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MagLiF workshop: Stagnation
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Diagnosing Stagnation with X-ray Spectroscopy

Stephanie Hansen
Sandia National Laboratories, Albuquerque, NM 87185 USA

D. Sinars, C. Nakhleh, M. Herrmann, R. Vesey, K. Peterson, P. Christenson

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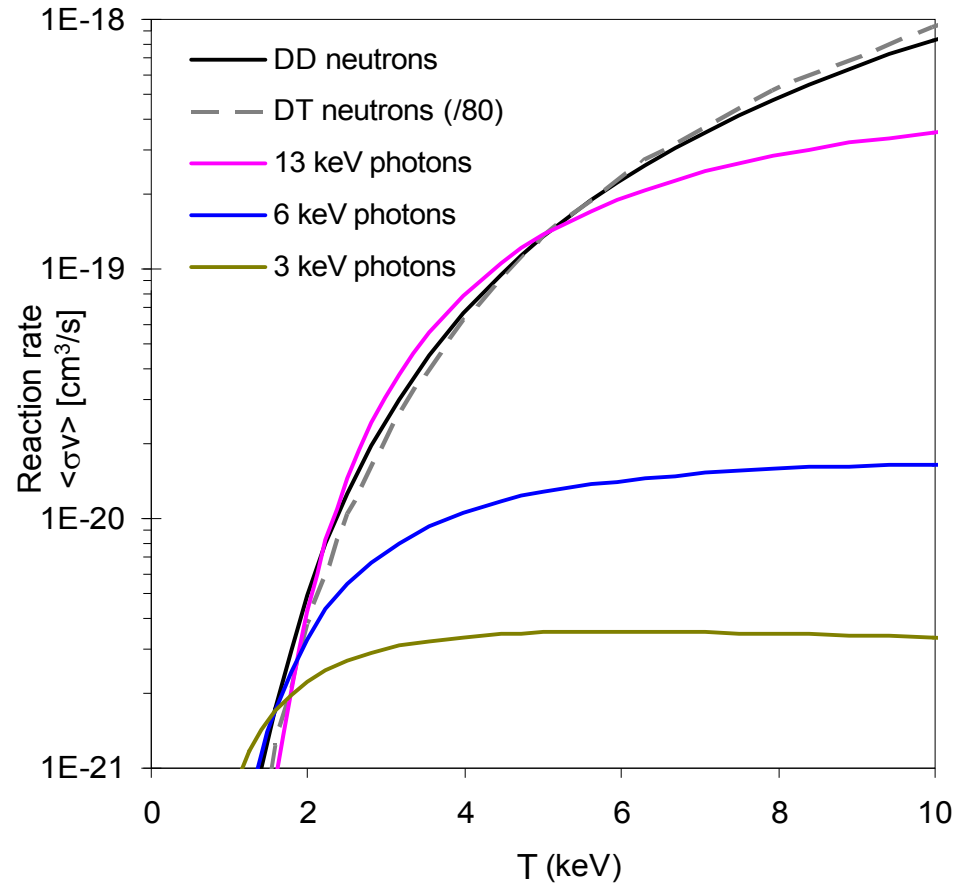
High-energy photons can escape Be liner and reveal information about the stagnating plasma

Neutron yields alone are indiscriminate:

$$R = n_T n_D < \sigma_{DT} v_{ion}(T) > Vol \ [n/s]$$

A given neutron yield can be generated by a multiplicity of burn plasmas whose density, volume, temperature and duration satisfy $Y = R\Delta t$

More extensive neutron diagnostics can constrain ρr and T_{ion}, but they do not (easily) reveal gradients, mix, B…

