Opacity Measurements on the National Ignition Facility: Preliminary Results

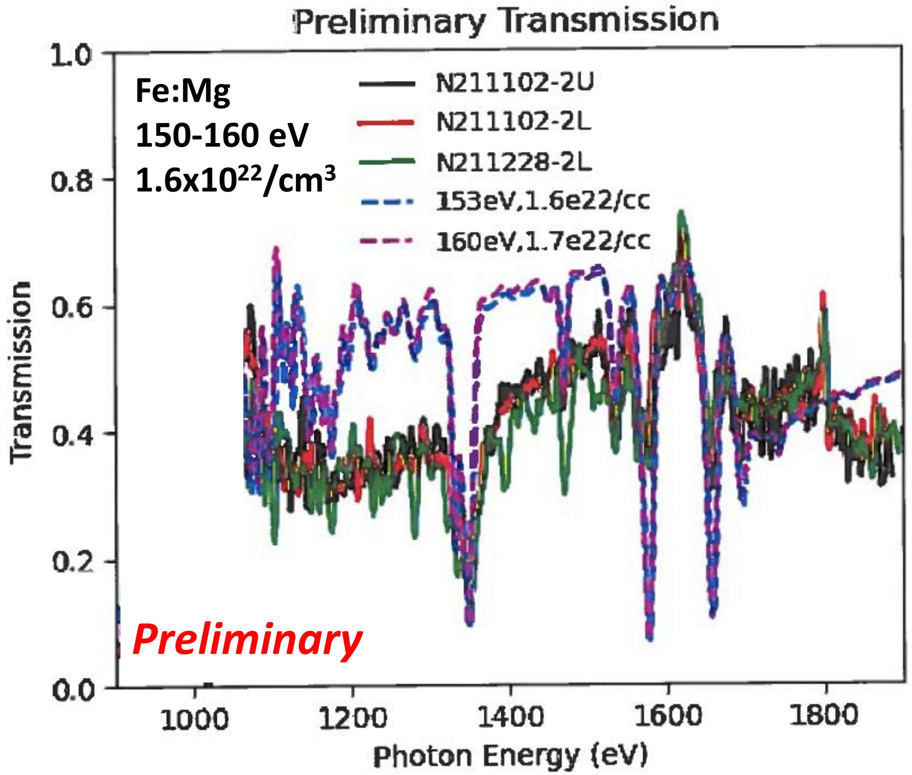
HEDS Seminar, August 16, 2022

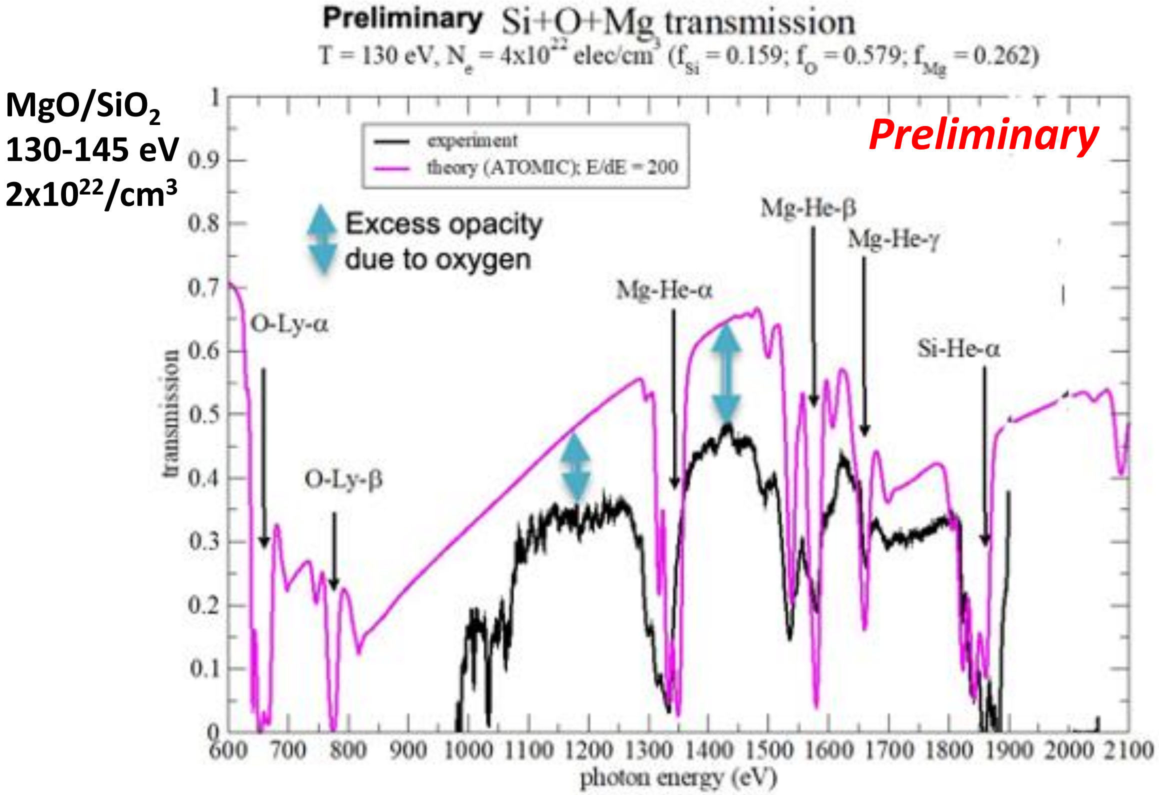
Presented by Bob Heeter, LLNL, on behalf of the Opacity-on-NIF campaign

Abstract: Opacity in a plasma is the material property characterizing X-ray absorption, a key coupling parameter between the “rad” and the “hydro” in radiation-hydrodynamic models. Opacity experiments on Z show significant disagreements with theory at temperatures > 160 eV and electron densities > 2x10^22/cm^3 [J.E. Bailey et al, Nature, 2015]. A higher opacity at these conditions would help resolve longstanding issues with the solar convective zone boundary and the ages of white dwarf stars. However, it has proven very difficult to reconcile theory with the Z data. This motivated development of comparable opacity experiments on the National Ignition Facility (NIF). The Opacity-on-NIF Campaign has begun producing data for X-ray energies 1000-2000 eV at temperatures 130-160 eV and electron densities 0.5 to >3x10^22/cm^3. Measurements at higher temperatures are currently precluded by the onset of high backgrounds. Preliminary transmission measurements for iron and oxygen, at conditions overlapping some of the Z measurements, show trends qualitatively similar to the Z data, but are not final. Quantification and correction of a potential systematic error sources is underway, and peer review in this area is invaluable to improving the accuracy. Ongoing work includes development of a time-gated spectrometer, together with target improvements, to reduce backgrounds, improve spectral resolution, and enable measurements at higher temperatures.

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory
under contract DE-AC52-07NA27344 and by Los Alamos National Laboratory under contract 89233218CNA000001.

NIF has recently delivered unexpectedly-low transmission measurements from both Fe:Mg and MgO/SiO_2 plasmas at T~150 eV, n_e~$2x10^{22}/cm^3$





- These preliminary NIF results are qualitatively similar to Z data, and may have significant implications for theory and astrophysics - but they will change pending corrections, and may have unknown errors.
- Before publication, to minimize risk of error, we would be grateful for peer-review comments regarding potential systematic error sources. This supports an FY22 L2 milestone.

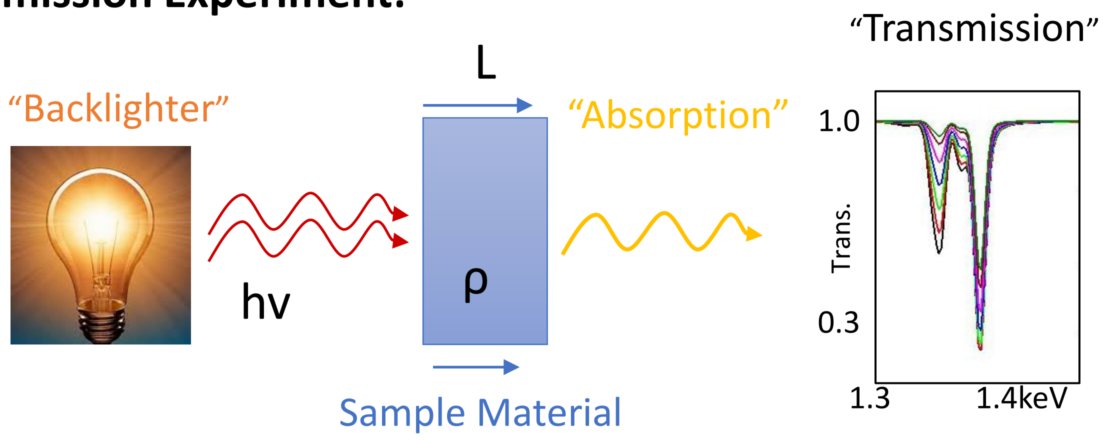
Section Break

Introduction and Motivation

Opacity in HED physics characterizes X-ray absorption (& emission), which couples the “rad” and the “hydro” in radiation-hydrodynamic models

Opacity, | , describes how a material absorbs or transmits electromagnetic radiation (at some frequency v)

Transmission Experiment:



κ = Opacity [cm^2/g]   (attenuation coefficient)
ρ = Density [g/cm^3]
L = Thickness [cm]
$\tau = \kappa\rho L$ = Optical Depth

$$\frac{Absorption}{Backlighter} = Transmission = e^{-\kappa\rho L}$$

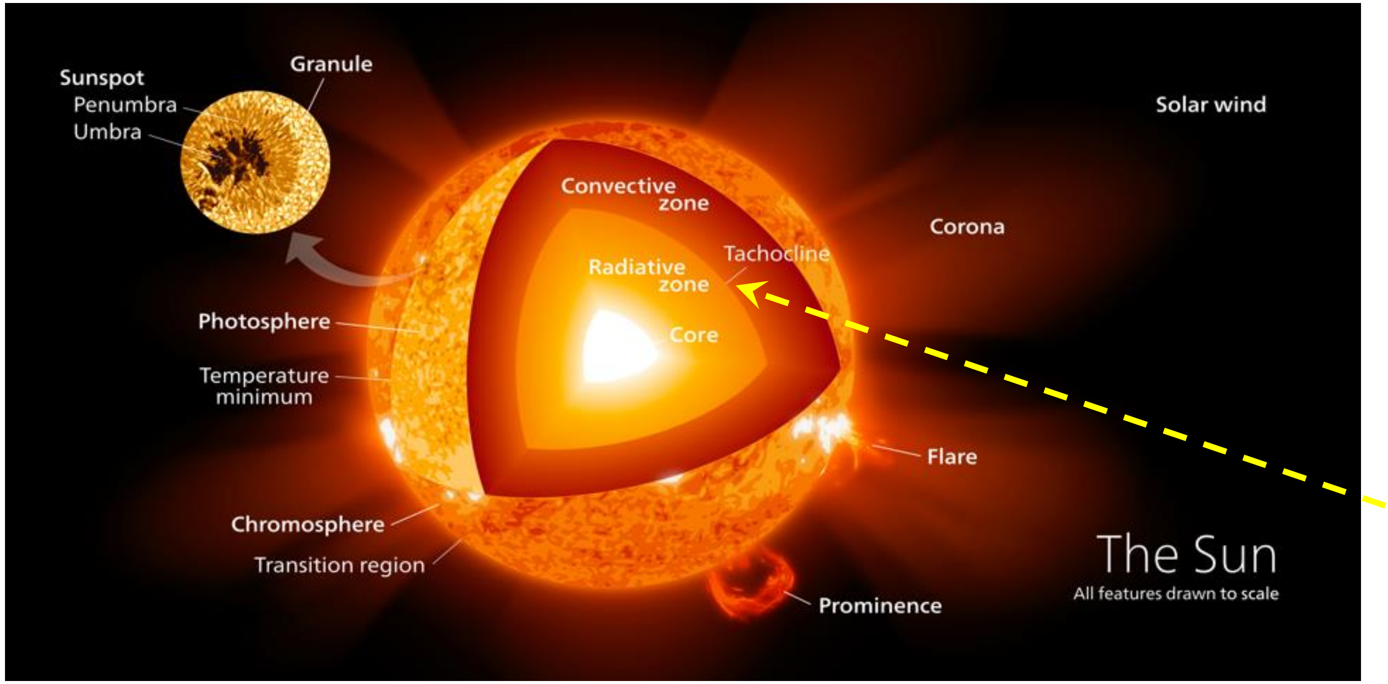
Transmission Experiments measure $\kappa = -\log(T)/\rho L$

Opacity includes bound-bound, bound-free, free-free, and scattering terms.

Bound-Bound “lines” are usually strongest.

Opacity is a function of density, temperature, and frequency
(or wavelength, or photon energy).

Opacities are "suspects" in two astrophysical mysteries. First, the base of the solar convective zone is not where standard models expect.



Source: https://en.wikipedia.org/wiki/File:Sun_poster.svg
Creator: https://commons.wikimedia.org/wiki/User:Kelvinsong

Conditions in Opacity Experiments vs. Sun:

"Anchor 1": 156 eV, 7×10^{21} e^-/cm^3

Anchor 1+: 156eV, 2×10^{22} e^-/cm^3

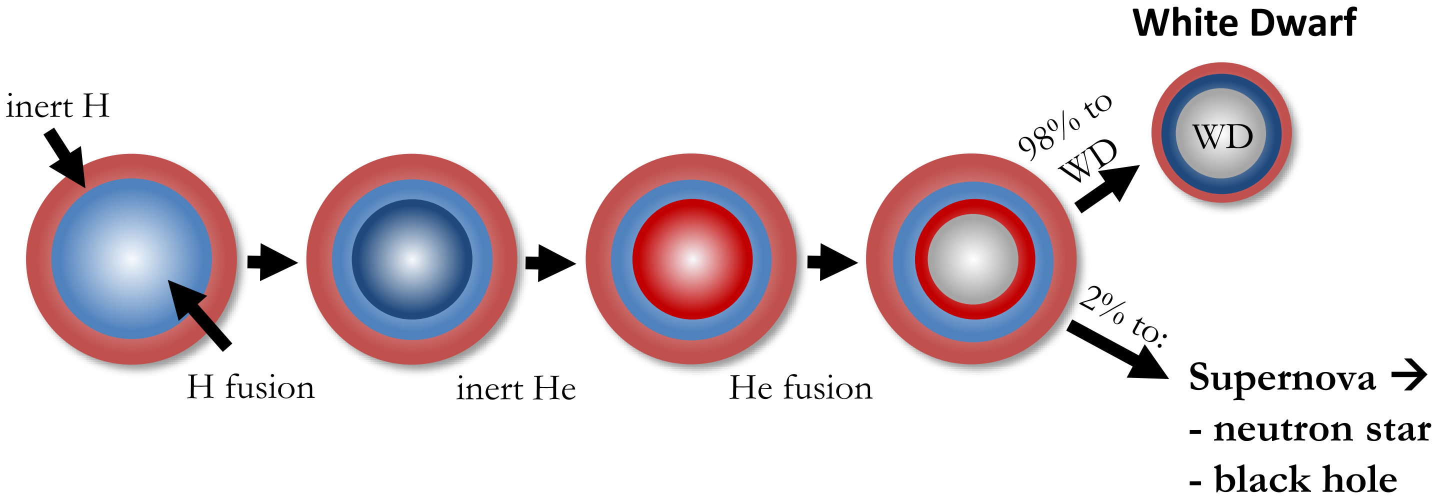
"Anchor 2": 180 eV, 3×10^{22} e^-/cm^3

"Base of CZ": 190 eV, ~1×10^{23} e^-/cm^3

- Solar models rely on *calculated* opacities.
- Radiative Zone: Few bound electrons → low opacity → free-streaming photons
- Convective Zone: Cooler at higher radius → more bound electrons → more opacity → convection

- Helioseismology accurately measures the location of the "CZ boundary", but solar models disagree.
- Doubling the opacity (or abundance) of trace elements including Fe and O would help restore agreement.

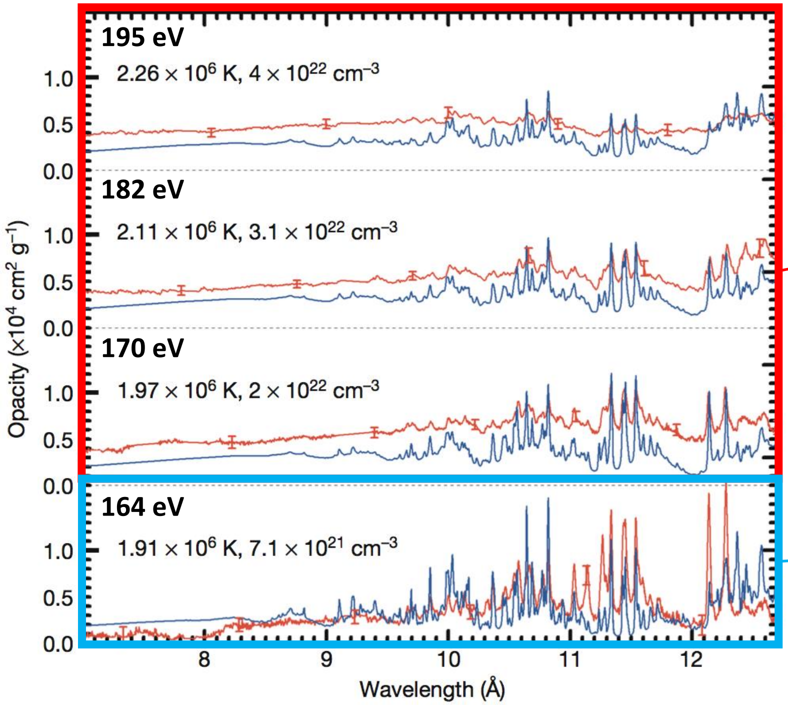
Opacity is also a “suspect” in a second astrophysical mystery: white dwarf stars used to infer the ages of our galaxy and of the universe



- White Dwarf (WD) stage begins when stars run out of fusion fuel. Then they slowly cool down.
- Temperature and rate of cooling give the age of a WD.
- Don Winget et al. (1987) used WD cooling models to derive an age for our galaxy of 10 billion years, much smaller than other methods - many then showed > 20 billion years.
- Age estimates have partly converged, but a gap remains between WD ages and other estimates.
- The rate of cooling depends on the opacity of oxygen & carbon in the envelope of a WD.
- **A higher opacity would imply slower cooling, hence a larger age for a given WD. This would reduce the gap.**

Current NIF experiments are focused on iron and oxygen, where data from Z disagree with theory, with potential impacts on these astrophysical problems.

About 10 years ago, iron opacity measurements on Z began to show deeply puzzling disagreements with calculated theoretical opacities.



Large disagreement with theory at higher T_e, n_e

Good agreement with theory at lower T_e, n_e.

Persistent disagreements include shapes of lines and overall level of opacity.

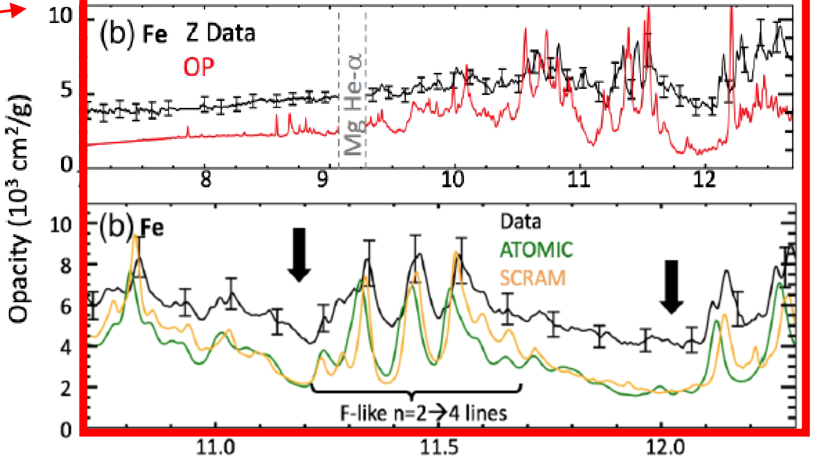
Opacity

Black: Z data

Red: OP

Green: ATOMIC

Orange: SCRAM



T. Nagayama et al, PRL 2019

A higher-than-predicted measurement of iron opacity at solar interior temperatures

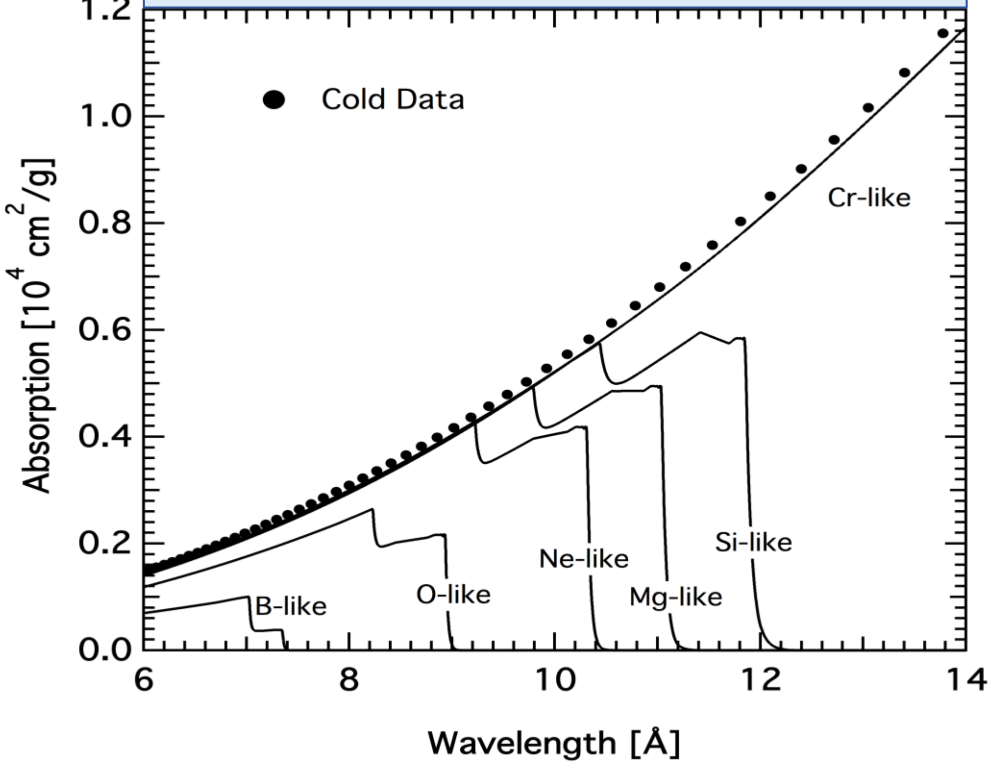
56 | NATURE | VOL 517 | 1 JANUARY 2015

J.E. Bailey, T. Nagayama, G.P. Loisel, G.A. Rochau, C. Blancard, J. Colgan, Ph. Cosse, G. Faussurier, C.J. Fontes, F. Gilleron, I. Golovkin, S.B. Hansen, C.A. Iglesias, D.P. Kilcrease, J.J. MacFarlane, R.C. Mancini, S.N. Nahar, C. Orban, J.-C. Pain, A.K. Pradhan, M. Sherrill, and B.G. Wilson

While data at lower density & temperature agree well with theory, data at more extreme conditions do not.

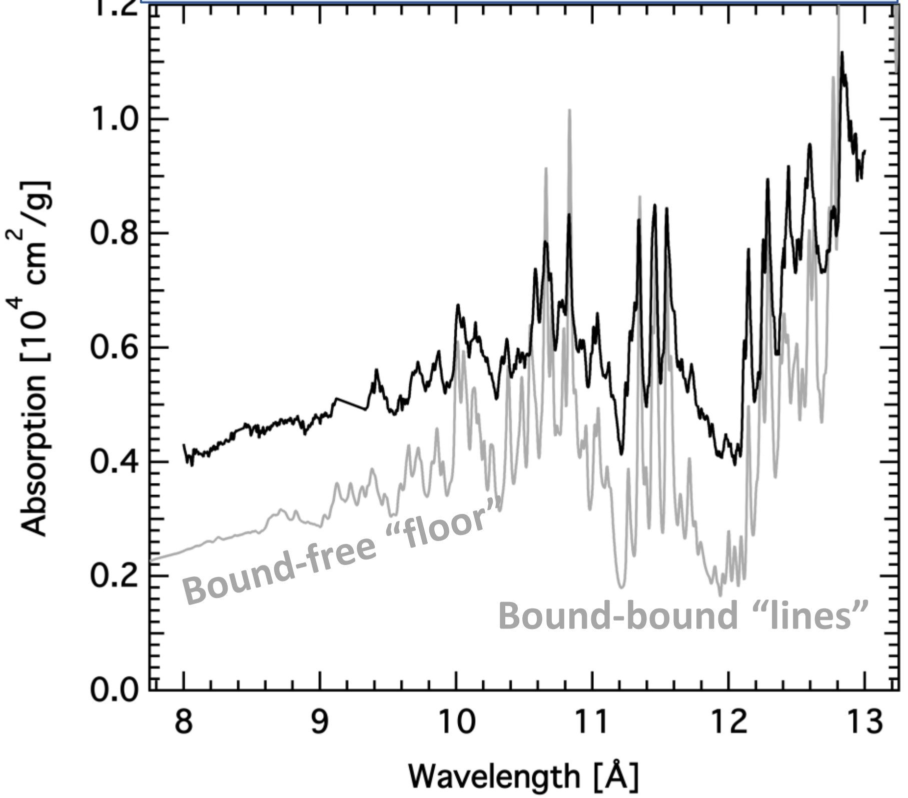
Atomic theory for hot iron cannot explain bound-free opacity higher than for cold iron, yet this is seen at Z

TOPAZ: bound-free absorption from ground states of various Fe ions



As electrons are removed, the absorption edge moves to higher energy, but absorption remains below cold iron

TOPAZ (gray) compared to Z data (black)



In some Z data the bound-free absorption is higher than for cold iron!

