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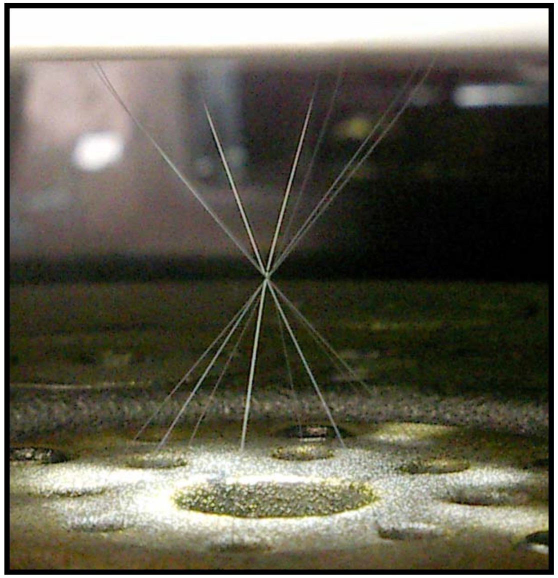
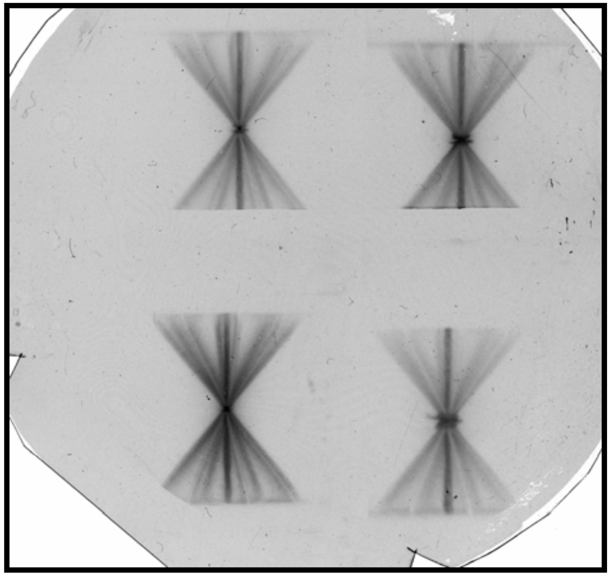
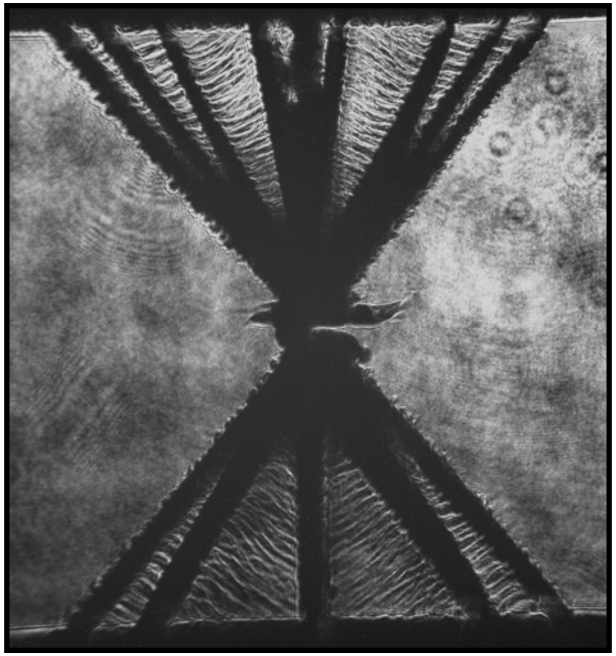




1 MA X-pinch experiments at Cornell University



March 22, 2007

HEDP Seminar

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
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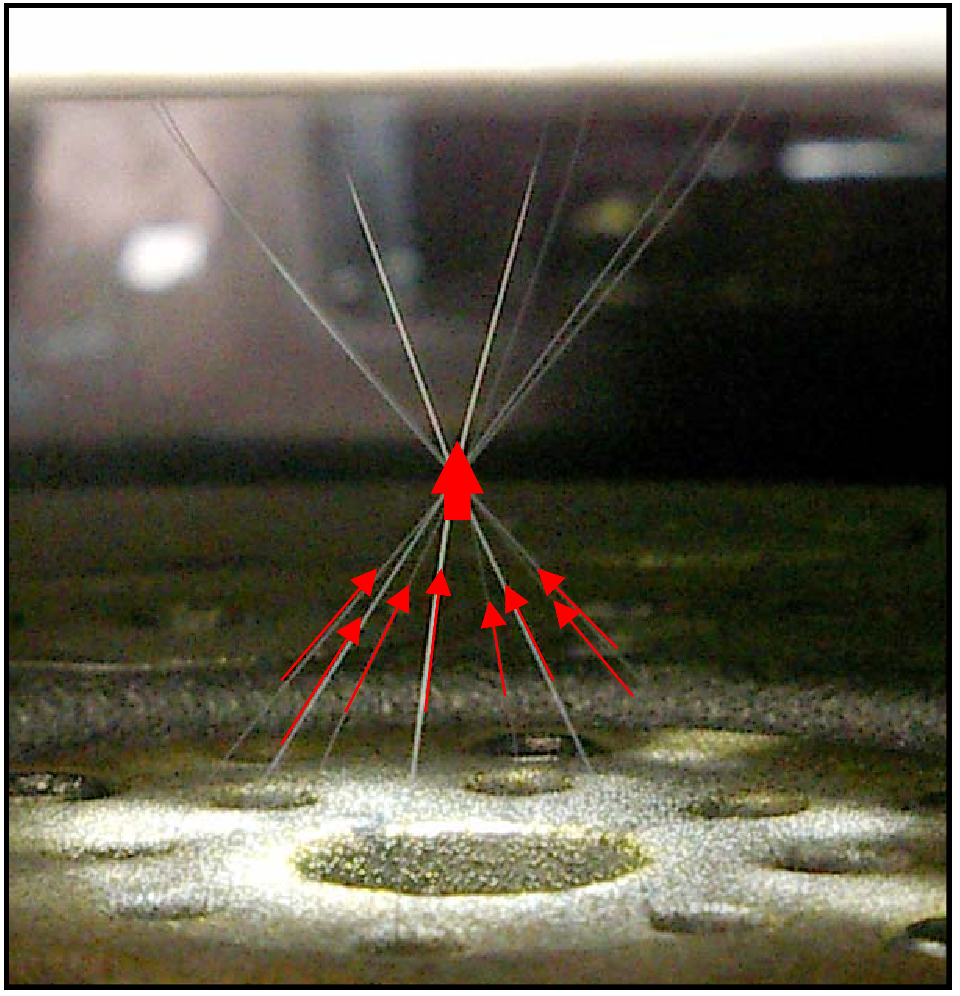
What is an X pinch?

An X pinch is produced by using multiple wires so that they cross and touch at one point.

Ideally the current in each leg is below the threshold for micropinch formation (~100 kA), but at the cross point the current exceeds the threshold and micropinches form reliably.

X pinches were proposed as a means for studying micropinch plasmas many years ago*. In recent years the properties of these plasmas have been studied with high-resolution diagnostics



* S.M. Zakharov, G.V. Ivanenkov, A.A. Kolomenskii, S.A. Pikuz, A.I. Samokhin, and J. Ulshmid, Sov. Tech. Phys. Lett. 8, 456 (1982).

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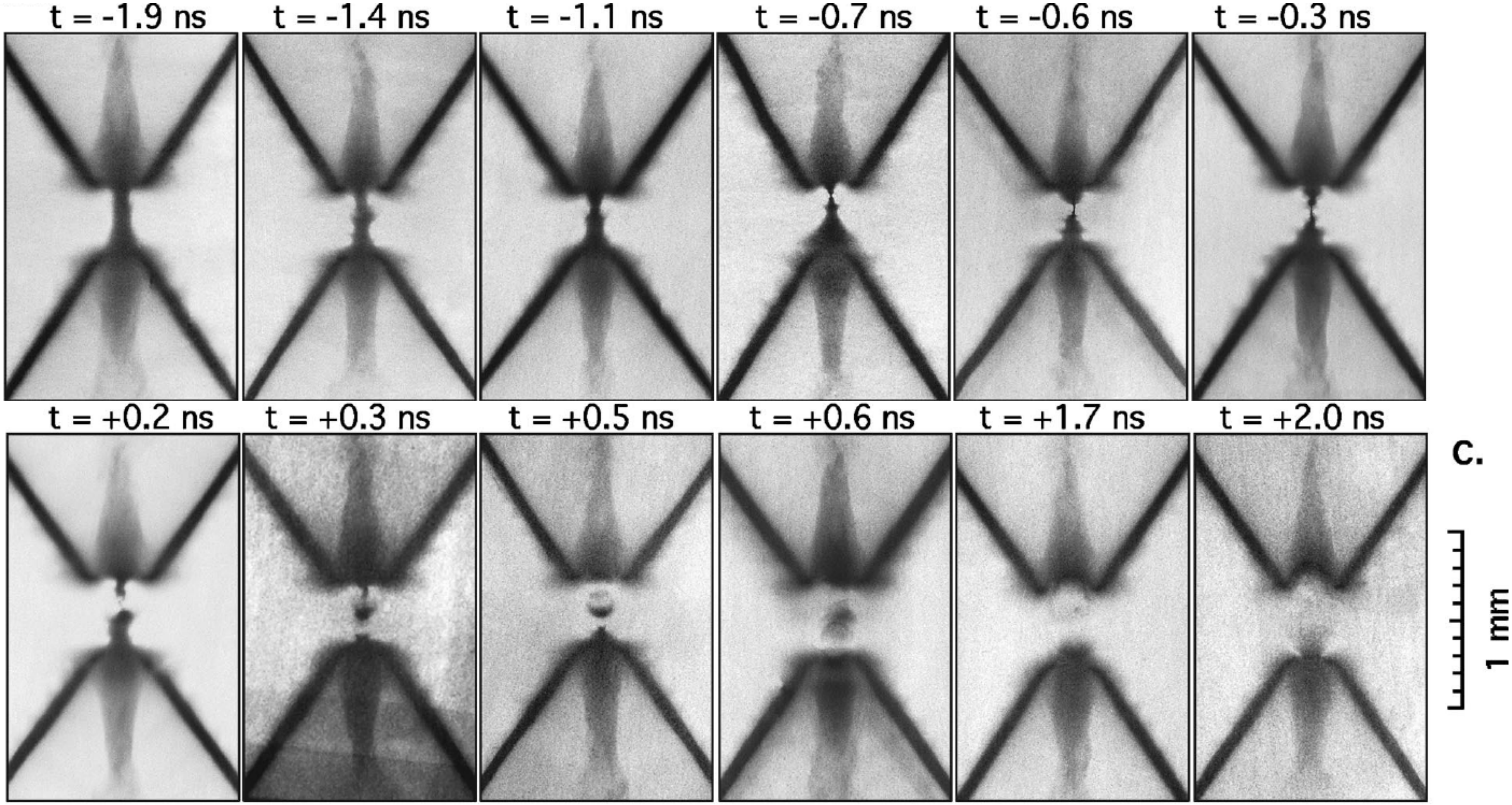
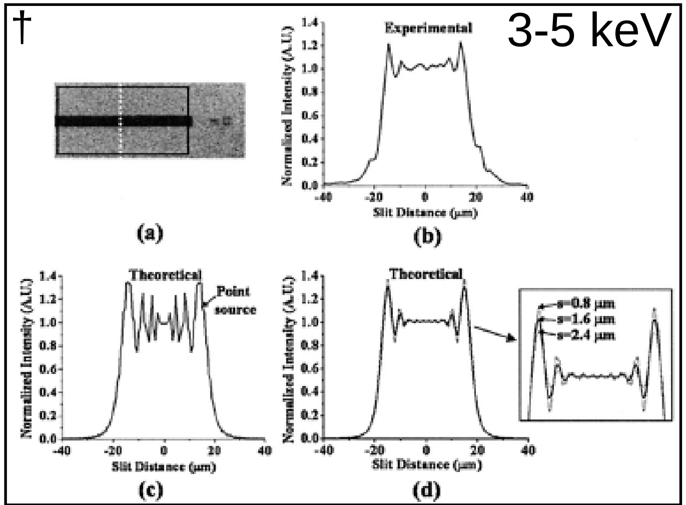
X pinches are means for creating short, high-current, unstable Z pinches at a predetermined spot



Mo 2-wire X pinches reliably formed ~300 μm tall, ~100 μm diameter plasma columns at cross point which collapsed to form 1-2 micropinches

Shelkovenko *et al.*, Phys. Plasmas 8, 1305 (2001).

X-pinch-produced micropinch plasmas have many interesting properties



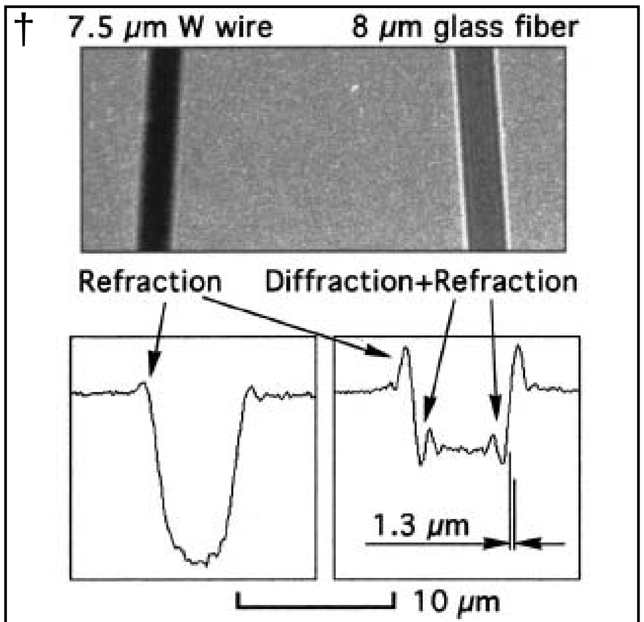
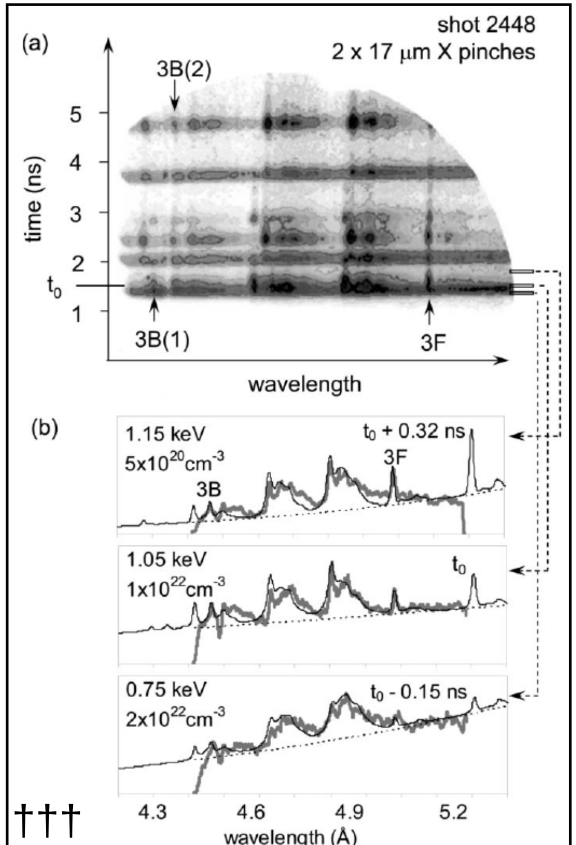


FIG. 5. High-magnification (×93) point-projection radiograph of 7.5 µm W and 8 µm glass fibers, along with a densitogram of each object, showing the effects of diffraction, refraction, and reflection.



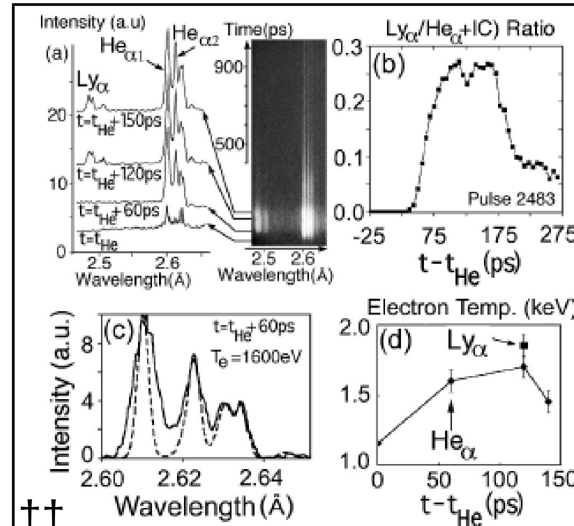


FIG. 3. (a) Example streak camera film scan from a Ti *X*-pinch spectroscopy test, together with spectral profiles at the indicated times. (b) The time-resolved line ratio of the H-like Ti (Ly_α) lines at 2.4903 and 2.4956 Å to the He-like Ti line at 2.6097 Å and its intercombination line. (c) Example optimized computational fit (dashed line) to the spectral line profiles of the He-like Ti line and its satellites (solid line). (d) Electron temperature as a function of time obtained from computational fits as in (c).

<u>Cornell Results at 200 kA:</u>

Diameter: 1.2±0.5 µm†

Duration: ~10-100 ps††

Te ~ 1 keV (Ti††, Mo†††)

ni ≥ 0.1 * solid density††,†††

Warm dense matter!

† B.M. Song *et al.*, Appl. Optics 44, 2349 (2005). T.A. Shelkovenko *et al.*, RSI 72, 667 (2001).

†† S.A. Pikuz *et al.*, PRL 89, 035003 (2002). D.B. Sinars *et al.*, JQSRT 78, 61 (2003).

††† S.B. Hansen *et al.*, PRE 70, 026402 (2004).

X pinches are being studied today in the U.S. (CU, UNR, UCSD), Russia, China, England, & France

Results from quick search for X-pinch articles in 2006-2007:

J.P. Chittenden et al., Phys. Rev. Lett. 98 (2007).
J.S. Green et al., Appl. Phys. Lett. 88 (2006).
A.V. Kharlov et al., Rev. Sci. Instrum. 77 (2006).
E. Baranova et al., Rev. Sci. Instrum. 77 (2006).
S.Y. Gus'kov et al., Journal De Physique 133 (2006).
L.E. Aranchuk et al., Journal De Physique IV 138 (2006)
X.B. Zou et al., Laser and Particle Beams 24 (2006).
T.A. Shelkovenko et al. Rev. Sci. Instrum. 77 (2006).
T.A. Shelkovenko et al., IEEE Trans. Plasma Sci. 34 (2006).
M.D. Mitchell et al., IEEE Trans. Plasma Sci. 34 (2006).
V.V. Ivanov et al., IEEE Trans. Plasma Sci. 34 (2006).
A.S. Safronova et al., IEEE Trans. Plasma Sci. 34 (2006).
V.L. Kantsyrev et al., IEEE Trans. Plasma Sci. 34 (2006).
V.L. Kantsyrev et al., J. Quant. Spectrosc. Radiat. Transf. 99 (2006).
A.S. Safronova et al., J. Quant. Spectrosc. Radiat. Transf. 99 (2006).
F.N. Beg et al., IEEE Trans. Plasma Sci. 34 (2006).
F.N. Beg et al., Appl.. Phys. Lett. 89 (2006).
R.B. Stephens et al., Journal De Physique 133 (2006).

A literature search for "X-pinch" returns >100 hits

400 kA pulser made for XP tests!

MHD calculations* can model the initial behavior of 200 kA X pinches

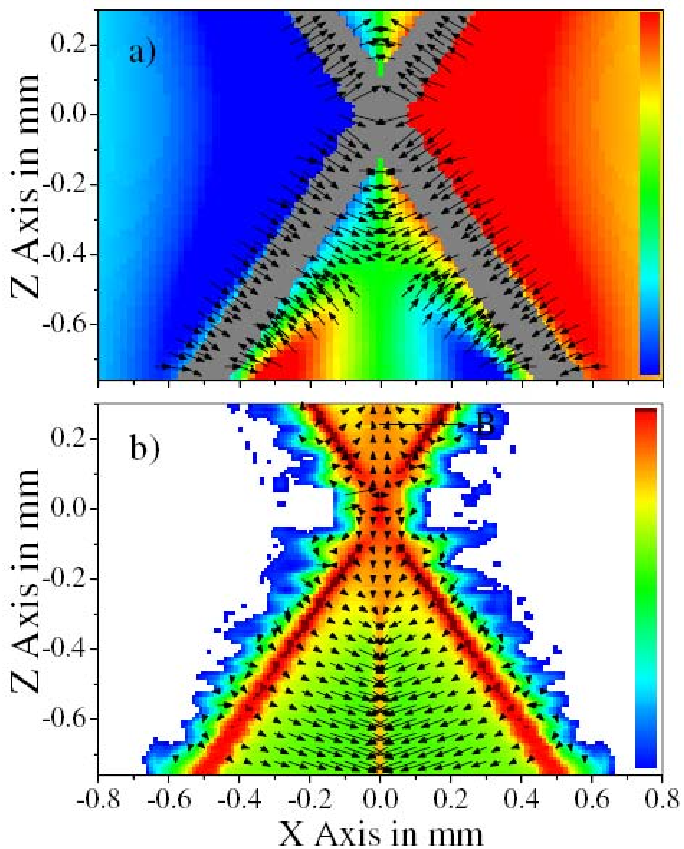


FIG. 1 (color online). Slices through the plane of the wires, showing (a) contours of B_y from -10 (blue) to 10 T (red) and vectors of $j \times B$ at 10 ns, (b) mass density contours from 10^{-4} (blue) to 10^3 kg/m^3 (red), and vectors of velocity at 26 ns.

- **Local magnetic field dominates in legs far from cross-point. Global field produces a magnetic null on the axis only within ±300 μm of cross-point.**
- **Usual ablation dynamics for coronal plasma in legs, results in axial jets.**
- **Ablation rate is function of magnetic field strength—the cores ablate completely in cross-point region and an implosion starts there first**
- **Zippered implosion results in an axial pressure gradient that produces axial mass flow from cross-point region, reducing its mass/length significantly**
- **Rapid radiative cooling and axial mass loss create unstable conditions in cross-point region that lead to formation of micropinch plasmas**

*Chittenden *et al.*, Phys. Rev. Lett. 98, 025003 (2007).

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MHD modeling predicts extreme micropinch plasma conditions consistent with 200 kA data

- **Modeling by Chittenden *et al.** predicts that micropinch parameters are determined as an equilibrium is approached between blackbody radiative cooling losses and ohmic heating**
- **Predicted equilibrium radius and x-ray power (Bennett relation)***

  $r\ (m) = 2.3e\text{-}18 * I^{-14/9} * \beta^{-4/3} * f^{13/9} * N^{10/9} * \ln\Lambda^{1/3}$

  $P\ (W/m) = 6.7e22 * I^{34/9} * \beta^{8/3} * f^{-11/9} * N^{-14/9} * \ln\Lambda^{1/3}$
- **The minimum radius, however, is probably limited to ~1 μm by other processes (eq. predicts 30 nm at 1290x solid density at 1 MA!)**
- **Assuming a lower limit of 1 μm on the radius, then Mo X pinches are predicted to radiate:**
  - **230 kA: 5 GW (~1x solid density)**
  - **1 MA: 80 GW (10x solid density)**
  - **10 MA: 3.4 TW (250x solid density)**
- **By contrast, the 192 laser beams on NIF are designed to each produce a ~2 TW, 5 kJ, ~0.5 mm x-ray source**

*Chittenden *et al.*, Phys. Rev. Lett. (2007).

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Sound simple? What does a high-current X-pinch look like in practice?

