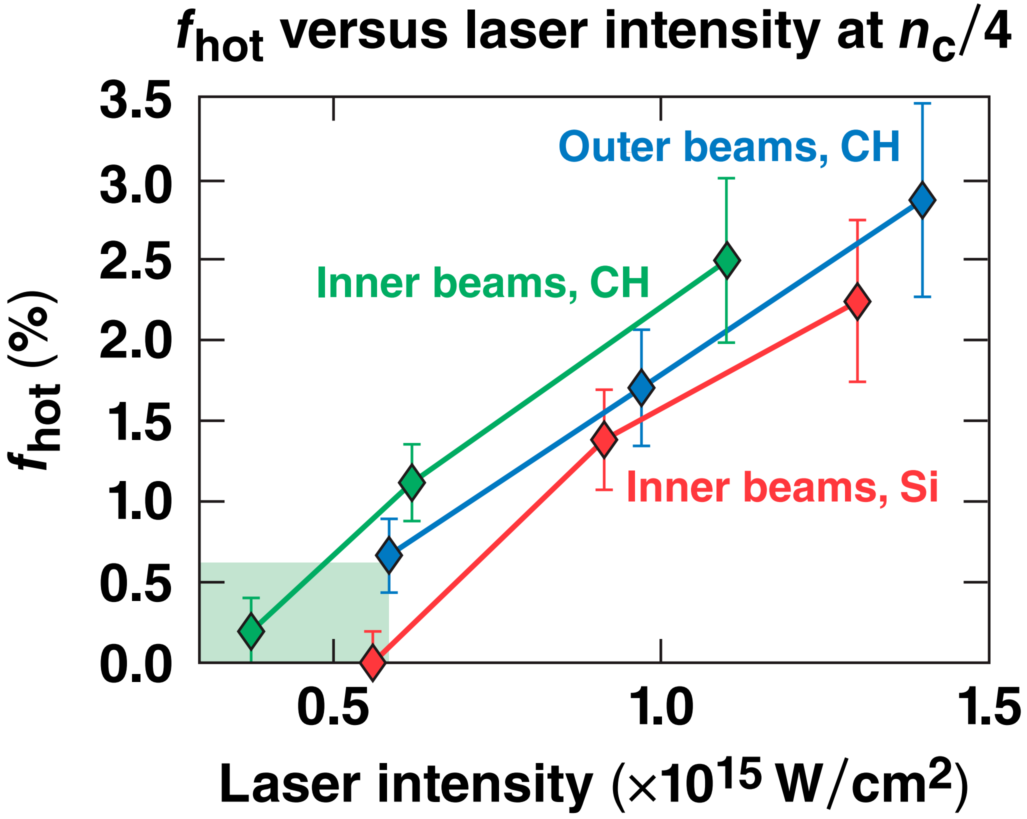
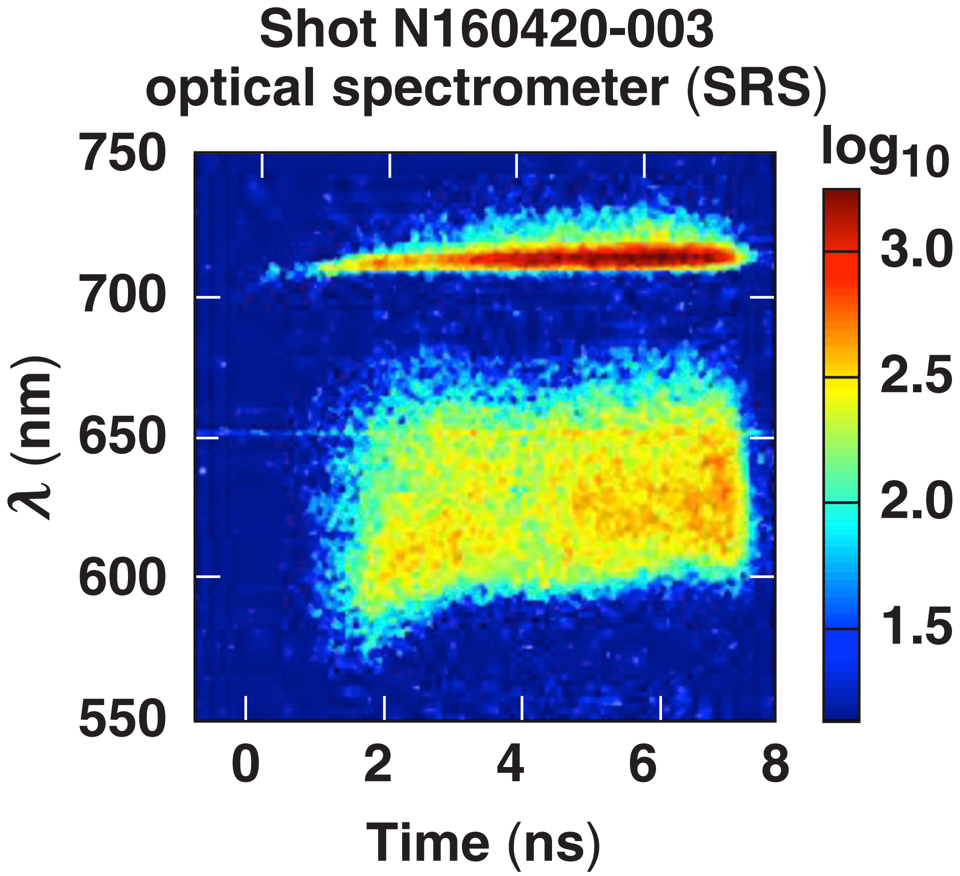
Planar Laser–Plasma Interaction Experiments at Direct-Drive Ignition-Relevant Scale Lengths at the National Ignition Facility





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Summary

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

- Experiments achieve scale lengths of L_n ~ 400 to 700 μm, electron temperatures of T_e ~ 3 to 5 keV, and laser intensities of 0.5 to 1.5 × 10^{15} W/cm^2
- Hot-electron generation of the order of f_{hot} ~ 0% to 3% and T_{hot} ~ 50 keV have been observed
  - $I_{n_c/4}$ ~ 5 × 10^{14} W/cm^2 may be acceptable for preheat
- Stimulated Raman scattering (SRS) is inferred to be the dominant LPI mechanism, although recent measurements ($3\omega/2$) have uncovered evidence of two-plasmon decay (TPD) as well
- Upcoming spherical experiments will diagnose hot-electron coupling (preheat) to an implosion

E27529

Collaborators

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Outline

- Motivation for direct-drive LPI experiments on the NIF and planar platform development
- Hot-electron results and LPI mechanisms: Predominantly SRS
- Future work: Hot-electron coupling

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- **Motivation for direct-drive LPI experiments on the NIF and planar platform development**
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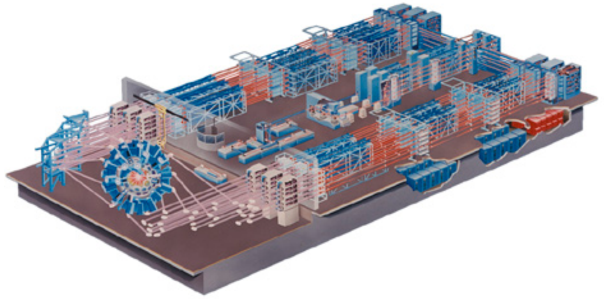
- Future work: Hot-electron coupling

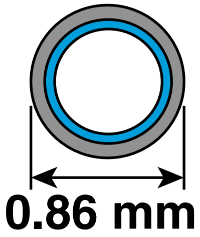
The National Direct Drive Program is underway at OMEGA and the NIF to demonstrate the ignition physics of direct drive

OMEGA

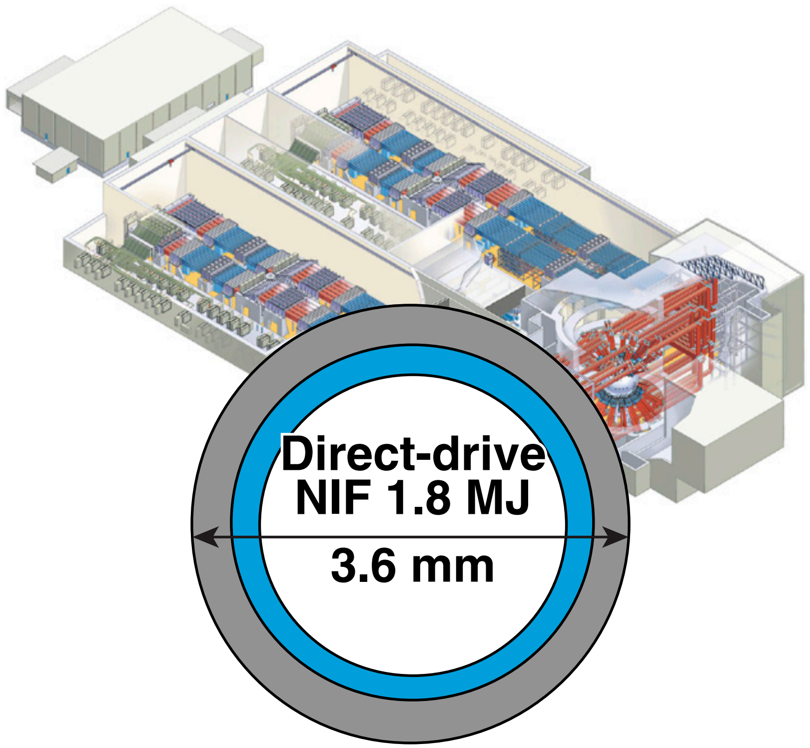


Scale 1:70
in energy

OMEGA 26 kJ



NIF



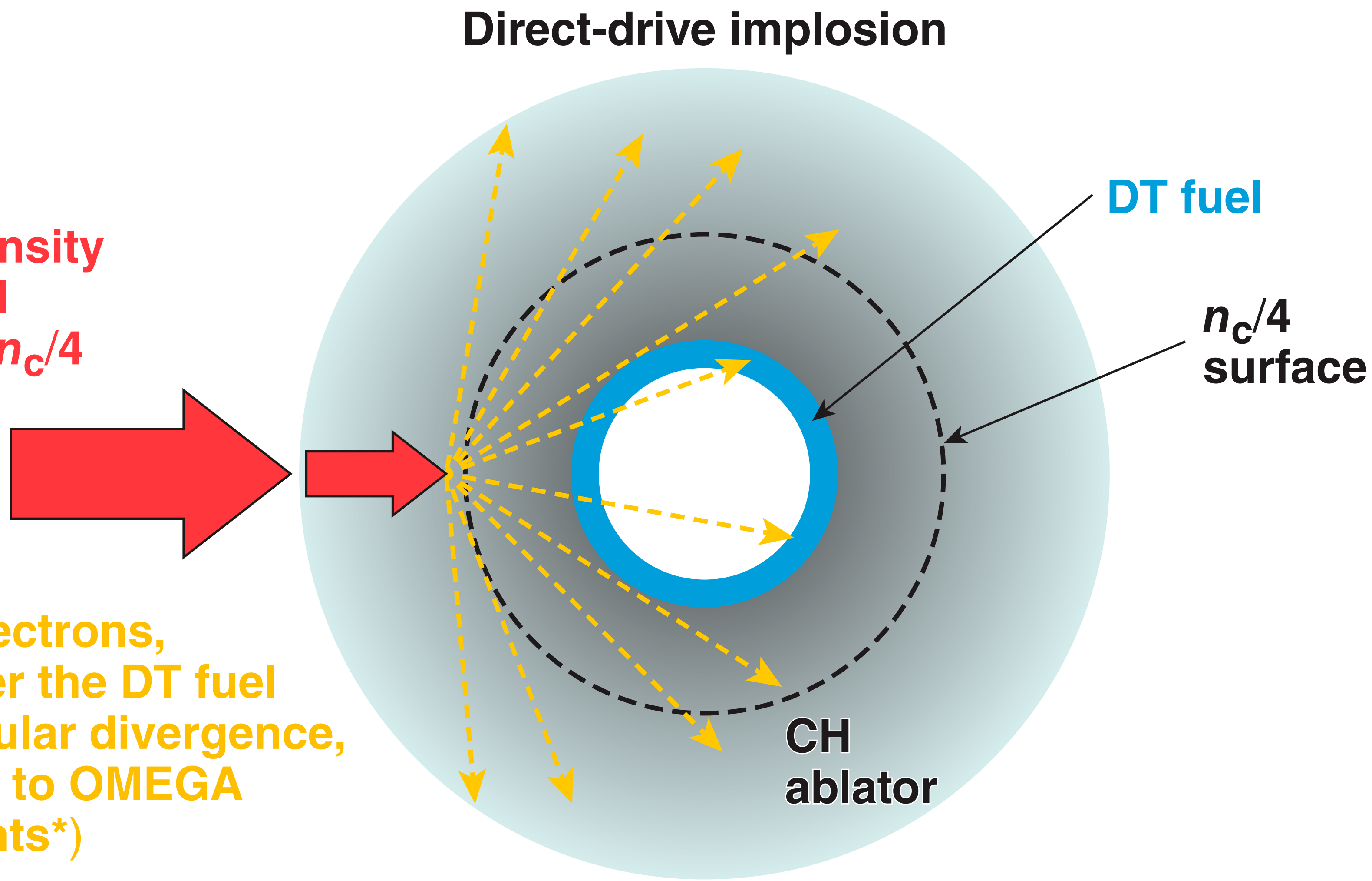
OMEGA 100-Gbar Campaign: Demonstrate hot-spot pressure of 100 Gbar in hydro-scaled implosions

NIF Megajoule Direct-Drive (MJDD) Campaign: Demonstrate laser–plasma coupling physics at the ignition scale

The MJDD campaign is predominantly focused on understanding and mitigating: laser imprint, cross-beam energy transfer (CBET), and LPI/hot-electron preheat.

Motivation

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



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

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

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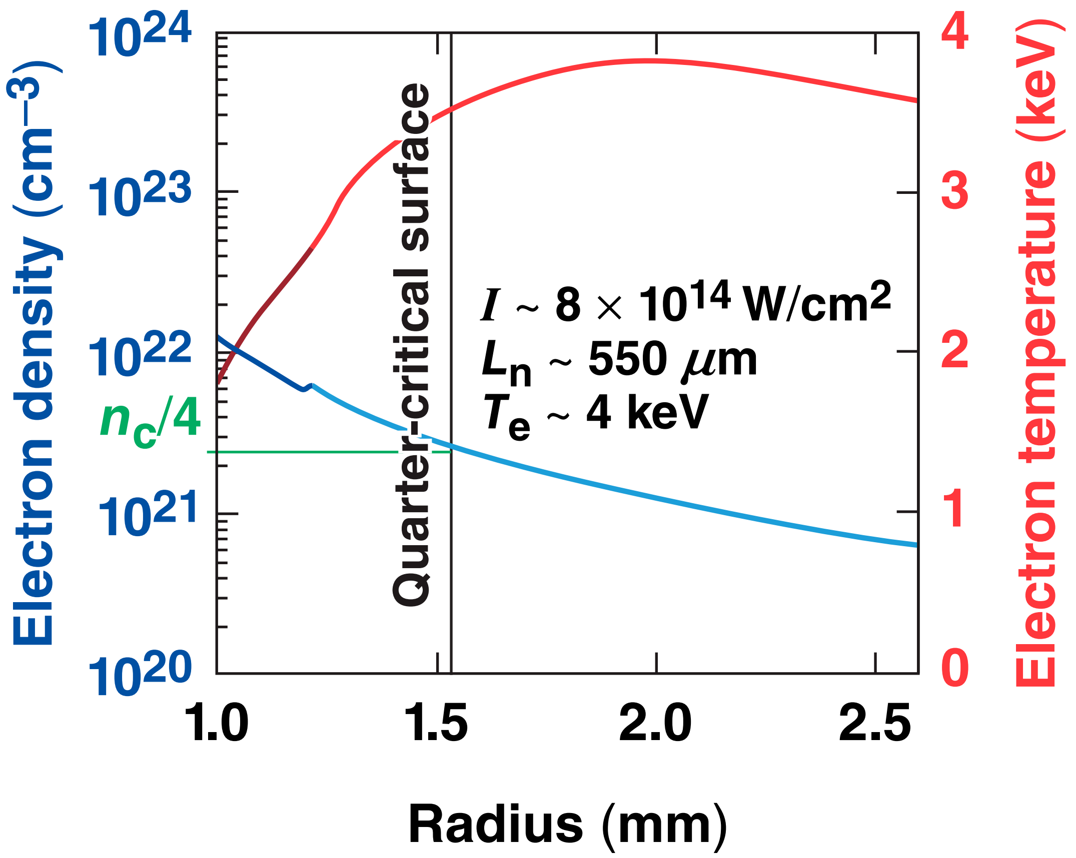
Motivation

Direct-drive ignition designs predict long density scale lengths and high electron temperatures at which LPI may generate hot electrons

1-D simulated plasma conditions for an igniting direct-drive design



Experiments must be performed at these conditions to understand LPI at the NIF/ignition scale.

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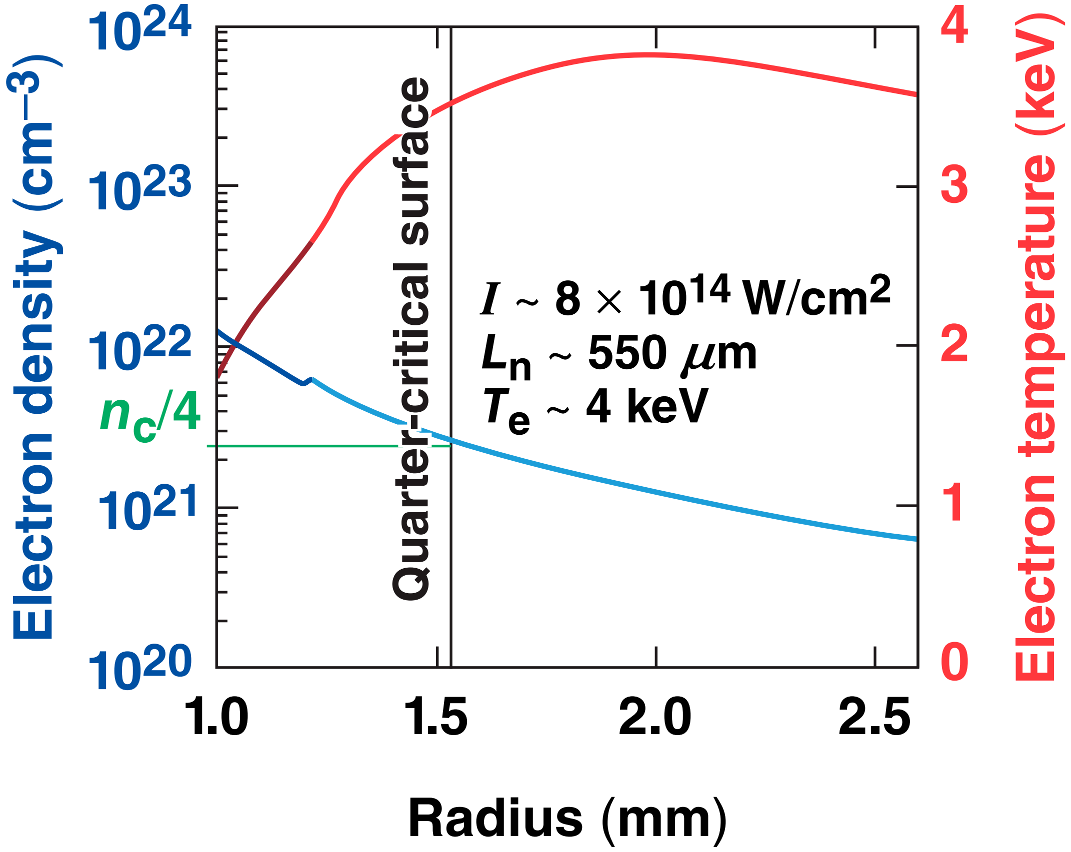
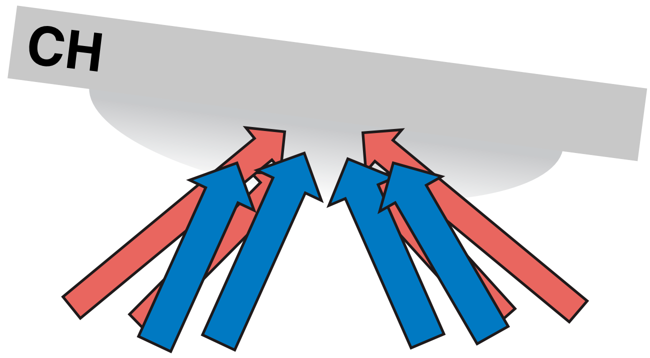
Planar experiments on the NIF were designed to achieve plasma conditions comparable to direct-drive ignition designs

1-D simulated plasma conditions for an igniting direct-drive design



Planar platform



2-D *DRACO*-simulated plasma conditions at $n_c/4$

	NIF ignition scale	NIF planar experiments
L_n (μm)	500 to 600	400 to 700
T_e (keV)	3.5 to 5	3 to 5
I_L (W/cm^2)	(6 to 8) × 10^{14}	(4 to 15) × 10^{14}

Experiments must be performed at these conditions to understand LPI at the NIF ignition scale.

E25732d

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*A. A. Solodov *et al.*, this conference.

Based on simulated plasma conditions, and considering overlapped laser intensities, these experiments are well above LPI thresholds

- Absolute instability thresholds for a single beam at normal incidence

TPD *

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

$$\rightarrow \eta_{\mathrm{TPD}} = I_{\mathrm{overlapped}}/I_{14,\mathrm{thr,TPD}} \sim 3 \text{ to } 8$$

SRS **

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

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

- These experiments overlapped up to 64 beams (16 NIF quads)

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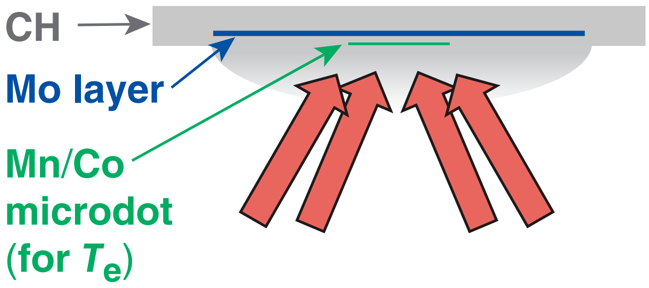
*A. Simon *et al.* Phys. Fluids 26, 3107 (1983).

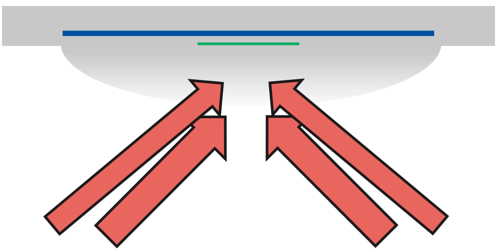
**C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).

