Interpreting the Electron Temperature Inferred from X-Ray Continuum Emission for Direct-Drive Inertial Confinement Fusion Implosions on OMEGA

D. Cao, R. C. Shah, S. P. Regan, R. Epstein, I. V. Igumenshchev, V. Gopalaswamy, A. R. Christopherson, W. Theobald, P. B. Radha, and V. N. Goncharov

Laboratory for Laser Energetics, University of Rochester

We present findings on which the x-ray–inferred electron temperature T_e will be interpreted for direct-drive ICF implosions on OMEGA: (1) an analytic description of the electron temperature as the emission-weighted, harmonic mean temperature; (2) an optimal x-ray energy that gives emission weighting closest to neutron weighting; (3) simulation results showing disparity between hot-spot electron temperature and ion temperature, even without fluid motion biasing for OMEGA-scale implosions; and (4) simulation results showing correlation of the implosion degradation with the hot-spot electron temperature and x-ray yield.

It can be shown that the inferred T_e from x-ray continuum emission represents an emission-weighted, harmonic average temperature of the emitting body. From an x-ray spectrum that can be both time and spatially integrated, the emitting body's temperature can be obtained by applying a linear fit in log space and calculating that fit's negative inverse slope, as shown in Fig. 1 for an example profile. This inferred temperature is found to follow the harmonic average relation

$$\frac{1}{kT_{\text{fit}}} = \frac{1}{I_\nu} \iint \varepsilon_\nu^{\text{FF}} \left[\frac{1}{kT_e(\mathbf{r})}\right] \mathrm{d}V \mathrm{d}t = \left\langle \frac{1}{kT_e(\mathbf{r})} \right\rangle, \tag{1}$$

where T_{fit} is the inferred electron temperature, k is the Boltzmann constant, I_ν is the total x-ray yield at photon energy $h\nu$, V is the volume, t is time, T_e is the true electron temperature, and $\varepsilon_\nu^{\text{FF}}$ is the free–free bremsstrahlung emissivity assuming full ionization.

As shown in Fig. 1(c) for the example profile, results from applying Eq. (1) give the same value as performing the linear fit exercise in Fig. 1(b). Since the inferred electron temperature will be a harmonic average, it will be generally lower than an emission-weighted, arithmetic average by ~100 eV as shown in Fig. 1(c).

With a physical understanding of the inferred temperature and its weighting on photon energy, it is next important to know the photon energy most optimal for inferring the hot-spot electron temperature. Given that complementary ion temperature measurements are neutron weighted, it would be most meaningful for the electron temperature to be weighted by the same spatial distribution as the neutron emission for the purpose of assessing implosion performance. By using a power law approximation $\varepsilon_\nu^{\text{FF}} \propto T^\eta$ for the emissivity, where the exponent η is given by

$$\eta = \frac{h\nu_0}{kT_0}, \tag{2}$$

it is found that photons with energies near $4kT_0$, where T_0 is the characteristic hot-spot temperature (e.g., has a neutron-weighted temperature of ~3.75 keV for OMEGA), are produced with a T^4 dependence (i.e., the same temperature dependence as neutron

