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STREAKED VISIBLE-LIGHT SPECTROSCOPY MEASUREMENTS OF ALUMINUM WIRE-ARRAY Z-PINCHES ON COBRA*

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Abstract

Streaked visible-light spectroscopy measurements are presented for aluminum (Al) wire-array z-pinch experiments on the 1-MA, 100-ns rise-time COBRA pulsed-power generator. For these measurements, a half-meter Czerny-Turner spectrometer was used in conjunction with the COBRA visible-light streak camera system. This allowed us to record visible-light spectra emitted from Al coronal plasma as a continuous function of time throughout the initiation, ablation, and implosion phases of the given wire-array z-pinch experiment. When using thick wires (~100-μm in diameter), the visible-band spectra observed consisted solely of continuum emission, which began at the moment of resistive voltage collapse. (Resistive voltage collapse occurs when coronal plasma first forms around the wire cores, and marks the transition from the initiation/resistive-heating phase to the ablation phase.) The continuum data collected are now being used to determine electron density. To determine electron density from this continuum data, an absolute calibration of the detection system was required. The details of these experiments and the absolute calibration technique are presented.

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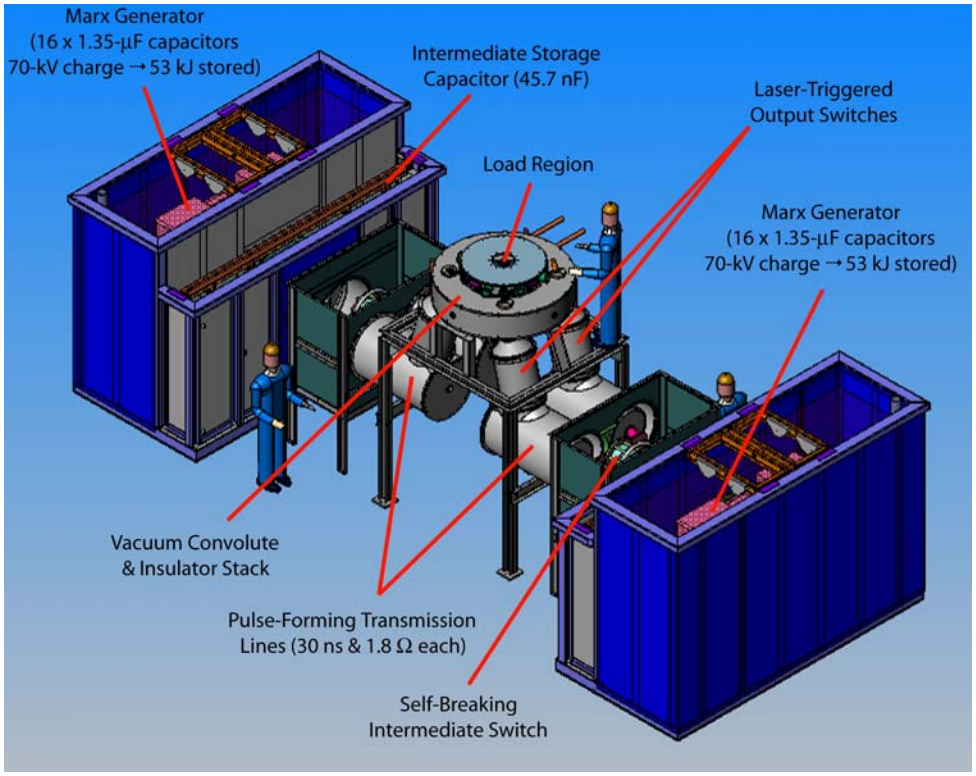
The COBRA generator

- Laser-triggered output switches enable current pulse shaping (0.8–1.2-MA peaks and 95–250-ns zero-to-peak rise times)
- Two Marx generators, each with 16, 1.35-μF capacitors
- 70-kV charge for 106 kJ of stored electrical energy
- Four parallel 1.8-Ω water pulse lines for low-impedance output of 0.45 Ω



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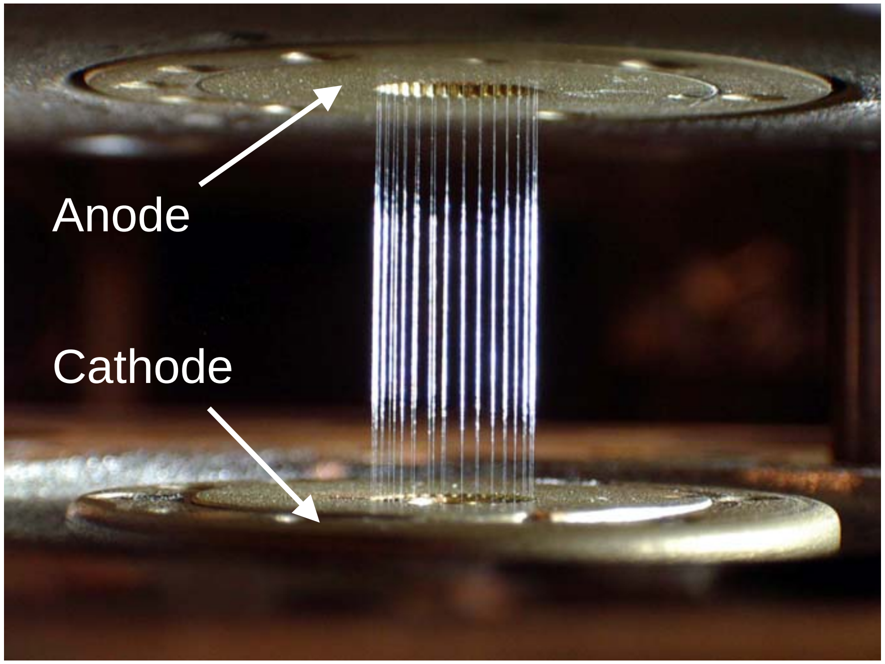
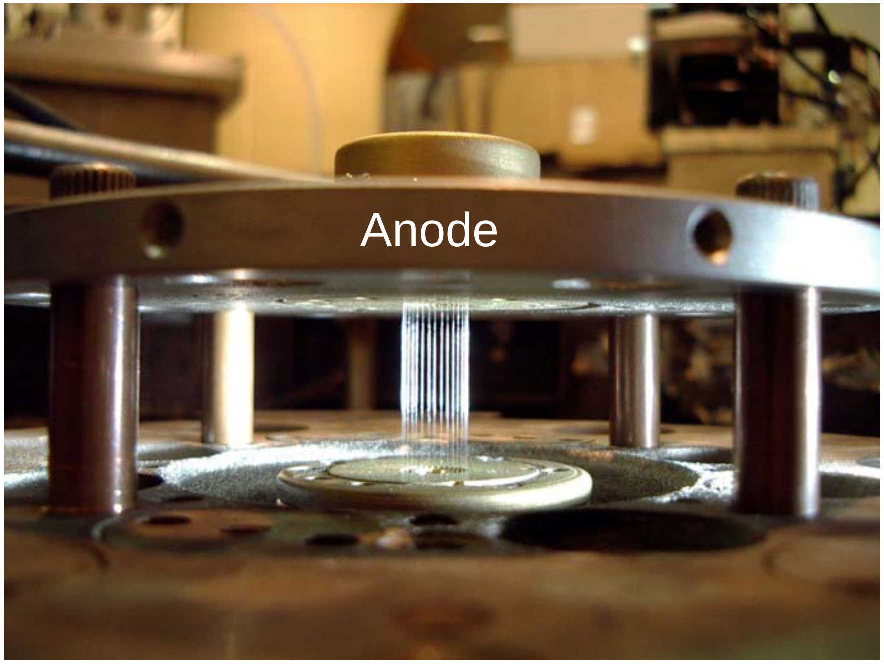
Load hardware

- CNC fabricated electrode inserts
- Wire spacing down to 785 μm
- Example below is 32 wires on an 8-mm array diameter (785-μm wire spacing)
- Four return current posts around circumference of anode plate allowed all diagnostics to have an unobstructed view of the array