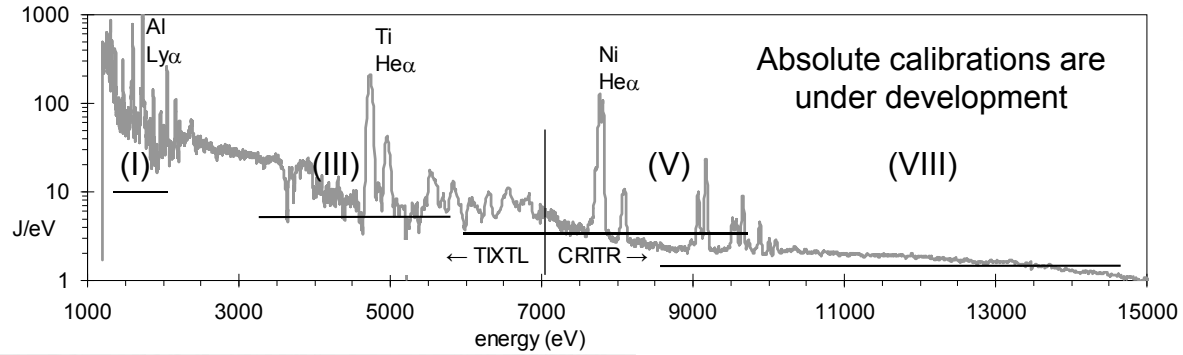


High-energy x-rays (> 10 keV) of dopants co-located with the fusion fuel [12] are reasonable neutron proxies

12. Wilson, J Phys Conf Ser (IFSA) **112** 022015 (2008) ~0.1% Kr degrades yield by ~30%

Z has extensive spectroscopic instrumentation

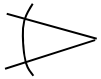
We routinely field up to eight spectrometers per shot, spanning the spectral range 1 – 20 keV with $\varepsilon/\Delta\varepsilon \sim 1000$



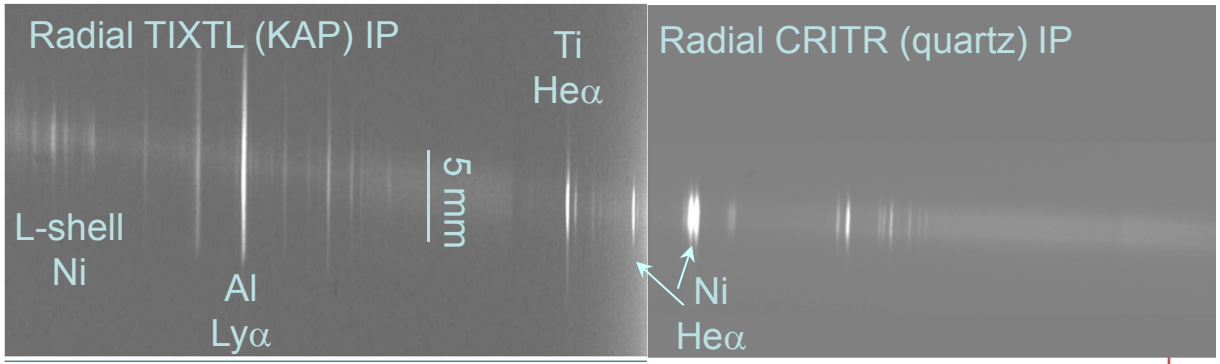
(4) TREX [3] / PODD [4]
1-D space res. (50 – 300 um)
time-gated (~ 0.5 ns)

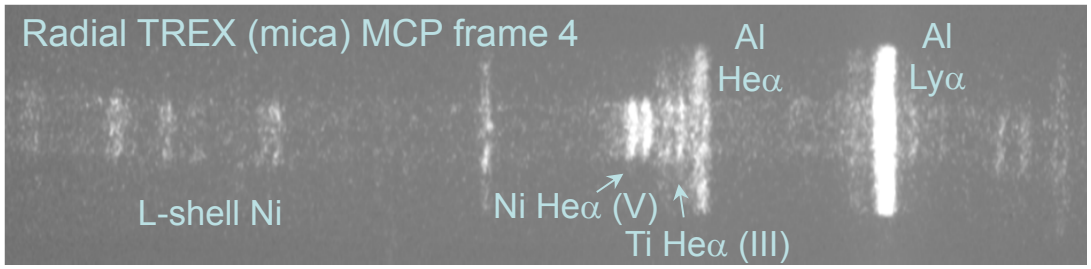
(4) TREX [5] / TIXTL
1-D space res.
time-gated + time-int

source



(2) CRITR [6]
1-D space res. (~ 80 um)
time-integrated





Spatial, temporal, and spectral resolution are all important.

3. Bailey *et al*., PRL **99**, 265002 (2007).
4. Gomez, Rochau, *et al.,* (in prep)
5. Lake *et al*., RSI **75**, 3690 (2004).
6. Sinars *et al*., RSI **82**, 063113 (2011).

