# Open L-Shell Spectroscopy of Non-Local-Thermodynamic-Equilibrium Plasmas

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## Motivation

- Spectra from non-local-thermodynamic-equilibrium (non-LTE) plasmas of open-shell configurations are necessary to benchmark and discriminate between conflicting atomic models
- Recent buried-layer experiments constrain the evolution of temperature $T_e$ and ion density $n_i$, and record Ge L-shell spectra
- While atomic kinetics models show good agreement with spectra recorded at higher density, they are unable to match data recorded at lower densities

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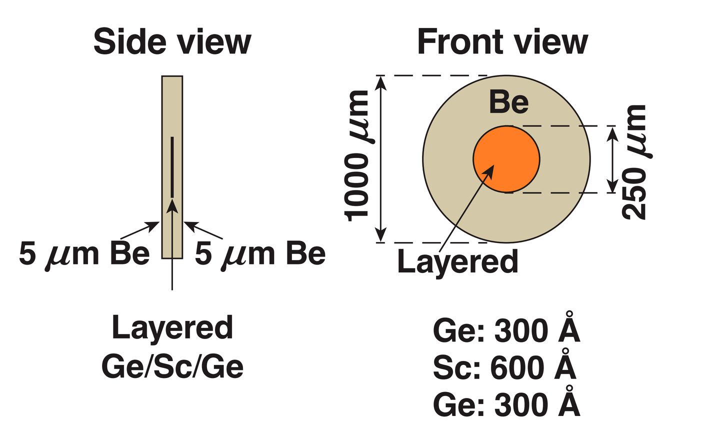
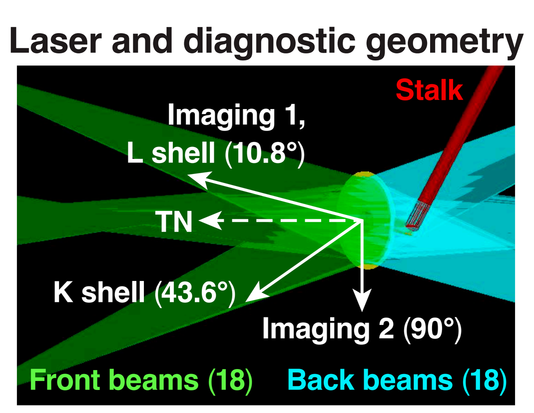
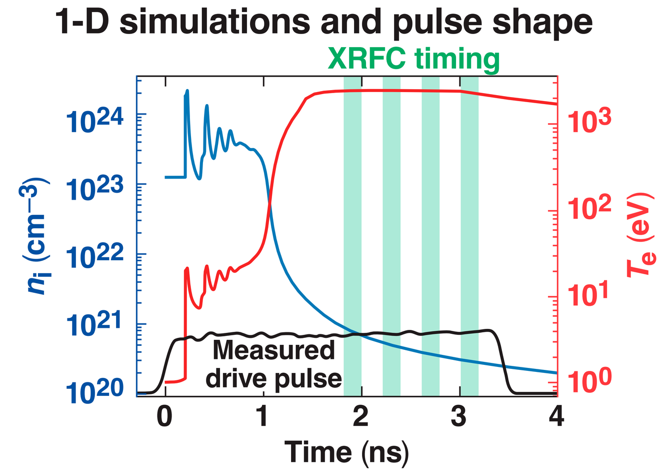
## Planar targets produce uniform, uniaxially expanding plasma and a quasi steady-state temperature [1]




- Sc K-shell, Ge L-shell spectra collected by elliptical crystal spectrometers (MSPEC) [2] and coupled to four-frame x-ray framing cameras (XRFC's)
- Diagnostics are timed coincident with isothermal expansion predicted by 1-D hydrodynamic simulations (right)

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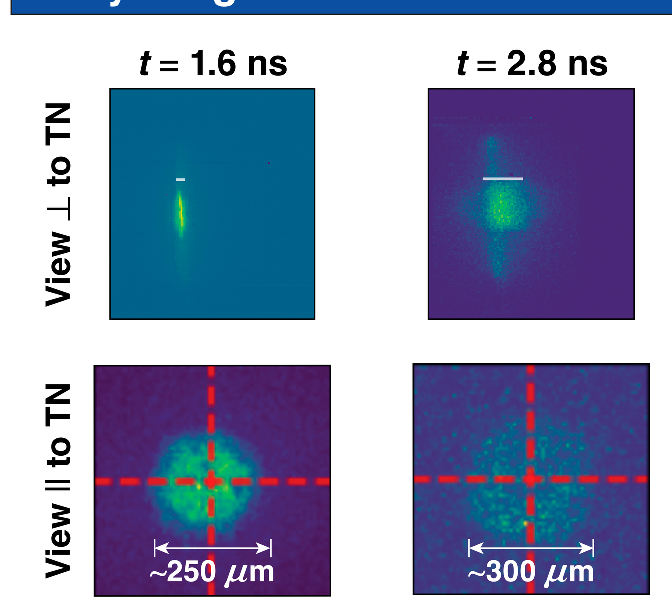
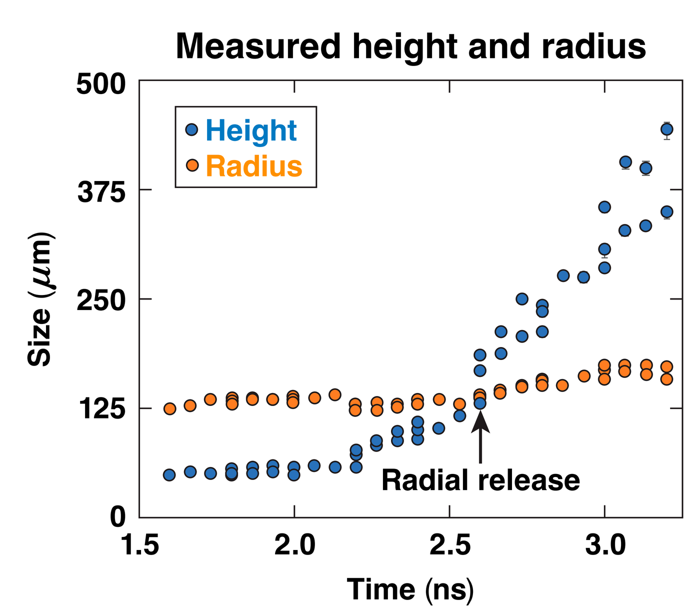
## X-ray images of self-emission constraint $n_i$ ($t$)




- Average ion density $n_i$ is inferred from time-resolved pinhole images of emission parallel and perpendicular to the target normal (TN)
- Measurements of height and radius from three equivalent shots demonstrate the repeatability of the platform prior to target disassembly

