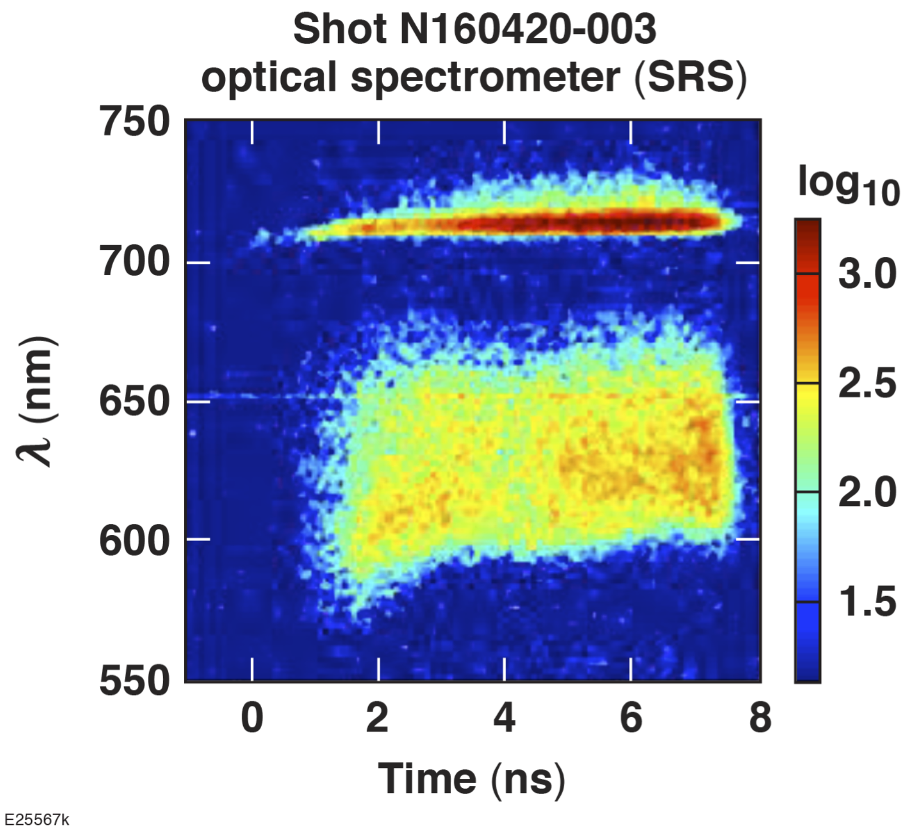
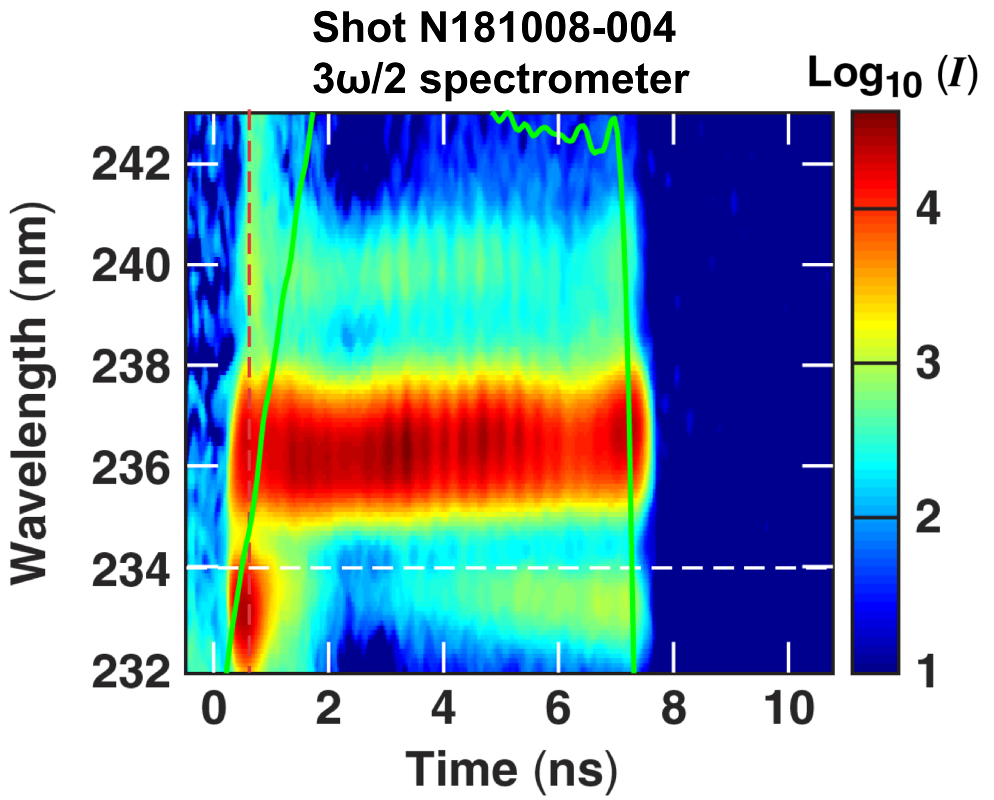
Hot Electron Generation Mechanisms in Ignition-Scale Direct-Drive Coronal Plasmas on the NIF





M. J. Rosenberg
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61st Annual Meeting of the
APS Division of Plasma Physics
Fort Lauderdale, FL
21-25 October 2019

Summary

Planar experiments at the NIF have studied LPI mechanisms responsible for hot-electron generation at direct-drive ignition-relevant coronal conditions

- **Planar experiments at scale lengths L_n ~ 600 μm and T_e ~ 3 to 5 keV show hot electron generation of f_{hot}~ 0% to 5% for laser intensities of 0.4 to 1.5 $\times$ 10^{15} W/cm^2**
- **Stimulated Raman scattering (SRS) is inferred to be the dominant LPI mechanism**
  - **SRS is observed both at n_c/4 and in the <n_c/4 region**
  - **hot-electron signatures more strongly correlate with underdense SRS**
- **3ω/2 measurements of SRS and/or TPD plasma waves at n_c/4 will provide a constraint on 3D modeling of hot electron generation mechanisms using LPSE***

* R. K. Follett *et al.* Phys. Plasmas. 24, 1031128 (2017)

Collaborators

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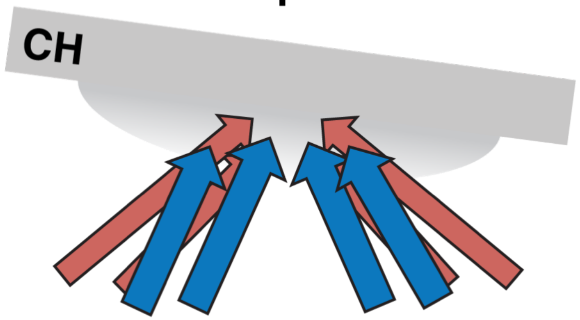
Planar experiments on NIF reproduce plasma conditions unique to direct-drive ignition designs, which long scale lengths may make susceptible to LPI and hot electron preheat

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) $\times 10^{14}$	(4 to 15) $\times 10^{14}$
η_{SRS}*	~10 to 17	~10 to 25
η_{TPD}**	~3 to 6	~3 to 8

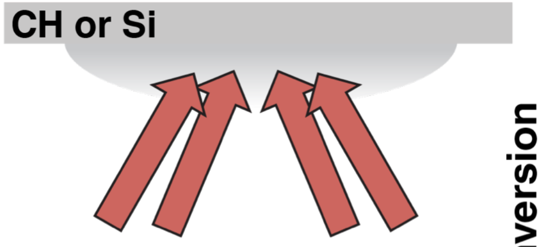
Planar platform



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

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

Hot-electron generation of f_{hot} up to 5% has been inferred in planar targets at intensities around 10^{15} W/cm^2 and SRS is observed



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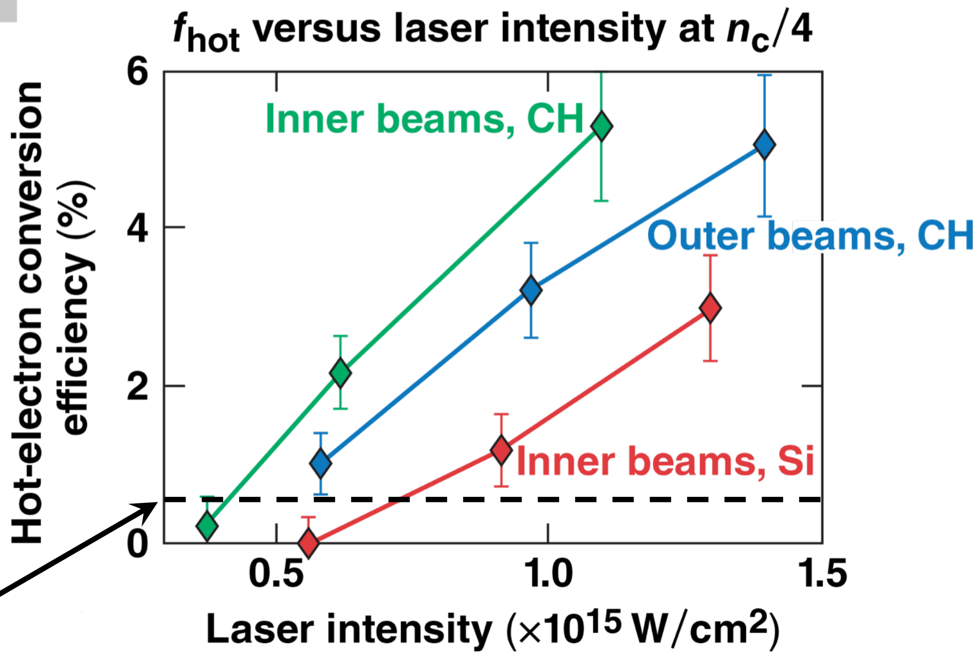
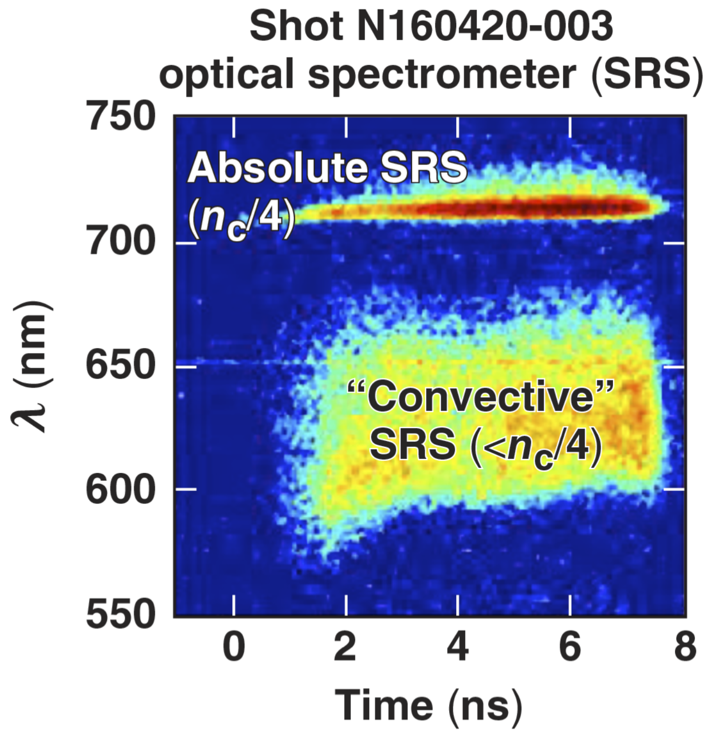


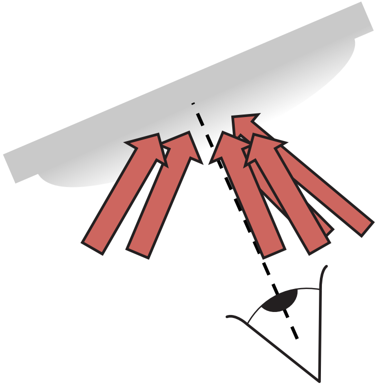
Tolerable preheat in ignition designs (if angular divergence is large)



Intensity around 5×10^{14} W/cm^2 may be acceptable for preheat, but we need to understand: (1) LPI mechanisms (for mitigation), (2) how hot e$^-$ diverge or couple to an implosion.*

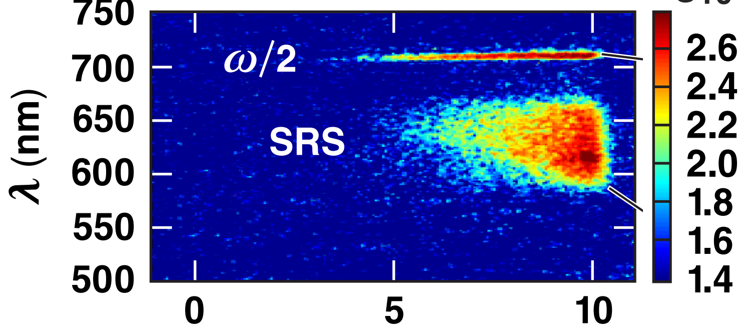
* A. Solodov *et al.* this conference.
M. Rosenberg *et al.* Phys. Rev. Lett. 120, 055001 (2018).

