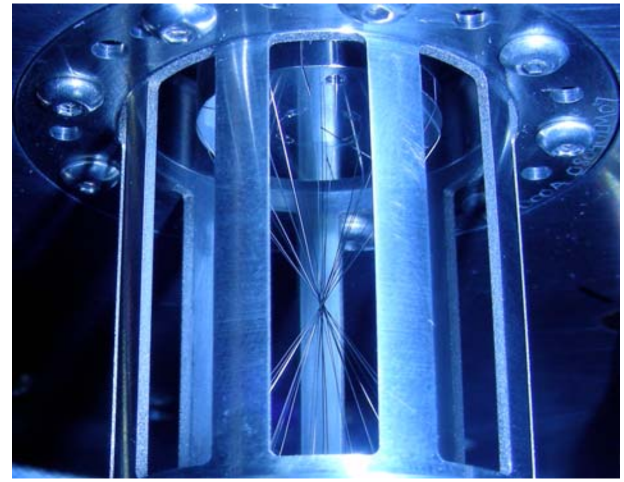
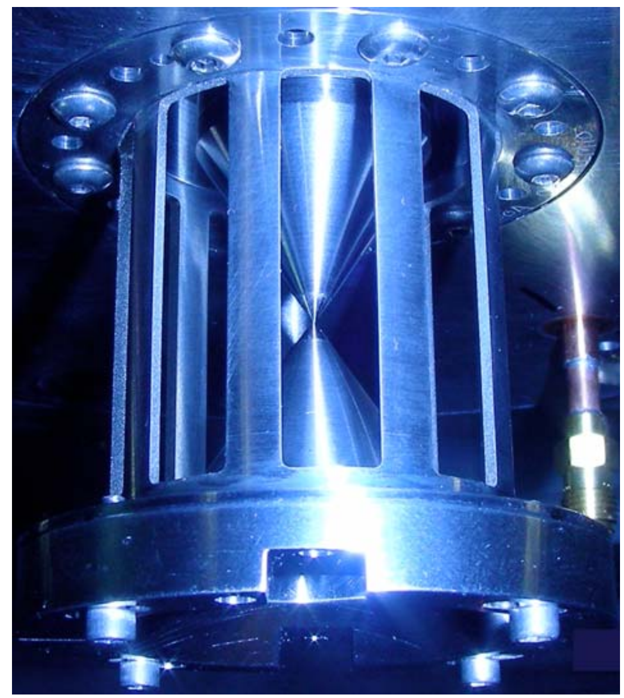
SAND2009-3065C

Wire Array Workshop April 6-9, 2009

6 MA X-pinch Scaling Experiments





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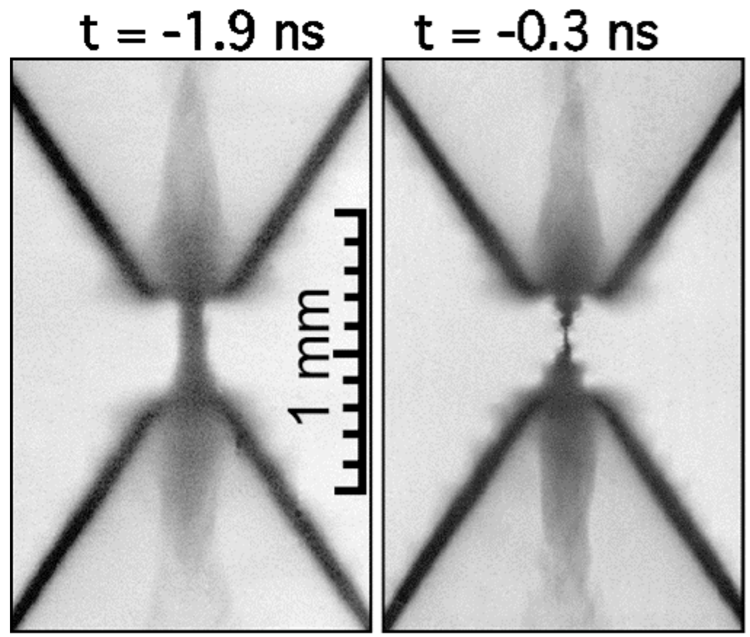
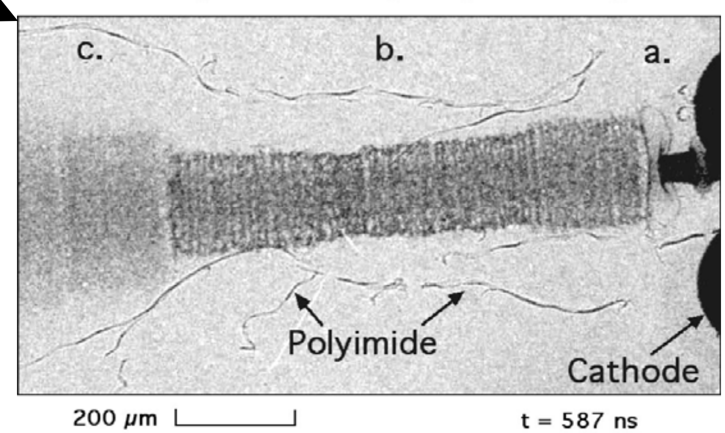
Why study X pinches?

Plasmas at 0.2 MA have extreme properties

- **Diameter: 1.2±0.5 μm[a]**
- **Duration: 10-100 ps[b]**
- **T_e: ~1 keV (Ti[b], Mo[c])**
- **n_i: ≥0.1 * Solid density[b,c]**
- **Material pressure at ~1 g/cm^3 & 1 keV is ~1 Gbar**
- **Magnetic pressure of 0.2 MA at 1 μm radius is ~1 Gbar**
- **Spot size, duration ideal for point-projection backlighting**



11.5 μm W with a 2.2 μm Polyimide Coating



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

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

[c] S.B. Hansen *et al.*, PRE 70, 026402 (2004).

Why study >1 MA X pinches?
Possibility of more extreme conditions

- **0.2 MA Mo X-pinch modeling reproduces observations†**
  - **Typical parameters: ~1 μm, ~2 keV, ~5 GW, ~2 ps**
  - **Model based on approximate Bennett equilibrium conditions and a balance between blackbody radiation and thermal heating**
  - **Axial mass flow leads to a collapse that is halted when the electron drift velocity exceeds the ion sound speed (critical line density)**
- **At 1 MA the model breaks down**
  - **Critical line density criterion: ~30 nm, 1290x solid density plasma**
- **Assume 100% of current collapses to a radius of 1 μm (Mo X pinch)**
  - **1 MA: 80 GW (10x solid density)**
  - **10 MA: 3.4 TW (250x solid density)**

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

How do X-pinch parameters scale with I?

On-axis mass creates "different" scaling

- **To scale a liner implosion self-similarly to different drive conditions, Π should be fixed***

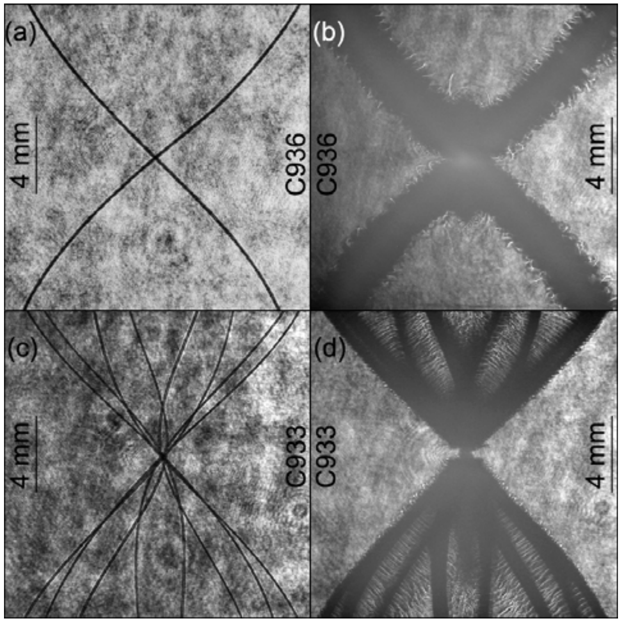
$$\Pi = \frac{\mu_0 I^2 \tau^2}{4\pi m_l r^2} \xrightarrow{m_l = \rho \pi r^2} \boxed{\frac{I_1^2 \tau_1^2}{\rho_1 r_1^4} = \frac{I_2^2 \tau_2^2}{\rho_2 r_2^4}}$$

- **Unlike a wire array, we cannot effectively increase the density by increasing the number of wires in the array**
- **For a fixed density but increasing current, we must increase the diameter of the X-pinch neck**
- **Increase in radius decreases JxB pressure, so that mass/length increases ~linearly, not as I^2 as with arrays**

* Ryutov, Derzon, & Matzen, Rev. Mod. Phys. 72, 167 (2000).

There are some practical issues with high-current X pinches

- **Mass/length is heavy!**
  - **0.4 MA: 0.38 mg/cm**
  - **1.0 MA: 1.5 - 3.0 mg/cm***
  - **6.0 MA: 9-18 mg/cm (I scaling)**
    108 mg/cm (I^2 scaling)
  - **18 MA 20-mm wire array: 6 mg/cm**
- **X-pinch configurations are complex**
  (18 mg/cm; Tungsten)
  - **256 x 22 μm; 4 x 172 μm; 1 x 345 μm**
  - **Large wire numbers "knotty"**
  - **Large wire sizes bad?***
- **All materials are not equal**
  - **Mo, W, NiCr work well at 0.2 MA****
  - **Al, S.S. work poorly at 0.2 MA****



* D.B. Sinars *et al*., Phys. Plasmas 15, 092703 (2008).
** S.A. Pikuz, private communication (2007).

We have tested X pinches in three different shot series on the 6 MA SATURN facility

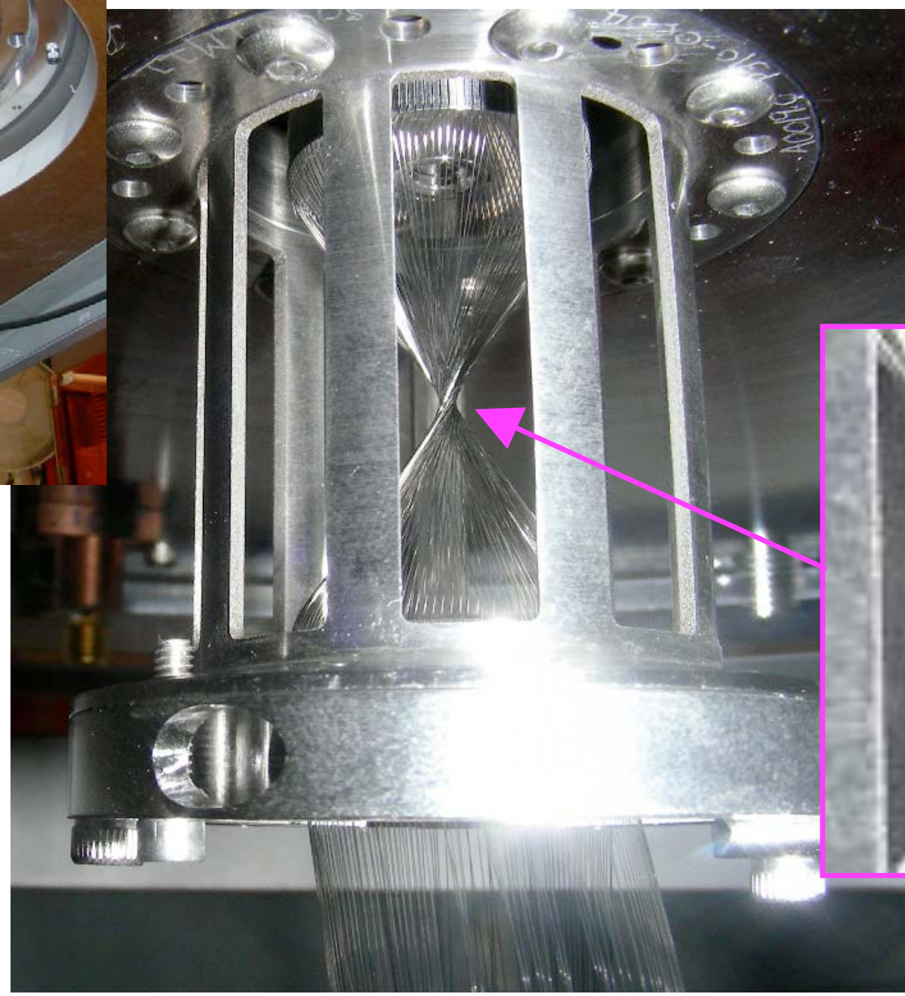
- Series 1 (April ‘08)
  - Single-array X-pinch mass scan
  - Showed ~linear mass scaling with current from 1 MA
- Series 2 (Sept. ‘08)
  - Nested X-pinch scan
  - Solid X-pinch tests (W)
  - Best results from solid XPs (~17 μm sizes?)
- Series 3 (March ‘09)
  - “Better” solid X-pinch tests (W/Cu; Cu/Ni; Ni/Cr)
  - Focus of rest of this talk

Primary goal of 1st three series: Identify a promising load geometry
Primary goal of next three series: Identify plasma parameters

High Wire-Number Single X Pinch (S3734)

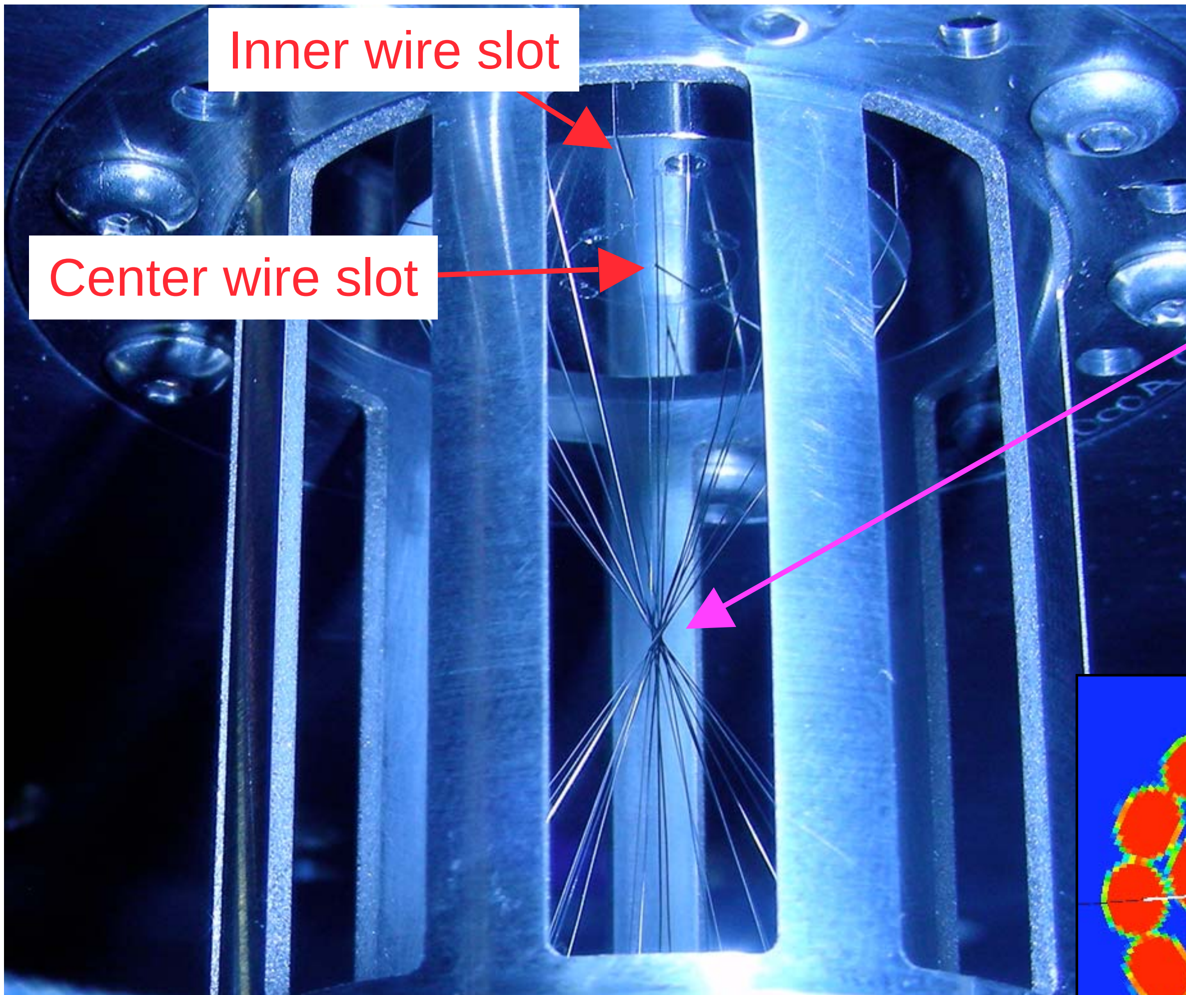
Large diameter W wires required extremely large weights to apply tension!

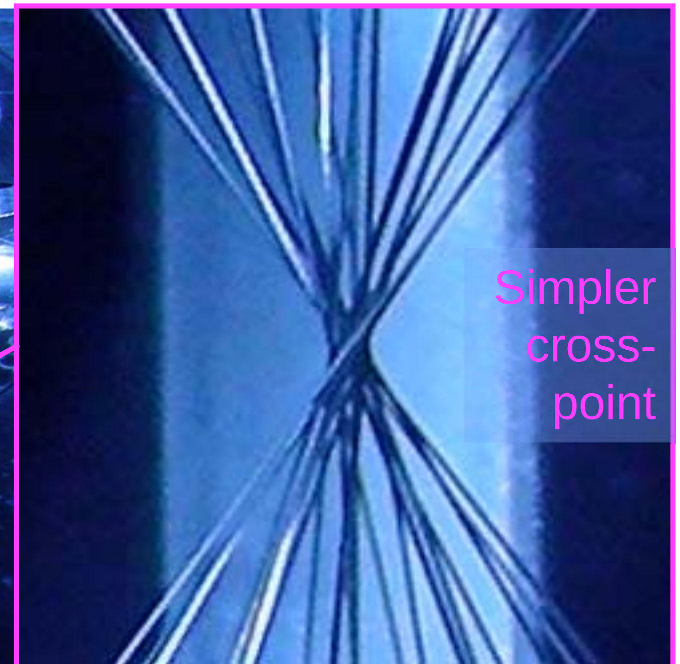
128 x 75 μm W array

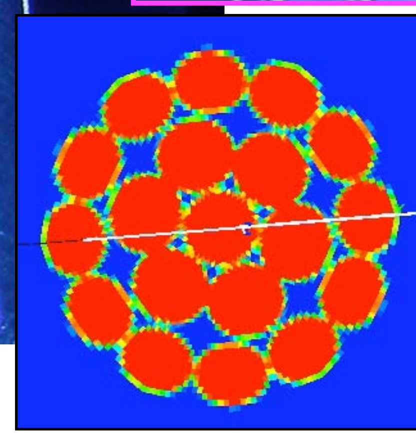


Extremely complex cross-point

Nested Array X Pinch (S3767)







Wire sizes chosen to get a compact cross-point

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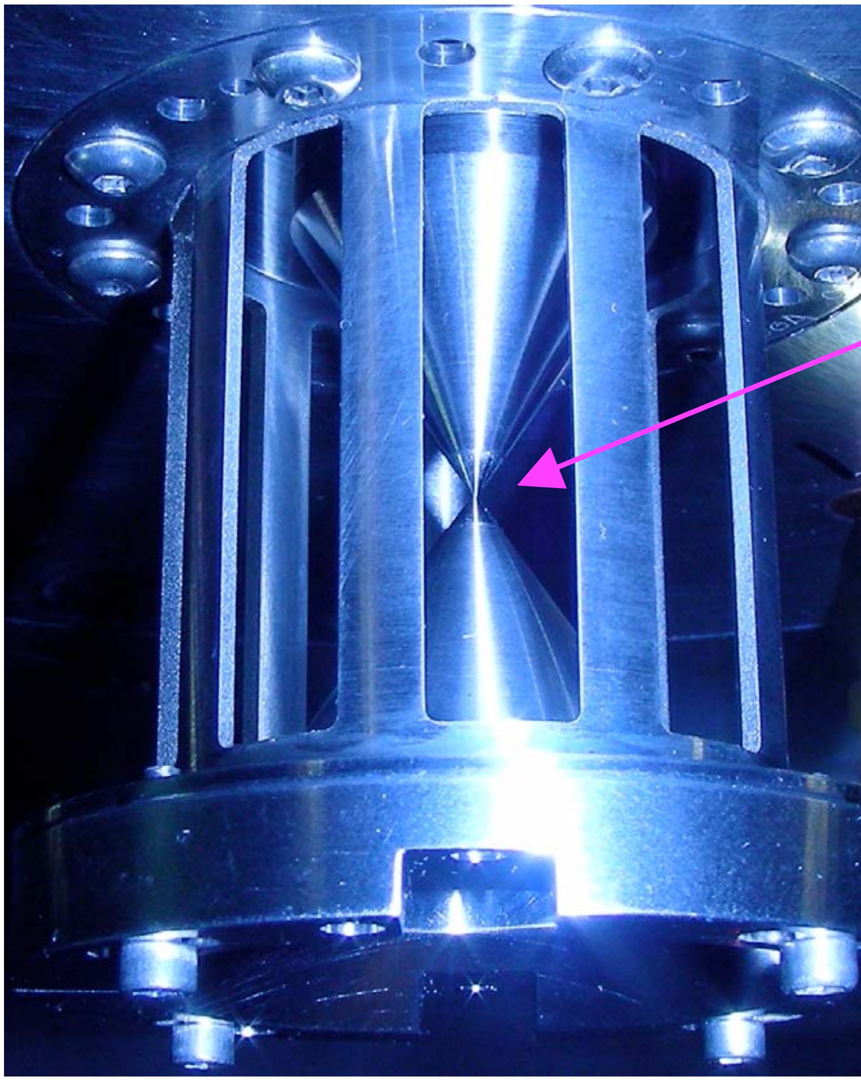
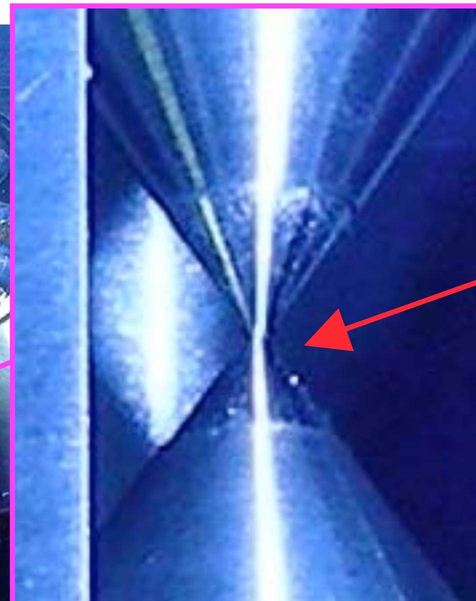
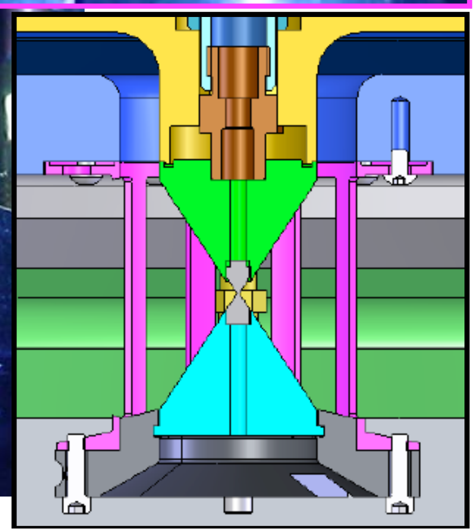
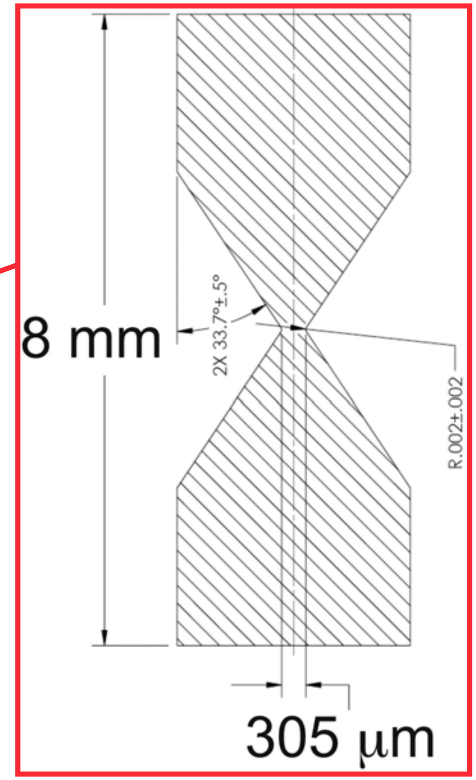
Solid X Pinch (S3769)





