Conduction-Zone Measurements Using X-Ray Self-Emission Images

A. K. DAVIS, D. T. MICHEL, S. X. HU, R. EPSTEIN, J. P. KNAUER, and D. H. FROULA

University of Rochester, Laboratory for Laser Energetics

Summary

X-ray self-emission images are used to diagnose the evolution of the electron temperature and density in the coronal plasma to determine the growth of the conduction zone

- The self-emission in these conditions can be described by a blackbody spectrum, which allows for the separation of the density and temperature contributions to the emissivity
- Spherical symmetry of the implosions and negligible absorption in the corona allow for the self-emission profiles to be Abel-inverted to find the emissivity
- Emissivity profiles are simultaneously measured with three different filters to determine the emission spectrum and temperature profile
- From the temperature and emissivity, the density in the conduction zone is determined for each measurement time
- Initial comparisons with *LILAC* simulations show good agreement between measurements and simulations

E25077

The emissivity of the plasma is determined by Abel-inverting the measured self-emission profile

Discretized radiation-transfer equation:

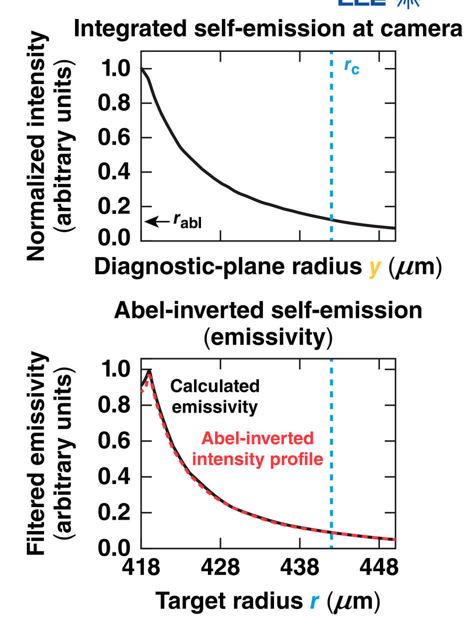
$$I(\nu, s+\Delta s, y) = I(\nu, s, y)e^{-\kappa'\Delta s} + (1-e^{-\kappa'\Delta s})\,B(\nu, s, y)$$

For $\kappa'_{\nu}\Delta s \ll 1$ (negligible absorption):

$$I(\nu, s+\Delta s, y) = I(\nu, s, y) + B(\nu, s, y)\,\kappa'\Delta s$$

Intensity at diagnostic plane:

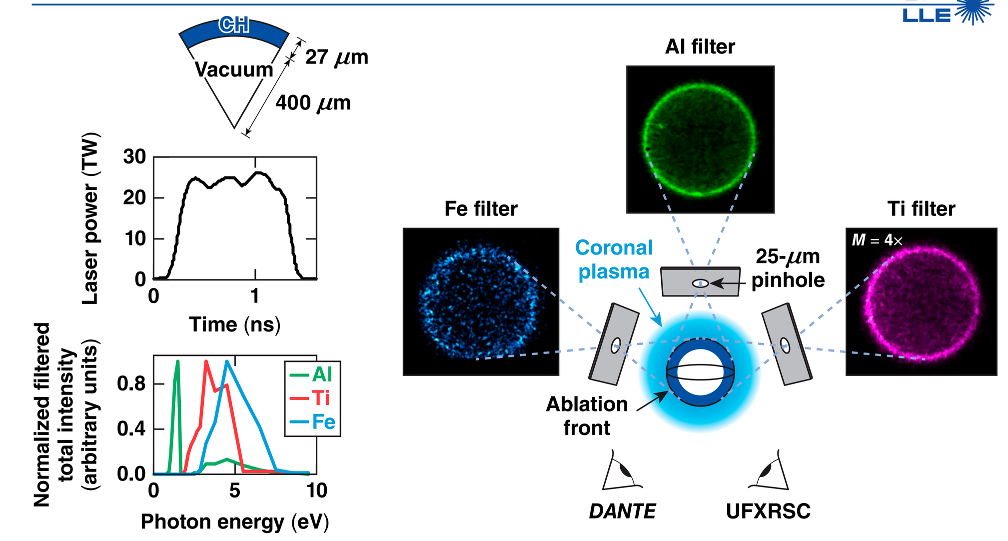
$$I(\nu, \mathrm{DP}, y) \approx \int_{-\infty}^{\infty} \epsilon\left[(s-s_0)^2 + y^2\right] ds$$



The Abel inversion is possible because the absorption is negligible in the corona a few microns outside of the ablation front for the x-ray frequencies measured.

E25080

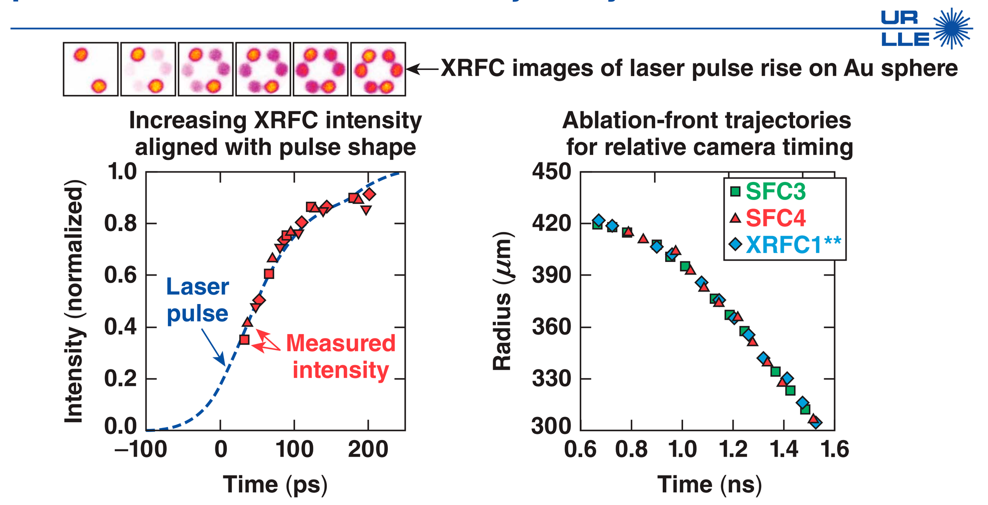
Three x-ray framing cameras were used in experiments to simultaneously measure the self-emission profiles at three wavelengths



DANTE and the ultrafast x-ray streak camera (UFXRSC) were used to cross-calibrate the emission between the three cameras.

E25083

Absolute-timing calibrations within 20 ps for the three framing cameras were obtained by measuring the rise of the laser pulse and the ablation-front trajectory with all three cameras*



More precise relative timing was obtained by cross-calibrating the absolute timing between the cameras using the trajectory of an imploding shell as a reference.

