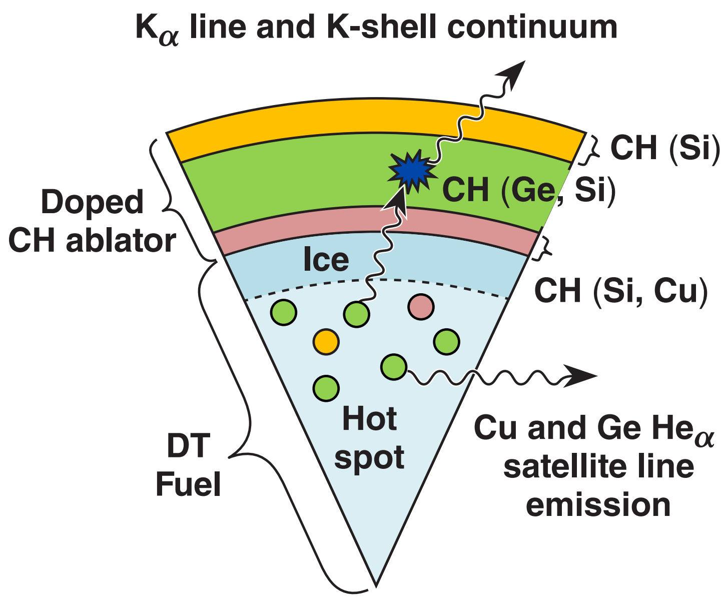
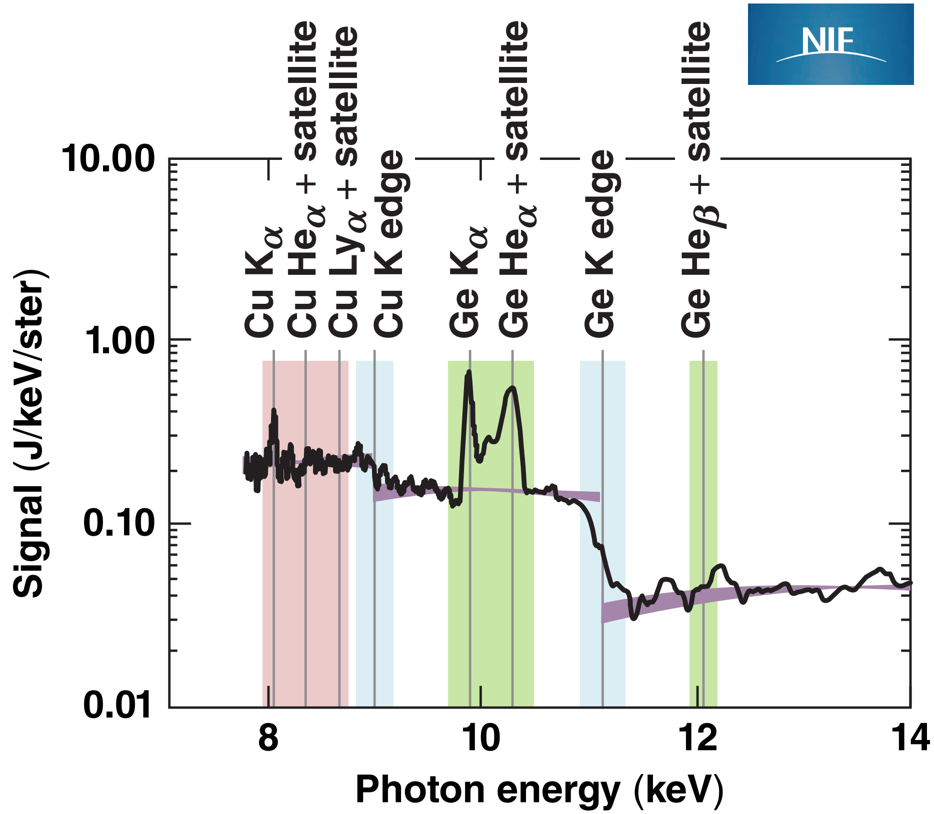
X-Ray Spectroscopy of Implosions at the National Ignition Facility





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44th Annual Anomalous
Absorption Conference
Estes Park, CO
8–13 June 2014

Summary

The hot-spot and compressed shell of ignition-scale implosions are diagnosed with x-ray spectroscopy

- Ablator mass mixed into the hot spot is inferred from the intensity of the He_{α} + satellite line emission of mid-Z ablator dopants*,**
- The origin of the hot-spot mix mass is investigated using Cu and Ge dopants placed at different radial locations in the ablator***
- The compressed-shell conditions are inferred from the absorption of x rays from the hot spot by the compressed Ge-doped CH
- Hydrodynamic mixing is predicted to increase the T_e and n_e of the Ge-doped CH in the compressed shell

These time-integrated measurements will be extended with streaked x-ray spectroscopy using the National ignition Facility (NIF) x-ray spectrometer (NXS).

*B. A. Hammel *et al.*, High Energy Density Phys. 6, 171(2010).
**S. P. Regan *et al.*, Phys. Plasmas 19, 056307 (2012).
***S. P. Regan *et al.*, Phys. Rev. Lett. 111, 045001 (2013).

Collaborators

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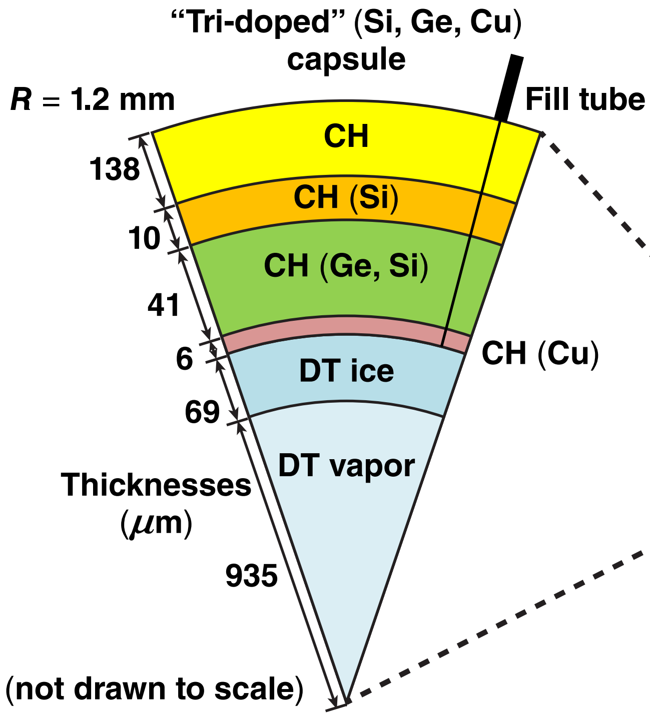
Outline

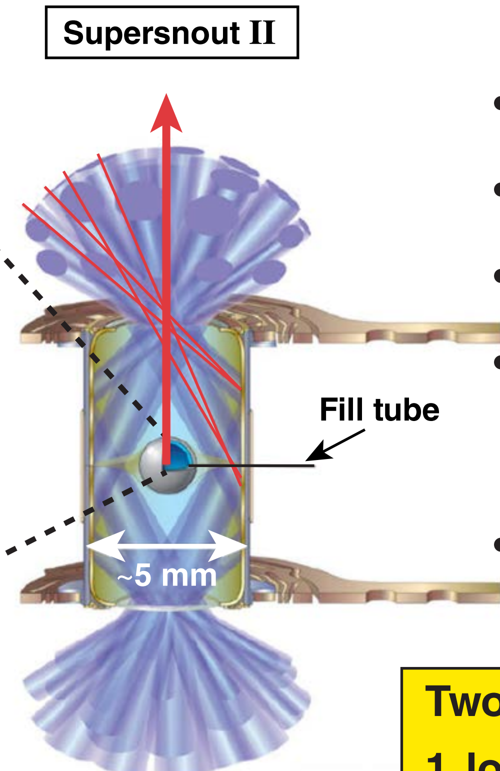
X-ray spectroscopy of implosions at the NIF

- NIF implosion experiment
  - Supersnout II
- X-ray emission spectroscopy of the hot spot
  - hot-spot mix
- X-ray absorption spectroscopy of the compressed shell
  - hydrodynamic mixing of shell layers
- Future direction
  - streaked x-ray spectroscopy on NIF
- Conclusion

Ignition-scale capsules with trace amounts of Ge and Cu are imploded with hohlraums on the NIF



CH, Si (1.15%)
CH, Si (1.53%), Ge (0.20%)
CH, Cu (0.14%)



192 beams
(λ = 351 nm)

- E_{UV} = 1.3 MJ to 1.8 MJ
- CH ablator
- Si dopant is a preheat shield
- Ge/Cu dopants are used for emission/absorption x-ray spectroscopy
- adiabat ($\alpha = P_{fuel}/P_{Fermi}$) is set by the laser drive

Two types of implosion are studied:

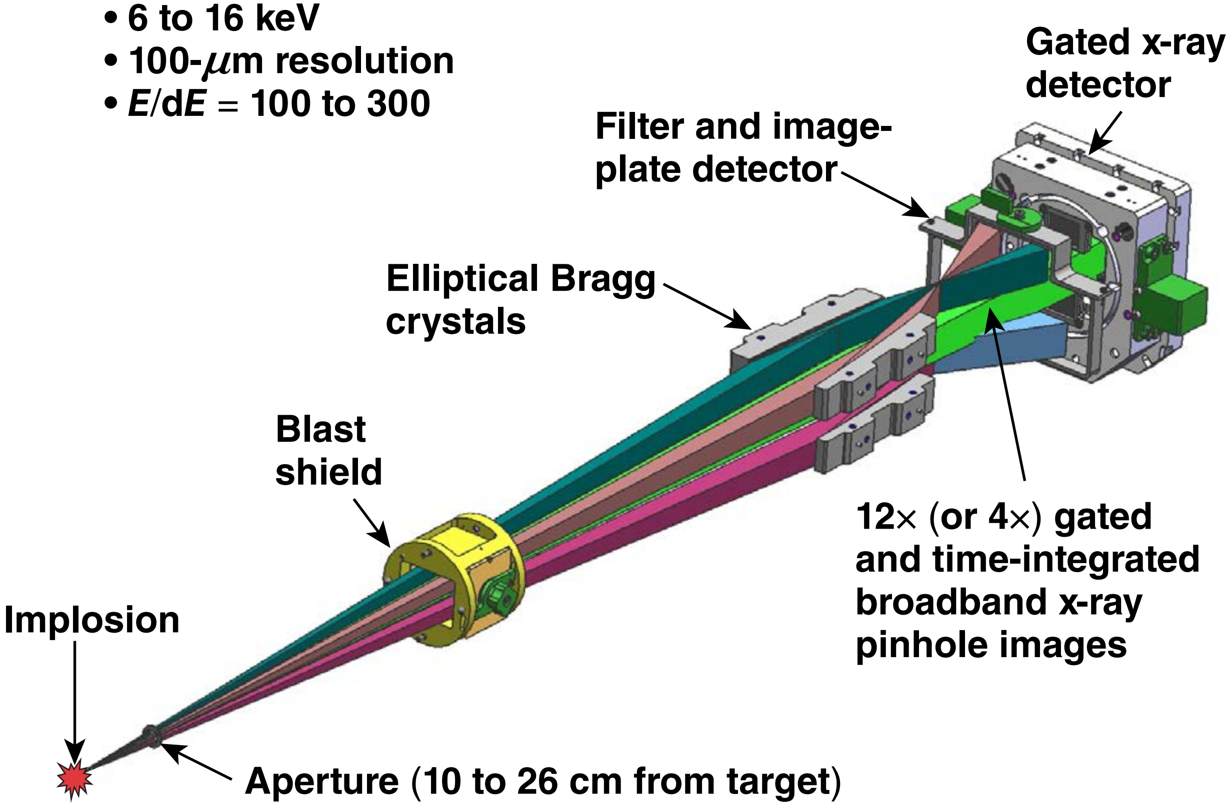
1. low-adiabat (α ~ 1)*
2. high-adiabat (α ~ 3)**

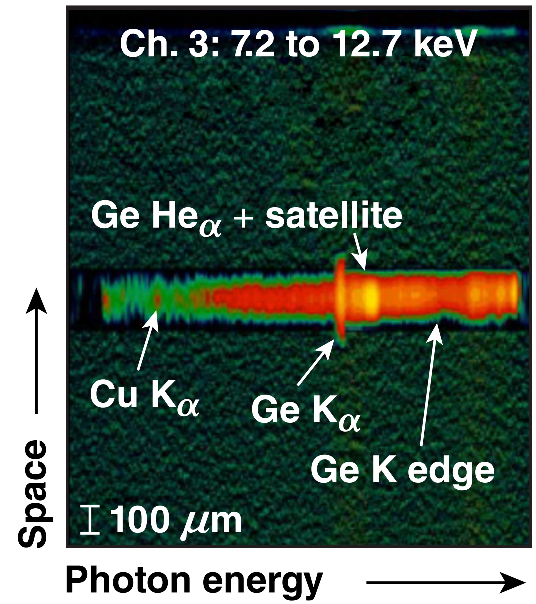
*M. J. Edwards *et al*., Phys. Plasmas 20, 070501 (2013).
**O. A. Hurricane., Nature 506, 343 (2014).

A time-integrated, 1-D imaging spectrometer was used to record x-ray spectra in the 6- to 16-keV range

Supersnout II

- 6 to 16 keV
- 100-μm resolution
- E/dE = 100 to 300





Supersnout II combines 1-D spectral imaging and broadband gated and time-integrated x-ray imaging in a single snout.

