Improved-Fidelity X-Ray Transmission Images of HID Lamps

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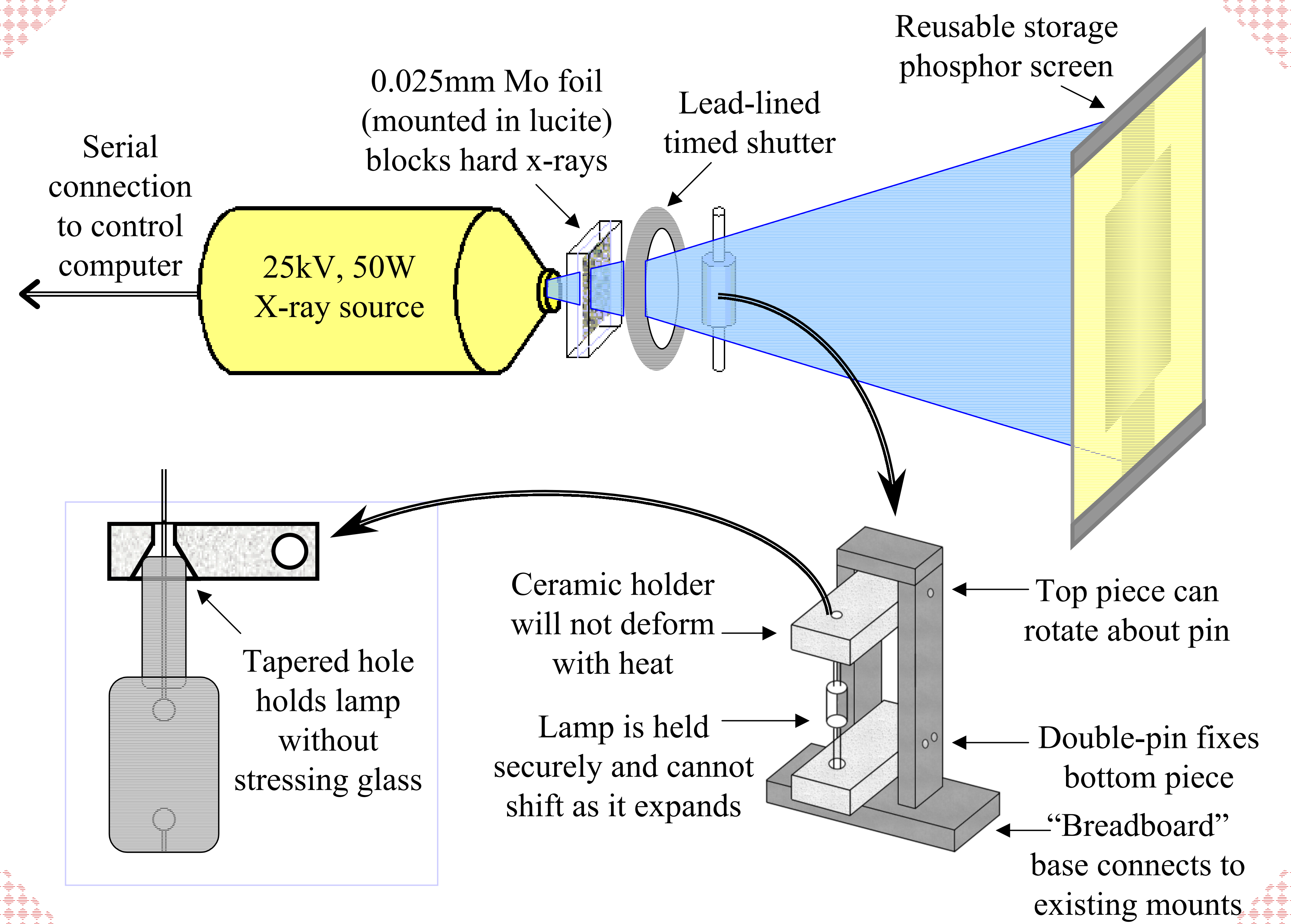
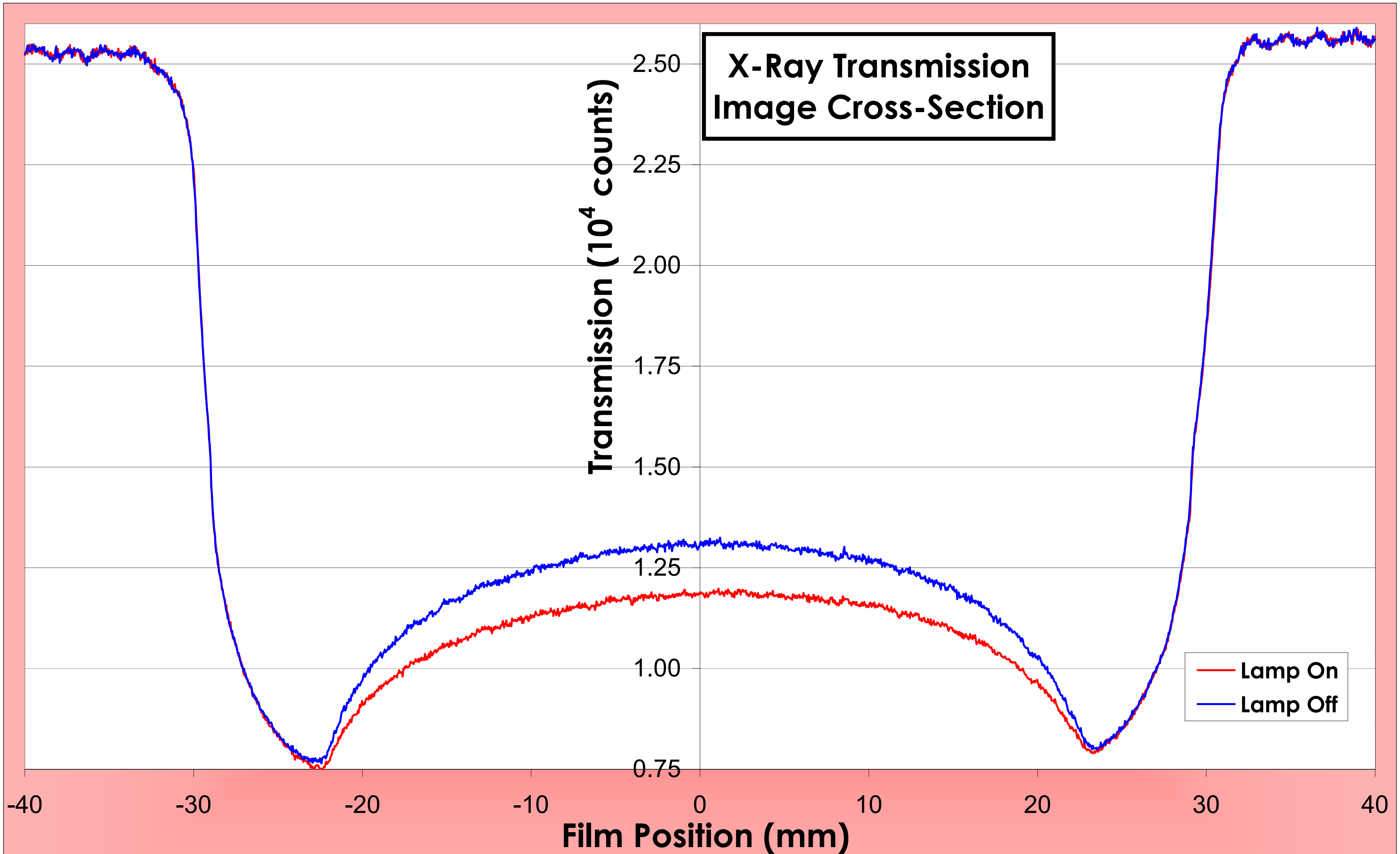
~Abstract~