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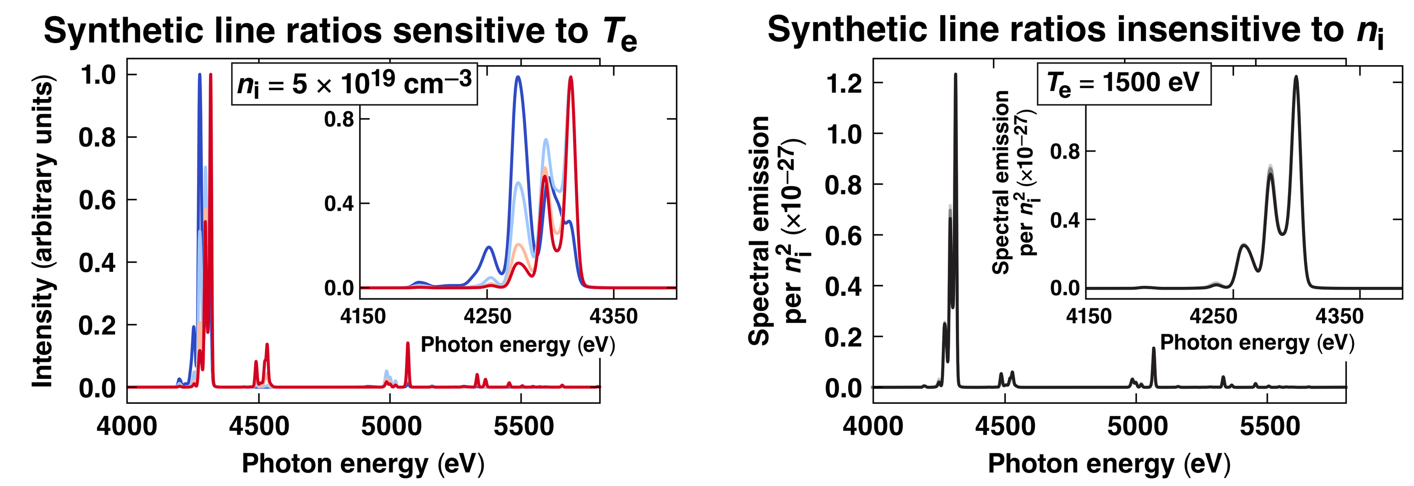
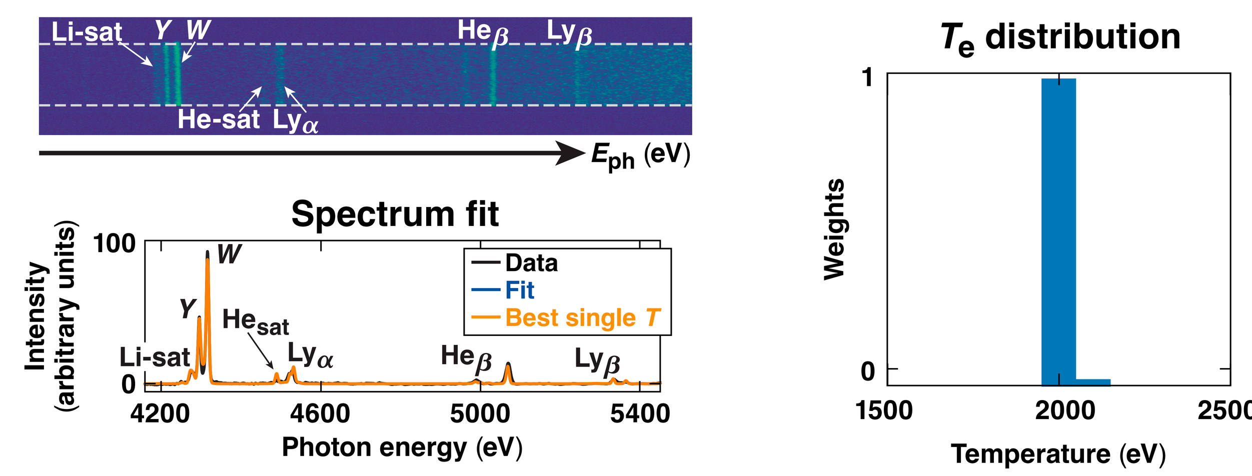
## Sc K shell constrains $T_e$ ($t$), supports spatial uniformity




- Spectra exhibit Li satellites, He-like $W$ ($2p_{3/2} \rightarrow 1s_{1/2}$), $Y$ ($2p_{3/2} \rightarrow 1s_{1/2}$), and He$_\beta$; and Ly$_\alpha$ and Ly$_\beta$
- Emission-weighted $T_e$ inferred by fitting Sc spectra to ensemble of single-$T_e$ spectra synthesized by 0-D calculation in the atomic kinetics model, *SCRAM* [3]

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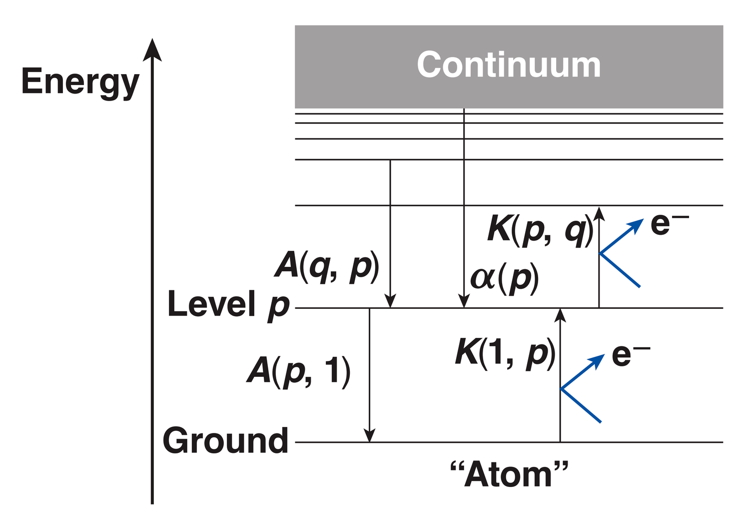
## Inaccurate collisional or radiative rates will predict inaccurate spectra




- Non-LTE spectra are determined by a balance of competing collisional and radiative rates
- State populations are found by solving coupled rate equations for population $n$ of each state $p$ of all charge states
- The accuracy of the atomic kinetics models is dependent on accuracy of rate coefficients

Rate equation for population $n$ of excited level $p$ [4]

$$n(p) = \frac{P(p)}{D(p)}$$

$$P(p) = n_e n_+ [n_e K_+(p) + \alpha(p)] + n_1 [n_e K(1,q)] + \sum_{1 \neq p \neq q} n(q) [n_e K(q,p) + A(q,p)]$$

