Inline Modeling of Cross-Beam Energy Transfer and Raman Scattering in NIF Hohlraums

Anomalous Absorption Meeting

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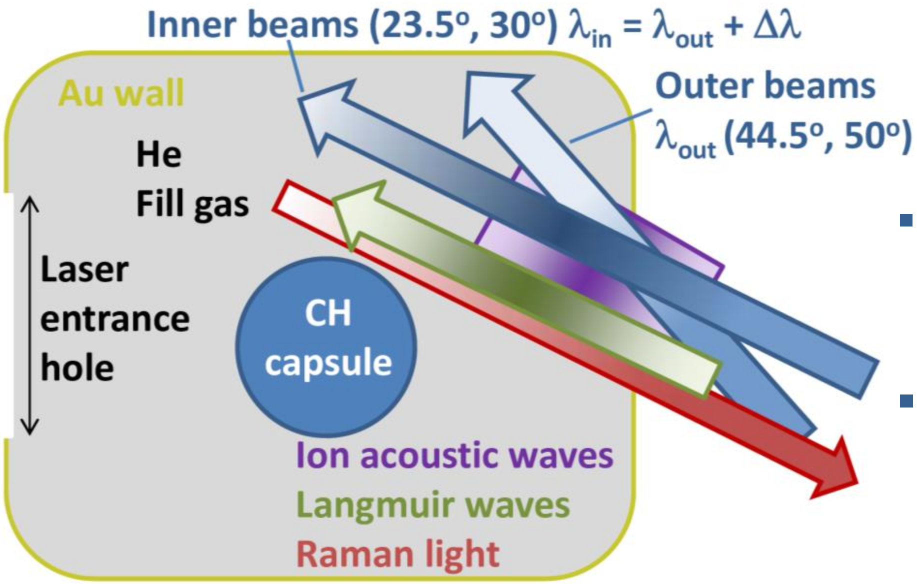
Hohlraum laser plasma interaction is "rich, complex physics:" hard to model!



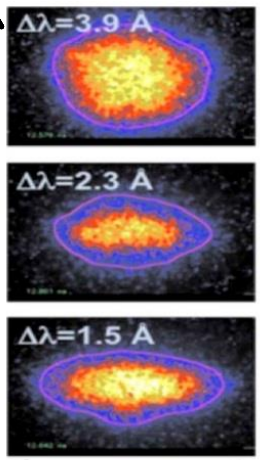
- **Important for high hohlraum fill density**
  - Low-foot, high-foot designs
- **Cross-Beam Energy Transfer (CBET)**
  - Form of Brillouin scattering
  - Laser 1 γ → Laser 2 γ + ion acoustic wave
  - To lower frequency laser in plasma frame
- **Stimulated Raman scattering (SRS)**
  - Laser γ → scattered γ + Langmuir wave
- **Stimulated Brillouin scattering (SBS)**
  - Laser γ → scattered γ + ion acoustic wave

CBET and SRS impact implosion shape

Hotspot x-ray image (2009 shots)

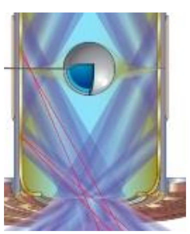
$\Delta\lambda = \lambda_{in} - \lambda_{out}$:
CBET to inners

Prolate: 'Sausaged'



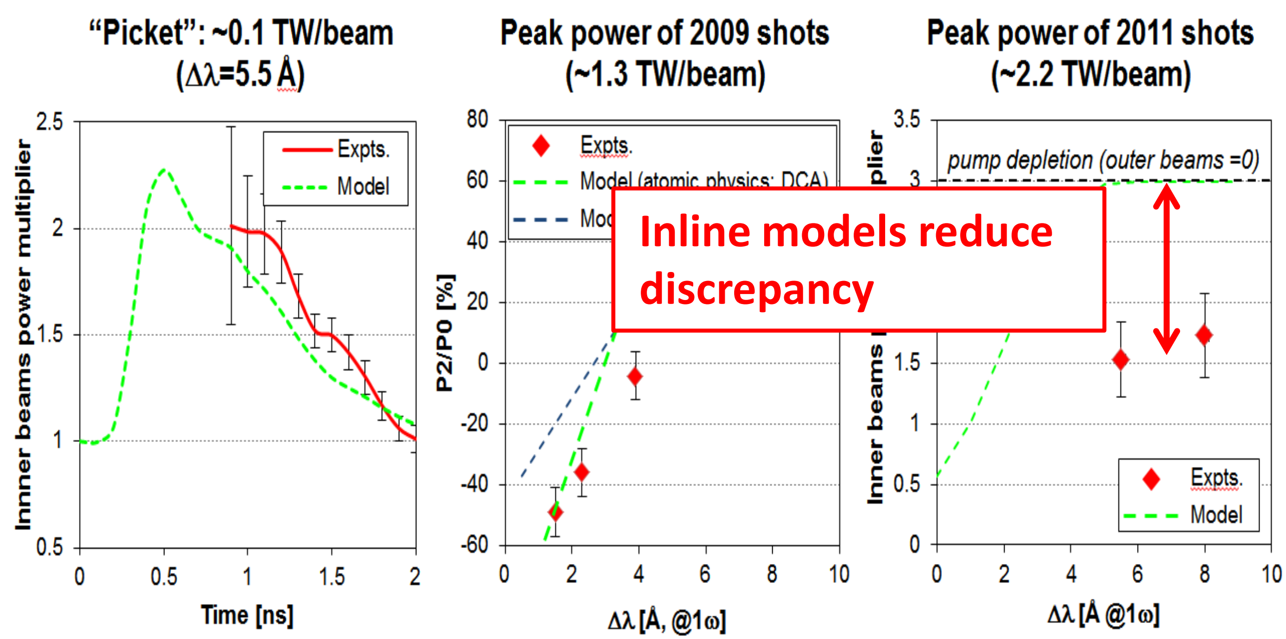
Oblate: 'Pancaked'

Hohlraum axis



2012 APS DPP Excellence in Plasma Physics Award

Agreement with linear model for CBET gets worse as laser power and Δλ keep increasing



Slide courtesy P. Michel, Anomalous Absorption 2013

Inline LPI models improve agreement with modeling and reveal SRS dynamics

Old script-based process

1. Rad-hydro run: no CBET, no backscatter removed
1. CBET post-processing script [P. Michel]
1. 2nd rad-hydro run: CBET, backscatter removed

- More sausaged implosion than data
- Limit CBET: ion wave amplitude clamp $\delta n_e/n_e$

Inline CBET, SRS removed at lens

- CBET calculated internally
- Ion wave energy deposition

Versus script:

- Picket: less CBET, due to inverse brem.
- Peak power: less CBET, due to SRS removed from inners

Inline CBET and SRS

- Pump laser depleted in target
- Langmuir-wave deposition
- Inverse brem. of SRS light

Inline SRS results:

- Langmuir waves driven near laser entrance
- LEH hotter: reduces CBET
- More polar x-ray drive
- Less sausaged implosion

HYDRA simulations

LASNEX simulations

Inline model: coupled-mode equations along laser rays: steady state, strong damping limit

Inverse brem. absorption

SRS coupling

CBET to other lasers

Laser 0

$$\partial_z I_0 = -\kappa_0 I_0 - \frac{g_R}{\omega_R} I_0 I_R - \sum_{i=1}^{23} \frac{g_{Ci}}{\omega_i} \min[I_0 I_i, \alpha_i \sqrt{I_0 I_i}]$$