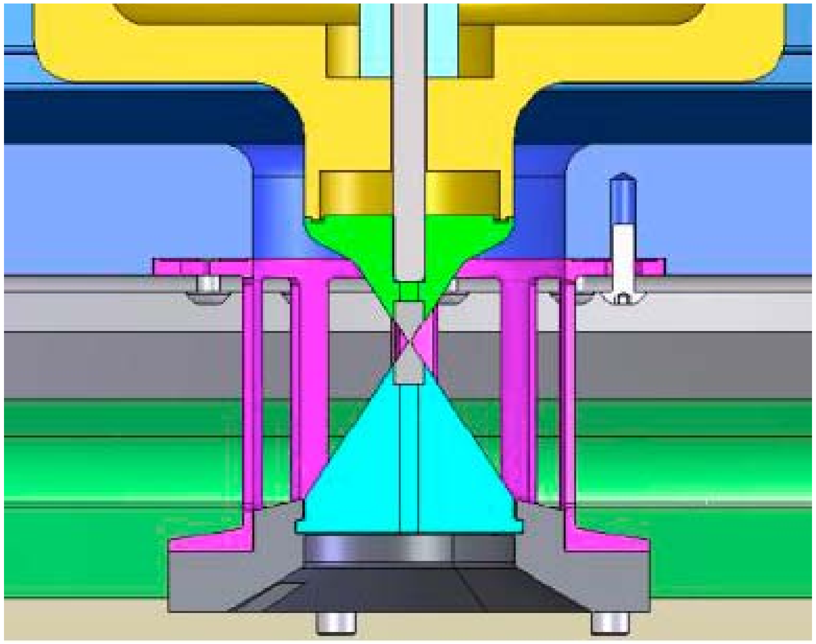


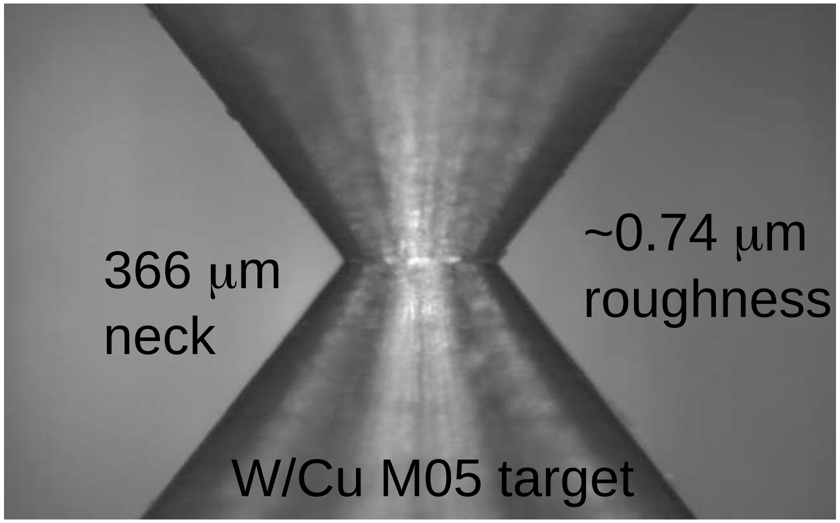


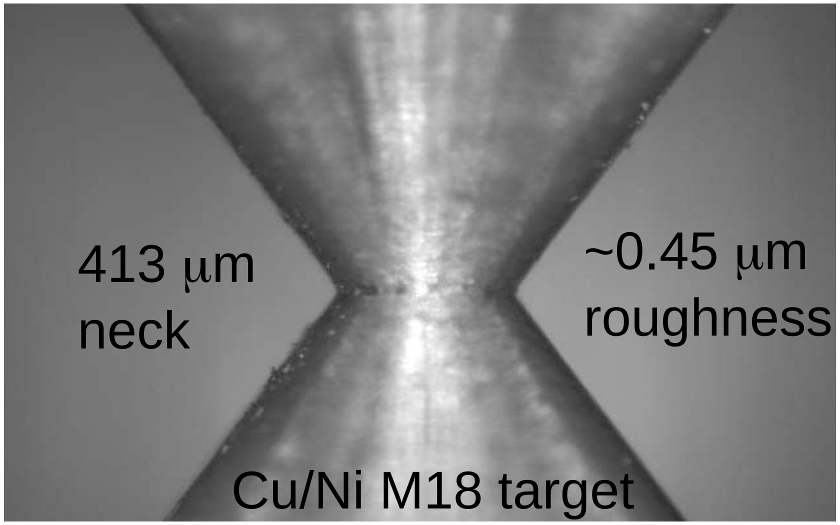
Load comprised of 3 W pieces; Limiting case of perfect cross-point

March 2009 solid X-pinch loads have showed the most promise so far….

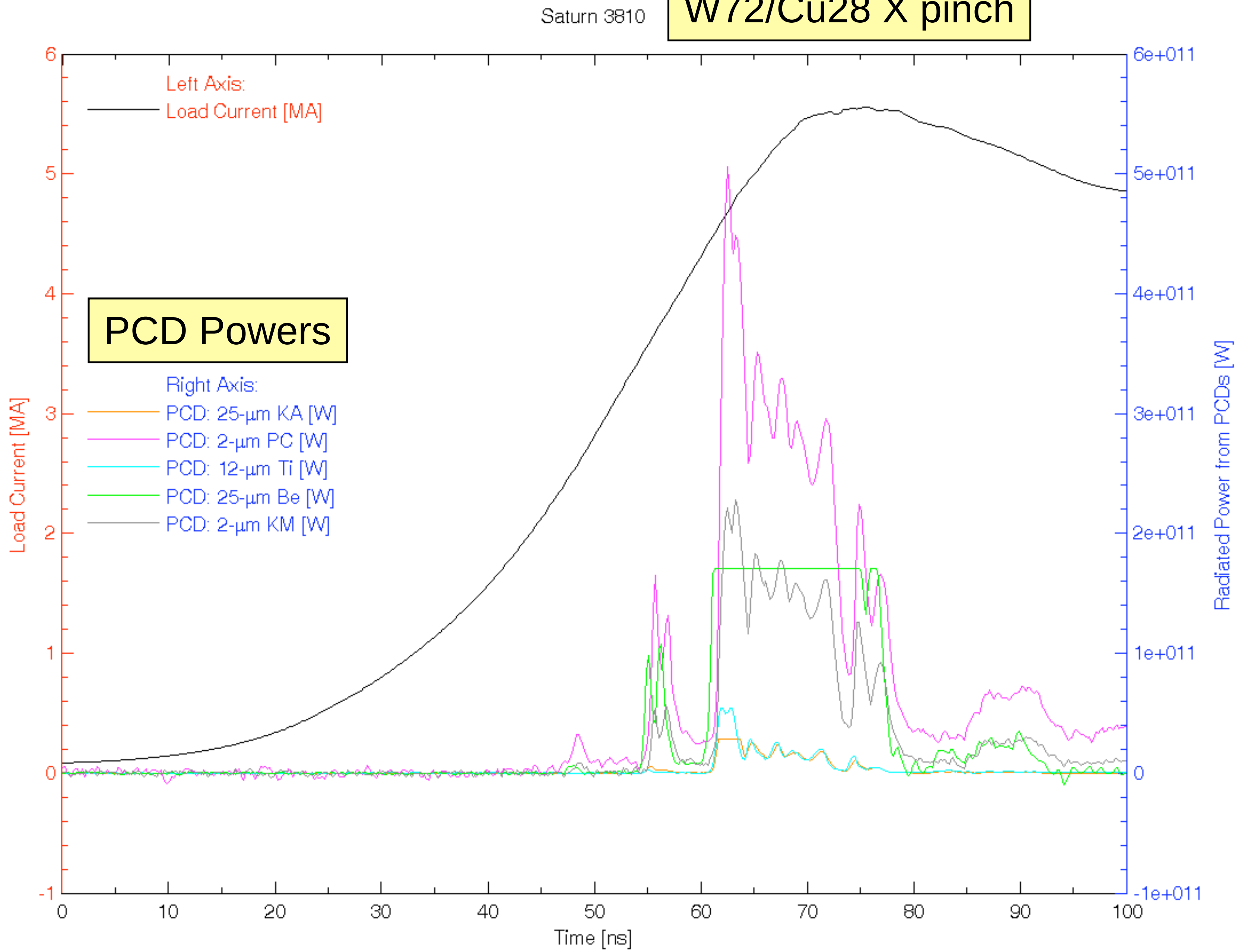
- Highest radiation powers
- Characterized by multiple narrow x-ray bursts
- Smallest apparent hard x-ray source sizes

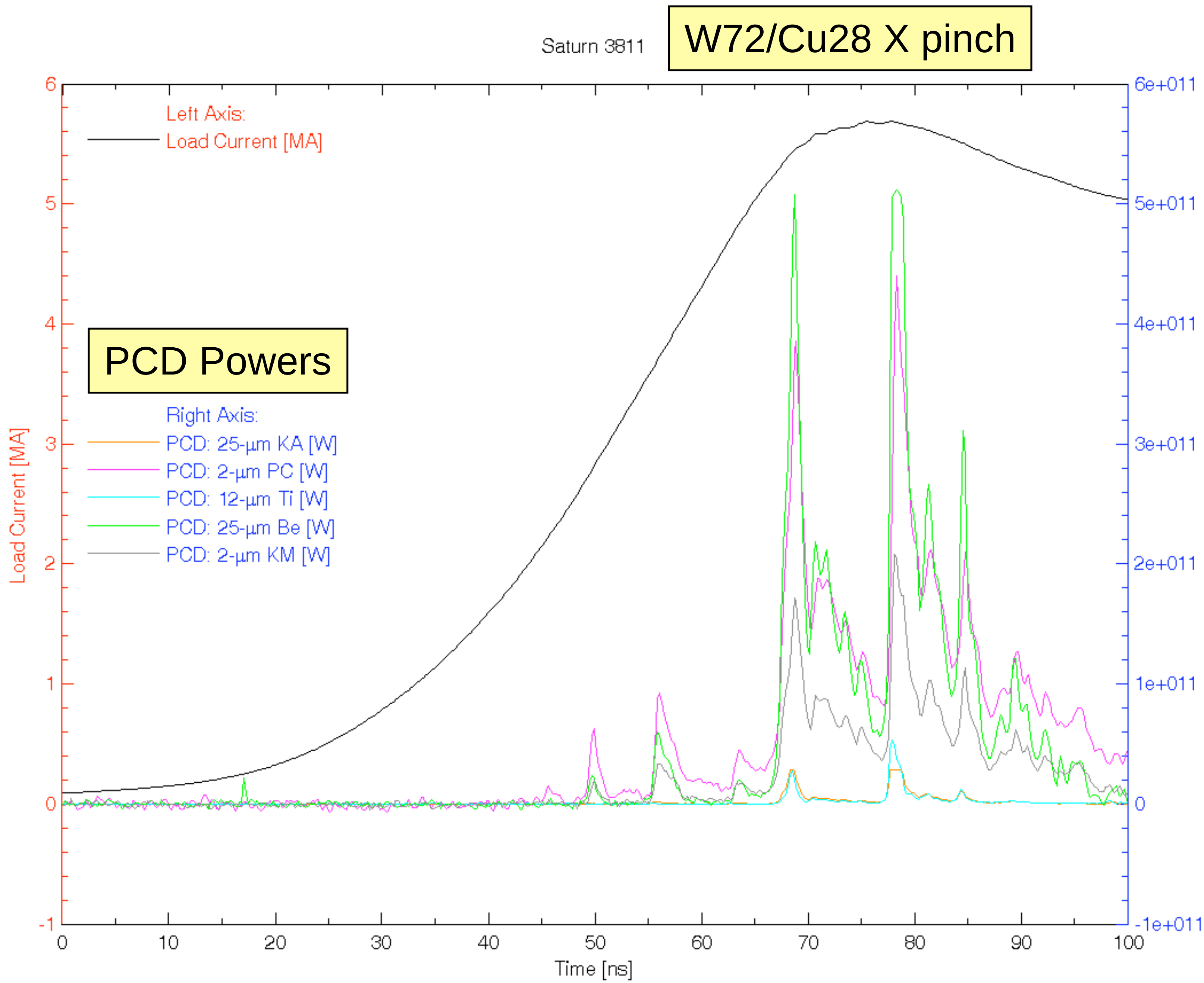


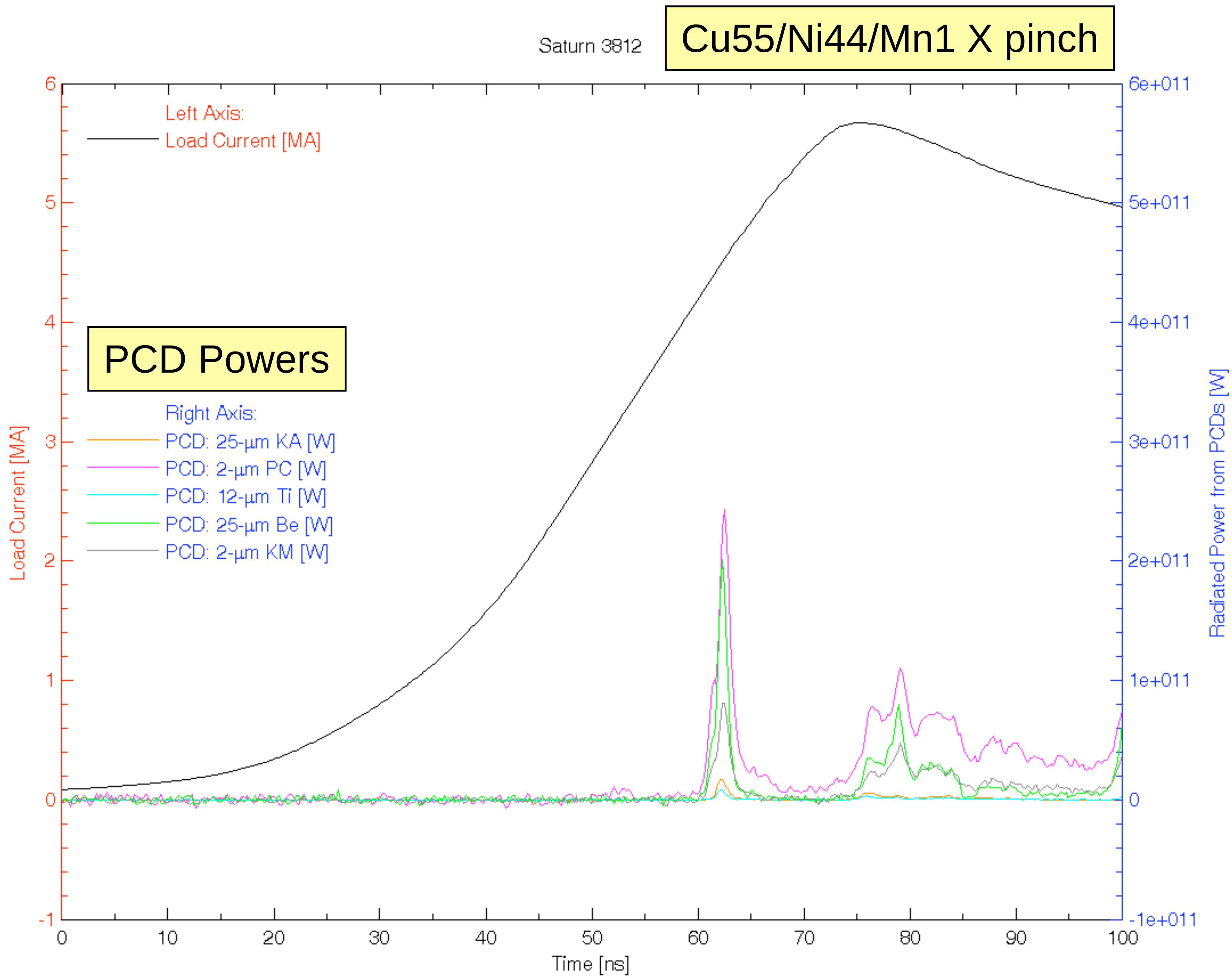




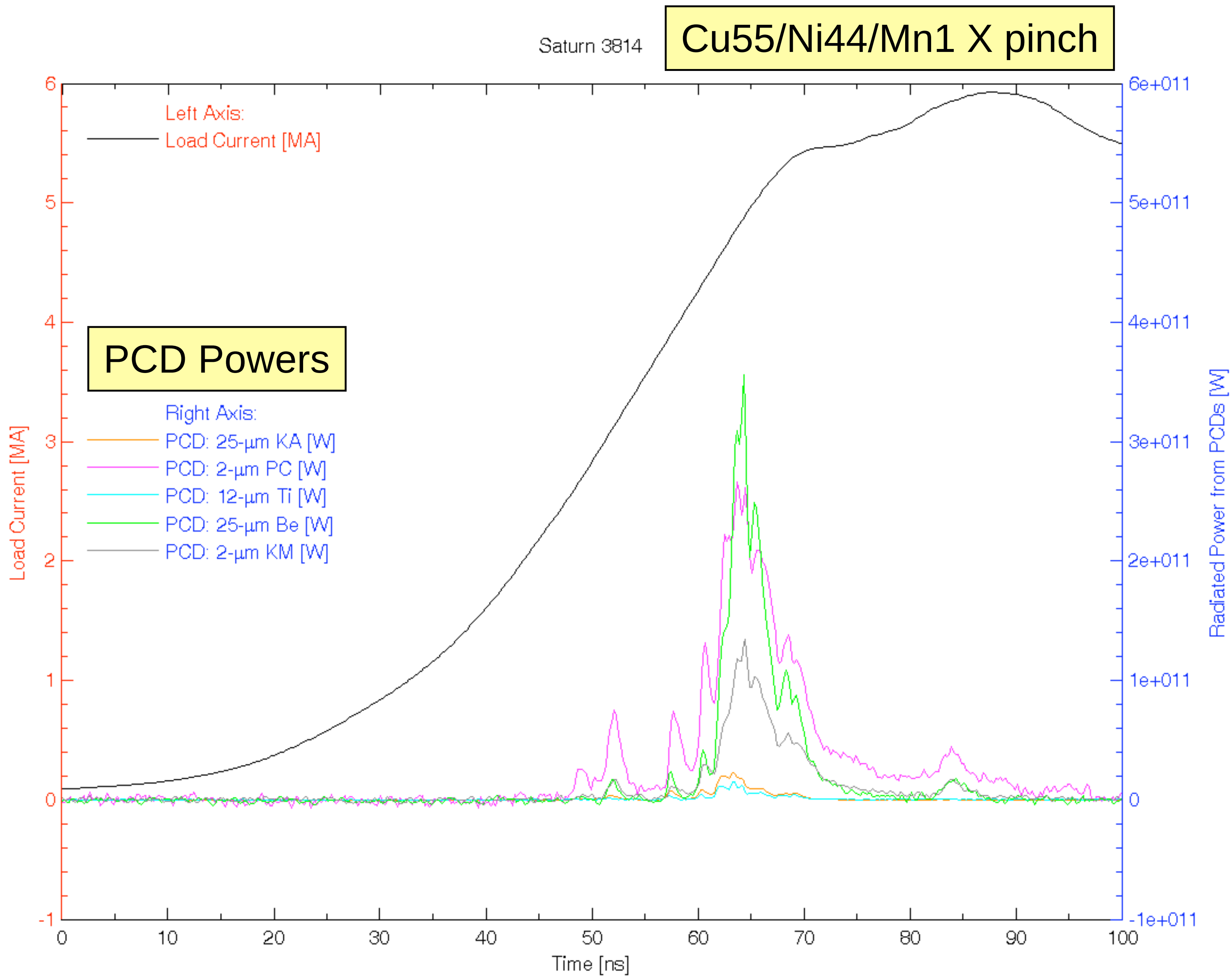
W72/Cu28 X pinch



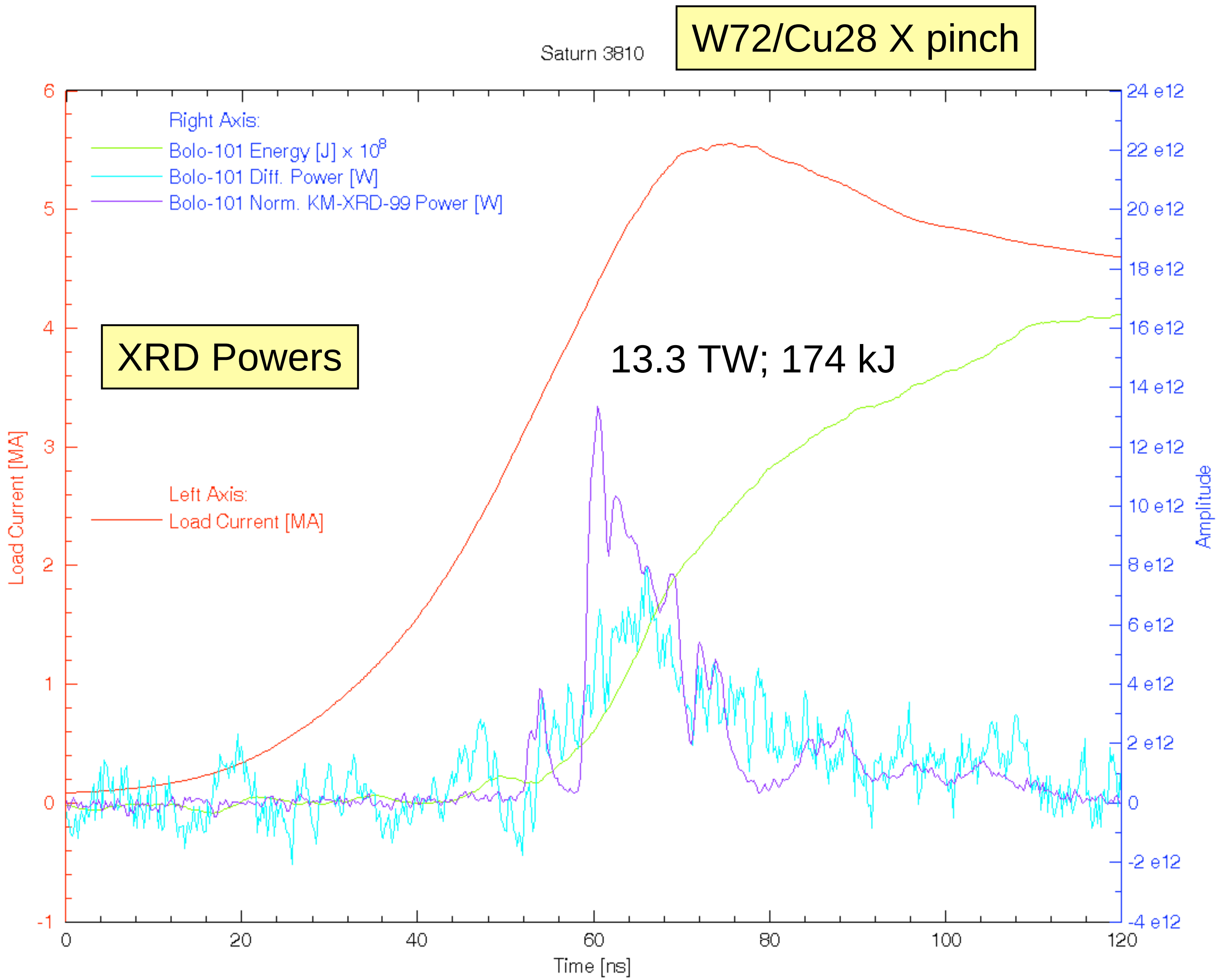

Saturn 3811
W72/Cu28 X pinch
PCD Powers
Left Axis:
Load Current [MA]
Right Axis:
PCD: 25-µm KA [W]
PCD: 2-µm PC [W]
PCD: 12-µm Ti [W]
PCD: 25-µm Be [W]
PCD: 2-µm KM [W]
Load Current [MA]
Radiated Power from PCDs [W]
Time [ns]
6
5
4
3
2
1
0
-1
6e+011
5e+011
4e+011
3e+011
2e+011
1e+011
0
-1e+011
0
10
20
30
40
50
60
70
80
90
100