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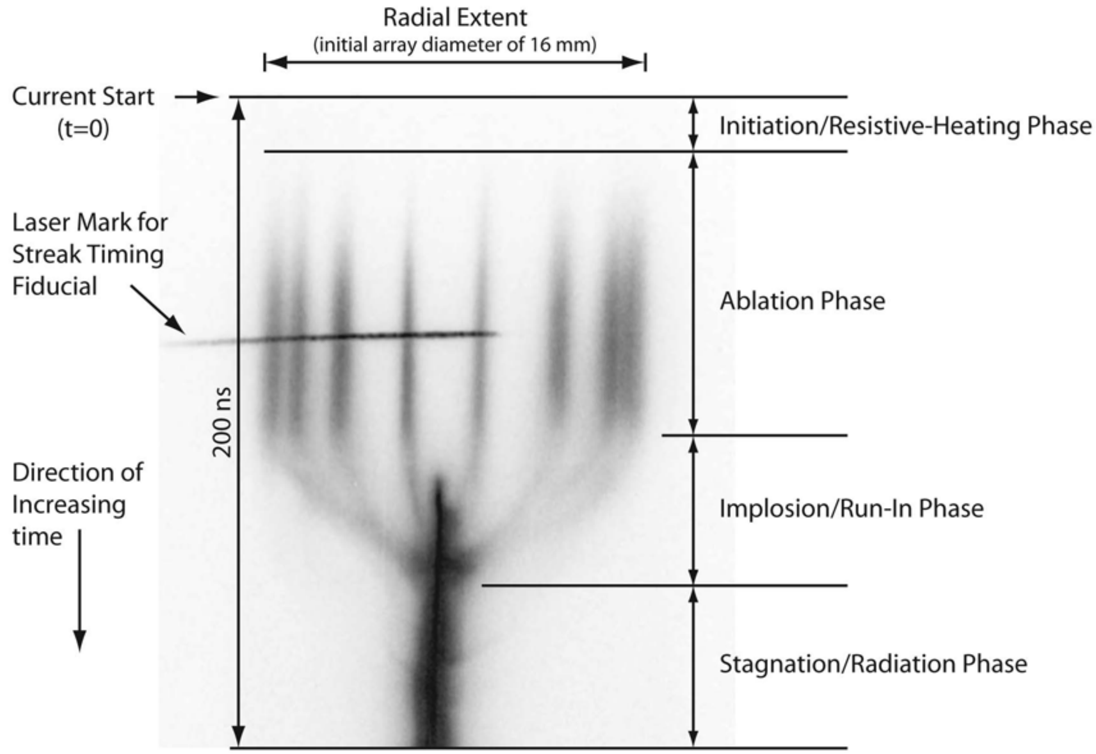
Phases of a wire-array z-pinch*

1. Current Initiation
2. Ablation
3. Implosion/run-in
4. Stagnation/radiation



*M. E. Cuneo, *et al.*, Phys. Rev. E **71** 046406 (2005)

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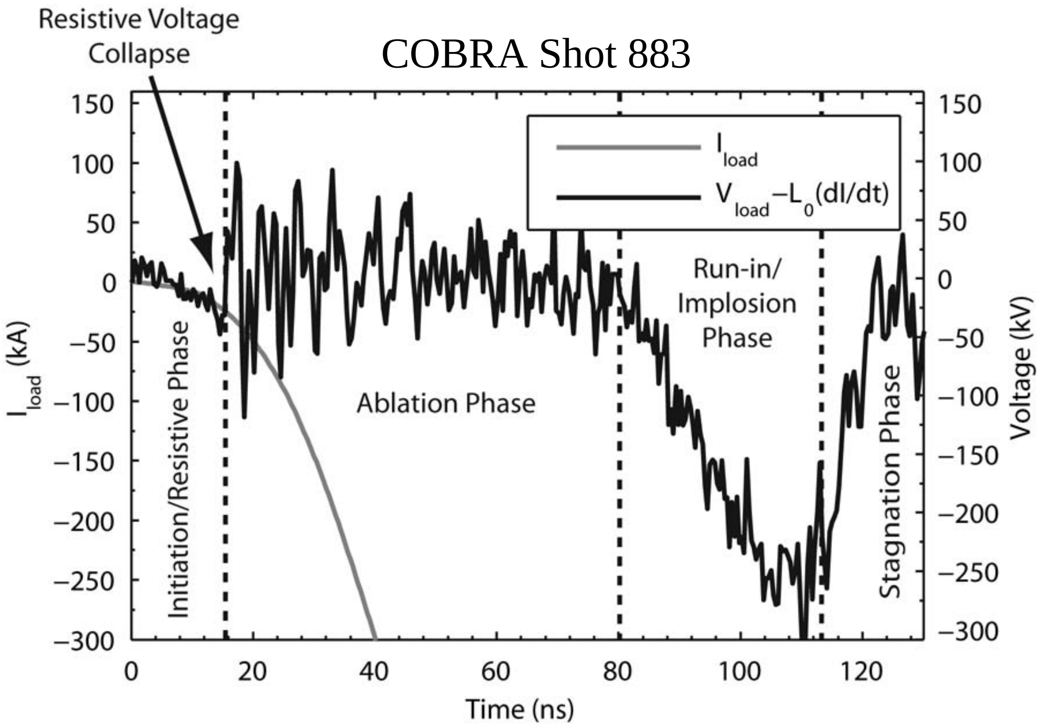

$$V_{load} = L\dot{I} + \dot{L}I + IR \approx L_0\dot{I} + IR$$

$$\Rightarrow V_{load} - L_0\dot{I} \approx IR$$

Phases of a wire-array z-pinch

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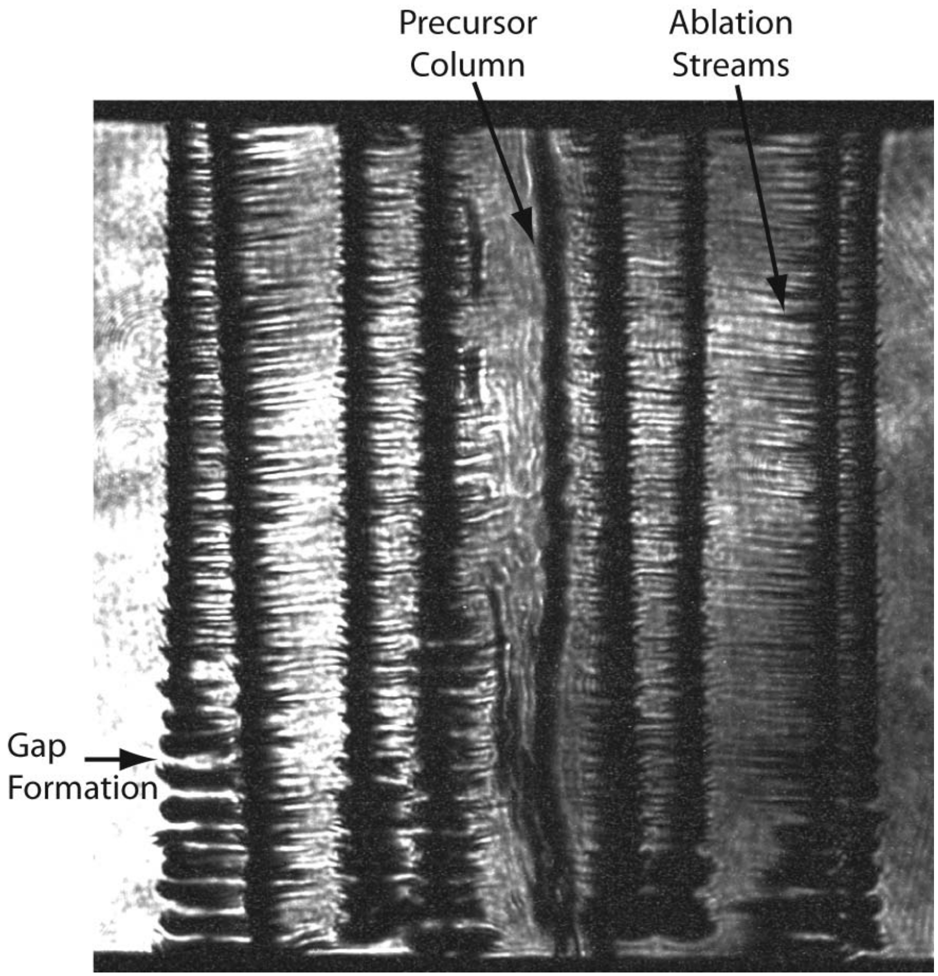

Laser shadowgraph during COBRA shot 375

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Phases of a wire-array z-pinch

1. Current Initiation
2. Ablation
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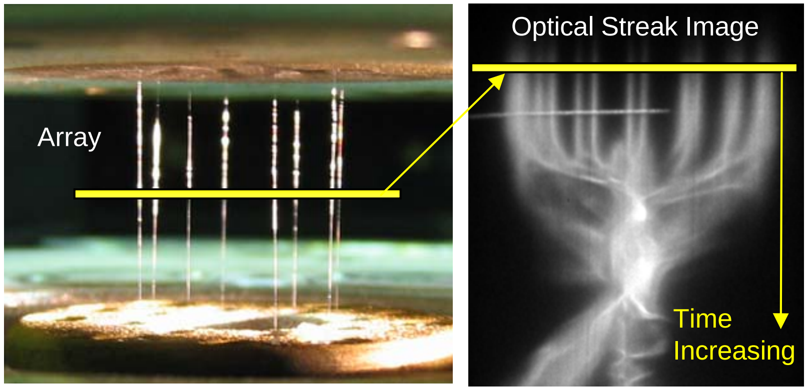
4. Stagnation/radiation

