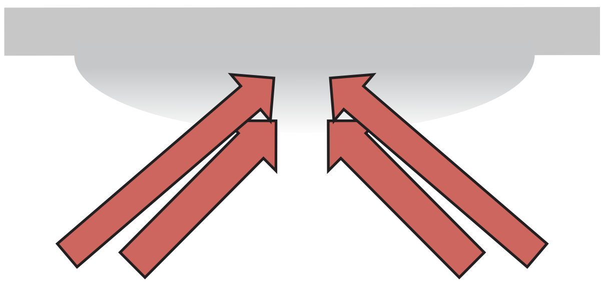
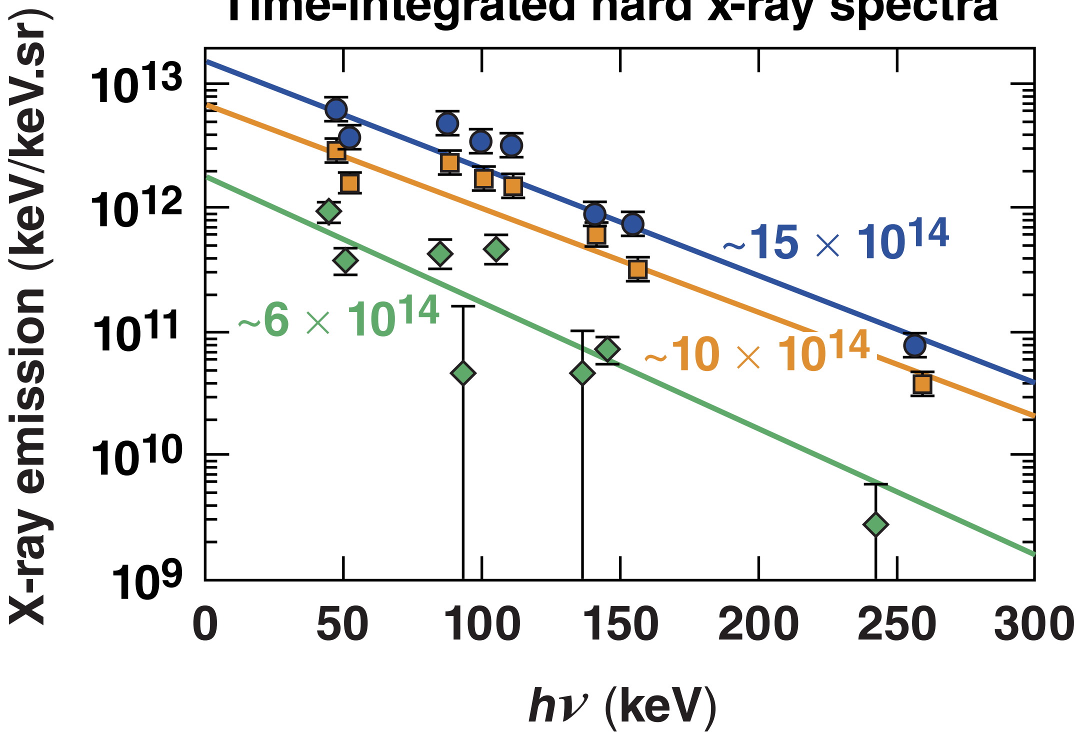
Planar Laser–Plasma Interaction Experiments at Direct-Drive Ignition-Relevant Scale Lengths at the National Ignition Facility

NIF planar-target experiment



32 to 64 NIF beams

Time-integrated hard x-ray spectra



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47th Annual Anomalous Absorption Conference
Florence, OR
11–16 June 2017

Summary

Planar experiments at the National Ignition Facility (NIF) have investigated laser–plasma interaction (LPI) hot-electron production at direct-drive ignition-relevant coronal conditions

- **NIF planar experiments achieve ignition-relevant scale lengths ($L_n \sim 400$ to 700 μm) and electron temperatures ($T_e \sim 4$ to 5 keV)**
- **The fraction of laser energy converted to hot electrons increased with laser intensity from f_{hot} ~0.5% to 2.3%—from 6 to 15 × 10^{14} W/cm^2—while T_{hot} was ~50 keV**
- **Stimulated Raman scattering (SRS) is inferred to be the dominant hot-electron source at these conditions**
- **The use of Si ablators reduces the observed SRS, f_{hot}, and T_{hot} relative to CH, using small angle beams**

These results indicate a viable ignition-design space for direct drive.

E25565b

Collaborators

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Outline

- Motivation for direct-drive planar LPI experiments on the NIF and platform development
- Hot-electron and scattered-light results: dominance of SRS
- LPI/hot-electron preheat mitigation strategies and future work

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- **Motivation for direct-drive planar LPI experiments on the NIF and platform development**
- Hot-electron and scattered-light results: dominance of SRS
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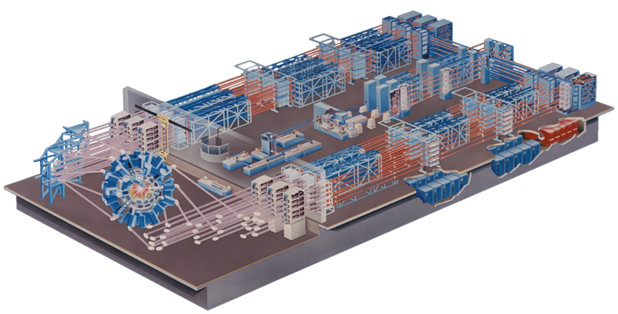
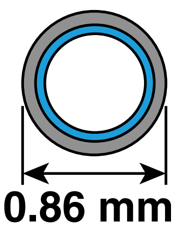
Motivation

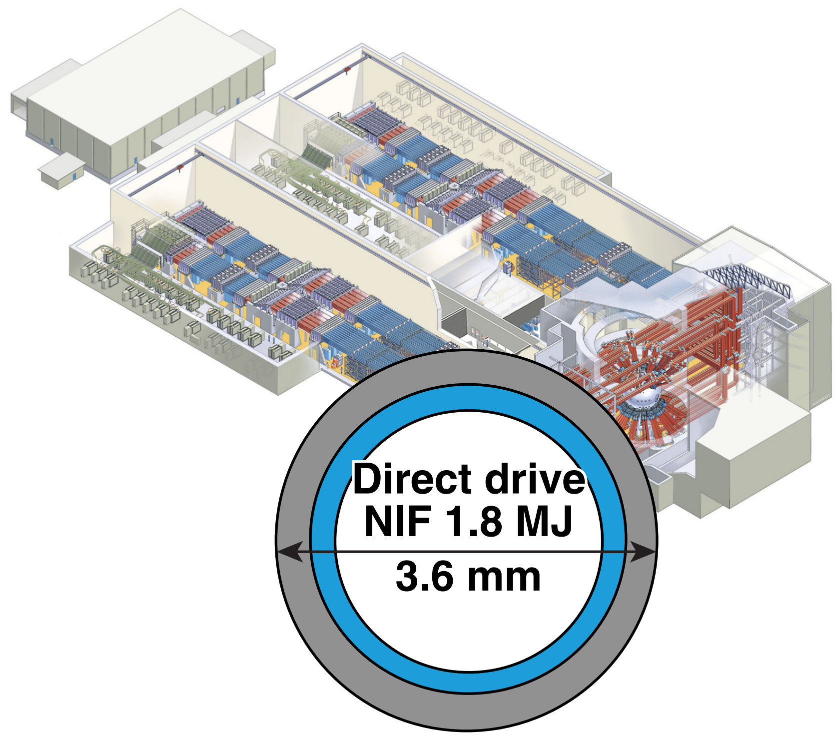
The National Direct-Drive Program includes OMEGA and NIF experiments to study direct-drive physics



Scale 1:70 in energy

OMEGA 26 kJ





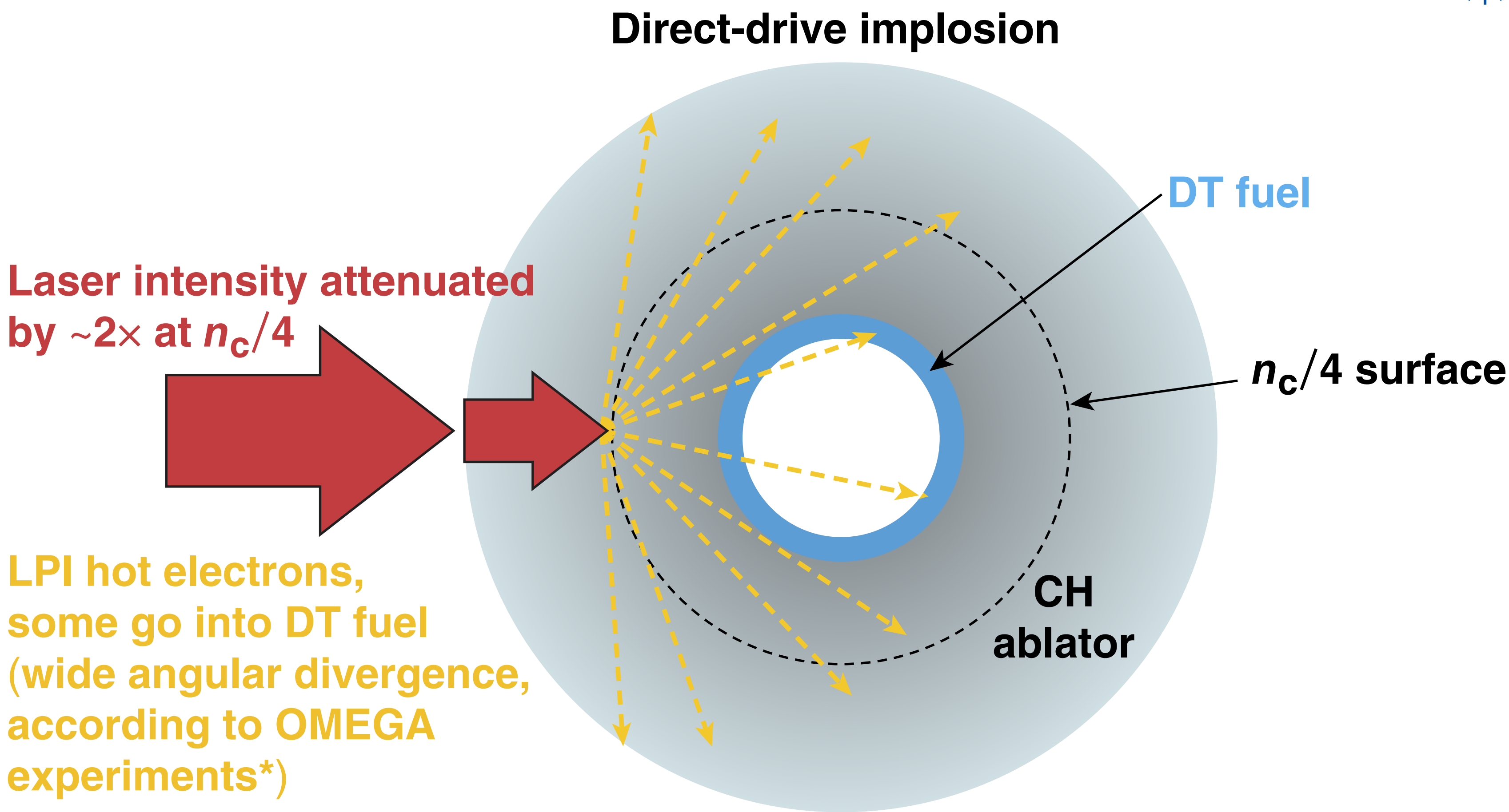
Laser coupling, preheat, imprint, and hydrodynamically scaled implosions

Laser coupling, preheat, and imprint at the MJ scale

TC10256w

Motivation

Hot-electron preheat is a potential concern for direct-drive–ignition designs



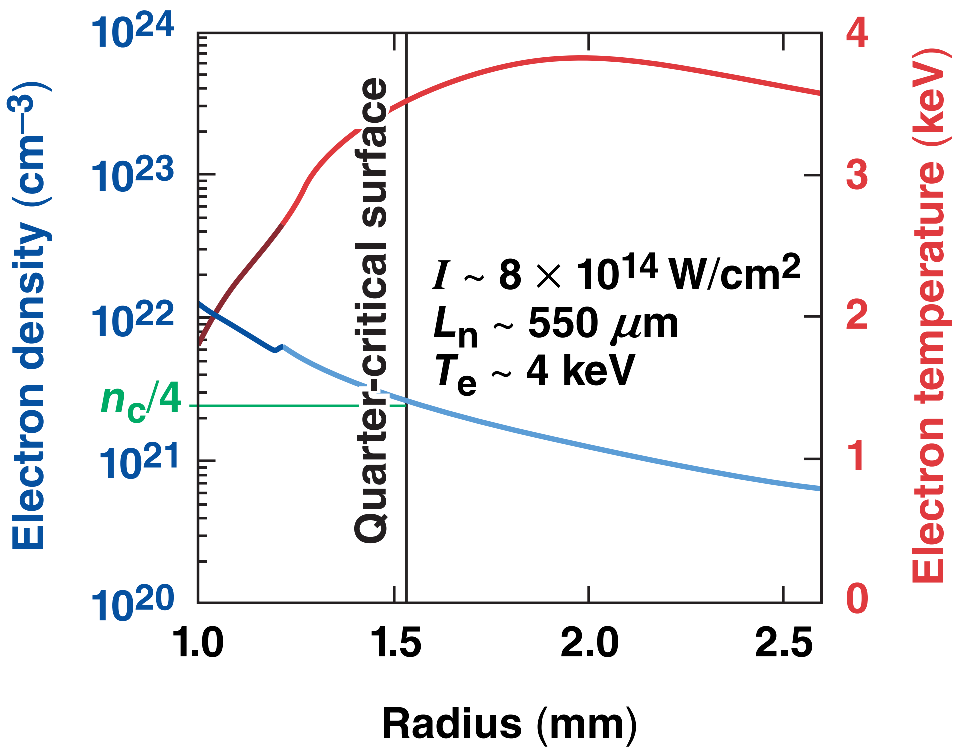
Limit of ~0.15% laser energy into fuel preheat + angular divergence → limit of ~0.7% laser energy into hot electrons generated.

