Filter Pack X-Ray Spectrum Reconstruction for Betatron Streaking Experiment

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Introduction

In laser wakefield acceleration, a laser drives a wakefield through a plasma, trapping and accelerating electrons from the plasma to energies that can reach a few GeV. As the electrons propagate, they oscillate within the wakefield and produce betatron X-rays that emit in the forward direction. By measuring the evolution of the X-ray energy, we can learn about the electron dynamics during propagation.[1]

To measure the change in X-ray energy as a function of time, a transverse density gradient was introduced in the gas that would be ionized into a plasma. This caused the laser wavefront to curve during propagation, causing the X-rays to streak across the X-ray camera as they were emitted. Thus, the angular position corresponds to a distinct time of emission and is correlated to the electron energy at that time.

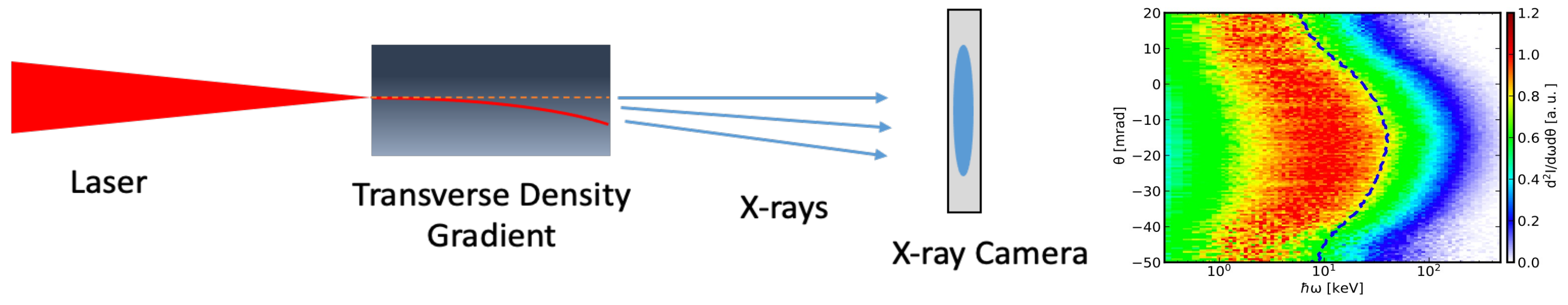

Figure 1: (Left) Sketch of the experimental setup where the laser travels through a transverse density gradient, causing the wakefield to curve and the emitted X-rays to streak across the camera. (Right) Simulation of X-ray energy changing with angle, with the critical energy marked as the dashed blue line.[1]

The betatron radiation in this setup has a synchrotron-like spectrum, so it has a critical energy that can change with time/angle. To find the critical energy at different angles, we used a filter pack installed in front of an X-ray camera. By measuring how the critical energy changes in space and therefore time, we can better understand how the electron energy changes through the plasma.

For more information on this experiment, see the talk by Yong Ma:

TO08.00013: Streaking of betatron X-rays in a curved laser wakefield accelerator

Background Flattening

The photon beam has an uneven spatial intensity distribution which needs to be flattened before we can extract transmission values.[3]

1. Retrieve background values from the spaces between the filter columns
2. Interpolate across the whole image to retrieve the intensity profile
3. Divide the original image pixelwise by this background profile