TC10729a

The ablation-surface instability* and the inner-shell deceleration instability initiate mix at different times and locations

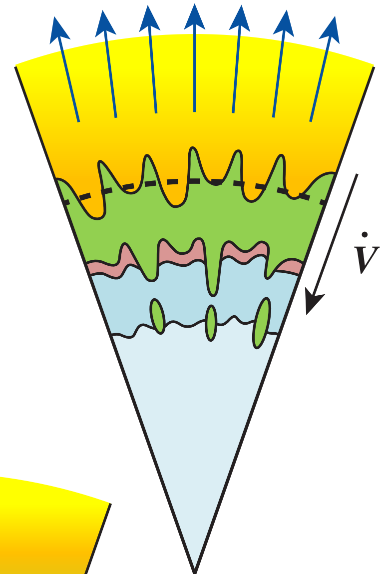
- **Find the instability criterion**

$$\vec{\nabla} P \cdot \vec{\nabla} \rho < 0$$

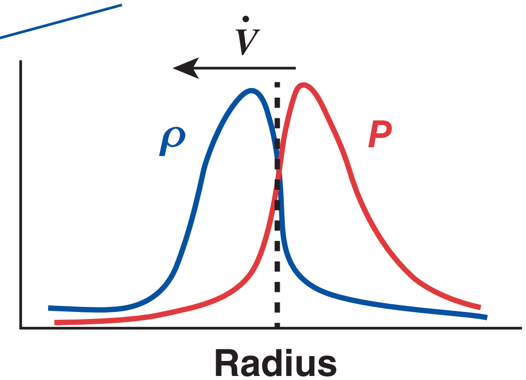
satisfied near the dashed lines

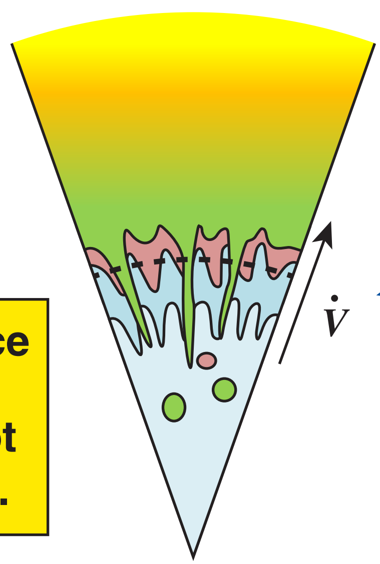
- - - - - - - - - - - - - - - - - -

CH (Si)
CH (Ge, Si)
CH (Cu)

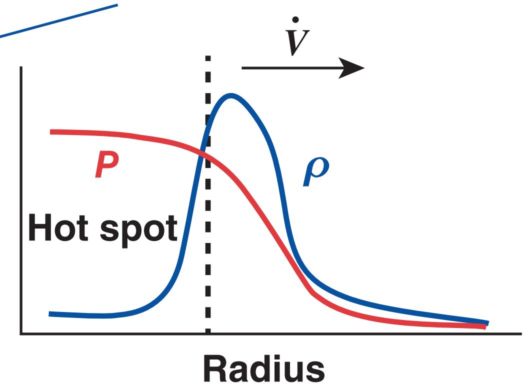


Ablative instability affects CH (Ge,Si)





Deceleration-phase instability affects CH (Cu)



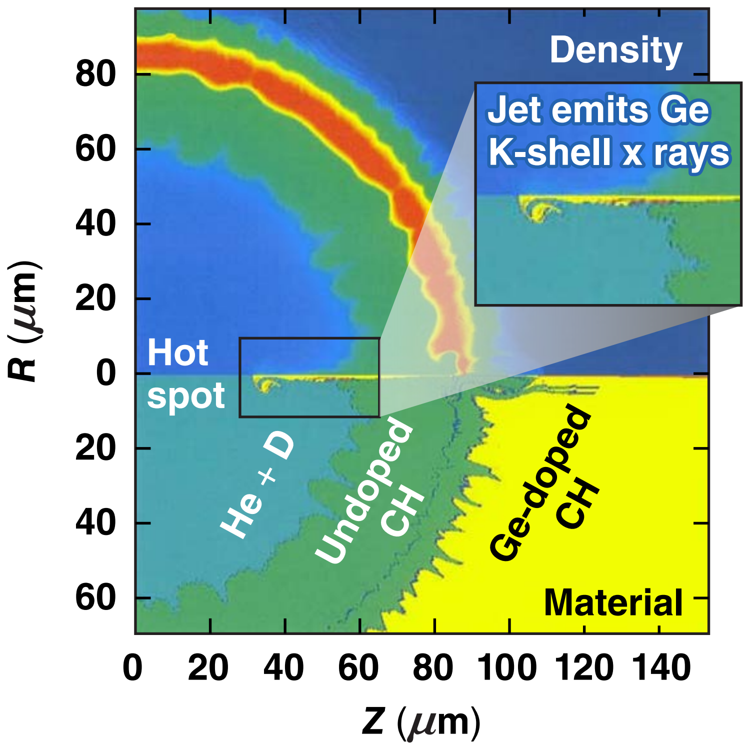
The ablation surface reaches the Ge-doped layer, but not the Cu-doped layer.

TC10785a

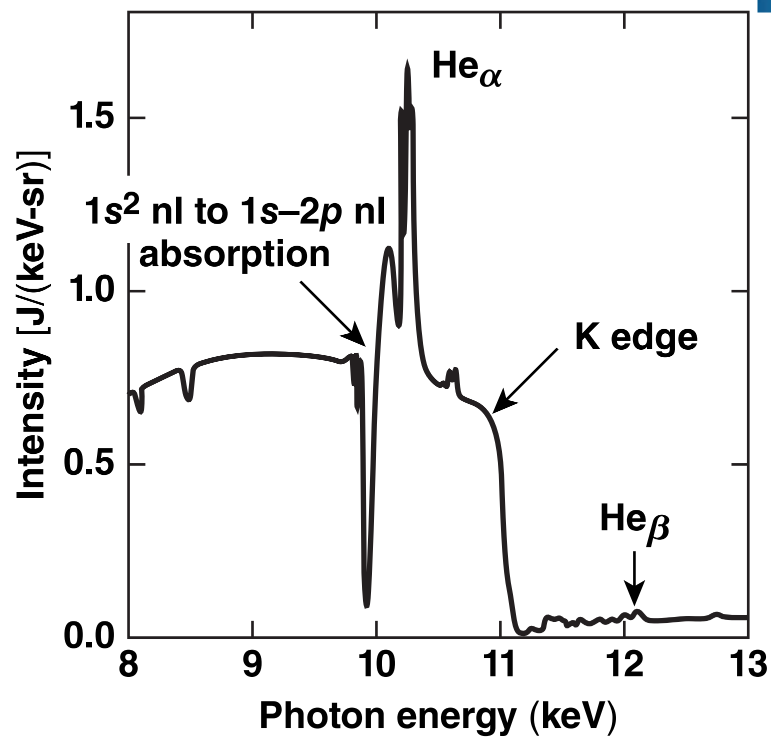
*V. A. Smalyuk *et al*., Phys. Rev. Lett. 112, 185003 (2014).

Two-dimensional simulations predict bubbles of material from the ablation surface are mixed into the hot spot (hot-spot mix)*

HYDRA 2-D simulation of symcap (perturbation on-axis)



*CRETIN*** K-shell emission from a ~5-ng jet of Ge-doped CH

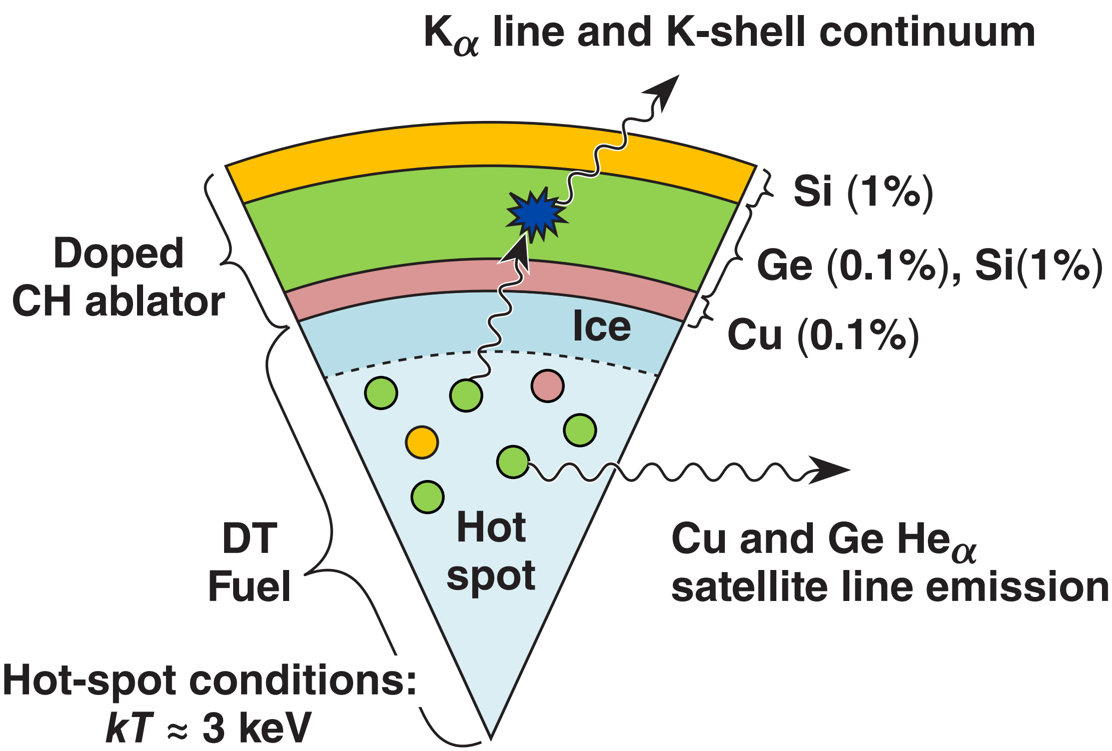


The symcap target replaces the DT cryo layer with a CH surrogate layer.

*B. A. Hammel *et al*., High Energy Density Phys. 6, 171 (2010).
**H. A. Scott, J. Quant. Spectros. Radiat. Transf. 71, 689 (2001).

TC10707a

Hot-spot mix and compressed-ablator ρR are diagnosed with x-ray spectroscopy near peak compression



Hot-spot conditions:
$kT \approx 3$ keV
$n_e \approx 10^{25}$ cm^{-3}
$\rho \approx 40$ g/cm^3

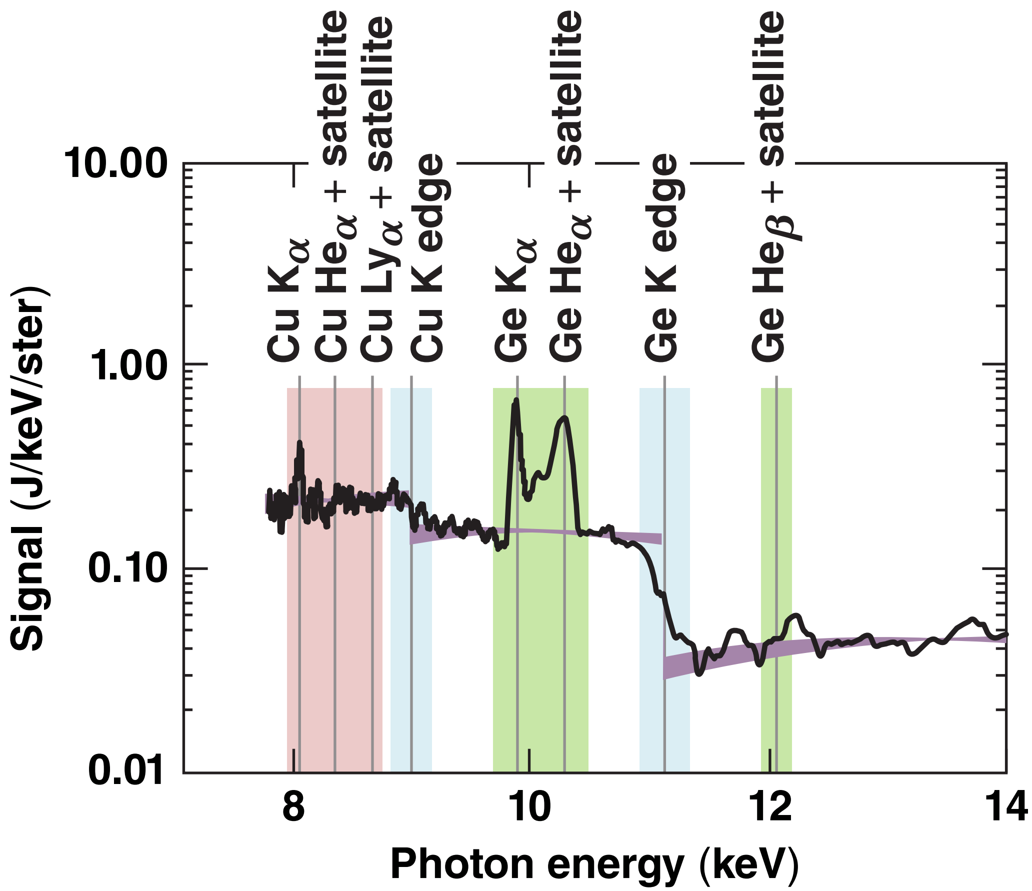
- Mix from the ablation surface instability[1–3] →
  - Ge hot-spot emission
- Mix from the ablator/fuel interface[1–3] →
  - Cu hot-spot emission

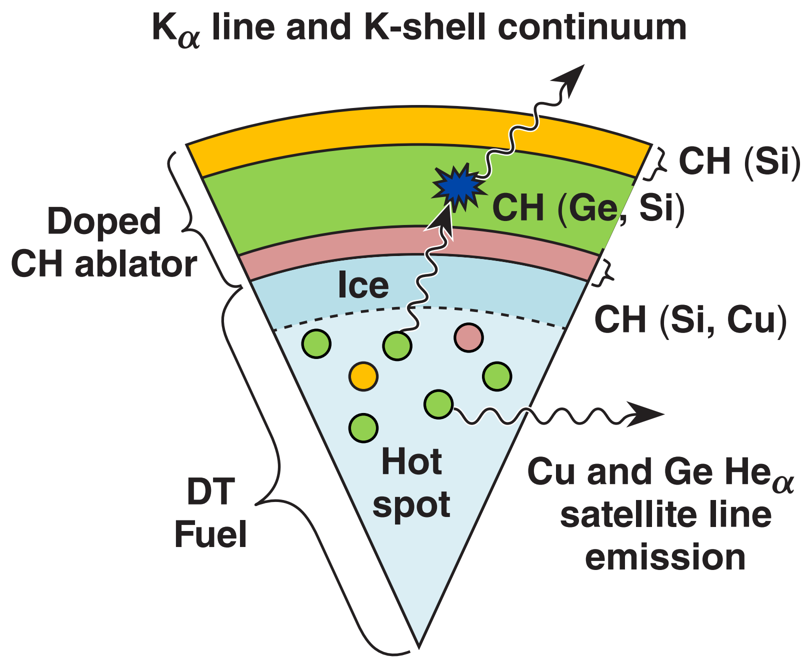
- X-ray continuum from the hot spot is attenuated by the K edges of dopants in the compressed ablator

[1]B. A. Hammel *et al*., High Energy Density Phys. 6, 171(2010).
[2]S. W. Haan *et al*., Phys. Plasmas 18, 051001 (2011).
[3]S. P. Regan *et al*., Phys. Rev. Lett. 111, 045001 (2013).