Various SRS mechanisms scale differently in ramp-pulse experiments:

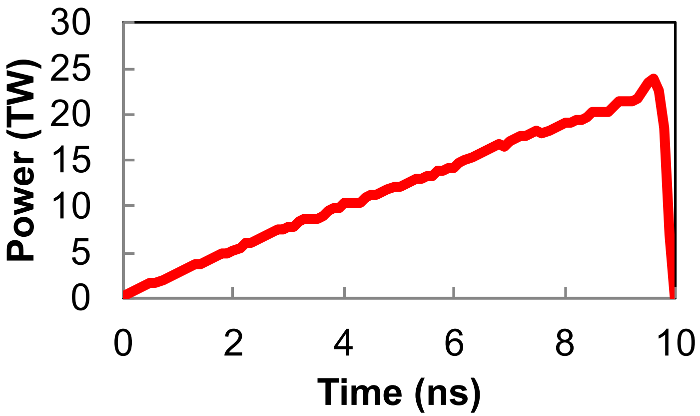


Optical streaked spectrometer (NBI Q33B)

Shot N161010-004 optical spectrometer



Laser Power



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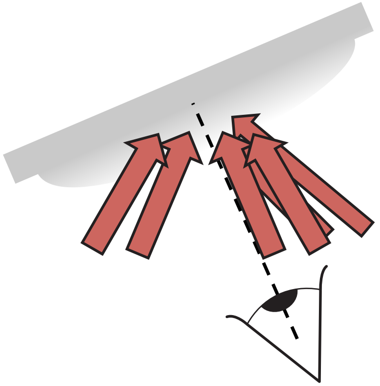
Various SRS mechanisms scale differently in ramp-pulse experiments: absolute $n_c/4$ SRS instability scales linearly with intensity;



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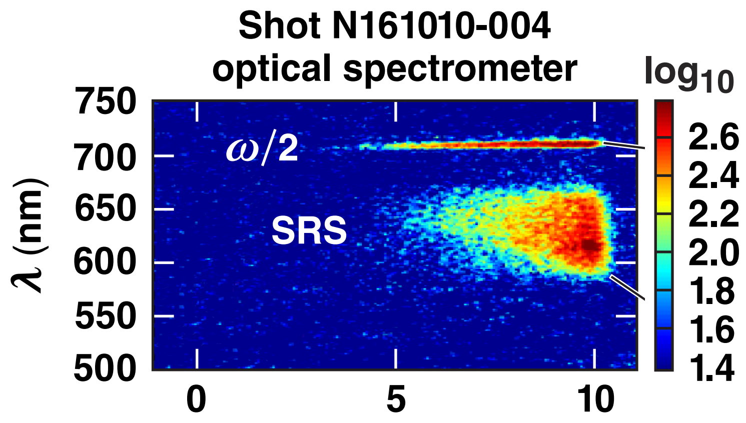

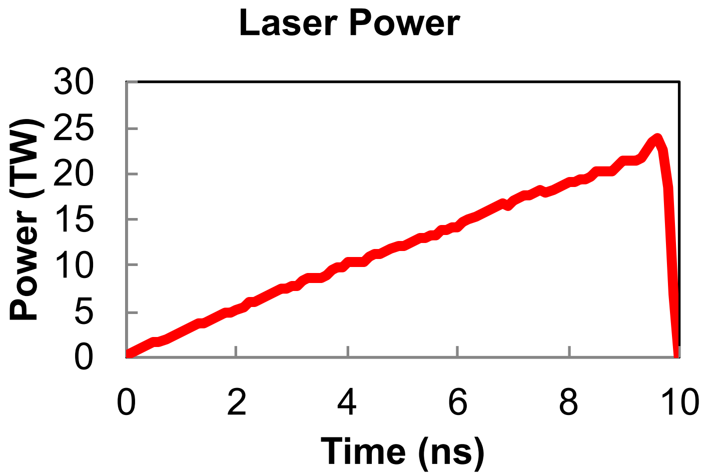

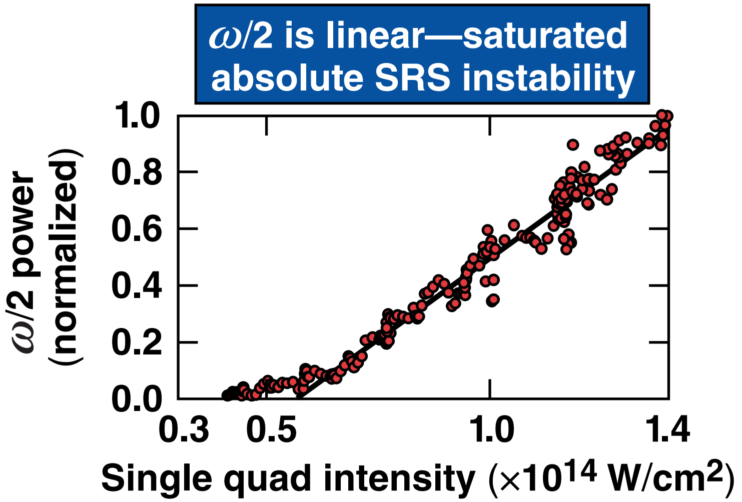

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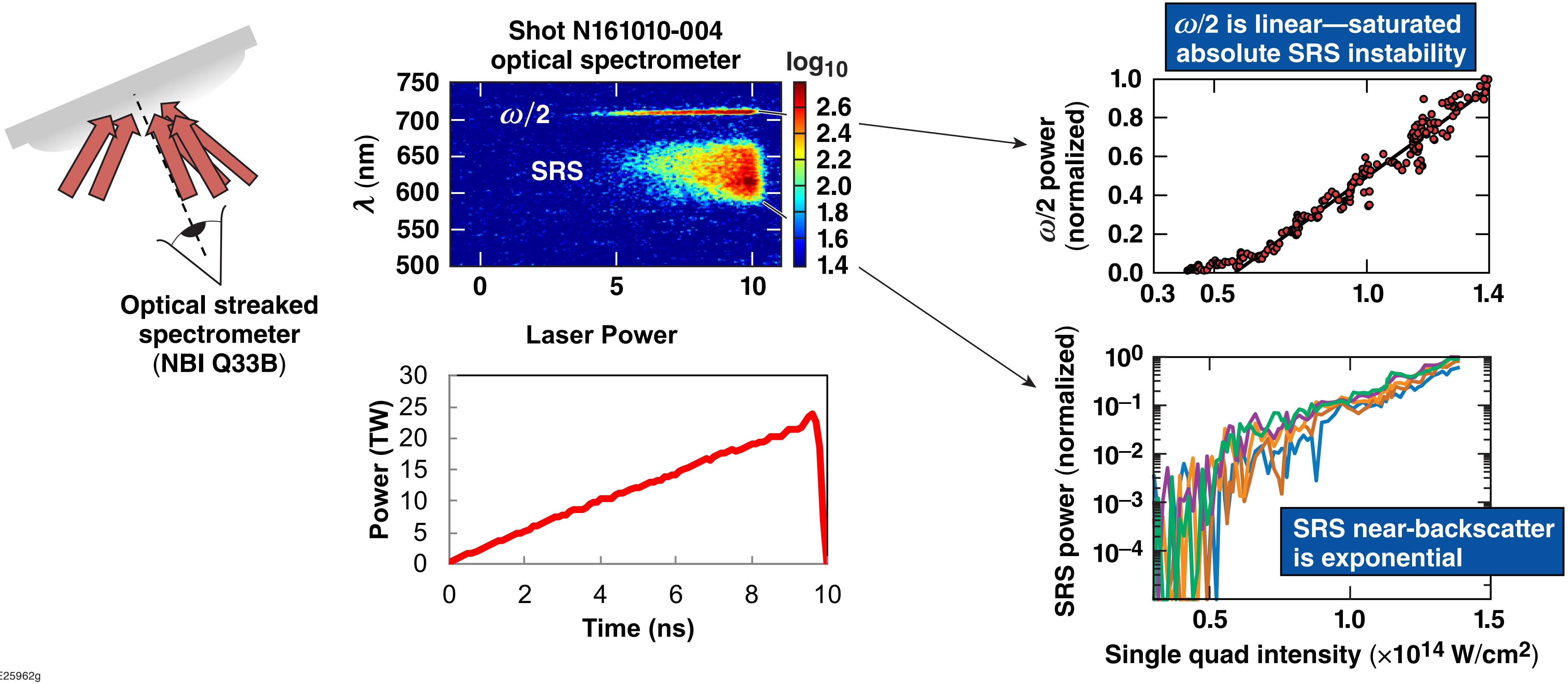
Various SRS mechanisms scale differently in ramp-pulse experiments: absolute $n_c/4$ SRS instability scales linearly with intensity; underdense ($<n_c/4$) SRS instability scales exponentially with intensity