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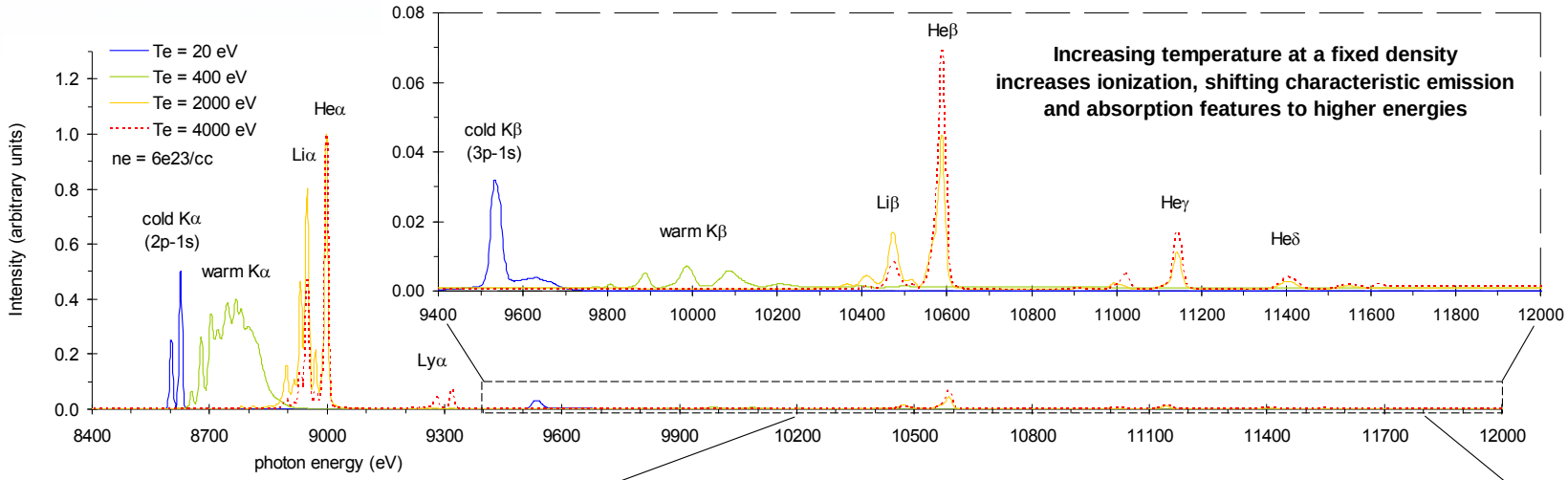
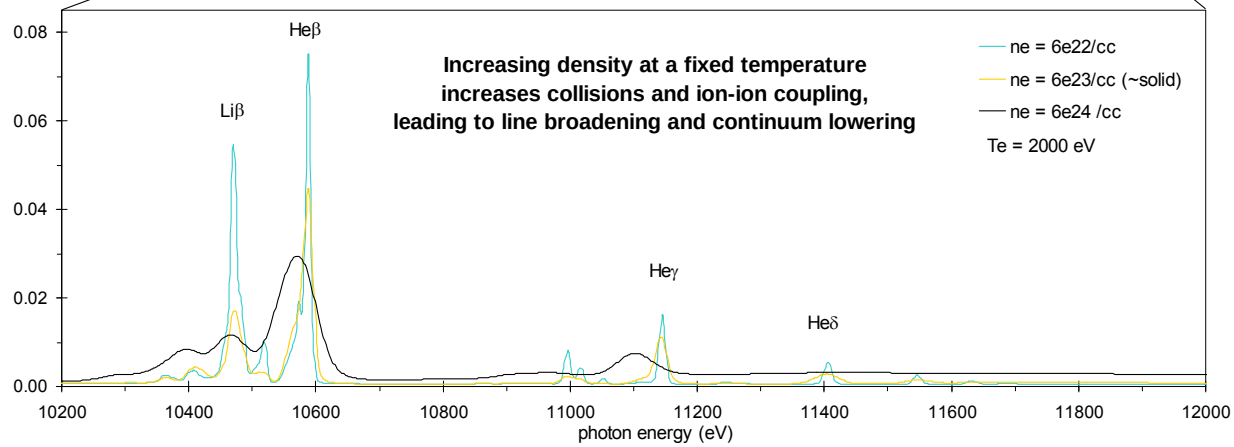
K-shell spectra are the traditional workhorses of spectroscopic plasma diagnostics