SRS light

$$-\partial_z I_R = -\kappa_R I_R + \frac{g_R}{\omega_0} I_0 I_R$$

$$p_L = \frac{\omega_L}{\omega_0 \omega_R} g_R I_0 I_R$$

SRS Langmuir wave

$$p_{Ai} = \frac{\omega_{Ai}}{\omega_0 \omega_i} g_{Ci} I_0 I_i$$

CBET acoustic wave

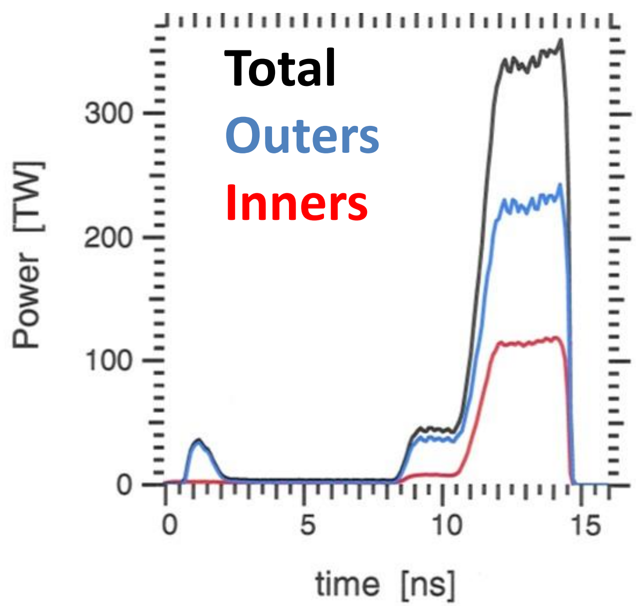
- **CBET Ion wave saturation clamp δn_e^{sat}:**

$$\delta n_e \propto \min\left[\sqrt{I_0 I_1}, \delta n_e^{sat}\right]$$

Inline models applied to NIF shot N121130: early "high-foot" plastic symcap

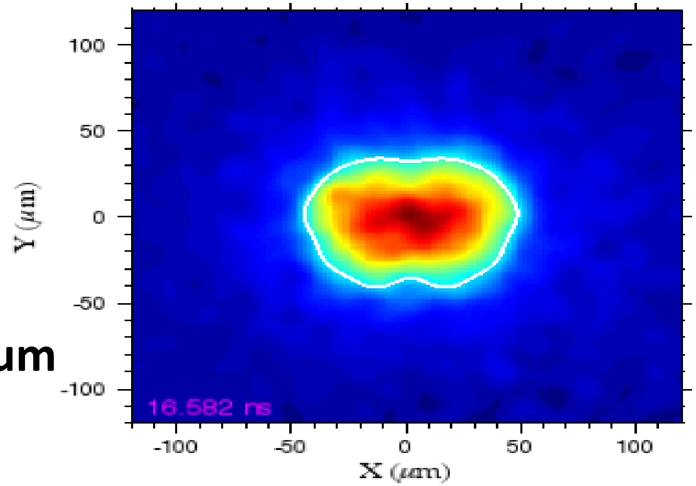
- E_{laser} = 1270 kJ P_{laser} = 350 TW
- $(\lambda_{23}, \lambda_{30}) - \lambda_{out}$ = (8.5, 7.3) Ang.
- CBET to inners: tune polar P2 shape
- CBET to 23's: tune azimuthal M4 shape
- Fill 1.45 mg/cc He
- Gold hohlraum: "575 scale"

Laser Power

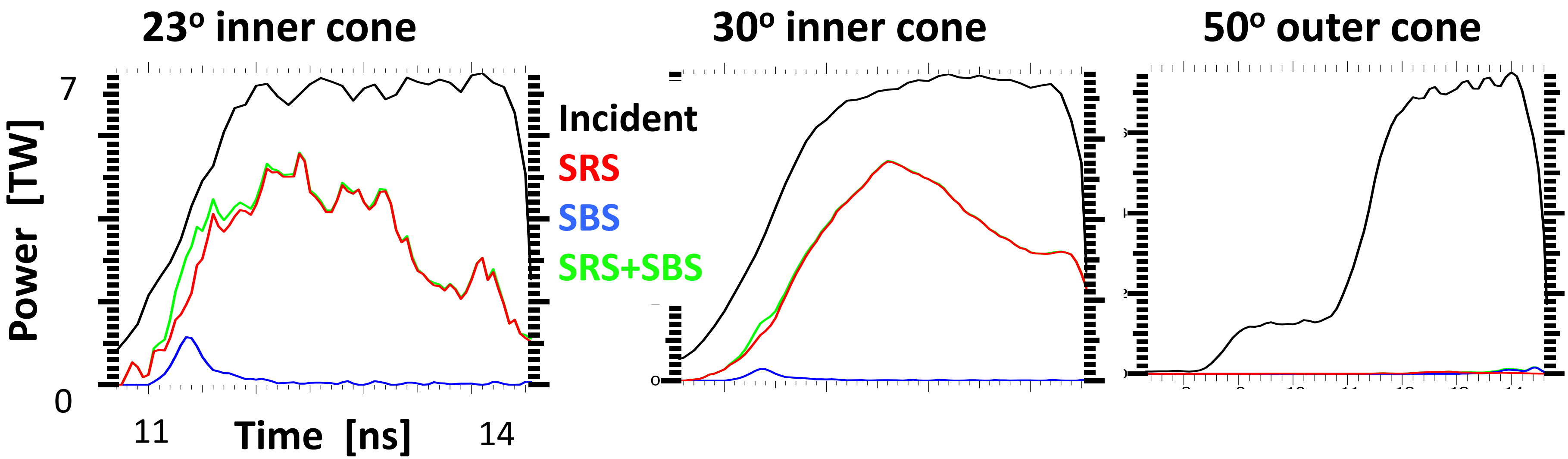


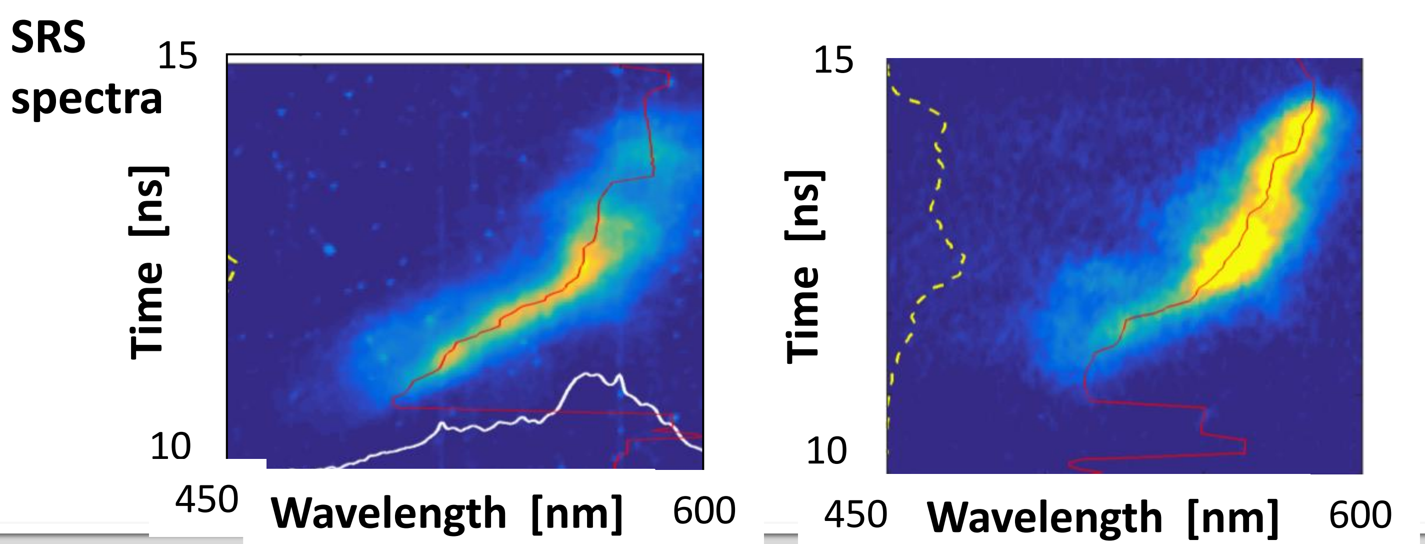
Hohlraum axis

Hotspot x-ray image: "Pancaked", P_2/P_0 = -0.12



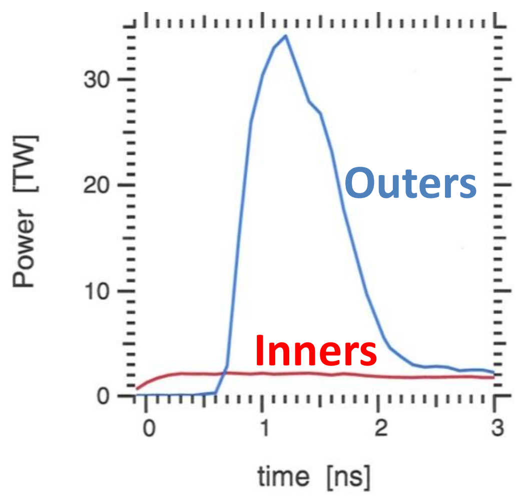
Inputs to runs: measured SRS power and maximum wavelength



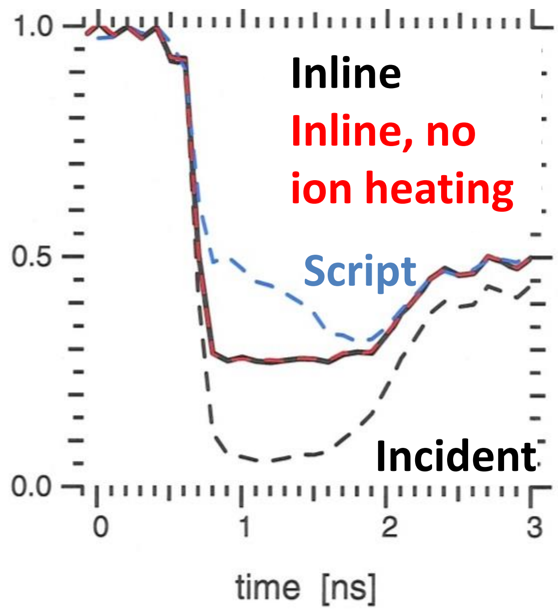


Picket: Hydra Inline CBET model gives less CBET than script, which neglects absorption