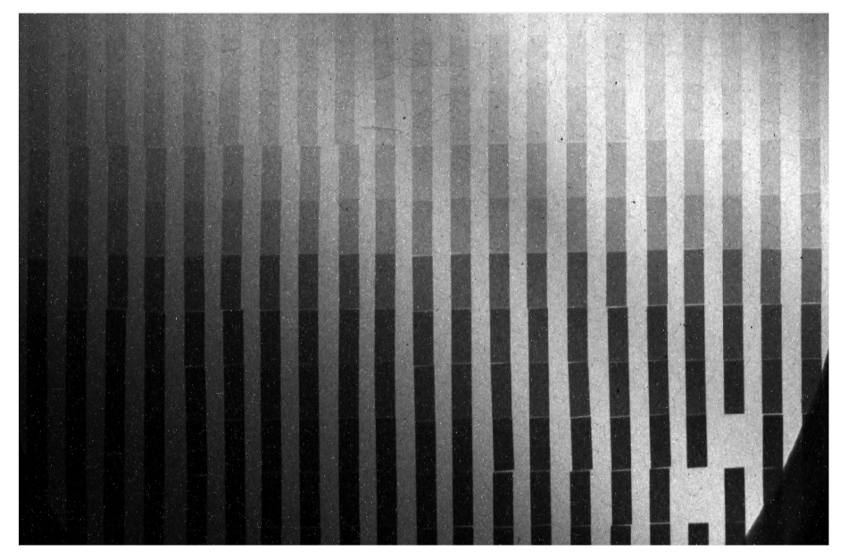

Figure 3: Original image

Figure 4: Interpolated spatial profile

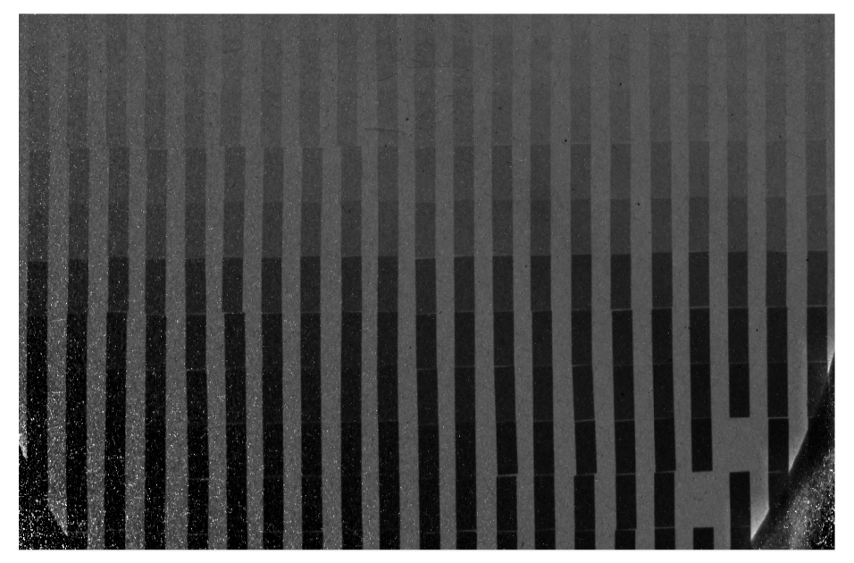

Figure 5: Flattened background

Filter Pack

The filter pack is made of multiple repeating columns with 11 filters in each column. The filters are varying thicknesses of aluminum or copper that will absorb photon energy differently based on the attenuation curve of each material.[2] Because of these differences, an incident photon energy spectrum will create a unique transmission pattern through the filters.

From this transmission pattern, we can determine the critical energy of a synchrotron-like spectrum that would have produced it. This can be done column by column to find the critical energy at different angles as the X-rays streak across the camera.

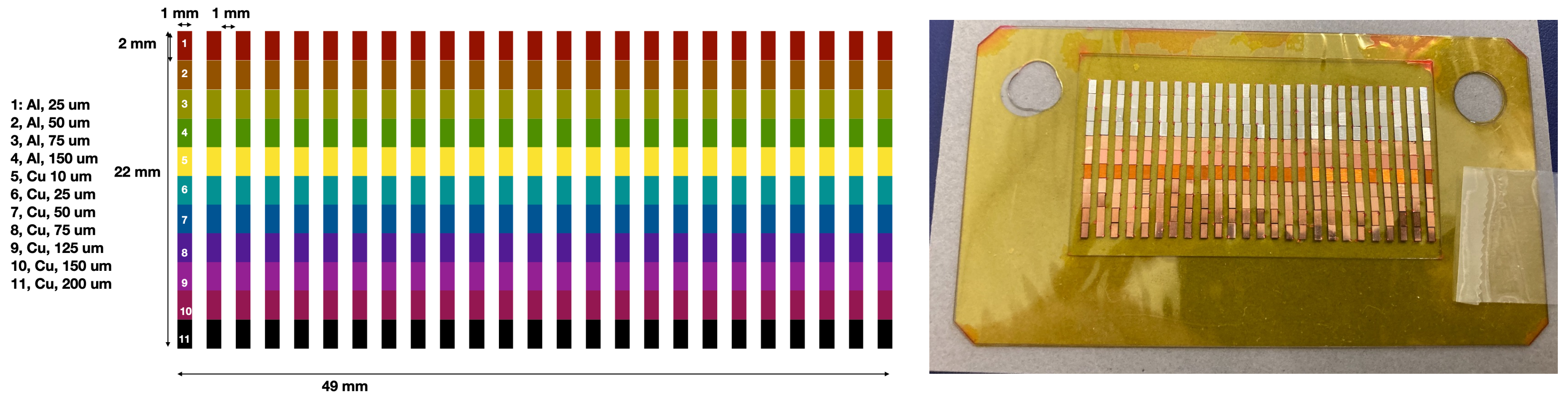

Figure 2: (Left) Color-coded filter pack schematic listing the thickness, position, and material of each filter. Each column is identical and contains aluminum and copper filters. (Right) Physical version of the filter pack used in the experiments.

