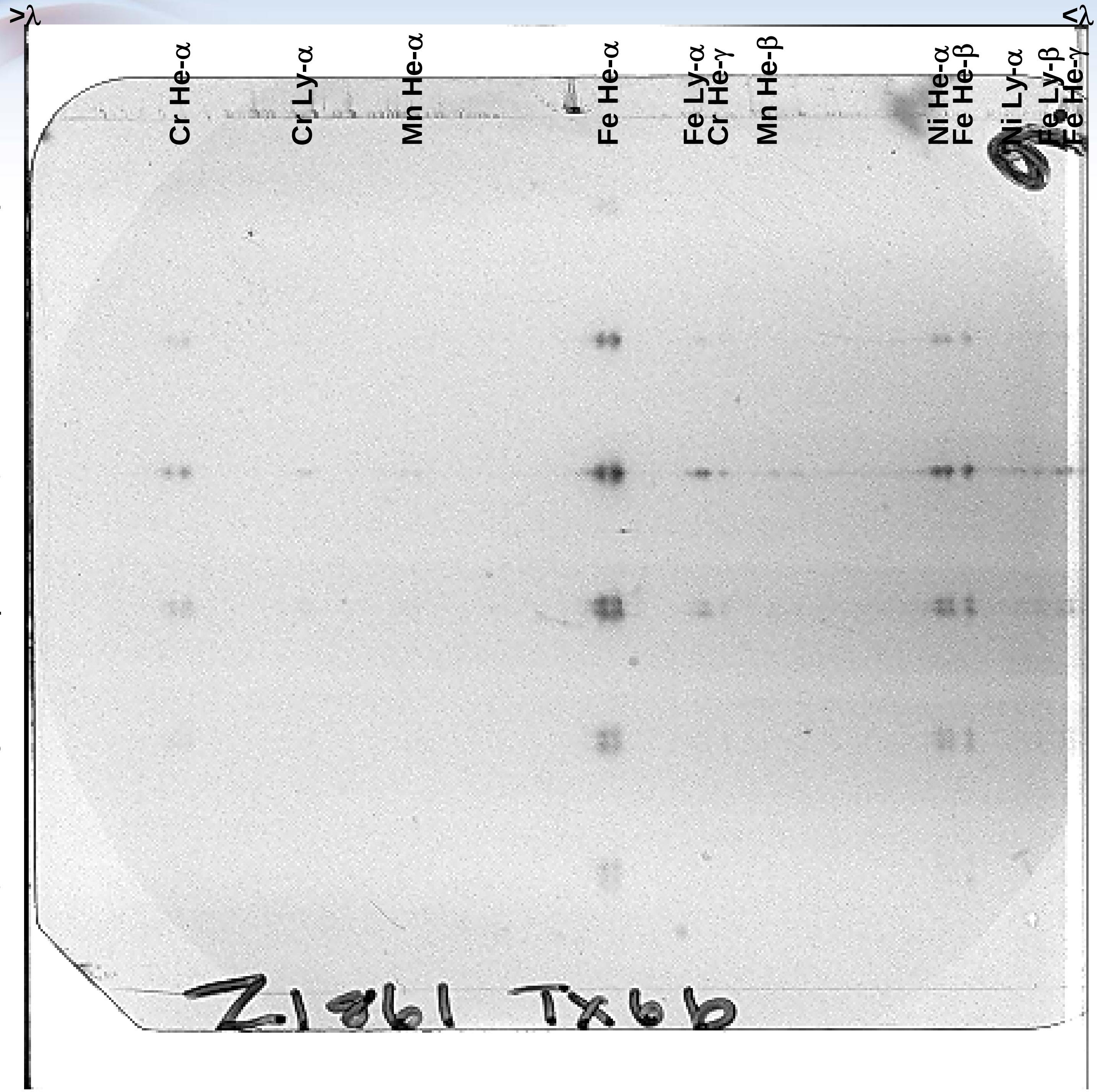
Z1861
65/32.5 mm dia. SS nested, 2.48 mg
TREX 6B

BMAVE=0 extrap. 2987.0 ns

TEP peak 3091.4 ns 104.4 ns

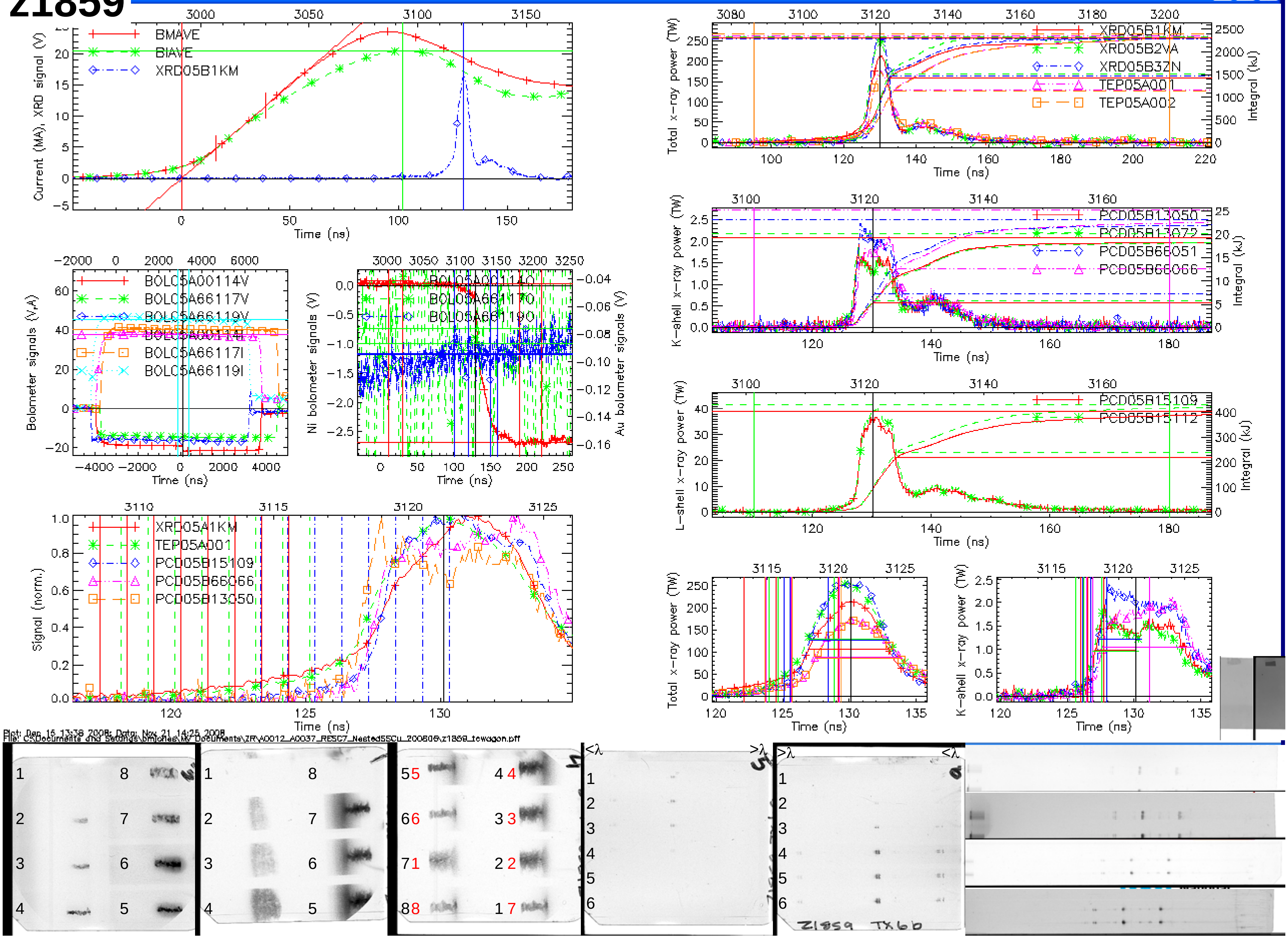
PCD peak 3091.4 ns 104.4 ns

1	3088.7 ns	-2.7 ns
2	3089.6	-1.8
3	3090.6	-0.8
4	3092.7	+1.3
5	3093.7	+2.3
6	3094.6	+3.2



Hollowness appears after peak x-ray power. Brightest continuum at peak power.

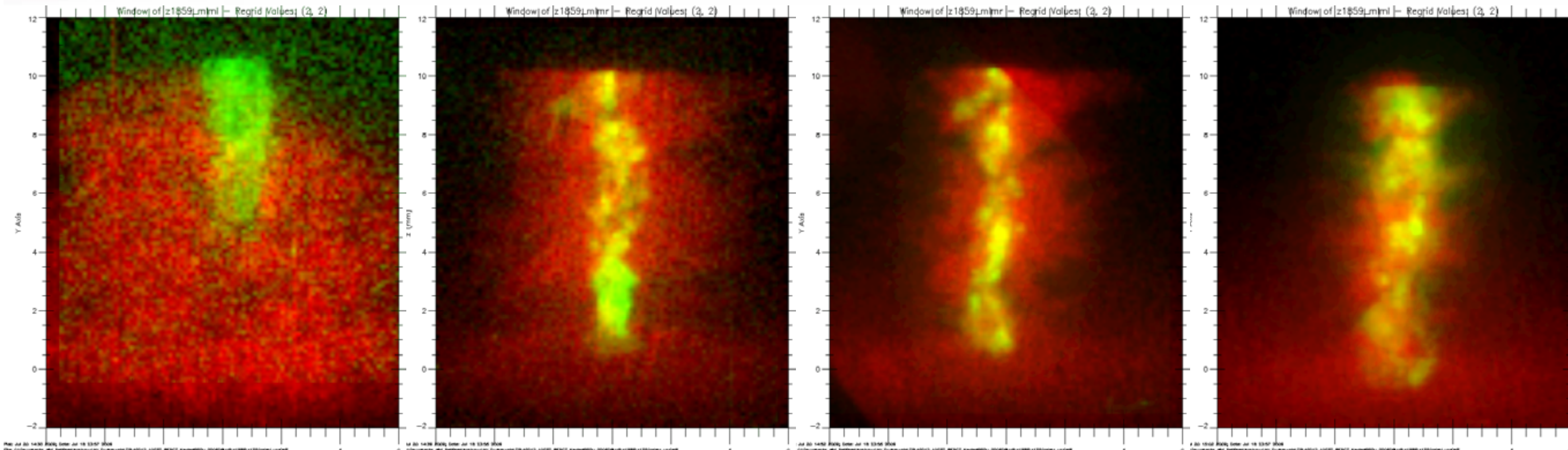
z1859


BMAVE
BIAVE
XRD05B1KM
Current (MA), XRD signal (V)
Time (ns)
BOLC5A00114V
BOLC5A66117V
BOLC5A66119V
BOLC5A00114I
BOLC5A66117I
BOLC5A66119I
Bolometer signals (V,A)
Time (ns)
BOLC5A00114O
BOLC5A66117O
BOLC5A66119O
Ni bolometer signals (V)
Au bolometer signals (V)
Time (ns)
XRD05A1KM
TEP05A001
PCD05B15109
PCD05B66066
PCD05B13050
Signal (norm.)
Time (ns)
XRD05B1KM
XRD05B2VA
XRD05B3ZN
TEP05A001
TEP05A002
Total x-ray power (TW)
Integral (kJ)
Time (ns)
PCD05B13050
PCD05B13072
PCD05B66051
PCD05B66066
K-shell x-ray power (TW)
Integral (kJ)
Time (ns)
PCD05B15109
PCD05B15112
L-shell x-ray power (TW)
Integral (kJ)
Time (ns)
Total x-ray power (TW)
Time (ns)
K-shell x-ray power (TW)
Time (ns)
Plot: Dec 15 13:38 2008; Data: Nov 21 14:25 2008
Z1859 TX6b

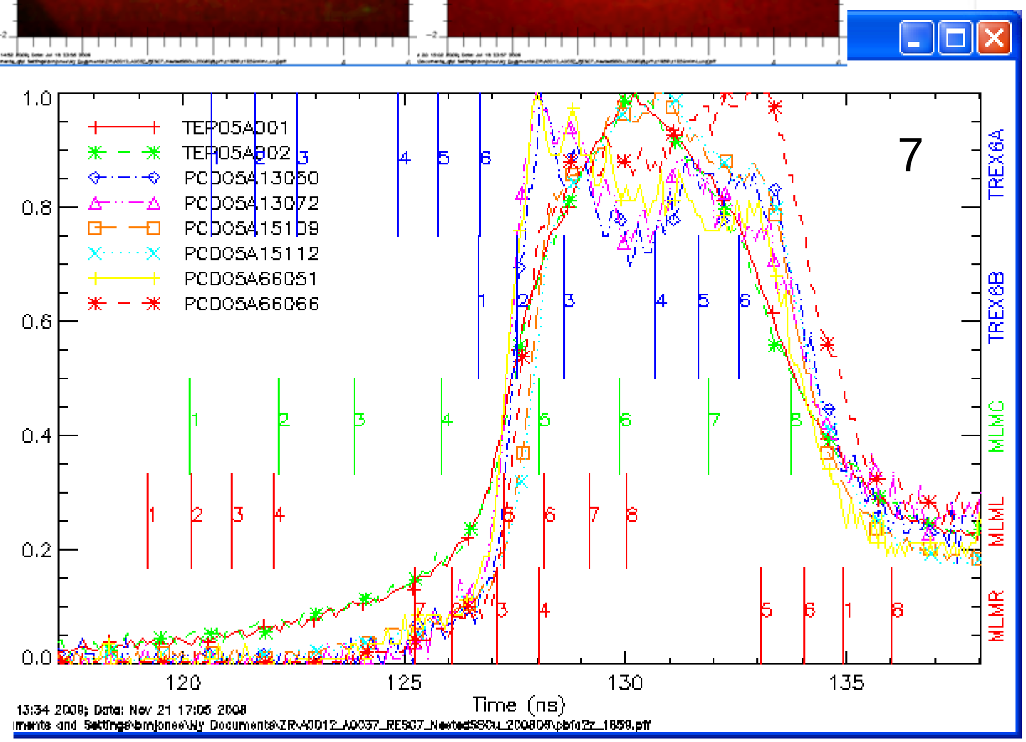
277 eV
~7 keV

Z1859 pinhole camera image overlay

1	2	3	4
z1859MLMLf4MLMCf2.psd	z1859MLMRf2MLMCf4.psd	z1859MLMRf4MLMCf5.psd	z1859MLMLf7MLMCf6.psd
MLMCf2 -8.06 ns	MLMCf4 -4.38 ns	MLMCf5 -2.15 ns	MLMCf6 -0.32 ns
MLMRf4 -8.16 ns	MLMRf2 -4.14 ns	MLMRf4 -2.16 ns	MLMLf7 -1.04 ns

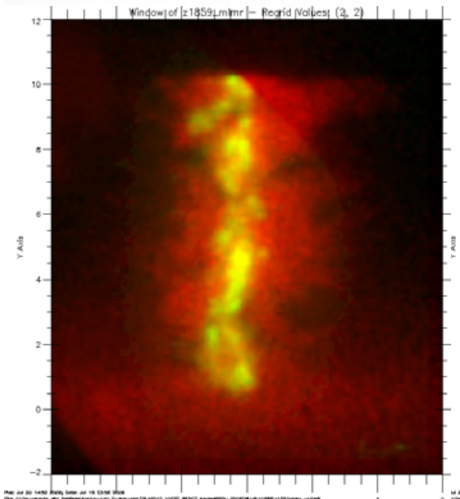


- **Plot 1: Hollow shell not obvious for very early frame; maybe it is but signal to noise is low. 277 eV image may be occulted, and K-shell image alignment is a guess. This is very dim and could be precursor emission; it is larger diameter than next few frames.**
- **Plot 2: K-shell excited on axis; no hollowness; small diameter; bright spots. Maybe cathode early pinch.**
- **Plot 3: K-shell excited on axis; no hollowness, small diameter, bright spots. Note that K-shell image shows dim emission out to radius of 277 eV; could be scattering. K-shell image alignment could be low ~0.5 mm due to parallax.**
- **Plot 4: This may be the point at which opacity becomes significant and clouds of cooler material are blocking K-shell emission from the core. This is first K-shell PHC frame after peak K-shell power, which might be when plasma becomes opaque to some K photons. TREX 6B f3 at -1.6 ns starts to see C shapes. Neither MLM nor TREX looks hollow yet. K-shell core size may be larger, mass accretion in the core.**

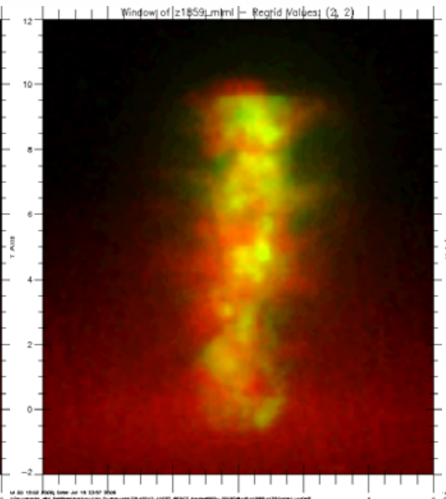


Z1859 pinhole camera image overlay

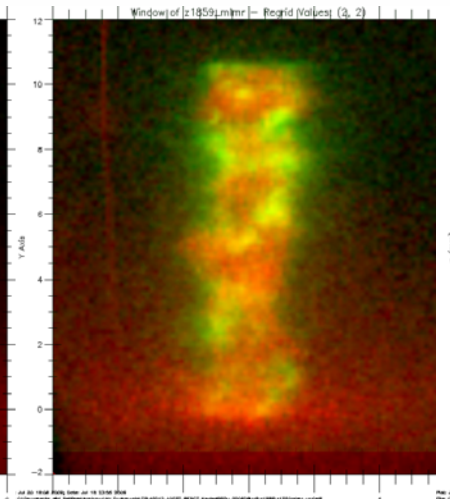
3
z1859MLMRf4MLMCf5.psd
MLMCf5 -2.15 ns
MLMRf4 -2.16 ns



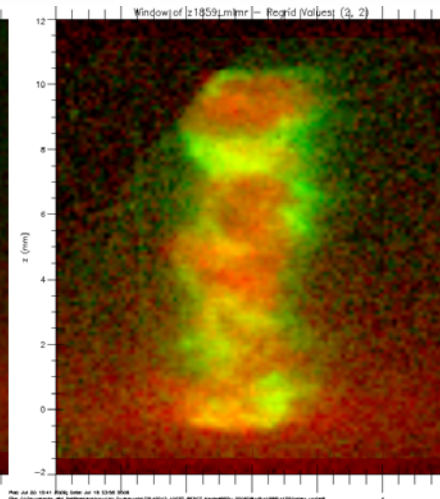
4
z1859MLMLf7MLMCf6.psd
MLMCf6 -0.32 ns
MLMLf7 -1.04 ns

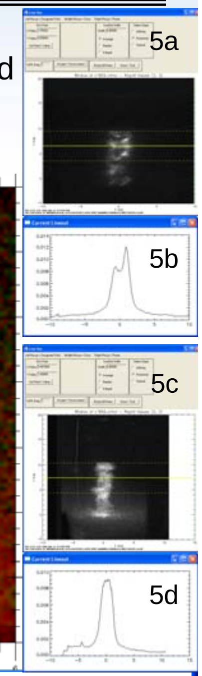


5
z1859MLMRf5MLMCf7.psd
MLMCf7 +1.69 ns
MLMRf5 +2.86 ns

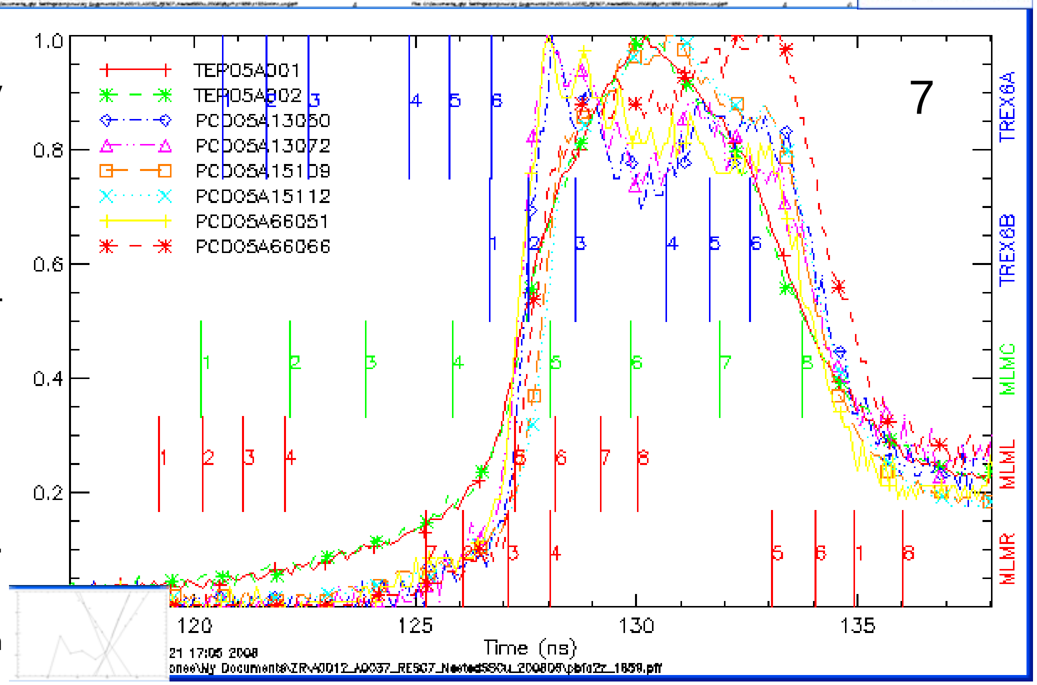


6
z1859MLMRf6MLMCf8.psd
MLMCf8 +3.52 ns
MLMRf6 +3.84 ns





- Plots 3-4: Same as on last page.
- Plot 5: Timing mismatch to nearest 277 eV frame, but K-shell frame clearly shows hollowness particularly in upper 6 mm which is viewed by PCDs and TREX (5a-b shows K-shell lineout). TREX 6B f4 at +0.4 ns is the first TREX frame from this shot to show hollowness. Compare PHC and TREX lineouts once TREX is processed. Looks like pinch is expanding compared to previous frame; could be mass accretion or instability growth or bounce with cooling in the core. Need to consider carefully whether TREX C-shaped lines are due to expanding plasma or blue absorption in the core with imploding Doppler shifted plasma.
- Plot 6: Could be clouds blocking core; hard to align images. Maybe better to look at K-shell image separately. K-shell looks larger diameter; could be timing mismatch. Hollowness? TREX 6B f6 at +2.3 ns looks like hollowness is going away in favor of more complex asymmetries. Pinch is expanding with growing instabilities. Presence of arcs viewed at 12 degrees in plots 5-6 implies K-shell opacity. Flat top of 277 eV lineout near peak x-rays (5c-d) implies opacity (surface radiator with photosurface) at 277 eV photon energy.
- Plot 7: Timing plot.
- Linear fit to FWHM/2 of MLML/R suggests implosion velocity of 21-33 cm/um. This is rough, by hand. Need to do more carefully and document.
- Linear fit to FWHM/2 of MLMCf6-8 gives 34 cm/us expansion velocity. Linear fit to FWHM/2 of MLMRf5,6,1,8 gives 21 cm/us expansion velocity. Is this a real expansion velocity due to a bounce, or the phase velocity of the accretion front? Is the velocity consistent with TREX Doppler effect in C-shaped lines?