Incident power



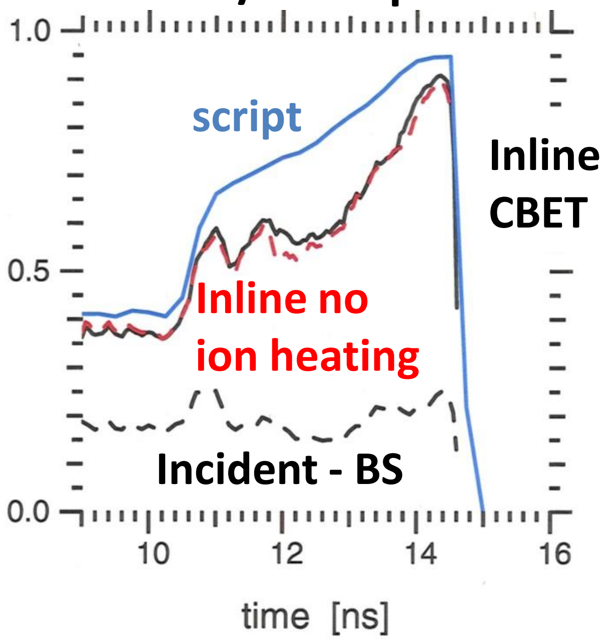
Cone fraction:
Inner / total power



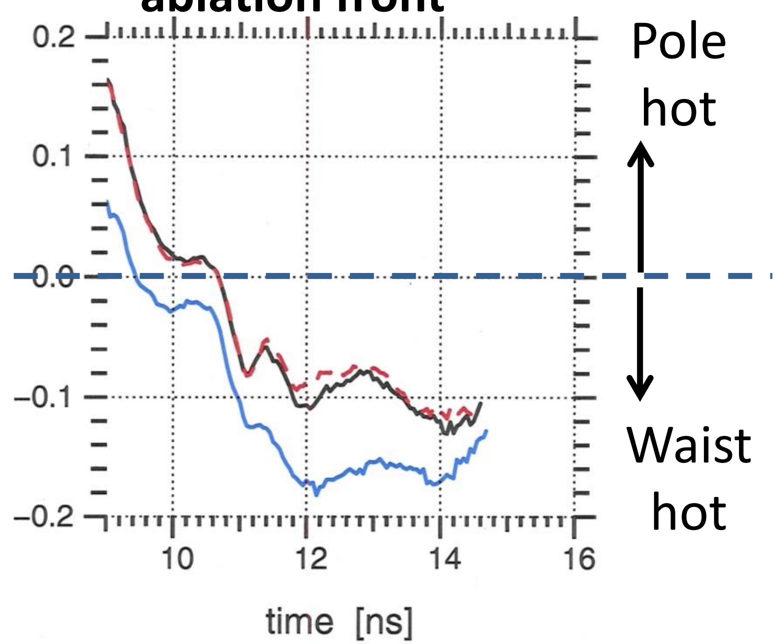
- Script neglects absorption, or else transferred power doesn't reach exit plane
- CBET clamp $\delta n_e^{sat} = 10^{-3}$ in all HYDRA runs

Peak power: inline CBET model gives less CBET than script, due to how SRS handled

Cone fraction:
Inner / total power



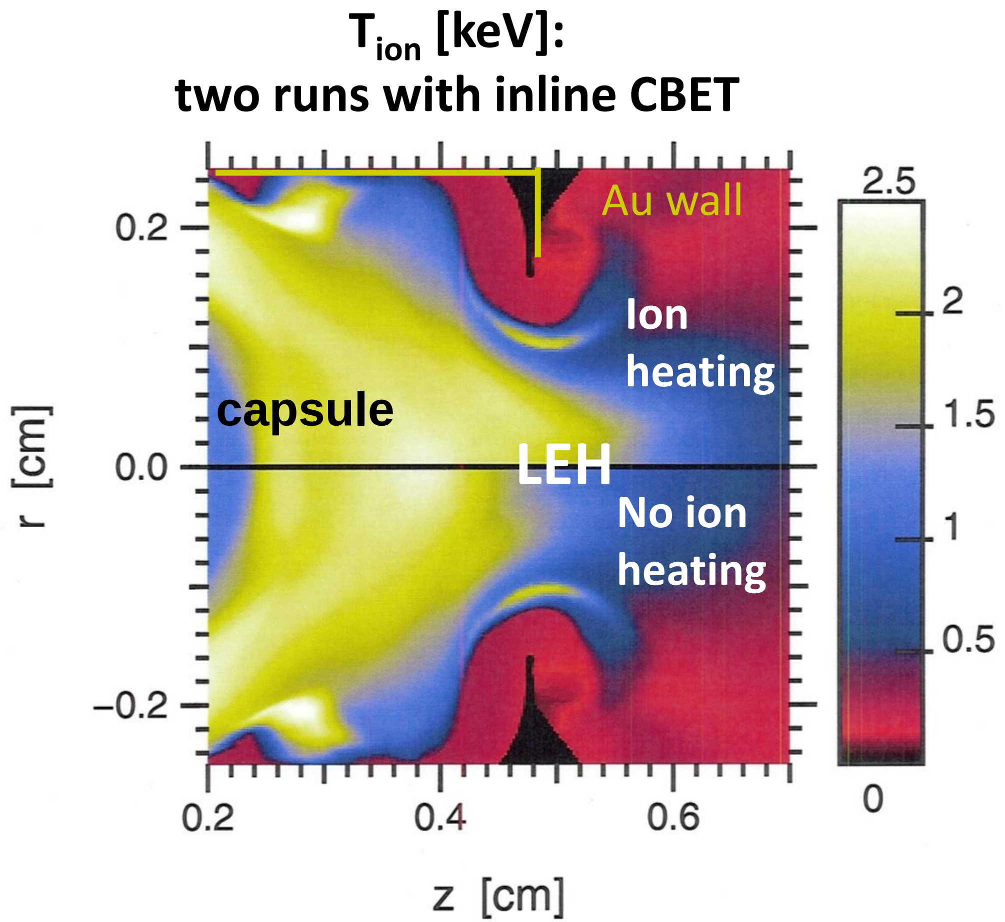
x-ray flux P2/P0 moment at ablation front

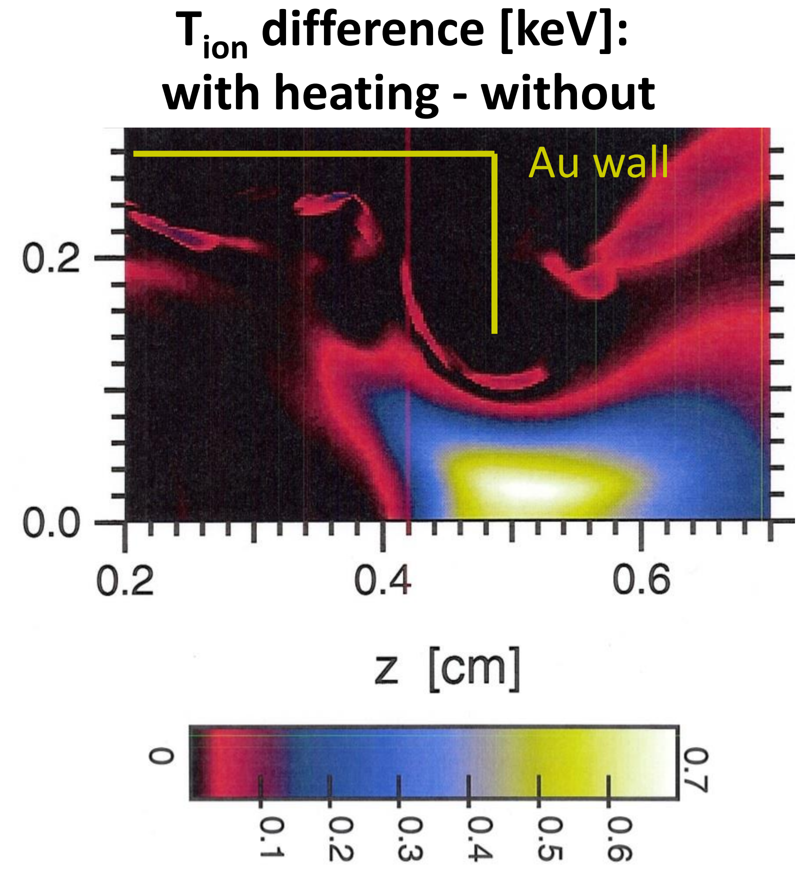


Script: more CBET for same plasma:
uses incident power, no backscatter removed

$$\partial_z I_0 = g I_1 I_0$$

Inline CBET: Ion-wave heating increases ion temperature ~ 700 eV in entrance hole





