Understanding Raman Scattering in NIF Ignition Experiments

D. J. Strozzi, D. E. Hinkel, E. A. Williams, R. P. J. Town,
P. A. Michel, L. Divol, R. L. Berger, J. D. Moody
Lawrence Livermore National Lab

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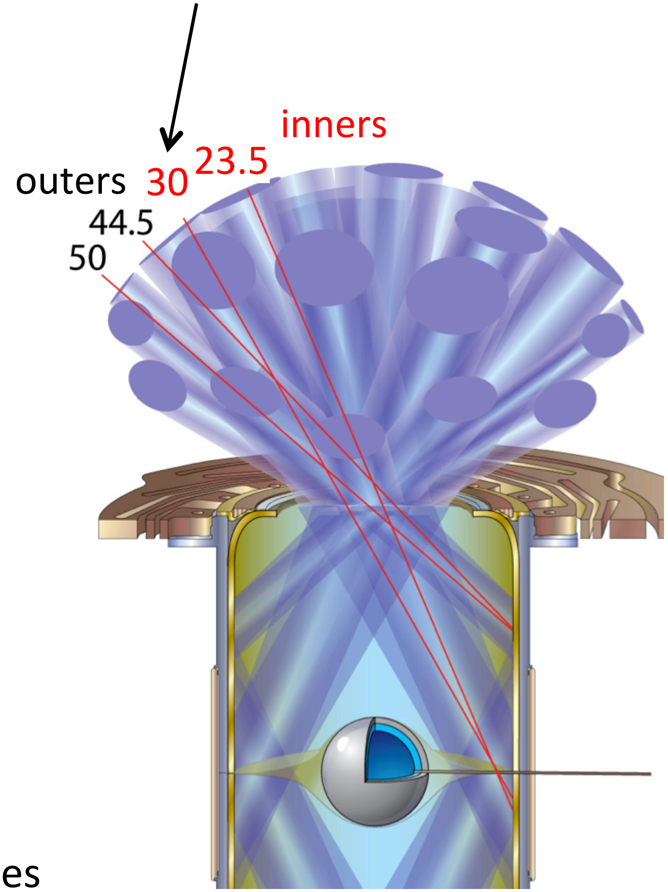
Linear gain analyses better match reflectivity trends with improved plasma and laser beam models

- **"High Flux Model" (HFM)** for rad-hydro:
  - DCA opacities, 0.15 electron heat flux limiter
  - Cross-beam energy transfer (linear model with clamp)
  - Measured backscatter removed
- **Linear gain spectrum** with HFM plasma conditions:
  - Close to measured SRS wavelength
  - Agreement better if multi-quad (overlapped beam) laser intensity used, rather than single-quad
- **Gain and reflectivity time histories:**
  - Gain increases in time, while reflectivity first increases and then decreases late in peak power
- **Spatially non-uniform cross-beam energy transfer:**
  - Gain decreases late in peak power, like measured reflectivity
- **Electron trapping:** pF3D simulations give SRS Langmuir waves above threshold for trapping nonlinearities

30° cone diagnostics:

FABS: full aperture backscatter station

NBI: near-backscatter imager

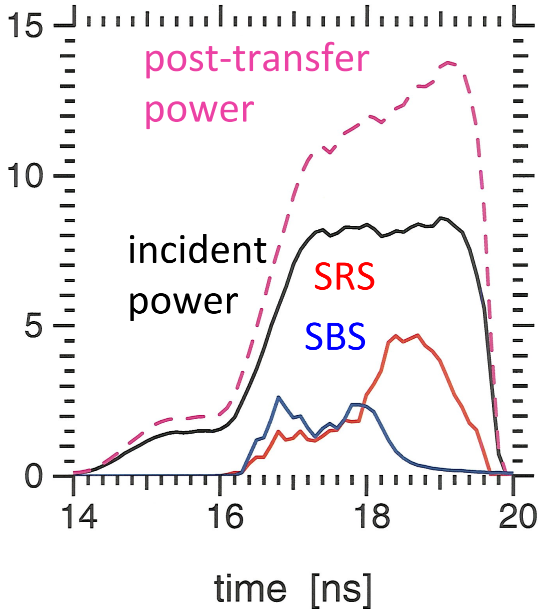


We study NIF shot N110214 - symmetry capsule (symcap) with ~1.3 MJ laser energy - 30° (inner) cone

- "Post-transfer" reflectivity = measured SRS / Lasnex power w/ cross-beam transfer.

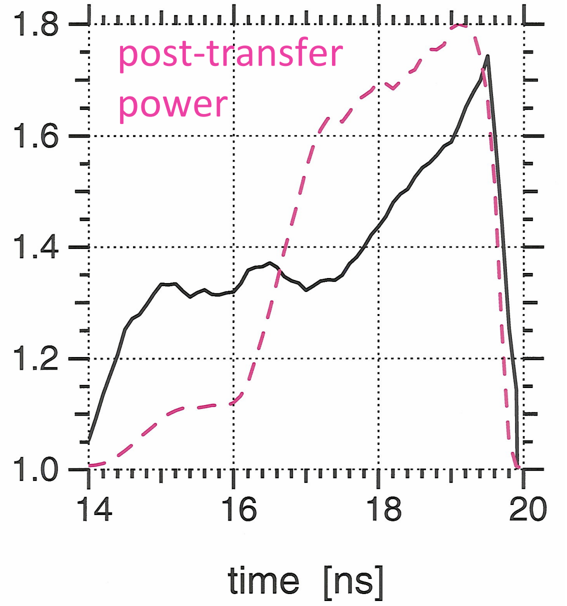
- SRS energy reflectivity [joules out / joules in]:
  - Incident power: 27%
  - Post-transfer power: 19%

Power on one quad [TW]

