Modeling the Interplay of Laser-Plasma Interactions and Hohlraum Radiation-Hydrodynamics

LLE Seminar

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L. Divol, G. D. Kerbel, C. A. Thomas

29 September 2017

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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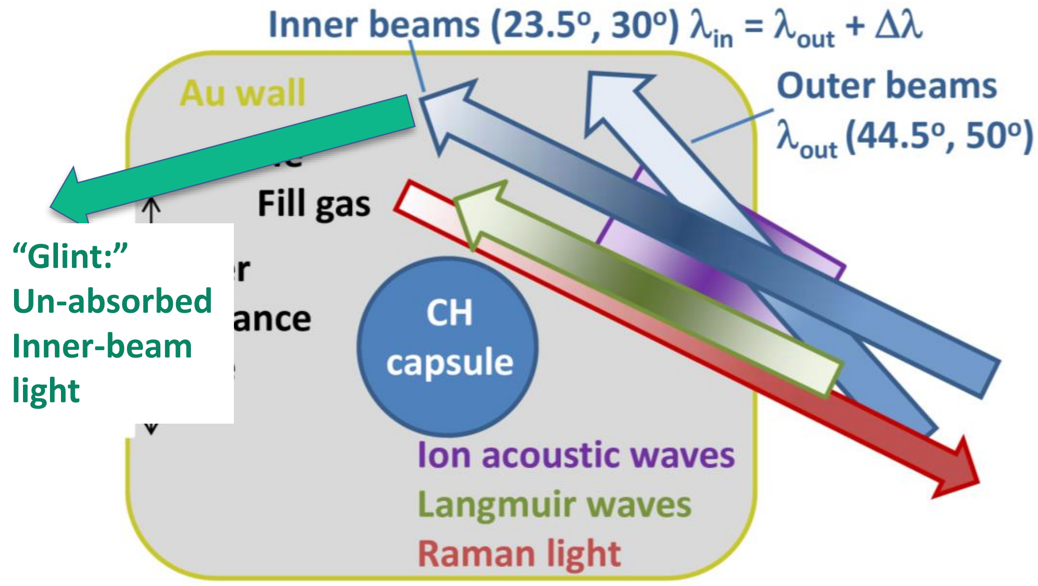
Hohlraum laser plasma interactions are key players in x-ray drive and shape

Important for high hohlraum fill density

Low-foot, high-foot designs



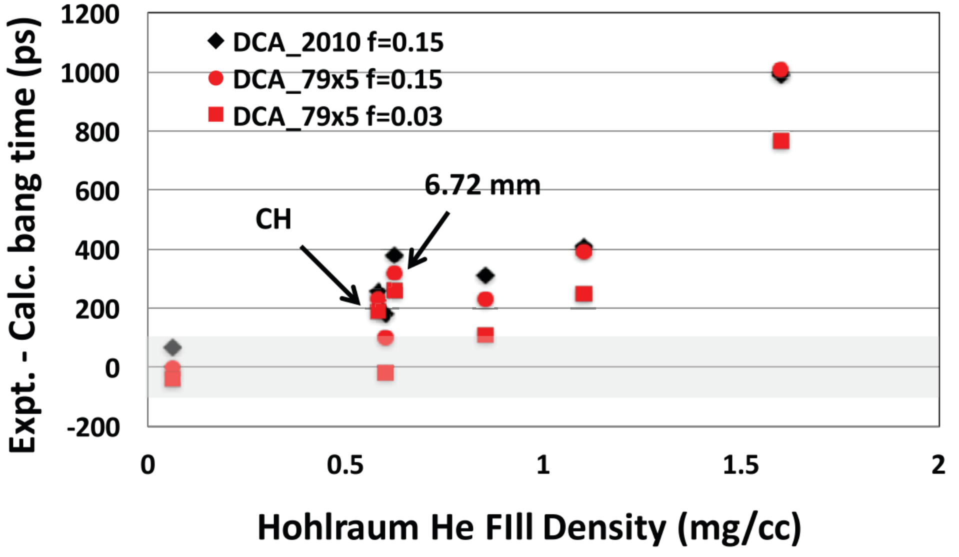
"Inline" LPI models recently added to HYDRA and LASNEX:
D. J. Strozzi et al., *Phys. Rev. Lett.* 2017

- **Cross-Beam Energy Transfer (CBET)**
  - Form of Brillouin scattering
  - Laser 1 γ → Laser 2 γ + ion acoustic wave
  - To longer wavelength laser in plasma frame
- **Stimulated Raman scattering (SRS)**
  - Laser γ → scattered γ + Langmuir wave
  - Energy loss
  - Affects shape
  - Energetic or "hot" electrons → preheat
- **Stimulated Brillouin scattering (SBS)**
  - Laser γ → scattered γ + ion acoustic wave
- **Glint: akin to direct-drive CBET**
  - Inner beams: escape opposite LEH → energy loss
  - Outer beams: can imprint on capsule, like direct drive

Drive deficit: “high-flux model” over-predicts hohlraum x-ray drive

“Low-flux model” ~1995 – 2008: NOVA, Omega
- XSN non-LTE atomic physics
- Low flux limit: f = 0.05

“high-flux model”: NIF 2009-now
- *Pure* vacuum hohlraums: low-flux model under-predicts drive
- DCA non-LTE
- High (~ no) flux limit: f = 0.15
- R. London – Omega shots ~2008; M. D. Rosen et al., HEDP 2011



[O. Jones et al., PoP 2017]

Gas-filled hohlraums: NIF 2010 - present
- High-flux model over-predicts drive
- Reduce laser power – “Oggie multipliers” [O. Jones et al., Phys. Plasmas 2012]
- Deficit increases with hohlraum fill density – along with SRS [O. Jones et al., Phys. Plasmas 2017]

Evidence for very low flux limit: two-stream flux limit [C. Thomas] or f = 0.03 [O. Jones, L. Suter]
- Drive deficit, “micro-dot” T_e measurements
- **Inner-beam glint** (unabsorbed light) may contribute – L. Suter

Conventional modeling over-predicts CBET to inner beams

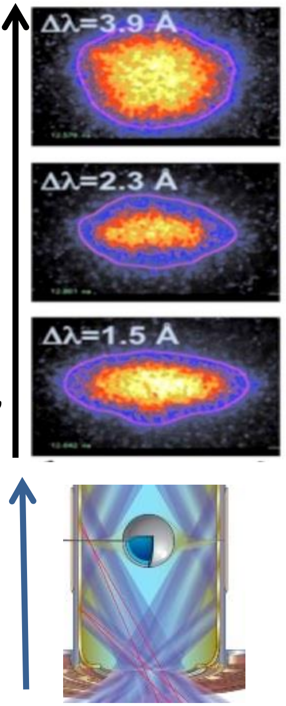
Hotspot x-ray image (2009 shots)

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

Prolate:
'Sausaged'