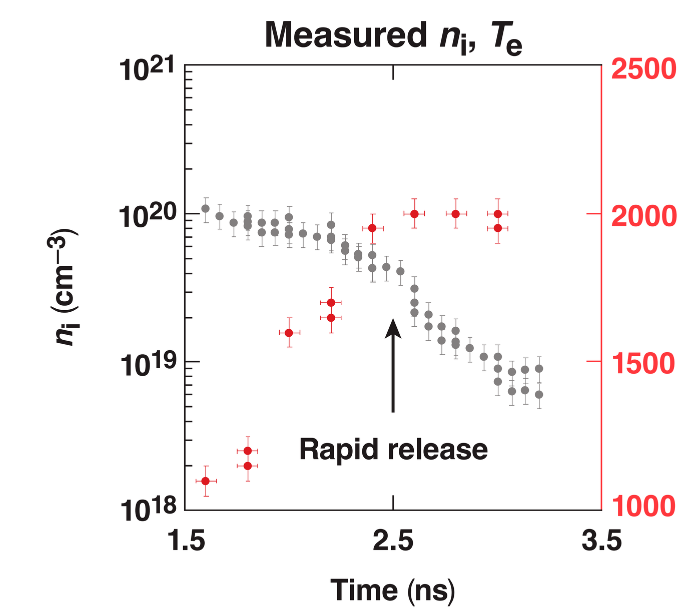
$$D(p) = n_e K(p) + A(p)$$

$+$ = ion level
1 = ground level
$K$ = collisional coefficient
$A$ = spontaneous emission rate
$\alpha$ = electron capture rate

E29271

## *SCRAM* accurately predicts the Ge charge-state distribution during 1-D expansion, but discrepancy emerges at late time

- Synthetic Ge L-shell spectra generated at $T_e$, $n_i$ inferred from diagnostics agree with observed spectra at early times
- After onset of radial expansion near 2.5 ns, synthetic spectra indicate substantial recombination, contrary to indications of a steady charge state in observed spectra




Prominent Li-like Ge lines

| Energy (eV) | Ion | $\vert\Psi_i\rangle$ | $\vert\Psi_f\rangle$ |
|---|---|---|---|
| 1731 | Li | $3d_{5/2}$ | $2p_{3/2}$ |
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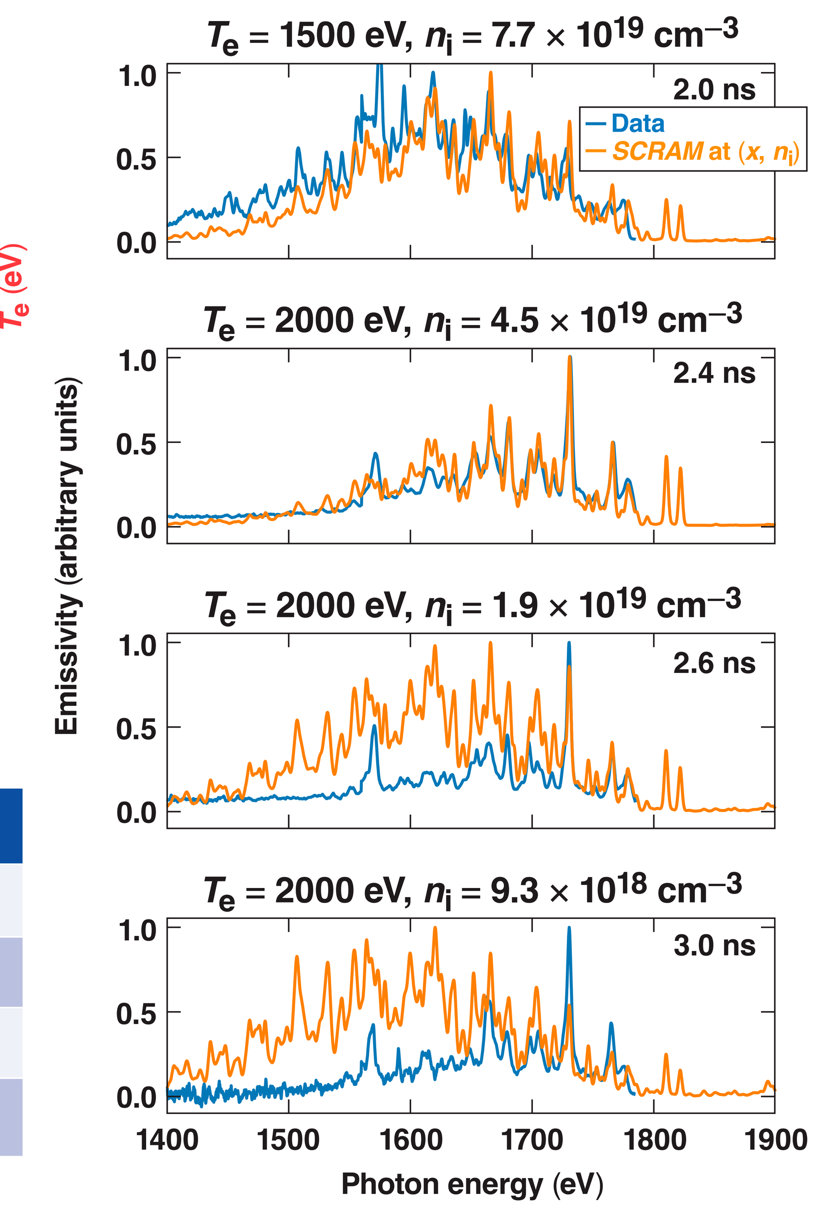


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## Discrepancy can be exploited as a mechanism to infer kinetic rates

- The buried layer is a viable platform to investigate recombination rates at densities $n_i < 10^{20}$ cm$^{-3}$
- The accuracy of recombination rates will be inferred from the charge-state distribution of spectra recorded after the end of the drive pulse
  - recombination at different densities can be probed by varying the duration of the drive pulse

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## References

[1] Y. Frank *et al.*, Phys. Plasmas 27, 063301 (2020).
[2] M. May, R. Heeter, and J. Emig, Rev. Sci. Instrum. 75, 3740 (2004).
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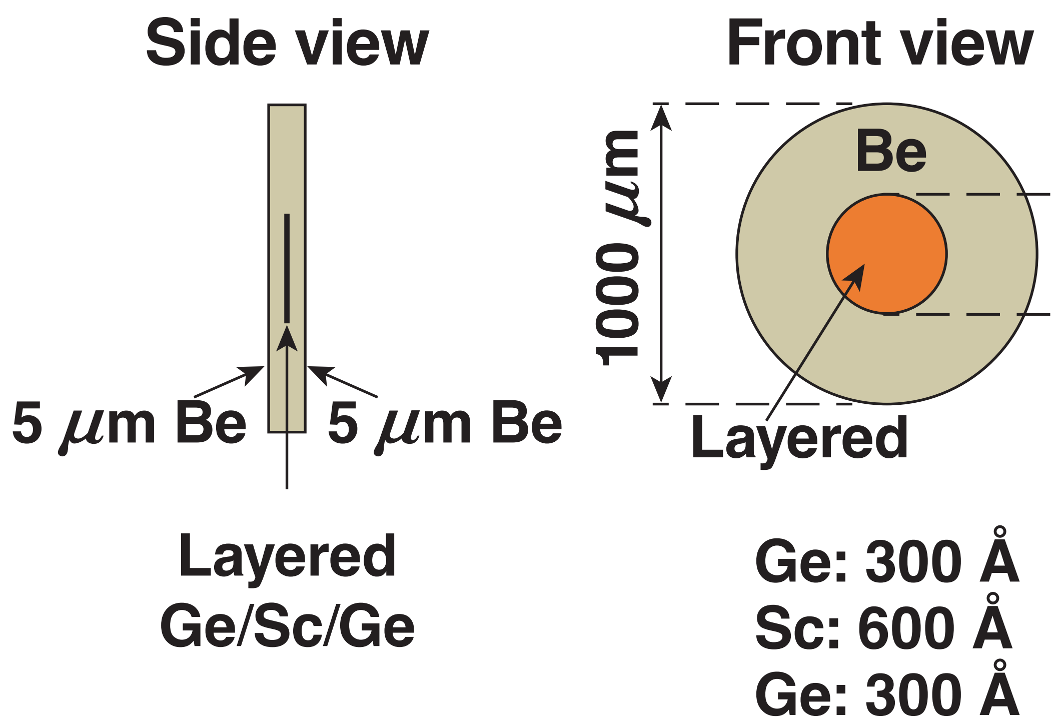