Time 14 ns: late peak power

Inline CBET: ion heating can have small effect on CBET

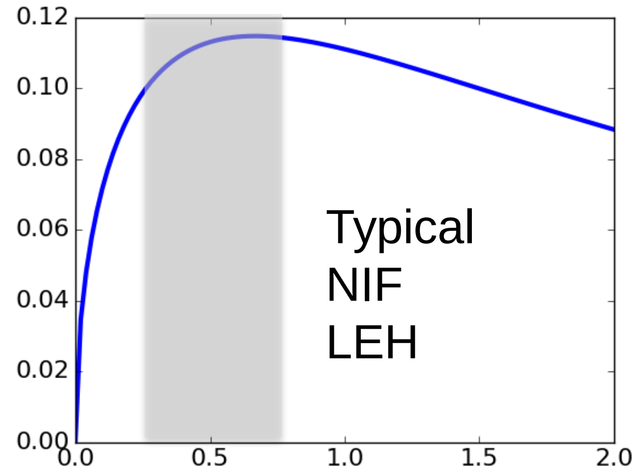
Off-resonance CBET gain rate: P. Michel et al., Phys. Plasmas 2013

$$v_{IAW} \ll v_{Ti} \ll v_{Te} \rightarrow$$

$$\partial_z I_0 \propto I_0 I_1 n_e Z \frac{T_i^{1/2}}{(T_i + ZT_e)^2}$$

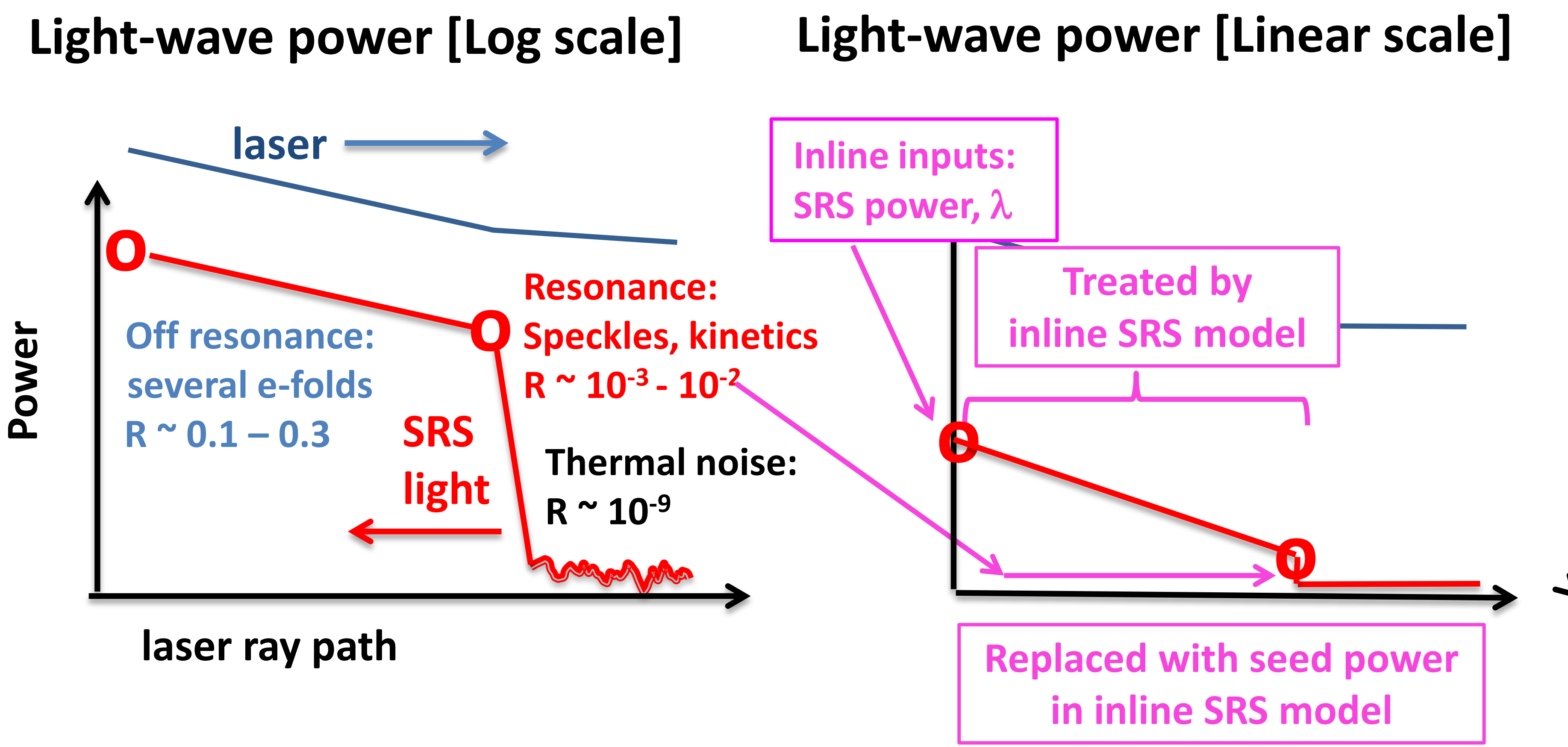
Ion heating can slightly increase CBET gain before it gradually drops

Gain rate (Z=2)



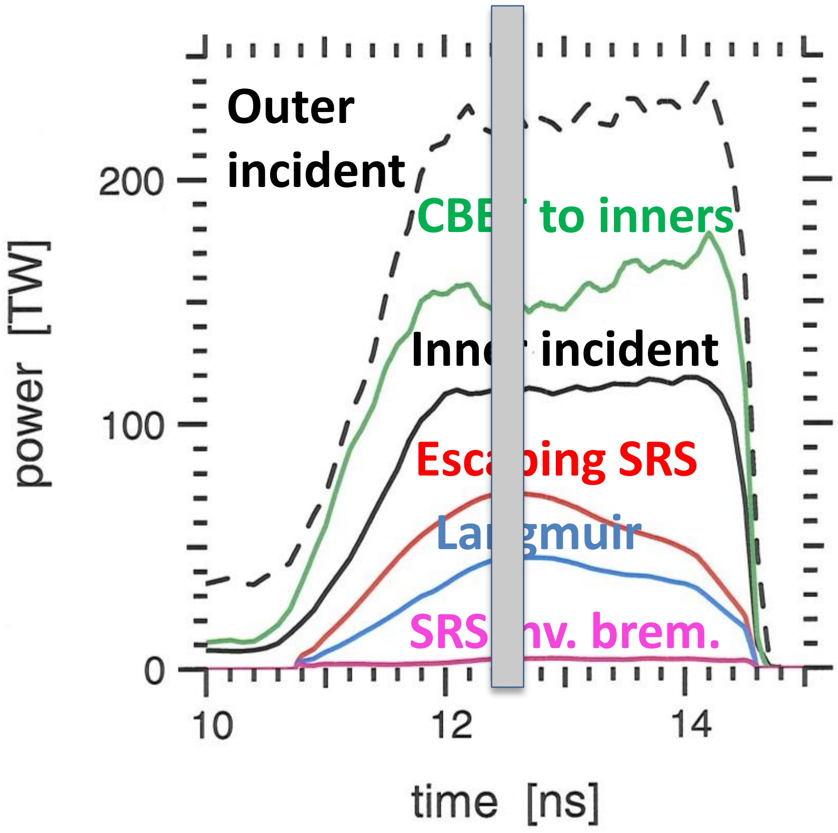
T_i / T_e

SRS exponentiates mostly on resonance, most of power growth off resonance



Inline SRS model in LASNEX: large CBET to inners, little SRS inverse brem. absorption