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

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

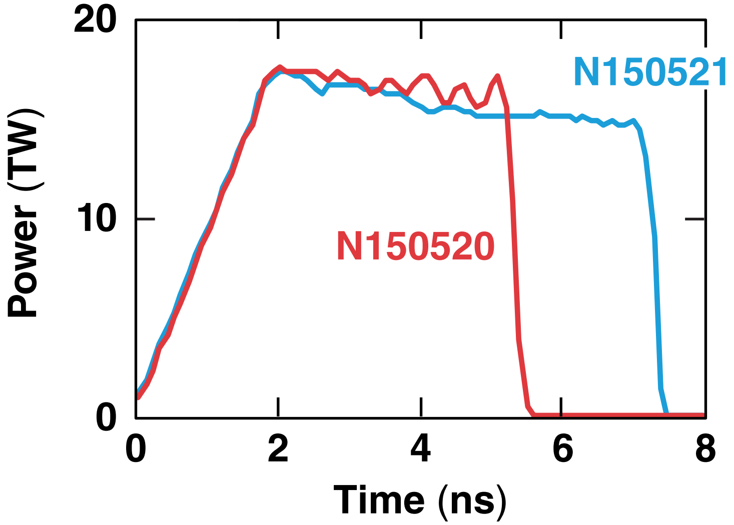


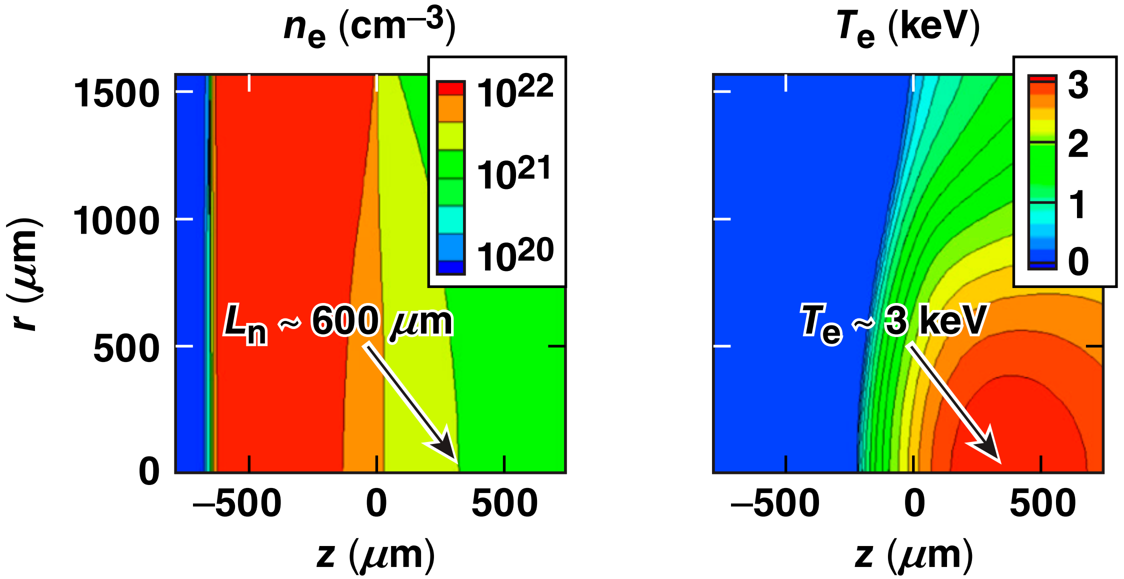
Shot N150521: 45° and 50° beams (60 beams total)



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

Total laser power





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

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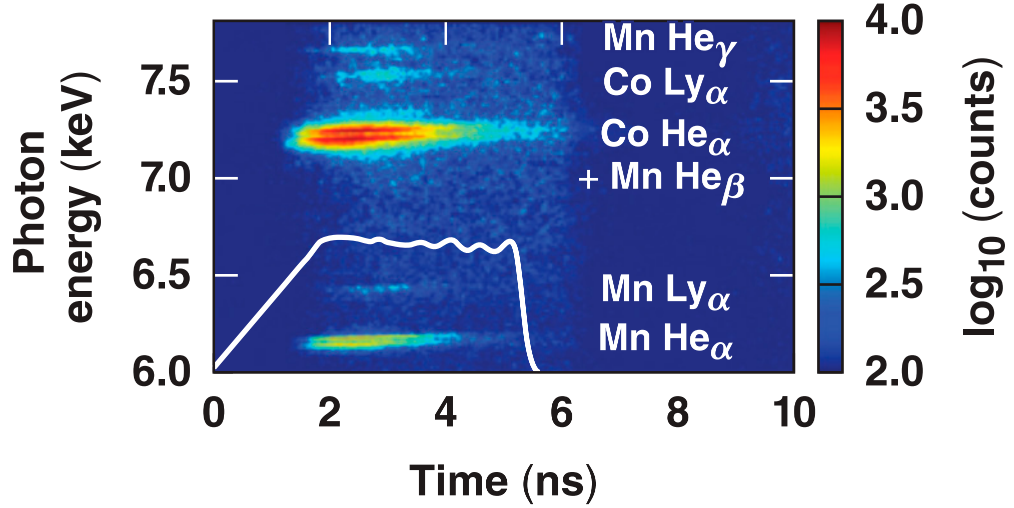
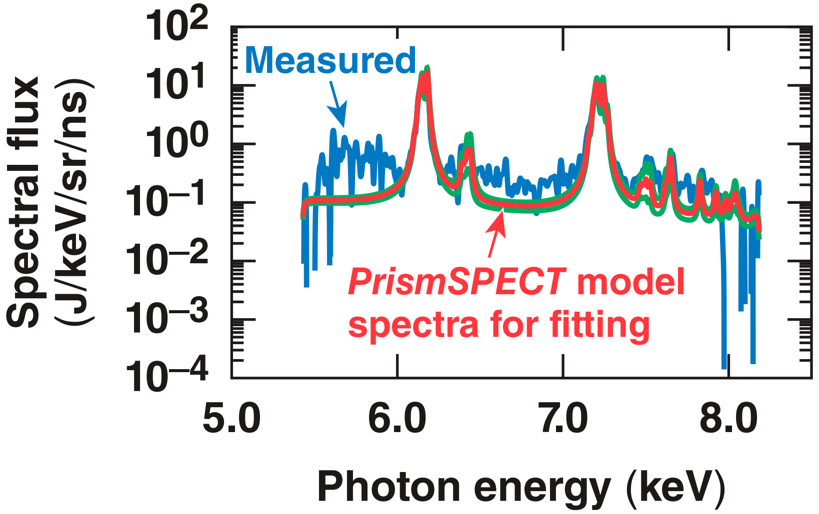
Microdot spectroscopy was used to infer electron temperatures around 3 keV, in reasonable agreement with *DRACO* modeling

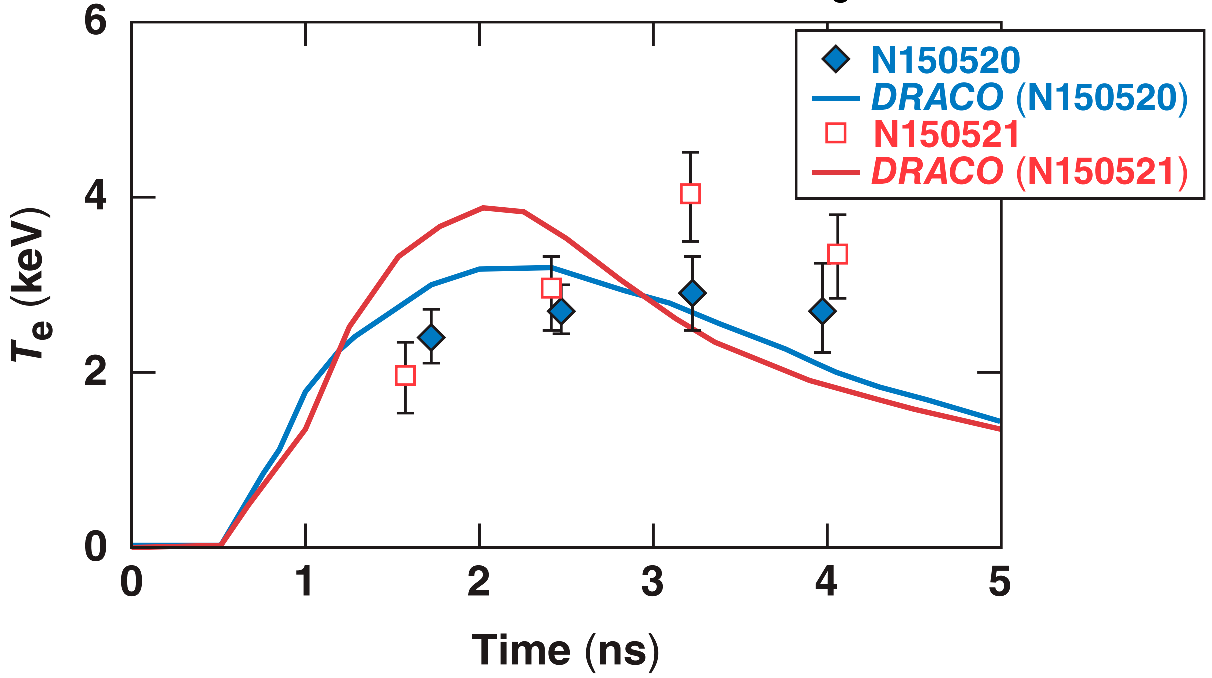
Time-resolved x-ray spectrum on shot N150520



Measured and modeled spectra at 2.5 ns on shot N150521



T_e inferred from spectral fitting versus *DRACO*-simulated T_e



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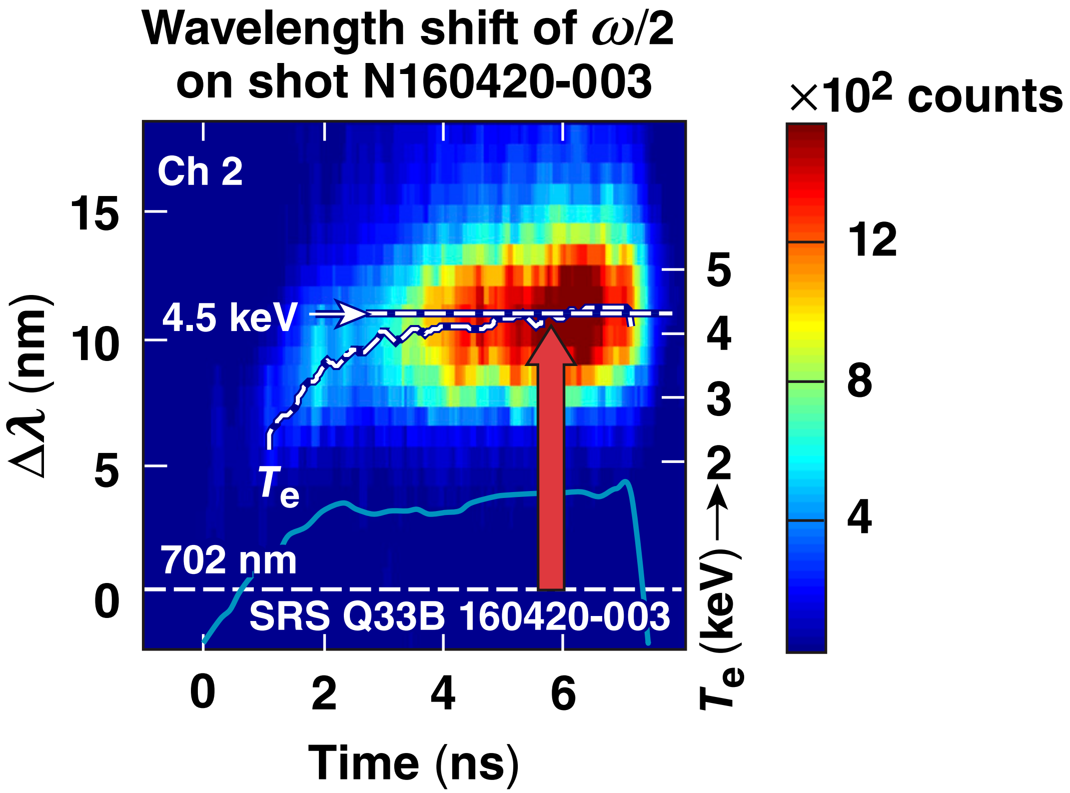
In subsequent experiments at higher laser intensity, the wavelength of $\omega/2$ emission was used to infer $T_e \sim 4.5$ keV at $n_c/4$



Stationary plasma **Plasma flow** **Diverging plasma**

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

$T_e \sim 4.5$ keV agrees with *DRACO*

These results validate hydro modeling of the plasma conditions and demonstrate that ignition-relevant coronal temperatures are achieved.

E25695b

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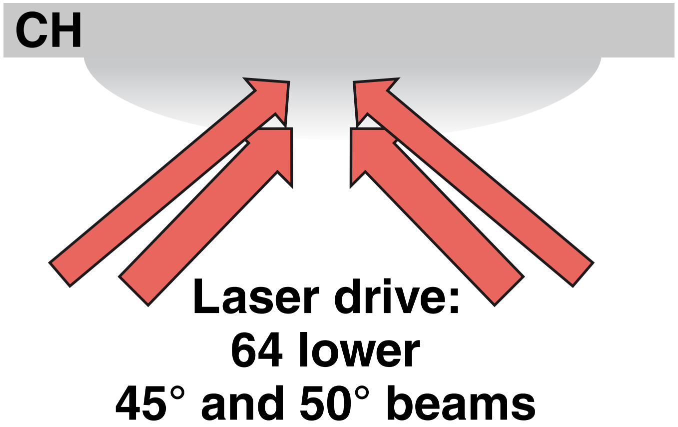
*W. Seka *et al.*, Phys. Fluids 28, 2570 (1985).

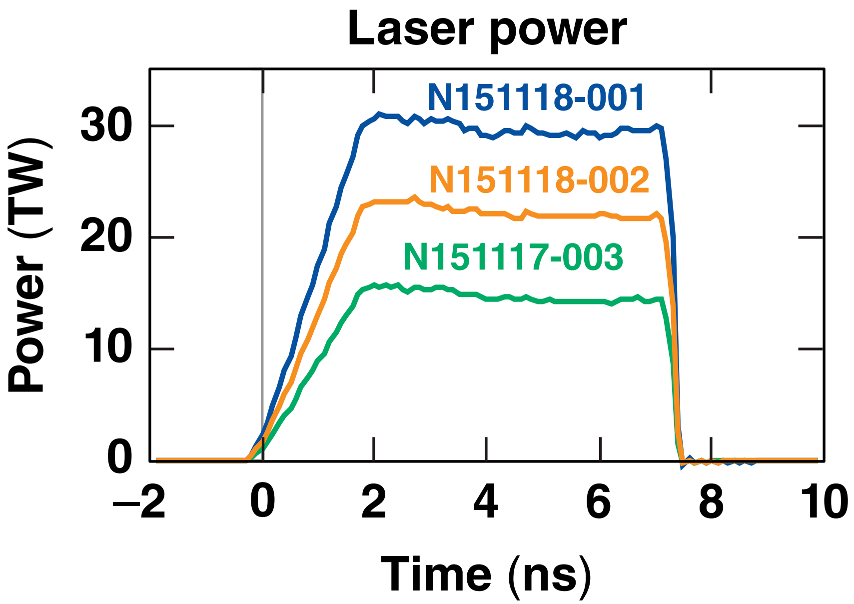
Outline

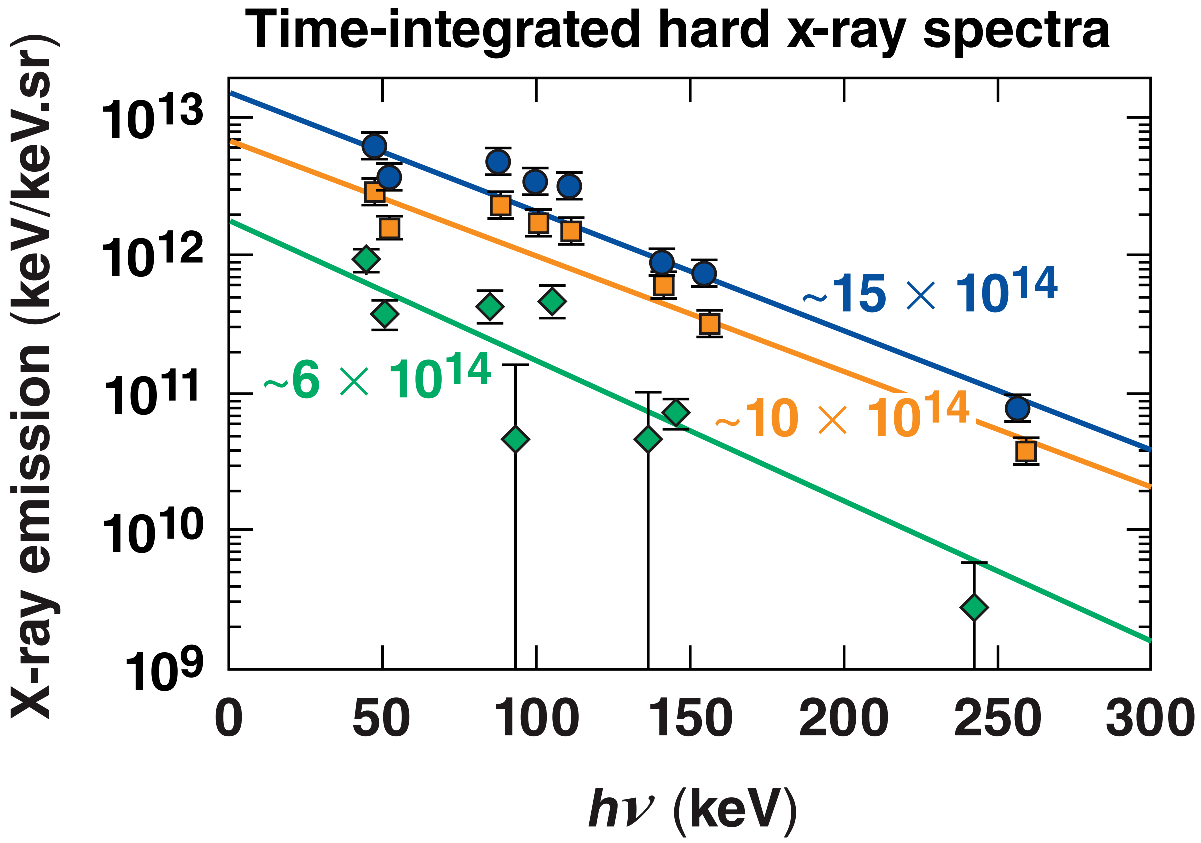
- Motivation for direct-drive LPI experiments on the NIF and planar platform development
- **Hot-electron results and LPI mechanisms: Predominantly SRS**
- Future work: Hot-electron coupling

Hard x-ray measurements have been used to infer f_{hot} and T_{hot} as functions of laser intensity in planar experiments



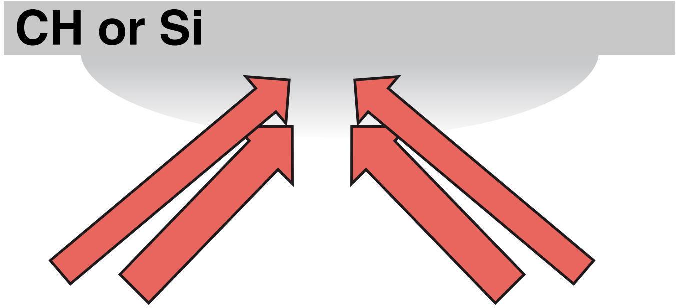
Laser drive:
64 lower
45° and 50° beams



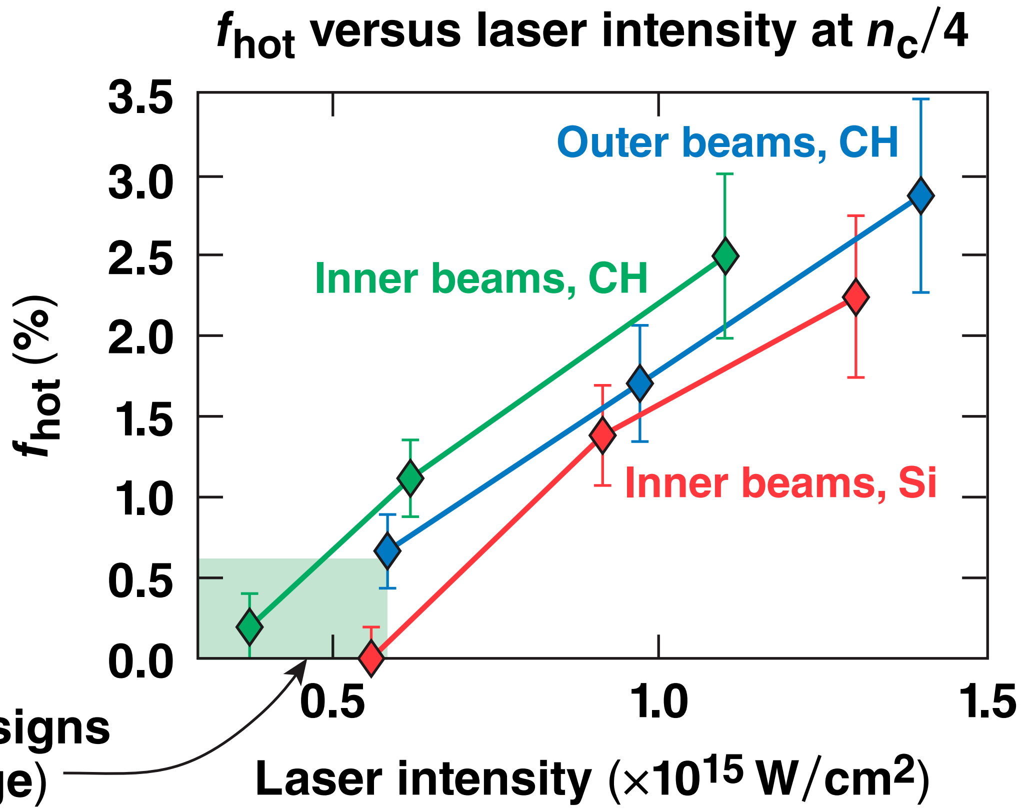


A. A. Solodov *et al.*, this conference.

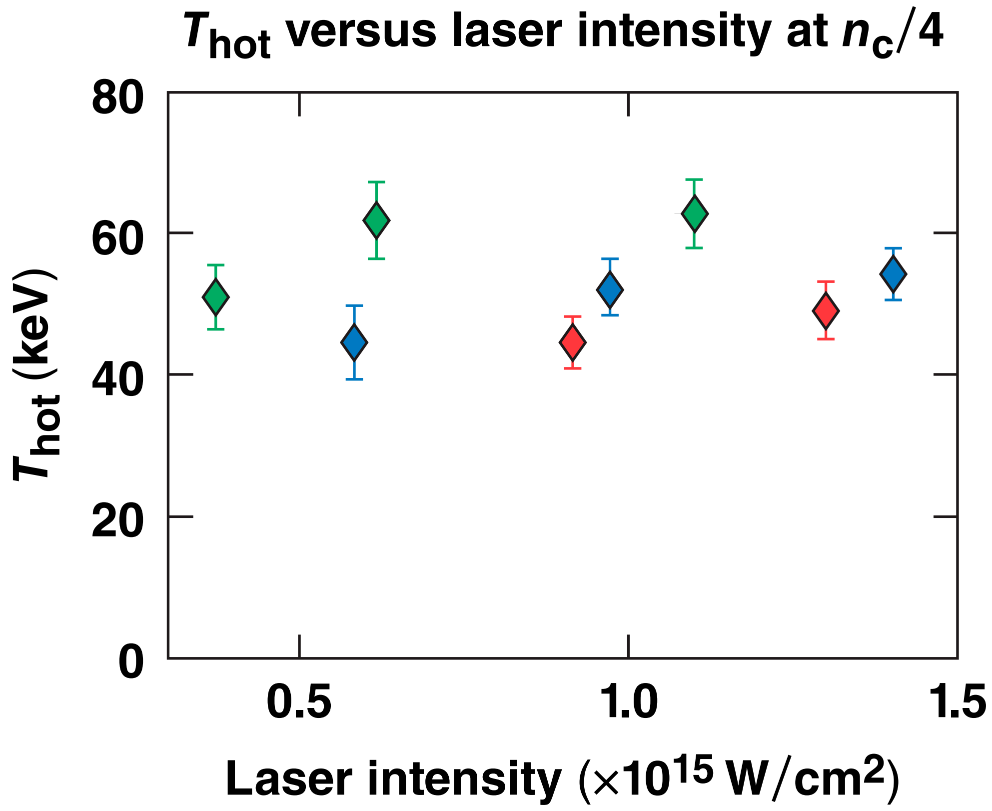
f_{hot} up to 3% and T_{hot} of 40 to 60 keV are measured in CH and Si targets for $n_c/4$ intensities up to 1.3 × 10^{15} W/cm^2; 5 × 10^{14} W/cm^2 may be acceptable for preheat



23° and 30° beams
or
45° and 50° beams



Tolerable preheat in ignition designs
(if electron divergence is large)



f_{hot} is close to levels thought to be tolerable in direct-drive ignition designs; need to understand (1) LPI mechanisms (for mitigation), (2) coupling of hot electron to implosion (preheat).