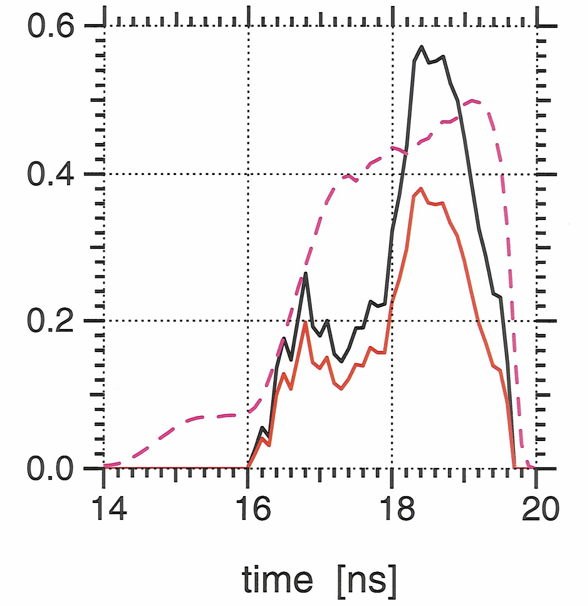


post-transfer power

incident power

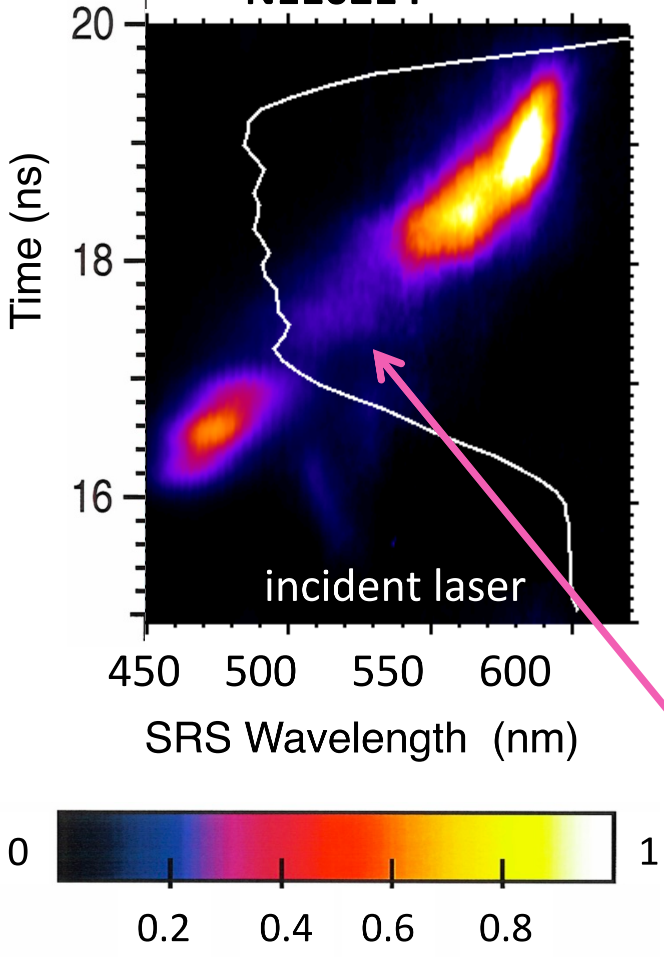


SRS reflectivity:
nominal, post-transfer

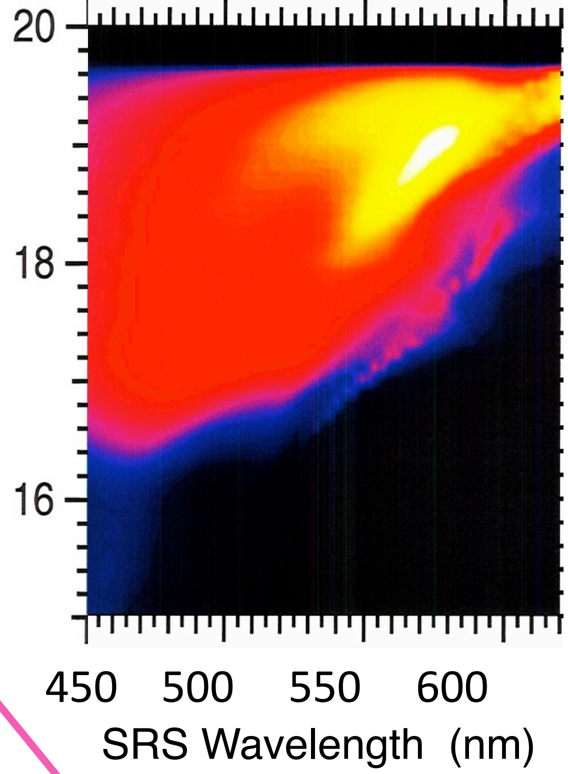


SRS wavelength increases in time, indicating SRS occurs at progressively higher density