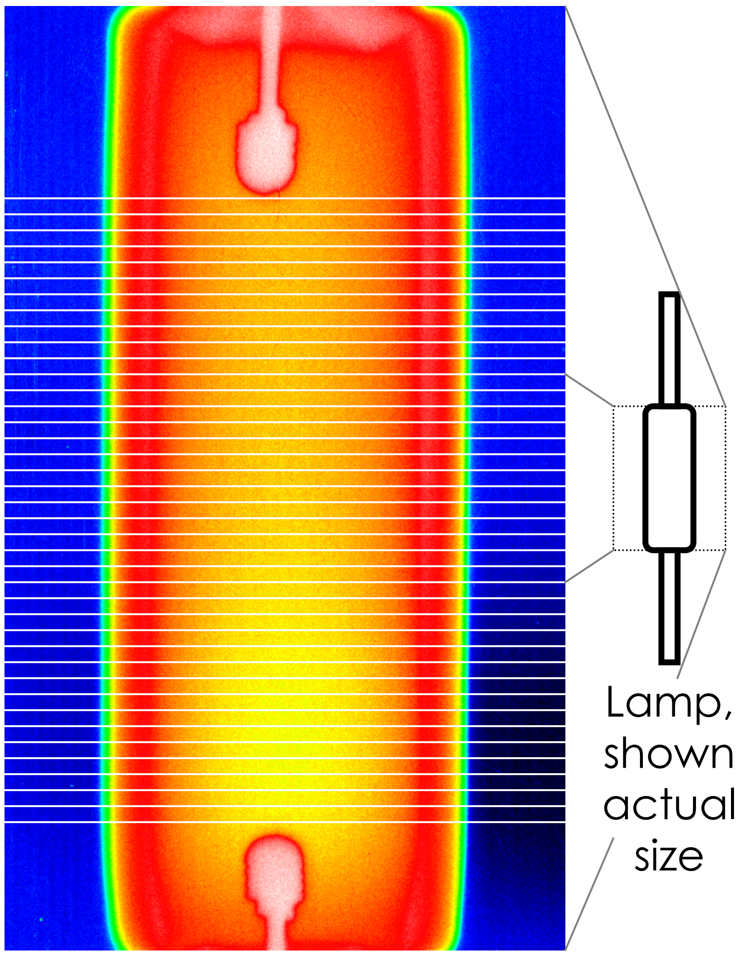
The linearity of modern X-ray detection systems has made possible detailed Hg density/temperature maps in High Intensity Discharge (HID) lamps [Curry, Sakai, & Lawler 2003]. These maps provide critical data in the near wall region and some information on the convective cell structure of HID lamps. In the current work an ultrabright microfocus (source diameter < 40 microns) X-ray tube with a Mo anode was used to produce magnified transmission images with a phosphor image plate detection system. Special attention was given to calibration of the system using cells containing reference solutions of Hg in nitric acid. Possible losses in image fidelity due to the spread of X-ray energies from the microfocus lab source, and due to forward scattering of X-rays were explored in detail using both reference solutions of Hg in nitric acid and numerical simulations. Results for pure Hg lamps and Metal-halide HID lamps will be presented.