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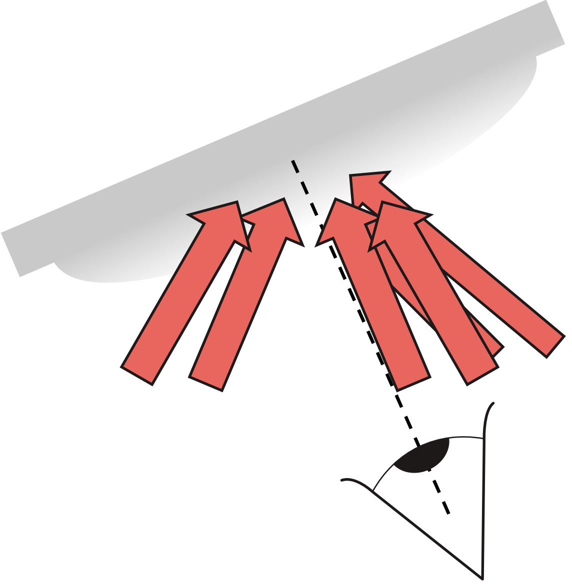
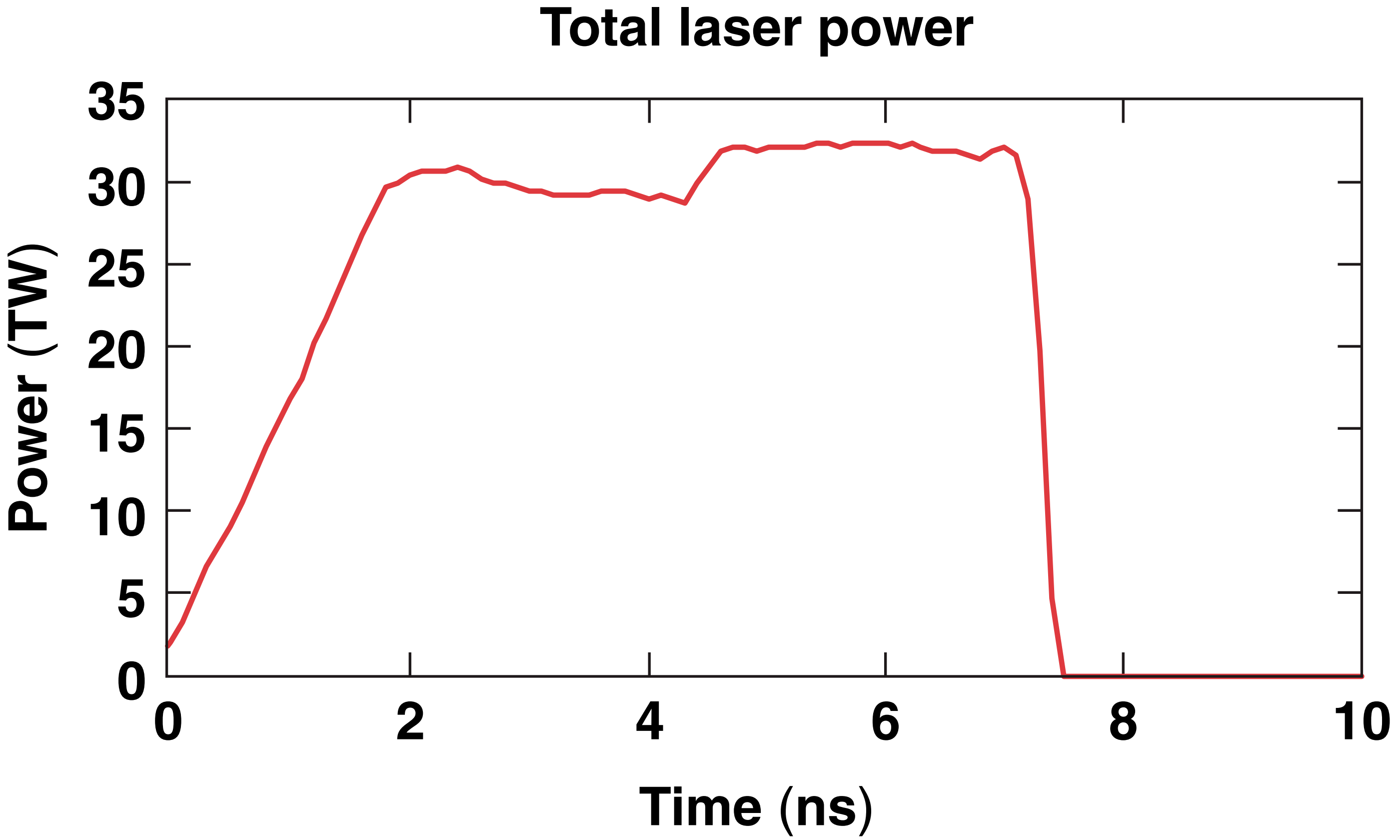
*M. Rosenberg *et al.* Phys. Rev. Lett. 120, 055001 (2018); A. A. Solodov *et al.*, this conference.

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)



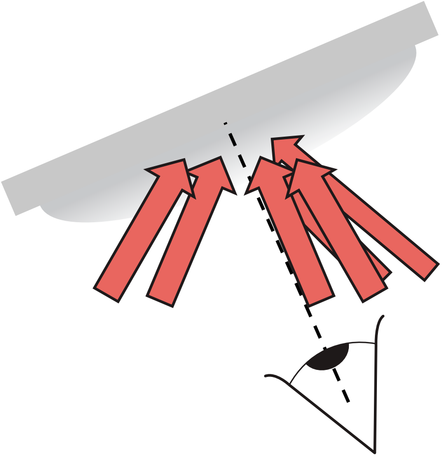
If TPD is dominant, expect to see an $\omega/2$ doublet feature, as has been observed previously on OMEGA.*

NBI: near-backscatter imager

*W. Seka *et al.*, Phys. Rev. Lett. 112, 145001 (2014).

E25566d

Optical data demonstrate different LPI physics on the NIF than on OMEGA—SRS dominates the scattered light spectrum (both at and below $n_c/4$)



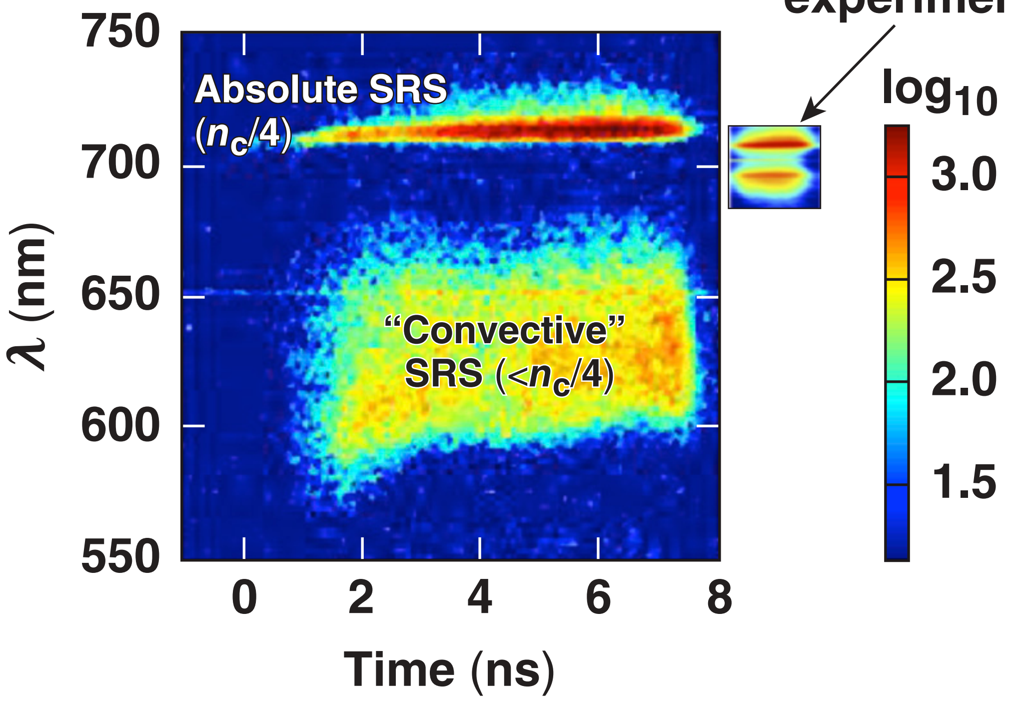
Optical streaked spectrometer
NBI Q33B

NIF: L_n = 525 μm
T_e = 4.5 keV

OMEGA:* L_n = 150 μm
T_e = 2.8 keV

Shot N160420-003
optical spectrometer (SRS)

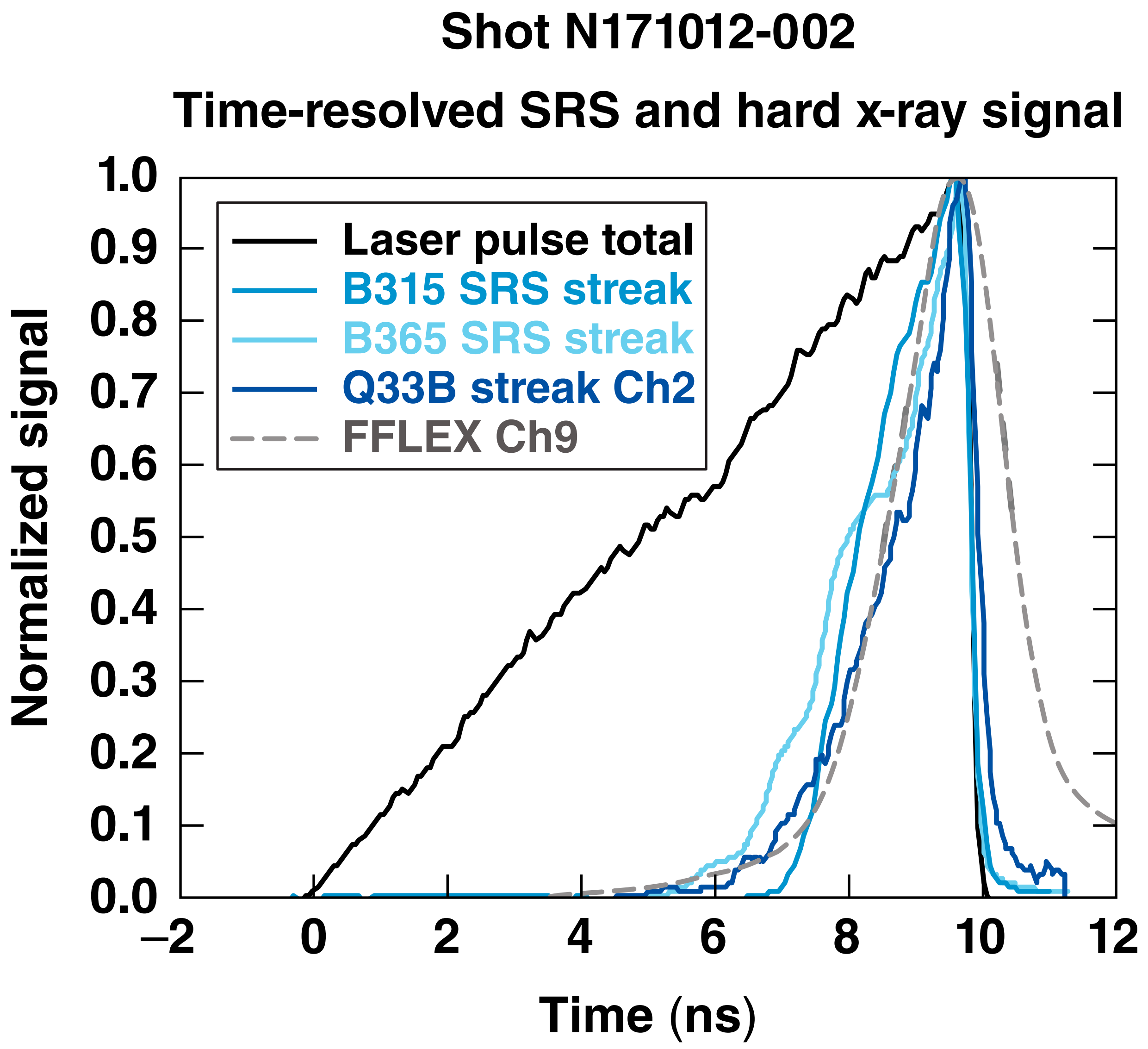
OMEGA spherical
experiment (TPD)

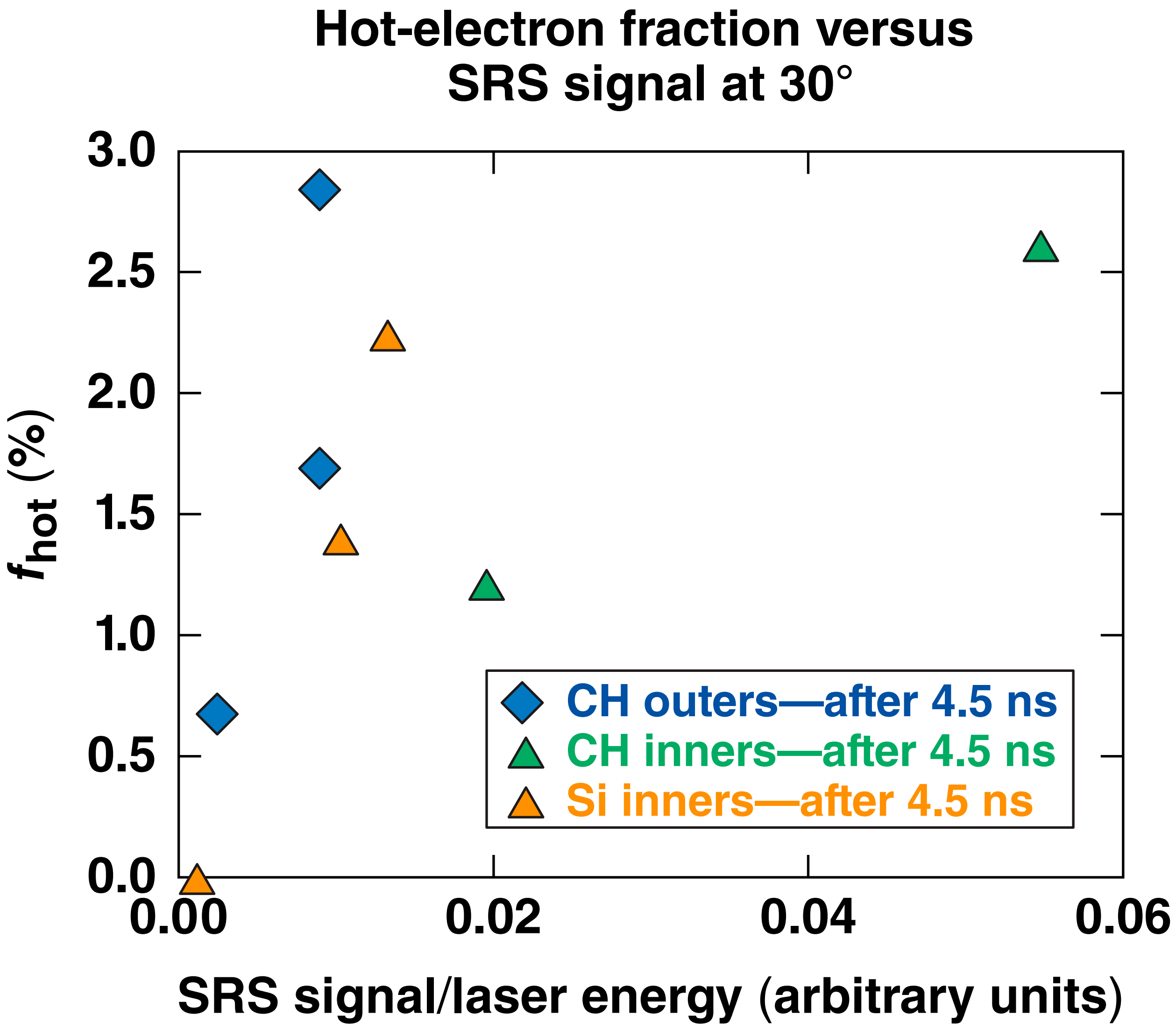


On the NIF, ~5% of laser energy is converted to SRS, consistent with the observed hot-electron fraction and suggestive of SRS being the dominant hot-electron source, although this does not rule out the presence of TPD.

M. Rosenberg *et al.*, Phys. Rev. Lett. 120, 055001 (2018).
*W. Seka *et al.*, Phys. Plasmas 16, 052701 (2009).

SRS observations correlate with hard x-ray measurements



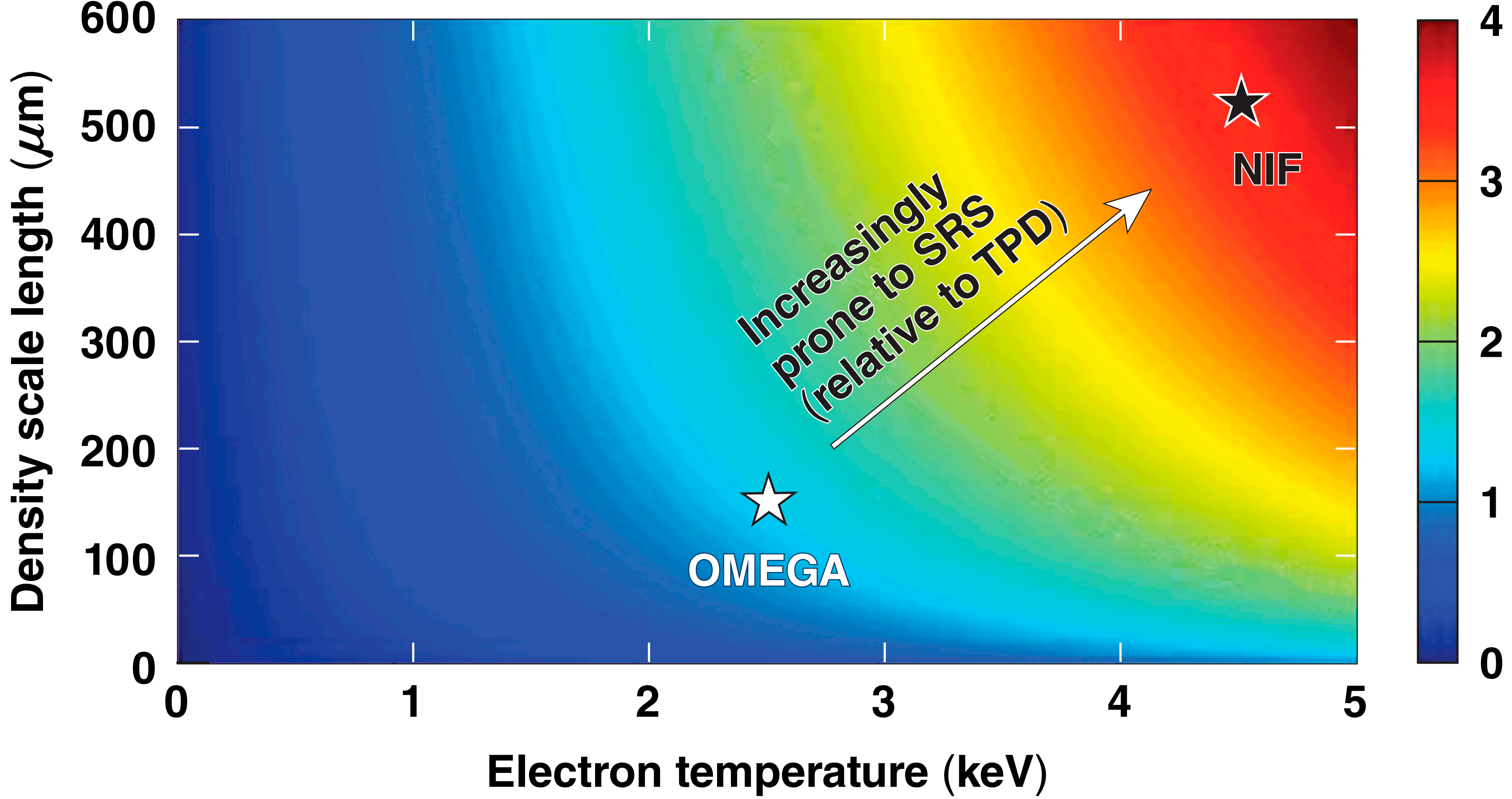


E27531

The dominance of SRS at the NIF scale may be partially explained by evaluating the absolute thresholds of SRS versus TPD

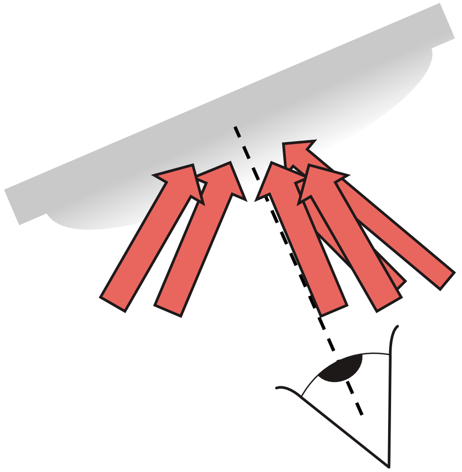
Ratio of absolute TPD and SRS thresholds

$(I_{\mathrm{thr,TPD}}/I_{\mathrm{thr,SRS}})$



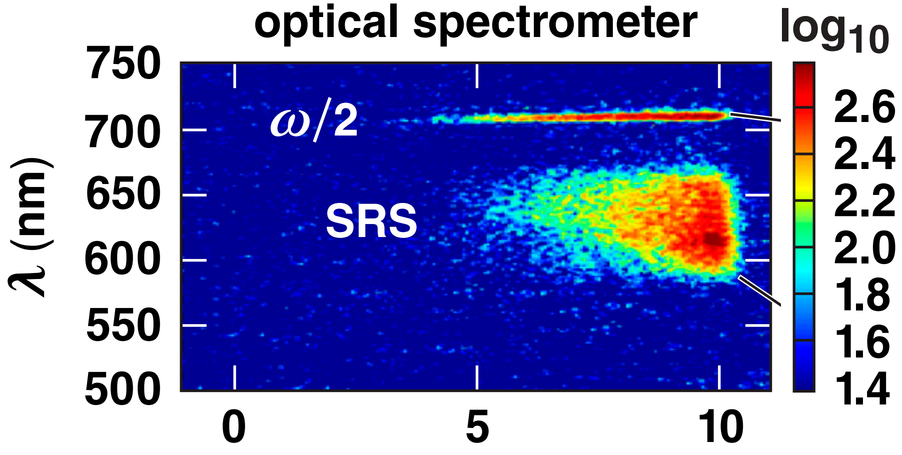
M. Rosenberg *et al.* Phys. Rev. Lett. 120, 055001 (2018).