- XP Pulser: 4x25 μm W X pinches OK at 0.4 MA in 40 ns
- COBRA: 8x50 μm W X pinch OK at 1 MA in 80 ns
- SATURN in short-pulse mode: ~6 MA in 50 ns
- Assuming mass scales as current squared, then mass goes from 3 mg/cm at 1 MA to ~108 mg/cm! This may be a bit heavy by a factor of ~2—it depends which X pinches one chooses to scale from
- Example 108 mg/cm X pinches:
  - 45 x 125-μm W X pinch (133 kA/wire in leg compared to 125 kA/wire in 8x50-μm at 1 MA)
  - 2 x 600-μm W X pinch
  - 1 x 844-μm W wire (perhaps between two cones?)
  - 1140 x 25-μm W X pinch (if using thin wires needed)

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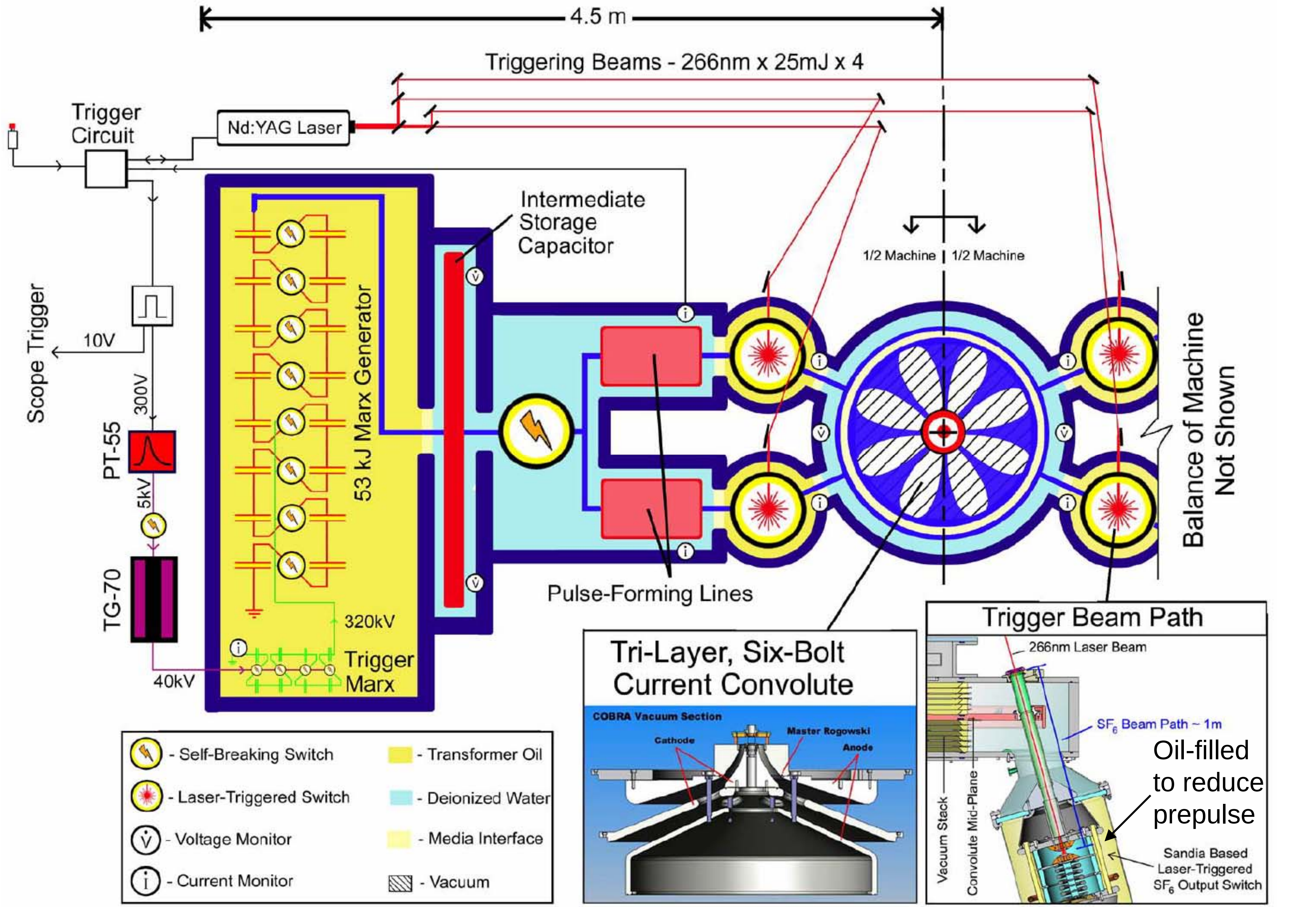
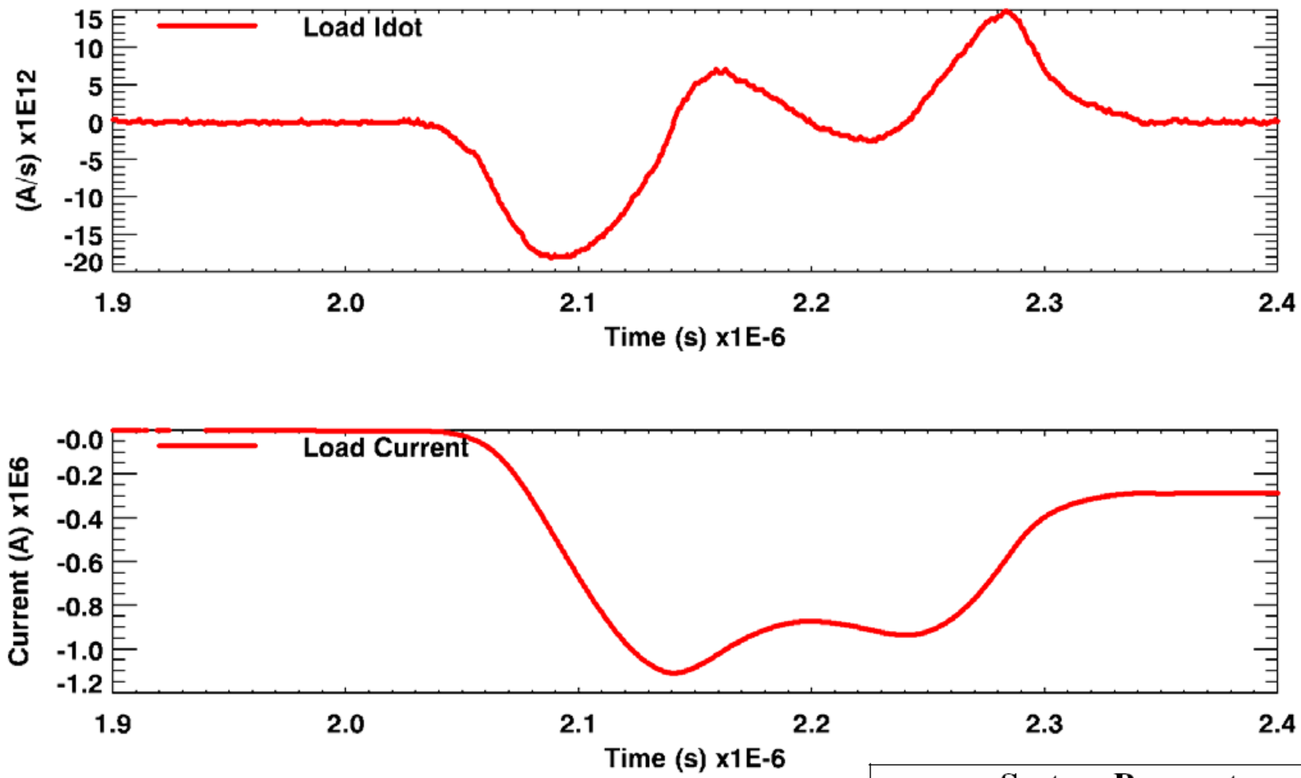
What types of experiments could we do at 1 MA to determine whether to pursue 6 MA tests?

- Understand role of wire number & wire size
  - Using few wires means very large diameters. Will such large wire diameters work at all?
  - Using large number of wires means a very complex cross-point region knot. Will that cause problems?
  - Using one wire (e.g., between two cones) might be simple, but will it allow enough axial mass transfer?
- Test scaling models for power & energy
  - Considerable data exists for Mo (and some W) at 200, 450 kA, will shots at 1 MA scale reasonably from those?
  - How does yield vary with wire material (Al,Ti,Mo,W?) [Opacity starts to become important with higher current]

To study these issues we used the new 1 MA COBRA facility at Cornell University



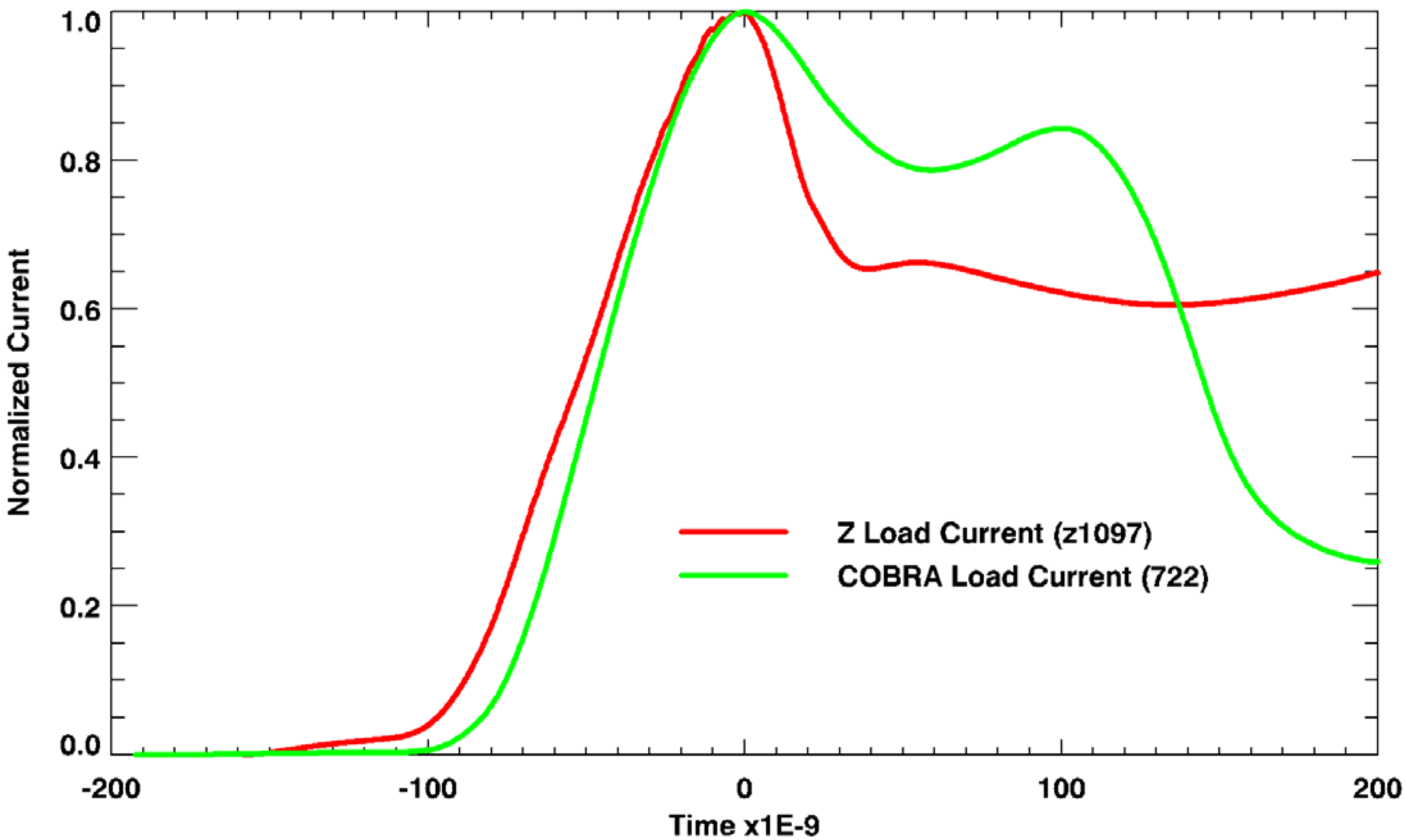
COBRA is a relatively versatile facility



- **1.1 MA peak current in ~80 ns ("Z"-like)**
- **Capable of multiple shots/day**
- **Has capability to generate a variety of pulse shapes (including a relatively constant current for ~200 ns**
- **Designed to have no appreciable prepulse**

System Parameter	Value
Marx Capacitors	32 x 1.35µf
Marx Charge Voltage	70kV
Intermediate Store Capacitance	~46nf
Pulse Forming Line Transit Time	30ns
Pulse Forming Line Impedance	1.8Ω
Roughing Pump Time	15-45min
Hard Vacuum Pump Time	30-45min
Firing Pressure	60 µTorr
Energy Delivered to Load	~5kJ
Repetition Rate	2-4 shots/day
Output Impedance	0.45Ω

COBRA has a slightly faster 10-90% rise time (and no prepulse) compared to Z



COBRA: 58 ns 10-90% rise time; 1.1 MA peak current
SATURN: ~40 ns 10-90% rise time; 6 MA peak current
Z: 69 ns 10-90% rise time; 18 MA peak current
ZR: ~75 ns 10-90% rise time?; 26 MA peak current?

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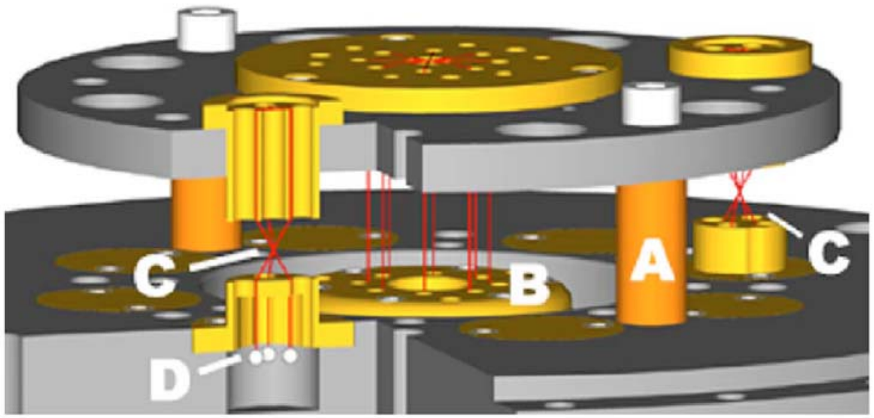
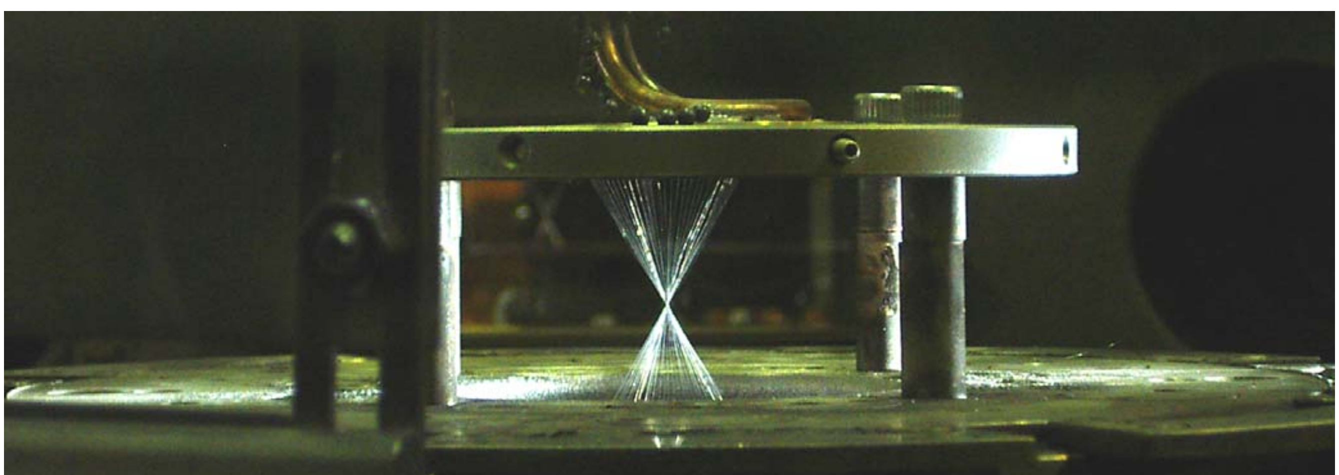
The X pinch was placed as the main load of the COBRA machine

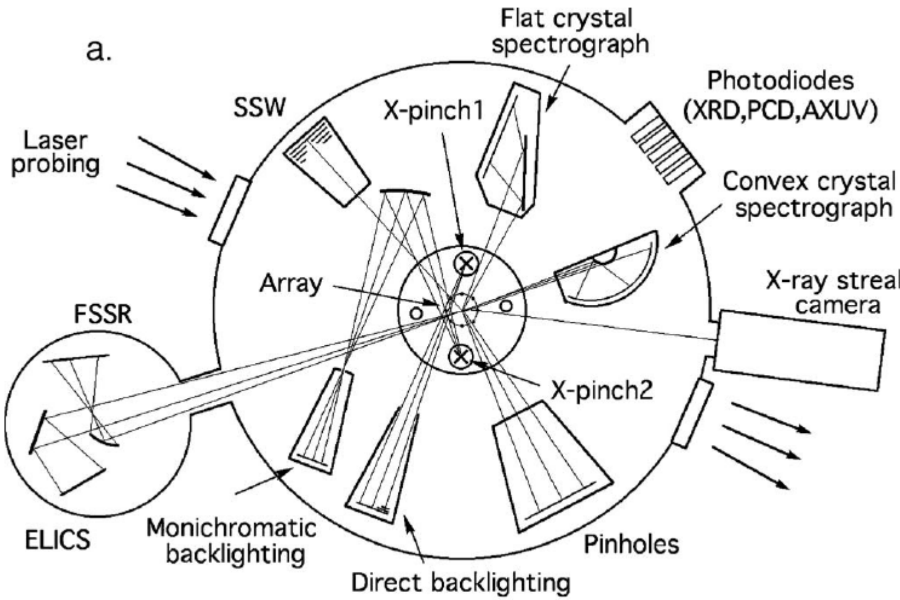


(X-pinch backlighters in the return-current canister were not used during all but one of these shots)

FIG. 1. (Color online) Wire array Z-pinch load assembly with section view of one of two X-pinch backlighters. (A) Return-current post; (B) COBRA pulser cathode; (C) backlighting X pinch; (D) lead weights.



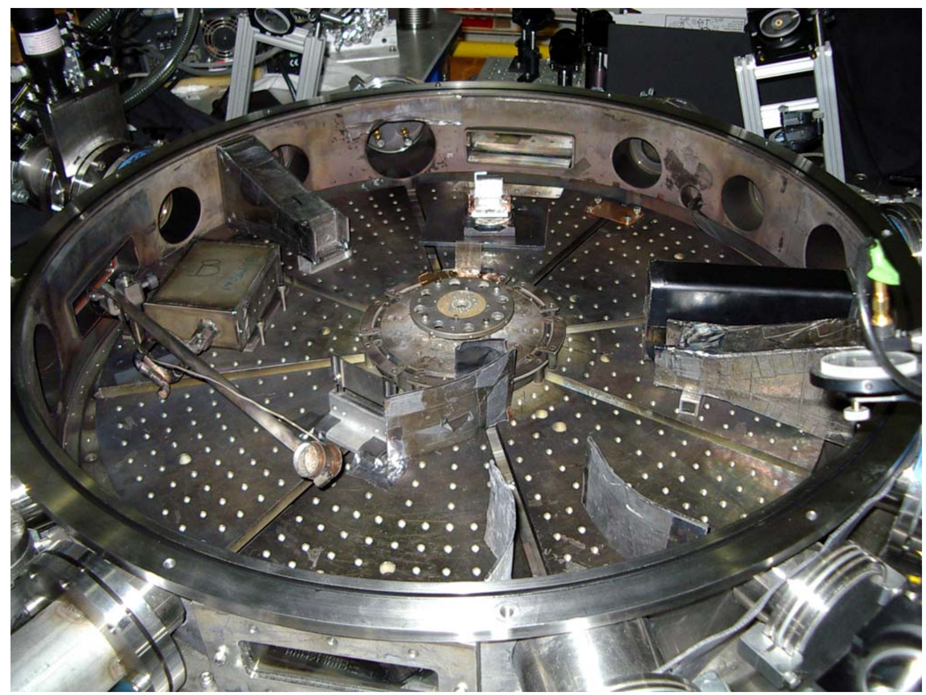
We were able to use a large number of existing diagnostics on the facility



Drawing from Shelkovenko *et al.*, RSI (2006).

PCDs, SiDs, BOLOs, shadowgraphy,
streaked optical self-emission,
slit-step-wedge camera,
time-integrated x-ray pinhole camera,
time-gated open pinhole camera,
spectrometers, backlit test meshes

Vacuum chamber diameter ~ 970 mm



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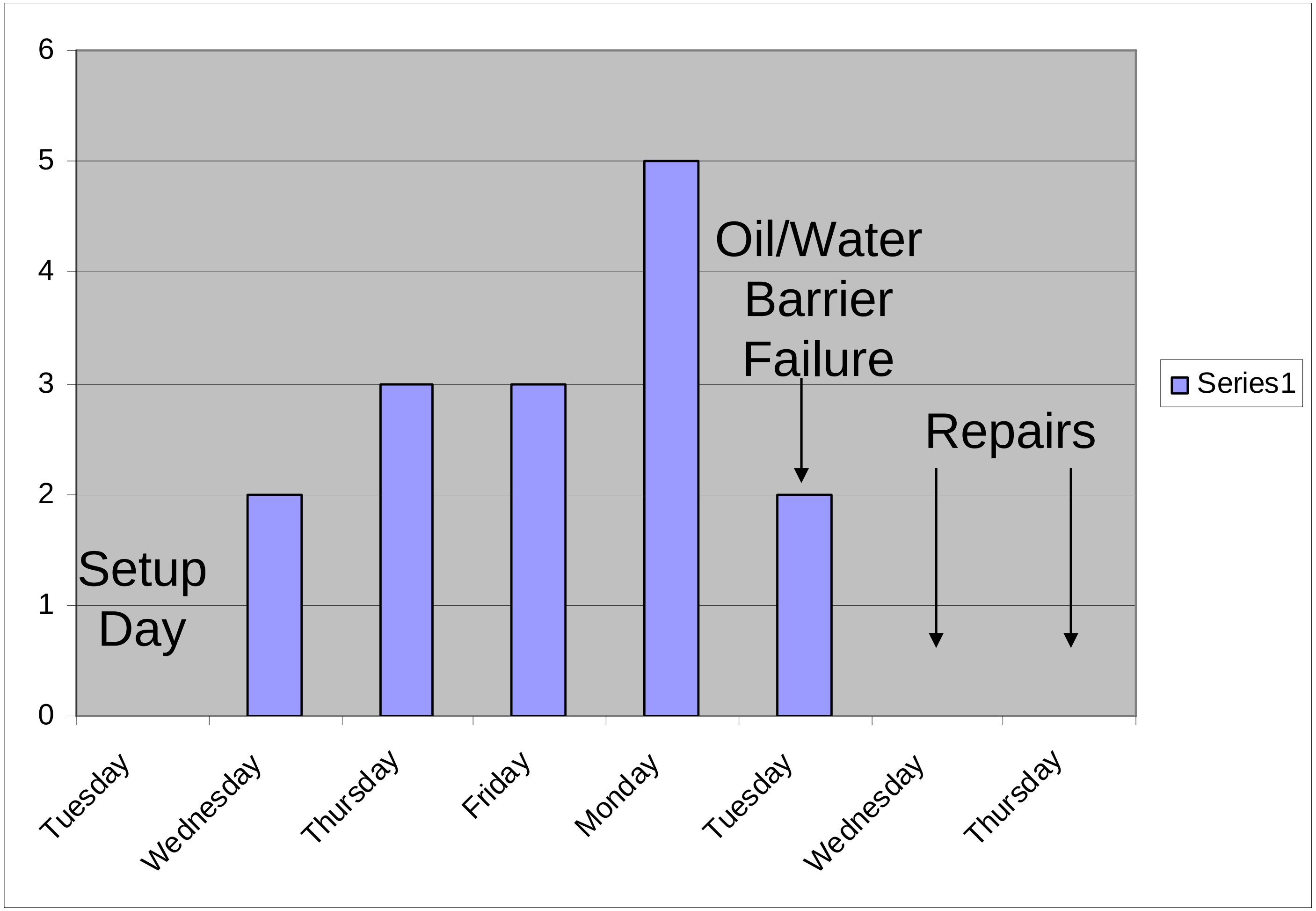
We obtained 15 shots before a machine failure halted the tests



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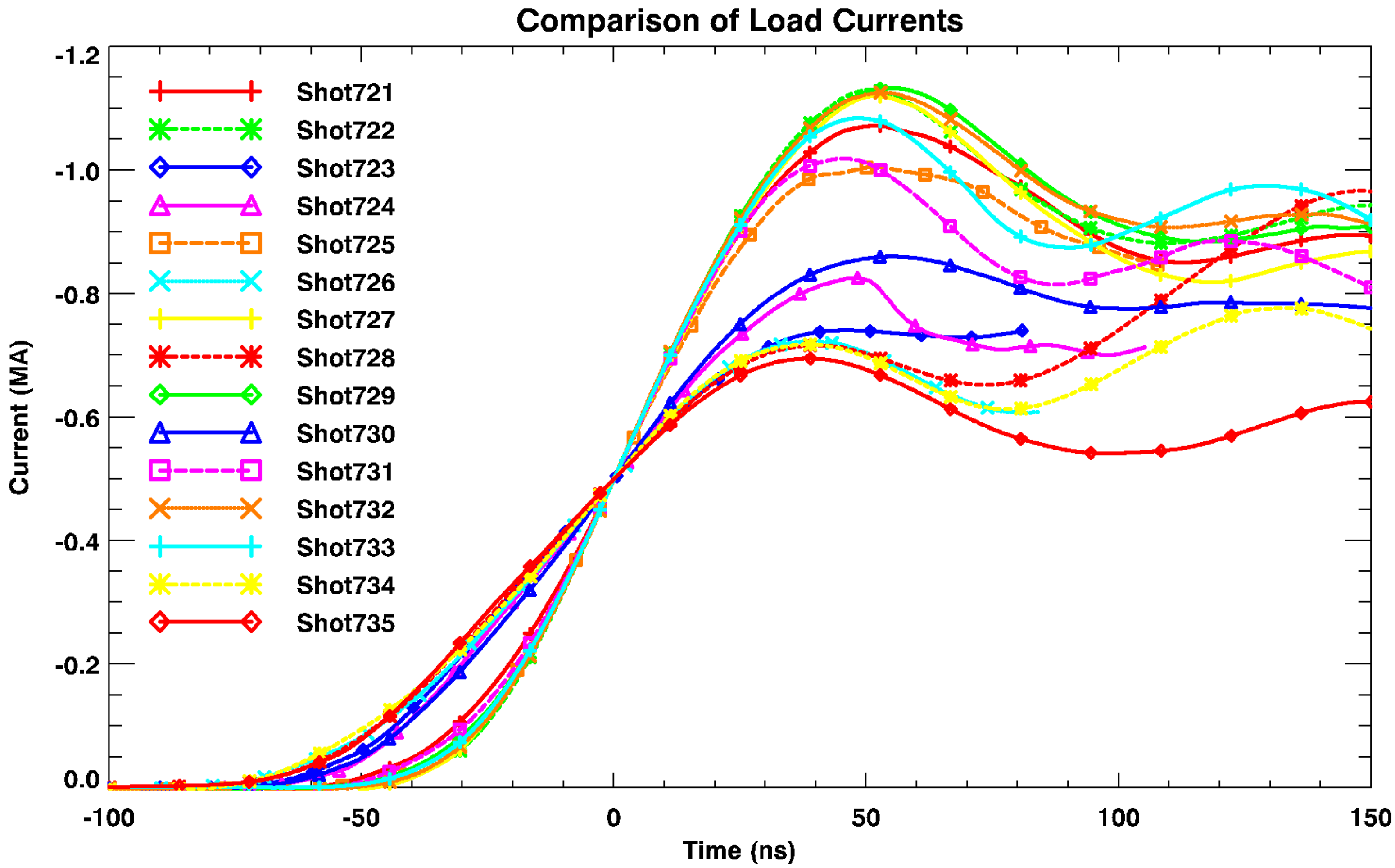
7 of the 15 shots had abnormal current delivery to the load



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The bad machine shots were all due to the same problem: Marx jitter

- Sometimes one side of the machine would fire earlier than the other side.
- If the second side's self-breaking gas switch didn't fire within 40-80 ns of the first side's, an opposing voltage swing appeared across the gas switch making it even more difficult to self-break.
- As a result, the bad shots all had the same, slower-rising current shape because the second switch would self-break after the first side's voltage swung back
- This problem can be mitigated by COBRA's laser triggering system, which was unavailable during these shots. The system was reinstalled later and corrected the problem even when marx banks were mistimed by as much as 80 ns.