TC10731a

The calibrated, spatially integrated x-ray spectrum contains features from the hot spot and the shell





Strong Ge features and weak Cu features are observed.

TC10710a

*S. P. Regan *et al.*, Phys. Rev. Lett. 111, 045001 (2013).

The mix mass is estimated from the brightness of the Ge and Cu He$_\alpha$ + satellite emission, assuming uniform plasma conditions

- The total time and spectrum-integrated line emission $\iint \langle P_{21}(h\nu)\rangle_{\text{meas}}\, \mathrm{d}h\nu\, \mathrm{d}t$ is measured

- The total line emissivity per ion $\langle p_2(T,\rho,R)A_{21}E_{21}\rangle$ is obtained from *PrismSPECT** as a function of T, ρ, and the average photon escape path length R.

- The total number of Ge ions under steady uniform conditions

$$N_{\text{Ge}} = \frac{\iint \langle P_{21}(h\nu)\rangle_{\text{meas}}\, \mathrm{d}h\nu\, \mathrm{d}t}{\langle p_2(T,\rho,R)A_{21}E_{21}\rangle \Delta t}$$

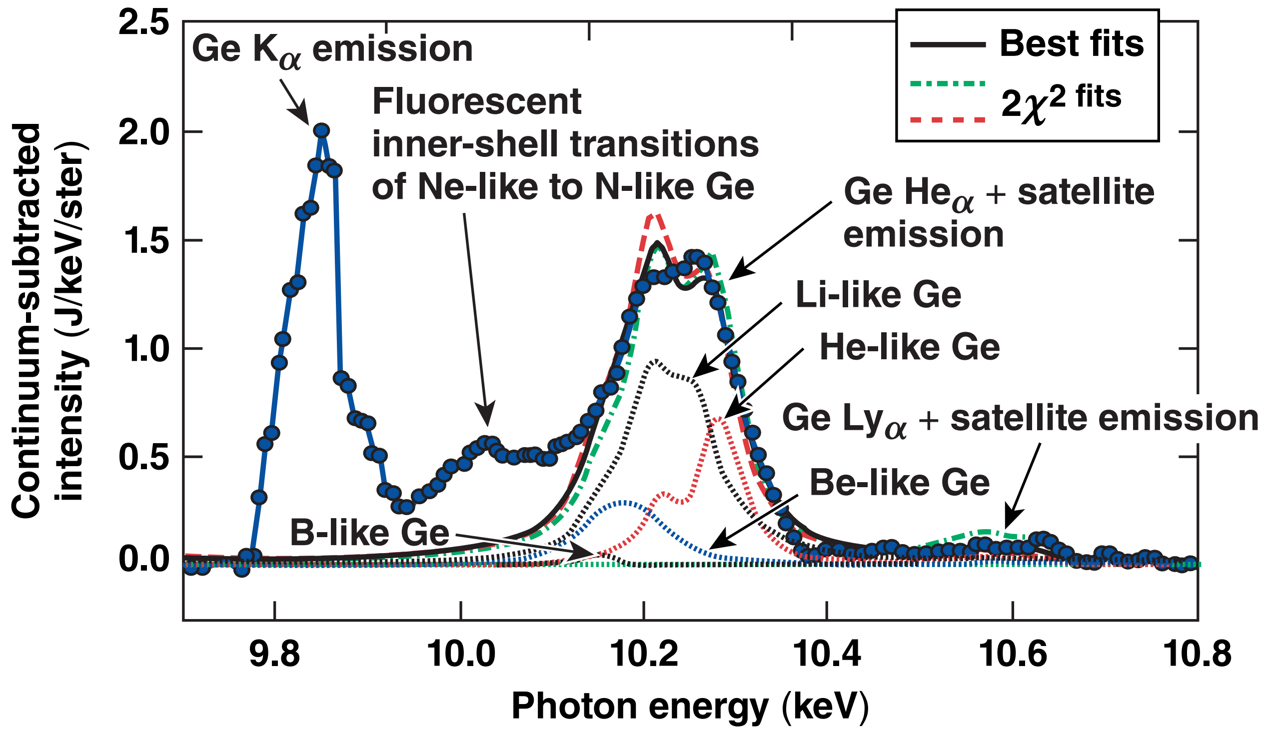
and the initial Ge atomic concentration give the total mix mass M.

Fitting the emission model to the data produces significant estimates of the three independent parameters T, ρ, and R.

TC10786a

*J. J. MacFarlane *et al*., High Energy Density Phys. 3, 181 (2007).

The spectrum is fit to the model to infer the hot-spot mix mass

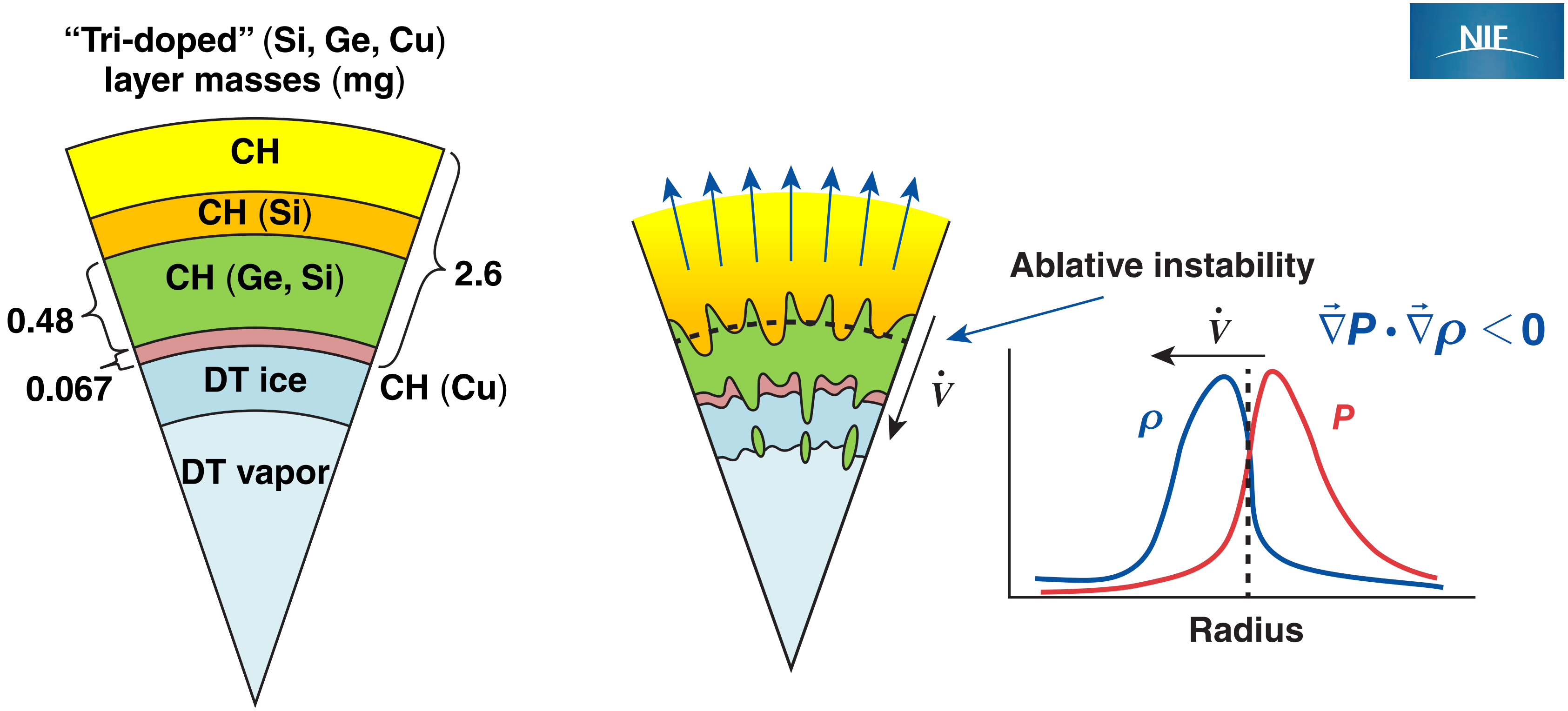


- n_e = 0.9 (+0.1,–0.5) × 10^{25} cm^{-3}
- T_e = 3.0 (+0.6,–0.4) keV
- ρR_{Ge} = 0.325 (–0.1,–0.025) mg/cm^2
- $M_{CH\,(Ge,\,Si)}$ = 34 (–13, +50) ng
- $M_{CH(Cu)}$ < 2 (–1, +1) ng, upper limit

The Ge-doped mix mass is at least 17× more than the Cu-doped mix mass.

E20074a

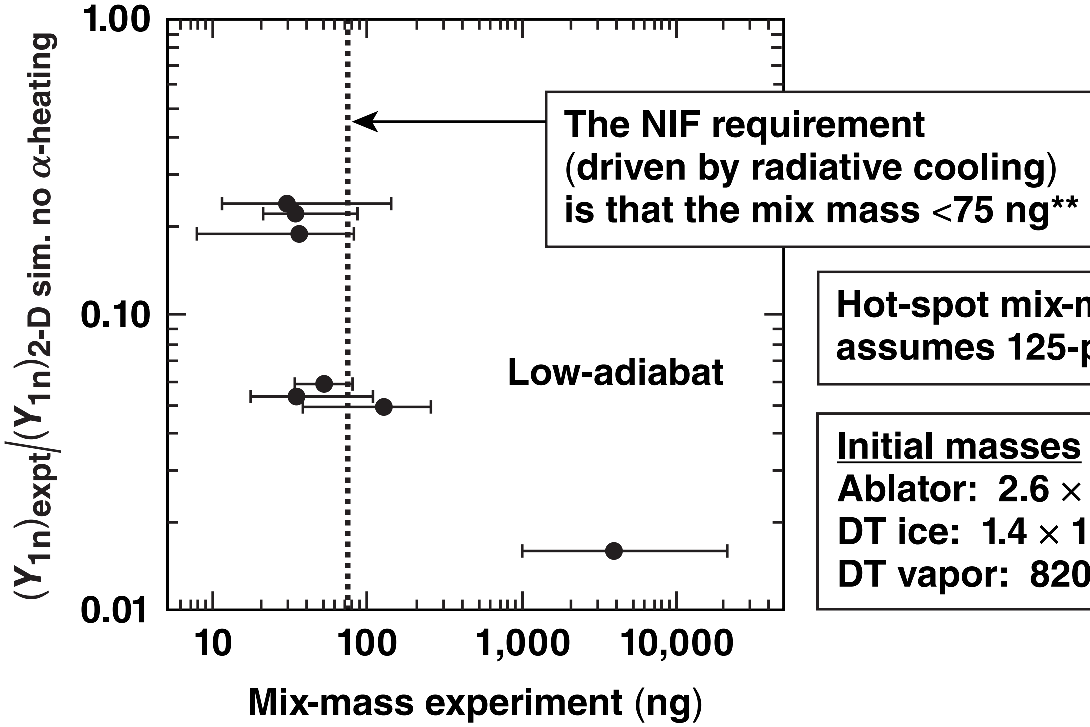
The ablation-front instability is primarily responsible for hot-spot mix*



The CH(Ge) mass is 7× the CH(Cu) mass, but at least 17× more CH(Ge) mix mass than CH(Cu) mix mass was observed.

*S. P. Regan *et al.*, Phys. Rev. Lett. 111, 045001 (2013).

