Radiation burn-through to infer iron opacity at solar conditions.

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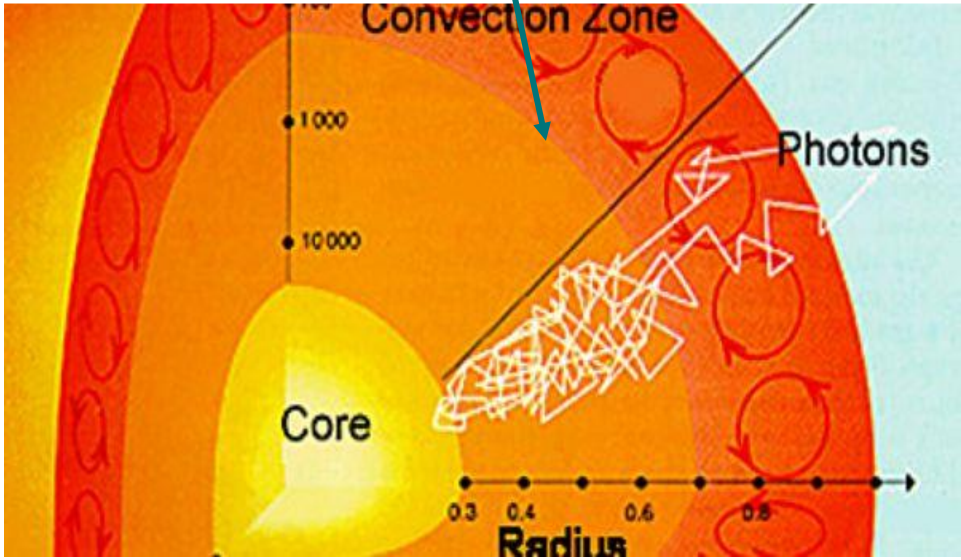
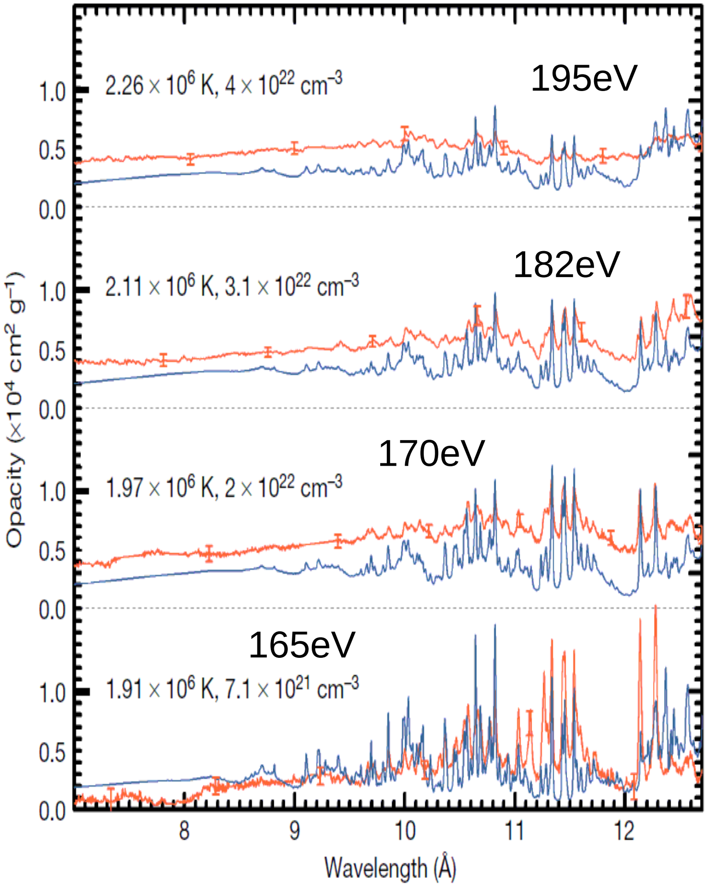
The iron opacity controversy.

The modelled CZ Boundary based on the accepted solar composition disagrees with helioseismic data.

Z results show Fe opacities 2-4 times larger than theory at CZ boundary conditions. Could this partly explain the disagreement?

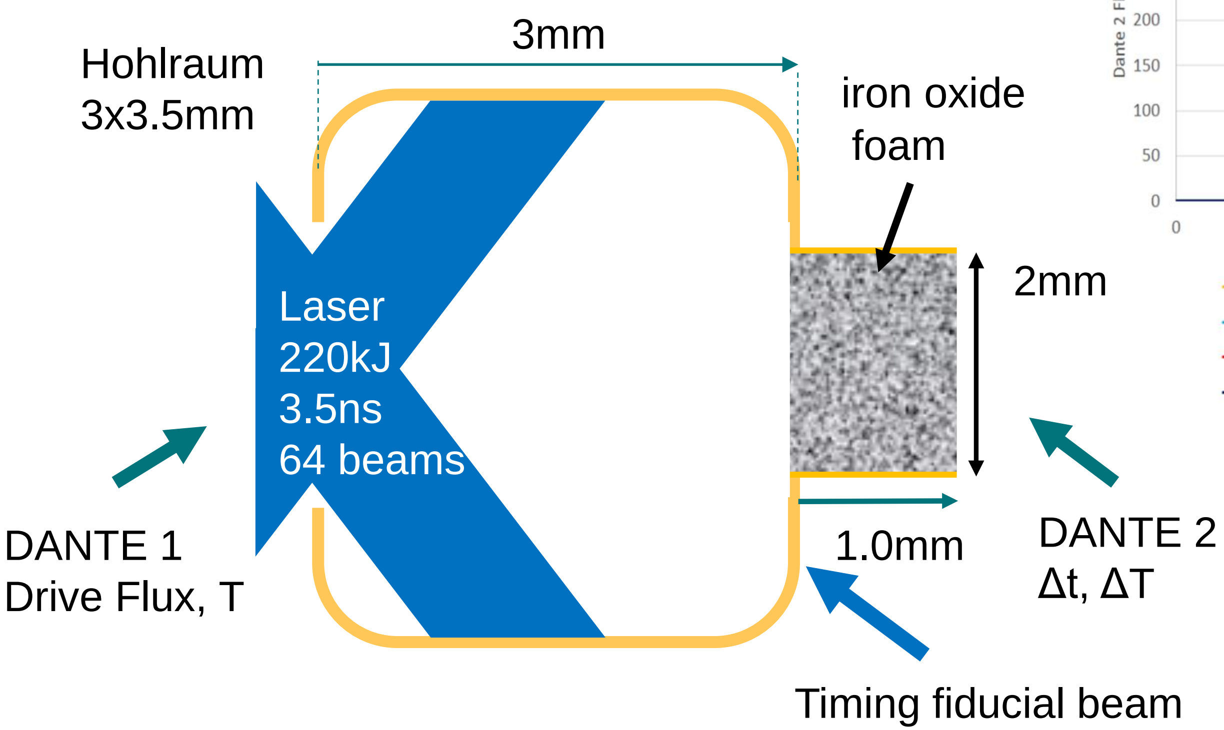


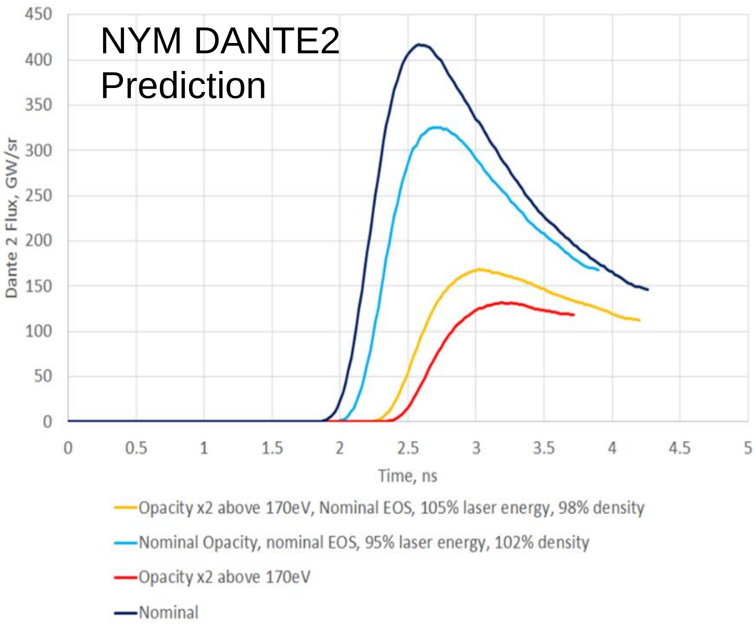


NIF Discovery Science Burn-through Experiment

- Target schematic for a radiation wave burn-through experiment to infer opacity. DANTE is an absolutely calibrated Calorimeter.