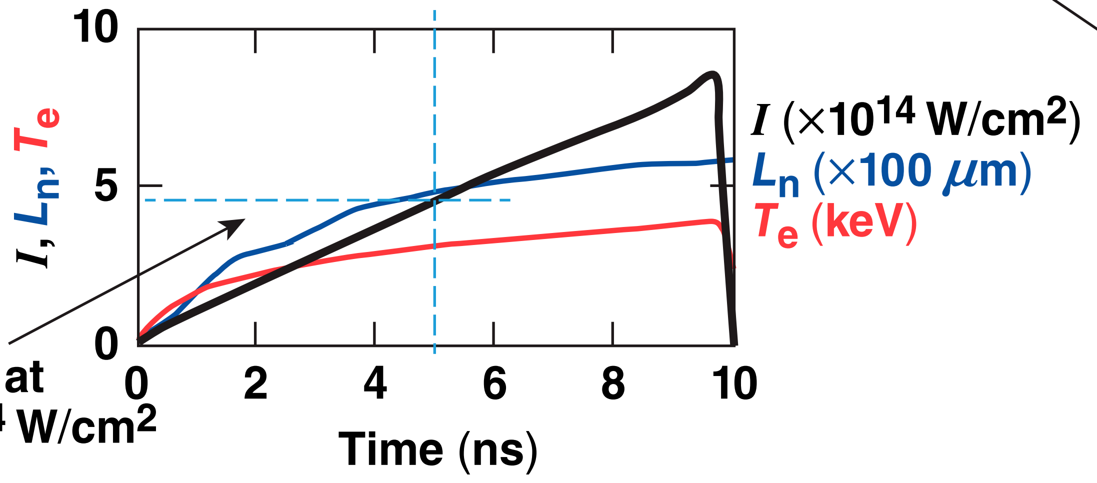
Ramp-pulse experiments show thresholds and growth of both unsaturated “convective” SRS and saturated absolute SRS



Optical streaked spectrometer (NBI Q33B)

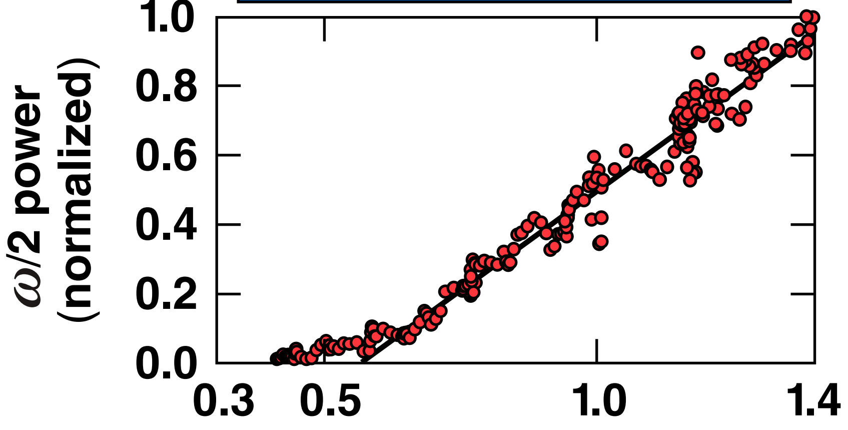
Shot N161010-004 optical spectrometer

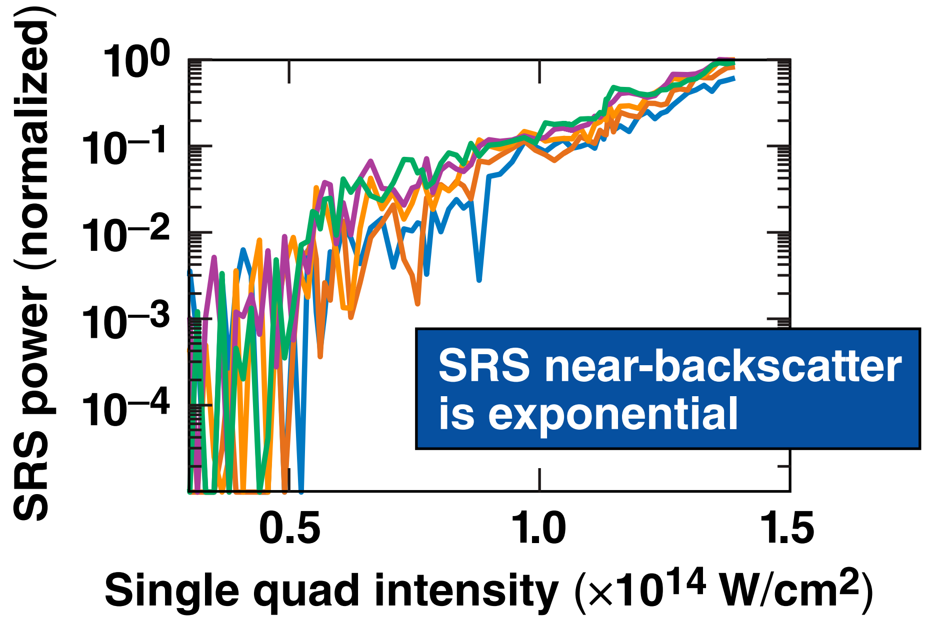




SRS onset at $I_{n_c/4}$ ~ 4.5×10^{14} W/cm^2

$\omega/2$ is linear—saturated absolute SRS instability

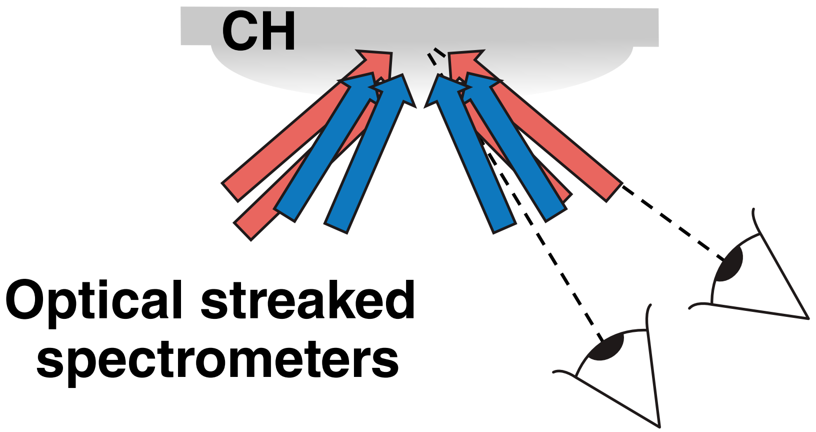


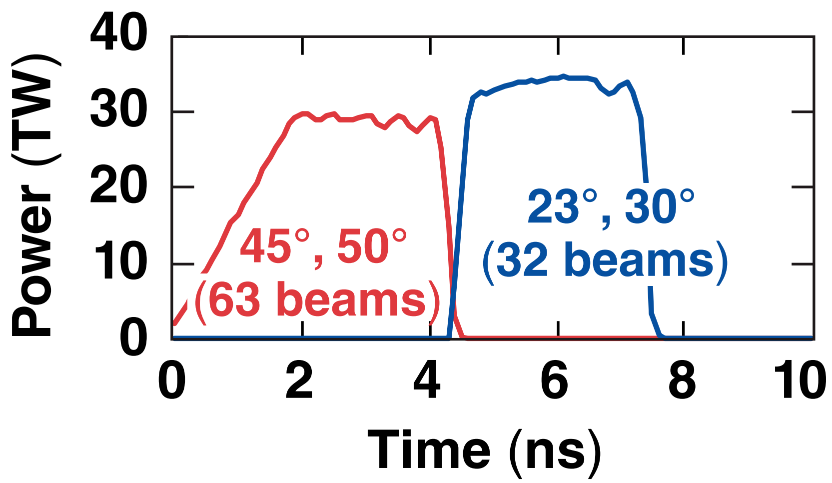


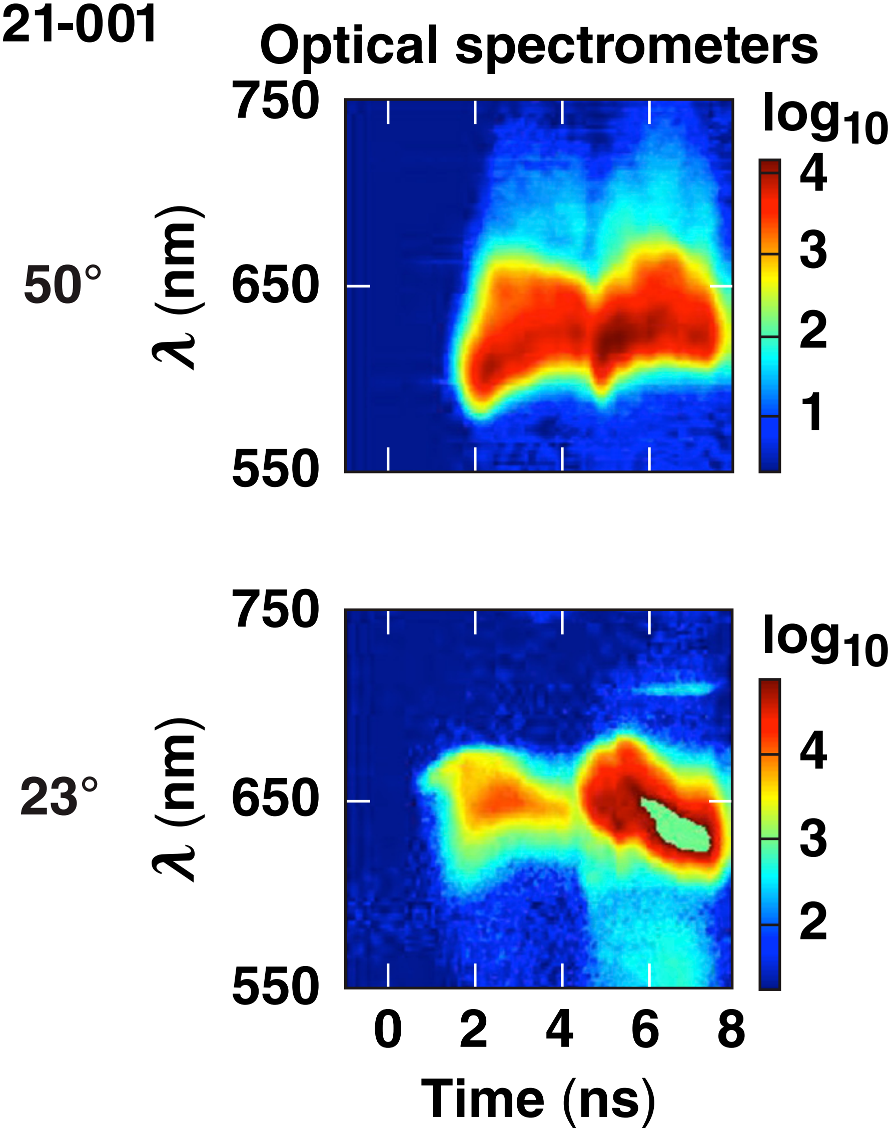
SRS near-backscatter is exponential

Sidescatter is observed as one of several SRS mechanisms

Shot N160421-001



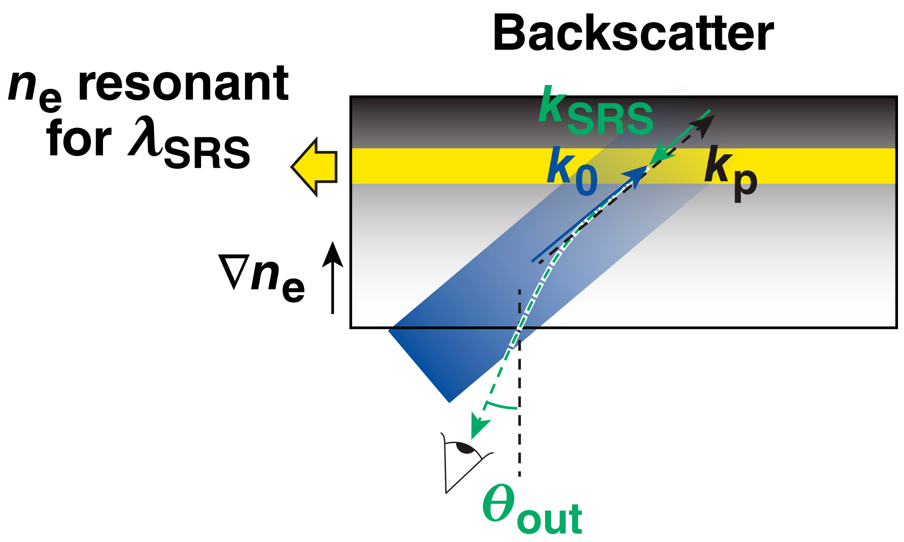


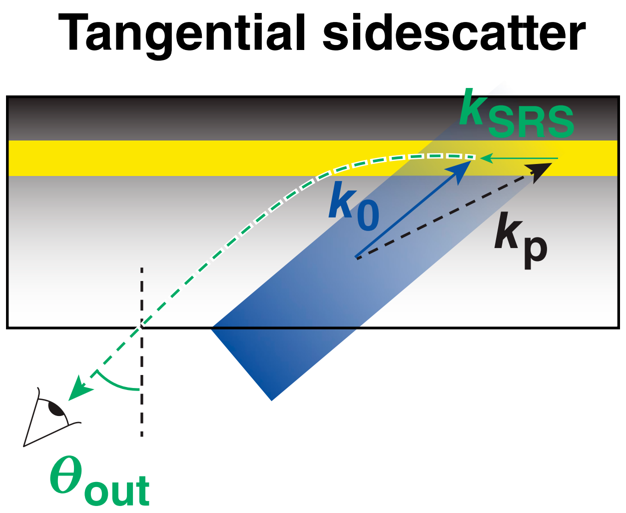


Observation at 50° can only be sidescatter.

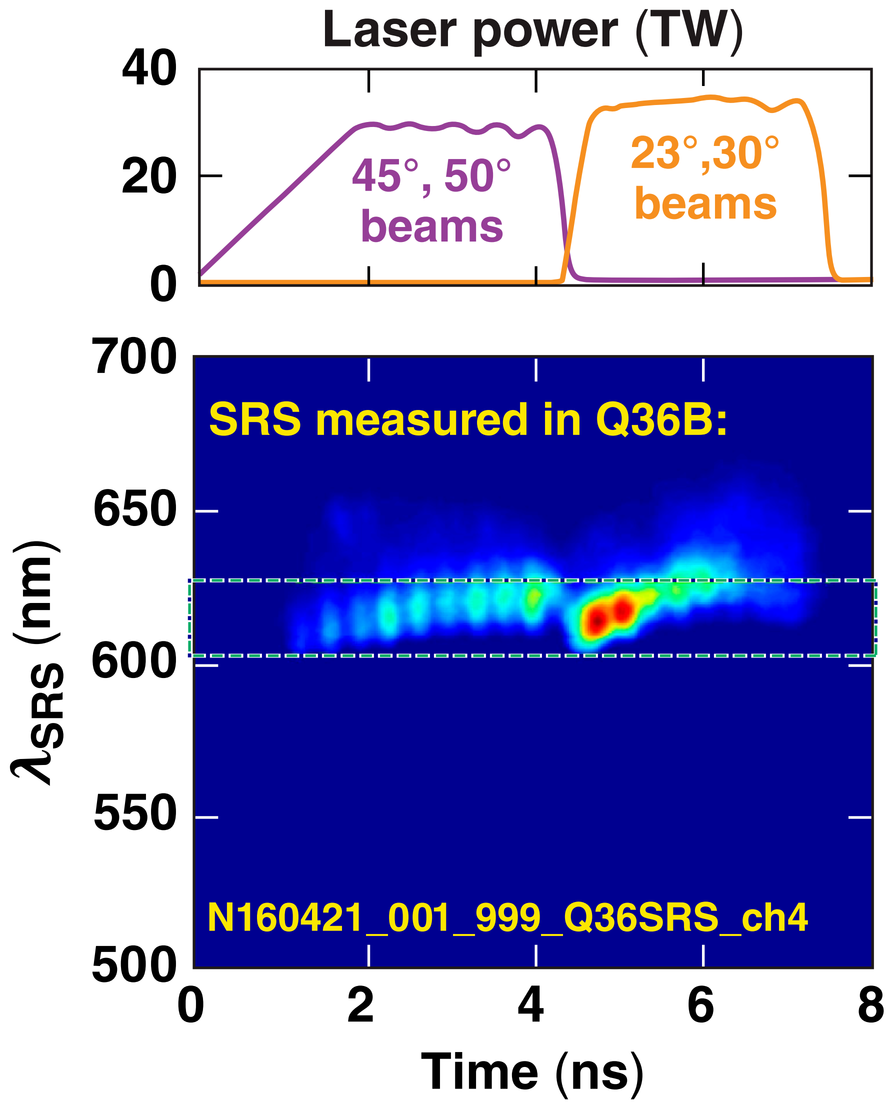
M. Rosenberg *et al.* Phys. Rev. Lett. 120, 055001 (2018).

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



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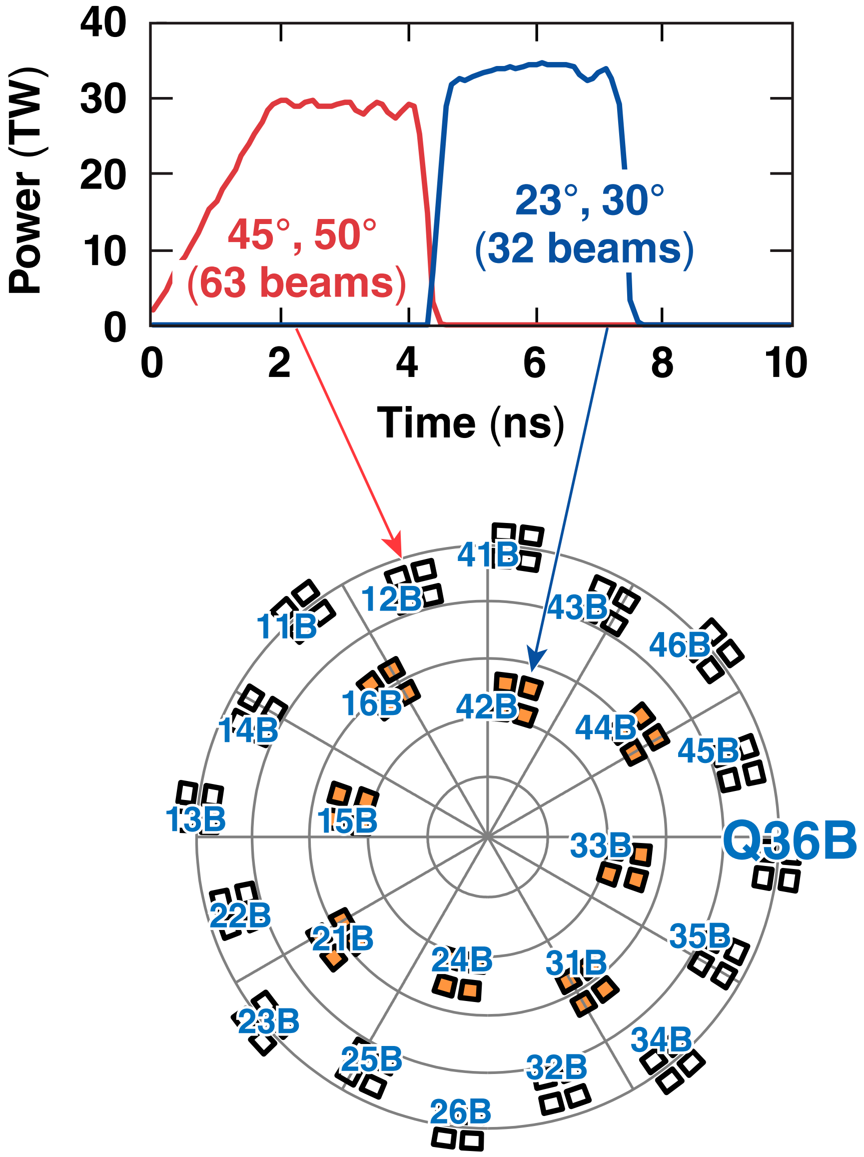
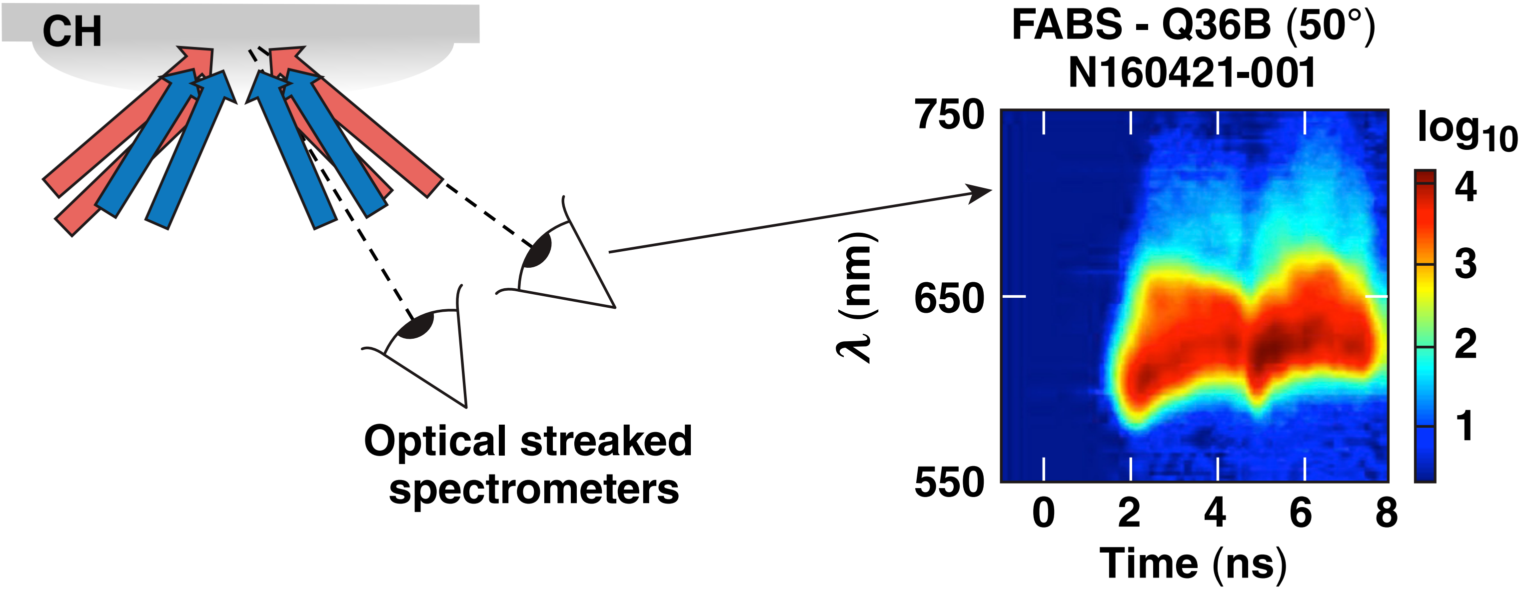
*P. Michel *et al.*, "Measurements and Modeling of Raman Side-Scatter in Inertial Confinement Fusion Experiments," submitted to Physical Review Letters.