Low neutron yields and hot-spot mix mass around the 75-ng limit are observed*



Hot-spot mix-mass analysis assumes 125-ps x-ray burnwidth

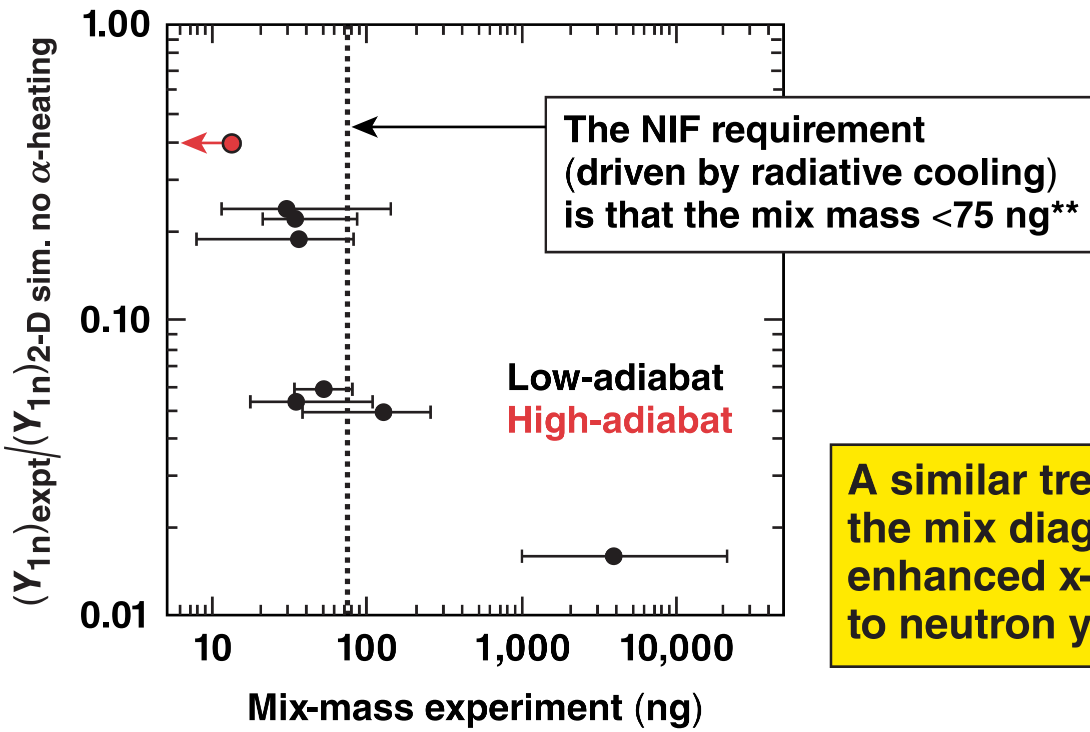
<u>Initial masses</u>
Ablator: 2.6×10^6 ng
DT ice: 1.4×10^5 ng
DT vapor: 820 ng

Mix mass from the pure CH ablator cannot be detected with x-ray spectroscopy → lower bound on hot-spot mix.

*S. P. Regan *et al.*, Phys. Rev. Lett. <u>111</u>, 045001 (2013).
**S. W. Haan *et al.*, Phys. Plasmas <u>18</u>, 051001 (2011).

E20075d

Less hot-spot mix and higher neutron yields are observed for the high-adiabat* implosion



A similar trend is observed using the mix diagnostic technique of enhanced x-ray production relative to neutron yield***.

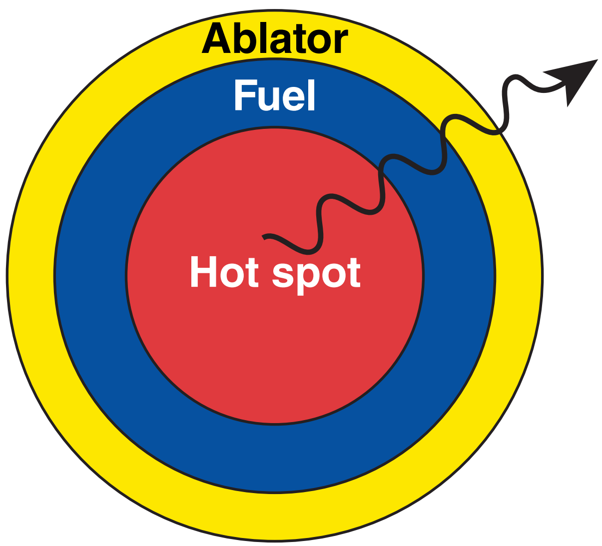
*H. S. Park *et al*., Phys. Rev. Lett. 112, 055001 (2014).
**S. W. Haan *et al*., Phys. Plasmas 18, 051001 (2011).
***T. Ma *et al*., Phys. Rev. Lett. 111, 085004 (2013).

High-Z dopants are used to diagnose the compressed ablator near stagnation

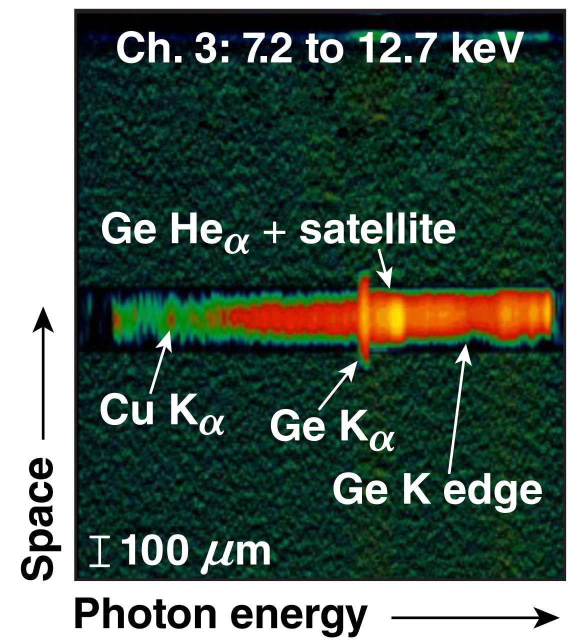
Compressed target at stagnation

Measured x-ray spectrum around stagnation

Ablator: CH with high-*Z* dopant (Cu, Ge)



1-D spectral image



$$I \propto e^{-h\nu/kT}\, e^{-\mu_{Ge}(n_e,T_e)\,\rho R_{Ge}}\, e^{-\mu_{Cu}\,\rho R_{Cu}}\, e^{-\mu_{CH}\,\rho R_{CH}}$$

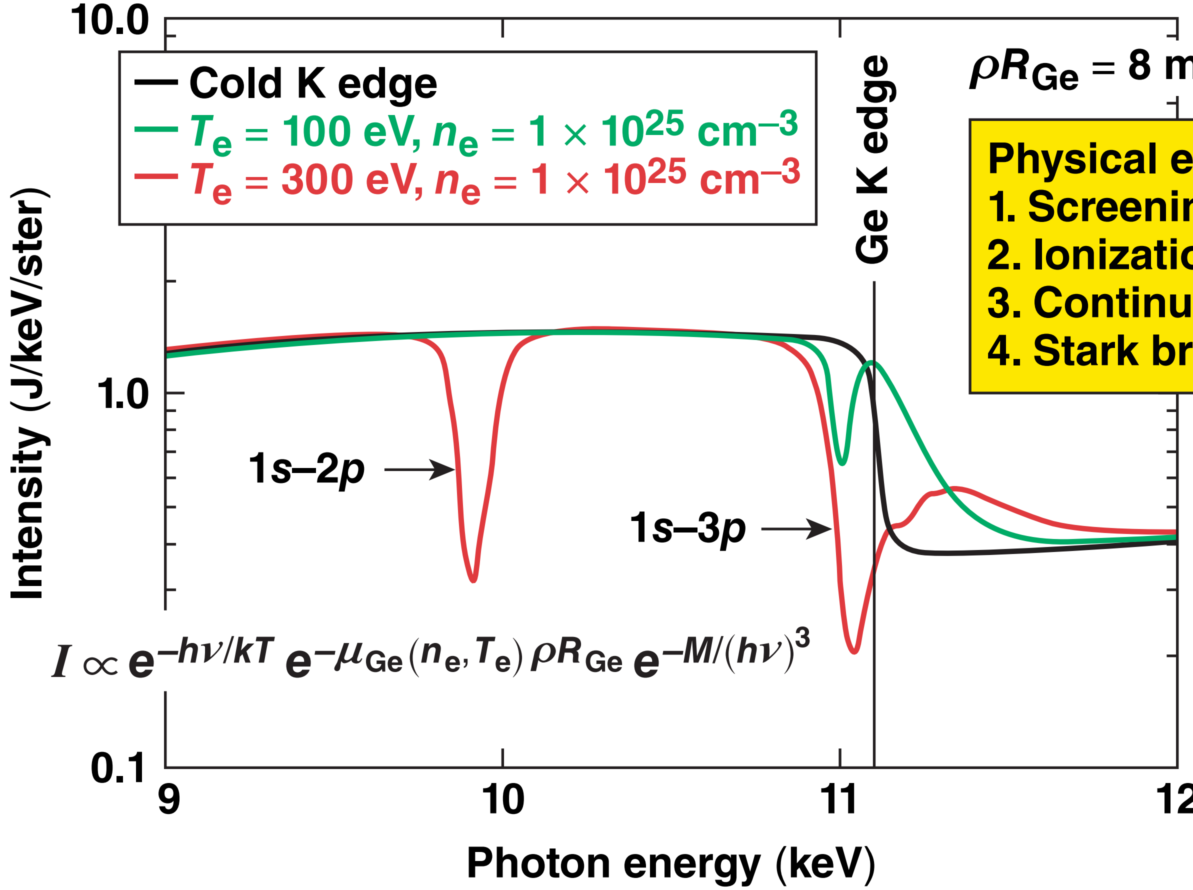
Hot-spot backlighter	Ge shell attenuation	Cu shell attenuation	CH shell attenuation

Adiabat: $\alpha \equiv P_{fuel}/P_{Fermi}$ (set by laser pulse shape)

E22511

The Ge opacity is sensitive to changes in n_e and T_e of the compressed ablator

Simulated emergent spectrum using *VISTA** opacity calculations

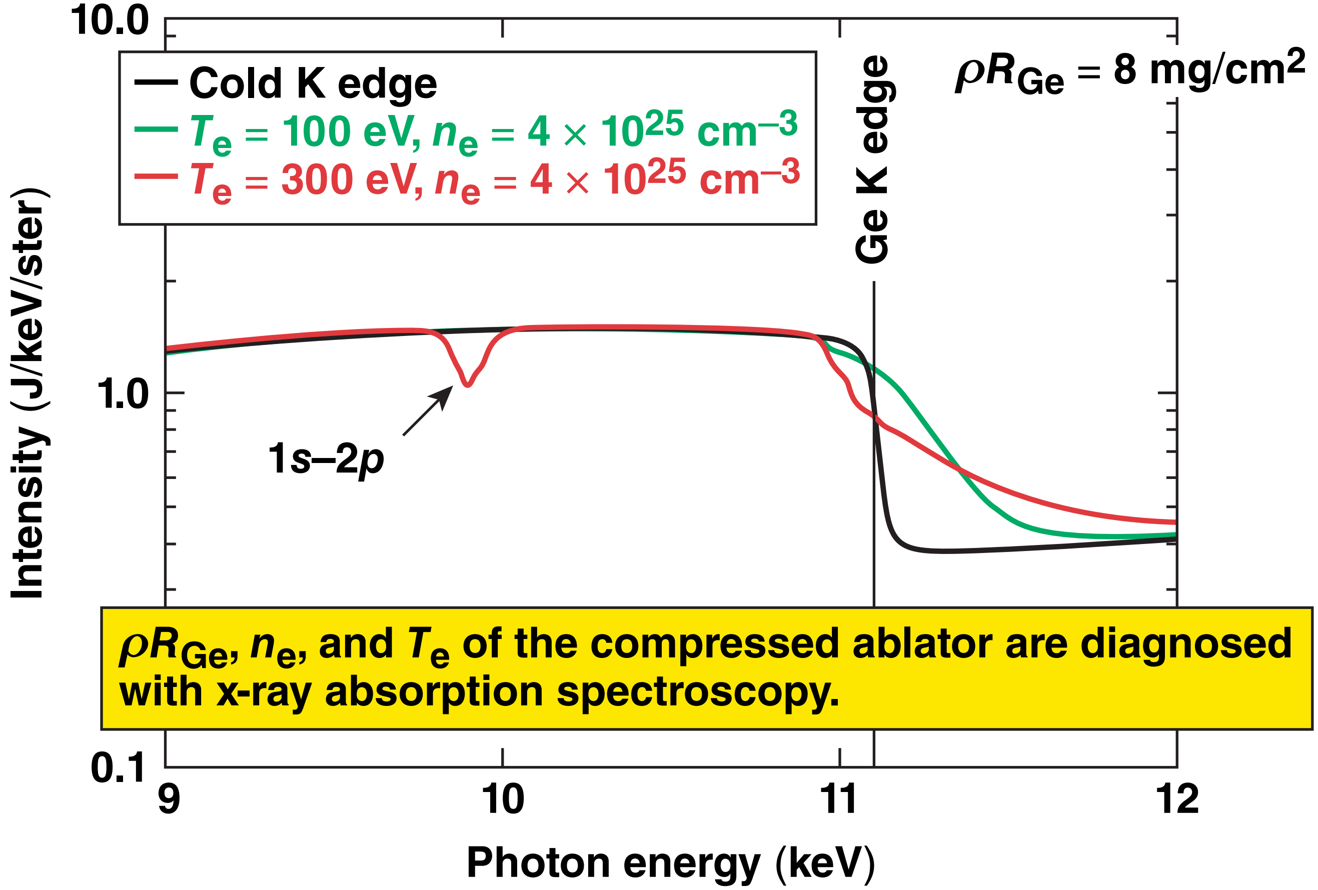


Physical effects:**
1. Screening (K-edge shift)
2. Ionization (1*s*–2*p*, 1*s*–3*p*)
3. Continuum lowering***
4. Stark broadening

*B. G. Wilson and M. H. Chen, J. Quant. Spectrosc. Radiat. Transf. 61, 813 (1999).
**D. K. Bradley *et al*., Phys. Rev. Lett. 59, 2995 (1987).
***J. C. Stewart and K. D. Pyatt, Jr., Astrophys. J. 144, 1203 (1966).