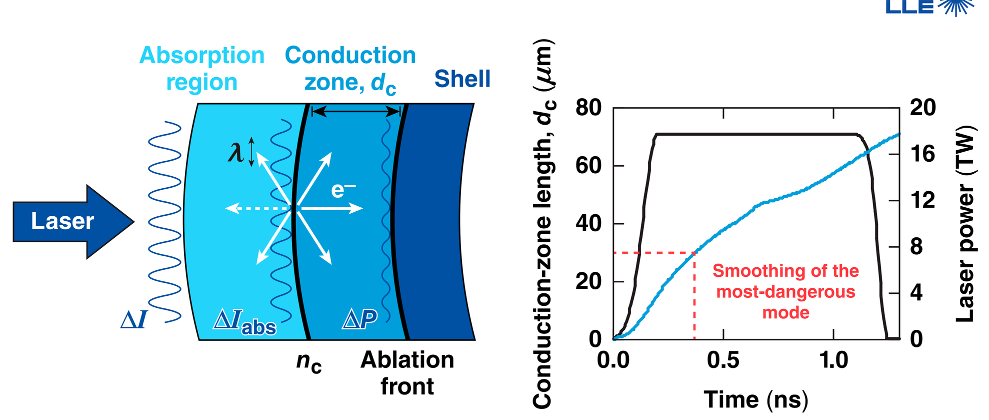
SFC: Sydor framing camera

*D. T. Michel *et al.*, High Power Laser Science and Engineering 3, e19 (2015).

**15-ps shift from absolute-timing calibration

E23820

In directly driven inertial confinement fusion implosions, the laser imprint is smoothed through electron thermal conduction once the conduction-zone length is larger than the size of the nonuniformities ($d_c > \lambda$)

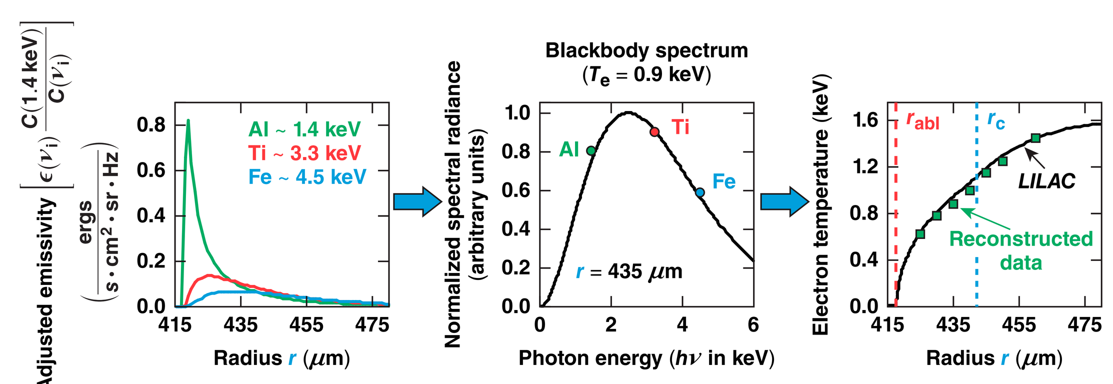


Characterizing the growth of the conduction zone is critical to determine the size of the nonuniformities imprinted on the target surface by the laser.

E25078

The x-ray filtration was varied to isolate the effect of the temperature on the emission

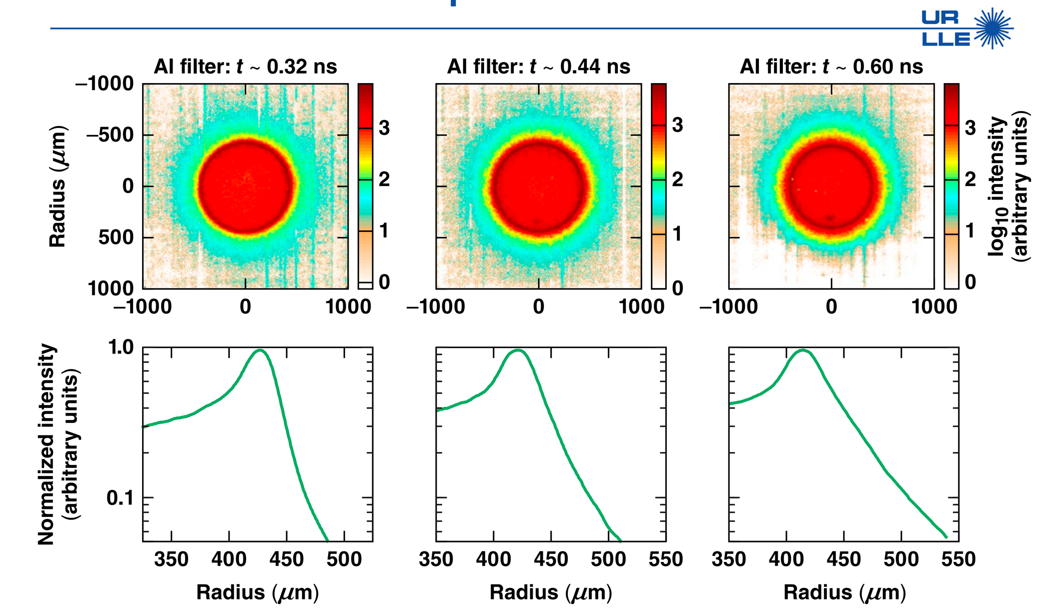
Each filter selects a known frequency: $\dfrac{B(\nu_2, T_e)}{B(\nu_1, T_e)} \approx \dfrac{\epsilon(\nu_2, n_i, T_e)}{\epsilon(\nu_1, n_i, T_e)}\dfrac{C(\nu_1)}{C(\nu_2)}$



Measuring the ratio of the emissivity for different frequencies makes it possible to determine the temperature by fitting it with a blackbody spectrum.

E25081

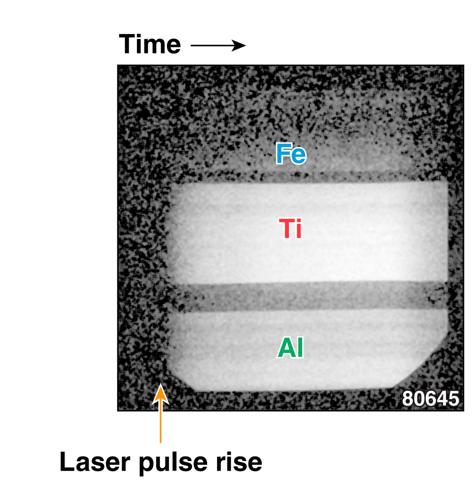
Images are taken at different times early in the laser pulse to determine the development of the conduction zone



Profiles are angularly averaged around the target to improve the signal-to-noise ratio.

E25084 80647

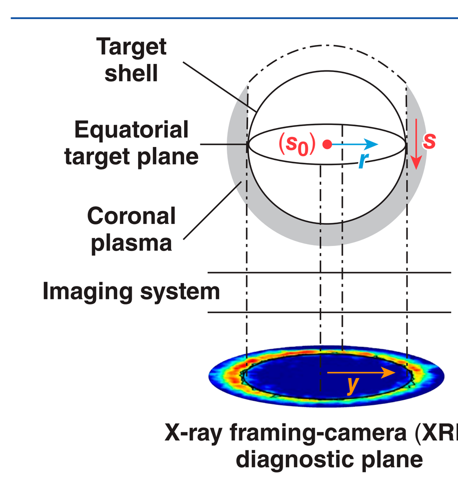
Absolute calibrations for the three framing cameras were obtained by simultaneously measuring the emission on the ultrafast x-ray streak camera



Similar absolute-calibration measurements were obtained using the *DANTE* diagnostic.