*B. Yaakobi *et al.*, Phys. Plasmas 20, 092706 (2013).

Motivation

Direct-drive (DD)–ignition designs predict long density scale lengths and high electron temperatures under which LPI may occur

One-dimensional simulated plasma conditions for an igniting direct-drive design



Experiments must be performed at these conditions to understand LPI and assess hot-electron levels at the NIF/ignition scale.

E25732c

Motivation

Currently, ignition-relevant coronal plasma conditions can only be achieved in NIF planar experiments

Two-dimensional *DRACO* simulated plasma conditions at $n_c/4$

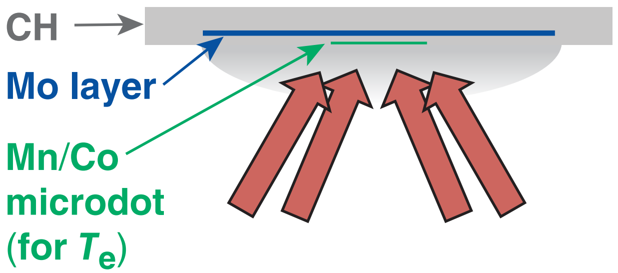
	NIF ignition designs	Ongoing NIF planar experiments	Ongoing NIF implosions	OMEGA implosions
L_n (μm)	600	400 to 700	360	150
T_e (keV)	3.5 to 5	3 to 5	3.2	2.8
I_L (W/cm^2)	(6 to 8) $\times 10^{14}$	(6 to 15) $\times 10^{14}$	5×10^{14}	(5 to 7) $\times 10^{14}$

Note: incident laser intensity is ~2× larger than intensity at $n_c/4$ at ignition-relevant conditions because of absorption

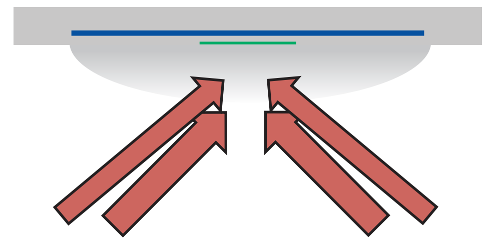
E26060a

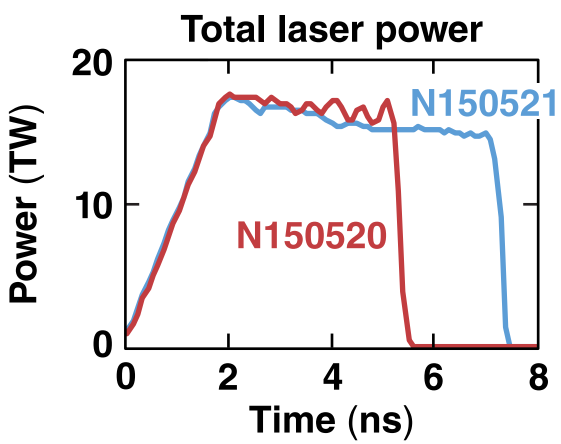
Two initial planar experiments were performed on the NIF to constrain plasma conditions

Shot N150520: 23° and 30° beams (32 beams total)

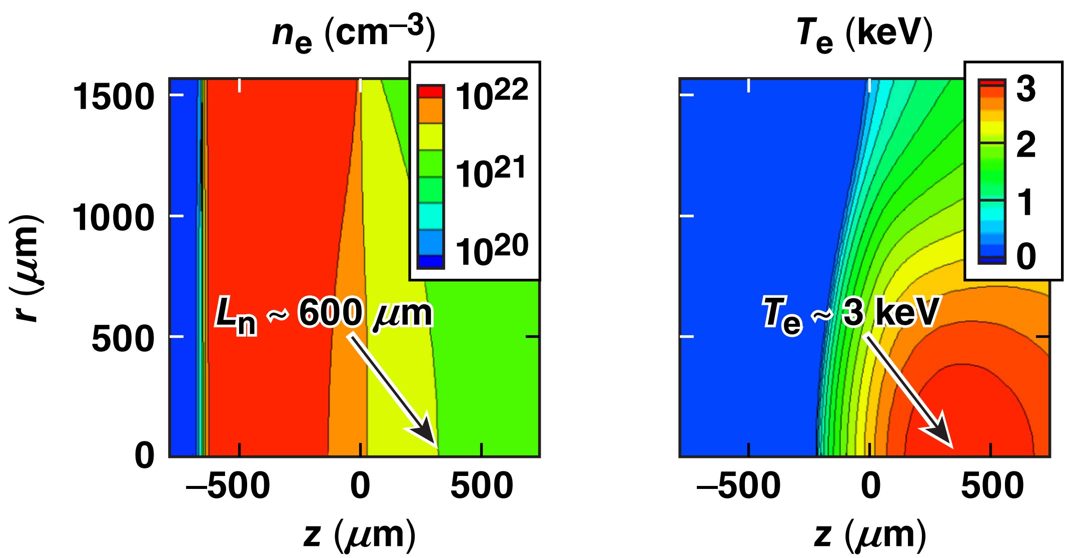


Shot N150521: 45° and 50° beams (60 beams total)





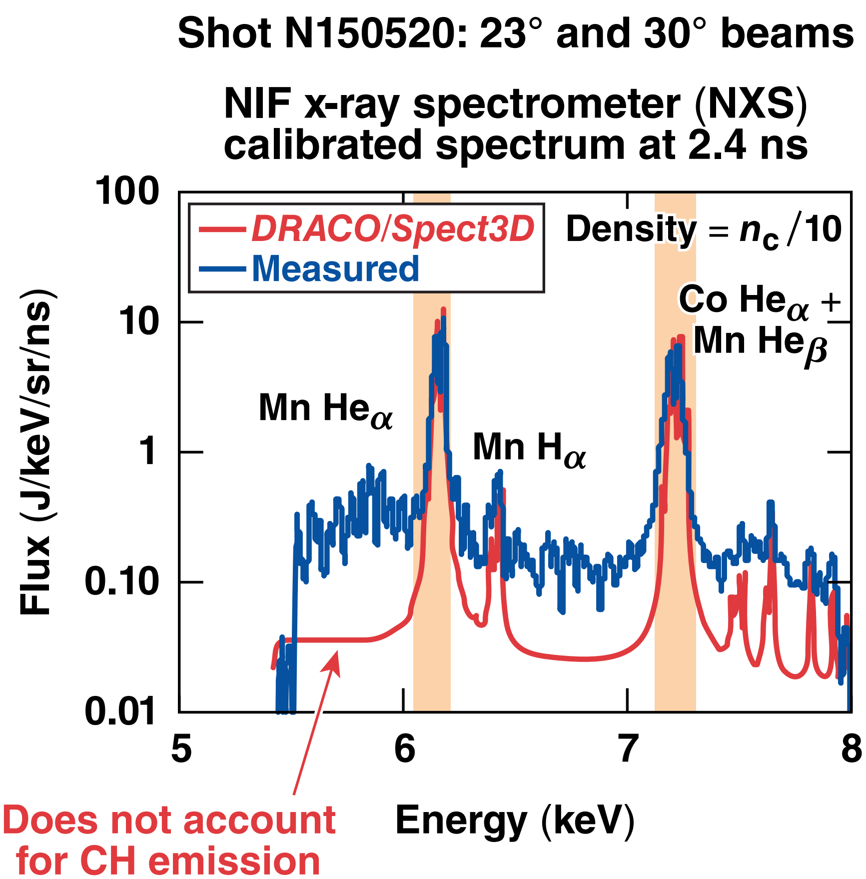
2-D *DRACO* simulation: N150521 at 4 ns

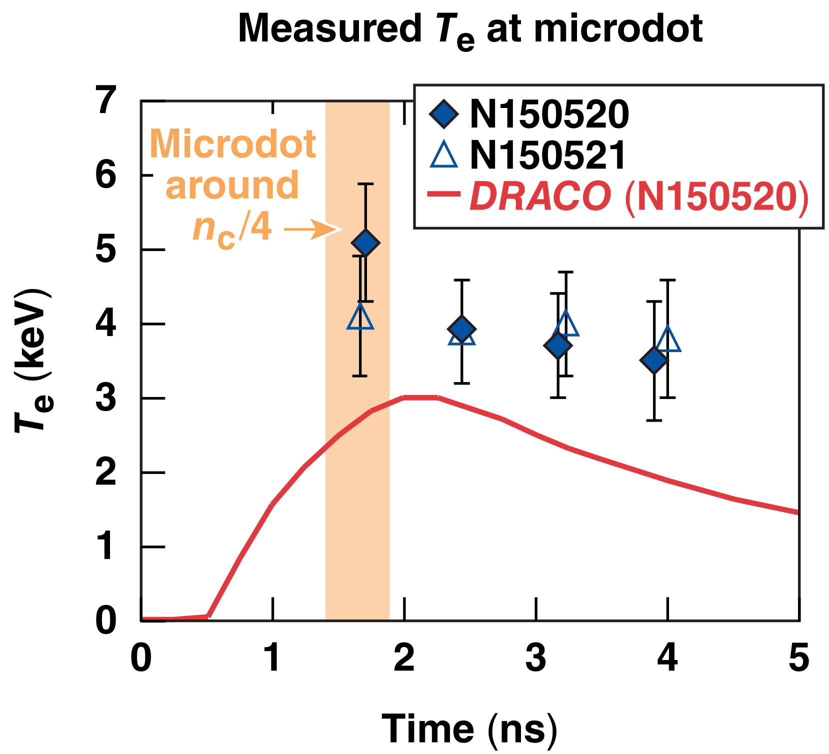


Cross-beam energy transfer does not have a strong influence on conditions at $n_c/4$.

E24122e

The isoelectronic ratio* of the Mn/Co K-shell emission lines is used to infer T_e = 4.6±1.1 keV at $n_c/4$





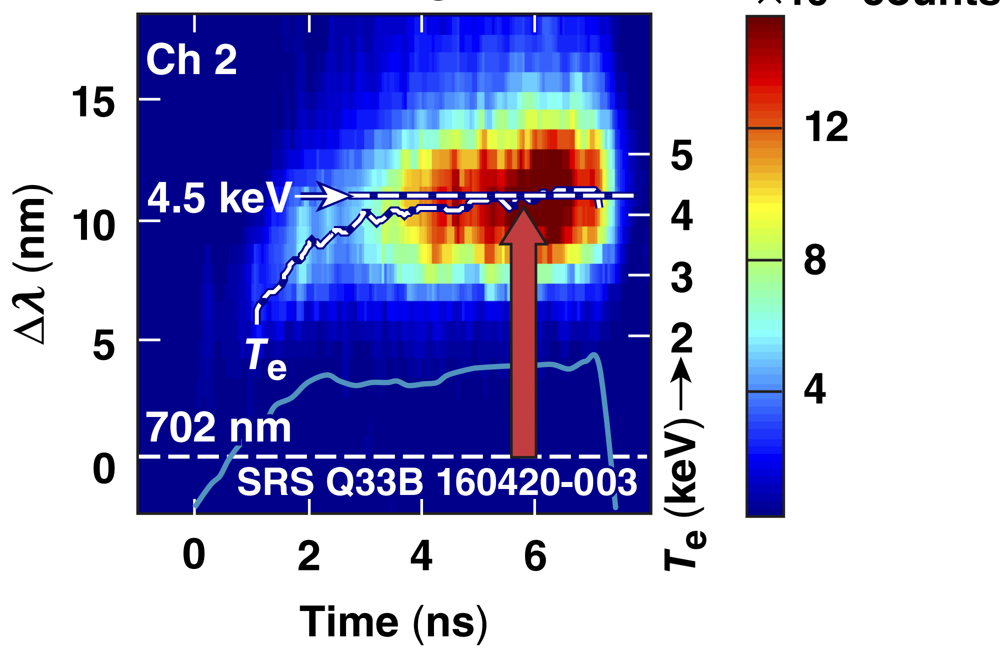
Based on modeling, discrepancy can be partially explained by self-heating of the microdot.

TC12489g

*R. Marjoribanks *et al*., Phys. Rev. A 46, R1747 (1992).

In subsequent experiments at higher laser intensity, the wavelength of $\omega/2$ emission was used to infer T_e ~ 4.5 keV at $n_c/4$

CH target



Stationary plasma　Plasma flow　Diverging plasma

$$\Delta\lambda_{nm} = 3.09 * T_{e,keV} - \delta\lambda_{Doppler} - \delta\lambda_{Dewandre}$$

These measurements match *DRACO* predictions of ignition-relevant T_e = 4.5 keV.

E25695a

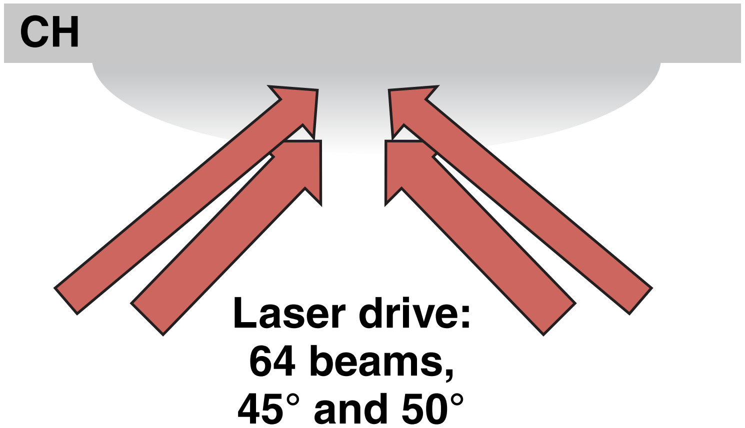
W. Seka *et al*., Phys. Fluids 28, 2570 (1985).