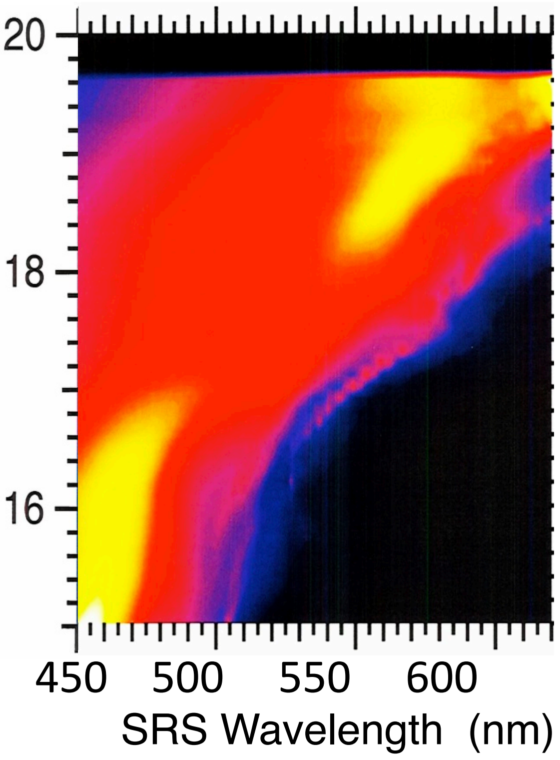
Measured SRS FABS spectrum N110214



multi-quad SRS gain: overlapping beams' intensity



"Specific gain"*: gain / LEH intensity

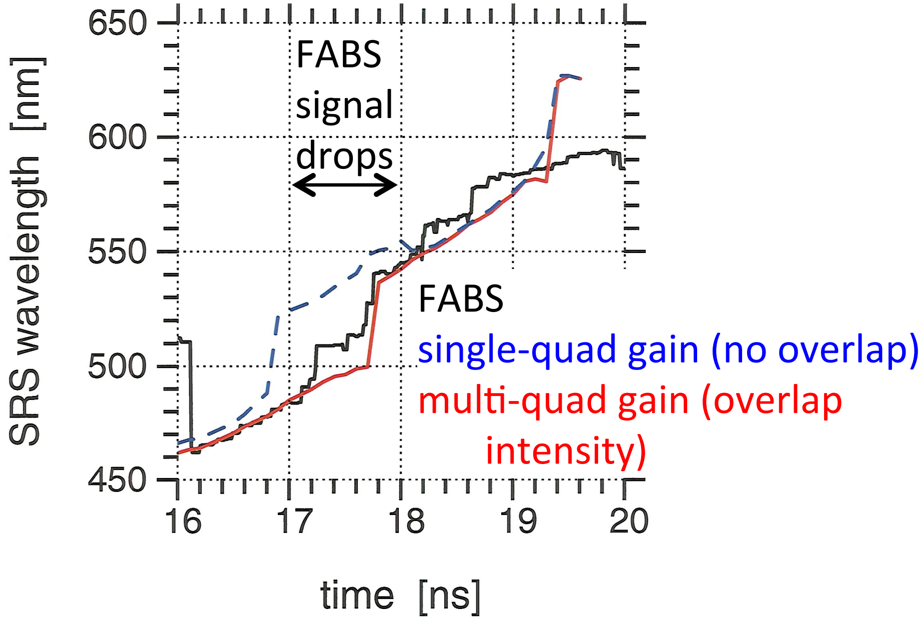


Drop in FABS signal due to motion of SRS light out of detector – total (FABS+NBI) SRS doesn't drop. [J. Moody, prior talk]

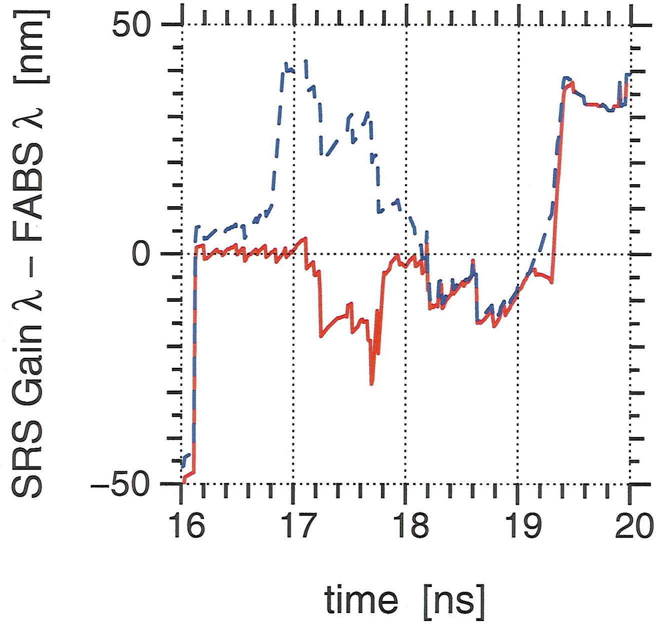
FABS = full aperture backscatter station
NBI = near-backscatter imager

*Suggested by L. Suter

With HFM (high-flux model), wavelength of peak multi-quad gain agrees well with FABS, indicating plasma conditions are ~ right



Wavelength of max FABS or gain spectra



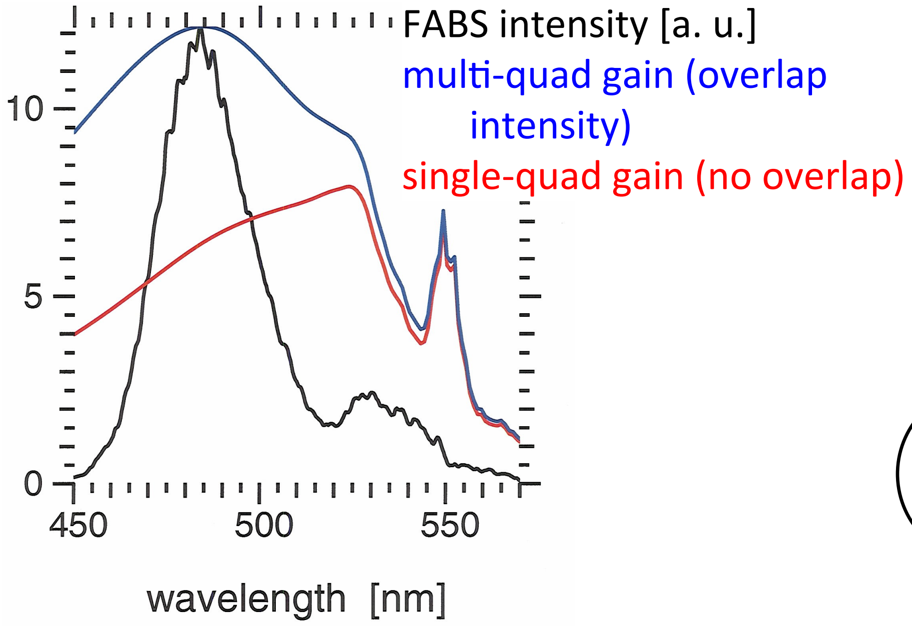
Gain wavelength – FABS wavelength

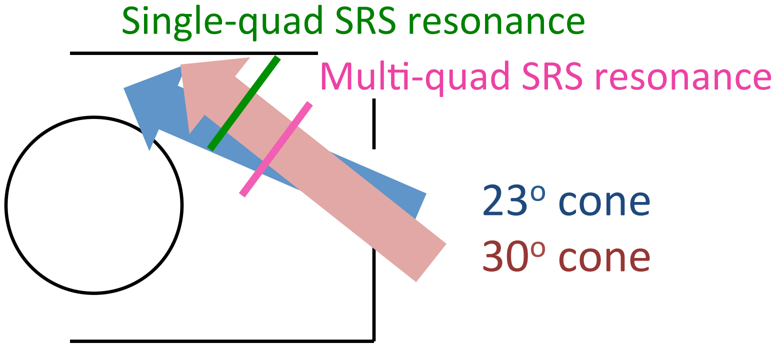
- Wavelength of max SRS separates power history from plasma conditions.