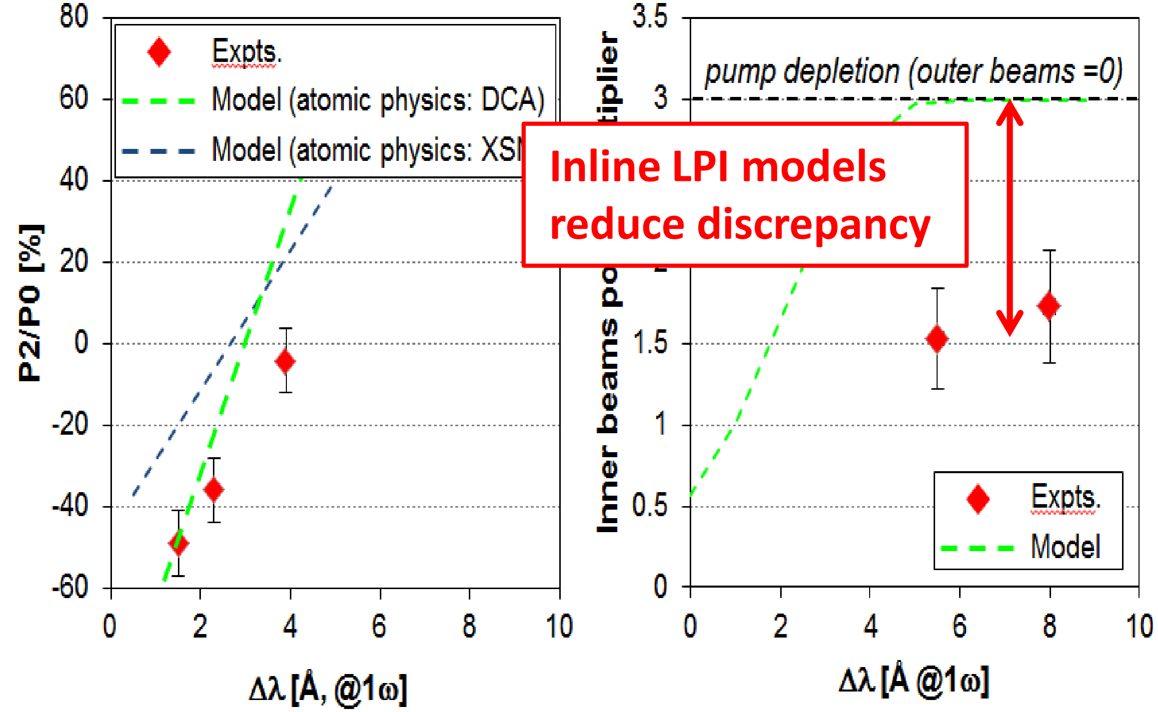
Oblate:
'Pancaked'

Hohlraum
axis



2012 APS DPP Excellence in Plasma Physics Award

Agreement with linear model for CBET gets worse with increasing laser power and $\Delta\lambda$



Slide courtesy P. Michel, Anomalous Absorption 2013

Inline LPI models improve agreement of modeling with data, reveal SRS dynamics

Old "script" process

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

- 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, vs. space
- Ion wave energy deposition

Versus script:

- Picket: less CBET, due to inverse brem.
- Peak power: less CBET, due to SRS removed from inners
- Still more sausaged than data

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

Reduced e- heat flux:

- Higher fill temperature
- Less IB absorption
- More glint

No inline SRS:

- Simulated bangtime late
  - "Too much winning"

Plus inline SRS:

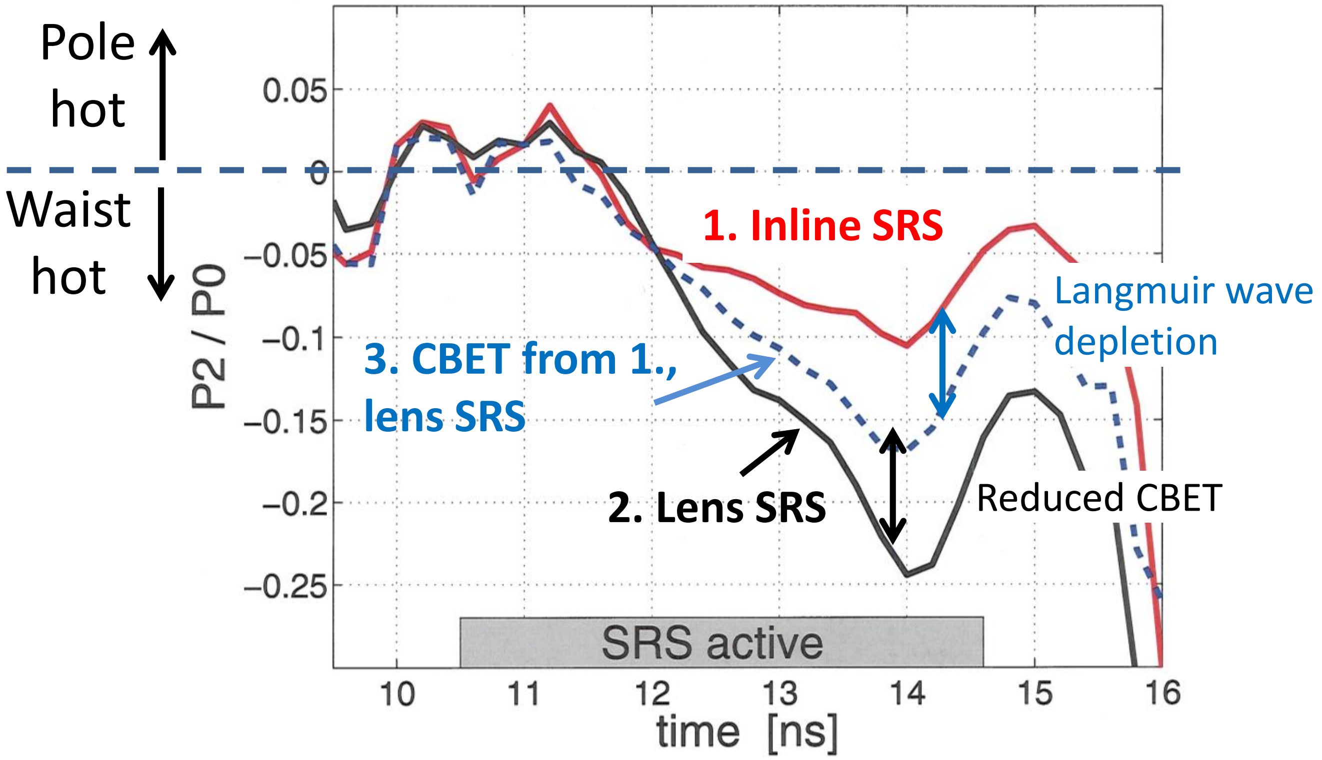
- Langmuir heating confined to LEH
- Further reduces CBET
- Moderate glint
- **Close on bangtime + shape!**

Part 1 of talk **Part 2** **Part 3**

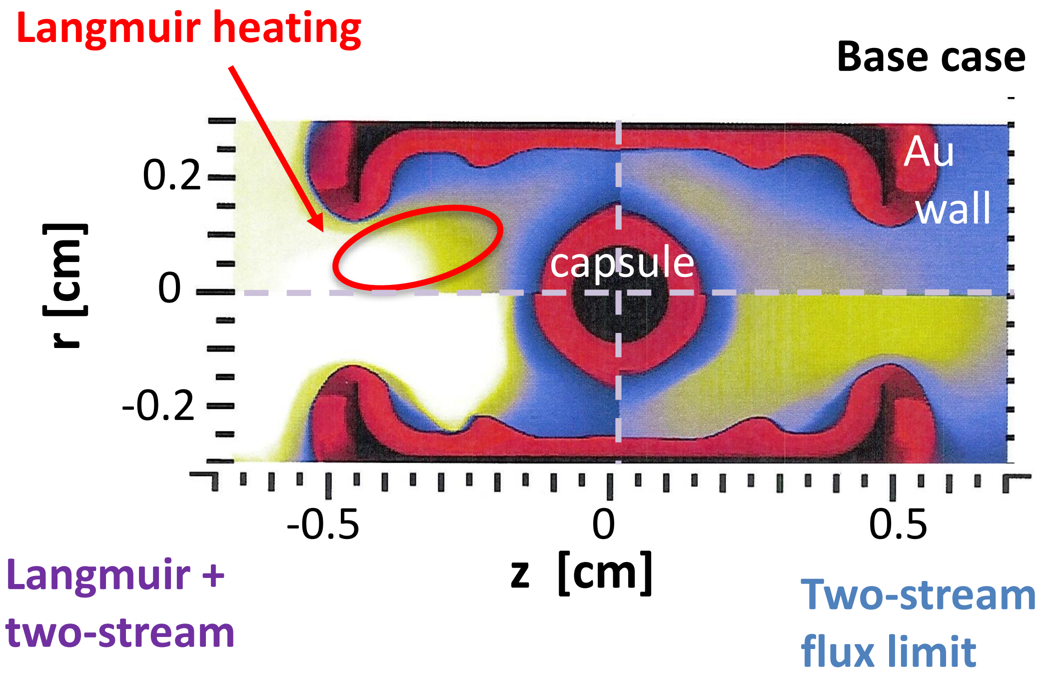
← **e- flux limit f = 0.15** → **Two-stream flux limit**