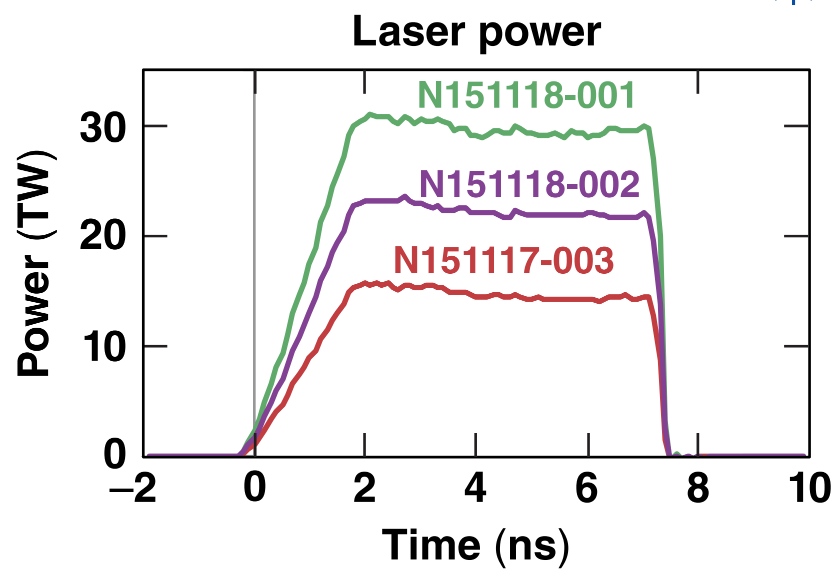
Outline

- Motivation for direct-drive planar LPI experiments on the NIF and platform development
- **Hot-electron and scattered-light results: dominance of SRS**
- LPI/hot-electron preheat mitigation strategies and future work

E26059b

Three experiments explored the scaling of hot-electron properties with laser intensity at ~500-μm scale lengths and ~4-keV temperatures





$n_c/4$ parameter	DD ignition*	Planar NIF**
I_L (W/cm^2)	6 to 8 $\times 10^{14}$	6 to 15 $\times 10^{14}$
T_e (keV)	4 keV	4 keV
L_n (μm)	550 μm	500 μm

Primary diagnostics

- Hard x ray → T_{hot}, E_{hot}/f_{hot}
- $\omega/2$ and SRS → LPI signatures

*T. J. B. Collins *et al*., Phys. Plasmas 19, 056308 (2012).
**A. A. Solodov, this conference.

E24812i

Considering overlapped laser intensities, these experiments are well above threshold for two-plasmon decay (TPD) and SRS

- **Absolute instability thresholds for a single beam at normal incidence**

TPD*

$$I_{14,\text{thr,TPD}} = 230\, T_{\text{e,keV}} \big/ L_{\text{n},\mu\text{m}}$$

$$\rightarrow \eta_{\text{TPD}} = I_{\text{overlapped}} \big/ I_{\text{thr,TPD}} \sim 3 \text{ to } 8$$

SRS**

$$I_{14,\text{thr,TPD}} = 2377 \big/ \left(L_{\text{n},\mu\text{m}}\right)^{4/3}$$

$$\rightarrow \eta_{\text{SRS}} = I_{\text{overlapped}} \big/ I_{14,\text{thr,SRS}} \sim 10 \text{ to } 25$$

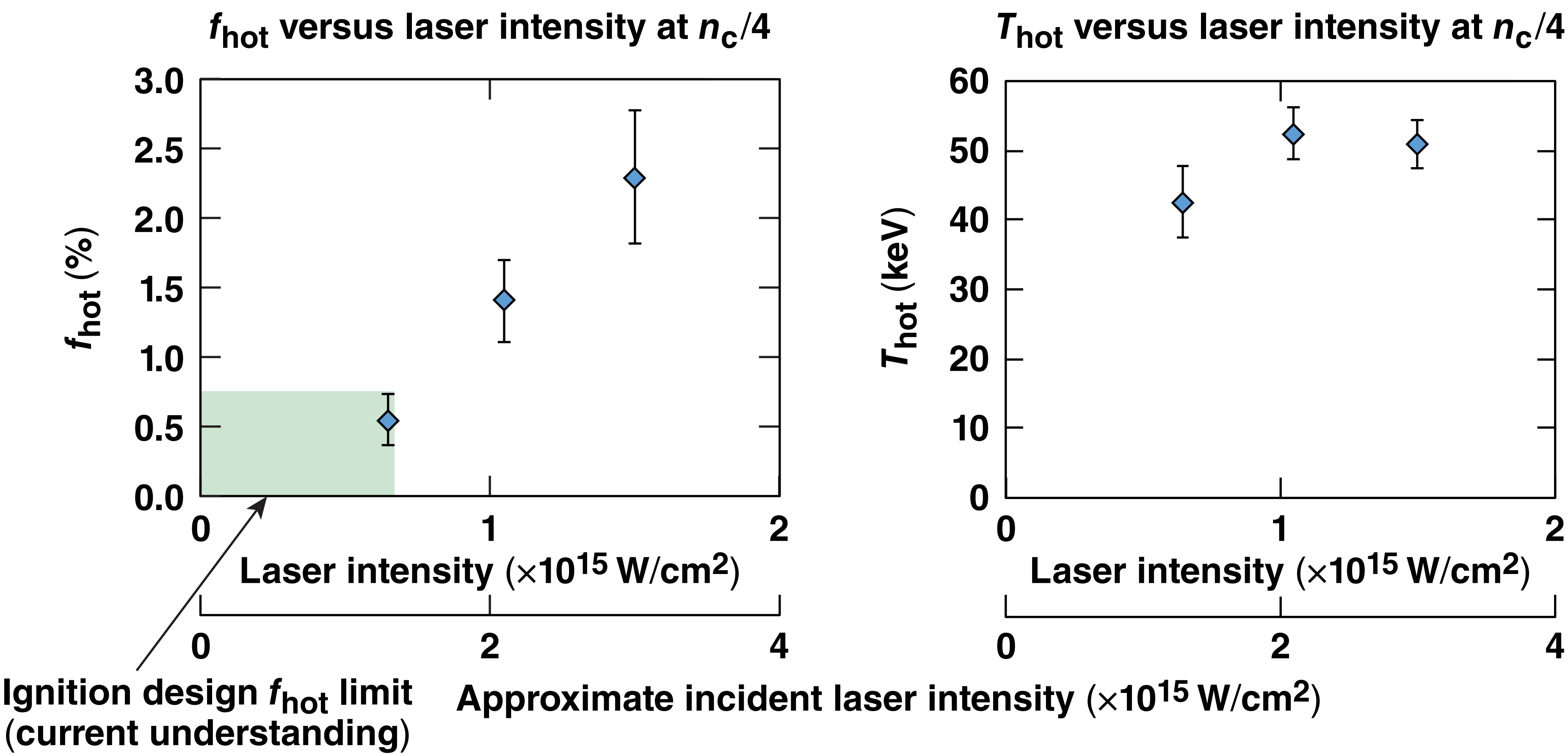
- **These experiments overlapped 64 beams (16 NIF quads)**

*A. Simon *et al*., Phys. Fluids 26, 3107 (1983).
**C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).

E26296

Time-integrated hard x-ray data show f_{hot} (E_{hot}/E_{laser}) increases with laser intensity, while T_{hot} is constant

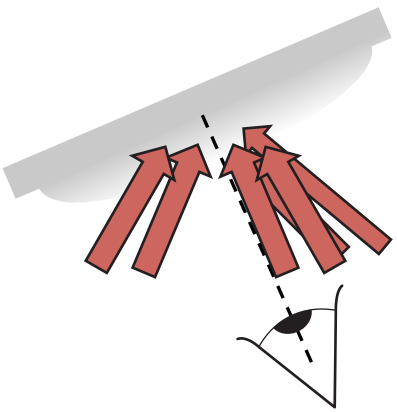
Shots N151117-18



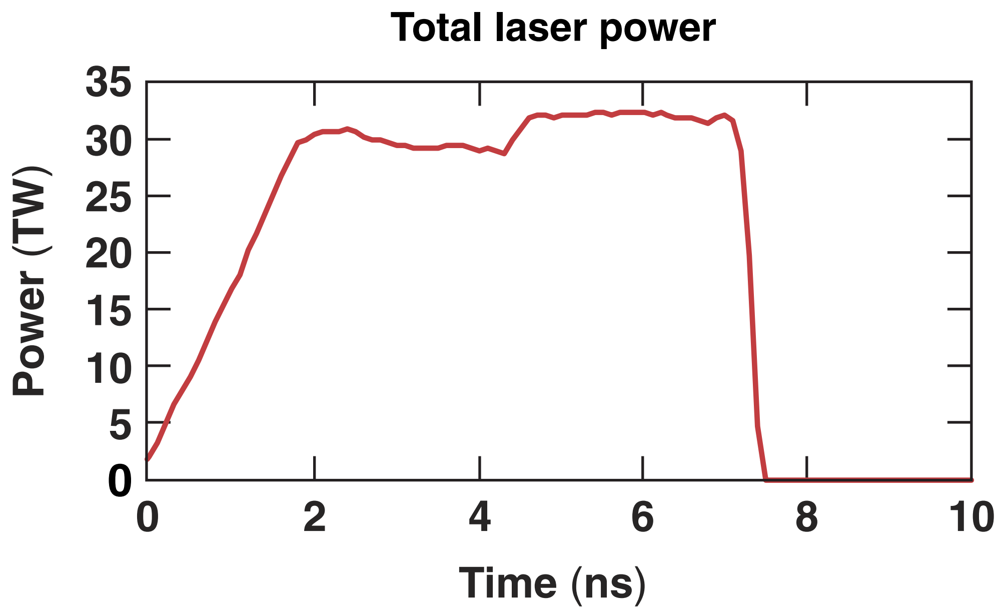
f_{hot} results are encouraging for direct-drive–ignition designs and constrain design space.

Scattered-light measurements to identify the hot-electron source were optimized by orienting the target normal to the optical diagnostics

View along target normal is optimal for $\omega/2$ since most emission occurs within ~10° of normal*



Optical streaked spectrometer (NBI** Q33B)

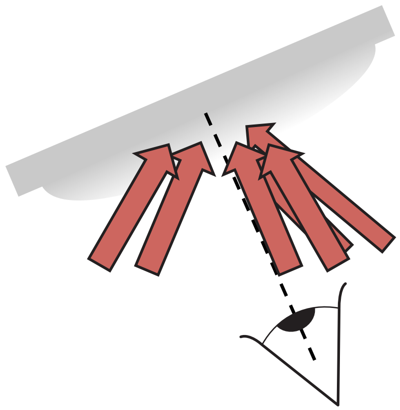


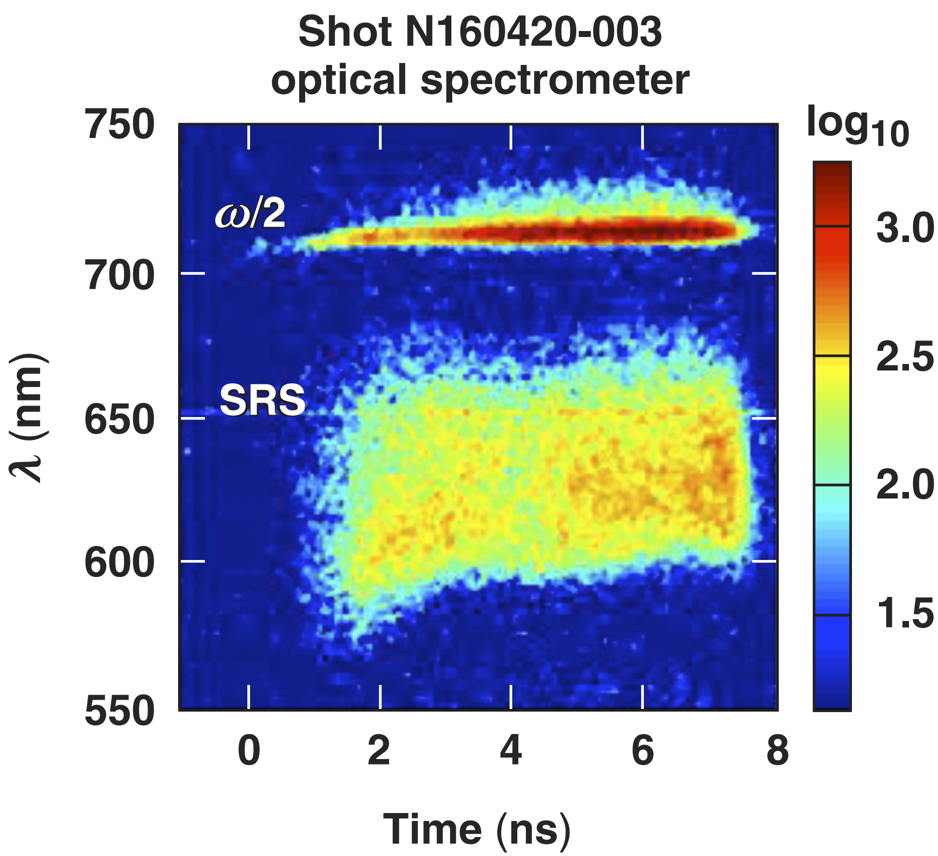
If TPD is dominant, expect to see broad spectral features at $\omega/2$, as have been observed previously on OMEGA.*

*W. Seka *et al.*, Phys. Rev. Lett. 112, 145001 (2014).
**Near-backscatter imager

E25566c

The optical spectrum indicates a sharp, red-shifted $\omega/2$ feature as well as SRS at shorter wavelengths