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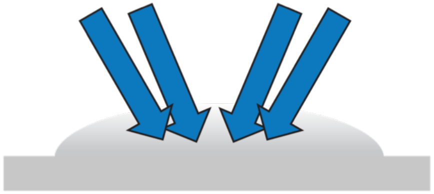
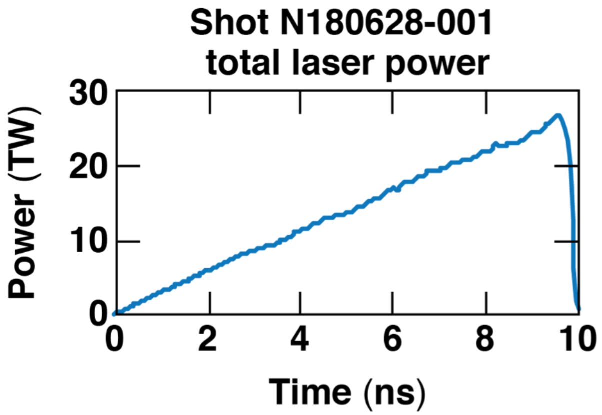
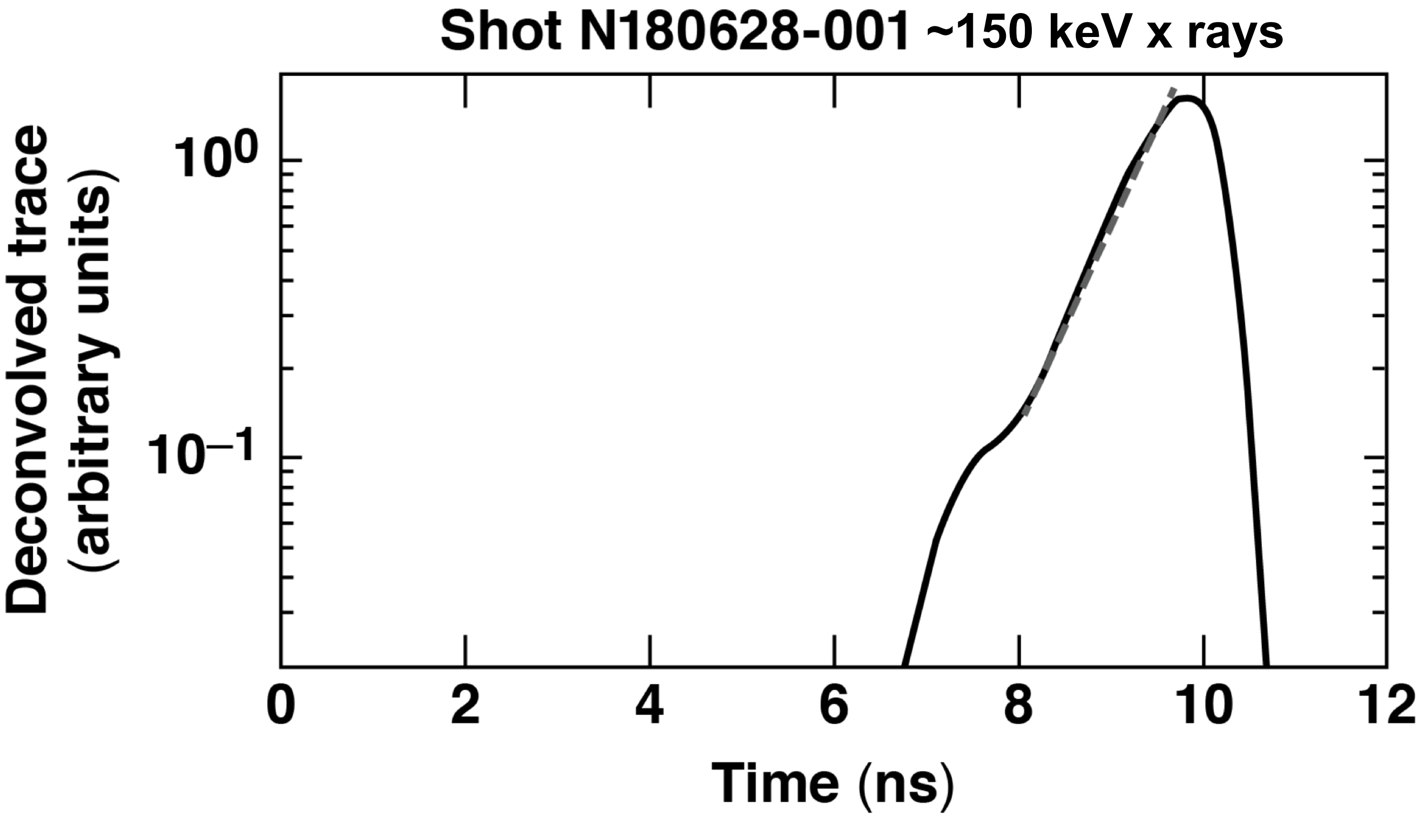
Hard x-ray (HXR) emission from hot electrons scales near-exponentially on ramp-pulse experiments



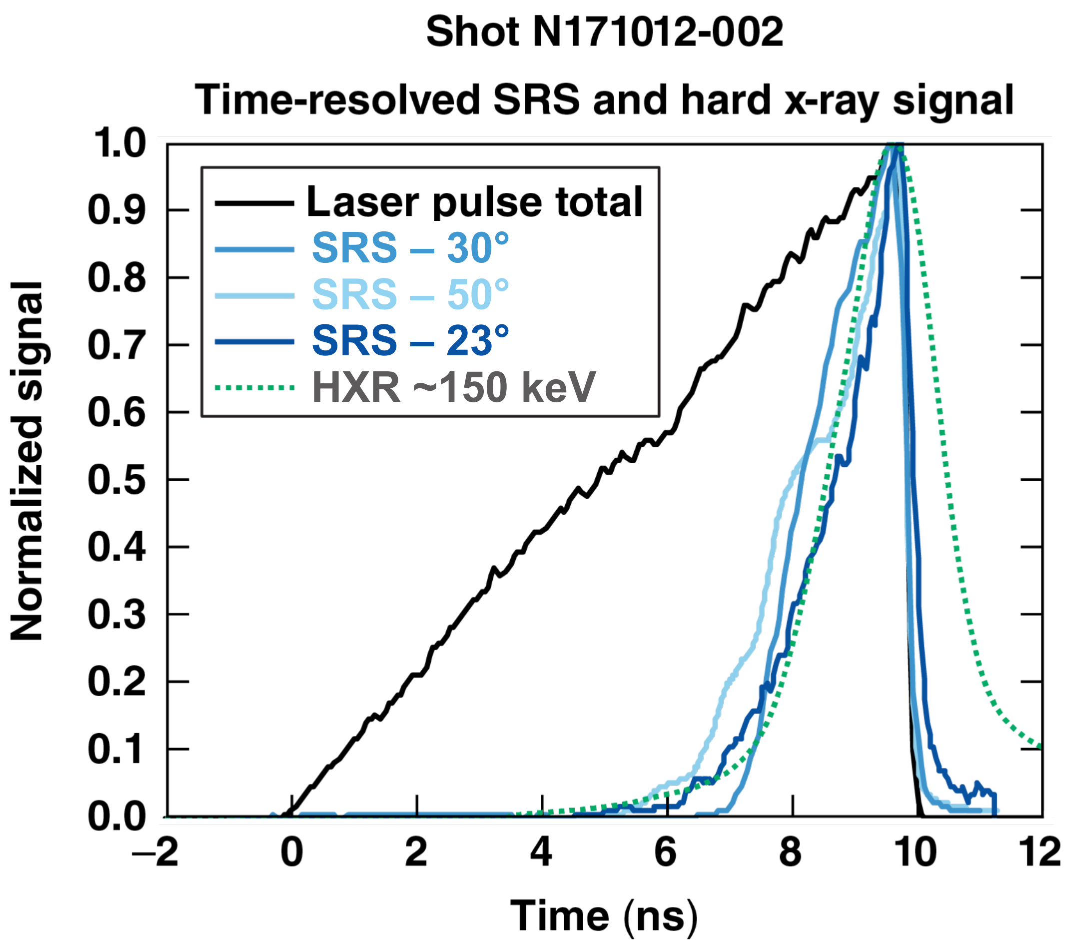


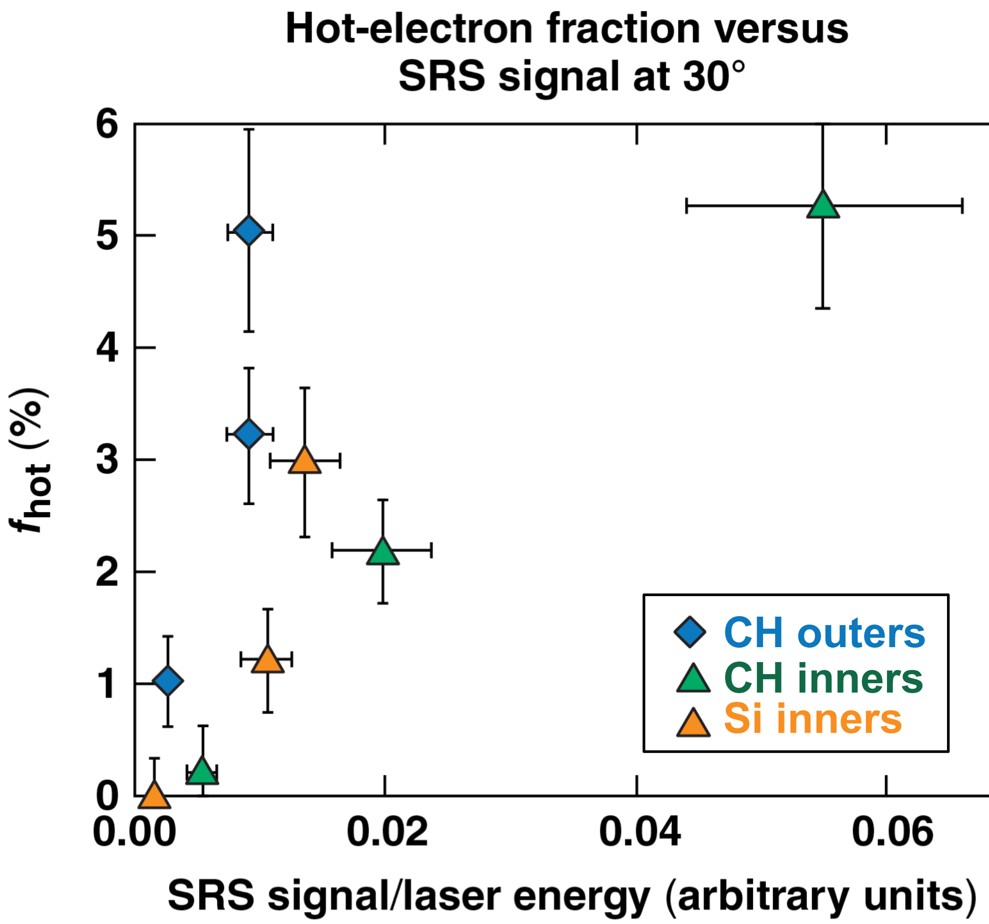


E28541

Exponential scaling suggests a connection between hot-electron generation and underdense SRS

Underdense SRS observations, including sidescatter*, correlate with hard x-ray measurements both in time and across different experiments