Reusable storage phosphor screen
0.025mm Mo foil (mounted in lucite) blocks hard x-rays
Lead-lined timed shutter
Serial connection to control computer
25kV, 50W X-ray source
Ceramic holder will not deform with heat
Top piece can rotate about pin
Tapered hole holds lamp without stressing glass
Lamp is held securely and cannot shift as it expands
Double-pin fixes bottom piece
"Breadboard" base connects to existing mounts



The 100-pixel averaged cross-section from the center of the lamp.

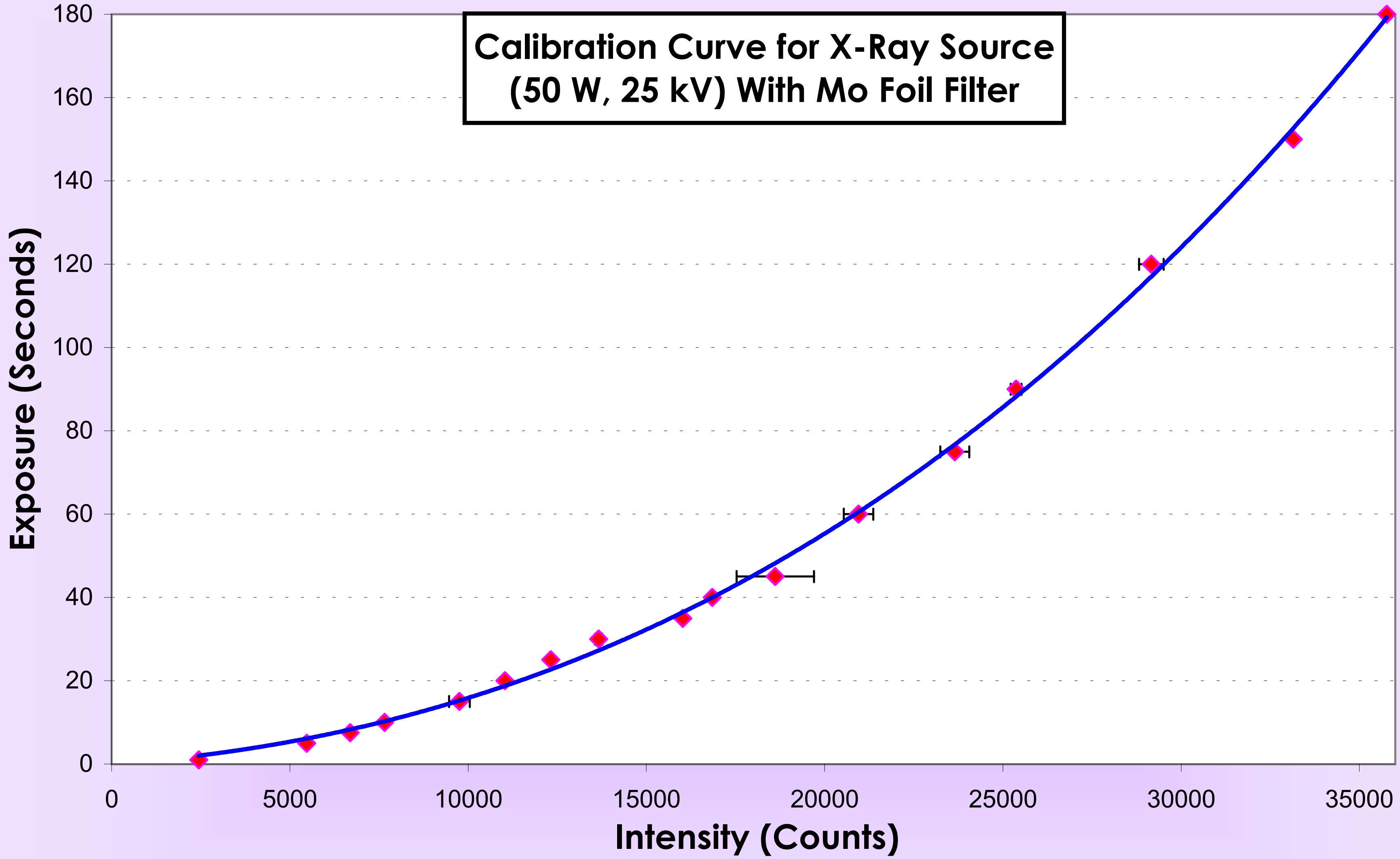
The phosphor screen is read by a scanner, and the image is saved as a digital file.