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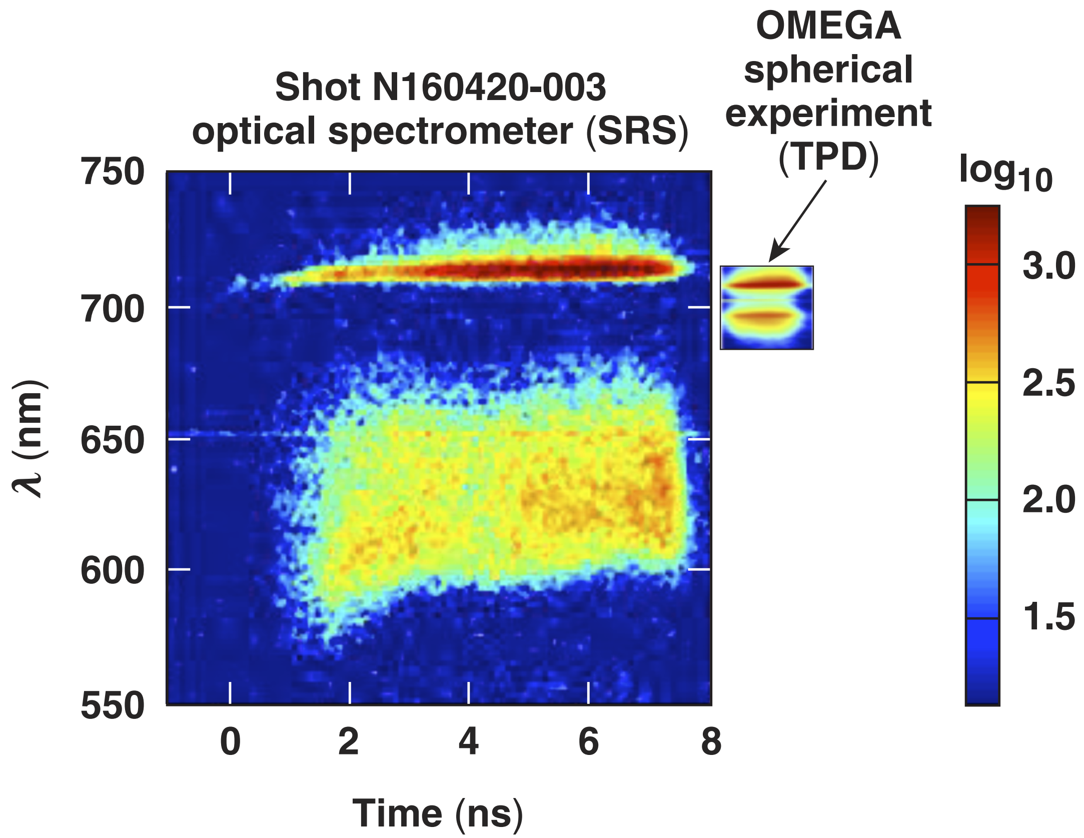
The $\omega/2$ feature observed on the NIF is in contrast to that observed on OMEGA, which showed both blue- and red-shifted $\omega/2$, and is attributed to TPD

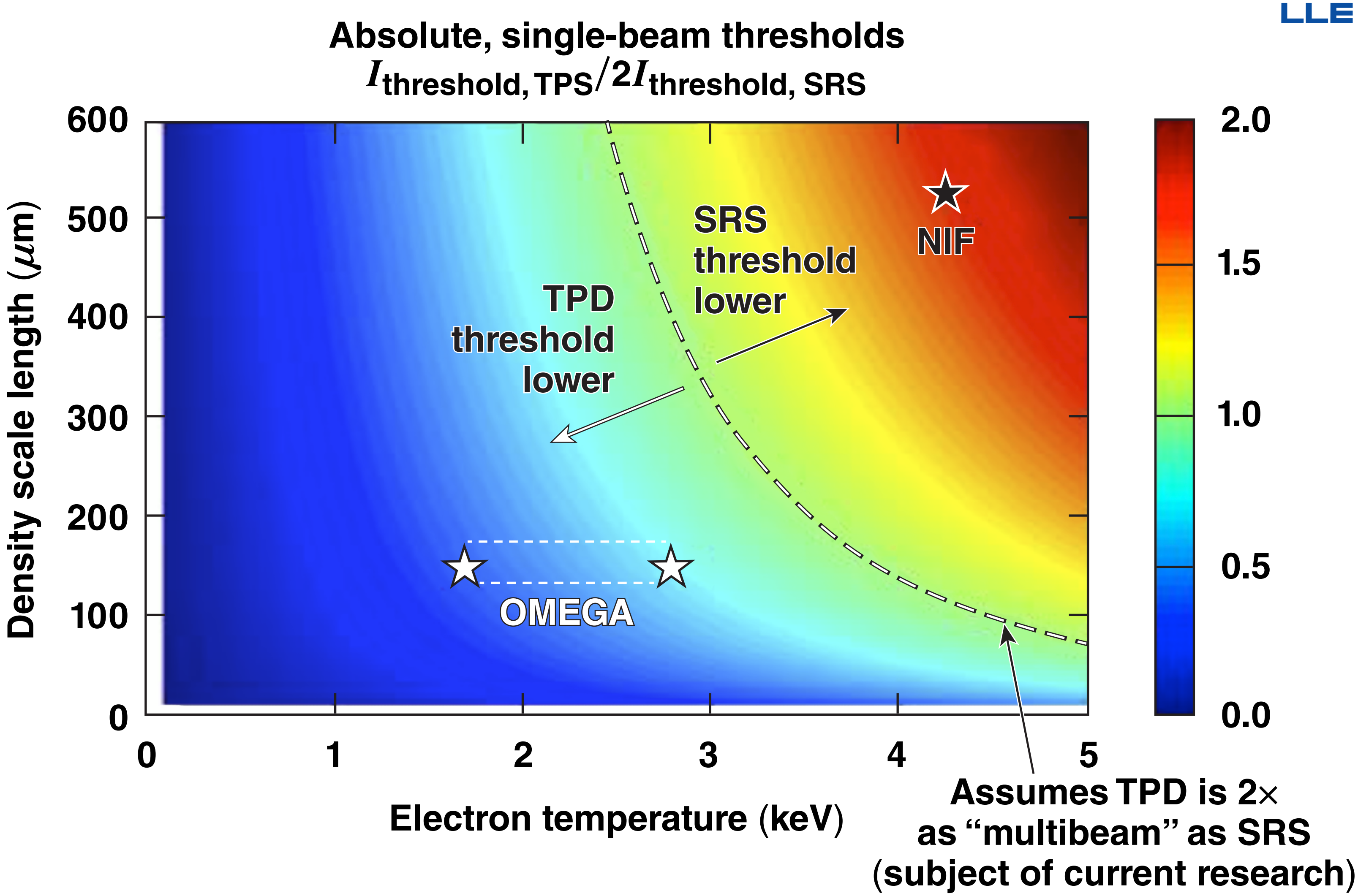


On the NIF, the observed $\omega/2$ emission is attributed to absolute SRS, although the presence of TPD cannot yet be ruled out.

E25567f

W. Seka *et al.*, WeO-5, this conference.

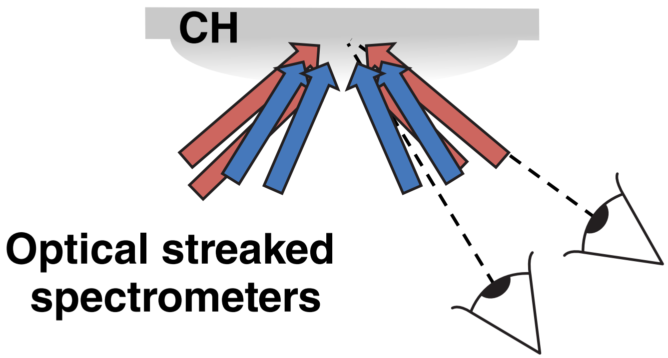
The dominance of SRS at the NIF scale is explained by evaluating the absolute thresholds of SRS* versus TPD**



*A. Simon *et al*., Phys. Fluids 26, 3107 (1983).
**C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).

E26298

Further evidence that SRS is the hot-electron source can be obtained by inferring the total SRS produced

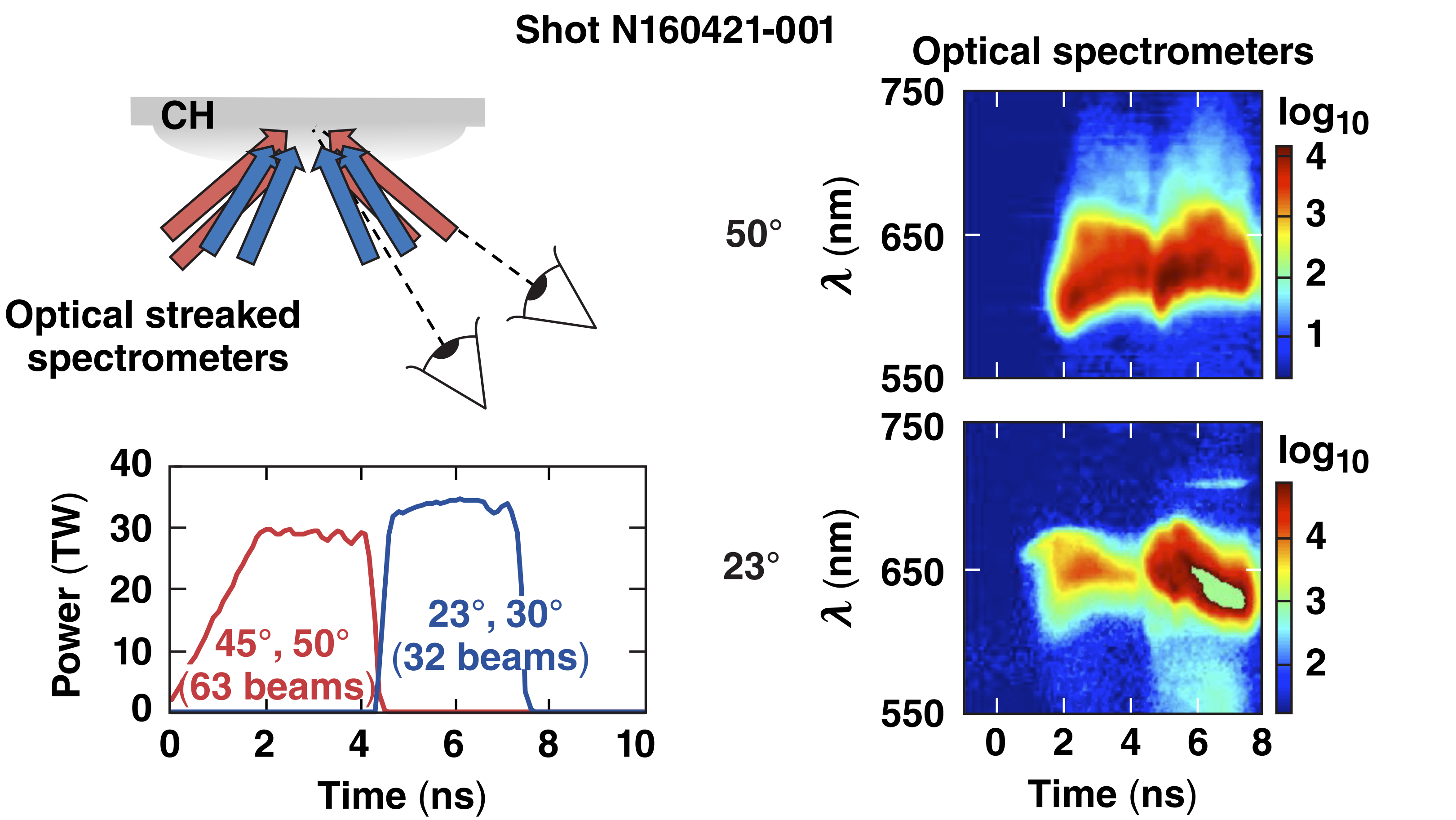


Diagnostic views are limited: absolute energy measurements are available at two locations

Extrapolating to the total SRS requires understanding the SRS mechanism.

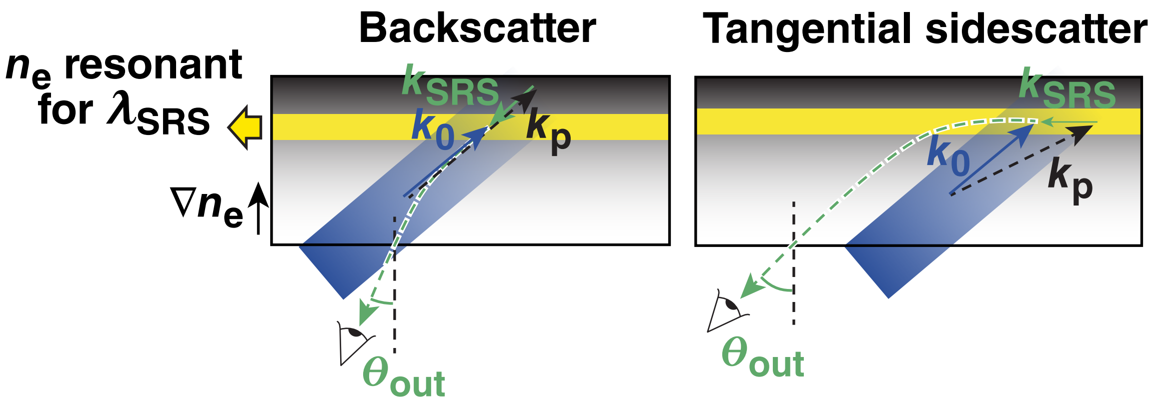
E25568c

Observation of SRS at multiple locations from different drive beams provides strong evidence of SRS sidescattering