The theoretical community has been justifiably reluctant to accept the Z data as accurate.

Following the Z results, the US set up a National Opacity-on-NIF campaign, now a 6-lab collaboration, to address these discrepancies. Our Team:

LANL

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B.G. DeVolder
K.A. Flippo
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T.J. Urbatsch
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J. Nilsen
M.B. Schneider
N.B. Thompson
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R. Zhang
J.P. Knauer
Y. Yang

SNL

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G.A. Rochau
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GA

H. Huang
K. Sequoia
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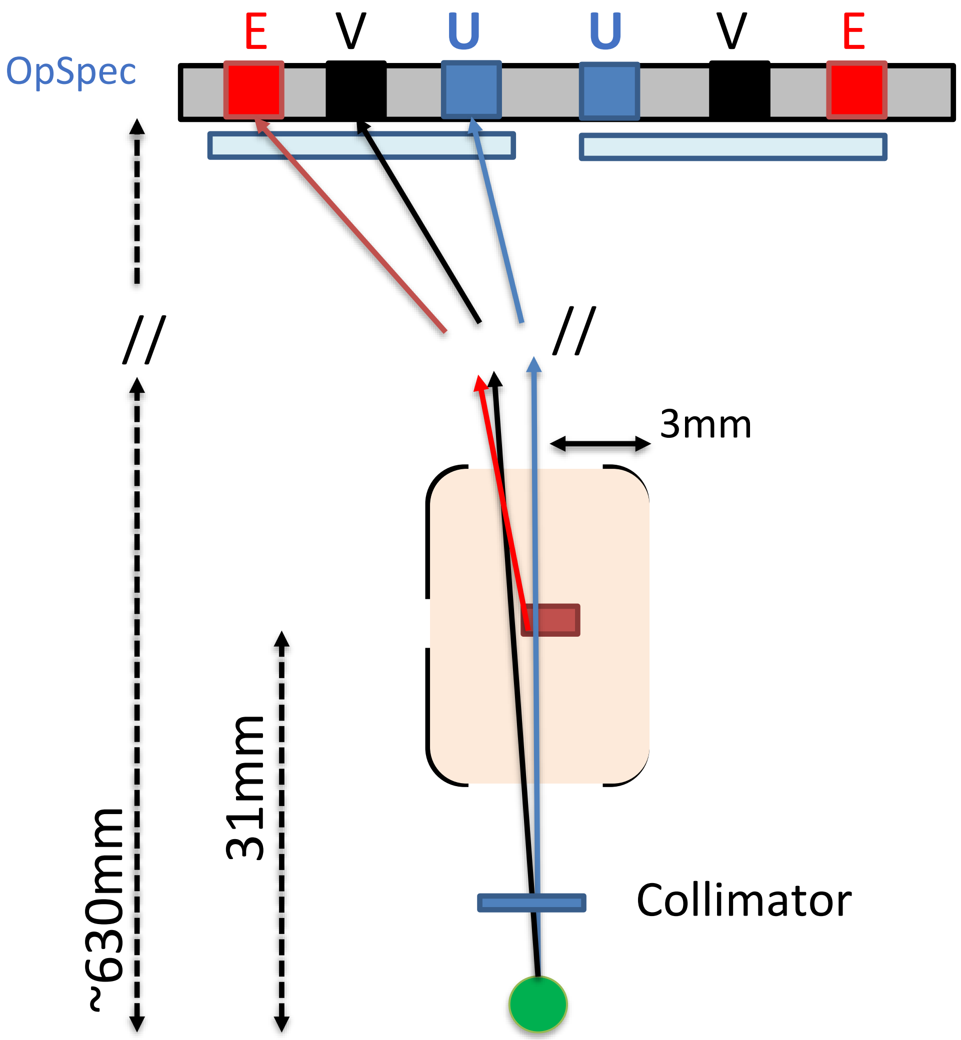
UT Austin

D.E. Winget
M.H. Montgomery
D.C. Mayes

If we've missed anyone, our apologies – please let us know.

The Opacity-on-NIF Experimental Platform

Opacity experiments based on point-projection transmission spectroscopy were developed from the late 1980s on Helen, Nova, OMEGA, and now NIF



Umbra (U): Backlighter transmitted through sample + self-emission

Backlighter View (V): Unattenuated Backlighter

Target self-emission (W): Background over whole image

Transmission T = (U – E) / (V – E)

- $T = e^{-\rho L \kappa}$

☐ Opacity $\kappa = -\log(T) / \rho L = f\,(T, \rho \mathbf{L})$

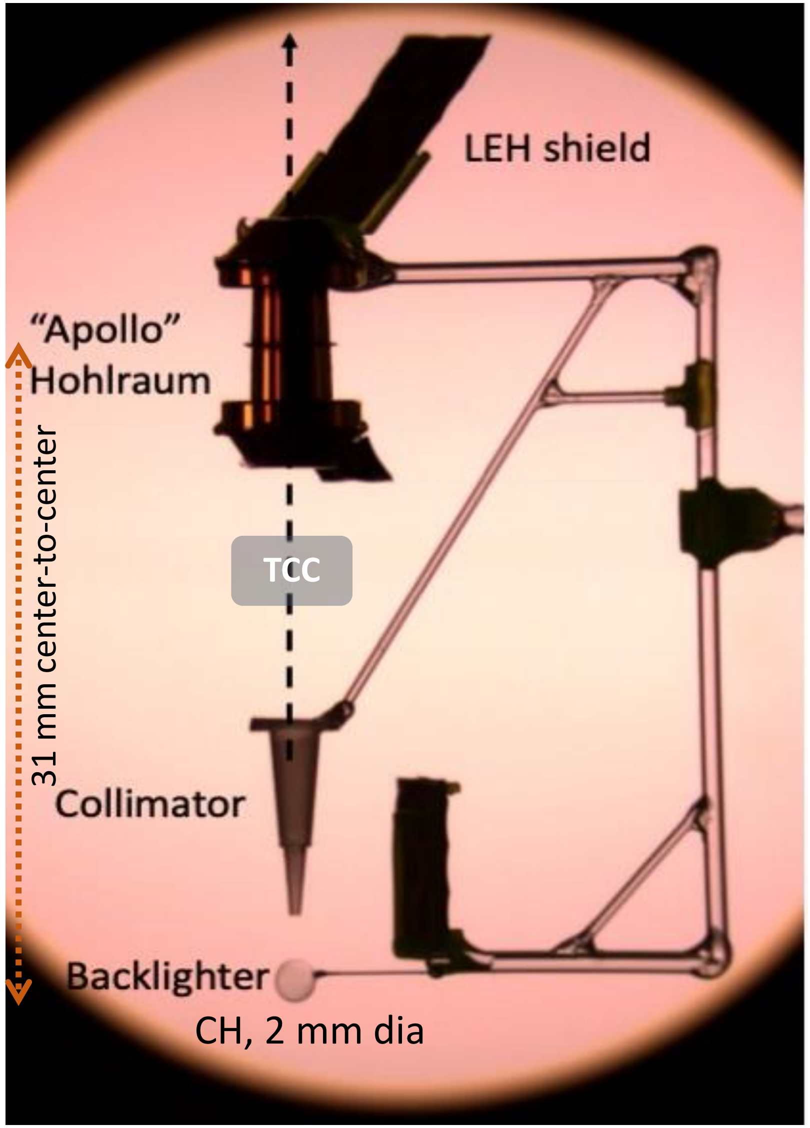
Uncertainty $(d\kappa / \kappa)^2 = (\,dT / (T \log T)\,)^2 + (\,d(\rho L) / \rho L\,)^2$

We don't know the true value, so this is uncertainty not error

- κ accurate to ±10% if both log(T) and ρL accurate to ±7%
- For sample expanding in 1-D, ρL stays same as initial ρL
- **log(T) is accurate to 7% if T is between 0.2 and 0.6 and T is accurate to ±0.02 … this is challenging.**

The NIF opacity target has an Apollo-McFee Hohlraum with shields, a plastic shell backlighter with shield, and a collimator (or “cone-i-mator”)

NIF Opacity Platform

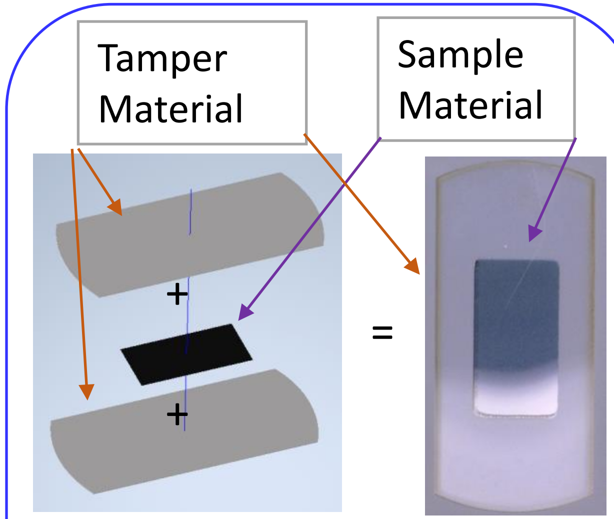


Kudos to Dan Mayes (UT Austin) for this approach to explaining this experiment.

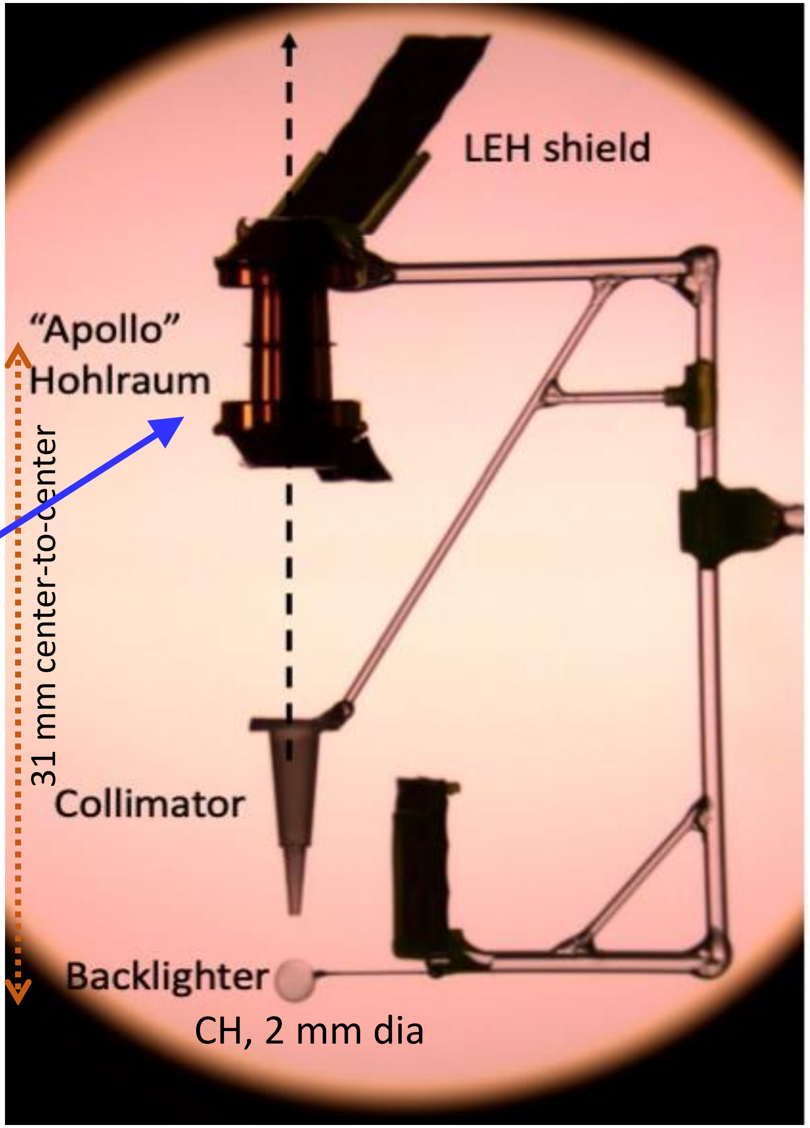
T. Cardenas et al, Fus. Sci. Tech (2018)
T. Day et al., to be submitted

At the hohlraum midplane lies the opacity sample foil, consisting of a 1x2 mm rectangular sample embedded in circular or band-aid shaped plastic tampers.

NIF Opacity Platform



Fe:Mg, Al:Mg, MgO or $MgO+SiO_2$ with CH tamper

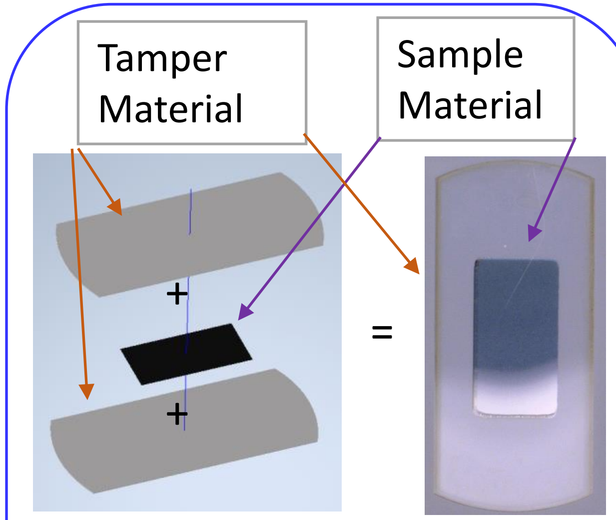


Kudos to Dan Mayes (UT Austin) for this approach to explaining this experiment.

The experiment starts with 1/3 to 1/2 of the NIF beams driving the hohlraum for ~5 ns, with a picket to break up the LEH windows followed by a main pulse

NIF Opacity Platform

Sample heated from both sides within hohlraum

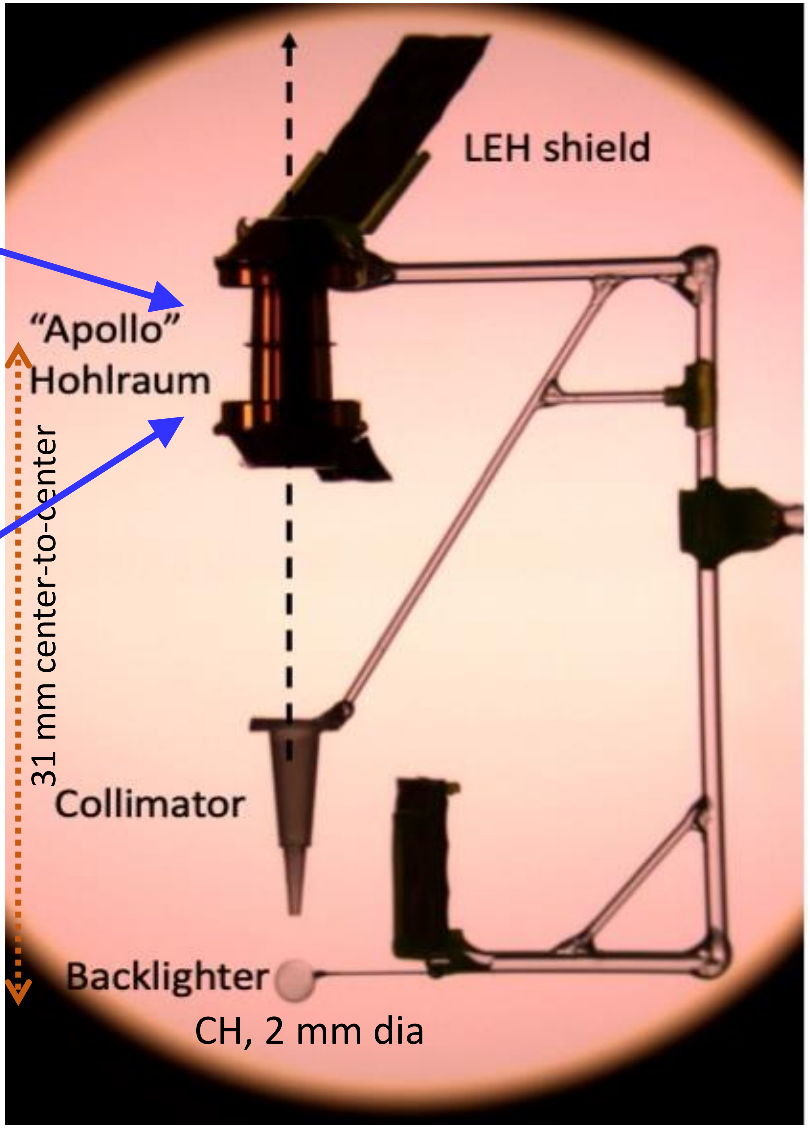


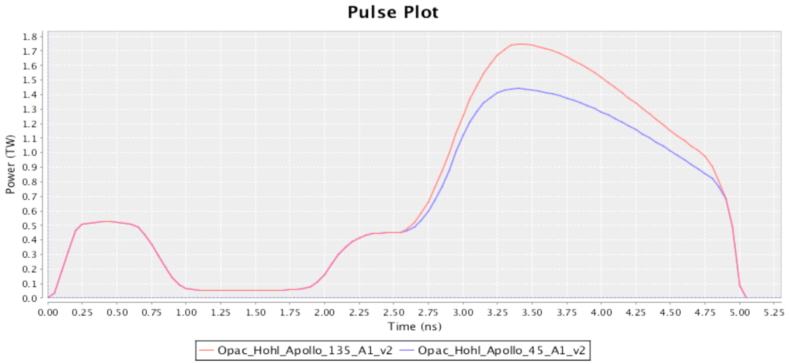
Tamper Material

Sample Material

Fe:Mg, Al:Mg, MgO or MgO+SiO$_2$ with CH tamper

Kudos to Dan Mayes (UT Austin) for this approach to explaining this experiment.





- Hohlraum Drive: 5 ns, including picket, trough and ~3ns main pulse
- Up to 96 beams & up to 380 kJ

E. S. Dodd, et al, POP (2018)

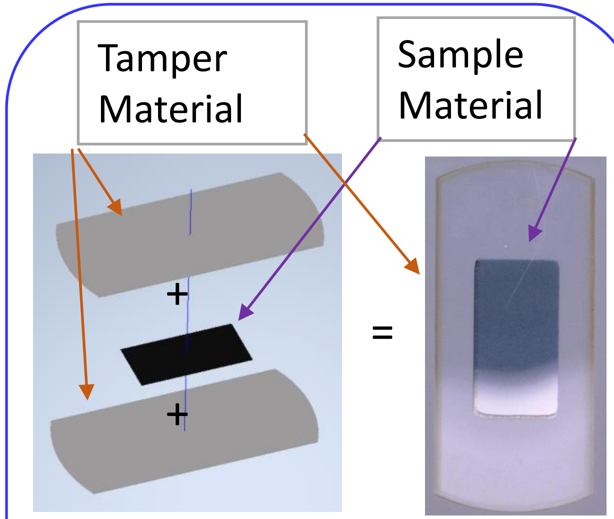
The drive power and duration control the sample temperature and expansion rate for a given tamper thickness.

The droopy main pulse keeps the sample temperature stable within a few eV for ~0.6 ns.

After 1-3 ns, the other 96 NIF beams drive the backlighter shell, resulting in a bright continuum X-ray flash lasting ~0.3 ns, at around 5 ns into the shot.

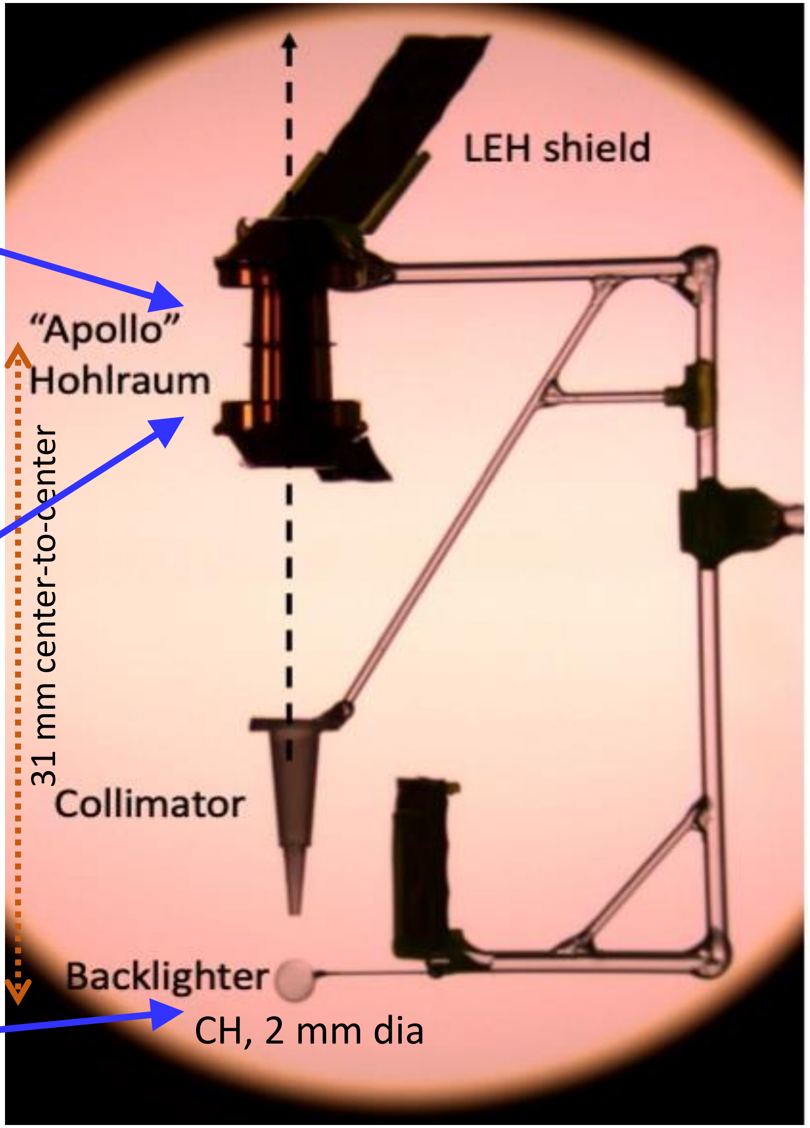
NIF Opacity Platform

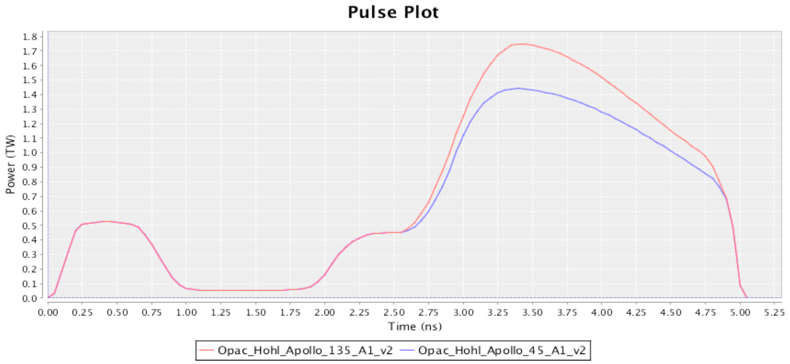
Sample heated from both sides within hohlraum



Fe:Mg, Al:Mg, MgO or $MgO+SiO_2$ with CH tamper

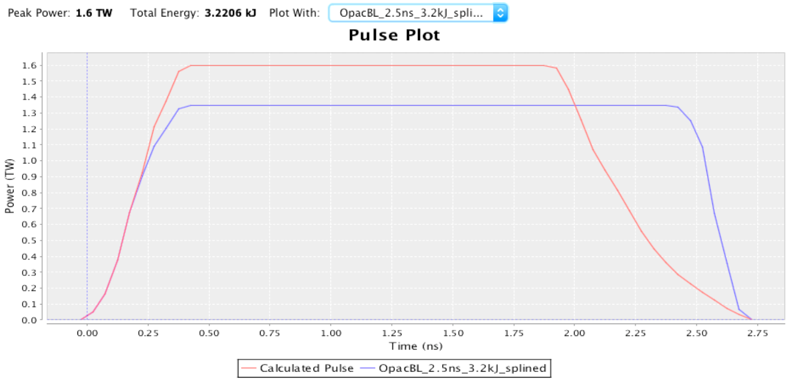
Backlit by capsule





- Hohlraum Drive: 5 ns, including picket, trough and ~3ns main pulse
- Up to 96 beams & up to 380 kJ

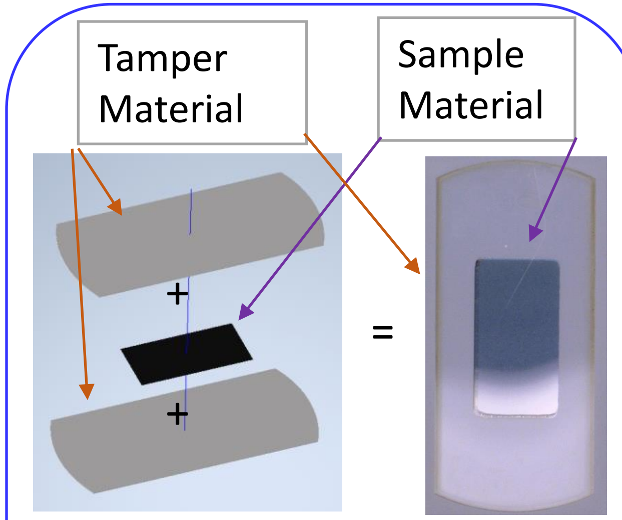
- Backlighter Drive: 2 ns sq. pulse
- Up to 96 beams & up to 340 kJ


Peak Power: **1.6 TW** Total Energy: **3.2206 kJ** Plot With: OpacBL_2.5ns_3.2kJ_spli...

X-rays from the backlighter propagate (point-projection) thru a collimator, thru the hohlraum and up to the Opacity Spectrometer in the Polar DIM.