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Cornell Experiment Summary (15 shots)

- Tungsten Wire Number Scan (3 mg/cm mass)
  - 2 x 100 μm W (2)
  - 8 x 50 μm W (4)
  - 32 x 25 μm W (1) [Record wire num.]
  - 64 x 18 μm W (1) [Record wire num.]
- Tungsten Wire Number Scan (1.5 mg/cm mass)
  - 2 x 70 μm W (1)
  - 8 x 35 μm W (1)
- X-ray source development (for backlighting, μpinch diag.)
  - 16 x 50 μm Manganin* (3)
  - 8 x 50 μm Manganin* (1)
  - 2 x 125 μm molybendum/rhenium alloy (1)

*Manganin is a Cu86 / Mn12 / Ni2 alloy by atomic number

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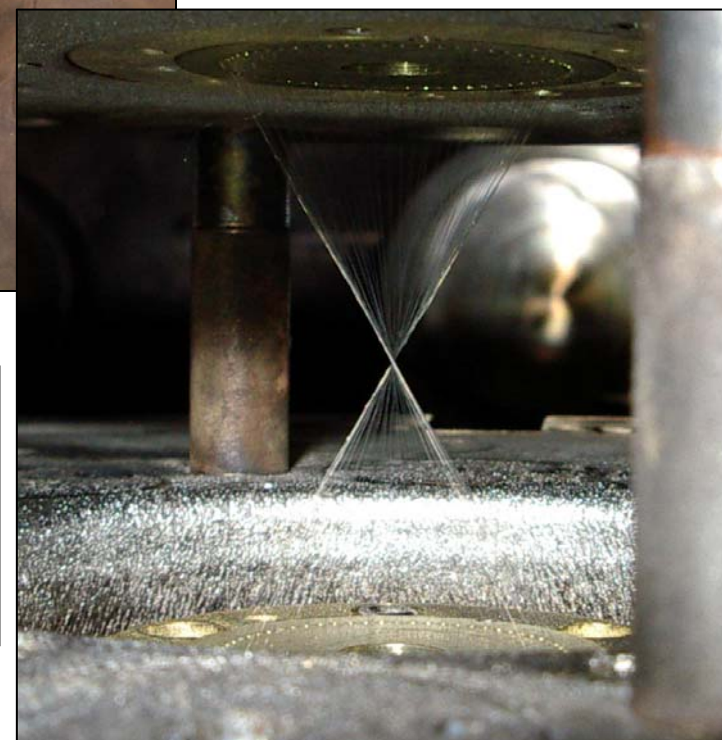
Hardware design and array assembly for the 32-,64-wire arrays was done by J. Douglass & T. Blanchard

Load was first assembled as a wire array on the bench

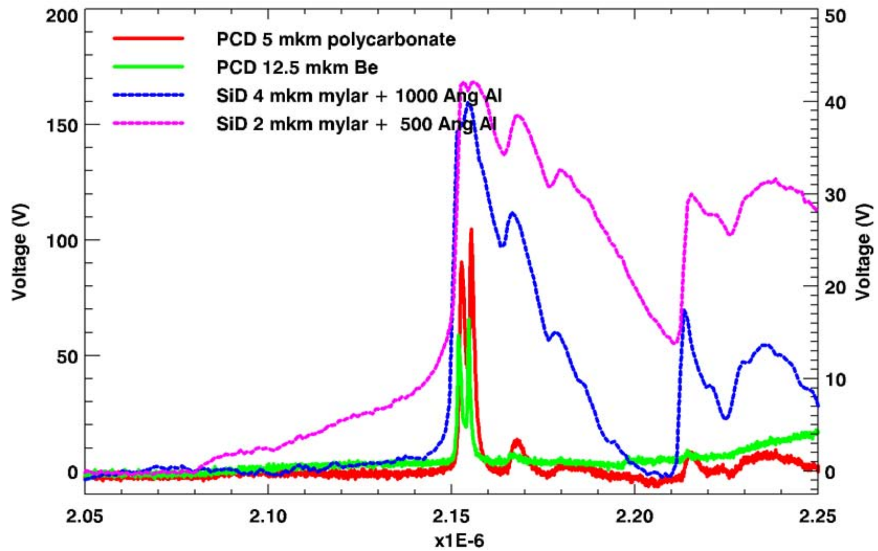
After installing the array in COBRA, the anode was slowly rotated ~190º while combing the wires to keep them taut

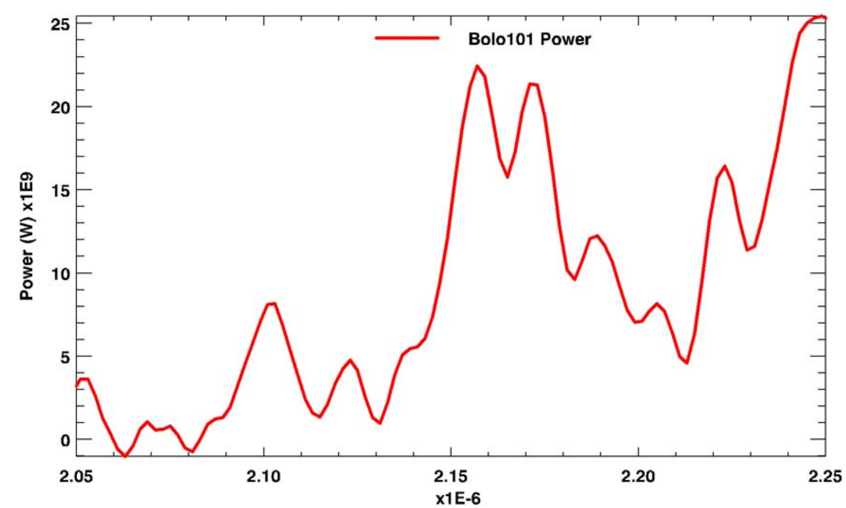
The “large” wires (18,25 μm) made the assemblies relatively robust



X-ray yield measured with bolometers
X-ray power estimated using SiDs, PCDs

- **PCDs routinely used at Cornell and were available on all shots**
- **“Victor’s” and a Sandia bolometer were used on all shots, though first several had poor scope resolution**
- **Si Diodes were added later but had problems getting them not to clip**
- **SiDs were probably in nonlinear response regime even when not clipped (i.e., signals close to bias voltage)**
- **SiDs and PCDs gave very different-looking signals—not clear that this is due entirely to filters. PCDs are also not well-correlated to BOLOs.**





Bolometer yields were about 2 kJ, typically divided among multiple x-ray bursts

- Tungsten Wire Number Scan (3 mg/cm mass)
  - 2 x 100 μm W (2): [3.1 kJ]; 2.2 kJ
  - 8 x 50 μm W (4) 4.1 kJ; 2.3 kJ; [1.3 kJ]; [0.5 kJ]
  - 32 x 25 μm W (1) 2.2 kJ
  - 64 x 18 μm W (1) [1.5 kJ]
- Tungsten Wire Number Scan (1.5 mg/cm mass)
  - 2 x 70 μm W (1) 3.8 kJ
  - 8 x 35 μm W (1) [5.2 kJ]
- X-ray source development (for backlighting, μpinch diag.)
  - 16 x 50 μm Manganin* (3) [0.5 kJ]; 1.4 kJ; 1.9 kJ
  - 8 x 50 μm Manganin* (1) 2.2 kJ
  - 2 x 125 μm Mo/Re alloy (1) [0.7 kJ]

[ ] denotes “bad-current” shots

Published 1 MA X-pinch experiments at UNR typically use less mass and low wire numbers

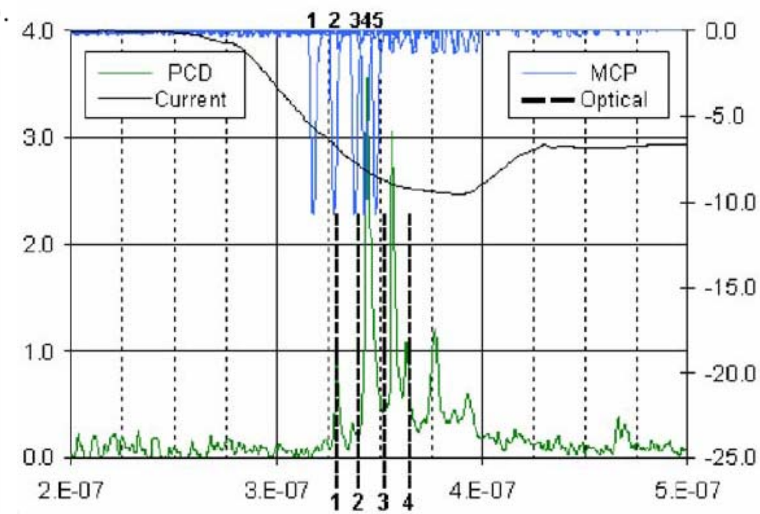
Table 1
X-ray yield and size of the X-pinch emitting region

Less Mass → More bursts → Higher yields?

	E_R	$\Phi(\lambda < 10.3\text{Å})$ mm	$\Phi(\lambda < 3.1\text{Å})$ mm
Mo 2 × 50 μm wires	1	3 × 4.5	2 × 2.5
Mo 2 × 50 μm wires asymmetric	1	3 × 5.4	1.3 × 3.2
Mo 4 × 30 μm wires	0.6	2.7 × 4.4	1.1 × 2.4
Cu 2 × 76.2 μm wires (0.8 mg/cm)	0.6	5.4 × 3.7	2.6 × 2.9
Cu 4 × 63.5 μm wires	0.4	4.3 × 4	1.5 × 2.2
Mo 2 × 65 μm and 2xW 45.7 μm wires asymmetric	1.2	3 × 3	1.8 × 2.4

Relative X-ray yield E_R normalized to the total emitted energy $E = 7.5$ kJ (XRD, 5 μm kimfoil) from a Mo 2 × 50 μm wire X-pinch, and sizes in mm of a central emitting region ($\lambda < 10.3\text{Å}$ & $\lambda < 3.1\text{Å}$, time-integrated images, perpendicular to the central X-pinch axis and along the central axis).

λ<10.3Å λ<4.4Å



V. Kantsyrev et al. / Journal of Quantitative Spectroscopy & Radiative Transfer 99 (2006) 349–362

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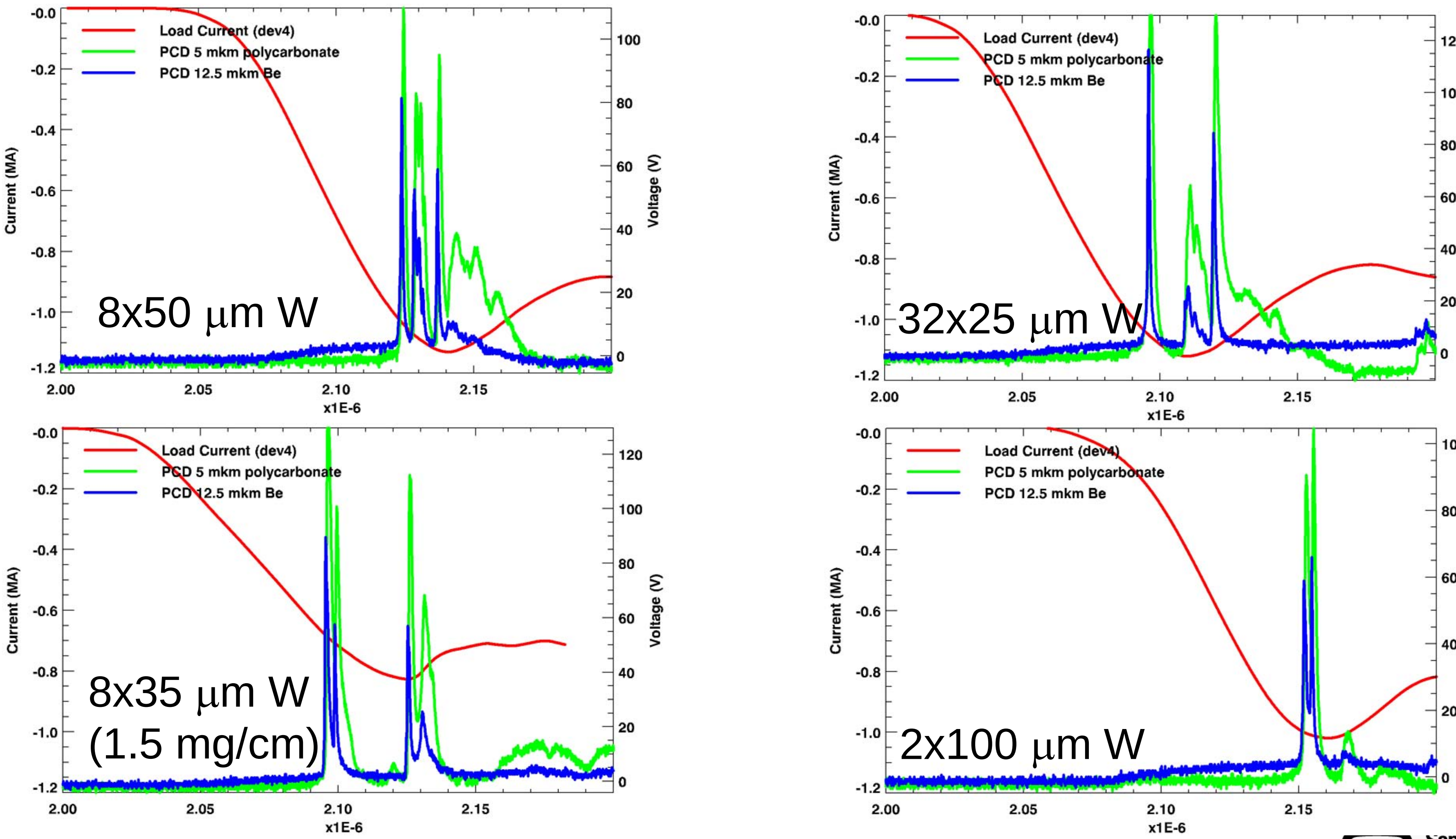
3 mg/cm XPs were intended to go near peak current to suppress multiple bursts & increase peak power



Generally unusual to get x-ray bursts after dI/dt goes positive

Power estimates made using published intrinsic responses put lower bounds on power

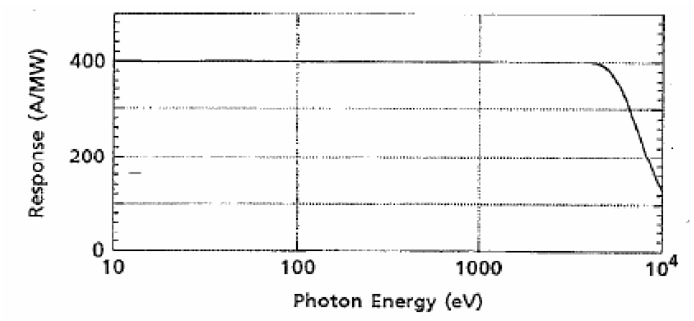
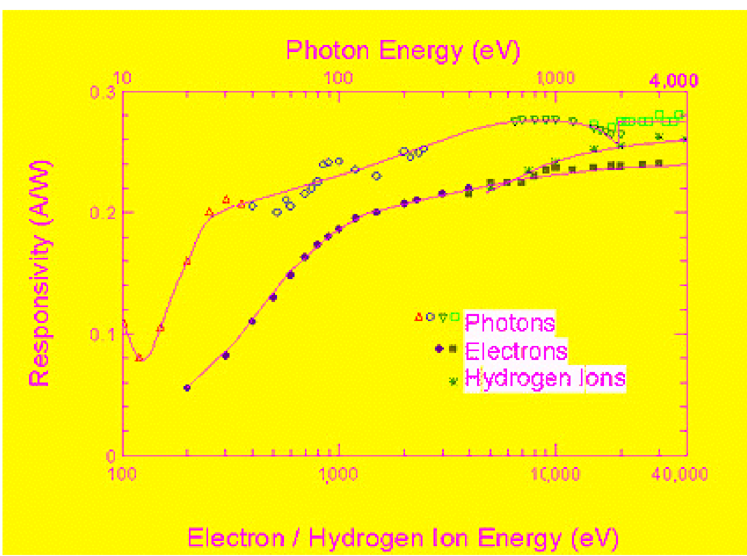
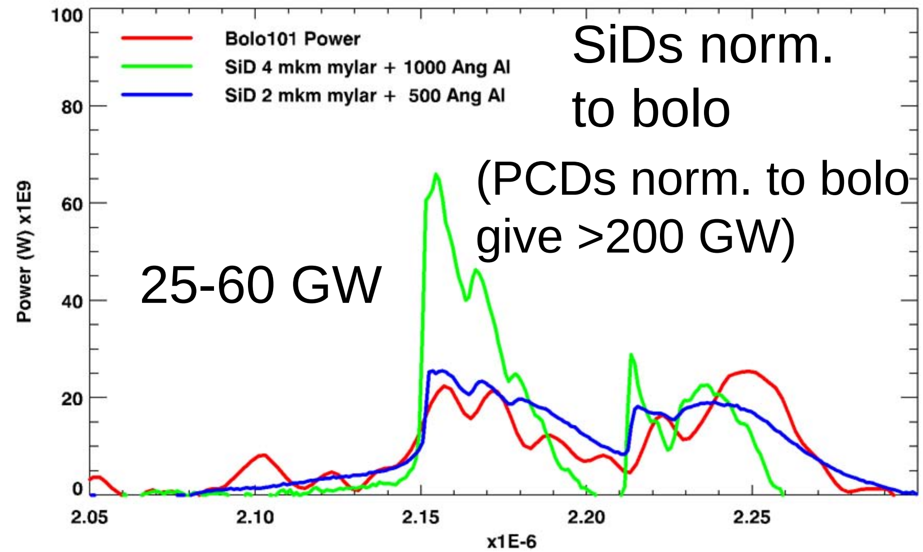


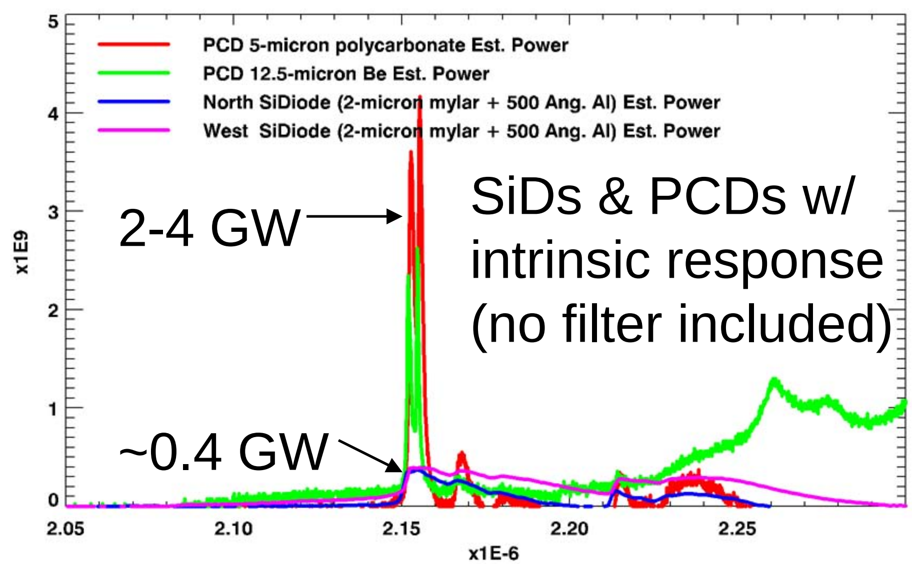
FIG. 3. The theoretical response of an unfiltered diamond PCD. The response at 1 keV is approximately 4×10^{-4} A/W at 100-V bias.

PCD: from Spielman, RSI (1995).