Focus of this study



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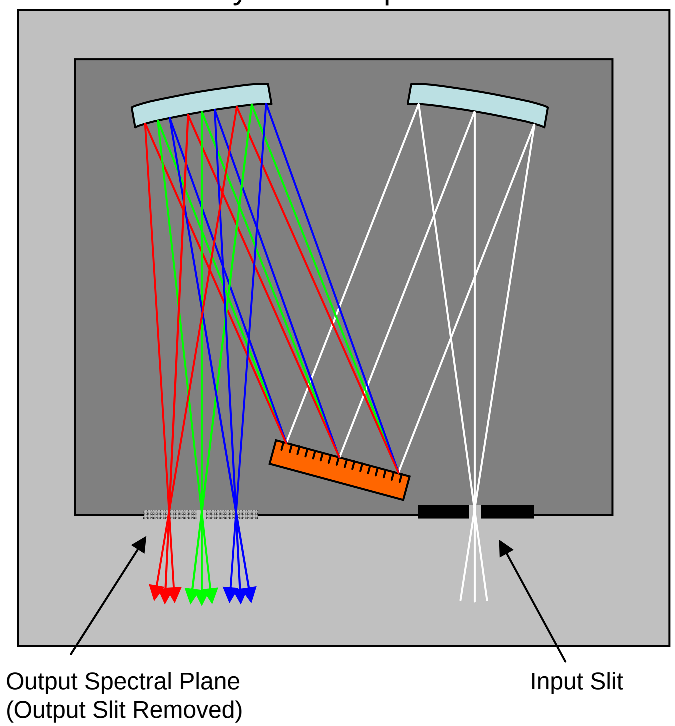
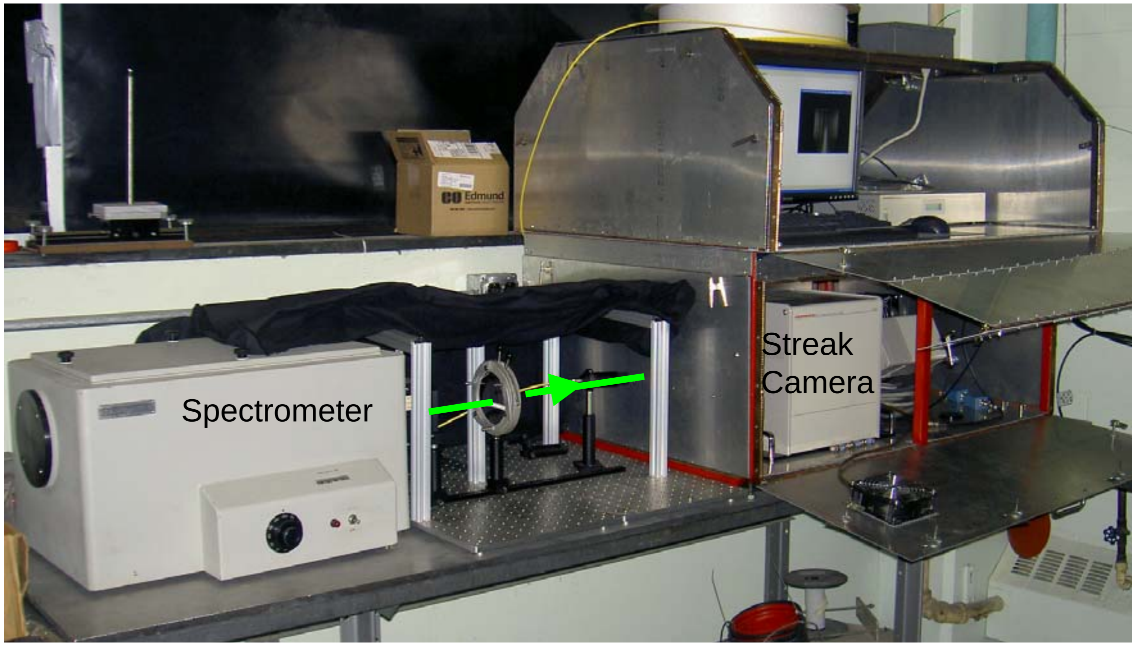
Visible-Streak Spectroscopy Original Objectives:

- To look for visible spectral lines early in the current pulse so that novel magnetic field measurements could be made (in addition to temperature, density, and Doppler measurements)

Czerny-Turner Spectrometer





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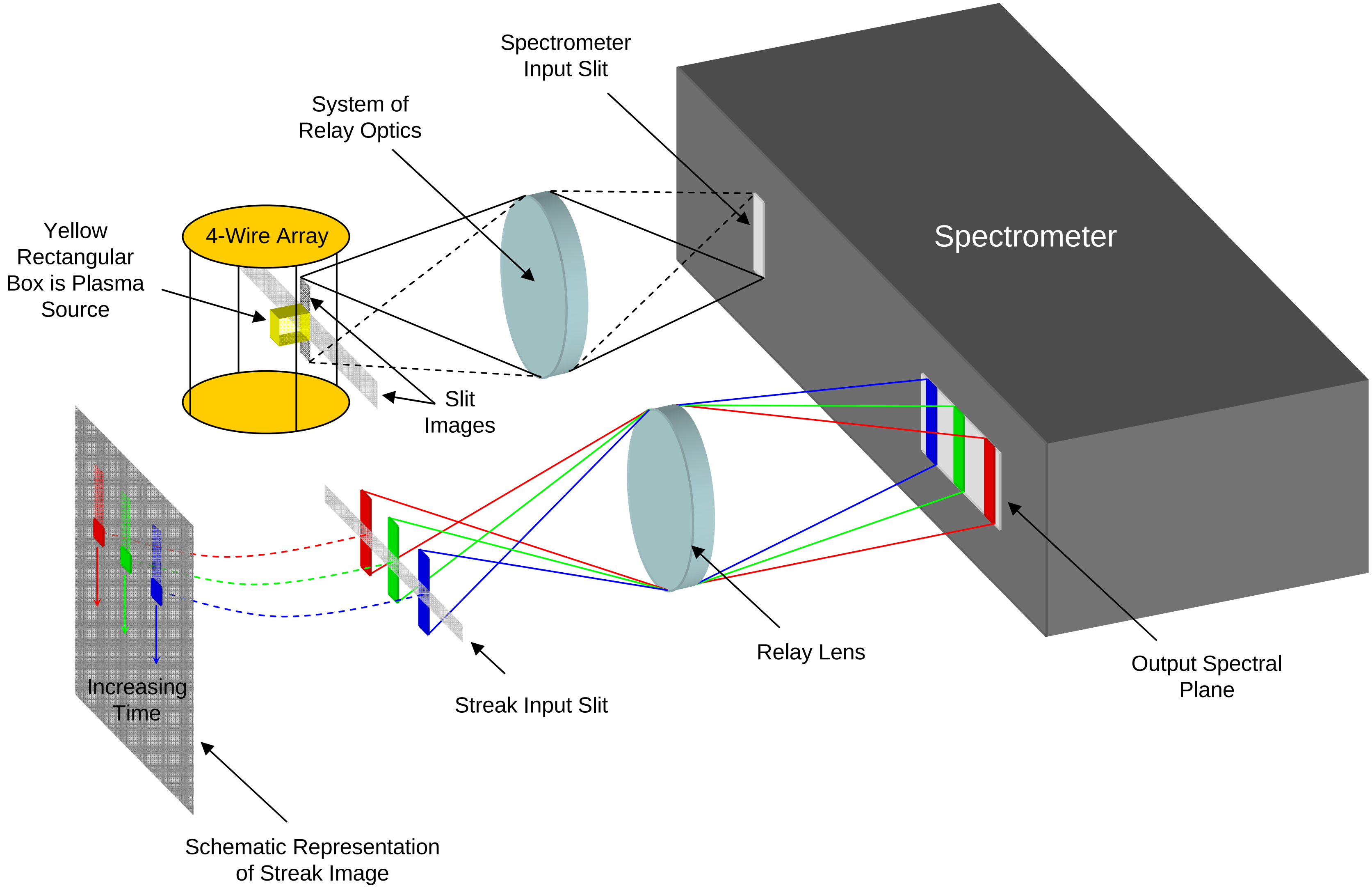
Visible-Streak Spectroscopy



