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Higher order and penumbral blurring correction methodology for Opacity spectrometer used on the NIF

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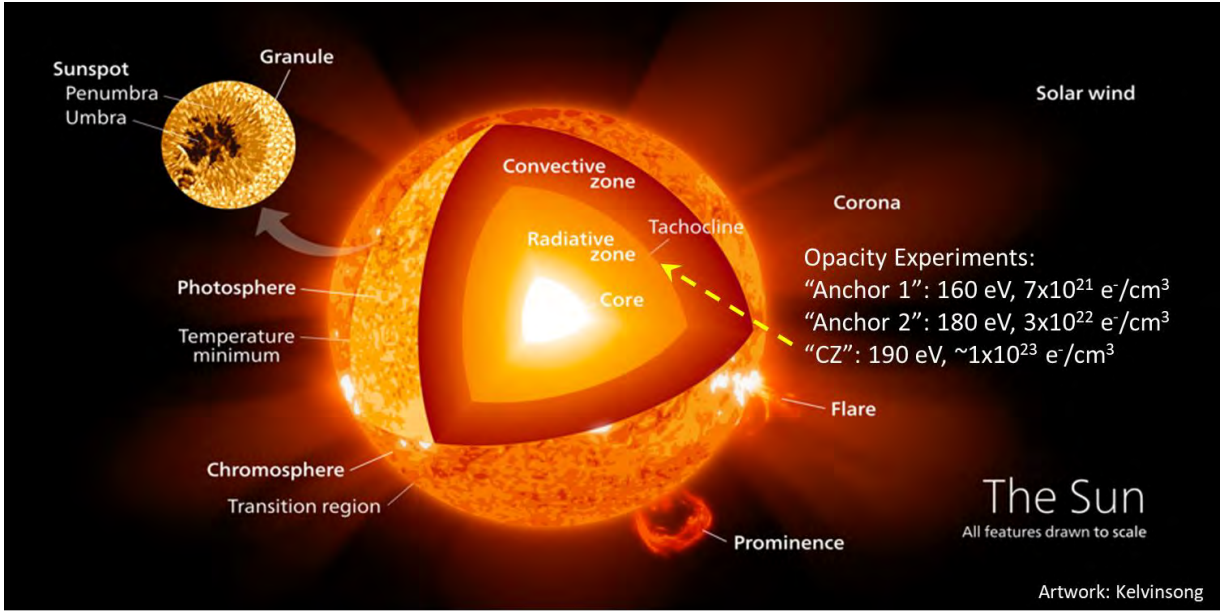
Introduction

- Opacity experiments are useful to probe solar interior conditions
  - Agree well (anchor 1)
  - Show a divergence of measurements and theory as more extreme conditions are met (anchor 2)
  - NIF platform has the capability to vary temperature and densities independently enabling further studies of these conditions



Source: https://en.wikipedia.org/wiki/File:Sun_poster.svg
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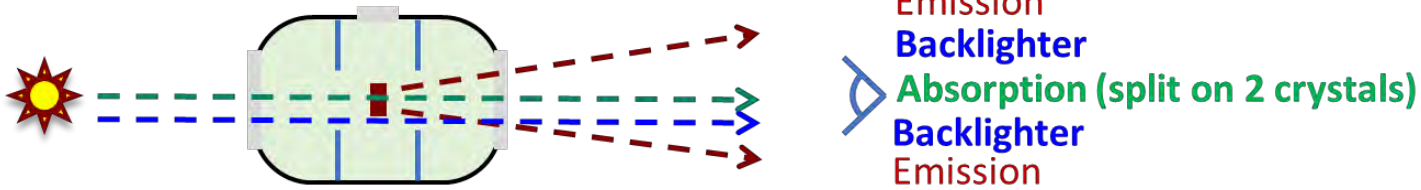
- Other presentations here that focus on the NIF new soft x-ray opacity spectrometer
  - UO03.00003 (T.S. Perry) updates on the NIF opacity platform
  - UO03.00004 (Y. Opachich) density measurements on NIF opacity platform
  - UO03.00005 (M.S. Wallace) Low Energy Design of the NIF Soft X-ray Opacity Spectrometer
  - **UO03.00007 (E. Smith) sample design**
  - **UO03.00008 (K. Gerez) backlighter design**

Opacity data is recorded via point-projection transmission spectroscopy with ~20X magnification