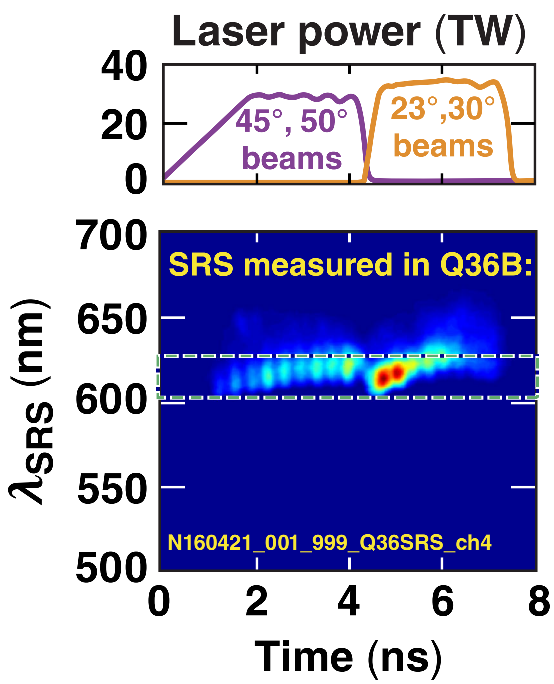


E25568d

This observation is explained by tangential SRS sidescatter, which allows for SRS observation at large angles and wavelength independent of drive-beam angle

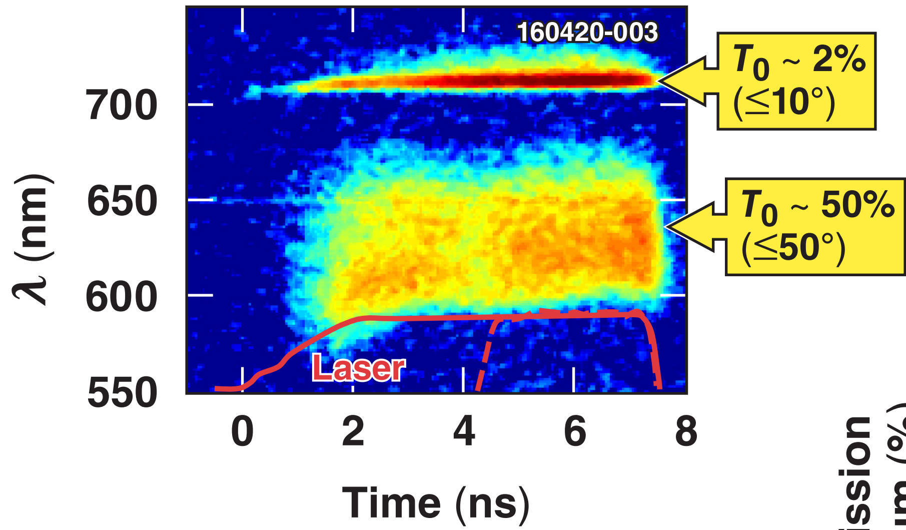


Tangential sidescatter exit angle does not depend on the incidence angle

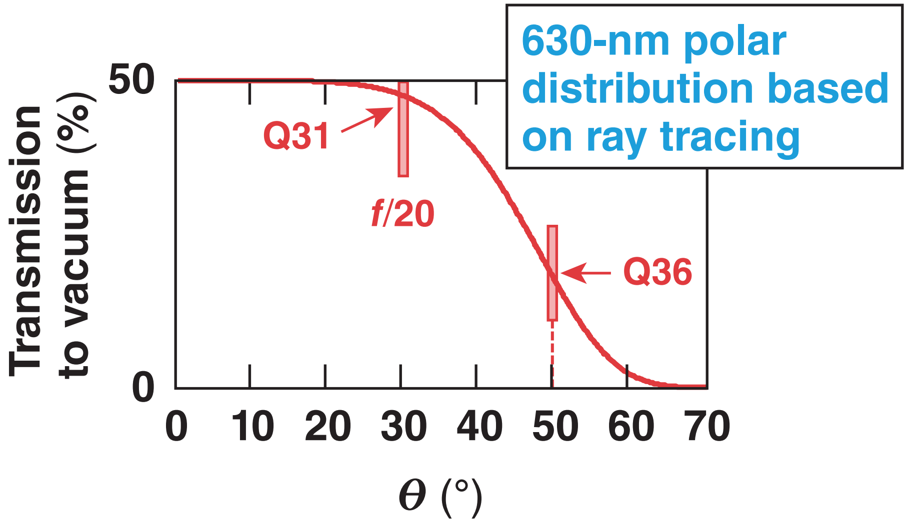


P. A. Michel *et al.*, WeO-4, this conference.

Knowledge of SRS mechanisms—absolute SRS (ω/2) and sidescattered SRS—allows for extrapolation to the total SRS generated



Distribution of observed sidescattered SRS based on ray-tracing of 2-D simulated plasma conditions



Approximately 5% of laser energy converted to SRS is consistent with the observed hot-electron fraction.

E26166a

W. Seka *et al*., WeO-5, this conference.

Outline

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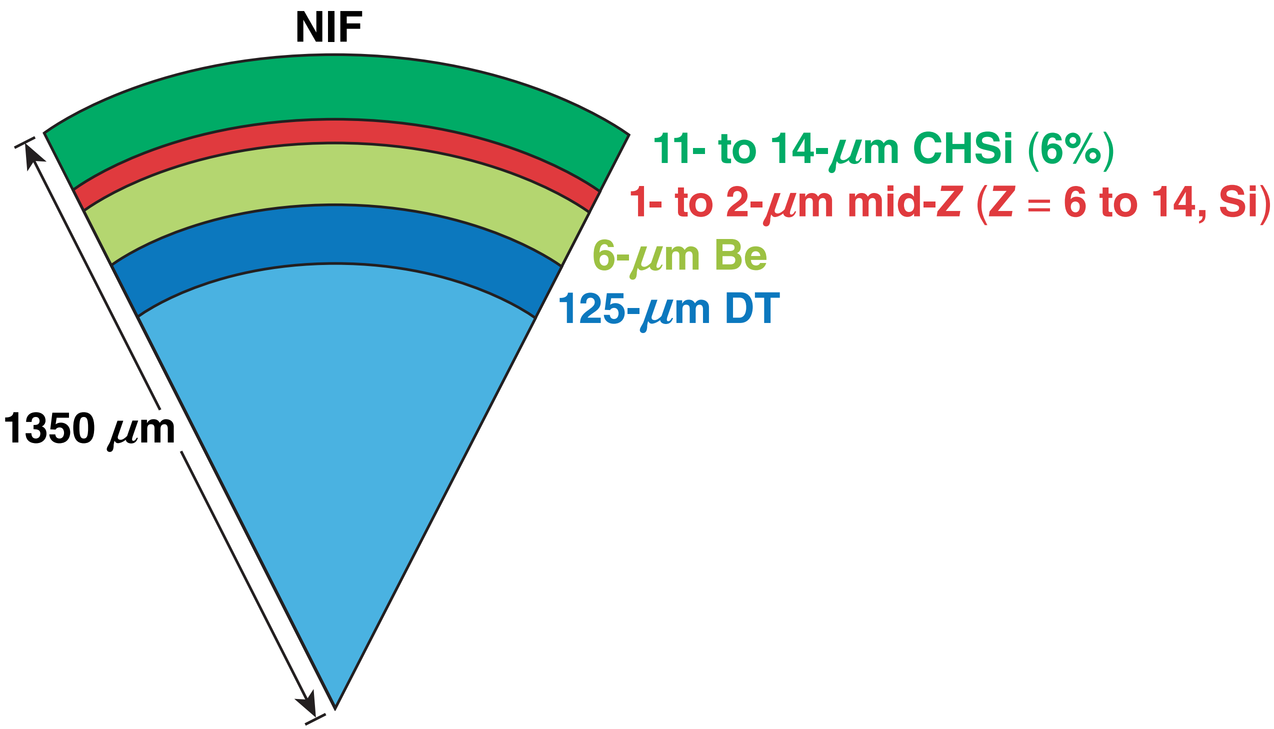
E26059c

The use of a Si layer in the ablator has been proposed as a means of reducing hot-electron generation from near-quarter-critical LPI

UR LLE

Direct-drive ignition design with multilayer ablator*

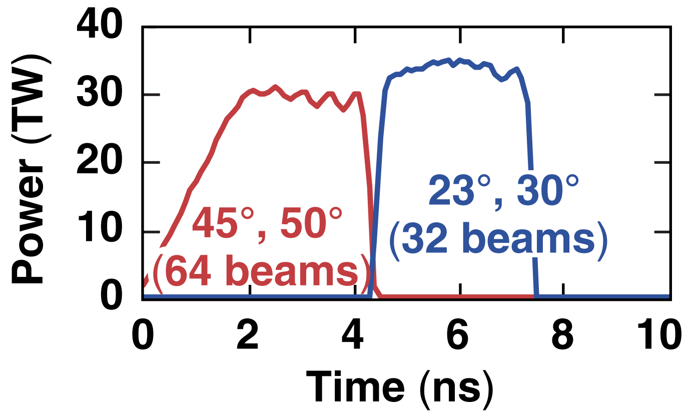


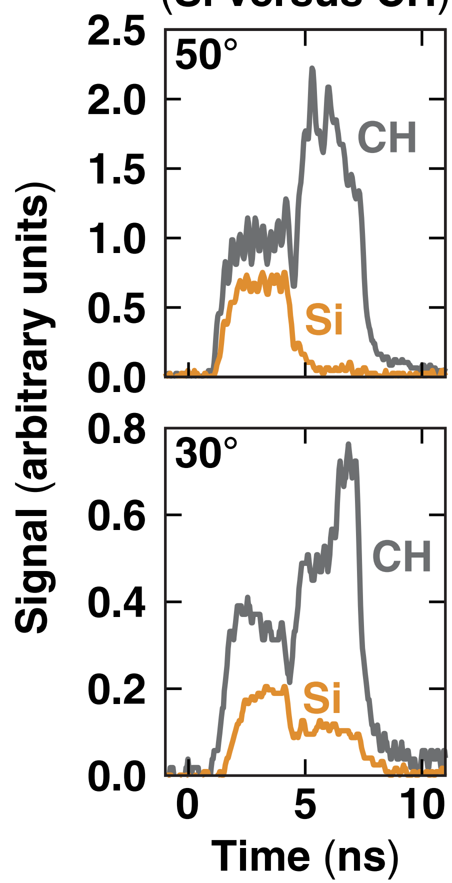
Si ablators produce shorter scale lengths, higher electron temperatures, and more collisional damping in order to reduce LPI near $n_c/4$.

TC10544h

*V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014).

Use of a Si ablator in planar experiments causes a reduction in observed SRS driven by small-angle beams, relative to CH



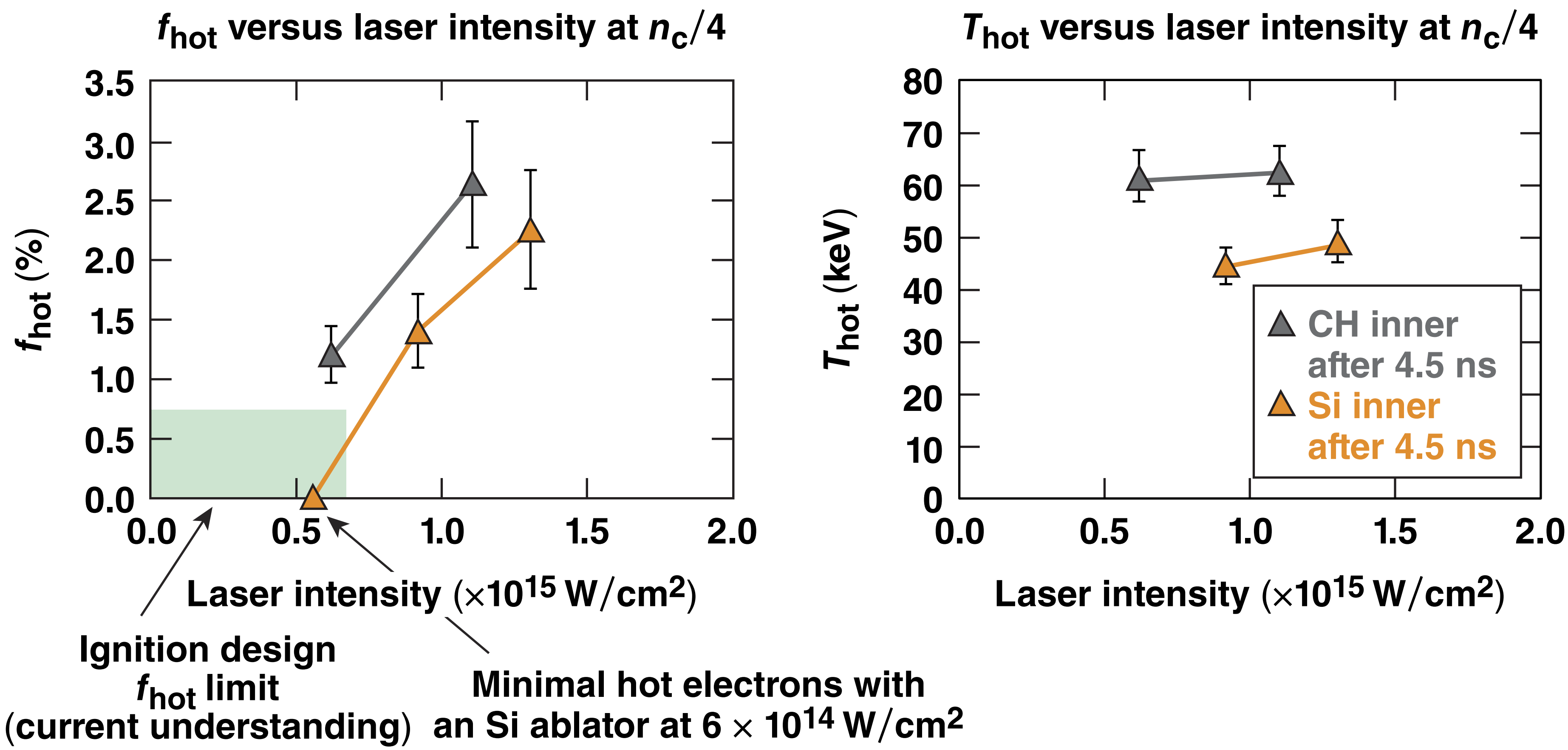


2-D *DRACO* simulated plasma conditions at $n_c/4$ during 23°, 30° beam drive

	CH ablator (N160421-001)	Si ablator (N160719-001)
L_n (μm)	690	560
T_e (keV)	4.4	5.2
I_L (W/cm^2)	1.1×10^{15}	0.92×10^{15}