Changes in temperature and density have signature effects on K-shell emission

K-shell spectroscopy can tell us a lot about fusion plasmas at stagnation

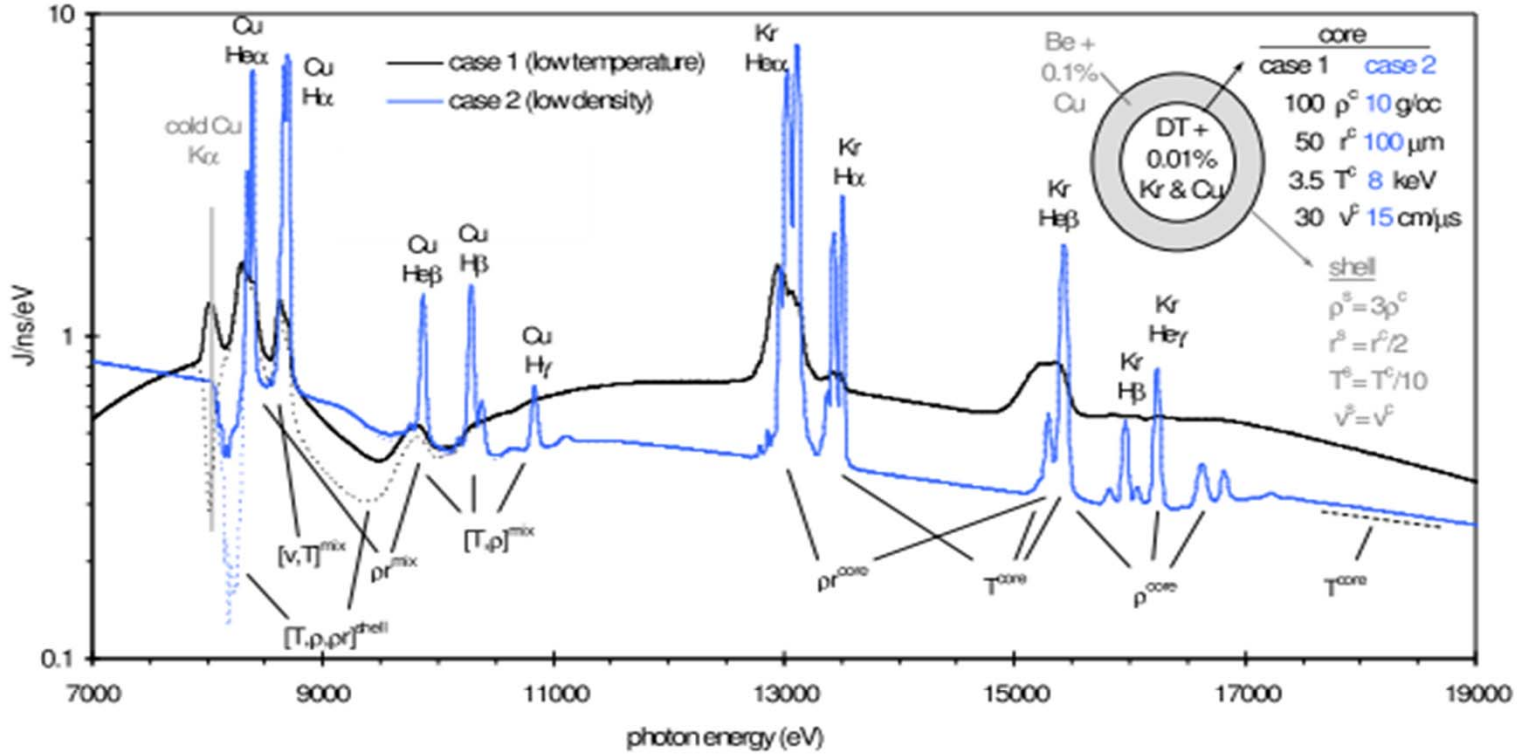


Fig. 1. (color online) Calculated emission spectra at stagnation from two spherical ICF targets with degraded yields, with the plasma conditions for the simple two-layer plasma models given in the upper right. The dark black lines are emission from a plasma with sub-nominal temperature (case 1) while the light lines are emission from a plasma with sub-nominal density (case 2). Both plasmas have a Kr fuel dopant and some shell material mixed in with the hot fuel. The dashed lines exclude the effect of fluorescence in the cold shell due to photoionization from the hot plasma core. The figure is annotated with the parameters that can be diagnosed from various emission, absorption, and fluorescence features.