E25086

The length of the conduction zone is determined by measuring the temperature and density of the coronal plasma



Emissivity in corona:

$$\epsilon \approx B(\nu, T_e) * \underbrace{C(\nu) * f(n_i, T_e)}_{\kappa'(\nu,\, n_i,\, T_e)}$$

ϵ = specific emissivity

I = specific intensity

$B(\nu, T_e)$ = blackbody source term*

$\kappa'(\nu, n_i, T_e)$ = specific opacity**

The temperature [$T_e(r)$] and density [$n_i(r)$] are determined from x-ray self-emission images [$\epsilon(\nu, r)$].

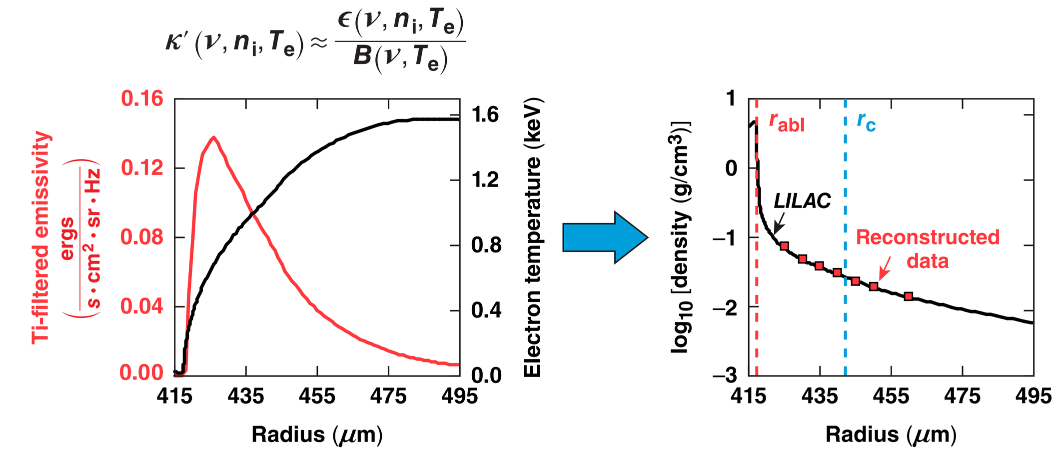
*Local thermodynamic equilibrium (LTE) approximation

**Tabulated

E25079

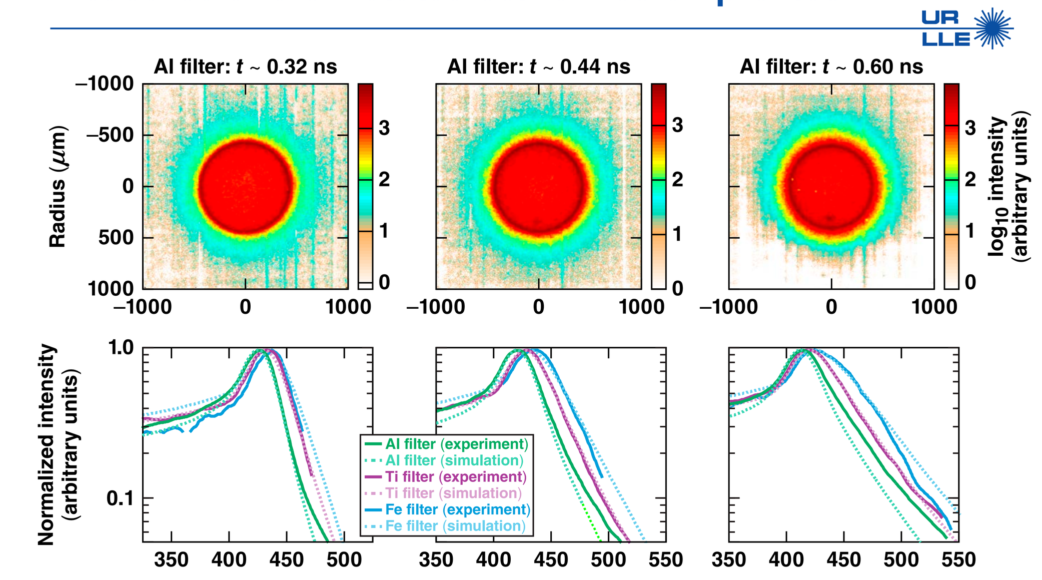
With the measured emissivity and temperature, the opacity is calculated and the density is determined using opacity tables

$$\kappa'(\nu, n_i, T_e) \approx \frac{\epsilon(\nu, n_i, T_e)}{B(\nu, T_e)}$$



E25082

Early comparisons show good agreement between measured and simulated self-emission profiles



A more in-depth analysis is in progress.

E25085 80647

Future work will apply the described method to reconstruct the density profile in several images and determine the growth of the conduction zone

- The framing-camera images will be absolutely calibrated to quantitatively reconstruct the temperature and density profiles from the experiments
- The growth of the conduction zone will be determined for various laser intensities
- The growth of the conduction zone will be compared for a square pulse and a square pulse with a picket

Results will be compared with simulations using several models for thermal transport and equation of state to benchmark the early-time evolution of the plasma.