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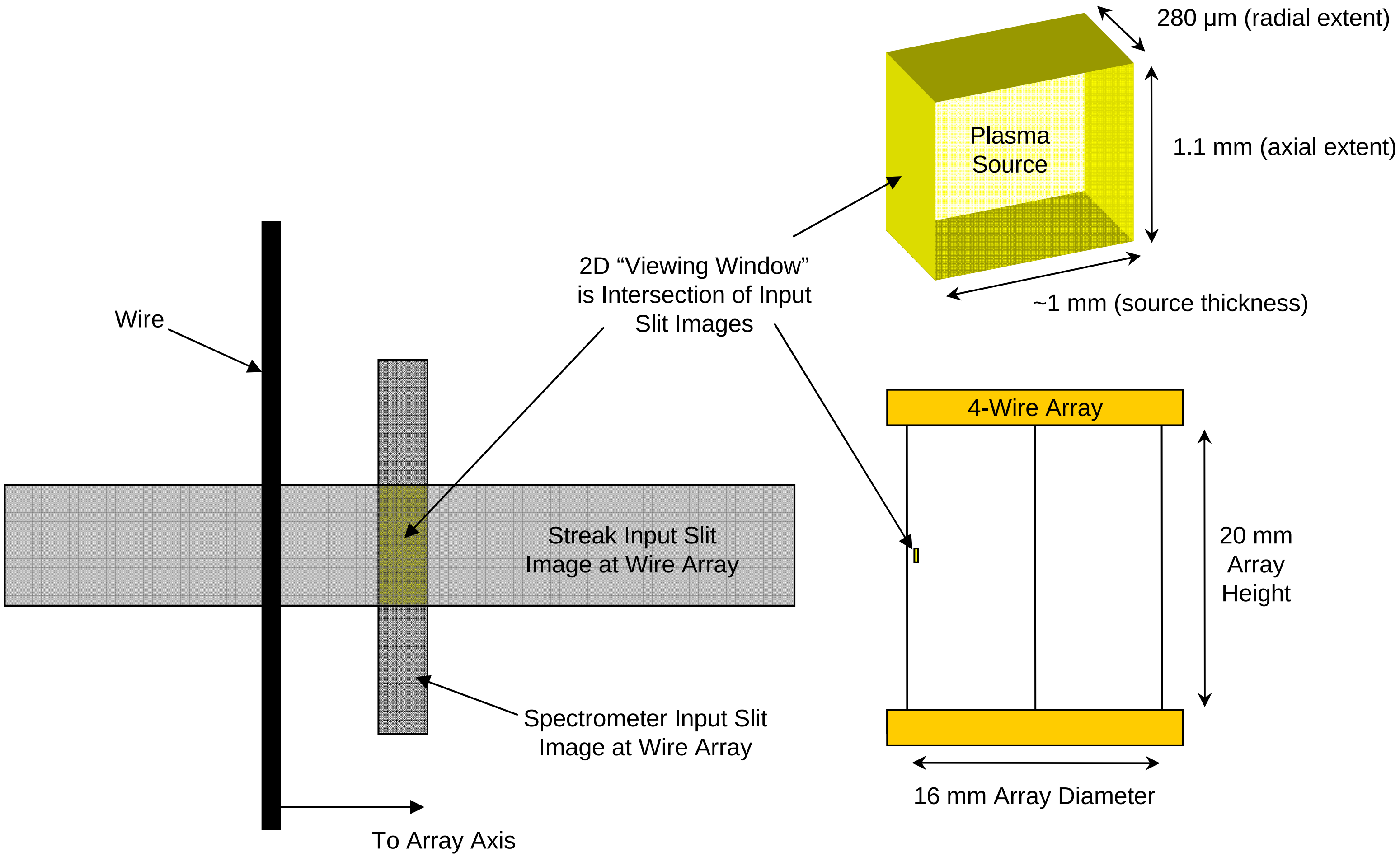
Visible-Streak Spectroscopy



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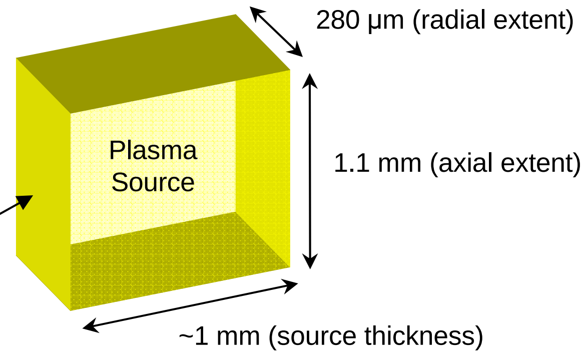
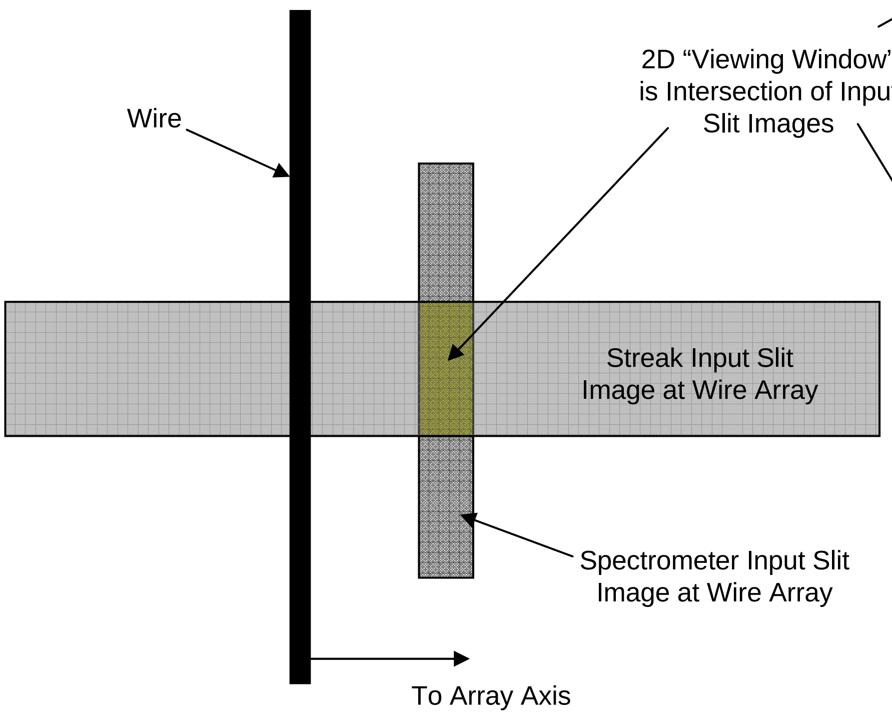
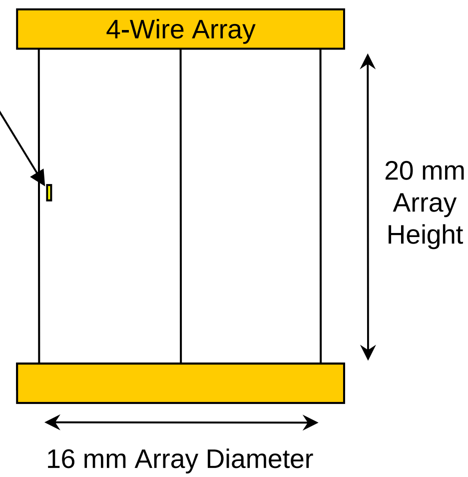
Visible-Streak Spectroscopy