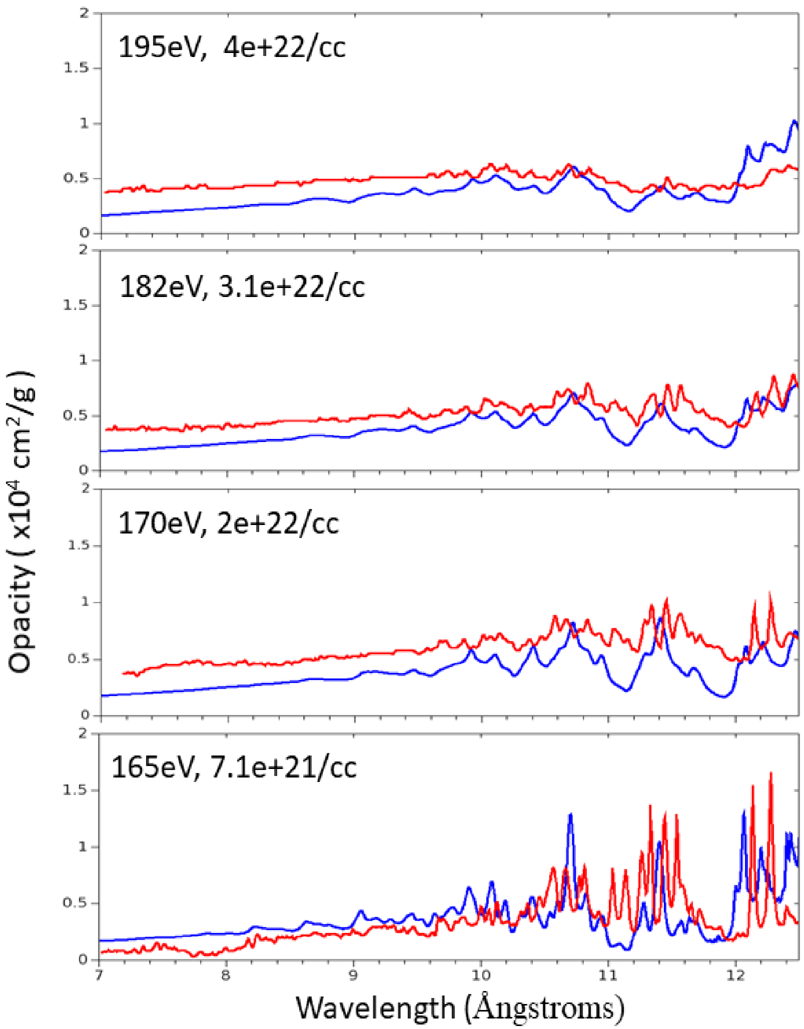
- Data modelled with the NYM radiation-hydrodynamics code.



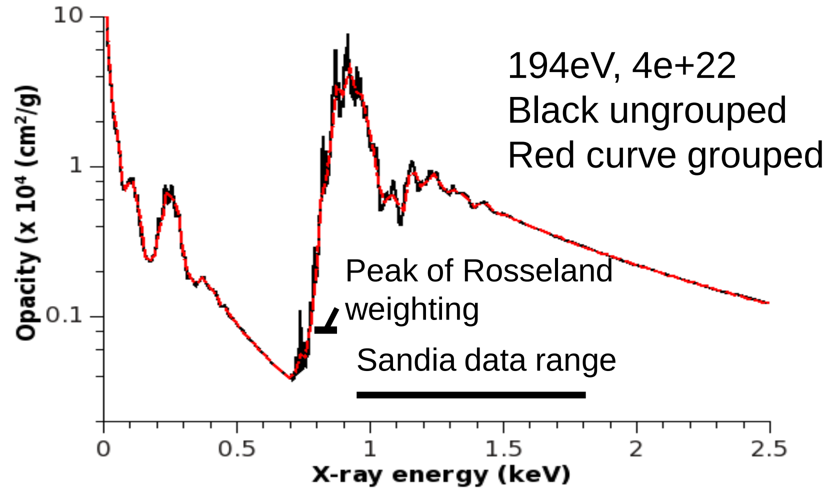


CASSANDRA opacities in the study

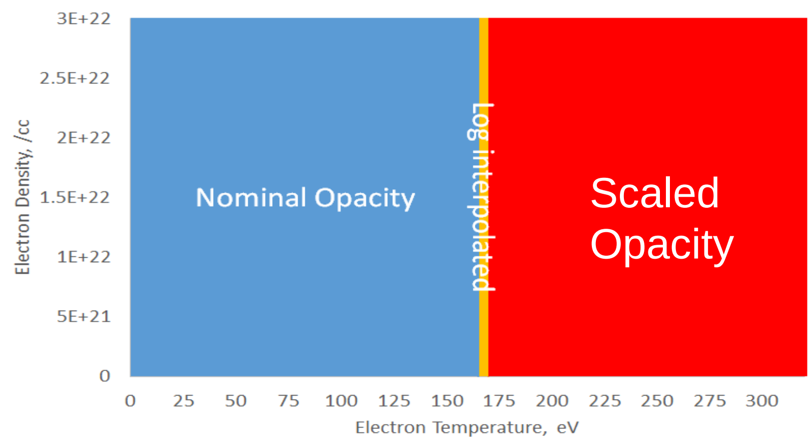
Sandia data — cf CASSANDRA —



NYM uses multigroup opacities (288 groups)



Fe opacity scaling



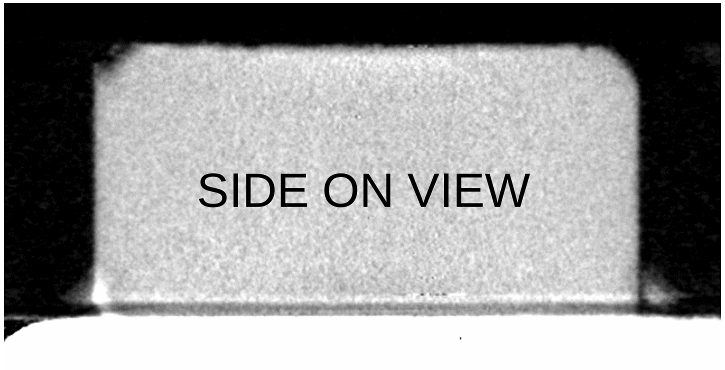
Foam size, density, uniformity and composition measured.

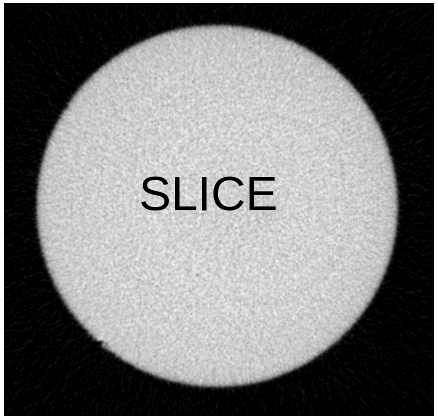
- Initial billet weighed using a sensitive balance to ±1.5% accuracy
- Cylinder machined from the billet then reweighed ±1.5% accuracy
- Tomographic radiography to check for cracks, voids or clumps.
- Offcuts assayed in-house to establish foam composition using :
  - EDAXS (electron induced x-ray fluorescence spectroscopy)
  - X-ray radiography of iron K-edge
- Composition characterisation externally by University of Leeds using EDAXS
- Composition characterised at University of Warwick using ICP-OES (Inductively Coupled Plasma – Optical Emission Spectroscopy) accurate to ppm.