X-ray transmission image of the lamp while off. Bin sizes are shown to scale.

The image is divided into a series of strips, each 100 pixels tall. The radial information is then binned over each strip, creating approximately 25 averaged intensity versus position files. 100 pixels on the image corresponds to 0.58 mm of the bulb's height.

Although this x-ray detection system is more linear than most, the data are still linearized by multiplication with a calibration curve.



Although the curve is nonlinear overall, it gives good linearity over small exposure gradients. It is also more linear than many alternate x-ray detection methods.To ensure linearity in the data, intensity values were multiplied by this curve. Error bars represent standard deviation of intensity values over the entire film.

Our data can be easily compared to theory. The measured transmission should be

$$T = T_0 e^{-\mu t}$$

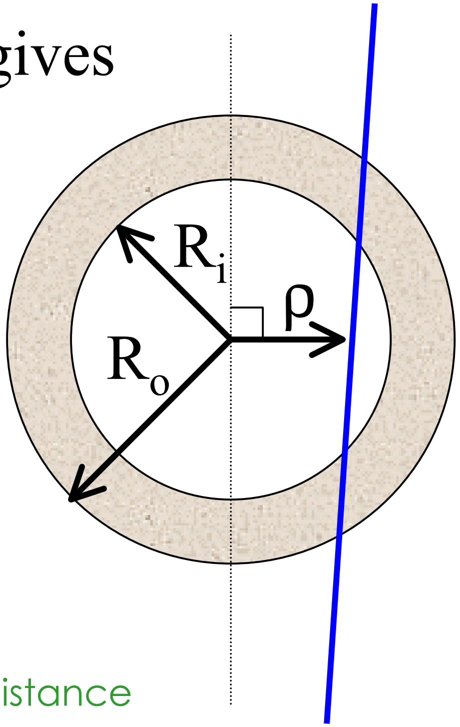
material thickness (t)

material absorption coefficient (μ)

signal for no absorption (T_0)

The cylindrical geometry of our fused silica lamp gives

$$t = \begin{cases} 2\left(\sqrt{R_o^2 - \rho^2} - \sqrt{R_i^2 - \rho^2}\right) & \textbf{for } \rho < R_i \\ 2\sqrt{R_o^2 - \rho^2} & \textbf{for } R_i < \rho < R_o \\ 0 & \textbf{for } R_o < \rho \end{cases}$$