E25569e

In comparison to the CH target, the Si target produced an ~30% lower f_{hot} and an ~15 keV lower T_{hot} for small-angle-beam drive



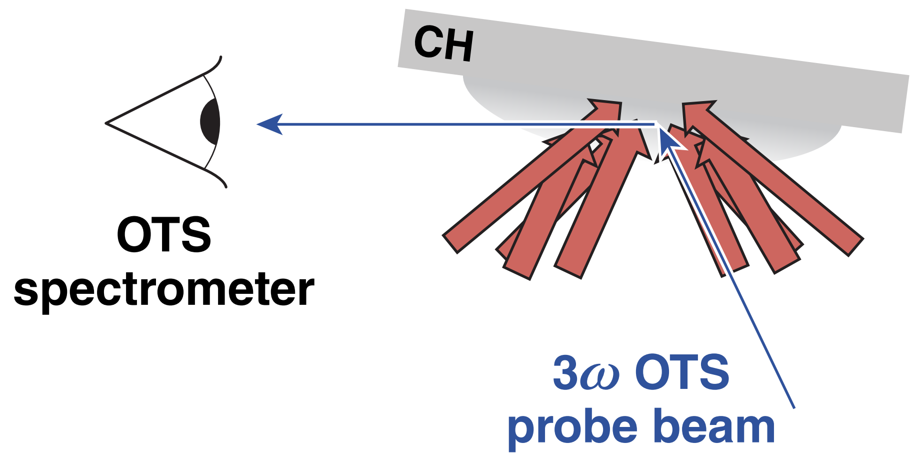
E26299

Future Work

The new optical Thomson-scattering (OTS) diagnostic on the NIF will be used to probe $3\omega/2$ emission and to measure plasma conditions

Experiments on 16 August 2017

Looking for $3\omega/2$ and probing thermal waves near $n_c/4$

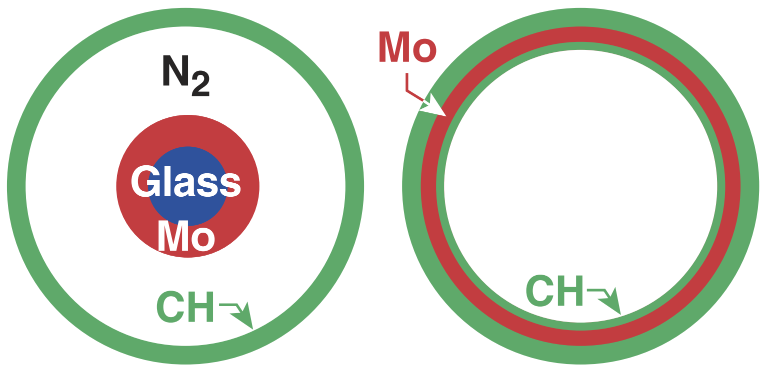


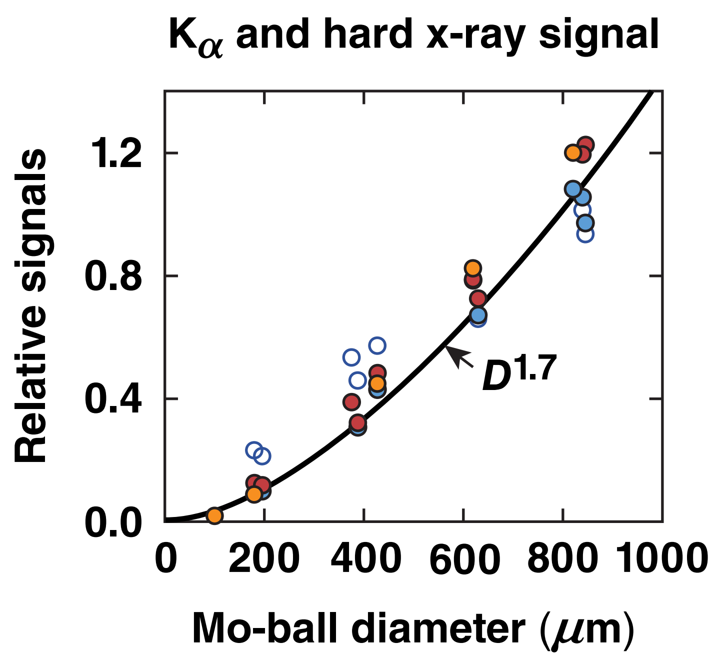
These experiments will assess the presence of TPD, confirm plasma conditions, and develop a platform for eventual use of 5ω Thomson scattering (TS) to probe plasma waves.

E26064a

Coupling of hot electrons to an implosion will be assessed by measuring their angular divergence using buried Mo layers

OMEGA experiments to be ported to the NIF





The increasing K_α signal with Mo shell diameter on OMEGA indicated a wide angular divergence in the TPD regime.

These NIF experiments will determine the relationship between hot-electron generation and the expected level of preheat in ignition-relevant implosions.

E21989b

*B. Yaakobi *et al.*, Phys. Plasmas 20, 092706 (2013).

Summary/Conclusions

Planar experiments at the National Ignition Facility (NIF) have investigated laser–plasma interaction (LPI) hot-electron production at direct-drive ignition-relevant coronal conditions

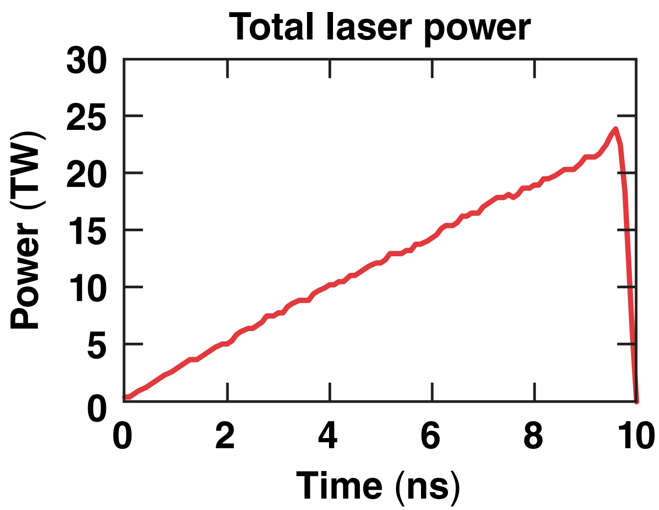
- NIF planar experiments achieve ignition-relevant scale lengths (L_n ~ 400 to 700 μm) and electron temperatures (T_e ~ 4 to 5 keV)
- The fraction of laser energy converted to hot electrons increased with laser intensity from f_{hot} ~0.5% to 2.3%—from 6 to 15 × 10^{14} W/cm^2—while T_{hot} was ~50 keV
- Stimulated Raman scattering (SRS) is inferred to be the dominant hot-electron source at these conditions
- The use of Si ablators reduces the observed SRS, f_{hot}, and T_{hot} relative to CH, using small angle beams

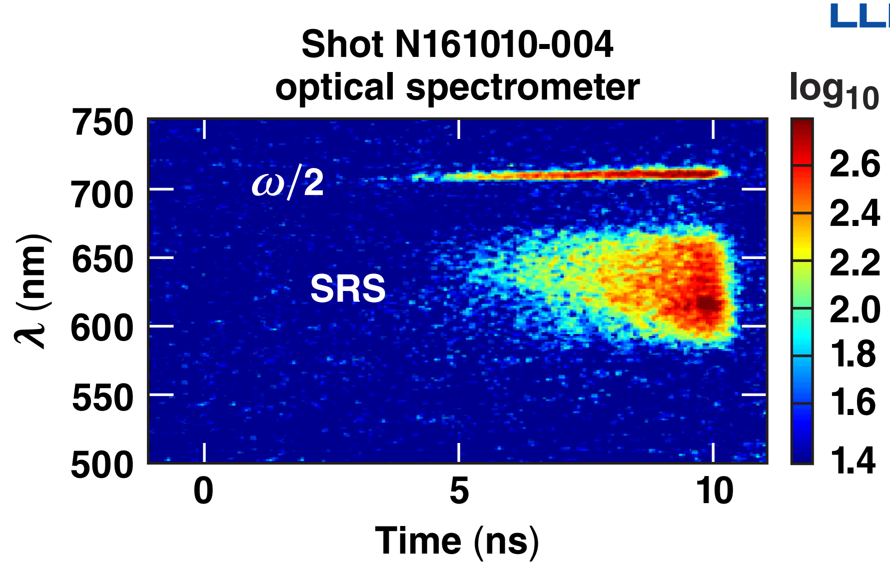
These results indicate a viable ignition-design space for direct drive.

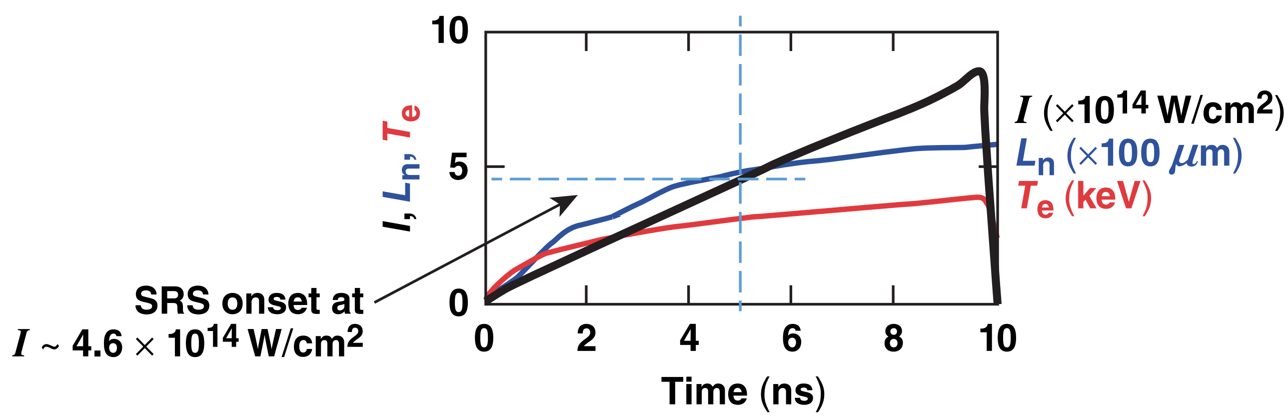
E25565b

Appendix

Despite varying plasma conditions in a NIF experiment using a ramped laser pulse, a similar SRS spectrum is obtained

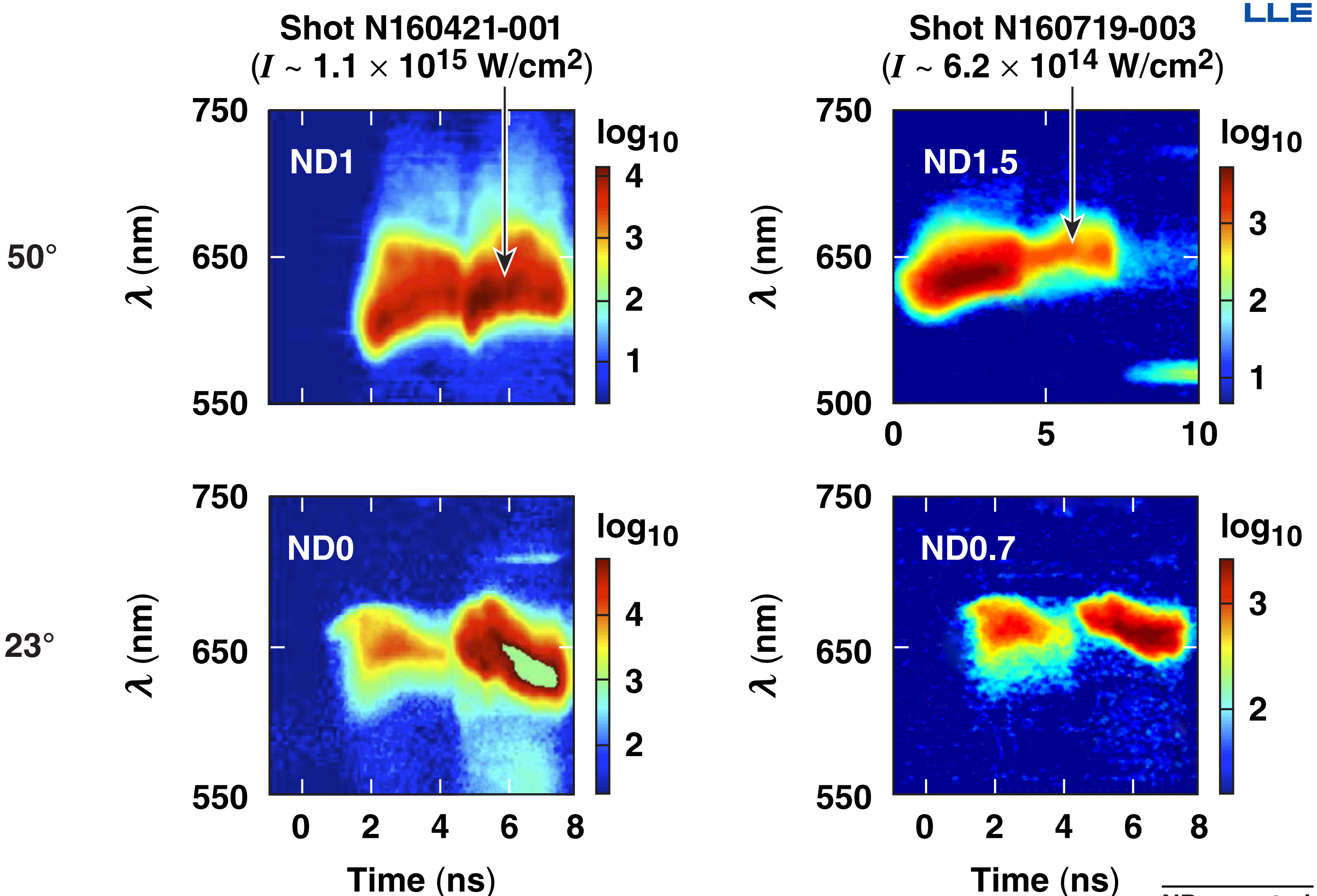






The observed spectrum is caused by SRS, which likely indicates that SRS is the dominant hot-electron source.