Peak SRS: shown on next slide



Langmuir wave energy: 119 kJ

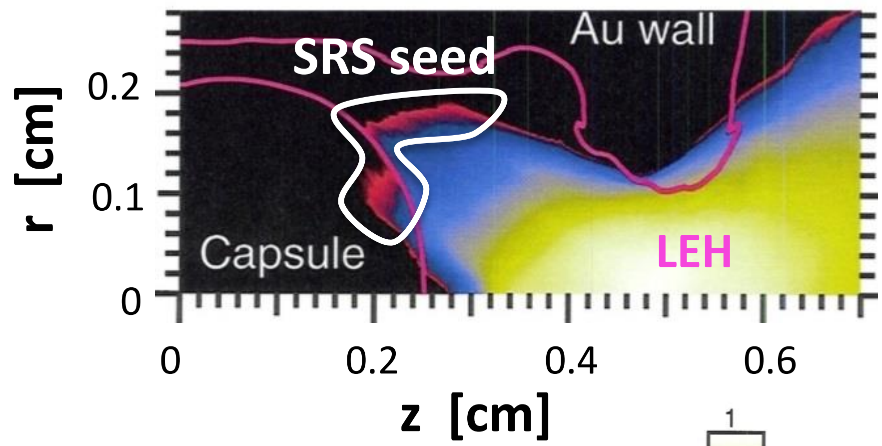
- Deposited locally in fluid T_e
- Upper bound on LEH effect
- Hot electron treatment is ongoing

- CBET clamp $\delta n_e^{sat} = 0.01$
- Approaching physical ion-wave nonlinearities: trapping, two ion wave decay

NIF high-foot shot N121130

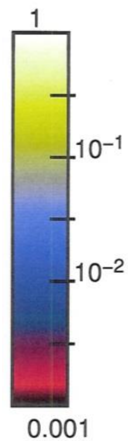
Inline SRS: Langmuir waves driven just inside entrance hole

SRS light keeps growing:
coupling > inv. brem.

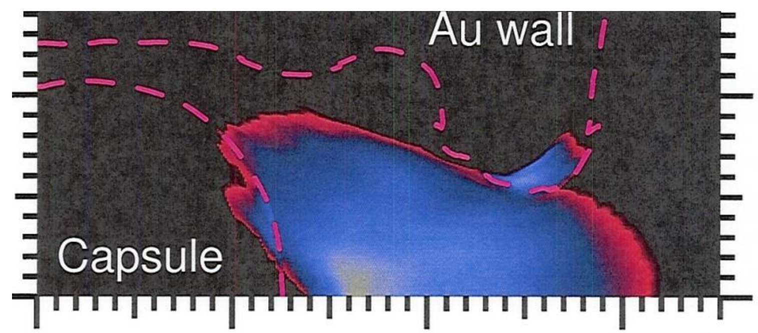


Time 12.6 ns:
peak escaping SRS power

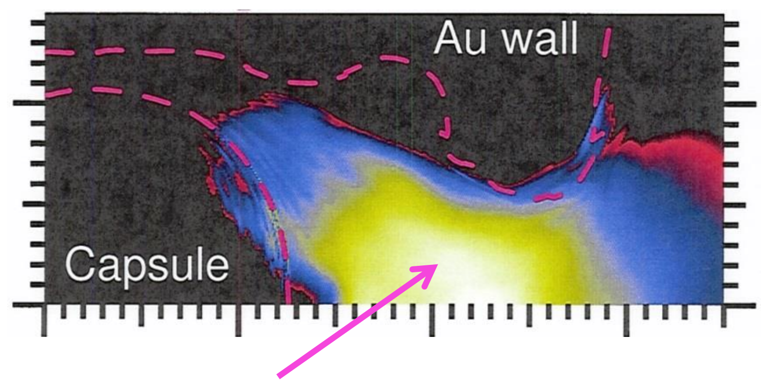
Log scale



SRS inv. brem. heating



Langmuir wave heating:
Makes LEH hotter



Conducts to wall → polar x-rays

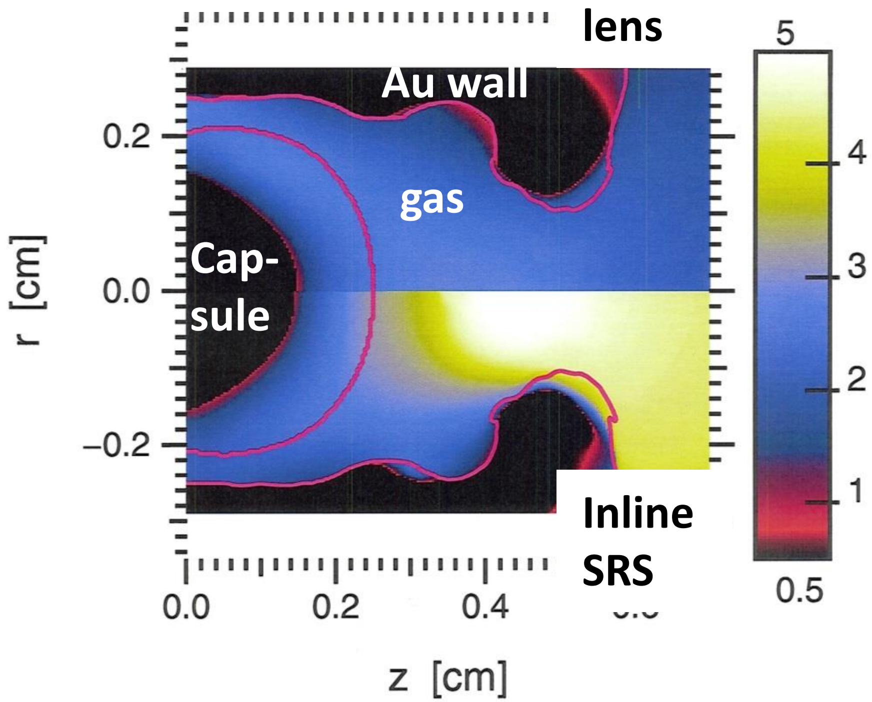
Compare inline SRS run to one with SRS removed at lens

Next slides compare two LASNEX runs:

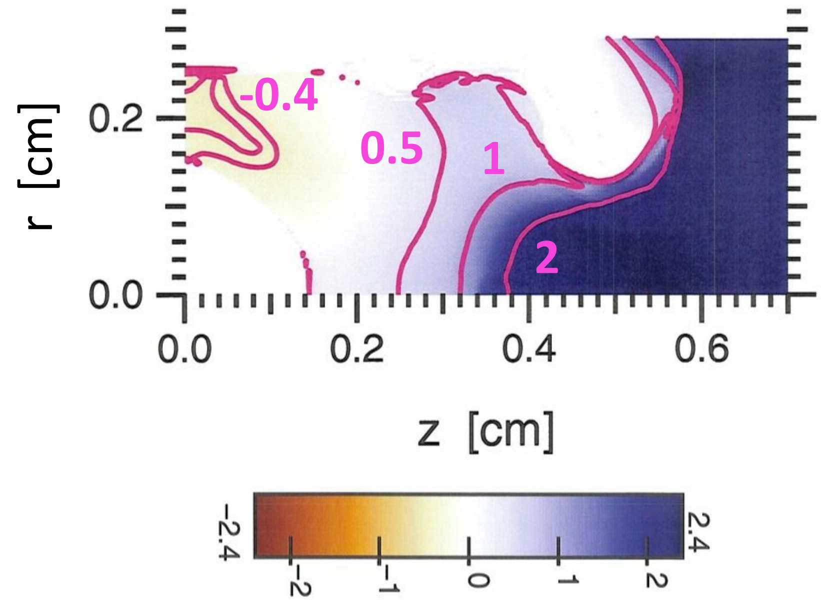
- **Same escaping SRS power**
- **Both with inline CBET, clamp $\delta n_e^{sat} = 0.01$**
- **Run 1: Inline SRS**
- **Run 2: SRS removed at lens, no SRS IB or Langmuir wave heating**

Inline SRS model increases LEH electron temperature 1 – 2 keV

T_e [keV]