Foam characterisation

- Iron oxide foam billet machined then radiographed on Brucker and XRADIA.
- Checks for non-uniformities and cracking - 4 micron resolution Brucker;

1 micron XRADIA. Cracked or non-uniform foams rejected.

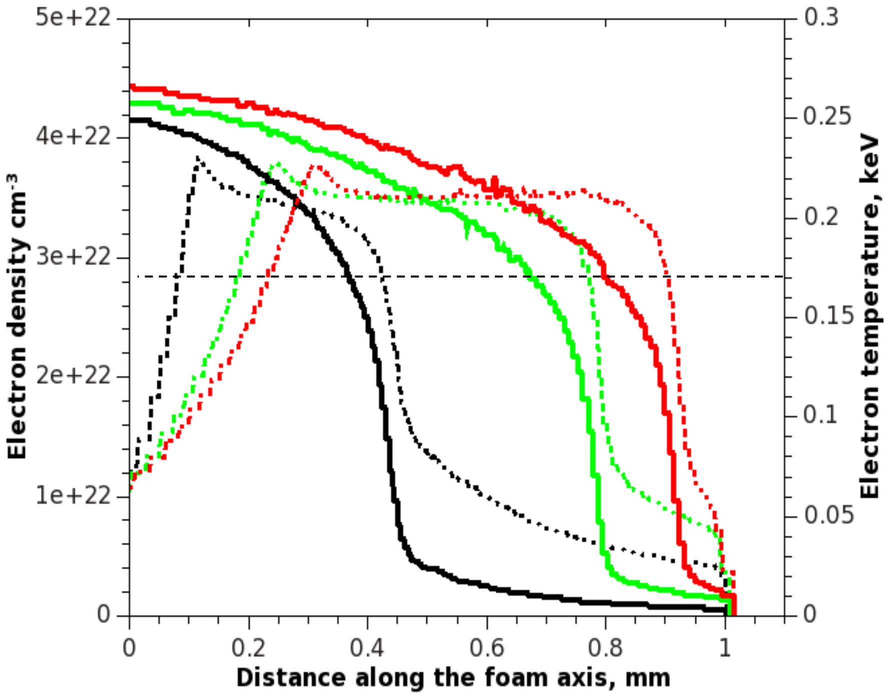




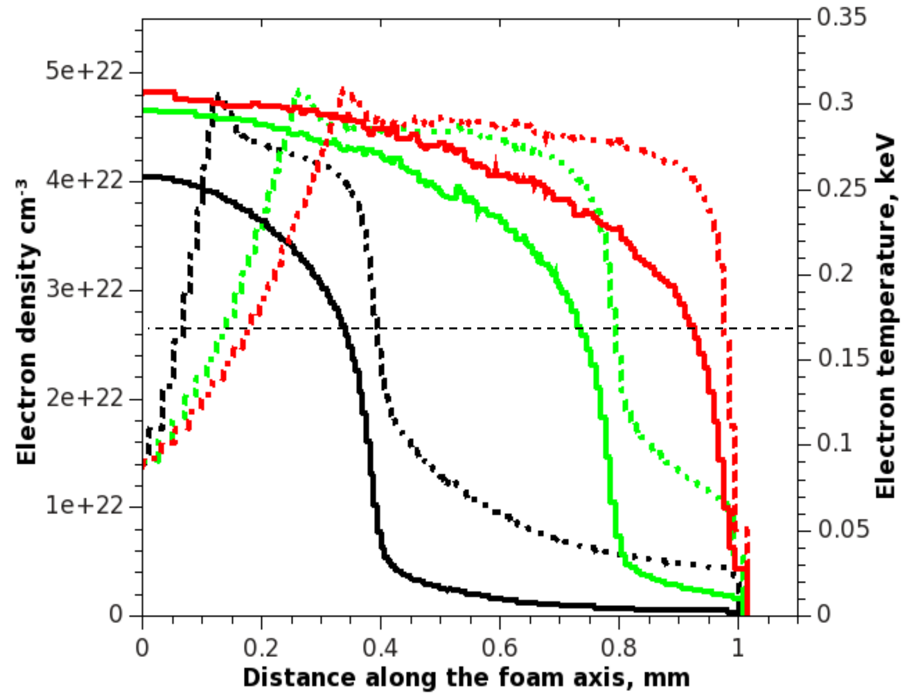
- The foam is not Fe_2O_3 (70% Fe wt) all techniques have the Fe at 50% wt.
- Foam modelled based on weight percentages.
- Slight Cl contamination from the fabrication process (7% by weight) but has negligible effect.

Modelled Te and Ne profiles during the front propagation

Shot 200525



Shot 210210

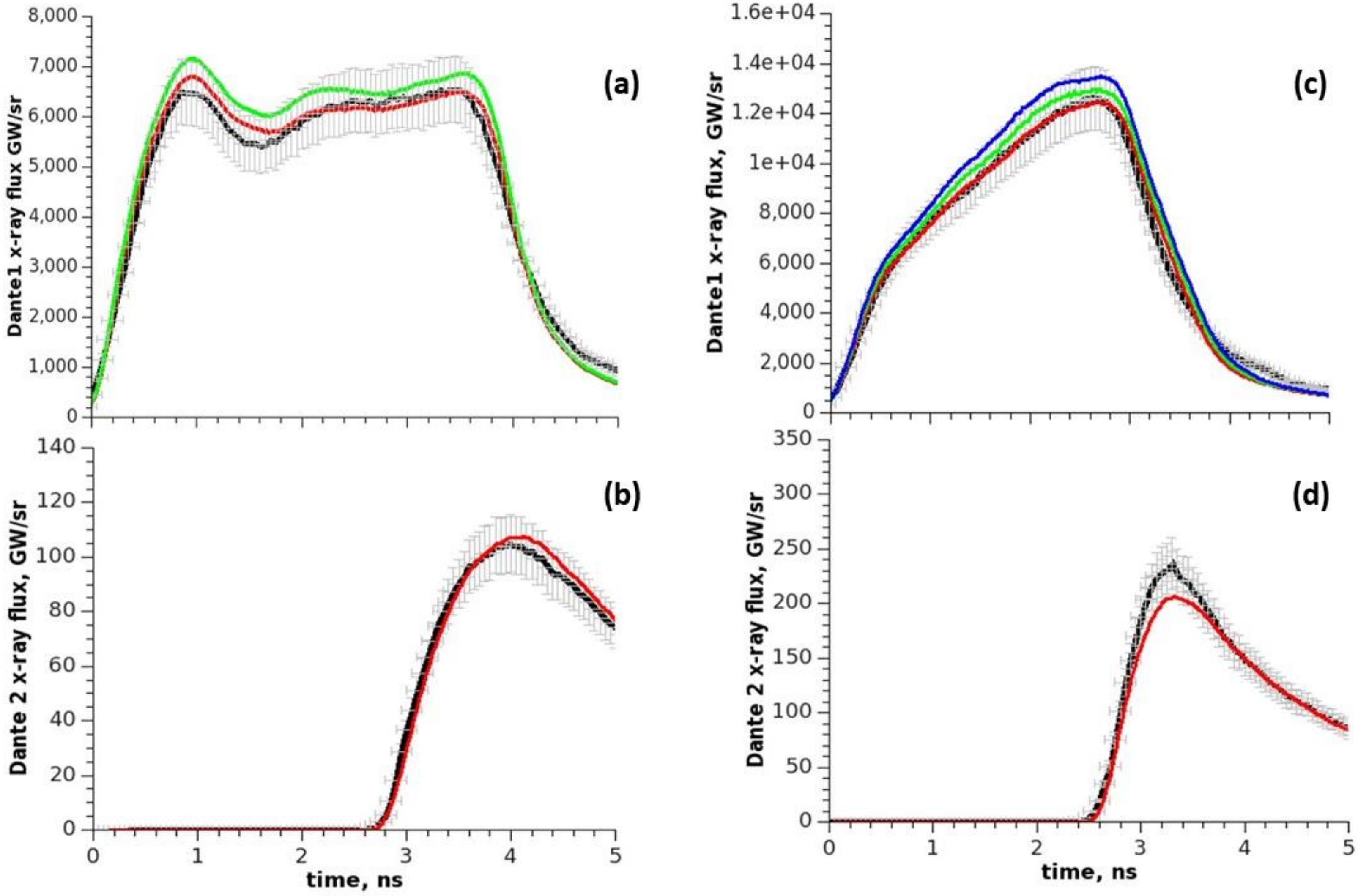


Solid lines Te (electron temp.); dotted lines Ne (electron density), at three times 1ns (black), 2ns (green), 2.5ns (red) for the two NIF shots.