Today's goal is you understand two plots

P2 moment: x-ray deposition at ablation front



Two-stream flux limit: Electron temperature [keV]



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Part 1 of talk

HYDRA simulations

$\delta n_{sat} = 10^{-3}$

Inline CBET and SRS

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

Inline SRS results:

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Part 2

Reduced e- heat flux

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- Less IB absorption
- More glint
- Simulated bangtime late
  - "Too much winning"

Plus inline SRS:

- Langmuir heating confined to LEH
- Further reduces CBET
- Moderate glint
- **Match bangtime and shape!**

Part 3

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

Inverse brem. absorption | SRS coupling | CBET to other 23 quads on same hemisphere

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

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

SRS Langmuir wave

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

CBET acoustic wave

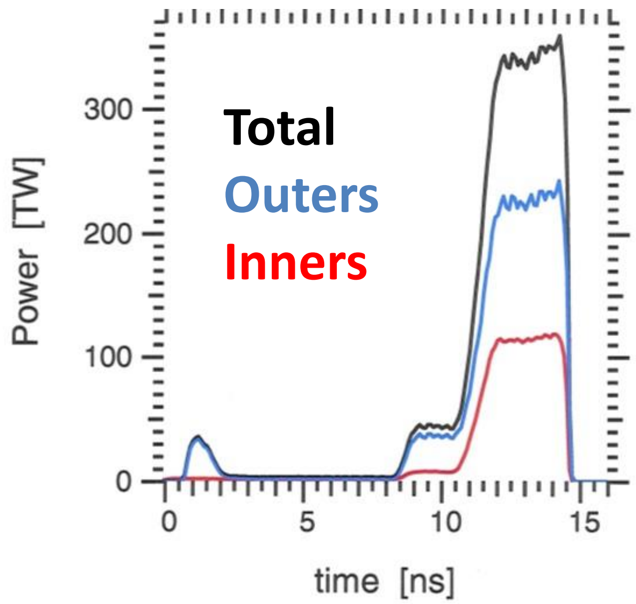
$$p_{Ai} = \frac{\omega_{Ai}}{\omega_0 \omega_i} g_{Ci} I_0 I_i$$

- **CBET Ion wave saturation clamp δn_e^{sat}:** $\delta n_e \propto \min\left[\sqrt{I_0 I_i}, \delta n_e^{\mathrm{sat}}\right]$

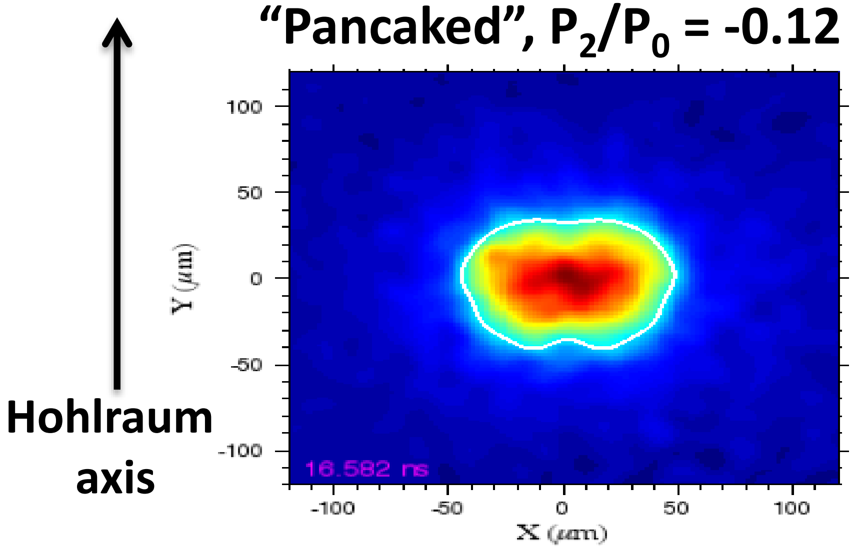
Inline models applied to NIF shot N121130: early "high-foot" plastic symcap