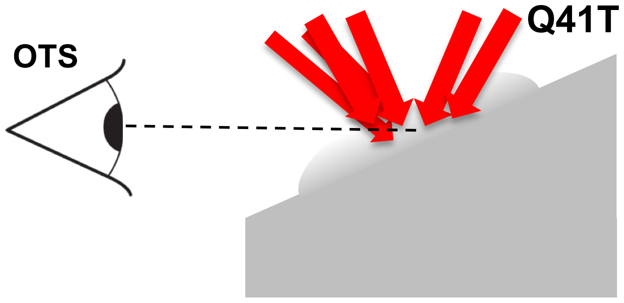


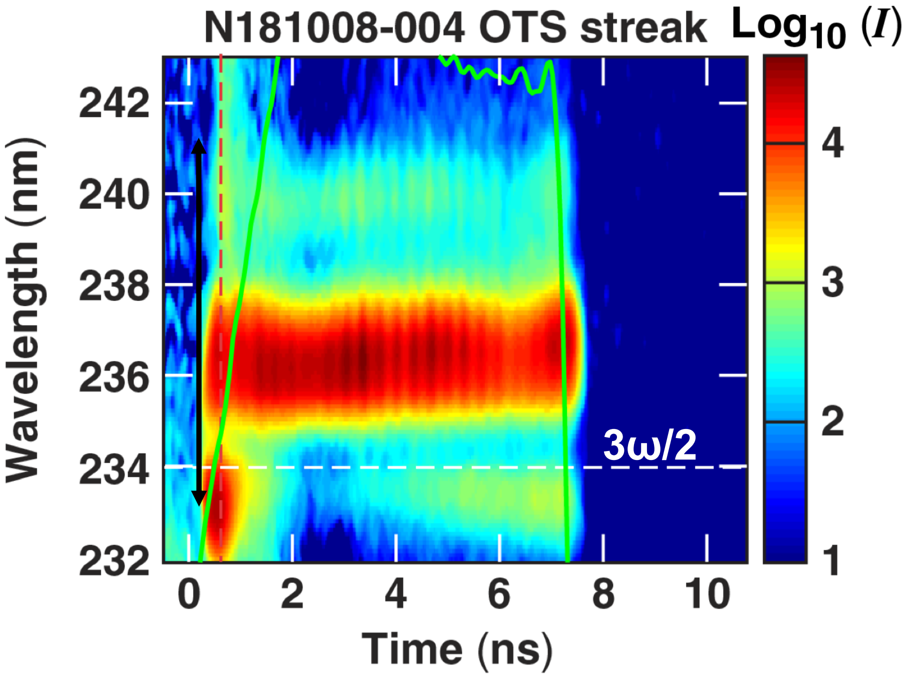


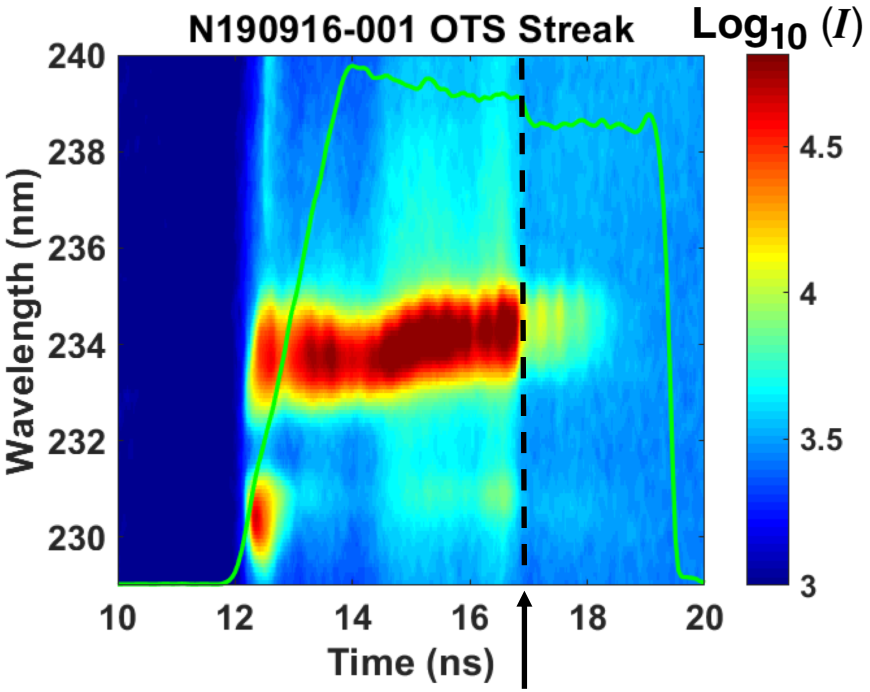
E27531b

* P. Michel *et al*., Phys. Rev. E 99, 033203 (2019)

In addition to SRS scattered light measurements, 3ω/2 emission contains information about SRS and/or TPD plasma waves near $n_c/4$







Turned off quad Q41T (4 beams) at largest angle (116°) to OTS

Knowing the probed plasma wave k-vector and the scattered light spectrum constrains 3D LPSE* simulations of SRS and TPD that will relate the observed features to specific instabilities

* R. K. Follett *et al.* Phys. Plasmas. 24, 1031128 (2017)

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  - hot-electron signatures more strongly correlate with underdense SRS
- 3ω/2 measurements of SRS and/or TPD plasma waves at $n_c/4$ will provide a constraint on 3D modeling of hot electron generation mechanisms using LPSE*

Knowing the density at which hot electrons are generated will guide hot electron preheat mitigation strategies for direct-drive ignition designs

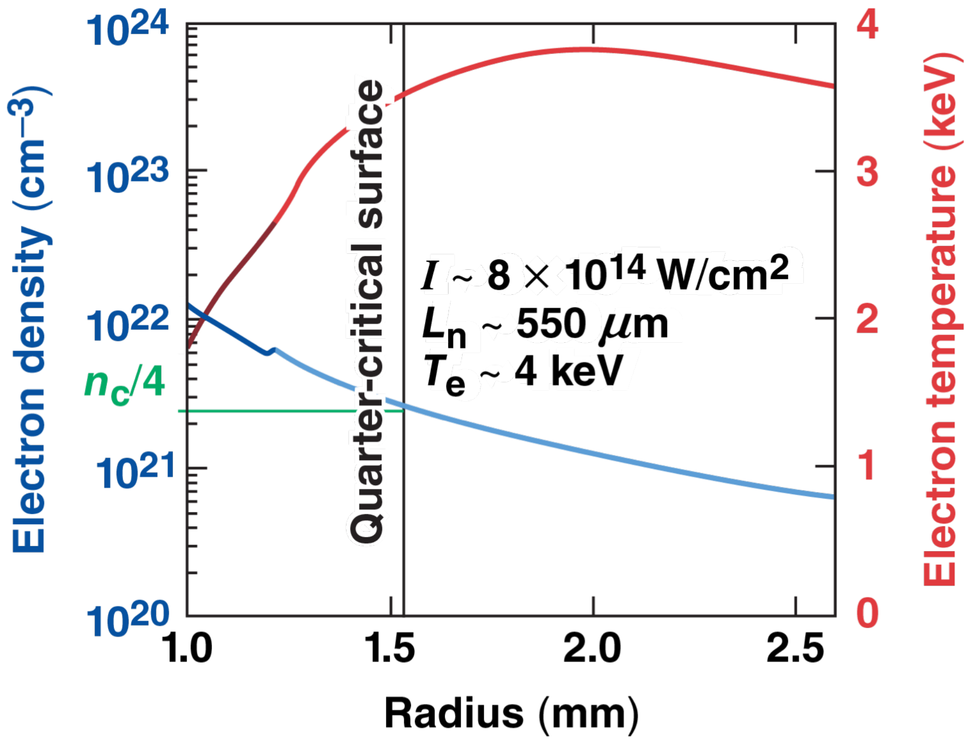
* R. K. Follett *et al.* Phys. Plasmas. 24, 1031128 (2017)

APPENDIX

Motivation

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

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

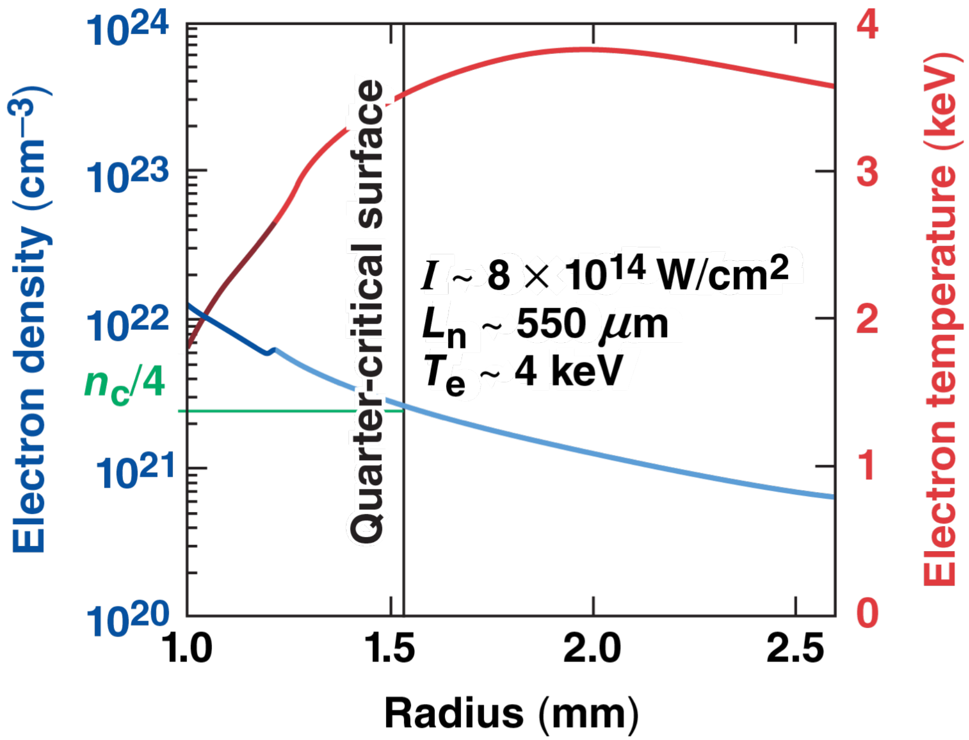


E25732i

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

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



E25732i

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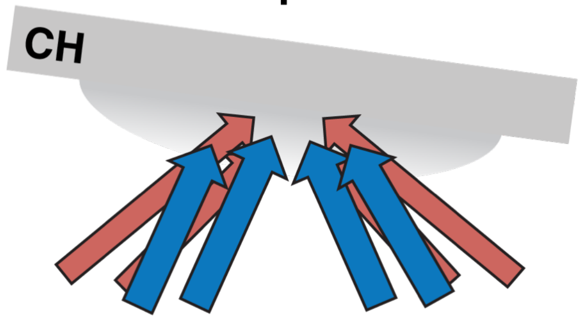
Planar platform



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

E25732h

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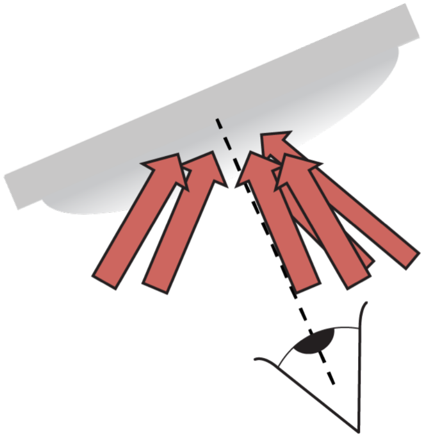
** A. Simon *et al.* Phys. Fluids 26, 3107 (1983).