The horizontal dashed line shows the lower electron temperature limit for the opacity scaling below which nominal values are always used.

Results and simulation comparisons with nominal opacity

200525 210210



Statistical model – Bayesian Inference

Let Z be the measurements, with z_{obs} the observed values, $f(x)$ is the simulation output flux profile having n elements and *x* is the simulation inputs

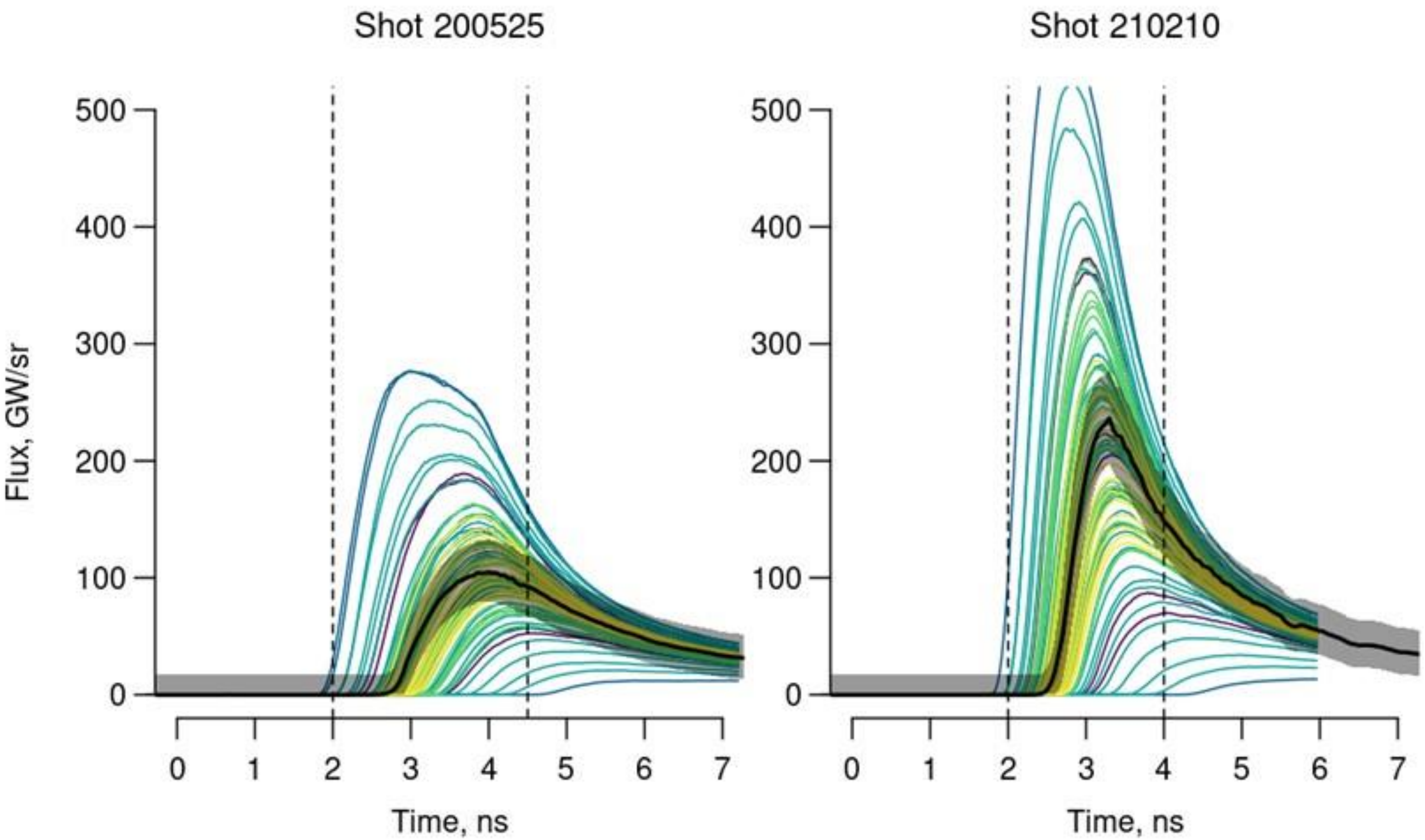
x = (energy, density, opacity, eos)

Suppose a 'best input' for $x=X^*$. To find X^* consider Bayesian inference

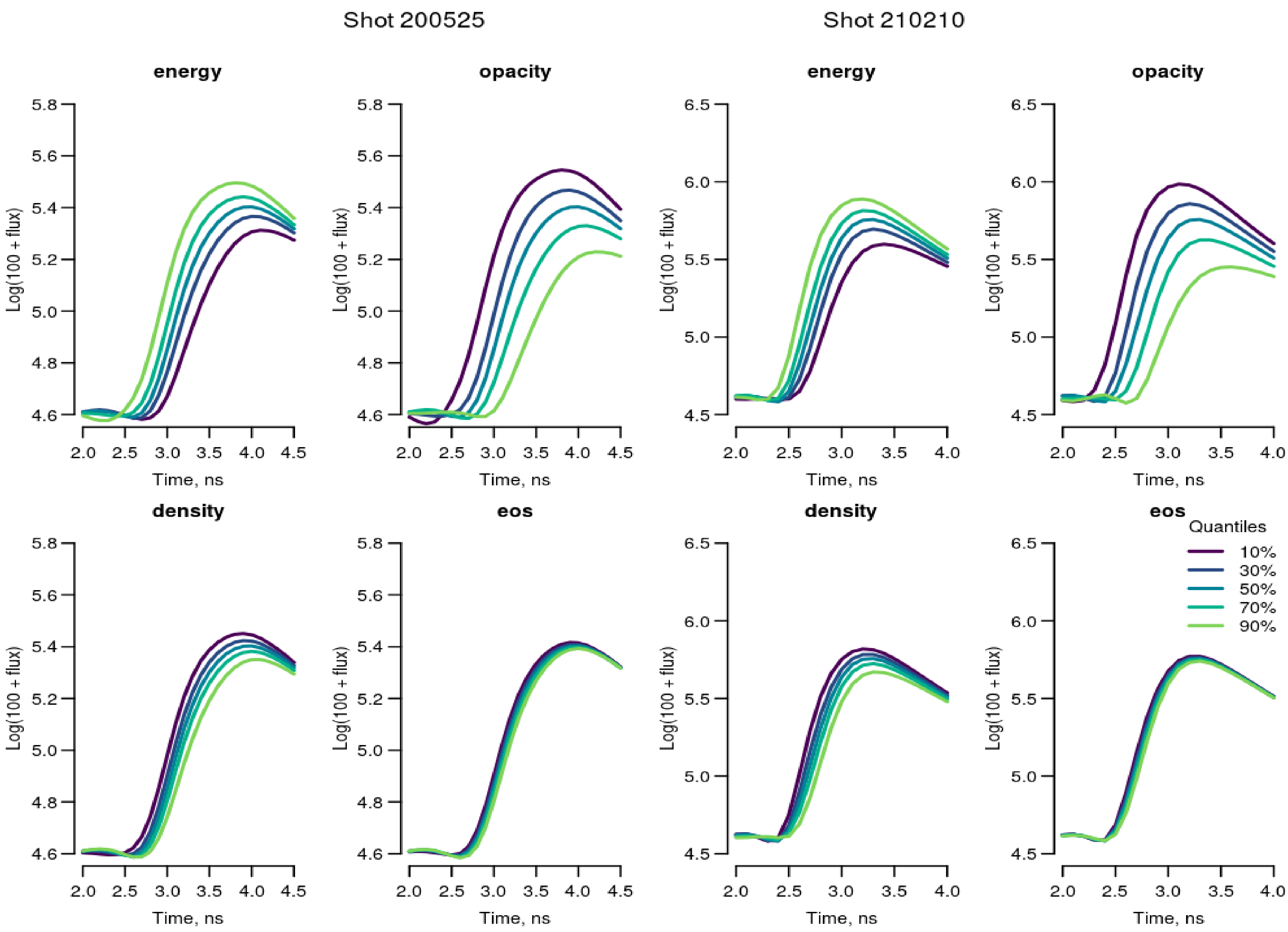
$$P(X^* = x | Z = z_{obs}) \propto P(Z = z_{obs} | X^* = x) . P(x)$$