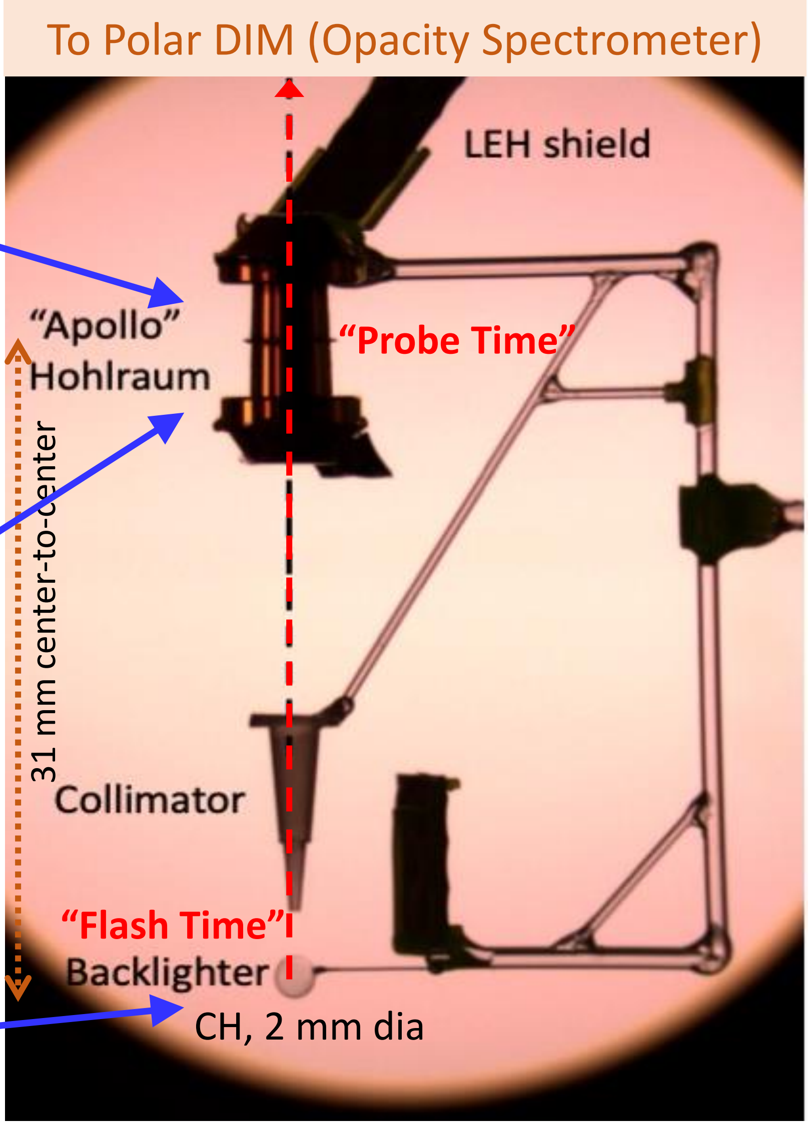
NIF Opacity Platform

Sample heated from both sides within hohlraum



Fe:Mg, Al:Mg, MgO or $MgO+SiO_2$ with CH tamper

Backlit by capsule



Backlighter "Flash Time" is measured using DANTE-1.

Due to time-of-flight effects, "Probe Time" is 0.21 ns after the flash time at DANTE-1.

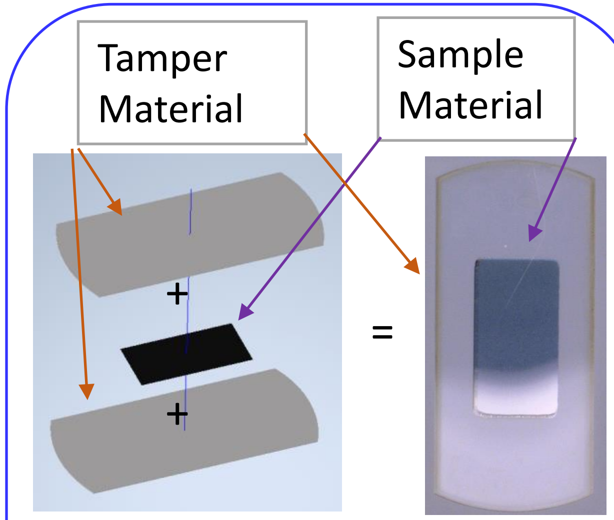
To vary temperature @ probe time:
Raise/lower hohlraum drive power.

To vary density @ probe time:
Adjust tamper thickness, or
Time the backlighter earlier/later.

Distinct regions of backlighter-only and absorption spectra are recorded on image plate… if at least 1 filter in the spectrometer survives.

NIF Opacity Platform

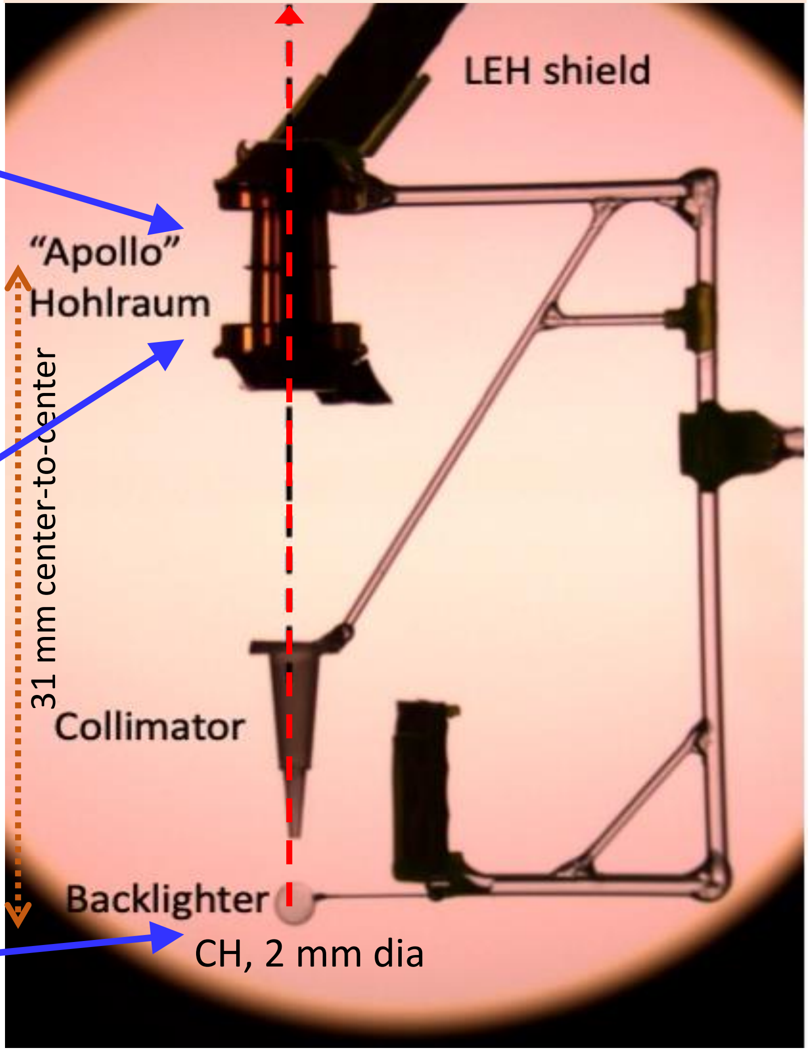
Sample heated from both sides within hohlraum

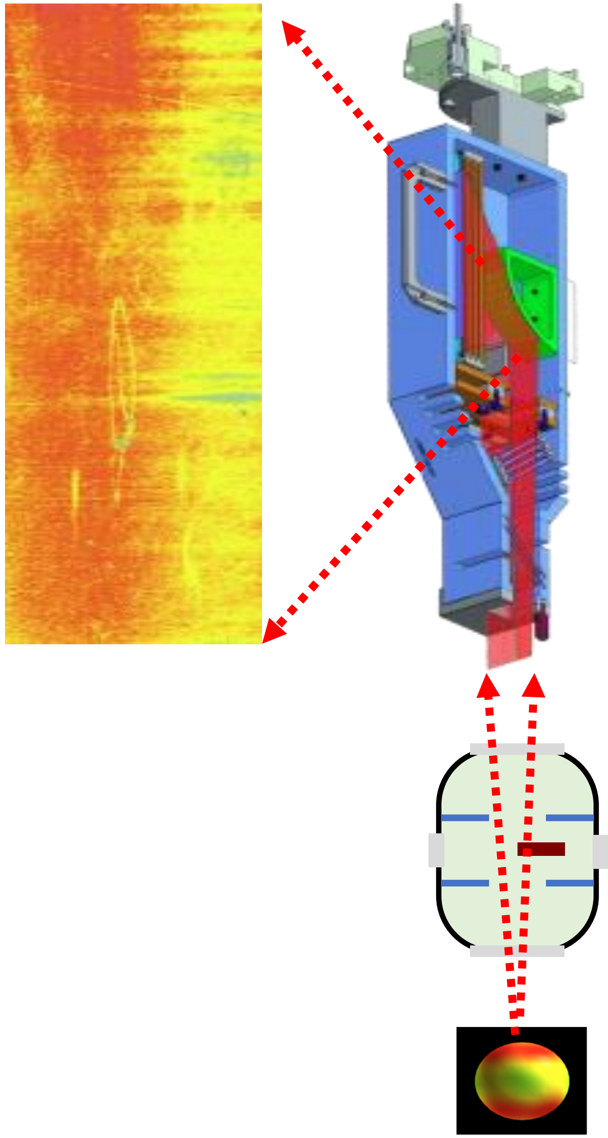


Fe:Mg, Al:Mg, MgO or $MgO+SiO_2$ with CH tamper

Backlit by capsule

To Polar DIM (Opacity Spectrometer)

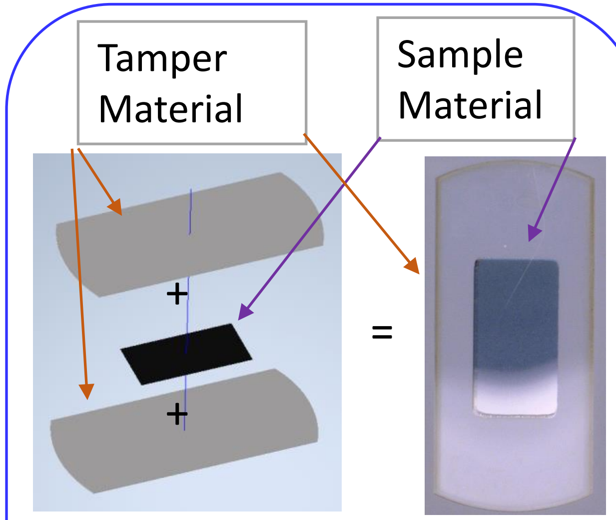




Sample Temperature and Density vs. time are measured independently through a side slot in the hohlraum, by DANTE-2 and a gated pinhole imager.

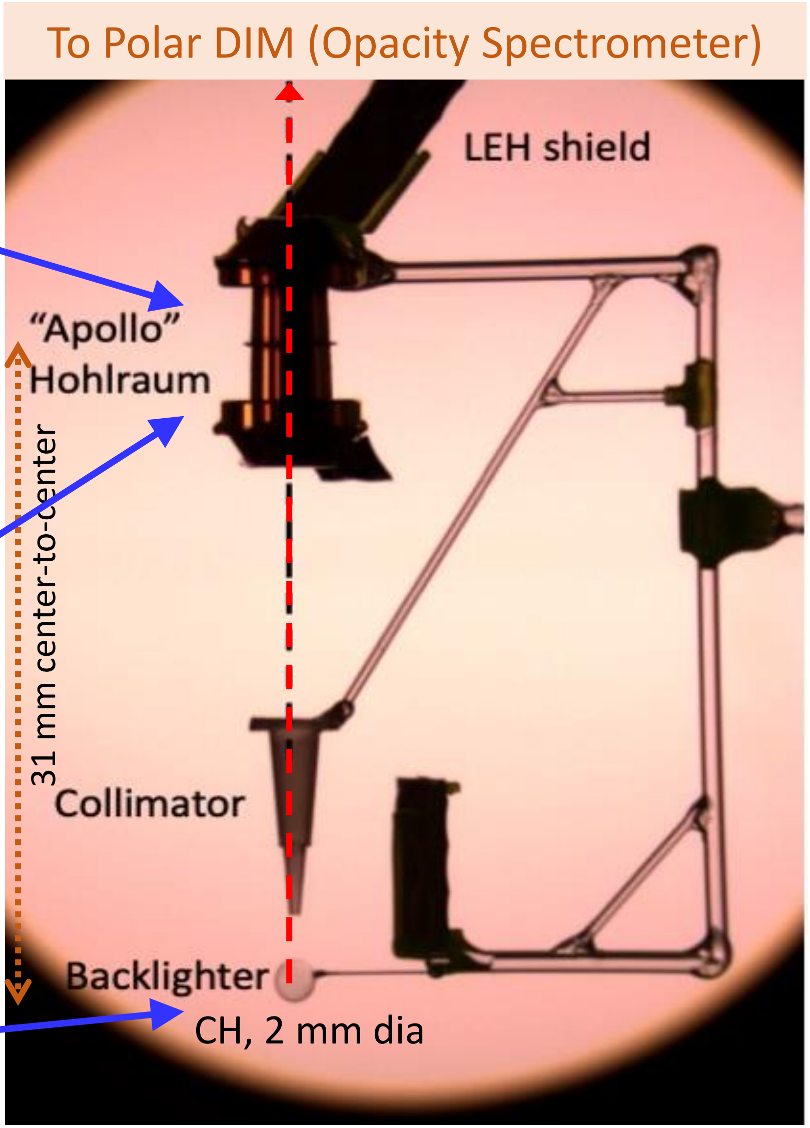
NIF Opacity Platform

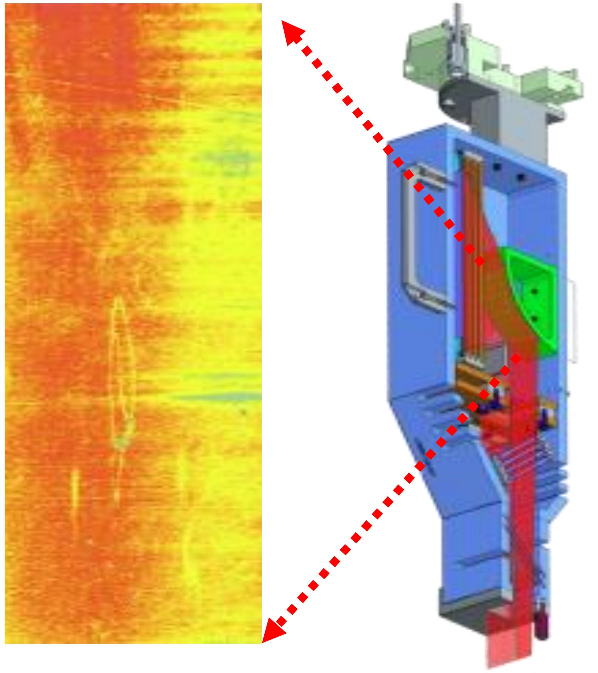
Sample heated from both sides within hohlraum



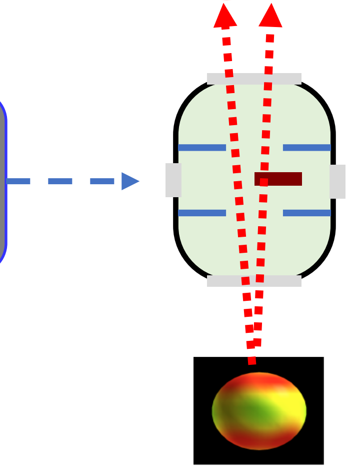
Fe:Mg, Al:Mg, MgO or $MgO+SiO_2$ with CH tamper

Backlit by capsule

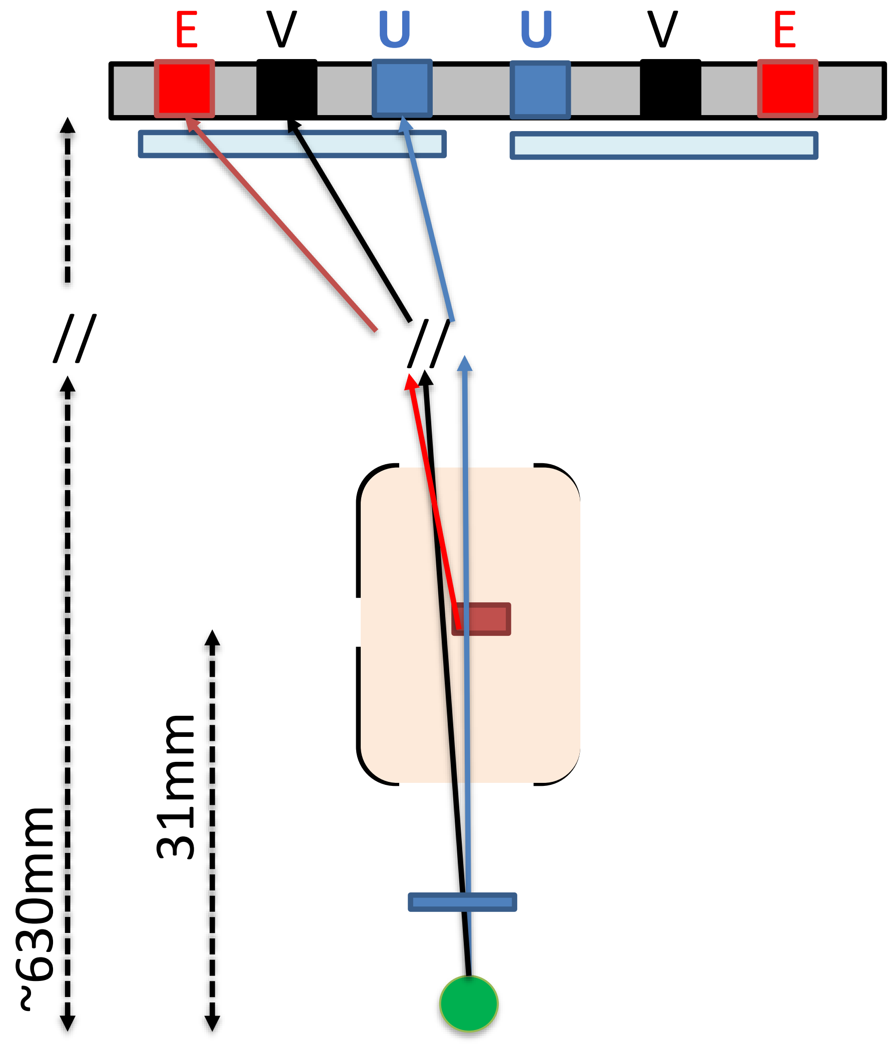




Dante (T_e)
GXD (n_e)



10% uncertainty in Opacity-on-NIF is required to match accuracy of Z experiments, constrain models and resolve astrophysical discrepaancies



R.F. Heeter *et al.*, *J. Plasma Phys.* (2017).

Transmission T = (U – E) / (V – E)

Transmission Experiments measure κ = -log(T)/ρL

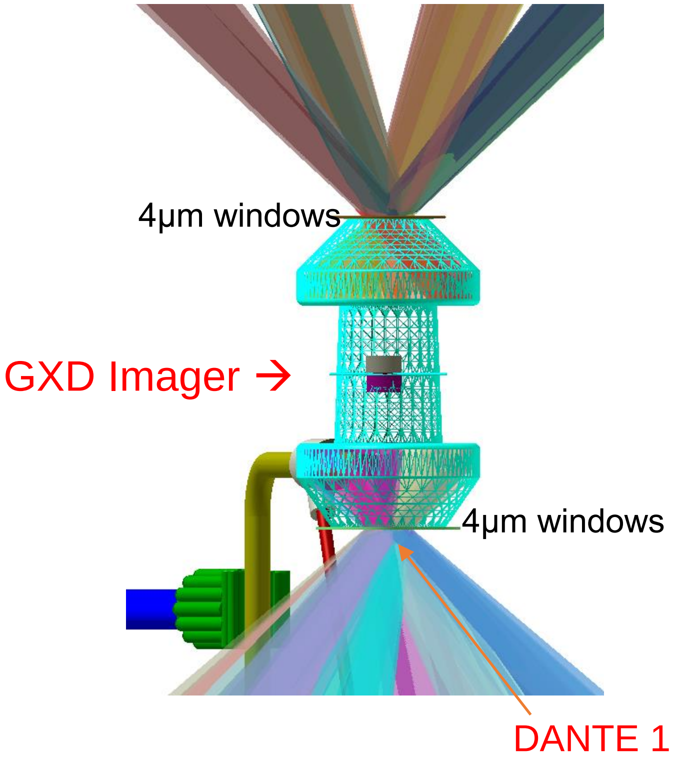
- κ accurate to ±10% if both log(T) and ρL accurate to ±7%

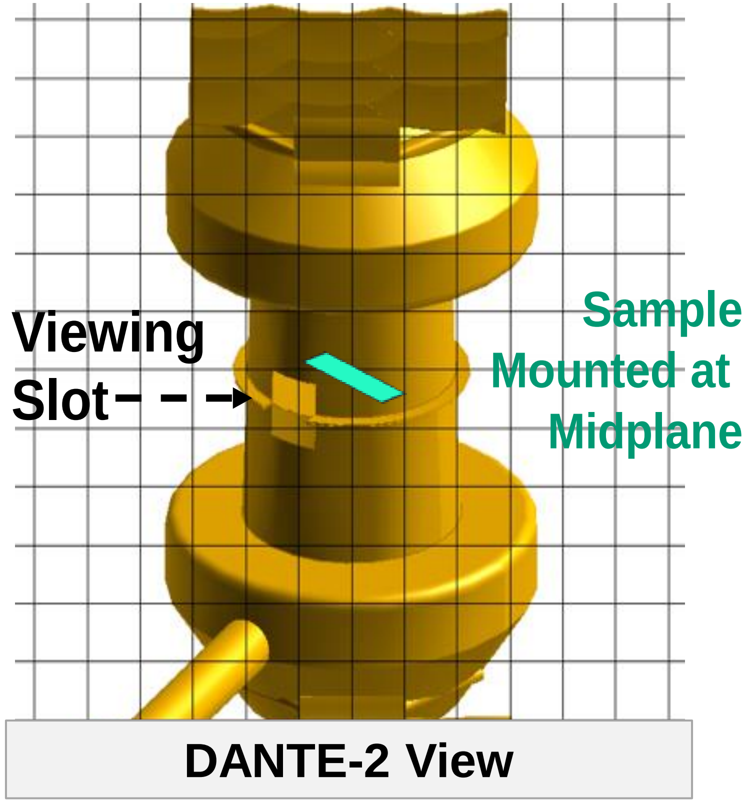
Quantity	Uncertainty Limit	Comments
Transmission	± 0.02 for 0.2 < T < 0.6	T = (U – E) / (V – E)
E, U and V spectral lineouts	± 1%	Photometrics & Scanner Noise; Minimize systematic errors
ρL (ions/cm^2)	± 7%	Minimal radial expansion
$\rho_o L_o$ (ions/cm^2)	± 5%	Pre-Shot metrology
Temperature (eV)	±5%	DANTE-2, K-shell dopants
Electron Density n_e (cm^{-3})	±20%	GXD, K-shell dopants, Timing

The DANTE temperature & GXD density measurements are independent of atomic models… a key strength of the NIF platform.

Opacity-on-NIF hohlraums are designed to heat the opacity sample in LTE, and prevent the spectrometer from viewing walls or blowoff plasma

Apollo-McFee Hohlraum





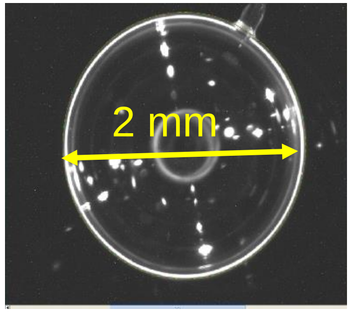
DANTE-2 View

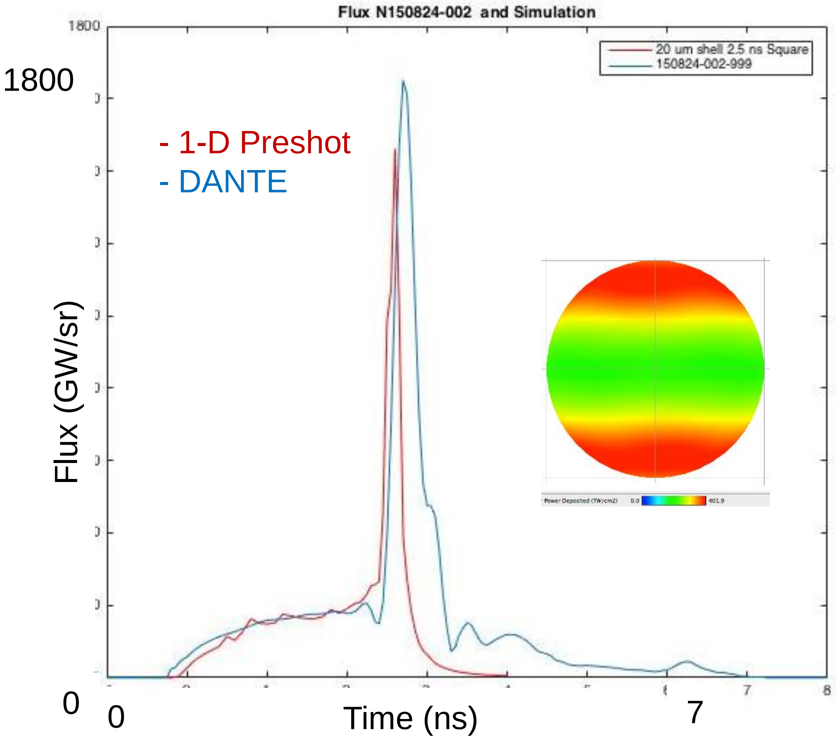
- DANTE-2 sees the central hohlraum wall near the sample.
- 2D LASNEX simulations show sample temperature is uniform and within a few eV of DANTE-2 at probe time.
- Viewing slot closure is negligible for photon energies > 1 keV (GXD), but more data are needed at lower X-ray energies.