Z1859

65/32.5 mm dia. SS nested, 4.96 mg

TREX 6B

BMAVE=0

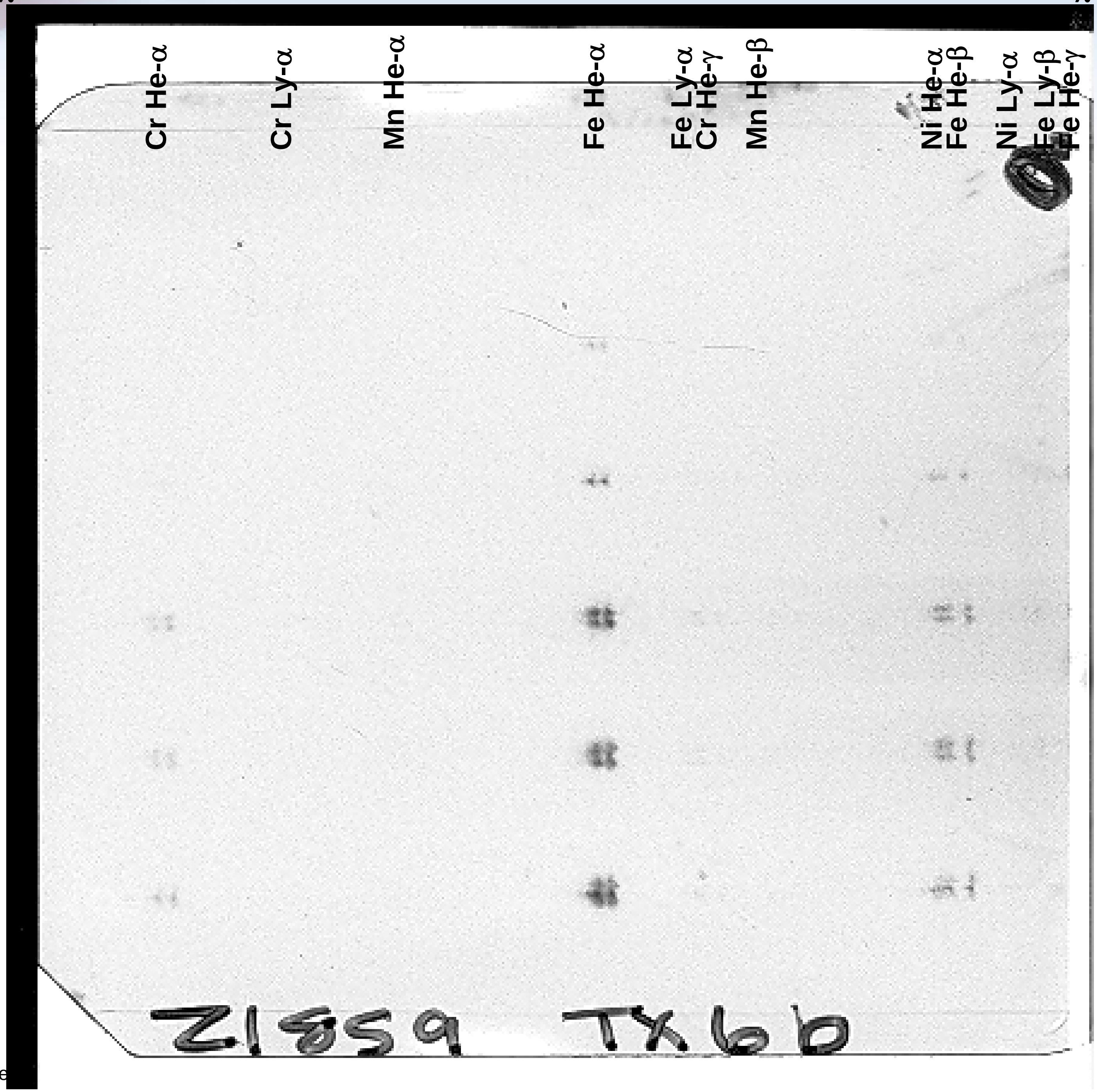
extrap. 2991.2 ns

TEP peak 3121.4 ns 130.2 ns

PCD peak 3119.2 ns 128.0 ns

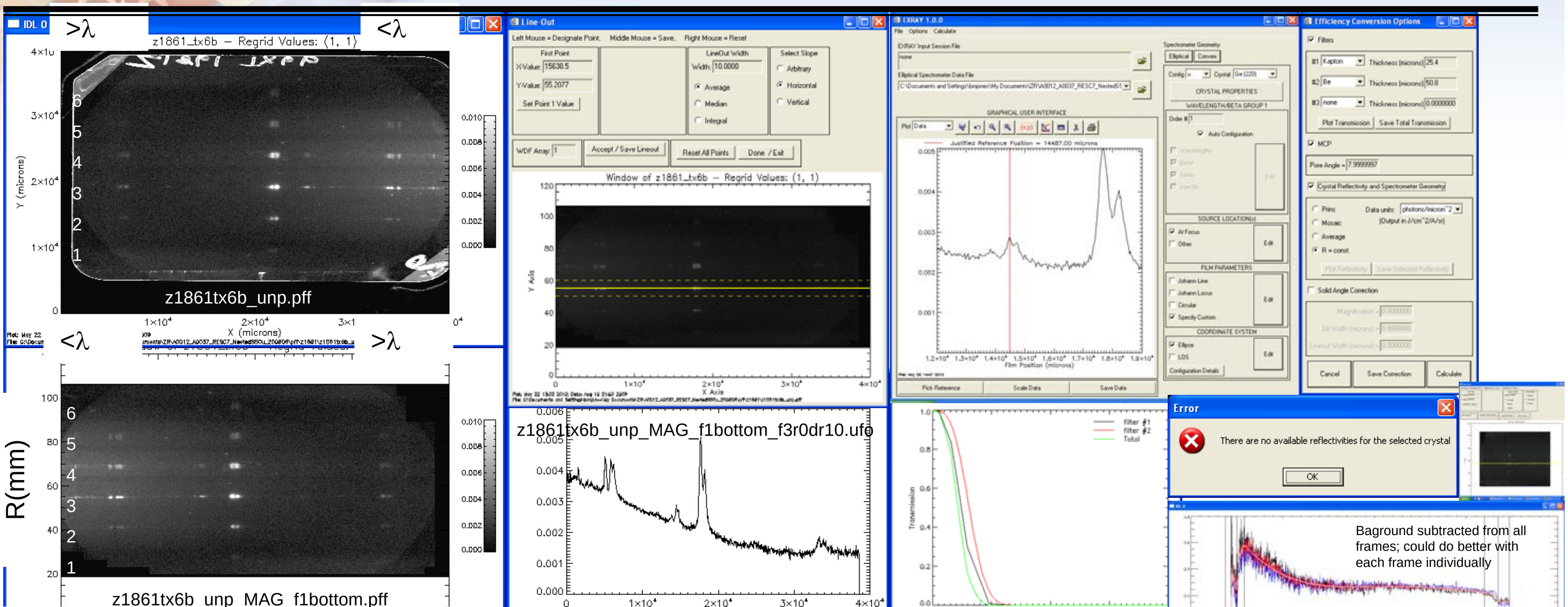
3117.8 ns	**-3.5 ns**	**1**
3118.7	**-2.6**	**2**
3119.8	**-1.6**	**3**
3121.8	**+0.5**	**4**
3122.8	**+1.4**	**5**
3123.8	**+2.4**	**6**

>λ **<λ**

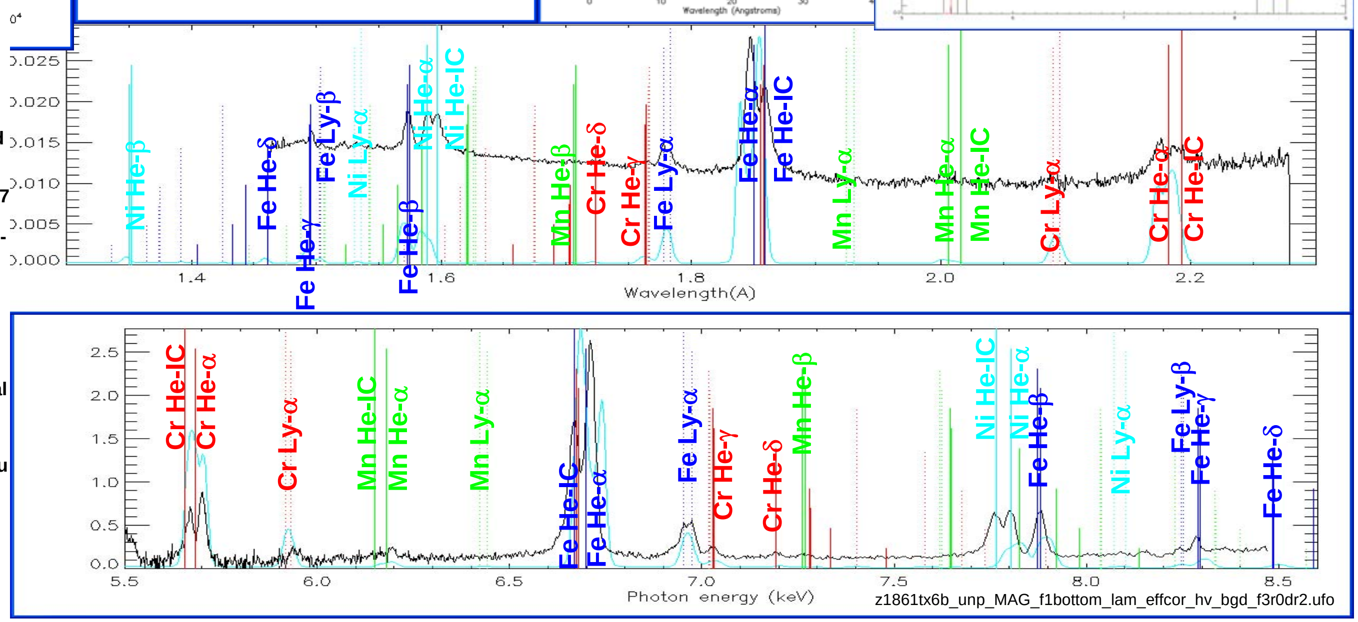


PCD power peaks earlier than total power—real? Hollowness appears after peak x-ray power. All lines appear C-shaped after peak power, blue side attenuated. Could be: Emitting region is accretion front which has radially inward velocity even as pinch size grows, emission from far side absorbed in core

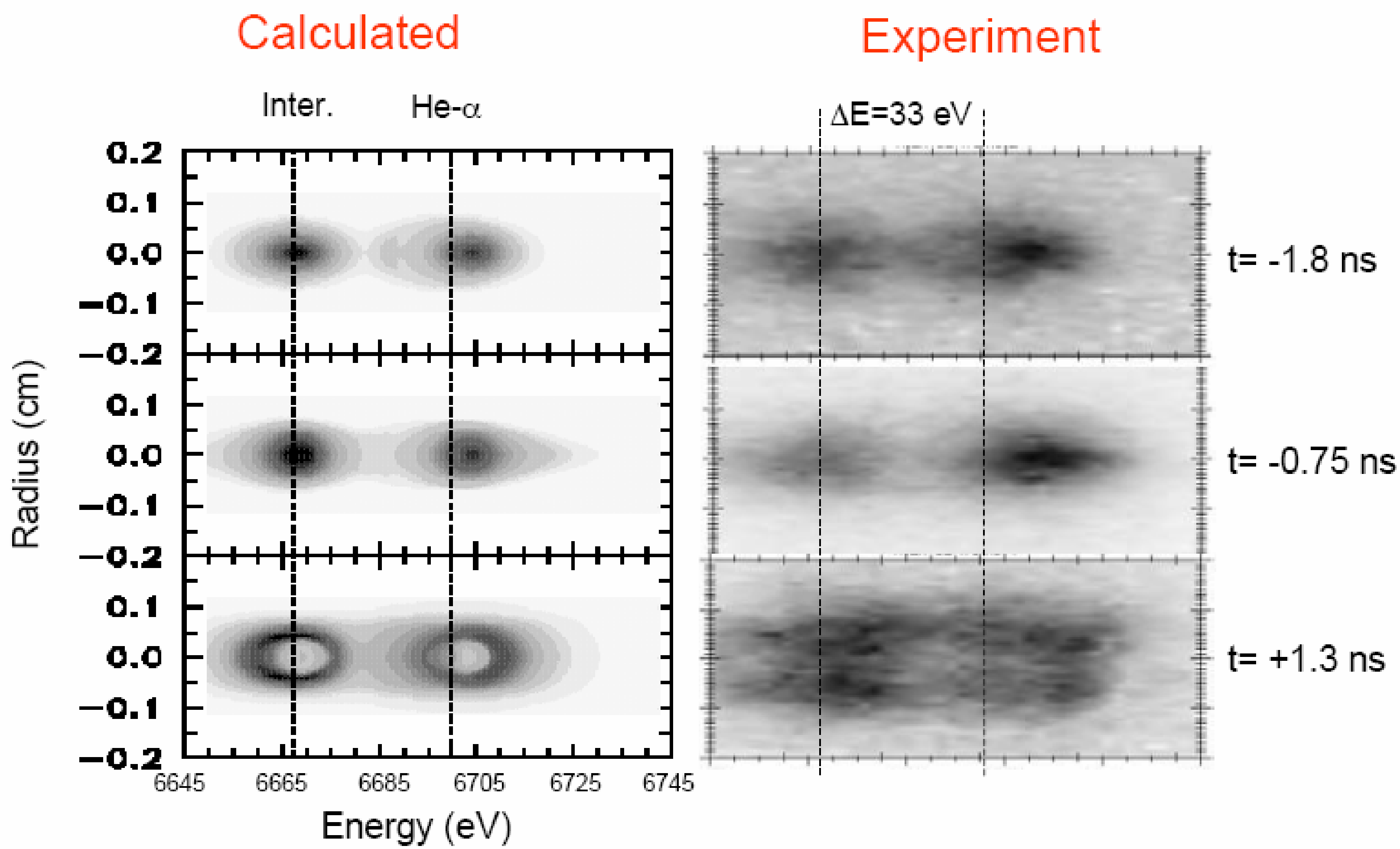
Z1861 TREX 6B, ellipse_u Ge 220, SS K-shell, film processing



- Process entire film at once
- Converted from OD to exposure, saved as z1861tx6b_unp.pff
- MAG=0.347 correction applied, R (mm), saved as z1861tx6b_unp_MAG_f1bottom.pff
- Exposure < 1 so data should be ok
- Lineout over frame 3 image, r=0, dr=10mm, for EXRAY dispersion axis assignment for entire film. No skew removed here, lineout location is through r=0 by eye. Saved as z1861tx6b_unp_MAG_f1bottom_f3r0dr10.ufo
- EXRAY: Pick reference: Fe Ly-a,1.77804 Å, film position 14487 um
- Detector radius 8.00; this is to match Fe He-b, Fe He-g, Cr He-b, maybe other wavelengths; saved as z1861tx6b_unp_MAG_f1bottom_f3r0dr10_lam.ufo; z1861tx6b_unp_MAG_f1bottom_lam.pff
- Efficiency correction (filter 1 mil Kapton+2 mils Be, MCP, geom, NO AVAILABLE XTL REFLECTIVITY), saved as z1861tx6b_unp_MAG_f1bottom_f3r0dr10_lam_effcor.ufo; z1861tx6b_unp_MAG_f1bottom_lam_effcor.pff
- @z1861_tx6b_hv20100424.pro; Convert to hv, subtract typical background saved as z1861tx6b_unp_MAG_f1bottom_lam_effcor_hv_bgd.pff
- Took lineout by hand centered on frame 3 and saved z1861tx6b_unp_MAG_f1bottom_lam_effcor_hv_bgd_f3r0dr2.ufo, plotted at bottom with @z1861_tx6af3byhand_lambdacheck_hv20090827.pro



Comparison of synthetic and experimental Fe Spectra for ZR#1861



"t=0 ns" corresponds to the time of peak K-shell power

- J. W. Thornhill *et al.*, ICOPS 2010 poster.
- Caveat: Need to assess error bar on assigning dispersion axis to determine whether we can really claim there is absorption of line on red side.