T_e difference [keV]:
inline SRS – SRS at lens

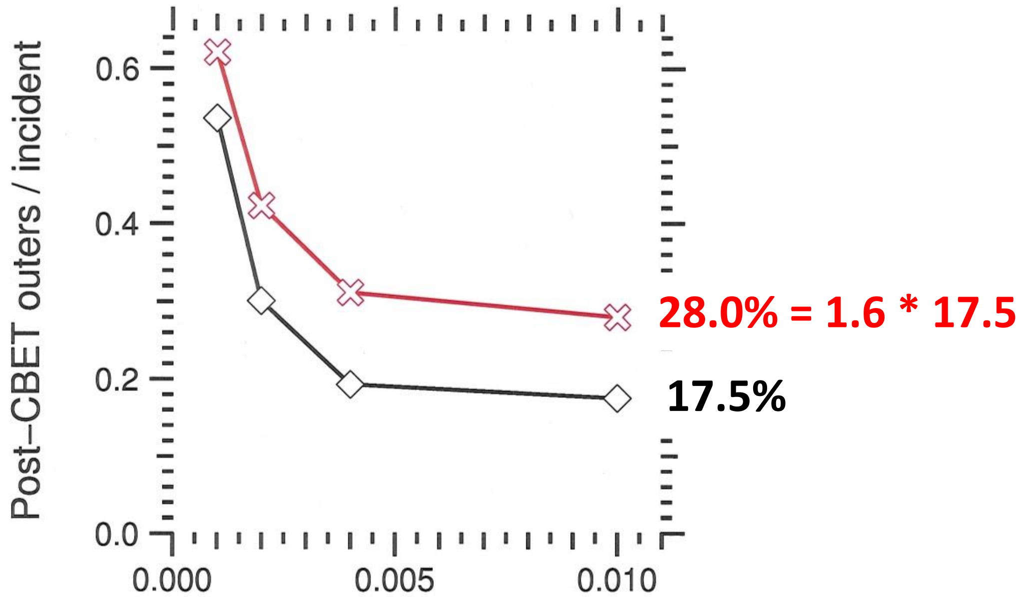


Time 12.6 ns:
peak escaping SRS power

Higher T_e reduces CBET:
off-resonant gain ~ $T_i^{1/2}/(T_i+ZT_e)^2$

Inline SRS model reduces CBET to inners, 60% more energy remains on outer beams

Post-CBET outer beam energy: 10.5 to 15 ns

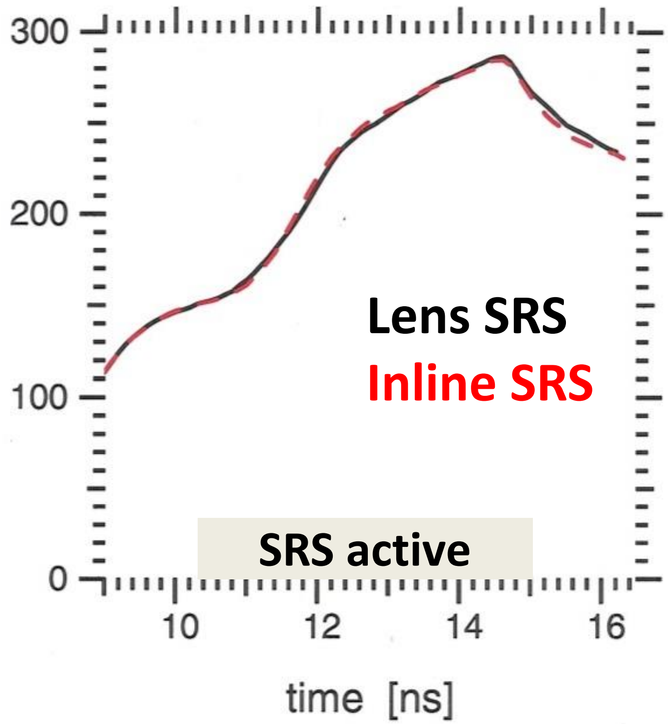


$\delta n_e^{sat}/n_e$ saturation clamp

Post-transfer outer beam power approaching finite value for large δn_e^{sat} : limited by plasma conditions, not artificial clamp

Inline SRS model has very little effect on total x-ray drive

Radiation temperature seen by capsule [eV]

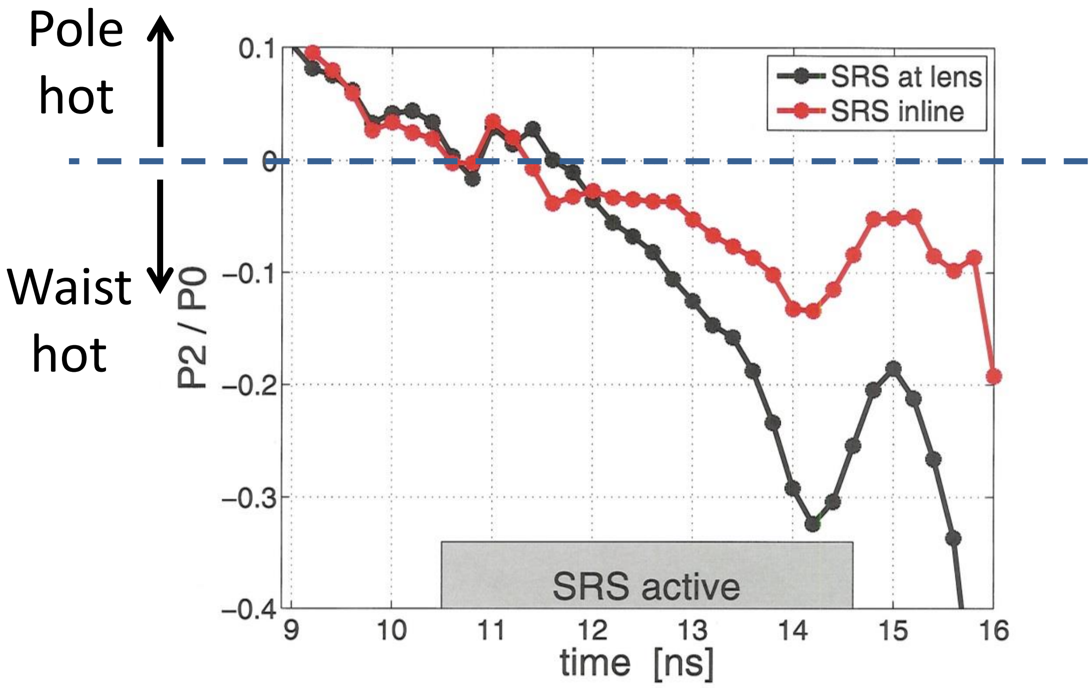


"Hohlraums are calorimeters"
– L. J. Suter

*Two curves almost overlay

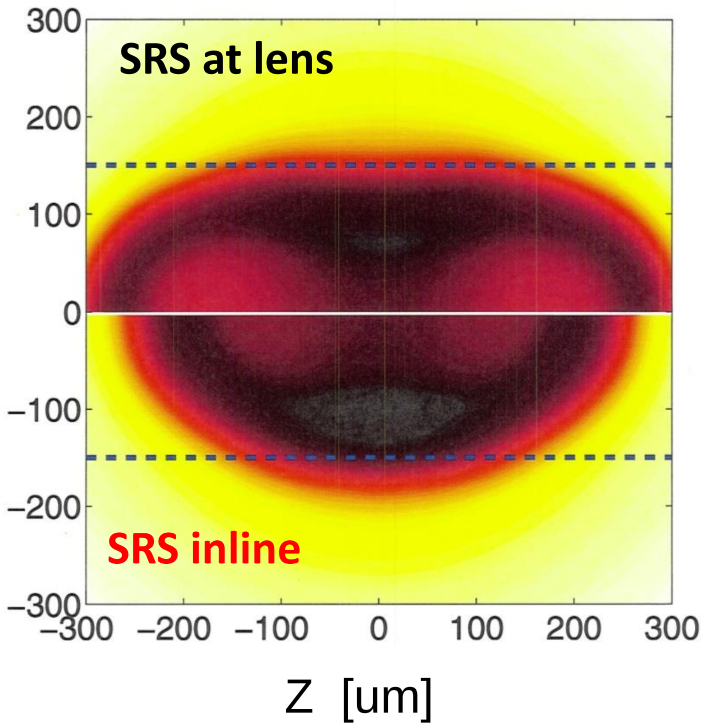
Inline SRS model: reduced CBET *and* Langmuir-wave pump depletion reduce waist x-ray drive

P2 moment: x-ray deposition at ablation front

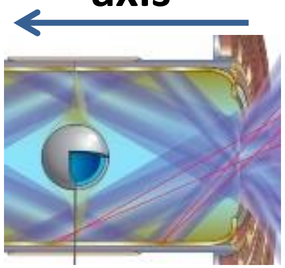


Inline SRS model gives less sausaged implosion, still differs from measurement

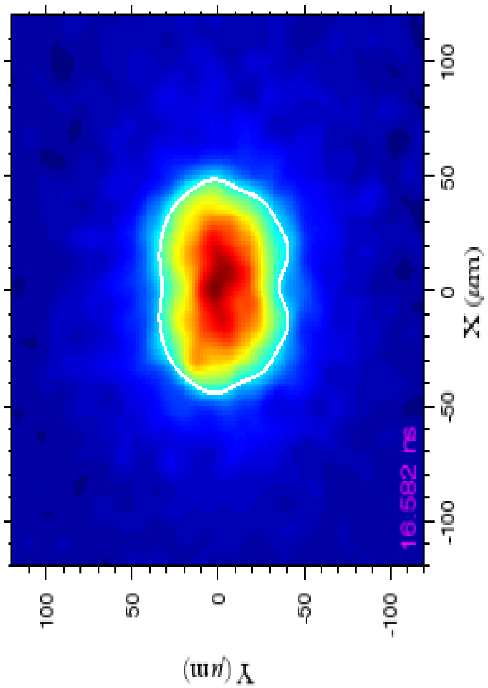
Simulated x-ray radiograph: "2D Convergent Ablator"