E25087

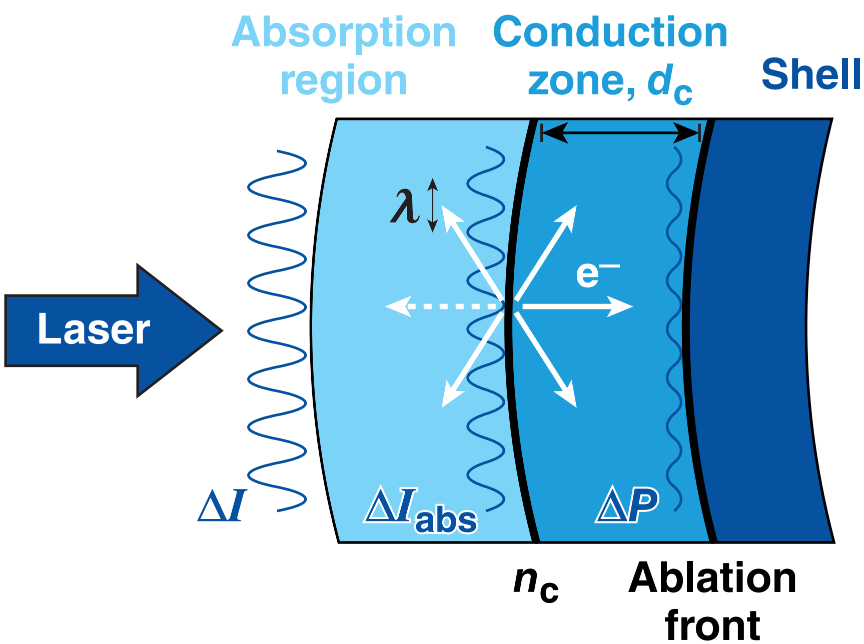
UNIVERSITY of ROCHESTER

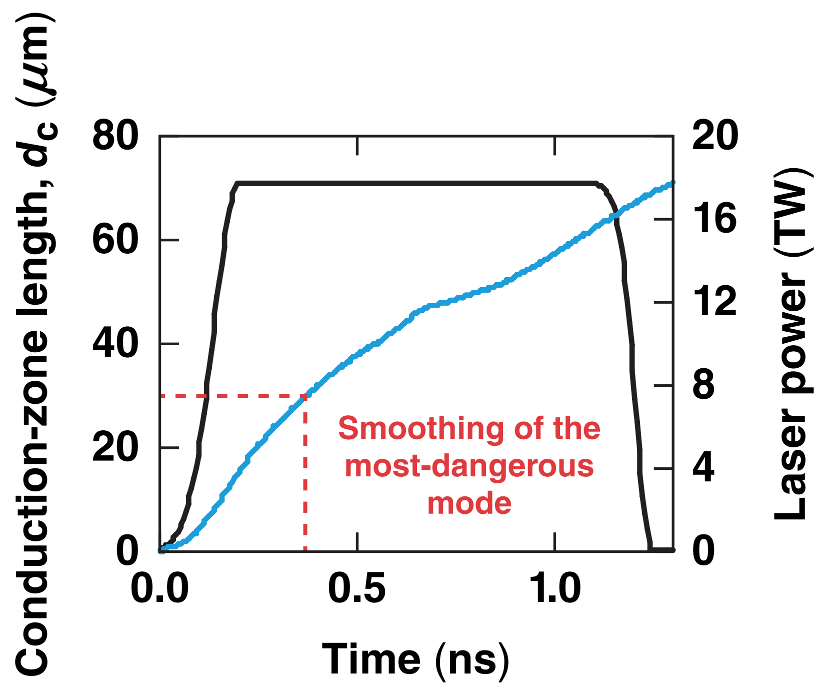
Summary

X-ray self-emission images are used to diagnose the evolution of the electron temperature and density in the coronal plasma to determine the growth of the conduction zone

- The self-emission in these conditions can be described by a blackbody spectrum, which allows for the separation of the density and temperature contributions to the emissivity
- Spherical symmetry of the implosions and negligible absorption in the corona allow for the self-emission profiles to be Abel-inverted to find the emissivity
- Emissivity profiles are simultaneously measured with three different filters to determine the emission spectrum and temperature profile
- From the temperature and emissivity, the density in the conduction zone is determined for each measurement time
- Initial comparisons with *LILAC* simulations show good agreement between measurements and simulations

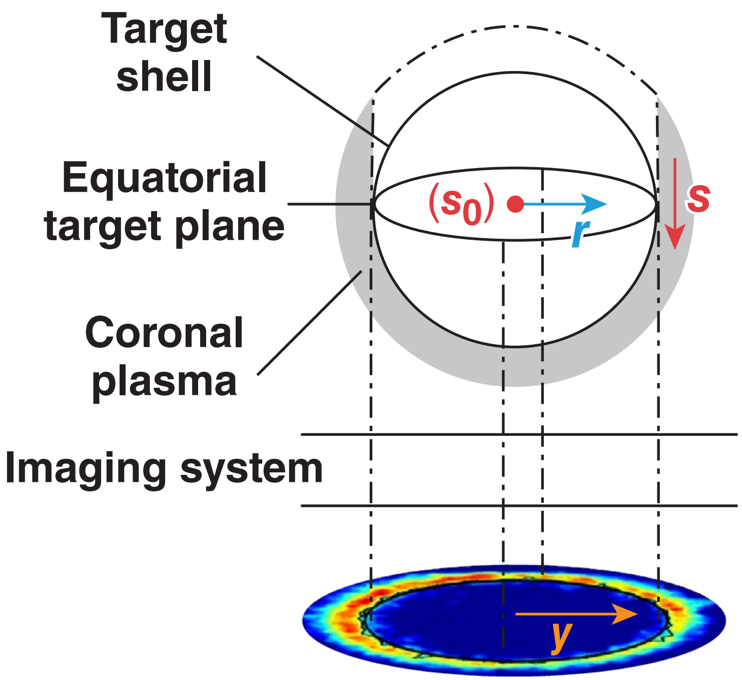
In directly driven inertial confinement fusion implosions, the laser imprint is smoothed through electron thermal conduction once the conduction-zone length is larger than the size of the nonuniformities ($d_c > \lambda$)





Characterizing the growth of the conduction zone is critical to determine the size of the nonuniformities imprinted on the target surface by the laser.

The length of the conduction zone is determined by measuring the temperature and density of the coronal plasma



X-ray framing-camera (XRFC) diagnostic plane

Emissivity in corona:

$$\epsilon \approx B(\nu, T_e) * \underbrace{C(\nu) * f(n_i, T_e)}_{\kappa'(\nu, n_i, T_e)}$$

ϵ = specific emissivity
I = specific intensity
$B(\nu, T_e)$ = blackbody source term*
$\kappa'(\nu, n_i, T_e)$ = specific opacity**

The temperature $[T_e(r)]$ and density $[n_i(r)]$ are determined from x-ray self-emission images $[\epsilon(\nu, r)]$.

*Local thermodynamic equilibrium (LTE) approximation
**Tabulated

E25079

The emissivity of the plasma is determined by Abel-inverting the measured self-emission profile

Discretized radiation-transfer equation:

$$I(\nu, s+\Delta s, y) = I(\nu, s, y)e^{-\kappa'\Delta s} + \left(1 - e^{-\kappa'\Delta s}\right)B(\nu, s, y)$$

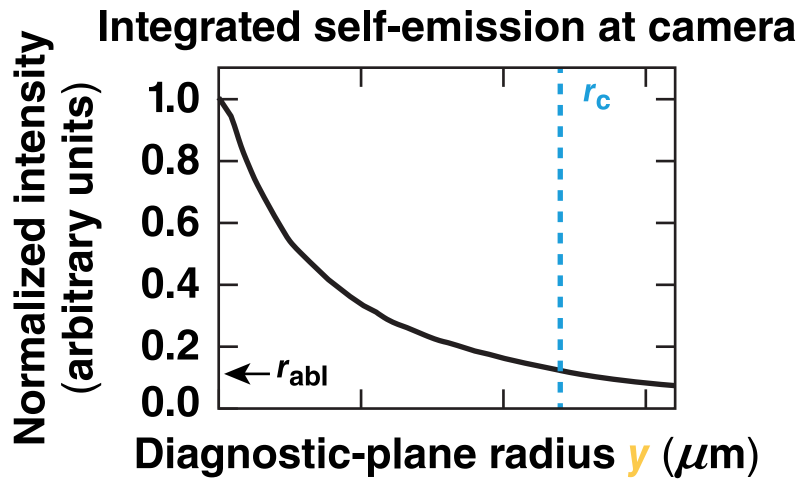
For $\kappa'_{\nu}\Delta s \ll 1$ (negligible absorption):