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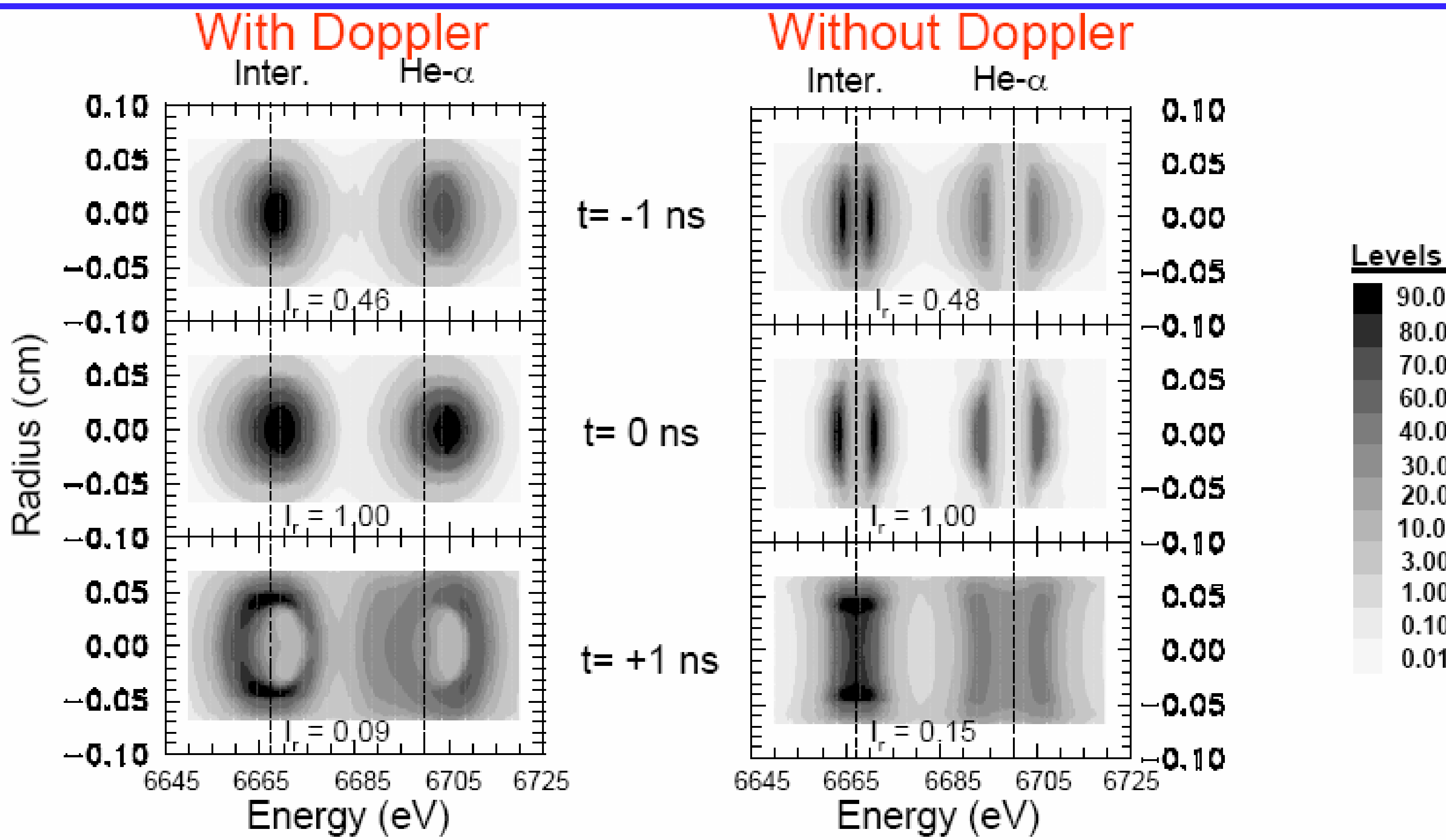
Inclusion of Doppler shifts dramatically alters synthetic spectra

Fe ZR#1861



I_r is the intensity divided by the peak intensity at t = 0 ns

- **J. W. Thornhill *et al.*, ICOPS 2010 poster.**

Larger diameter (80 mm) nested Cu wire array had reduced yield, less uniform implosion

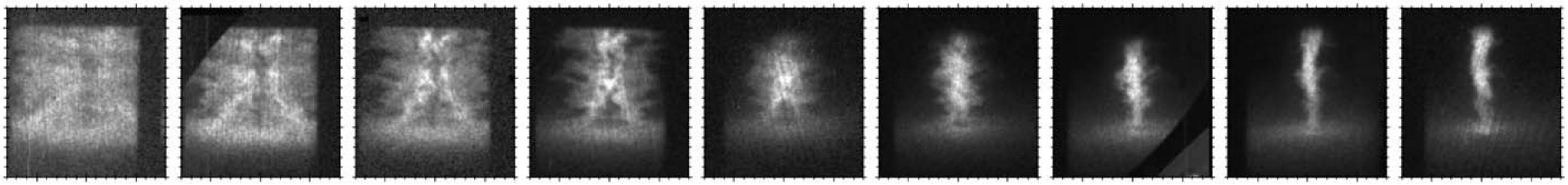
B. Jones *et al.*, *ICOPS 2009.*

	K-shell		Total radiation	
Diameter (mm)	**Power (TW)**	**Yield (kJ)**	**Power (TW)**	**Yield (kJ)**
65	**5.3**	**28.5**	**210**	**1950**
80	**1.9**	**9.6**	**150**	**1980**

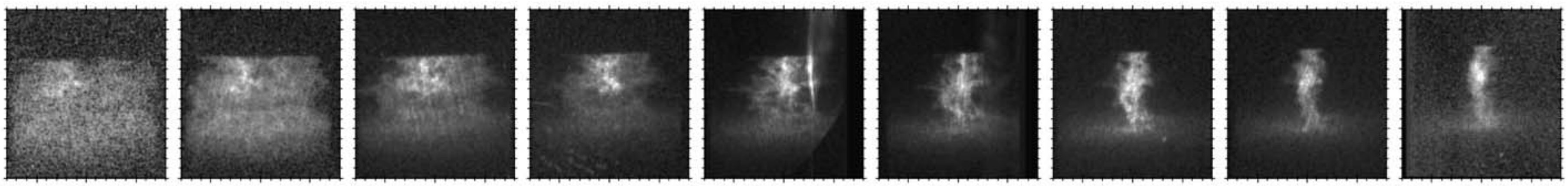
65 mm diameter nested Cu, 2.5 mg, **z1862**

-8 ns -7 ns -6 ns -5 ns -4 ns -3 ns -2 ns -1 ns 0 ns

277 eV



277 eV



80 mm diameter nested Cu, 2.5 mg, **z1866**

- **Large diameter wire arrays with large interwire gaps may suffer from severe magnetic Rayleigh-Taylor instability**
- **3D MHD modeling may help identify nesting geometries with improved MRT mitigation (J. P. Chittenden, C. A. Jennings)**

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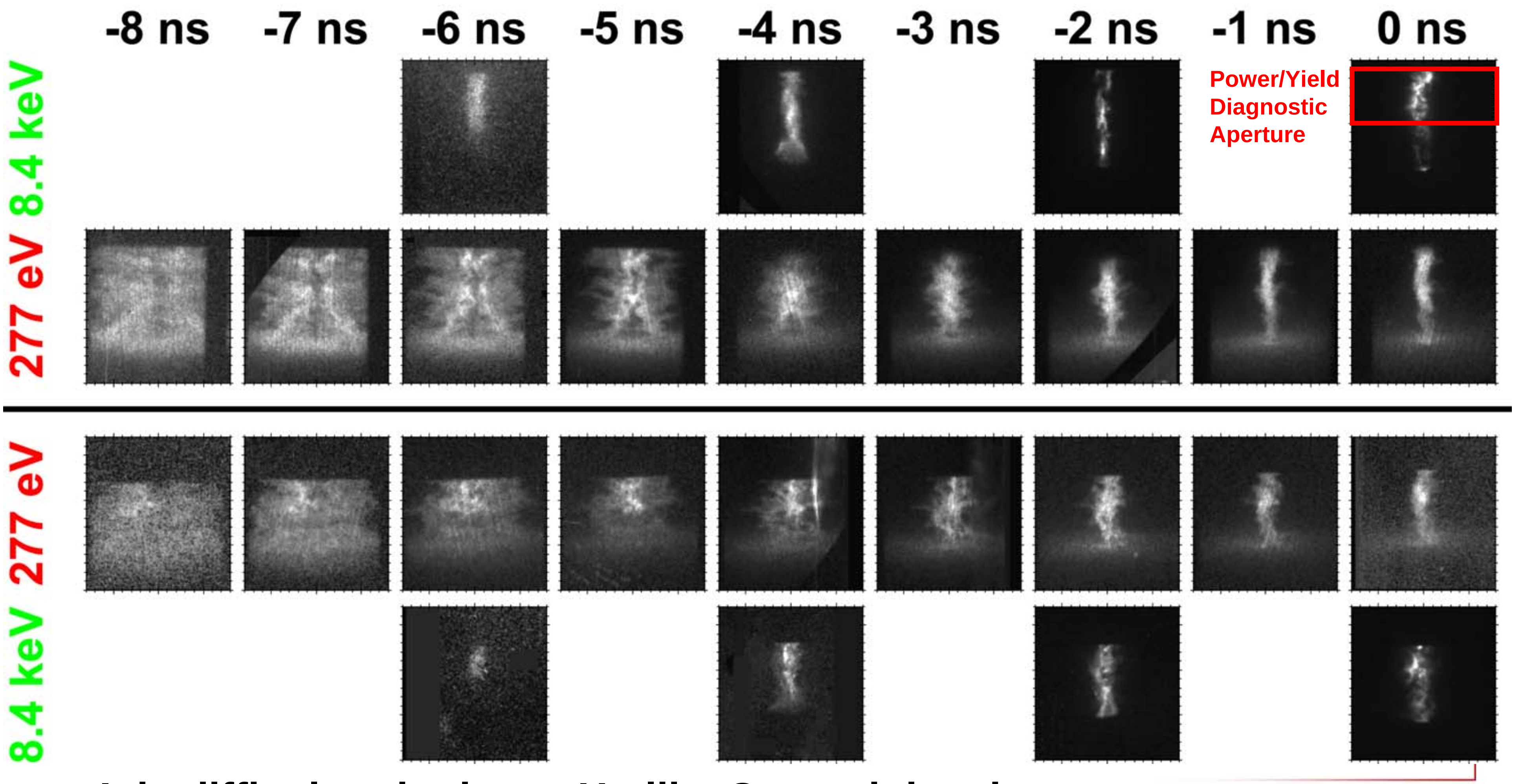
Bright spots may dominate Cu K-shell emission even for the better performing loads

B. Jones *et al.*,
ICOPS 2009.



- It is difficult to ionize to He-like Cu, and the charge state will be sensitive to local plasma conditions

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4/1/2009-5/1/2009, Z1905-1920, A0046 shot overview

Shot	A #	Wire mater-ial	Array dia. (mm)	Wire #	Wire dia. (um)	Array mass (mg/cm)	Cath. Step (mm)	Total yield (MJ)	K yield (kJ)	K-shell 10-90% rise (ns)
z1905	A0046-A	Cu	65/32.5	112/56	11.43	1.53	2x2	2.2	12±2	3.1±0.7
z1906	A0046-B	Cu	65/32.5	88/44	10.26	0.97	2x2	1.5	6±2	2.4±0.2
z1919[†]	A0046-C	Cu	65/32.5	88/44	11.43	1.20	2x2	1.8	16±4	2.46±0.06
z1920	A0046-D	Cu	65/32.5	88/44	11.43	1.20	2x2	1.9	14±4	4.2±0.1

* <5% correction for K-shell axial structure (TIXTL)
[†] Scalloped middle anode to lengthen magnetic nulls

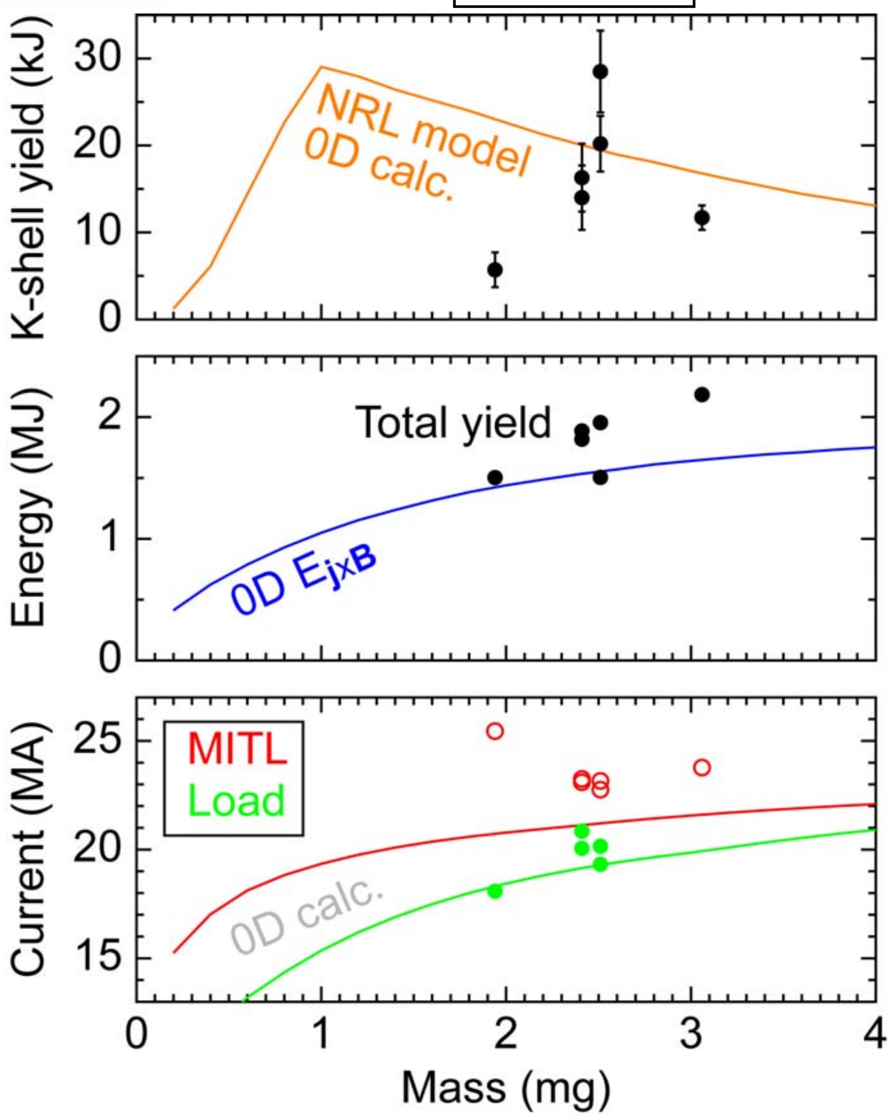
- **Goals:**
  - **Cu mass scan for 65 mm nested arrays**
  - **Start to study Cu L-shell (TIXTL)**
- **All loads 20 mm tall, 82 kV Marx charge, pre-pulse suppression, older feed**

- **Cu had ~4% Ni dopant**
- **TIXTL filter transmission correction assuming all photons at Cu He-α 8.4 keV**

Cu mass scan shows significant deviation between experiment and model at lower mass

B. Jones *et al.*, *ICOPS 2009.*

82 kV



- **Significant shot-to-shot variation is apparent at ~2.5 mg**
  - **May result from bright spot emission of Cu K-shell x-rays**
- **Drop in K-shell yield is expected at higher mass due to reduced η and radiative cooling**
- **Drop in K-shell yield at lower mass disagrees with scaling model**
  - **Seen also with SS loads pre-refurbishment, but less severe**
- **Convolute losses are large**
- **Circuit model used for 0D calculations needs improvement**
  - **Comes close on load current but not on MITL current**

This 0D modeling is with constant Zflow; newer AOABL has variable Zflow

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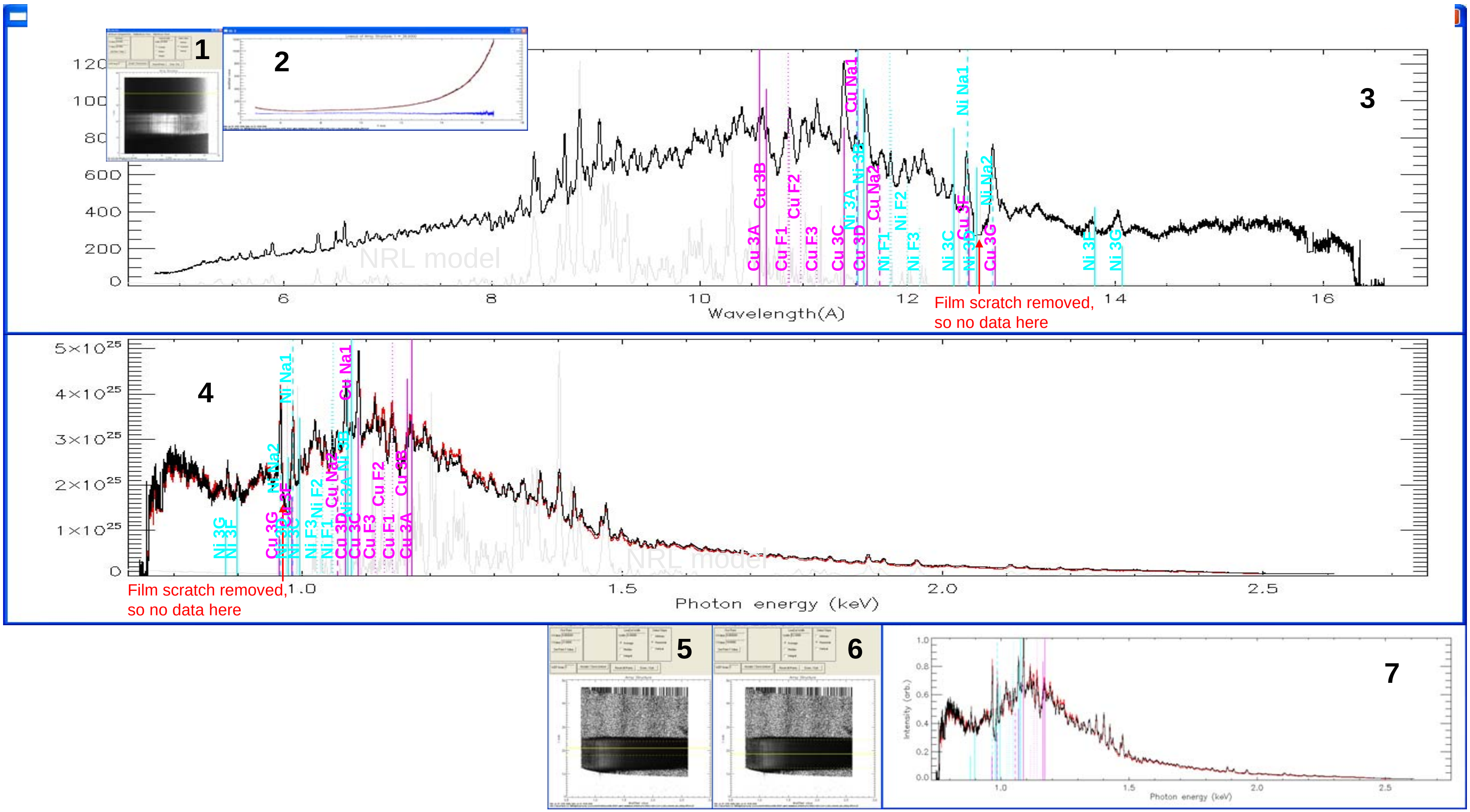
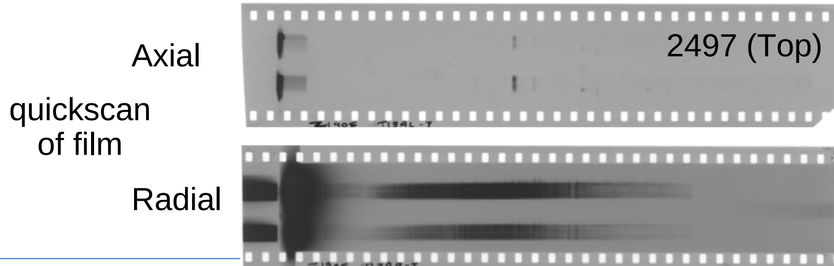
z1905 TIXTL L processing – final

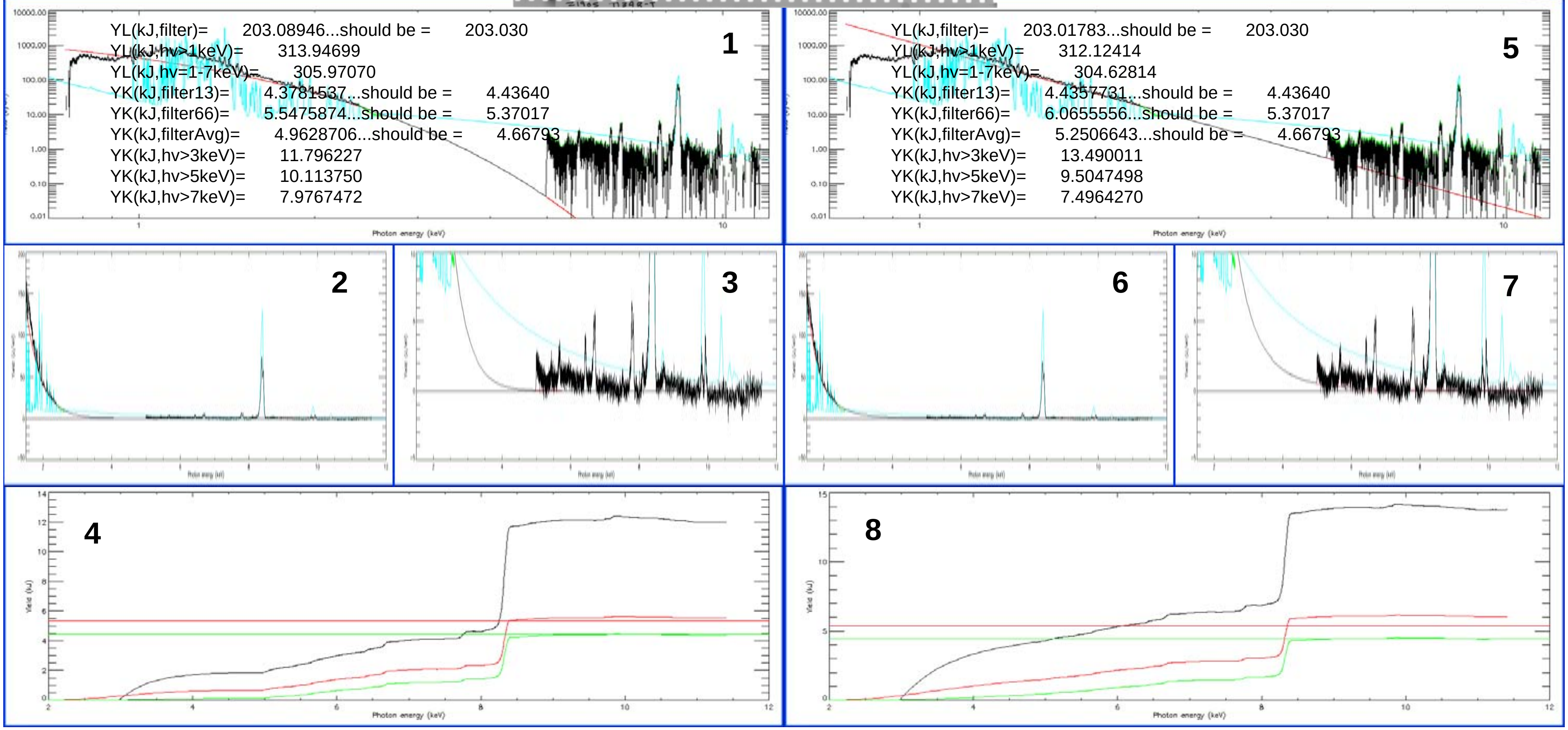
- Plots 1-2: Background subtraction performed using lineout above the image. Saved as z1905_t13ar-t_300_rs_lam_ODe_ec_bg.pff. Also converted to intensity vs. hv including $d\lambda=\lambda^2/hc*dE$ factor, saved as z1905_t13ar-t_300_rs_lam_ODe_ec_bg_hv.pff
- Plot 3: Lineout over 6 mm near anode, saved as z1905_t13ar-t_300umslitprep_rmnlskew_lambda_ODtoExp_EffCorr_bg_z21dz6.ufo. Lineout also taken over full 12 mm pinch height, saved as z1905_t13ar-t_300umslitprep_rmnlskew_lambda_ODtoExp_EffCorr_bg_z18p5dz12.ufo.
- Plot 4: Same lineout converted to spectral intensity (arb. units) vs. photon energy including $d\lambda=\lambda^2/hc*dE$ factor, saved as z1905_t13ar-t_300umslitprep_rmnlskew_lambda_ODtoExp_EffCorr_bg_hv_z21dz6.ufo. Also taken over full pinch height (red curve), saved as z1905_t13ar-t_300umslitprep_rmnlskew_lambda_ODtoExp_EffCorr_bg_hv_z18p5dz12.ufo
- Plots 5-7: Correction factor for axial structure 0.9885 (was 0.9895 with OD background-subtracted prior analysis) calculated by integrating 6 mm aperture (black) and 12 mm full view (red) lineouts. This says that there is much less L-shell structure than K-shell structure.