Hohlraum axis



Measured x-ray self emission: "Pancaked", $P_2/P_0 = -0.12$



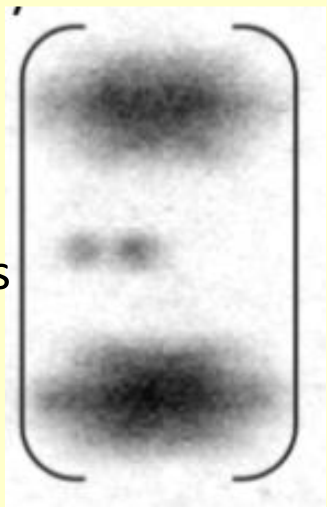
Experimental tests of inline models

eHXI (T. Doeppner): x-rays > 50 keV

near vacuum hohlraum very low hot e-'s	Low-foot, high gas fill high hot e-'s

Outer beams

Diag. patches



N141105

N130315

Optical Thomson Scattering
- ~FY17 on NIF
- Plasma conditions in LEH
- Langmuir waves in LEH

"Microdot" platform
- M. Barrios, N. Izumi
- Mid-Z patches on target surfaces
- Spectroscopy → T_e

Inline model extensions: focus on improved electron transport

Hot electrons

- Langmuir wave energy deposited locally in fluid T_e: upper bound on LEH effect
- Landau damping -> energetic or "hot" electrons
- Should be modeled as such, e.g. LASNEX suprathermal package [D. Kershaw]

Underdense plasma modeling

- Determine CBET and SRS coupling
- Determined by electron physics: heat transport, IB absorption:
  - Nonlocal heat flow
  - Ion acoustic turbulence: return current instability, enhanced absorption
  - Magnetic fields

Inline Brillouin Scattering: being added to HYDRA [S. Sepke]

Summary: Inline CBET and SRS models implemented in HYDRA and LASNEX

Inline CBET

- Reduces CBET vs. script:
  - Picket: script neglects absorption
  - Peak power: script doesn't remove SRS power
- Ion-wave heating increases T_{ion} in entrance hole, small effect on CBET

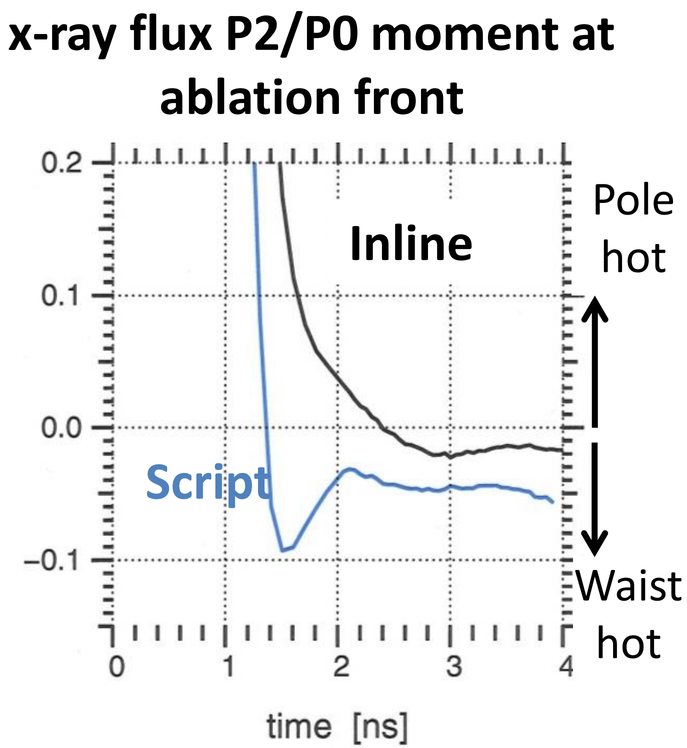
Inline SRS

- Langmuir waves driven just inside entrance - far from inner-beam spots
- LEH hotter --> less CBET
- Net effect is more polar drive, same total x-ray drive
- Little absorption of SRS light

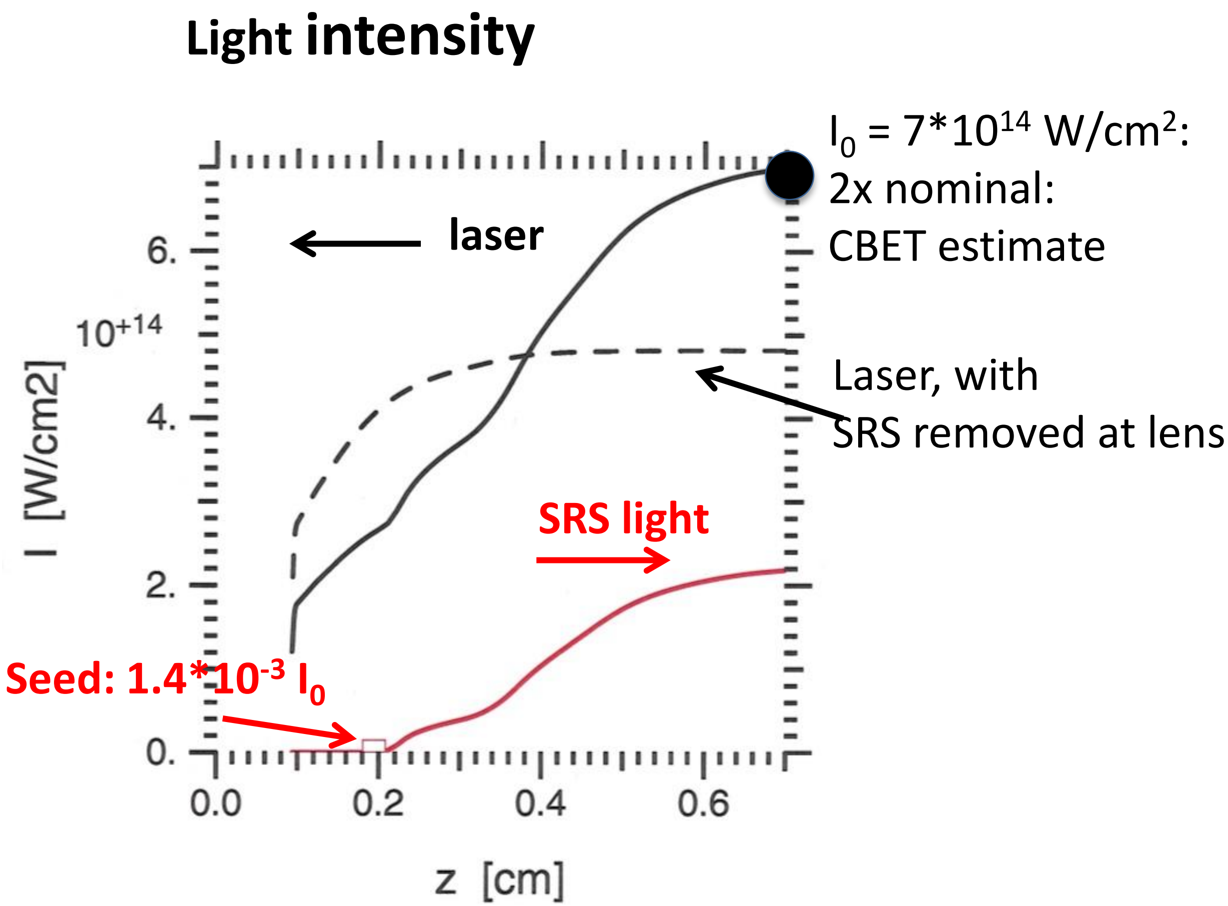
Inline models change underdense plasma conditions, especially in entrance hole, help explain implosion shape data