Equations

To find the critical energy of the synchrotron-like spectrum, an energy $\mathrm{E_c} = \hbar\omega_c$ is chosen as a guess to use in the following equation:

$$S(E) = \left.\frac{d^2 I}{d\omega d\Omega}\right|_{\theta=0} \approx \left(\frac{\omega}{2 * \omega_c}\right)^2 K_{\frac{2}{3}}^2\left(\frac{\omega}{2 * \omega_c}\right)$$

This equation applies specifically to on-axis photons.[4] The guessed spectrum is multiplied by the filter transmissions and quantum efficiency of the camera, then integrated over the energy range to produce a calculated signal for each filter, $\mathrm{Y_m}$ as shown in the following equation. This is compared to the measured signal Y using the equation:

$$\mathrm{Y_m} = \int_{E_{min}}^{E_{max}} S(E) * Q(E) * T(E) dE \qquad \Delta = \sqrt{\frac{\sum_i \left(Y_{m,i} - Y_i\right)^2}{N_i}}$$

where Q(E) is the camera's quantum efficiency, T(E) is the filter transmission, i is the filter number and $\mathrm{N_i}$ is the number of filters.[3] This process is repeated for many different initial energy guesses in order to find the minimum that corresponds to the guess that best matches the data. This value is taken to be the measured critical energy. This process is repeated for each filter column in the image to reveal how this critical energy changed as the X-rays streaked across the camera.

Plots

After the background has been flattened, the transmission values through each filter are recorded and plotted. These $\mathrm{Y_i}$ values are compared to the calculated values to determine how well the guessed critical energy's spectrum matches the data.