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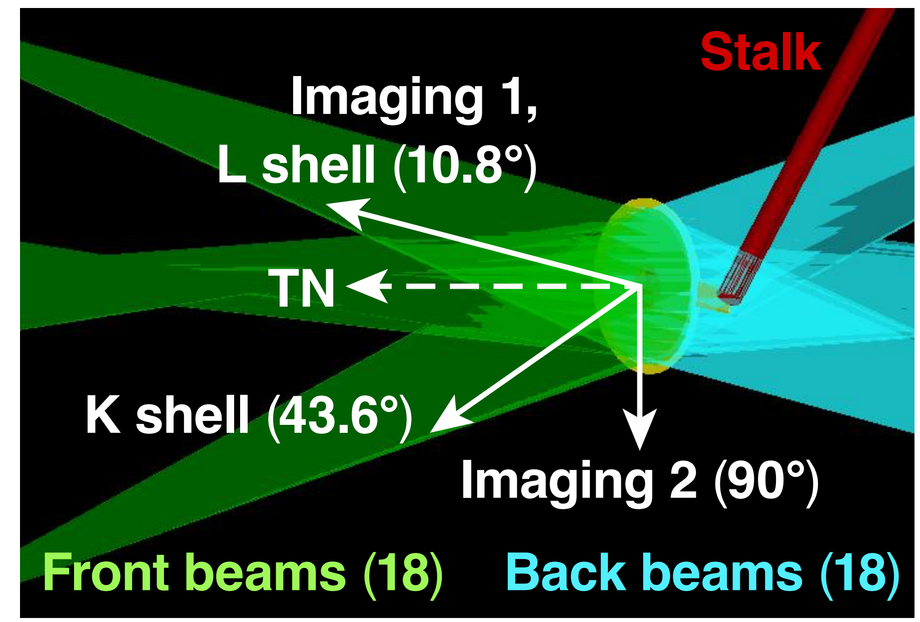
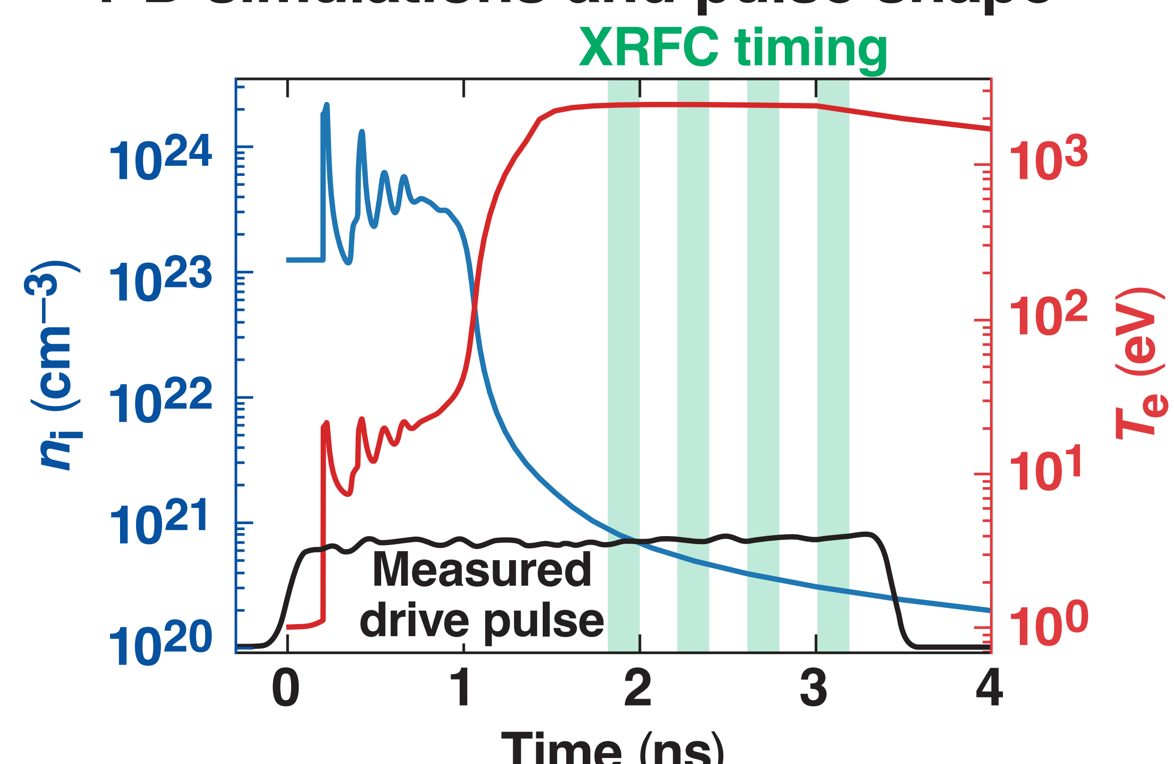
- Diagnostics are timed coincident with isothermal expansion predicted by 1-D hydrodynamic simulations (right)