- Early peak power: 17-18ns:
  - Single-quad gains peak at a longer wavelength.
  - FABS signal reduced due to motion of SRS.
  - longer wavelengths refract more, so FABS light may be shorter wavelength than total SRS light.

Multi-quad SRS gains peak at shorter wavelength since beams overlap near laser entrance hole

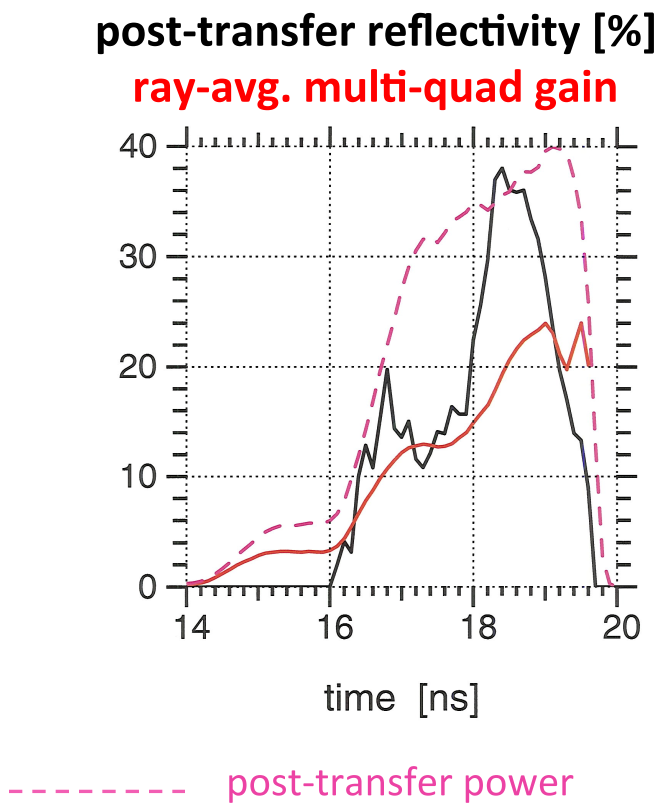
time = 17 ns:
early peak power





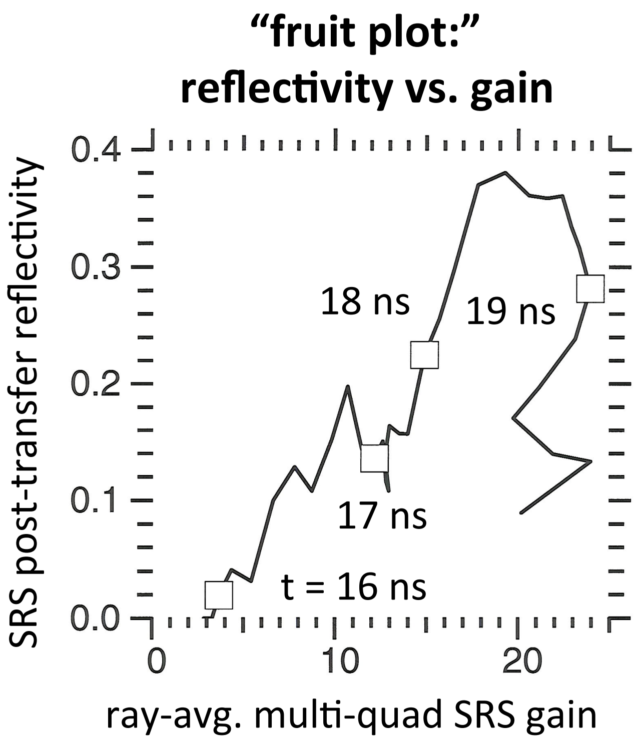
Multi-quad SRS gains peak at shorter wavelength than single-quad gains:
beams overlap more near the LEH, where the electron density, and plasma frequency, is lower.

Spatially uniform transfer: reflectivity scales with gain until late in peak power



post-transfer reflectivity [%]

ray-avg. multi-quad gain



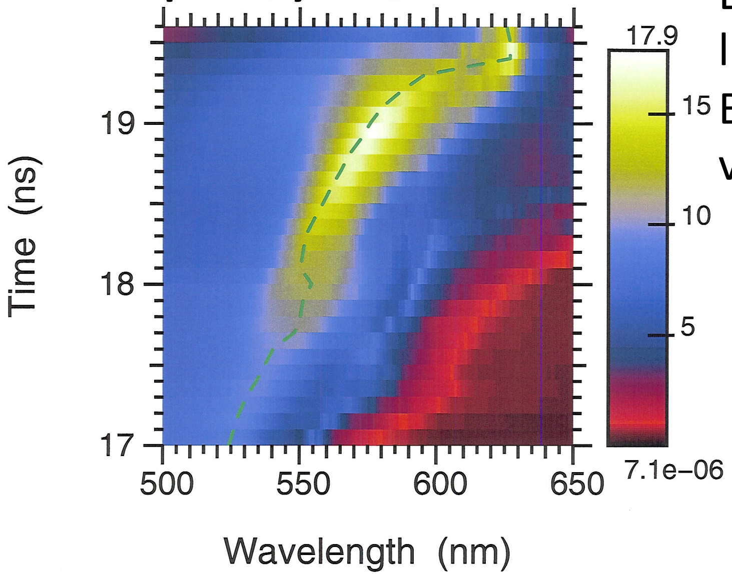
"fruit plot:" reflectivity vs. gain

- Gain tracks reflectivity until ~ 18.5 ns (mid-late peak power).
- At late time, reflectivity drops but gain doesn't.
- Late-time gain coming from long wavelengths - generally not observed in FABS.