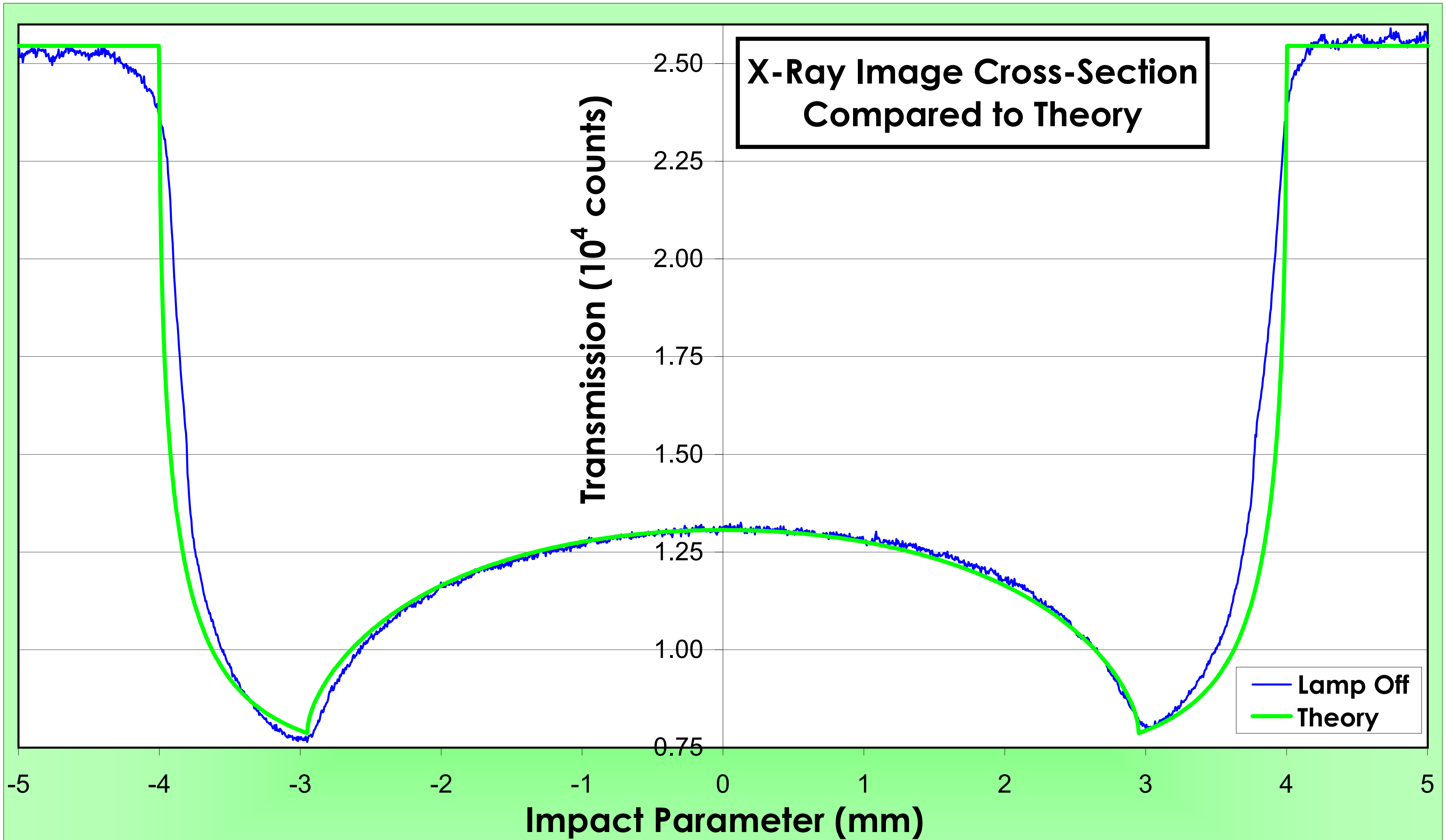


Keeping in mind the magnification:

$$\rho_{film} = \frac{d_{lamp}}{d_{film}} \rho$$

source-to-lamp distance (d_{lamp})

source-to-film distance (d_{film})



Transmission cross section (lamp center) of the cold lamp compared to the profile predicted by the absorption coefficient of fused silica. The absolute baseline is arbitrary, but the theoretical curve is otherwise quantitative.