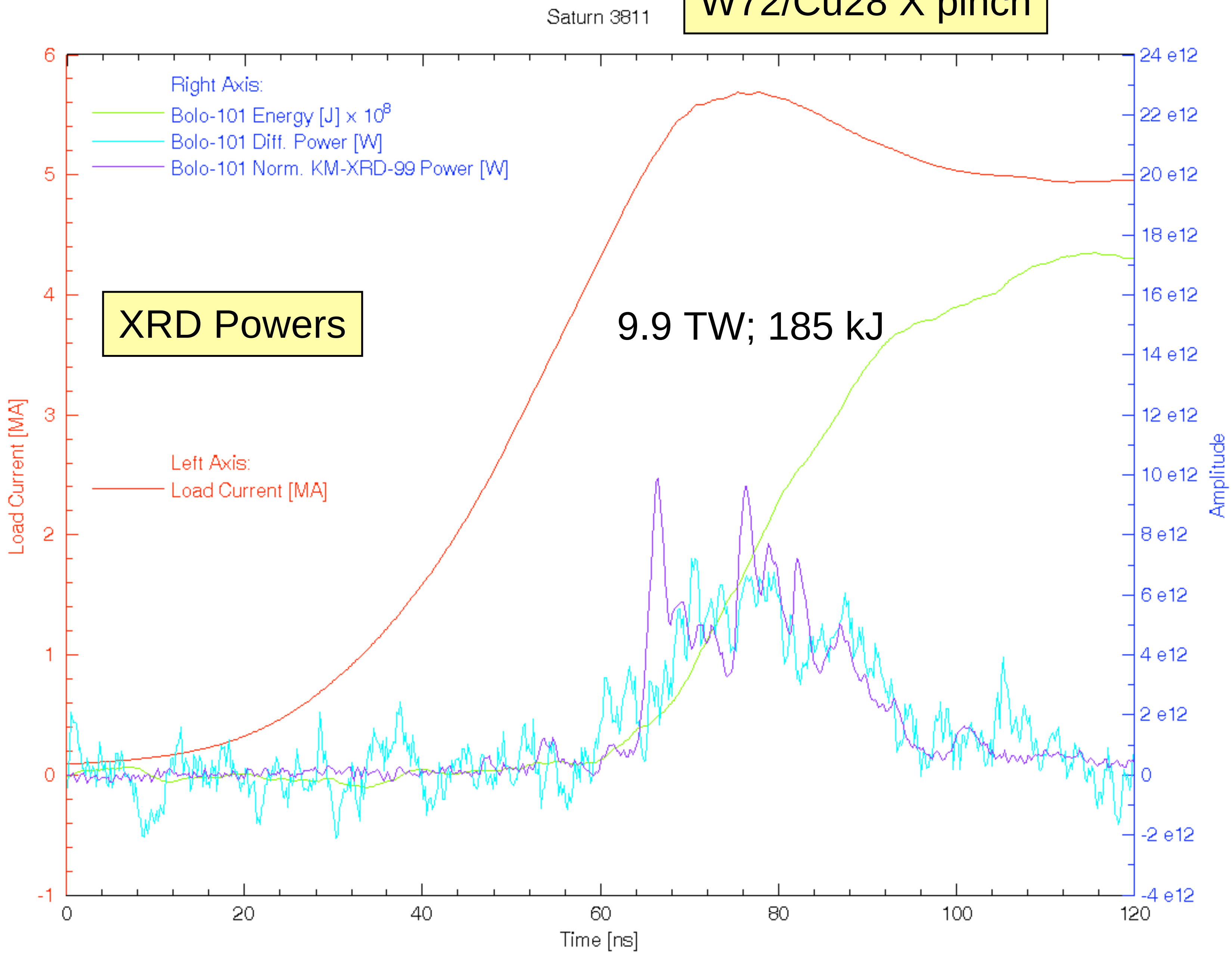
Saturn 3812
Cu55/Ni44/Mn1 X pinch
PCD Powers
Left Axis:
Load Current [MA]
Right Axis:
PCD: 25-µm KA [W]
PCD: 2-µm PC [W]
PCD: 12-µm Ti [W]
PCD: 25-µm Be [W]
PCD: 2-µm KM [W]
Load Current [MA]
Radiated Power from PCDs [W]
Time [ns]
6
5
4
3
2
1
0
-1
6e+011
5e+011
4e+011
3e+011
2e+011
1e+011
0
-1e+011
0
10
20
30
40
50
60
70
80
90
100

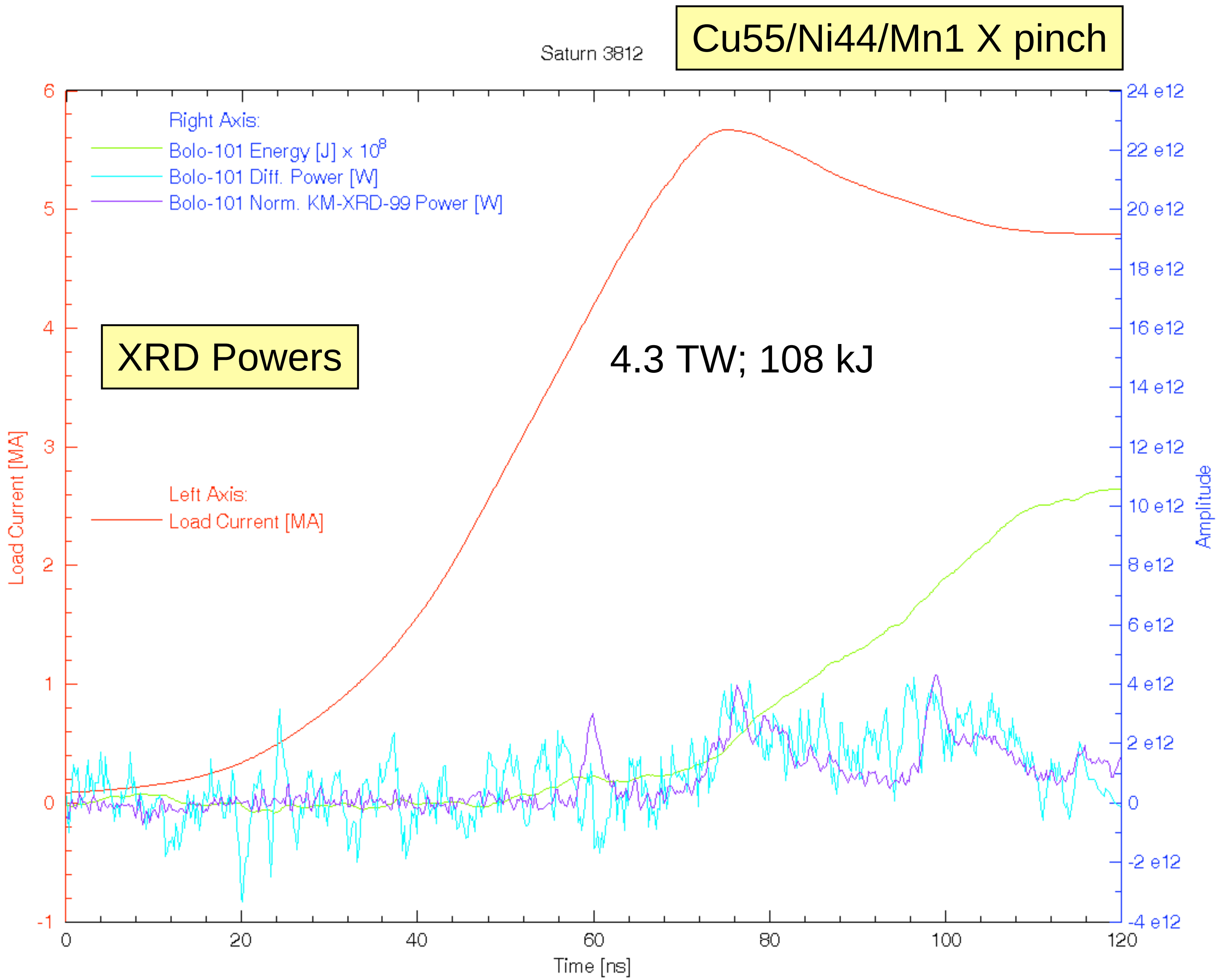


Saturn 3814
Cu55/Ni44/Mn1 X pinch
PCD Powers
Left Axis:
Load Current [MA]
Right Axis:
PCD: 25-μm KA [W]
PCD: 2-μm PC [W]
PCD: 12-μm Ti [W]
PCD: 25-μm Be [W]
PCD: 2-μm KM [W]
Load Current [MA]
Radiated Power from PCDs [W]
Time [ns]
6
5
4
3
2
1
0
-1
6e+011
5e+011
4e+011
3e+011
2e+011
1e+011
0
-1e+011
0
10
20
30
40
50
60
70
80
90
100

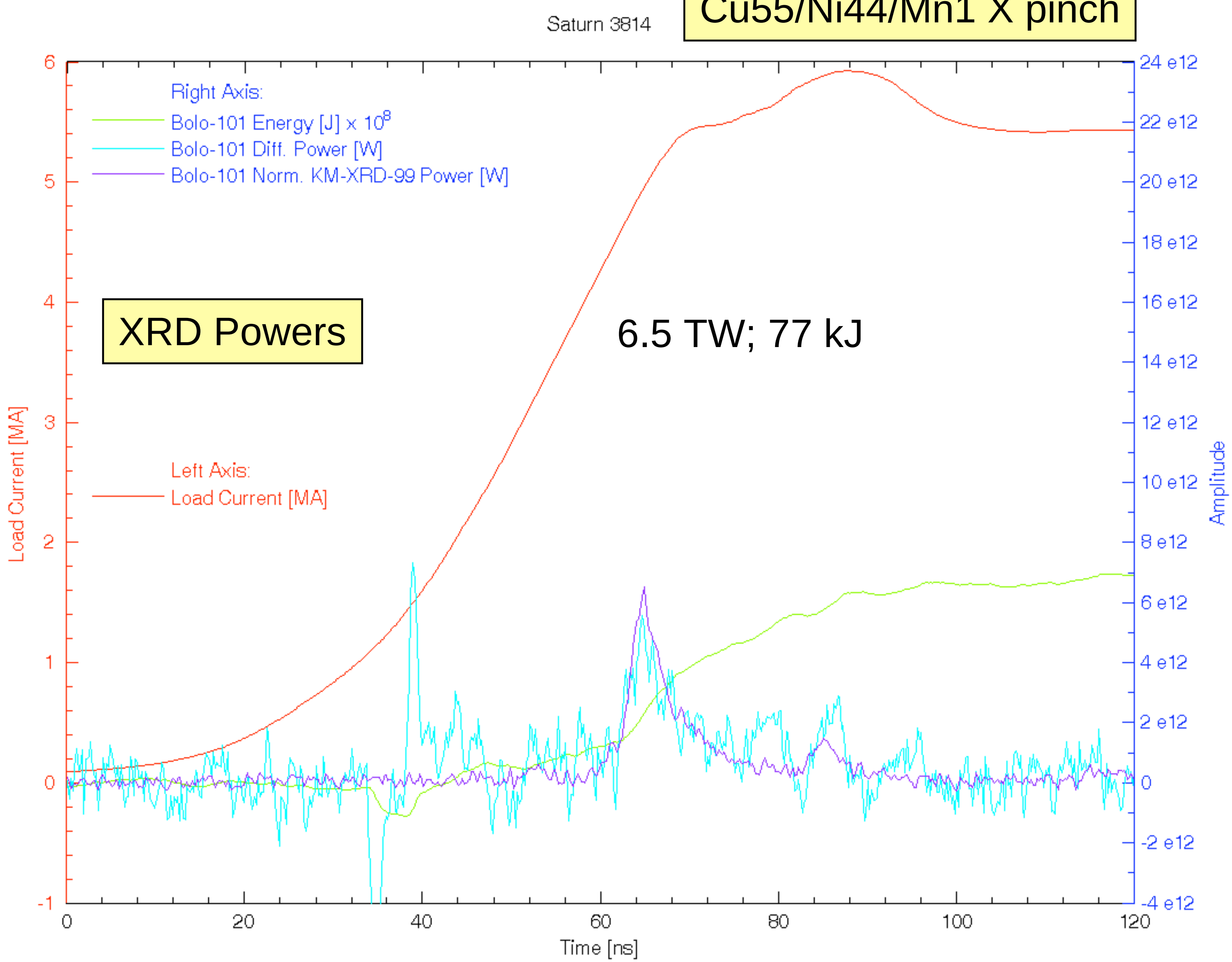

W72/Cu28 X pinch
Saturn 3810
Right Axis:
Bolo-101 Energy [J] x 10^8
Bolo-101 Diff. Power [W]
Bolo-101 Norm. KM-XRD-99 Power [W]
XRD Powers
13.3 TW; 174 kJ
Left Axis:
Load Current [MA]
Load Current [MA]
Amplitude
Time [ns]
6
5
4
3
2
1
0
-1
0
20
40
60
80
100
120
24 e12
22 e12
20 e12
18 e12
16 e12
14 e12
12 e12
10 e12
8 e12
6 e12
4 e12
2 e12
0
-2 e12
-4 e12

W72/Cu28 X pinch

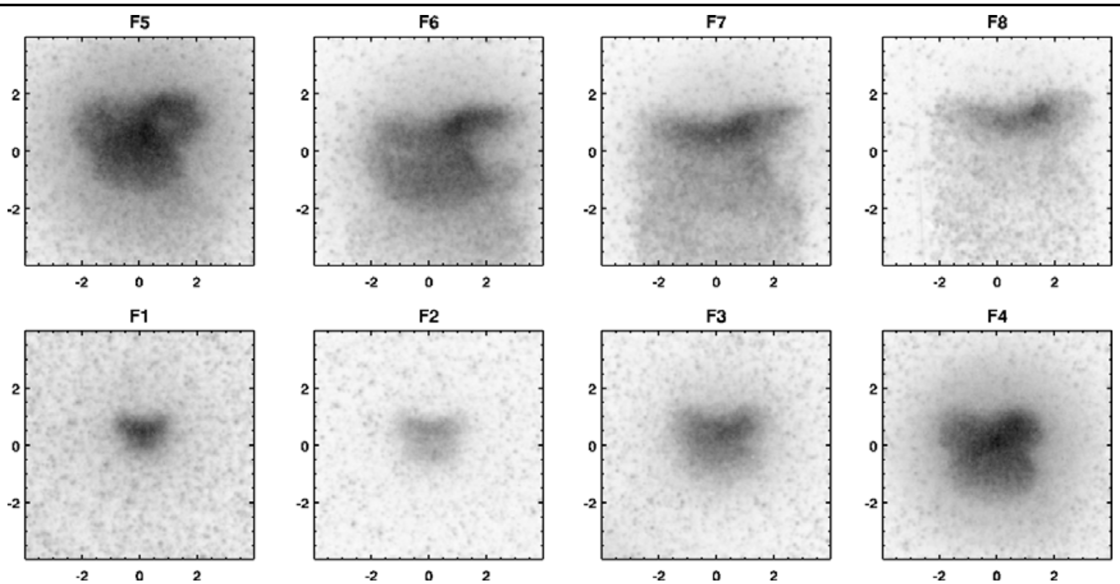



Cu55/Ni44/Mn1 X pinch
Saturn 3812
Right Axis:
Bolo-101 Energy [J] x 10^8
Bolo-101 Diff. Power [W]
Bolo-101 Norm. KM-XRD-99 Power [W]
XRD Powers
4.3 TW; 108 kJ
Left Axis:
Load Current [MA]
Load Current [MA]
Amplitude
Time [ns]
6
5
4
3
2
1
0
-1
24 e12
22 e12
20 e12
18 e12
16 e12
14 e12
12 e12
10 e12
8 e12
6 e12
4 e12
2 e12
0
-2 e12
-4 e12
0
20
40
60
80
100
120

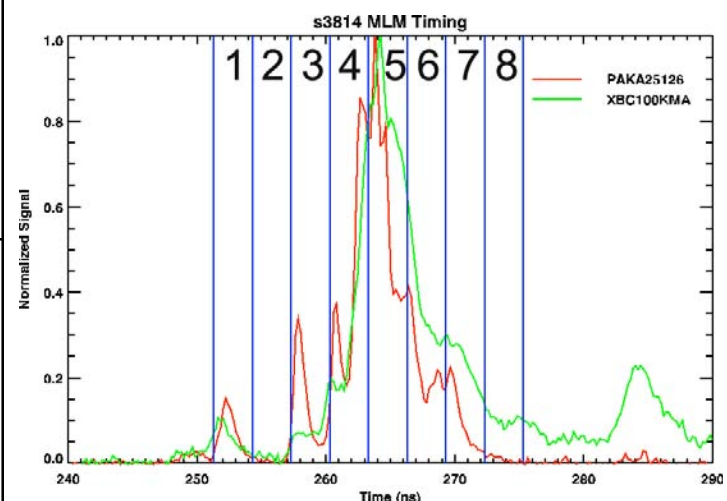
Cu55/Ni44/Mn1 X pinch

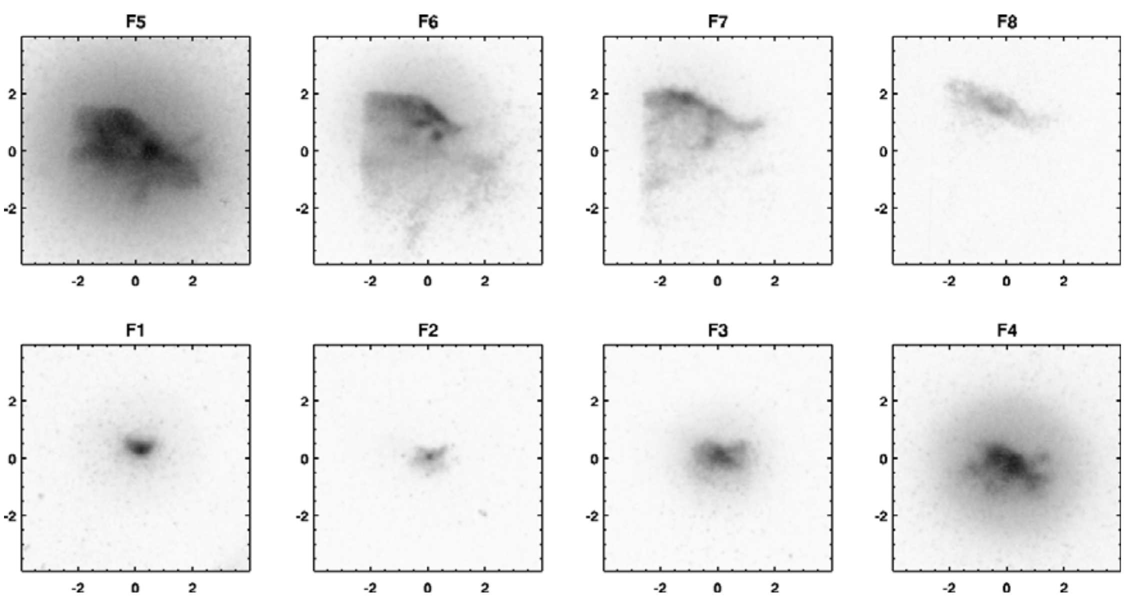


Cu/Ni X-pinch gated pinhole camera images show ~3 mm source size for soft x rays



S3814
MLM1
277 eV images
3ns IFT; 3ns gate
~540 μm resolution



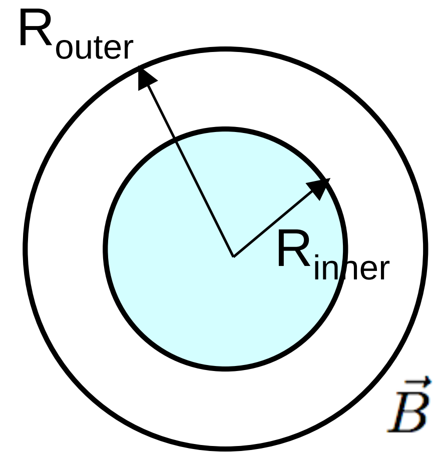


S3814
MLM2
>1 keV images
3ns IFT; 3ns gate
~200 μm resolution (2 keV)

The work done by the JxB force can be quickly estimated for coaxial geometries

Magnetostatic potential energy:

$$U = \frac{1}{2\mu_0}\int_{allspace} B^2 dV = \frac{1}{2}LI^2$$



$$\vec{B} = \frac{\mu_0 I}{2\pi r}\widehat{\phi},$$

$$for\ R_{outer} > r > R_{inner}$$

For a coaxial system:

$$W' = \frac{\mu_0}{4\pi}\int_0^{t_{final}} I^2(t)\ln\frac{R_{out}}{R_{pinch}(t)}dt$$