Continuum lowering* reduces the 1*s*–3*p* and 1*s*–2*p* absorption features

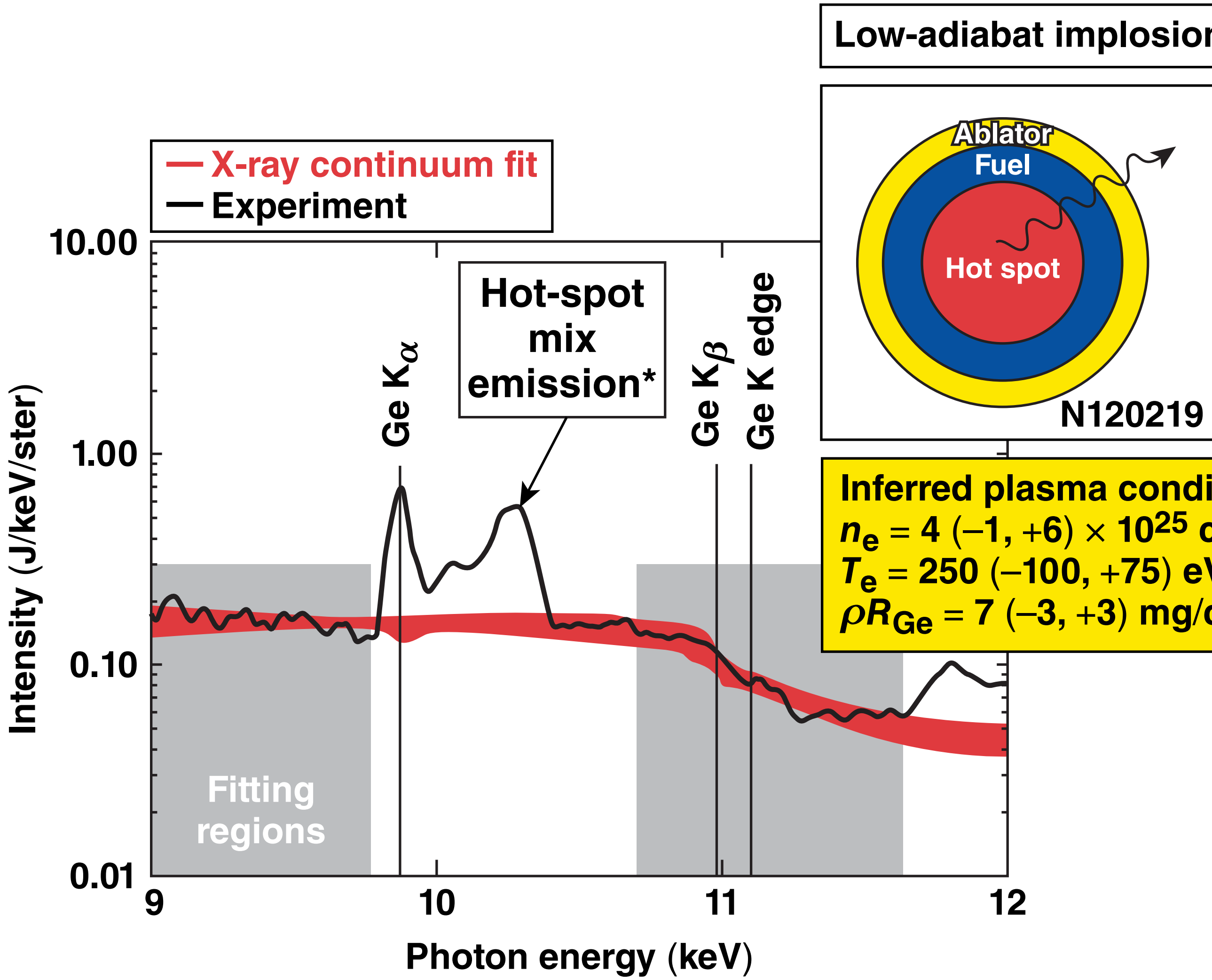
Simulated emergent spectrum using *VISTA*** opacity calculations



ρR_{Ge}, n_e, and T_e of the compressed ablator are diagnosed with x-ray absorption spectroscopy.

*J. C. Stewart and K. D. Pyatt, Jr., Astrophys. J. 144, 1203 (1966).
**B. G. Wilson and M. H. Chen, J. Quant. Spectrosc. Radiat. Transf. 61, 813 (1999).

A range of compressed plasma conditions is inferred for the low-adiabat implosion



Inferred plasma conditions

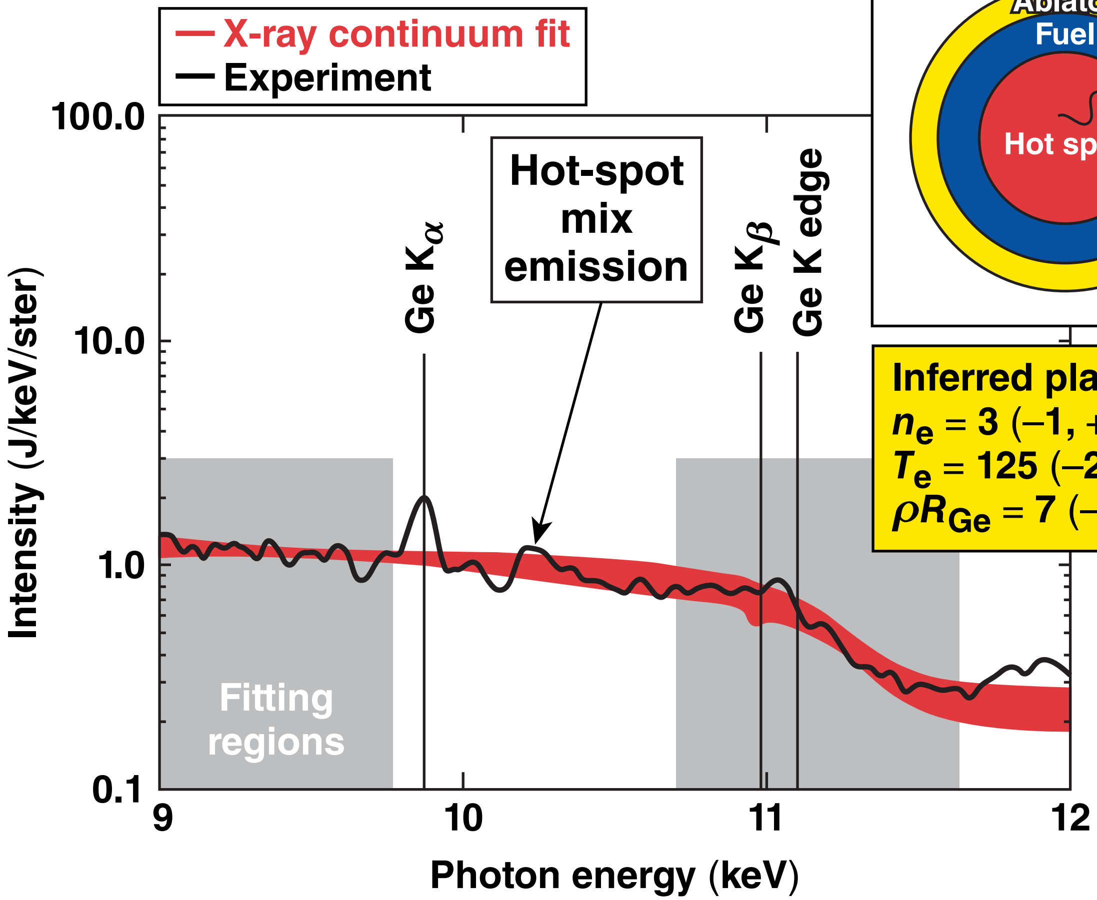
n_e = 4 (–1, +6) × 10^{25} cm^{-3}

T_e = 250 (–100, +75) eV

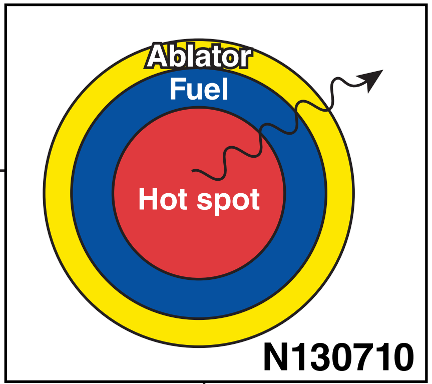
ρR_{Ge} = 7 (–3, +3) mg/cm^2

*S. P. Regan *et al*., Phys. Rev. Lett. 111, 045001 (2013).

Similar analysis was performed for the high-adiabat implosion



High-adiabat implosion

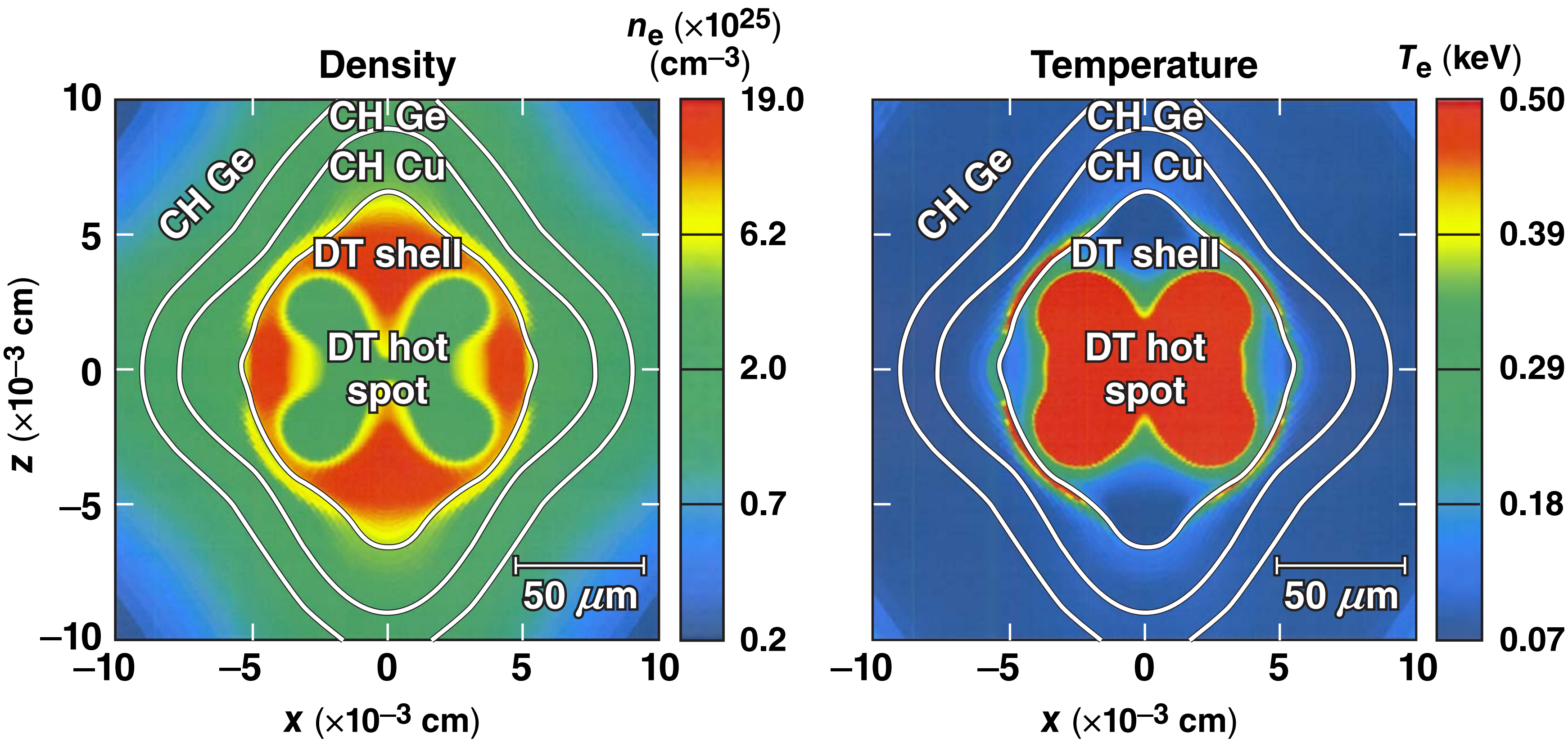


Inferred plasma conditions
n_e = 3 (–1, +7) × 10^{25} cm^{-3}
T_e = 125 (–25, +75) eV
ρR_{Ge} = 7 (–2.5, +2) mg/cm^2

E22514

Two-dimensional simulations show density and temperature in the DT-fuel layer is higher than in the compressed ablator