- 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

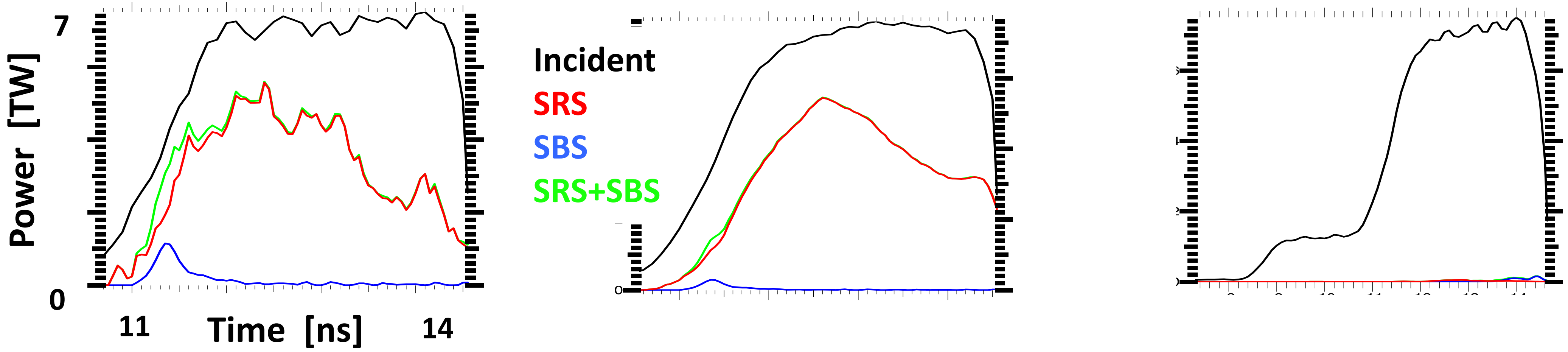


Hotspot x-ray image: "Pancaked", P_2/P_0 = -0.12

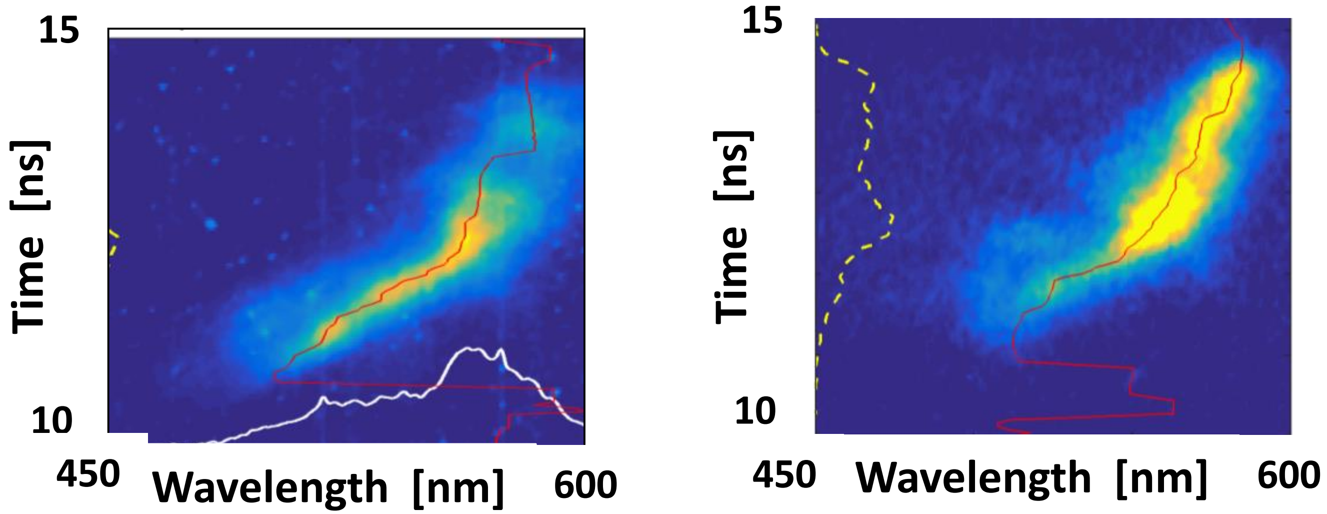


Inputs to runs: measured SRS power and maximum wavelength

23° inner cone | 30° inner cone | 50° outer cone



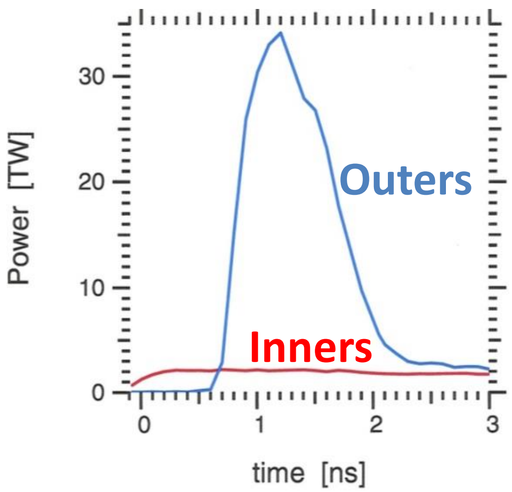
SRS spectra



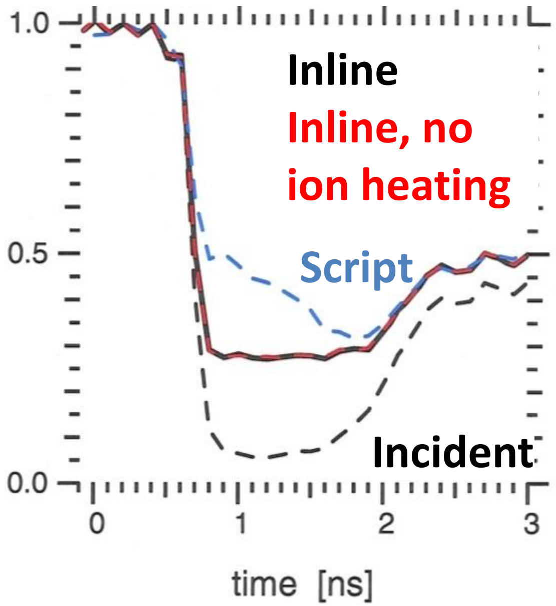
Advice:
Don’t shoot these targets!
If you must, and want to model them, keep listening.

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

Incident power



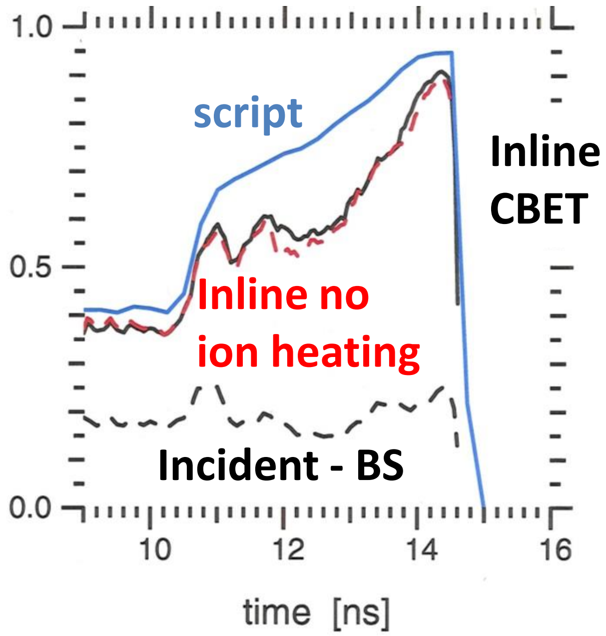
Cone fraction: Inner / total power



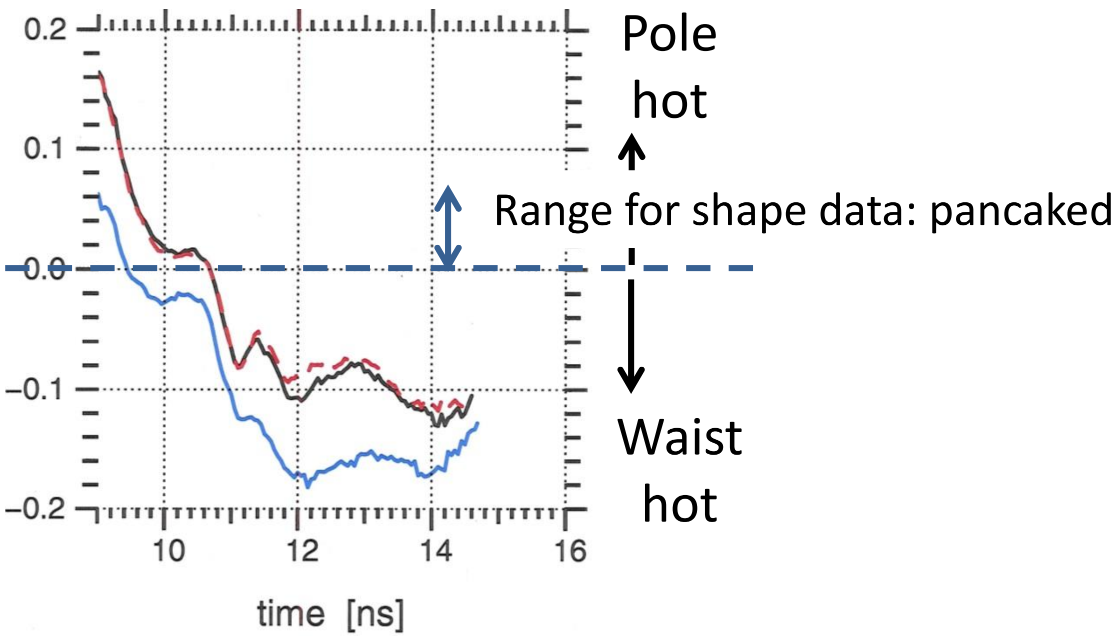
- Script neglects absorption, or else transferred power doesn't reach exit plane
- CBET clamp $\delta n_e^{sat} = 10^{-3}$ in all HYDRA runs

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

$$\partial_z I_{in} = g I_{out} I_{in}$$

Ion heating has little effect on CBET, unlike in P. Michel et al., Phys. Rev. Lett. 2012

But: SRS may develop after CBET takes place → need inline SRS treatment too

Inline LPI models improve agreement of modeling with data, reveal SRS dynamics

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Versus script:

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Part 1 of talk

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

Part 2
LASNEX simulations
$\delta n_{sat} = 10^{-2}$

Reduced e- heat flux

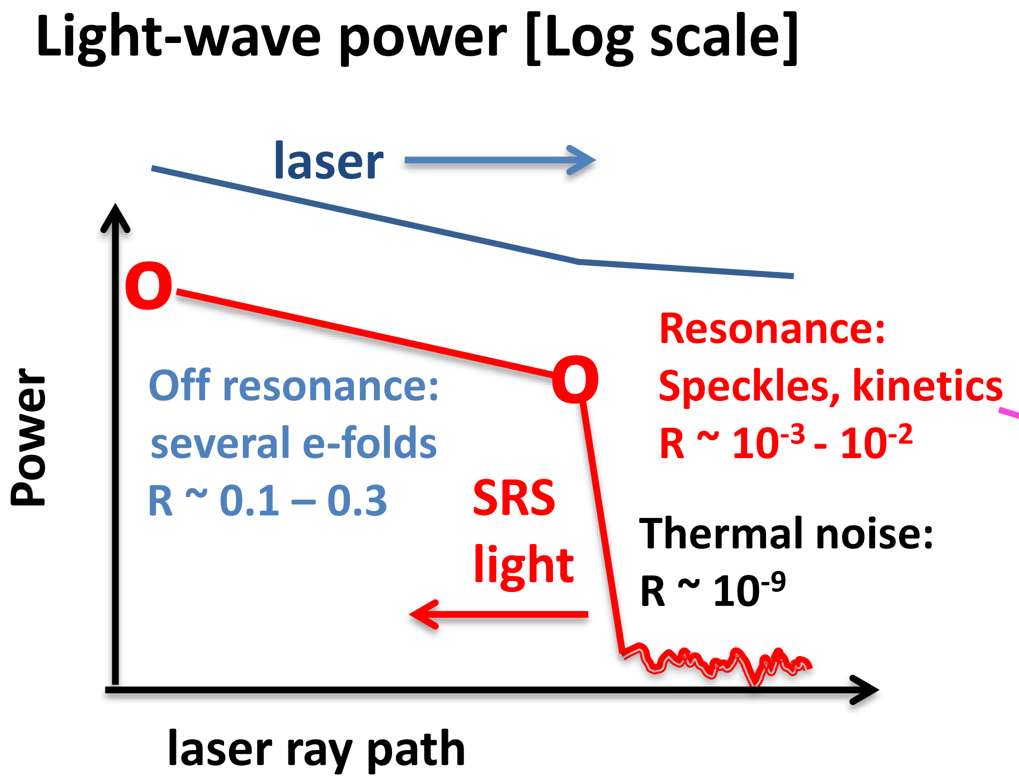
- Higher fill temperature
- Less IB absorption
- More glint
- Simulated bangtime late
  - "Too much winning"

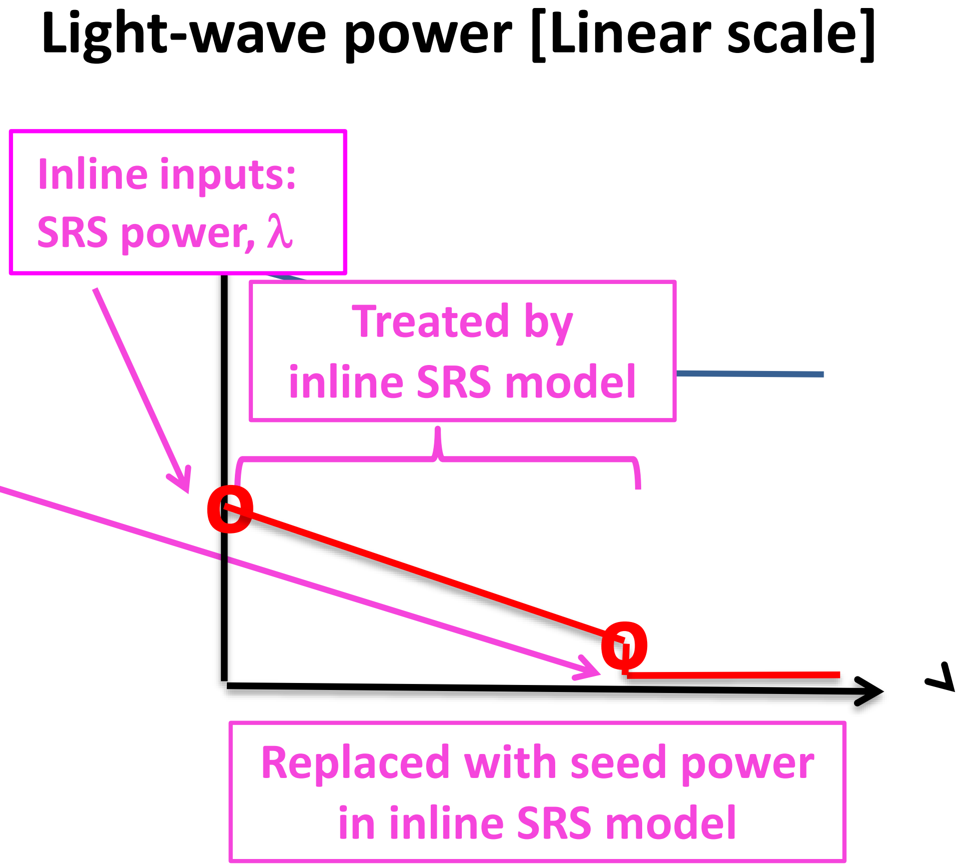
Plus inline SRS:

- Langmuir heating confined to LEH
- Further reduces CBET
- Moderate glint
- **Match bangtime and shape!**

Part 3

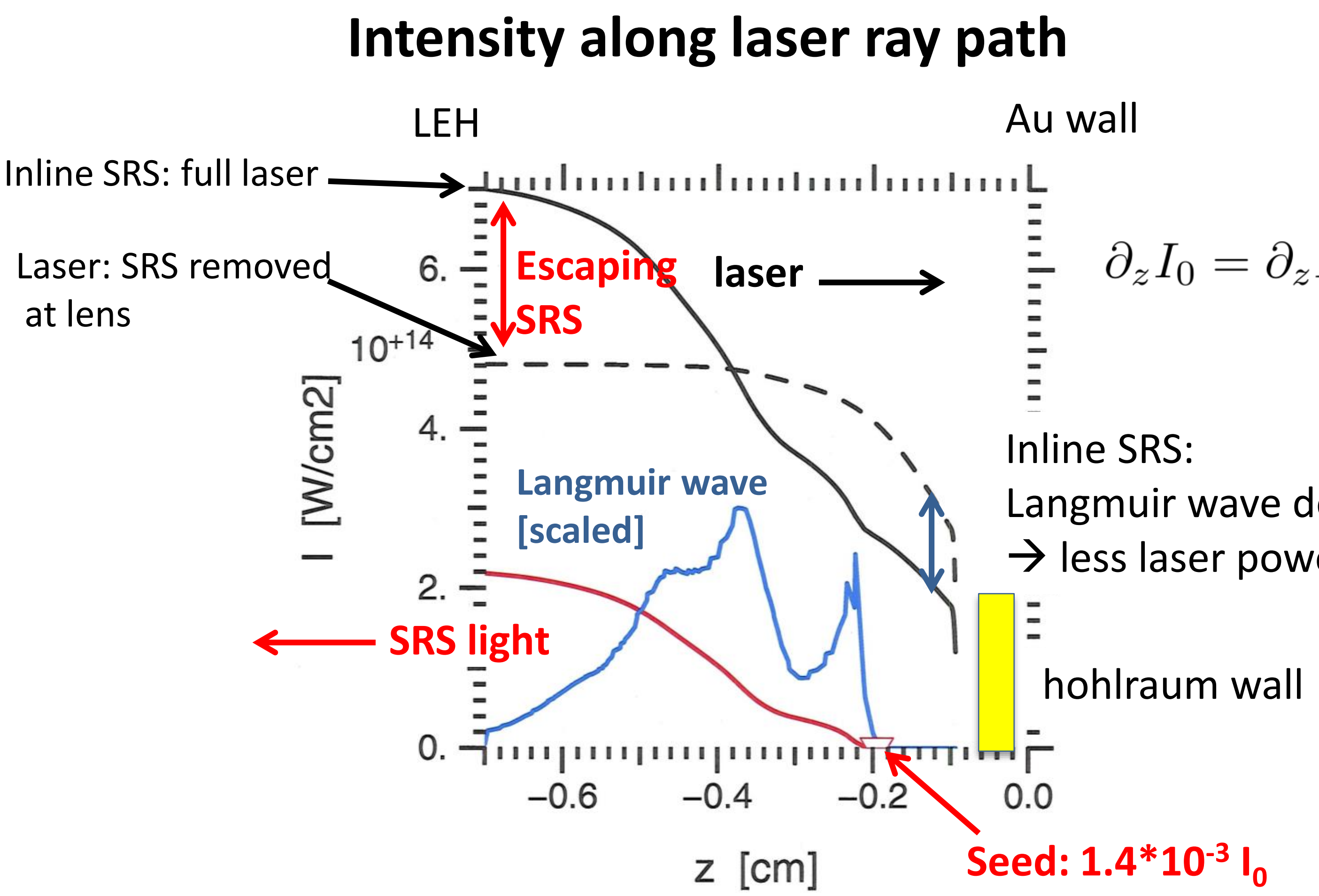
SRS exponentiates mostly on resonance, most power growth off resonance





Not a predictive SRS model: user gives SRS power and wavelength.
Inline model gives self-consistent laser depletion and Langmuir wave deposition.