For a constant current:

$$W'_{static} = \frac{\mu_0 I_0^2}{4\pi}\int_0^{t_{final}} \ln\frac{R_{out}}{R_{pinch}(t)}dt = \frac{\mu_0 I_0^2}{4\pi}\ln\frac{R_0}{R_{final}}$$

JxB Work varies with:

- Current
- Convergence Ratio

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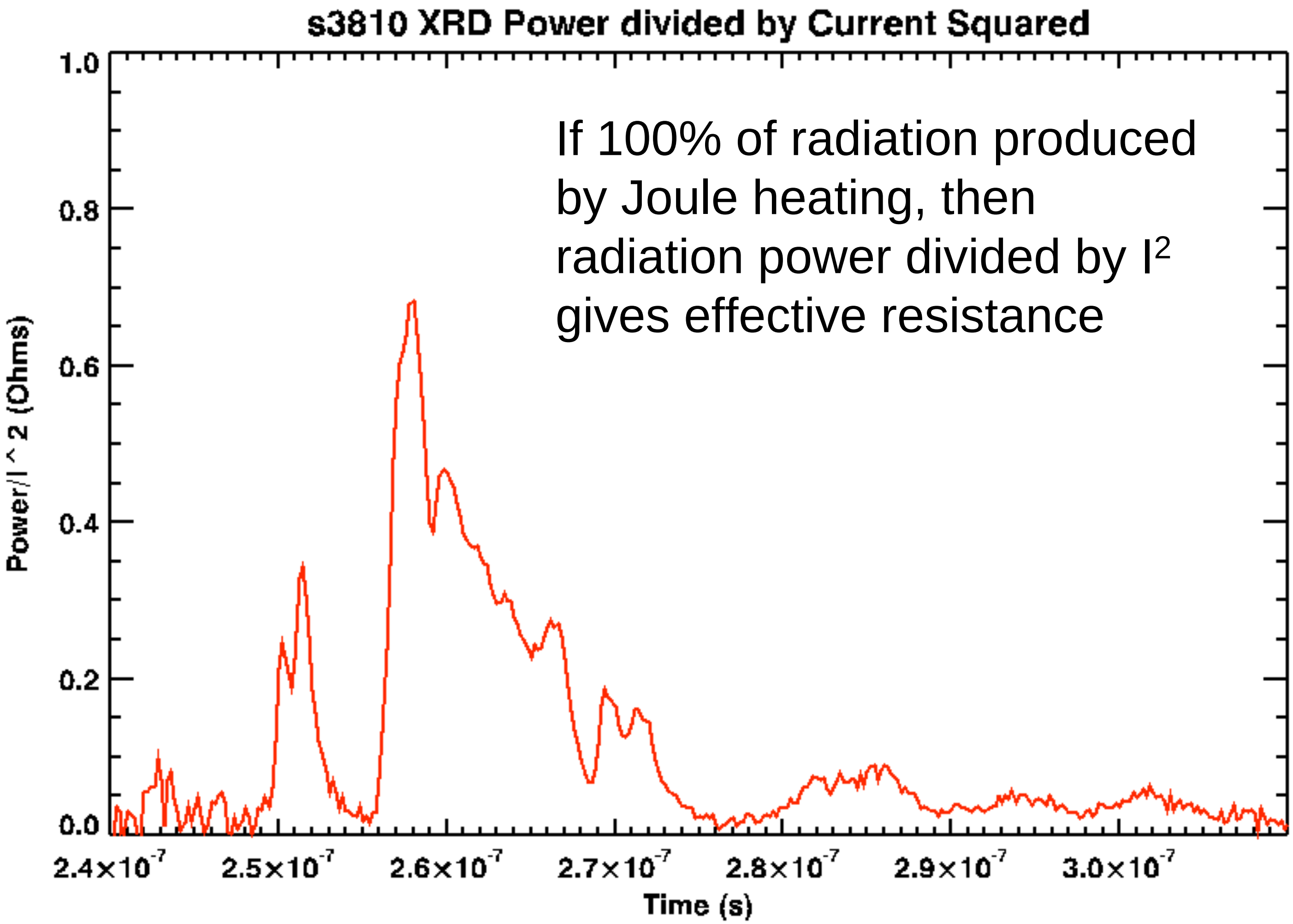
X pinches have “zero” kinetic energy and even at large convergence ratios JxB work is too small

- All mass starts on axis--main work done is compressional JxB (PdV) work
- W/Cu X pinch initial neck diameter = 366 μm
- Example JxB work estimates
  - 10 μm final collapse radius: CR=36.6, ln(36.6)=3.6
  - 1 μm final collapse radius: CR=366, ln(366)=5.9
  - Work ~3e6 * ln(CR) * Pinch height (in m)
  - Extreme case of 3 mm tall, 1 μm diameter pinch: Work ~ 3e6*5.9*0.003 = 53.1 kJ
- Measured Yields: 175 kJ, 184 kJ
- Must be dominated by Ohmic heating? *

* Consistent with assumptions in Chittenden *et al.*, Phys. Rev. Lett. (2007).

Power/I² (“Resistance”) for W/Cu X-pinch test s3810



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SATURN X pinches have relatively high average energy/power line densities

Shot #	Material	Radiated Energy Yield [kJ]:	Peak Radiated Power (Bolo-Normalized) [TW]:
3808	Ni80/Cr20	164	6.6
3809	Cu55/Ni44/Mn1	96	6.1
3810	W72/Cu28	174	13.3
3811	W72/Cu28	185	9.9
3812	Cu55/Ni44/Mn1	108	4.3
3814	Cu55/Ni44/Mn1	77	6.5

- **SATURN W/Cu X pinches:**
  - **~11.5 TW, ~180 kJ, from a ~3 mm tall region**
  - **~4 TW/mm; ~60 kJ/mm**
- **SATURN planar arrays:**
  - **~15 TW, ~300 kJ, from a 20 mm tall region**
  - **<0.1 TW/mm; ~15 kJ/mm**
- **Z tungsten Z pinch (Deeney PRE):**
  - **~240 TW, ~1800 kJ, from a 20 mm tall region**
  - **~12 TW/mm; ~90 kJ/mm**

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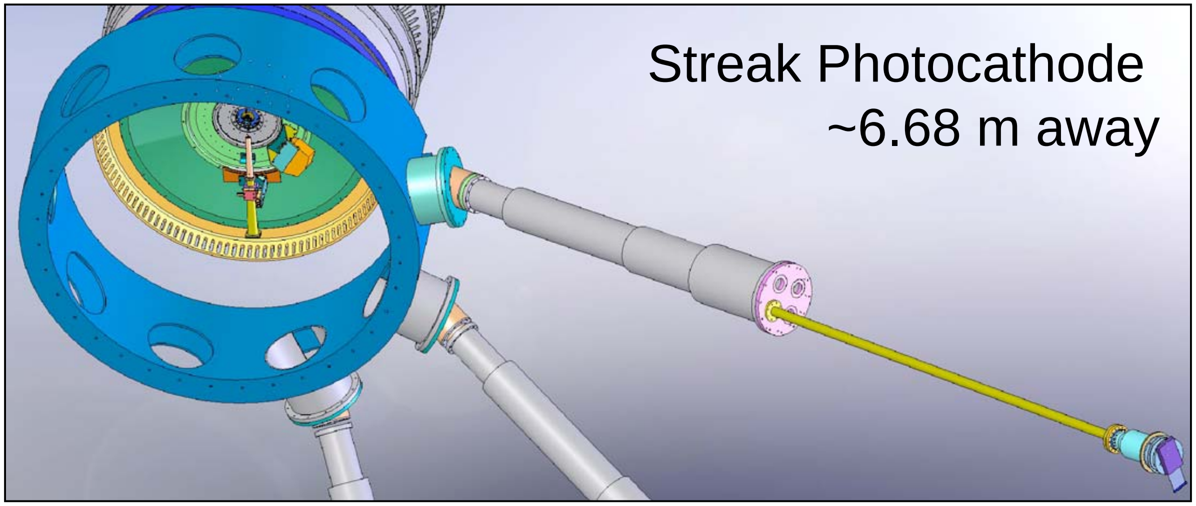
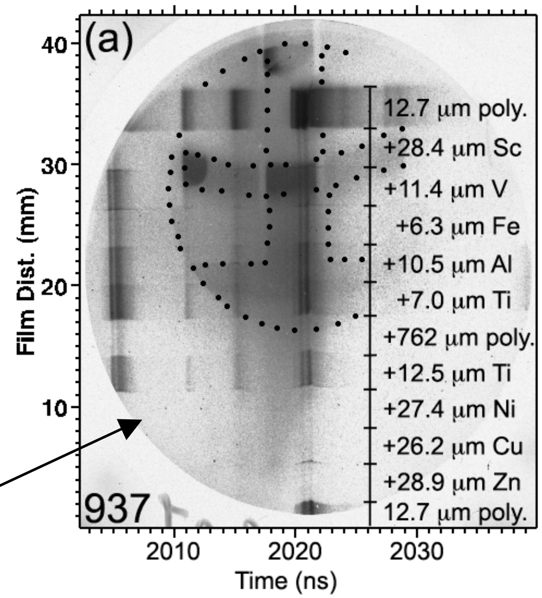
Could the actual powers be higher?

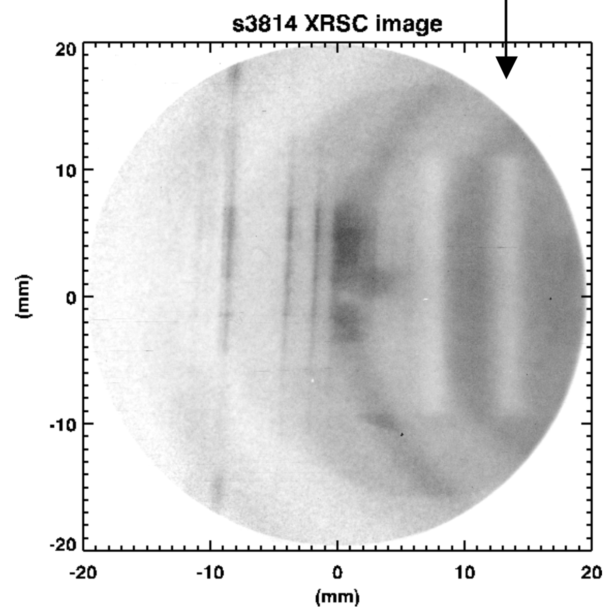
Streak camera data measuring x-ray emission duration from Cu/Ni X-pinch



Struggled with too much signal and a damaged power supply. After adding 250 μm polyimide, got data on final shot of series (s3814)

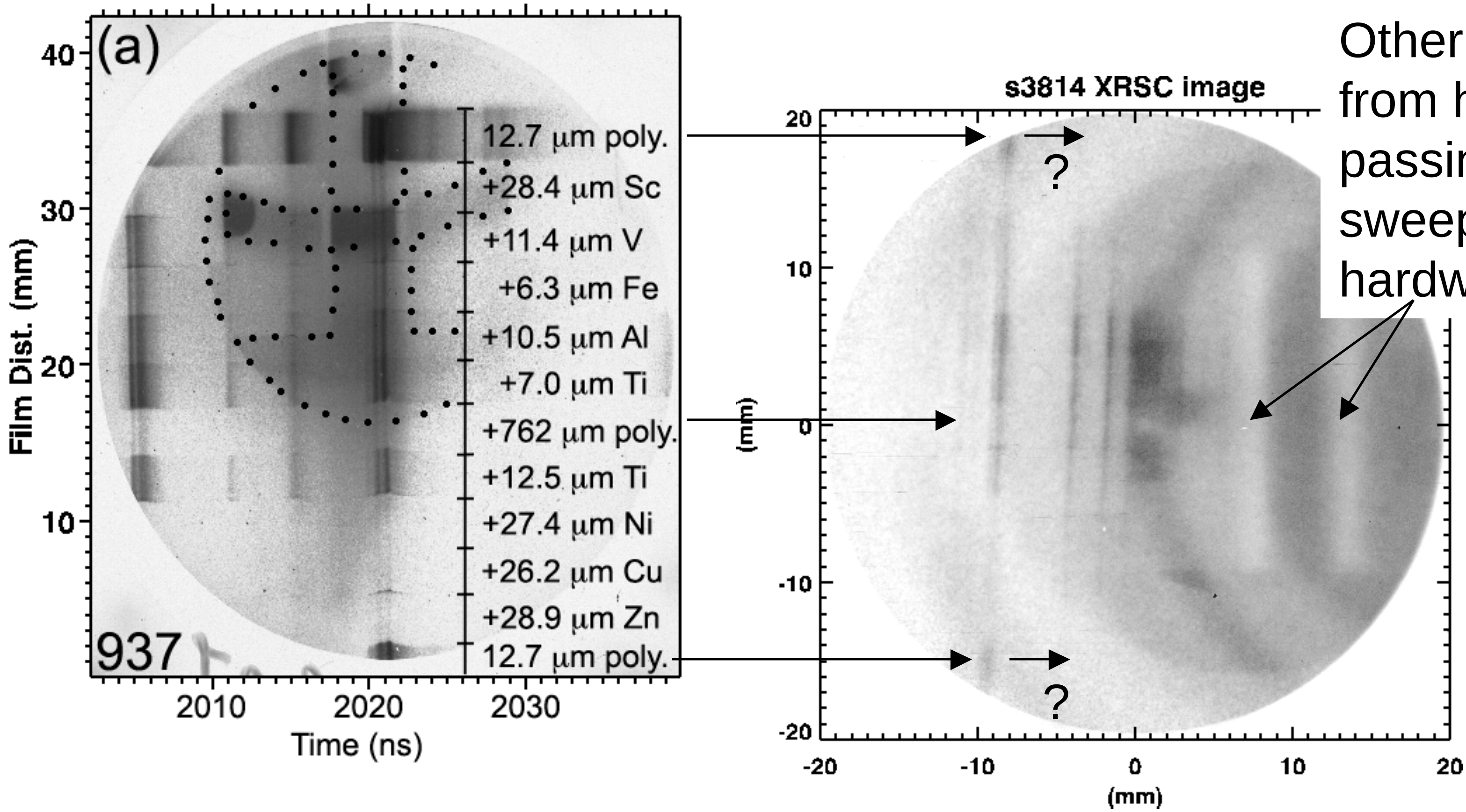
Photocathode covered with array of filters as on 1 MA X-pinch experiments*





* D.B. Sinars *et al.*, Phys. Plasmas (2008).

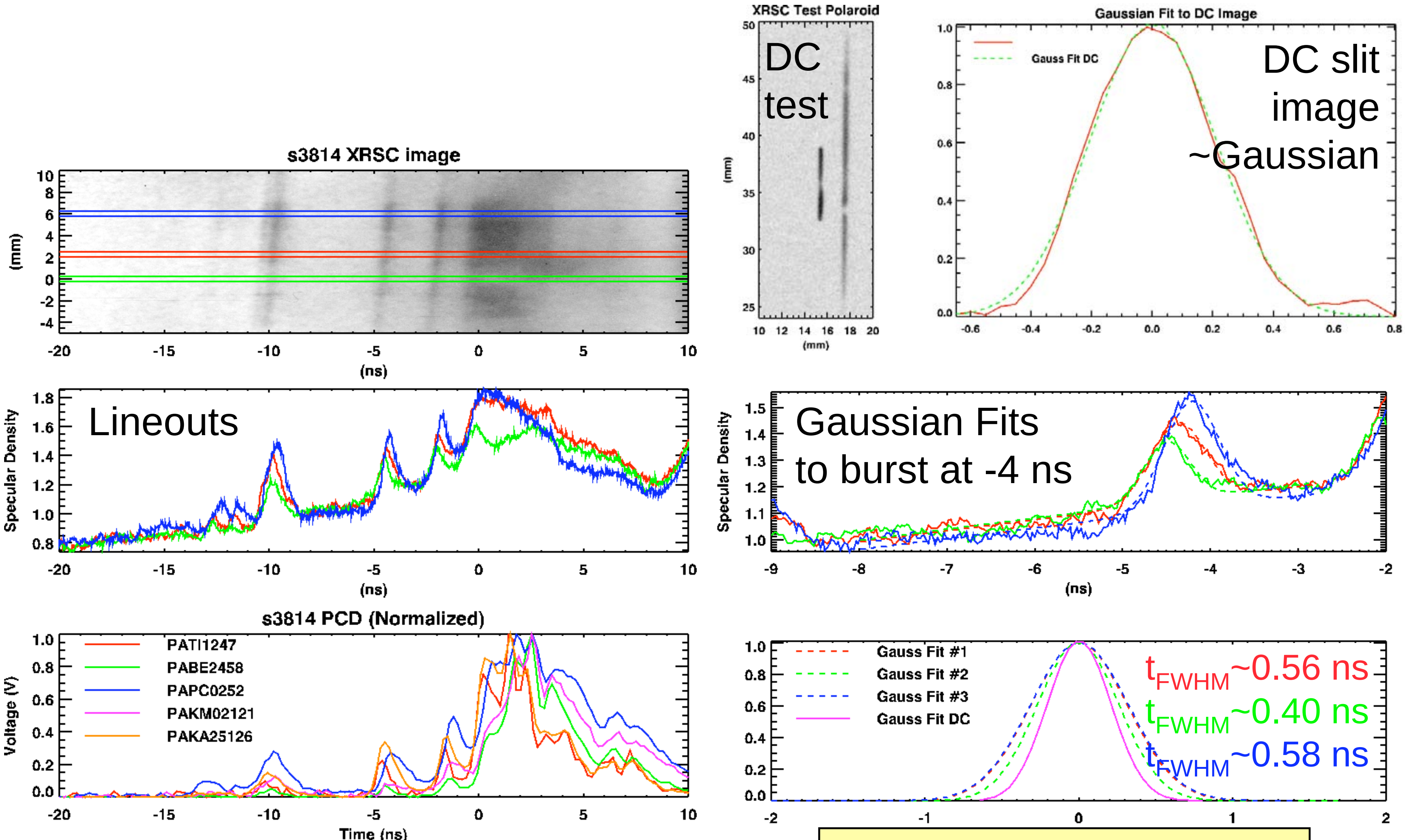
X-ray streak data doesn’t quite make sense--thinnest-filter streaks on end disappear



Other structure from hard x rays passing through sweep plate hardware

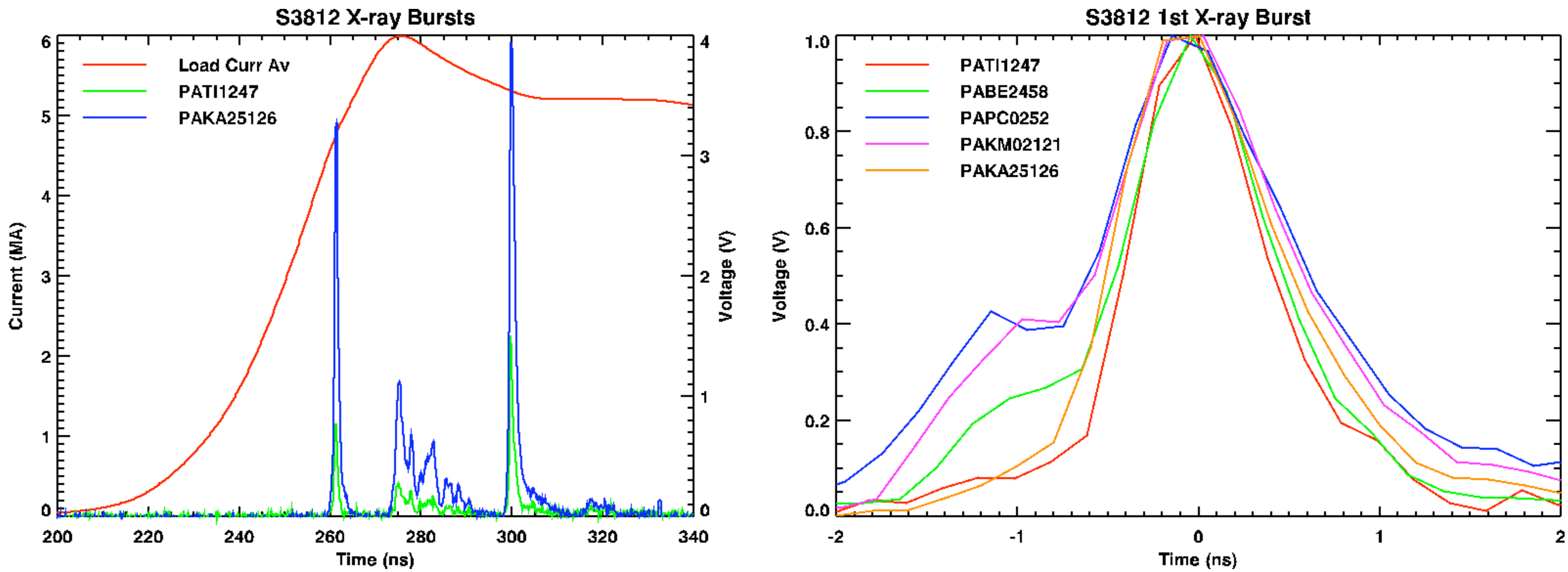
Had some problems with power supply--could not get perfect focusing on ends post-shot. The problem could be with the focusing.

Analysis of Cu/Ni X-pinch X-ray Streak Camera Data (s3814) shows sub-ns bursts



Better streak data needed

Another Cu/Ni X pinch had a lone burst with a 0.8-1.1 ns FWHM on hard-filtered PCDs



Bottom line: If true x-ray bursts are <0.5 ns duration (as on 0.2 MA experiments), how accurate will traditional bolometer/XRD/PCD measurements be?