Posterior probability distribution — Likelihood — Prior distribution

DANTE data compared to simulation for various inputs



Varying one input at a time



Statistical method - Likelihood function

- Adopt a 'best input model' to link the simulation and data to construct a likelihood function for the 'best' setting of input parameters.

- For the likelihood function *L(x)* for inputs *x*, assume *φ* is the Gaussian probability density function, z_{obs} are the measured data points, *f* simulated data points and *σ* their standard deviations. There are n points in the profile. For a 'perfect' simulation

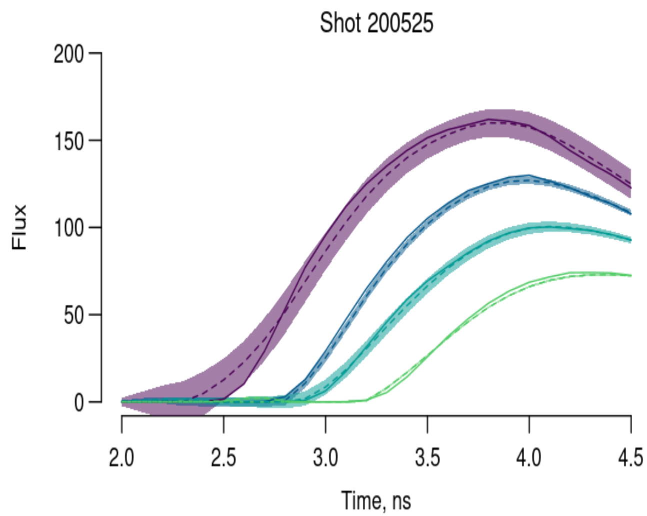
$$L(x) = \prod_{i}^{n} \varphi\left(z_i^{obs}, f_i\,(x), \sigma_i^2\right)$$

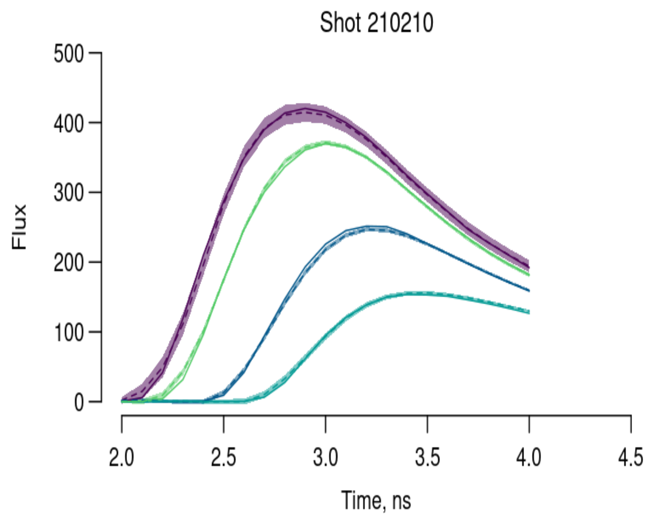
For a sum of squared deviations misfit criteria

$$-2logL(x) = \sum_{i=1}^{n} \frac{\left(z_i^{obs} - f_i(x)\right)^2}{\sigma_i^2}$$

- Minimising the deviance requires thousands (or millions) of simulations which is not possible, (simulation wall clock time 8 hours). Also in reality the simulator is not perfect but has an error that cannot be tuned away by changing *x*

Gaussian Process Emulator





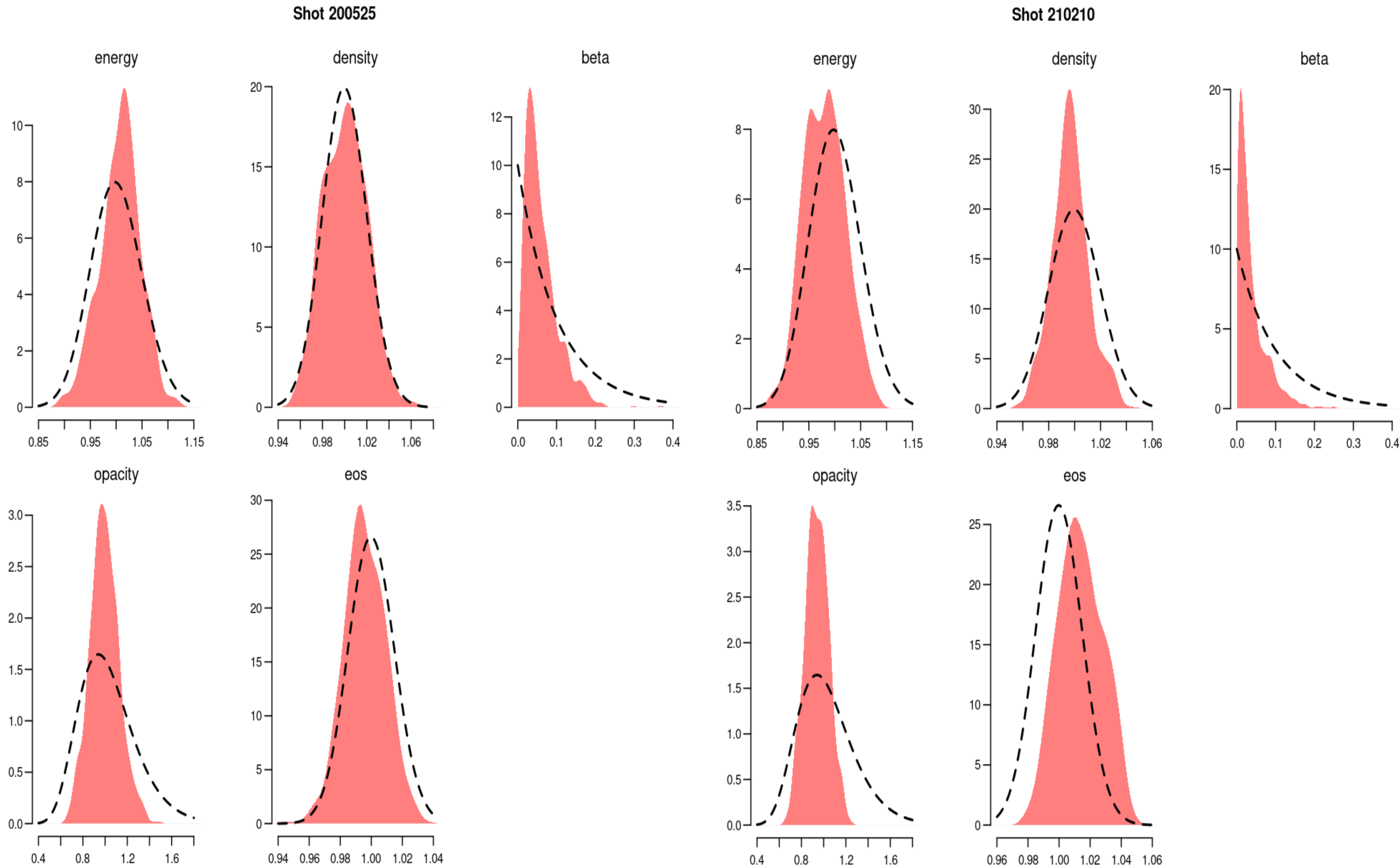
- The simulations are replaced by a Gaussian Process Emulator, so the likelihood function can be evaluated at any point in parameter space.
- The Emulator is “trained” on the simulator runs.