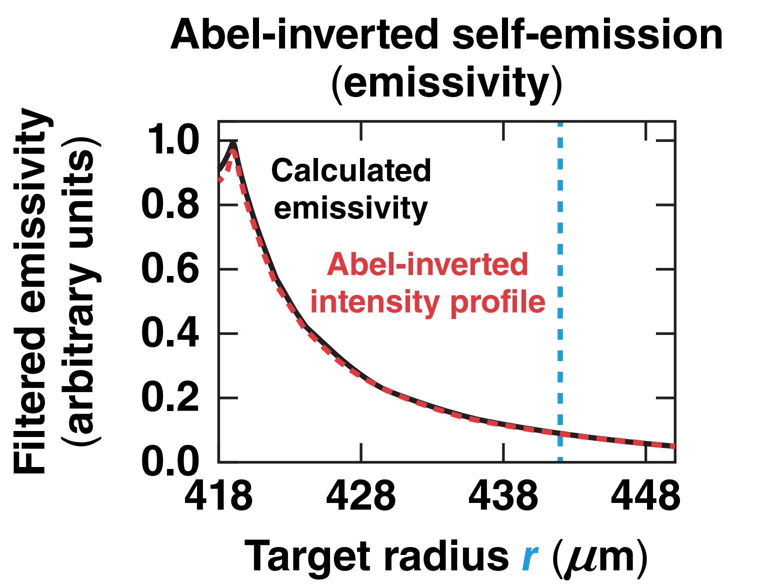
$$I(\nu, s+\Delta s, y) = I(\nu, s, y) + B(\nu, s, y)\,\kappa'\Delta s$$

Intensity at diagnostic plane:

$$I(\nu, \mathrm{DP}, y) \approx \int_{-\infty}^{\infty} \epsilon\left[(s - s_0)^2 + y^2\right]ds$$

The Abel inversion is possible because the absorption is negligible in the corona a few microns outside of the ablation front for the x-ray frequencies measured.

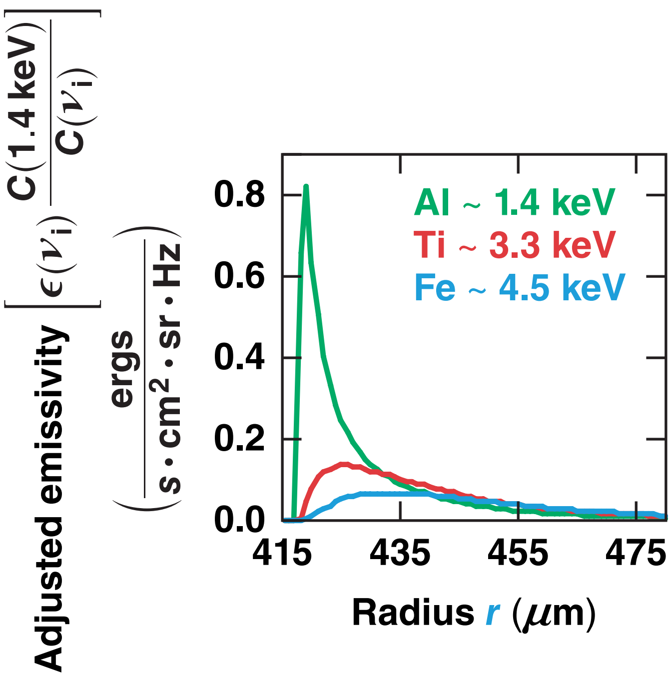


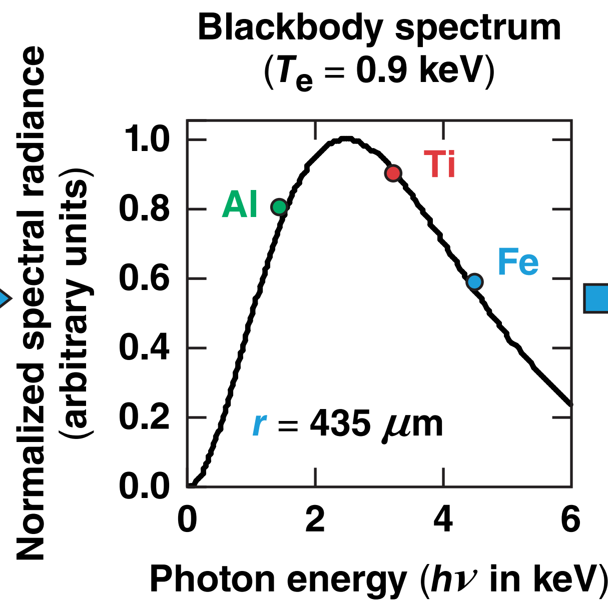


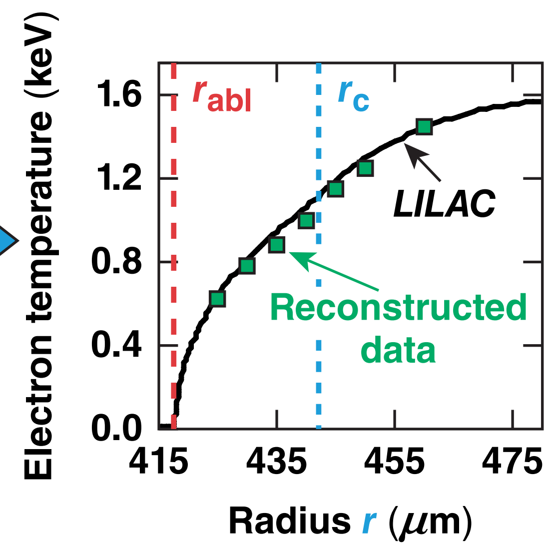
E25080

The x-ray filtration was varied to isolate the effect of the temperature on the emission

Each filter selects a known frequency: $\dfrac{B(\nu_2, T_e)}{B(\nu_1, T_e)} \approx \dfrac{\epsilon(\nu_2, n_i, T_e)}{\epsilon(\nu_1, n_i, T_e)} \dfrac{C(\nu_1)}{C(\nu_2)}$