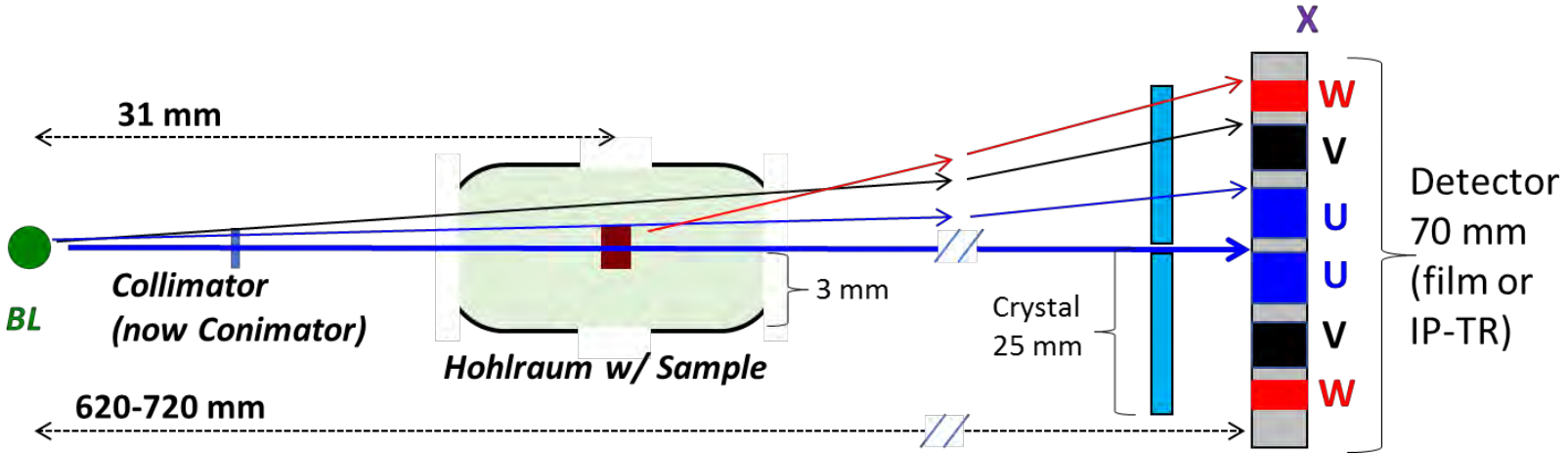
To match the Z data quality and avoid the noise issues seen at Omega, transmission requirements were derived to get transmission measured to ±0.02 achieves opacity to ±10%:

- $T(h\nu) = e^{-(\rho L)\kappa(h\nu)}$
- **T = (absorption – emission) / (backlighter – emission)**
- **Opacity is $\kappa = -\log(T)/\rho L = f(T, \rho L)$**
  - … so uncertainty $(dk/k)^2 = (dT / (T \log T))^2 + (d(\rho L) / \rho L)^2$
  - ***Remember: we don't know the true value, so this is uncertainty not error***
- ***Opacity, $\kappa(h\nu)$, is accurate to ±10% if both log(T) and ρL are accurate to ±7%***
  - Sample is expanding in 1-D, so ρL during measurement is same as initial ρL
  - **Measurement of sample ρL to ±7% requires precise target characterization.**
- **log(T) is accurate to 7% if T is between 0.2 and 0.6 and T is accurate to ±0.02**



R.F. Heeter *et al., J. Plasma Phys.* (2017). Thanks to M. Schneider, N. Krasheninnikova

Opacity data is recorded via point-projection transmission spectroscopy with ~20X magnification



- **Umbra (region "U"):** Backlighter transmitted through sample + Sample self-emission + background
- **Backlighter View (region "V"):** Unattenuated backlighter + Sample self-emission + background
- **Sample Self-Emission (region "W"):** Self-emission "W" + scattered background
- **Scattered background (recorded "off the crystal" as region "X" – formerly "G")**
- **Transmission:** $T = (U-W) / (V-W)$

The two crystals should ideally record identical transmission data, but asymmetries occur due to imperfect backlighter-collimator alignment.