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



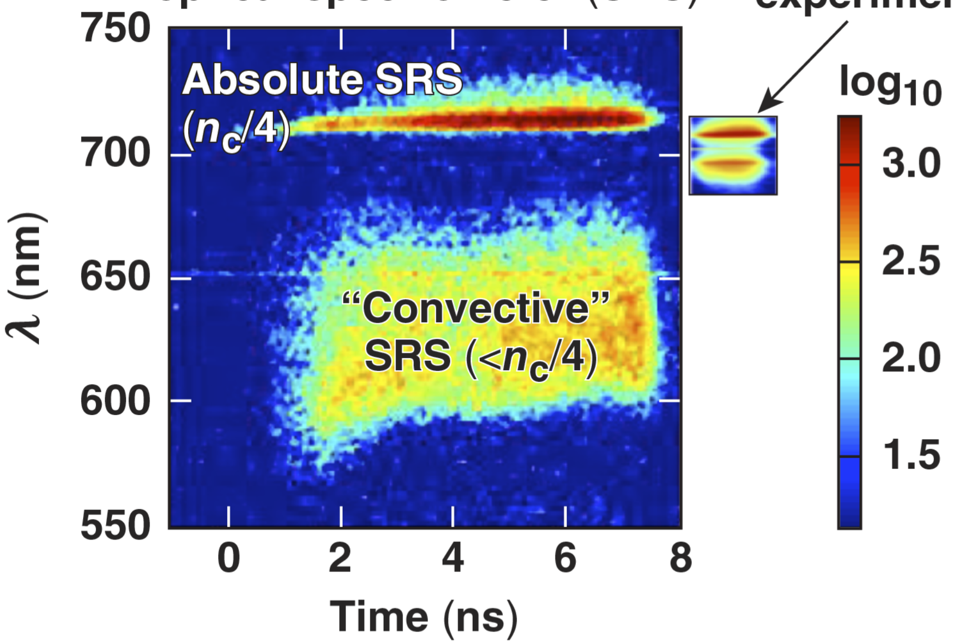
Optical streaked spectrometer NBI Q33B

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)



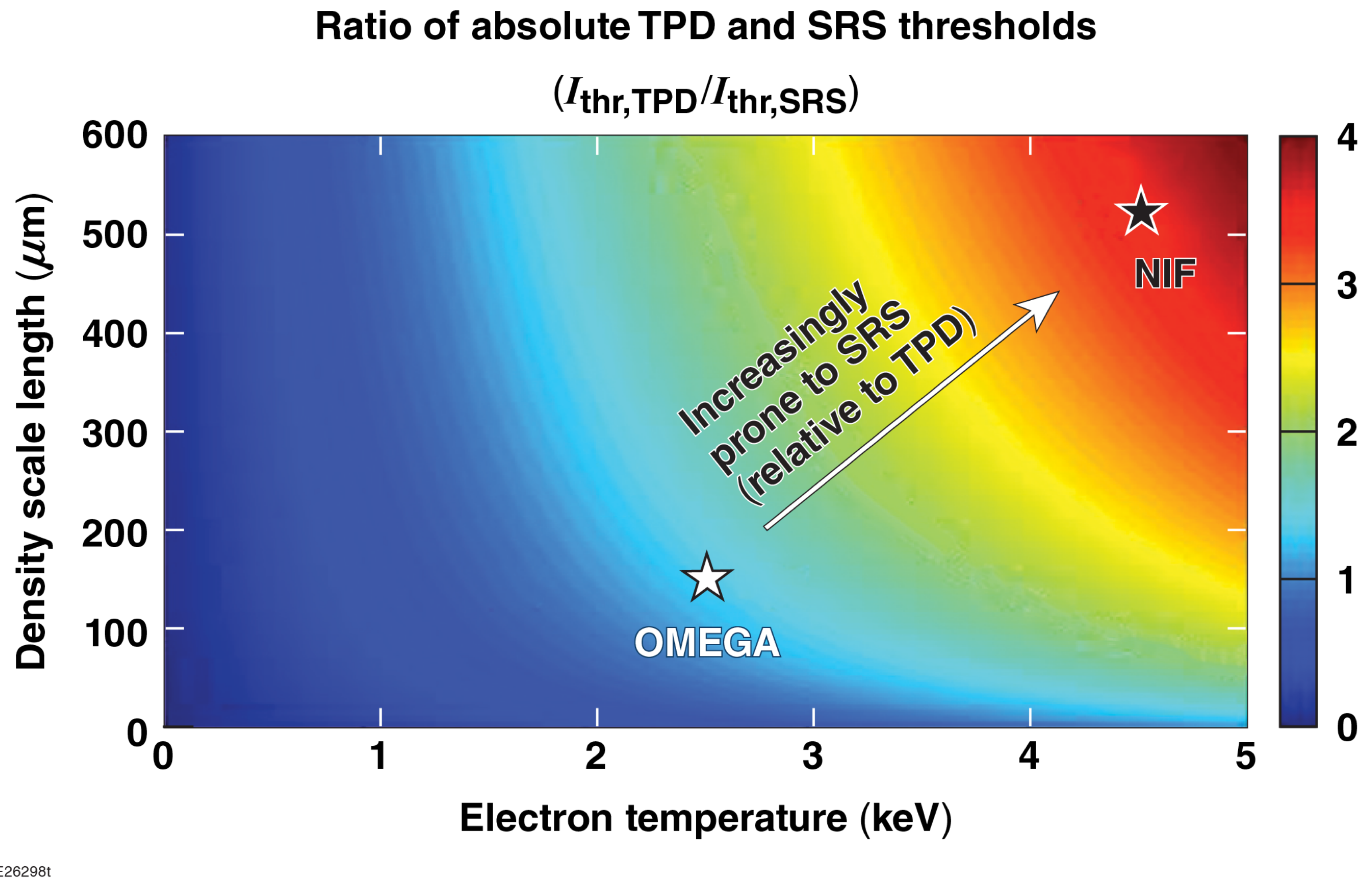
E25567j

This data suggests SRS is the dominant hot-electron source, but 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).

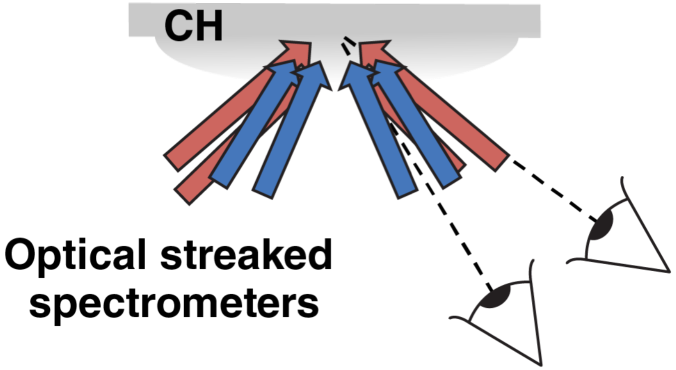
The dominance of SRS at the NIF scale may be partially explained by evaluating the absolute thresholds of SRS versus TPD

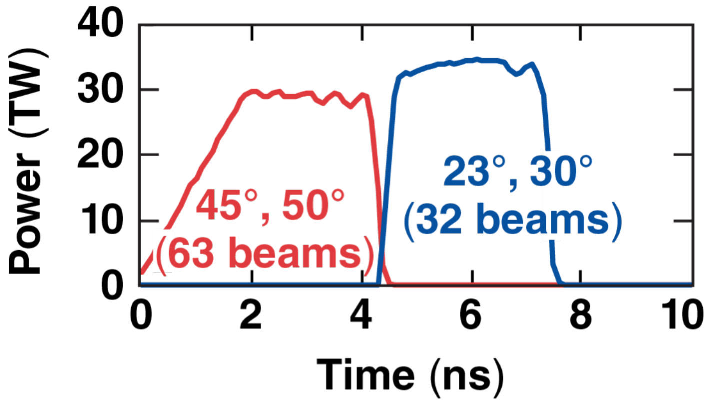


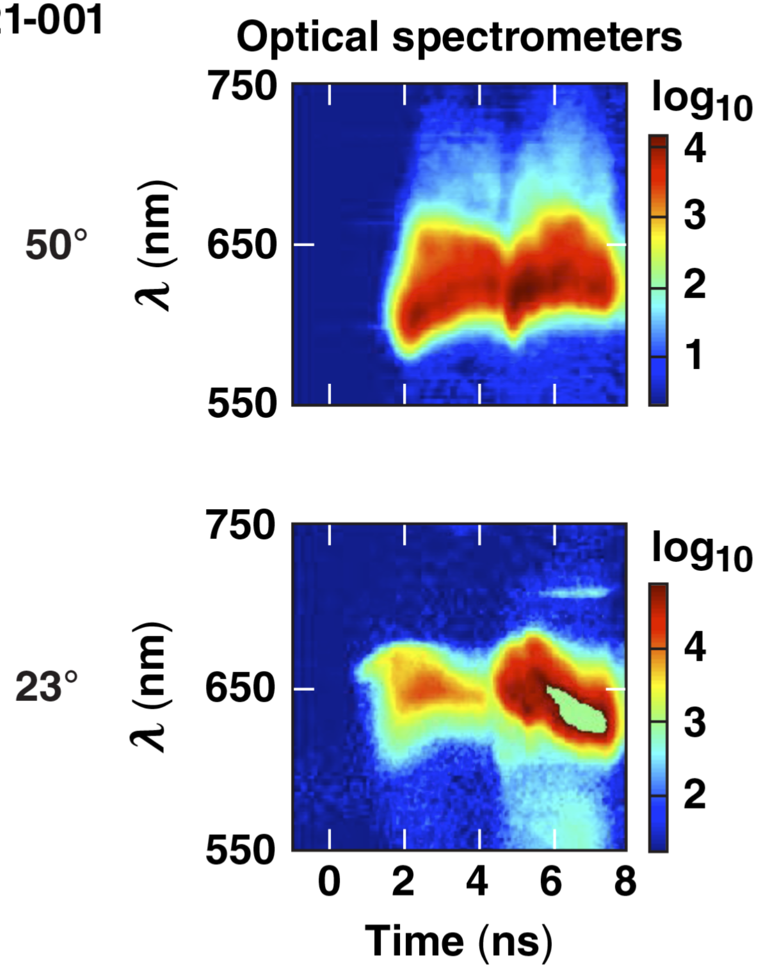
M. Rosenberg *et al.* Phys. Rev. Lett. 120, 055001 (2018).

SRS sidescatter is observed and is thought to be a key underdense SRS mechanism

Shot N160421-001





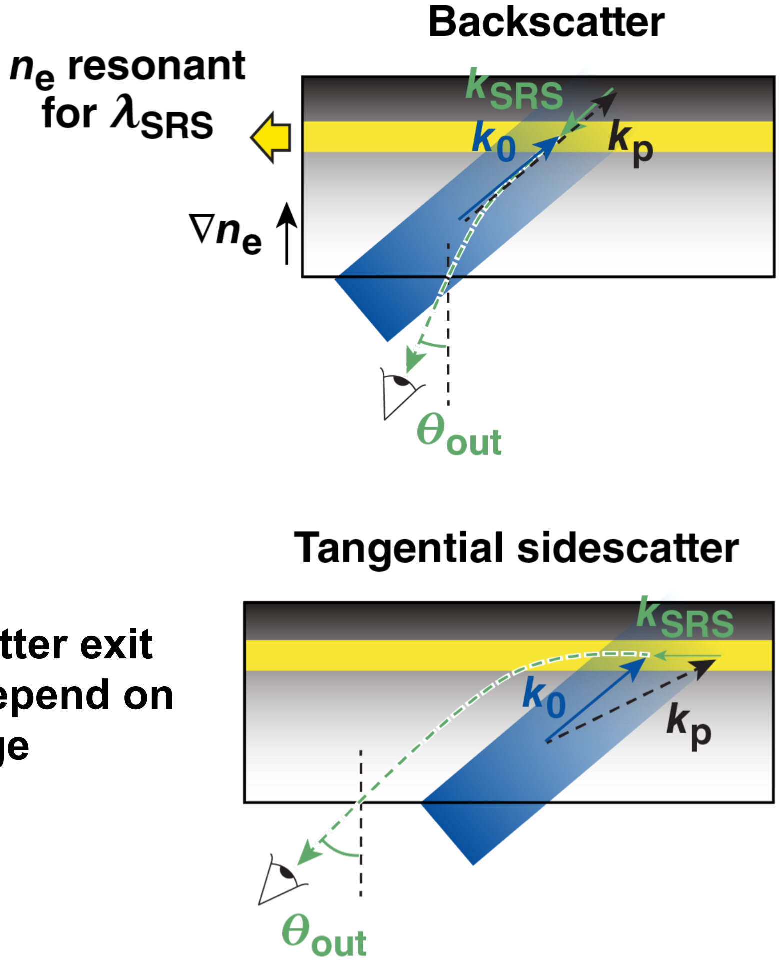


Observation at 50° can only be sidescatter. Tangential SRS sidescatter theory* predicts scattered light wavelength independent of beam angle, as observed.