SRS depends strongly on inner-beam laser intensity in CH ablators



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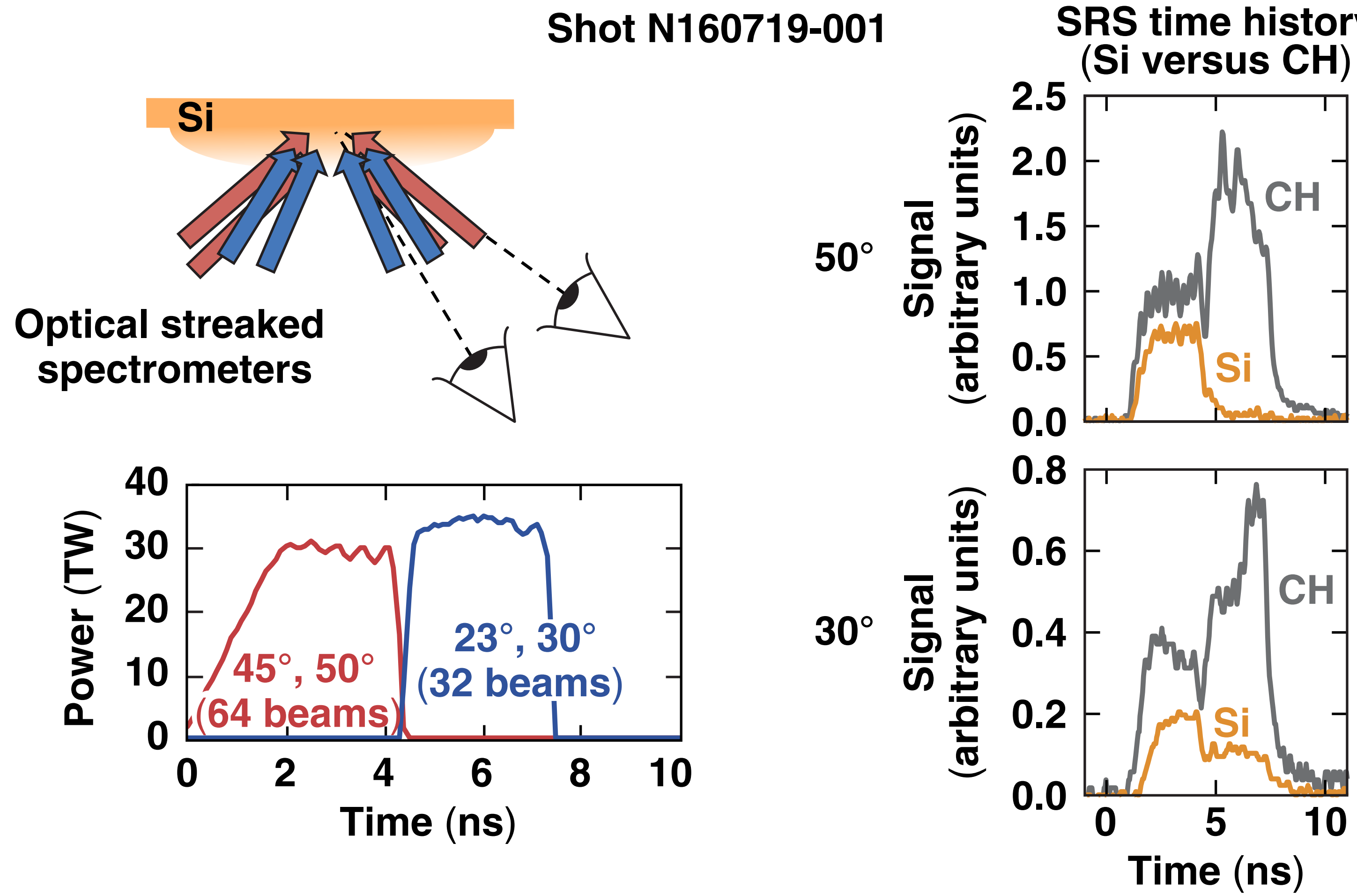
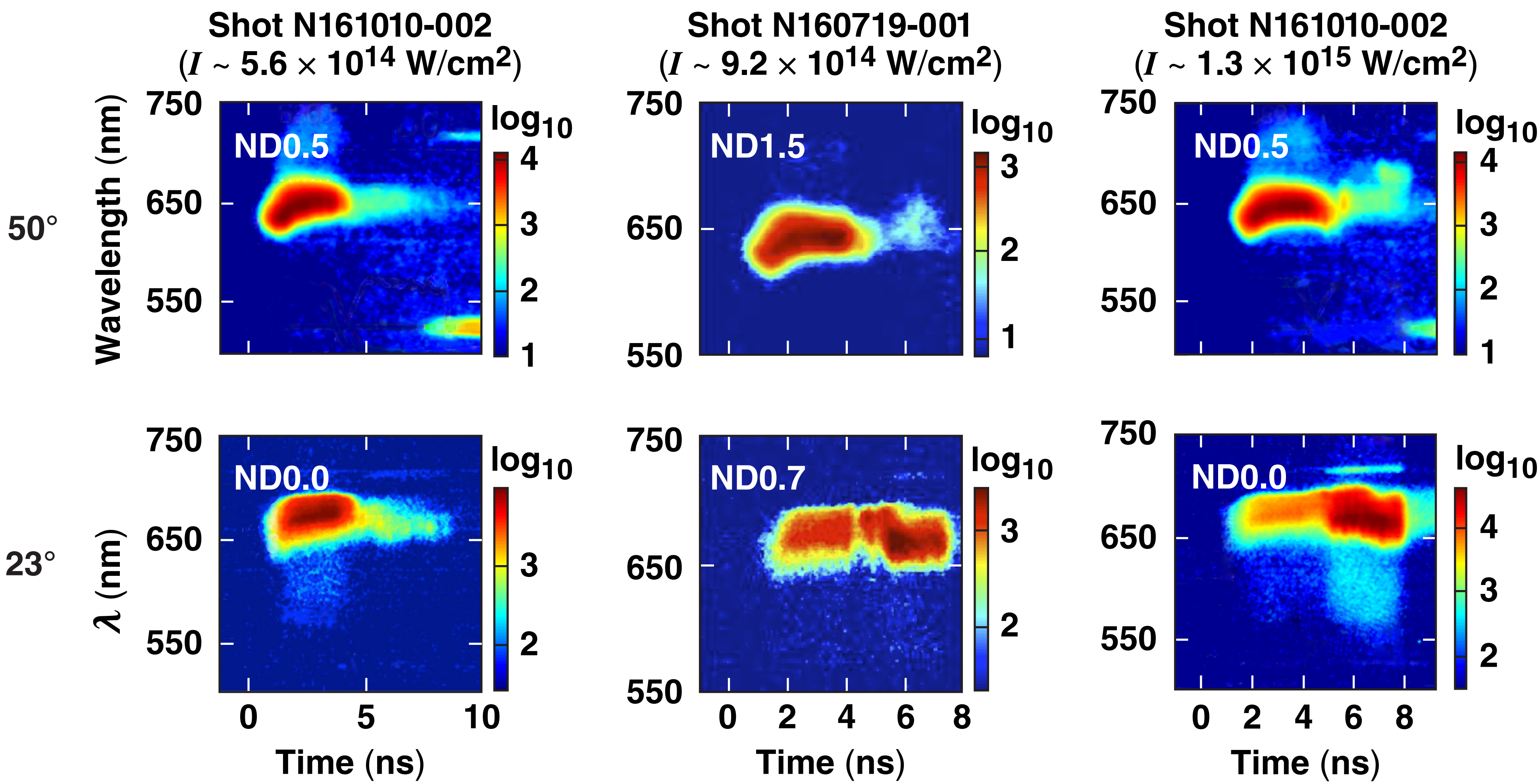
ND = neutral density

The use of an Si ablator in planar experiments causes a reduction in observed SRS driven by small-angle beams, relative to CH



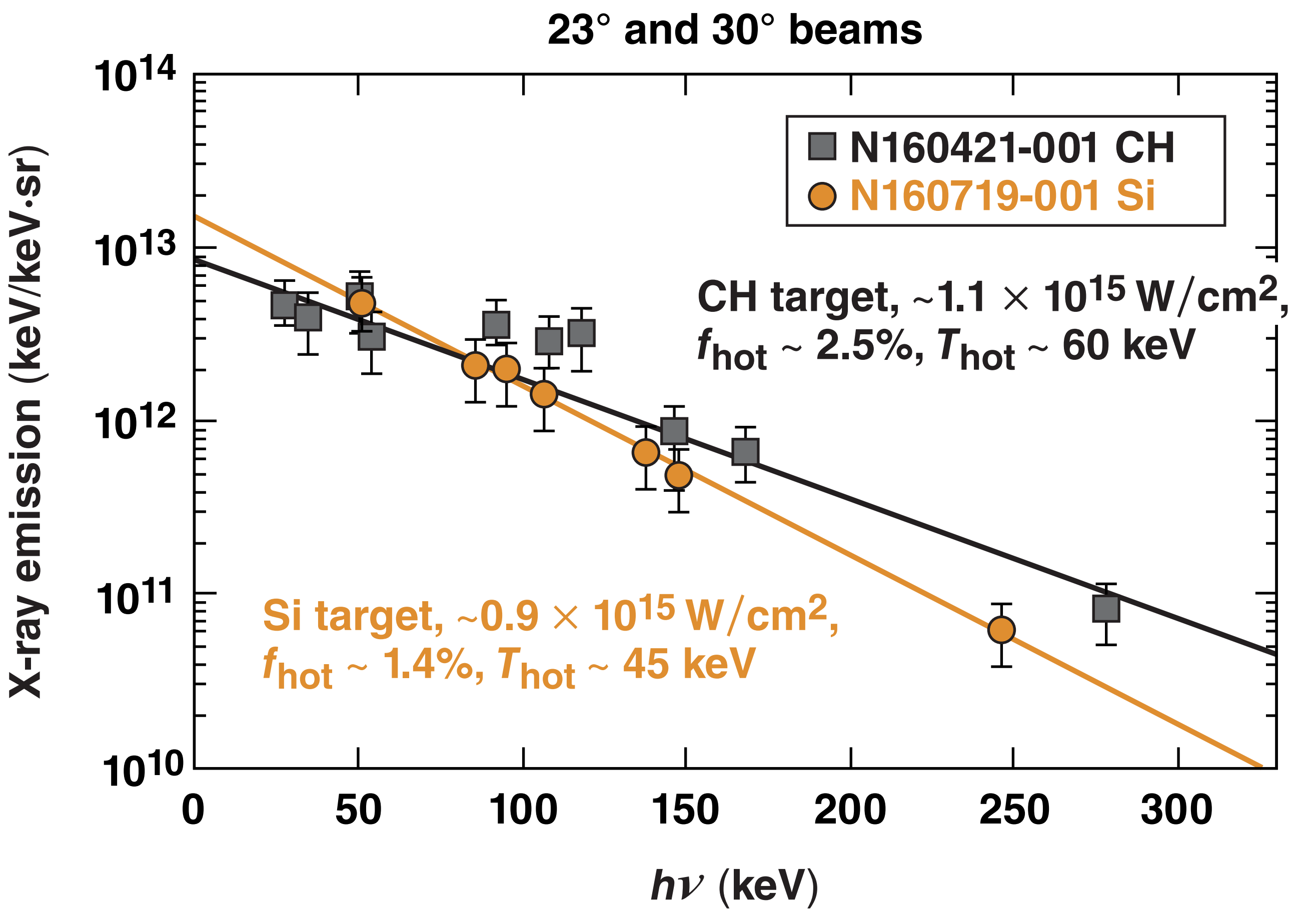
E25569d

For an Si ablator, the SRS intensity at 23° depends strongly on inner-beam laser intensity, but SRS observed at 50° is still minimal



E25967a

Compared to the CH target, the Si target produced an ~40% lower f_{hot} and an ~15-keV lower T_{hot} for small-angle-beam drive

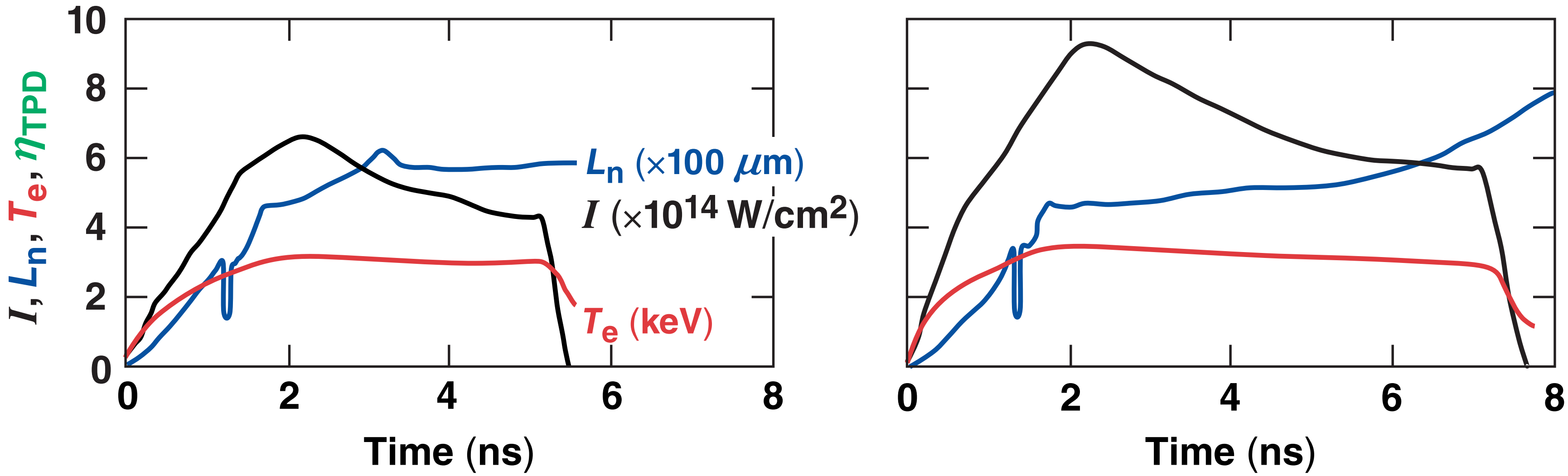


E25733b

Long-scale-length (>500-μm), high-temperature (>3-keV) coronal plasma conditions are predicted by 2-D *DRACO* simulations