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R.F. Heeter *et al.*, *Journal of Plasma Physics* **83**, 595830103 (2017)

Extracting the first order correction from the IP data

Starting with Eq. 1 from Marrs 2014

$$I = \sum_n kS_nT_nR_n \frac{dE_n}{d\Theta}\frac{d\Omega}{dA}MPF_n$$

The MPF term (from MCP) is replace with the Image plate term which is proportional to the energy term ~nE_1 and will get folded in to k. $\frac{dE_n}{d\Theta}\frac{d\Omega}{dA}$ is a function of the order and a constant solid angle. From Braggs law $\frac{dE_n}{d\Theta}$ becomes $n\frac{dE_1}{d\Theta}$ which is rolled in to our k constant. Which we will call K'. T_n in the Marrs paper is the filter transmission which we change to F_n. S_n is our source term and R_n is the reflectivity for each order

$$I_n = \sum_n k' S_n F_n R_n n^2$$

We want to extract I_1 but don't know I_2 or I_3.

$$\frac{I}{I_1} = k' \sum_n \frac{I_n}{I_1} = \frac{S_n}{S_1}\frac{F_n}{F_1}\frac{R_n}{R_1} = Q_n$$

Then $Q_1 = 1$ and

$$I_1 = \frac{I}{(1 + Q_2 + Q_3)}$$

The three components of the Q's

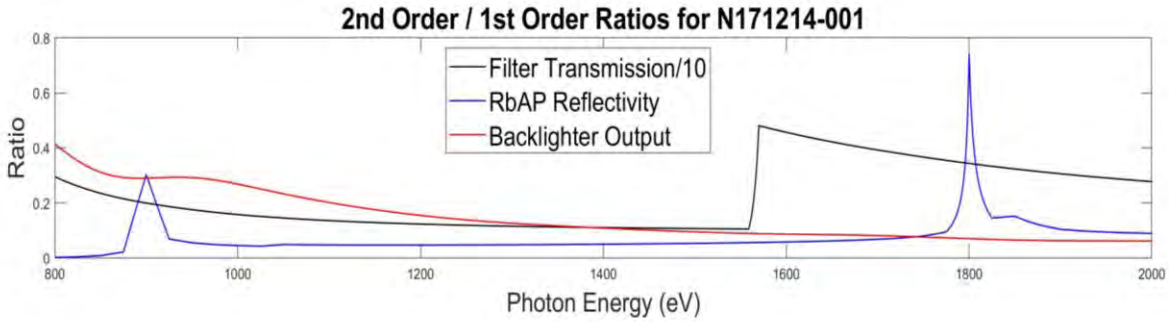
The filter transmission (F_n) were taken from CXRO and based on the nominal thickness supplied by the vender

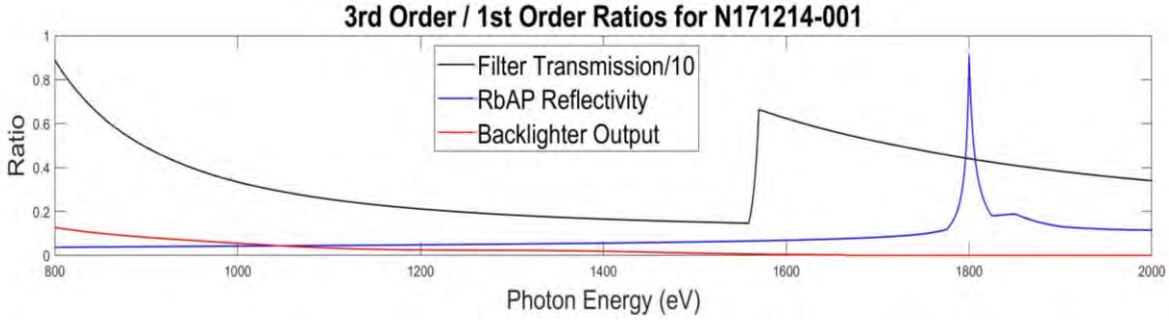
- The total filter transmission is calculated using the OpSpec geometry
- The Black line illustrates the 2nd order over 1st order filter contributions

The Reflectivity (R_n) is calculated using XOP for both KAP and RbAP for 1st, 2nd, and 3rd order

- The 2nd order over 1st order ratio is plotted in blue

Total signal is the product of the 3 contributions





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Sn component of the Q's

In the Absorption region:

The Source **(S_n)** is comprised of the backlighter and the transmission from the sample.