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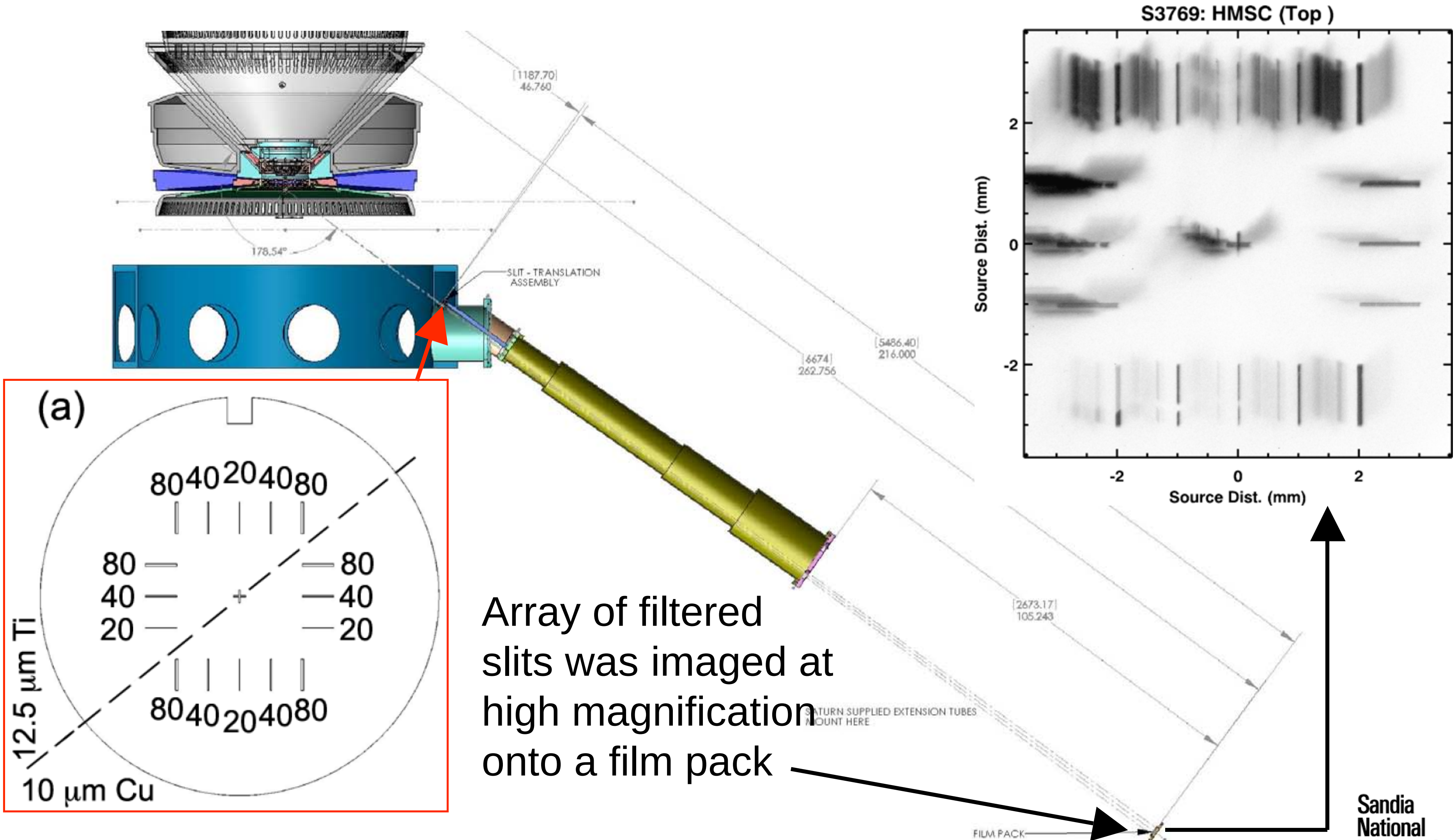
A high-magnification slit camera was used on first 2 series to measure the x-ray source size



Array of filtered slits was imaged at high magnification onto a film pack

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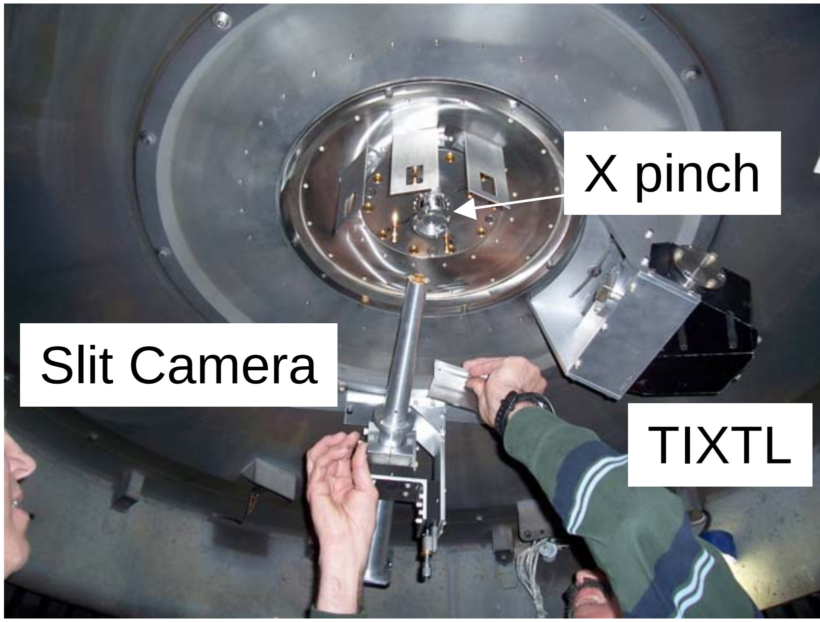
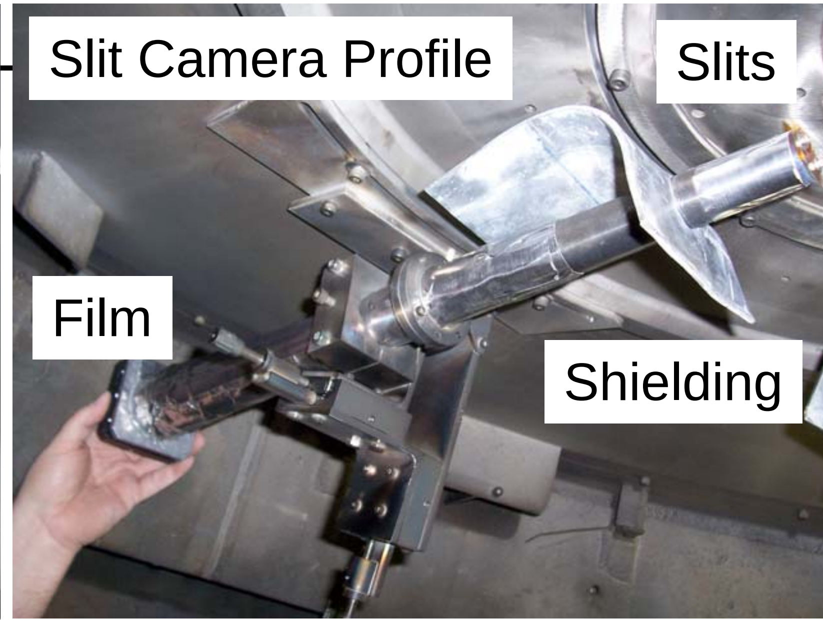
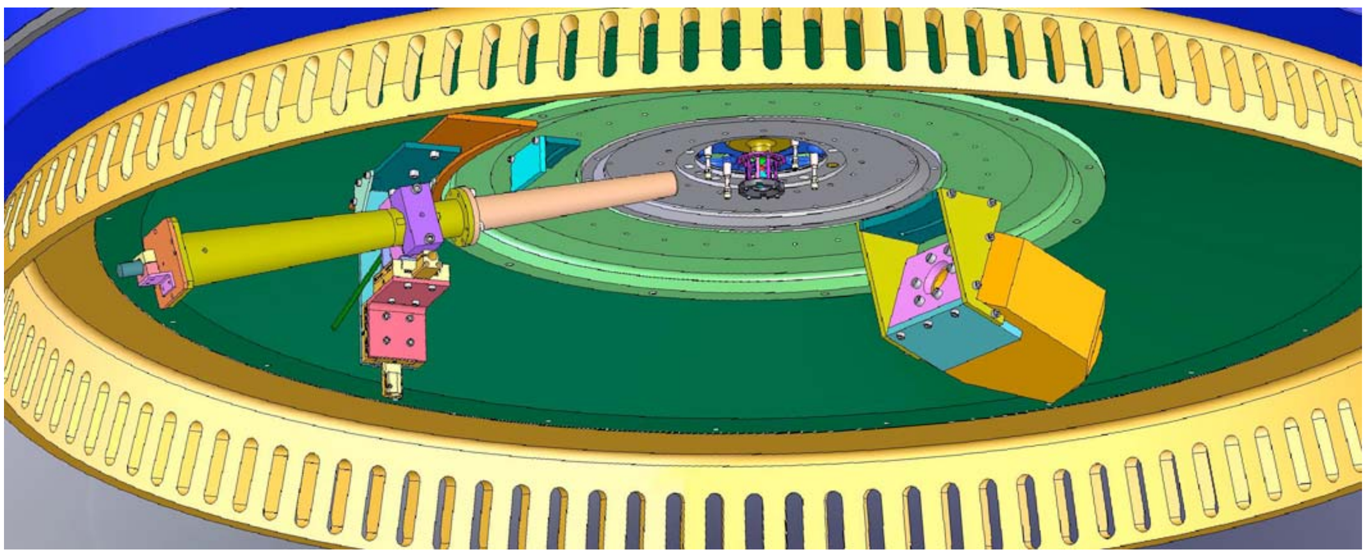
Recent series used an in-chamber slit camera & time-integrated convex spectrometer

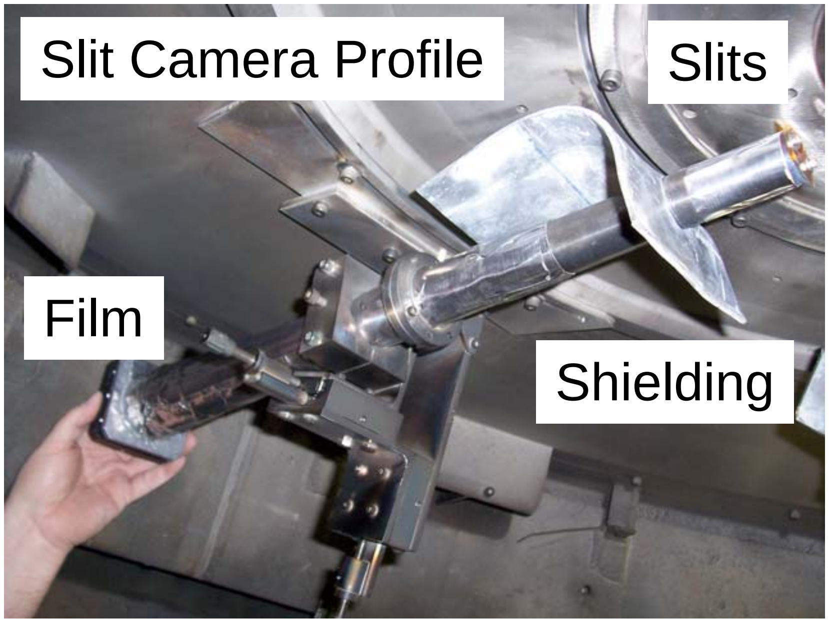






- Slits ~0.1 m from X-pinch
- Magnification ~6.6x
- Reduced diffraction blurring (slits ~1.2 m before)

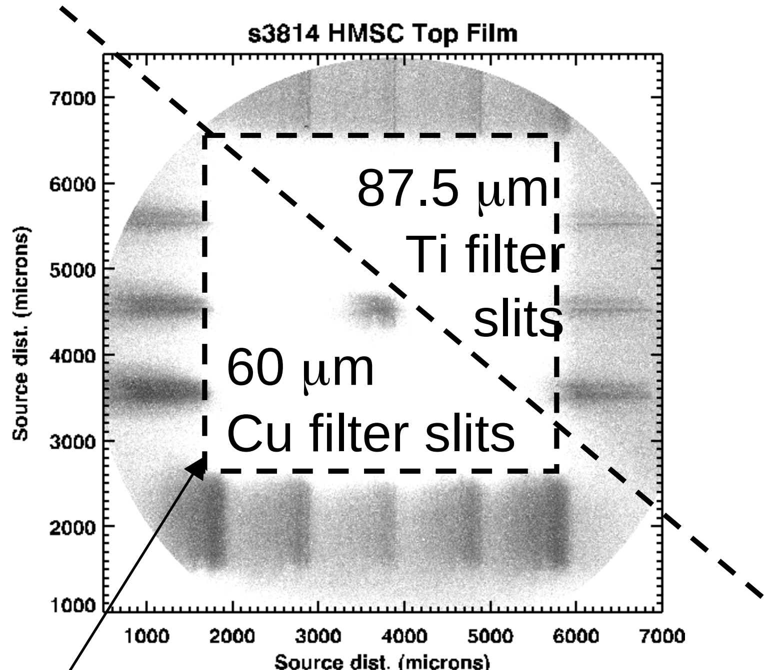
Hard x rays penetrating the Ta slit substrate created significant background on the film



Initially tried to shield film pack with external shielding.

Tests quickly showed that background was coming straight through the slit assembly itself

25 μm Ta slit substrate
+50 μm polyimide filter



Best result obtained when a ~4 mm thick Pb cube placed behind Ta slit piece

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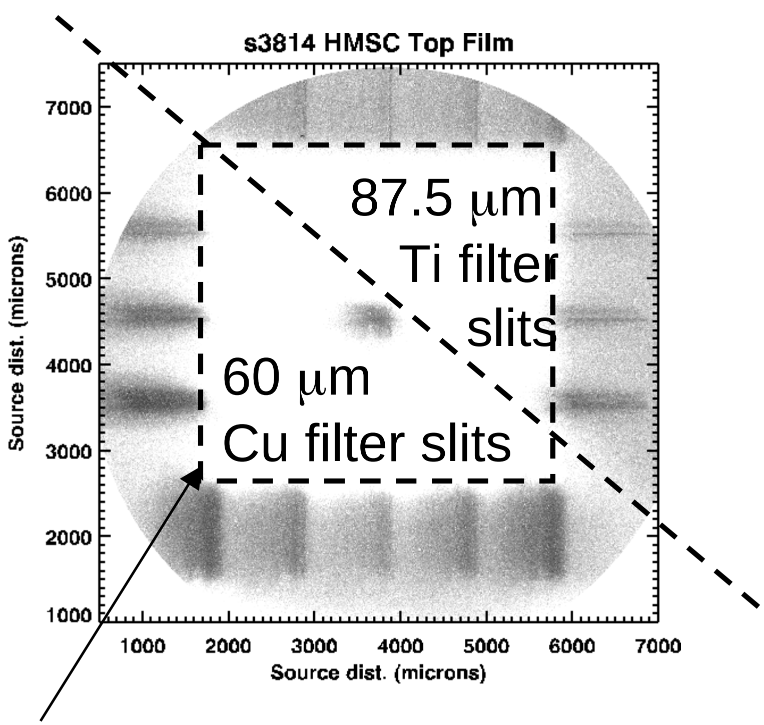
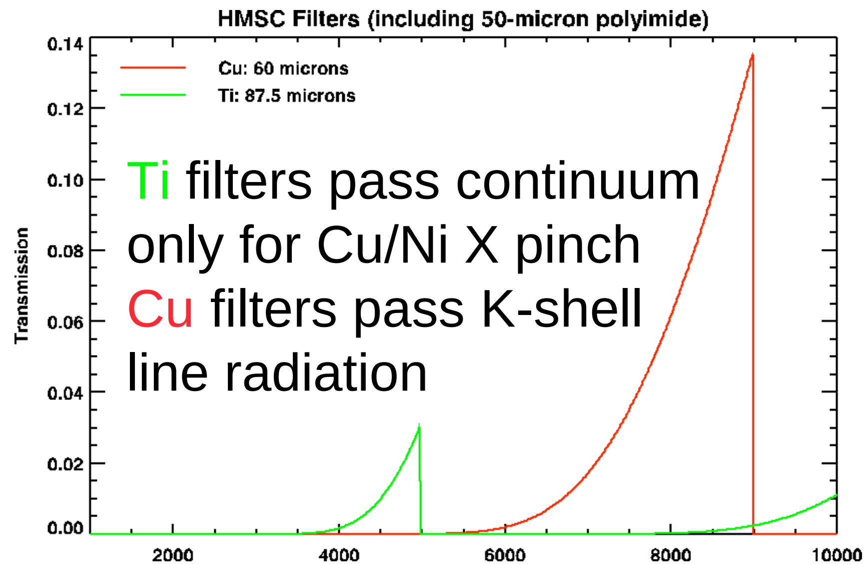
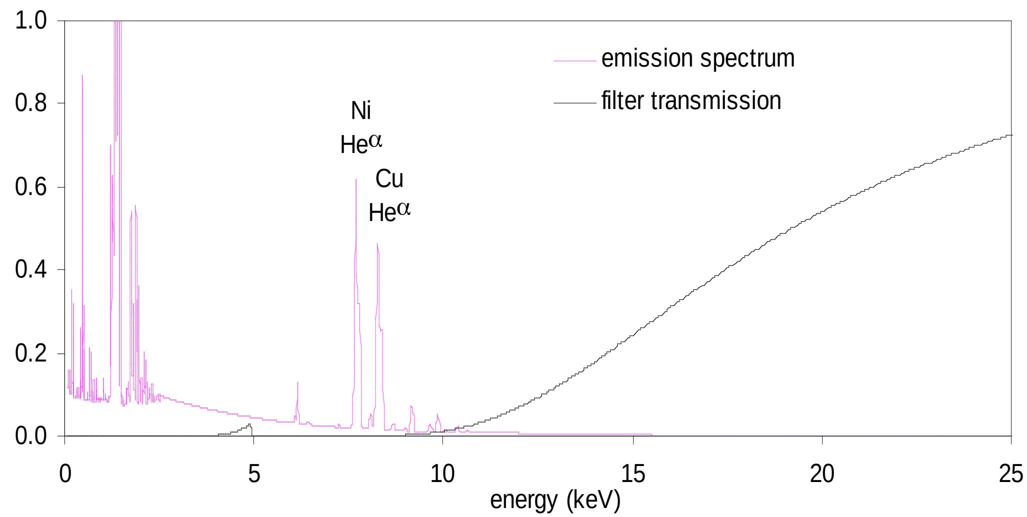
For Cu/Ni X pinches, filtered slits passed either continuum or K-shell line radiation

25 μm Ta slit substrate
+50 μm polyimide filter

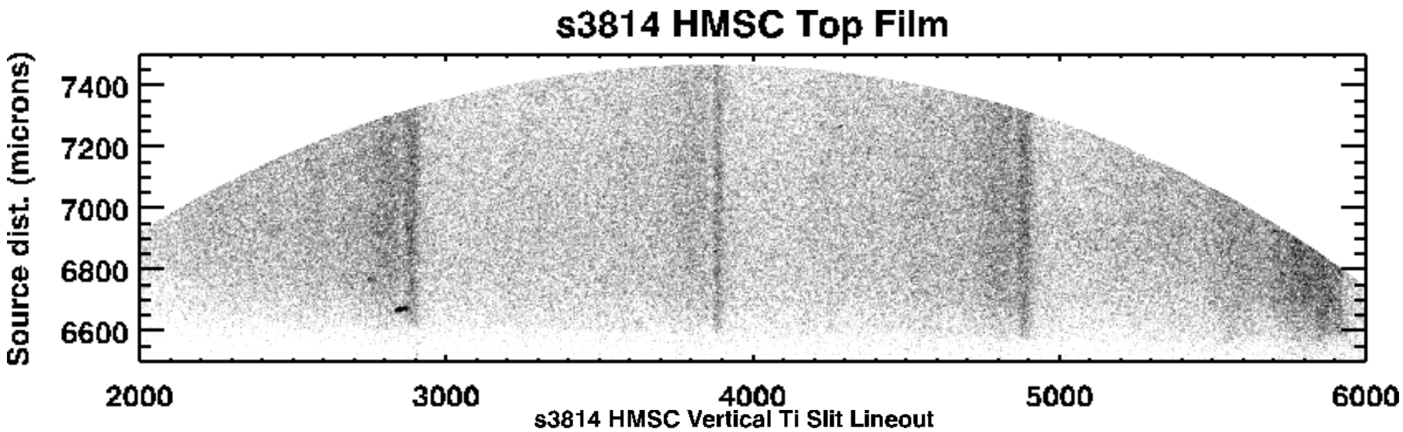


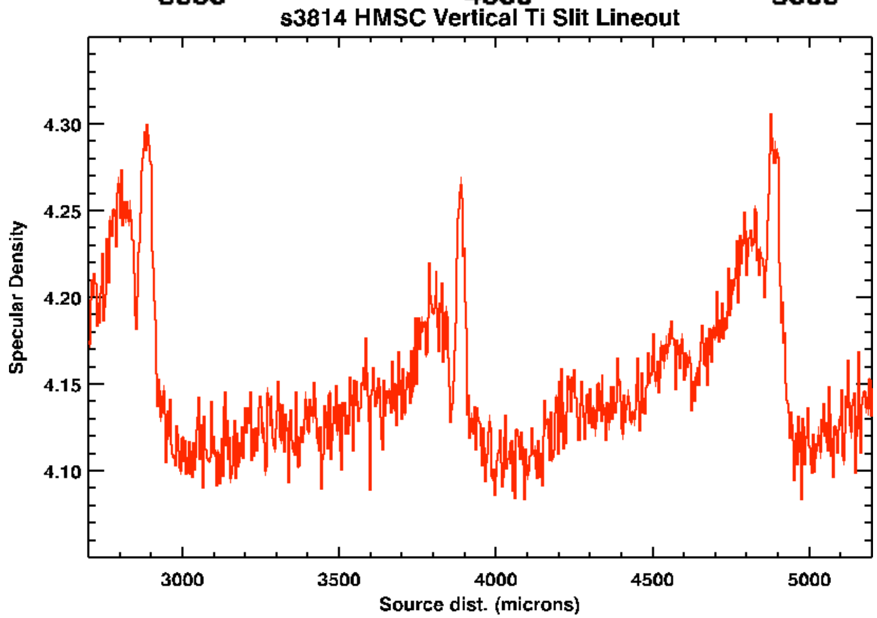




Best result obtained when a ~4 mm thick Pb cube placed behind Ta slit piece

Vertical Ti slit images show at least one narrow x-ray spot for Cu/Ni X pinch (s3814)