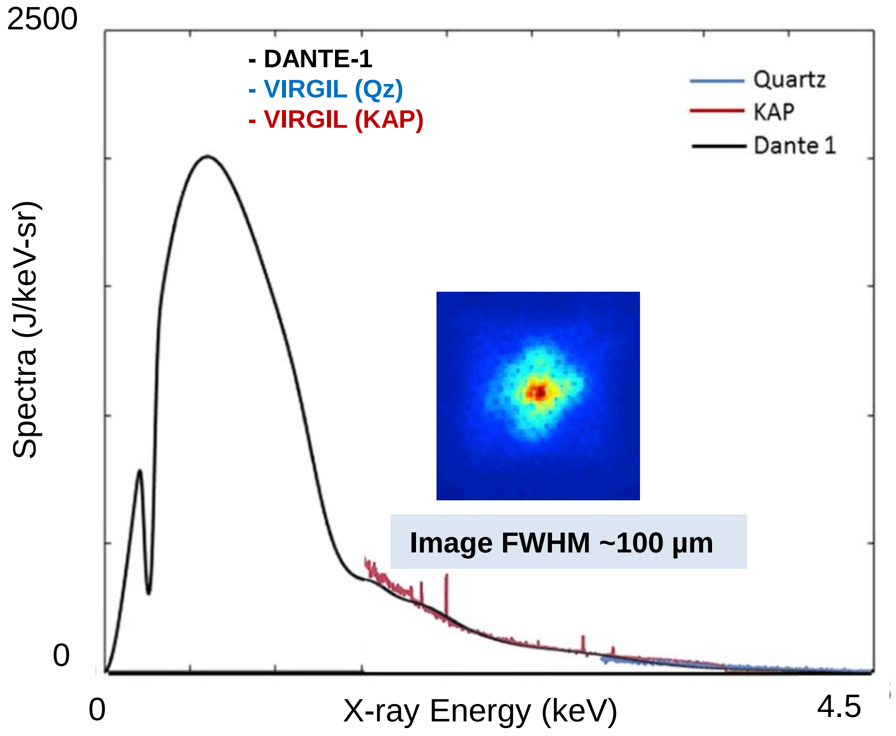
- Lasers aim into ‘pockets’ so sample does not see the laser “hot spots”.
- Hohlraum has 3º conical shape so spectrometer cannot see walls.
- LEH windows (1-4 um CH) block hohlraum blow-off to extend measurement window.

E. S. Dodd, et al, POP (2018)

Backlighter: A 2mm dia., 20μm thick CH shell, directly driven by 1/3 to 1/2 of NIF, creates a bright, 100μm FWHM, continuum X-ray flash peaked around 1 keV for ~300ps







See Y.P. Opachich *et al.*, *Phys. Plasmas* (2017)

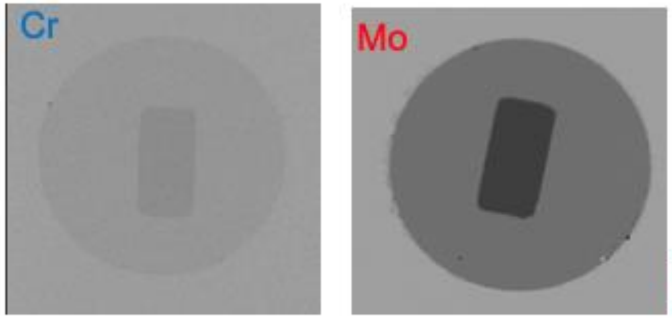
The backlighter provides excellent photometrics and time-resolution, but it has an Achilles heel which it took time to figure out…

Sample Conditions:

Areal Mass Density,
Temperature and
Electron Density

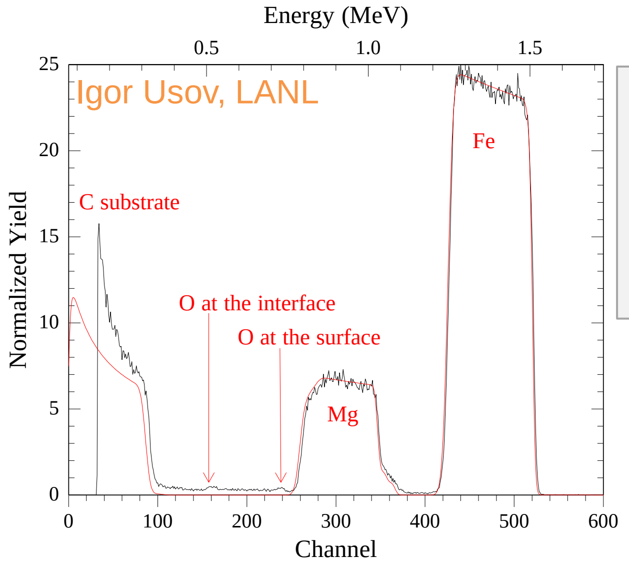
Sample areal density, tamper thickness and quality are measured by LANL and GA systems and evaluated by Heather Johns

Sample uniformity and quality are assessed using LANL's DCS (3-color X-ray radiography) and optical imaging.

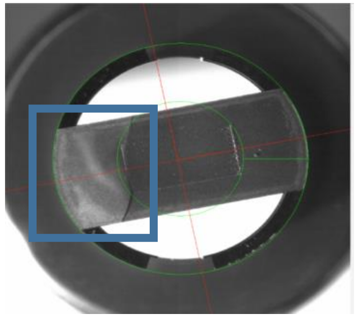


DCS images of a sample using the Cr source (5410eV) and the Mo source (2291eV)

N. Lanier, C. Hamilton, J. M. Taccetti, RSI **83**,10E521(2012)



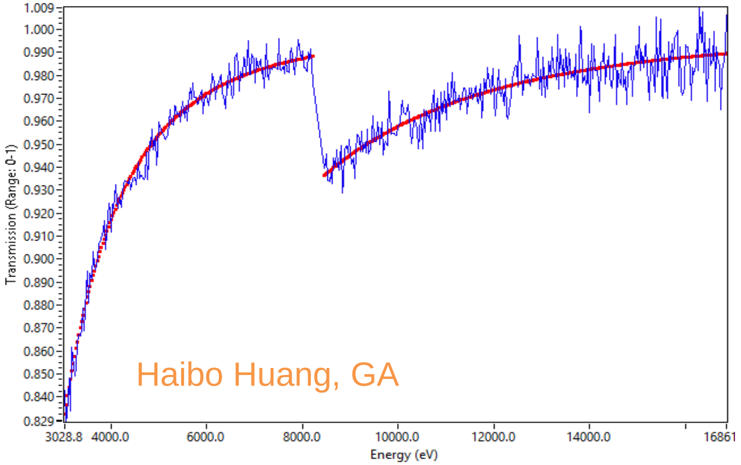
LANL RBS on witness: ρL(7%), composition



Optical imaging helps to reject defective samples

Profilometry of top and bottom coats characterizes tamper thickness (2.5%).

GA AutoEDGE pre-shot cold x-ray transmission: ρL

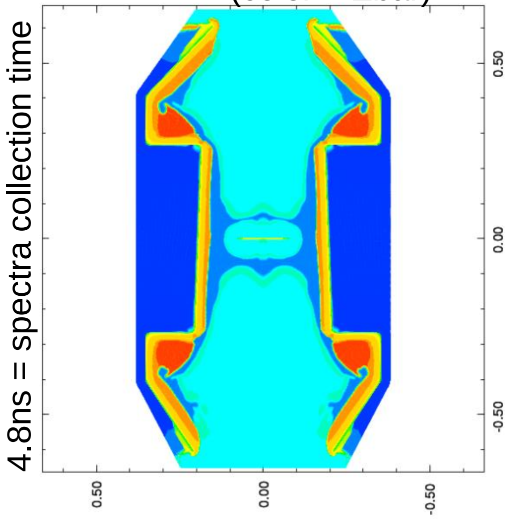


The areal density (ρL) used to infer opacity from transmission is the variance-weighted average of sample measurements.

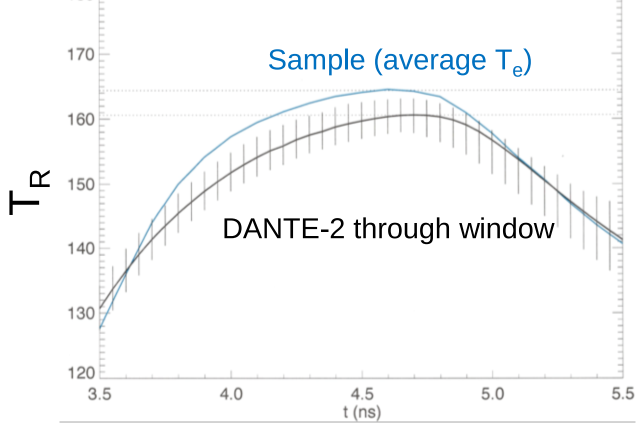
2D Hohlraum and 1D Sample simulations tune each experimental setup, to keep sample stable in position and temperature, and time diagnostics

Design Process for Anchor 1: 156 eV, 7x10^{21}/cm^3

Evan Dodd (color = Zbar)



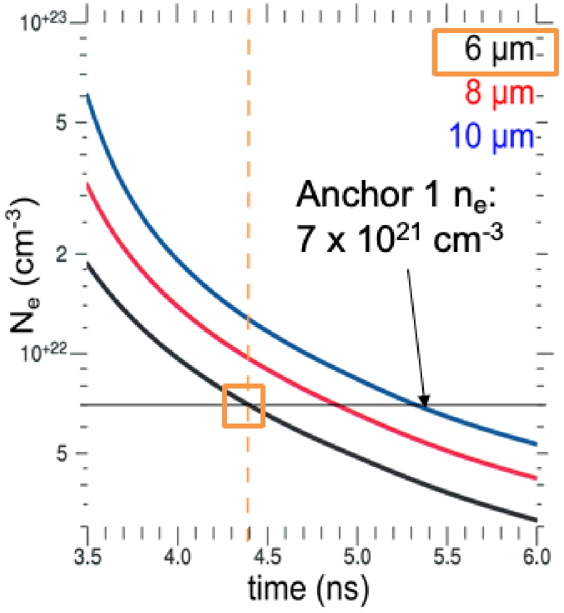
Evan Dodd (LANL)



T_e = 156eV at 4.4ns

This also gives post-shot offset from DANTE-2 to sample temperature.

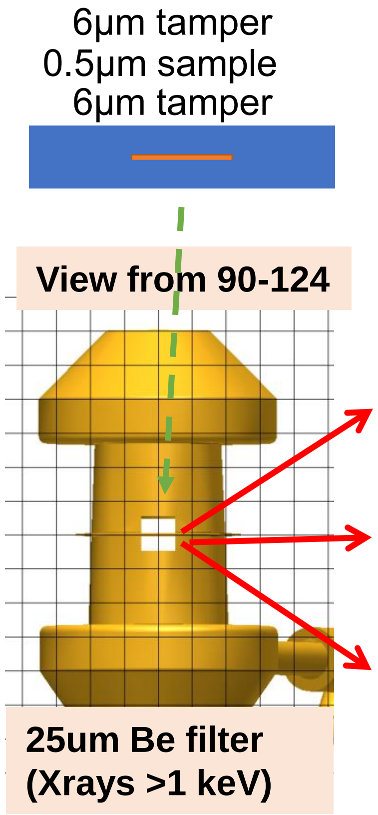
M. Martin (LLNL) →
N. Krasheninnikova (LANL)



Use 6um tamper for A1 density

- Upper vs. Lower laser drives are somewhat asymmetric to keep sample steady in conical hohlraum.
- Hohlraum runs provide sample Temperature-vs-time and feed FDS to 1D sample runs.
- Sample runs guide tamper thickness to reach desired density at the same time as temperature.

Density is measured by edge-on gated imaging of the sample expansion, which appears to be uniform and consistent with pre-shot simulations



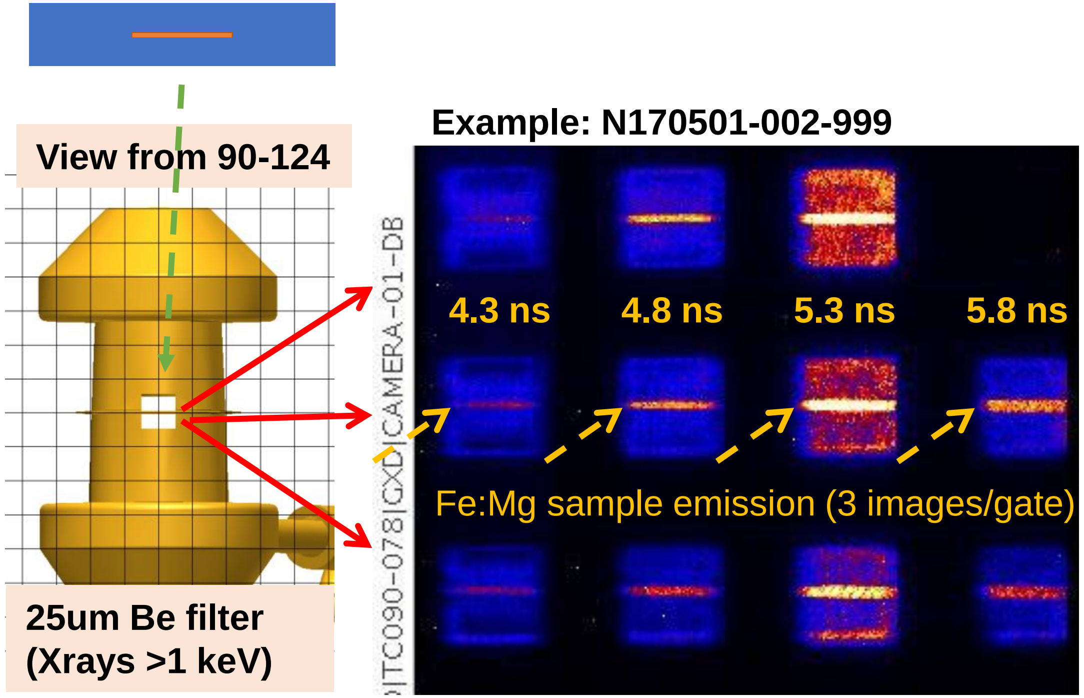
6µm tamper
0.5µm sample
6µm tamper

View from 90-124

25um Be filter (Xrays >1 keV)

Density is measured by edge-on gated imaging of the sample expansion, which appears to be uniform and consistent with pre-shot simulations

6µm tamper
0.5µm sample
6µm tamper



View from 90-124

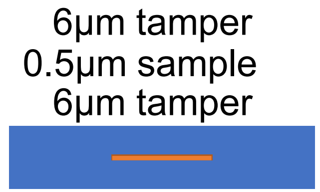
25um Be filter (Xrays >1 keV)

Example: N170501-002-999

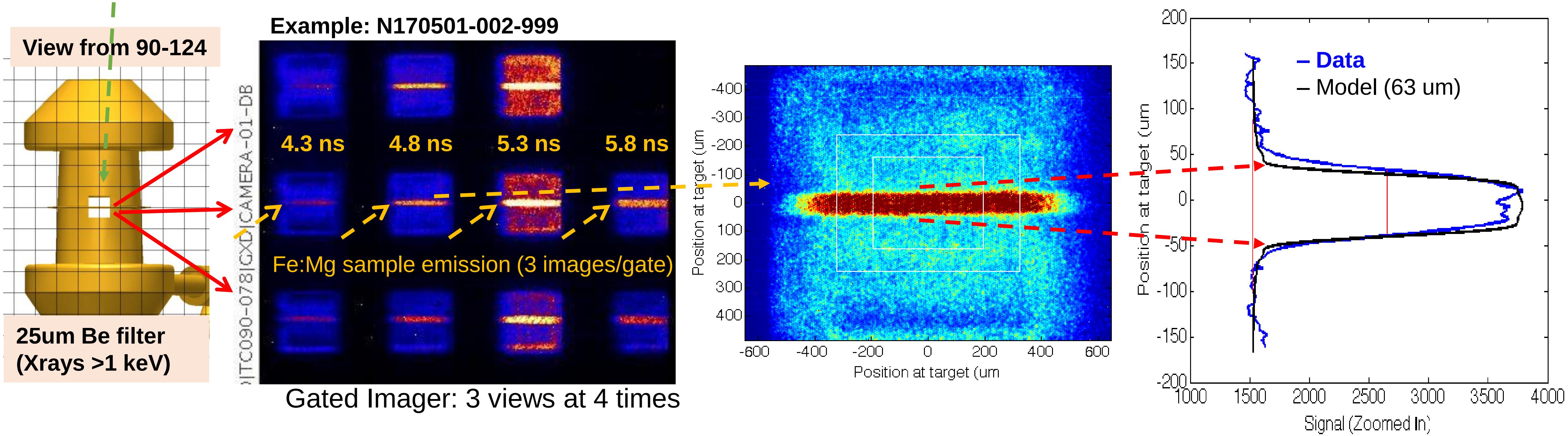
Fe:Mg sample emission (3 images/gate)

Gated Imager: 3 views at 4 times

Density is measured by edge-on gated imaging of the sample expansion, which appears to be uniform and consistent with pre-shot simulations



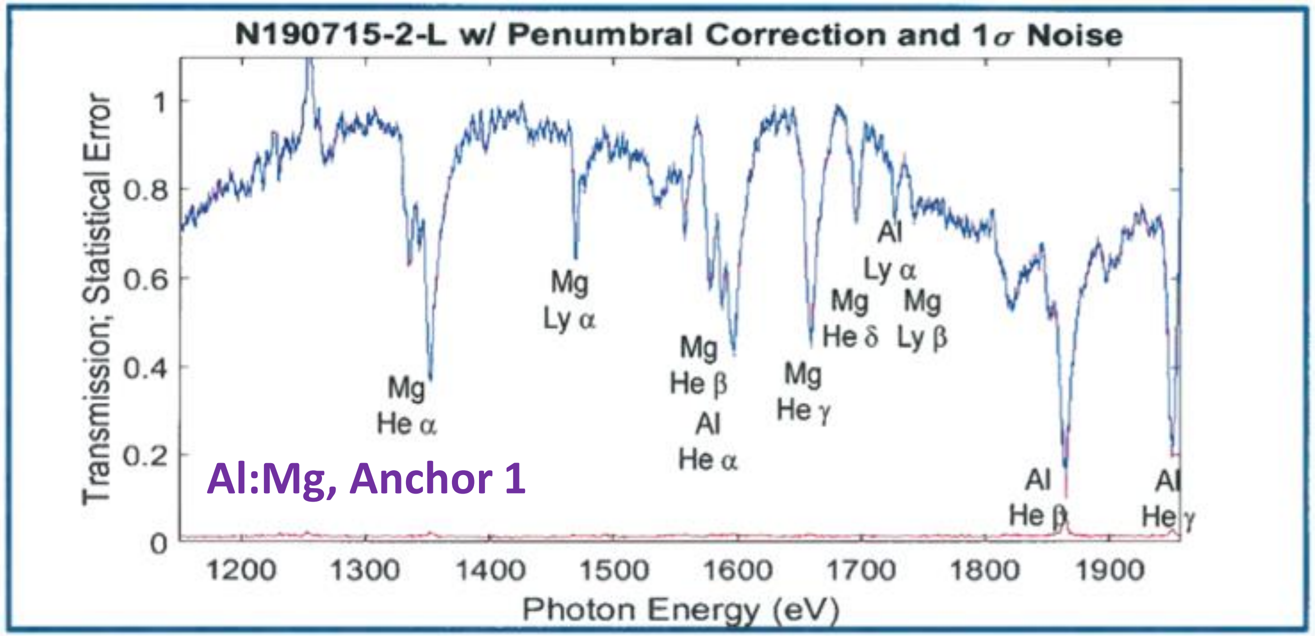
For more details: Y.P. Opachich *et al.*, submitted to *Rev. Sci. Instrum.* (HTPD 2022)

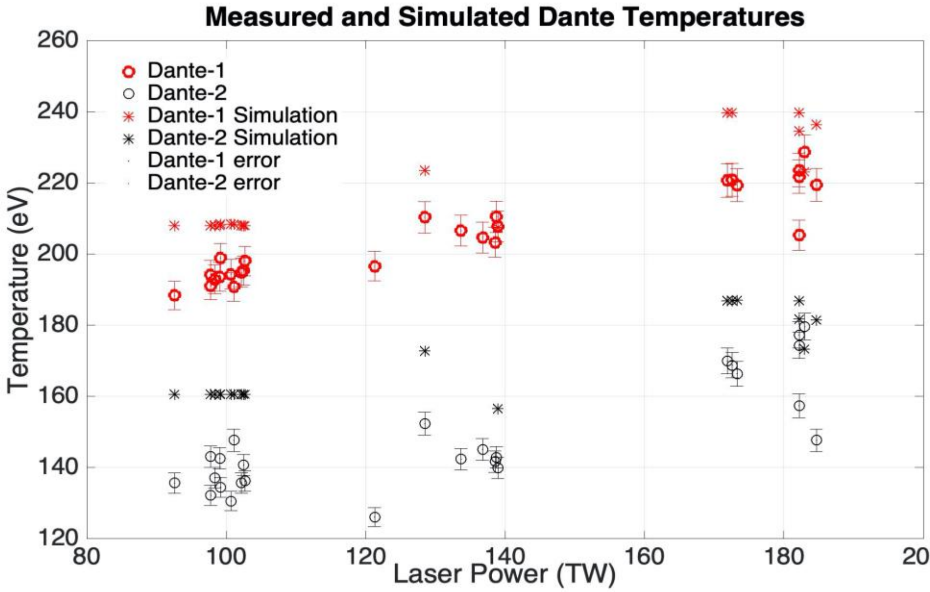


Gated Imager: 3 views at 4 times

- **Density extraction: $\rho(t) = \rho_0 L_0 / L(t)$ using pre-shot $\rho_0 L_0$ (metrology) and measured $L(t)$**
- **For typical samples at Anchor 1, $n_e = 7\text{x}10^{21}/\text{cm}^3$ at 50 µm expansion (4.3 - 4.6 ns)**
- **Uncertainty ~15% based on $\rho_0 L_0$ uncertainty ±5%, $L(t_{flash})$ about ±11%.**

Sample temperature is measured using both DANTE-2 and diagnostic line ratios (comixed Mg and/or Al), and the methods agree for $n_e < 10^{22}/cm^3$.





LASNEX wall temperature	**173 eV**
Line ratios sample temperature	**159±10 eV**
Dante wall temperature	**152±3 eV**
Dante-2 inferred sample temperature	**156±4 eV**

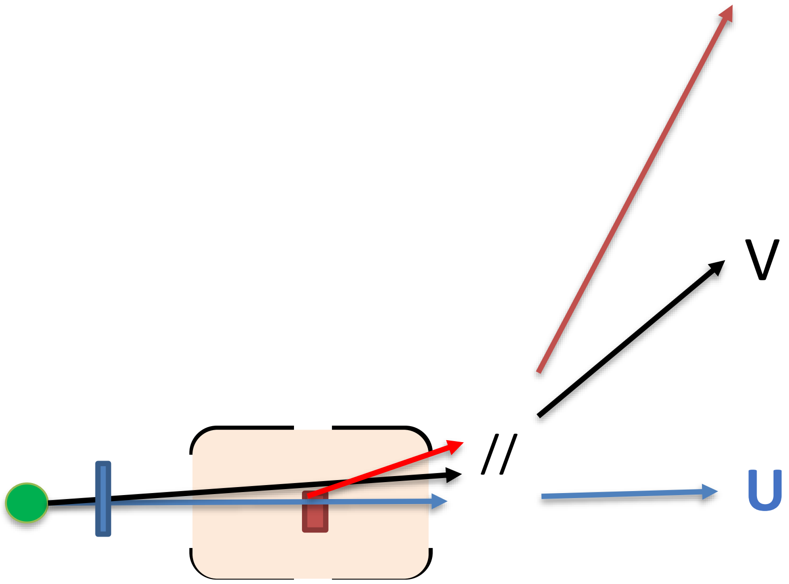
See Y.P. Opachich, *et al.* “DANTE as a Primary Temperature Diagnostic for the NIF Iron Opacity Campaign,” *Review of Scientific Instruments*, 2021. DOI:10.1063/5.0040972

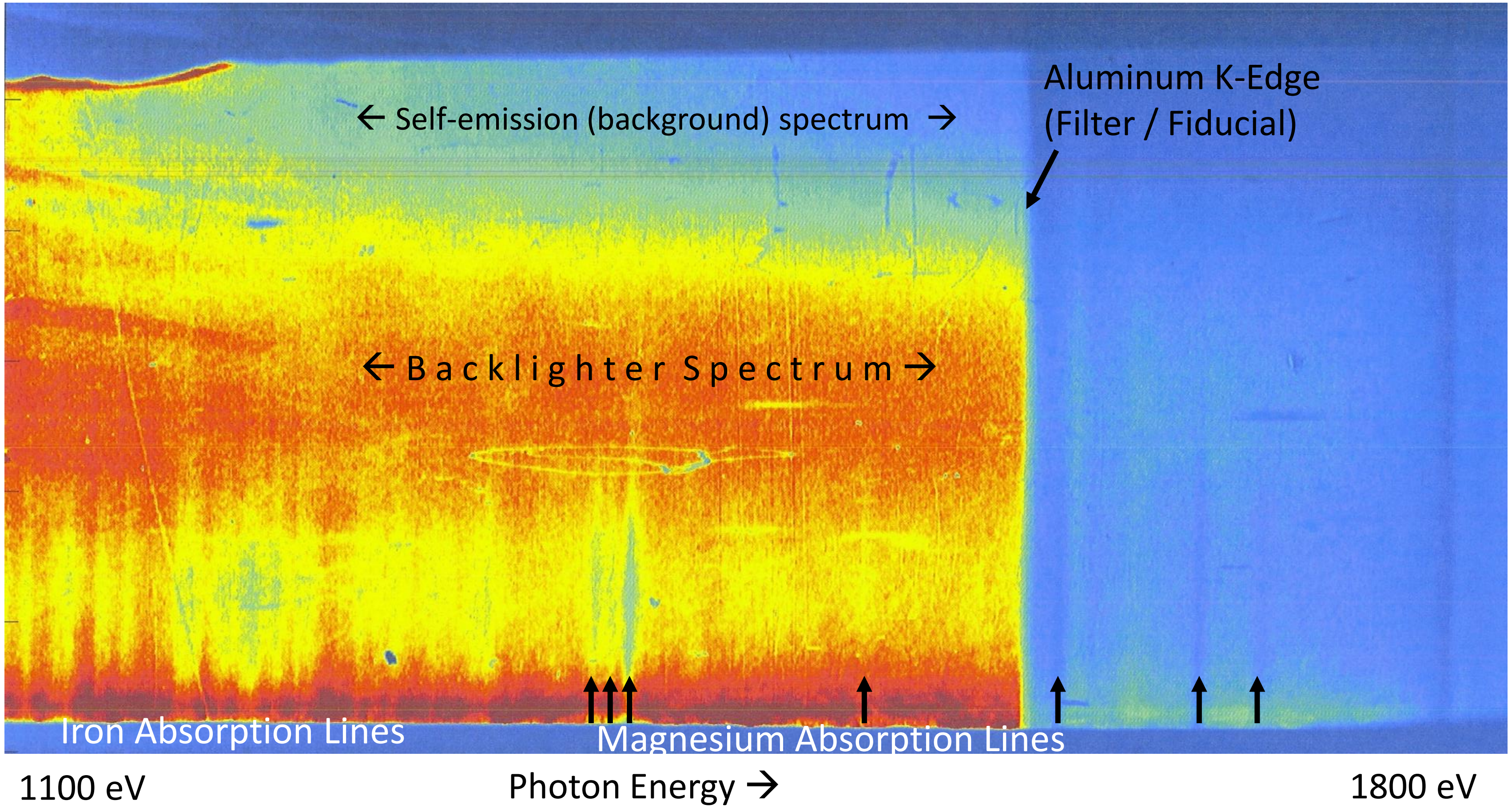
- LASNEX overestimates DANTE-2 temperatures by about 20 eV.
- LASNEX sees sample typically 0-5 eV hotter than DANTE-2.
- Sample temperatures from DANTE-2 and line ratios agree within error bars.
- Having both measurements reduces uncertainty.
- Work in progress on more detailed Mg & Al spectral analyses for various shots.