- 2-D *HYDRA* simulation of low-adiabat implosion near stagnation



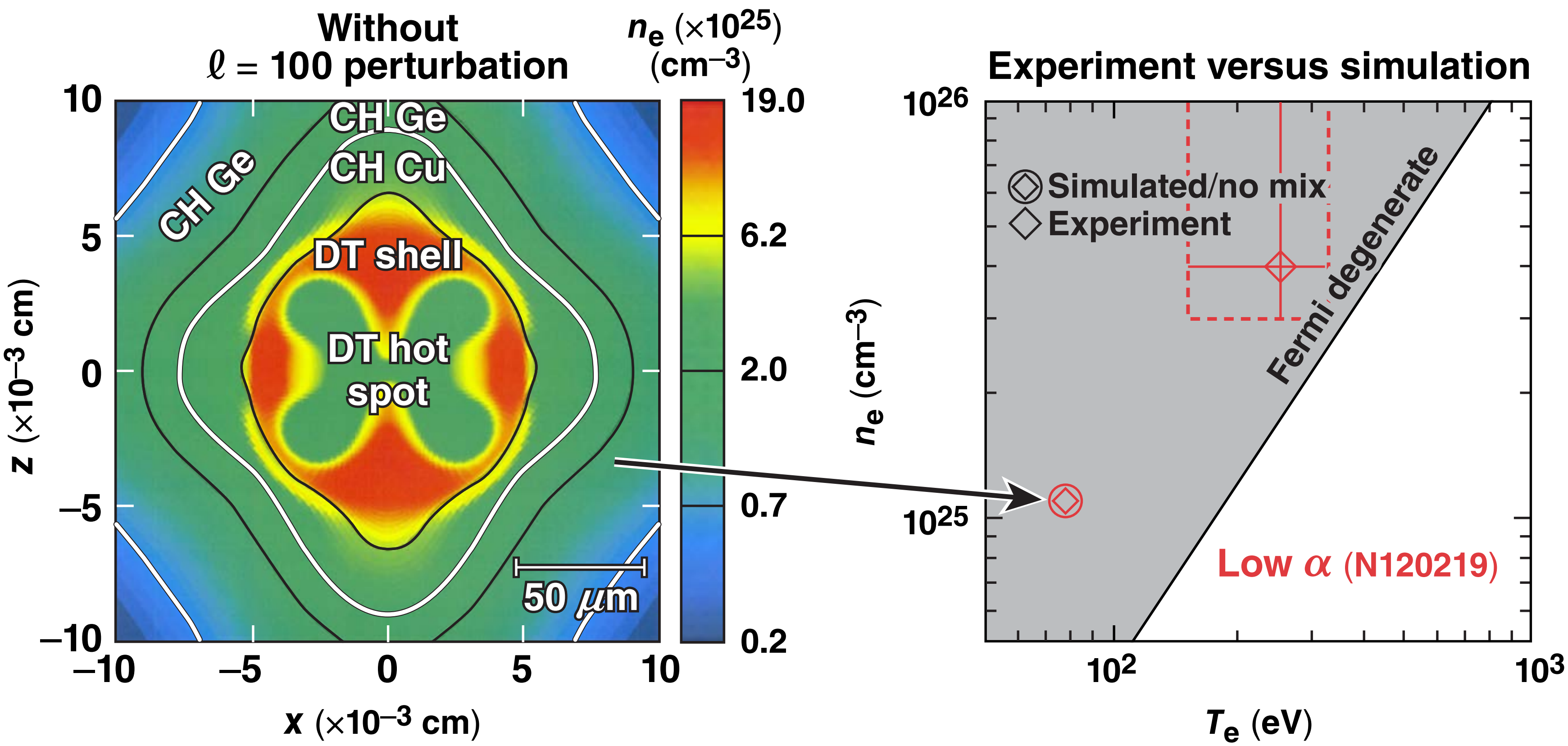
Simulated spatially and temporally averaged T_e and n_e of the compressed ablator are compared with the experimental results.

E23243

Low-adiabat

Simulated T_e and n_e of the compressed ablator without mix are much lower than the experiment

- 2-D *HYDRA* simulation of the low-adiabat implosion

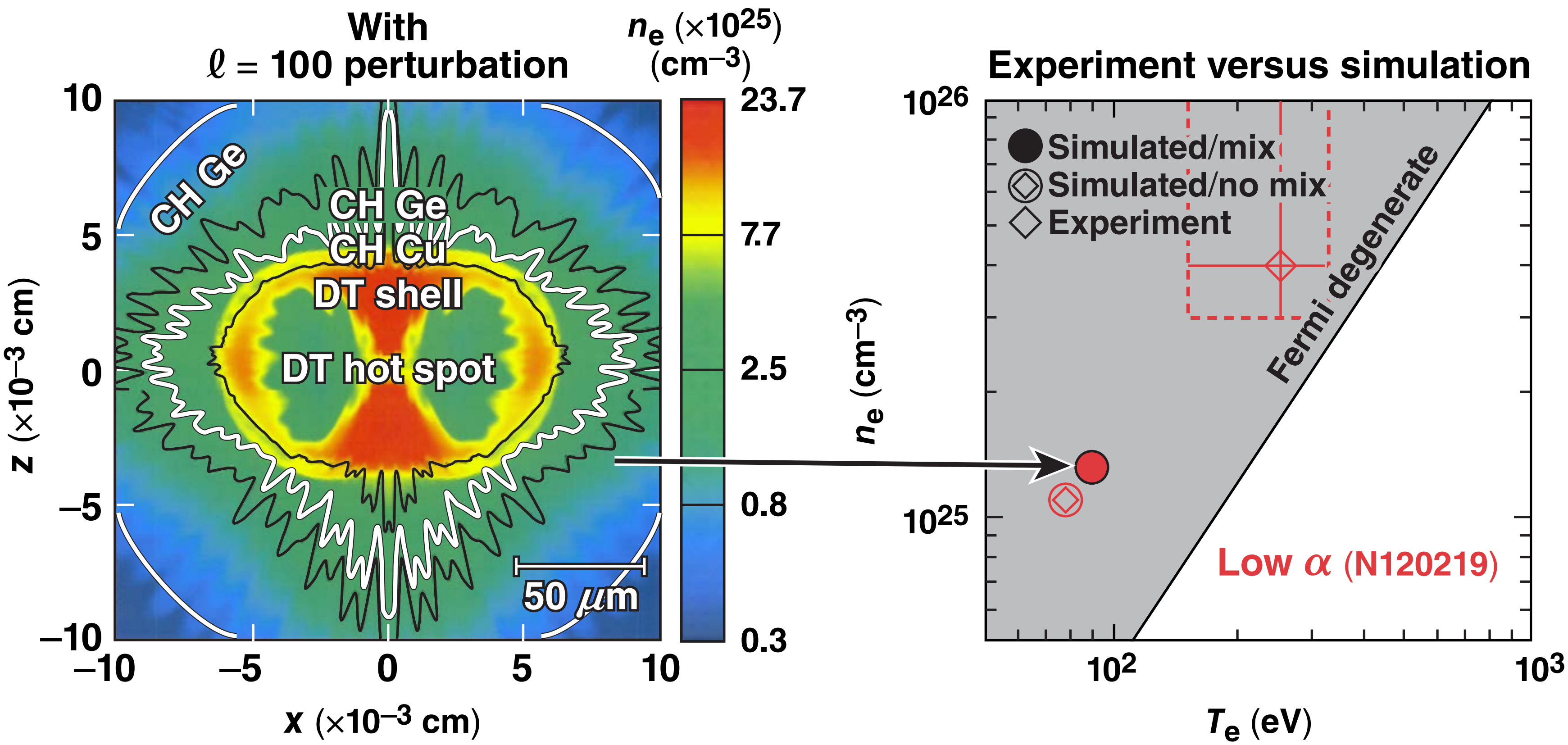


E23244

Low-adiabat

The effects of hydrodynamic mixing of the target layers was explored with an $\ell = 100$ perturbation

- 2-D *HYDRA* simulation of the low-adiabat implosion



The $\ell = 100$ mode perturbation slightly increases the simulated values.

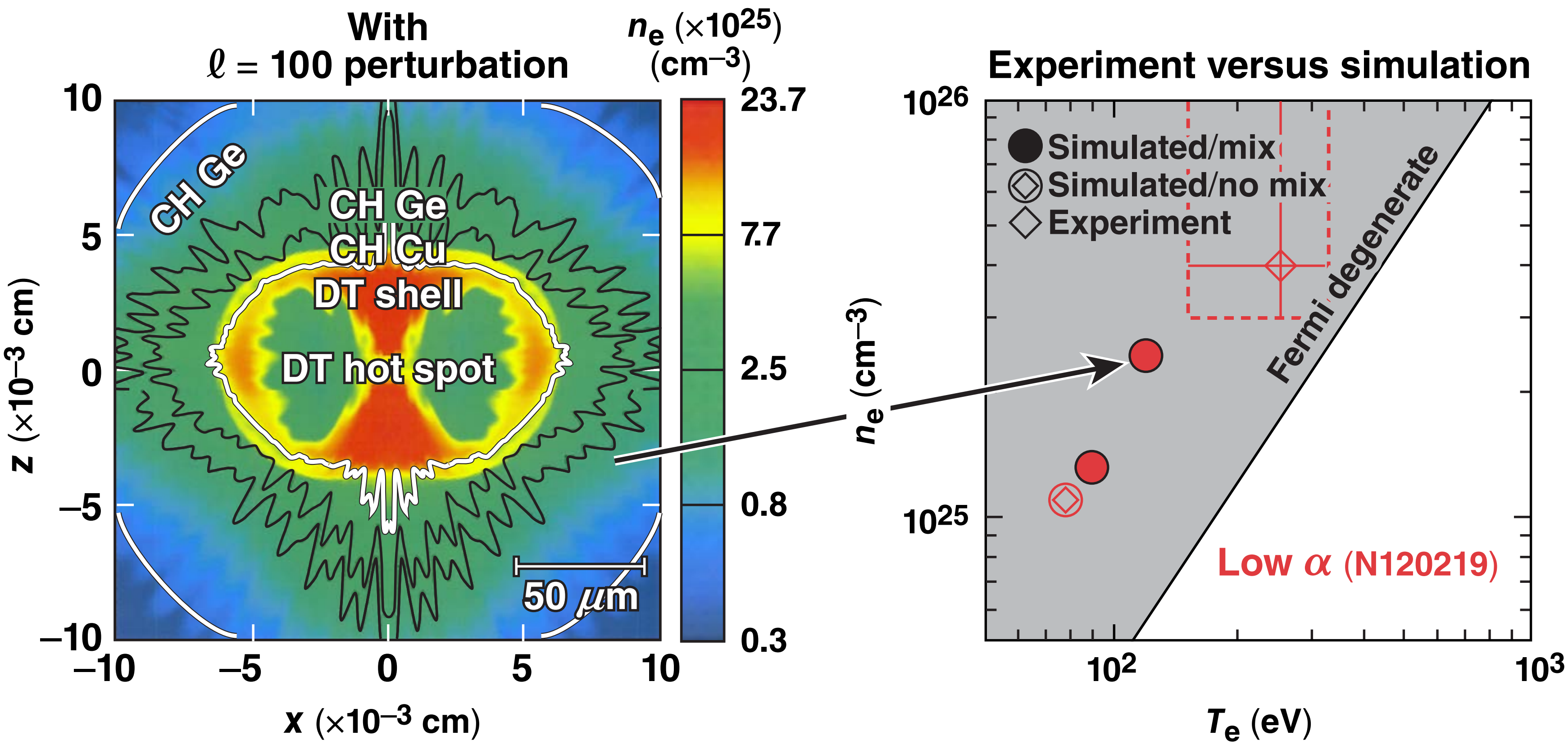
E23245

University of Rochester

Low-adiabat

Spatial average of simulated values over the entire compressed ablator is closer to experiment

- 2-D *HYDRA* simulation of the low-adiabat implosion

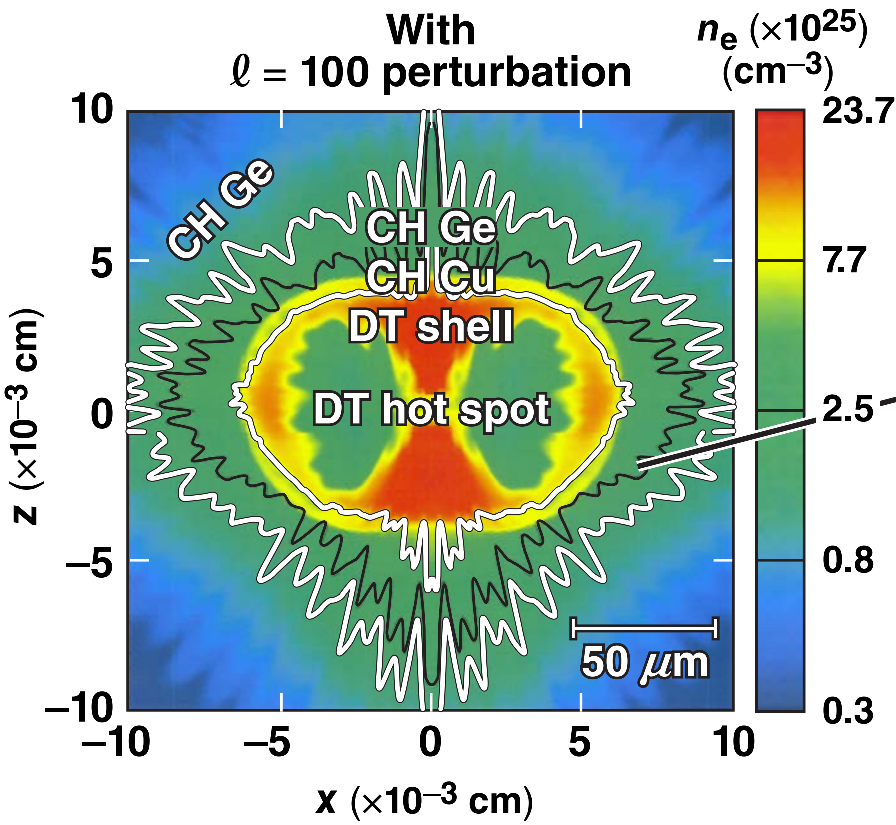


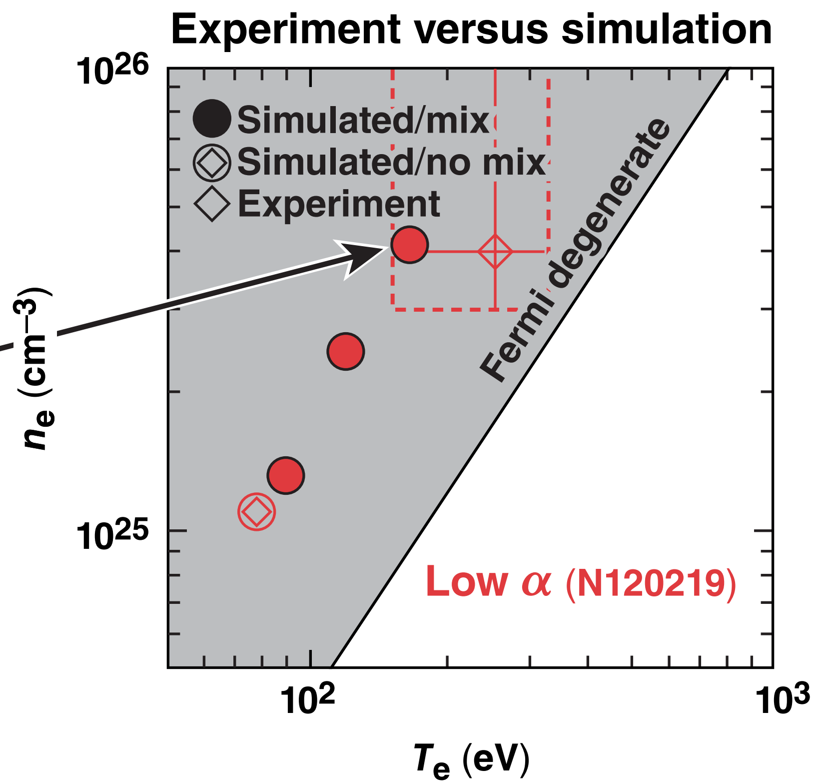
Significant mixing of CH(Ge) and CH(Cu) layers must occur.