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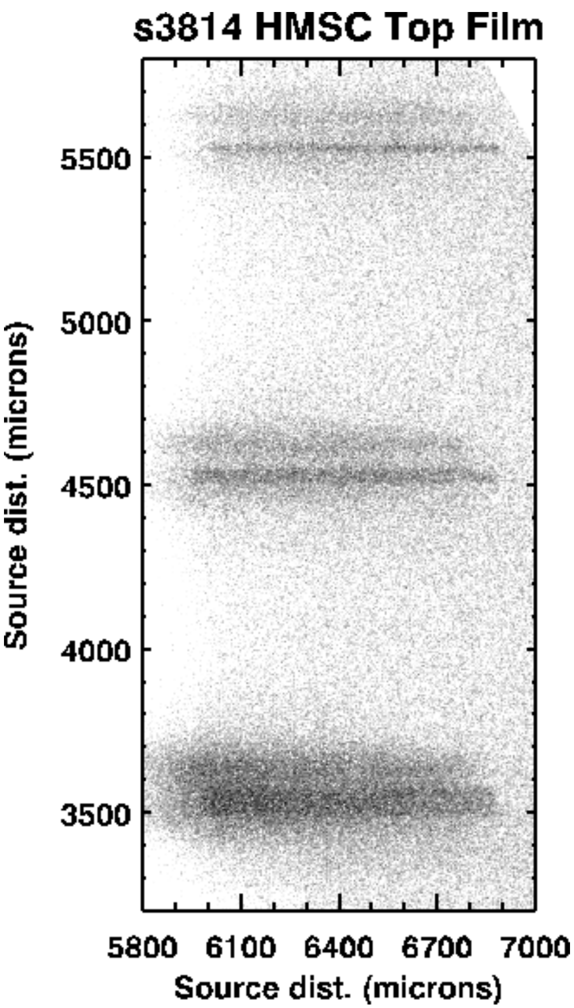
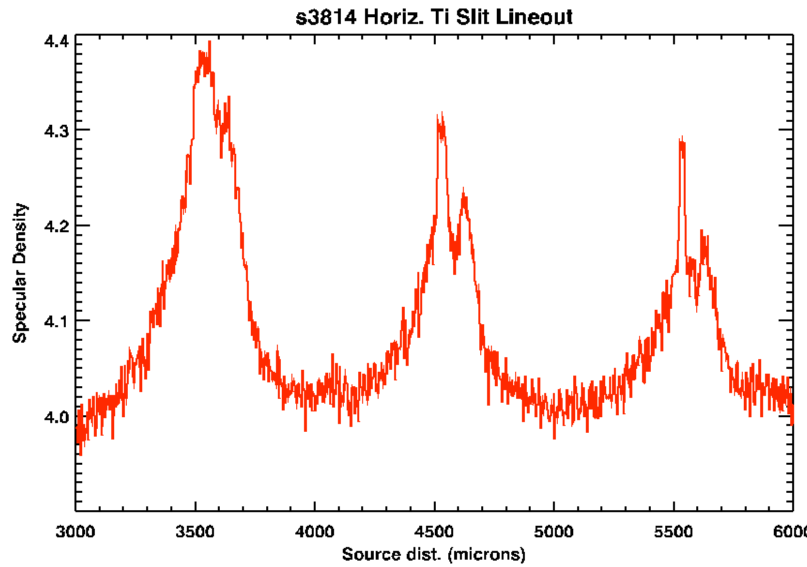
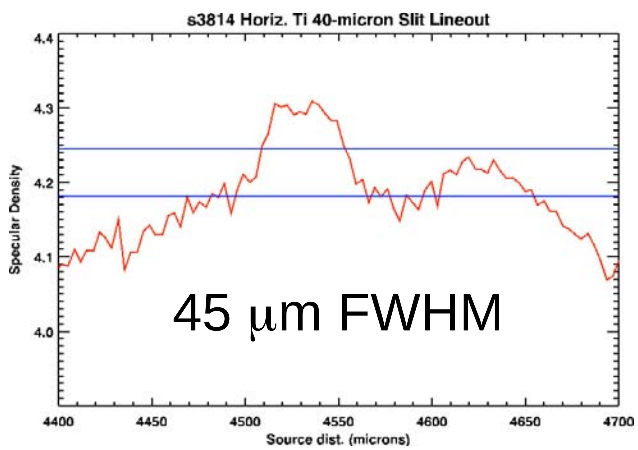
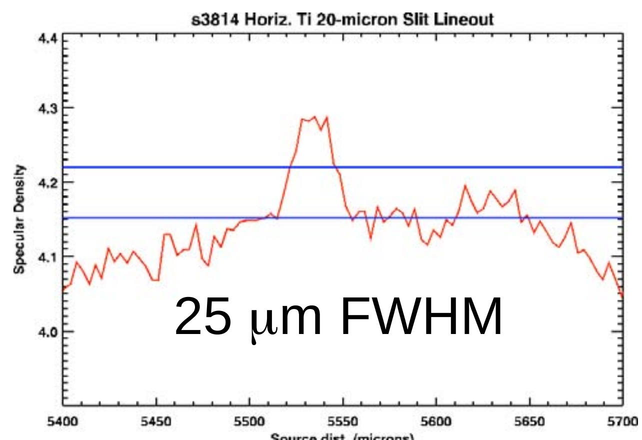
Horizontal Ti slit images also show a small x-ray source from Cu/Ni X pinch





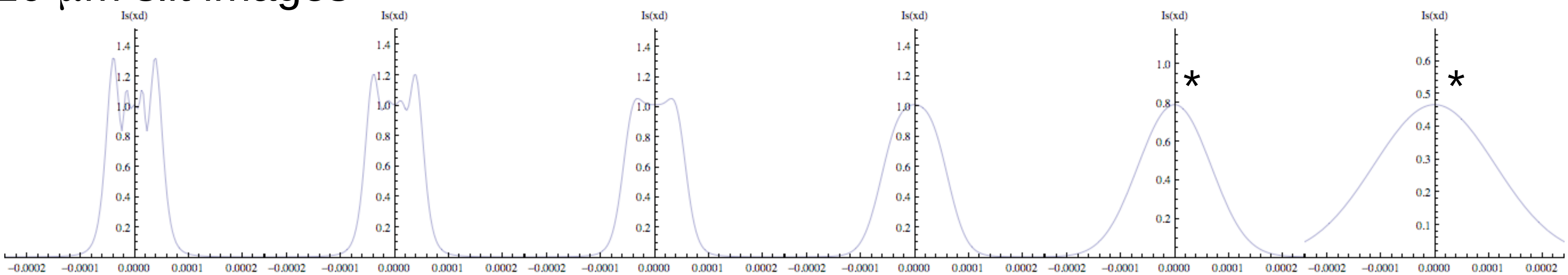




Both consistent with a ~5-10 μm source?

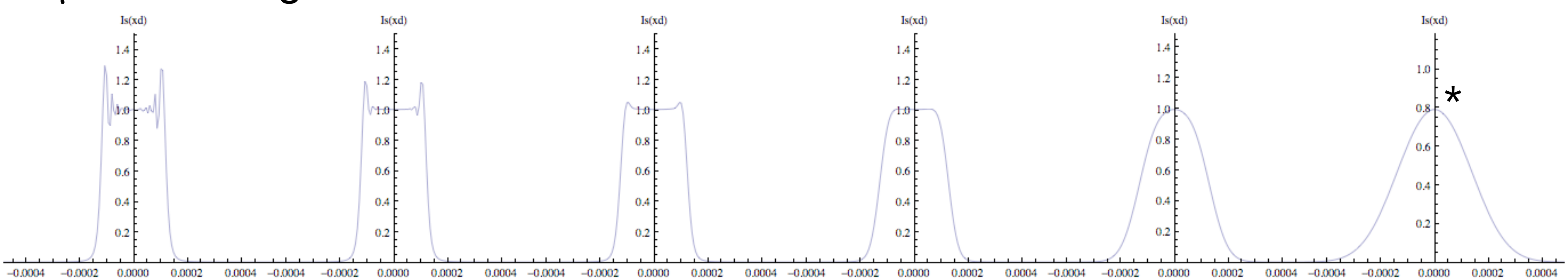
Calculated slit images show effect of changes in source size on slit measurements

20 μm slit images



1 μm | 2 μm | 4 μm | 8 μm | 16 μm | 32 μm

40 μm slit images



1 μm | 2 μm | 4 μm | 8 μm | 16 μm | 32 μm

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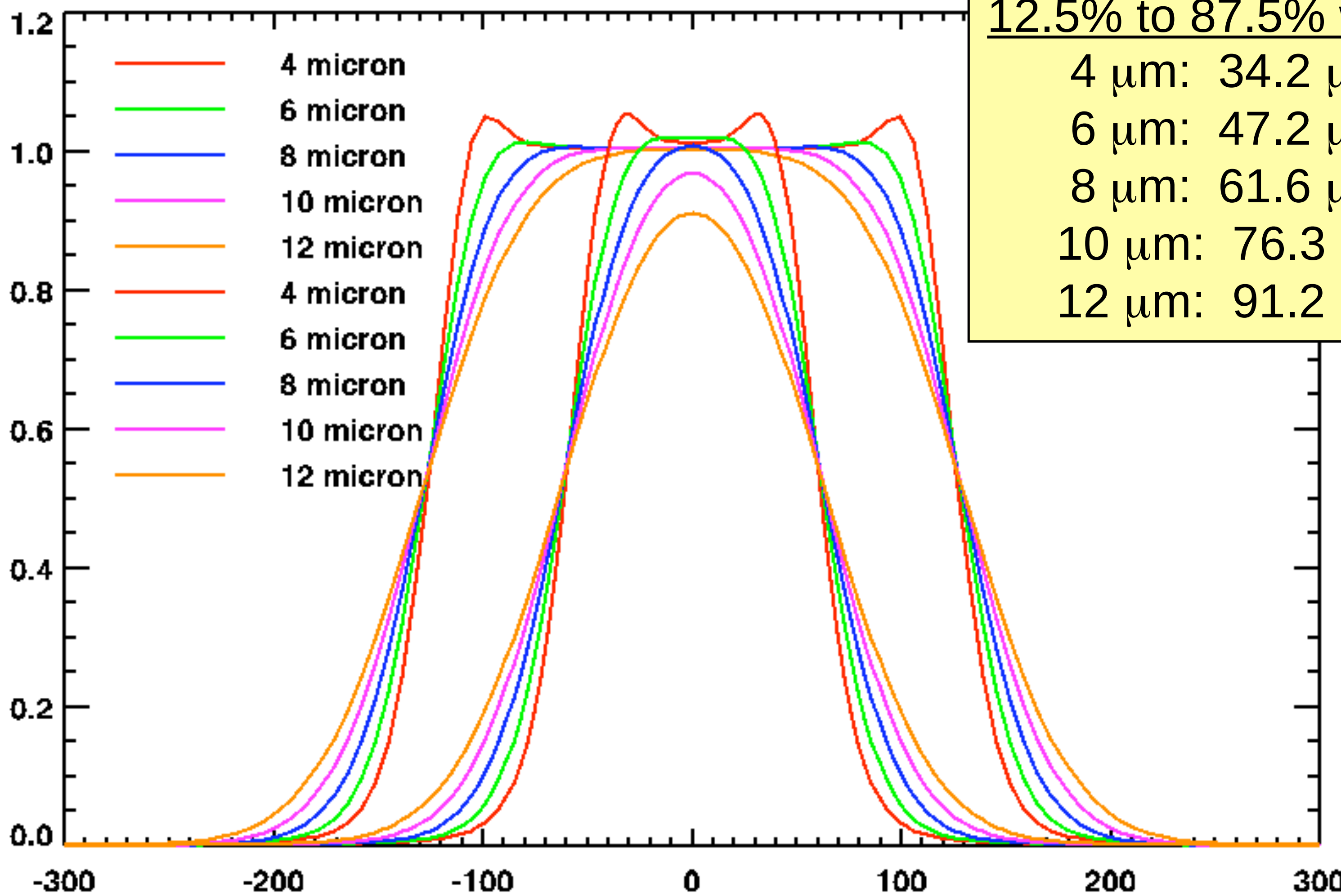
Calculated 40- and 20-μm slit images for selected x-ray source sizes



<u>12.5% to 87.5% widths</u>

4 μm: 34.2 μm

6 μm: 47.2 μm

8 μm: 61.6 μm

10 μm: 76.3 μm

12 μm: 91.2 μm

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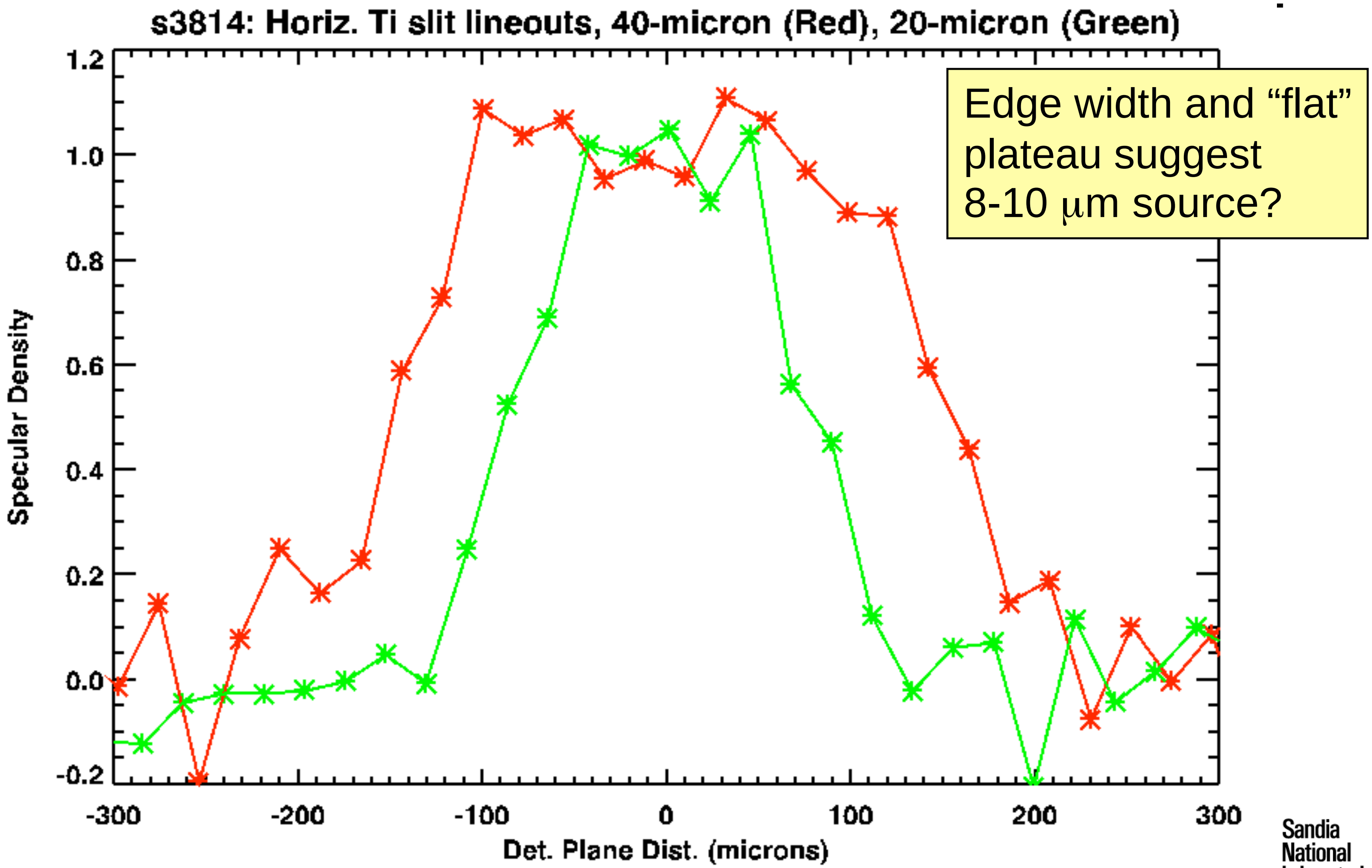
Lineouts appear to show relatively flat tops to the slit images and ~67 μm edge spreads



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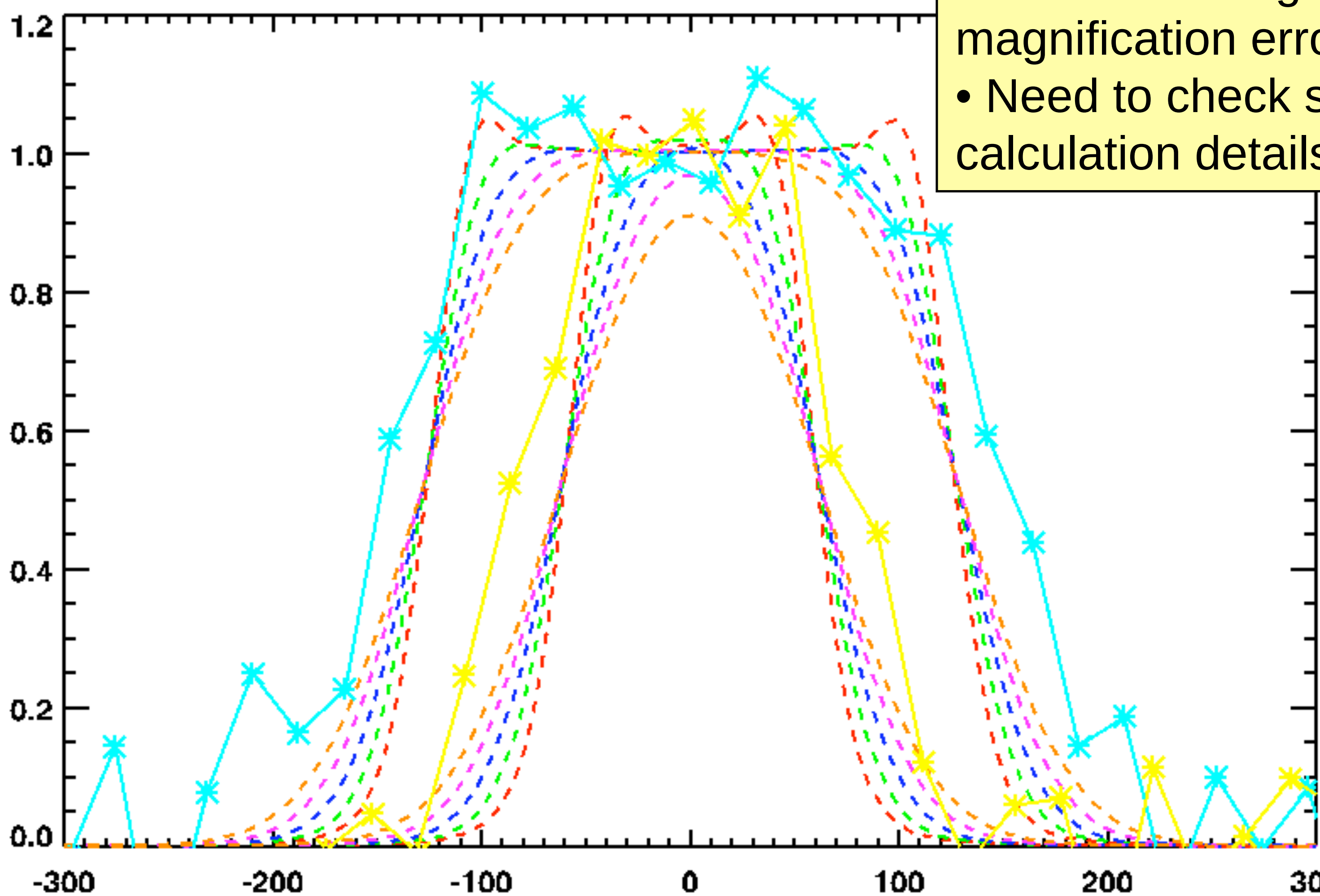
Disclaimer: Calculations think overall width should be ~1.2x narrower

- 20% is too large to be a magnification error
- Need to check slit width calculation details



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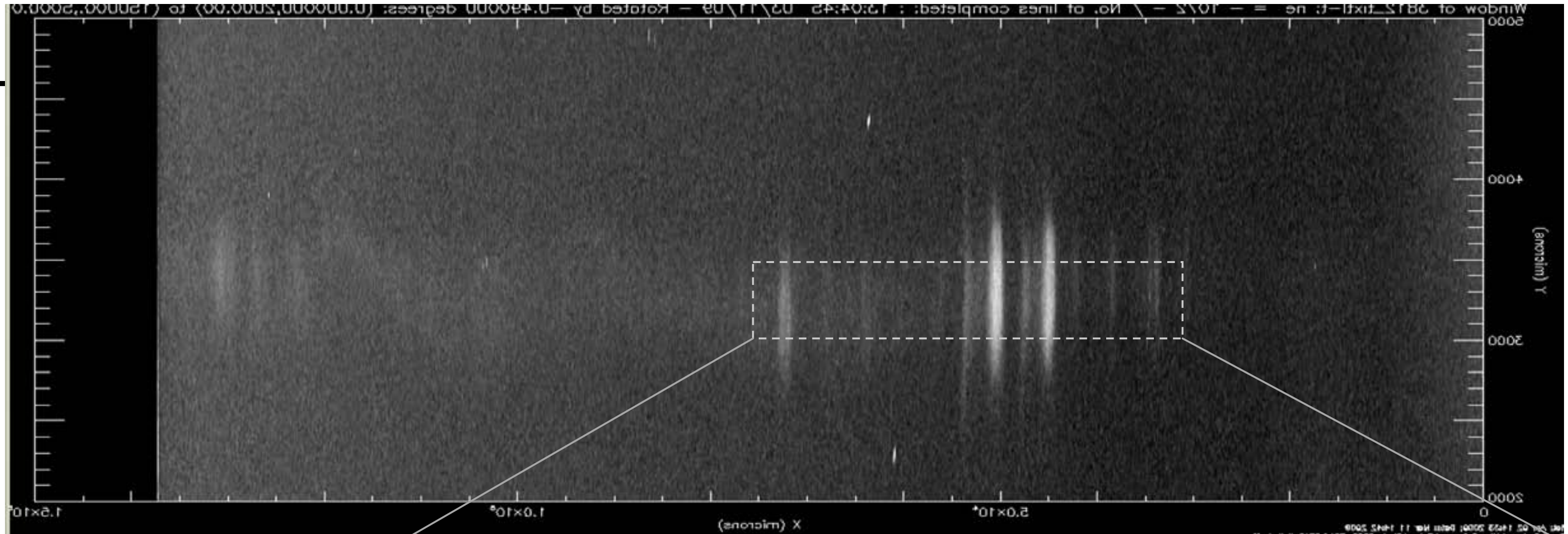
Quick analysis of time-integrated K-shell spectra from Cu/Ni X pinch shows hot plasma

s3812_
CuNi



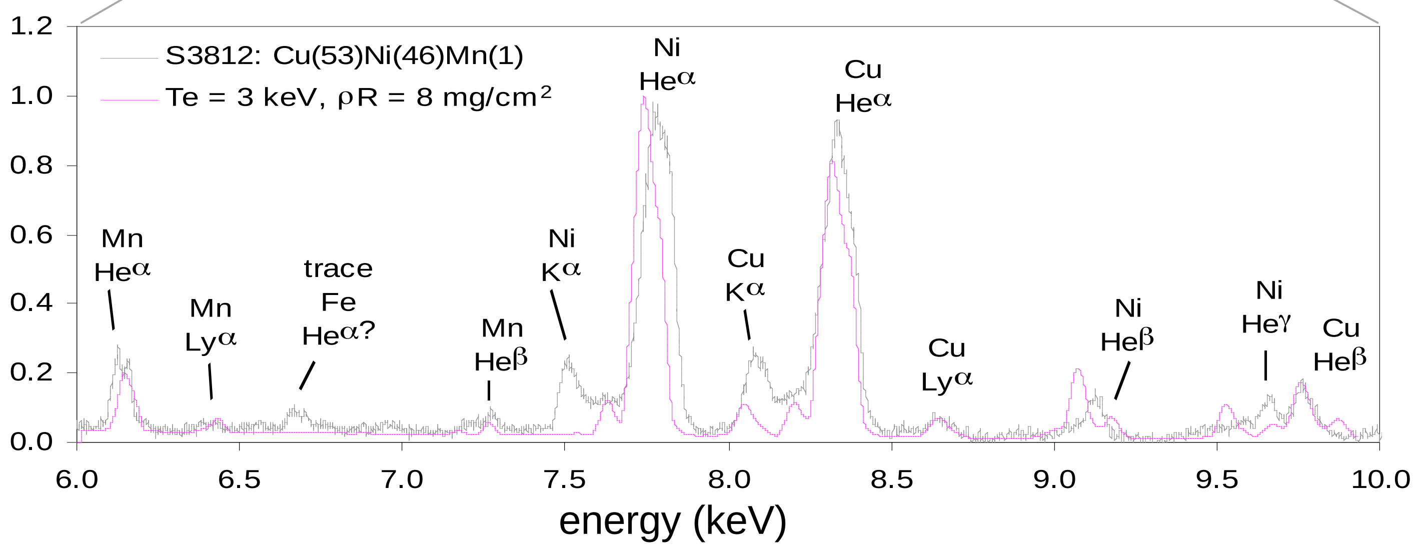
First cut diagnostics:

Estimate ρR by fitting Mn/Ni Heα ratio

Estimate Te by fitting Ly α/Heα ratios

Poor fit above 9 keV

Temperature gradients evidenced by cold Kα features



K-shell size >10 μm (~50 μm?), so density ~1.6 g/cc?? More work needed

High-current X pinches are a work in progress

- We are halfway through a 3-year research project
  - Have identified a promising geometry
    - May want to slightly increase implosion time again
  - Have made progress in making precision measurements of plasmas created
    - Try to improve streak time resolution
    - Try to reduce background on slit camera
    - Try to understand spectroscopic information--what can we learn about density, B-field?
- Are we producing small plasma spots with extreme plasma parameters?
  - Seem to be getting close….
- Are X pinches a waste of the taxpayer's money?
  - I hope not!