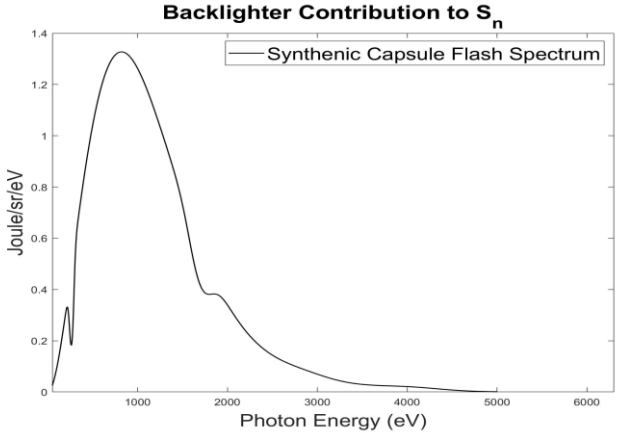
- Here $S_n = S'_n T_n$, where S'_n is the backlighter and T_n is the transmission from the sample

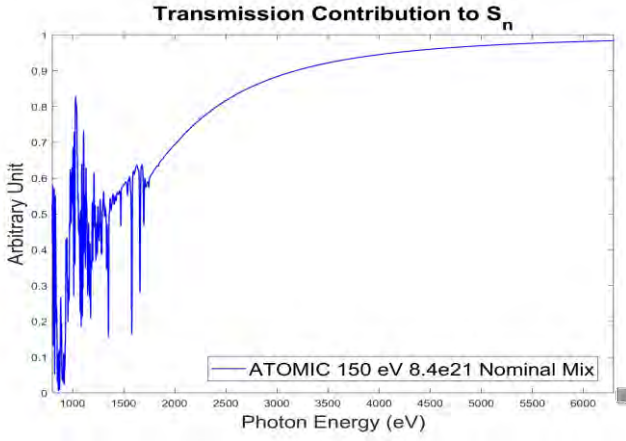
$$Q_n = \frac{S_n}{S_1}\frac{F_n}{F_1}\frac{R_n}{R_1}$$

Becomes

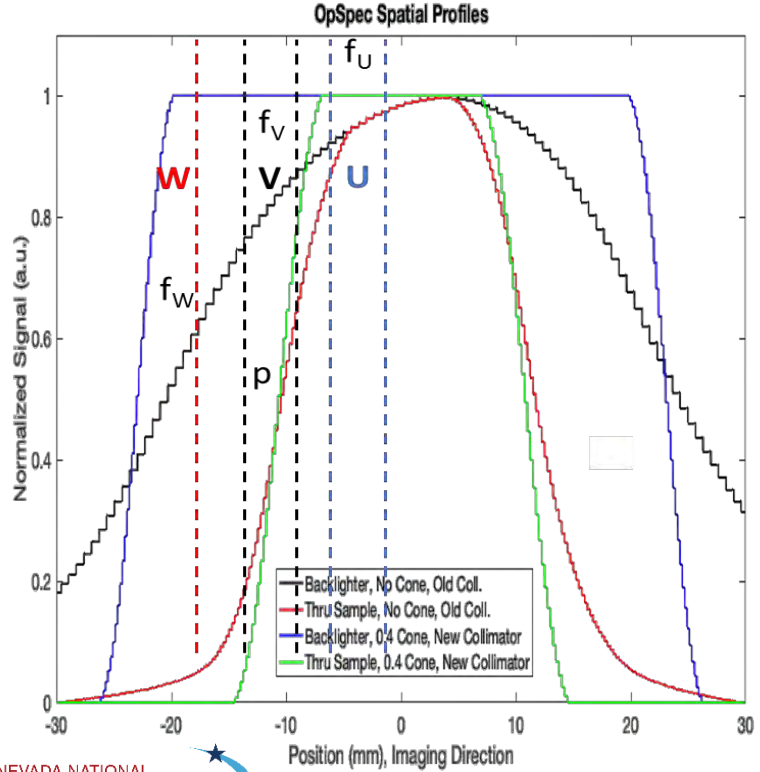
$$Q_n = \frac{S'_n}{S'_1}\frac{T_n}{T_1}\frac{F_n}{F_1}\frac{R_n}{R_1}$$

This must now be folded into the **penumbral blurring correction**





Higher order correction with penumbral blurring



Signals:
Absorption Band: $U = \Sigma_n [T_n f_{Un} B_n + E_n] + X$
Backlighter Band: $V = \Sigma_n [T_n' f_{Vn} B_n + E_n] + X$
Emission Band: $W = \Sigma_n [f_{Wn} B_n + E_n] + X$

$R = (U-W) / (V-W)$
("naïve transmission ratio")