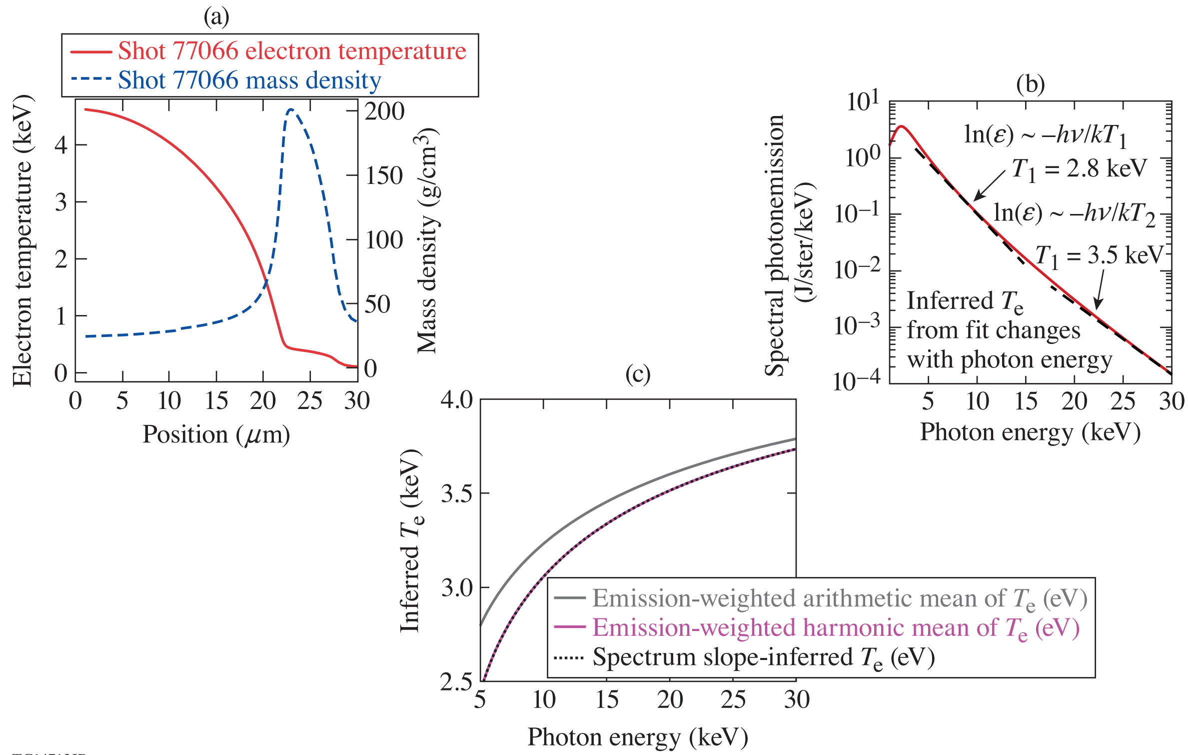

Figure 1
The process used to extract instantaneous, spatially averaged hot-spot temperature from hard x-ray emission. From a hot spot represented by the profiles in (a), the escaping photons create the x-ray spectrum[1] in (b). The electron temperature is inferred from the log slope of the spectrum in (b) and changes with photon energy caused by the distribution of temperatures within the hot spot. This in turn creates an array of slope-inferred temperatures as shown in (c). This inferred electron temperature is equivalent to the emission-weighted harmonic mean electron temperature from the hot spot and is generally lower than the emission-weighted, arithmetic mean electron temperature. A time-integrated T_e can be inferred using the same process from a time-integrated x-ray spectrum.

production from deuterium–tritium fusion). At this photon energy, the inferred electron temperature can be said to have an emission weighting that closely, but not equally, resembles neutron weighting. This can be seen in Fig. 2(a), which compares the normalized x-ray emission and neutron production for an isobaric temperature and density profile.[2]

For OMEGA-scale implosions, simulations show that the neutron-weighted ion temperature is not well approximated by the electron temperature, regardless of the photon energy used. This is shown in Fig. 2(b) using *LILAC*[3] post-shot simulations of all past DT cryogenic shots performed on OMEGA that are stored in the simulation database.[4] At all photon energies, the functional mapping between the electron temperature and the neutron-weighted ion temperature does not follow a clear $y = x$ trend. Moreover, the consequent mapping uncertainty in ion temperature can be as large as ~400 eV according to scatter in Fig. 2(b), compared to the precision error of ~130 eV from current neutron time-of-flight diagnostics on OMEGA.

This imprecise surrogacy between the ion and electron temperatures is caused by the hot spot's thermal nonequilibrium state for the simulated OMEGA implosions. The persistence of this thermal nonequilibrium can be surprising, considering that the equilibration time, which scales[5] as $\tau_{ei} \sim T^{3/2}\rho^{-1}$, is typically of the order of 10 ps or only about 10% of the burnwidth FWHM. It was found, however, that electron thermal conduction was responsible for inhibiting thermal equilibration from dominating. It is expected that hot spots will be more equilibrated for higher convergence ratio implosions at a larger scale.