z1905 TIXTL processing – merge L and K spectra, norm to PCDs

- **Using lineouts that capture the full height of the image in order to include SS K-shell lines near the cathode and see if that makes a significant difference. Still normalizing to PCD yields with axial variation correction (<5%). L-shell fitting for in gap is the same.**
- **Plots 1-4 use exponential, saved as z1905_TIXTLLandKnormPCDBJ20090701exponentialFullHeight.ufo**
- **Plots 5-8 use power law, saved as z1905_TIXTLLandKnormPCDBJ20090701powerlawFullHeight.ufo**
- **There is some funny problem with offsets when including the full height, which leads to negative bias and negative slope in the integrated curves. Problem is not too severe. Still only using lineout above image for zeroed point correction. Problem gets worse if I average in lineout from below image.**





8/21/09-8/26/09, 3/30/10, 6/1/10, Z1975-77, 2080, 2103, A0065, A0118 shot overview

Shot	A #	Wire mater-ial	Array dia. (mm)	Wire #	Wire dia. (um)	Array mass (mg/cm)	Pinch height (mm)	Total yield (MJ)	K yield (kJ)	K-shell 10-90% rise (ns)
z1975	A0065-A	Cu	65/32.5	96/48	11.30	1.28	20	1.9	26±3	3.2±0.2
z1976	A0065-B	Cu	65/32.5	112/56	11.30	1.50	12*	1.6	25‡±6	2.2±0.3
z1977	A0065-D	Cu	65/32.5	96/48	11.30	1.28	12*	1.6	31±4	2.39±0.06
z2080	A0118-A	SS304	70/35	108/54	8.41	0.71	12*	0.8	53±8	1.90±0.08
z2103	A0118-B	SS304	70/35	108/54	7.96	0.64	24†	1.0	77±10	1.93±0.08

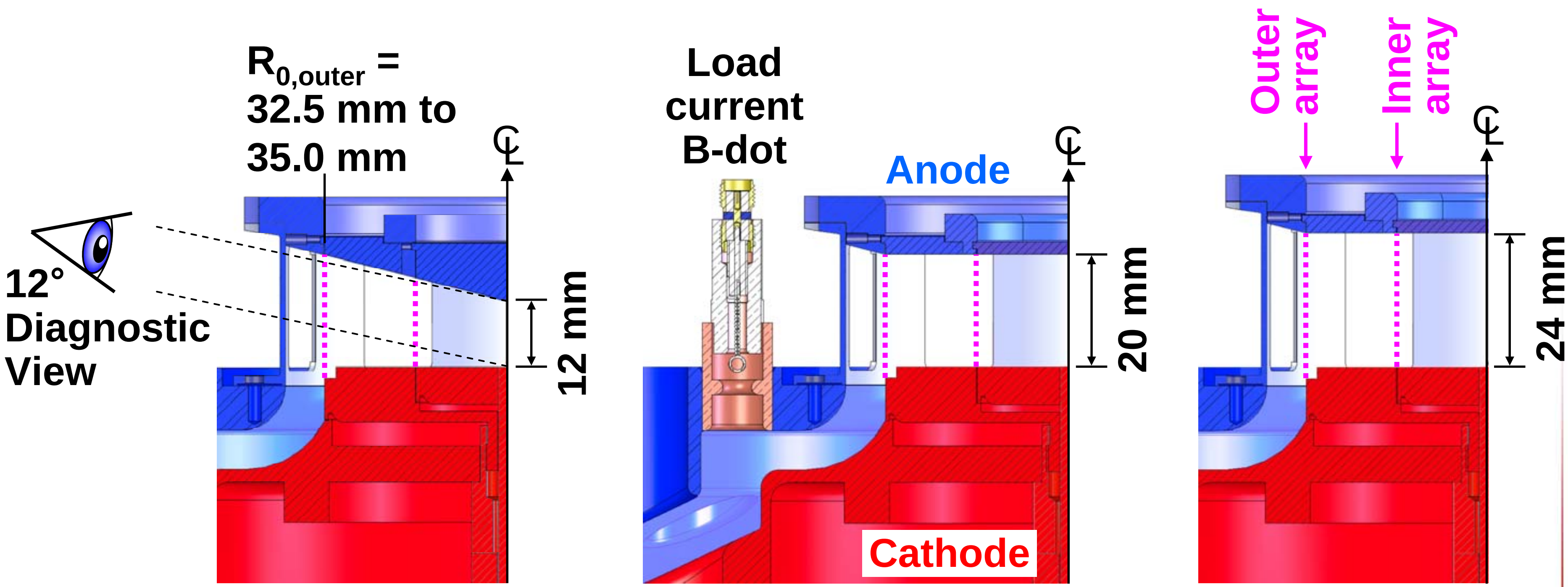
*Angled anode, 20 mm initial outer array height reducing linearly to 12 mm at r=1mm

† 24 mm tall load, flat anode with taller return current can

‡TIXTL not processed

- **Goals:**
  - **Study pinch height variations for Cu and SS loads**
  - **Study gated Cu L-shell (TREX)**
  - **Study SS K-shell side-on vs. end-on (z2081-82, 70/35 mm, 0.7 mg/cm, but good data were not obtained)**
- **All loads 2x2 mm cathode step, 80 kV Marx charge, no pre-pulse suppression, newer feed**
- **Cu had ~4% Ni dopant**
- **All shots except z1976 use TIXTL spectrum to calculate PCD filter transmission/diamond absorption correction (< 10% different than assuming all photons at He-α energy)**
- **Z1975-77, PDI K yields were about 5 kJ lower than PCD yields above**

Z load hardware was modified for 12-24 mm pinch length, with angled anode preserving diagnostic view



- All arrays are nested with 2:1 mass per unit length ratios (outer:inner)
- Ø70 on 35 mm stainless steel wire arrays at 12, 20, 24 mm length
- Ø65 on 32.5 mm Cu (4% Ni) wire arrays at 12, 20 mm length

B. Jones *et al.*,
ICOPS 2010.

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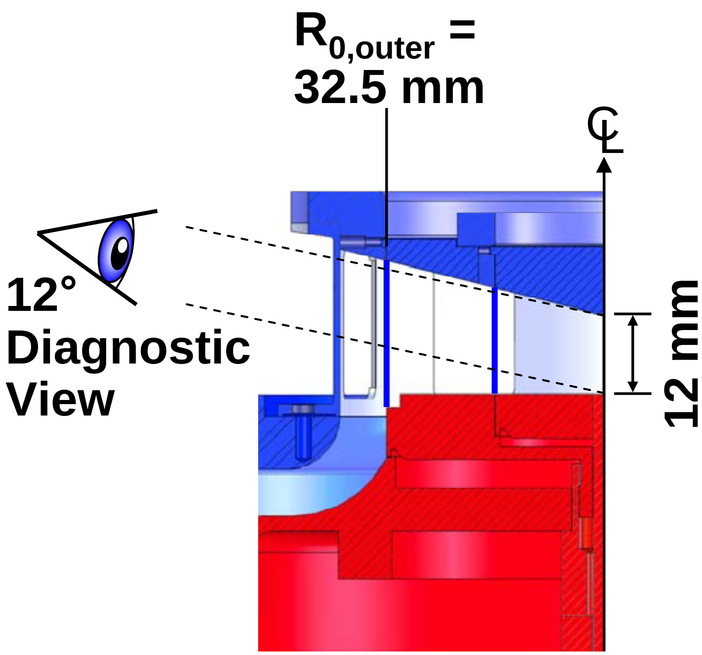
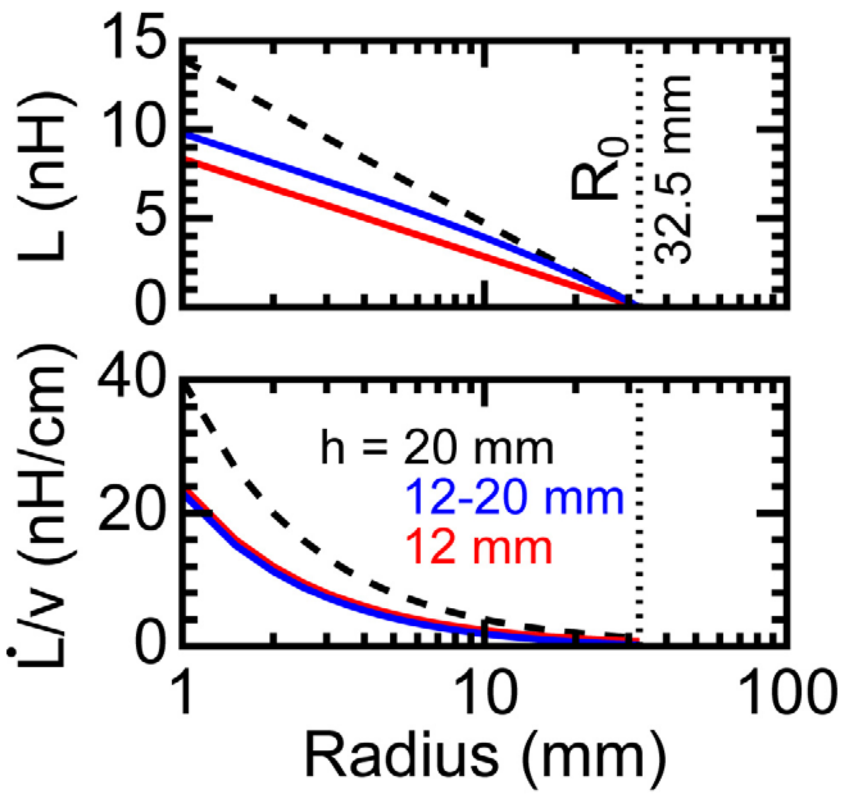
Angled anode lowers inductance, provides nearly identical L-dot to flat anode with reduced AK gap



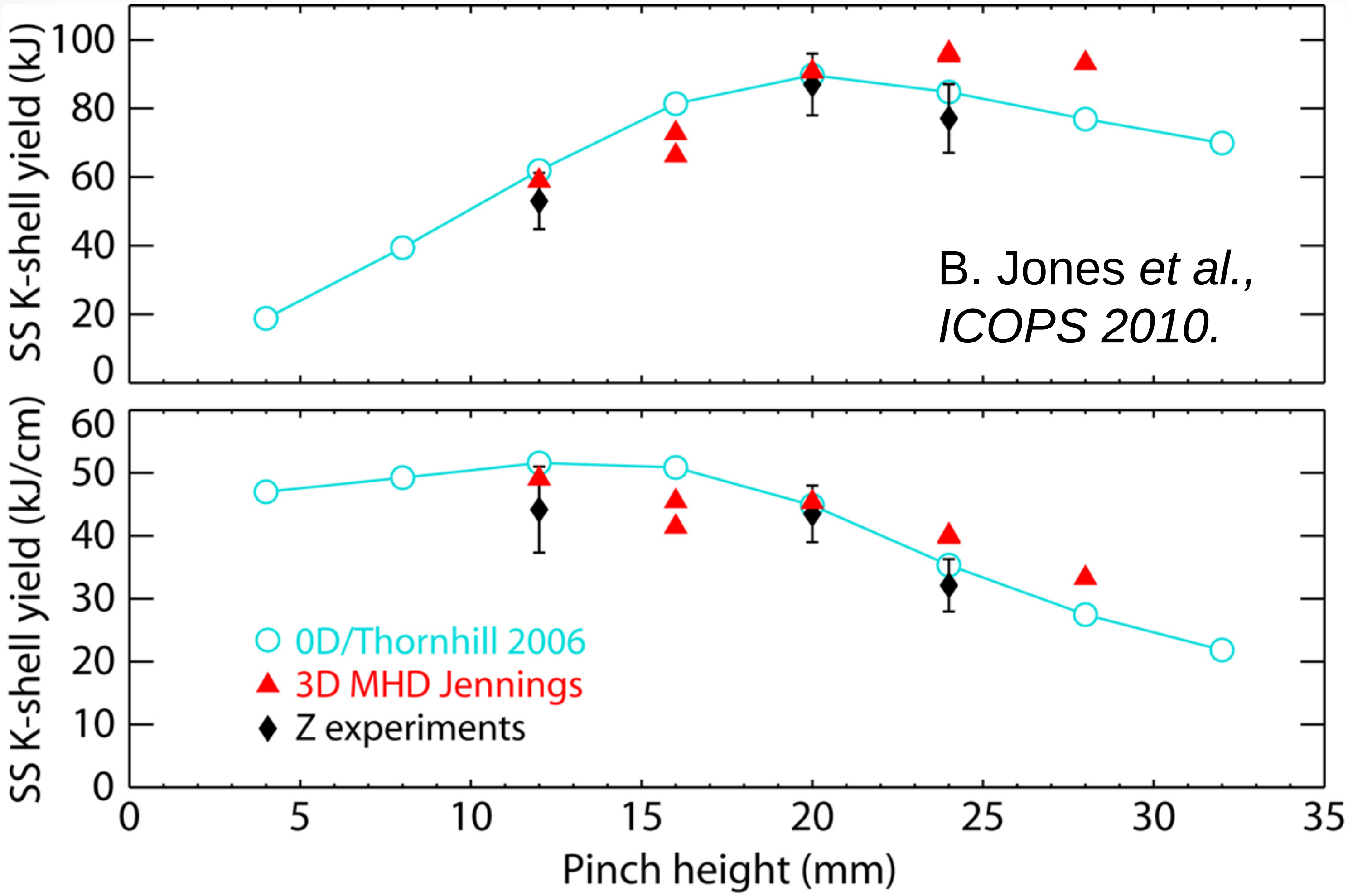


B. Jones *et al.*, *ICOPS 2010.*

$$\frac{dL}{dt} = \frac{dL}{dR}\frac{dR}{dt} = v\frac{dL}{dR}$$

- **Lower L-dot may reduce convolute current loss**

Pre-shot models reasonably predicted trends in SS pinch length variation experiments on Z



- **Waisman 0D model includes angled anode for < 20 mm height**
- **Thornhill** *et al.*, IEEE TPS **34,** 2377 (2006) **K-shell yield model**
- **Jennings 3D MHD Gorgon benchmarked to 20 mm height**

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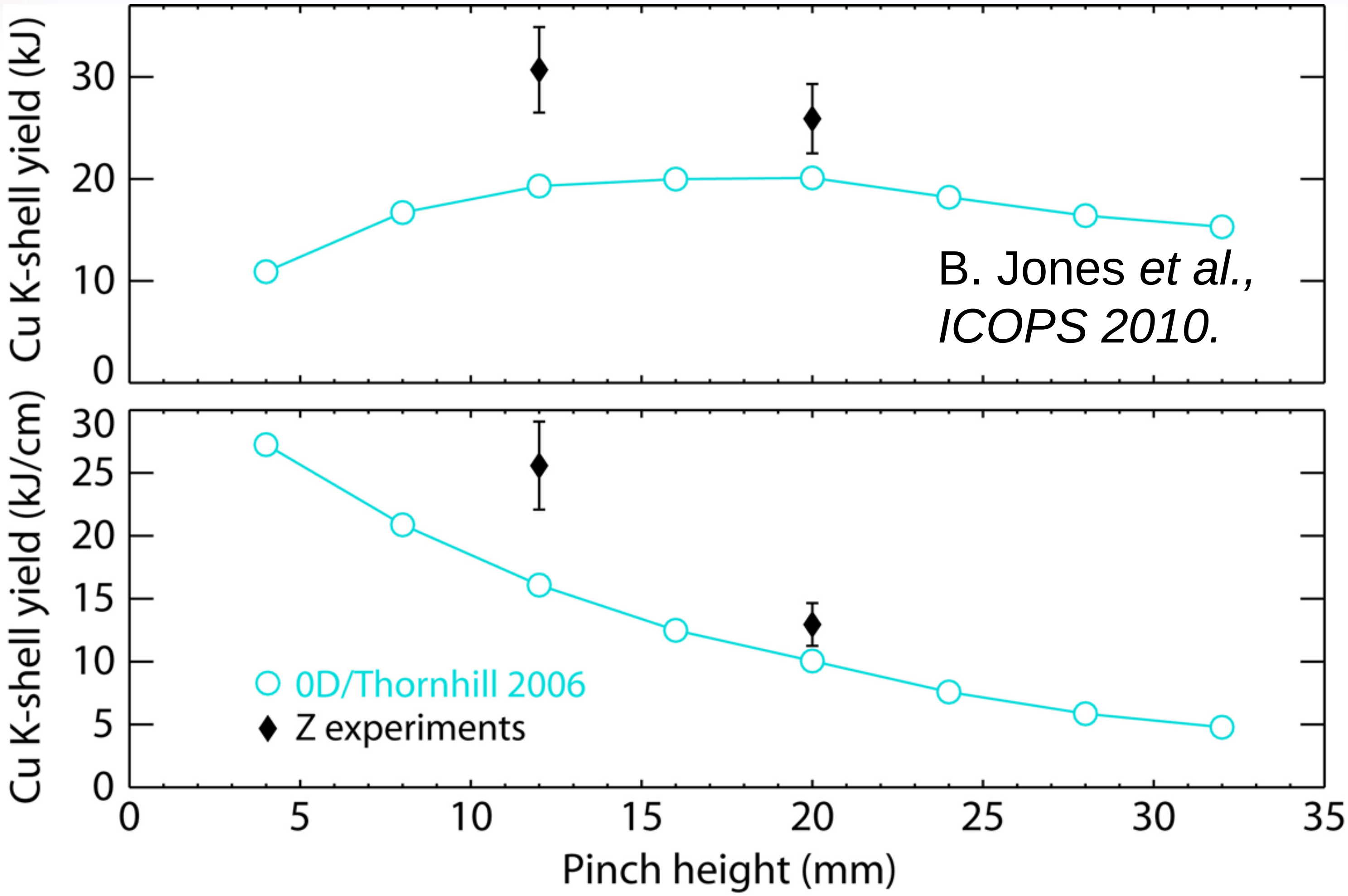
Cu is higher Z, more sensitive to η, benefits more from lower load inductance



- **Waisman 0D model includes angled anode for < 20 mm height**
- **Thornhill** *et al.*, IEEE TPS **34,** 2377 (2006) **K-shell yield model**