E26063c

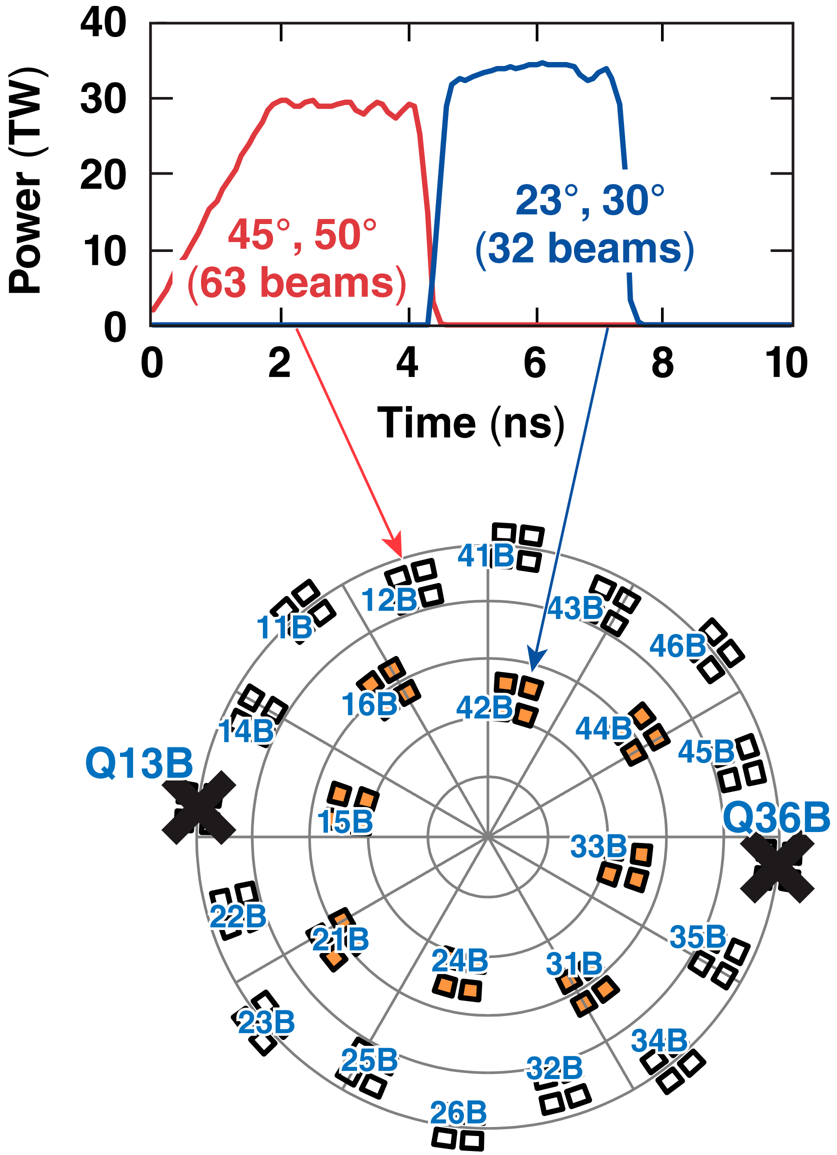
Single-beam and potential multibeam SRS effects have been identified in experiments with beams selectively turned off

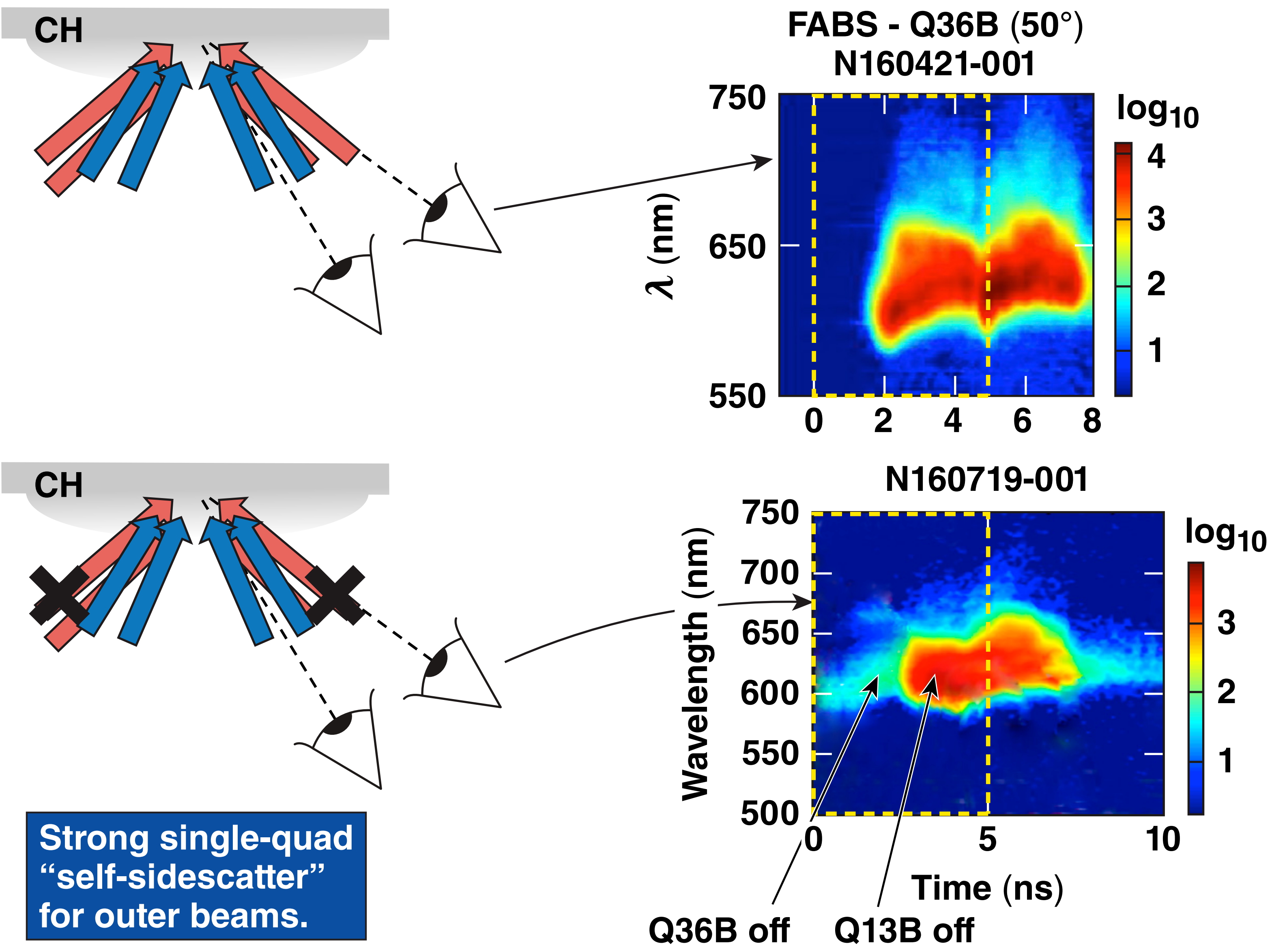




FABS: full-aperture backscatter stations

Single-beam and potential multibeam SRS effects have been identified in experiments with beams selectively turned off





Strong single-quad "self-sidescatter" for outer beams.

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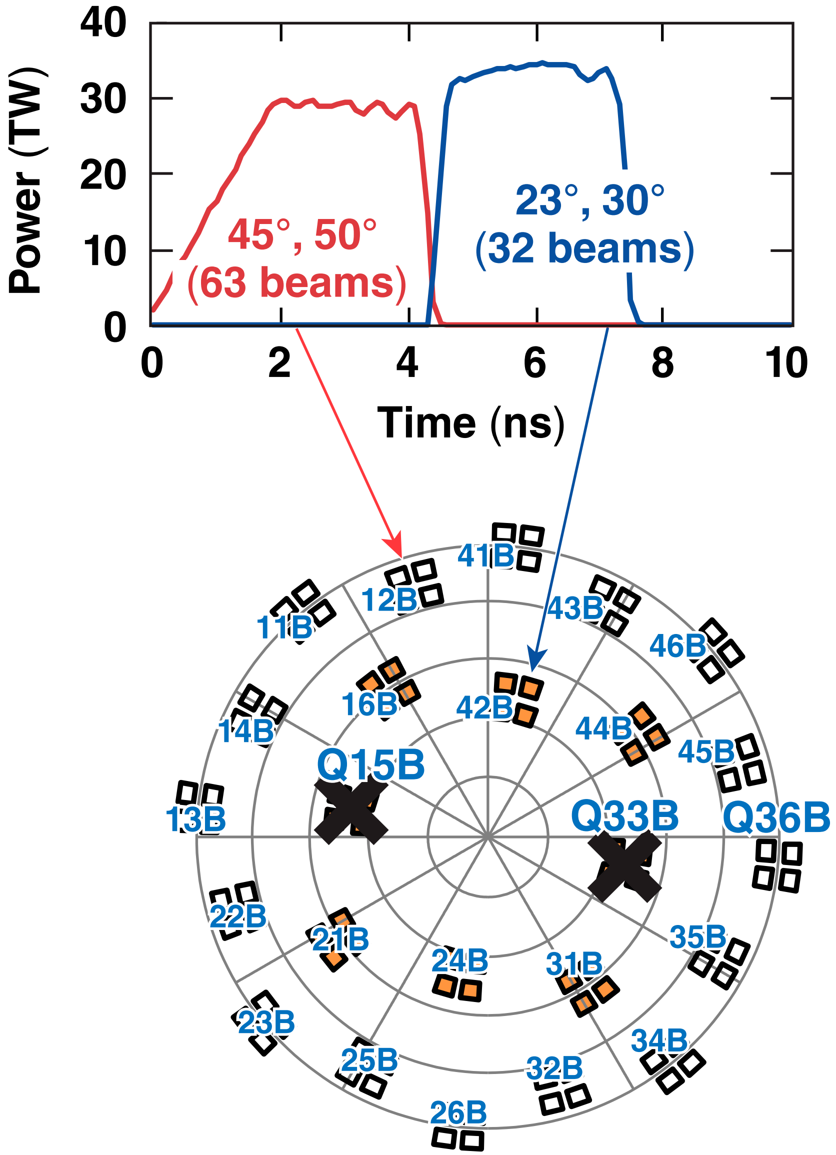
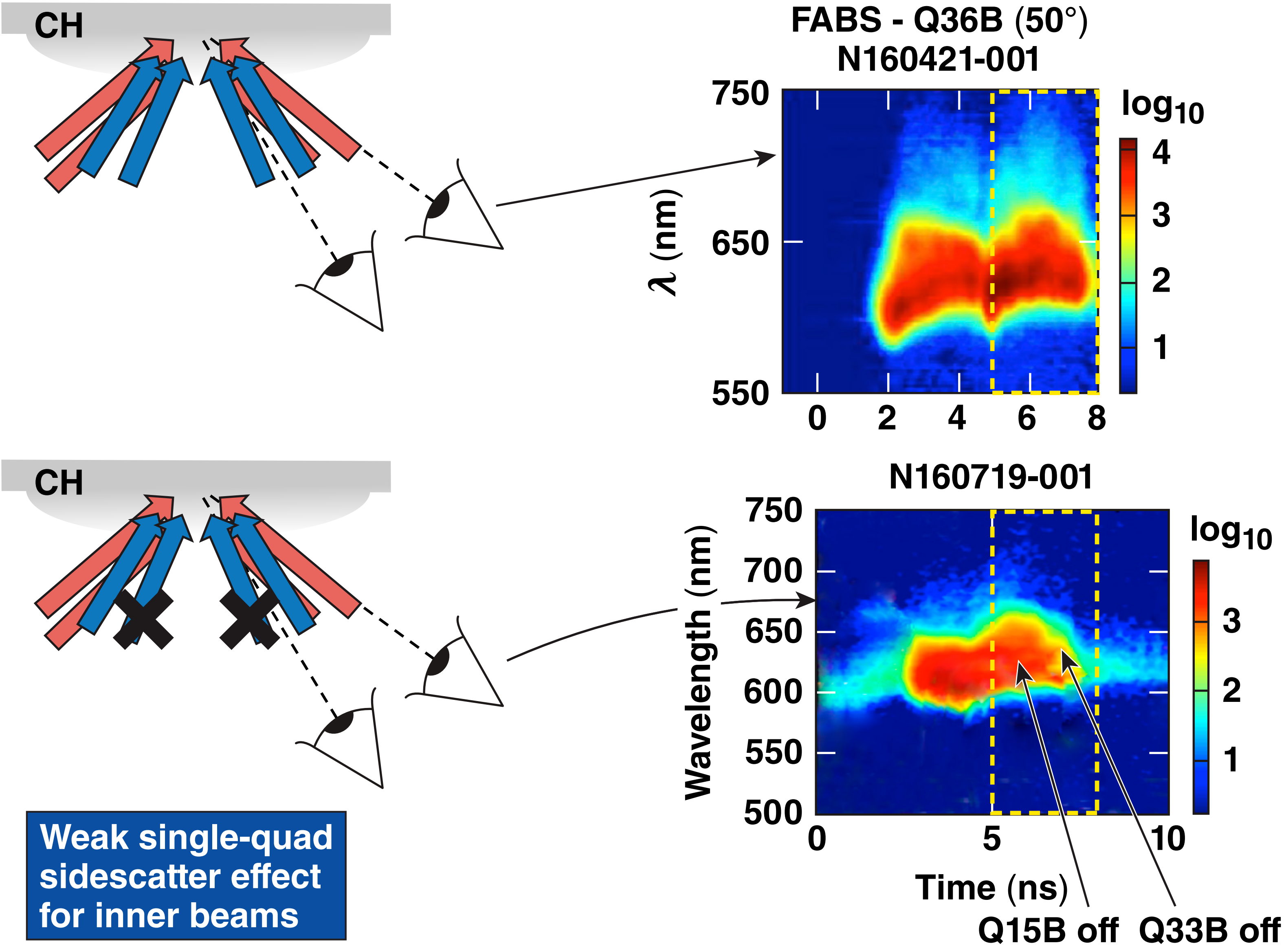
Single-beam and potential multibeam SRS effects have been identified in experiments with beams selectively turned off

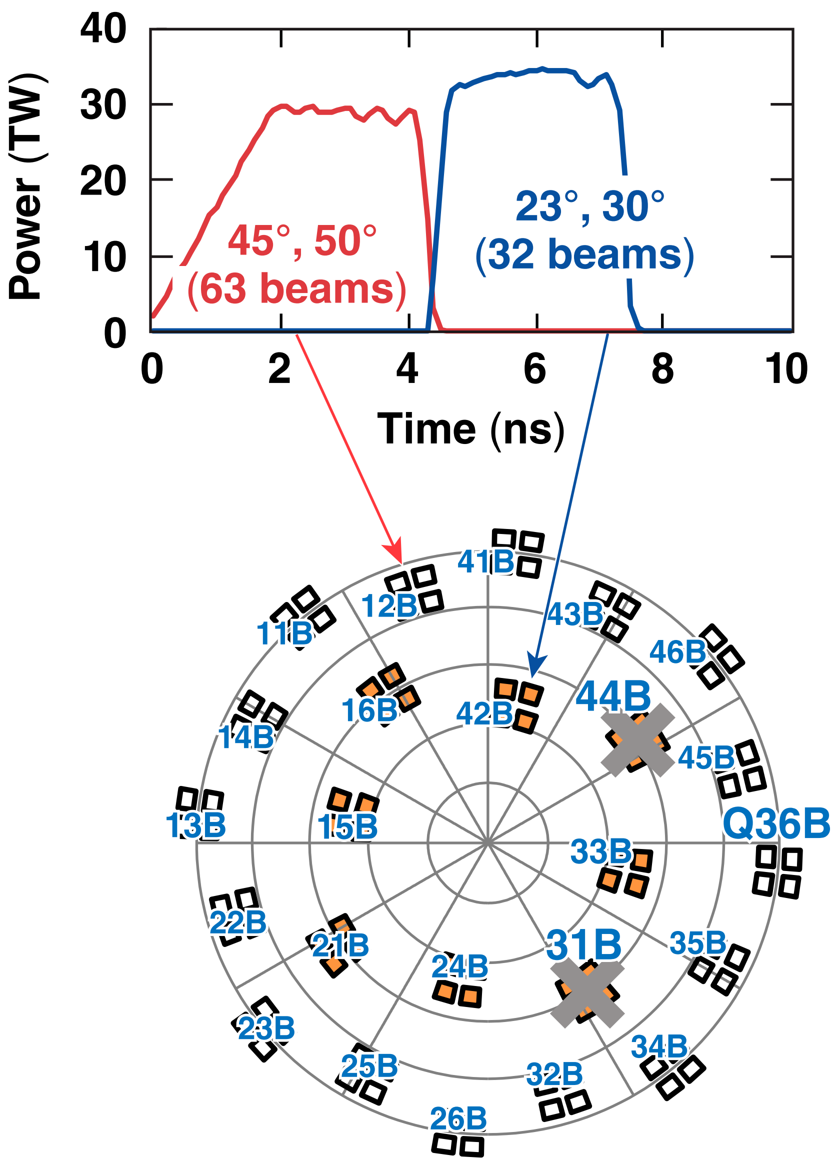


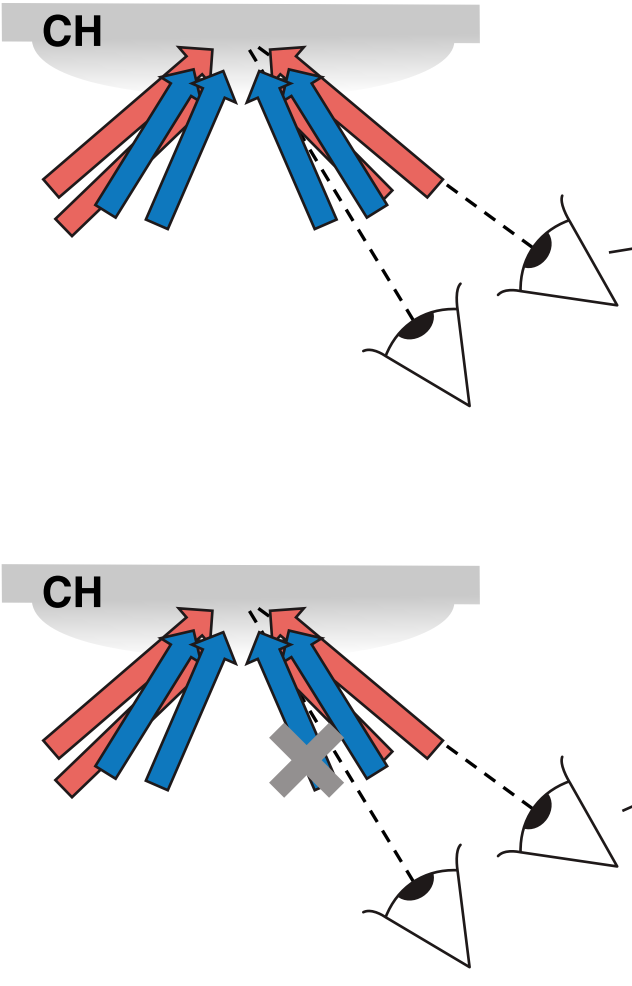


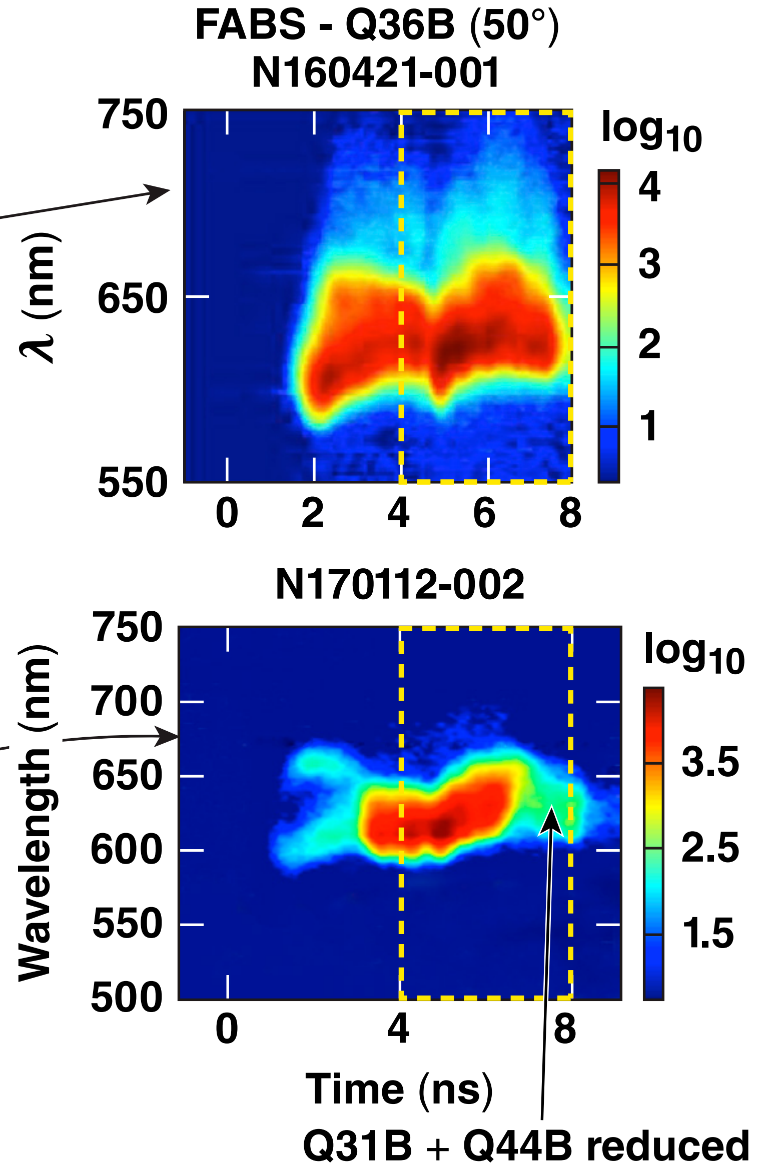
Weak single-quad sidescatter effect for inner beams