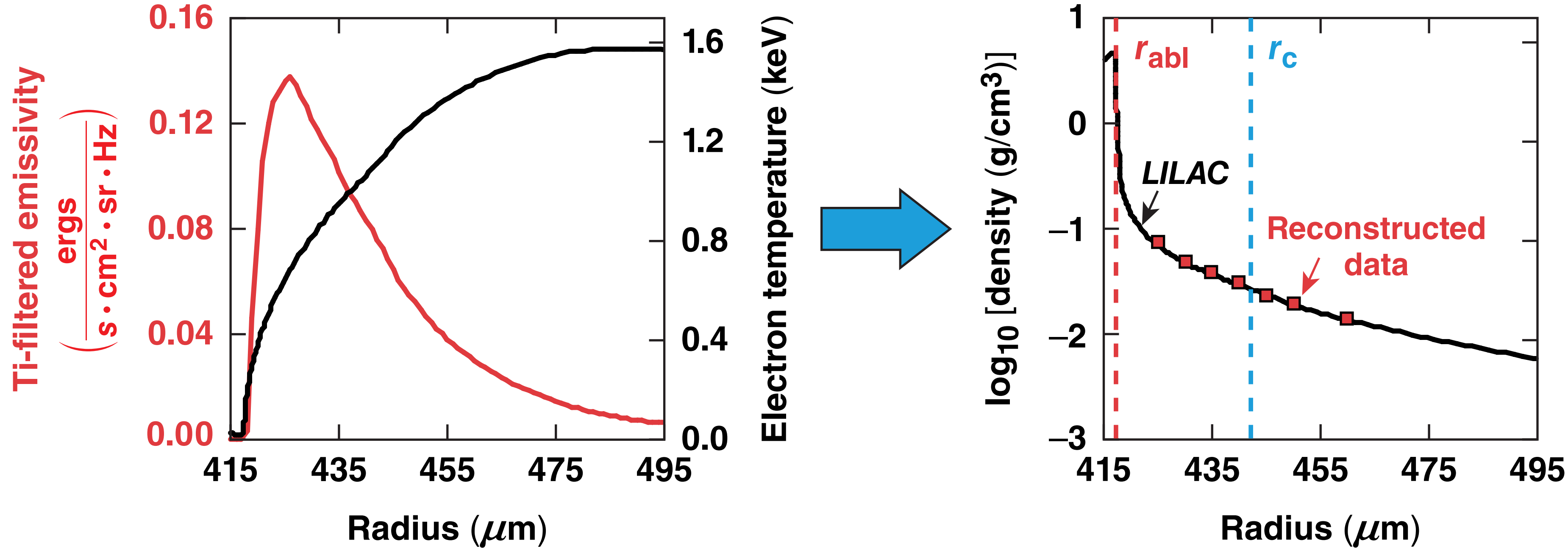
Measuring the ratio of the emissivity for different frequencies makes it possible to determine the temperature by fitting it with a blackbody spectrum.

E25081

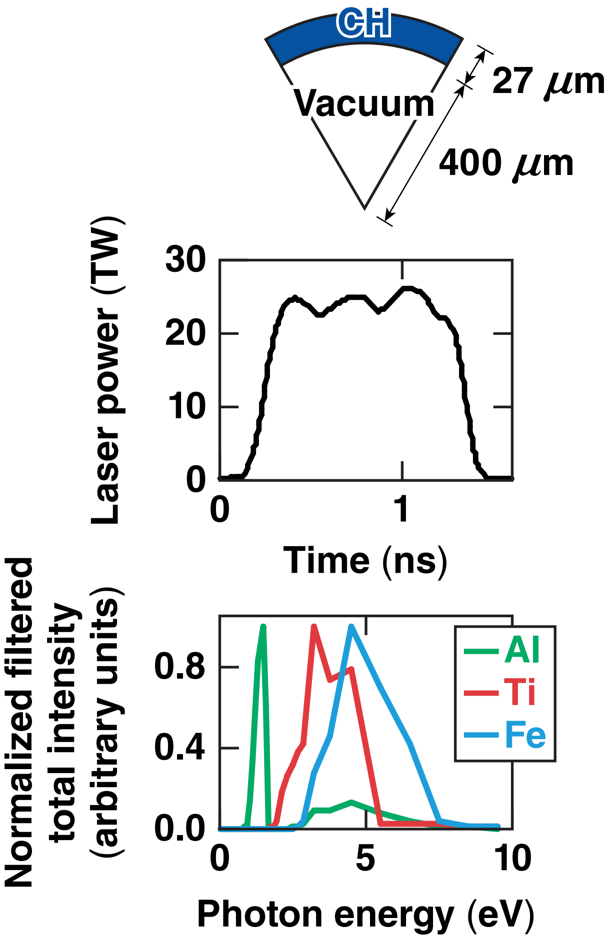
With the measured emissivity and temperature, the opacity is calculated and the density is determined using opacity tables

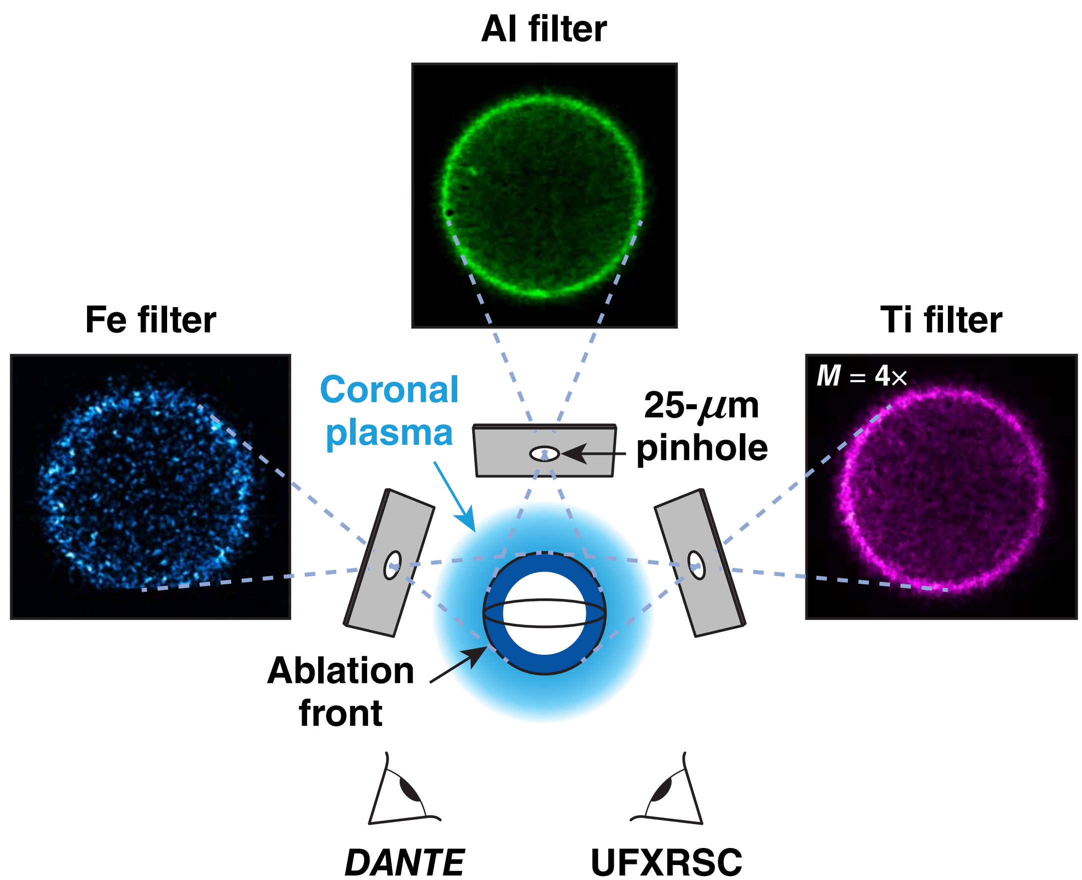
UR LLE

$$\kappa'(\nu, n_i, T_e) \approx \frac{\epsilon(\nu, n_i, T_e)}{B(\nu, T_e)}$$



Three x-ray framing cameras were used in experiments to simultaneously measure the self-emission profiles at three wavelengths