$$f(x) \sim N\left(\mu_f(x), \sum\nolimits_f (x)\right)$$

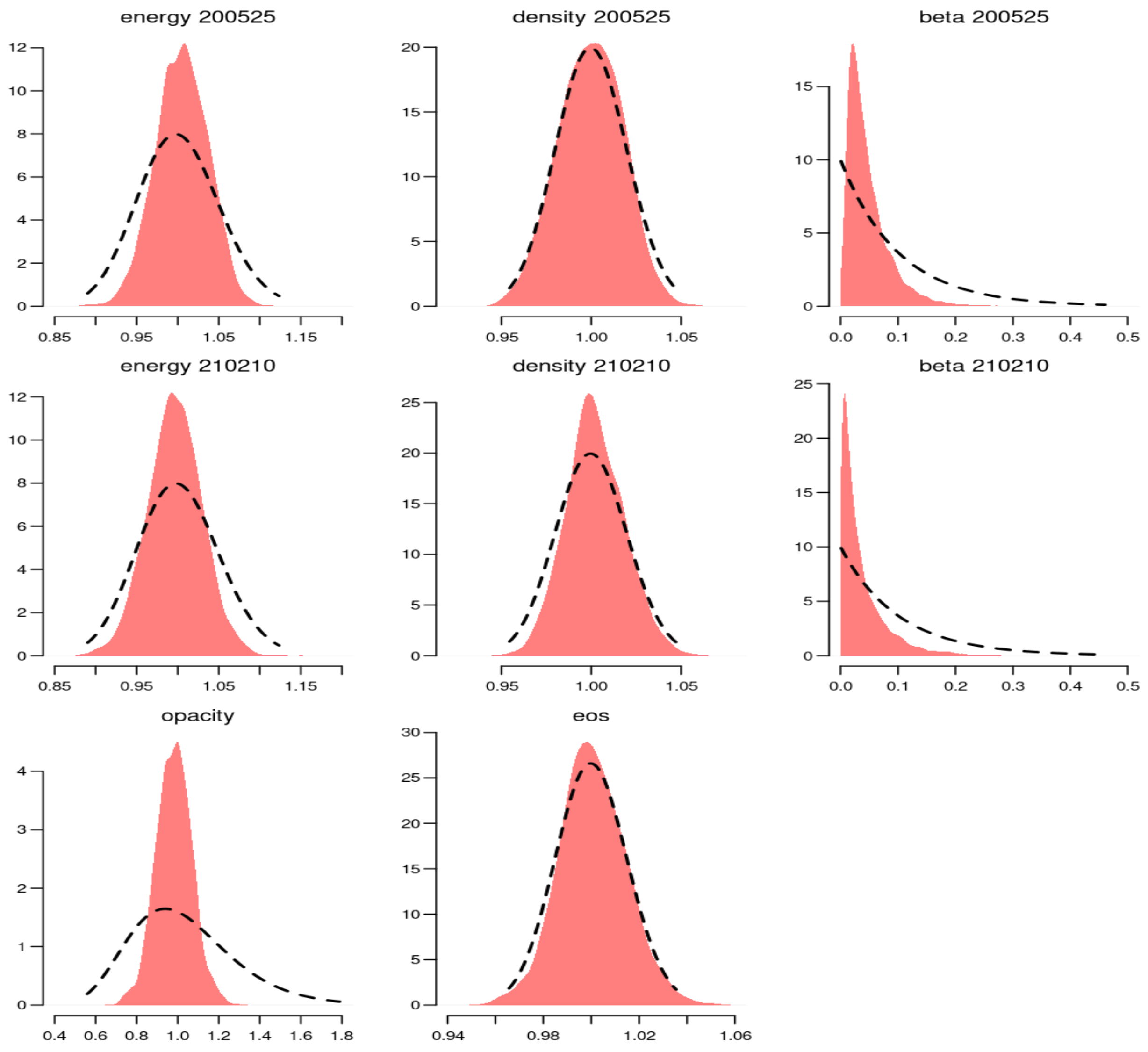
$$\mathrm{L}(x) = \varphi\left(z^{obs}; \mu_f(x), \sum\nolimits_z + \sum\nolimits_D + \sum\nolimits_f (x)\right)$$

- Performance of the emulator mean function for f for representative runs. Shading shows the 95% prediction interval of the emulator.

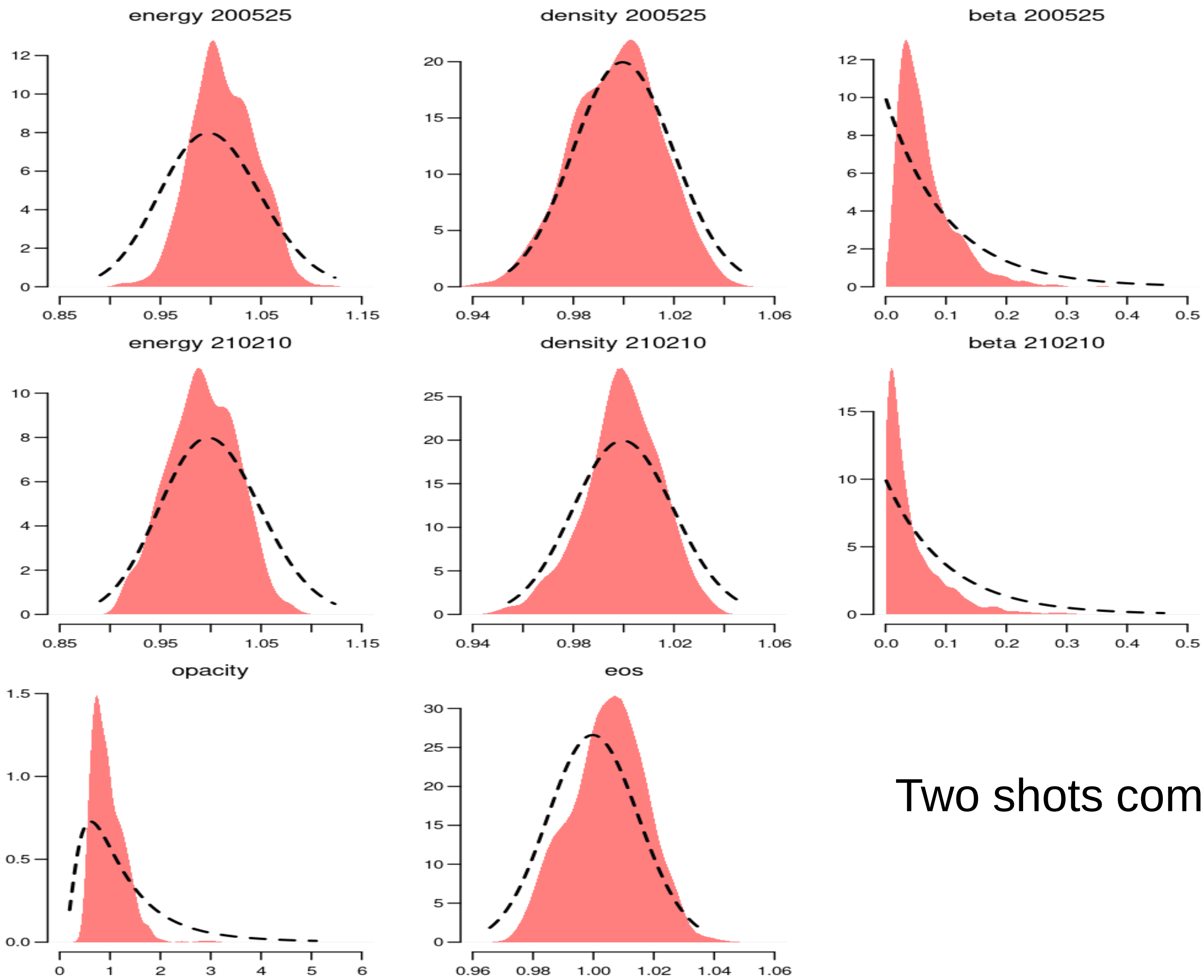
Probability densities for the two shots treated separately



Probability densities after combining the two shots



Opacity scaling in the 970-1800eV Sandia data range only .