Inline SRS model solution along one ray

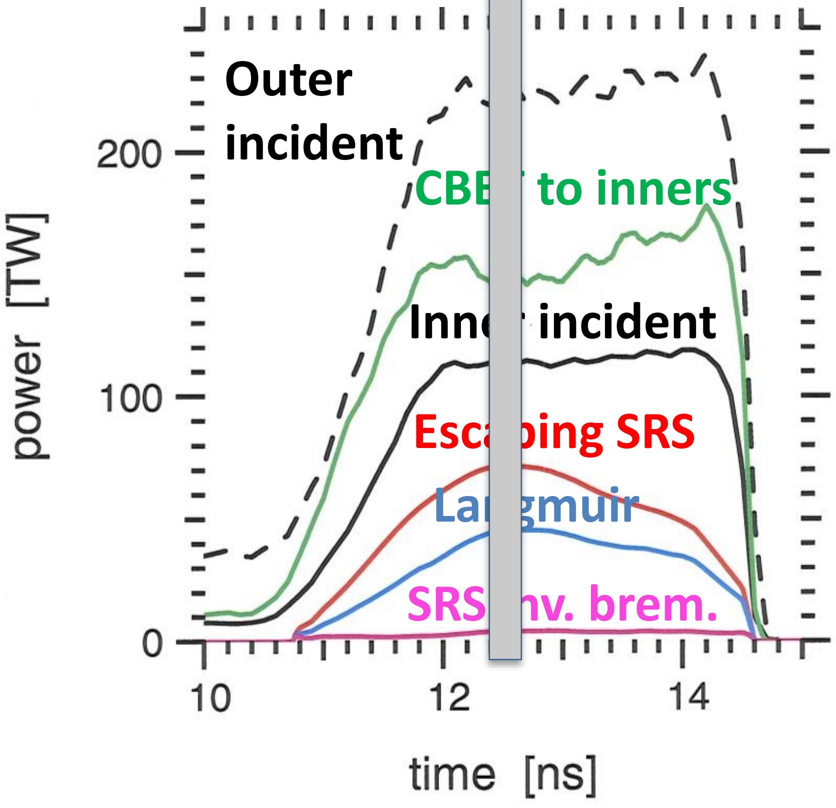


$$\partial_z I_0 = \partial_z I_R - p_{\text{Langmuir}}$$

Inline SRS:
Langmuir wave depletion
→ less laser power on wall

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

Peak SRS: shown on next slide



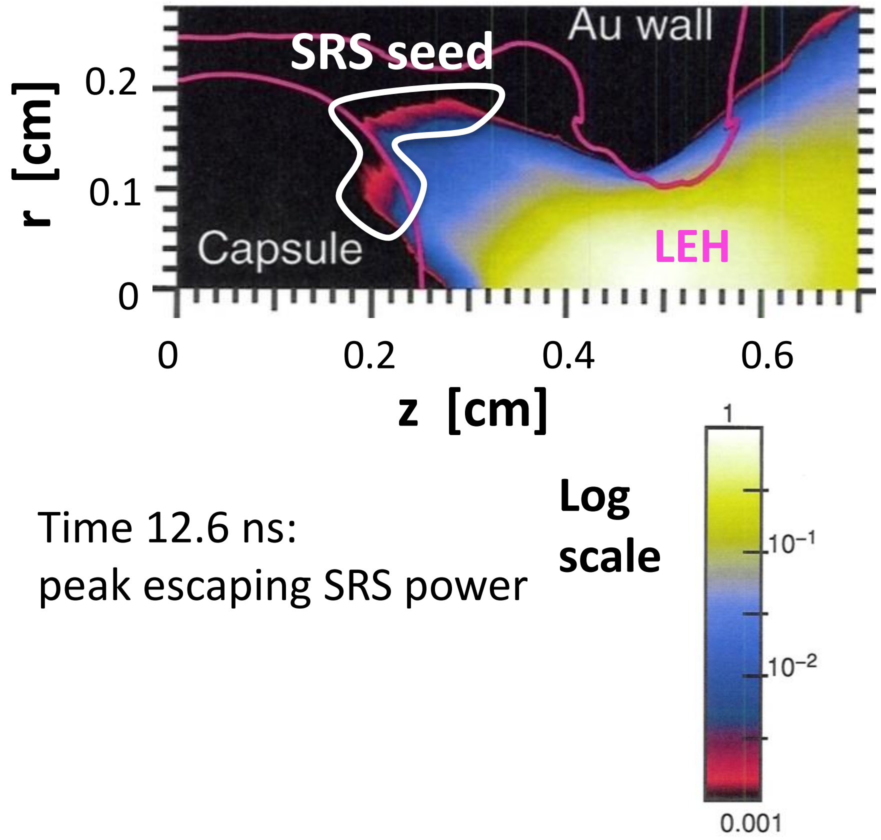
NIF high-foot shot N121130

Langmuir wave energy: 119 kJ

- Deposited locally in fluid T_e
- Upper bound on LEH effect – for given flux limit
- Hot electron treatment is ongoing

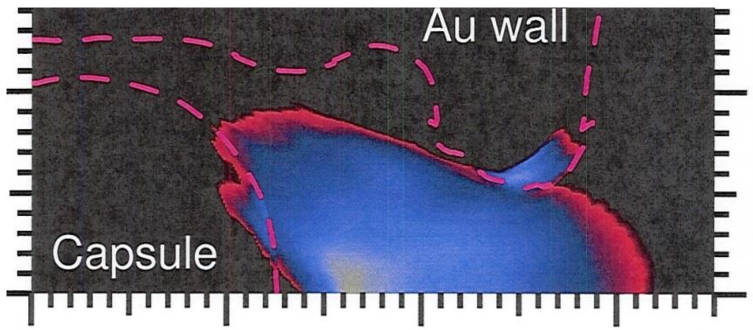
Inline SRS: Langmuir waves driven just inside entrance hole

SRS light keeps growing: coupling > inv. brem.