### Laser and diagnostic geometry




### 1-D simulations and pulse shape

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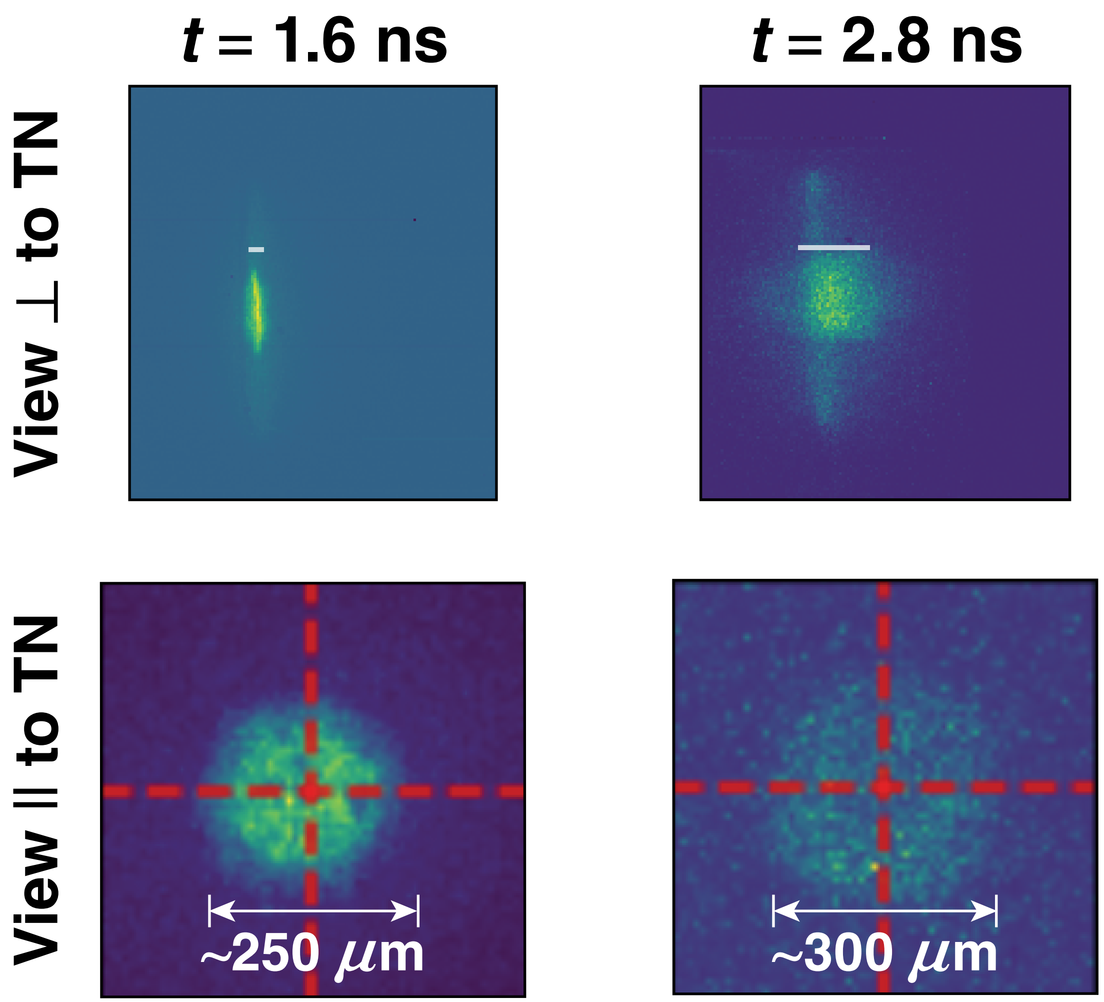