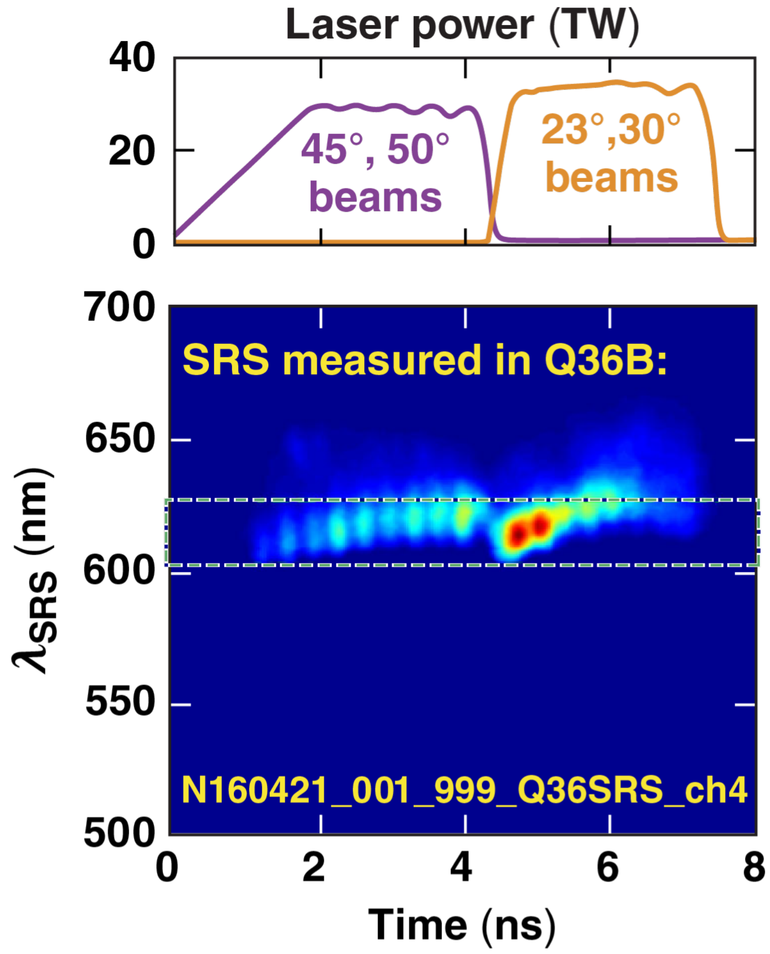
E25568i

M. Rosenberg *et al.* Phys. Rev. Lett. 120, 055001 (2018).
*P. Michel *et al.* Phys. Rev. E 99, 033203 (2019).

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



Tangetial sidescatter exit angle does not depend on the incidence ange



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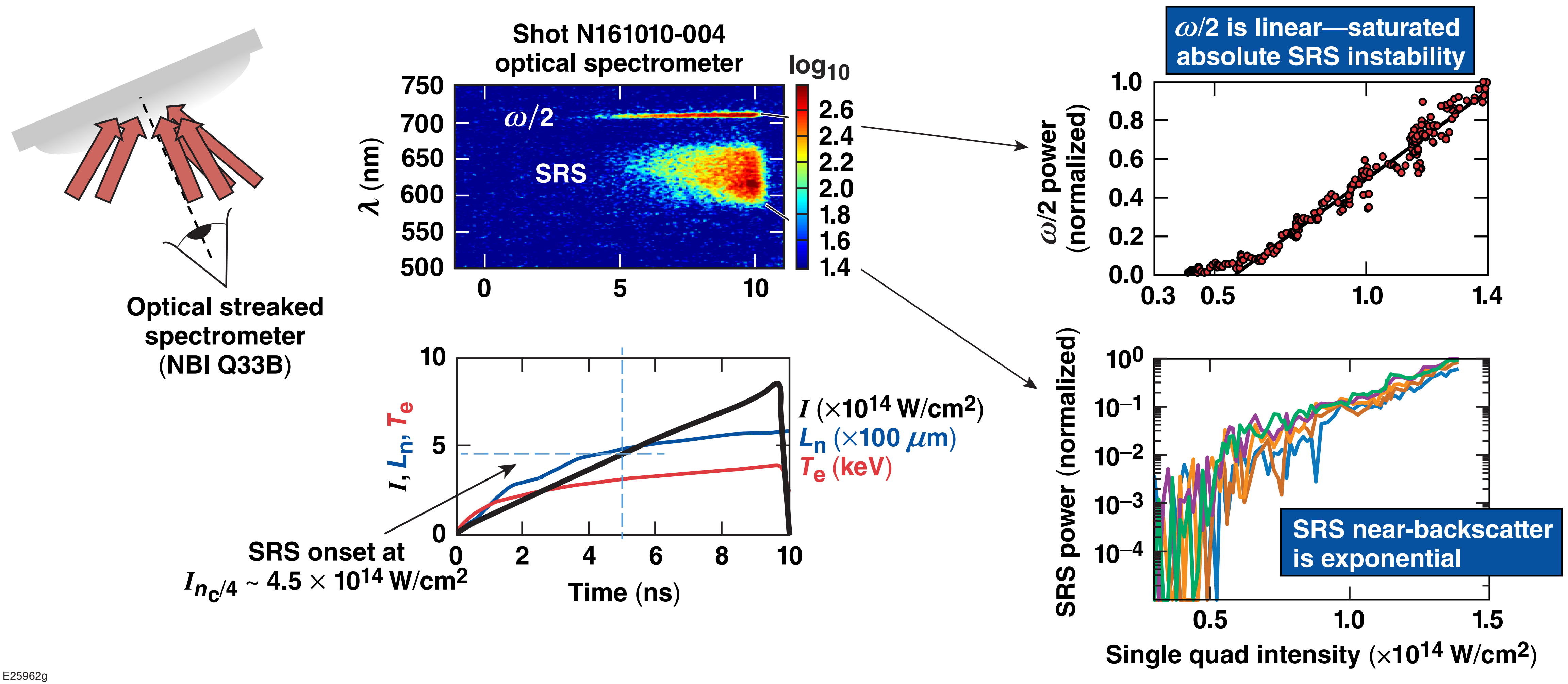
Various SRS mechanisms scale differently in ramp-pulse experiments: absolute $n_c/4$ SRS instability scales linearly with intensity; underdense ($<n_c/4$) SRS instability scales exponentially with intensity



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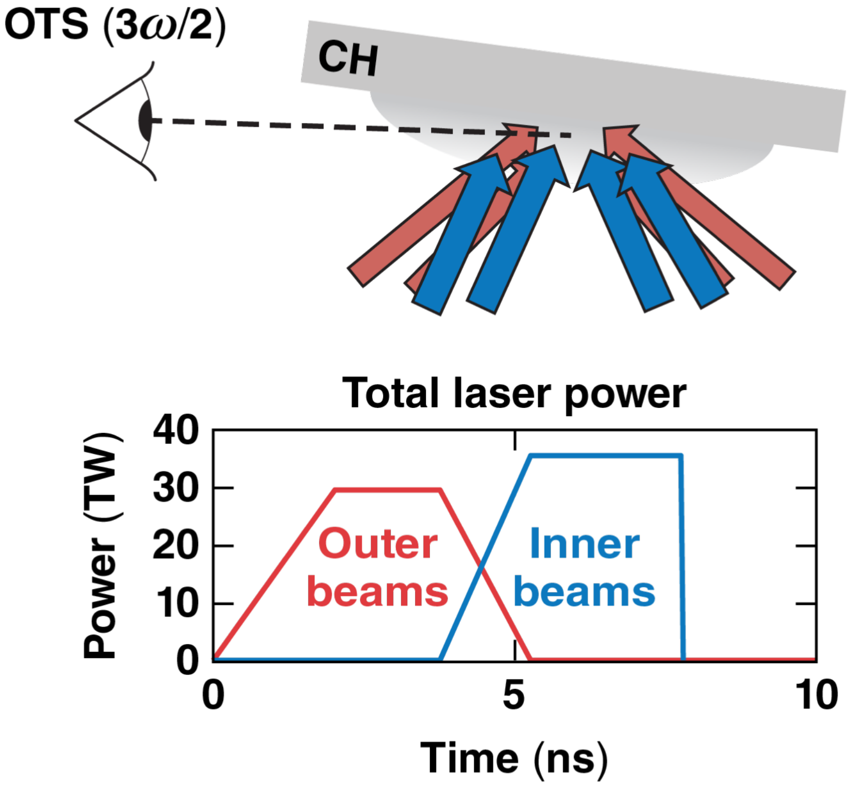
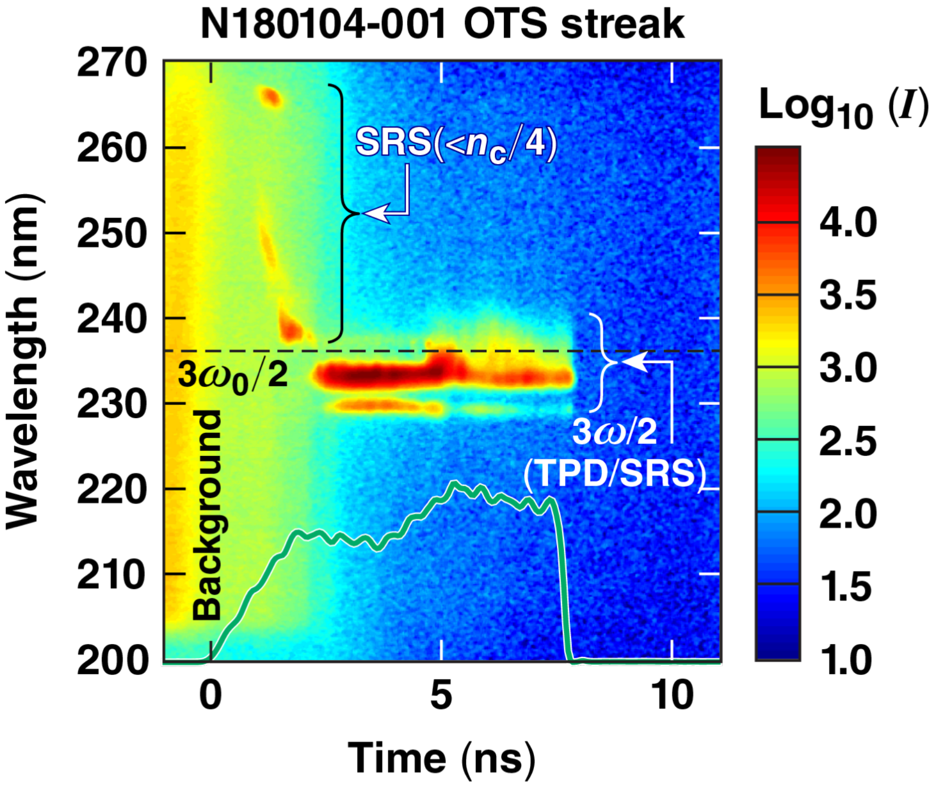
In addition to SRS measurements, recent experiments diagnosed Thomson-scattered light from plasma waves at and below $n_c/4$