- But upon streaking the visible spectrum…







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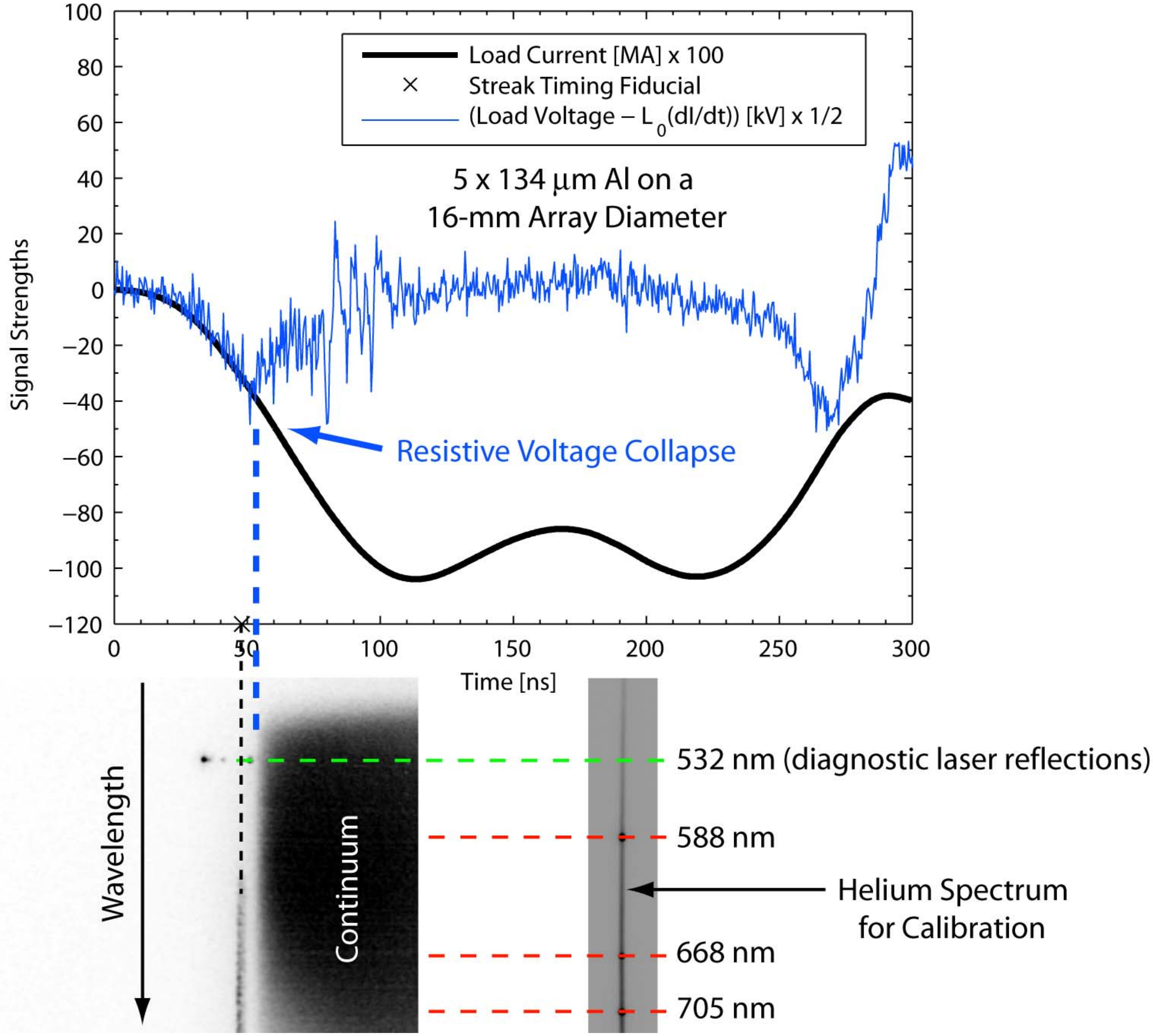
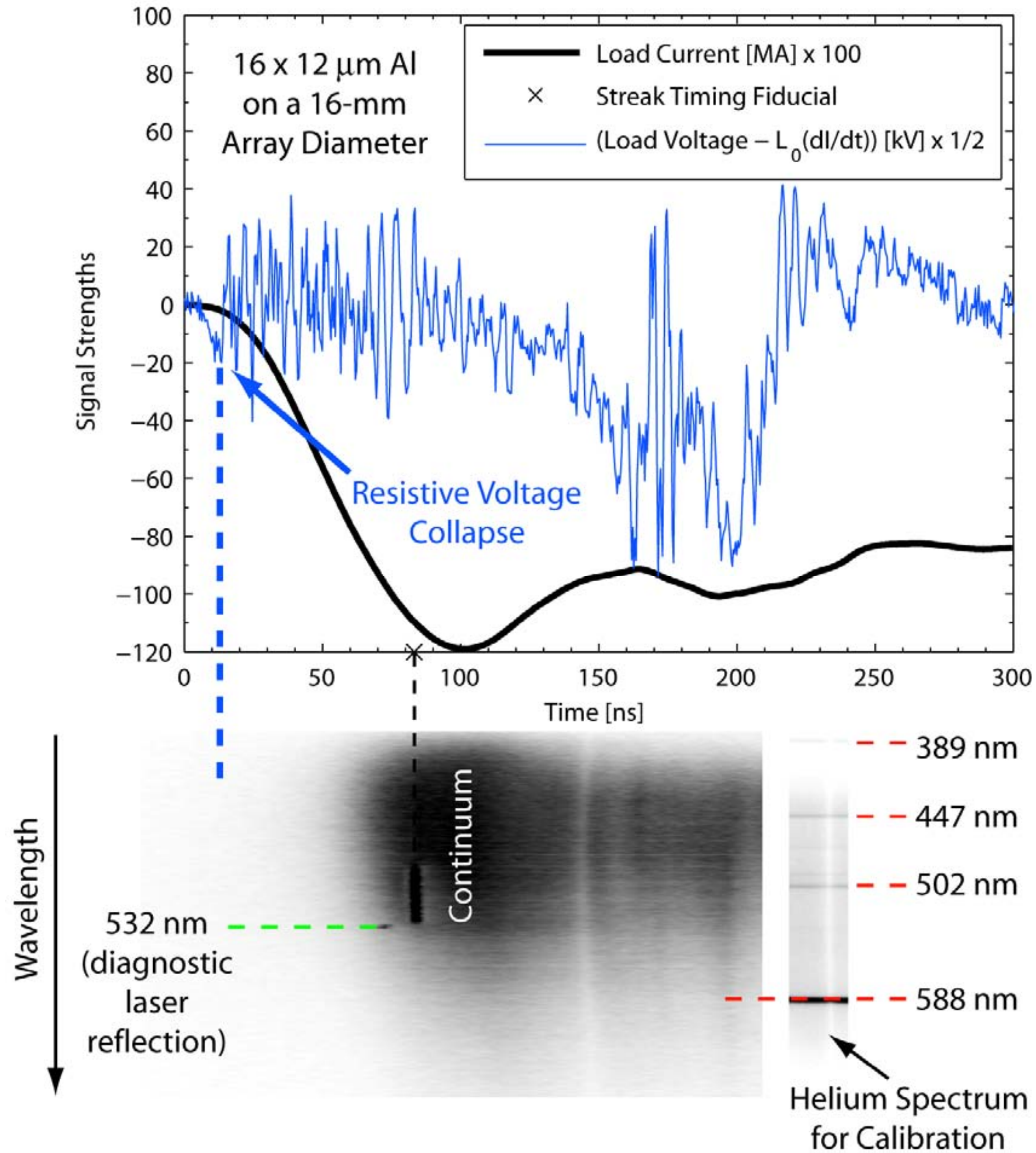
- Found only continuum beginning at the time of breakdown to within about 3-ns resolution
- But thick wires cause breakdown to occur late, when the voltage and current are large (i.e., about 80 kV and 400 kA, respectively)



- Use more wires with smaller wire diameter to move breakdown earlier (i.e., lower voltage and current)
- Still see only continuum, but not until well after breakdown
- Thus, optical efficiency too low for light intensity at 10–30 ns
- Not possible to say from this whether visible lines are present 10–30 ns into the current pulse



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Visible-Streak Continuum Objectives:

- Use the existing visible streak system to take more continuum data
- Calibrate the visible streak system absolutely so that electron density can be determined from the continuum data

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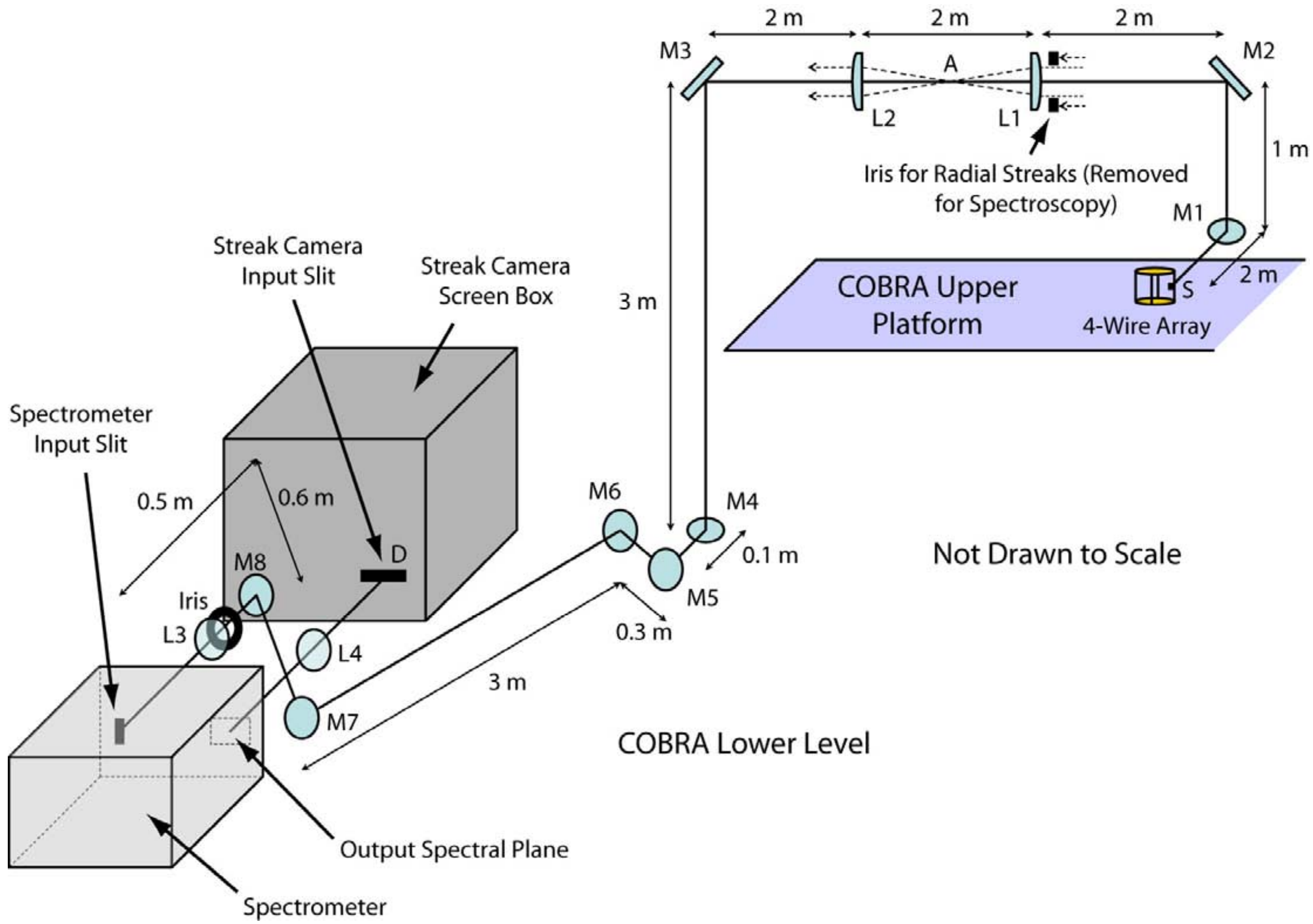
Optical System Calibration:



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Optical System Calibration:

$$\eta_{AD} = \eta_{633,AD} \cdot \eta^{4}_{633,45^\circ-Al} \cdot \eta^{2}_{633,8^\circ-Al} \cdot \eta^{2}_{633,45^\circ-MgF_2-Al} \cdot \eta_{633,G_{21^\circ-D_v}} \cdot \eta^{3}_{633,L}$$

$$\eta_{4\pi R,SA} = \frac{\pi(45/2)^2}{4\pi(5130)^2} = 4.8 \times 10^{-6}$$

$$\eta_{SA} = \eta_{4\pi R,SA} \cdot \eta^{2}_{45^\circ-Al} \cdot \eta_{L} \cdot \eta_{plate-glass}$$

$$\eta_{SD} = \eta_{SA} \cdot \eta_{AD}$$

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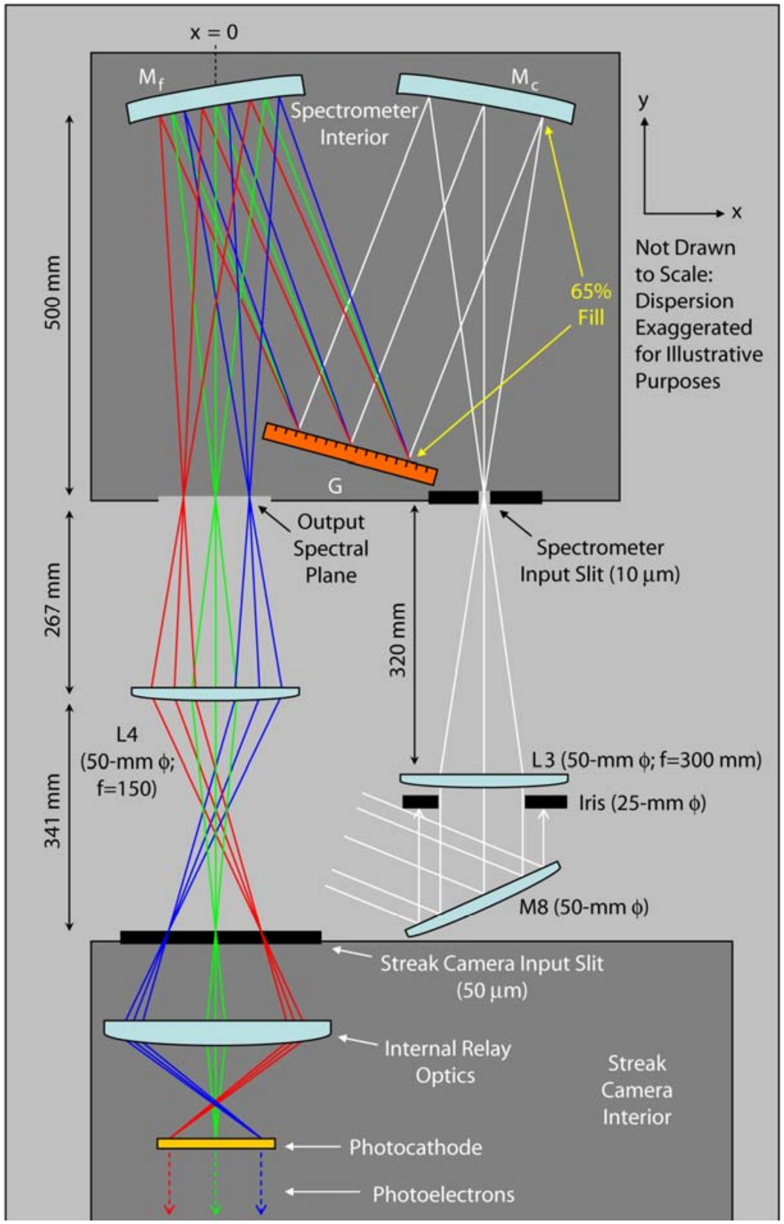
No photons unaccounted for:

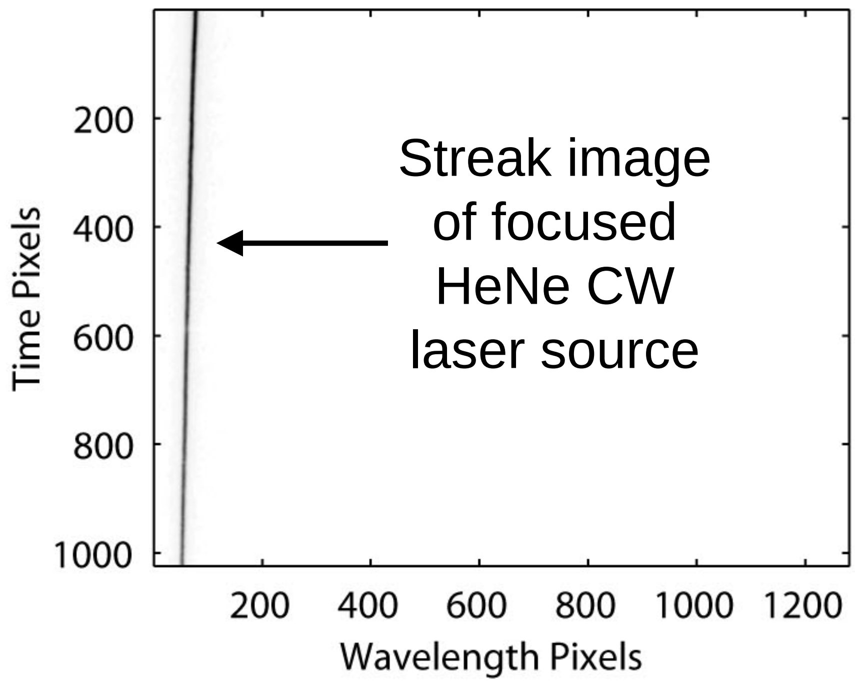
- All white light and dispersed light within the desired bandwidth must be intercepted by the spectrometer’s internal mirrors and the relay optics from the spectrometer output to the streak camera photocathode

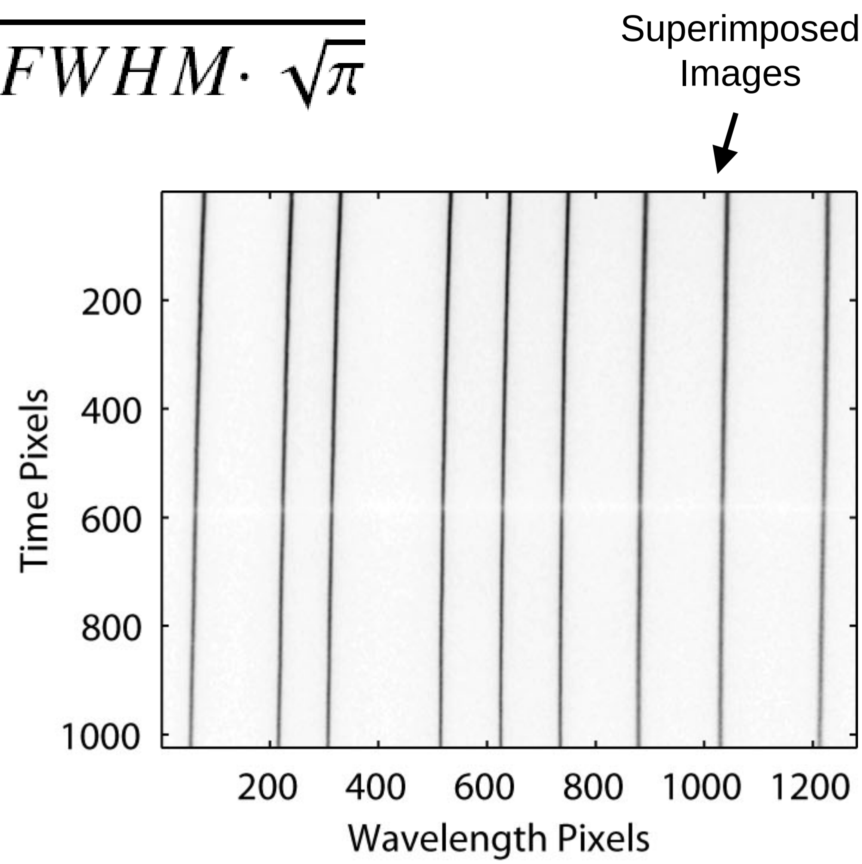
- The desired bandwidth must fit on the photocathode



Streak Camera Pixel Intensity Calibration:

$$C_{633,ij} = \frac{2I\sqrt{\ln 2}}{g'_{ij}\nu \cdot FWHM \cdot \sqrt{\pi}}$$





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Streak Camera Pixel Intensity Calibration (Derivation):

Assume 2D Gaussian distribution for beam intensity of CW HeNe laser → $g(x,y) = g_0 e^{-\left[\frac{(x-x_0)^2}{2\sigma_x^2}+\frac{(y-y_0)^2}{2\sigma_y^2}\right]}$ (1)

Introduce explicit time dependence due to streak speed v (where v is in pixels per second) → $g(x,y,t) = g_0 e^{-\left\{\frac{[x-x_0]^2}{2\sigma_x^2}+\frac{[y-(y_0^i+vt)]^2}{2\sigma_y^2}\right\}}$

Integrate out time dependence to synthesize static streaked image → $g(x) = \int_{-\infty}^{\infty} g(x,y,t)\,dt$

Result is a function of only x → $g(x) = \frac{g_0\sigma_y\sqrt{2\pi}}{v} e^{-\frac{(x-x_0)^2}{2\sigma_x^2}}$ (2)