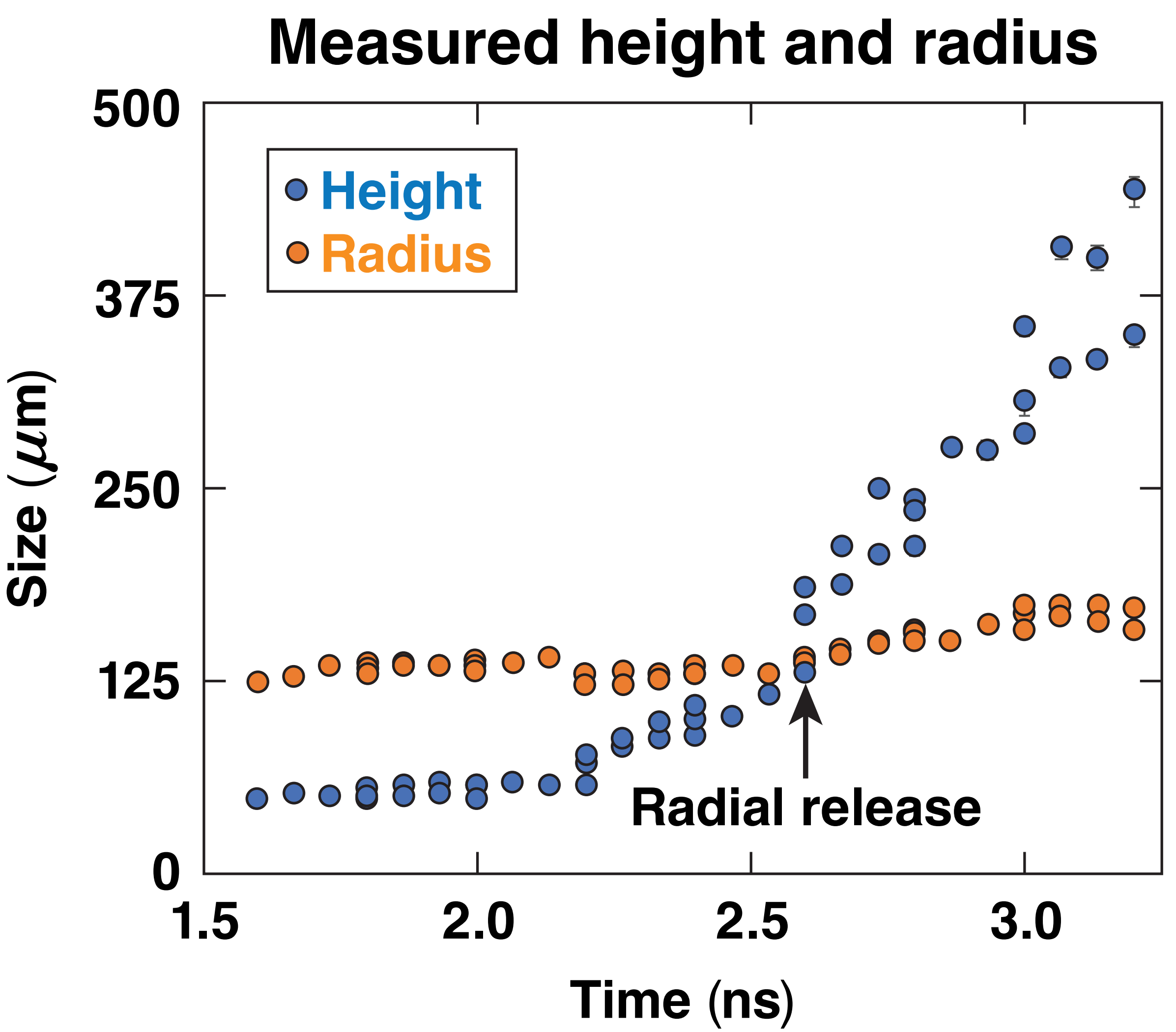


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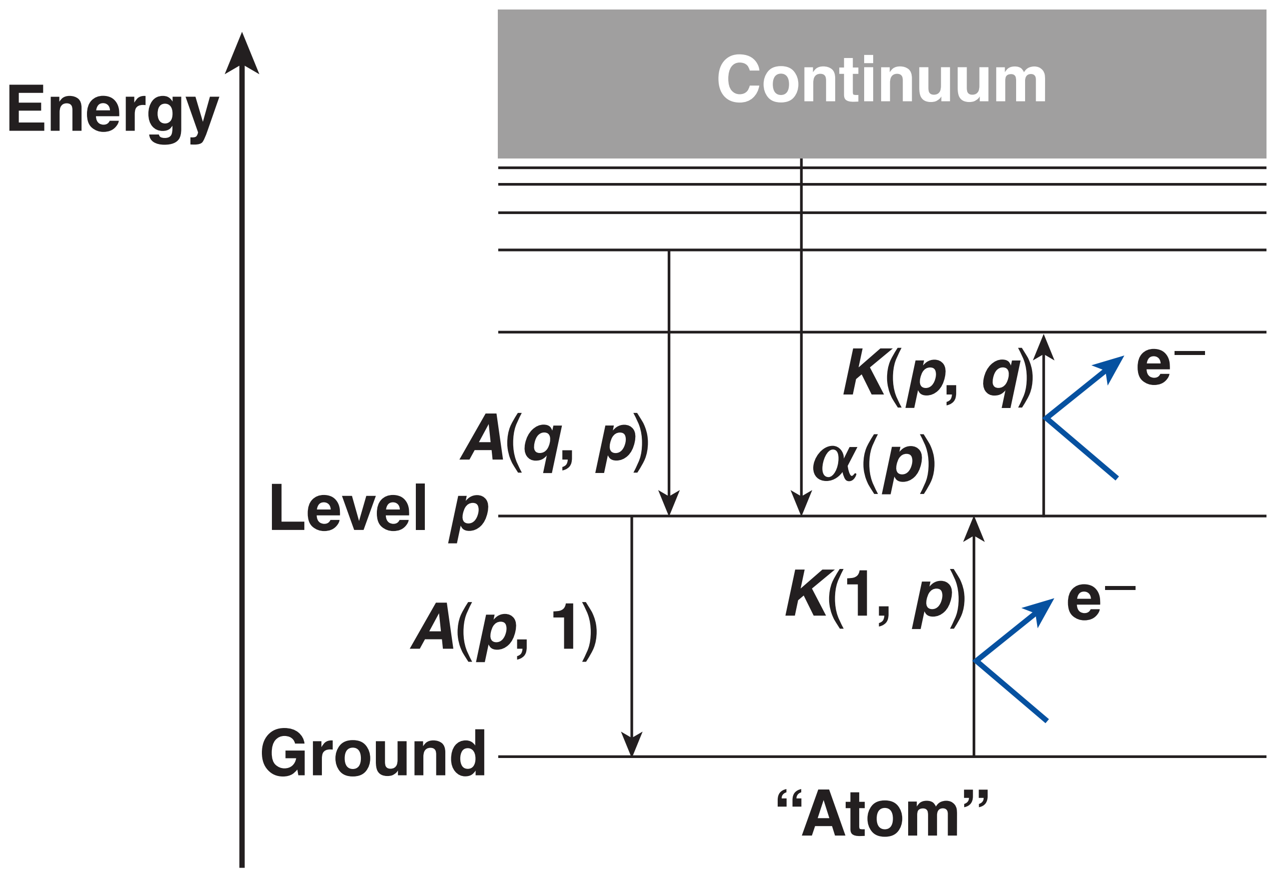


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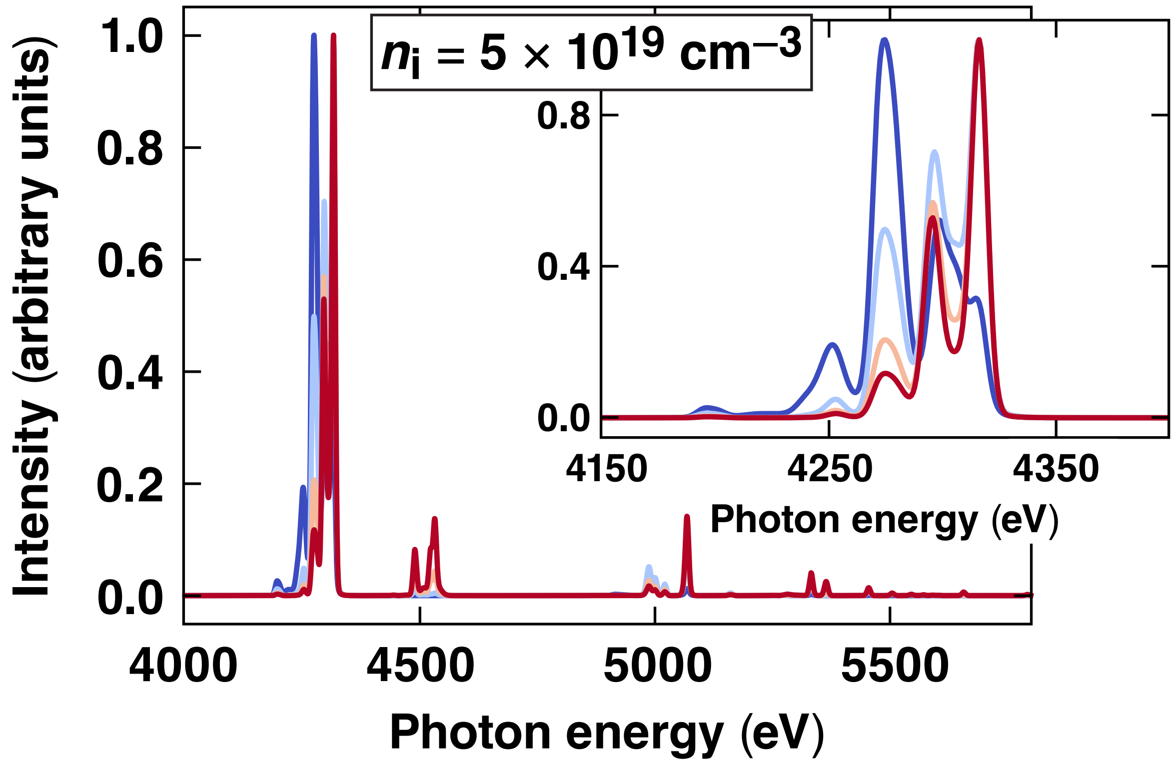