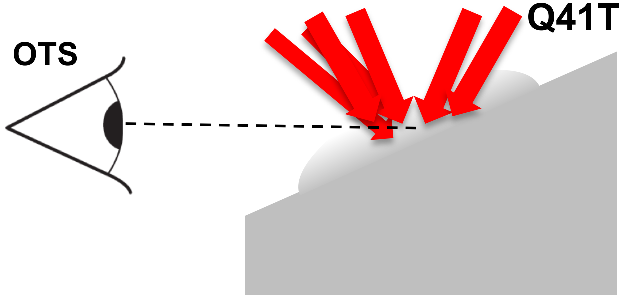


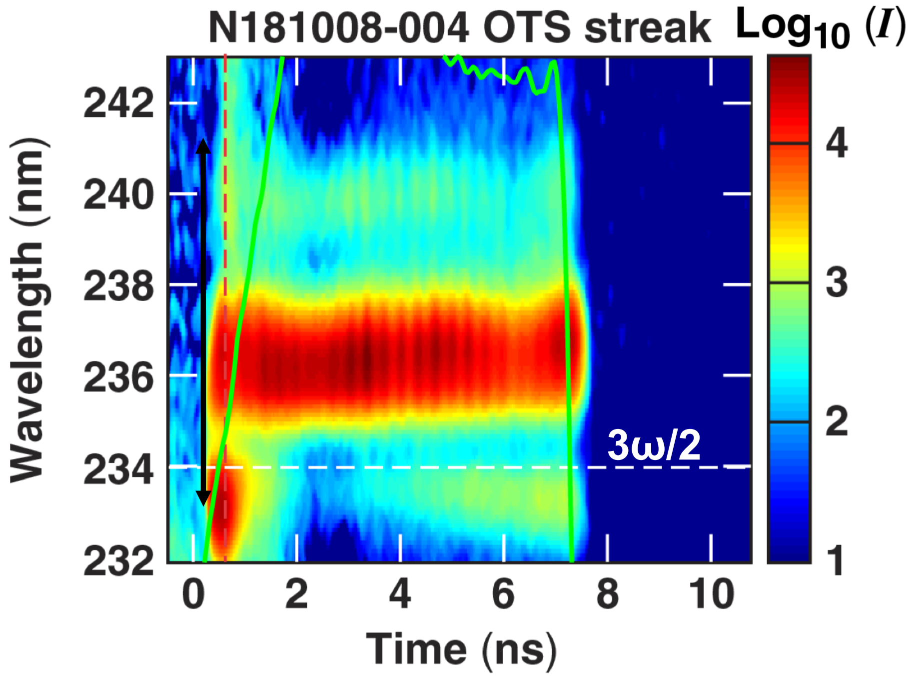
E27332c

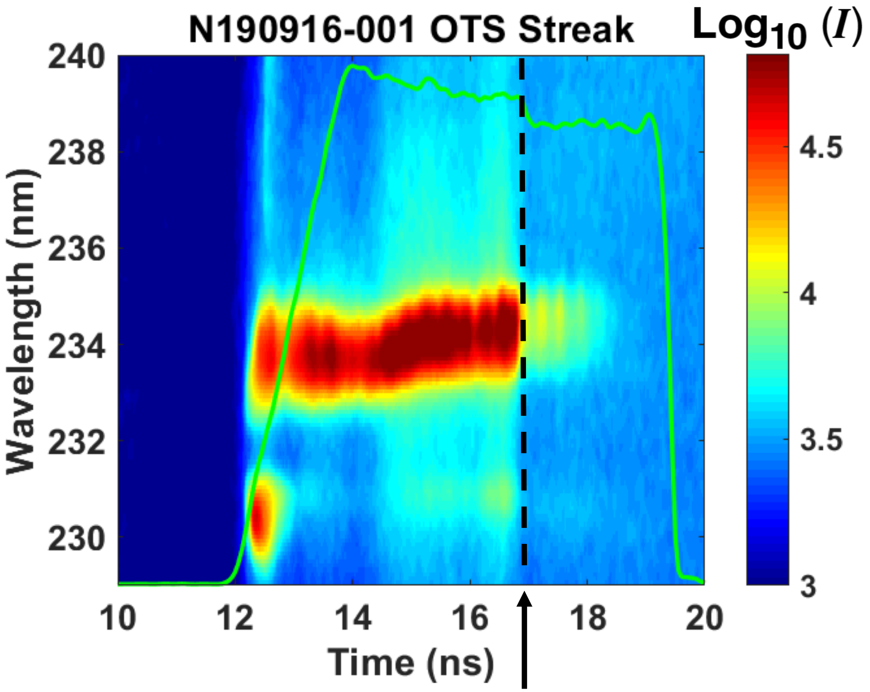
Wave-matching conditions likely not satisfied for probing underdense SRS, but 3ω/2 feature contains information about plasma waves at $n_c/4$

OTS: optical Thomson scattering

In addition to SRS scattered light measurements, 3ω/2 emission contains information about SRS and/or TPD plasma waves near $n_c/4$





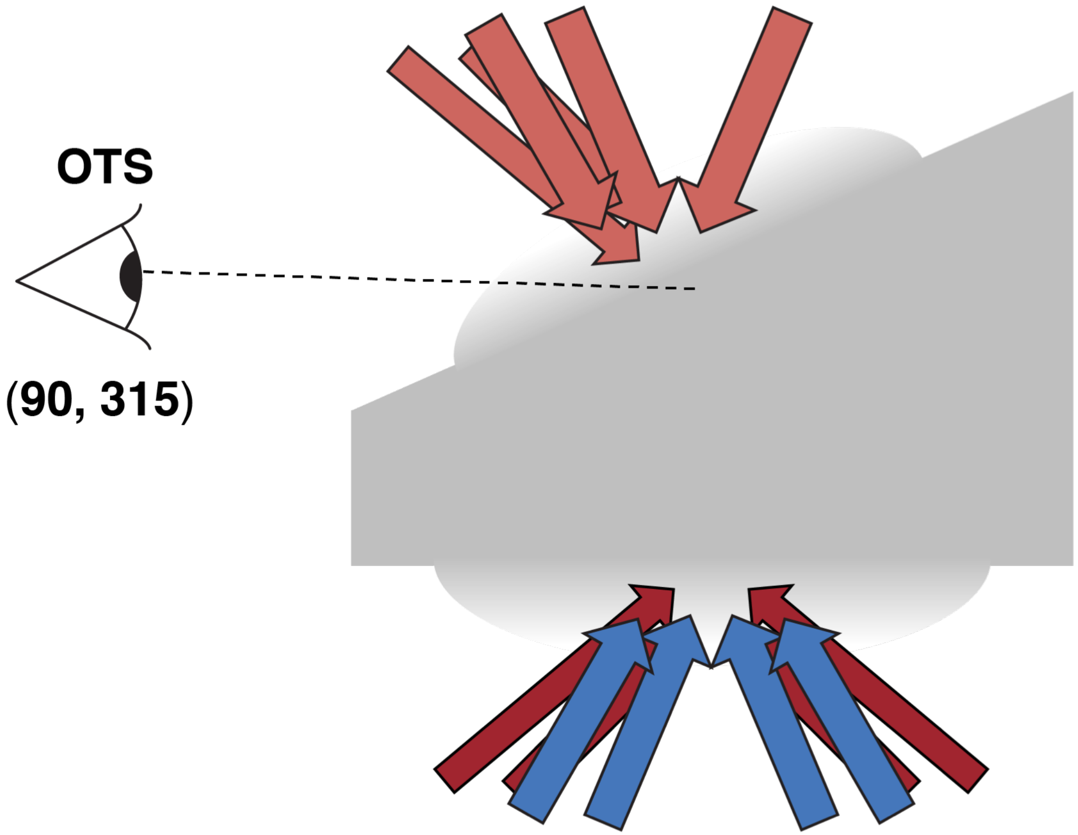


Turned off quad Q41T (4 beams) at largest angle (116°) to OTS

Knowing the probed plasma wave k-vector and the scattered light spectrum constrains 3D LPSE* simulations of SRS and TPD that will relate the observed features to specific instabilities

* R. K. Follett *et al.* Phys. Plasmas. 24, 1031128 (2017)

Experiments in September aim to identify the exact quarter-critical plasma waves that are being probed, with the help of new 3-D SRS/TPD modeling in *LPSE*



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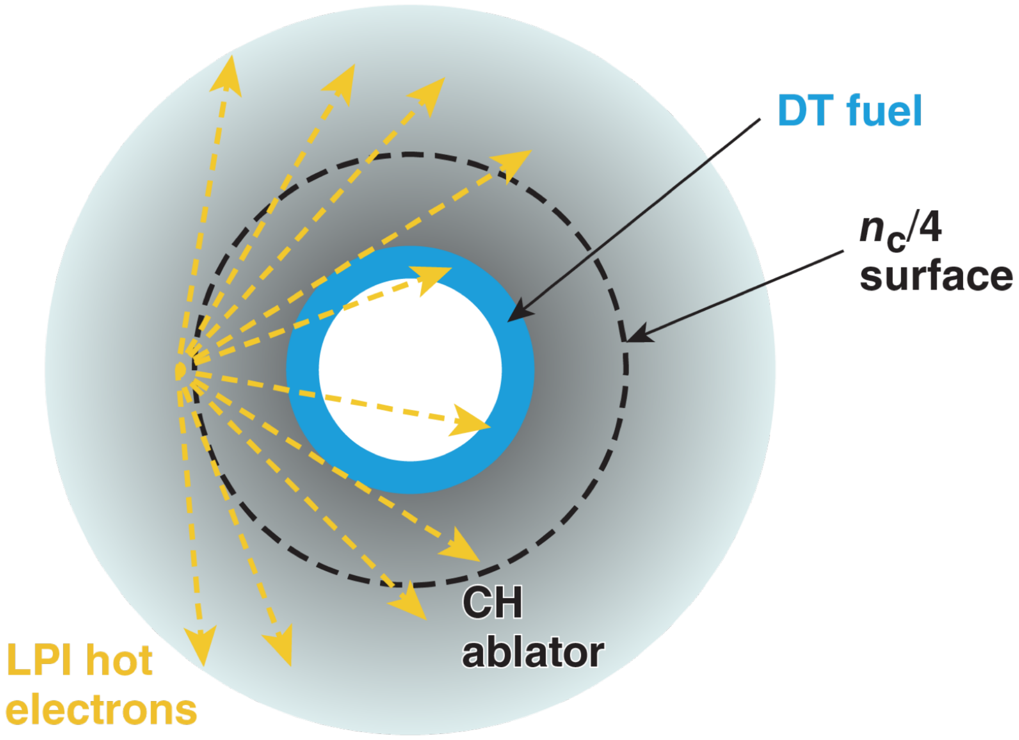
The tolerable fraction of hot electrons generated (f_{hot}) depends on how the electrons couple to an implosion