$U-W = \Sigma_n [(T_n f_{Un} - f_{Wn}) B_n]$.
Assume $F_{Un} = F_{U1}$; $F_{Wn} = F_{W1}$ etc.
$B_n/B_1 = (S_n/S_1)*(F_n/F_1)*(R_n/R_1)n^2$
Define $Q_n = (T_n f_{Un}-f_{Wn})B_n/((T_1 f_{U1}-f_{W1})B_1) =$ **$[(T_n f_{Un}-f_w)/(T_1 f_{Un}-f_W)](B_n/B_1)$**.
Then **$(U-W) = (T_1 f_{U1}-f_{W1})*B_1*Q_{sum}$** where $Q_{sum} = \Sigma_n (Q_n)$

$V-W = \Sigma_n [(T'_n f_{Vn} - f_{Wn}) B_n]$.
$Q'_n = [(T_n' f_{Vn}-f_w)/(T_1' f_{Vn}-f_W)](B_n/B_1)$.
$(V-W) = (T_1' f_{V1}-f_{W1})B_1 Q'_{sum}$ where $Q'_{sum} = \Sigma_n (Q'_n)$.

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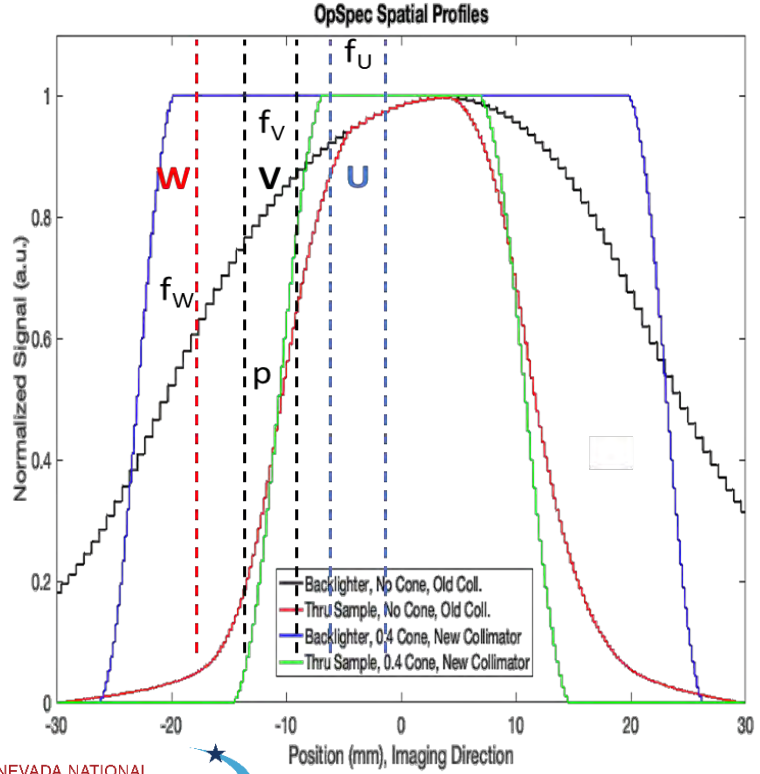
Higher order correction with penumbral blurring



(U-W) = $(T_1 f_{U1} - f_{W1})^* B_1^* Q_{sum}$ and **(V-W) = $(T_1' f_{V1} - f_{W1}) B_1 Q'_{sum}$**

R = (U-W)/(V-W) = $(T_1 f_U - f_W)\, B_1^* (Q_{sum}) / (T_1' f_{V1} - f_{W1}) B_1^* Q'_{sum}$
$R(Q'_{sum}/Q_{sum}) = (T_1 f_U - f_W) / (T_1' f_{V1} - f_{W1})$

Define **$Y = R(Q'_{sum}/Q_{sum})$**, so above equation becomes $Y = (T_1 f_U - f_W) / (T_1' f_{V1} - f_{W1})$
$T_1' = p_1 + T_1 (1-p_1)$. (from prior bob slide)
$Y = (T_1 f_U - f_W) / (f_V(p+T_1(1-p)) - f_{W1})$

Then

$(T_1 f_U - f_W) = Y\,(f_V(p+T_1(1-p)) - f_{W1}) = Y\, f_v p + Y f_v T_1 (1-p) - Y f_w$
$T_1\,(f_u - Y\, f_v (1-p)) = f_w + Y\, f_v\, p - Y\, f_w$