Two shots combined

Summary/Conclusion

- Varying opacity scaling for Te > 170eV Ne 2-5e+22/cc shows best fit to the DANTE2 data for the nominal values of iron opacity as calculated with the CASSANDRA opacity code, which predicts similar values to other state of the art codes.
- Inferred opacity values at the experimental conditions are expressed as a scaling factor over the iron opacity spectrum– post median 0.985; 95% credible interval 0.81, 1.18.
- The radiation burn-through is less sensitive to opacity scaling of only the x-ray energies 970eV-1800eV of the Sandia experiment but the data suggest the nominal opacity is the most probable value (scaling factor median 0.957; 95% credible interval 0.52, 1.79)
- Recent reanalysis (A&A Magg et al, 2022) of the solar elemental composition claims there is no discrepancy with helioseismic data.

Summary/Conclusion

- More information can be found in a paper and suppl. materials published in PoP in June 23 - doi:10.1063/5.0141850

Radiation burnthrough measurements to infer opacity at conditions close to the solar radiative zone–convective zone boundary

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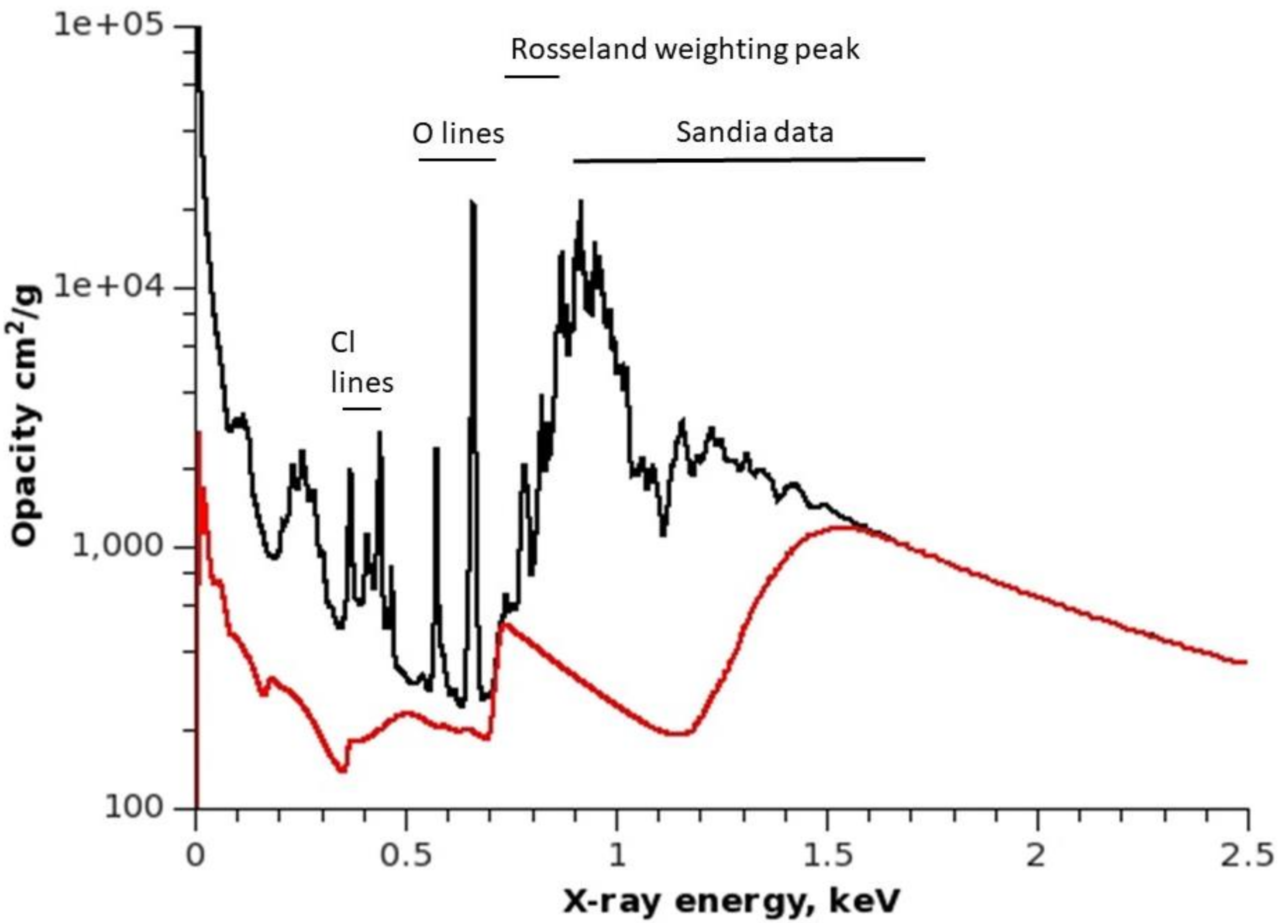
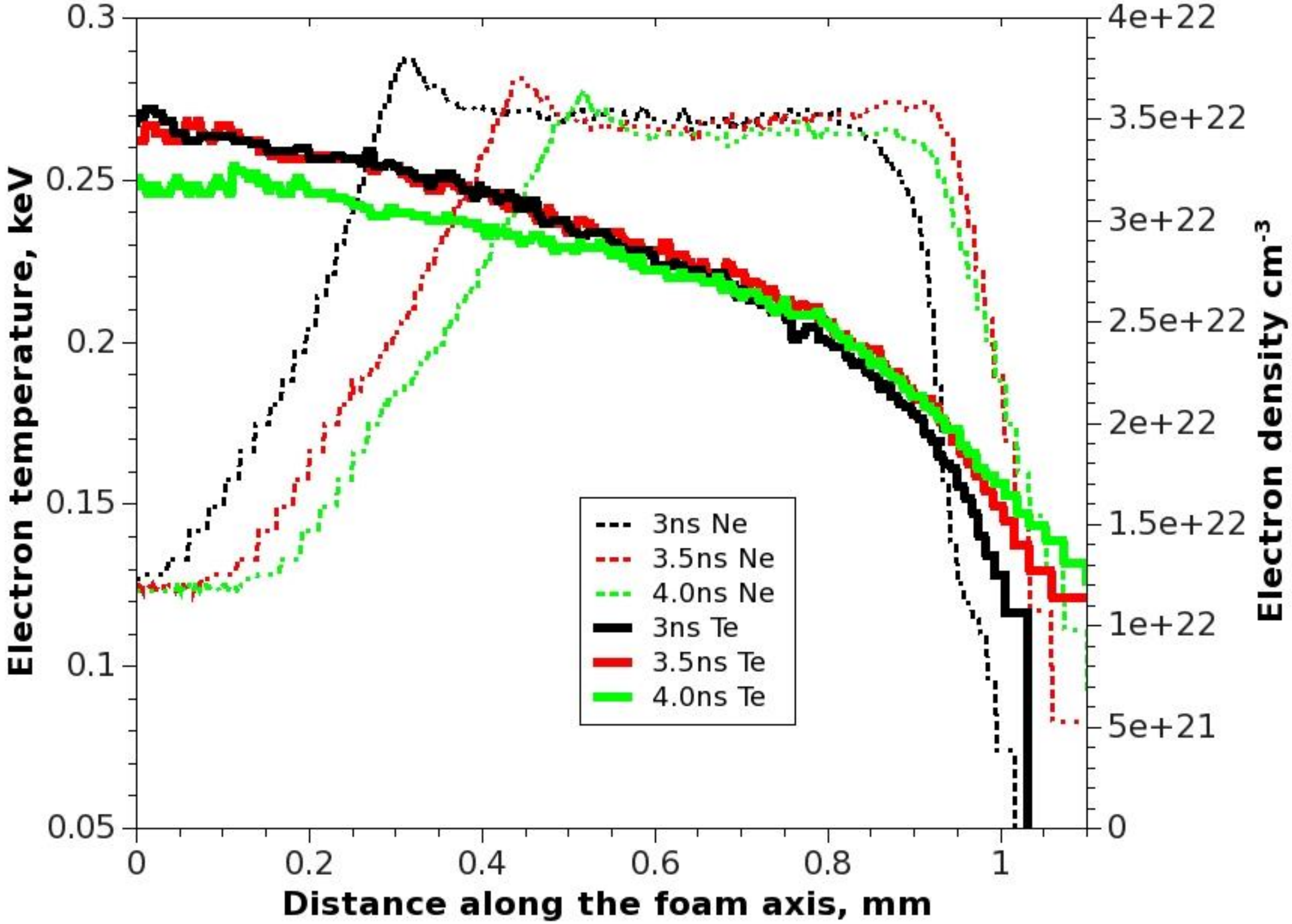
Additional Slides