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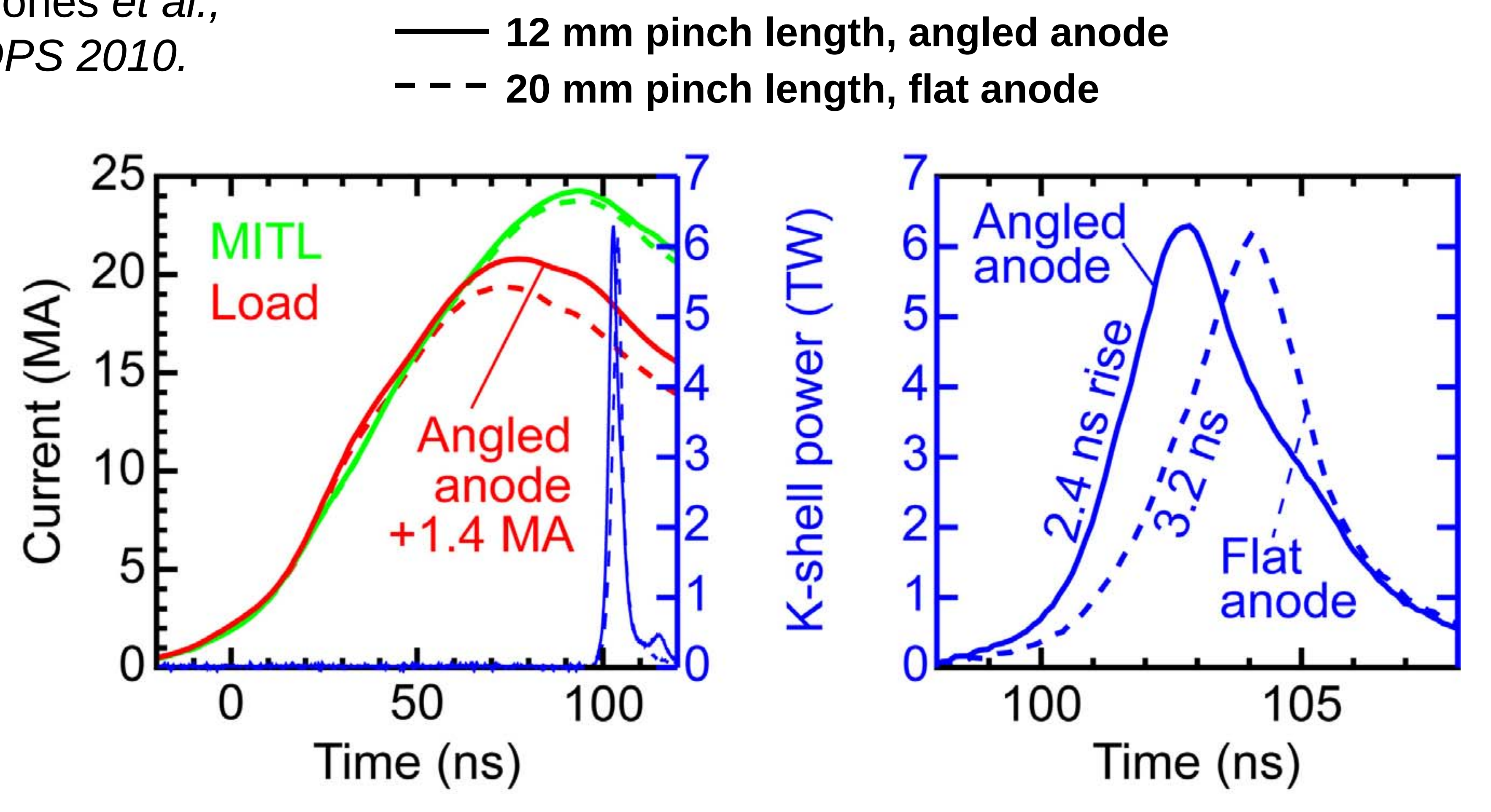
+1.4 MA load current measured for shorter Cu pinch due to reduced inductance at stagnation

B. Jones *et al.*, *ICOPS 2010.*



- **0D model predicted +1.0 MA for 12 mm pinch length vs. 20 mm**

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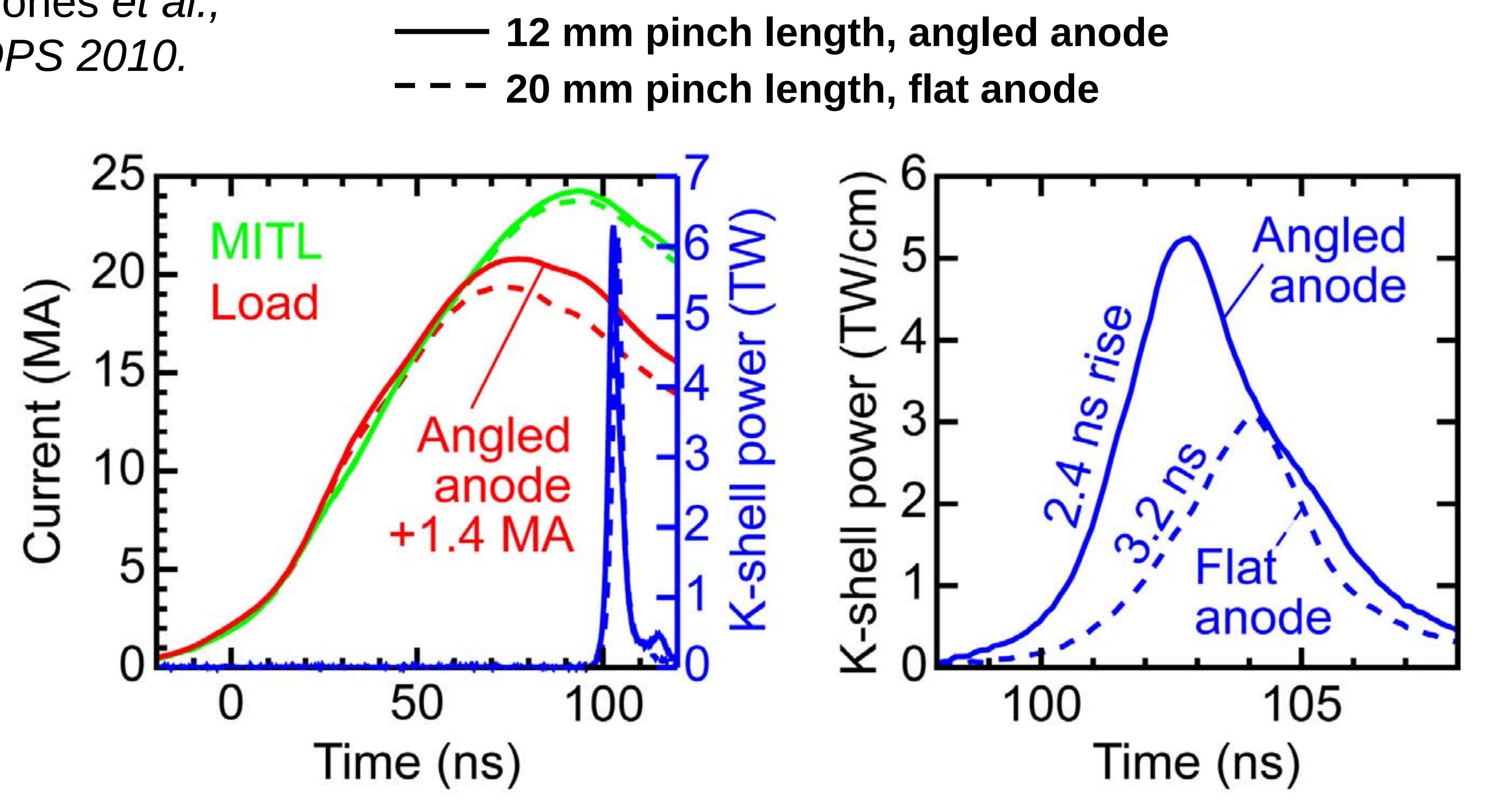
Cu K-shell power per unit length nearly doubled for shorter pinch length

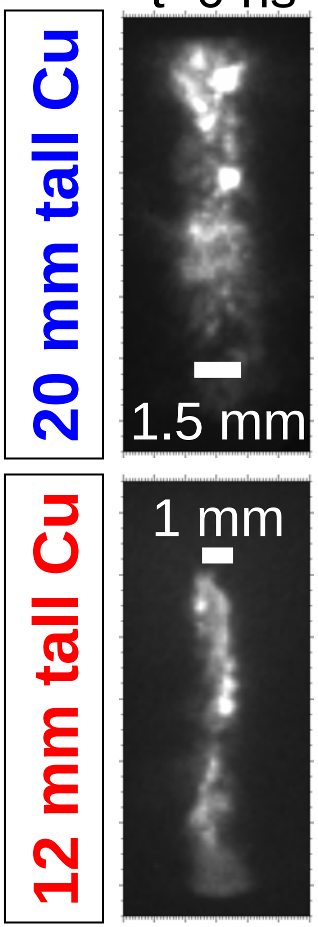
B. Jones *et al.*, *ICOPS 2010.*



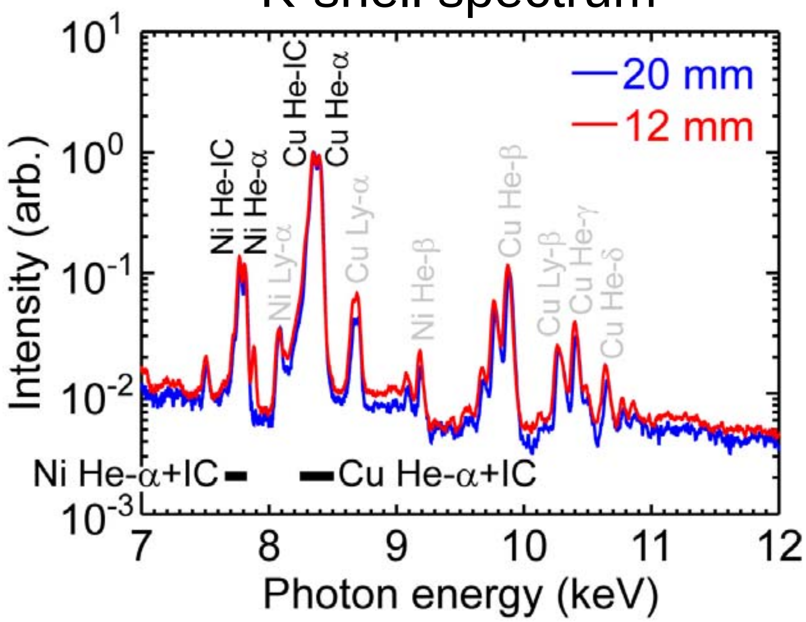
- **0D model predicted +9% implosion velocity for 12 mm vs. 20 mm**

Greater compression and higher density were achieved in the shorter pinch

K-shell PHC
t=0 ns

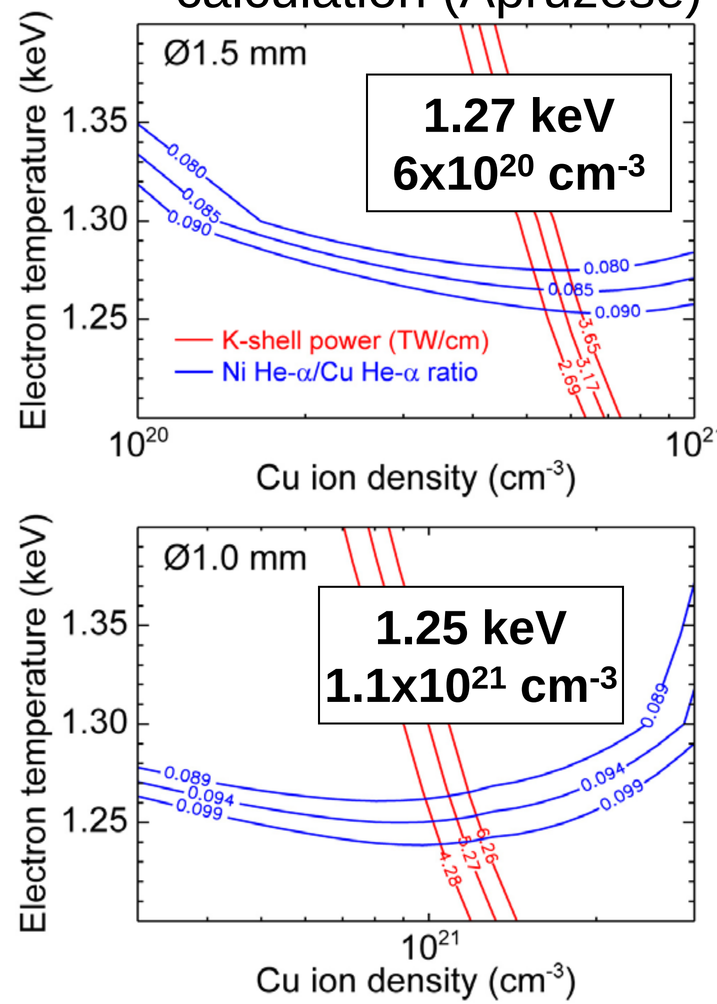


Time-integrated
K-shell spectrum



B. Jones *et al.*,
ICOPS 2010.

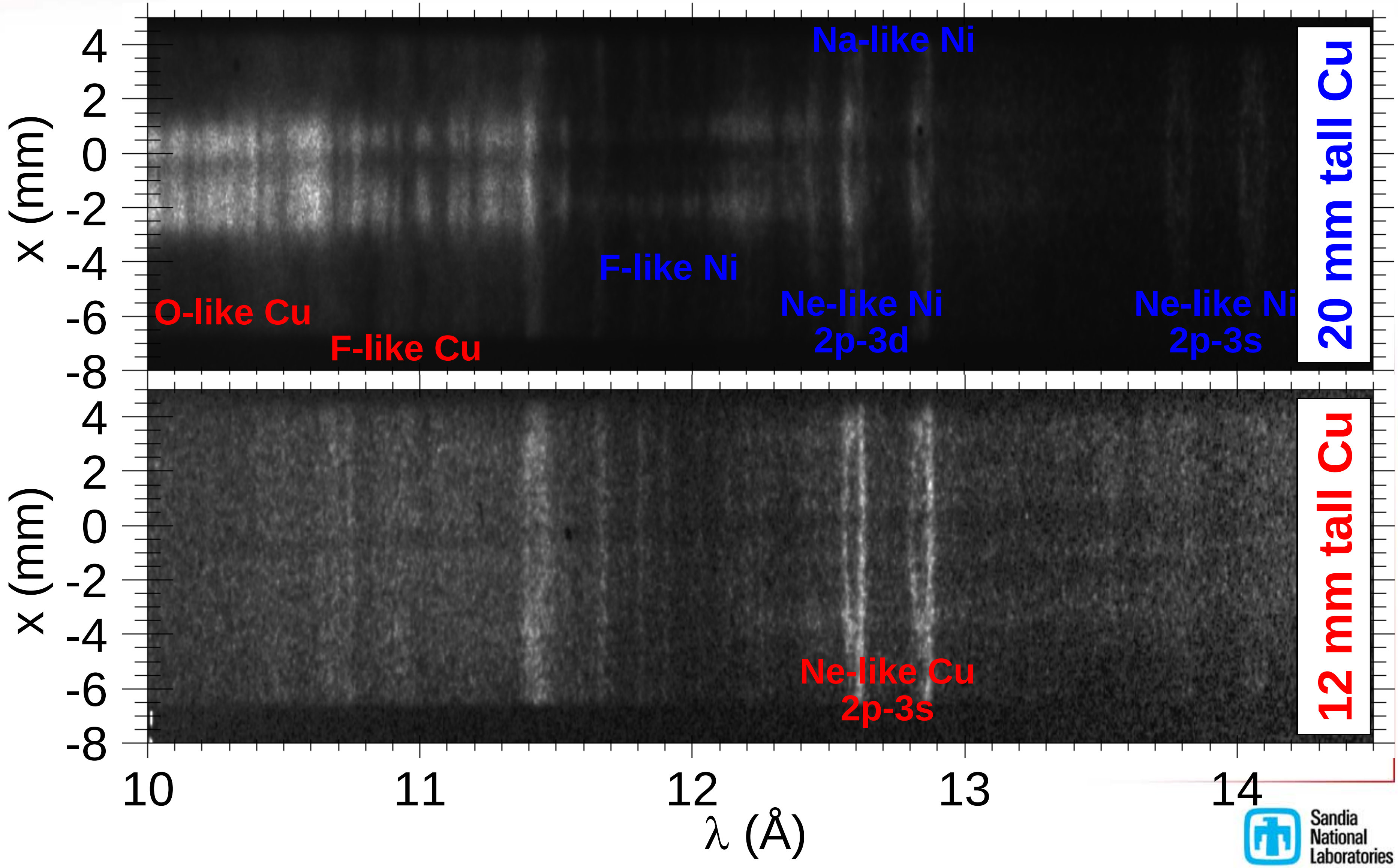
Collisional-Radiative
calculation (Apruzese)



- **Inferred K-shell mass participation is 85, 70% for the 20, 12 mm loads**
- **Structure in images may mean higher density bright spots, lower mass fraction**

Cu L-shell at -3 ns shows significant differences in radial structure and line intensities

B. Jones *et al.*, *ICOPS 2010.*



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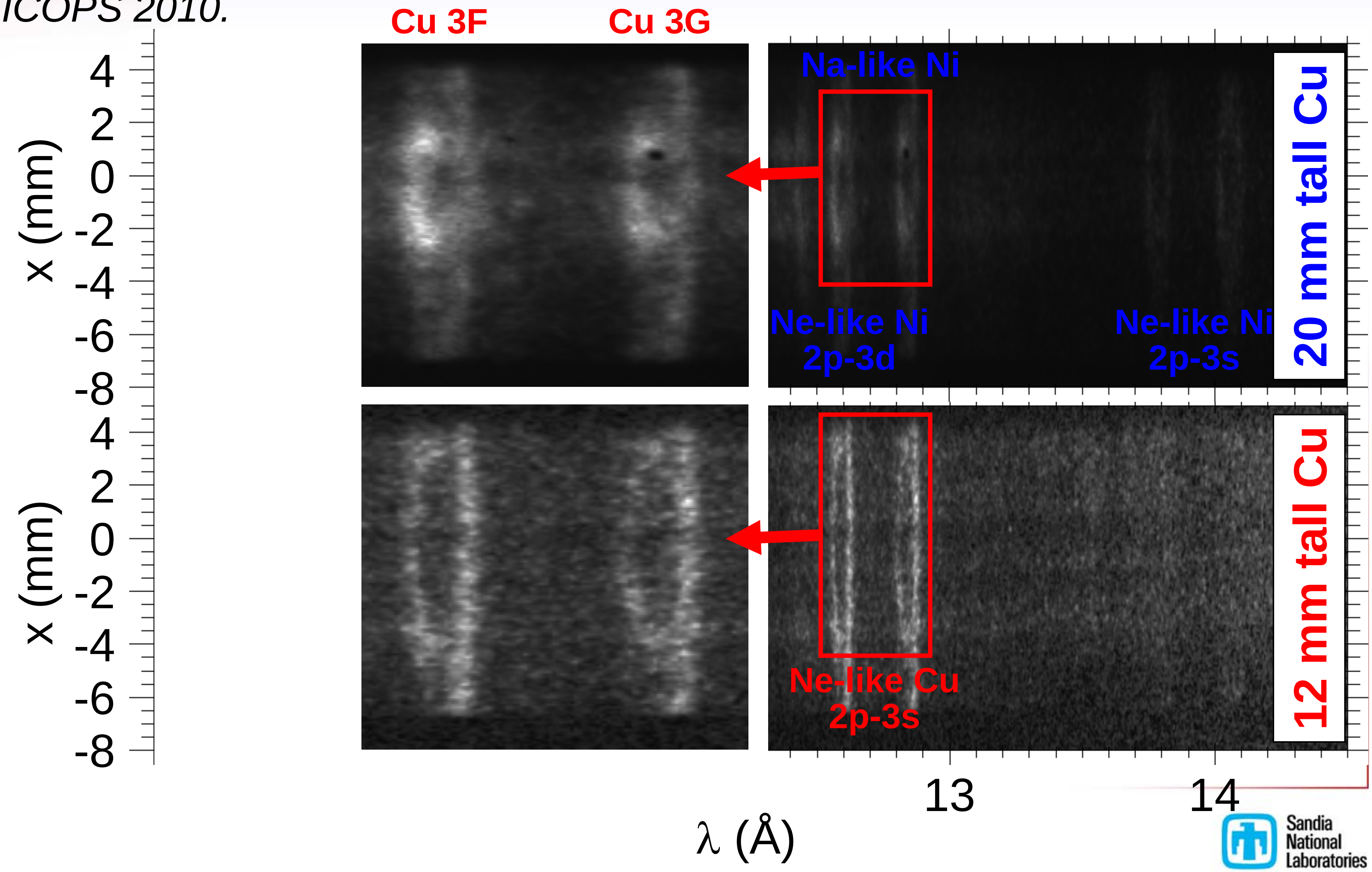
Cu L-shell lines show Doppler splitting, oval signature of imploding shell