Then our 1st order Transmission (including 2nd & 3rd order correction and penumbral blurring correction) is:

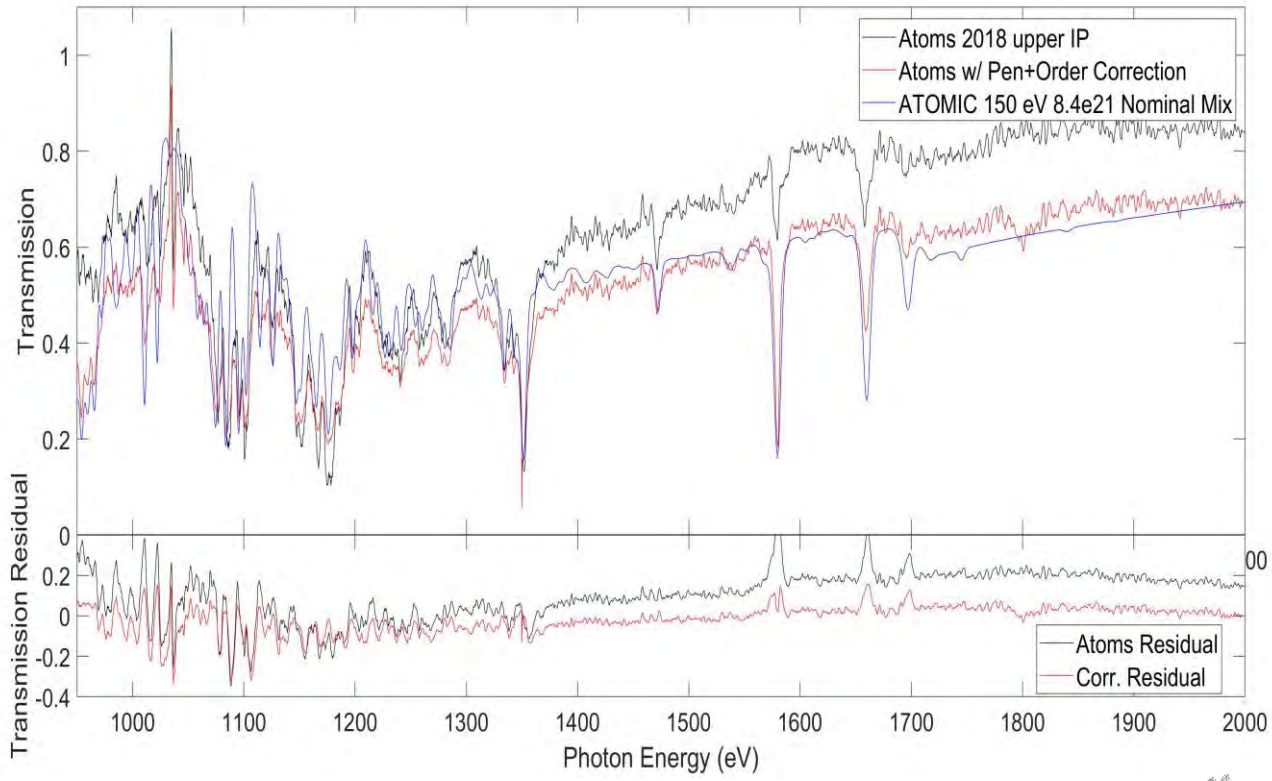
$T_1 = [Y\, f_v\, p + f_w (1-Y)\,] / [\, f_u + Y\, f_v\, (p-1)\,]$

Atoms: 1st order transmission of the upper Image plate

Applying the 1st order correction to the data we get:

- Black data is the published Atoms data using just the naïve transmission ration R=U-W/V-W
- Blue line in the ATOMIC 150eV, 8.4e21 calculation for the nominal mix of the sample
- Red line is the 1st order correction applied with the penumbral blurring correction.
  - Note the higher energy correction.

Low graph is the residual plot



Summary and Future Work

Summary

- 2nd order and 3rd order correction to the transmission data have been analyzed and processed with 2018 ATOMS data and compared with ATOMIC code modeling
  - 4th (or greater) order reflectivity impacts could still be a contributor to the data depending on which crystal (KAP or RbAP) is used.
- Relative measurements of the penumbral blurring folded into correction to the transmission

Future Work

- Exploration on relative impacts for >4th order
- Quantitative analysis of penumbral blurring effects

Questions?

Higher order and penumbral blurring correction methodology for Opacity spectrometer used on the NIF