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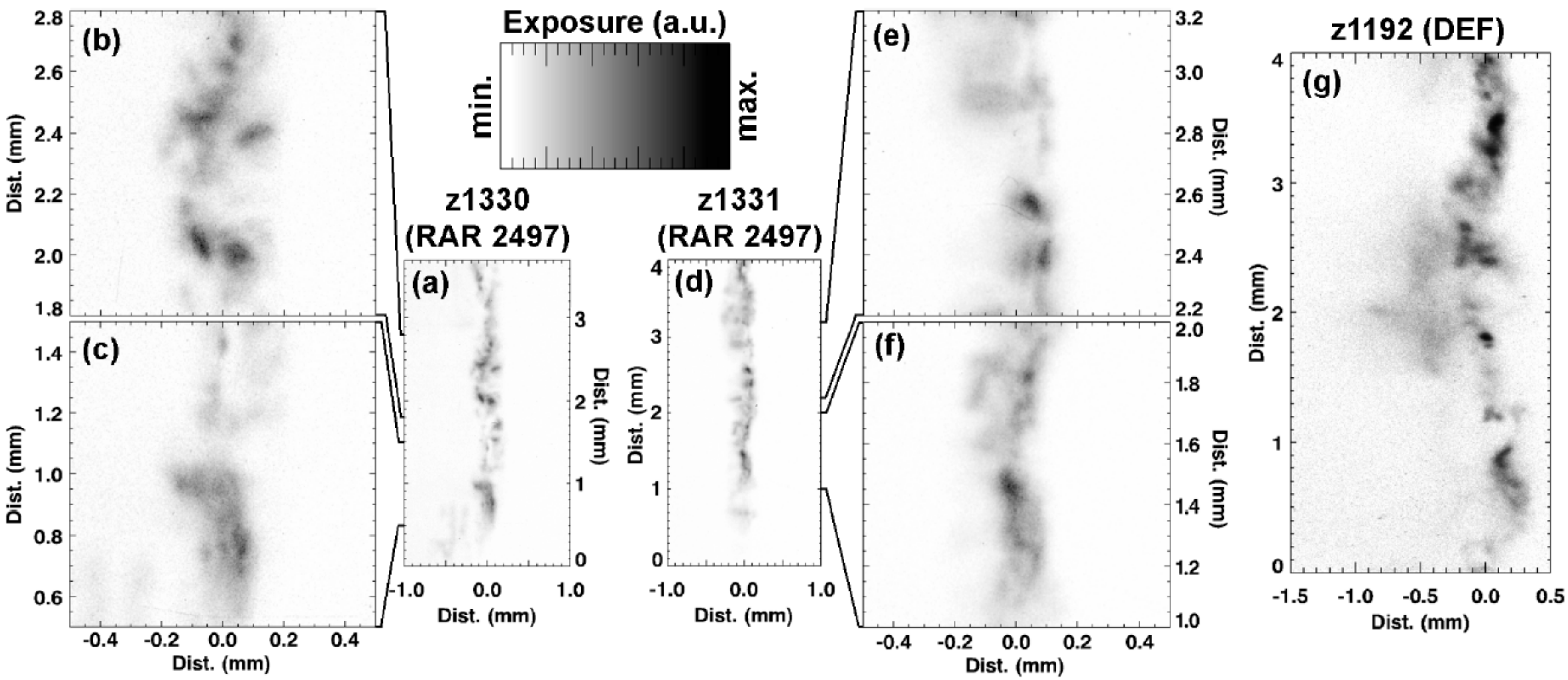
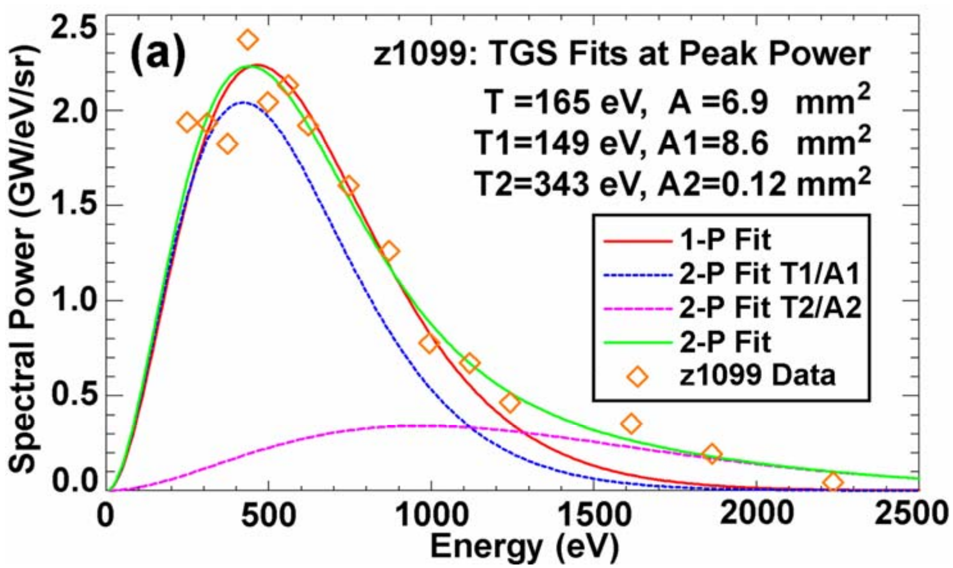
An Aside: Small-scale structures are also seen at very high photon energies



Time-integrated self-emission at 6151 eV (~10-20 μm resolution)
Emission generally contained within a 400 μm diameter (CR ~ 50?)
Structure as small as 50-100 μm visible in images!

Do "micro-pinches" play a significant role in the total radiation?

- Single-blackbody fits do not match the high-energy tail of emission spectrum
- Can match spectrum using a two-blackbody fit
  - Second blackbody a high-temperature, small-area radiation source
  - Area under this blackbody curve ~30% of total energy radiated by the pinch!
  - Film exposure at 6151 eV roughly consistent with this x-ray source area & extrapolated x-ray yield
- Can also match spectrum with single-blackbody plus bremsstrahlung spectrum (but why so small a diameter?)



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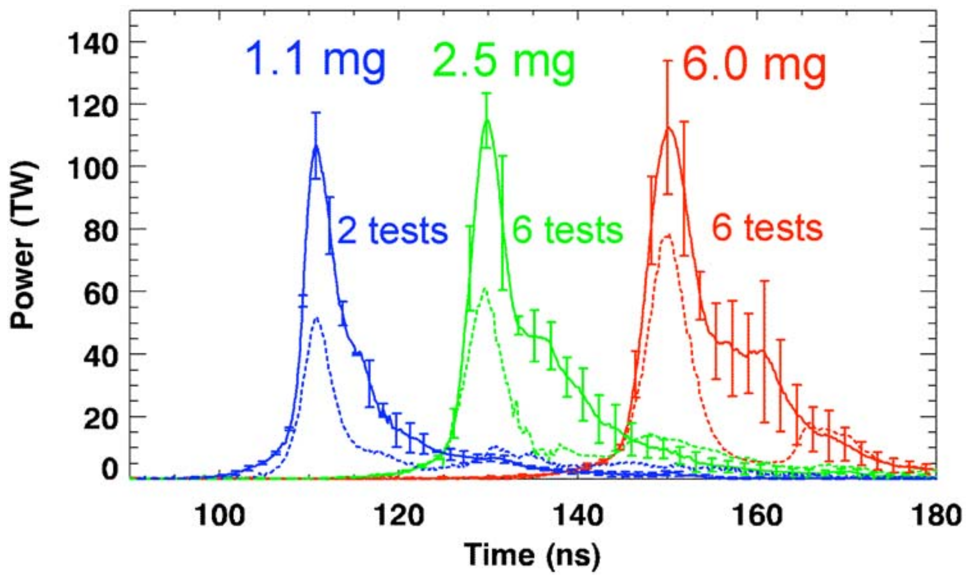
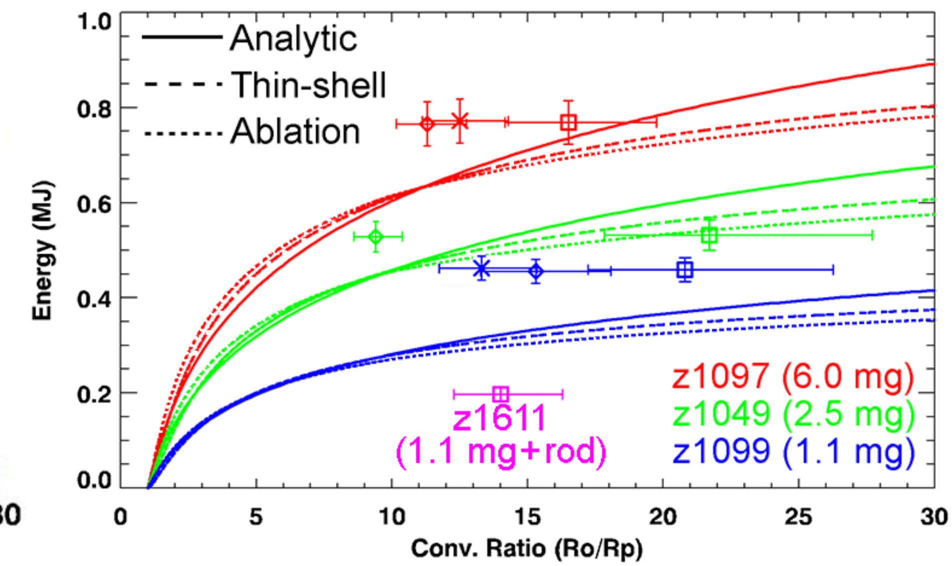
Main radiation pulse in shots with on-axis rods *can* be explained by observed *JxB* work





- **Main pulse radiation/energy lowered by presence of rod without affecting τ_{imp}, τ_{rise}, τ_{FWHM}.**
- **In contrast to bare-axis shot, 1.1 mg array-on-rod radiation can be explained by observed *JxB* work**

Array Mass	E_{main} (kJ)	E_{total} (kJ)	E^{rod}_{main} (kJ)	E^{rod}_{total} (kJ)
1.1 mg	440±28	832±21	195	488
2.5 mg	532±46	1106±106	306	689
6.0 mg	692±66	1278±239	428	748

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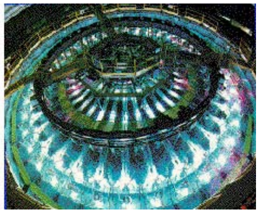
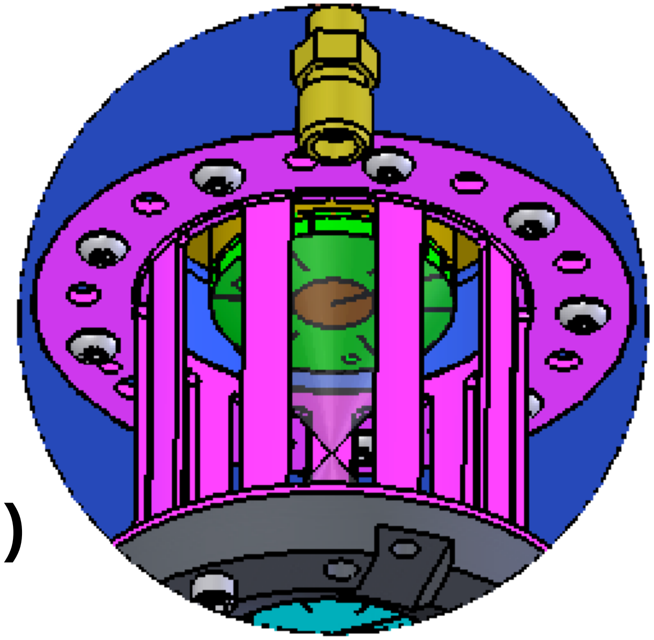
Goal of SATURN experiments was to try and create small spots



- Timing: XRDs, PCDs
- X-ray Energy: Bolometers
- Dynamics: X-ray pinhole cameras (gated & time-integrated)

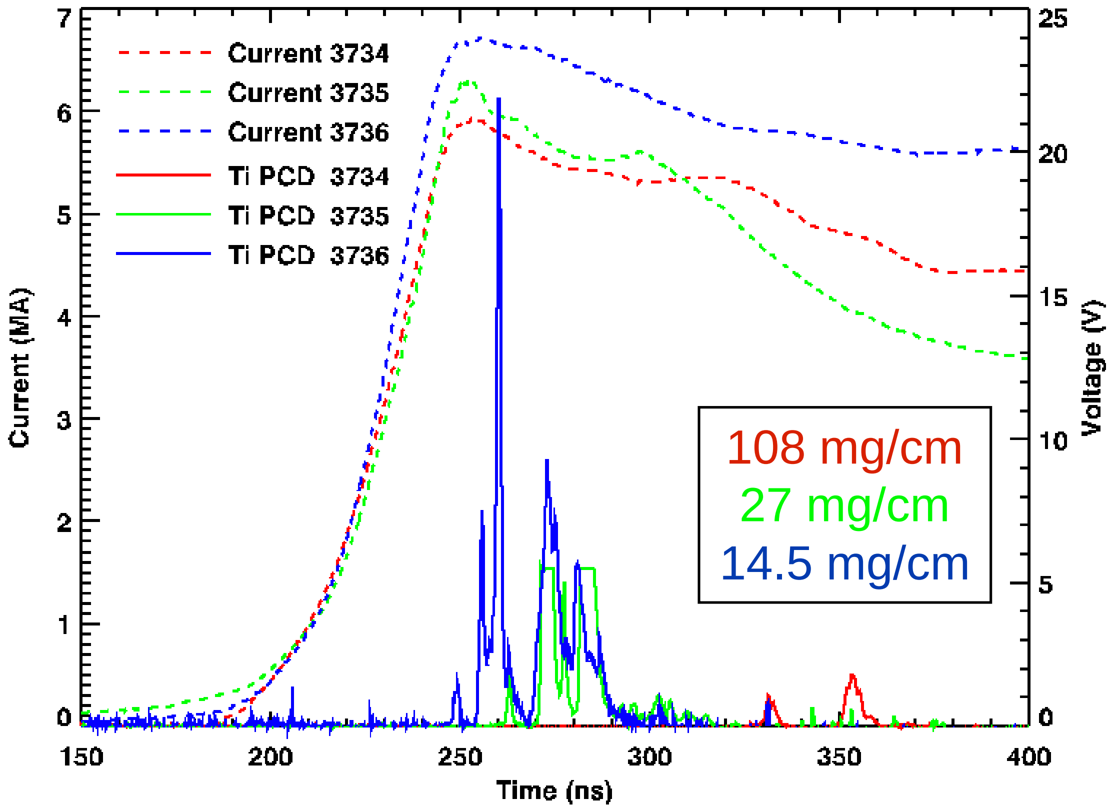


- X-ray Spot Size: High-magnification slit camera
- All diagnostics view load ~35° below horizontal!

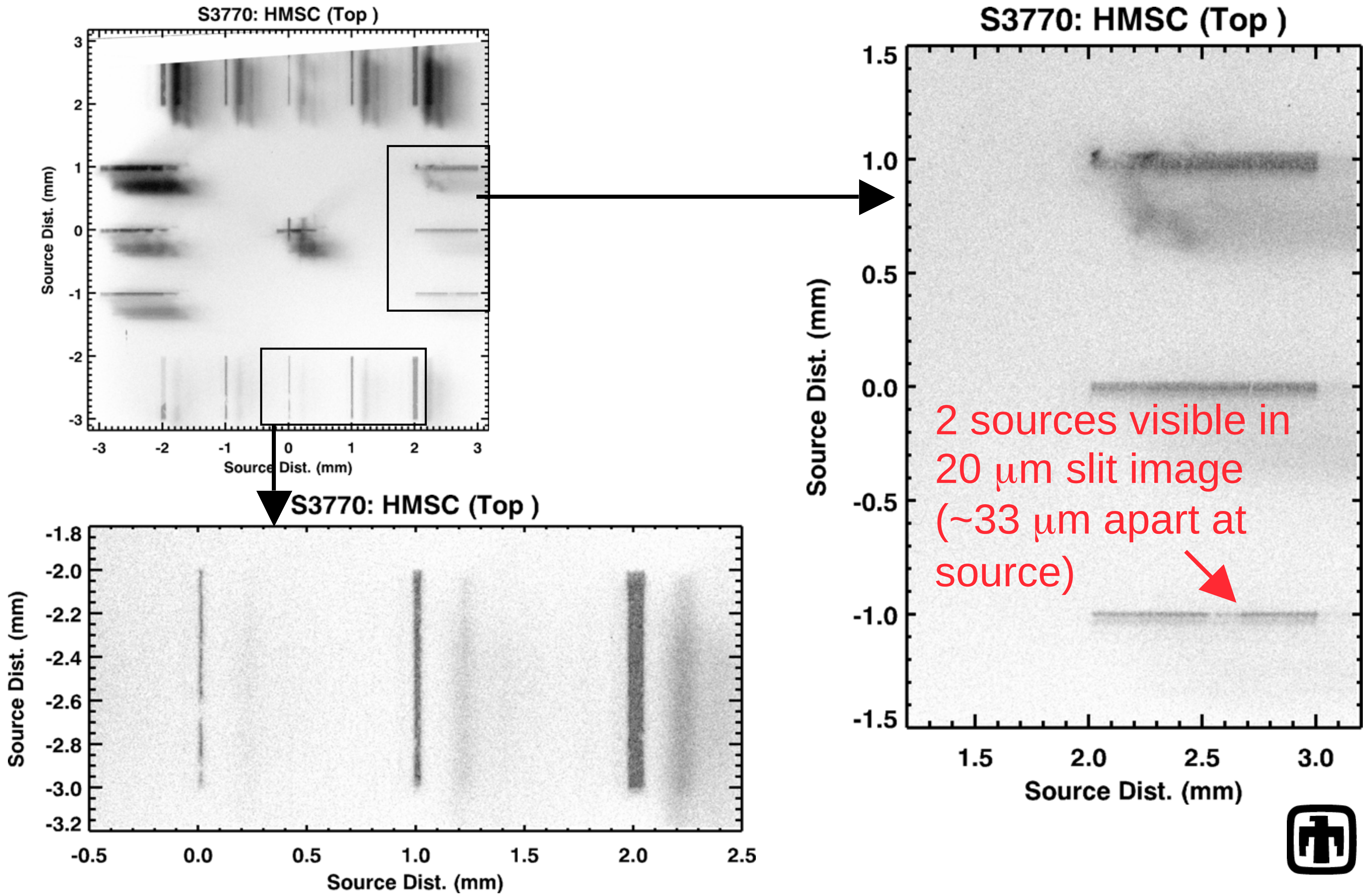
Extra Slides

Single-array X-pinch scan consistent with linear scaling of mass/length with current

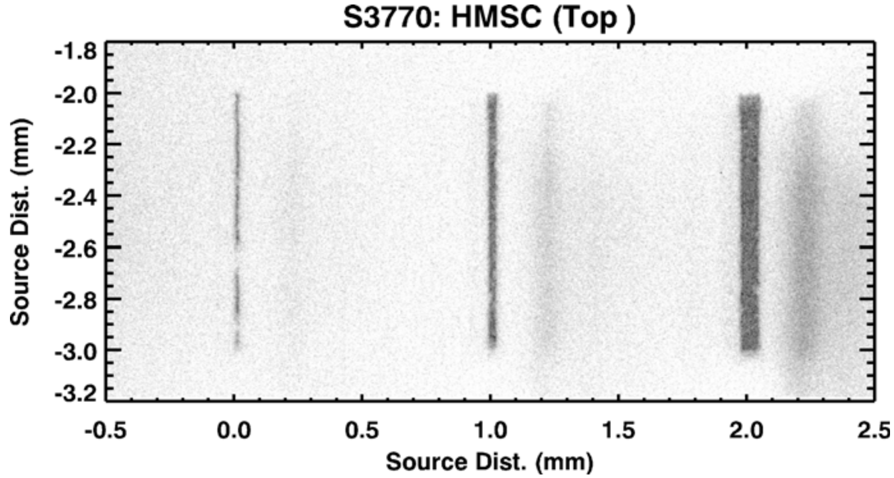
- **XP wire arrays [30 mm tall, 20 mm diam]**
  - **S3734: 128 x 75 μm W (108 mg/cm)**
  - **S3735: 64 x 53 μm W (27 mg/cm)**
  - **S3736: 32 x 53 μm W (13.6 mg/cm)**
- **Arrays probably overtwisted, making the necks relatively long**



Example slit images from a solid X-pinch test (S3770)