B. Jones *et al.*, *ICOPS 2010.*



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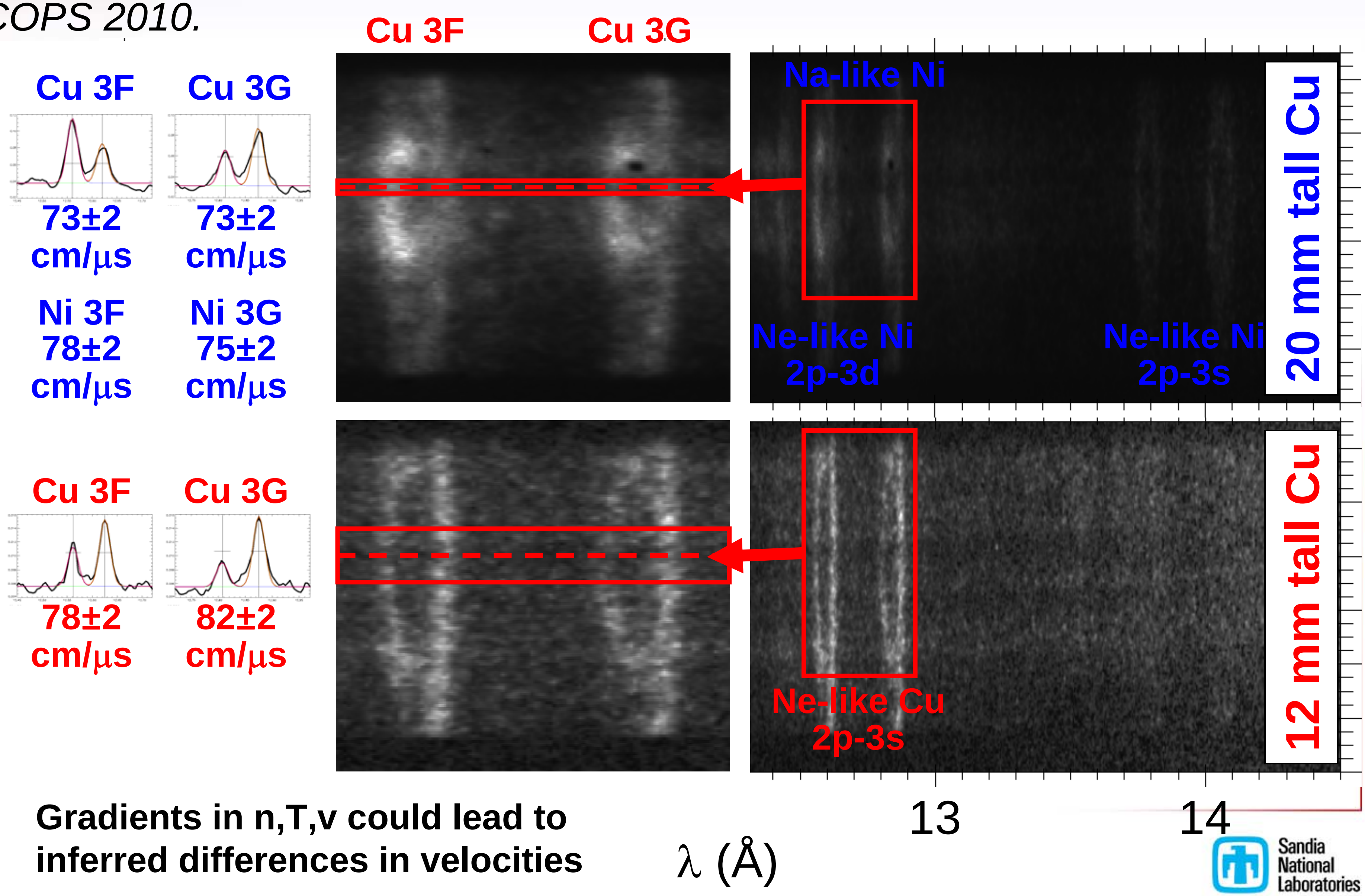
Cu L-shell shows ~10% greater velocities for the shorter load

B. Jones *et al.*,
ICOPS 2010.



- **Gradients in n,T,v could lead to inferred differences in velocities**

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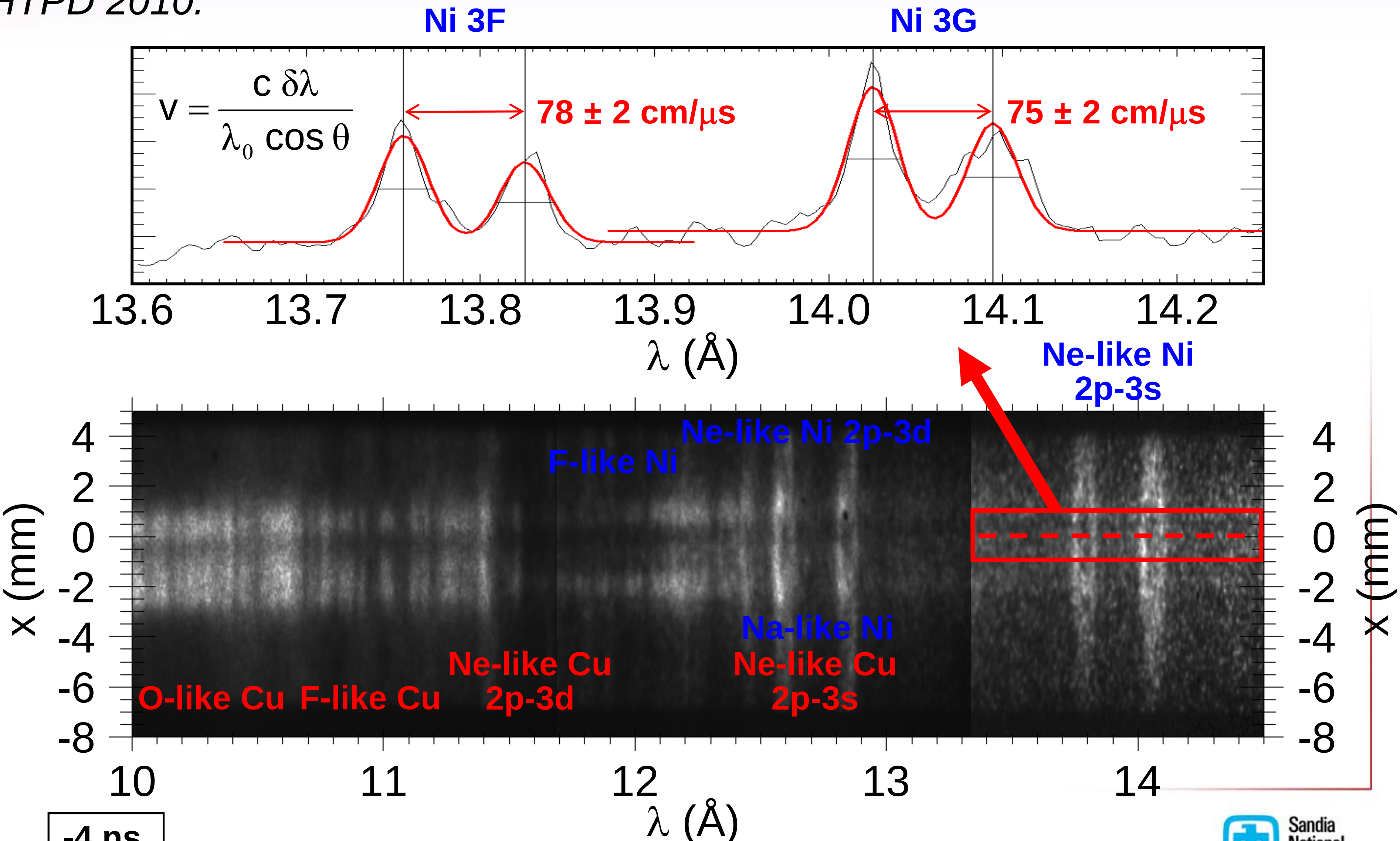
Doppler splitting of L-shell lines in Cu/Ni wire array implosion provides average radial velocity

B. Jones *et al.*, *HTPD 2010.*



-4 ns

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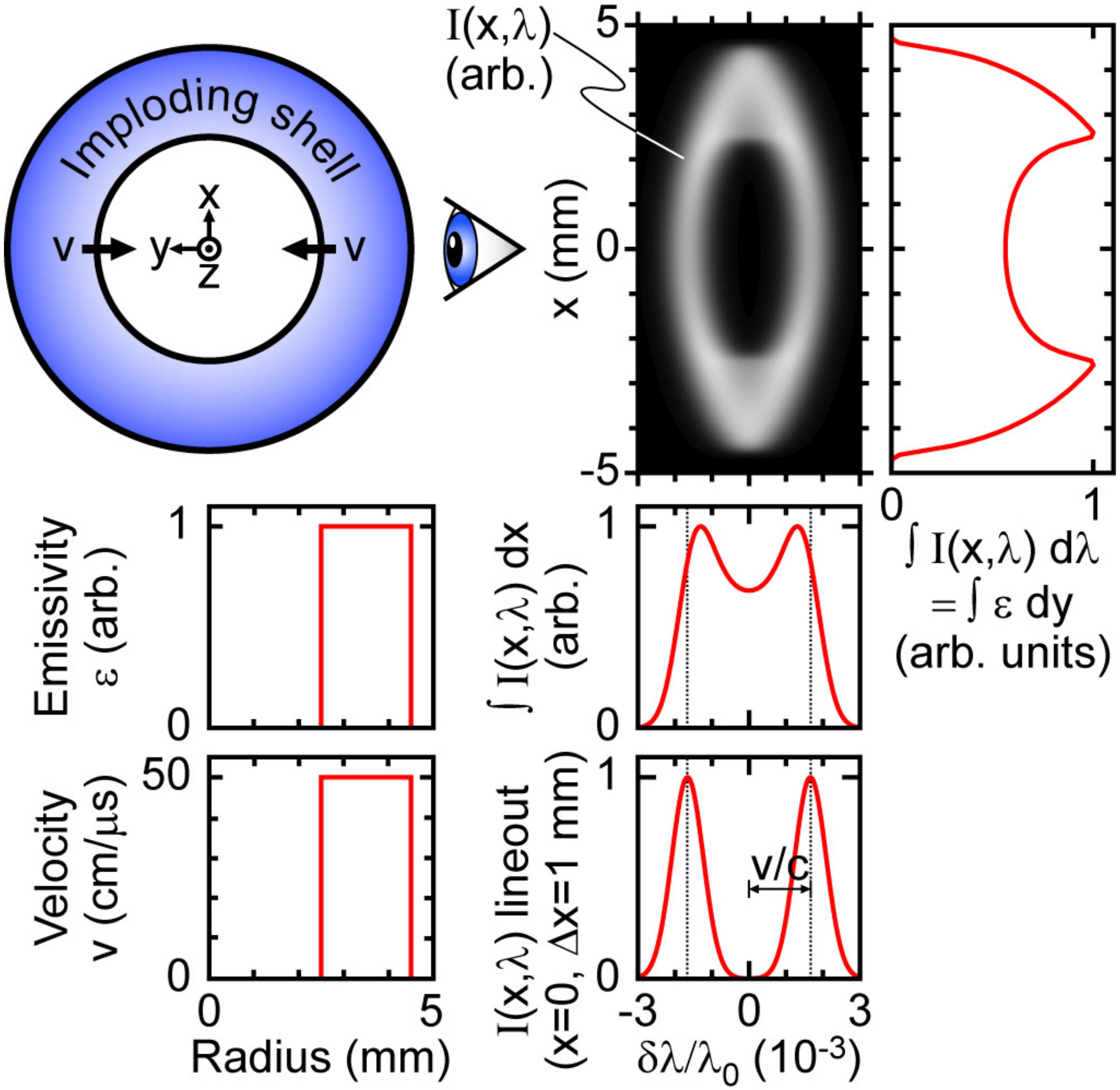
Basis set for time- and space-resolved x-ray spectrometer—Doppler effect in moving shells

B. Jones *et al.*, *HTPD 2010.*



- **Consider the source to be a sum of moving shells—spectrometer resolves Doppler splitting and spatial structure**
- **Analytical forward transform of emitting, moving shell from (r,v) space into (x,λ) space on the detector**
  - **Convolved with representative λ/Δλ~1000 spectral resolution, 200 μm spatial resolution**

BASEX forward transform is used to study plausible plasma ε,v profiles encoded in images

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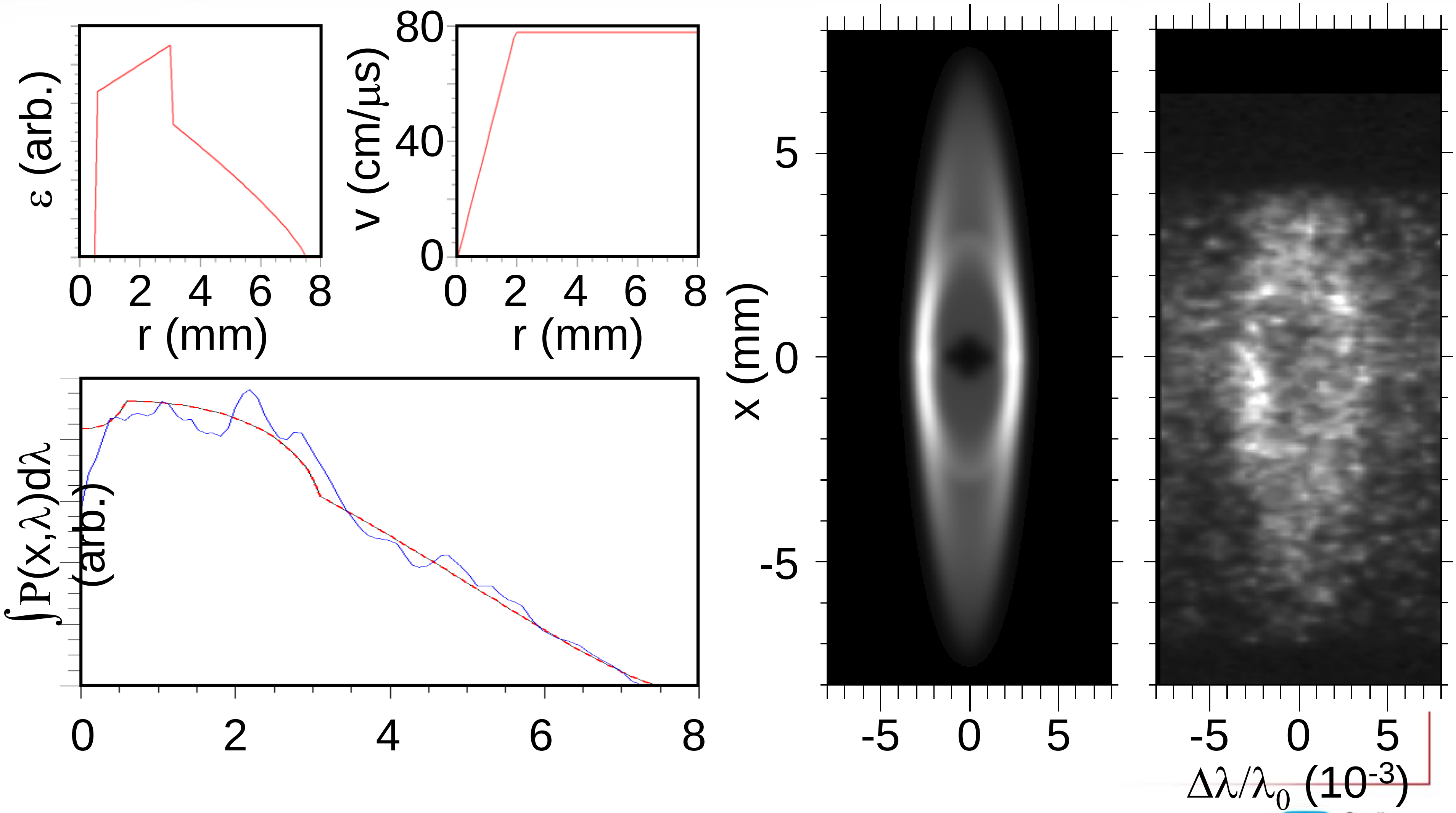

- **Smoothing for 400 μm spatial, λ/Δλ=1000 spectral resolution**

7/12/10-7/16/10, Z2119-2123, A0131 shot overview

Shot	A #	Wire mater-ial	Wire #	Wire dia. (um)	Top REH+ TREX	Can thick (mm)	Angled can	B-dots	Total yield (MJ)	K yield (kJ)	K-shell 10-90% rise (ns)
Z2119	A0131-A	SS304	108/54	8.4	X	1	X	Horiz.	1.4	78±8*	1.50±0.06
Z2120	A0131-B	SS304	108/54	8.4	X	1	X	Horiz.	2.1	90±9*	1.29±0.06
Z2121	A0131-C	Brass	100/50	8.4		1		H+V	1.7	18±4	5.5±0.3
Z2122	A0131-D	Cu(Ni)	60/30	10.2		1		H+V	1.8	41±7	3.7±0.2
Z2123	A0096-B	Brass	100/50	8.4		3		Vert.	1.7	24±4	5.2±0.3

* Dave Ampleford is getting lower PCD yields; analysis is being reviewed.

- **Goals:**
  - Assess effect of angled can on testing environment, perform tests for HSC
  - Evaluate Cu K-shell output from larger diameter array, as studied March 2010 with SS
  - Compare Cu/Zn K-shell output from brass array with higher wire number
  - Study line widths using end-on and side-on TREXs
  - Commission CRITR-RR (radially resolved), compare various spectrometers
- All loads 70/35 mm array diameters, 20 mm tall, ~0.69 mg/cm, similar to 3/10 SS
- 80 kV Marx charge, NO pre-pulse suppression, newer feed
- Cu had ~4% Ni dopant; Brass was ~70% Cu, 30% Zn; All had 2x2mm cath.step
- TIXTL filter transmission correction assuming all photons at:
  Fe He-α 6.7 keV (SS), or
  Cu He-α 8.4 keV (Cu, brass)
- Averages of four PCDs, filtered with:
  2 x 5 mils Kapton, 2 x 10 mils Kapton (SS), or
  1 x 5 mils Kapton, 2 x 10 mils Kapton, 1 x 30 mils Kapton (Cu, brass)

Shot	A #	Wire mater-ial	Wire #	Wire dia. (um)	Top REH+ TREX	Can thick (mm)	Angled can	B-dots	Total yield (MJ)	K yield (kJ)	K-shell 10-90% rise (ns)
PDI fielded											
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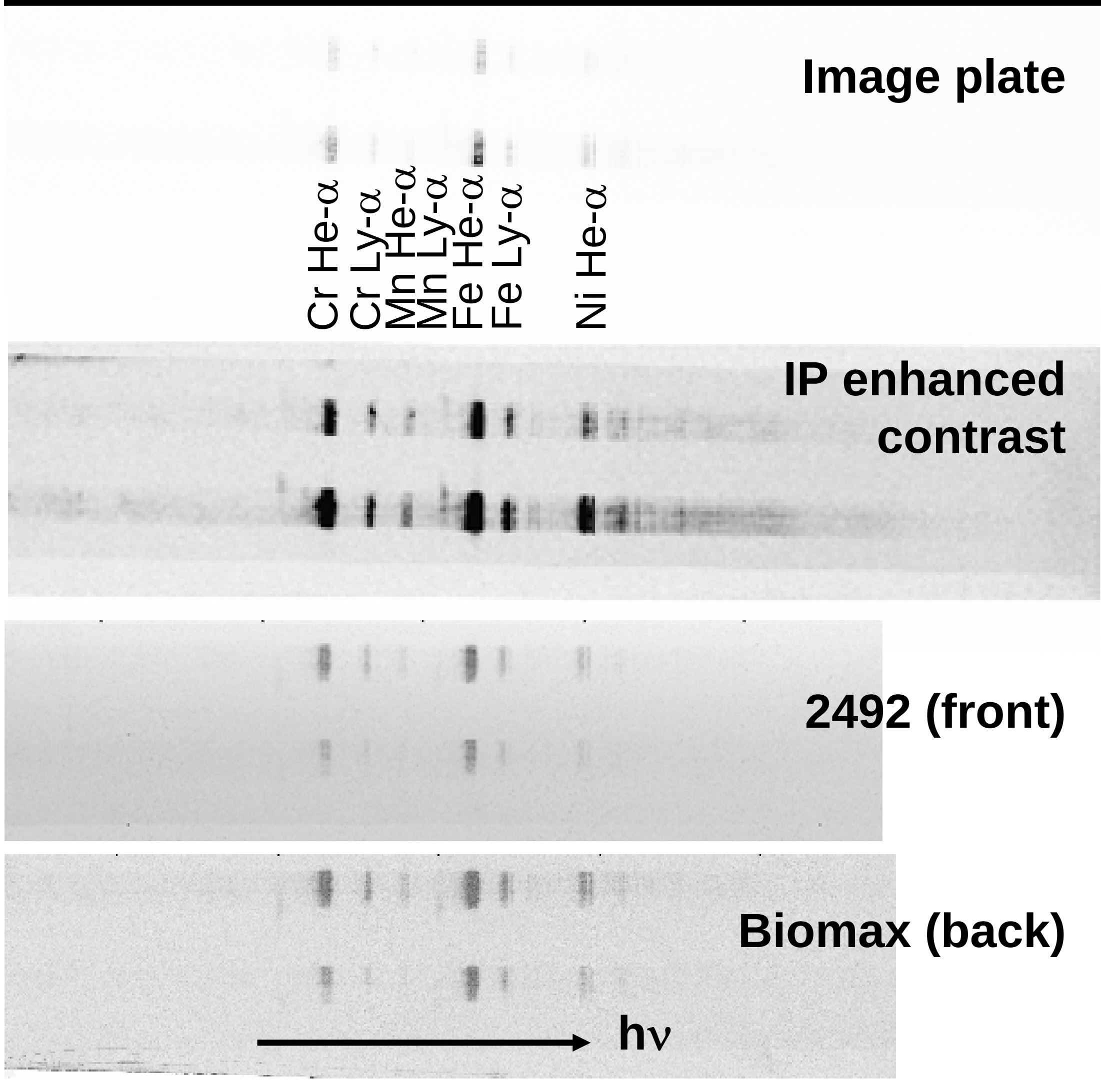