SiD: from http://www.ird-inc.com/





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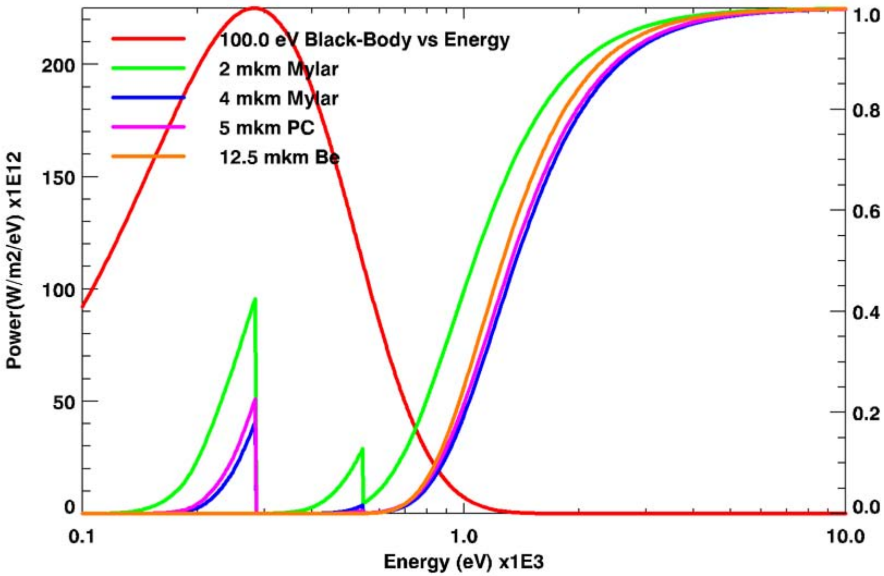
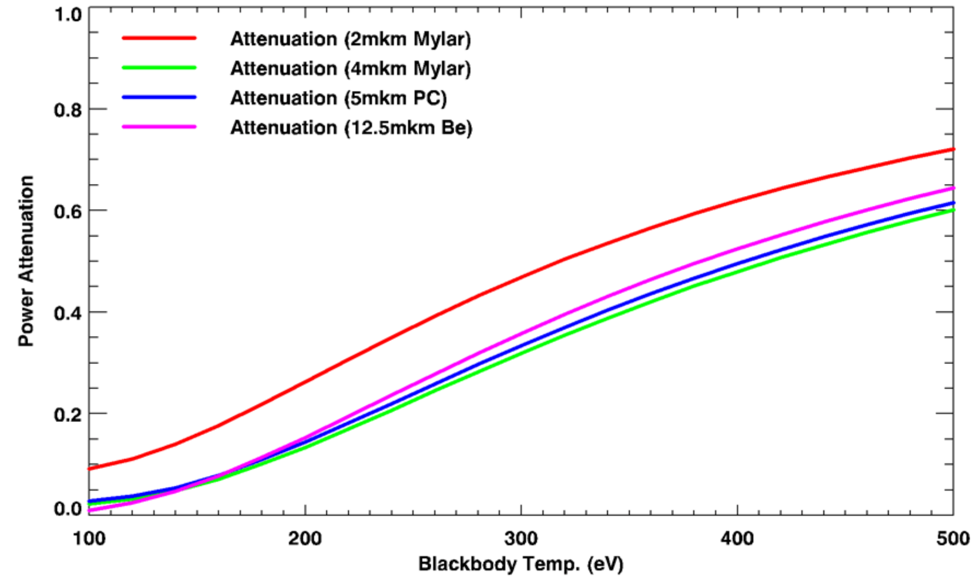
Insufficient data exists to figure out the effect of the filter attenuations





The use of a filter complicates the interpretation of the SiD/PCD waveforms because of the variable attenuation vs. photon energy

Attempting to pull out an absolute power from the diodes using their intrinsic response would require a knowledge of the blackbody temperature (or an array of filters with different spectral cuts)

The SiD/PCD data collected is not really sufficient to make accurate statements about the measured powers
At this point would guess that peak powers ~10 GW

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Any future x-ray power measurements need to be improved

- **Option 1: Use accurately calibrated SiDs without filters for comparison with bolometers and their own intrinsic response**
- **Option 2: Use an array of diodes with different filters (like the XRD array on Z). Determine best fit to data using intrinsic response and filter cuts to constrain the blackbody temperature. ***
- **Option 3: Use a "TEP-like" instrument? ****
- **Other ideas?**

* See, e.g., D.L. Fehl *et al.*, Rev. Sci. Instrum. 76, 103504 (2005).
** H.C. Ives *et al.*, PRST-A&B 9, 110401 (2006).

Relative x-ray power estimates: 12.5 μm Be (5 μm PC) PCD Voltages

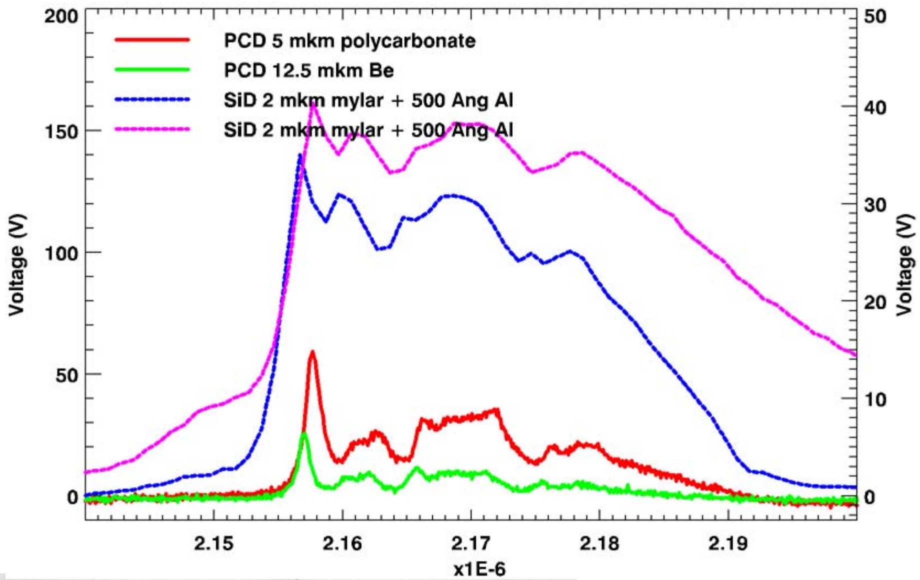
- **Tungsten Wire Number Scan (3 mg/cm mass)**
  - **2 x 100 μm W (2):** [? ?]; 60/65 90/105
  - **8 x 50 μm W (4)** 37/100/30; 82/52/59; [15/7]; [0]
    ---/---/---; 110/80/95; [27/15]; [0]
  - **32 x 25 μm W (1)** 115/27/85 130/65/130
  - **64 x 18 μm W (1)** [87 120]
- **Tungsten Wire Number Scan (1.5 mg/cm mass)**
  - **2 x 70 μm W (1)** 65/50/30 110/87/65
  - **8 x 35 μm W (1)** [90/60+57/25 130/100+110/67]
- **X-ray source development**
  - **16 x 50 μm Mang. (3)** [0]; 15/12/7; 26/10
    [0]; 30/22/8; 59/35
  - **8 x 50 μm Mang. (1)** 60/20 105/40
  - **2 x 125 μm Mo/Re (1)** [4] 21

[ ] denotes "bad-current" shots

W radiates better than Manganin

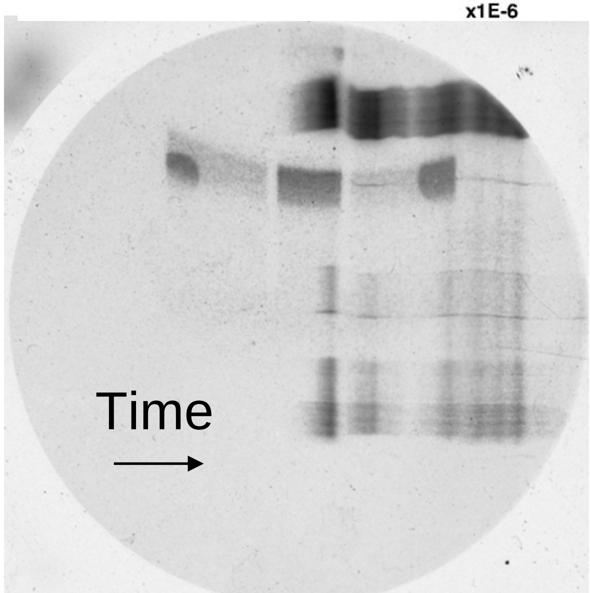
Highest Power: 32x25 μm W

Comparison between X-ray streak camera data and PCD/SiD shows considerably more detailed structure in high-energy x rays



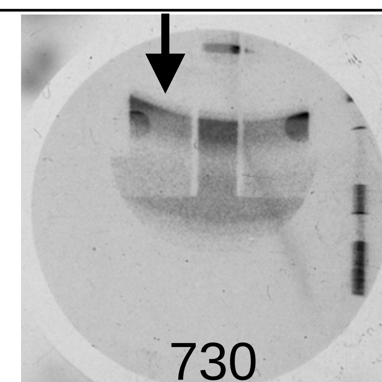
X-ray streak camera looked at the self-emission from entire X pinch through an array of 12 filters

Streak camera only successfully timed on a few shots. It had strange wiggly behavior and only 8 of 12 filters visible…?

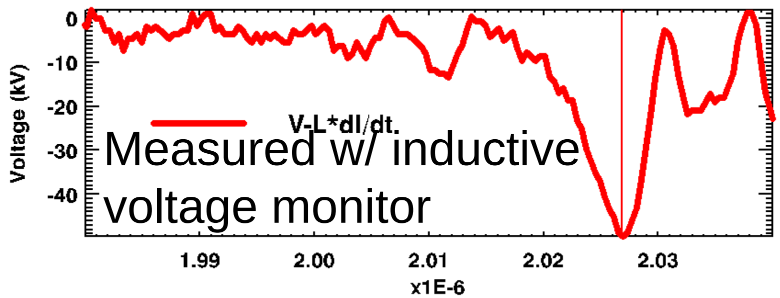


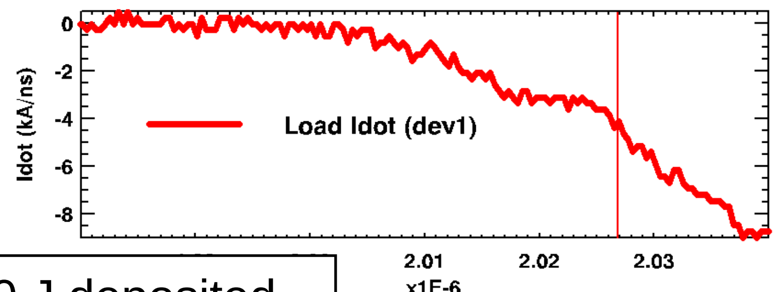
12.7 μm polyimide
Ross Triplet (Zn,Cu,Ni)
12.7 polyimide+12.5 Ti
775 μm polyimide
12.7 polyimide + 7 Ti
12.7 polyimide + 10.5 Al

Time-integrated straight-thru emission (backlighting thru XRSC hardware!!!)

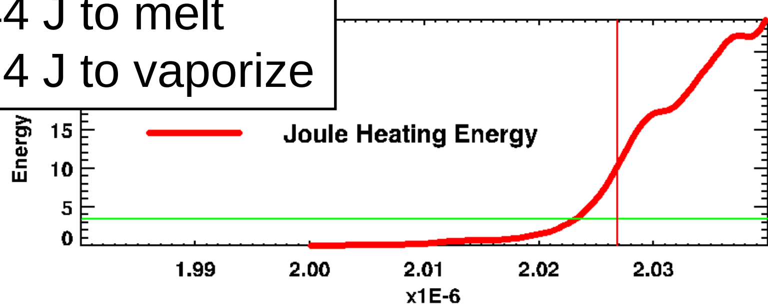


X pinches were observed to have a wire initiation & ablation phase just like wire arrays

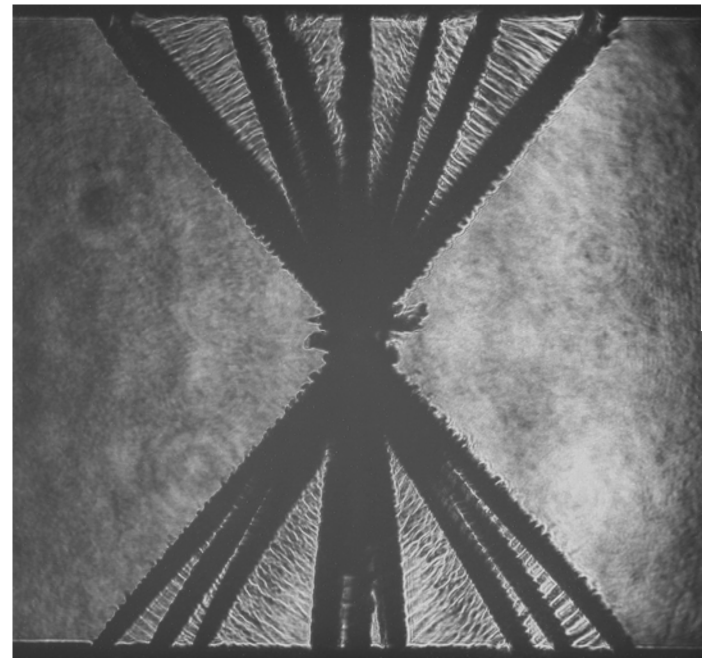




~10 J deposited
3.44 J to melt
35.4 J to vaporize



Not sure if wire initiation has been measured before in X pinches?



Coronal plasma ablation streams perpendicular to wires (not new)

Results similar to ~0.01 kA/ns single-wire energy deposition in W (e.g., D.B. Sinars *et al.*, Phys. Plasmas (2001).)

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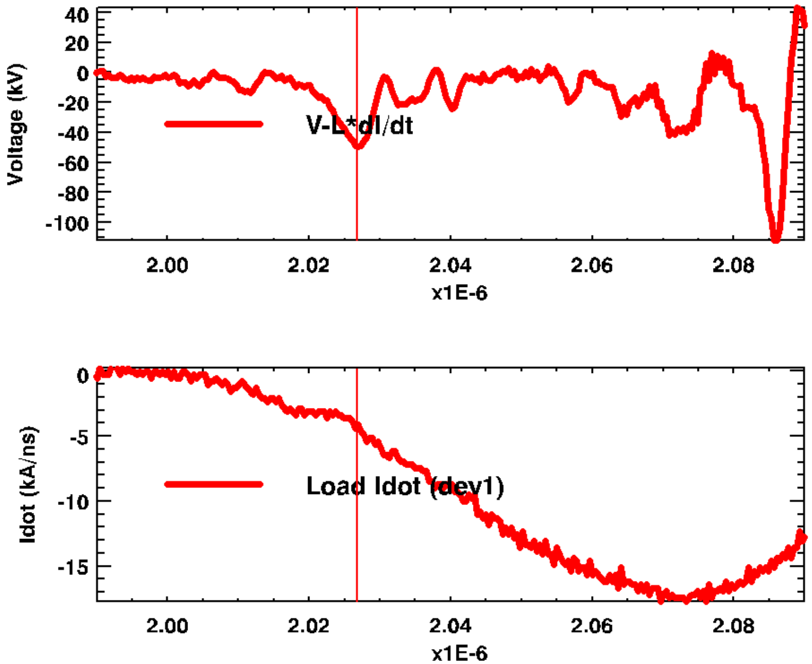
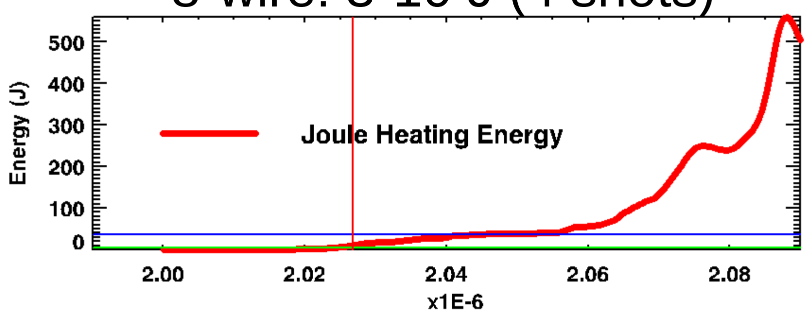
Voltage collapse in 2-wire XPs not obvious, using dI/dt as fiducial gives similar results to others

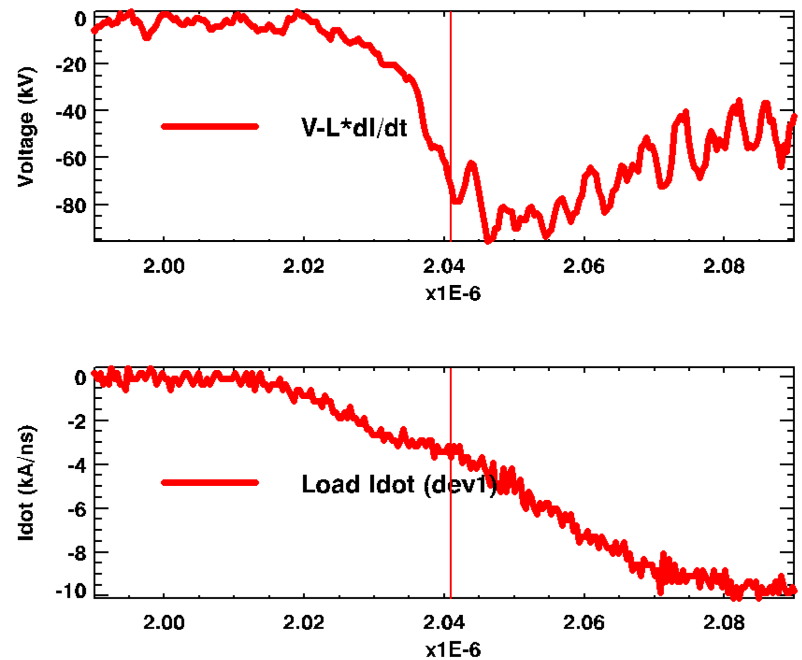
Clear voltage collapse in 8x50 μm W XP



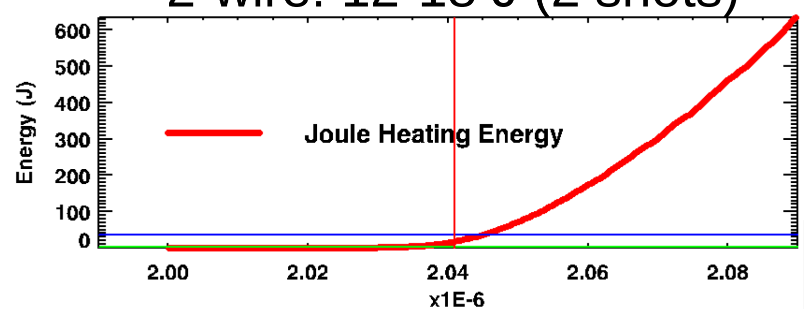
8-wire: 3-10 J (4 shots)



Voltage stays high, but with ringing in 2x100 μm W XP



2-wire: 12-18 J (2 shots)



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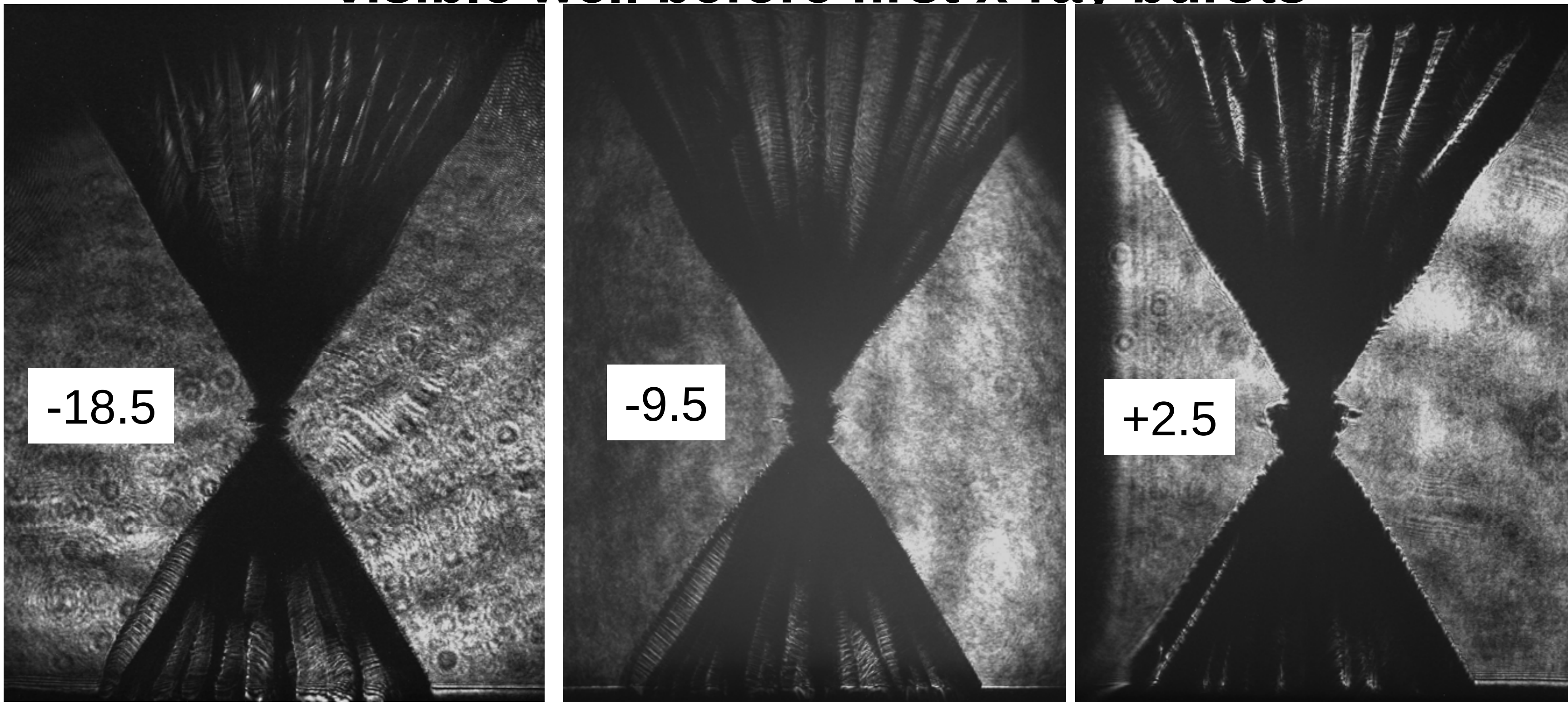
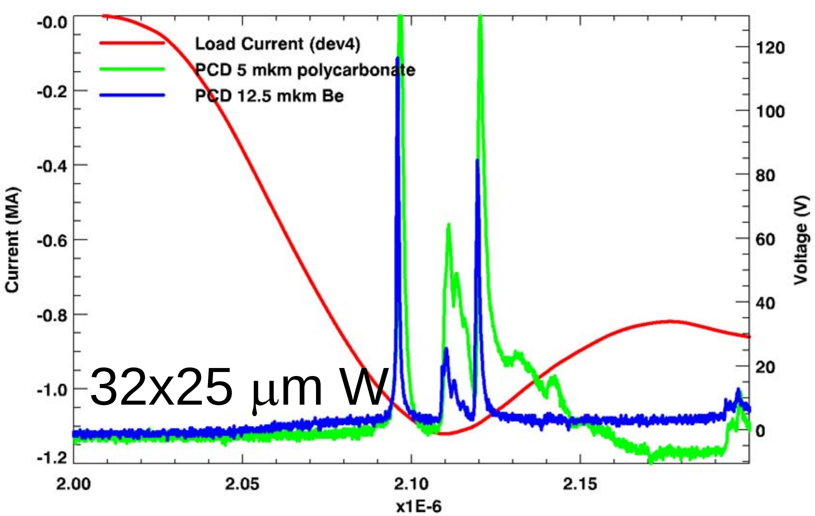
The 2-wire XPs may have received more resistive wire heating than the higher wire number XPs

- **Tungsten Wire Number Scan (3 mg/cm mass)**
  - **2 x 100 μm W (2): 18 J; 12 J**
  - **8 x 50 μm W (4) 5-10 J; 3-5 J; [3-8 J]; [5-7 J]**
  - **32 x 25 μm W (1) 5-8 J**
  - **64 x 18 μm W (1) 6-7 J**
- **Tungsten Wire Number Scan (1.5 mg/cm mass)**
  - **2 x 70 μm W (1) 8-10 J**
  - **8 x 35 μm W (1) [2.5-5 J]**
- **All of the 2-wire X pinches appear to have had more energy deposited before the "voltage collapse" (change in dI/dt). Those three shots did not have a clear voltage collapse.**
- **The listed ranges are due to the uncertainty as to when the voltage collapse occurs.**

[ ] denotes "bad-current" shots

Expansion in cross-point region is visible well before first x-ray bursts



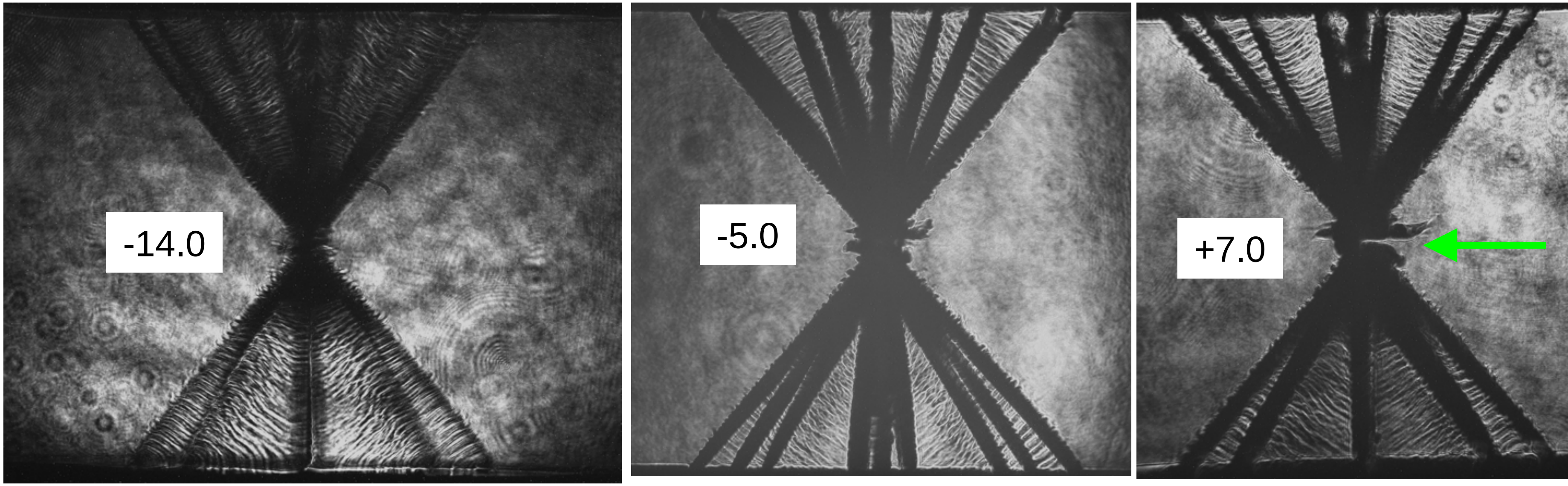


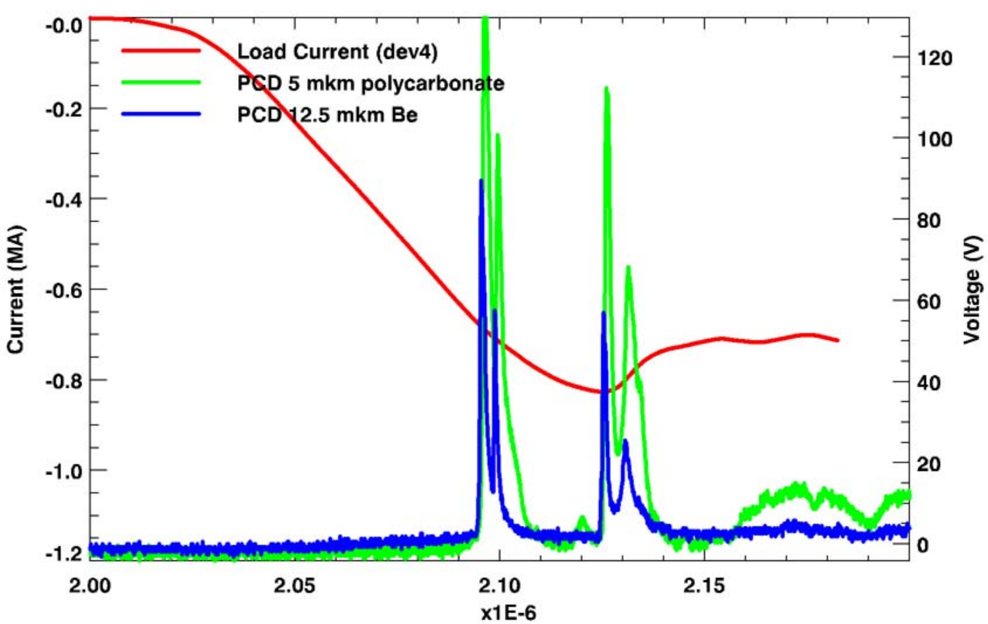
Is the cross-point region actually forming very small-diameter necks as with 200 kA X pinches?