The column density of Hg can be expressed in terms of the signal received at the detector:

$$F[\rho] = \frac{1}{\sigma} \ln\left(\frac{S_0[\rho]}{S[\rho]} \right)$$

signal with lamp off

signal with lamp on

Hg absorption cross section

If we take the column density to be of the form

$$F[\rho] \approx 2\sqrt{R^2 - \rho^2} \sum_{i=1}^{N} a_{2i} G_{2i}^{R}[\rho]$$

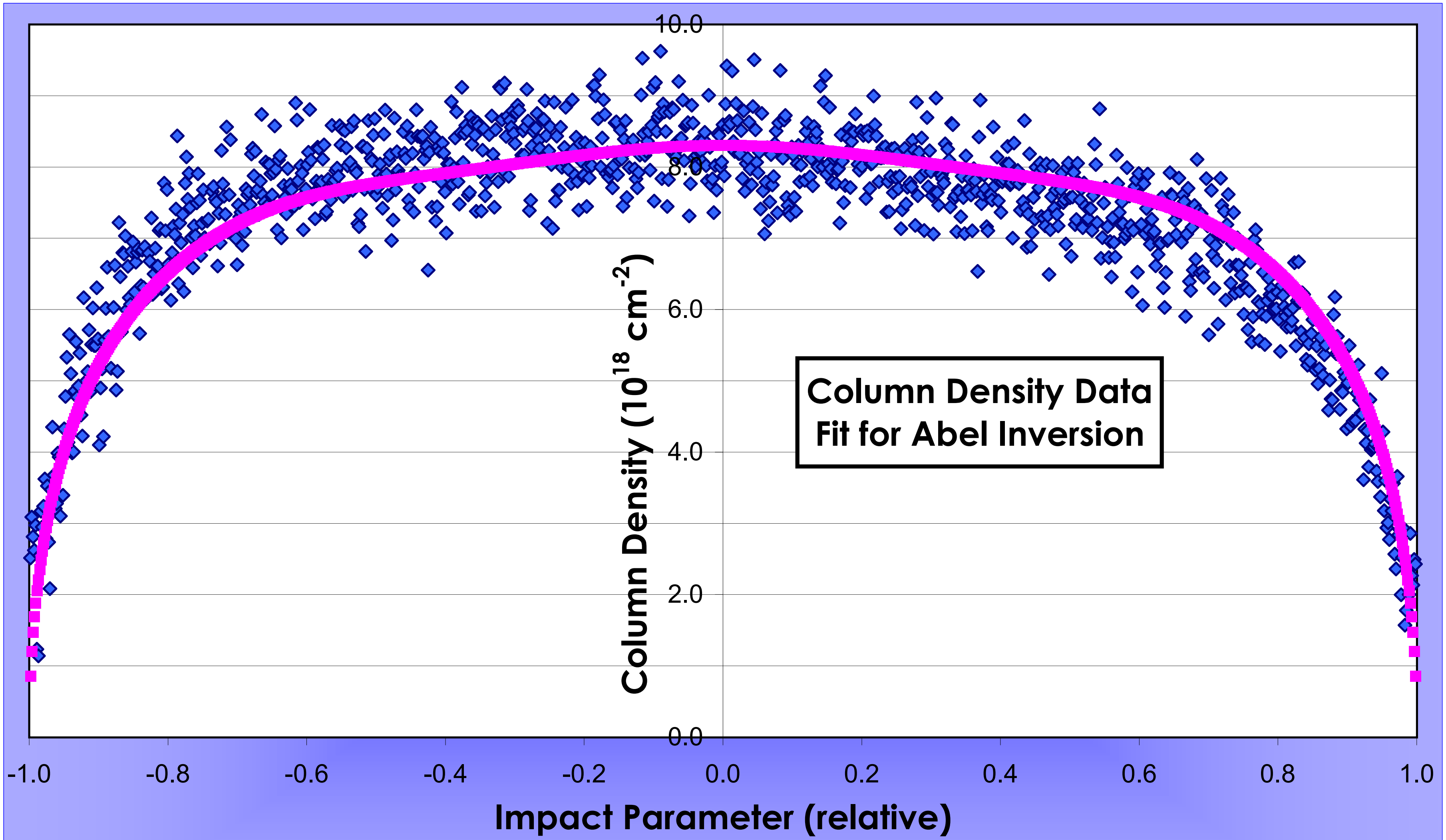
fit coefficient

$$G_{2i}^{R}[\rho] = n! \sum_{m=0}^{n} (-1)^m \frac{m!\, 2^{2m}}{(n-m)!\,(2m+1)!} R^{2(n-m)} \left(R^2 - \rho^2\right)^m$$