More detailed calculations of cross-beam transfer introduce spatial non-uniformity in the intensities

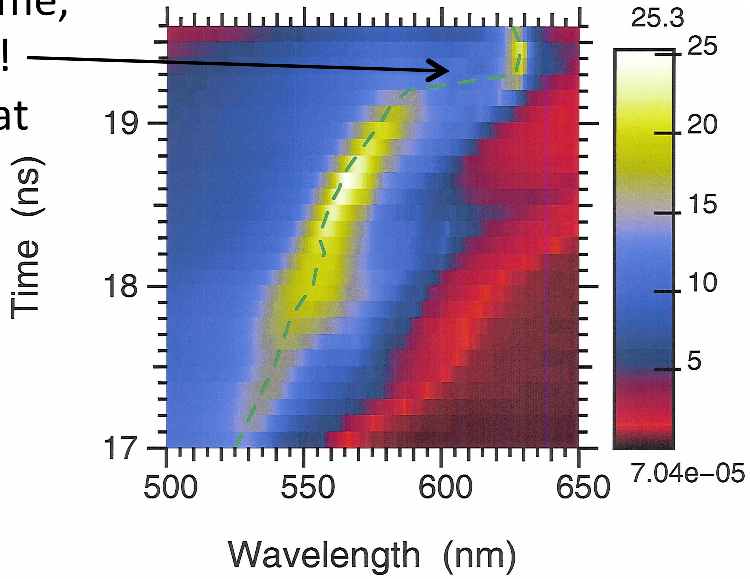
- Current HFM: distributes transferred power uniformly across the beam
- Account for spatial non-uniformity: run SLIP at one time (18 ns): E. A. Williams, later talk
- Provides 3D spatial beam intensity multiplier. Use this mask at all times
- Calculate SRS gain with spatially non-uniform transfer, and single intensities

single-quad SRS gain, spatially uniform xfer



Drops late in time, like reflectivity! But has “blip” at very end.

single-quad SRS gain, spatially non-uniform xfer

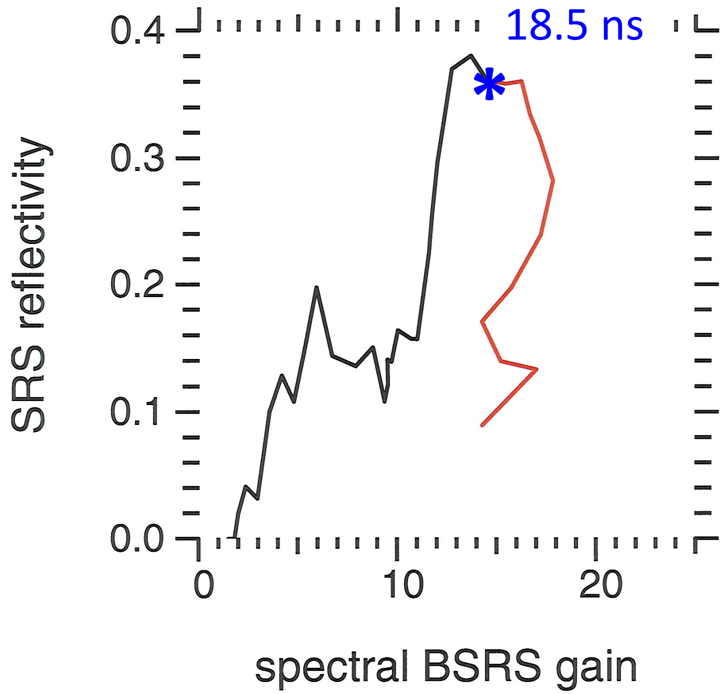


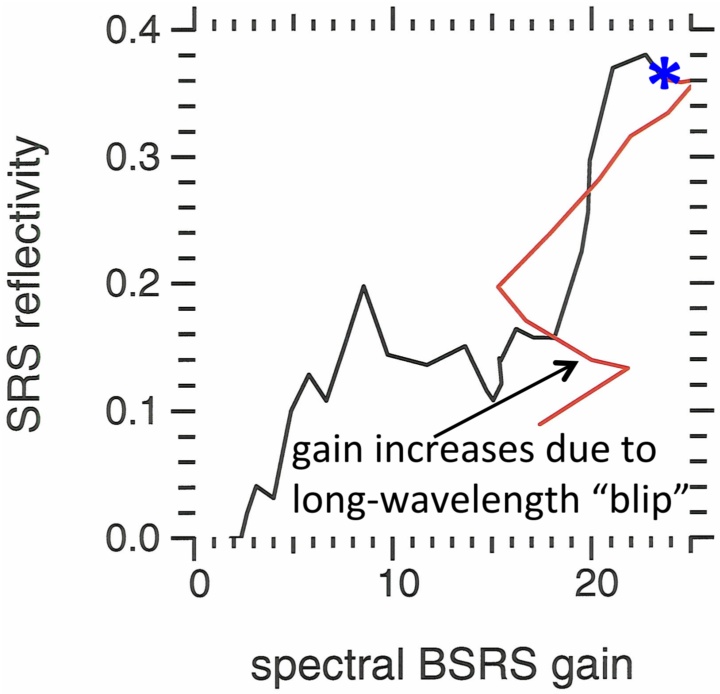
The spatial non-uniformity of cross-beam transfer improves the correlation between SRS and gain

SRS gain with spatially non-uniform beam transfer tracks reflectivity better than with uniform transfer

Uniform Transfer

Non-uniform Transfer

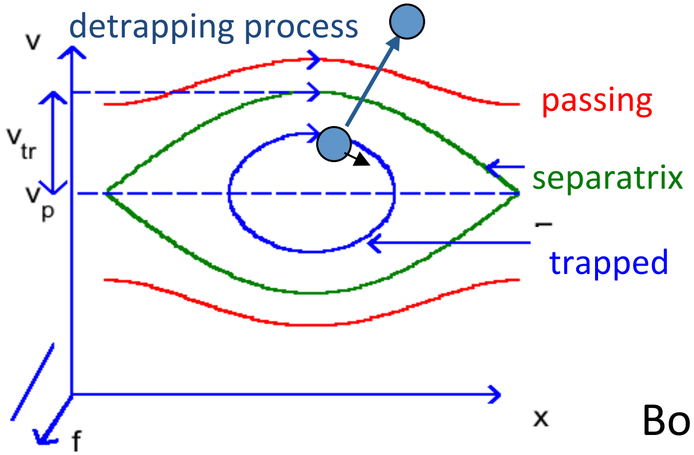




gain increases due to long-wavelength “blip”

Threshold for electron trapping nonlinearity given by “bounce number” N_B

- **Electron trapping nonlinearities**:
  - Landau damping reduction, frequency shift, Langmuir-wave self-focusing.
  - Effective only if electrons resonant w/ Langmuir wave complete ~ 1 bounce orbit before being detrapped.