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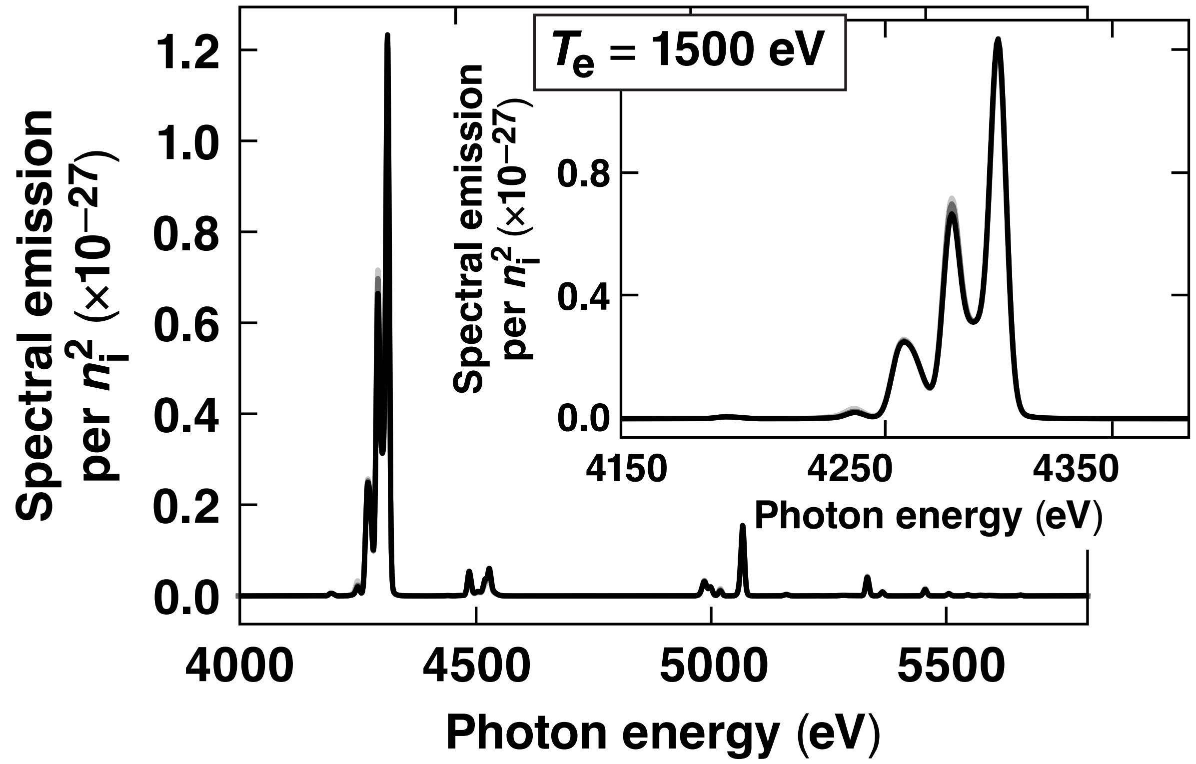
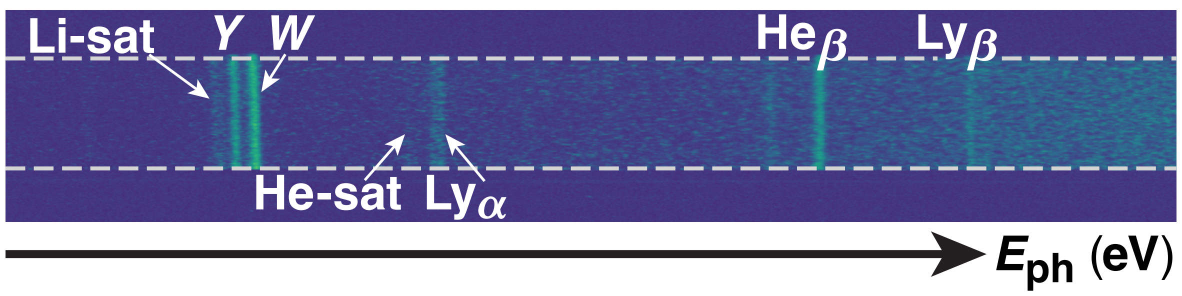
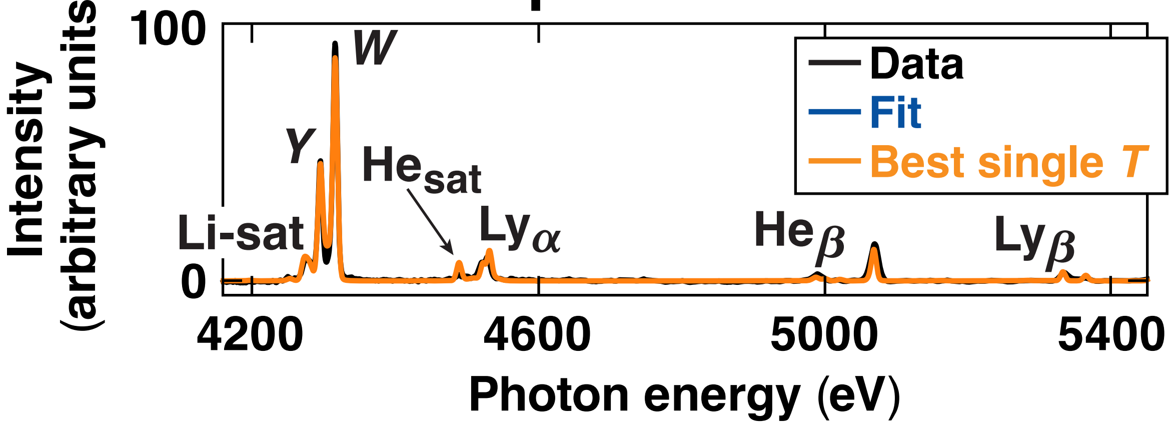
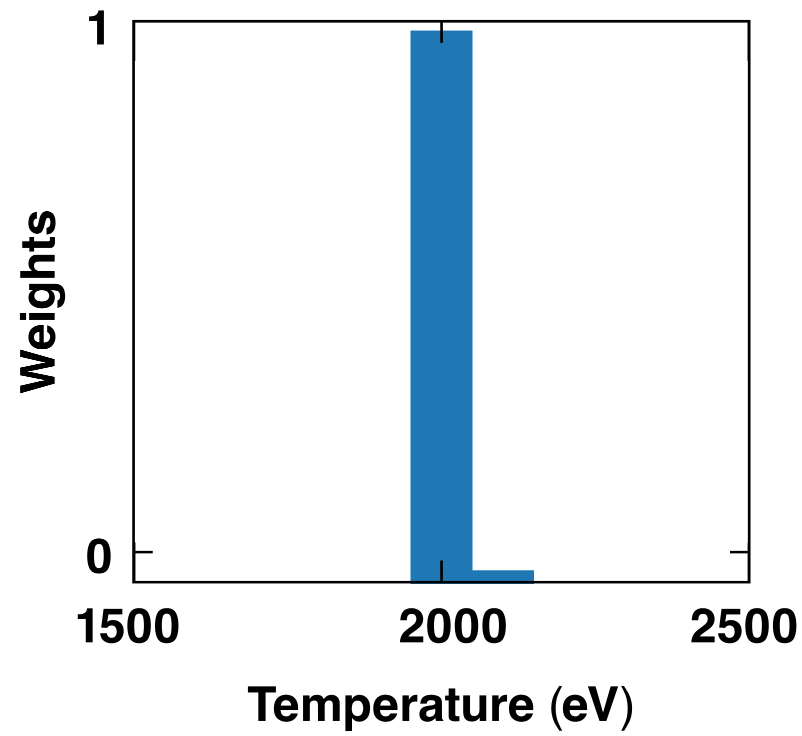