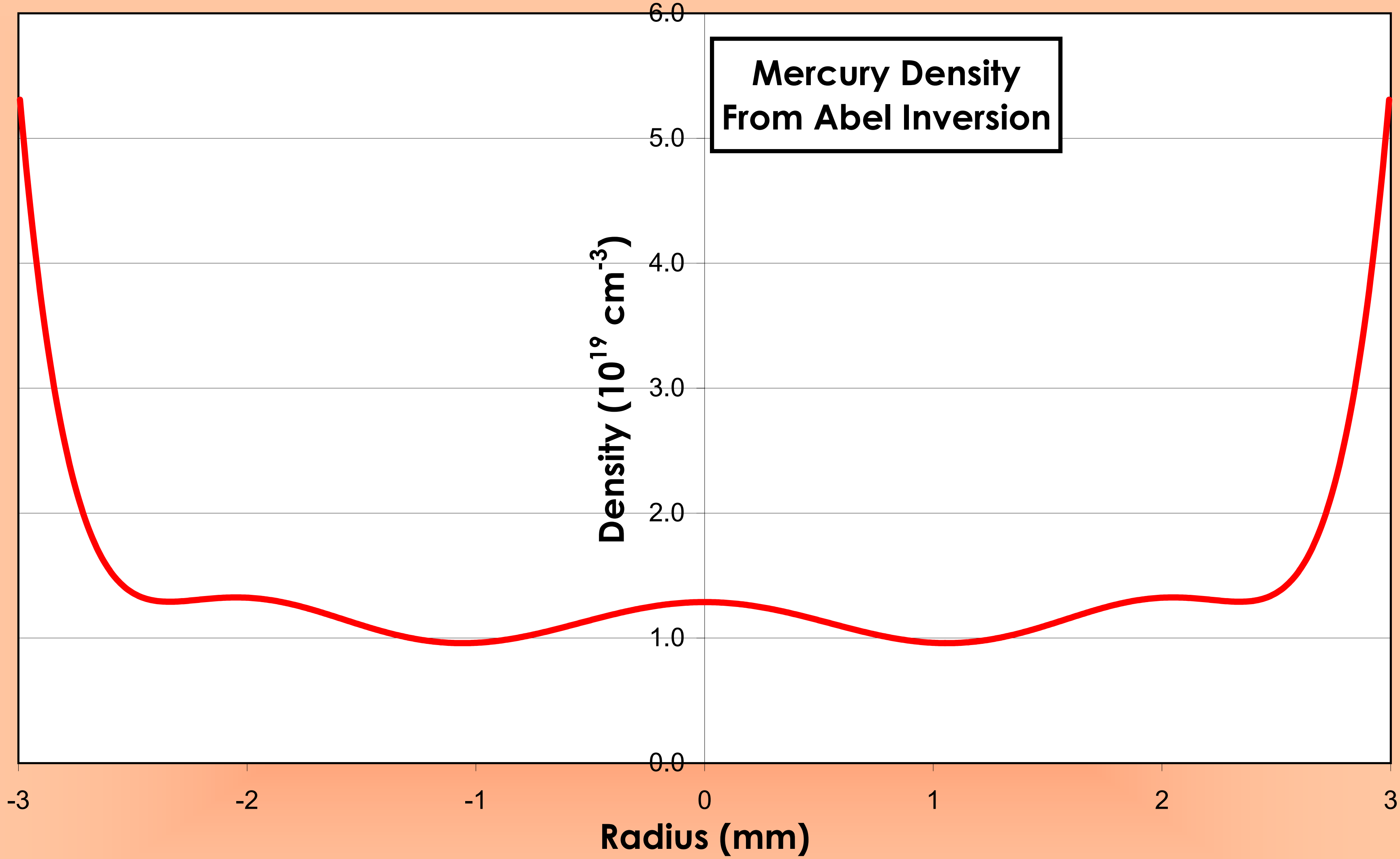
Abel inversion gives us a simple polynomial form for the radial density:

$$n[r] = \sum_{i=0}^{N} a_{2i} r^{2i} \approx a_0 + a_2 r^2 + a_4 r^4 + a_6 r^6 + a_8 r^8$$