Important detrapping processes:

1. Speckle sideloss (geometric effect): $N_{B,sl}$
2. Collisions: electron-electron and electron-ion treated together: $N_{B,coll}$

(SSD way too slow to matter)

Bounce number: $N_B \equiv \frac{\tau_{de}}{\tau_B} = \frac{\text{detrapping time}}{\text{bounce period}} \sim \delta n^{1/2}$

sideloss: $N_{B,sl} = \left[\frac{\delta n}{\delta n_{\mathrm{sl}}}\right]^{1/2}$ $\delta n_{\mathrm{sl}} = 2.67\left(\frac{8}{F}\frac{\lambda_{De}}{\lambda_0}\right)^2$

Bounce period: $\tau_B \equiv \frac{2\pi}{\omega_{pe}}\sqrt{\frac{n_e}{\delta n}}$

collisions: $N_{B,coll} = \left[\frac{\delta n}{\delta n_{\mathrm{coll}}}\right]^{3/2}$

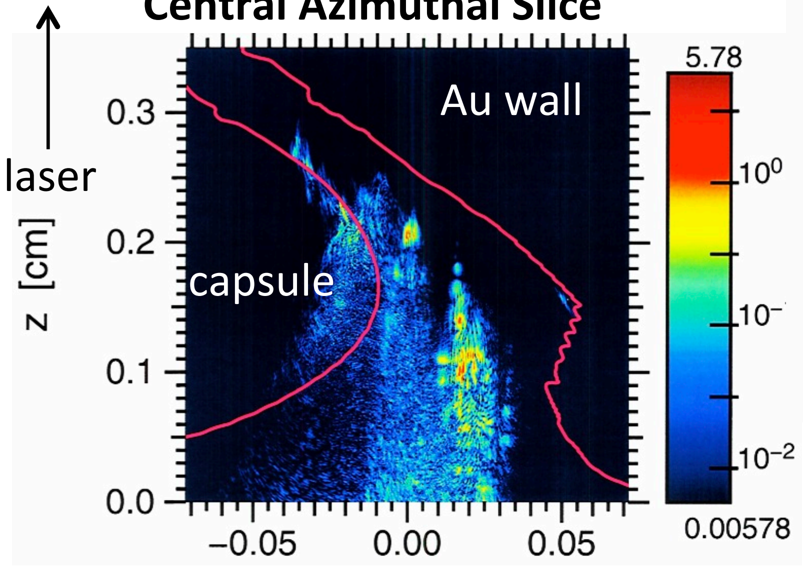
Joint bounce number: $N_B^{-1} = N_{B,sl}^{-1} + N_{B,coll}^{-1}$ Independent detrapping rates add.

Trapping assessment of pF3D run suggests trapping occurs in parts of the 30 degree beam

pF3D:
- parallel, paraxial envelope code
- linear plasma response used

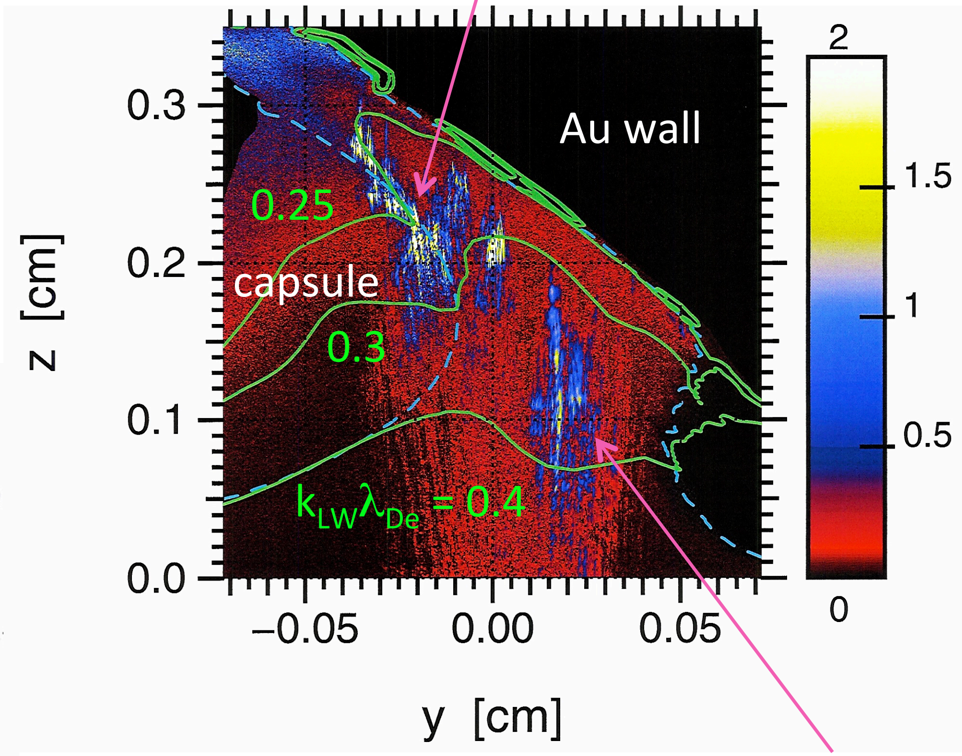
N110214 profiles, time = 18 ns:
- Trapping can change the local gain
- pF3D SRS reflectivity ~ 20%

SRS Intensity
Central Azimuthal Slice



Risk of trapping or Langmuir Decay Instability

bounce number $N_B \sim [\delta n_{LW}]^{1/2}$
(sideloss and collisions)



Risk of trapping

Conclusions

- "High Flux Model" rad-hydro with spatially uniform cross-beam energy transfer:
  - SRS gain spectrum agrees well with measurements
  - Especially when multi-quad laser intensity used
  - Except for long-wavelength gains late in time – not seen in experiments

- Spatially uniform transfer: reflectivity and gain correlate until late in peak power
  - Late in time, reflectivity drops but gain does not