If there is plasma expanding from the cross-point, is it carrying significant current? What fraction of the current might be flowing in small necks?

In one case a horizontal gap is visible after the 1st x-ray burst

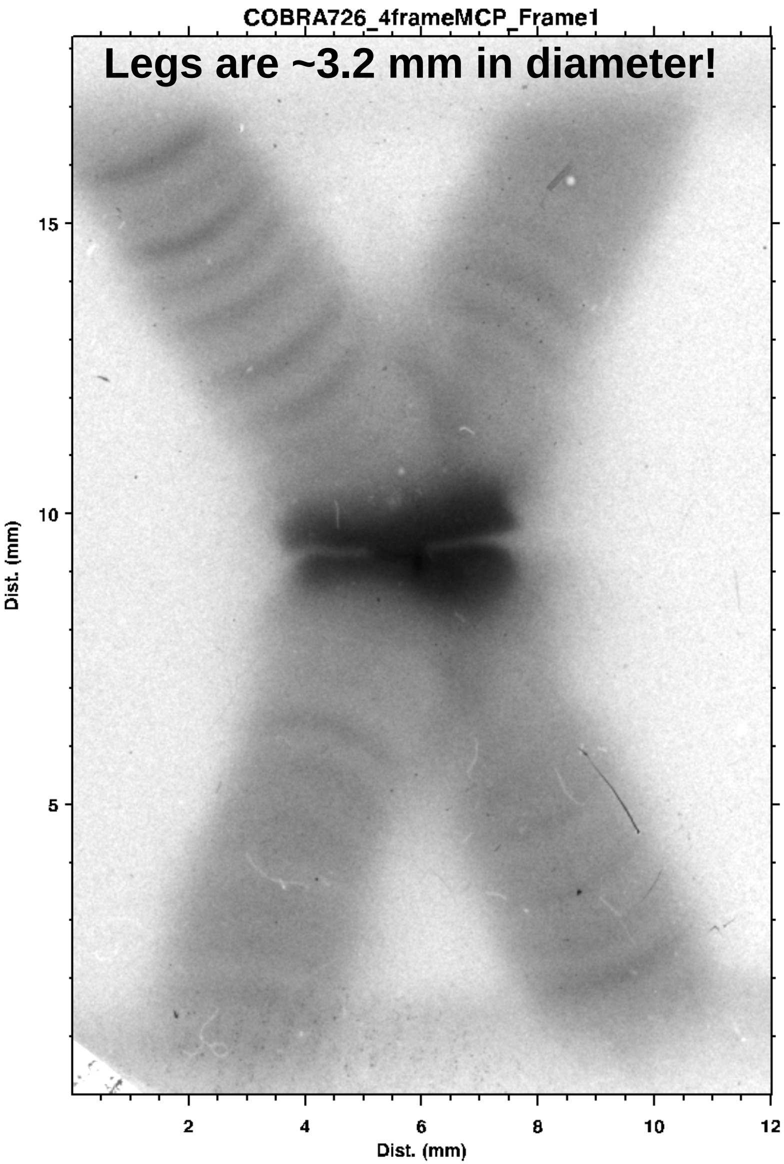
724

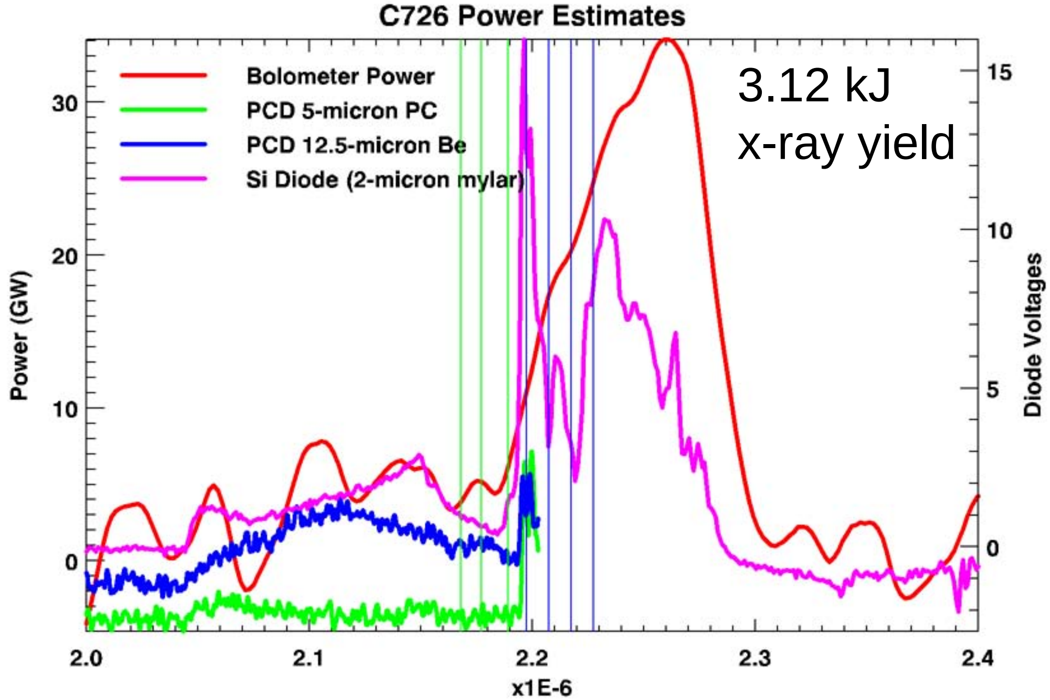


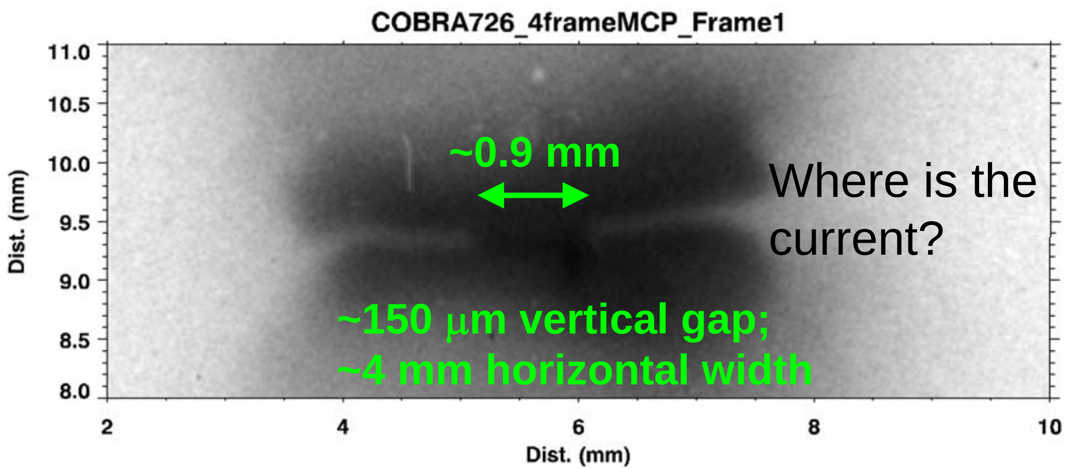


If small necks are forming in the cross-point region, the spatial resolution (~100 μm) and long pulse duration (few ns) may make it difficult to see with laser backlighting

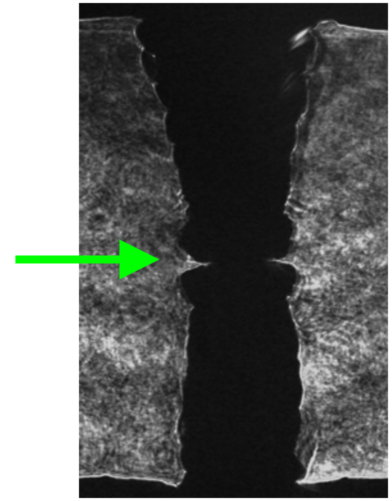
2 x 100-μm W X pinch showed an amazing aspect ratio for the cross-point region



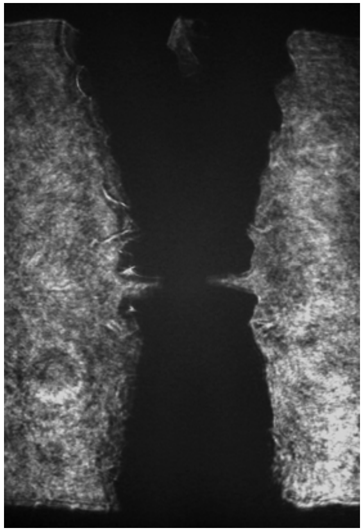




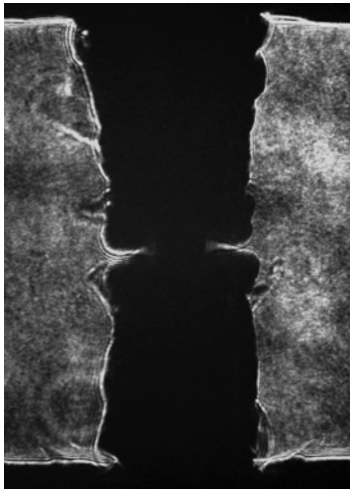
Side-on optical backlighting of 2x125 μm Mo/Re XP shows compression in plane of XP as well



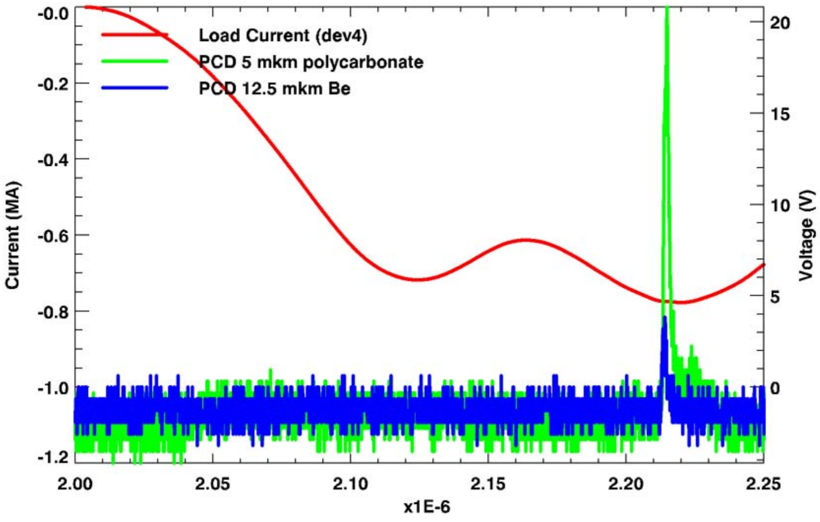
-66.1



-57.1



-45.1



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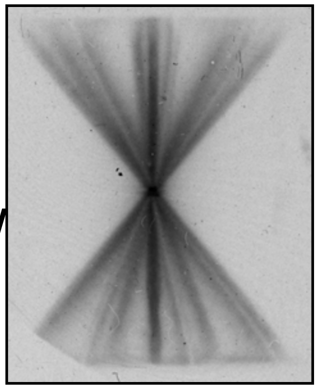
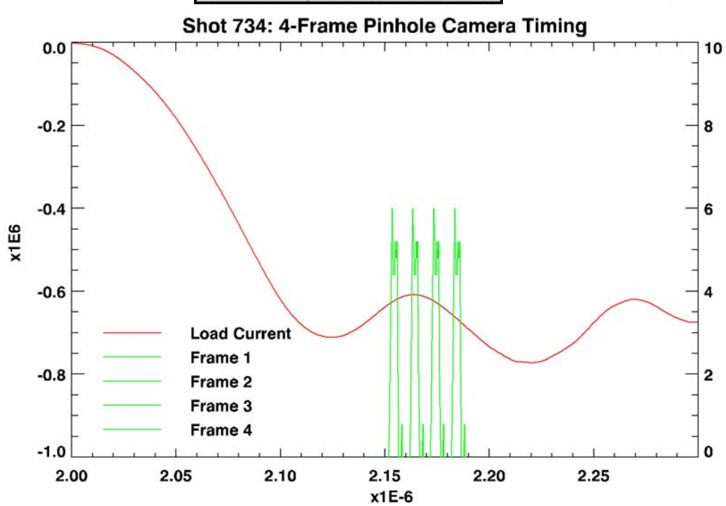
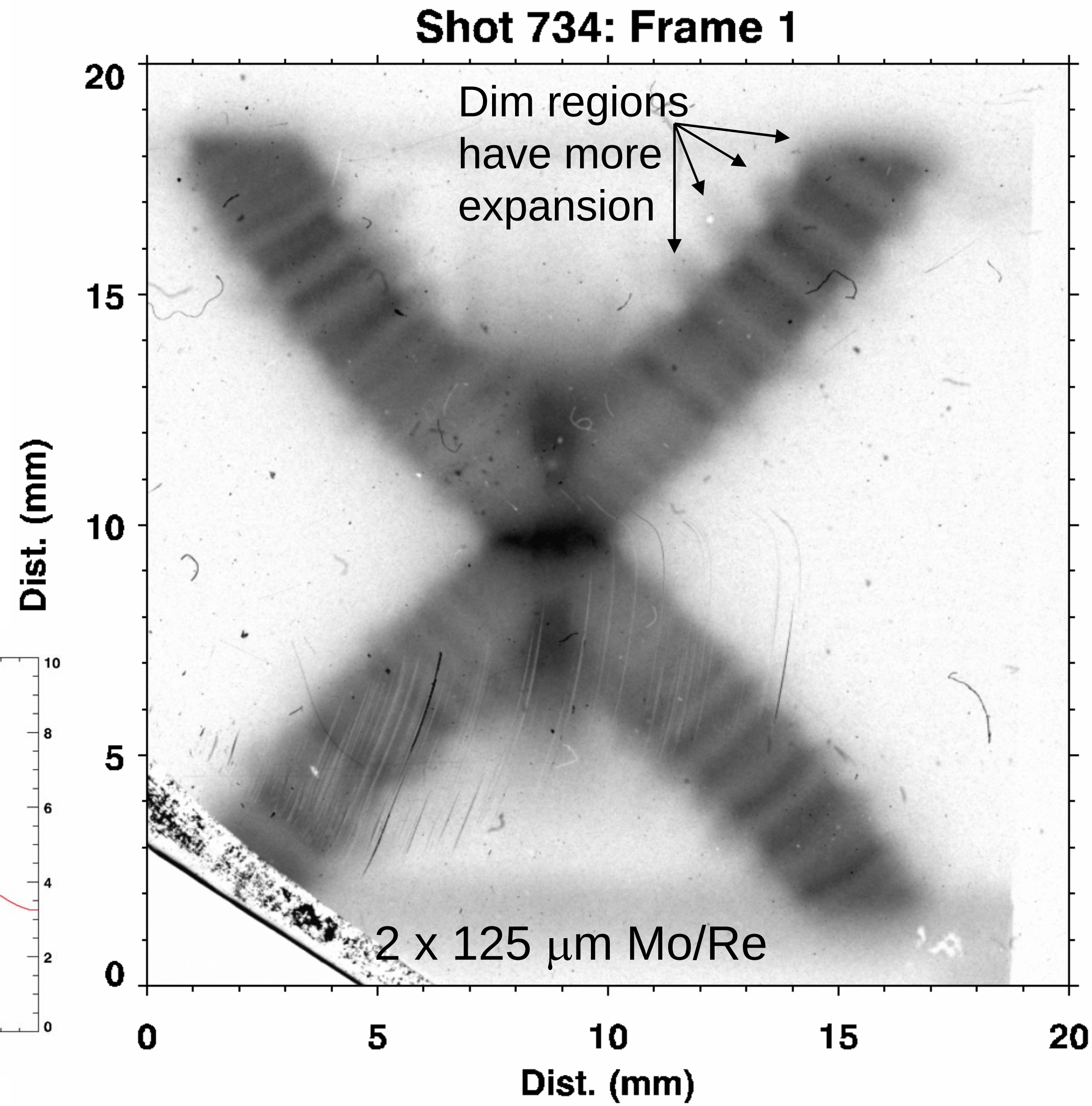
The striations in the legs of 2-wire XPs appear to be caused by non-uniform wire expansion

Also note that 2-wire XPs have very subdued axial jets relative to higher wire numbers

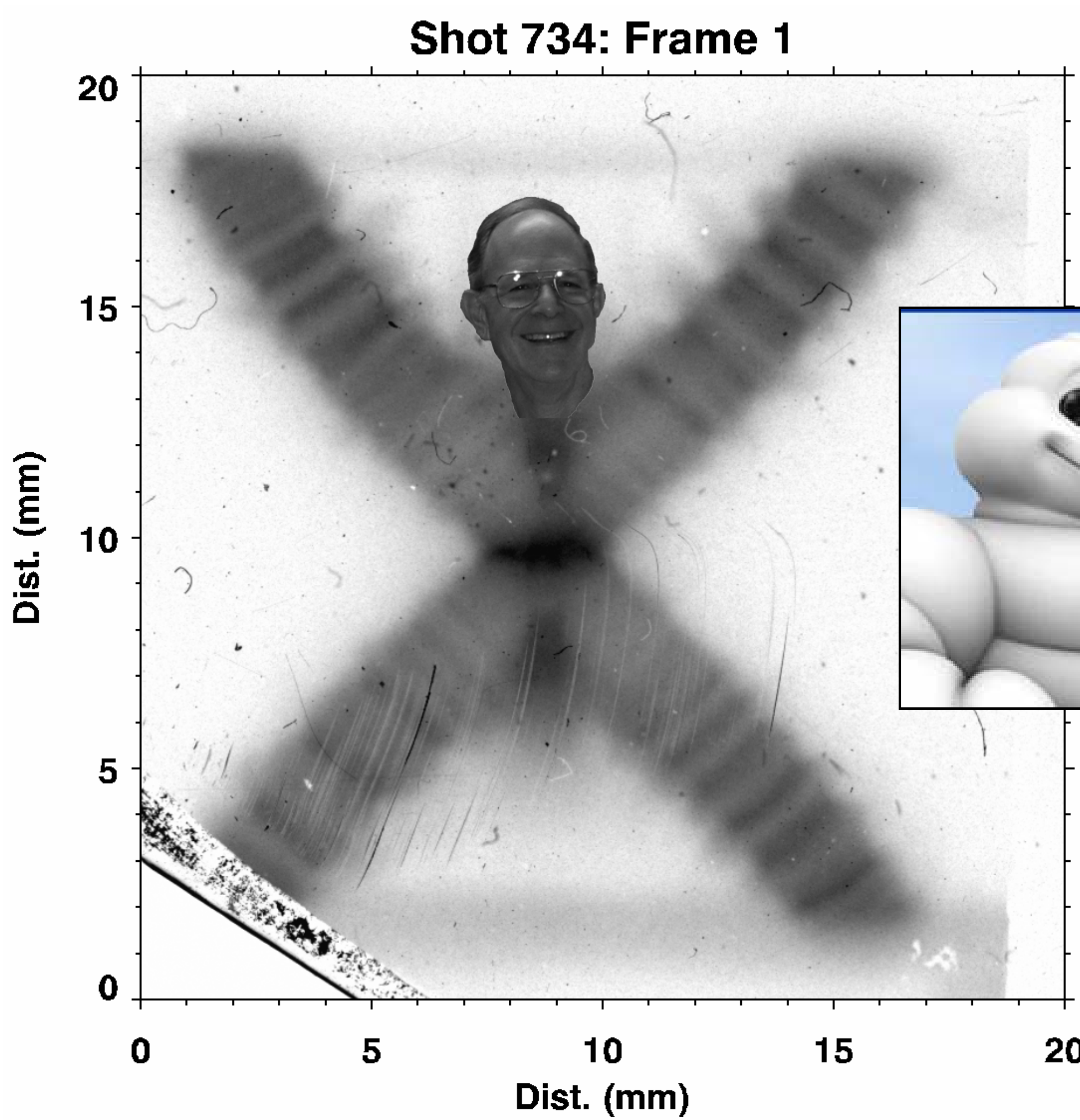
8x50 μm W

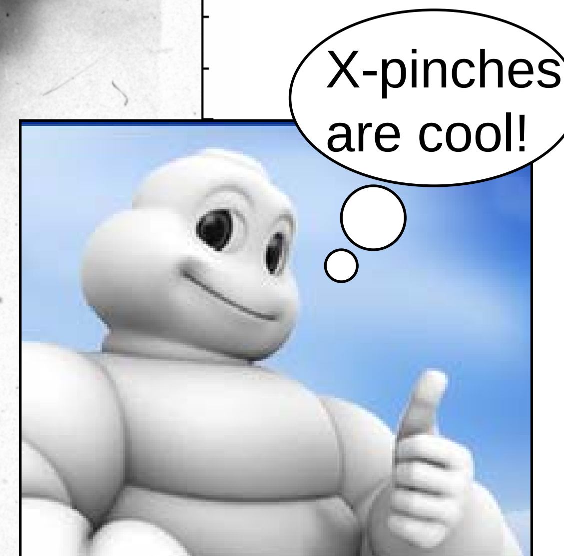




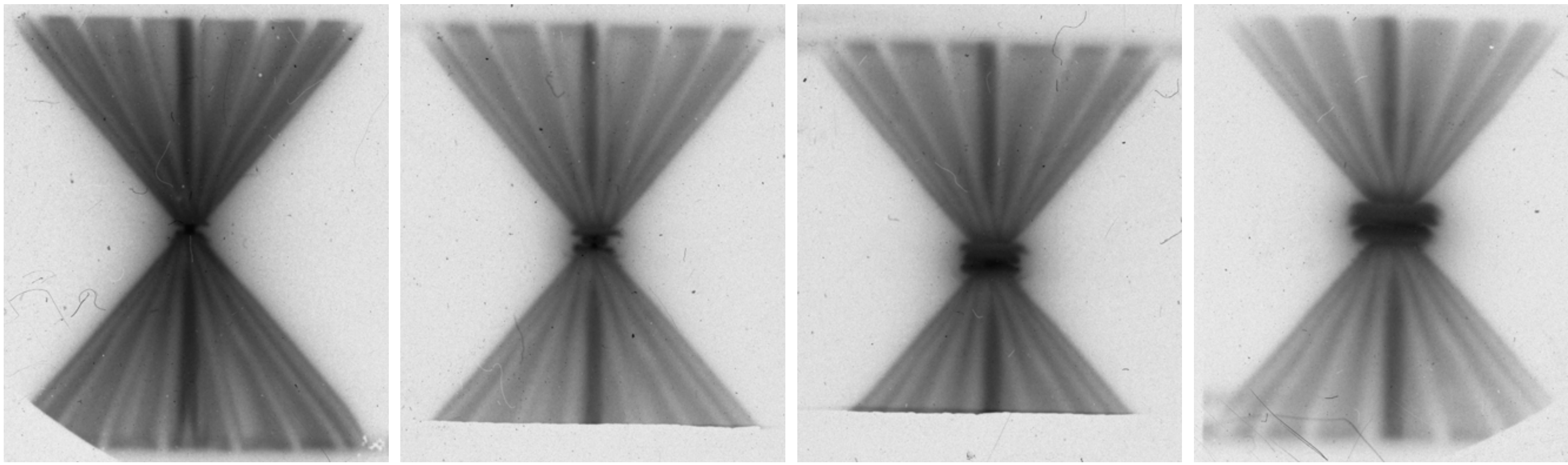


Prof. Hammer described the two-wire X pinches as "Michelin tire men"