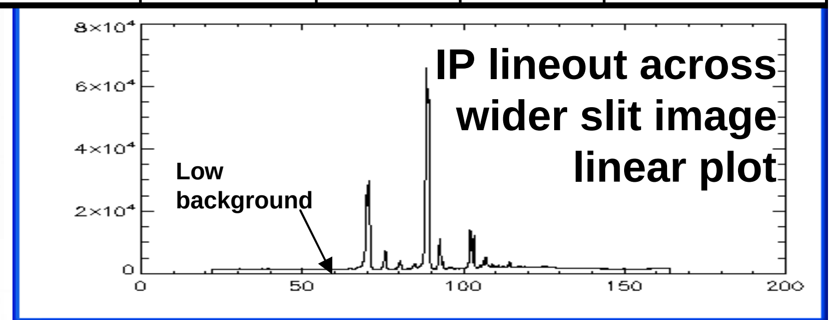

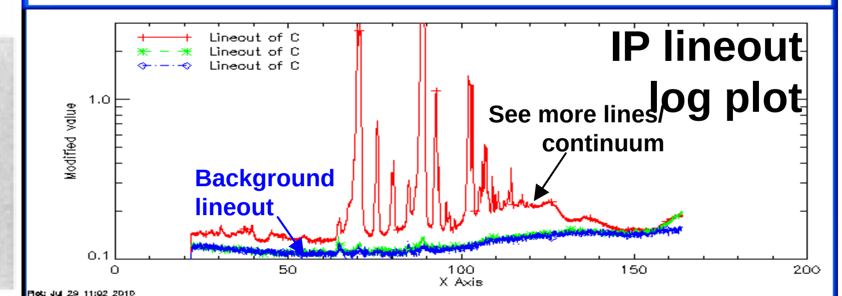

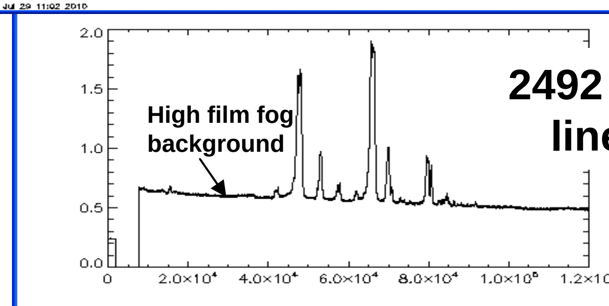

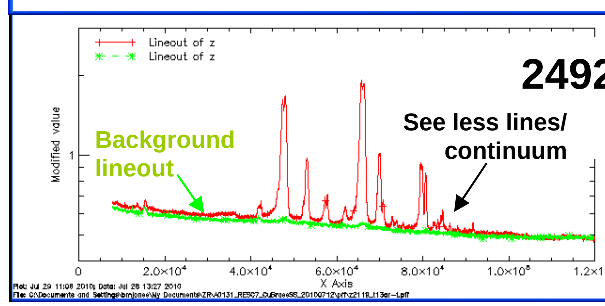

- Image plate is being studied to replace TIXTL film
- These data will provide IP vs. film comparison

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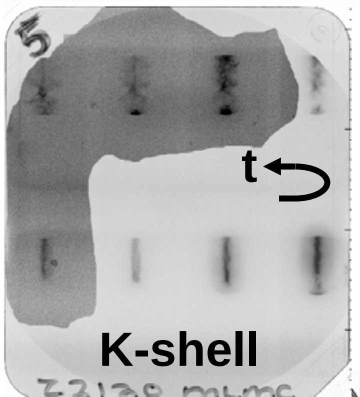
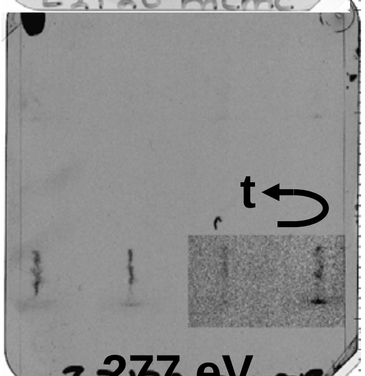
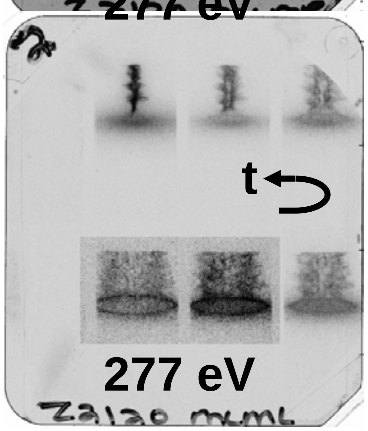
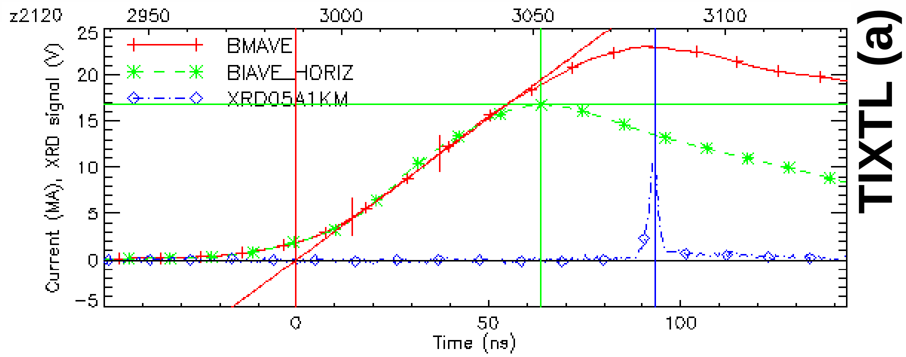
Shot	A #	Wire mater-ial	Wire #	Wire dia. (um)	Top REH+TREX	Can thick (mm)	Angled can	B-dots	Total yield (MJ)	K yield (kJ)	K-shell 10-90% rise (ns)
Z2120	A0131-B	SS304	108/54	8.4	X	1	X	Horiz.	2.1	90±9	1.29±0.06

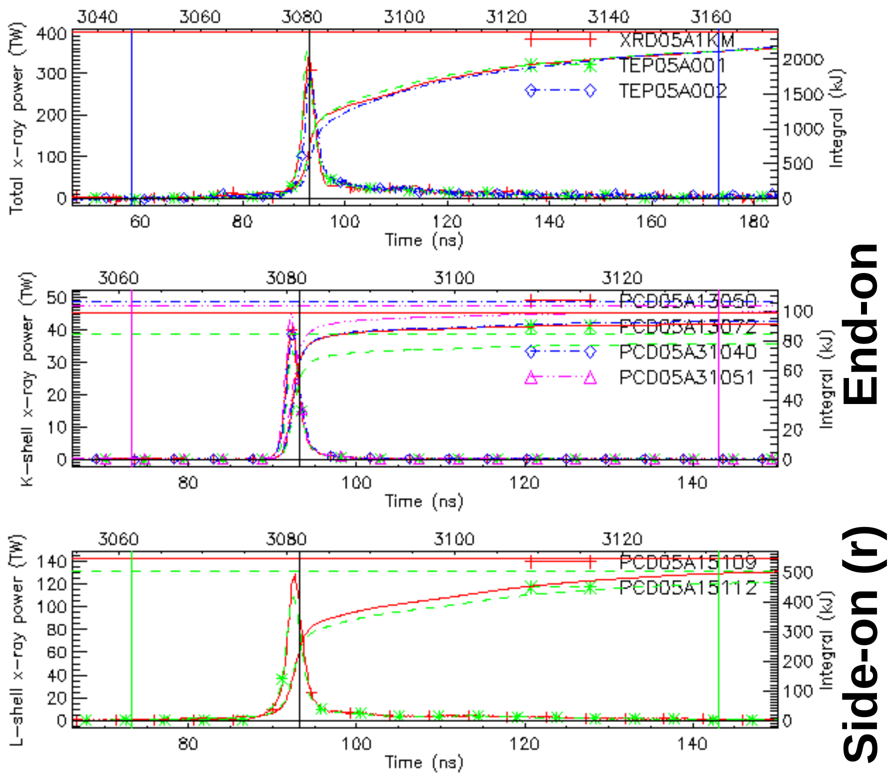
PDI fielded, 6xCalorimeter

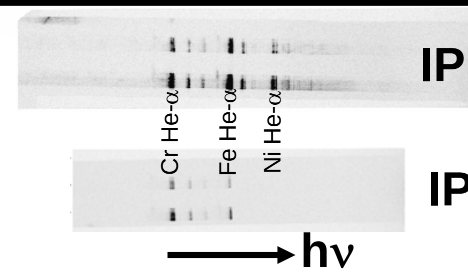




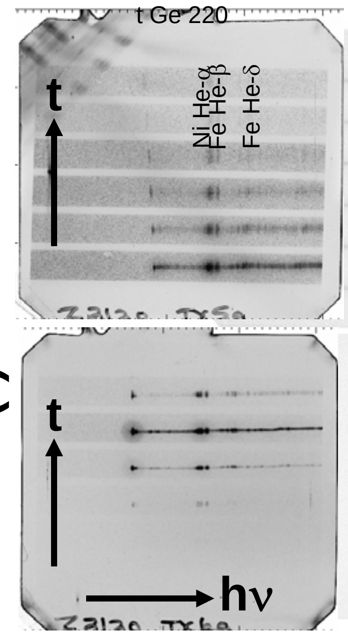


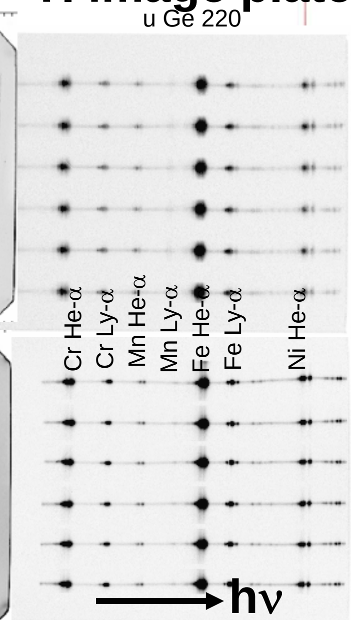






Ge TIXTL seems to be missing higher hν lines again





PDI fielded, 6xCalorimeter		Wire mater-ial	Wire #	Wire dia. (um)	Top REH+ TREX	Can thick (mm)	Angled can	B-dots	Total yield (MJ)	K yield (kJ)	K-shell 10-90% rise (ns)
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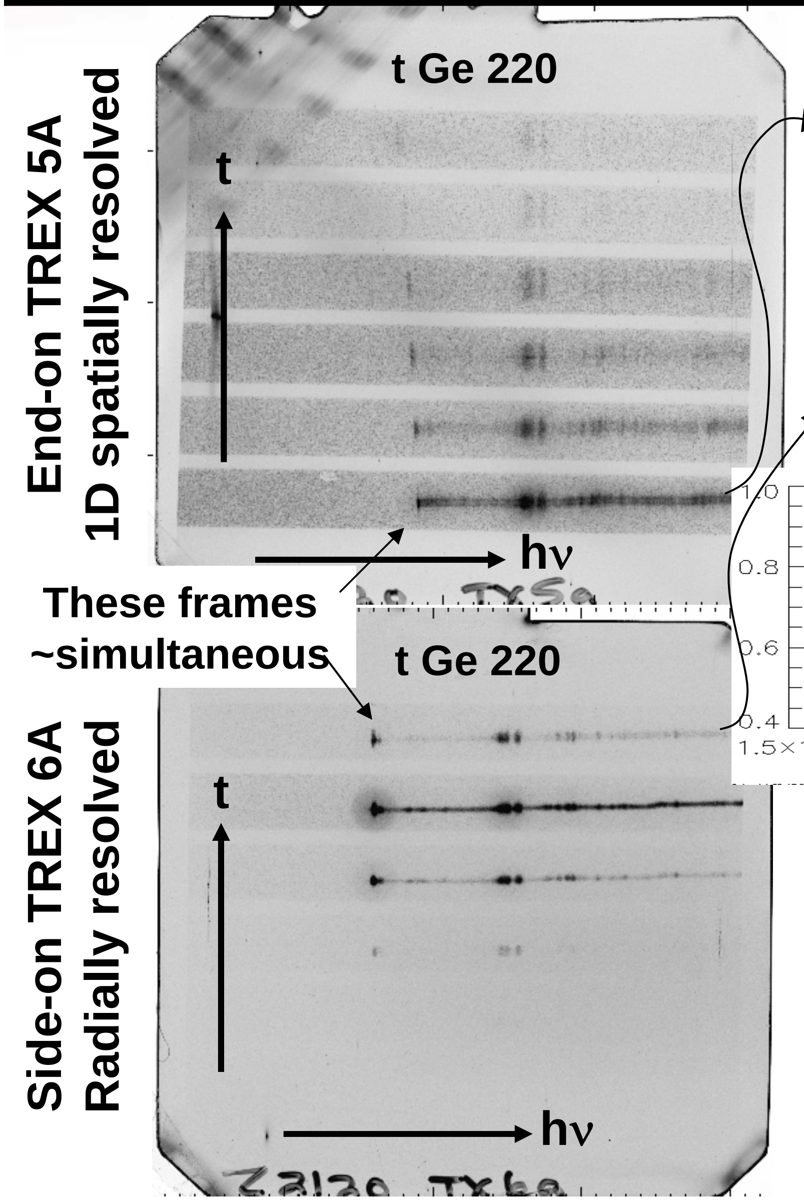

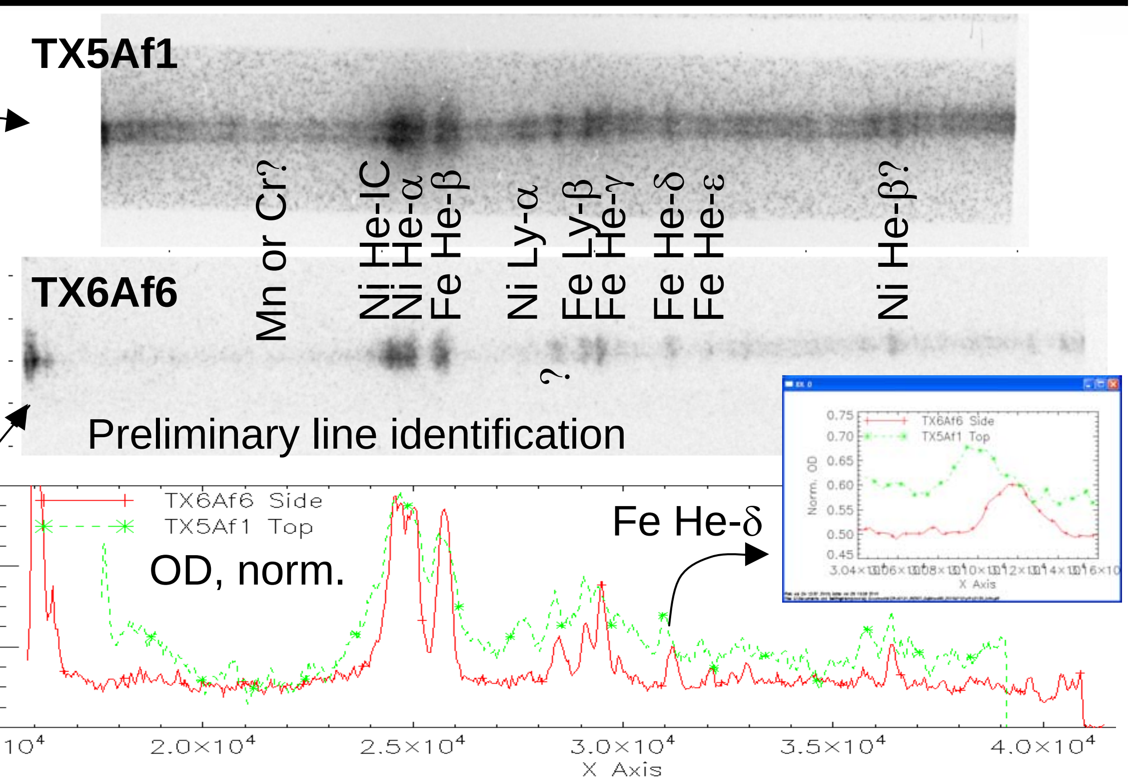

- Not obvious in quick look that line shapes are narrower from top view
- Need to process film with EXRAY and look at line shapes in detail
- Need to check timing with NSTec
- Consider spectral resolution; u Ge 220 has been characterized some, but not t Ge 220

Shot	A #	Wire mater-ial	Wire #	Wire dia. (um)	Top REH+ TREX	Can thick (mm)	Angled can	B-dots	Total yield (MJ)	K yield (kJ)	K-shell 10-90% rise (ns)
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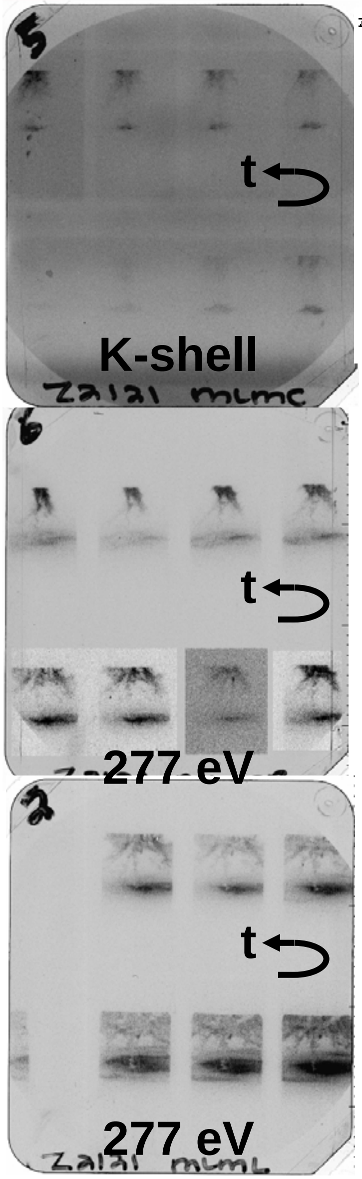
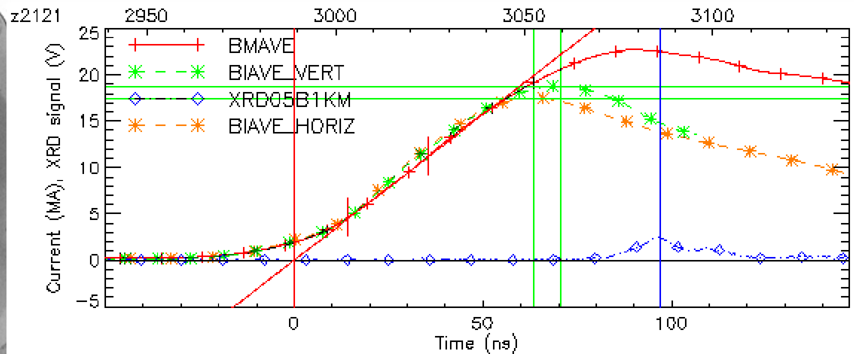
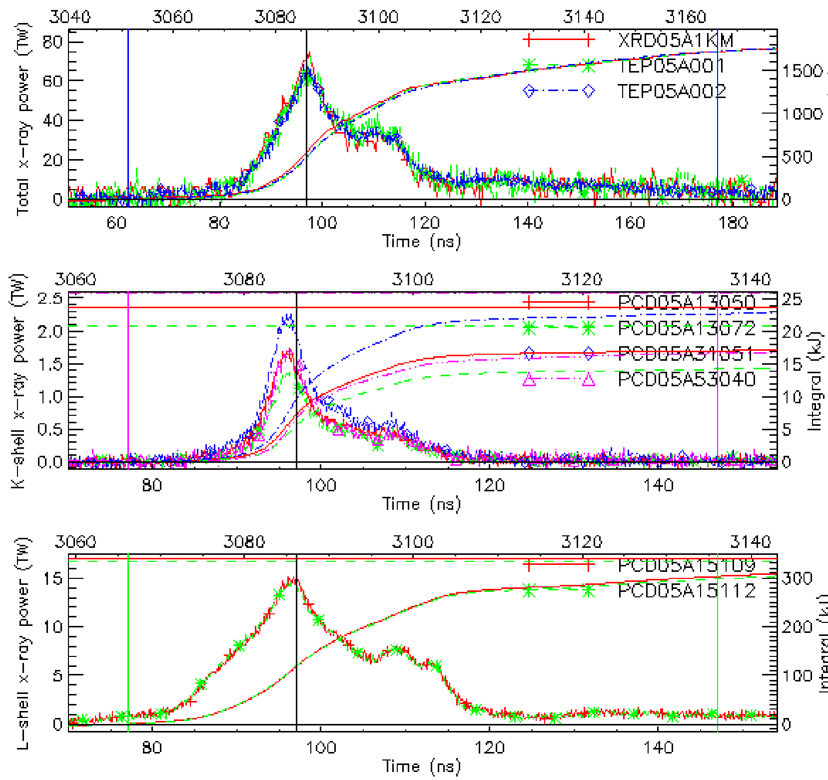
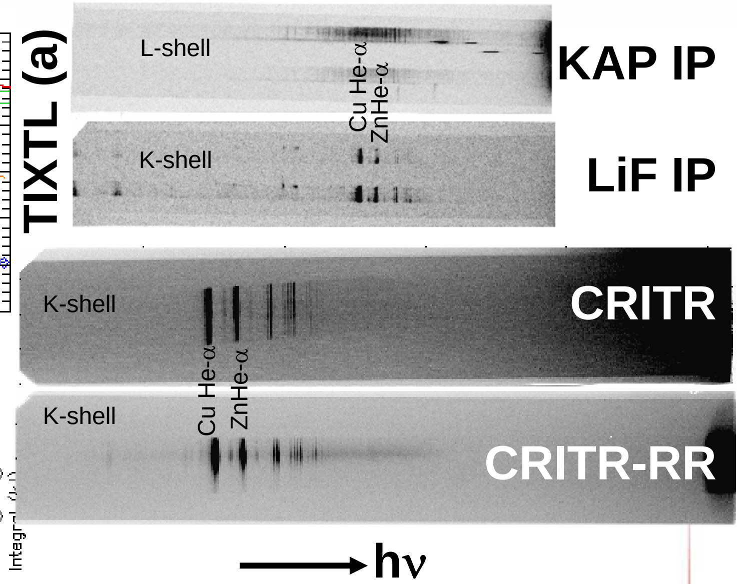