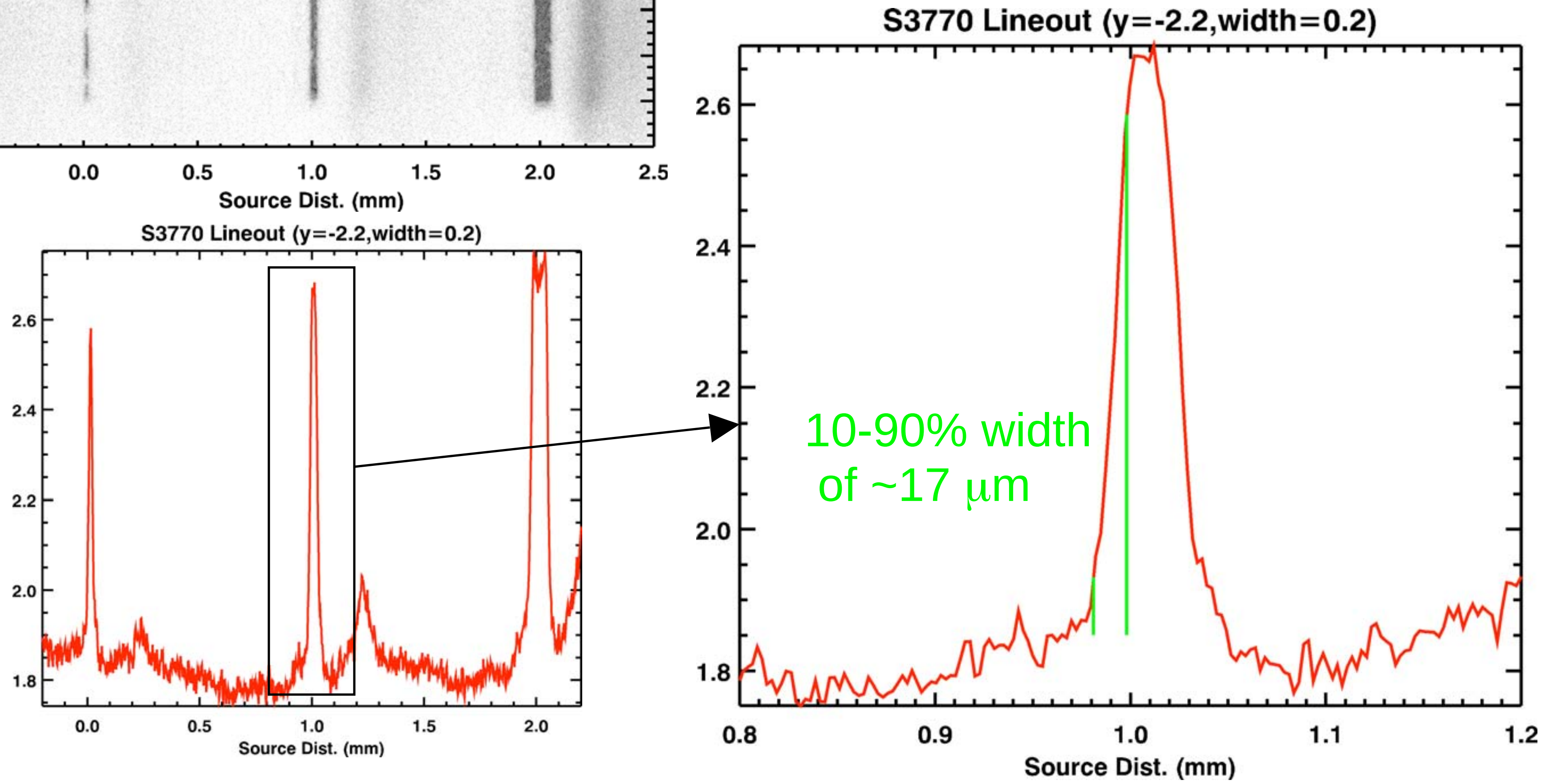


Lineouts consistent with a source size ≤17 μm diameter (~diffraction limit)

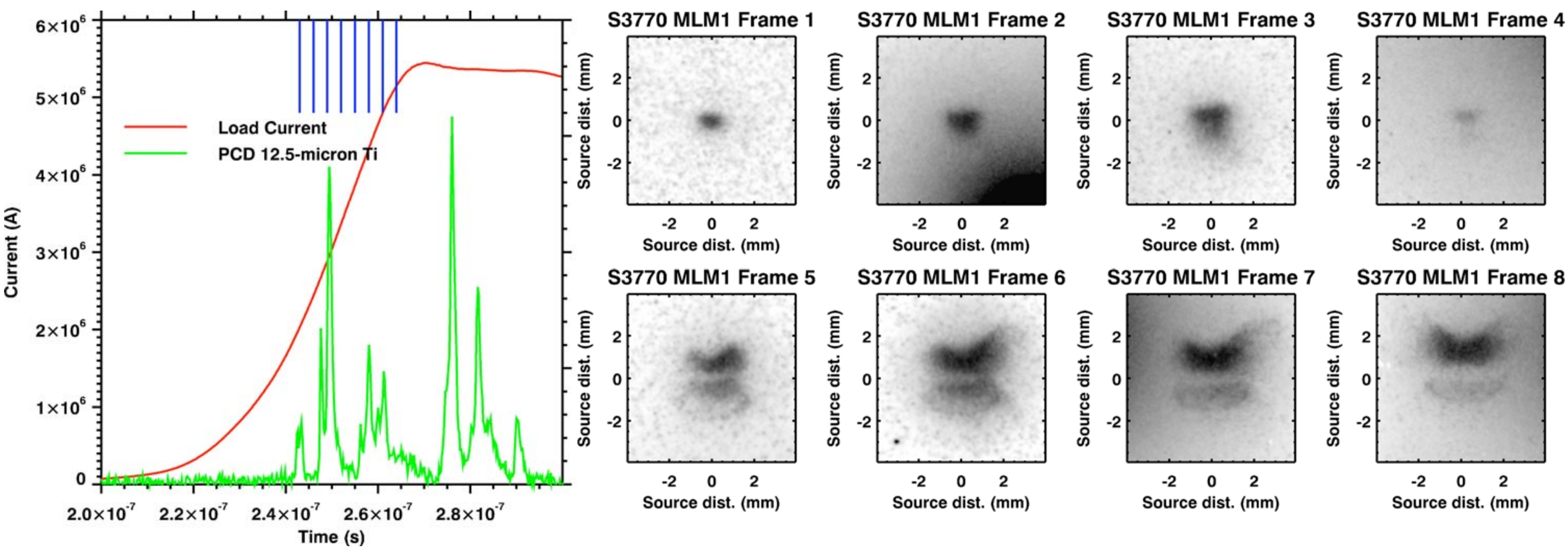


Fresnel diffraction limit:

$$\delta \sim \sqrt{\lambda d} \sim \sqrt{(3.6\mathring{A})(1.1m)} \sim 20\mu m$$



MLM pinhole images may imply small x-ray spots made early in pulse (2-3 MA)



PCD has same filtration as 1/2 of slit camera images
MLM images are in soft 277 eV x rays, but show global dynamics
Mass/length ~14 mg/cm, probably needs to increase
Early timing consistent with ongoing simulations (Chittenden, Yu)

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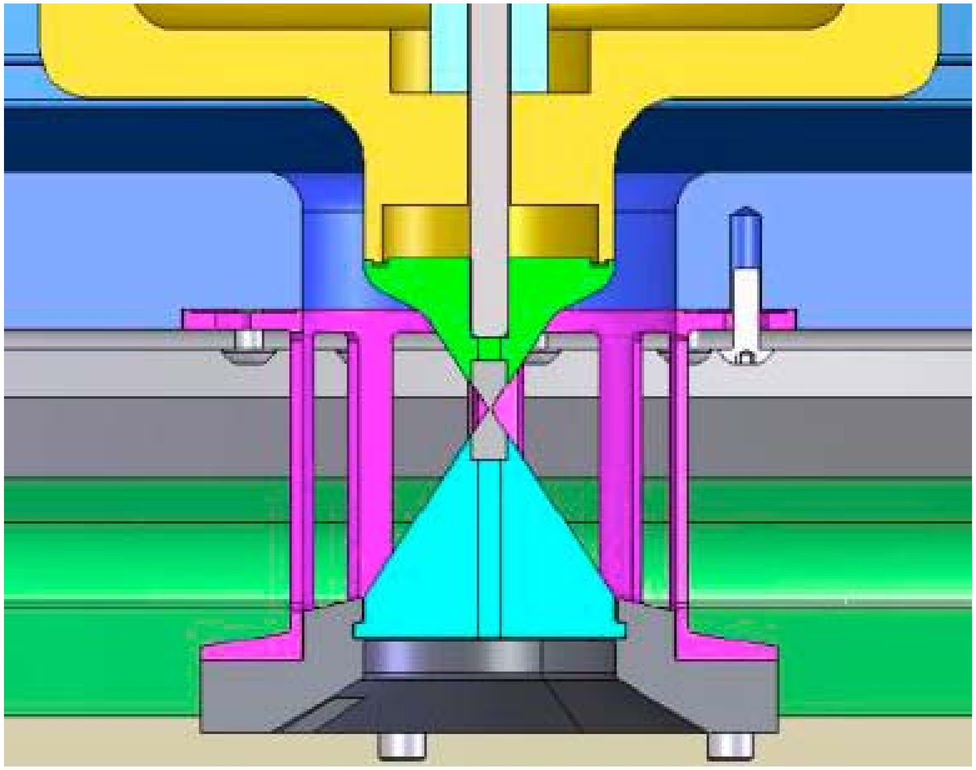
Load Hardware



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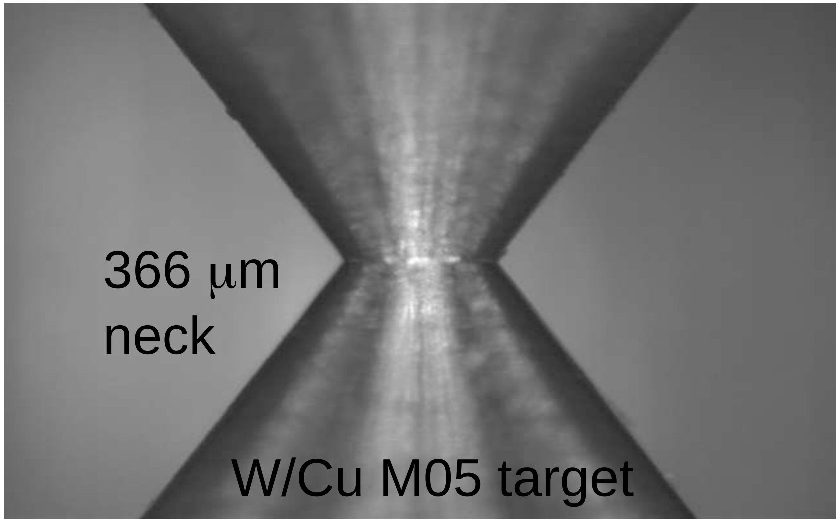
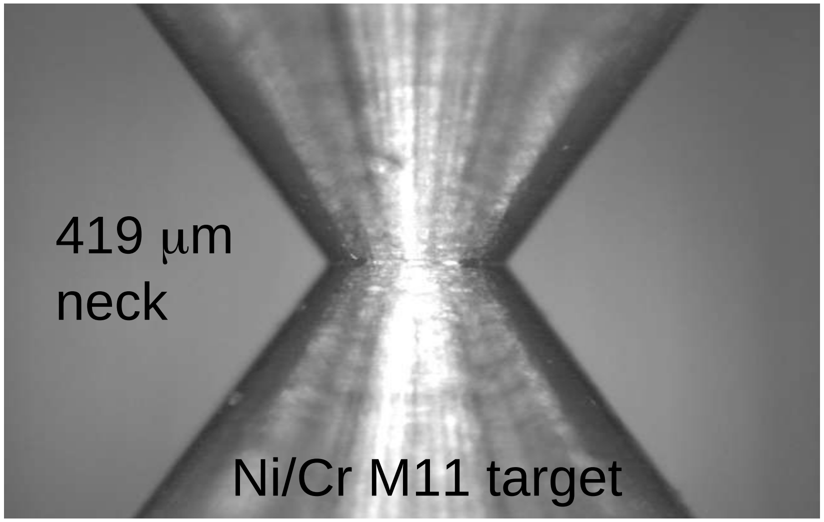
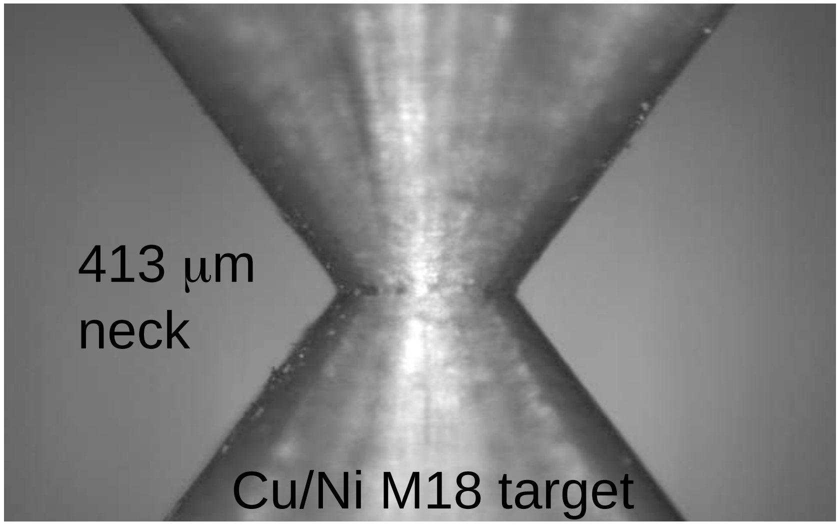
Photos of cross-point region







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Measured roughness of W/Cu X-pinch "Hourglass" (Cylindrical Portion)

Veeco

Mag: 10.2 X
Mode: VSI

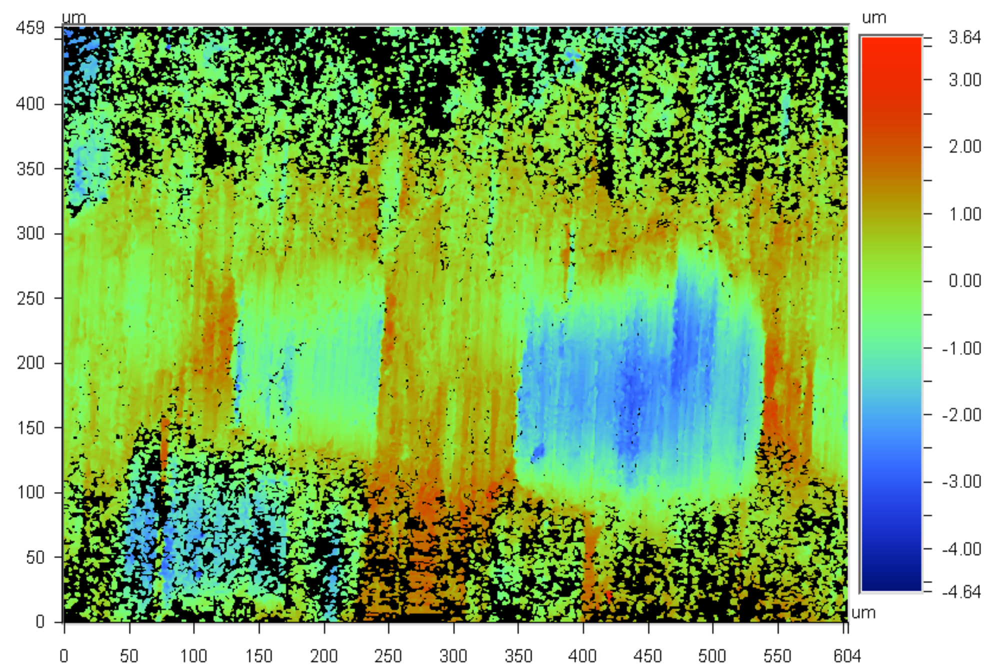
Surface Data

Date: 02/19/200
Time: 12:29:12

Surface Statistics:
Ra: 741.33 nm
Rq: 936.86 nm
Rz: 5.94 um
Rt: 8.28 um

Set-up Parameters:
Size: 736 X 480
Sampling: 821.67 nm

Processed Options:
Terms Removed:
Cylinder & Tilt
Filtering:
None



Title: P300-0094-000A P05
Note:

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Measured roughness of Cu/Ni X-pinch “Hourglass” (Cylindrical Portion)

Veeco

Mag: 10.2 X
Mode: VSI

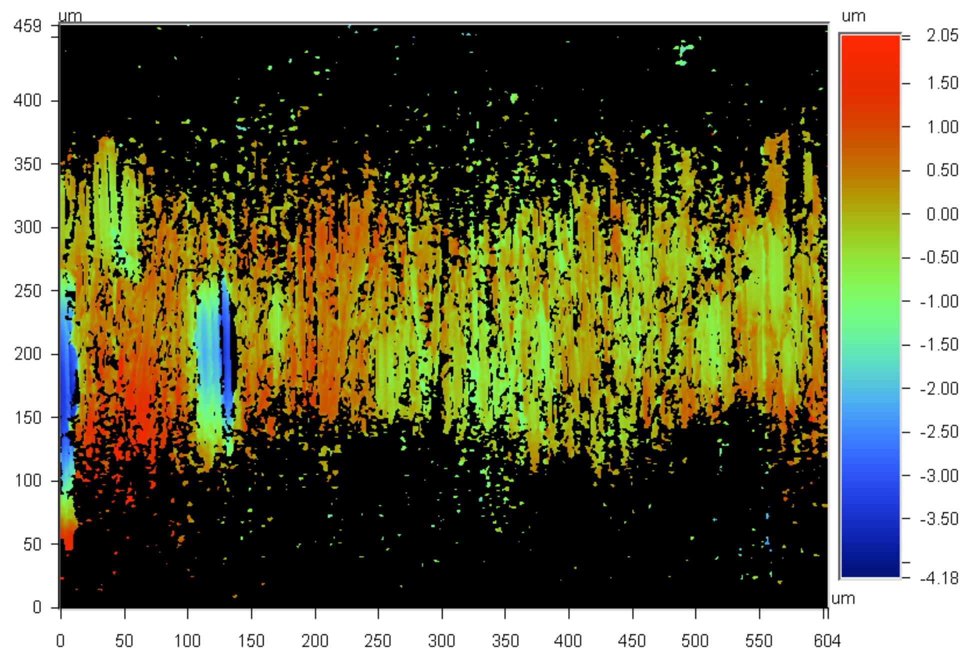
Surface Data

Date: 02/18/200
Time: 15:34:21

Surface Statistics:
Ra: 449.61 nm
Rq: 662.64 nm
Rz: 5.56 um
Rt: 6.23 um

Set-up Parameters:
Size: 736 X 480
Sampling: 821.67 nm

Processed Options:
Terms Removed:
Cylinder & Tilt
Filtering:
None



Title: x-pinch.090120M18
Note: cylinder portion

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Measured roughness of Ni/Cr X-pinch "Hourglass" (Cylindrical Portion)

Veeco

Mag: 10.2 X
Mode: VSI

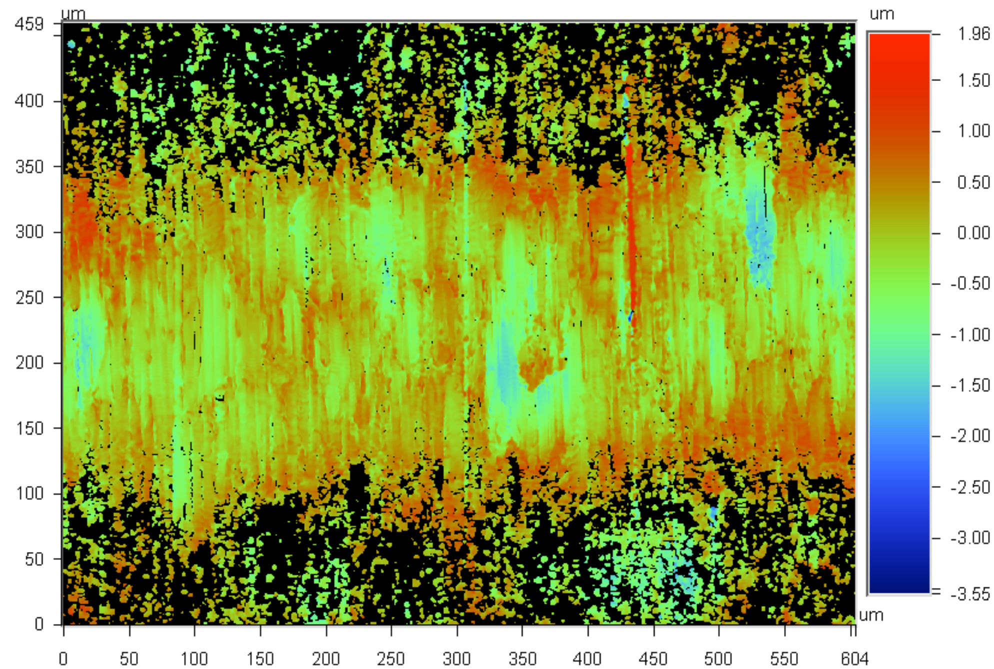
Surface Data

Date: 02/19/200
Time: 12:40:42

Surface Statistics:
Ra: 351.56 nm
Rq: 450.16 nm
Rz: 3.89 um
Rt: 5.51 um

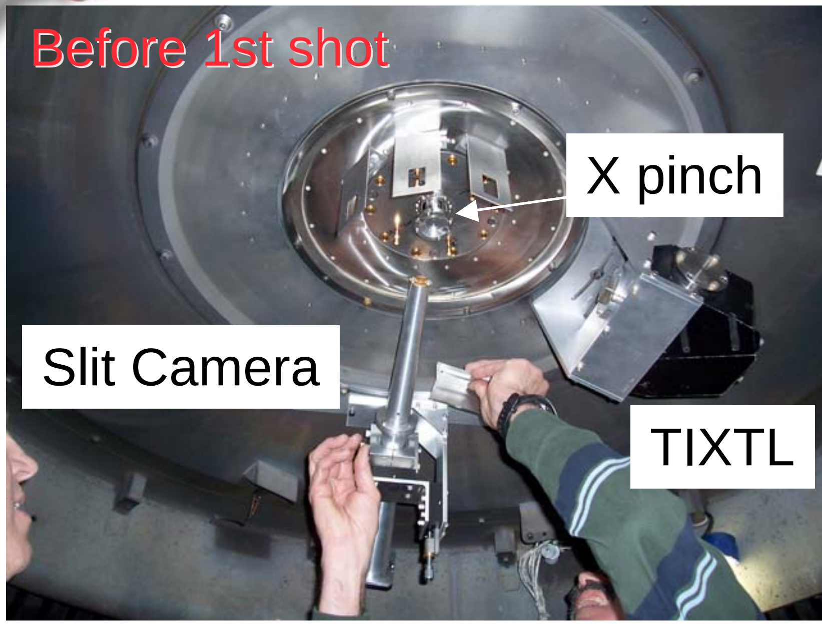
Set-up Parameters:
Size: 736 X 480
Sampling: 821.67 nm

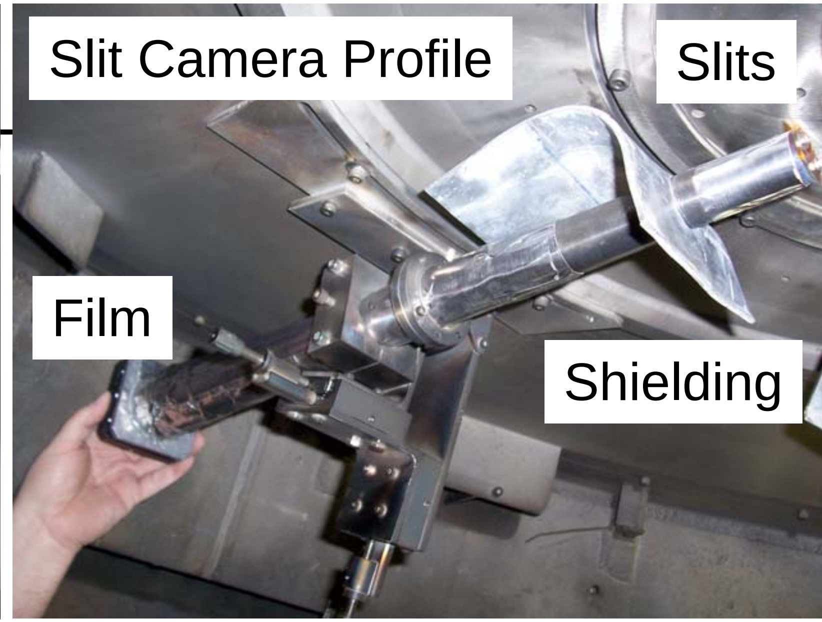
Processed Options:
Terms Removed:
Cylinder & Tilt
Filtering:
None



Title: P300-0095-000A 10
Note:

In-chamber Hardware Photos





Shielding was damaged each shot from spokes in return can flying outward