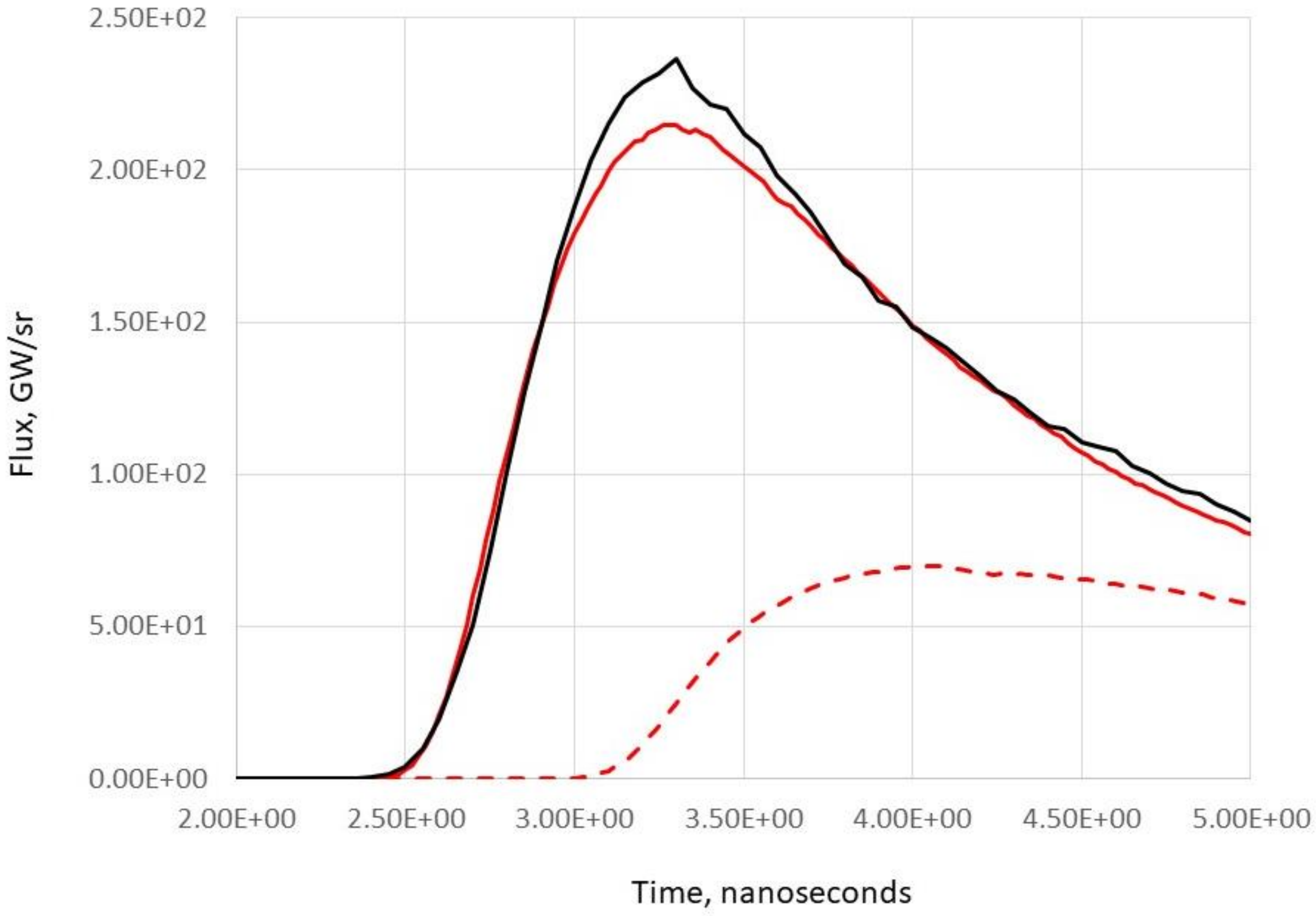
Total foam opacity Te 200eV, Ne 5e+22



Simulated foam profiles at later times

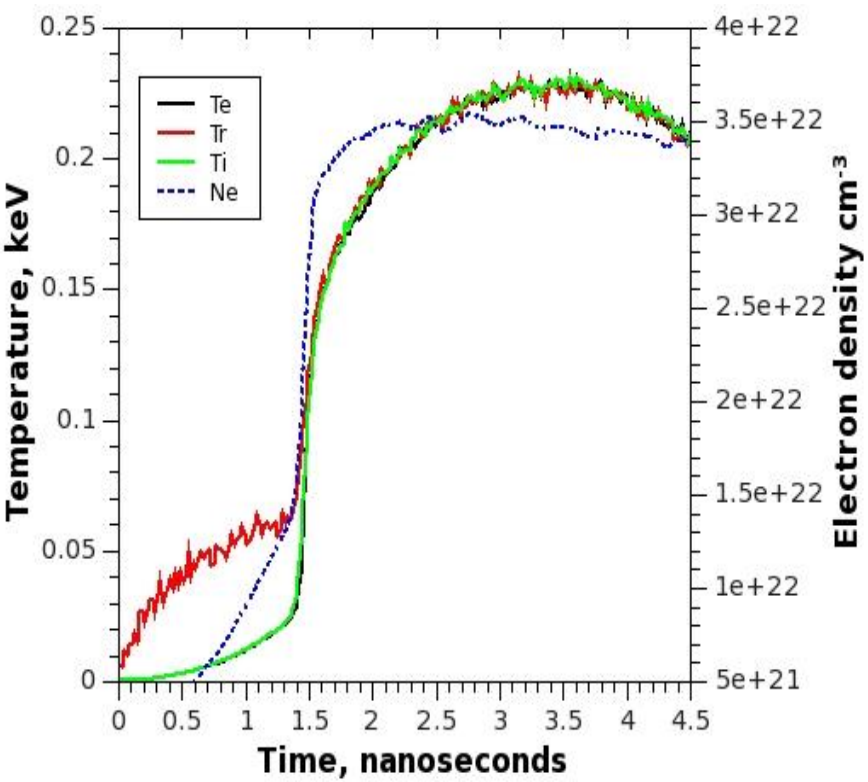


Effect of scaling opacity by x2



LTE approximation is valid

Time history in the centre of the foam.



Time history 0.2mm from hohlraum end of the foam