### Spectrum fit




### $T_e$ distribution

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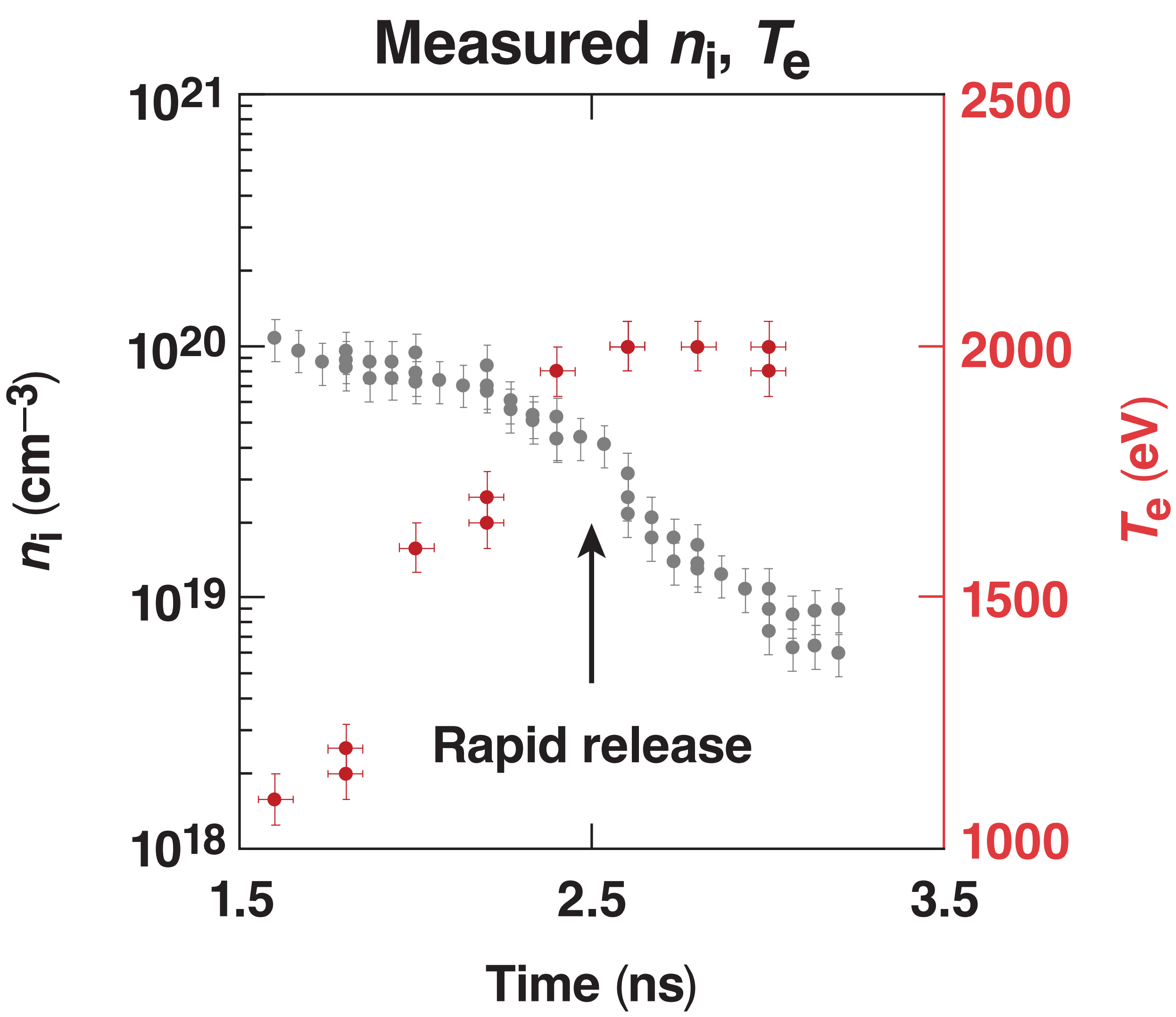


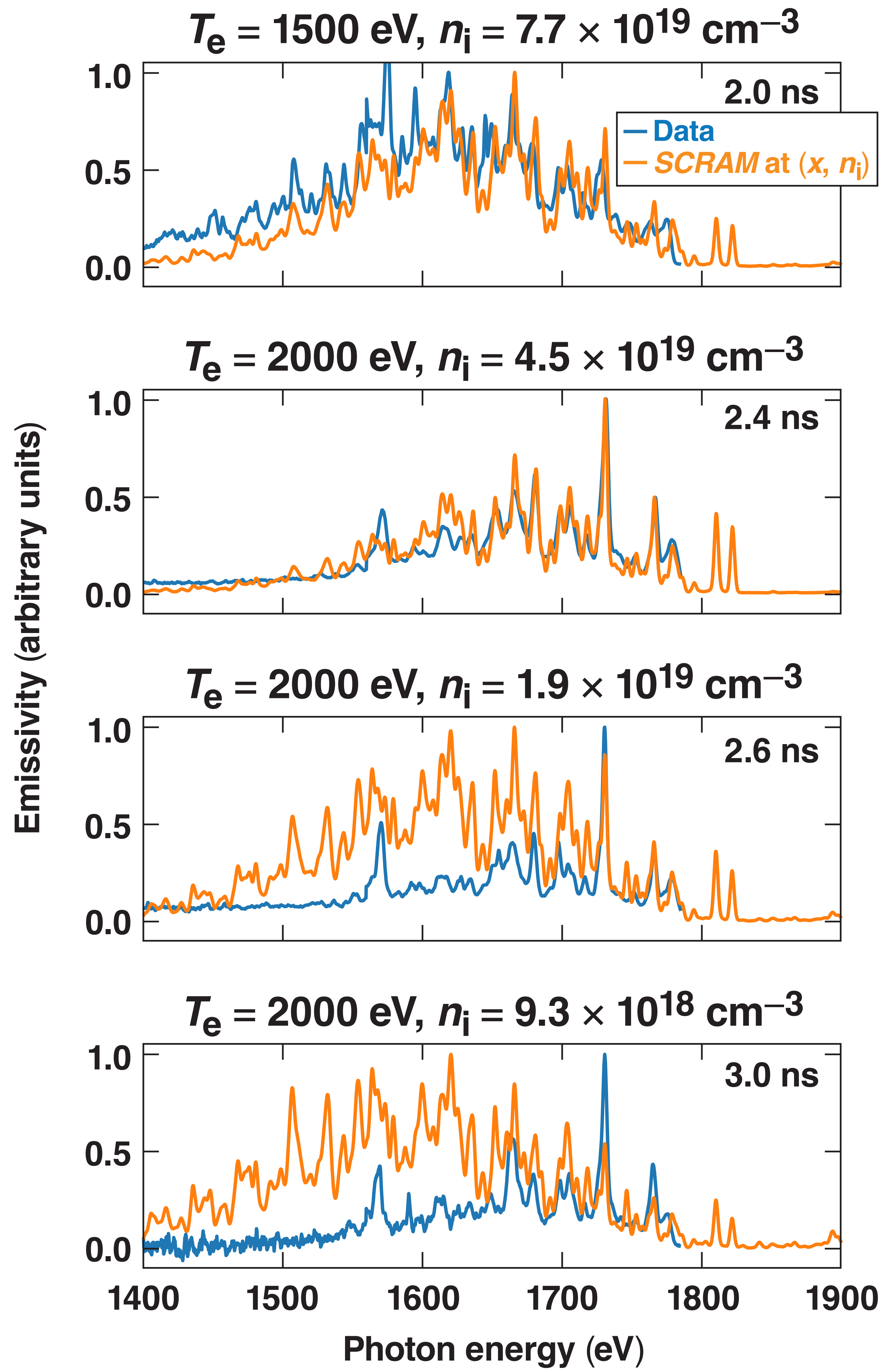


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