E27566b

Single-beam and potential multibeam SRS effects have been identified in experiments with beams selectively turned off



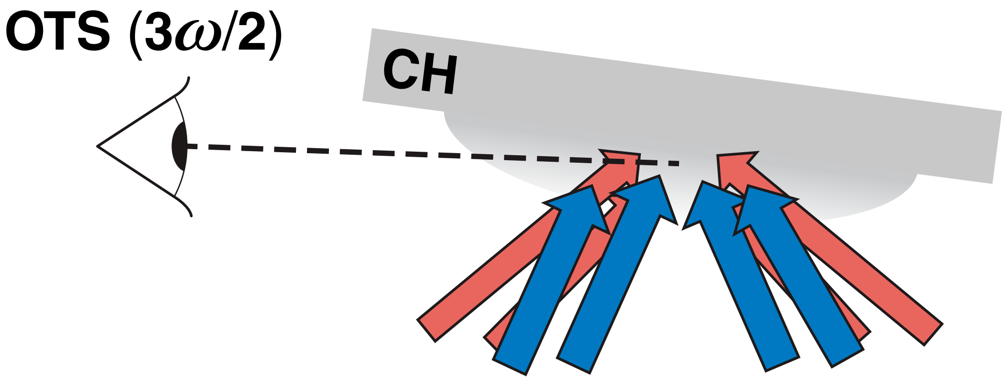


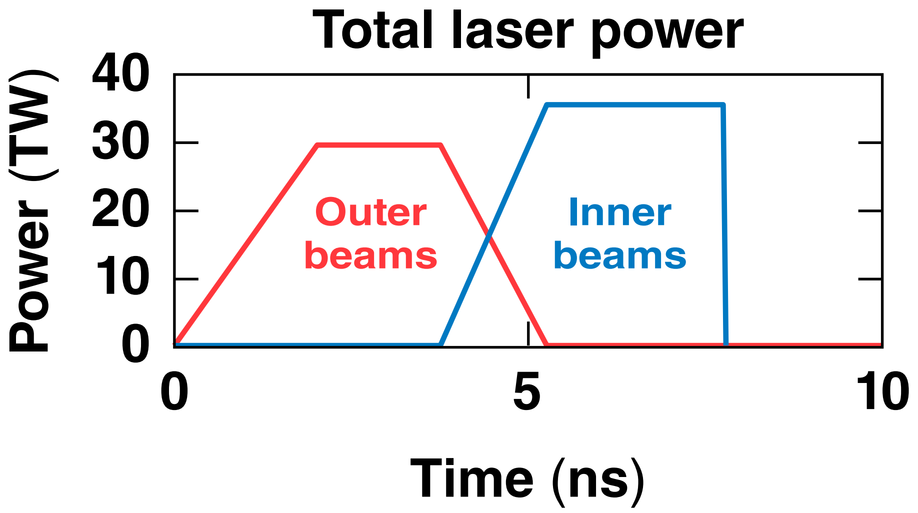


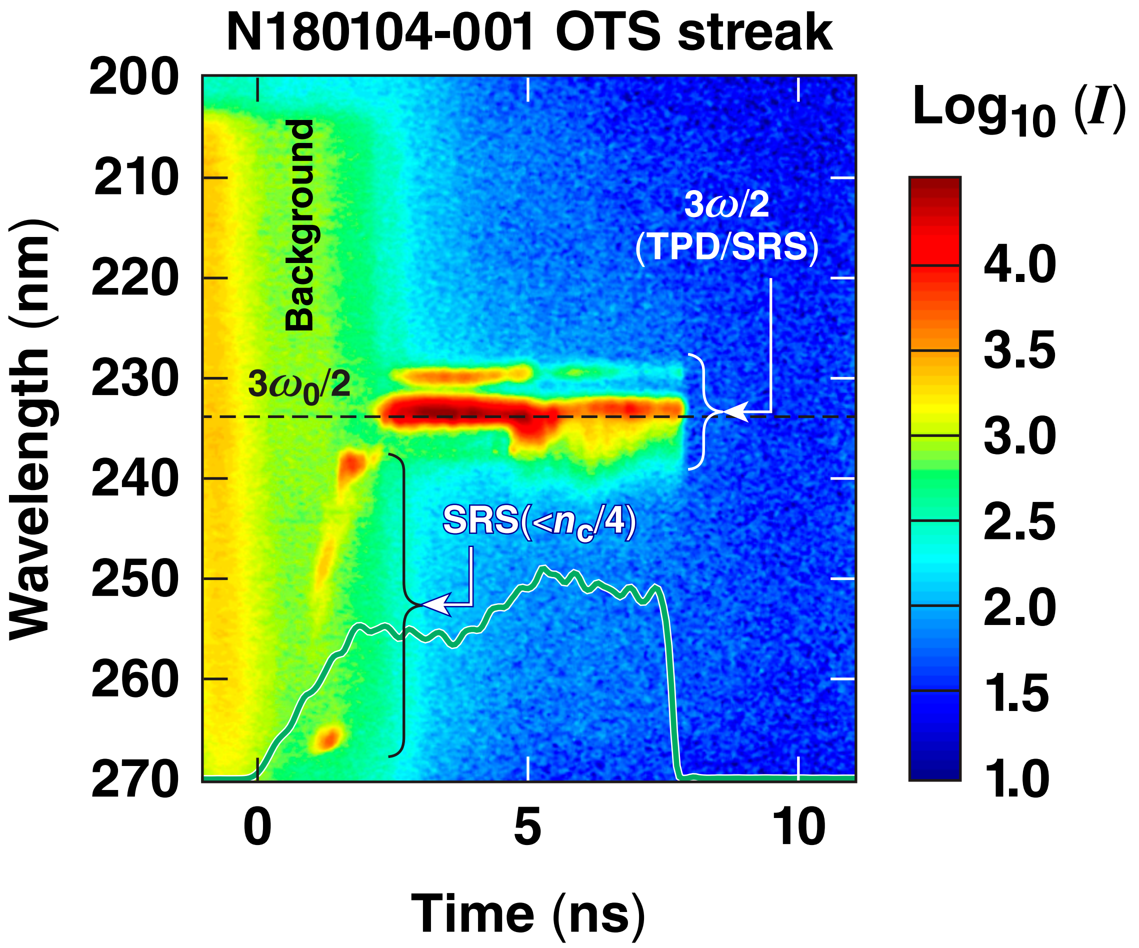
Sidescatter of inner beams into 50° view mainly from near-neighboring azimuth quads.

E27567

In addition, recent experiments diagnosed 3ω/2 emission, which revealed evidence of TPD





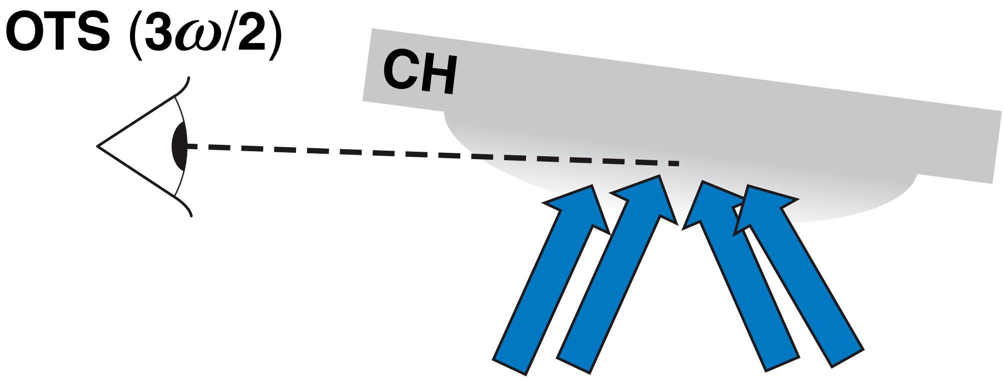


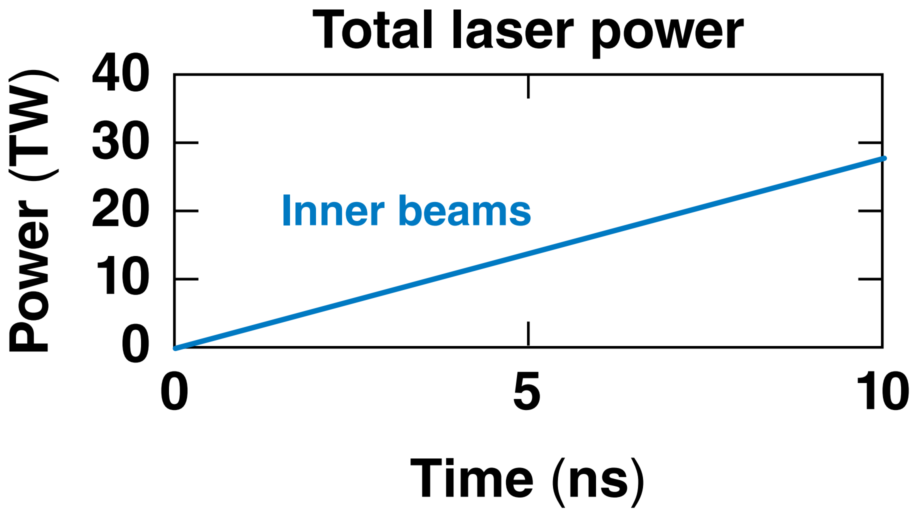
The 3ω/2 doublet is suggestive of some TPD activity, although this is consistent with a SRS-dominated regime.

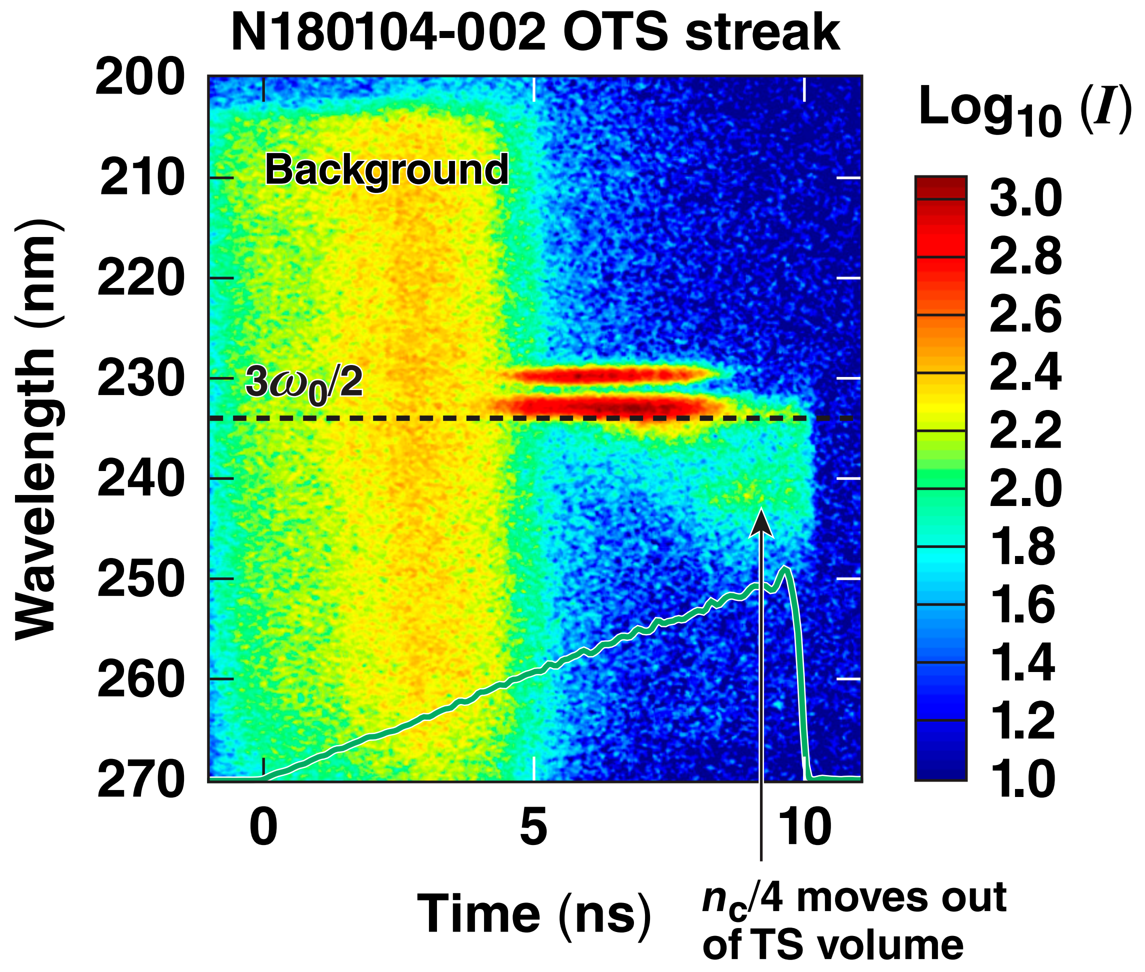
E27532

OTS: optical Thomson scattering

In addition, recent experiments diagnosed $3\omega/2$ emission, which revealed evidence of TPD





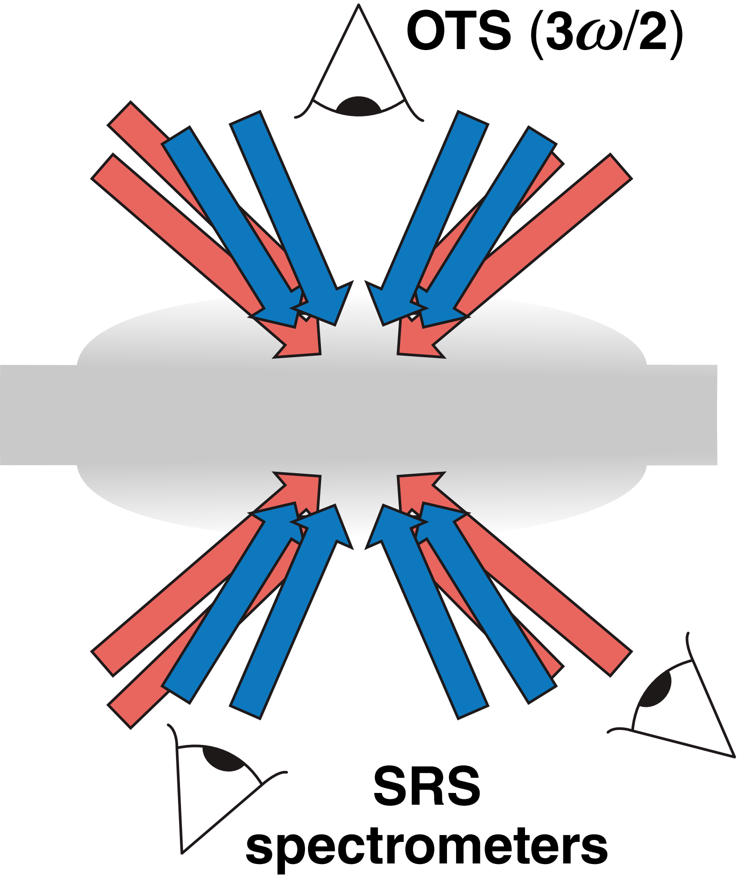


Caveat: observed scattered $3\omega/2$ light is sensitive to hydrodynamics.

E27568

The next planar experiments will measure 3ω/2 along target normal to determine the prevalence of absolute and convective SRS/TPD instabilities

June and October 2018 experiments



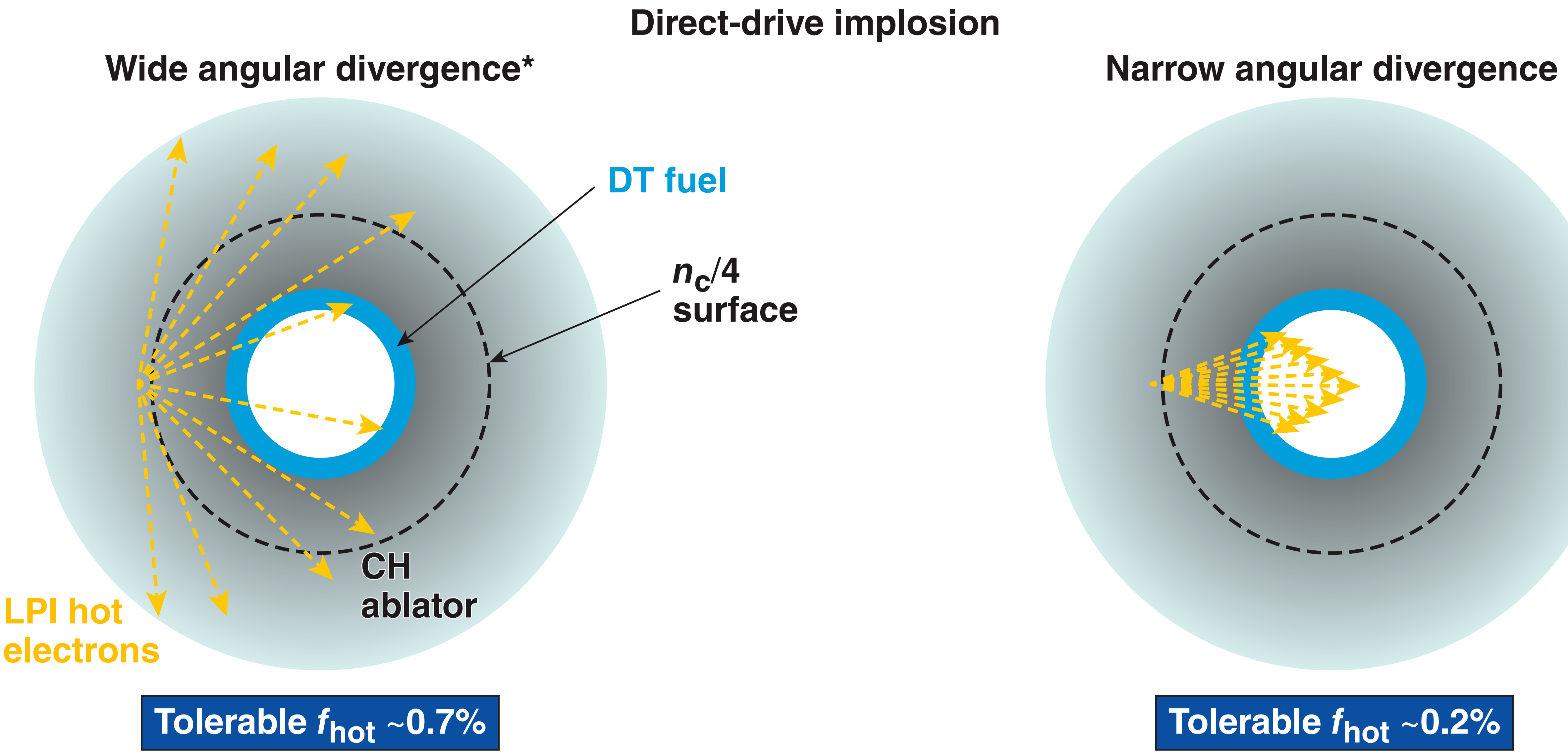
The 3ω/2 measurement along target normal will provide access to plasma waves at all densities at all times

Knowledge of where the dominant LPI is occurring is critical for mitigation (if needed).

Outline

- Motivation for direct-drive LPI experiments on the NIF and planar platform development
- Hot-electron results and LPI mechanisms: Predominantly SRS
- **Future work: Hot-electron coupling**

Reminder: The tolerable fraction of hot electrons generated (f_{hot}) depends on how the electrons couple to an implosion



Tolerable f_{hot} ~0.7%

Tolerable f_{hot} ~0.2%

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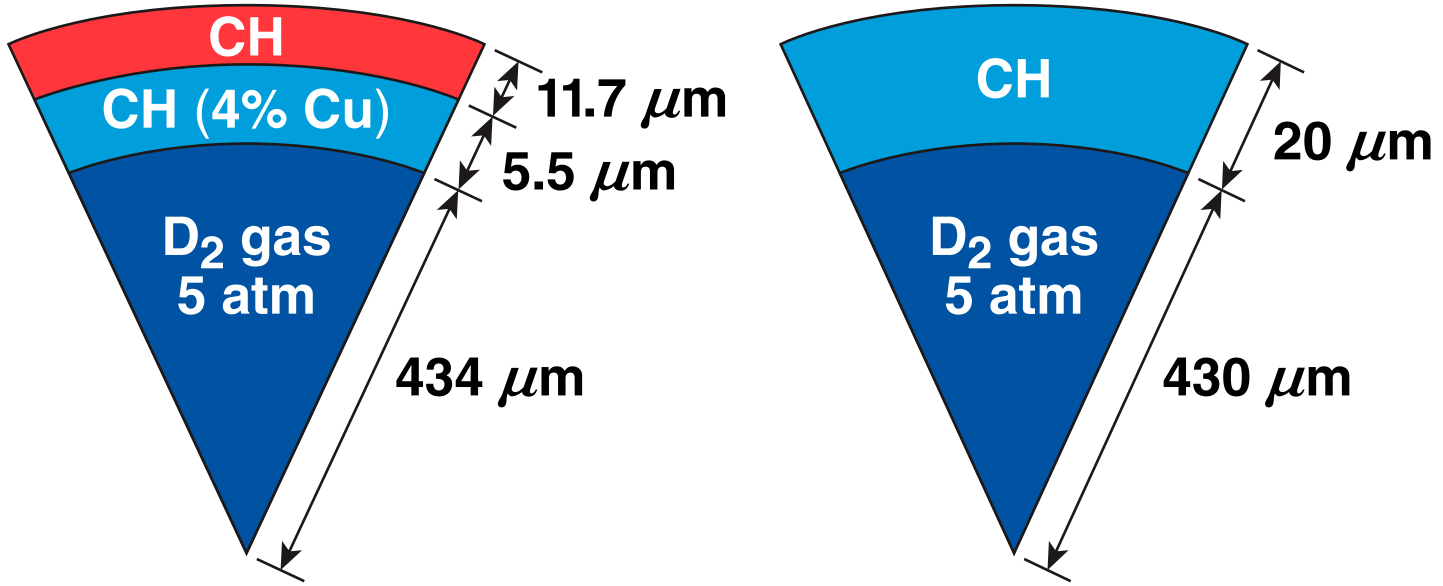
*OMEGA experiments described in B. Yaakobi *et al.*, Phys. Plasmas 20, 092706 (2013).