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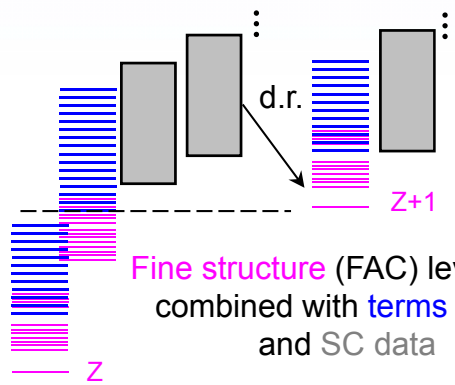
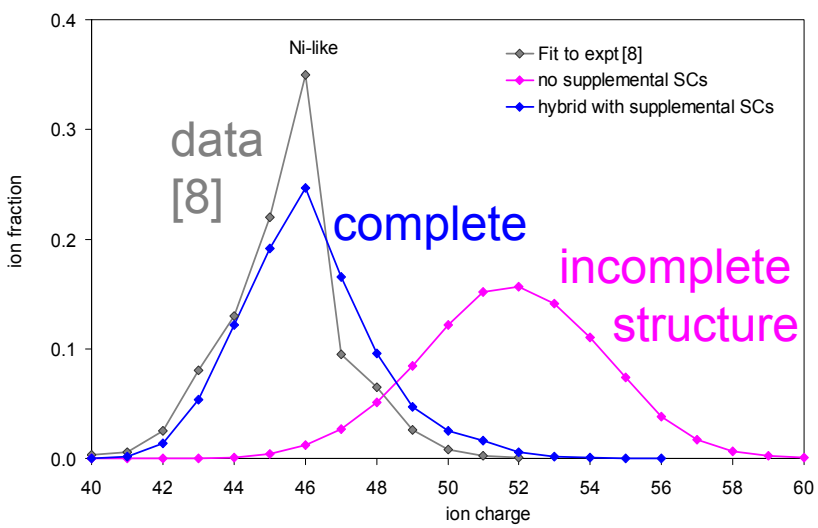
We have developed reliable non-LTE atomic models with spectroscopic accuracy

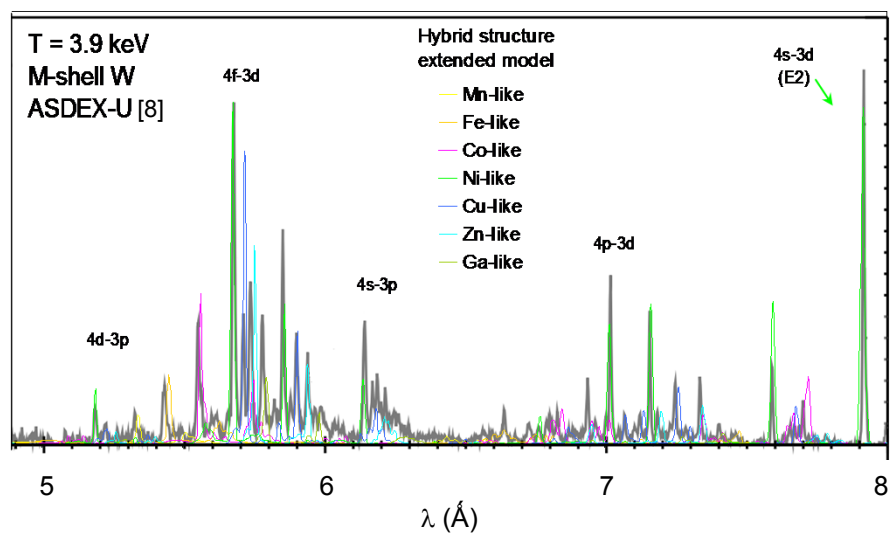
Hybrid level structure [7] ensures statistical completeness in high-*n* states, multiply excited states, and d.r. channels…



Fine structure (FAC) levels are combined with terms (UTA) and SC data

… while retaining spectroscopic accuracy in resonance lines, important satellite features, and emission from metastable states.