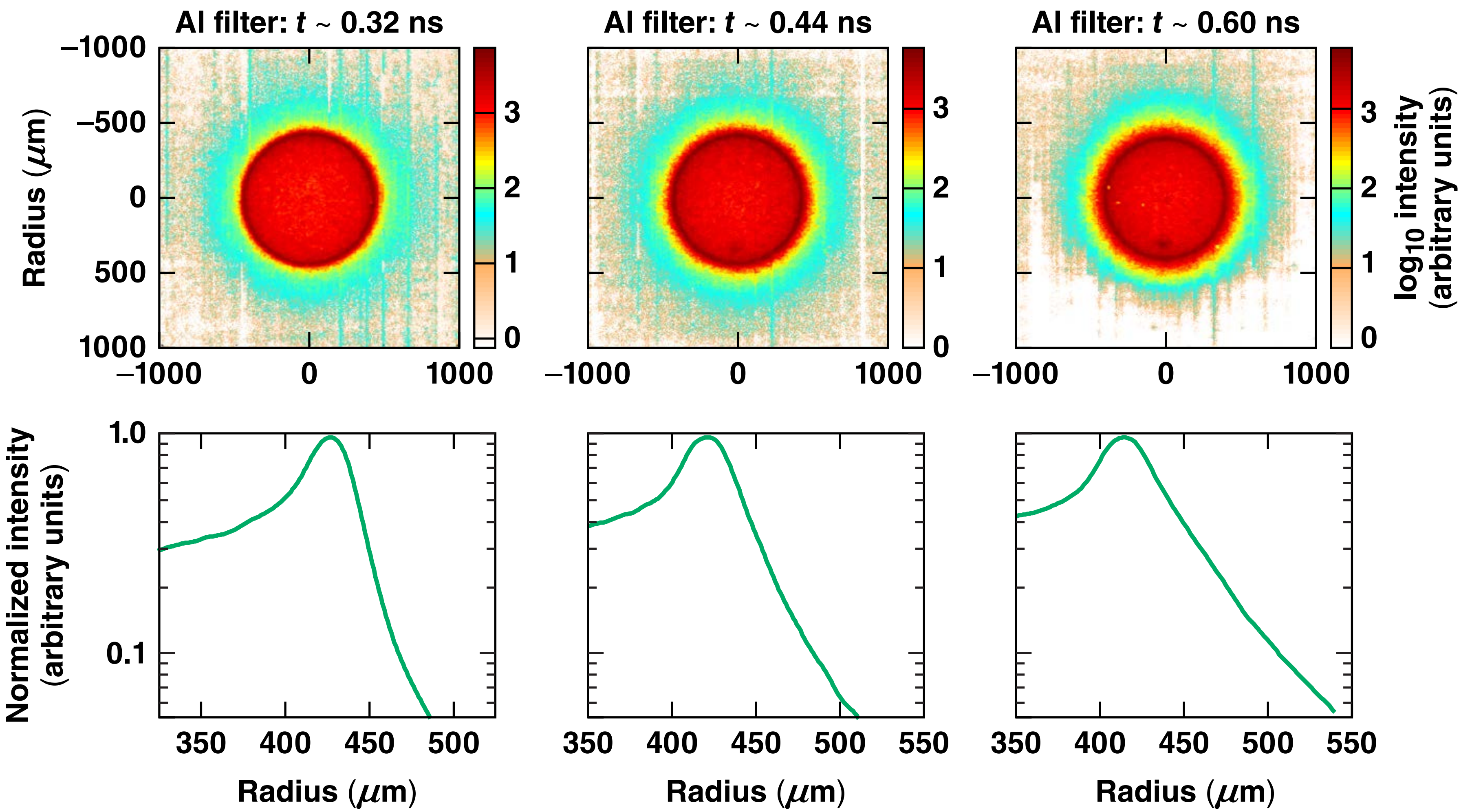




DANTE and the ultrafast x-ray streak camera (UFXRSC) were used to cross-calibrate the emission between the three cameras.