Shot N150520: 23° and 30° beams | **Shot N150521: 45° and 50° beams**

Post-shot *DRACO*-simulated conditions at $n_c/4$*



The empirical TPD and theoretical SRS thresholds are exceeded in this experimental design: $\eta_{TPD} = I_{14}\, L_{n,\mu m}/(230\ T_{e,keV}) \sim 4$ to 5, $\eta_{SRS} = I_{14}\, L_{n,\mu m}^{4/3}/2377 \sim 10$ to 13.**

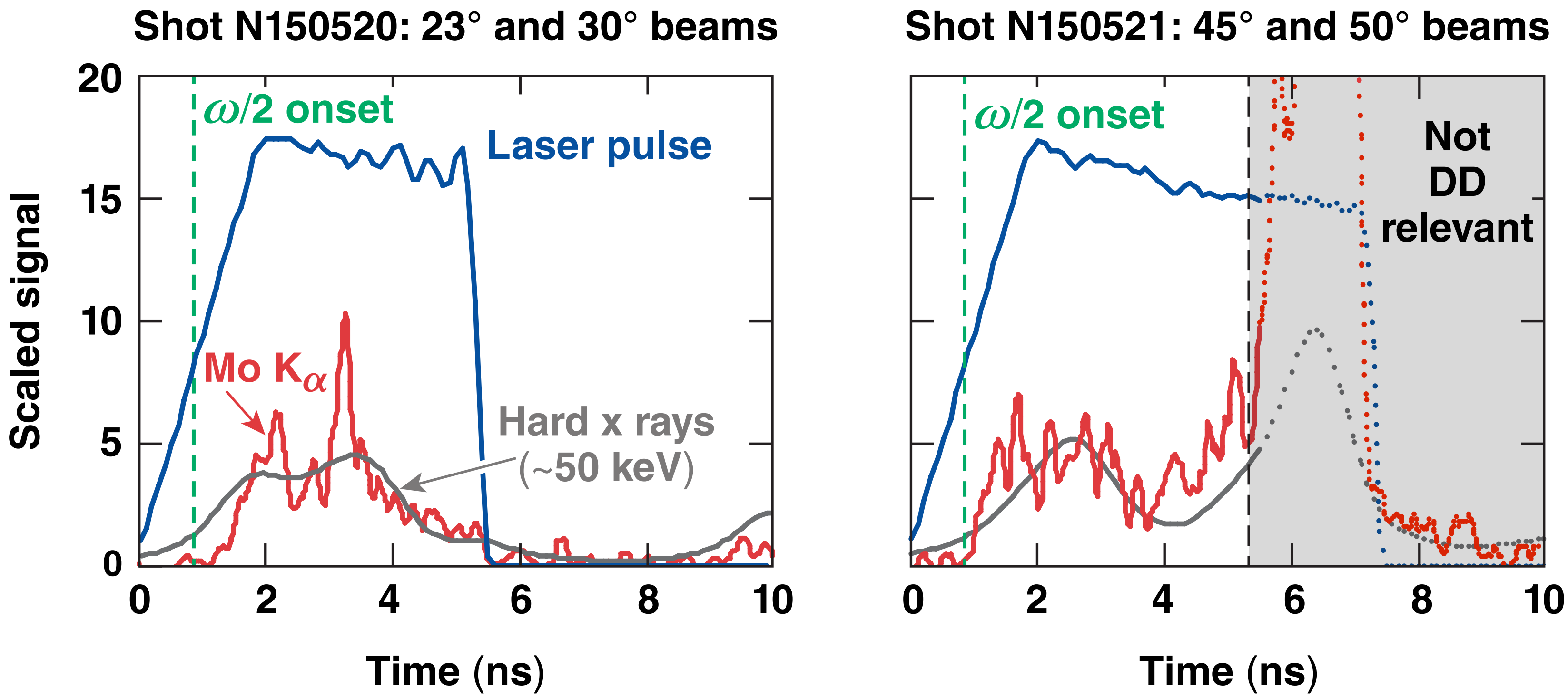
*A. A. Solodov *et al*., presented at the Ninth International Conference on Inertial Fusion Sciences and Applications (IFSA 2015), Seattle, WA, 20–25 September 2015

**A. Simon *et al*., Phys. Fluids 26, 3107 (1983);
C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).

E24714d

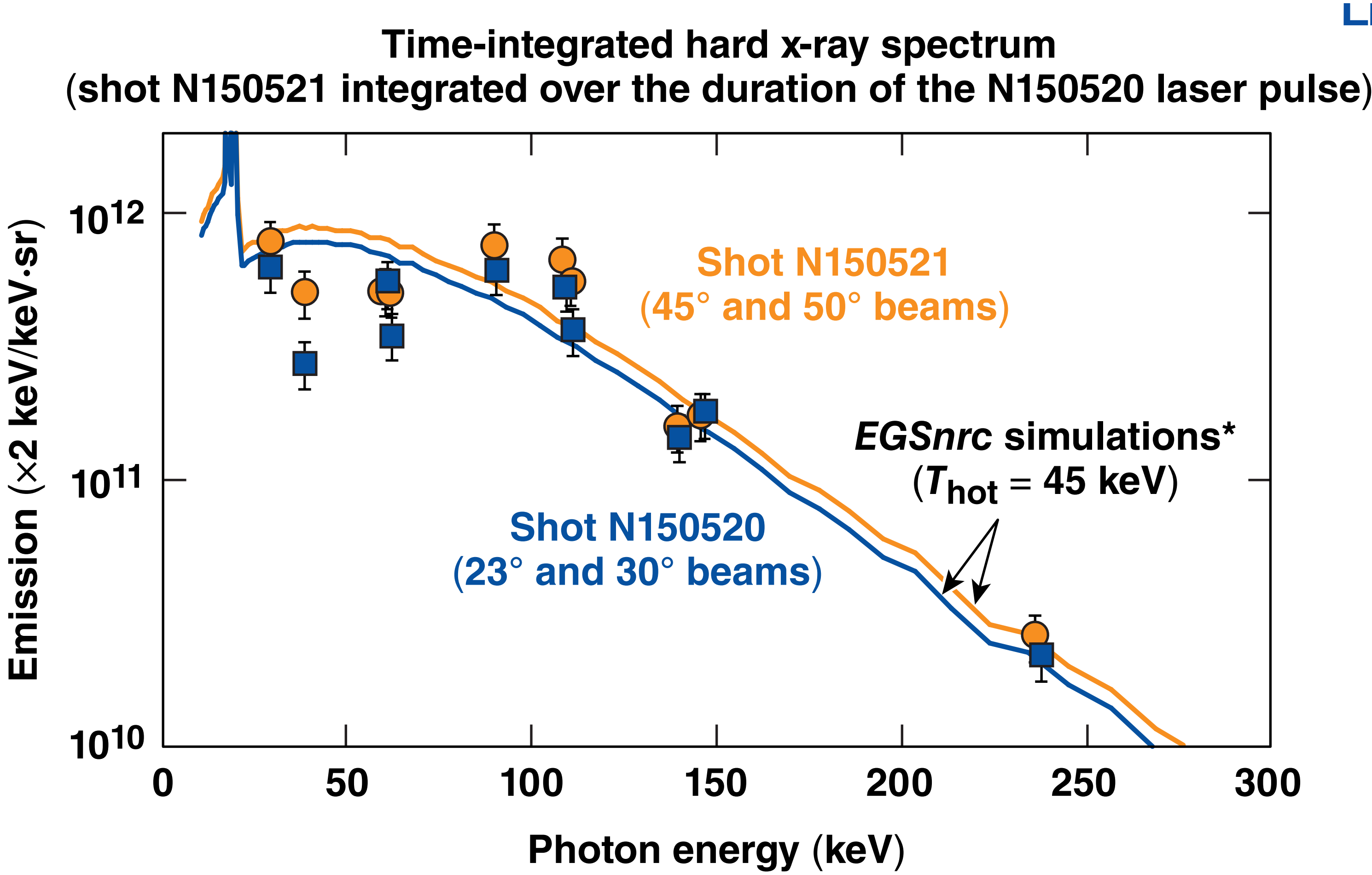
Hard x-ray and Mo K_α emission caused by LPI-generated hot electrons were observed

UR LLE



E24128g

Time-integrated hard x-ray spectra indicate T_{hot} ~ 45±5 keV, f_{hot} ~ 1% for both experiments

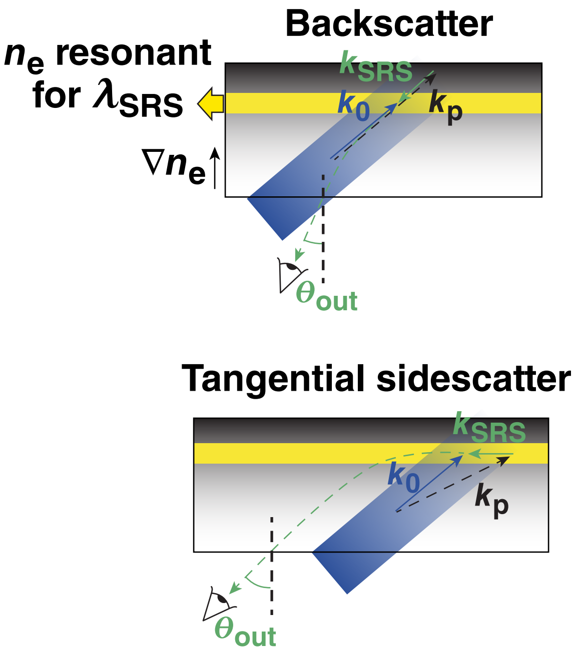


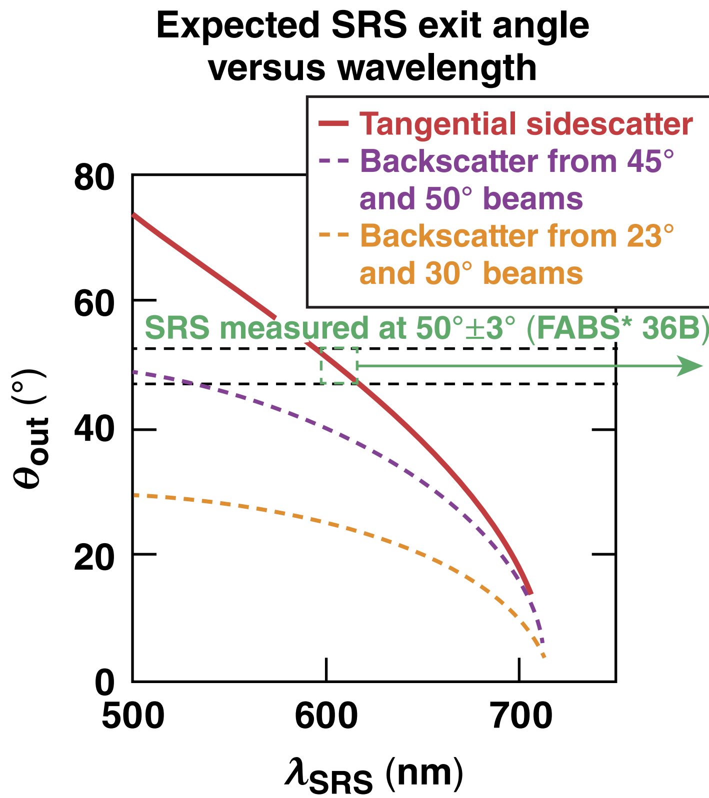
The beam angle of incidence did not have a strong effect on f_{hot} and T_{hot}.

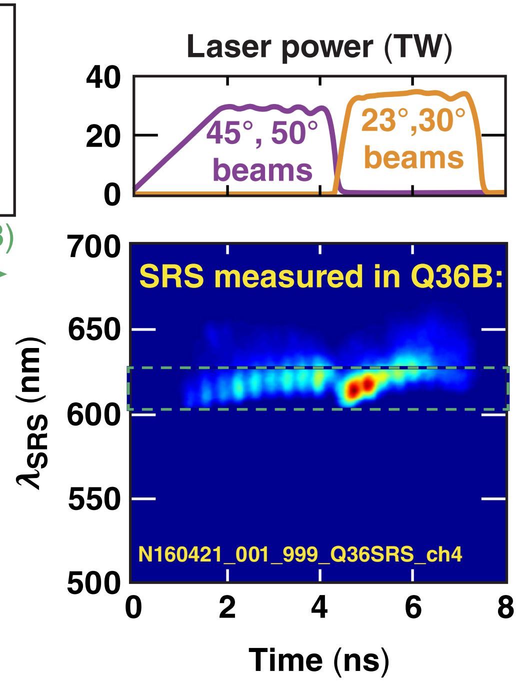
*A. A. Solodov *et al*., presented at the Ninth International Conference on Inertial Fusion Sciences and Applications (IFSA 2015), Seattle, WA, 20–25 September 2015.

E24130e

This observation is explained by tangential SRS sidescatter, which allows for SRS observation at large angles and wavelength independent of drive-beam angle







- Tangential sidescatter exit angle does not depend on the incidence angle

P. A. Michel *et al.*, WeO-4, this conference.
*Full-aperture backscatter station

E26063a