BACKUP BELOW

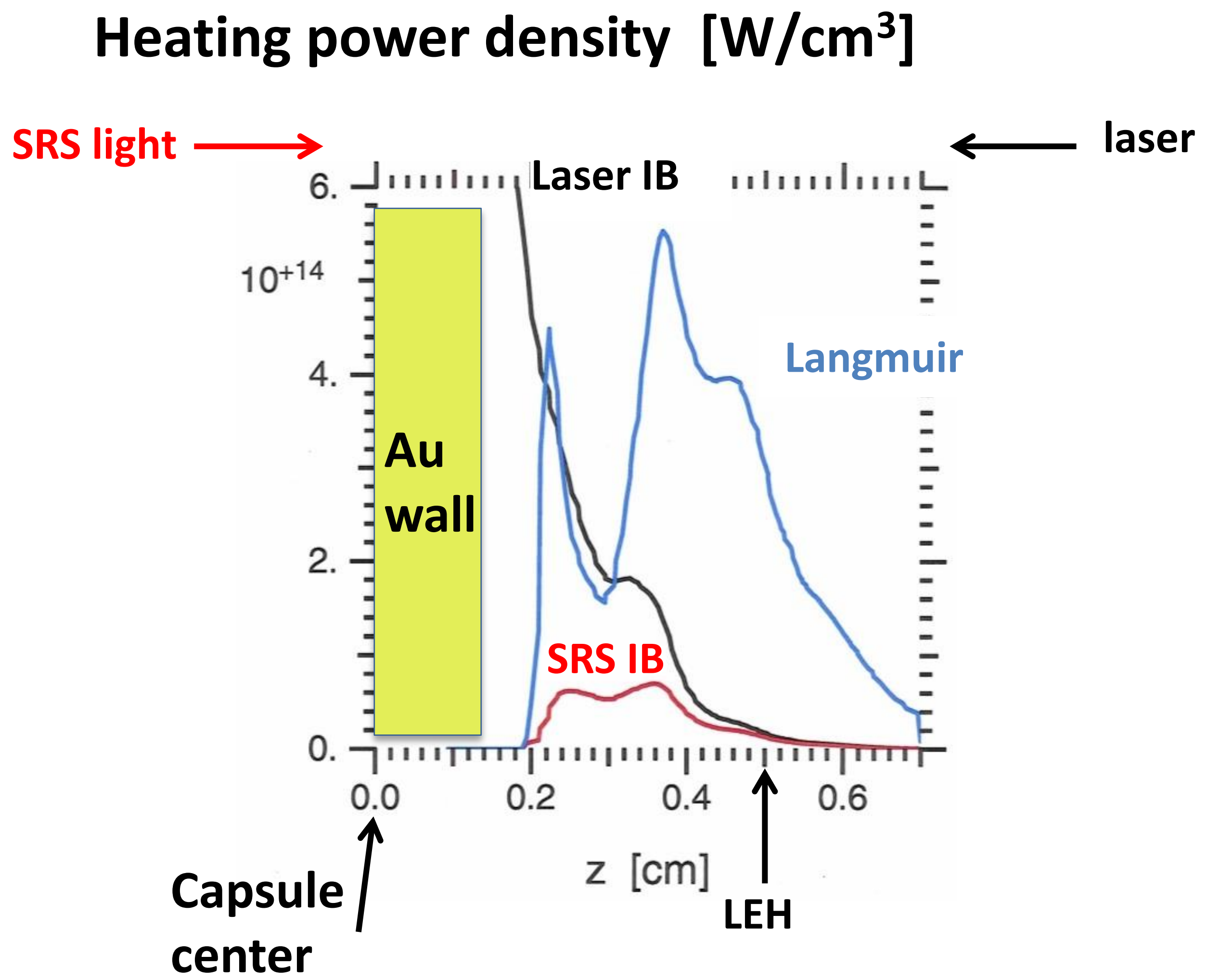
Hydra inline CBET picket



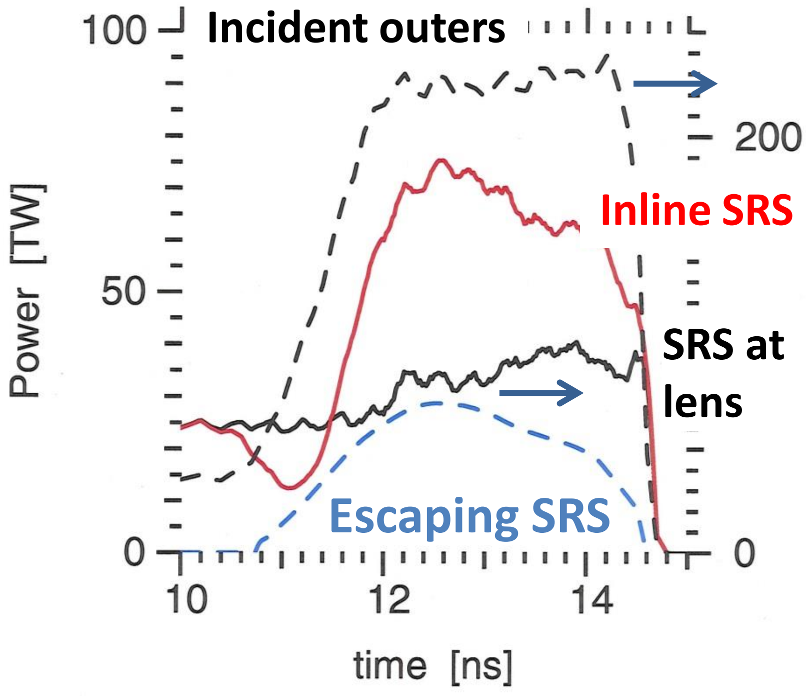
Inline SRS model solution along one ray



Inline SRS model: Langmuir wave heating dominates in low Z

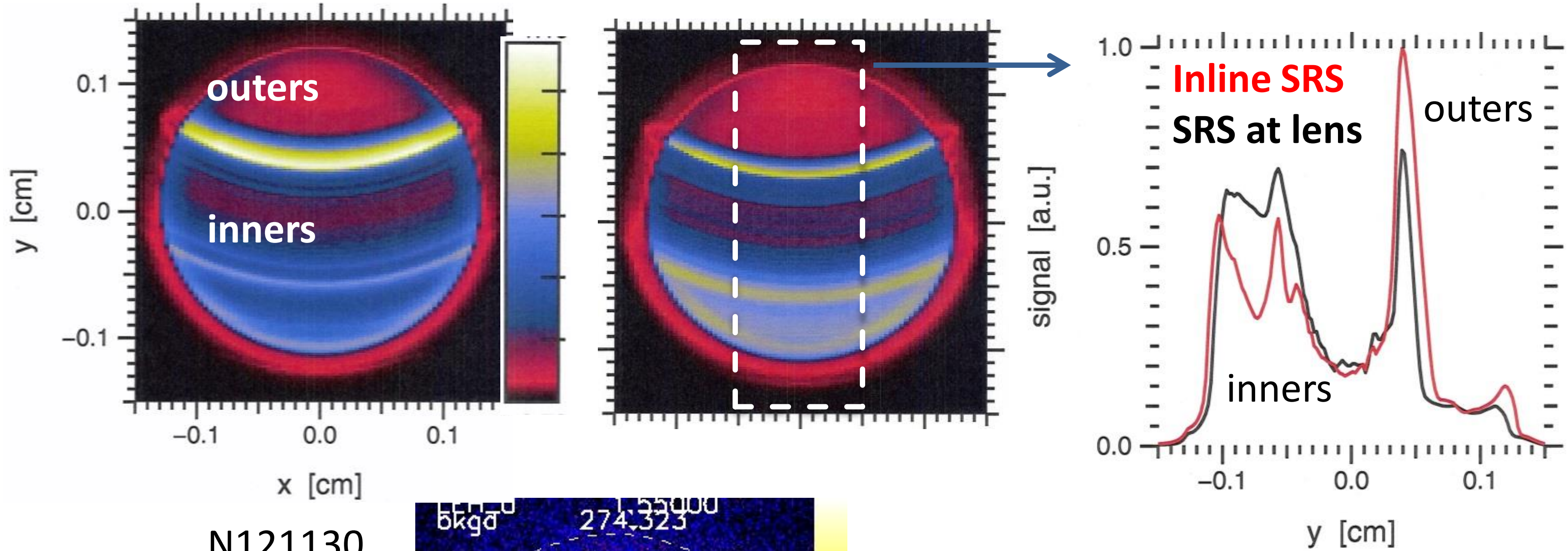


Post-CBET outer beam power

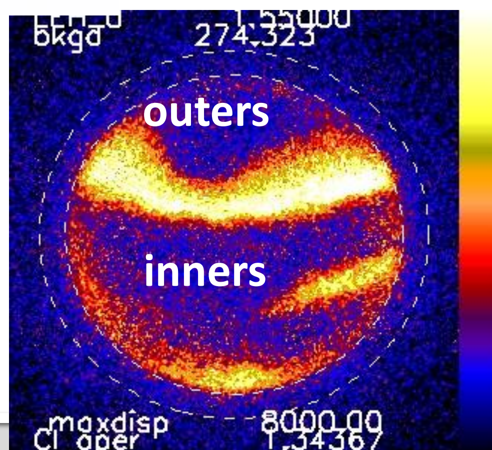


Static x-ray imager (SXI): brighter outer beam spots with inline SRS model

Inline SRS | **SRS at Lens** | **Summed over box in x**



N121130
shot data



SXI "hard channel": 3-5 keV x-rays
M B. Schneider et al., Rev. Sci. Inst. 2012