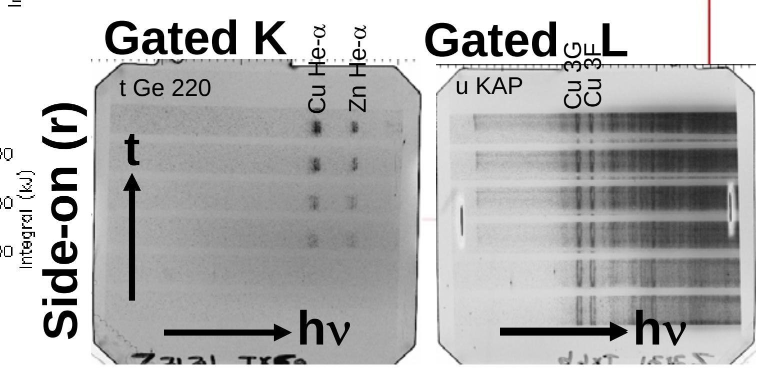


Horiz. B-dots come in low vs. Vert.





CRITR (axial) and CRITR-RR (radially resolved) have ~7-20 keV spectral range, high sensitivity, 0 deg. view



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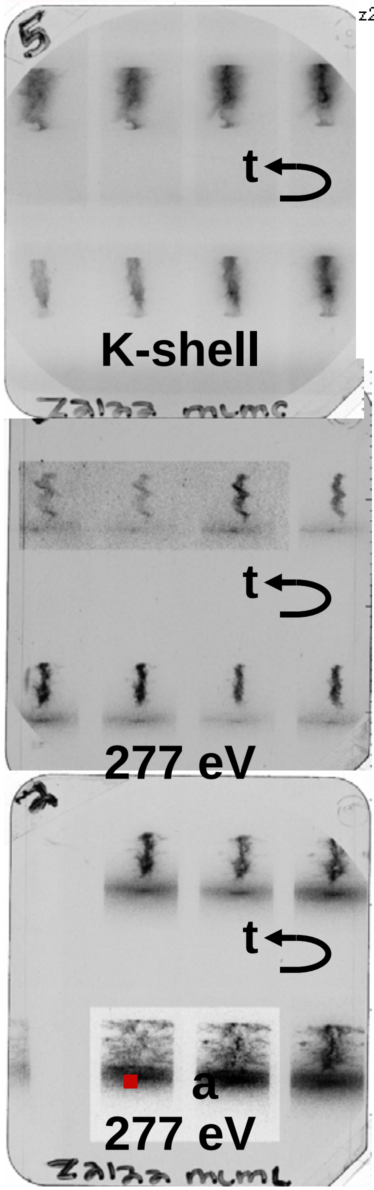

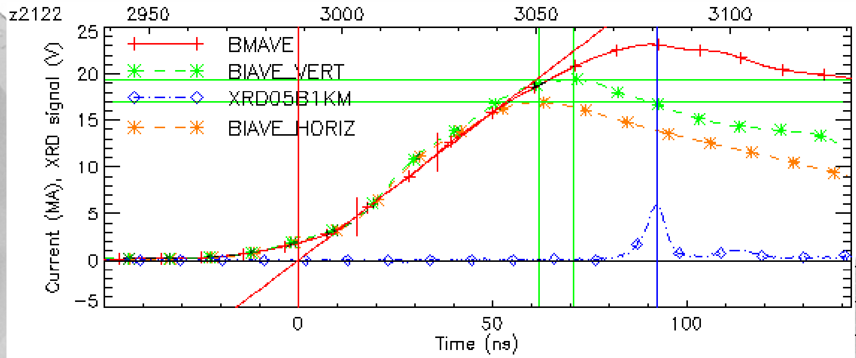

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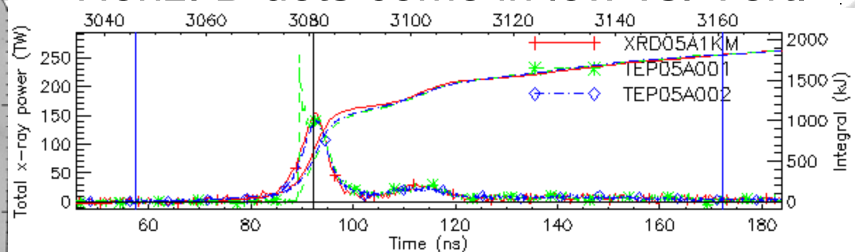

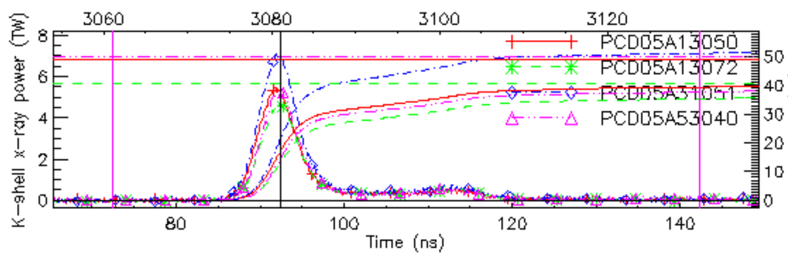

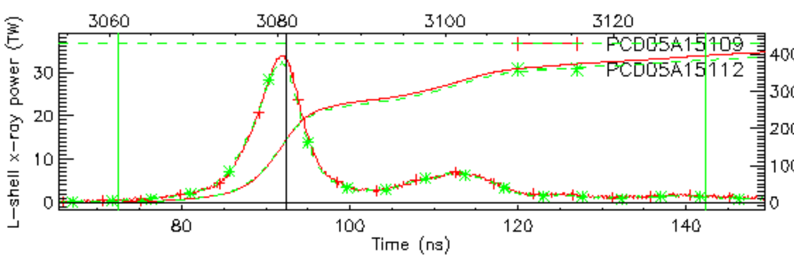

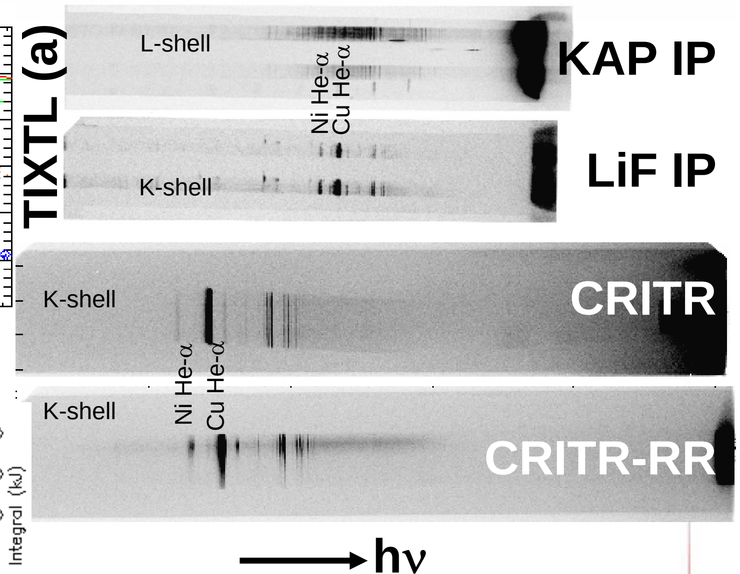

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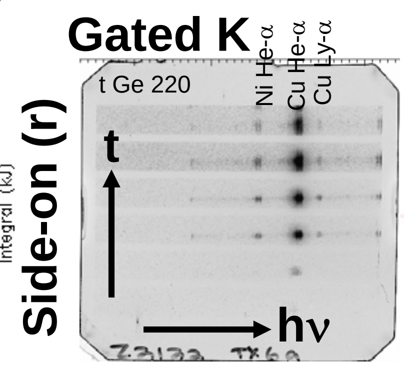

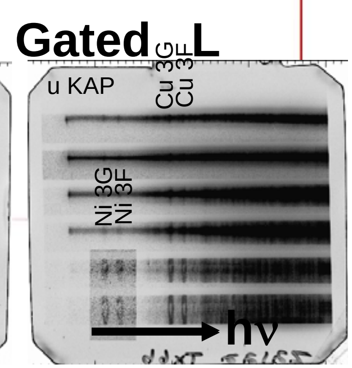

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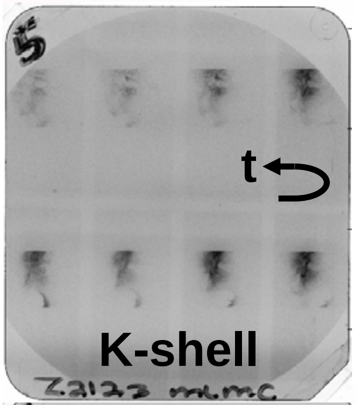

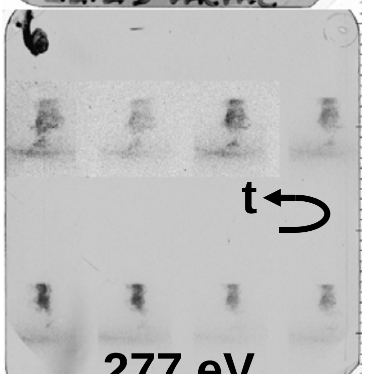

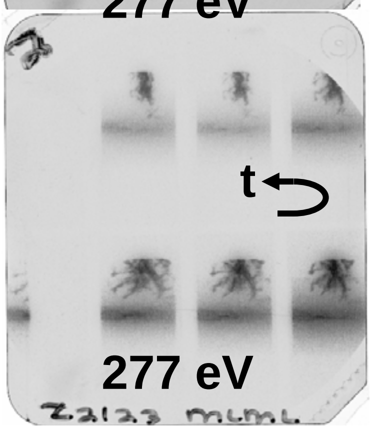

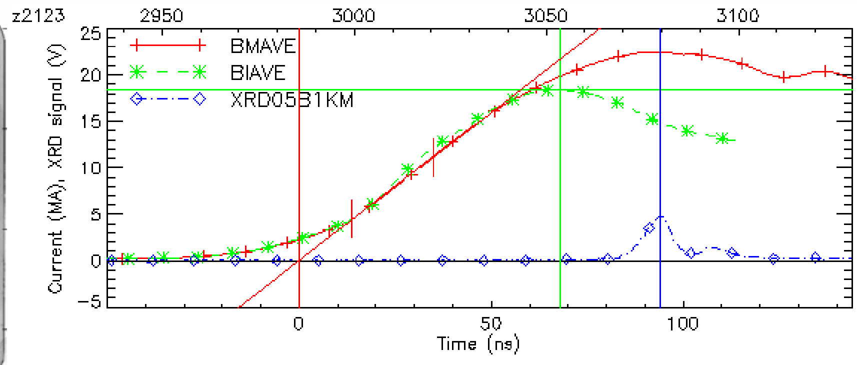

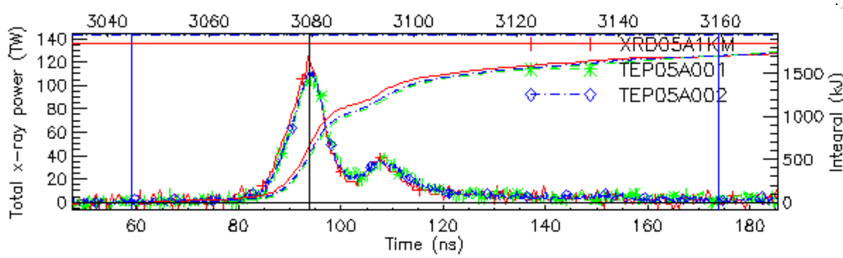

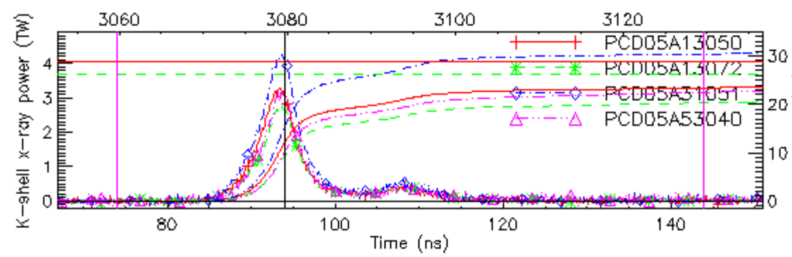

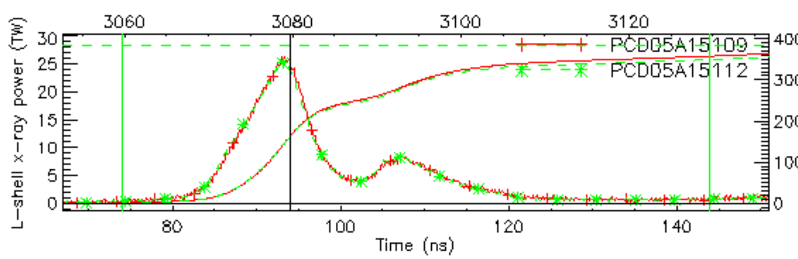

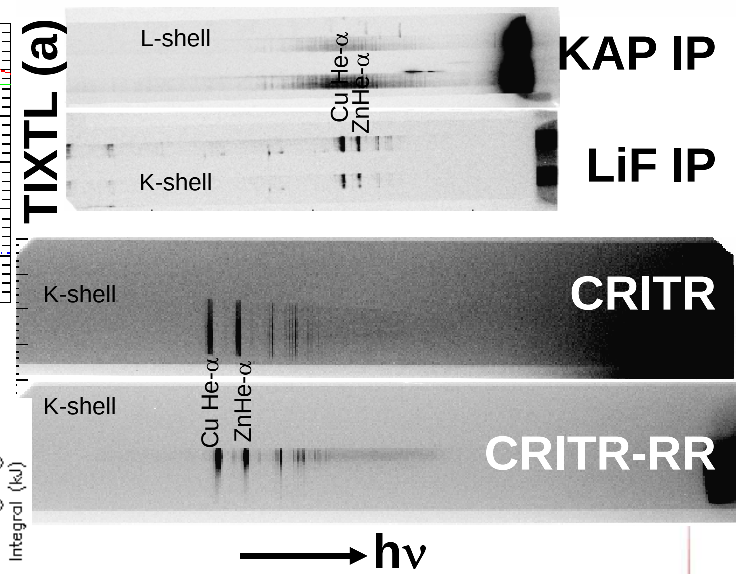

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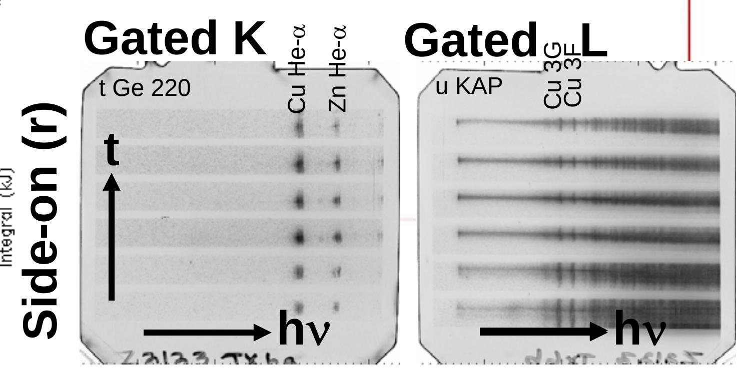
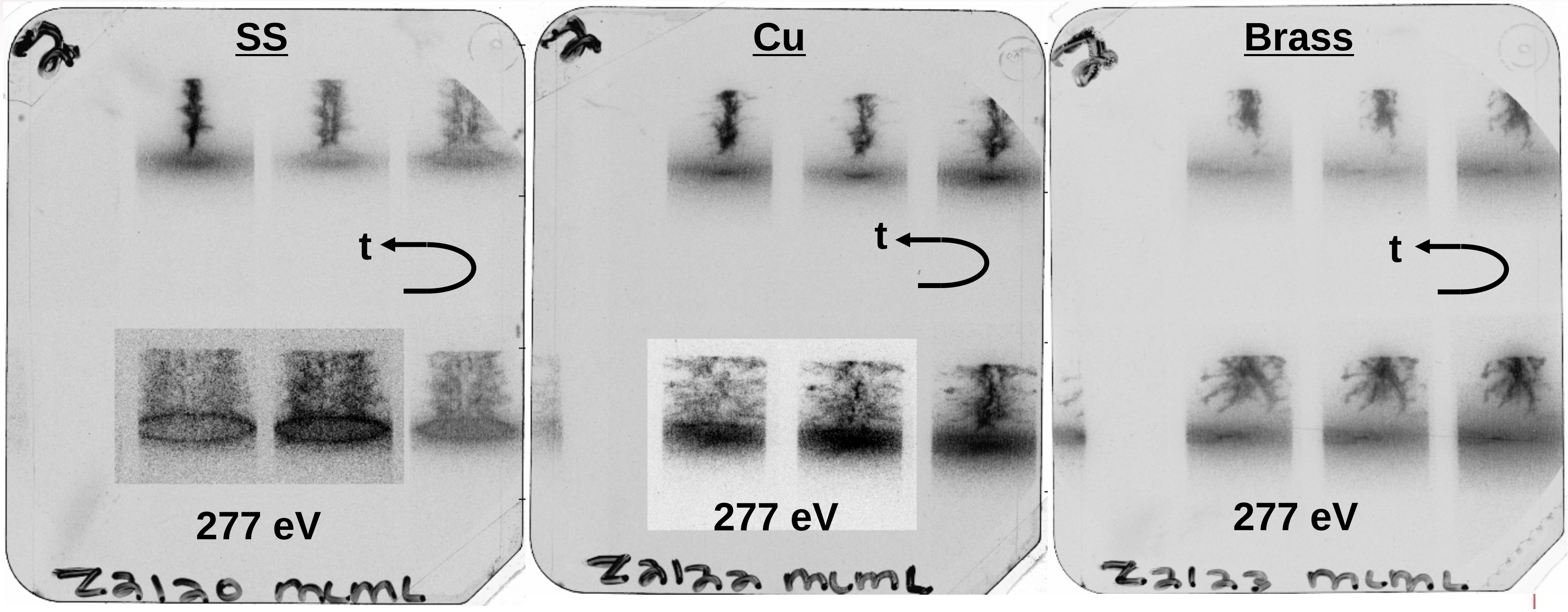


Should we try brass again, or is there something funny about that wire?



- SS shows nice imploding shell, little or no cathode non-uniformity
- Cu shows less well defined shell and longer K-shell x-ray rise, perhaps due to low wire number, little cathode non-uniformity. Try 65 mm Cu with lower mass next?
- Brass shows significant cathode non-uniformity, even longer K-shell rise time, long trailing fingers and worse compression—early cathode implosion? Current contact issue? Work function of metals? Could Zn
alloyed in wire have been inclusions that affected wire initiation?
Suggest brass initiation study at a university (UNR?)?
- We have a lot of good 277 eV images. Can these be simulated in post-processing? What process creates these photons? Can we extract plasma n or T profiles from the data?