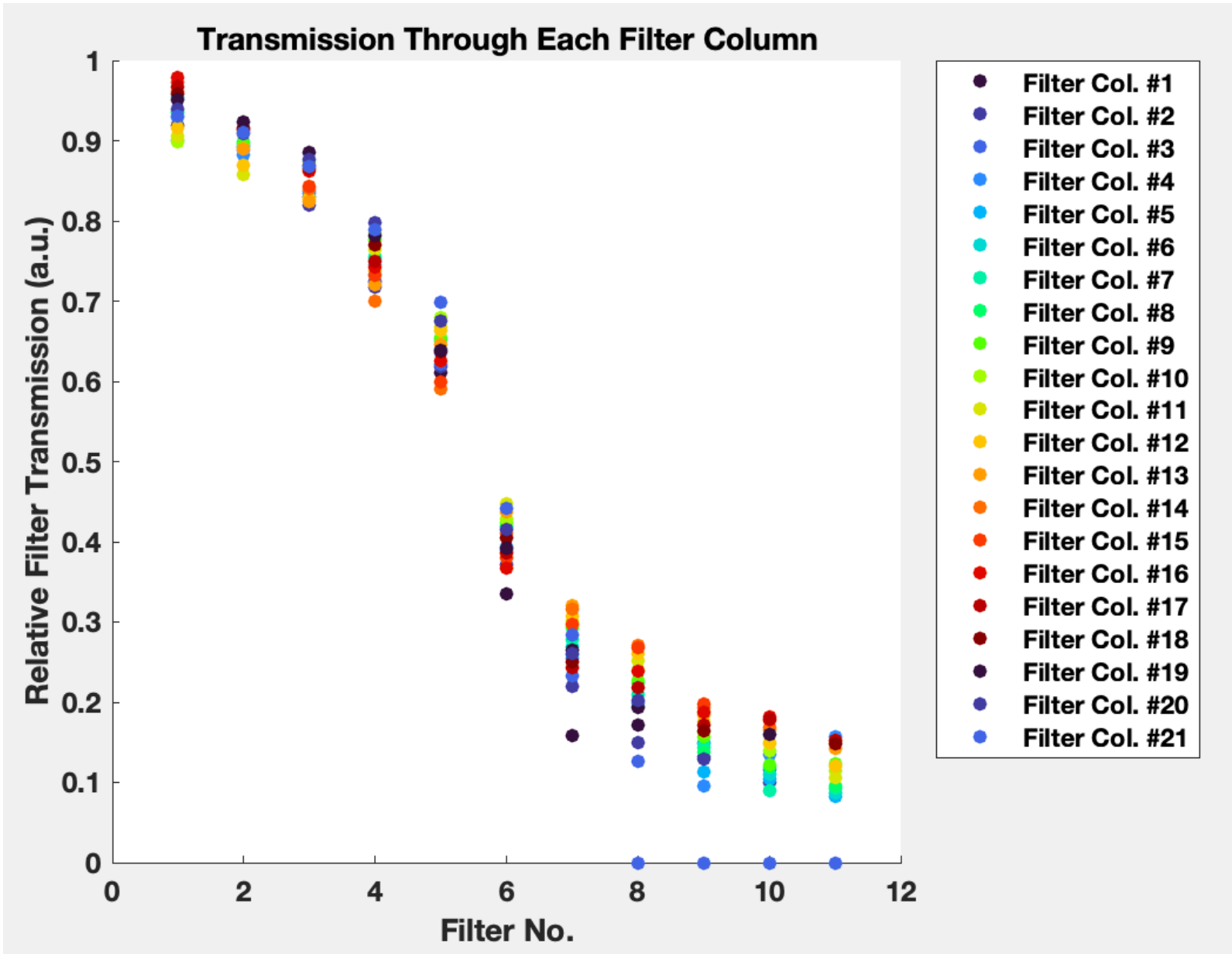

Figure 6: Relative transmission through the filters of each column, with missing or blocked filters counted as zeros.

Many guesses for the critical energy are sampled and the resulting Δ values are plotted here. In this example, for column 13, they dip down to a minimum at 24 keV which we take to be the correct critical energy for the spatial position of this column.

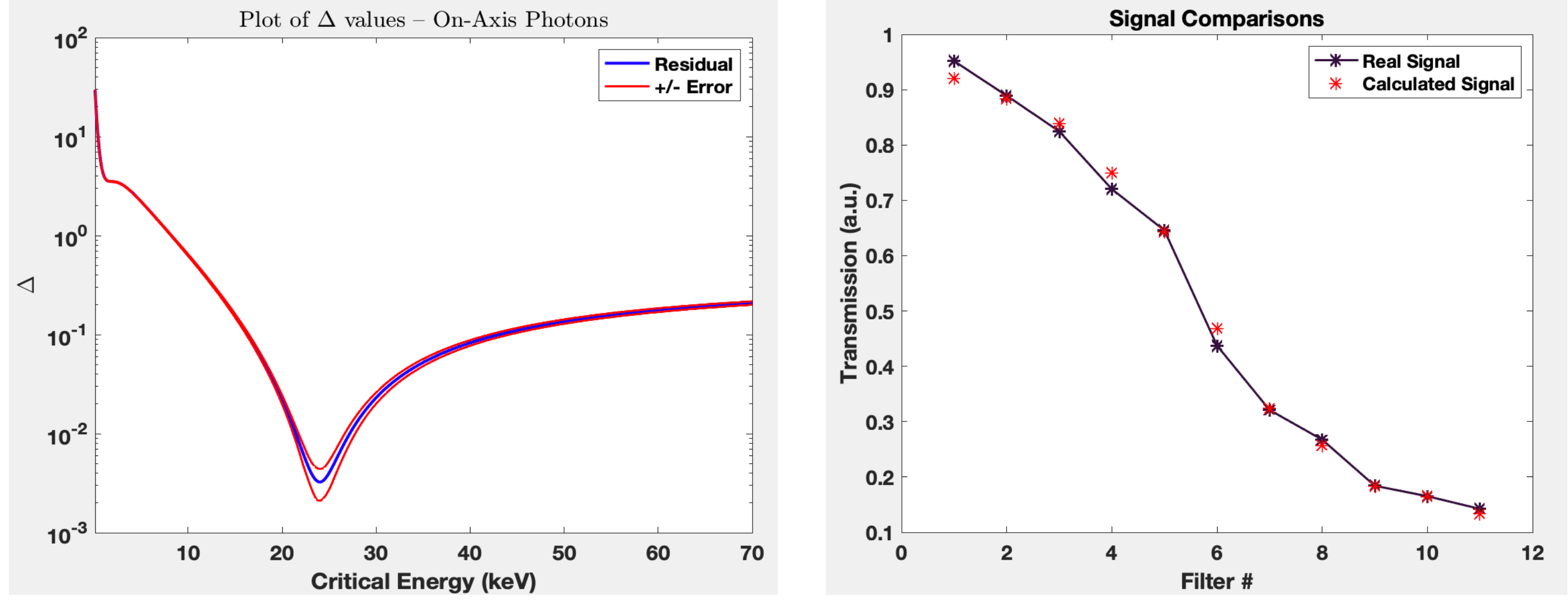

Figure 7: (Left) Plot of residuals versus guessed critical energy. (Right) Calculated filter signals for the best guess for the critical energy (red) compared with the real signal (black).