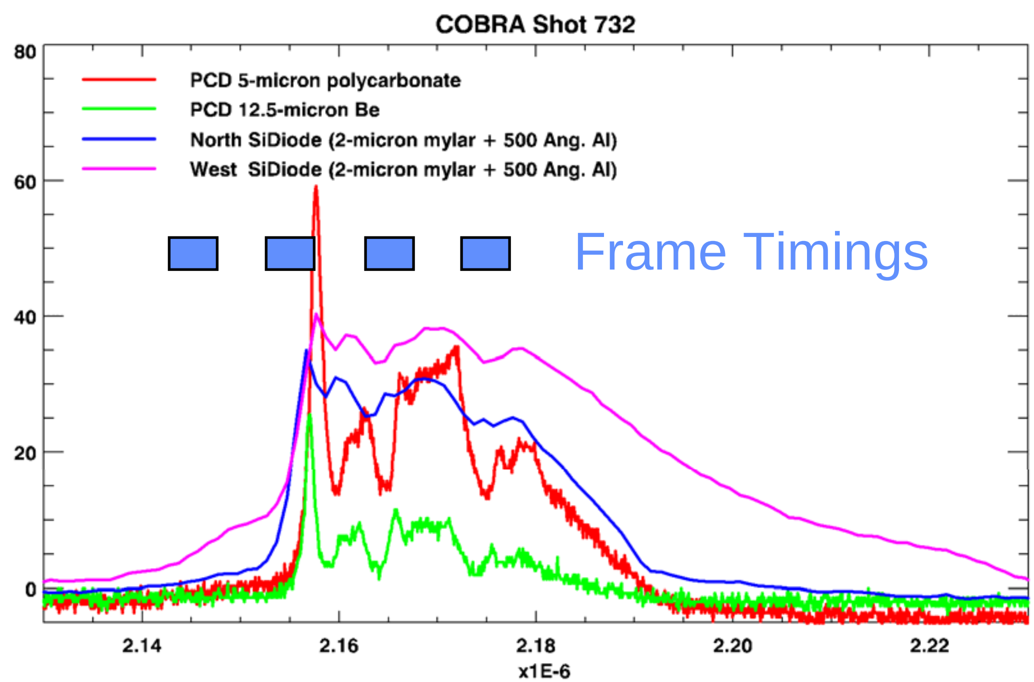


4-Frame camera images suggest that some soft x-ray emission comes from the legs & axial jet

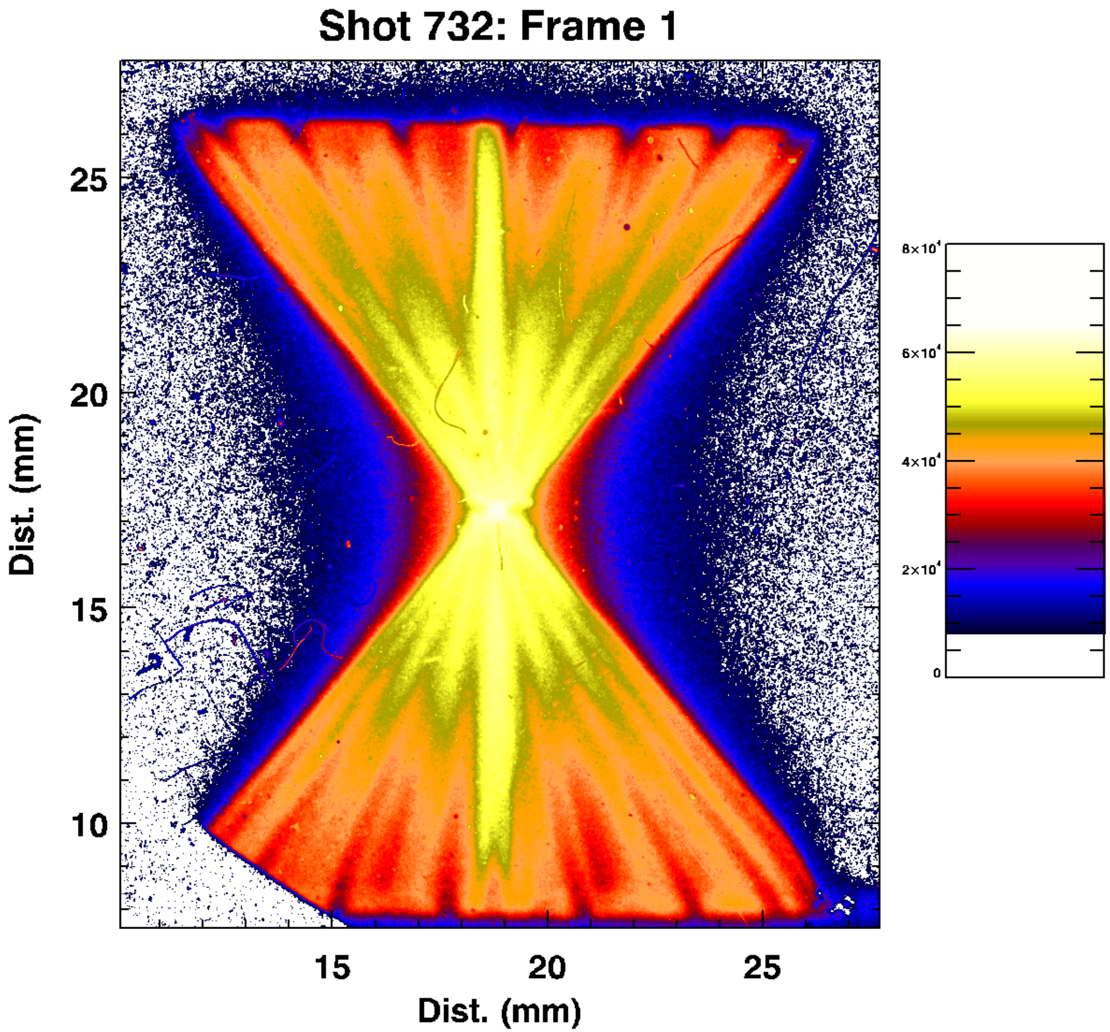


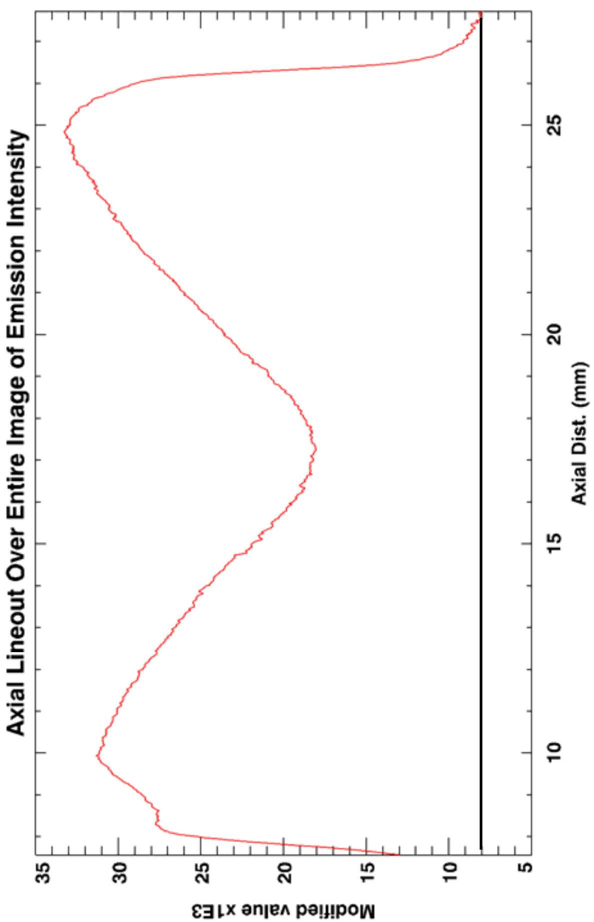
Note that image intensities don't correlate with measured x-ray powers

Comparison of intensity from various regions is only valid if spectral content is similar (open pinhole means signal is determined by spectral response of MCP)



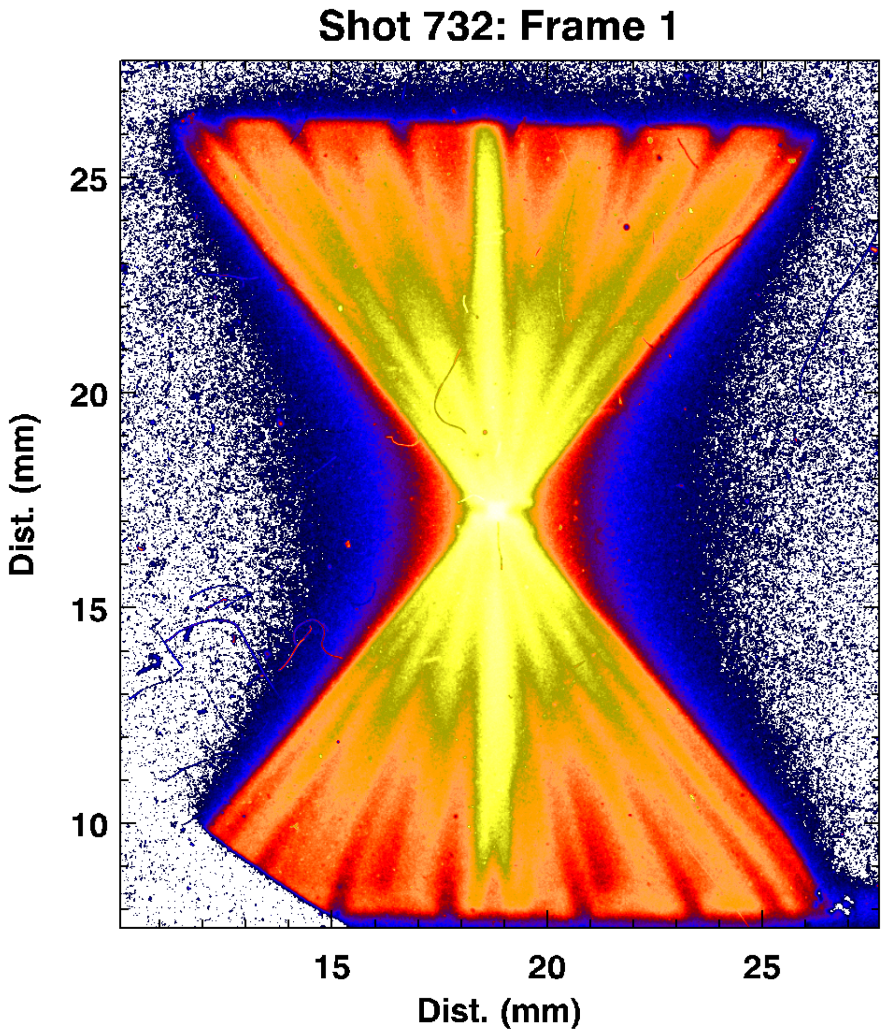
Axial lineout over image implies more emission from legs than cross-point, but this is misleading

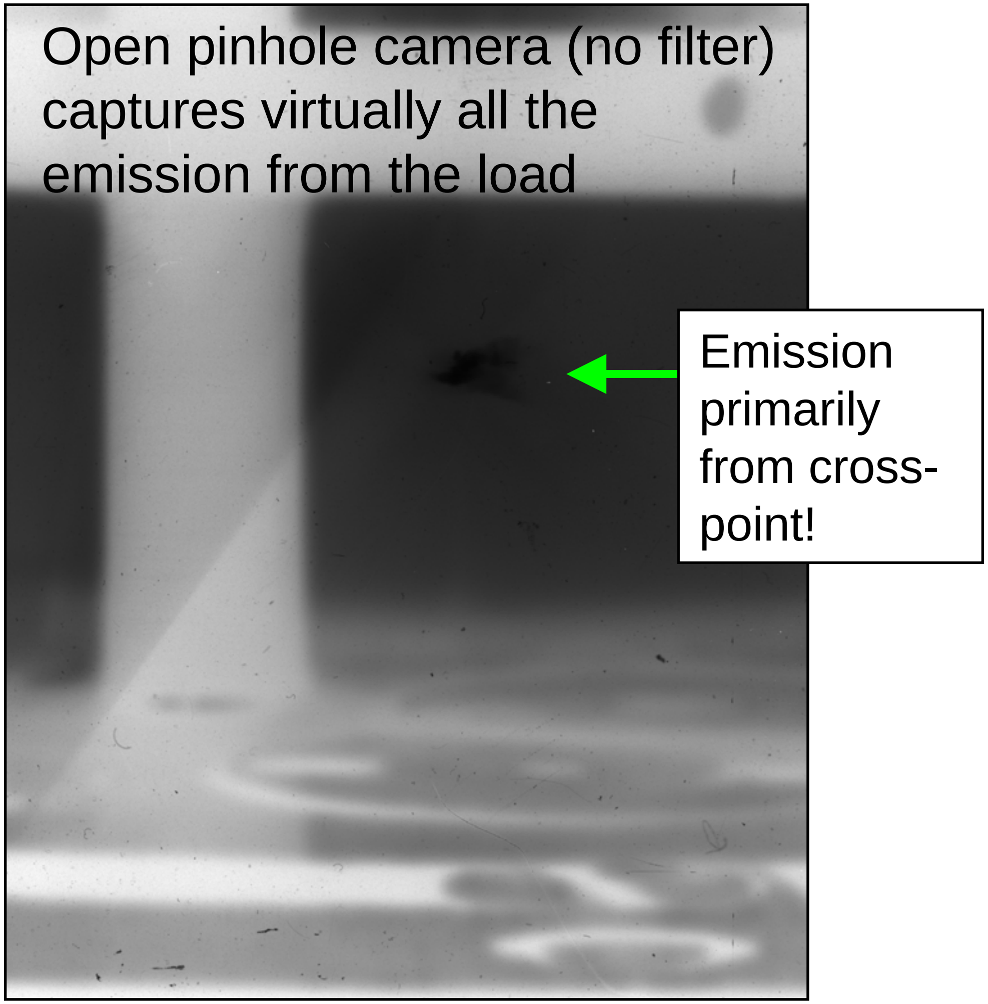




Assumptions: Similar photon spectrum from different regions; linear film response

Time-integrated open pinhole camera image clearly shows that bulk of emission is from cross-point





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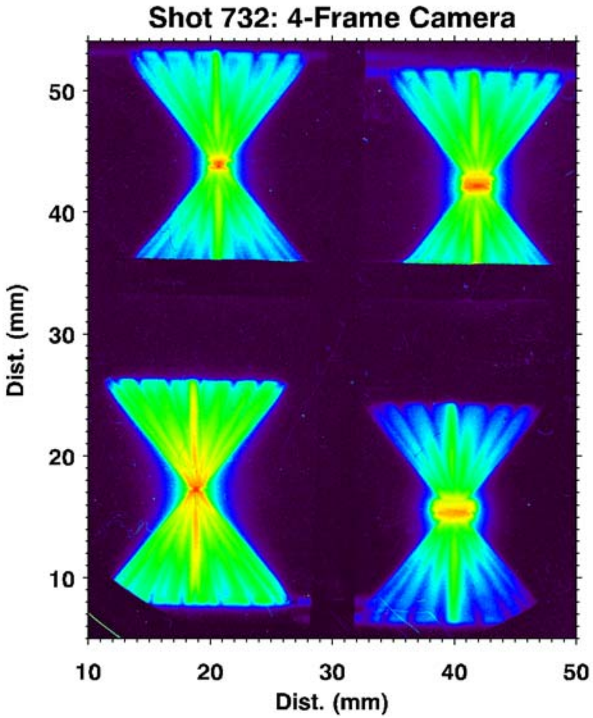
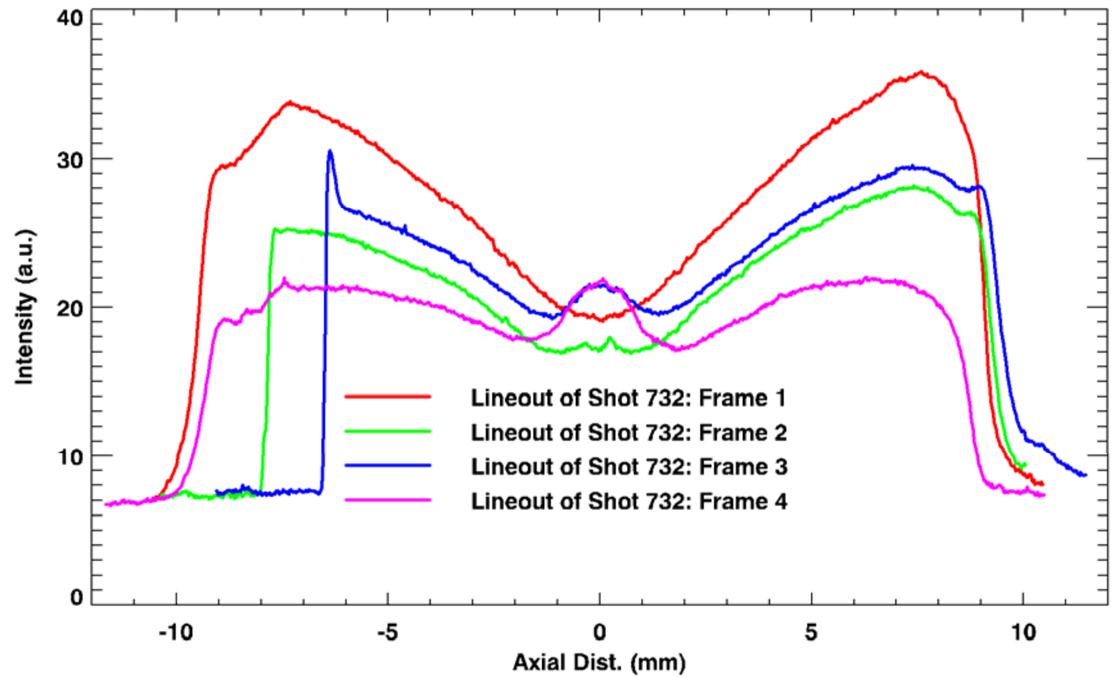
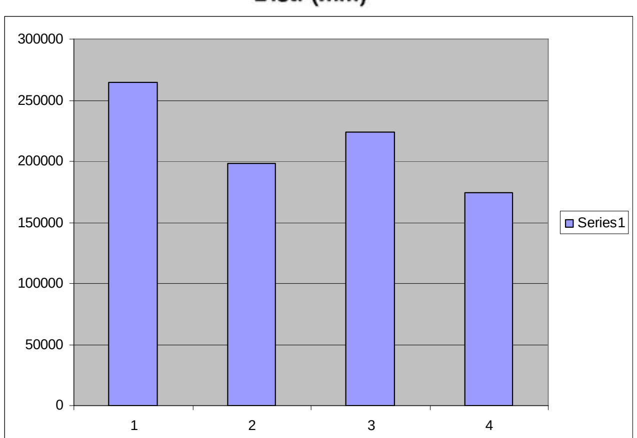
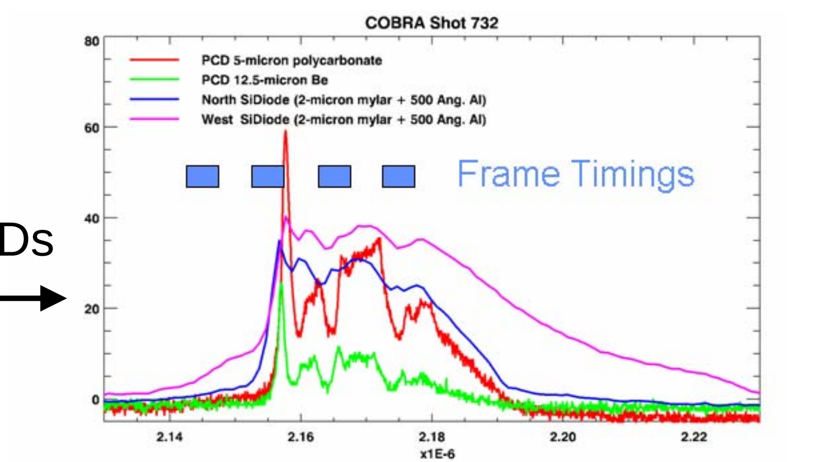
Radially-averaged brightness of soft x-ray emission from legs may decrease with time; axial jet is always brighter than any individual leg







But…no clear correlation between image intensity and SiDs



Summary of time-integrated x-ray pinhole camera sizes

- Tungsten Wire Number Scan (3 mg/cm mass)
  - 2 x 100 μm W (2): [3.1 kJ]; 2.2 kJ
  - 8 x 50 μm W (4) 4.1 kJ; 2.3 kJ; [1.3 kJ]; [0.5 kJ]
  - 32 x 25 μm W (1) 2.2 kJ
  - 64 x 18 μm W (1) [1.5 kJ]
- Tungsten Wire Number Scan (1.5 mg/cm mass)
  - 2 x 70 μm W (1) 3.8 kJ
  - 8 x 35 μm W (1) [5.2 kJ]
- X-ray source development (for backlighting, μpinch diag.)
  - 16 x 50 μm Manganin* (3) [0.5 kJ]; 1.4 kJ; 1.9 kJ
  - 8 x 50 μm Manganin* (1) 2.2 kJ
  - 2 x 125 μm Mo/Re alloy (1) [0.7 kJ]

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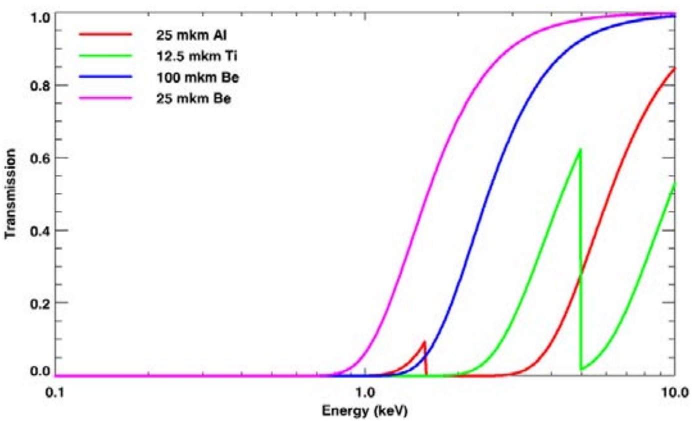
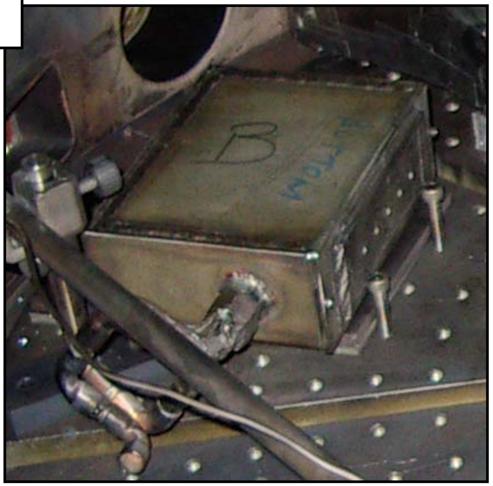
Pinhole imaging offers one means for estimating the source size, but it is limited