Low-adiabat

Spatial average of simulated values over the inner compressed ablator is comparable to experiment

- 2-D *HYDRA* simulation of the low-adiabat implosion





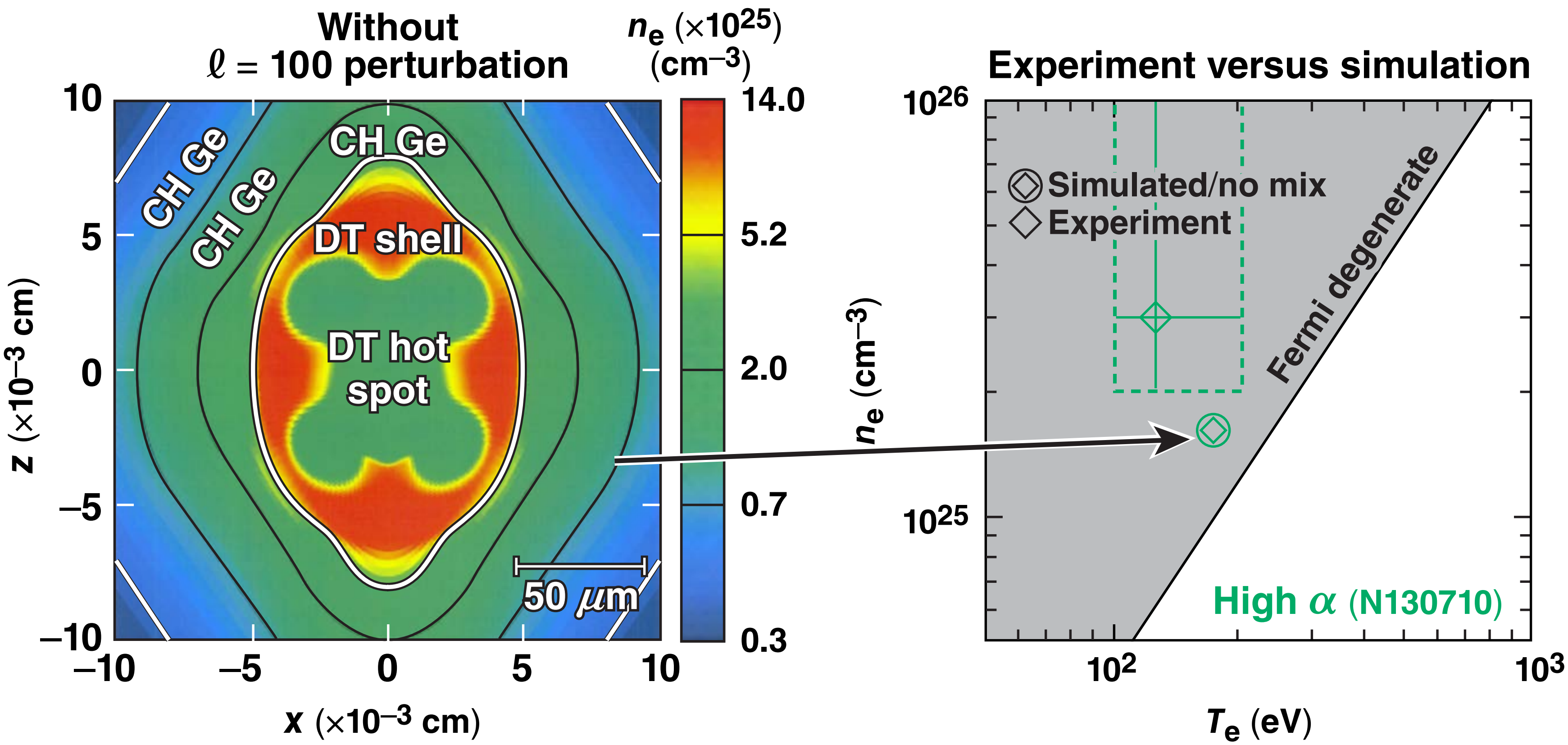
Measurement may be weighted to the highest T_e and n_e.

E23247

High-adiabat

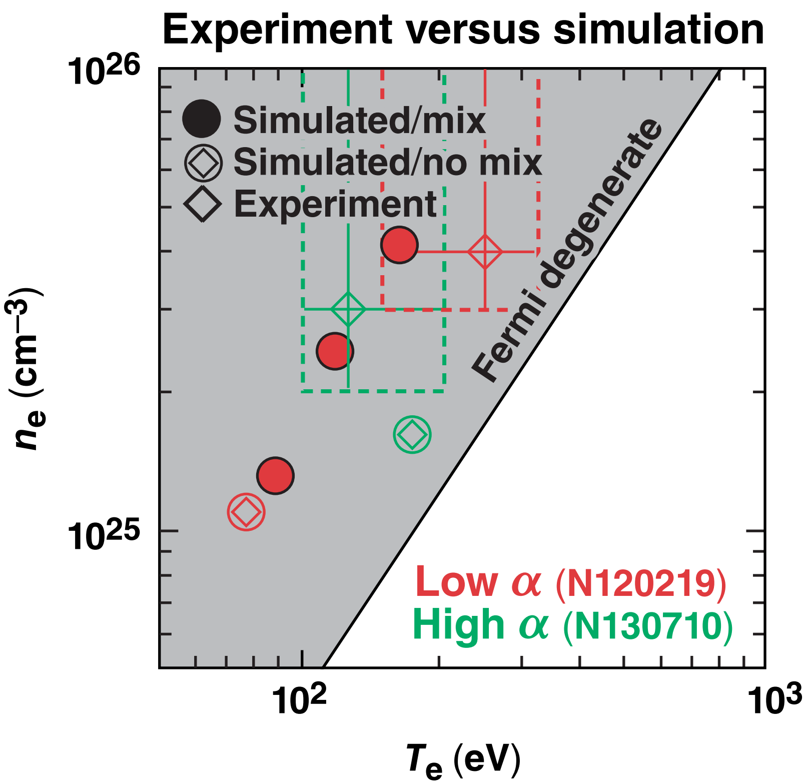
The 2-D simulation without mixing for the high-adiabat implosion is close to the experimental result

- 2-D *HYDRA* simulation of the high-adiabat implosion



Less hydrodynamic mixing of target layers is inferred for the high-α implosion compared to the low-α one.

Hydrodynamic mixing is predicted to increase the T_e and n_e of the Ge-doped CH in the compressed shell



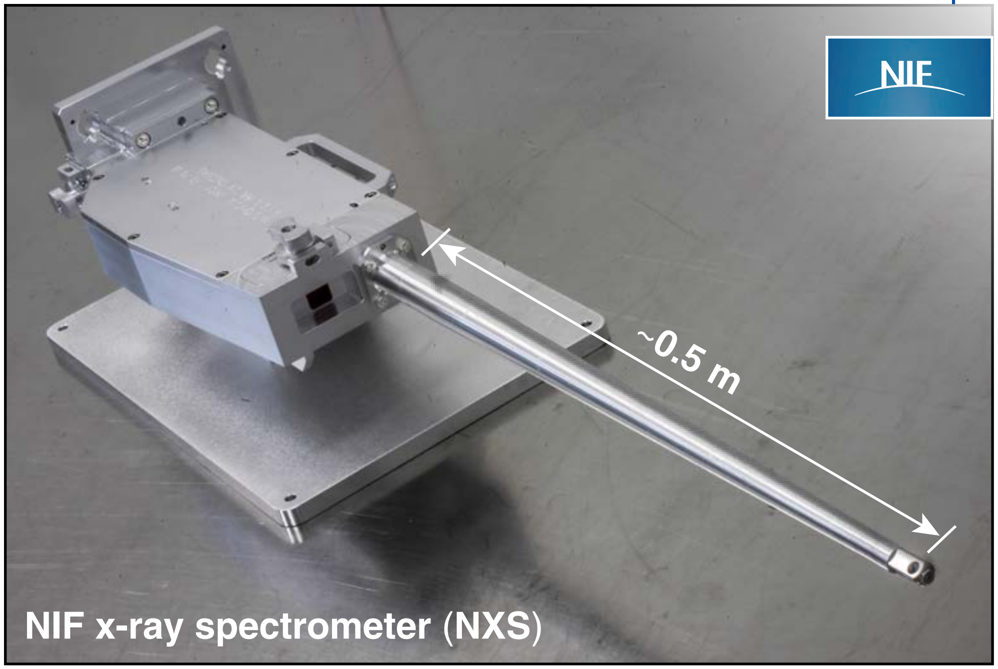
The low-adiabat implosion has more hydrodynamic mixing of the target layers than the high-adiabat one.

Future direction

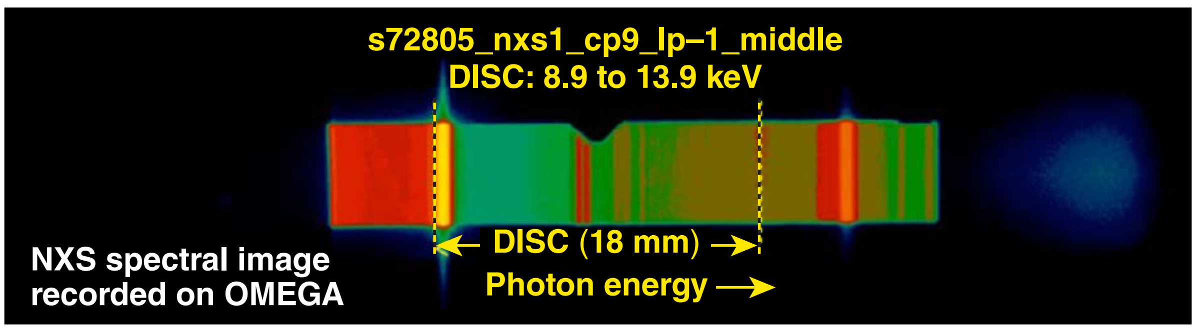
Time-resolved x-ray spectroscopy will be recorded on the NIF with the NXS

NXS/DISC
- Partially overlapping spectral windows in 2- to 18-keV range
- *E*/d*E*~100
- d*t* ≥ 8 ps
- mm-scale x-ray sources
- absolute calibration

DISC = Diagnostic insertion manipulator imaging streak camera*



A time-integrated photometric calibration of NXS was performed on OMEGA



Performance qualification shot on the NIF was successfully completed on 3 June.

*Y. P. Opachich *et al*., Rev. Sci. Instrum. 83, 125105 (2012).