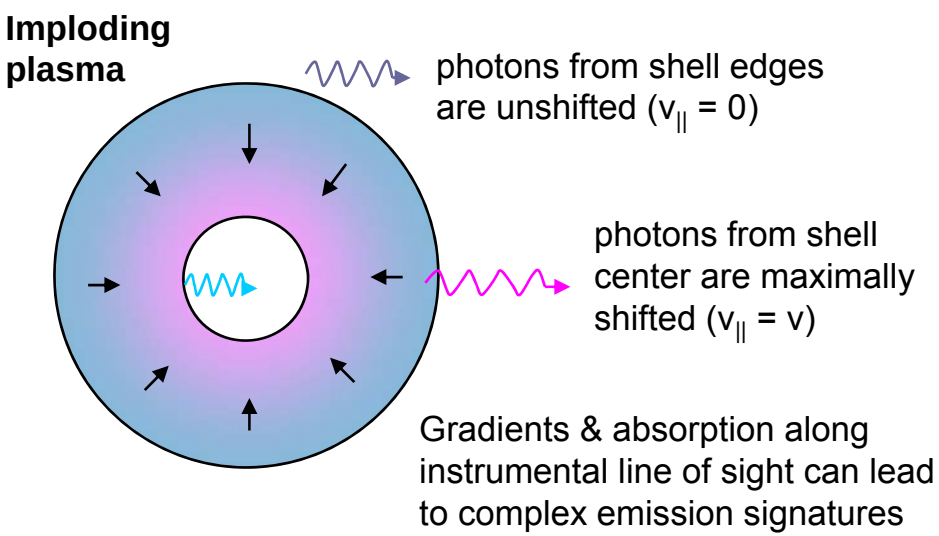




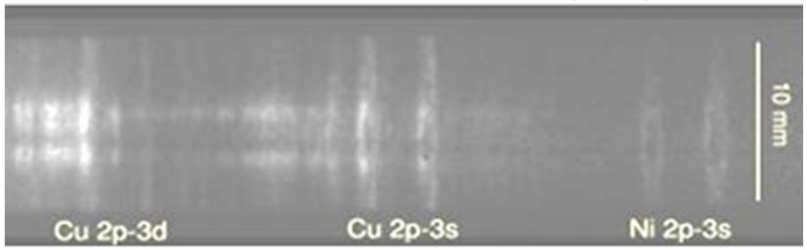
To keep things tractable, we only model in detail what can be measured in detail

7. Hansen, Bauche, Bauche-Arnoult, and Gu, HEDP **3**, 109 (2007); Hansen Can. J. Phys **89**, 633 (2011)
8. Pütterich et al. Plasma Phys. Control. Fusion **50**, 085016 (2008)

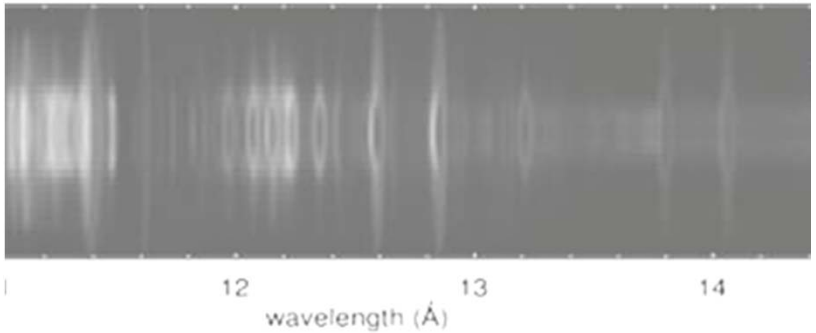
A good atomic model is not enough: self-consistent radiation transport is critical



Time-gated, radially resolved expt. spectrum



Model with full transport including Doppler effects



We are developing a tabular, iterative on-the-spot approach that fully integrates Doppler effects, determining self-consistent emissivities using 3-D ray tracing in Cartesian geometry and generating spatially resolved line profiles for ions and mixtures of arbitrary complexity [11].