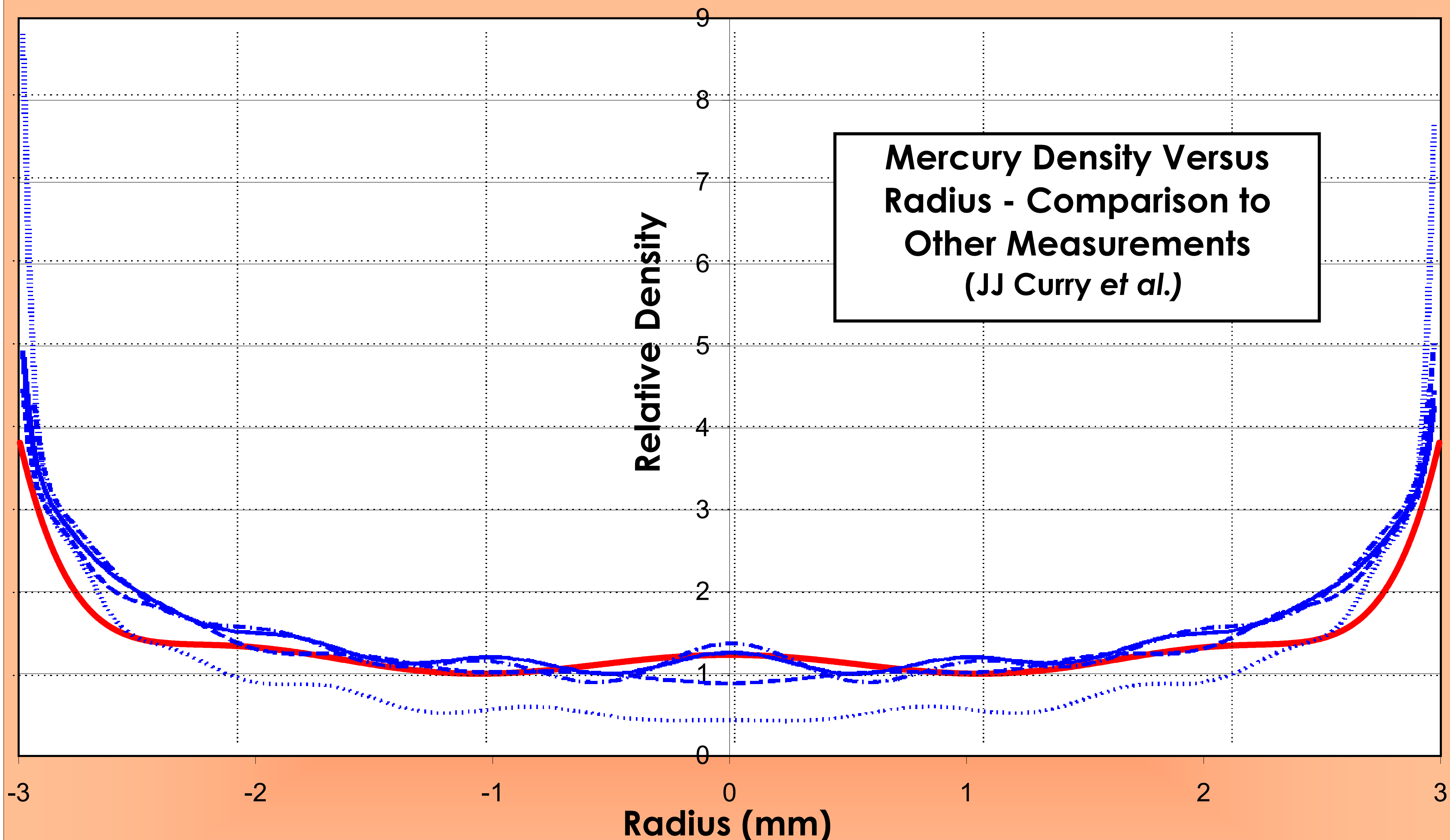
[Curry, Sakai, and Lawler 1998]



Experimental column density measurements (blue) and the impact parameter expression for the Abel inversion (pink). The function is least-square fit to the data using a matrix calculation.



Mercury density in the center of the lamp versus radius. The density is expected to scale with temperature, so the data are seen to be consistent with estimates of the temperature gradient of the lamp.



Relative mercury density versus radius. The red line indicates the result of the presented work. It is scaled to $1.04 \cdot 10^{19}$ cm^{-3}. Blue lines indicate relative density measurements taken by a collaborating group at NIST where several lamp chemistries were studied.

Implications

- We have an existing optical-ultraviolet absorption system capable of measuring absolute atom and ion densities [Bonvallet and Lawler 2003]. Combined with absolute elemental densities from X-ray fluorescence, this gives a full spatial map of all constituents of an operating lamp.

- This experiment represents a major step toward an inexpensive and compact system for x-ray work. Once the system is completely realized, it will provide routine measurement of absolute elemental densities.

References

Bonvallet G A and Lawler J E 2003 *J. Phys. D* **36**, 1510

Curry J J, Sakai M, and Lawler J E 1998 *J. Appl. Phys.* **84**, 3066

Smith D J, Bonvallet G A, and Lawler J E 2003 *J. Phys. D* **36**, 1519

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