Section Break

Transmission Spectroscopy
at Anchor 1 (T~155 eV, n_e~7x10^{22}/cm^3)
Iron-Magnesium

OPSPEC data shows the absorption spectrum, backlighter spectrum, and backgrounds





The first successful NIF opacity shot, N20171214-1, wasn't perfect but taught us a lot.

The early Anchor 1 data did not initially agree with theory; multiple corrections were identified

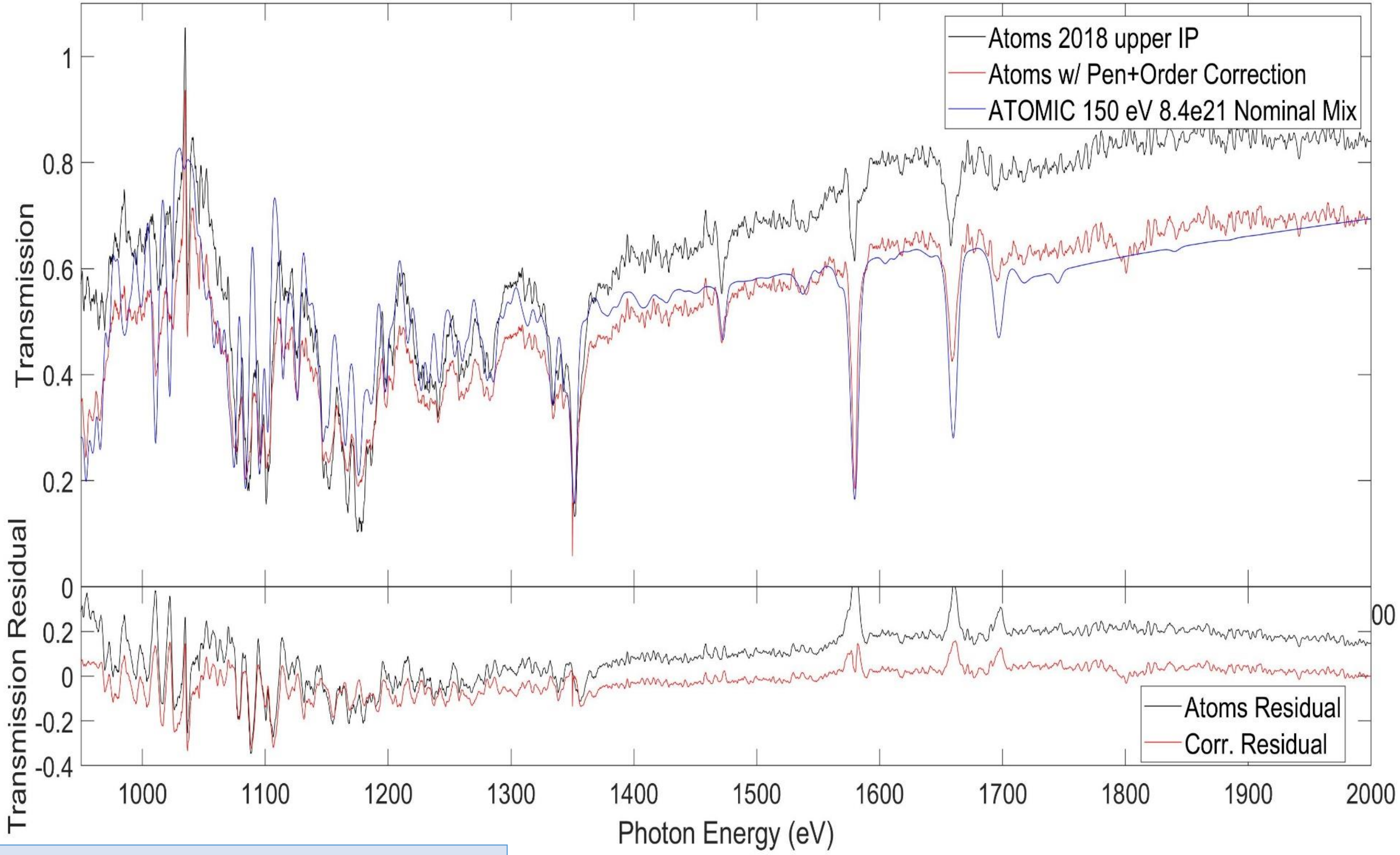
- **Black:** N20171214-1 “naïve transmission” T=(U-E) / (V-E) as published in R.F. Heeter et al., *Atoms*, 2018

- **Blue:** ATOMIC calculation by C.J. Fontes at 150eV, 8.4e21 for the nominal mix of the sample and OpSpec resolution.

- **Red:** NIF data corrected for backlighter “penumbral blur” and 2nd order background. Reanalysis done largely by Eric Dutra and Heather Johns.

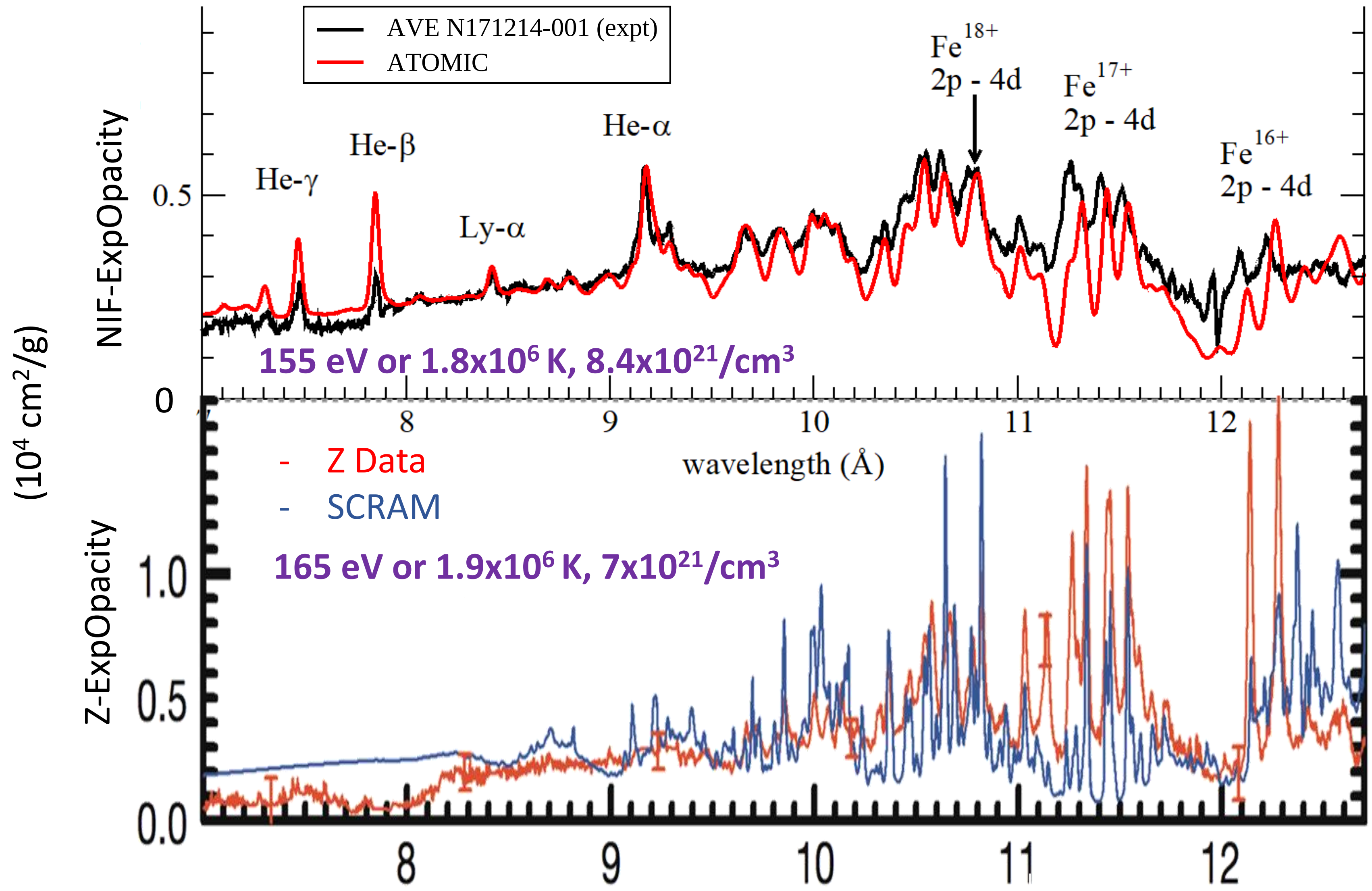
- **Lower graph:** Residuals vs. ATOMIC.

These corrections are not tightly constrained by data – too much room for “human-optimization”
→ improve platform esp. backlighter



For details on corrections, see E. C. Dutra *et al.*, submitted to *Rev. Sci. Instrum.* (HTPD 2022)

Preliminary Anchor 1 comparison: (Top) penumbral-corrected NIF data w/ ATOMIC. (Bottom) Sandia Z data w/ SCRAM (from J.E. Bailey, Nature 2015)



The NIF and Z data are not expected to look exactly the same, due to differences in spectral resolution.

But each dataset can be compared with models at appropriate resolution.

The general agreement between the NIF data and ATOMIC seems comparable to that between the Z data and SCRAM, especially from 8-11 Å.

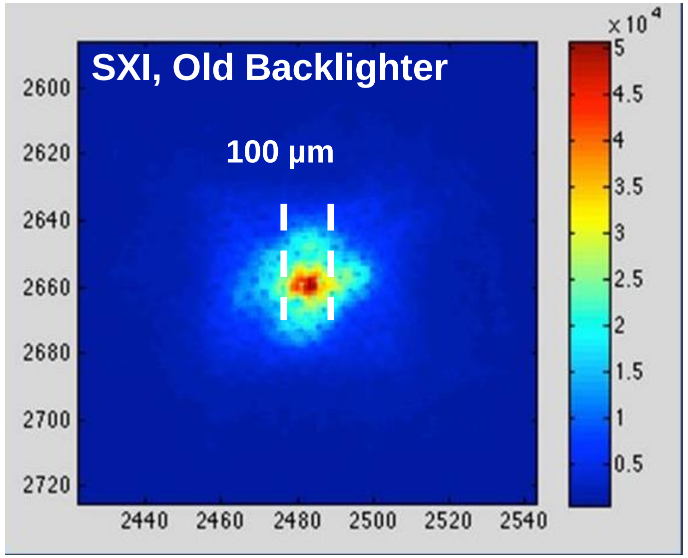
This was heartening!!

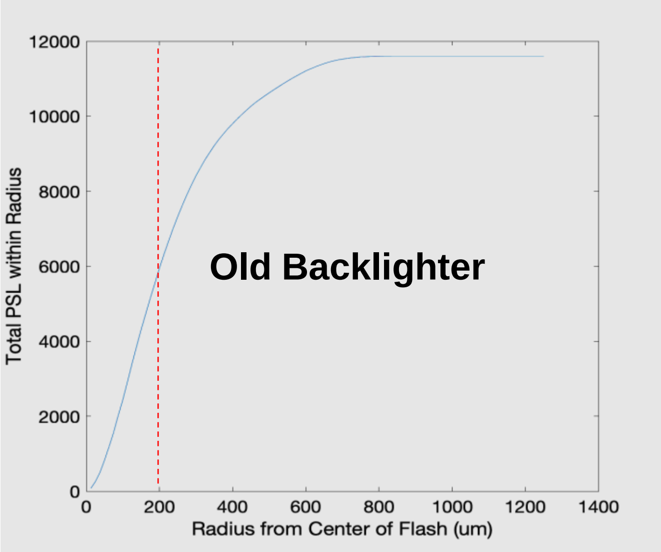
NNSA National Nuclear Security Administration | Lawrence Livermore National Laboratory | Sandia National Laboratories | UR LLE | University of Rochester | Nevada National Security Site | General Atomics
Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA
Los Alamos National Laboratory | NIF The National Ignition Facility
8/26/2022 p. 32
LLNL-PRES-838979

Improvements to Backlighter, Hohlraum and Spectrometer

(Did one of these introduce unexpected systematic errors?)

The bare-shell backlighter produced a broad “halo”, so a cone-on-shell design was adopted to produce a more point-like x-ray source

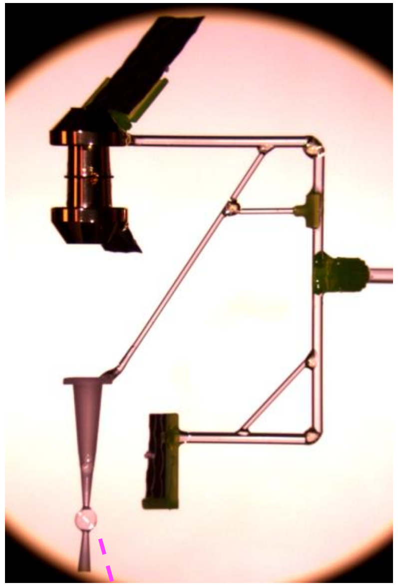


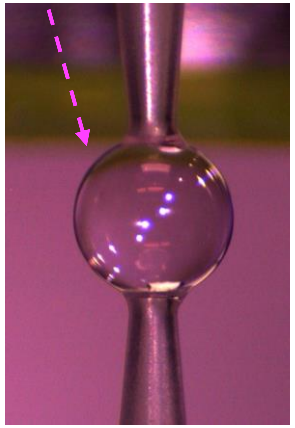


Deeper analysis of old backlighter showed:
~20% of signal from r < 100 um “hot spot”
~50% of signal from r < 200 um
~87% of signal from r < 400 um “halo”

…Not really a point backlighter!

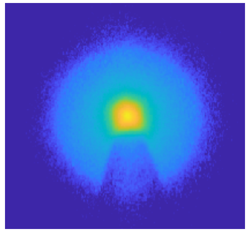
Previous collimator was too large and too far from backlighter, leading to strong penumbral effects.





New Cone-on-Shell Backlighter

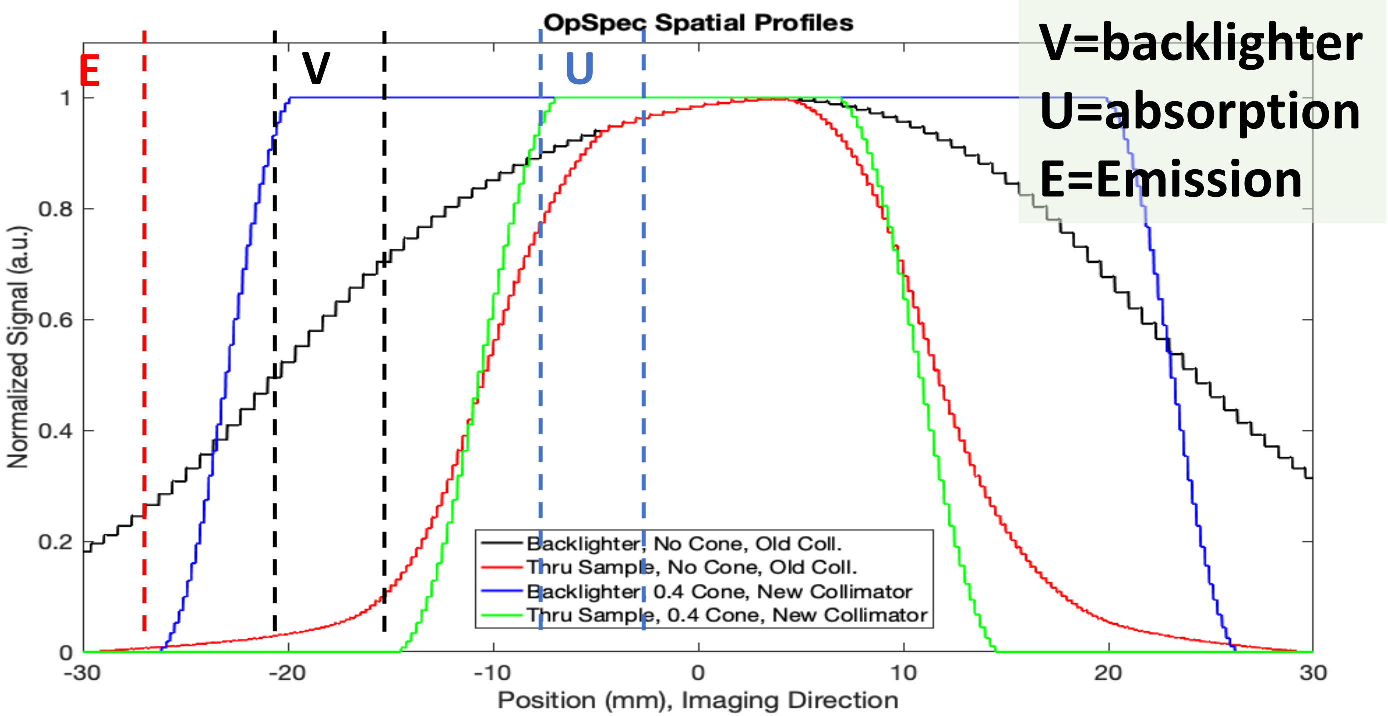
Backlighter laser pointing optimized by S. Craxton and HS students E. Garcia, R. Zhang (Univ. Rochester).

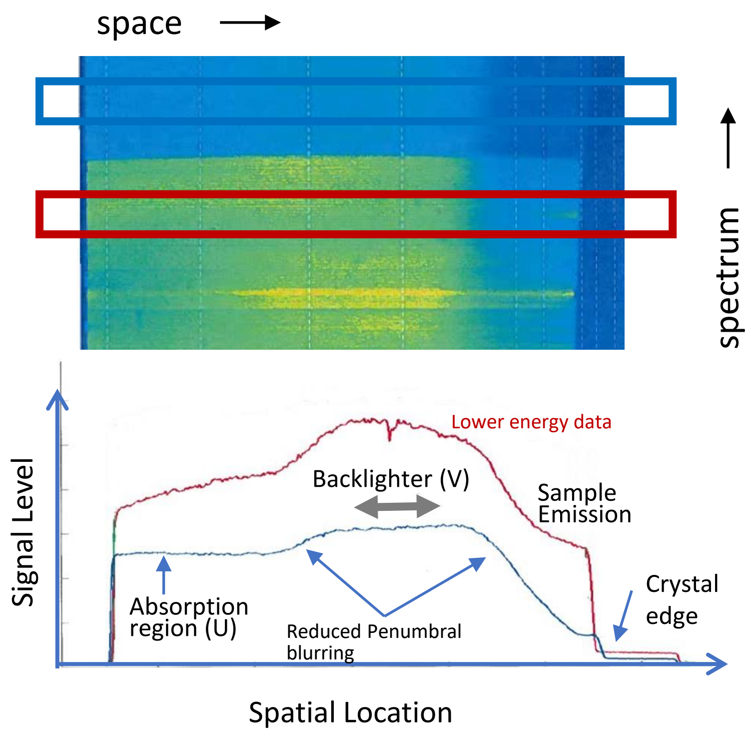


SXI-L Image

Lower cone prevents OpSpec seeing any early-time “run-in” emission.

Spatial profile modeling of the new vs. old backlighters is supported by data from the new backlighter, with much cleaner U, V and E regions





With the old bare-shell backlighter, every detector pixel saw a mix of backlighter (black) and absorption (red) signals.

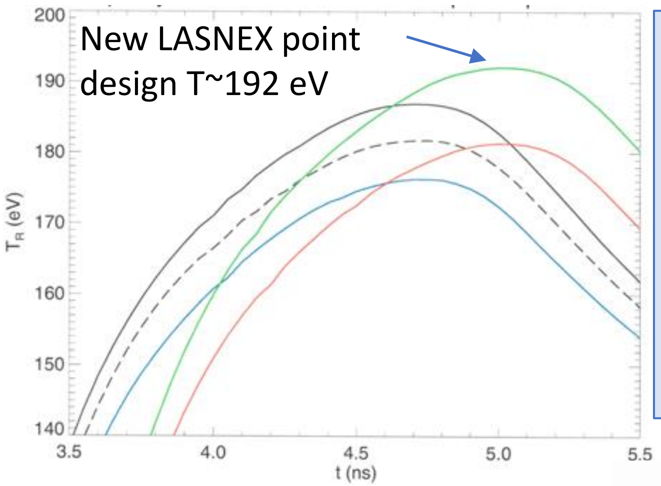
New backlighter with “cone-i-mator” (modeled blue and green curves at left; shot data at right) produces well-defined absorption and backlighter regions on detector for accurate transmissions.

Hohlraum variations include LEH windows (CH, Be, none), laser-spot lining (none, Be), and reduced-picket, extended-drive, higher-power pulses

For Anchor 2: **T**~185 eV, ρ~3x10^{22} e$^-$/cm^3

Higher temperature → more laser power.

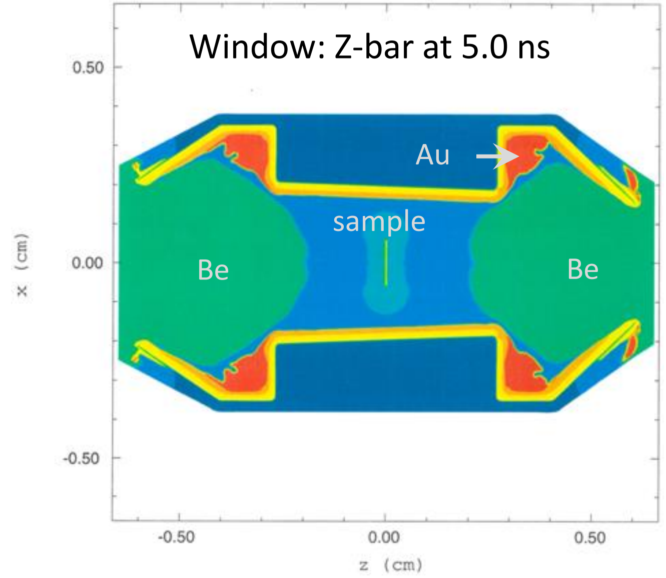
Higher density → thicker tampers → longer pulse.