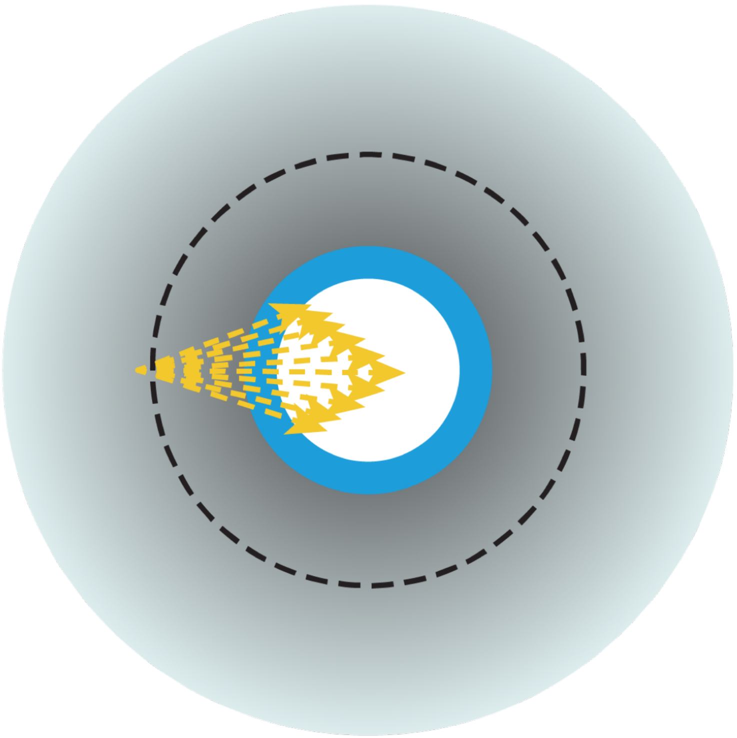
Direct-drive implosion

Wide angular divergence*



Tolerable f_{hot} ~ 0.7%

Narrow angular divergence



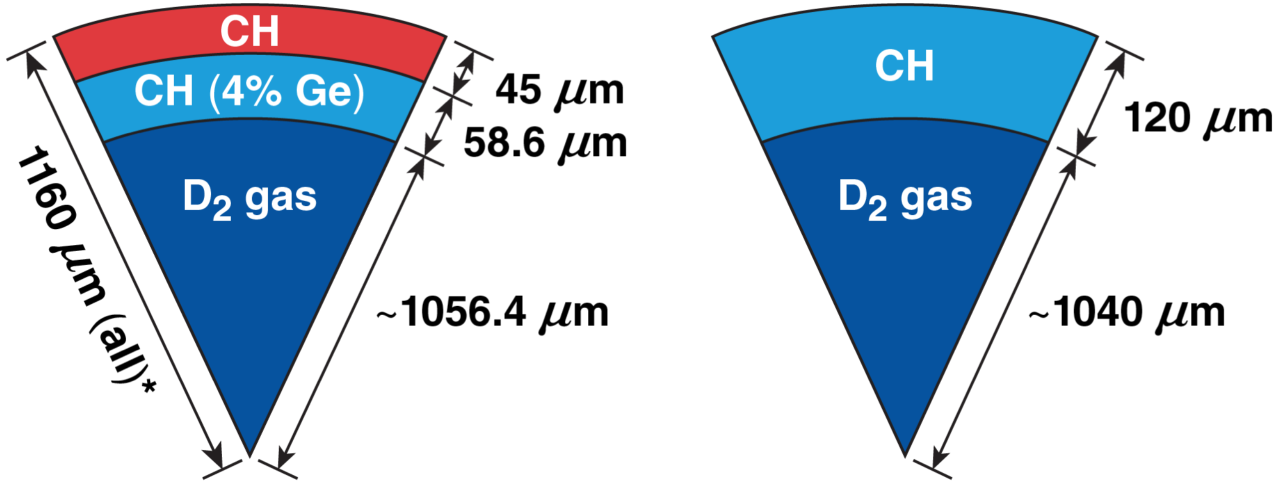
Tolerable f_{hot} ~ 0.2%

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

A spherical-geometry platform has been implemented on the NIF to diagnose coupling of hot electrons to an imploding shell

Experiments in September 2018 and March 2019

NIF target designs

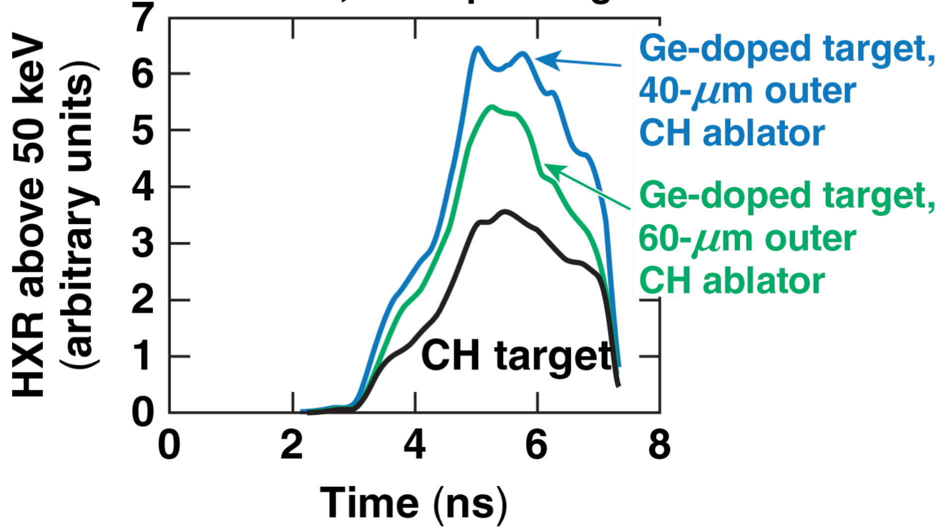


*Platform adapted from OMEGA:
A. Christopherson *et al.*, APS-DPP Meeting (2016)

E27049f

Predicted NIF hard x-ray data

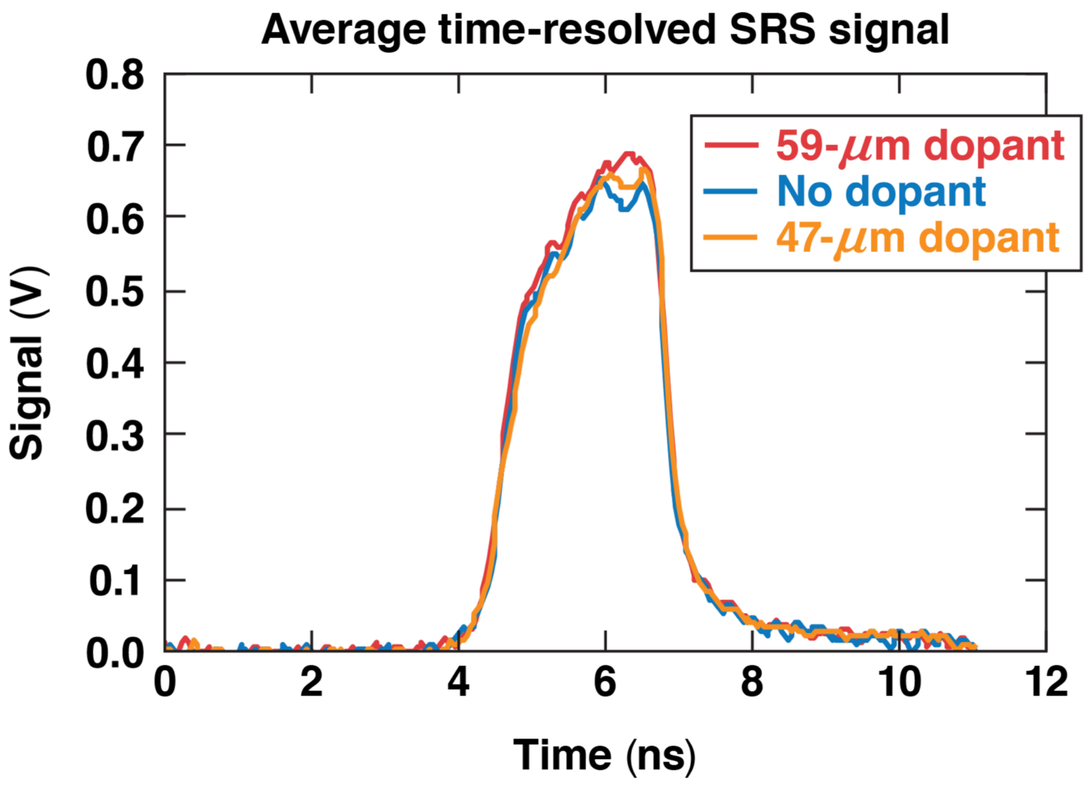
LILAC simulations for T_{hot} = 55 keV, hot-electron divergence full angle of 2π, Ge-doped target at 3.9%

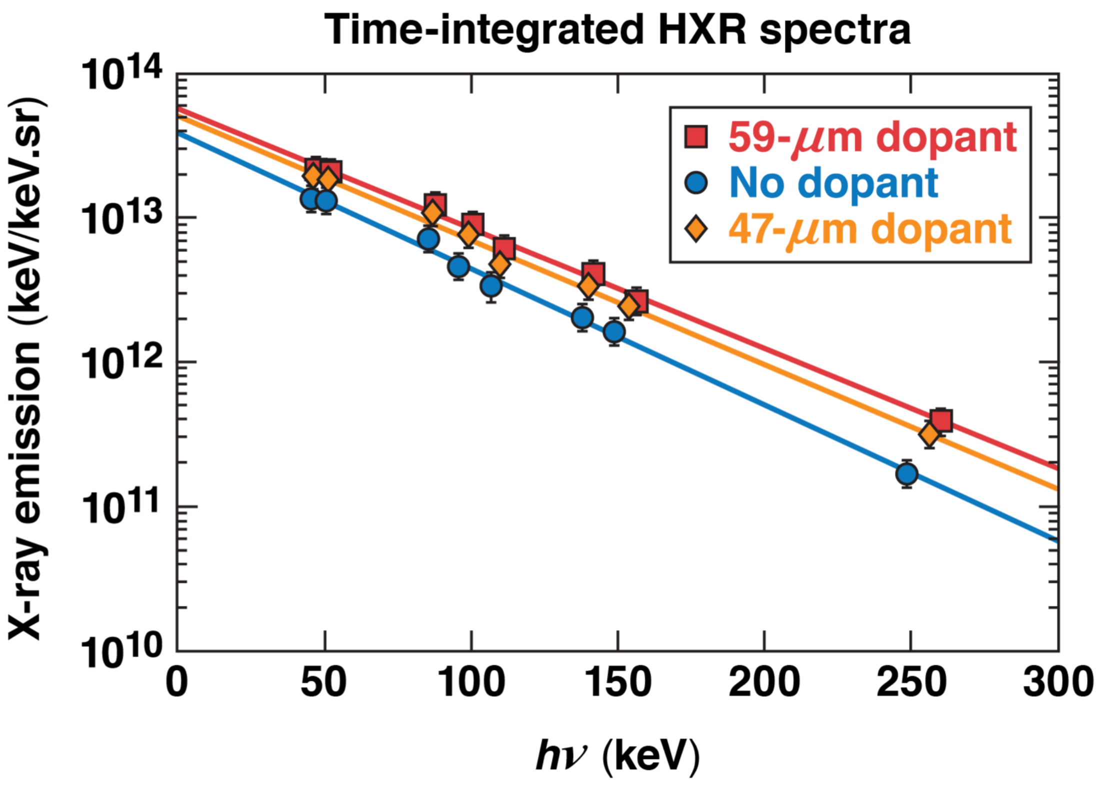


Difference in hard x-ray signals between mass-equivalent CH and multilayered implosions → hot-electron energy deposited in the inner shell layer.

See also A. A. Solodov, this conference.

Experiments demonstrate an identical SRS/hot-electron source and a ~2× enhancement of HXR signal in the doped targets





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Hard x-ray enhancement is consistent with a wide angular divergence and ~XX% of hot-electron energy deposited as preheat in the inner shell layer.

See also A. A. Solodov, this conference.