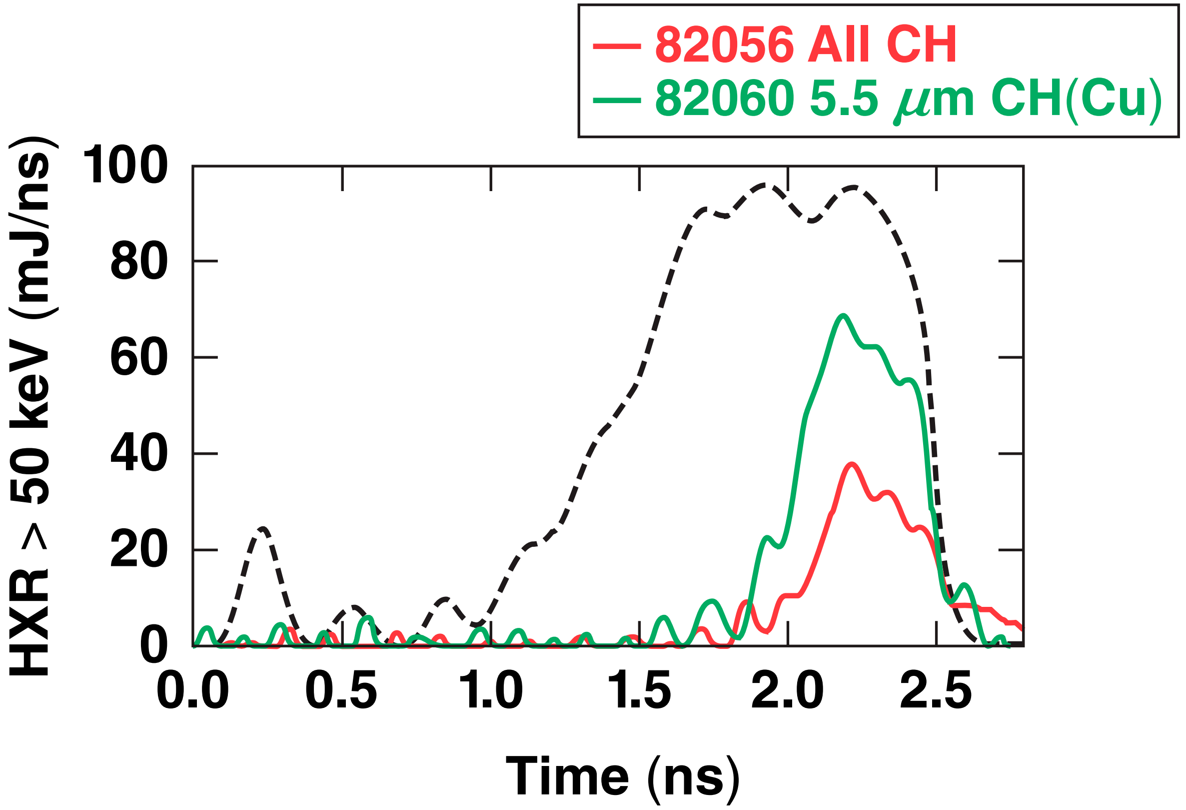
E27569

A spherical-geometry platform was developed on OMEGA to diagnose coupling of hot electrons to an imploding shell

OMEGA target design



OMEGA experiment hard x-ray (HXR) data



Difference in HXR signals between mass-equivalent CH and multilayered implosions → hot-electron energy deposited in the inner shell layer.

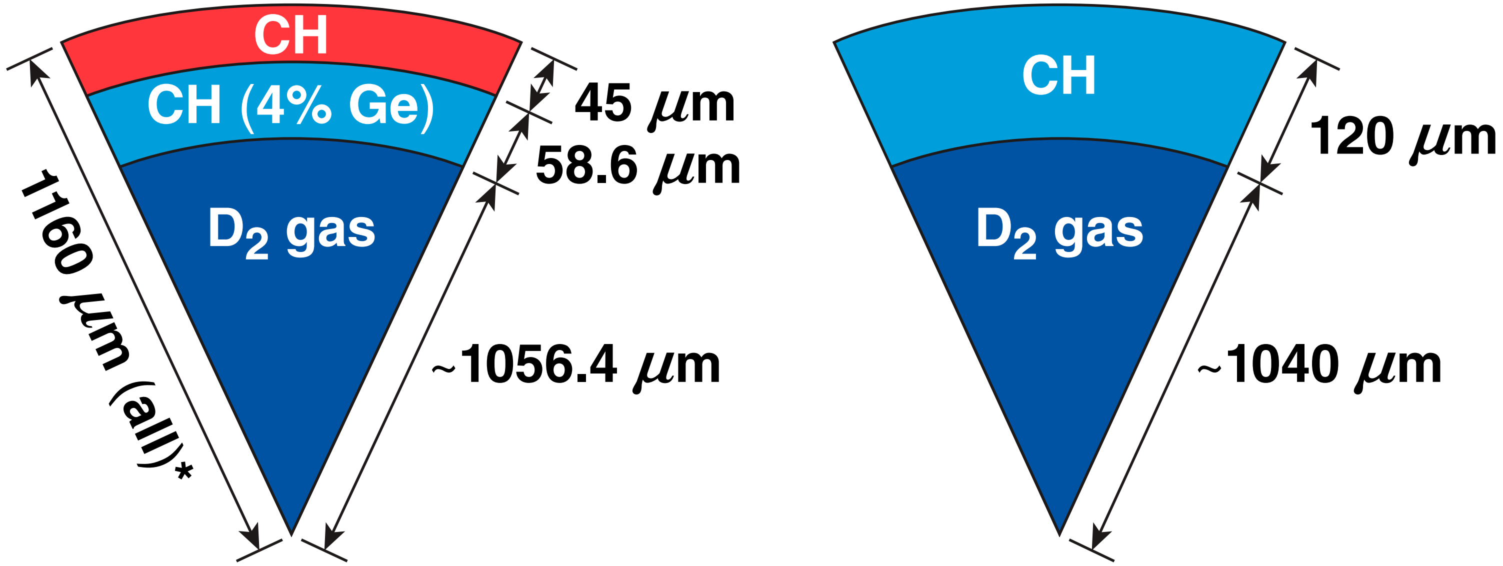
E27570

A. R. Christopherson *et al.*, Bull. Am. Phys. Soc. 61, BAPS.2016.DPP.NO5.7 (2016).

This platform is being adapted to the NIF in order to determine hot-electron coupling in a different LPI regime at longer scale lengths

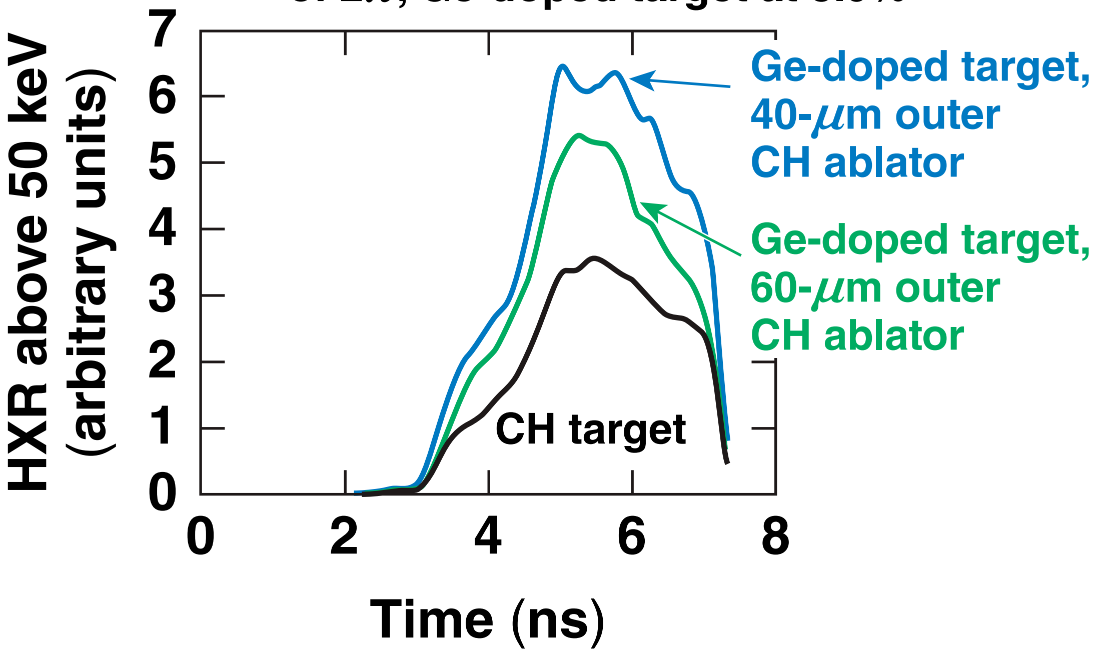
Experiments in September 2018 and March 2019

NIF target designs



Predicted NIF hard x-ray data

LILAC simulations for T_{hot} = 55 keV, hot-electron divergence full angle of 2π, Ge-doped target at 3.9%



Hot-electron energy coupled to an implosion constrains usable laser intensities in direct-drive ignition designs.

E27049b

Summary/Conclusions

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

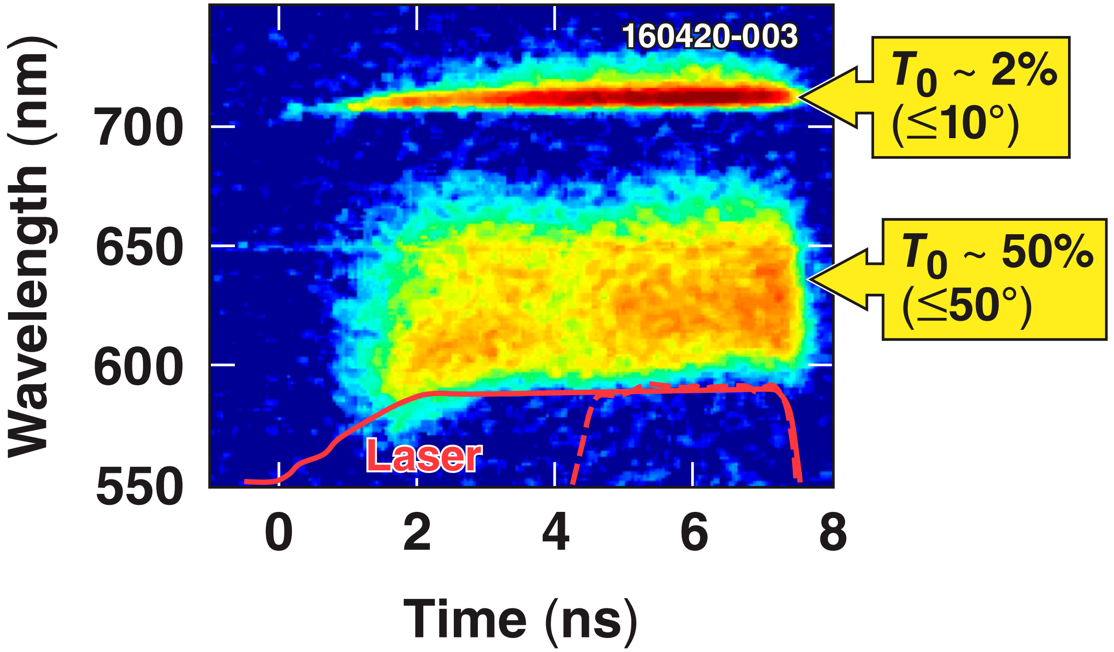
- Experiments achieve scale lengths of $L_n \sim 400$ to $700\ \mu$m, electron temperatures of $T_e \sim 3$ to 5 keV, and laser intensities of 0.5 to 1.5×10^{15} W/cm^2
- Hot-electron generation of the order of $f_{hot} \sim 0\%$ to 3% and $T_{hot} \sim 50$ keV have been observed
  - $I_{n_c/4} \sim 5 \times 10^{14}$ W/cm^2 may be acceptable for preheat
- Stimulated Raman scattering (SRS) is inferred to be the dominant LPI mechanism, although recent measurements ($3\omega/2$) have uncovered evidence of two-plasmon decay (TPD) as well
- Upcoming spherical experiments will diagnose hot-electron coupling (preheat) to an implosion

Overall: encouraging results (so far) for direct drive in a new LPI regime.

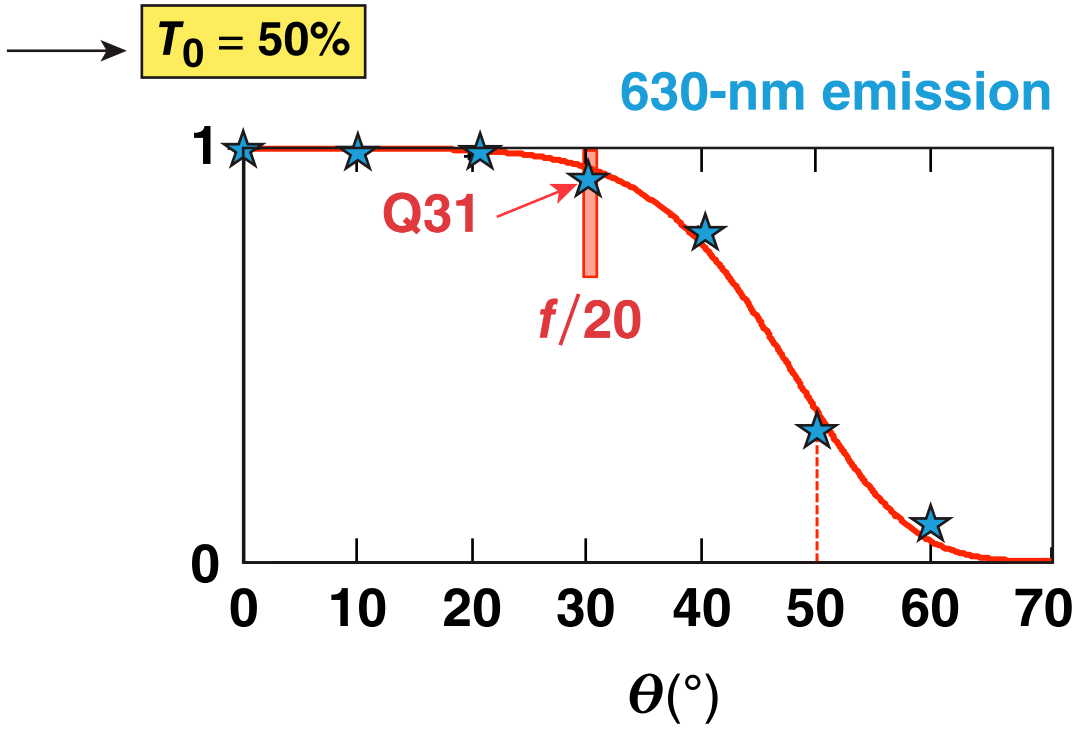
E27529

APPENDIX

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



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

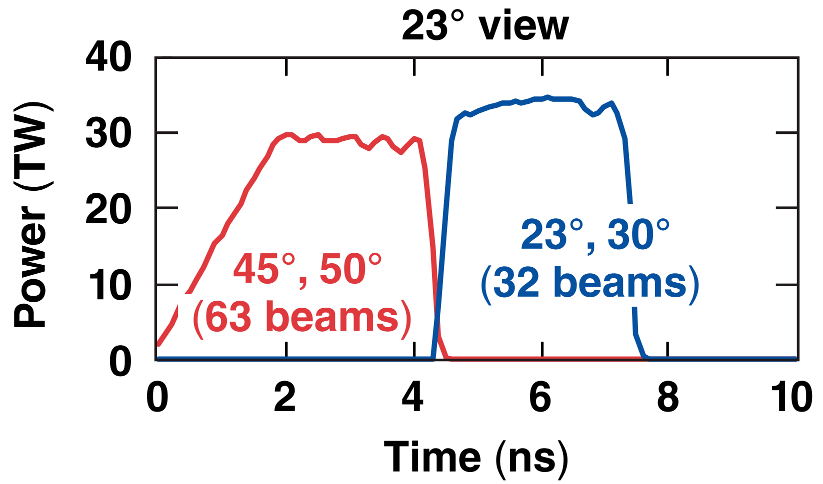


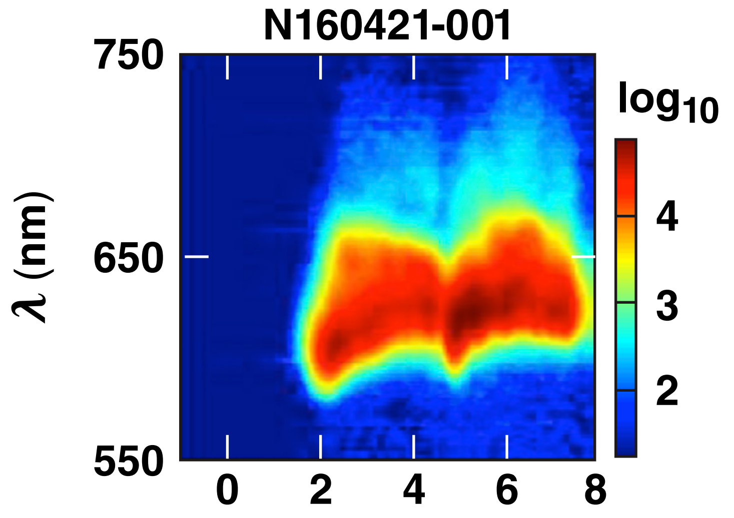
Approximately 5% of laser energy converted to SRS is consistent with the observed hot-electron fraction.

E26166b

W. Seka *et al.*, presented at the 47th Annual Anomalous Absorption Conference, Florence, OR, 11–16 June 2017.

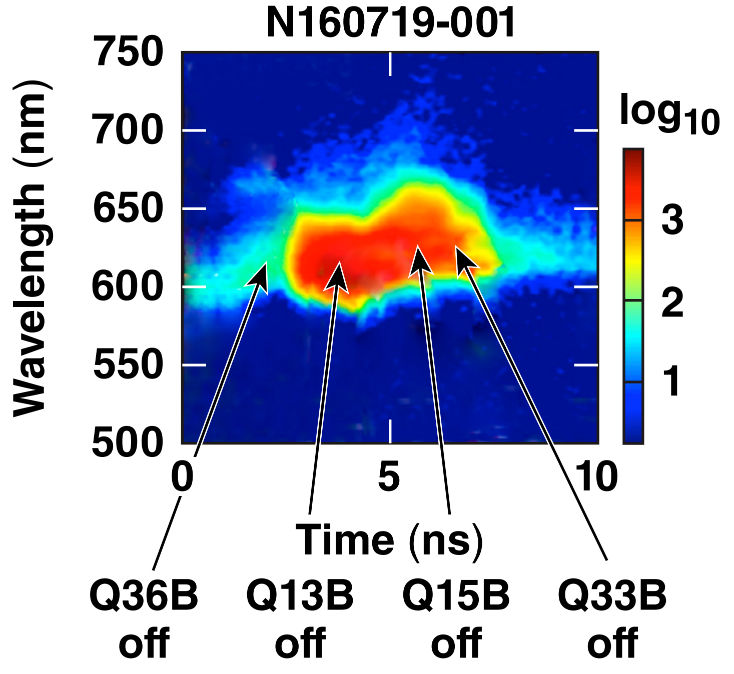
Various single-beam and potential multiple-beam effects have been identified in experiments with beams selectively turned off

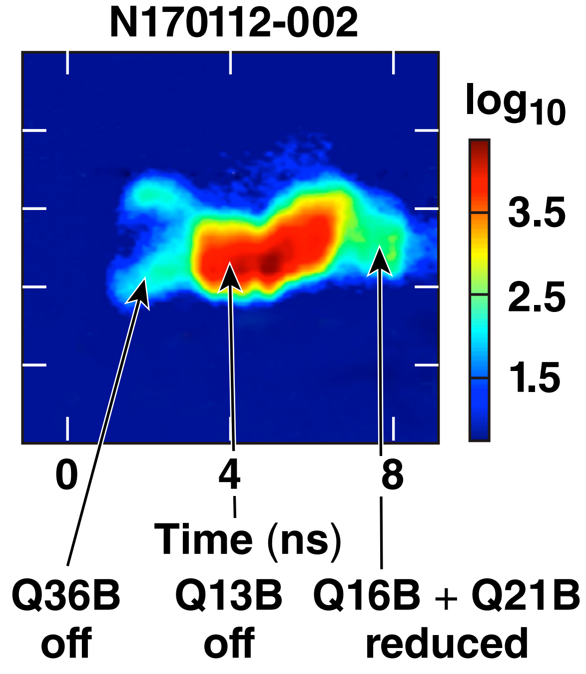




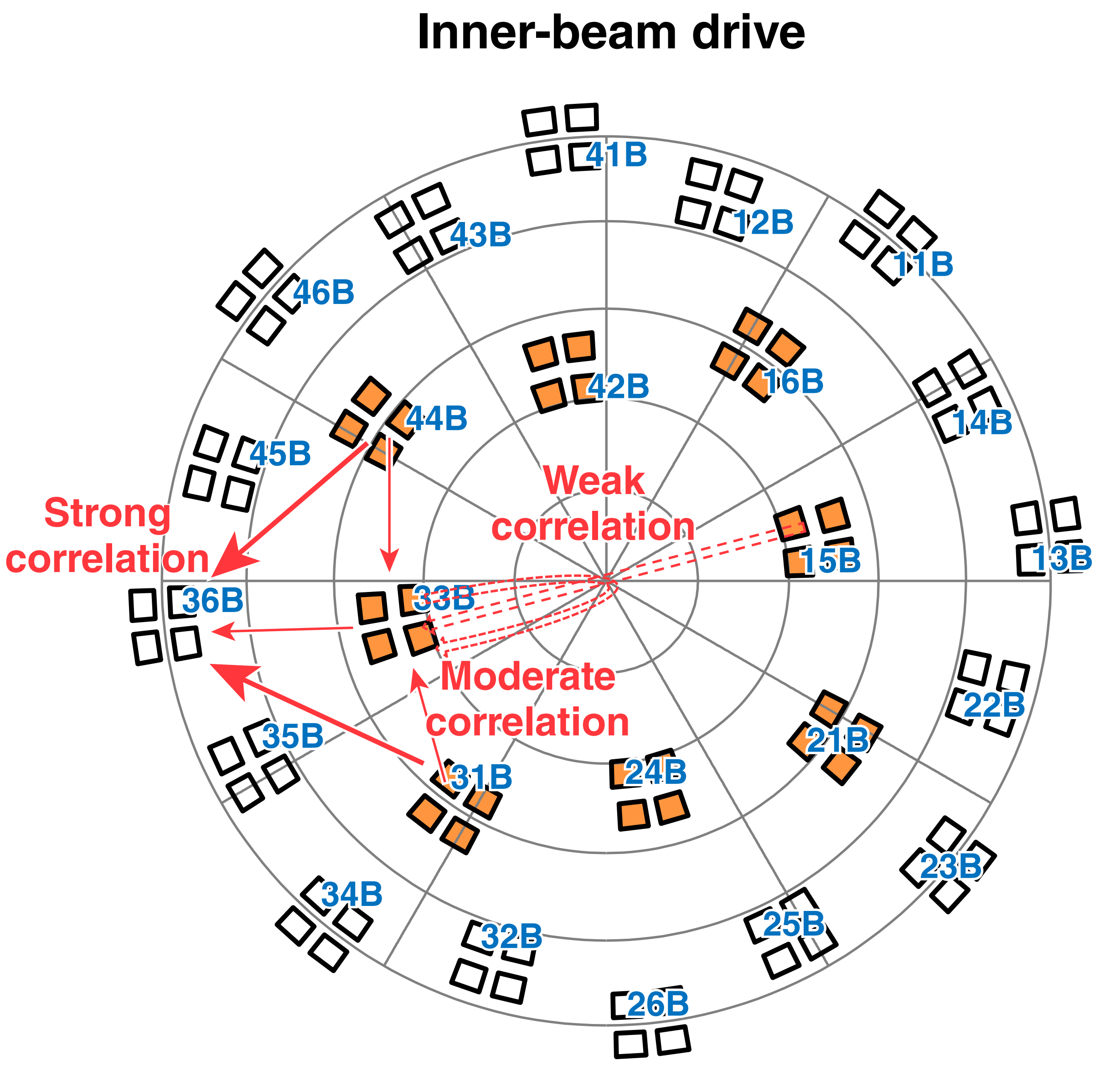
Neighboring quads have some (multibeam?) effect on inner-beam SRS.