The hot-spot and compressed shell of ignition-scale implosions are diagnosed with x-ray spectroscopy

- Ablator mass mixed into the hot spot is inferred from the intensity of the He_{α} + satellite line emission of mid-*Z* ablator dopants*,**
- The origin of the hot-spot mix mass is investigated using Cu and Ge dopants placed at different radial locations in the ablator***
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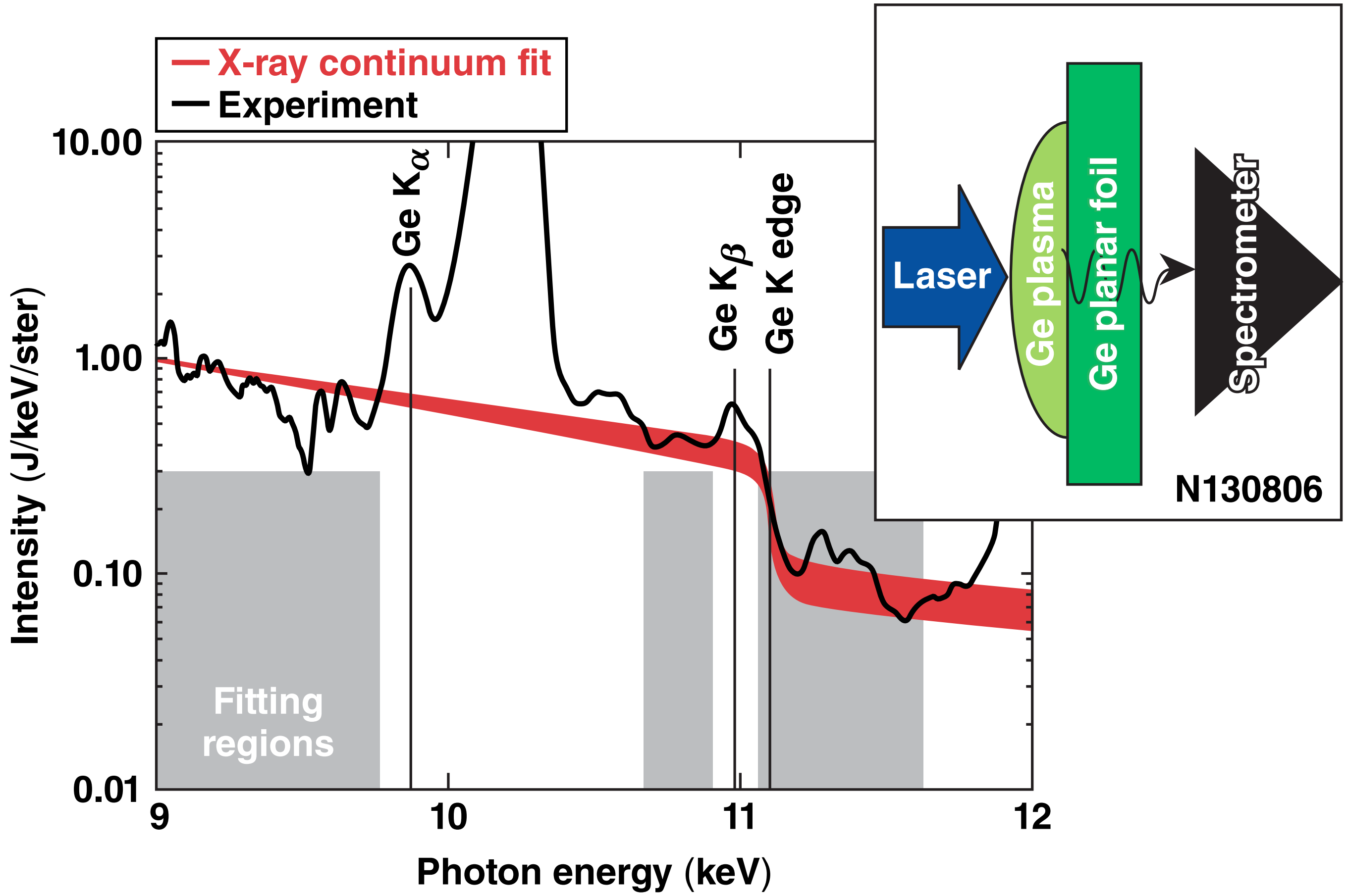
- Hydrodynamic mixing is predicted to increase the T_e and n_e of the Ge-doped CH in the compressed shell

These time-integrated measurements will be extended with streaked x-ray spectroscopy using the National ignition Facility (NIF) x-ray spectrometer (NXS).

*B. A. Hammel *et al*., High Energy Density Phys. 6, 171(2010).
**S. P. Regan *et al*., Phys. Plasmas 19, 056307 (2012).
***S. P. Regan *et al*., Phys. Rev. Lett. 111, 045001 (2013).

The cold Ge K edge was measured using a laser-driven, planar Ge target



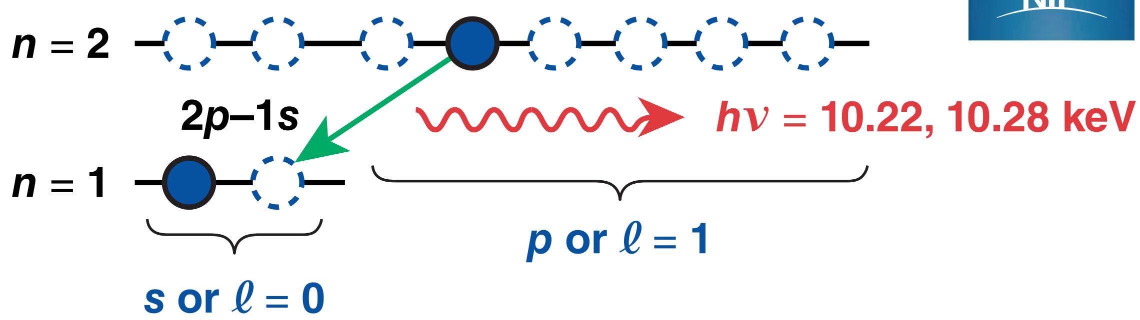
ρR_{Ge} = 8.3 (–2.8, +0.1) mg/cm^2 is inferred from this calibration shot using the cold opacity.*

*http://henke.lbl.gov/optical_constants/filter2.html.

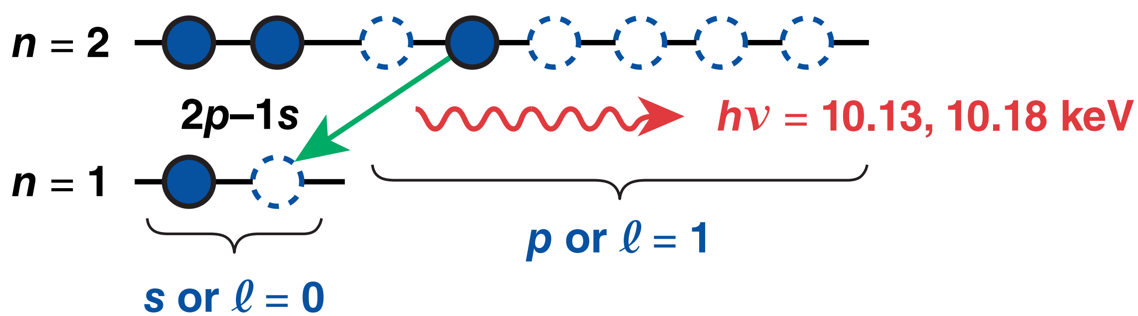
The "He_{α}" feature is composed of 2*p*–1*s* transitions from L-shell ionization species

Core conditions:
kT ≈ 2 keV
Z ≈ 26 (C-like) through 30 (He-like)

He_{α} resonance and intercombination lines



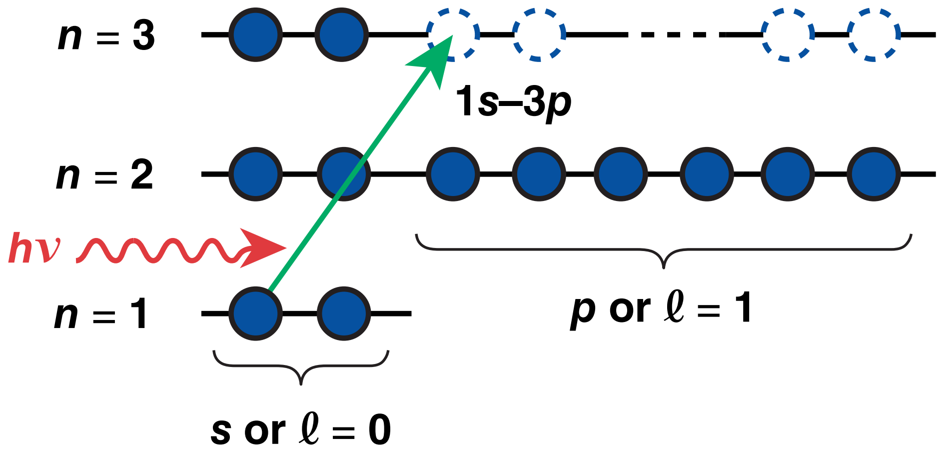
Be-like satellites of the He_{α} resonance lines



Autoionizing states are formed primarily by dielectronic recombination.

The 1s–2p absorption lines of Ge in the ablator are visible only for Z > 22 or for kT > 400 eV

For 0.1% Ge in CH, $0.03 \leq \rho \leq 3$ g/cm^3

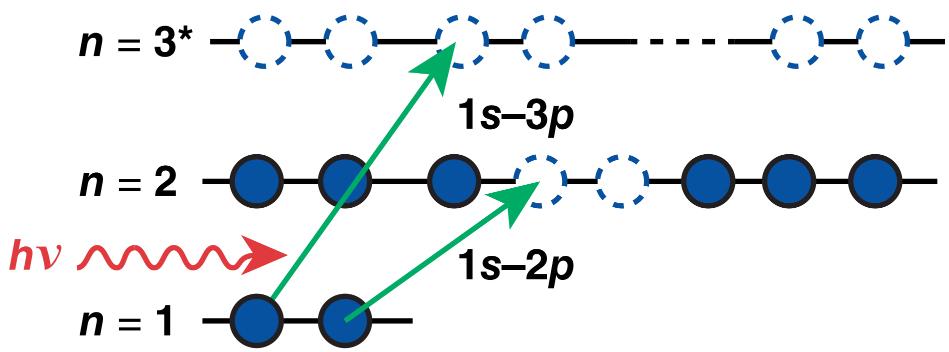


$kT \leq 400$ eV
22 (Ne-like) ≥ Z > 4 (Ni-like)

($kT \geq 300$ eV for Cu)

$kT \geq 400$ eV
Z > 22 (Ne-like)

*n = 3 may be removed by continuum lowering



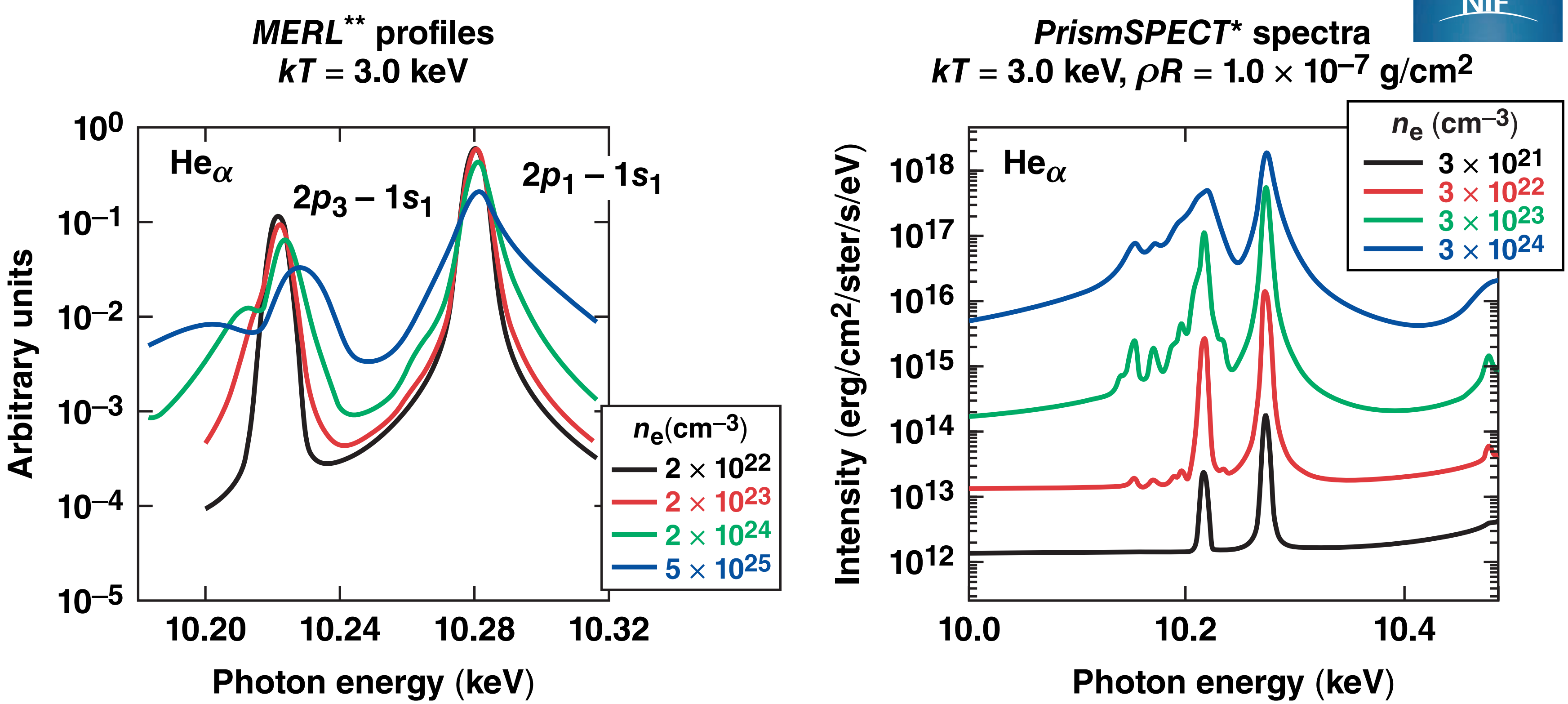
TC10709

*PrismSPECT** is an atomic detailed configuration accounting (DCA) spectrum simulation and analysis tool

- The Ge model includes 10,205 levels from the Ne-like through fully stripped ionization species, selected from a database of 32,176 levels
  - single excitations through $n = 10$ and double excitations through $n = 3$
  - collisional and radiative excitations and decays, autoionization, and dielectronic recombination
- The key resonance-line-emitting configurations are "spin-orbit" split
- Radiation-transport effects are calculated self-consistently for homogeneous objects with an "escape-probability" model
- Measured spectra are compared with model spectra for 7068 combinations of n_e, T_e, and ρR_{Ge}
- Line profiles are obtained using a semi-empirical formulation by Hans Griem**

*J. J. MacFarlane *et al.*, High Energy Density Phys. 3, 181 (2007).
**H. R. Griem, Phys. Rev. 165, 258 (1968).

Profiles of the critical H- and He-like spectral lines in *PrismSPECT** are obtained from the multi-electron radiator line (*MERL*) code**



*J. J. MacFarlane *et al.*, High Energy Density Phys. 3, 181 (2007).
**R. C. Mancini *et al.*, Comput. Phys. Commun. 63, 314 (1991).