<u>5-pinhole camera:</u>

50 μm diam.; 25 μm Al filter
50 μm diam.; 12.5 μm Ti filter
50 μm diam.; 100 μm Be filter
50 μm diam.; 25 μm Be filter
5th not used (very hard filter)

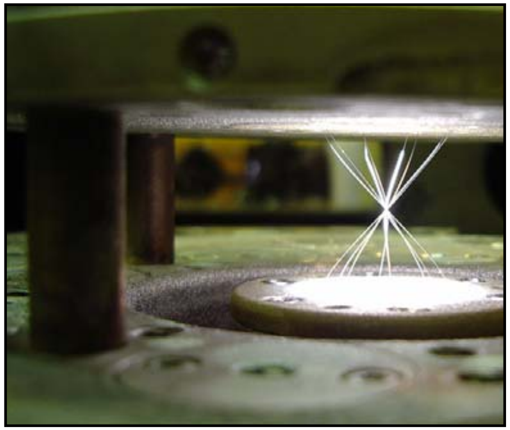




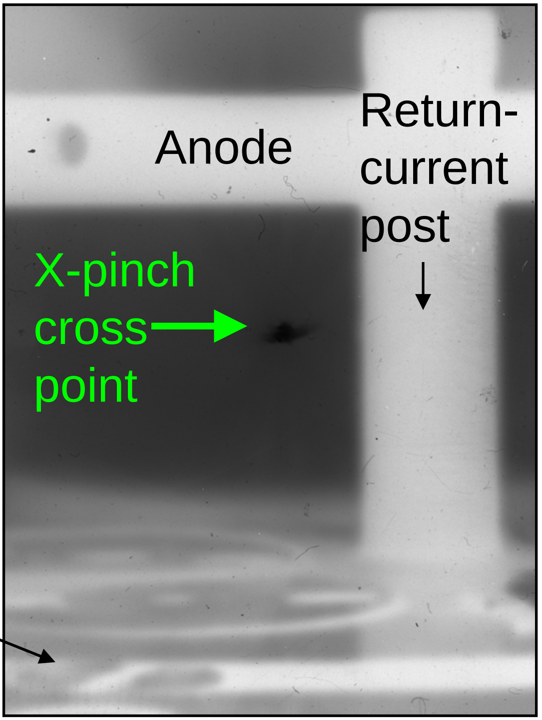
<u>Open-Pinhole Camera:</u>

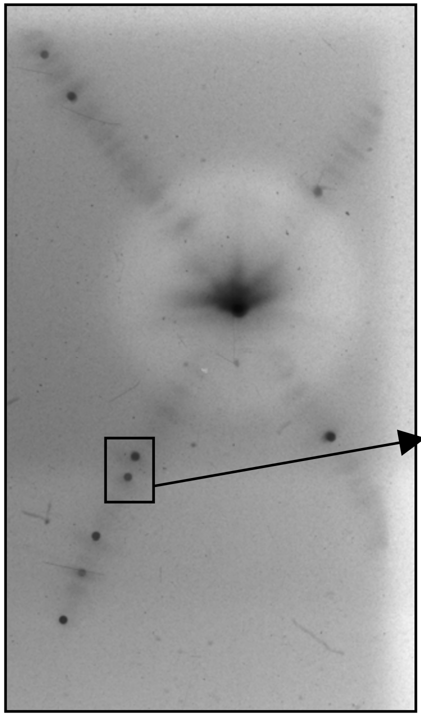
100-μm unfiltered pinhole

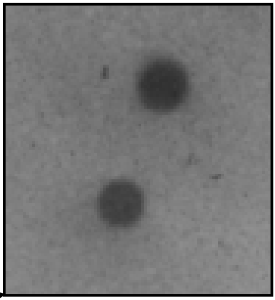
Captures very soft x-ray emission from load region. Can see details of load hardware!



Screw head

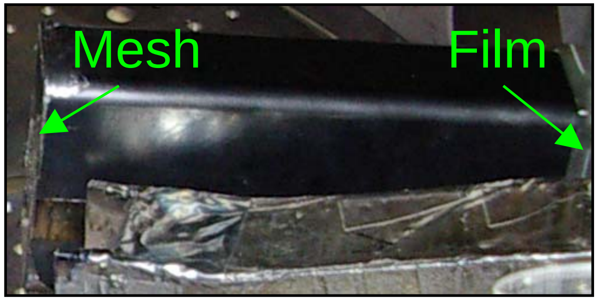




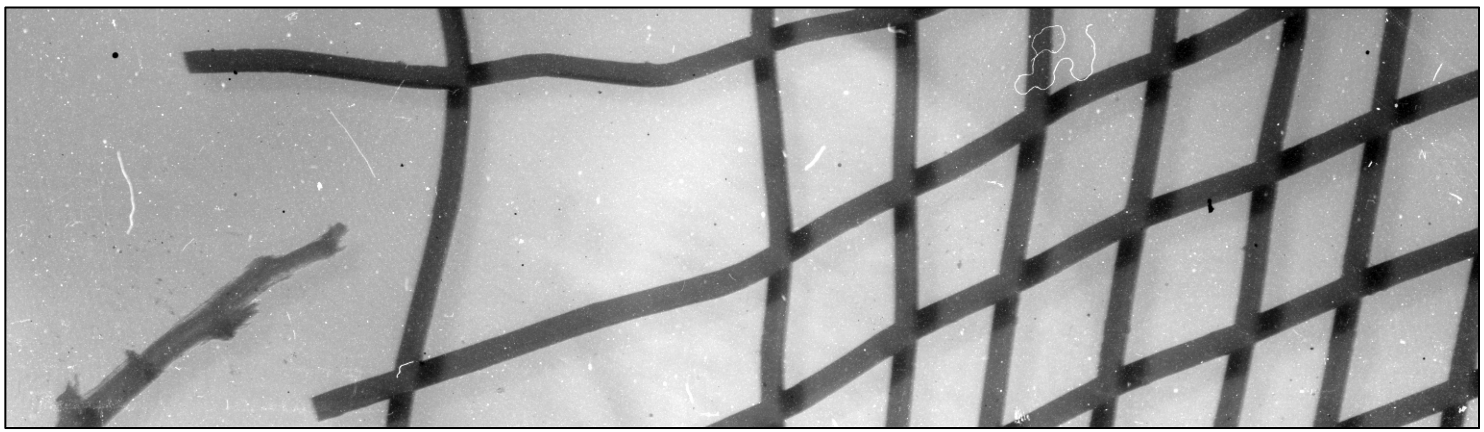


Pinhole-limited x-ray spots in legs

X-pinch backlit meshes provide perhaps the most sensitive source size estimates for 1st burst

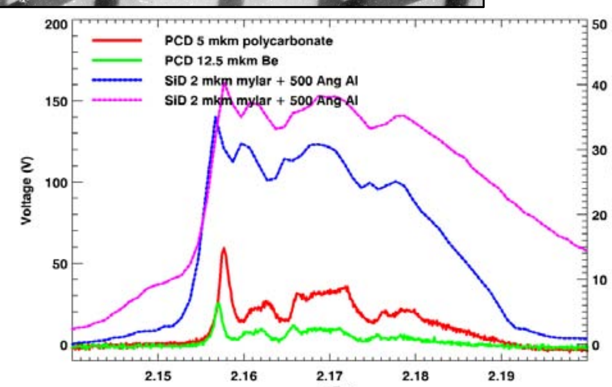


Mesh-backlit images:
X pinch used to backlight a test mesh at M=1.98x. Resolution allows estimate of source size for most intense x-ray bursts. For years it was argued that sources were ~1 μm on basis of high resolution of radiographs



Detailed analysis of mesh images still pending

Ex.: Shot 732: Lineout shows ~60-70 μm resolution of mesh (neglecting faint image) This is despite the many x-ray bursts following the 1st one! This may suggest that the later bursts are from large-area sources that don't contribute much to images



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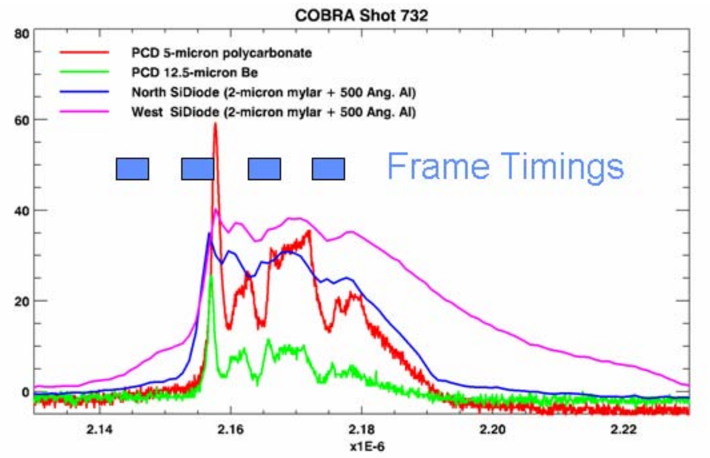
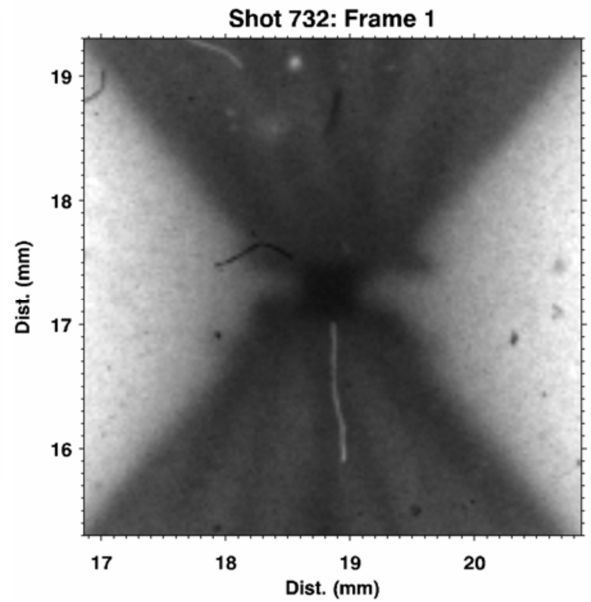
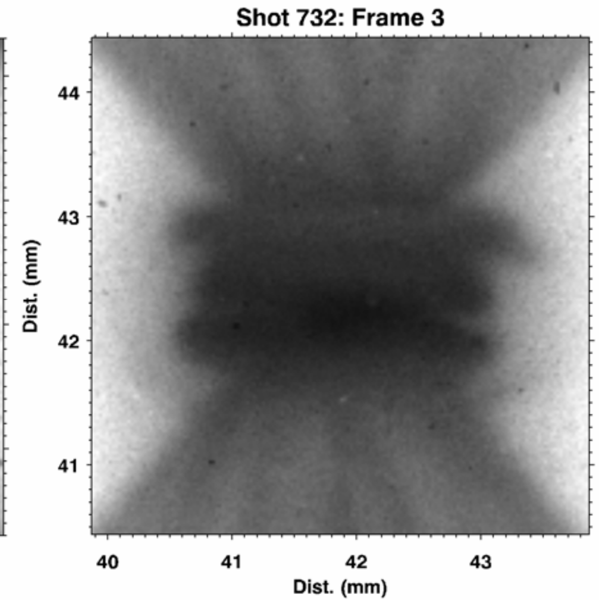
The cross-point region undergoes a rapid explosion following the first x-ray burst (may explain why later bursts are large area)



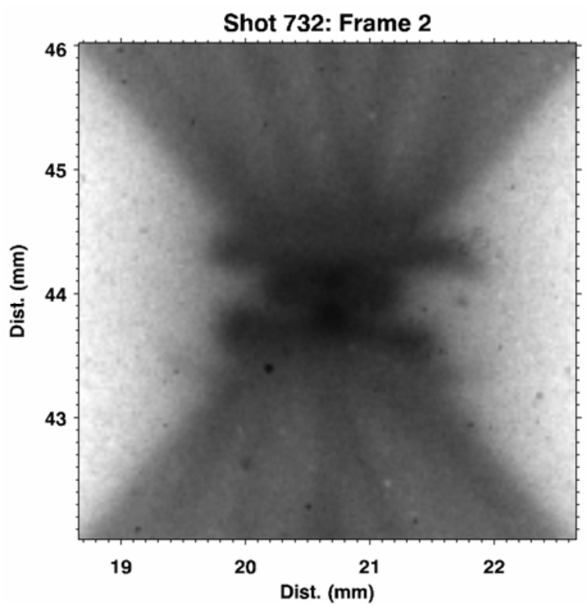


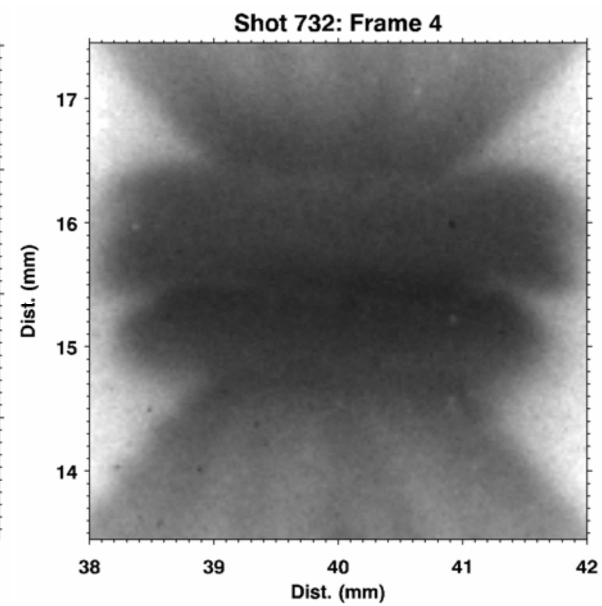


4x4 mm images of cross-point region; 10-ns inter-frame time

Radial expansion velocity 20±2 km/s

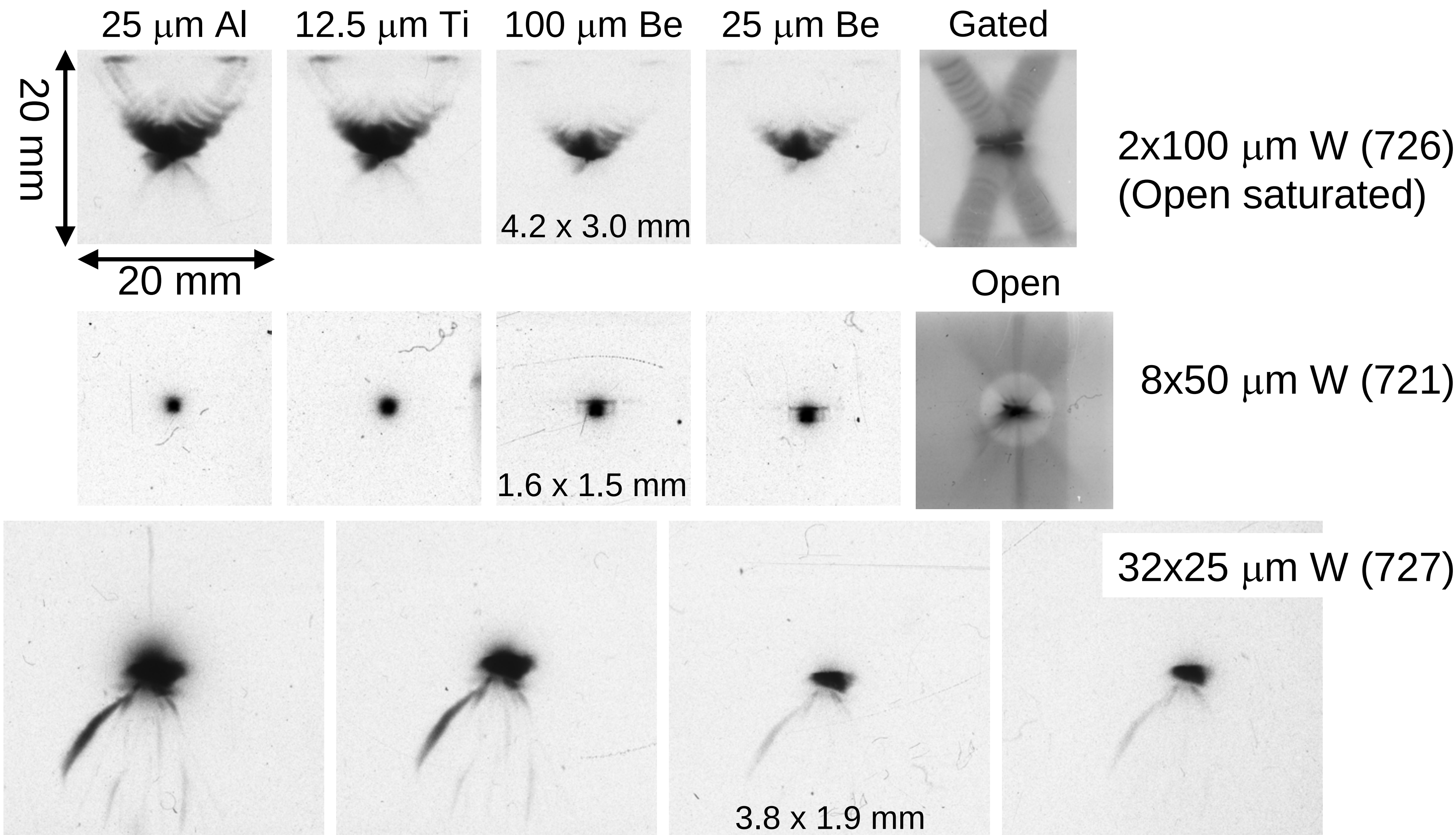
Axial expansion velocity 11±2 km/s



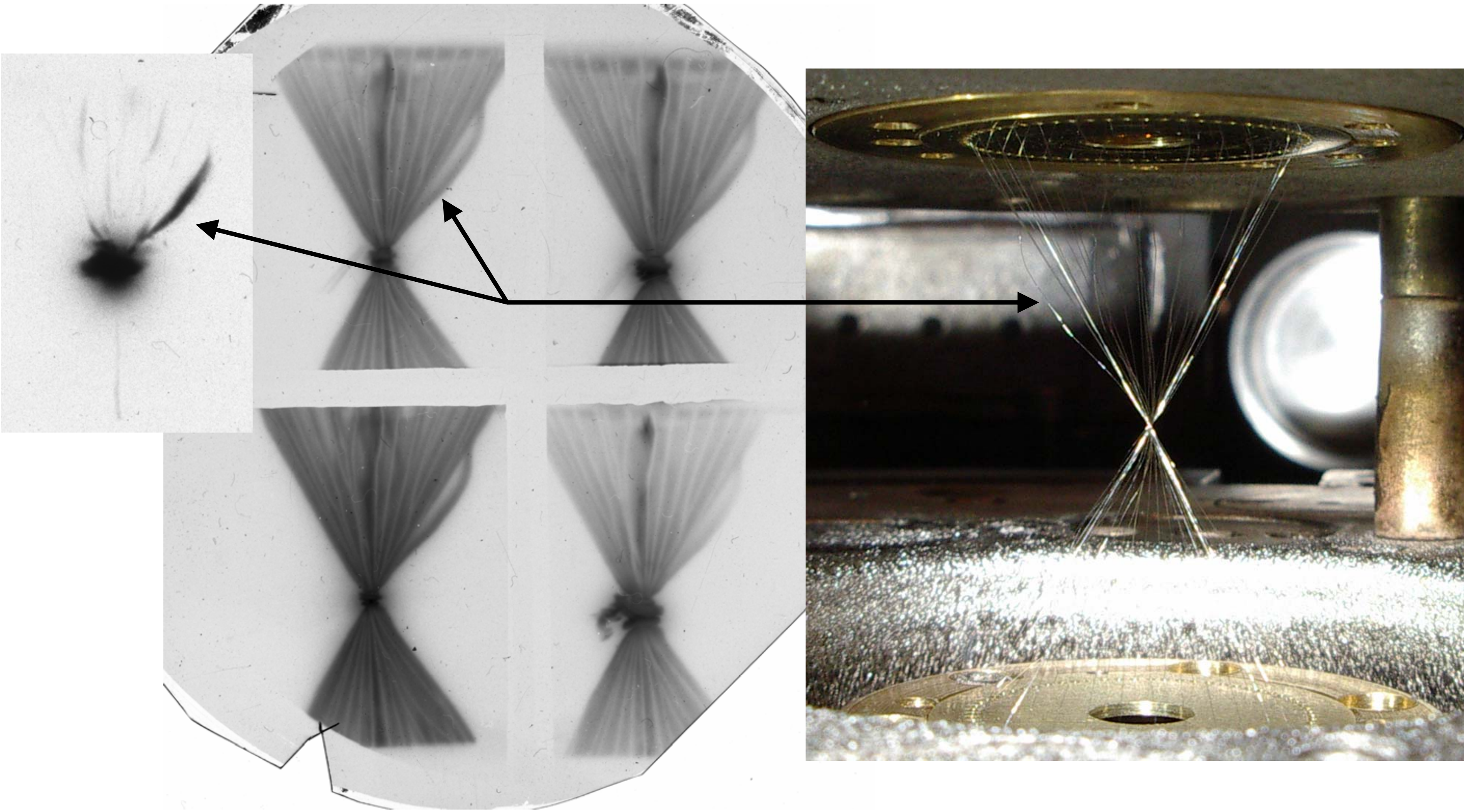


Problem: Most films saturated; pinhole sizes large

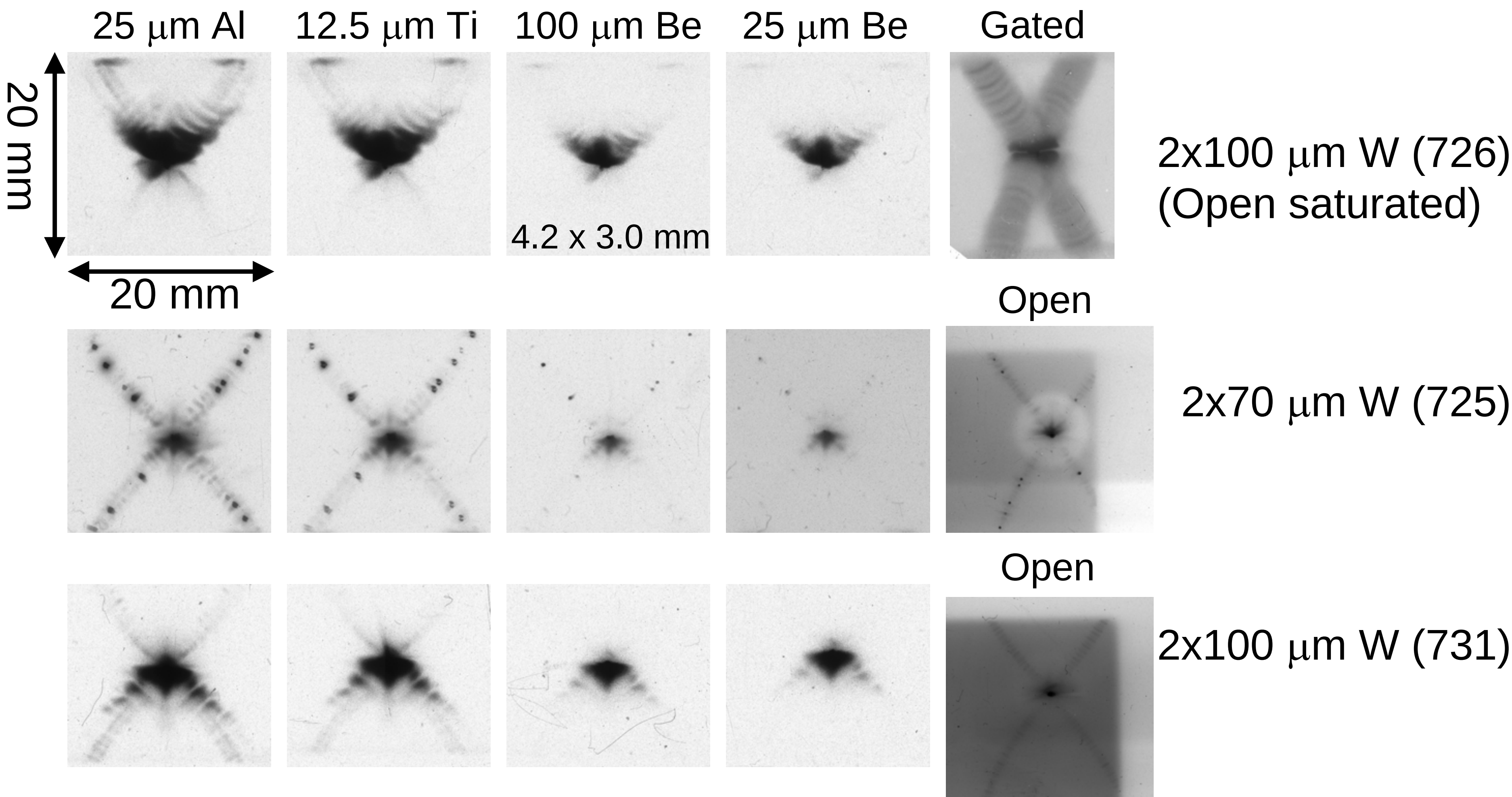
Time-integrated x-ray pinhole camera images place upper bound on x-ray source size



Loose wires were observable in soft x-ray diagnostics for 32 x 25 μm W X pinch



The legs of the 2-wire X pinches produced significant radiation (and sometimes bright spots!)