Streak Camera Pixel Intensity Calibration (Derivation):

To find expression for g_0, start from (1) again, and integrate out static x- and y-dependence directly in order to relate to total beam intensity I →

$$
\begin{aligned}
g^*(x) &= \int_{-\infty}^{\infty} g(x,y)dy \\
&= g_0\sigma\sqrt{2\pi}e^{-\frac{(x-x_0)^2}{2\sigma^2}} \qquad (\sigma_x \approx \sigma_y \equiv \sigma) \\
&= g_0^* e^{-\frac{(x-x_0)^2}{2\sigma^2}},
\end{aligned}
$$

Total beam intensity I →

$$
\begin{aligned}
I &= \int_{-\infty}^{\infty} g^*(x)dx \\
I &= g_0^*\sigma\sqrt{2\pi} \\
I &= 2g_0\pi\sigma^2, \\
g_0 &= \frac{I}{2\pi\sigma^2} \qquad (3)
\end{aligned}
$$

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Streak Camera Pixel Intensity Calibration (Derivation):

Plug expression (3) for g_0 into (2), giving: ⟶ $$g(x) = \frac{I}{\sigma v \sqrt{2\pi}} e^{-\frac{(x-x_0)^2}{2\sigma^2}}$$

Use only the pixel locations, i,j, of peak intensity in the series of 1D, x-dependent line-outs (i.e., use only $x=x_0$) ⟶ $$g(x) \to g_{ij} = \frac{I}{\sigma v \sqrt{2\pi}} \qquad (x = x_0)$$

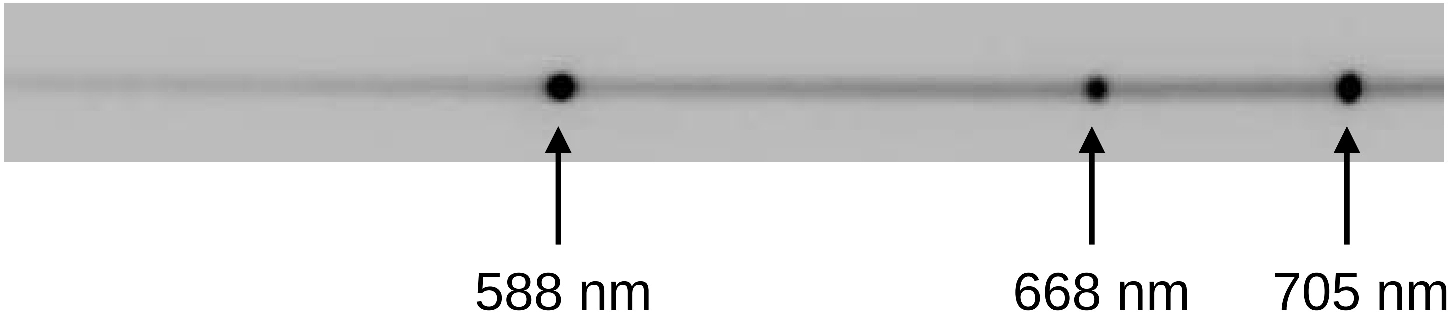
Introduce calibration factor, $C_{633,ij}$, for these pixel locations (for the 633-nm photons being used) ⟶ $$g'_{ij} \cdot C_{633,ij} = g_{ij} = \frac{I}{\sigma v \sqrt{2\pi}}$$

Solve for the $C_{633,ij}$ ⟶ $$C_{633,ij} = \frac{I}{g'_{ij} \sigma v \sqrt{2\pi}}$$

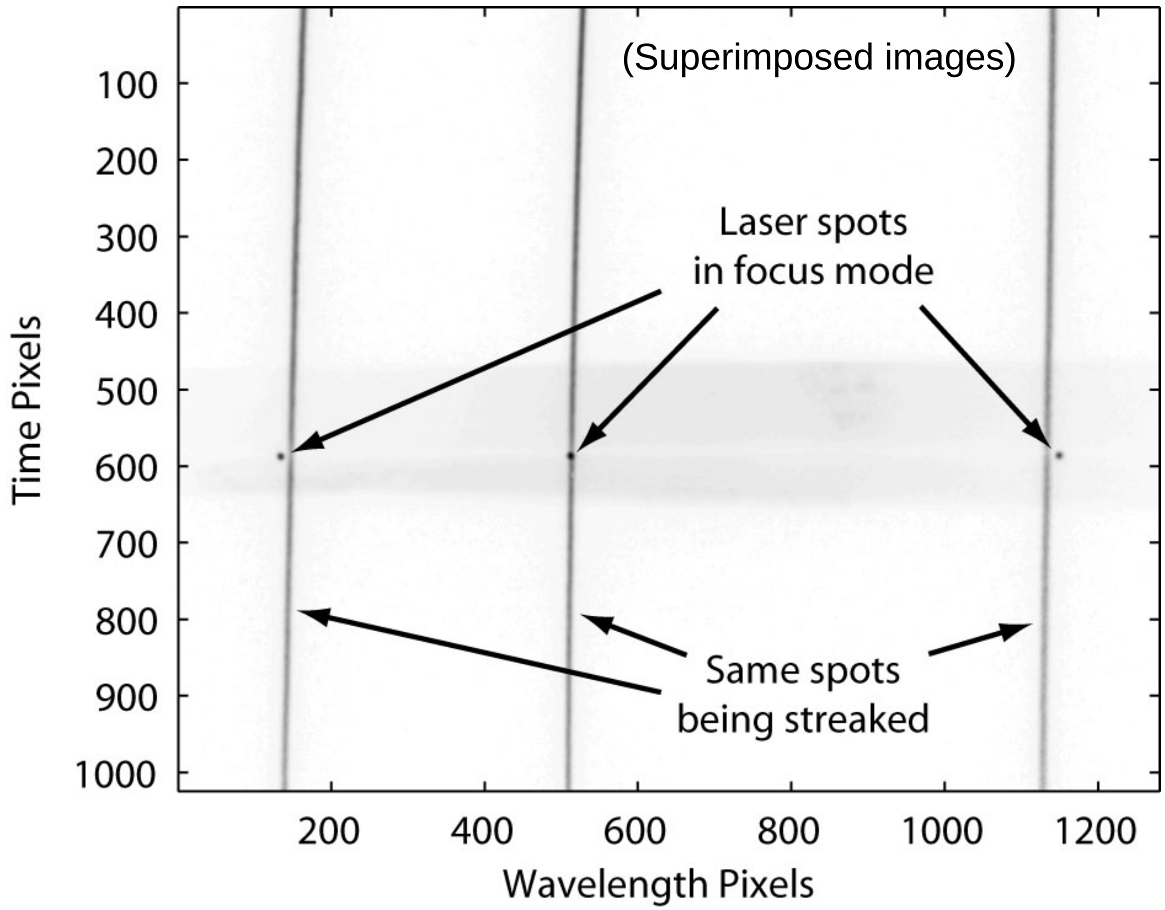
Introduce fundamental relationship between standard deviation, σ, and full-width at half maximum (FWHM) for Gaussian distributions ⟶ $$C_{633,ij} = \frac{2I\sqrt{\ln 2}}{g'_{ij} v \cdot FWHM \cdot \sqrt{\pi}} \qquad \left(\sigma = \frac{FWHM}{2\sqrt{2\ln 2}}\right)$$

Wavelength Calibration:

- Helium discharge lamp used to illuminate entrance slit of spectrometer
- Static images taken using the streak camera system's focus mode prior to each shot



Streak-Tube Aberration Corrections:



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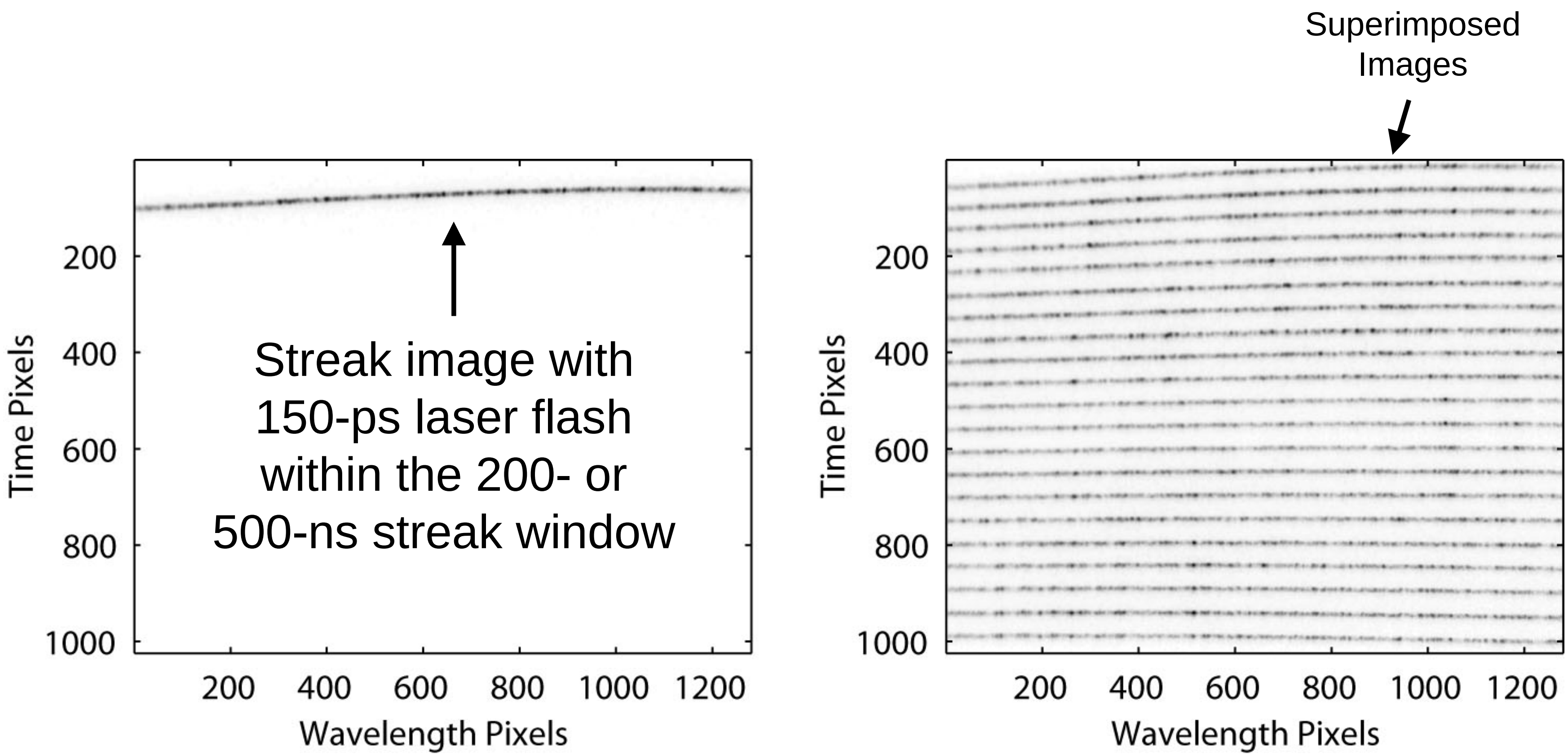
Streak-Tube Aberration Corrections:



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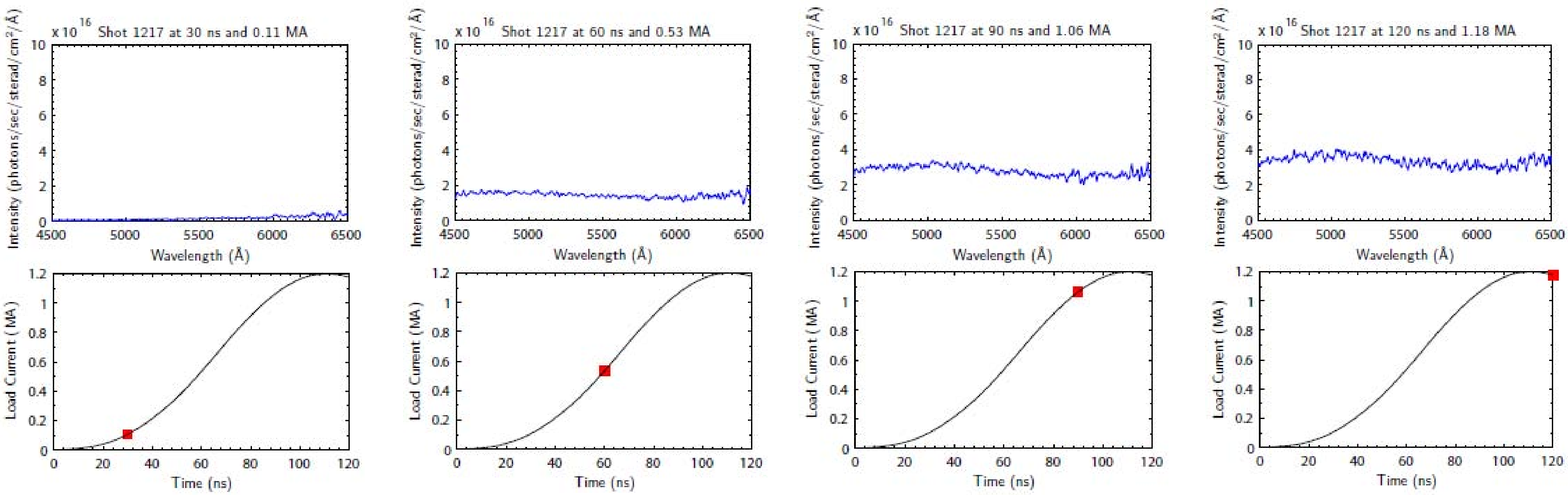
Continuum Results:

- Absolute calibration → [photons/sec/sterad/**cm²**/Å]



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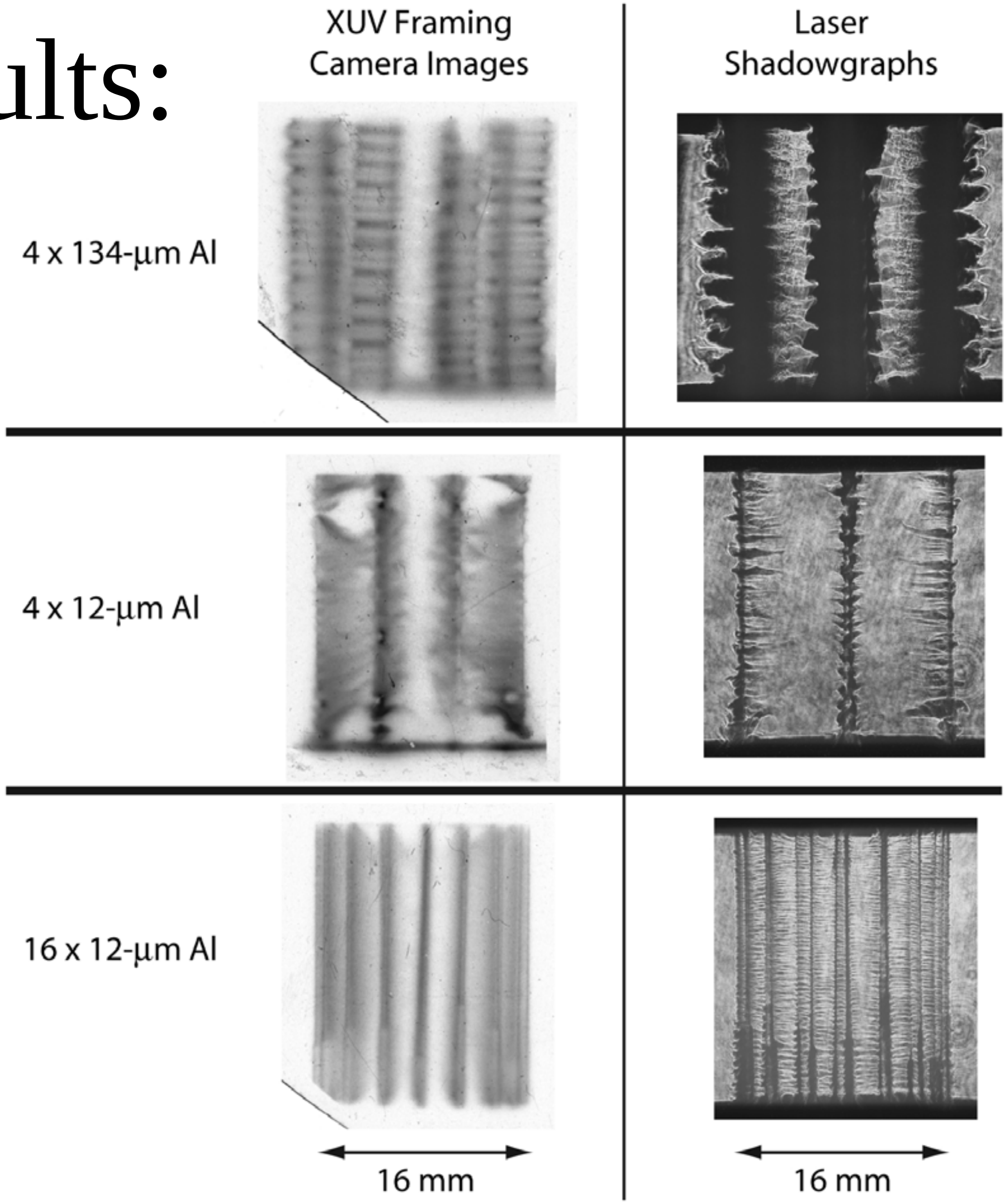
Continuum Results:

- Absolute calibration [photons/sec/sterad/**cm^3**/Å]
- Source thickness estimated from XUV framing camera and laser shadowgraph data
- Final dataset delivered to Weizmann Institute



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Conclusions:

- Spectroscopic measurements of the coronal plasma in aluminum wire-array z-pinch experiments showed only continuum radiation in visible wavelengths
- The continuum emission began at the time of wire breakdown for thick 134-μm wires
- The volume continuum intensity was in the range of about 1–6 x 10^{17} photons/sec/sterad/cm^3/Å, with a nearly constant spectral dependence
- The continuum intensity was proportional to the driving current
- Spectroscopic modeling and simulation efforts are underway to determine the electron density from the continuum measurements

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