Despite the non-surrogacy between the electron and ion temperatures, 3-D simulations suggest the difference of the electron temperature from the 1-D prediction $\left(\Delta T_e = T_e^{\text{inferred}} - T_e^{\text{1-D}}\right)$ can be useful as an implosion diagnostic. Figure 3 shows a comparison of the inferred electron temperature and x-ray yield between the two cases. One simulation represented an ideal case where the implosion was perfectly 1-D and another included perturbations typically observed on OMEGA from target offset ($\Delta r = 5.4\ \mu$m), beam imbalance ($\sigma_{rms} = 3.5\%$), and beam port geometry as well as laser imprint modulations ($\ell_{max} = 200$). Both simulations use target parameters from OMEGA shot 89224, an $\alpha \sim 5$ implosion with an in-flight aspect ratio $\left(\text{IFAR} = R_{shell}/\Delta R_{shell}\right)$ of ~40 and peak implosion velocity of 480 km/s.

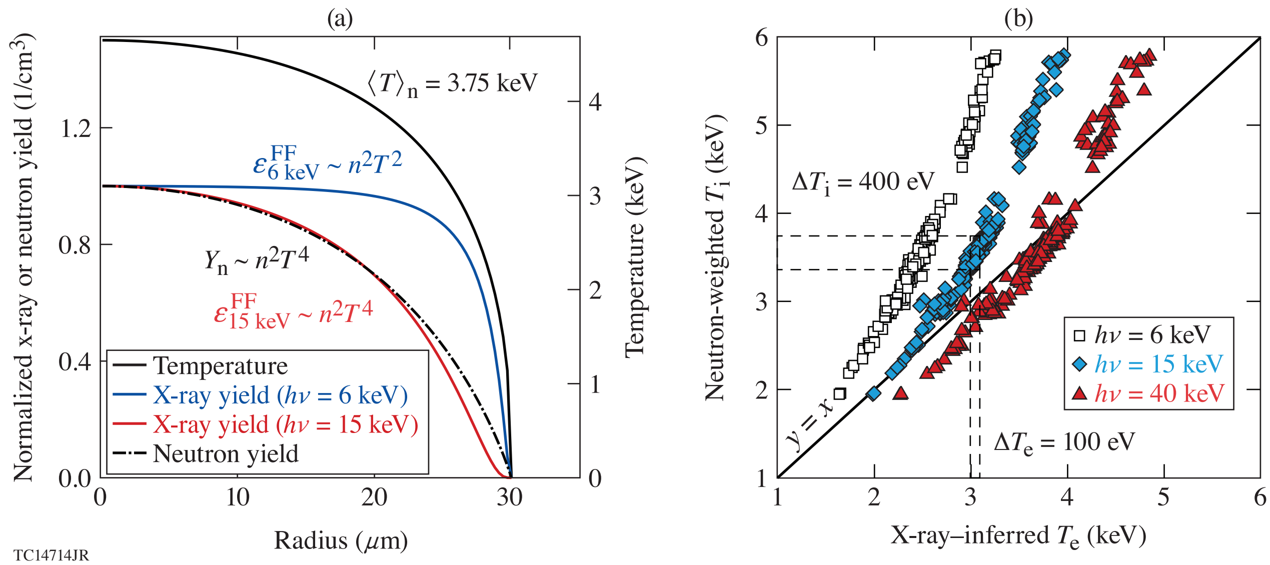

Figure 2
(a) Normalized x-ray and neutron yields comparison for a representative, isobaric hot-spot profile,[2] where $T_e = T_i$. At photon energy near 4× the neutron-weighted temperature, the emission approximately follows the neutron production. (b) The neutron-weighted ion temperature to the x-ray inferred electron temperature for all OMEGA DT cryogenic post-shot simulations in the simulation database.[4] The scatter in both plots suggests that direct surrogacy between the inferred electron temperature and the neutron-weighted ion temperature is not robust.