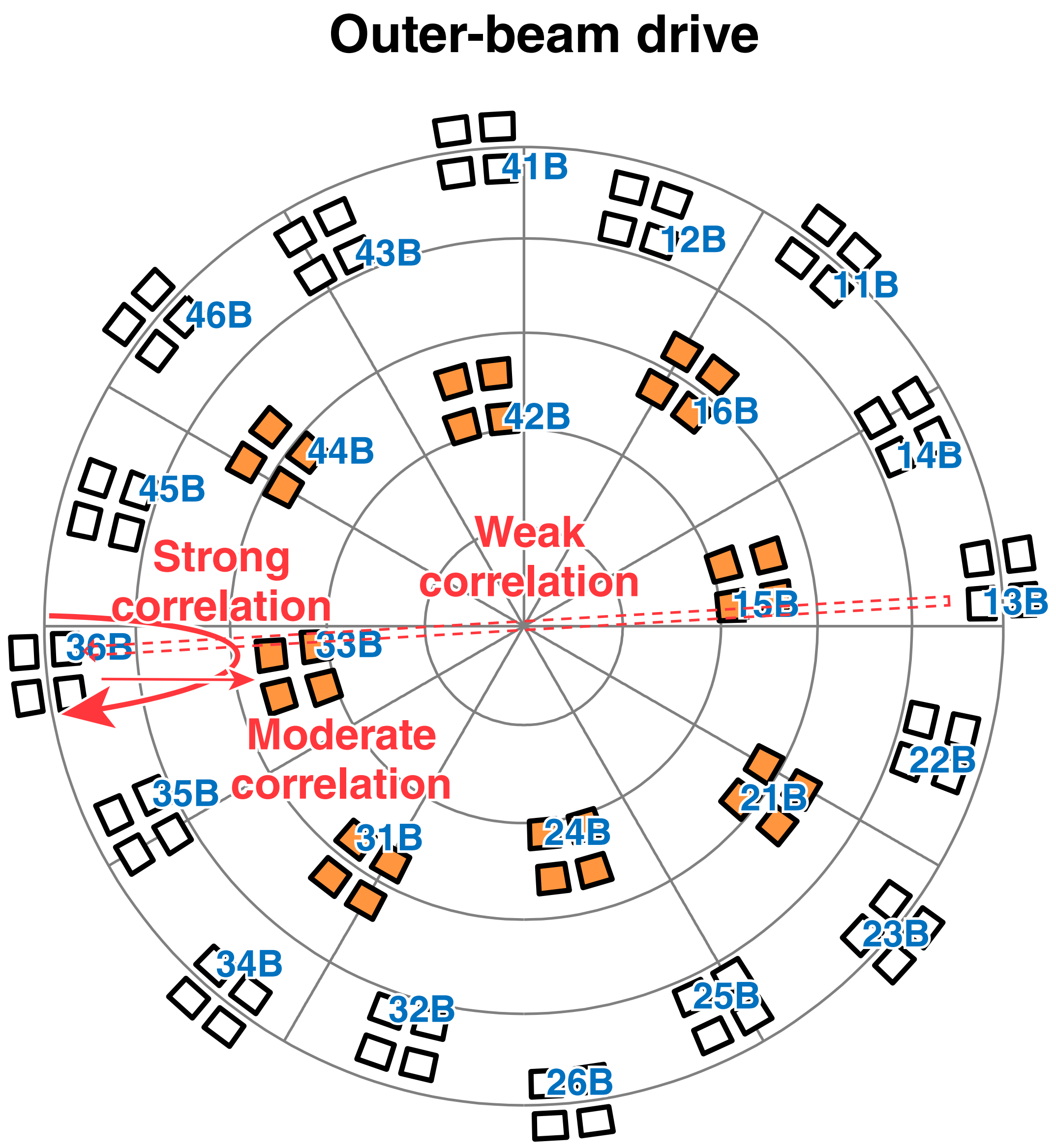
Some near-backscatter from outers refracted into the inner-beam location.





Various single-beam and potential multibeam effects have been identified in experiments with beams selectively turned off

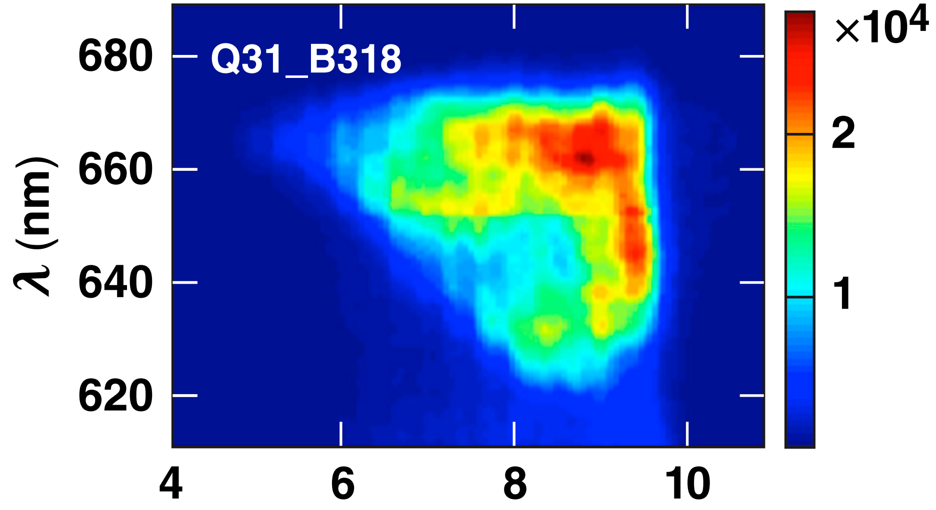




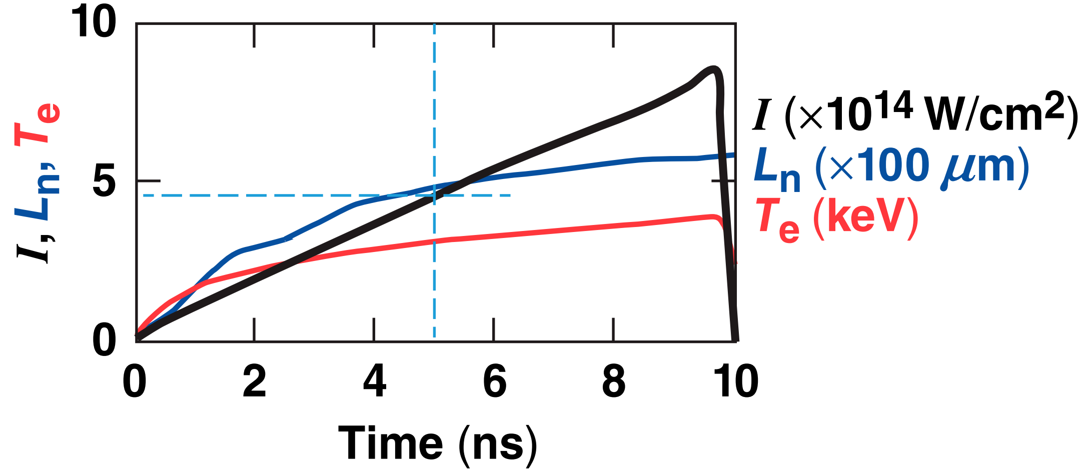
E27046a

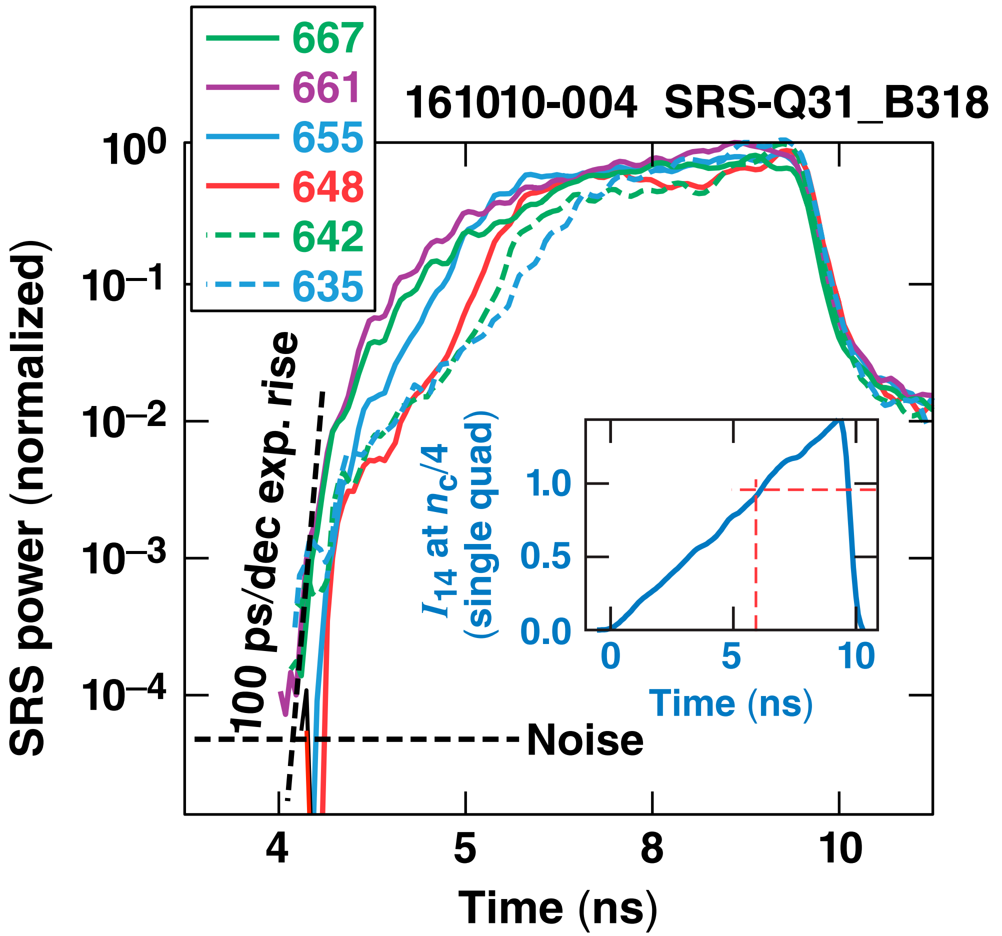
Ramp-pulse experiments show thresholds and growth of both non-saturated "convective" SRS and saturated absolute SRS

Shot N161010-004
optical spectrometer



21° view



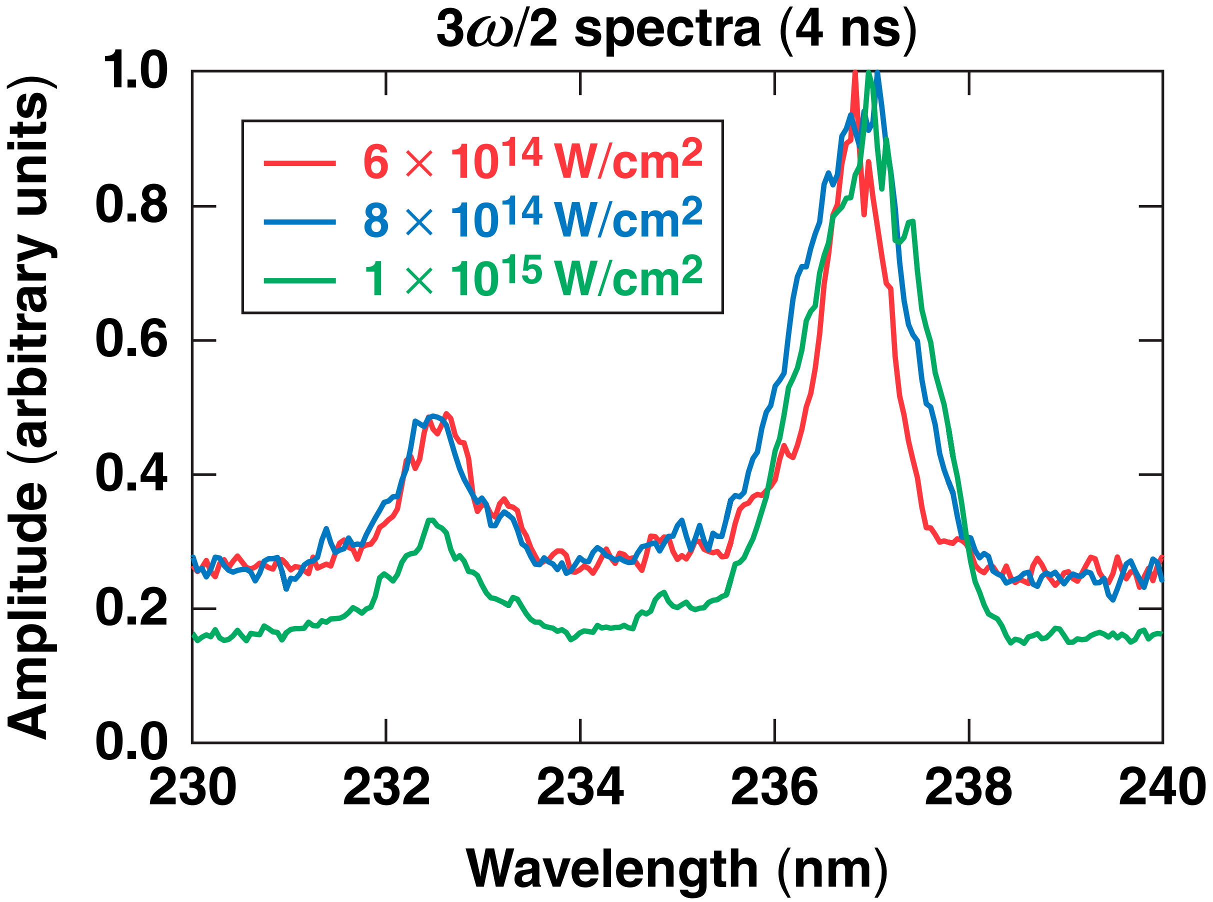


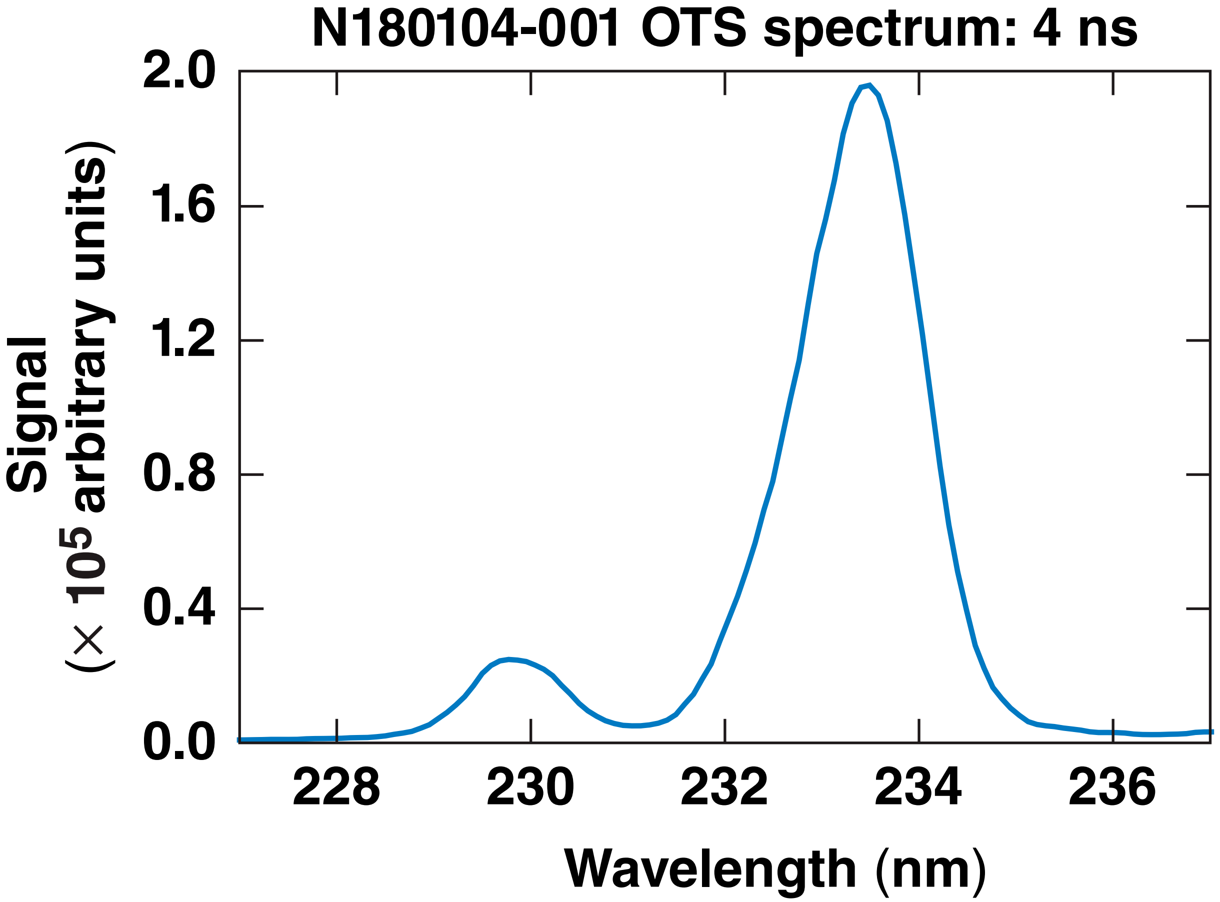
Sidescatter has rapid exponential rise (absolute instability) followed by a slower rise (convective instability?).

N180104 Experiments

LPSE simulations (TPD only) qualitatively reproduce the $3\omega/2$ doublet spectrum from N180104-001 at early times

R. Follett simulations 2017-09-19



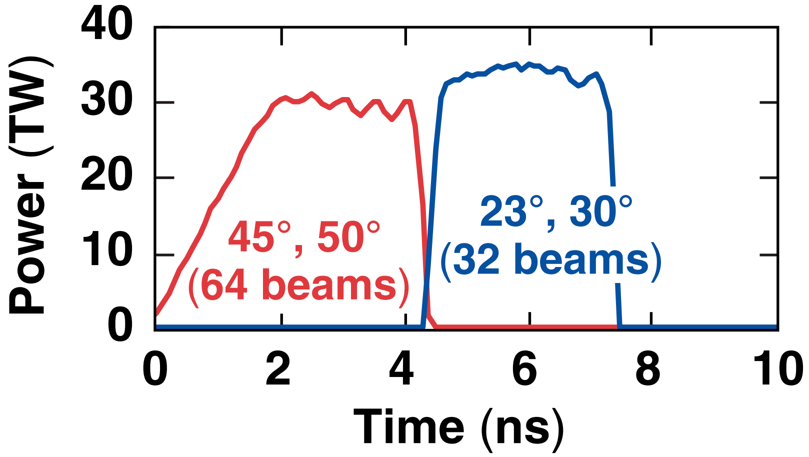


Caveat: preliminary *LPSE* simulations with SRS and TPD may also be consistent with this—SRS seeding TPD, or both instabilities occurring simultaneously.

E27551

Si targets produce reduced SRS reflectivity in comparison to CH, a similar trend to the hot-electron results

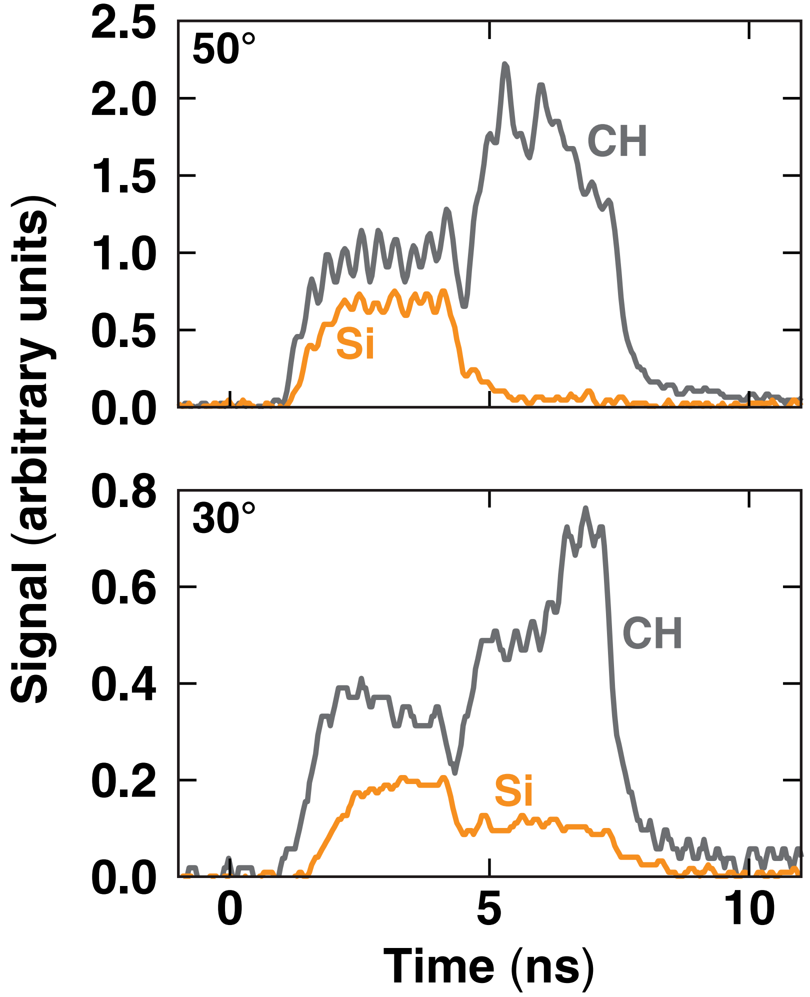
Shot N160421-001 CH
Shot N160719-001 Si



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 (nm)	690	560
T_e (keV)	4.4	5.2
I_L (W/cm^2)	1.1×10^{15}	0.92×10^{15}

SRS time history (Si versus CH)



E25569f