New LASNEX point design T~192 eV

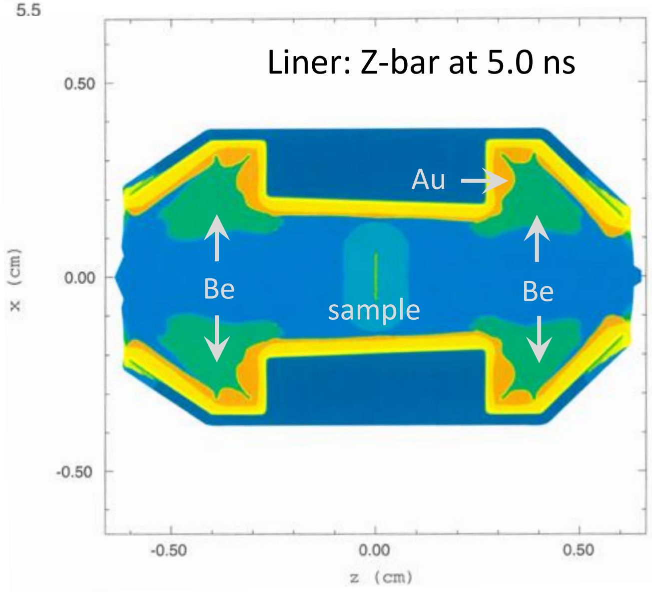
Selected LASNEX runs:
2.5 μm CH + A2v3
6.0 μm CH + A2v3 dashed
no window & Be liner + A2v3b
6.0 μm Be + A2v3
6.0 μm Be + A2v3b

Calculation shows temperature measured by Dante. Sample temperature is ~5 eV higher than Dante wall temperature. But DANTE usually < LASNEX…



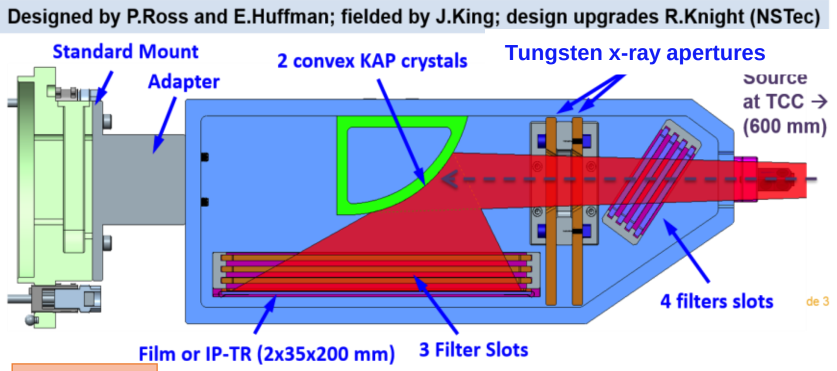
Hohlraum with Be windows

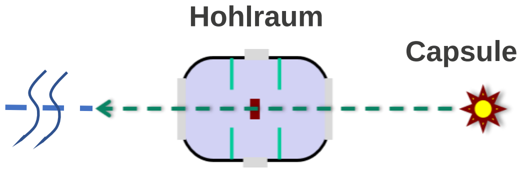
- New “window-less” Be-lined hohlraums give higher sample temperatures, less background.
- But could ablated Be from lining stagnate on-axis and reduce apparent sample transmission?
- For A2, try Window + Lining?

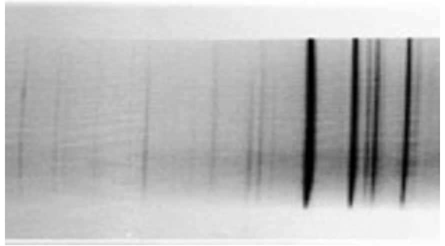


Hohlraum with Be lining

The opacity spectrometer OPSPEC has evolved to improve data survival, filter transmission, data quality, and to greatly reduce backgrounds



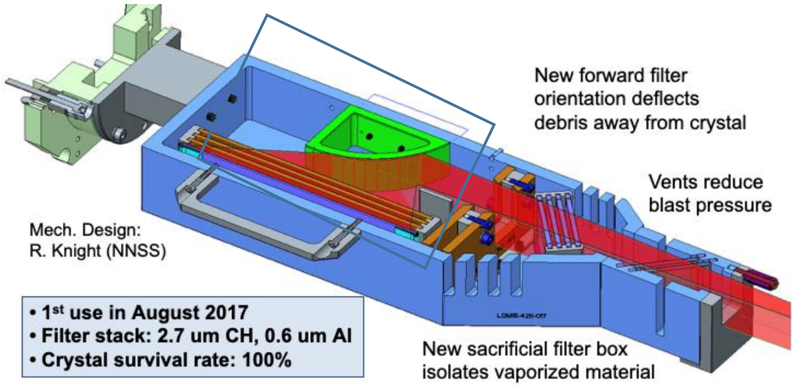




2021: 100% Pre-shot crystal calibration @ NNSS

2016

P.W. Ross *et al.*, *Rev. Sci. Instrum.* (HTPD 2016)



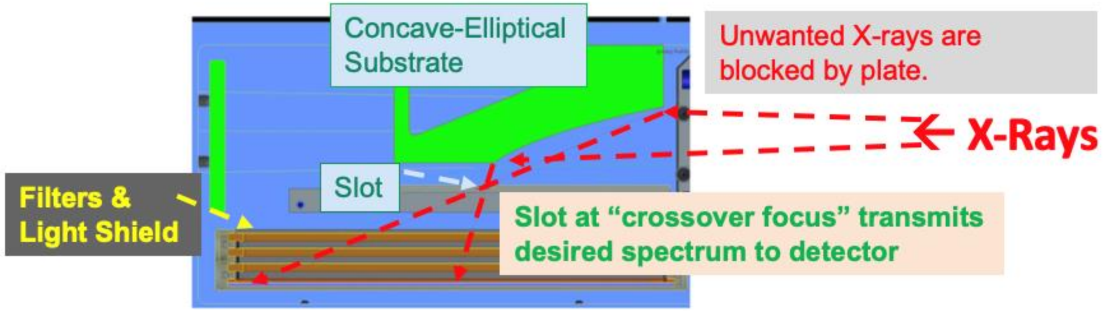
- 1st use in August 2017
- Filter stack: 2.7 um CH, 0.6 um Al
- Crystal survival rate: 100%

2017

2018: Sum of 5 filters = 2.7 um CH, 0.6 um Al

J.A. King et al., Rev. Sci. Instrum., 2018

2019-Present: Concave elliptical crystal + crossover focus slot.



2019

2022: Sum of 6 filters = 1.1 um CH, 0.6 um Al, 0.3 um NaF

M.S. Wallace et al., Rev. Sci. Instrum., 2020 (2nd paper submitted 2022)

Section Break

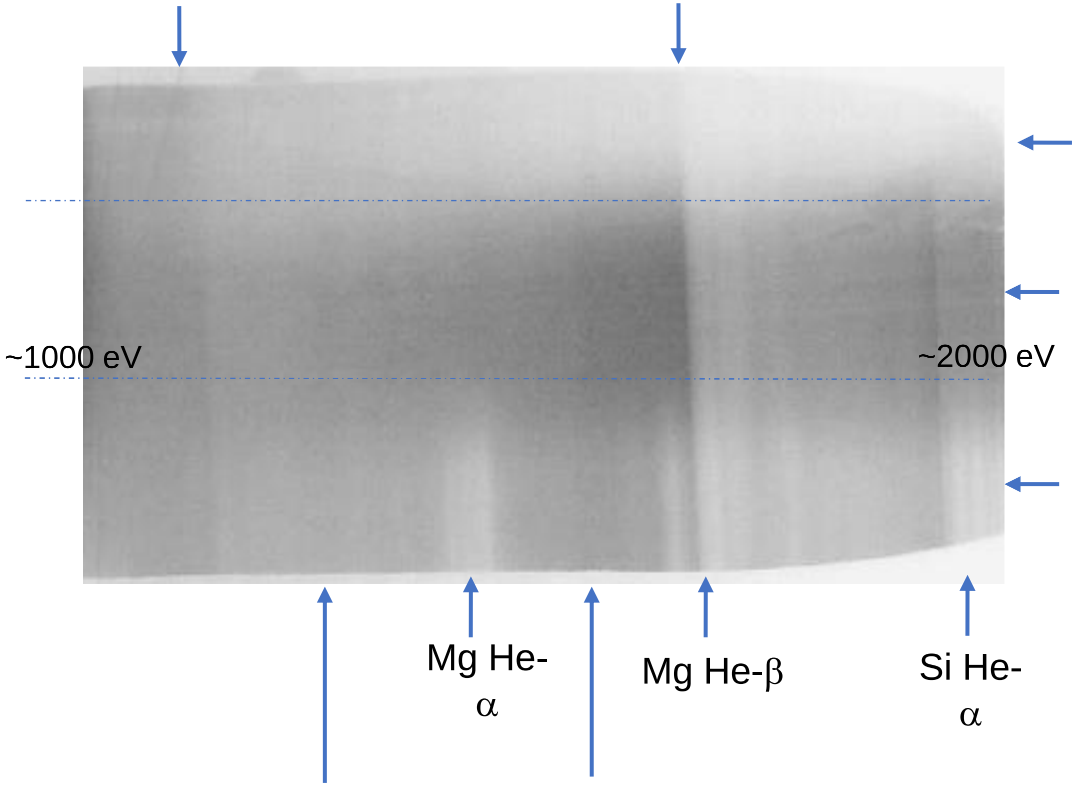
Transmission Spectroscopy at Higher Electron Density ($2\text{-}3\times10^{22}/\text{cm}^3$): Magnesium Oxide / Silicon Dioxide

(Discovery Science: UT Austin, D. Winget)

Recent spectra from the Discovery Science Oxygen Opacity campaign illustrate the improvements in the NIF opacity platform

Oxygen data taken on 6/15/21

Samples were MgO and SiO_2 layers tamped on each side with 15 um CH



Background increases at lower energies

Aluminum filter edge

~1000 eV

~2000 eV

Self-emission & backgrounds *reduced*

Backlighter spectrum *w/ clean boundaries*

Sample absorption spectrum *w/ clean boundaries*

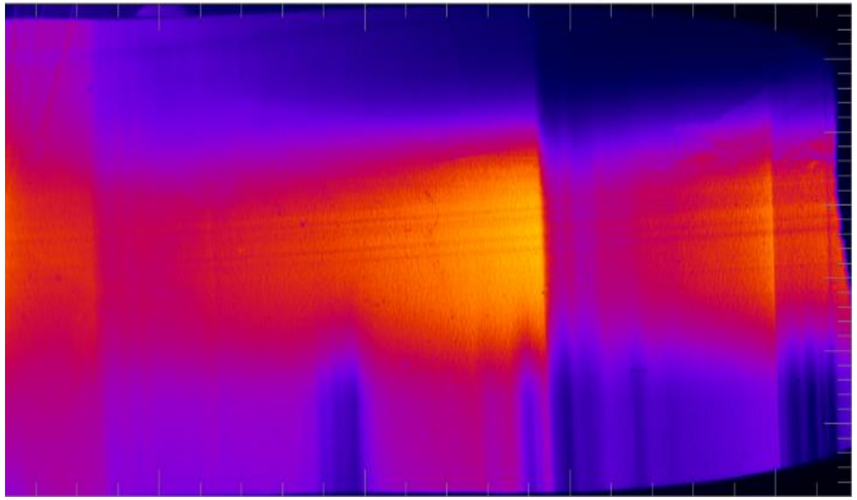
Mg He-α

Mg He-β

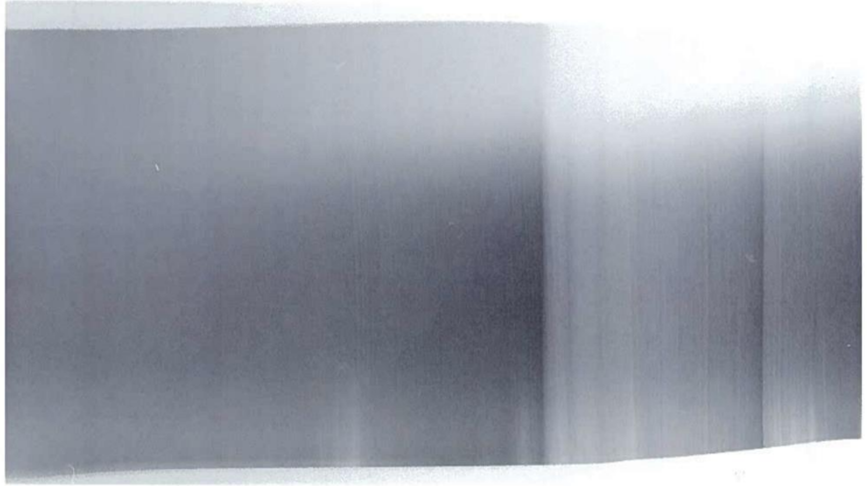
Si He-α

Oxygen absorption

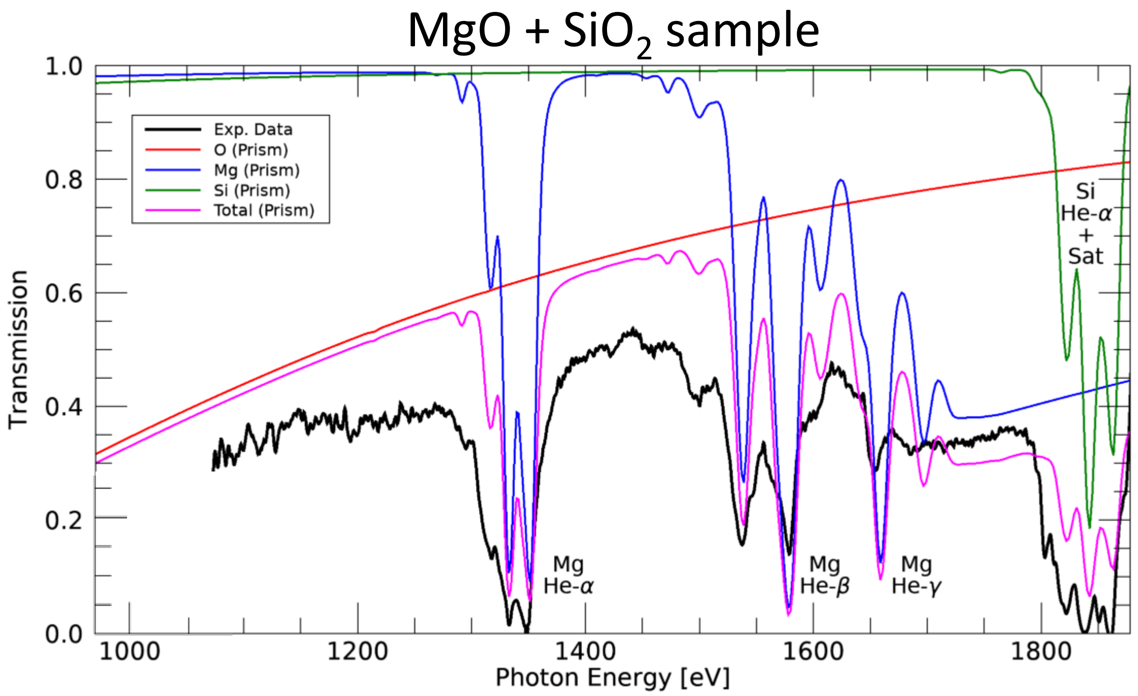
Same 2021 data, in color (D. Mayes)

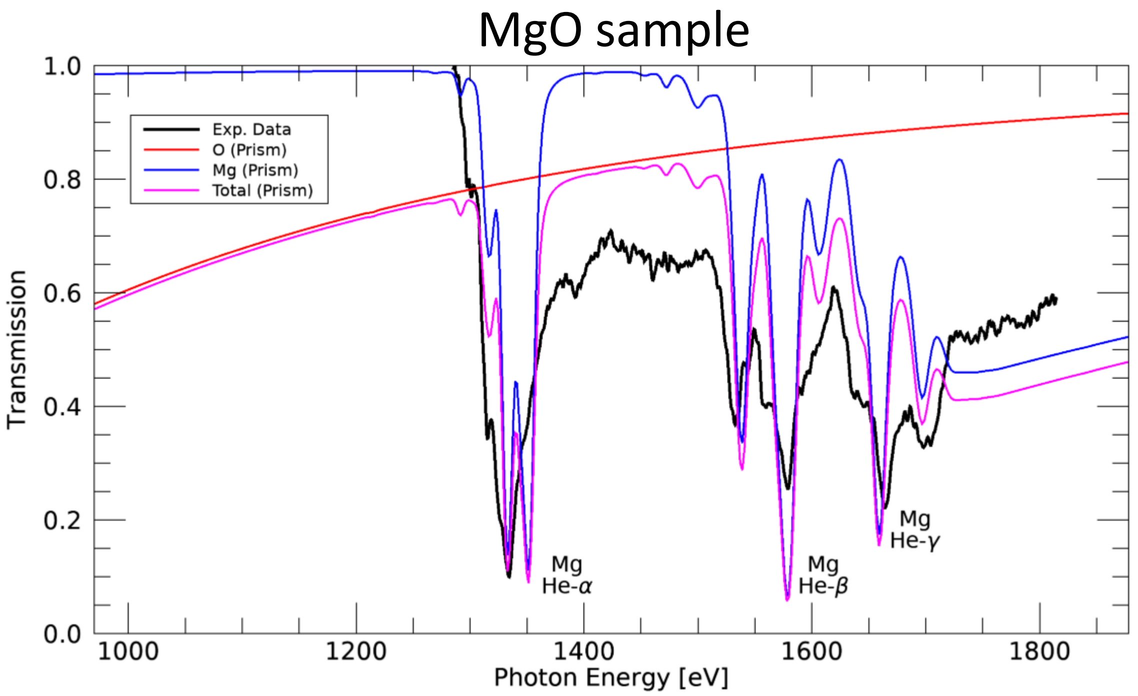


Repeat Oxygen data taken on 3/16/22



Transmission spectra show Mg & Si line features, plus 2 regions of bound-free transmission just from the oxygen. (O lines too low in energy.)


MgO + SiO_2 sample

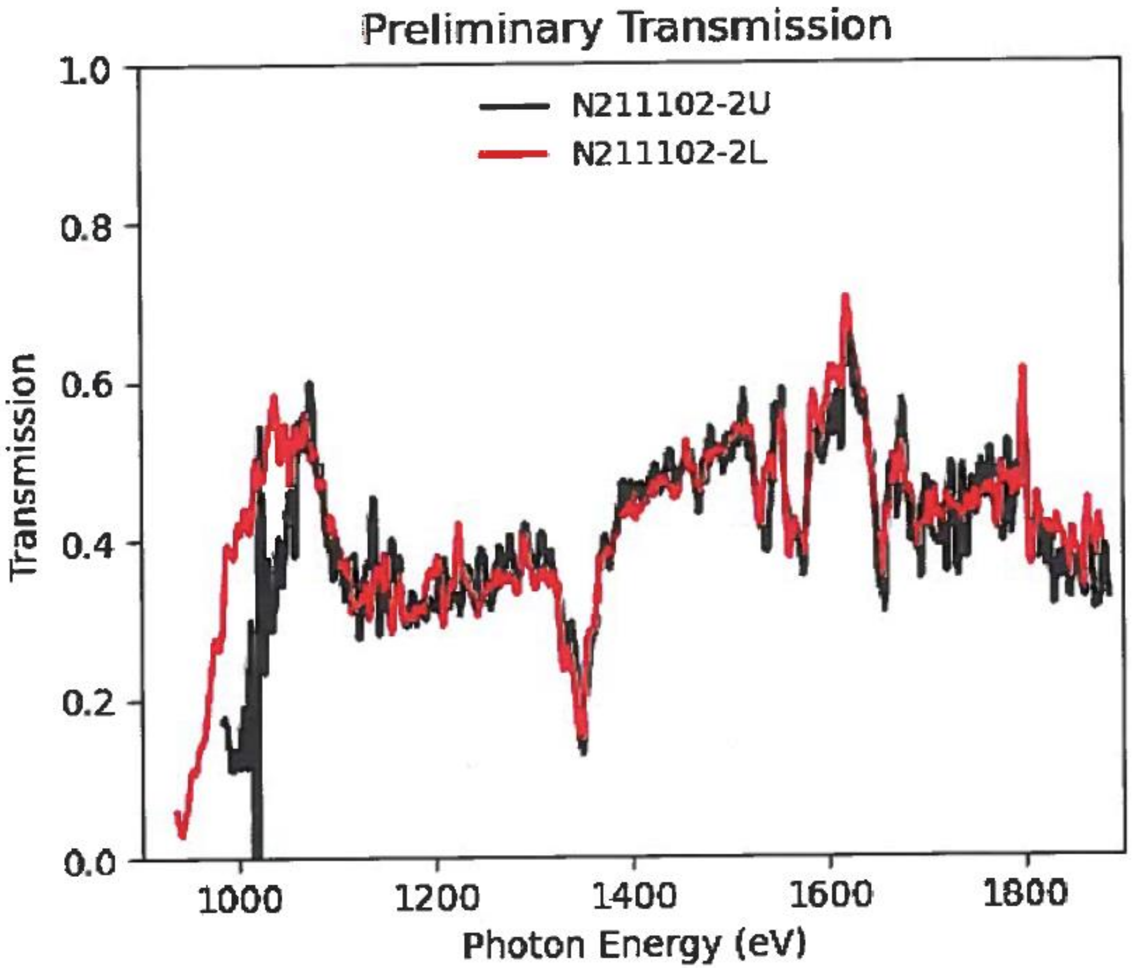

MgO sample

- 2021 Conditions: T ~ 130 eV and n_e ~ $2\times10^{22}/cm^3$ *(expansion not seen & T suspect due to large circular tamper)*
- 2022 Conditions (prelim): T ~ 142 eV, n_e ~ $2\times10^{22}/cm^3$ *(clean measurements w/ band-aid style tamper)*
- Both MgO+SiO_2 samples and MgO samples show low transmission - with different areal densities (Beer's Law)
- Is low transmission due to high opacity, to larger-than-expected fractions of H- or He-like oxygen ("EOS issue"), or due to a systematic error in the measurement ("Under-Cooked Sample")?

Transmission Spectroscopy at Higher Electron Density (2-3x10^{22}/cm^3) Iron-Magnesium

In FY22 NIF measured transmission of Iron-Magnesium samples tamped by 15um CH per side, at T~150-160 eV and n_e~$2x10^{22}/cm^3$, also called “Anchor 1+”

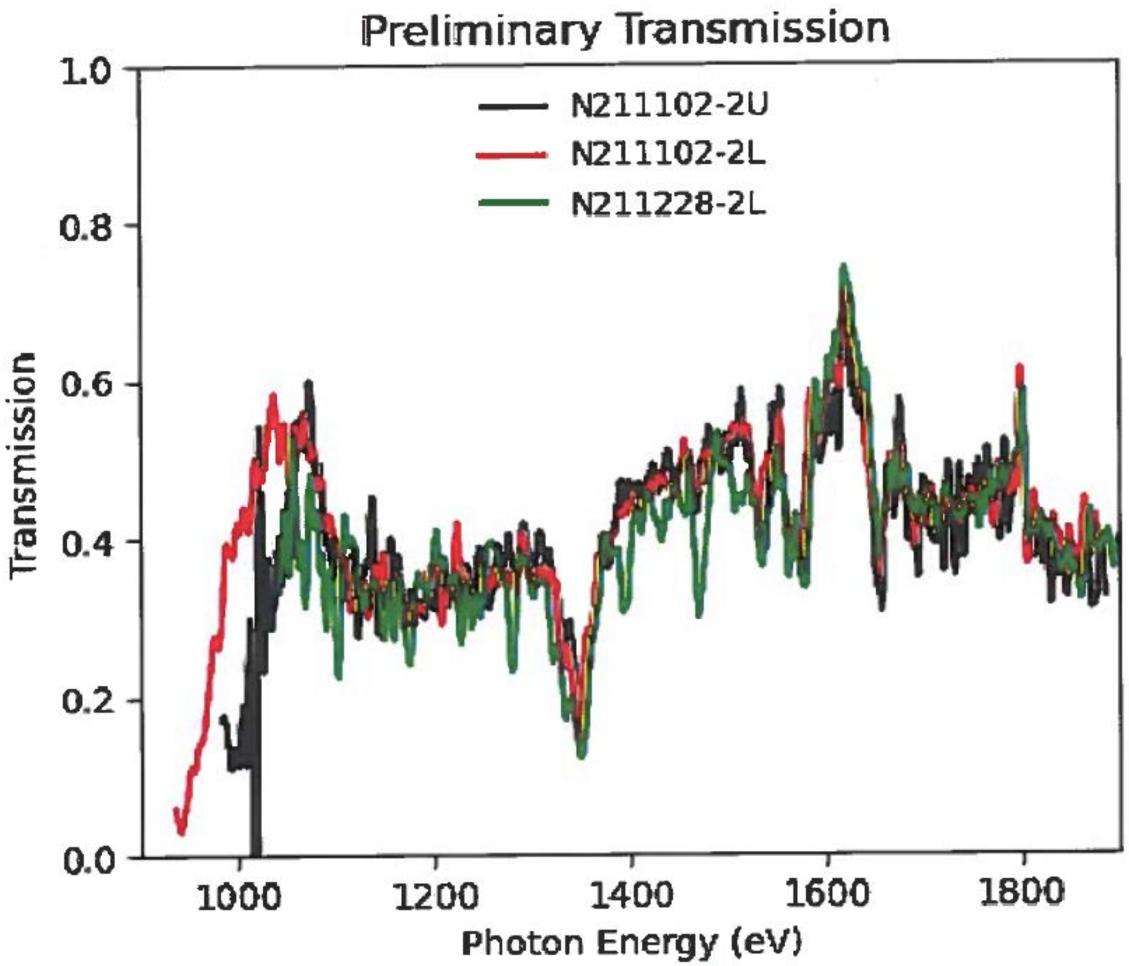
The intent was to first change density from Anchor 1 ($7x10^{21}$) to Anchor 2 ($3x10^{22}$), then work gradually up to Anchor 2 temperature.



Analysis by Harry Robey
(LANL @ LLNL)

The N211102-002 transmission data was consistent for both upper and lower crystals, increasing confidence.