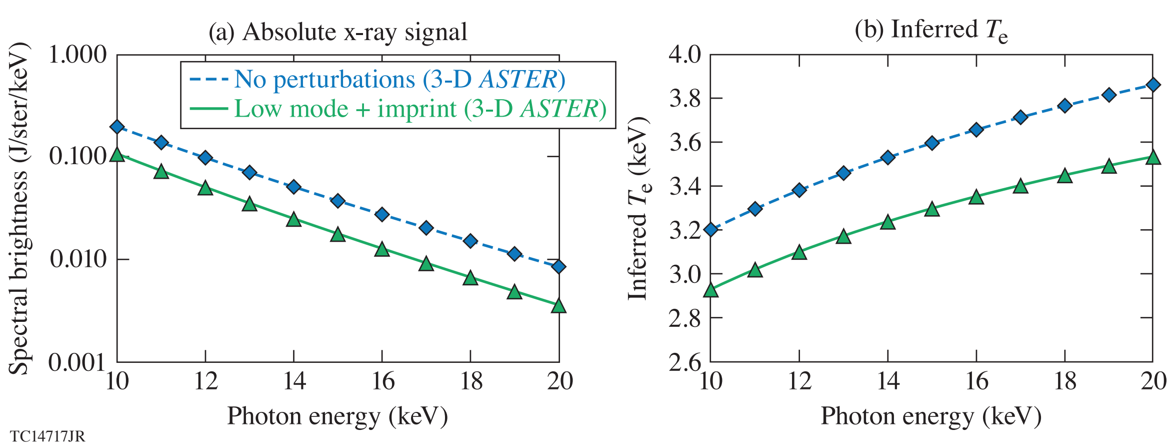

Figure 3
(a) Comparison of the electron temperature inferred from x-ray continuum emission as a function of photon energy between two *ASTER*[6] simulations with different levels of implosion perturbations. (b) Comparison of the x-ray emission as a function of photon energy for the same two *ASTER* simulations. The inferred electron temperature and the x-ray yield are not only sensitive to implosion degradation but are also sensitive enough to be measurable in experiments. The additional information these observables provide not only gives more opportunities for validating simulations, but also expands the capability of diagnosing fuel assembly during stagnation.

Between the 1-D and perturbed simulations, the neutron-weighted ion temperature dropped from 4.67 keV to 4.35 keV, and the neutron yield dropped from 4 to 2×10^{14}, a result stemming from decreased hot-spot compression. Similar to the neutron-weighted ion temperature, the electron temperature dropped by almost the same amount (~300 eV) throughout the 10- to 20-keV emission energy range. These changes being similar is not a coincidence; the 10- to 20-keV emission energy range is centered on the optimal energy range at which emission weighting is closest to neutron weighting. The drop being almost consistent across the entire range suggests the weighting is robust across a wide energy space. Most importantly, these changes in the electron temperature and absolute x-ray emission are larger than the expected detector uncertainty of ~5% and, therefore, expected to be observable. Measuring the electron temperature for a variety of cryogenic implosions on OMEGA should reveal trends more reliable than those depending on the neutron-weighted ion temperature. In addition, methods published by R. Epstein *et al*.[7] and T. Ma *et al*.[8] can be used for estimating hot-spot mix amounts with the absolute x-ray emission measurements. With the existence of a T_e measurement, the thermal-equilibrium assumption can also be removed and thereby improve the estimate's accuracy for implosions on OMEGA.

Interpretation and sensitivity analysis of the hot-spot electron temperature inferred from hard x rays have been performed. The electron temperature inferred from hard x-ray continuum emission was shown to be an emission-weighted, harmonic mean electron temperature. As this value varies with photon energy, it was shown both analytically and with simulations that the optimal photon energy for approximate neutron weighting is near 15 keV or more generally near 4× the neutron-weighted hot-spot temperature. Simulations also suggest, however, that one should not expect the hot-spot electron and ion temperatures to be equal in value for OMEGA-scale implosions caused by thermal nonequilibrium. For perturbed implosions, the deviation of the inferred electron temperature from 1-D is predicted to be sensitive to implosion performance. The drop in electron temperature is of the same order as the drop in the ion temperature, and the x-ray yield-over-clean ratio should similarly track the neutron yield-over-clean ratio. This sensitivity is expected to be significant enough to be observed in experiments and will be exploited for evaluating and optimizing future OMEGA DT cryogenic implosions.

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