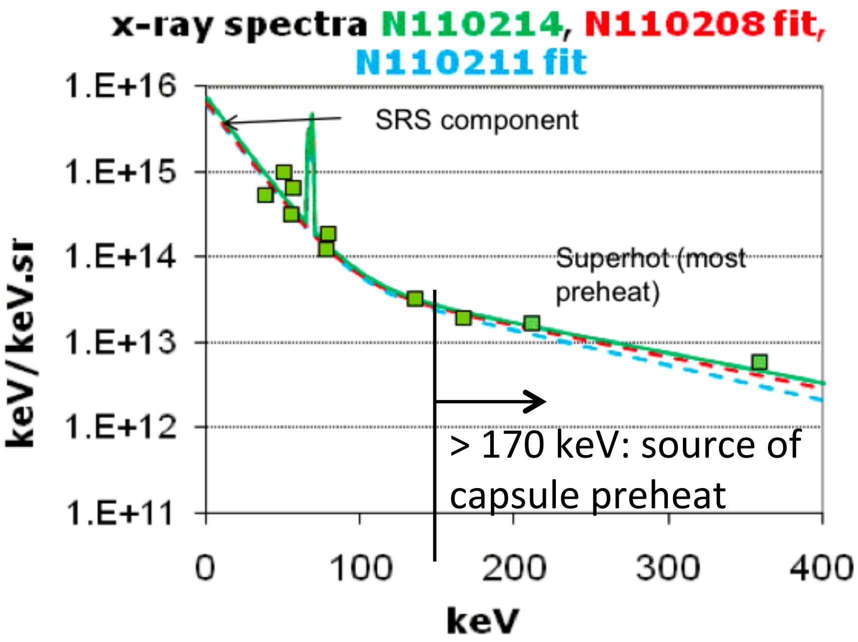
- Spatially non-uniform transfer: the correlation of reflectivity and gain improves

- Electron trapping: pF3D simulation shows regions in the beam where Langmuir wave amplitudes above threshold
  - May play a role in some of the SRS seen

A cross-beam transfer model, including spatial non-uniformity and plasma profile modification, is being added to Hydra

Backup slides after here

Observed SRS is consistent with the colder component of the hot electron spectrum



> 170 keV: source of capsule preheat

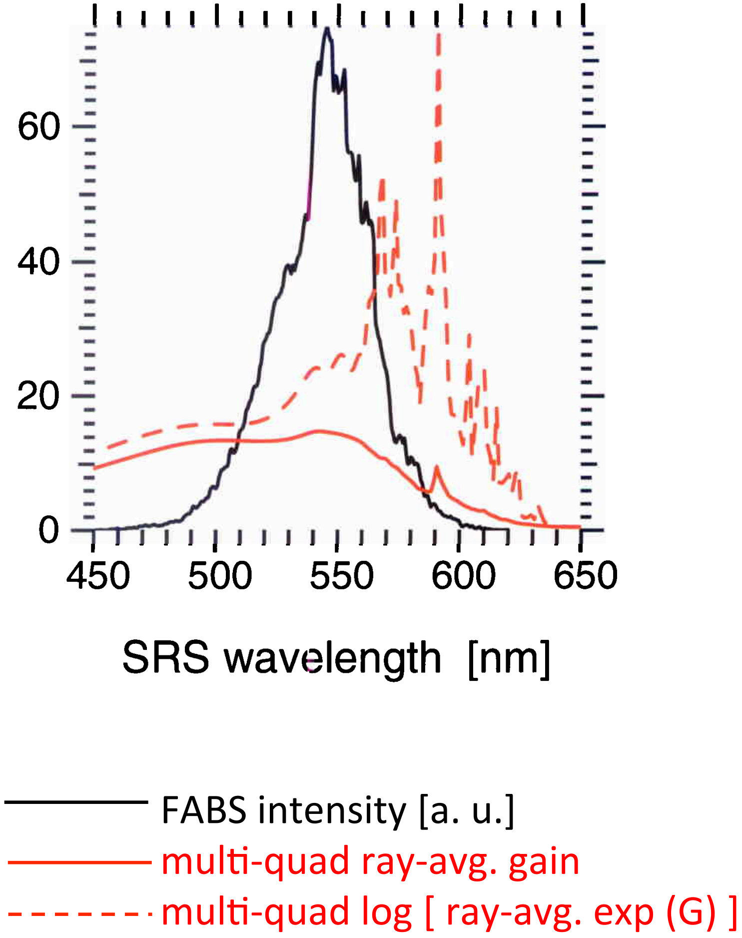
$$\frac{dN}{dE} \sim \frac{E_1}{T_1^2}\exp[-E/T_1] + \frac{E_2}{T_2^2}\exp[-E/T_2]$$

“SRS component”:
E_1 = 70 kJ, T_1 = 18 keV
0.5 $m_e v^2_{ph,LW}$ = 18 keV for λ_{SRS} = 570 nm
“conventional” backward SRS, measured in FABS/NBI

“Superhot component”:
E_1 = 0.8 kJ, T_1 = 124 keV
independent LPI process, such as: two-plasmon decay, backward SRS at $n_{crit}/4$, forward SRS, …