After the critical energy has been found for each column, they can be plotted here to better illustrate the changing energy across the screen. This understanding of the changing critical energy should give us insight into the electron dynamics during their propagation through the plasma.

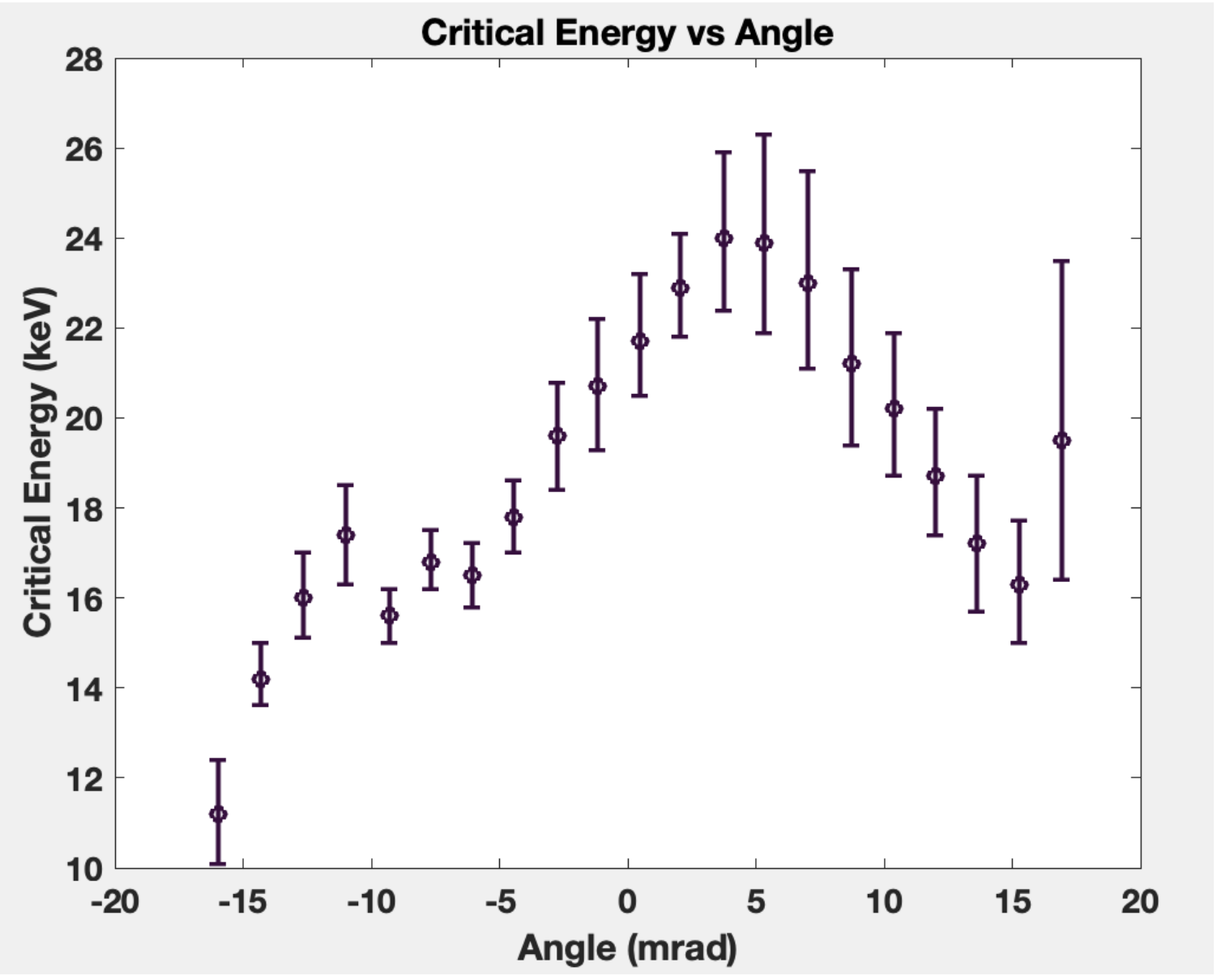

Figure 8: Critical energy versus angle showing the change in energy as the X-rays streak across the camera.

Acknowledgements

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References

[1] Ma, Y. *et. al.*, Phys. Plasmas **25**, 113105 (2018). [2] NIST. *Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients from 1 keV to 20 MeV for Elements Z = 1 to 92 and 48 Additional Substances of Dosimetric Interest.* [3] Wood, J. Doctoral dissertation, Imperial College London, pp. 96-101. (2016). [4] Jackson, J.D., *Classical Electrodynamics*, 3rd ed. (Willy, New York, 2001).