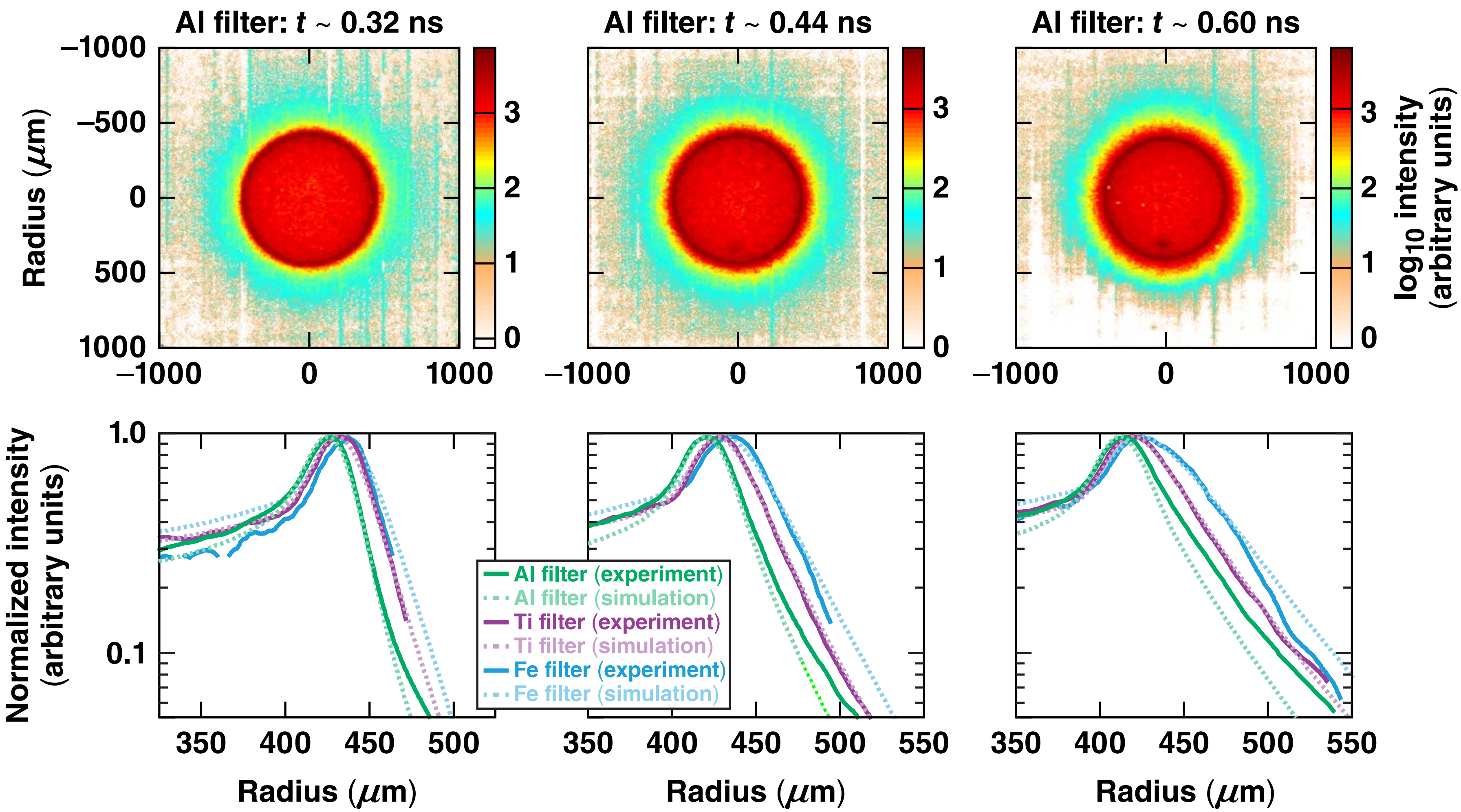
E25083

Images are taken at different times early in the laser pulse to determine the development of the conduction zone



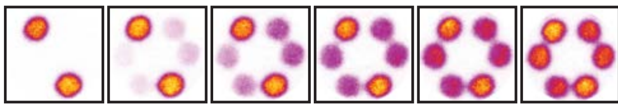
Profiles are angularly averaged around the target to improve the signal-to-noise ratio.

Early comparisons show good agreement between measured and simulated self-emission profiles



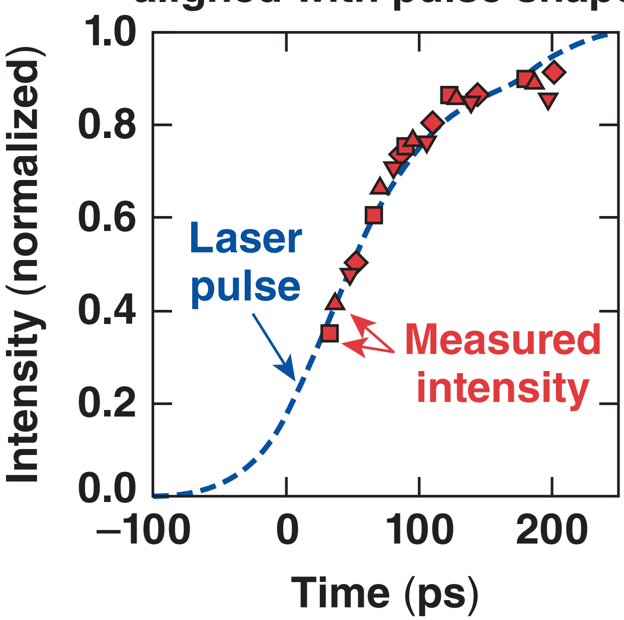
A more in-depth analysis is in progress.

Absolute-timing calibrations within 20 ps for the three framing cameras were obtained by measuring the rise of the laser pulse and the ablation-front trajectory with all three cameras*

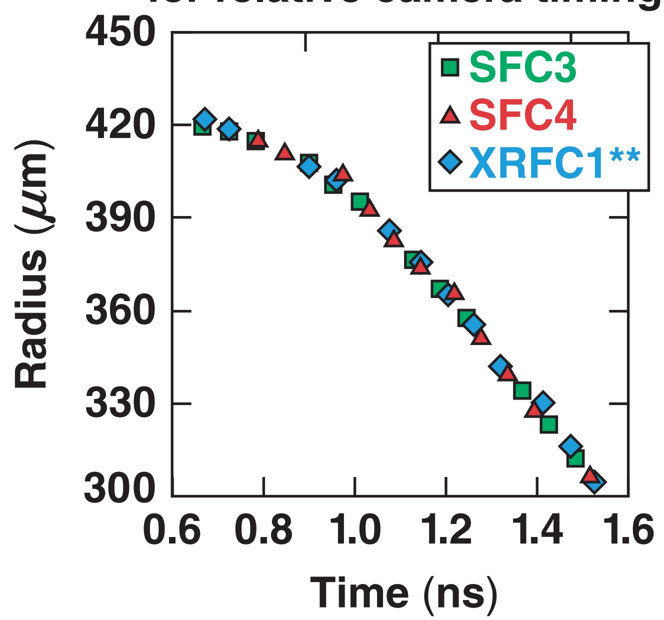


XRFC images of laser pulse rise on Au sphere

Increasing XRFC intensity aligned with pulse shape



Ablation-front trajectories for relative camera timing



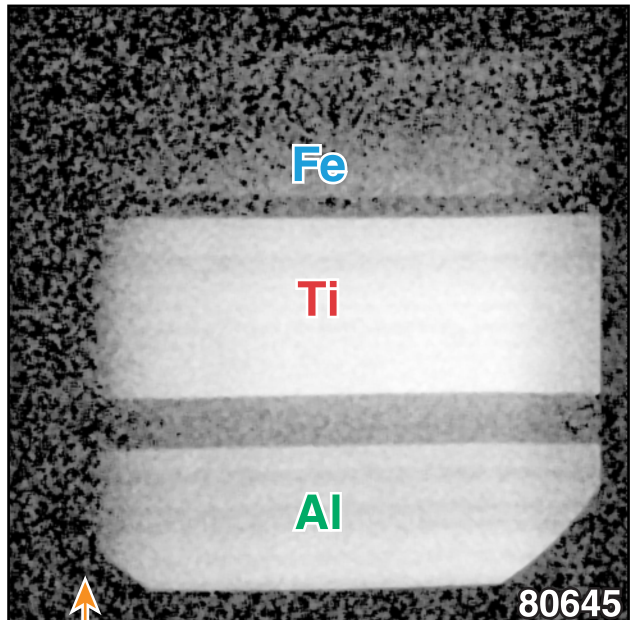
More precise relative timing was obtained by cross-calibrating the absolute timing between the cameras using the trajectory of an imploding shell as a reference.

E23820

SFC: Sydor framing camera
*D. T. Michel *et al.*, High Power Laser Science and Engineering 3, e19 (2015).
**15-ps shift from absolute-timing calibration

Absolute calibrations for the three framing cameras were obtained by simultaneously measuring the emission on the ultrafast x-ray streak camera

Time ⟶



Laser pulse rise

Similar absolute-calibration measurements were obtained using the *DANTE* diagnostic.

Future work will apply the described method to reconstruct the density profile in several images and determine the growth of the conduction zone

- The framing-camera images will be absolutely calibrated to quantitatively reconstruct the temperature and density profiles from the experiments
- The growth of the conduction zone will be determined for various laser intensities
- The growth of the conduction zone will be compared for a square pulse and a square pulse with a picket

Results will be compared with simulations using several models for thermal transport and equation of state to benchmark the early-time evolution of the plasma.