Less than 2 months later, a repeatability test, N211228 delivered nearly the same temperature and density, with transmission nearly on top of prior shot



Analysis by Harry Robey
(LANL @ LLNL)

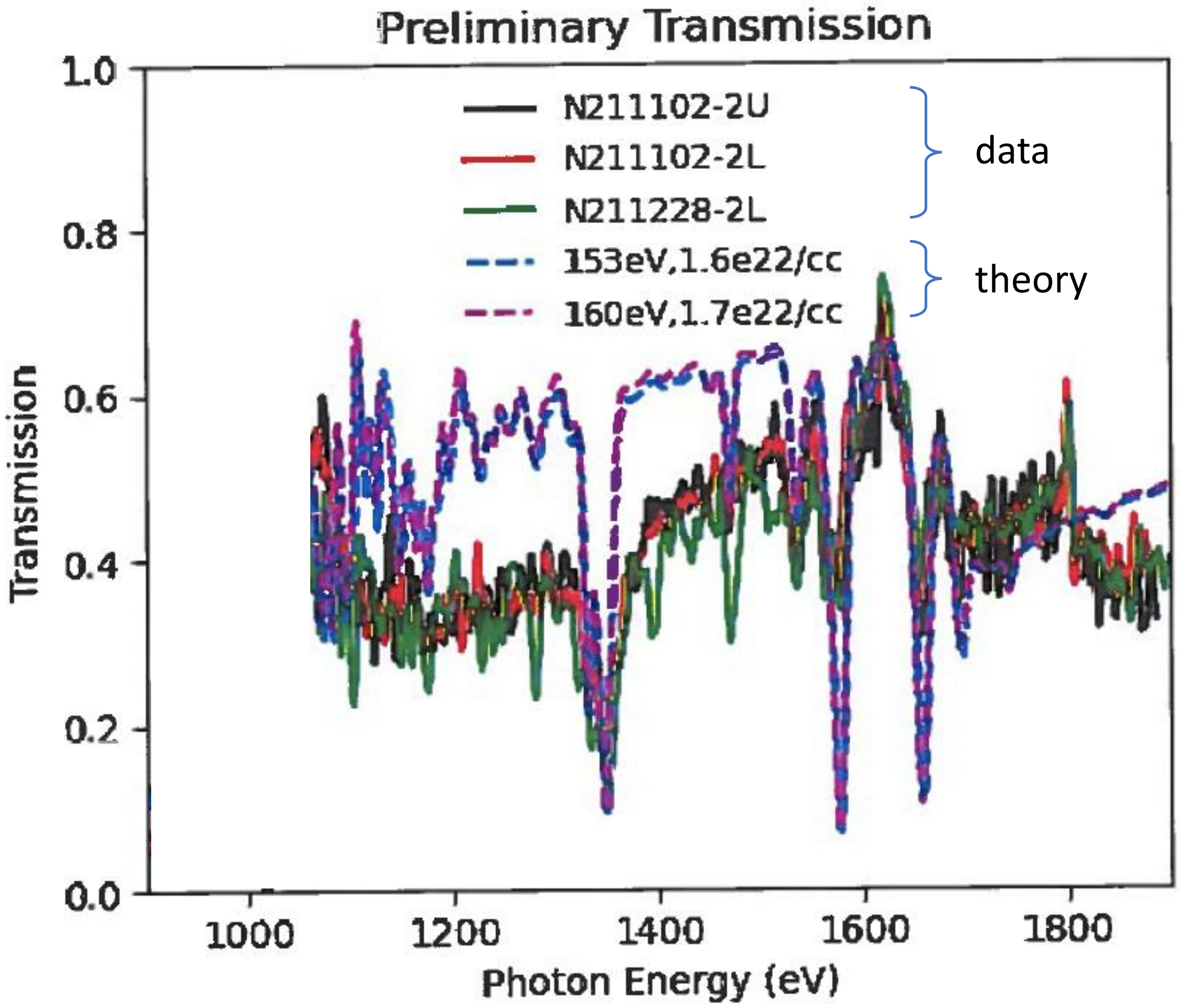
Aside from a small difference in temperature (+7eV for N211228), the result is highly similar.

The measured temperature and density are consistent with "Anchor 1+"

Shot (Sample)	Time at transmission (ns)	Inferred Expansion (HYDRA) (μm)	Inferred Density (Element 1) (10^{20} ions/cm^2)	Inferred Density (Element 2) (10^{20} ions/cm^2)	Inferred n_e (HYDRA) (10^{22} e^-/cm^3)	DANTE2-Inferred Sample Temp (HYDRA) (eV)
N211228-002 (Fe/Mg)	4.7	40.9 (48.6)	3.9 (Fe)	15.5 (Mg)	**2.2** (1.8)	**164 ± 4** (175.1)
N220316-002 (MgO)	5.0	41.4 (81.6)	1.8 (O)	1.8 (Mg)	**2.8** (1.6)	**145 ± 4** (158.2)

Analysis by Kathy Opachich (LLNL), using sample data from LANL and GA compiled by Heather Johns, and 1D HYDRA simulations by Natalia Krasheninnikova (LANL).

Comparing with theory (ATOMIC) shows a discrepancy in the mean transmission for E < 1600 eV



A significant number of line positions are in agreement with theory, but overall transmission is low and many experimental features are muted.

By changing the tamper thickness, the electron density was tripled, and the data now show discrepancies with theory *which are greater than the expected uncertainty.*

The new platform does not require penumbral corrections, but are there other sources of error?

The higher-density NIF data show similar discrepancies to what has been seen on Z at similar density.

Section Break

Potential Systematic Errors: Identification Quantification and Correction

There is a long list of potential sources of systematic error to understand and quantify or eliminate.

Sources of Error Affecting Sample Conditions

Areal Density:
EDGE might not get Si, Al, Mg, O areal density correct (E_{min} too high).
EDGE relies on cold opacities which aren't perfectly known.
RBS data from witness has some variance vs. actual sample.
RBS relies on cross-section and other data not perfectly known.
Radial pressure/density wave might increase areal density?

Temperature:
Backlighter might perturb sample conditions (hotter) – *not significant*.
Sample might be "under-cooked" compared to DANTE-2 "oven temp".
Spectroscopic tracer Z*-vs-T may be inaccurate at high density.

Density:
Sample expansion might be nonuniform ("cold core").
Sample expansion analysis might be missing details.
Cross-timing might be inaccurate ("DANTE-1 flash time error")
Sample/tamper mixing ("invisible tamper in the sample").

Sources of Error Affecting Transmission Measurement

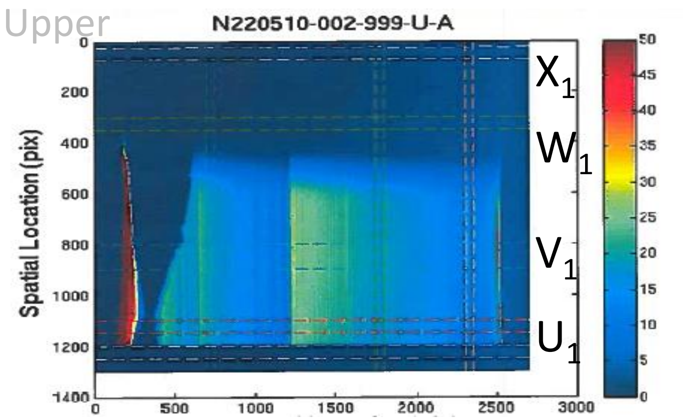
Backlighter:
Backlighter output might be non-isotropic.

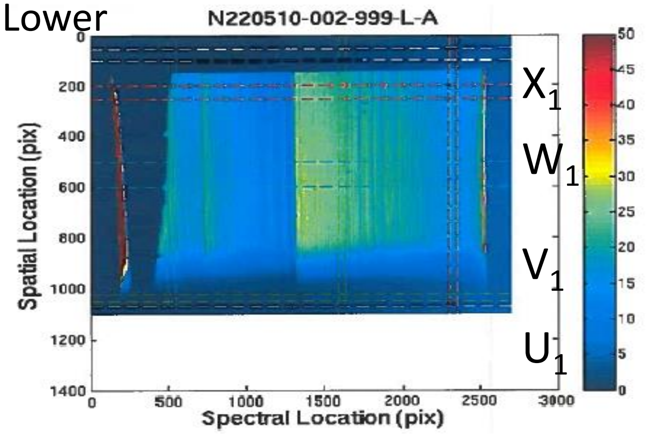
Transmission thru Hohlraum & Sample:
Tamper conditions might be nonuniform. (Null sample test.)
Sample conditions might be nonuniform.
Hohlraum plasma filling (stagnation on axis adds absorption).
Hohlraum plasma filling (outer backlighter attenuation)
Target self-emission might be nonuniform. (Tested 8/11/22.)

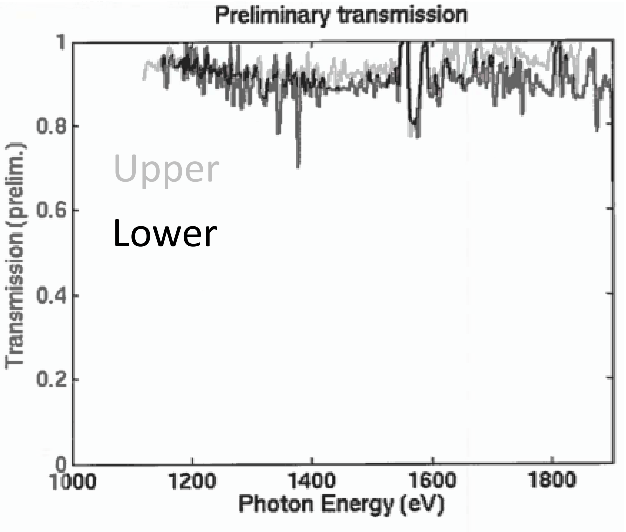
Spectrometer:
Spectrometer internal (scattered) background. (Real Issue!)
Crystal artifacts, bowing near ends, 2nd order…
Image plate scanner-to-PSL-exposure nonlinearity
X-Ray Film better but need calibration (in progress using SSRL)

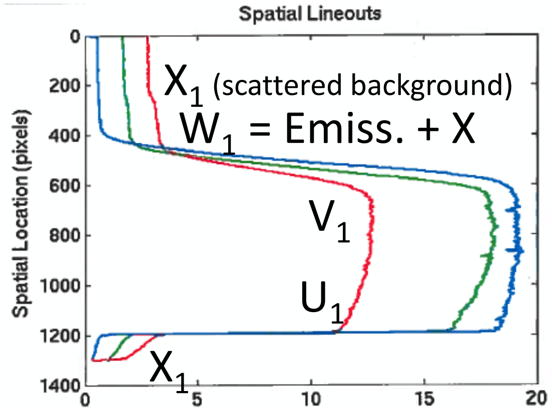
Are there any other potential sources of systematic error? Has something been overlooked?

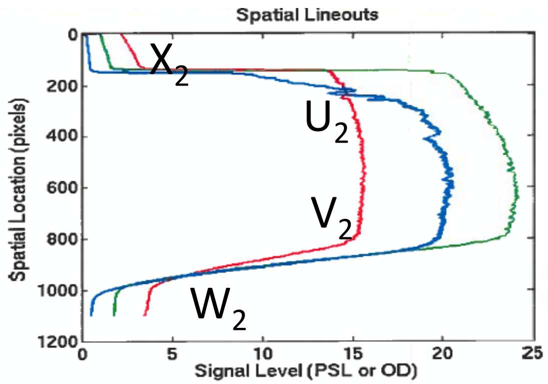
Recent results (shot N220510) with no sample may explain part of the discrepancy between experiment and theory, but not all











- Transmission (U-W)/(V-W) should be 1 but was measured ~0.9! *Spatial profile ~10% lower 'U' near center line.*
- Scattered light background X (underlying the image) is also smaller near center line: maybe it's not spatially uniform?

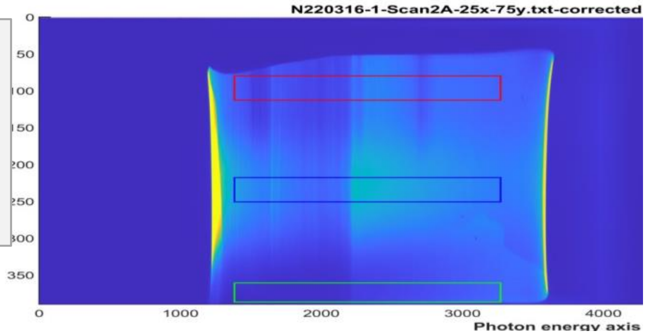
One of the possible causes of the “10% low null transmission” is nonuniformity of the scattered (not diffracted) light within the spectrometer

- Some photons in the spectrometer scatter or fluoresce rather than Bragg-diffracting.
- The earlier analysis assumed the scattered light background was spatially uniform.
- Background measured in Sept. 2021 for one instrument configuration, by fielding the spectrometer “without crystals” (hence: no Bragg diffraction, but still have scattering).
- Background is *not* perfectly uniform in the vertical “space-resolving” direction.
- For MgO/SiO2, correcting for the nonuniform background results in a transmission shift of 0.01 to 0.05, significant but *moving the data farther from agreement with theory*.
- Similar analysis in progress for iron suggests shifts towards theory in some parts of spectrum, but more work needed.

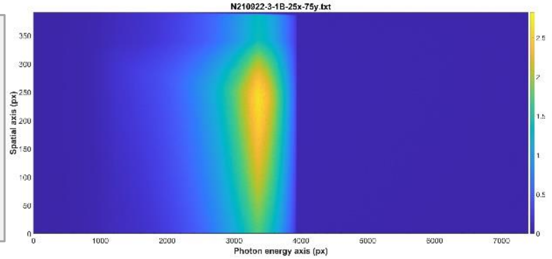
Work shown here conducted by U. Nevada Reno Ph.D. student E. Gallardo-Diaz as a summer project.

This correction is significant but is not expected to bring the observed X-ray transmission into agreement with theory.

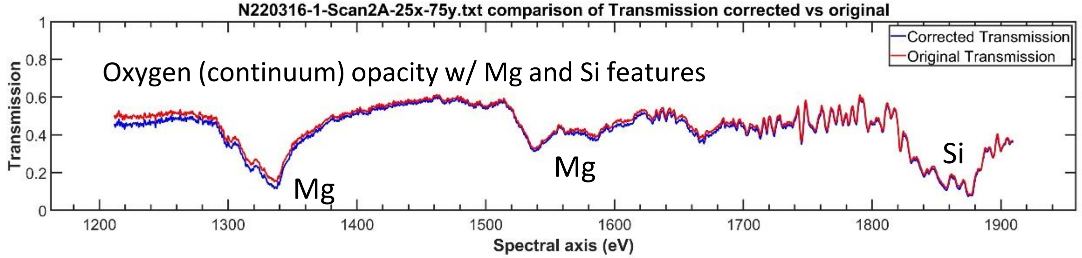
N220316-1
MgO/SiO2
Discovery
Science



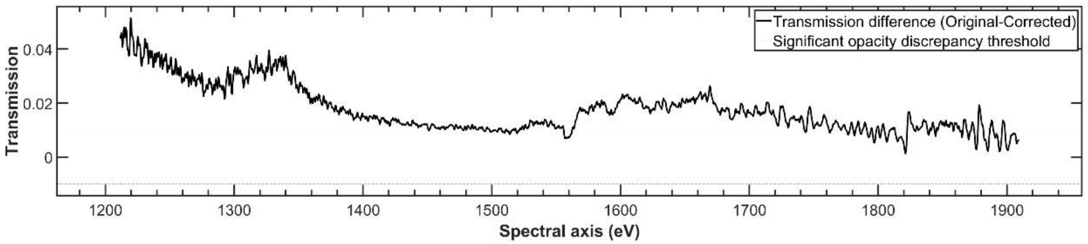
Scattered light background (spatially aligned, color scale greatly enhanced)



X-ray transmission with/without correction



Transmission change due to correction

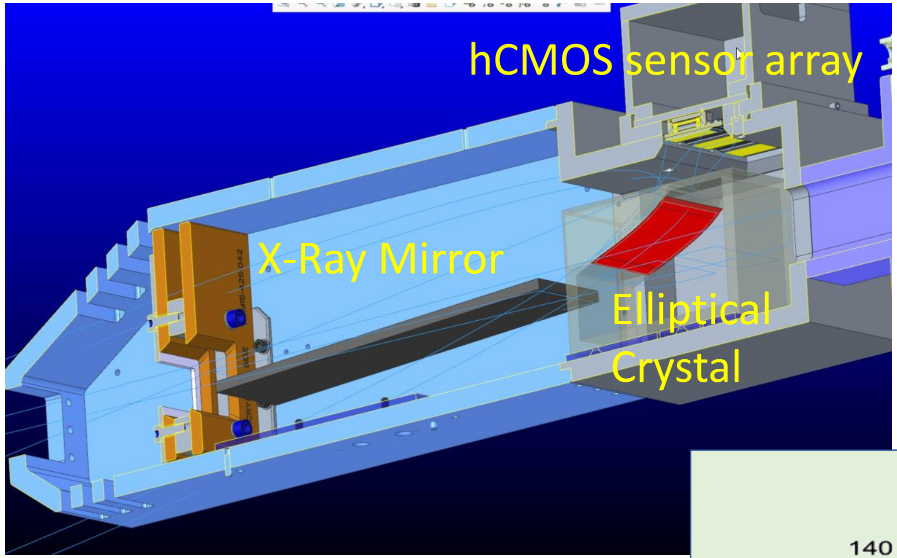


Much remains to be done to firm up these preliminary results

- Ongoing: Take & apply calibration data to correct transmissions
- Next: In conjunction with Discovery Science team, complete analysis & publish
- **FY23: Time resolved spectrometer (OpSpecTR) will be coming on line**
- FY23: More data at Anchor 1 to recheck platform where prior data agrees
- FY23: Detailed experiment / theory comparisons for A1 & A1+ (FY23 L2 milestone)
- FY24: With OpSpecTR, push drive up and take data at higher temperature (A2)

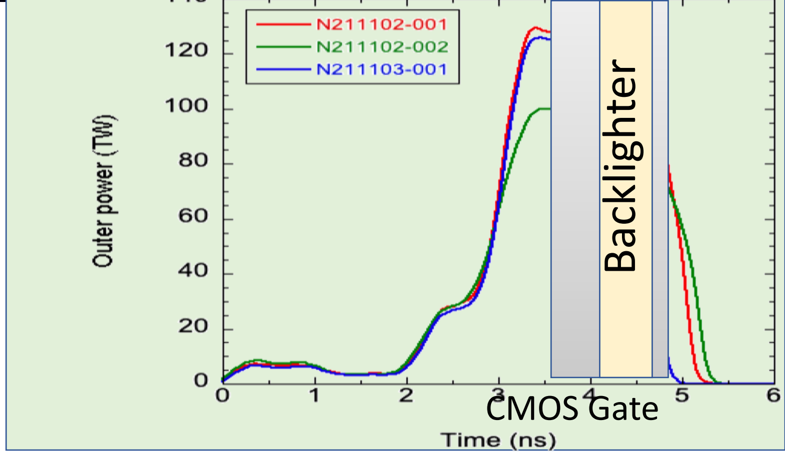
Time-Resolved NIF Opacity Spectrometer (strategic reserve project) completed Conceptual Design and is heading for FDR now, initial data FY23, L2 data FY24

- Use hCMOS sensors to time-gate NIF opacity measurements around the time of the backlighter.
- Time-gating avoids late-time background emission and is expected to reject >80% of backgrounds, especially at higher temperatures.
- Use X-ray mirror and 3 hCMOS sensors to measure absorption, backlighter and emission-background spectra to get transmission.

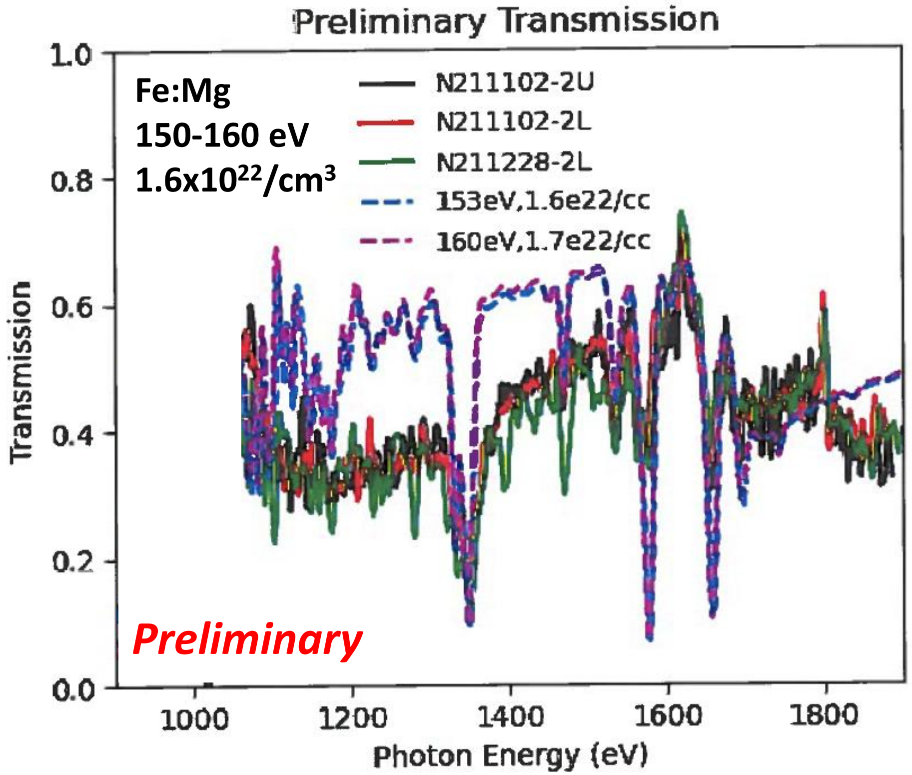


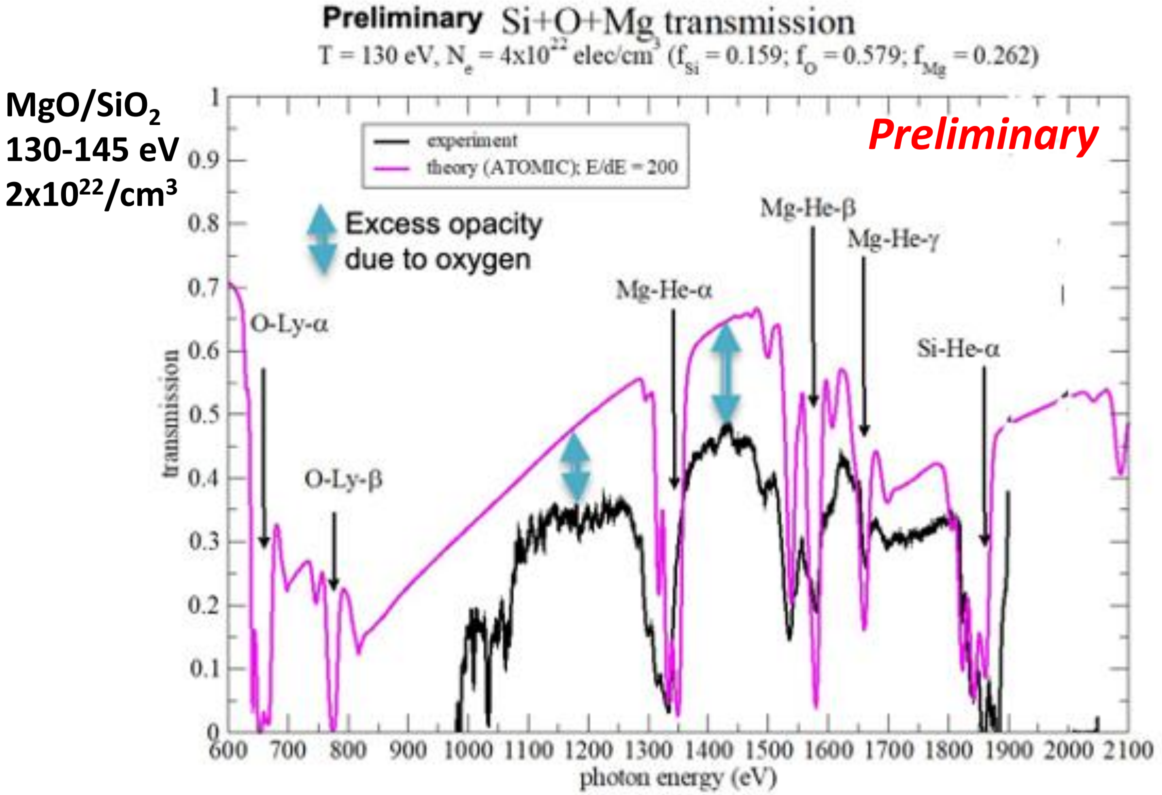
Left) Time-Resolved Opacity Spectrometer snout design, with new components in gray and yellow. (Electronics airbox not shown.)

Right) Time-gating strategy for NIF Opacity measurements. Goal is to avoid late-time background emission which persists to ~10 ns.



NIF has recently delivered unexpectedly-low transmission measurements from both Fe:Mg and MgO/SiO$_2$ plasmas at T~150 eV, n_e~2x10^{22}/cm^3





- These preliminary NIF results are qualitatively similar to Z data, and may have significant implications for theory and astrophysics - but they will change pending corrections, and may have unknown errors.
- Before publication, to minimize risk of error, we would be grateful for peer-review comments regarding potential systematic error sources. This supports an FY22 L2 milestone.

Supporting Material

Because of the large number of quantum states involved opacity codes are forced to make approximations

Different opacity codes use similar models. Code developers gravitate toward more “successful” methods. Variations between codes probably underestimate the real physical uncertainty.