Legs seldom visible in higher-wire number XPs

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Upper bound on x-ray source sizes (width x height in mm)

- Tungsten Wire Number Scan (3 mg/cm mass)
  - 2 x 100 μm W (2): [4.2x3.0]; 3.7x2.4
  - 8 x 50 μm W (4) 1.6x1.5; 2.1x1.1; [2.7x0.7]; [--]
  - 32 x 25 μm W (1) 3.8x1.9
  - 64 x 18 μm W (1) [3.3x0.8]
- Tungsten Wire Number Scan (1.5 mg/cm mass)
  - 2 x 70 μm W (1) 1.9x1.2
  - 8 x 35 μm W (1) [--]
- X-ray source development (for backlighting, μpinch diag.)
  - 16 x 50 μm Mang. (3) [--]; 1.3x1.7; 1.7x1.9
  - 8 x 50 μm Mang. (1) 1.7x1.0
  - 2 x 125 μm Mo/Re (1) [0.66x0.61]

[ ] denotes “bad-current” shots

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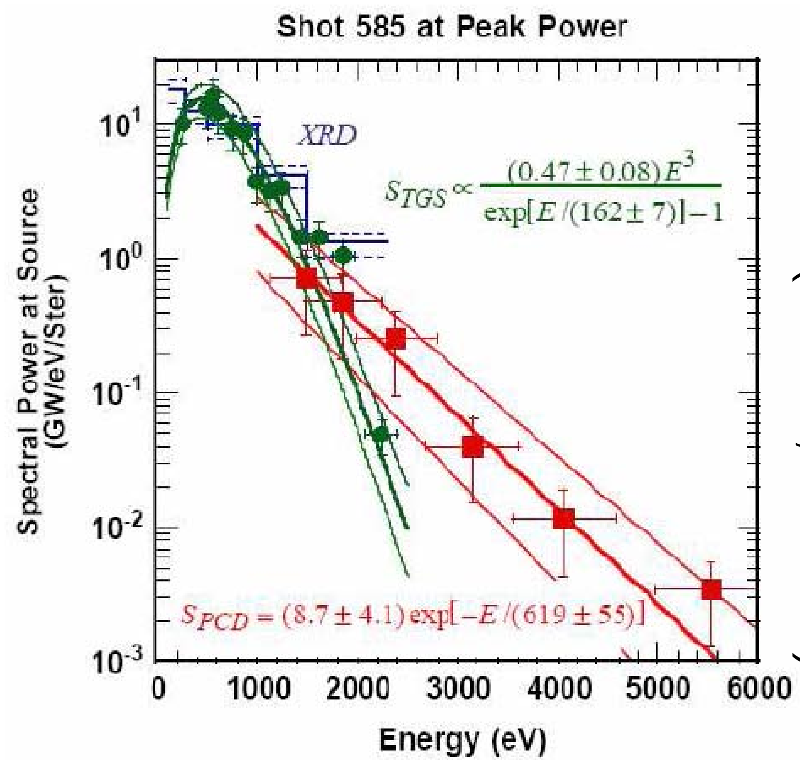
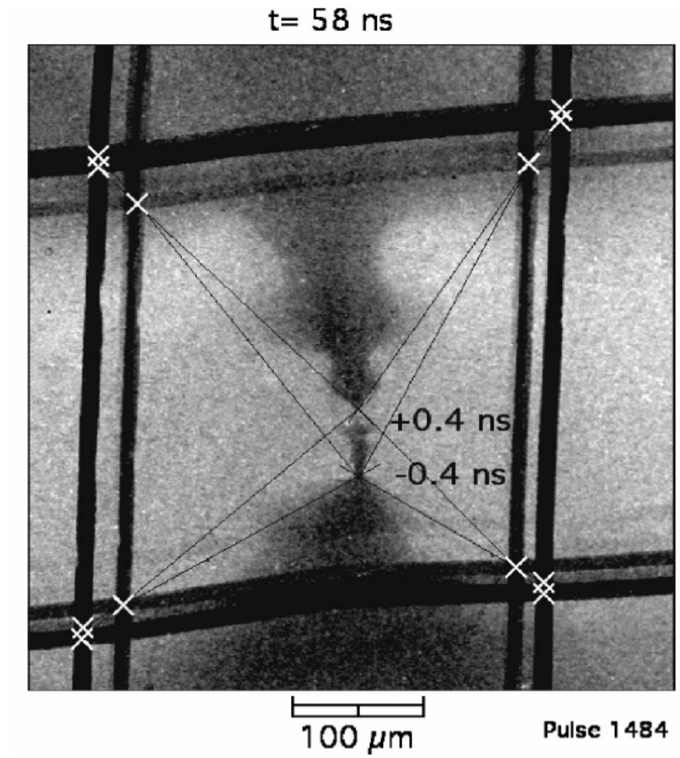
Could micropinches similar to those found in X pinches exist in our wire-array z pinches on Z?



M.E. Cuneo (in Foord, PRL 2004).



Shelkovenko, PoP 2001

Soft x-ray spectrum in 100-2000 eV range generally well fit by ~170 eV blackbody

The >2000 eV photons must either come from small-area, high-temperature thermal sources or small-area, localized beams

Even in cases where we know current reaches small diameters (X pinches), are the sources thermal or beam-produced? (This is an old debate going back to plasma focus devices in 1950s.)

Time-integrated self-emission at 6151 eV shows very fine structure (50-100 μm)

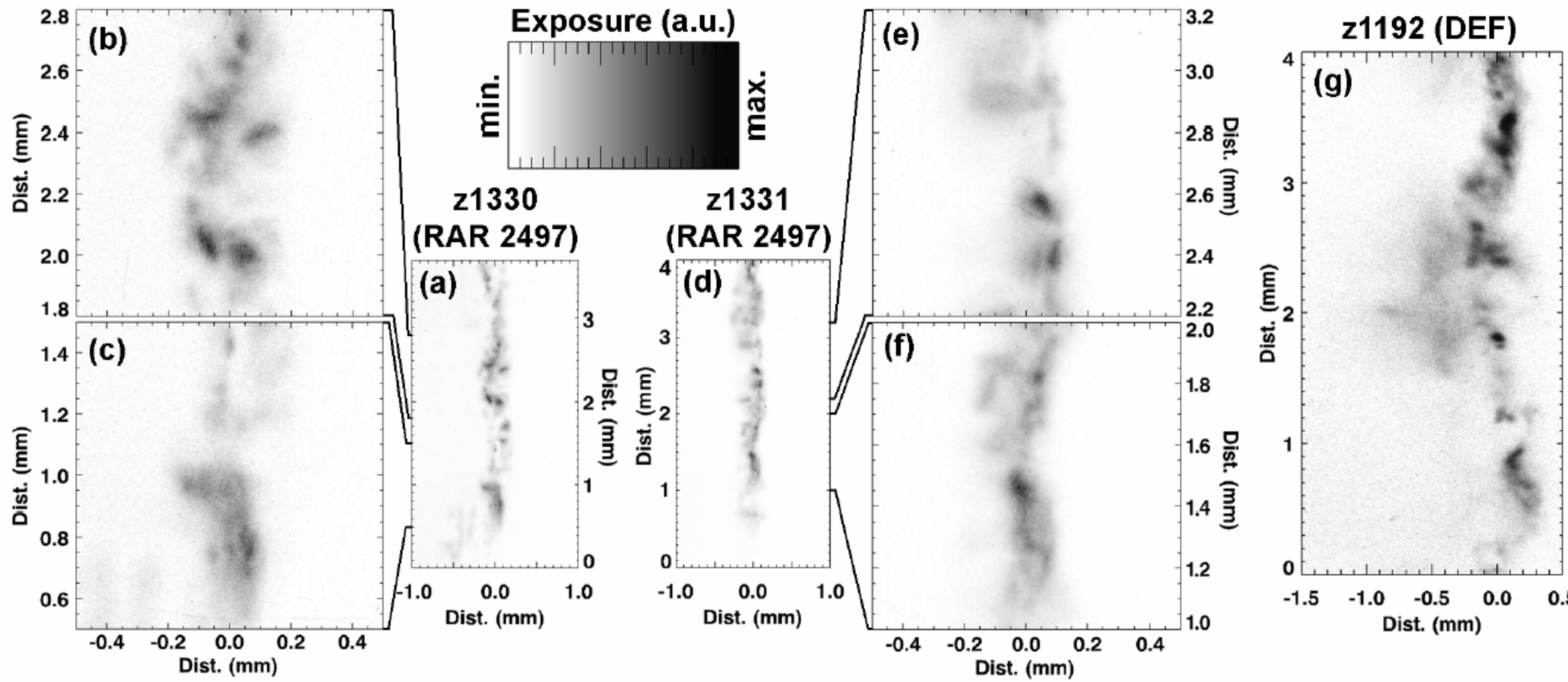


FIG. 2: Time-integrated 6151 eV self-emission images from three example tests. On these tests either the backlighter exposure on the first film was too low to be seen (parts (a)-(f)) or there was no backlighter source (part (g)). The film exposure levels of each image were adjusted to provide useful contrast for these figures. A wall in the return-current canister blocked any self-emission from regions ≥0.4 mm.

D.B. Sinars *et al.*, to be published someday…?

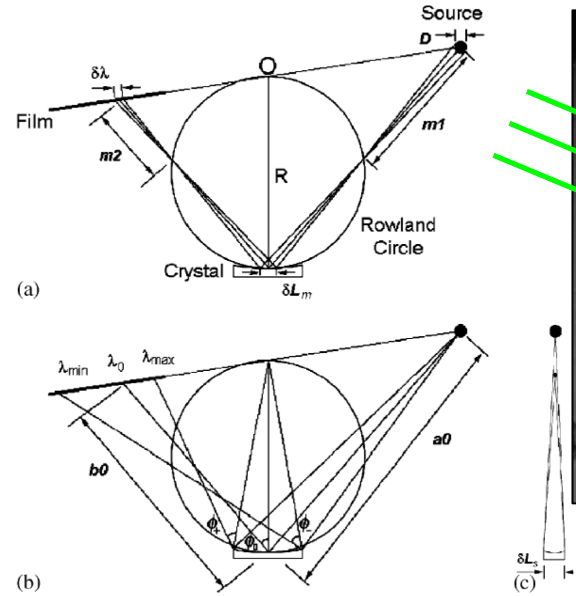
Sandia National Laboratories

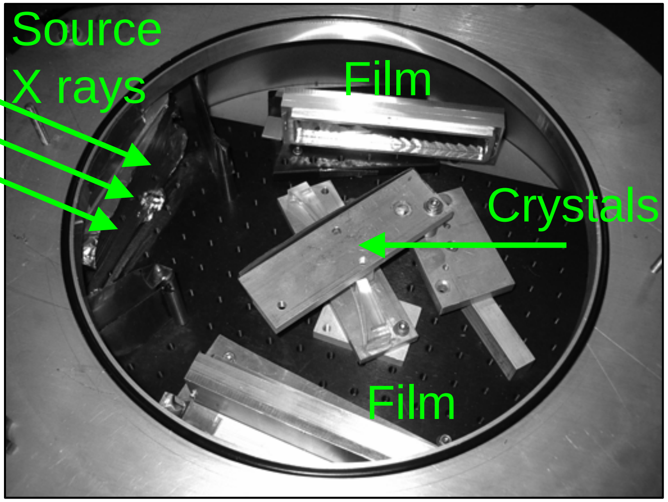
X pinches are also a nice potential test bed for strong magnetic field diagnostics

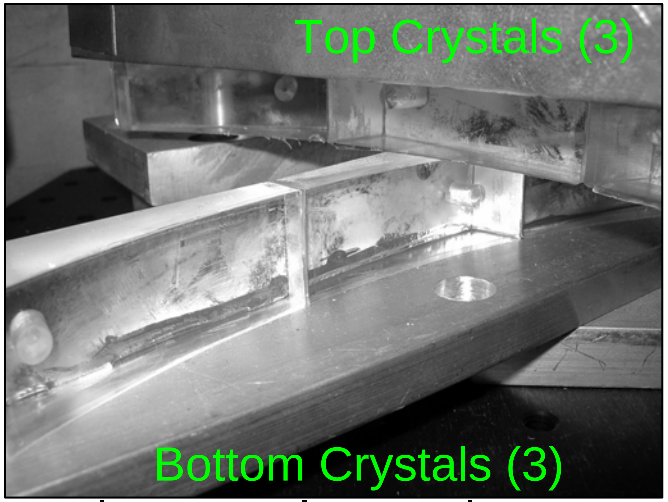
- **Point of maximum magnetic field strength is predetermined by geometry early in time**
- **If 6 MA were flowing inside a 100-micron radius, the max. magnetic field would be 120 MG!**
- **Hot plasma in cross-point region might increase options for spectroscopic dopants***
- **Large wire sizes improve chances for unusual alloys to be feasible (for spectrosc. dopants)***
- **Diagnostics developed/tested on XPs could later be applied to any z-pinch load**

* Y. Maron has proposed using Zeeman triplet diagnostics to measure the B-field

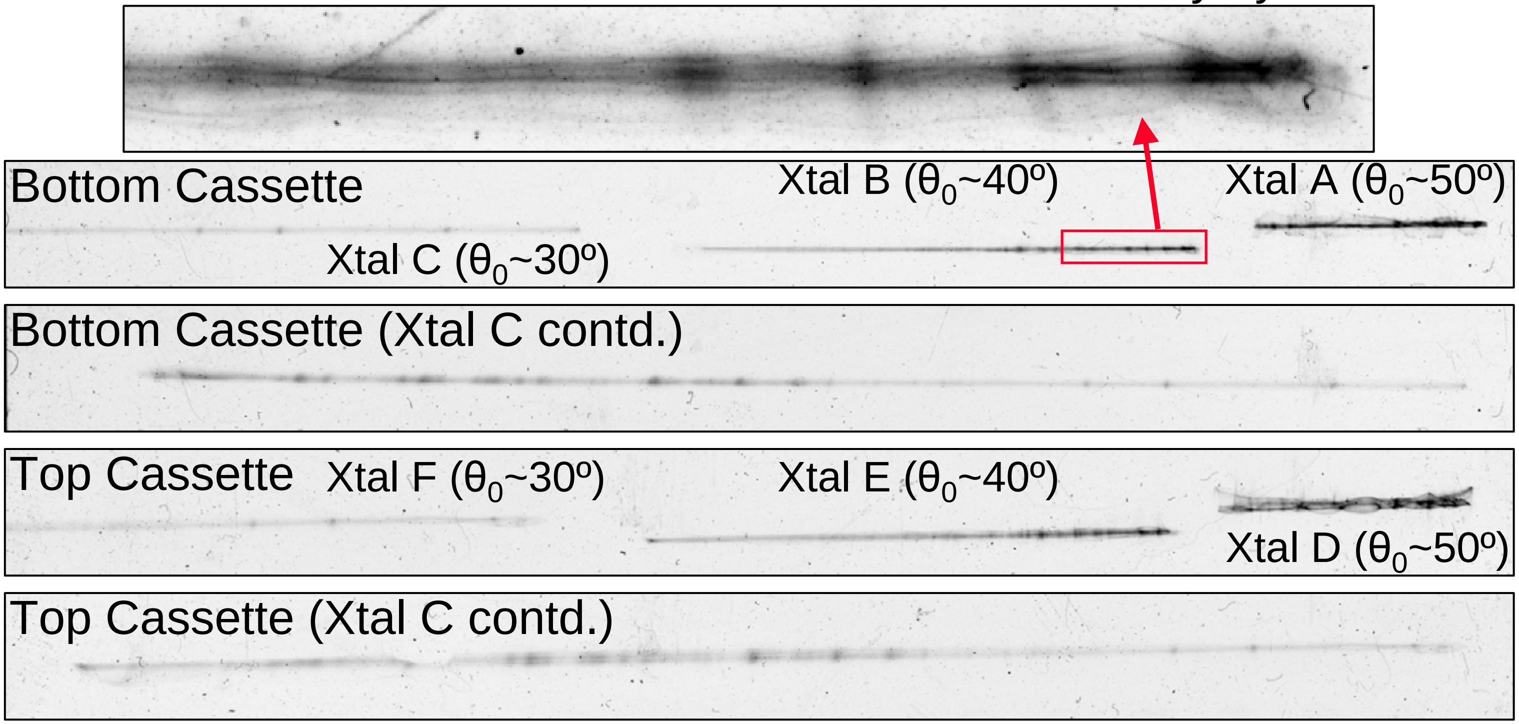
Spectroscopy data was also collected for later analysis







Mica crystals were bent locally by Pikuz & Douglass



Initial Conclusions

- High-wire-number X pinches (32, 64) worked very well (32-wire produced highest powers). Two-wire X pinches did manage to produce x-ray bursts from the cross point despite extreme aspect ratios, but had pinching in legs.
- 1 MA X pinches produced ~2 kJ of x rays and estimated peak powers of ~10 GW. Open pinhole camera images suggest that bulk of the emission is from cross-point.
- More work is needed to determine the x-ray spot sizes—are they still micron-scale? (Self-backlit mesh images may provide best estimates at this point.)
- Under-massing the X pinch increases the chances of getting multiple x-ray bursts, but over-massing makes the performance and timing sensitive to the peak current amplitude.

Where do we go from here?

- **Additional 1 MA experiments at Cornell?**
  - **Invitation was made to return after ICOPS meeting to finish off the data set**
  - **Shots would focus on improving the power/energy diagnostics and filling in holes in the tungsten wire number scan**
  - **Predictions by Chittenden *et al.* were for Mo X pinches, which might perform better on SATURN for opacity reasons. Should field some Mo XPs.**
  - **Would be interesting to try "1-wire" XP in between two conical electrodes—would it work?**
- **Future 6 MA experiments at SATURN?**
  - **Applied for LDRD funding in FY08. Goal would be to study scaling of x-ray sources from 1 MA to 6 MA. This scaling can only be done today at Sandia.**
  - **Might be a useful platform for magnetic field diagnostic development**

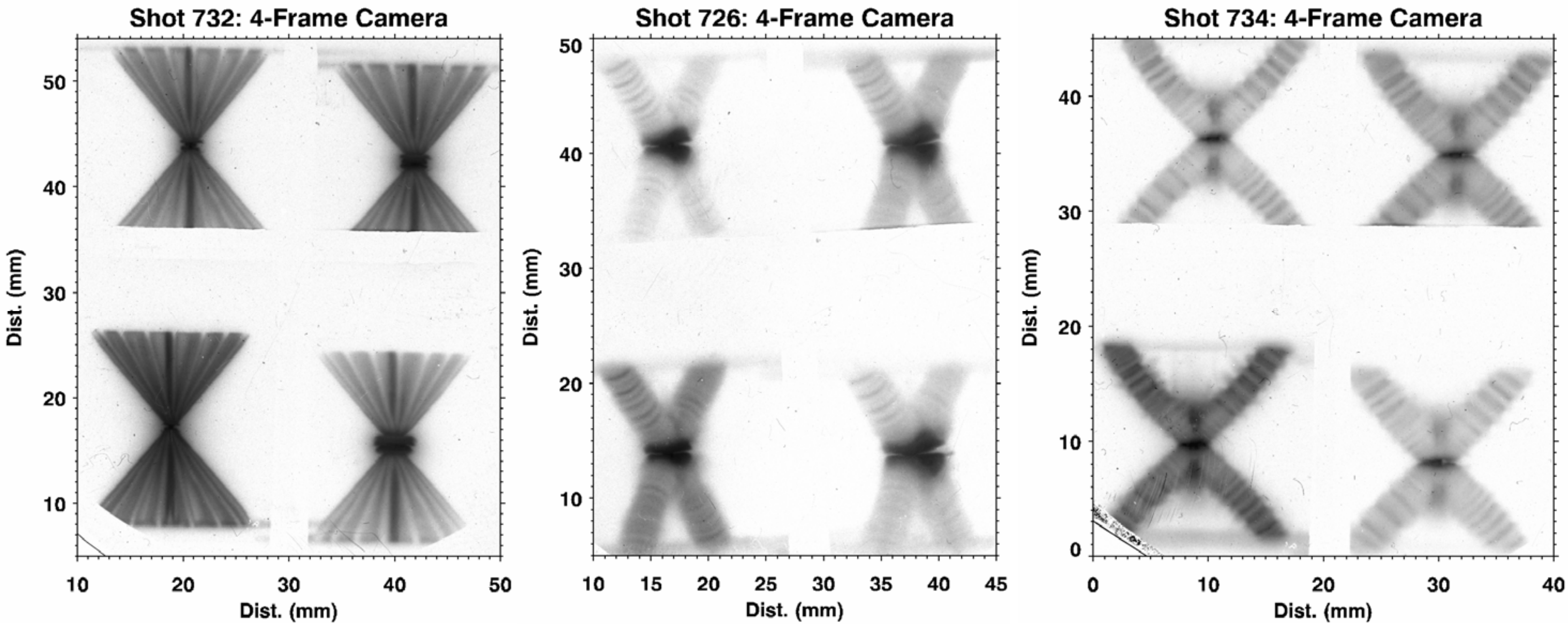
Backup Slides

High-Level Summary of Shots

721: 8x50u W	Idot-Good	Xray-Yes	4.17 kJ	4F-n/a	LB-No	XRSC-n/a
722: 8x50u W	Idot-Good	Xray-Yes	2.25 kJ	4F-Yes	LB-Yes	XRSC-n/a
723: 8x50u W	Idot-Bad	Xray-Yes	1.32 kJ	4F-Yes	LB-n/a	XRSC-No
724: 8x35u W	Idot-Bad	Xray-Yes	5.20 kJ	4F-Yes	LB-Yes	XRSC-Y
725: 2x70u W	Idot-Good	Xray-Yes	3.80 kJ	4F-Block	LB-Yes	XRSC-Y0
726: 2x100u W	Idot-Bad	Xray-No	3.12 kJ	4F-Yes	LB-Yes	XRSC-Y0
727: 32x25u W	Idot-Good	Xray-Yes	2.15 kJ	4F-Yes	LB-Yes	XRSC-No
728: 16x50u M.	Idot-Bad	Xray-No	0.52 kJ	4F-Yes	LB-Yes	XRSC-No
729: 16x50u M.	Idot-Good	Xray-Yes	1.35 kJ	4F-Yes	LB-Block	XRSC-No
730: 64x18u W	Idot-Bad	Xray-Yes	1.47 kJ	4F-Yes	LB-Yes	XRSC-Y
731: 2x100u W	Idot-Good	Xray-Yes	2.23 kJ	4F-pretrig	LB-Yes	XRSC-Y
732: 16x50u M.	Idot-Good	Xray-Yes	1.87 kJ	4F-Yes	LB-Yes	XRSC-Y
733: 8x50u M.	Idot-Good	Xray-Yes	2.24 kJ	4F-Yes	LB-Yes	XRSC-No
734: 2x125u Mo/Re	Idot-Bad	Xray-Tiny	0.74 kJ	4F-Yes	LB-Yes	XRSC-No
735: 8x50u W	Idot-Bad	Xray-No	0.55 kJ	4F-Yes	LB-Focus	XRSC-No

15 shots in 6 days; 8 of 15 were good machine shots (53%)

Comparing image intensities from one frame to another may in fact be suspect without a pinhole size and/or MCP response comparison



It is extremely unlikely that these images, which were taken at different times in the current pulses, would always have the first frame the most intense, followed by the third frame, and then the second & fourth. It is more likely that the first frame is the most sensitive, followed by the third, and then the other two.