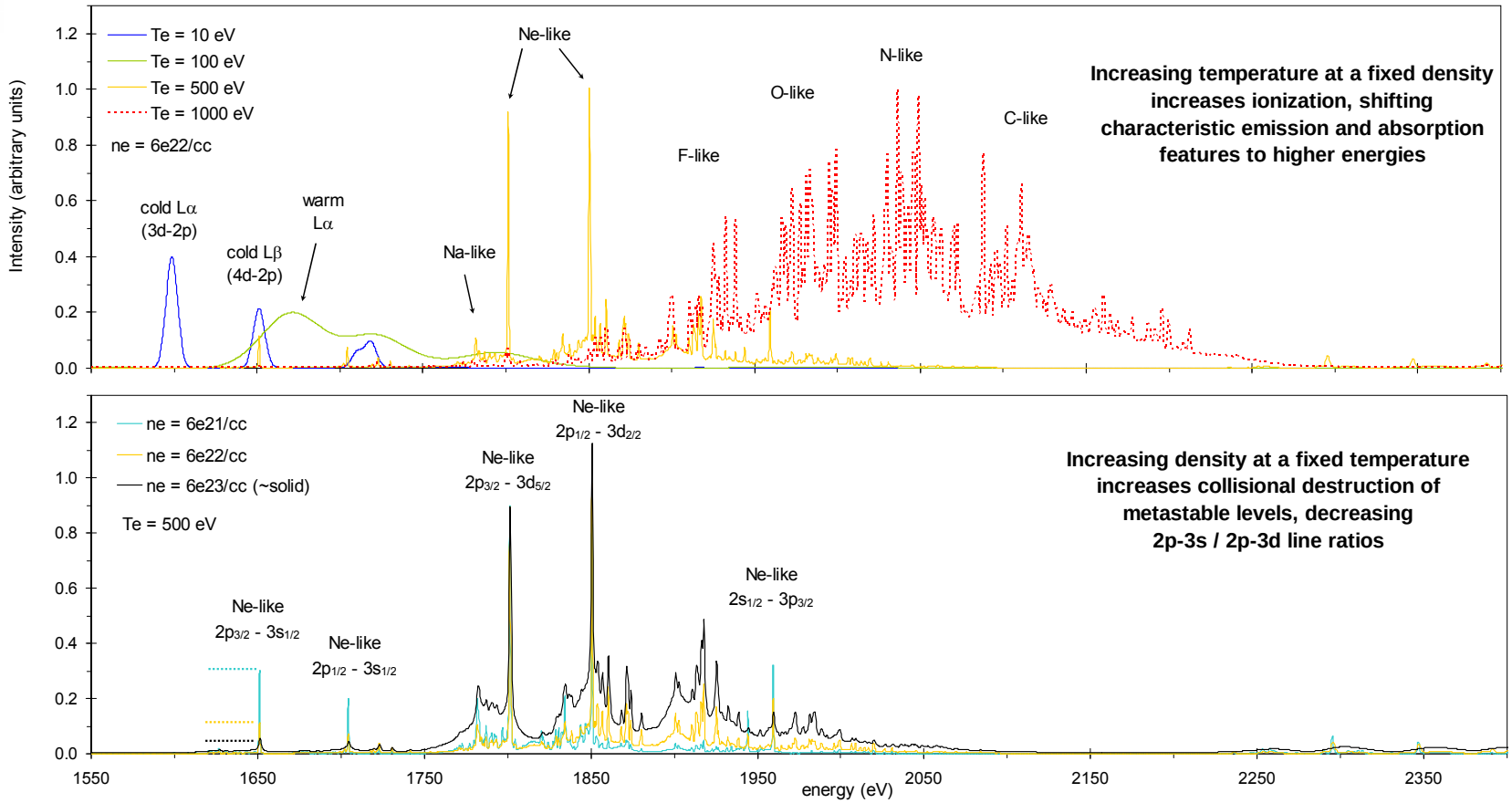
Self-consistent transport is important both for diagnostics based on simple plasma models and for post-processing simulations

11. Hansen *et al.* HEDP **7**, 303 (2011).

How can we combine all of the data we collect for a complete picture of the stagnation plasma?

- **Spectroscopy can tell us about T, rho, rho-r, gradients, mix…**
- **PCDs give absolute x-ray yields & timing: important consistency checks**
- **X-ray imaging directly informs dimension**
- **Neutrons also tell us about T, rho-r, duration**
- **is everything consistent?**
  - **Springer's isobaric model**
  - **Is pressure balance (thermal, magnetic, kinetic) a valid constraint?**

Reliable hybrid models offer new diagnostic opportunities with L-shell spectra



L-shell diagnostics have attractive features including unambiguous temperature dependence and resolution-independent density sensitivity