Significant gain can occur at longer wavelengths than measured on FABS

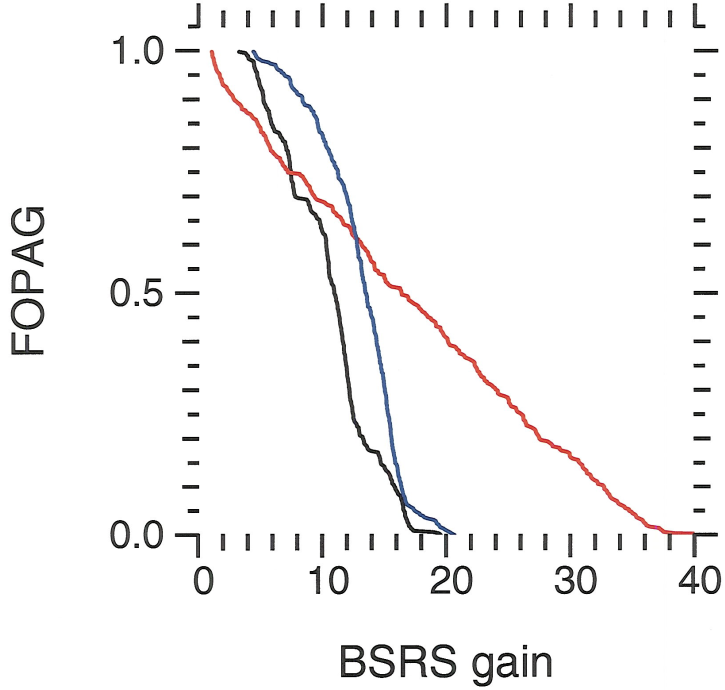
time = 18 ns – mid peak power



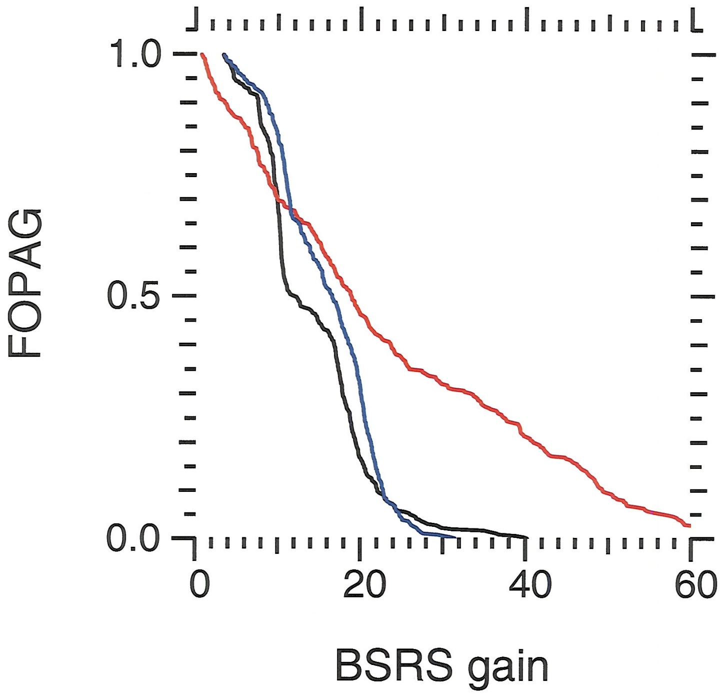
- Long-wavelength SRS washed out in ray-averaging, since each ray has a narrow peak (weak damping) at a different wavelength.
- Long-wavelength SRS may not occur: shorter-wavelength SRS occurs at lower density, nearer the LEH, and may deplete the pump.
- If it does occur, it will be more refracted than shorter-wavelength light [c.f. J. Moody's talk] and may miss the FABS detectors.
- Also, it will be more absorbed in the target by inverse bremsstrahlung.

Spatially varying beam transfer gives a wider distribution of ray gains

time = 17.5 ns



time = 18 ns



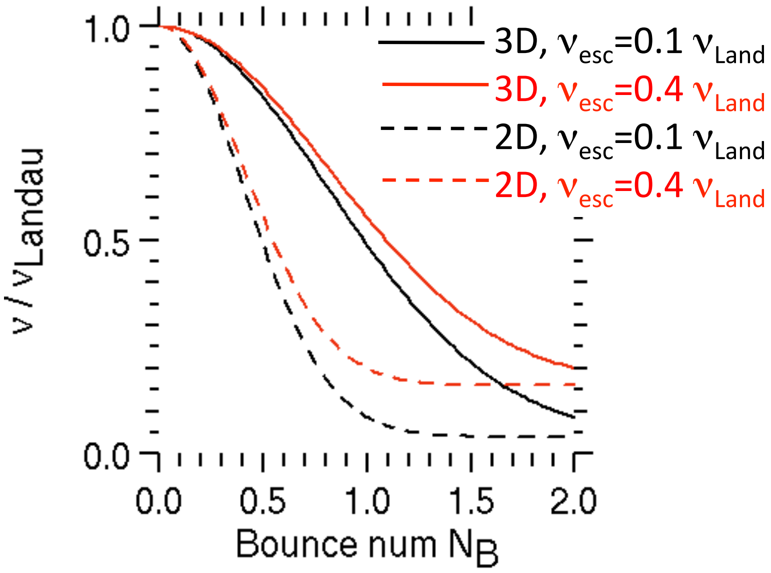
single-quad gain, uniform xfer
multi-quad gain, uniform xfer
single-quad gain, varying xfer

FOPAG = fraction of ray power above a gain.

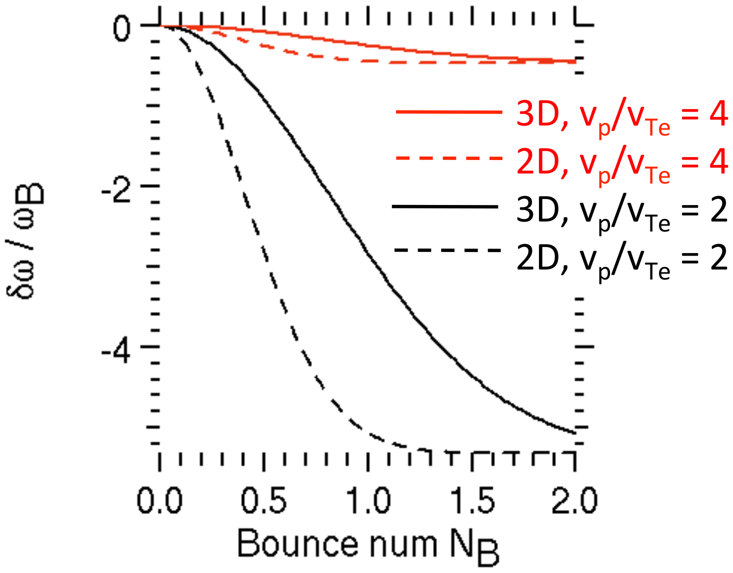
For each ray: find the max gain within λ = +- 10 nm of $<\lambda_{max}>_{avg}$.

Damping reduction and frequency shift in finite-radius Langmuir wave: theory by H. A. Rose

Damping Reduction:
more rapid in 2D than 3D



Frequency Downshift:
rapidly increases with $k\lambda_D$



Fraction of coupling above a bounce number: allows quantification of trapping

$$\frac{dE_{scat}}{dt}\Big|_{coup} \propto E_{las}\delta n_{epw}$$