EOS Models

- **Boundary conditions in ion-sphere model**
- **N_{max} issues**
- **Treatment of electrons in scattering states**
- **Mixing is not done using Opacity EOS**

Atomic Physics

- **Optimization of self-consistent potential**
- **Scaling of Slater parameters**
- **Inclusion of QED and Breit interactions**

Statistical versus Ab-Initio Methods

- **Refinement of super-configurations**
- **Intermediate coupling**
- **Full configuration interaction**
- **Quantal free-free versus parameterized**
- **Collective effects on free-free & scattering**

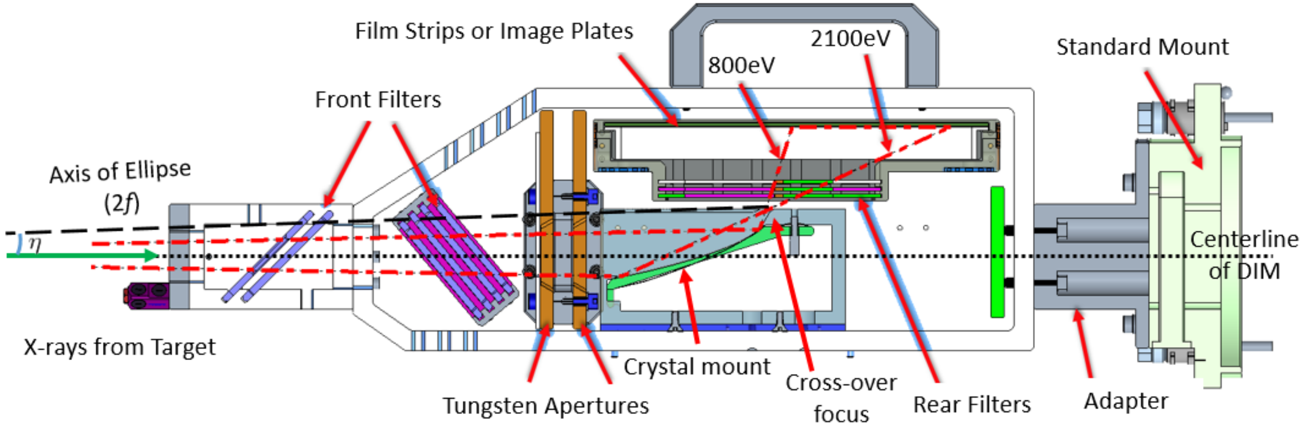
Line Broadening

Width formula from electron collisions

Far-wing behavior

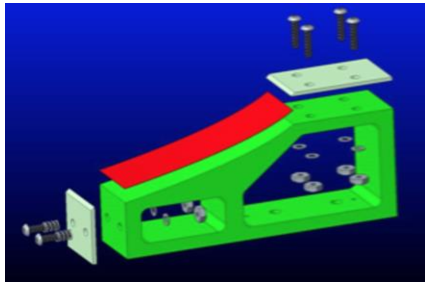
Currently no theory can explain the observed discrepancies in the Z data

The elliptical crystal mounts have evolved through 5 generations to a design which is much more reliable

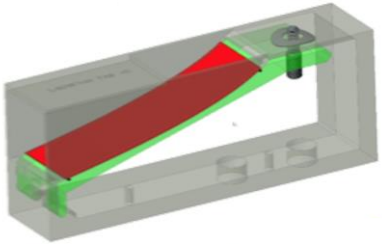


The opacity spectrometer required several improvements:

- Elliptical crystal mounts were improved giving higher yield for good crystals
- Dual detector was improved for easier fielding and is now used routinely
- Now all crystals are calibrated before each shot by NNSS

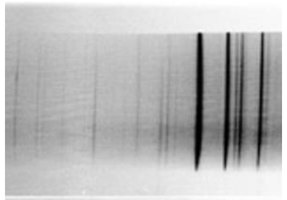


Crystal mount
Version 1



Crystal mount
Version 5 with swing arm

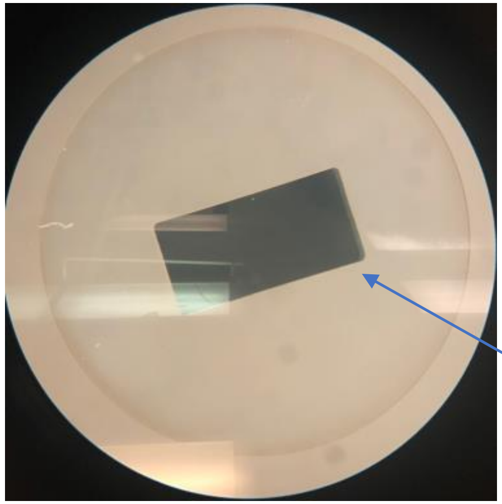
Dual detector
cartridge



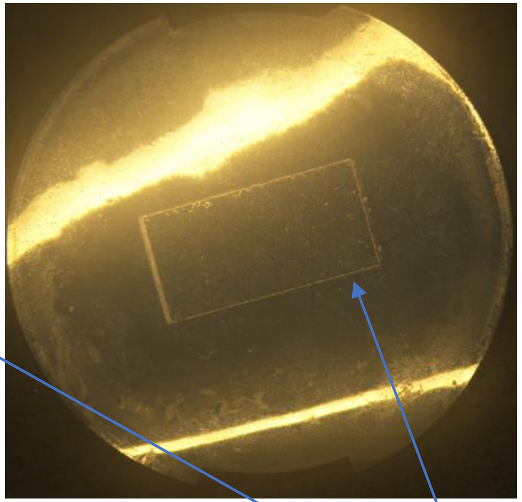
Pre-shot crystal
calibration

The opacity campaign has a library of 16+ sample types reflecting evolving goals

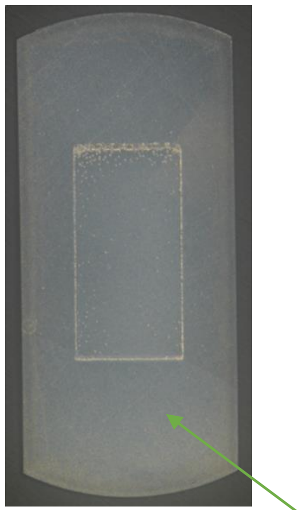
2016-Present



2020



2021- Present



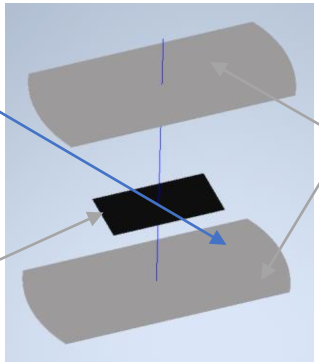
T. Day

- Higher target density requires thicker tampers
- A1: ~14µm total (2016+)
- A2: 30µm of CH!
  - (2020) Be can be thinner
  - (2021) CH. Bandaid design

Samples

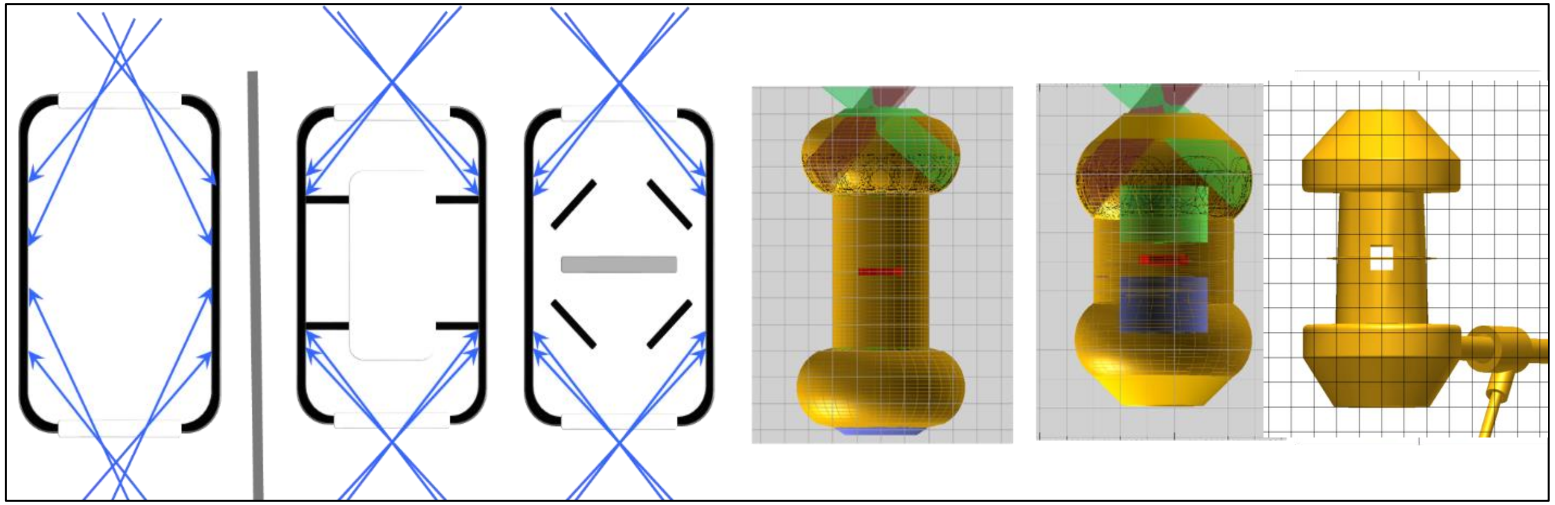
Tamper material

Co-deposited foil materials



Significant effort went into hohlraum design and the design went through several iterations

Traditional ICF | Nova Opacity | "Lamp Shade" | "McFee-Nova" | "McFee-LampShade" | "McFee-Apollo"

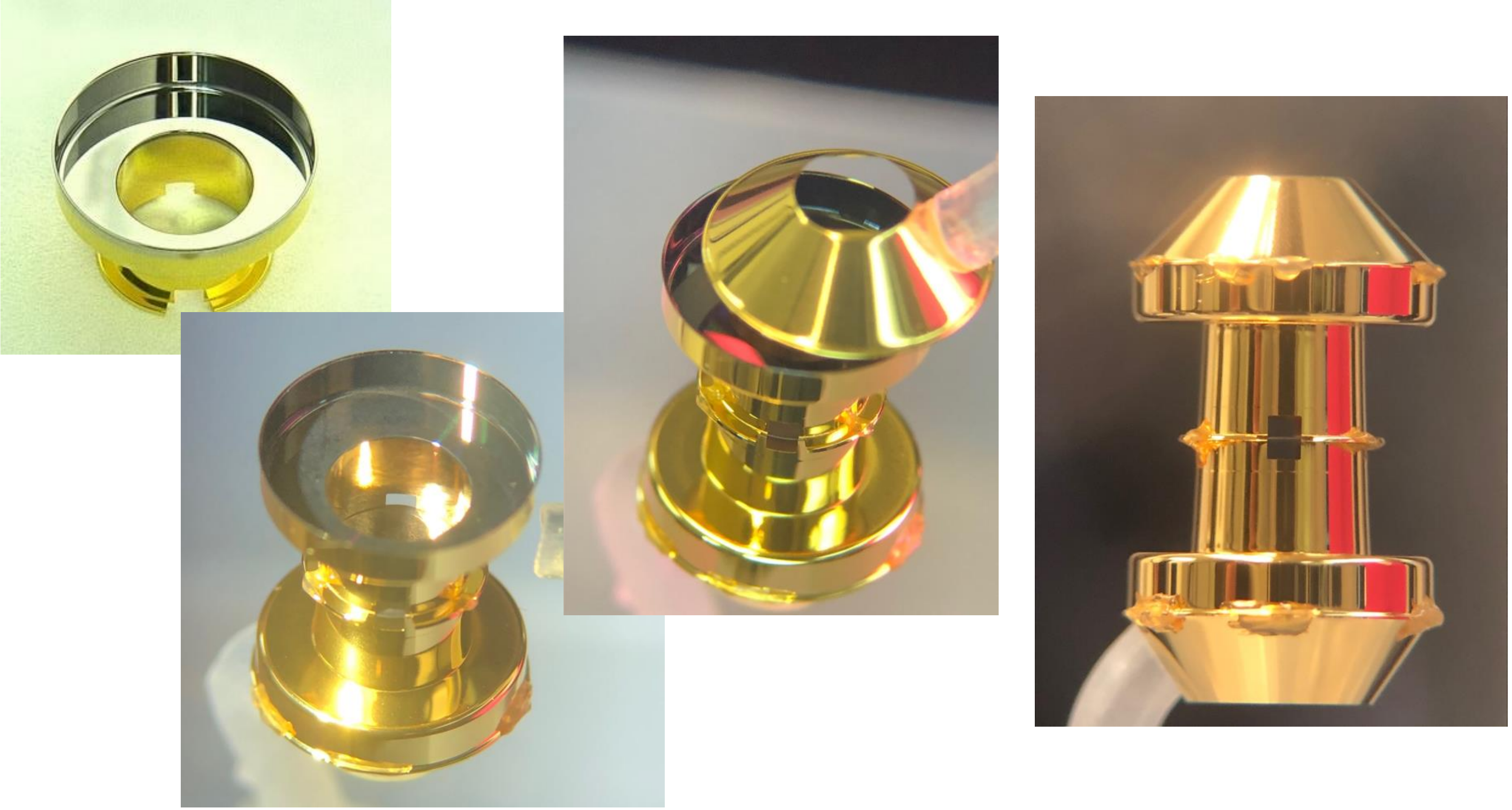


The hohlraum has to (1) keep sample from seeing NLTE laser spots (2) keep the spectrometer from seeing gold blow-off from hohlraum walls and (3) reach the required temperatures

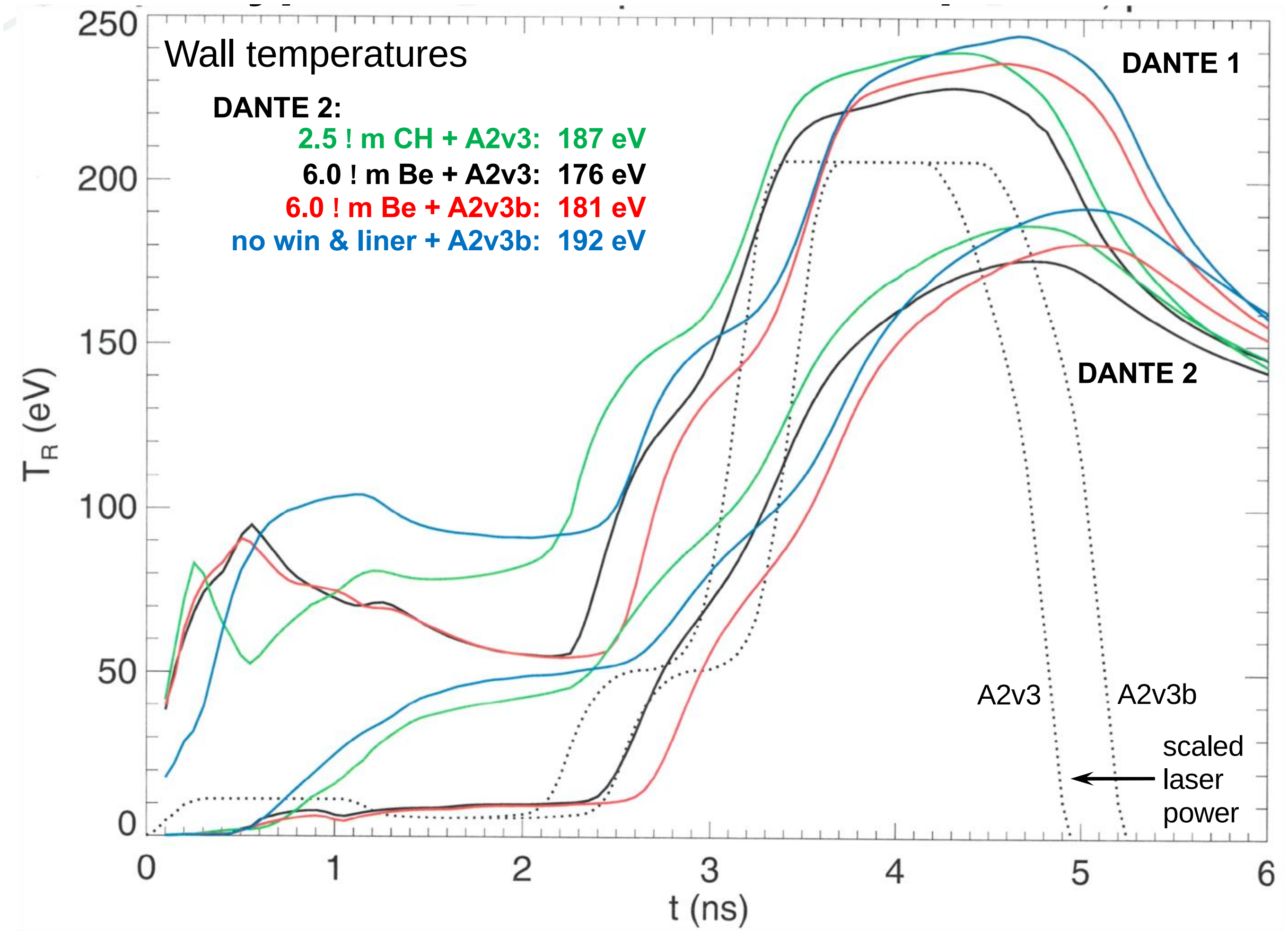
E. S. Dodd, et al, POP (2018)
T. Cardenas, et al, Fus. Sci. Tech (2018)

The latest hohlraums include Be lining, windows, and an upper LEH collimator

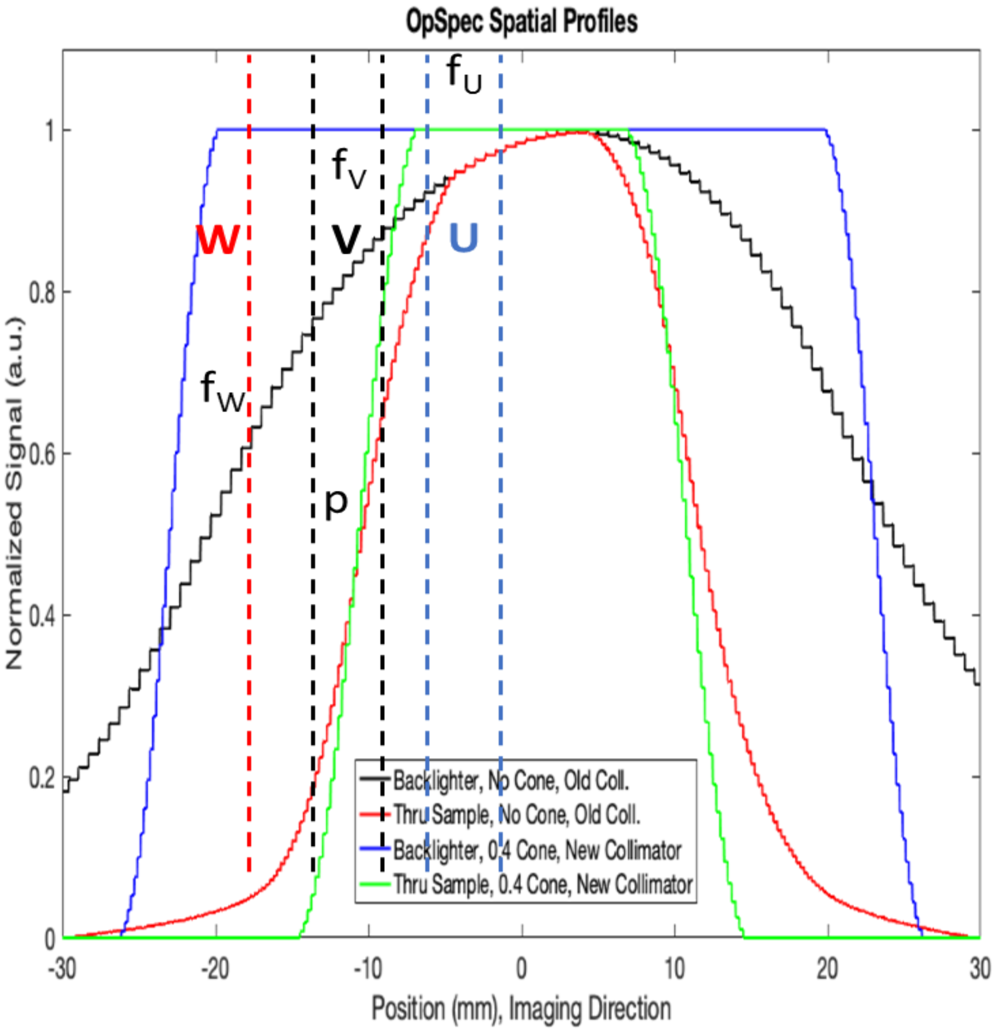
New 4-part, Be-lined hohlraum (GA) with Be-tamped Fe:Mg sample (LANL+GA) assembled by LANL have been used since October 2020.



Hohlraum drive has been adjusted to reduce background from the picket on the LEH window, and support thicker tamped samples requiring longer pulses.



For early data with bare-shell backlighter, data can be corrected for both penumbral blurring and 2nd order diffraction background, but it's complex…



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: $W = \Sigma_n [\, f_{Wn} B_n + E_n \,] + X$

$R = (U\text{-}W) / (V\text{-}W)$

("naïve transmission ratio")

$\mathbf{U\text{-}W = \Sigma_n [\, (T_n f_{Un} - f_{Wn}) B_n \,].}$

Assume $F_{Un} = F_{U1}$; $F_{Wn} = F_{W1}$ etc.

$\mathbf{B_n/B_1 = (S_n/S_1)*(F_n/F_1)*(R_n/R_1)n^2}$

Define $Q_n = (T_n f_{Un} - f_{Wn})B_n/((T_1 f_{U1} - f_{W1})B_1) = \mathbf{[(T_n f_{Un} - f_W)/(T_1 f_{Un} - f_W)](B_n/B_1)}$.

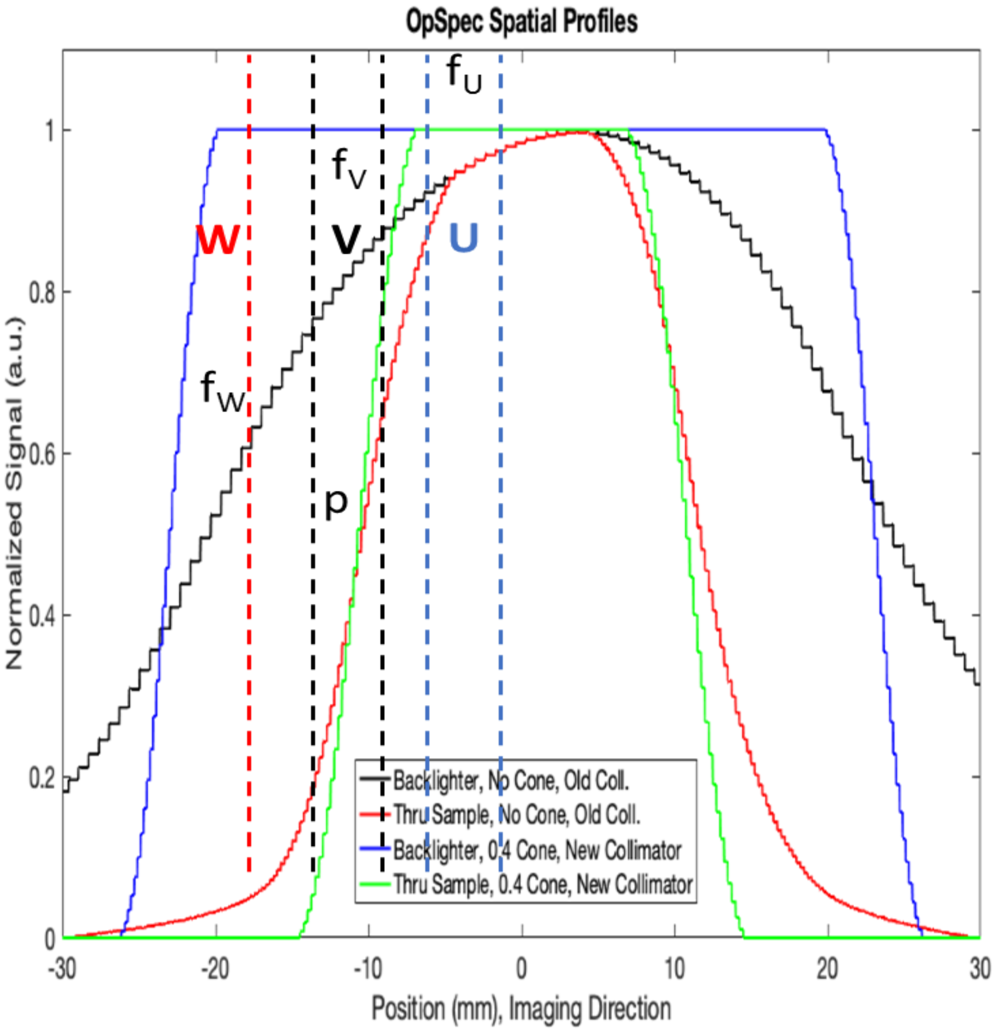
Then $\mathbf{(U\text{-}W) = (T_1 f_{U1} - f_{W1})*B_1*Q_{sum}}$ where $Q_{sum} = \Sigma_n (Q_n)$

$\mathbf{V\text{-}W = \Sigma_n [\, (T'_n f_{Vn} - f_{Wn}) B_n \,].}$

$Q'_n = [(T_n' f_{Vn} - f_W)/(T_1' f_{Vn} - f_W)](B_n/B_1)$.

$\mathbf{(V\text{-}W) = (T_1' f_{V1} - f_{W1}) B_1 Q'_{sum}}$ where $Q'_{sum} = \Sigma_n (Q'_n)$.

One can get to a corrected transmission this way, but a more direct approach with fewer parameters and less human judgment is desirable.



$(U-W) = (T_1 f_{U1} - f_{W1})*B_1*Q_{sum}$ 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 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 the 1st order Transmission (including 2nd & 3rd order correction and penumbral blurring correction) is:

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

Many differences and questions persist about the best method to make comparisons

- Opacity-on-Z
  - Density, Temperature from lines
  - Limited backgrounds
  - Density, temperature can’t be independently controlled
  - Higher resolution spectra
- Opacity-on-NIF
  - Density and temperature can be independently controlled
  - Backgrounds are a problem, but many improvements have been made.
  - Independent density and temperature
  - Sample behavior can be much better characterized
- Theory
  - Comparing spectra at slightly different conditions
  - What spectral characteristics are most important and most constraining?
  - Etc.