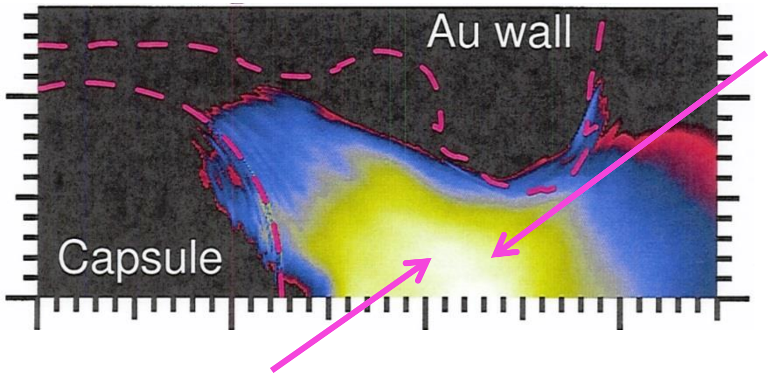


Time 12.6 ns:
peak escaping SRS power

SRS inv. brem. heating



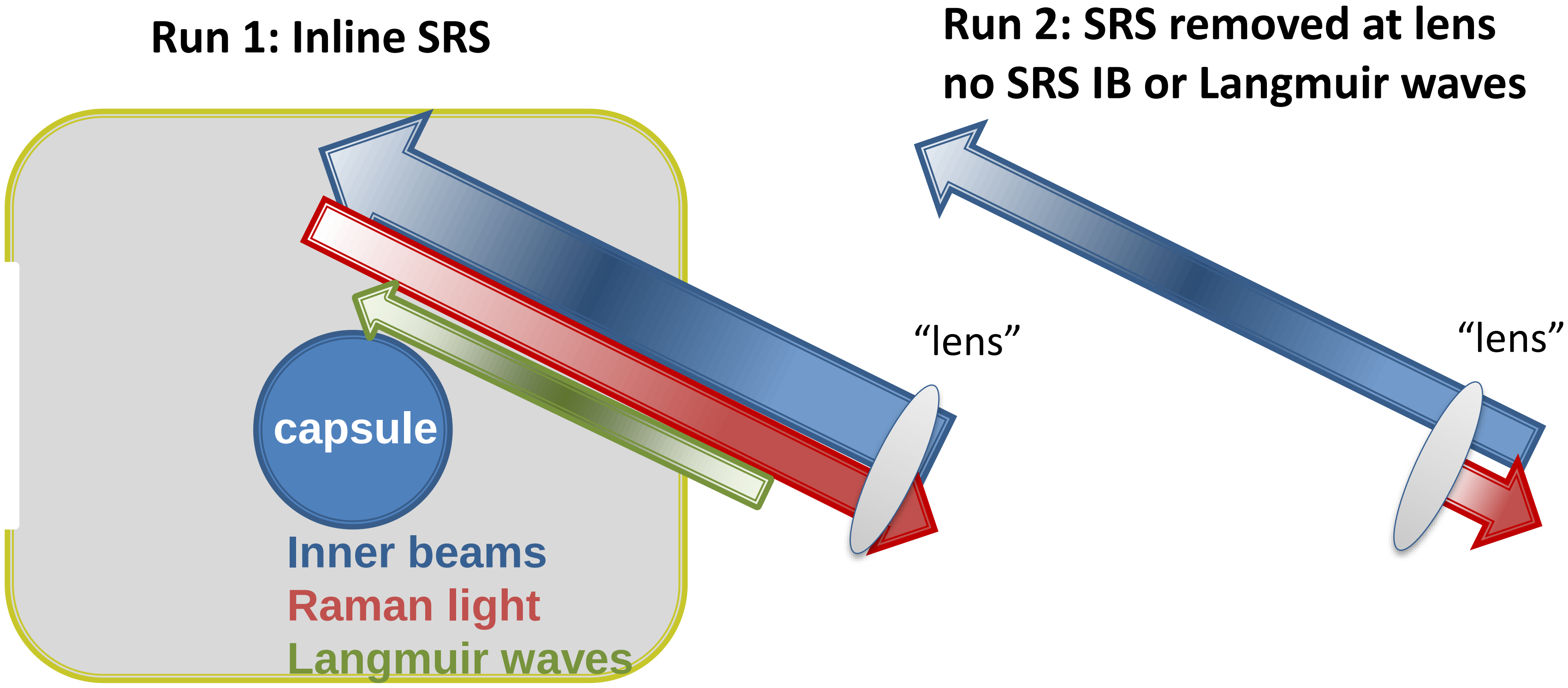
Langmuir wave heating: Makes LEH hotter



Thomson scattering could show if Langmuir waves are here

Conducts to wall → polar x-rays

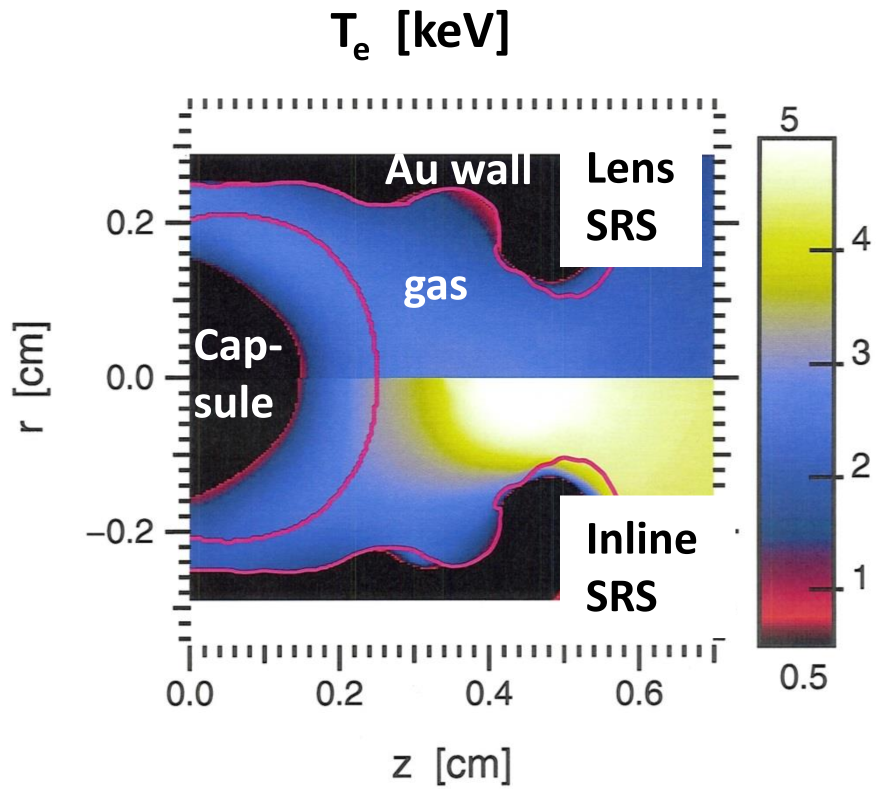
Compare two LASNEX runs: inline SRS vs. SRS removed at lens

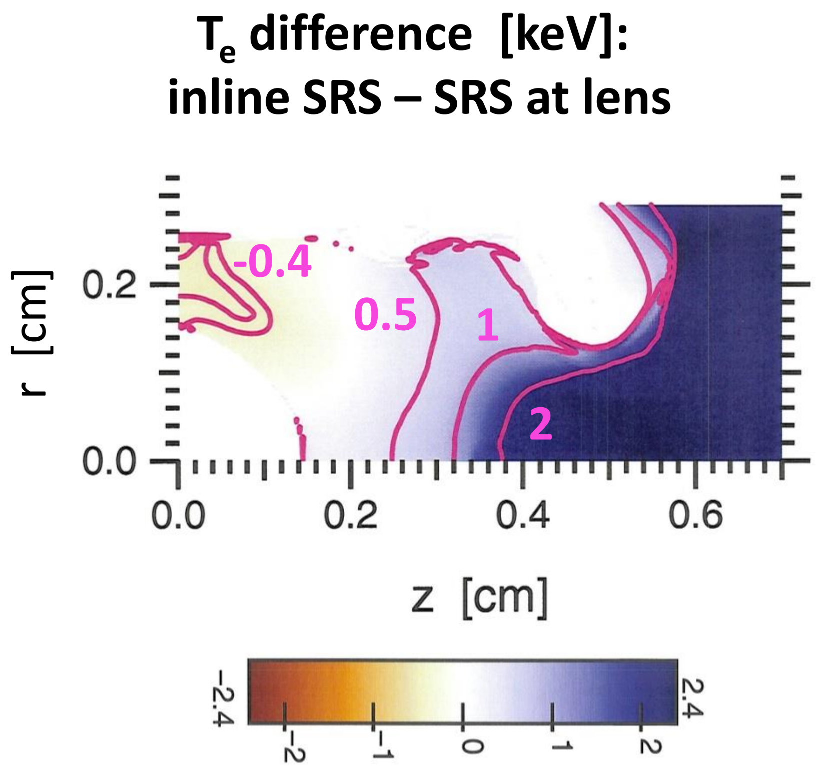


Common to both runs:

- Same escaping SRS power
- Inline CBET model, clamp $\delta n_e^{sat} = 0.01$

Inline SRS model increases LEH electron temperature 1 – 2 keV



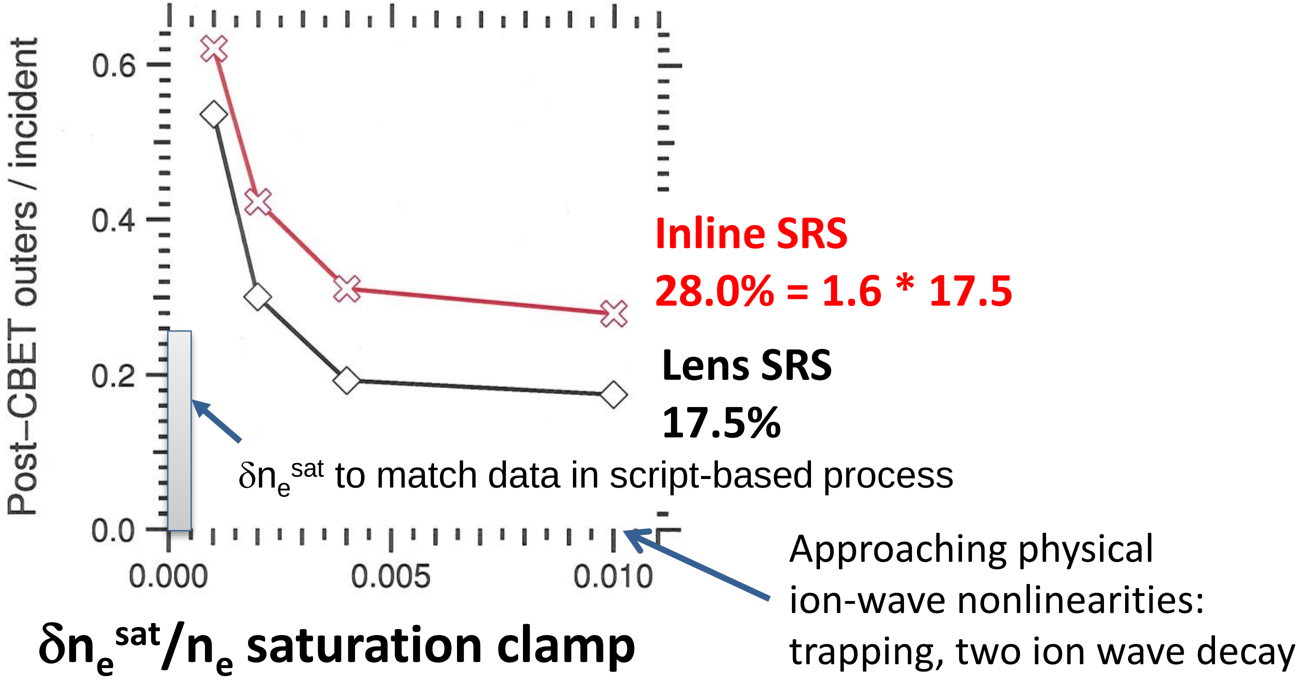


Time 12.6 ns:
peak escaping SRS power

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

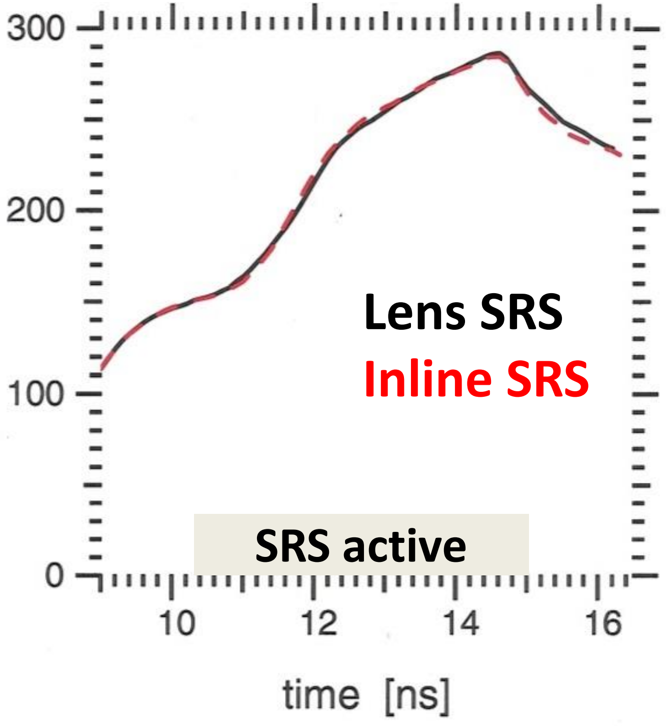
Post-CBET outer beam energy:
10.5 to 15 ns



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

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

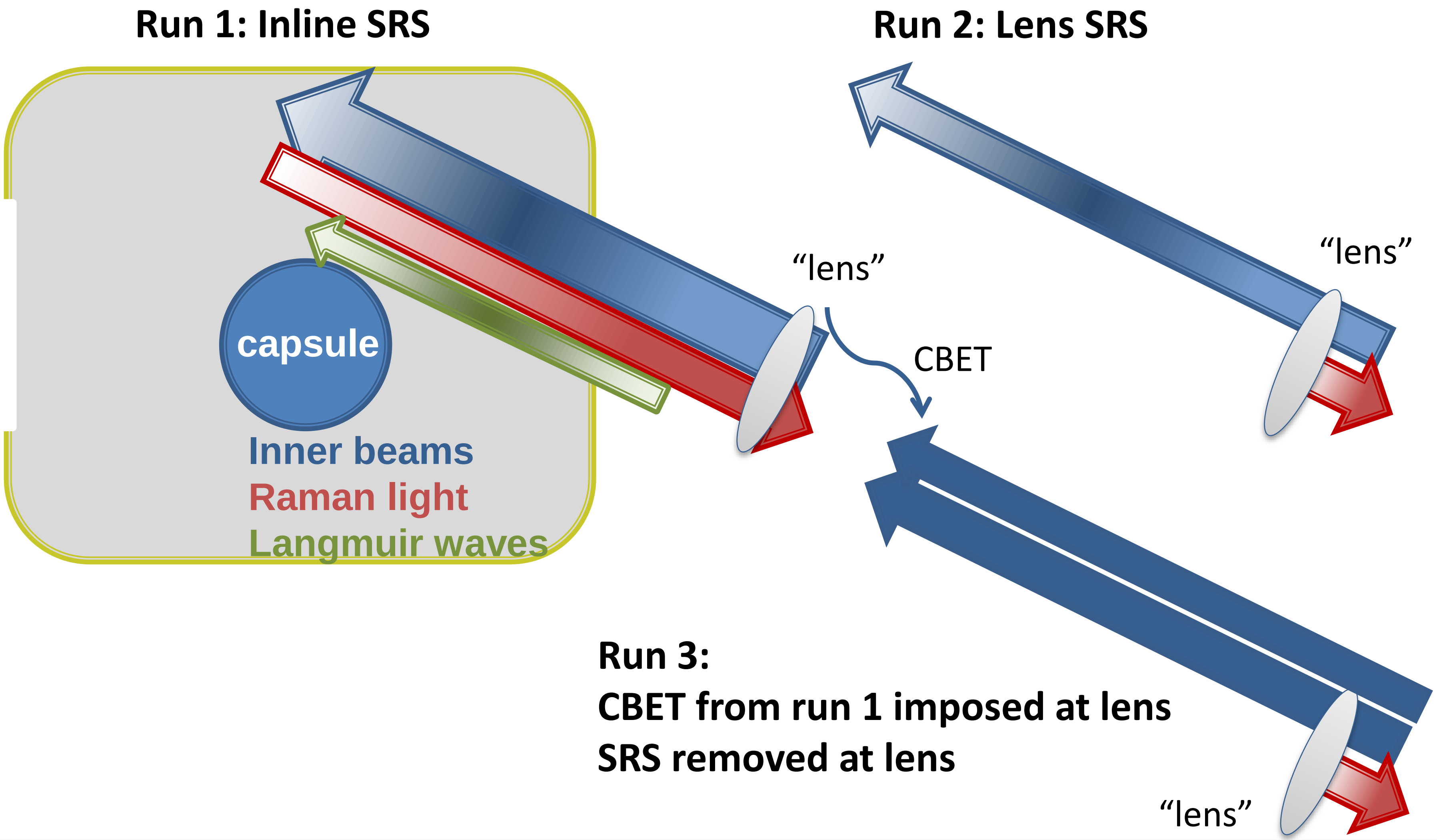
Radiation temperature seen by capsule [eV]



"Hohlraums are calorimeters"
– L. J. Suter

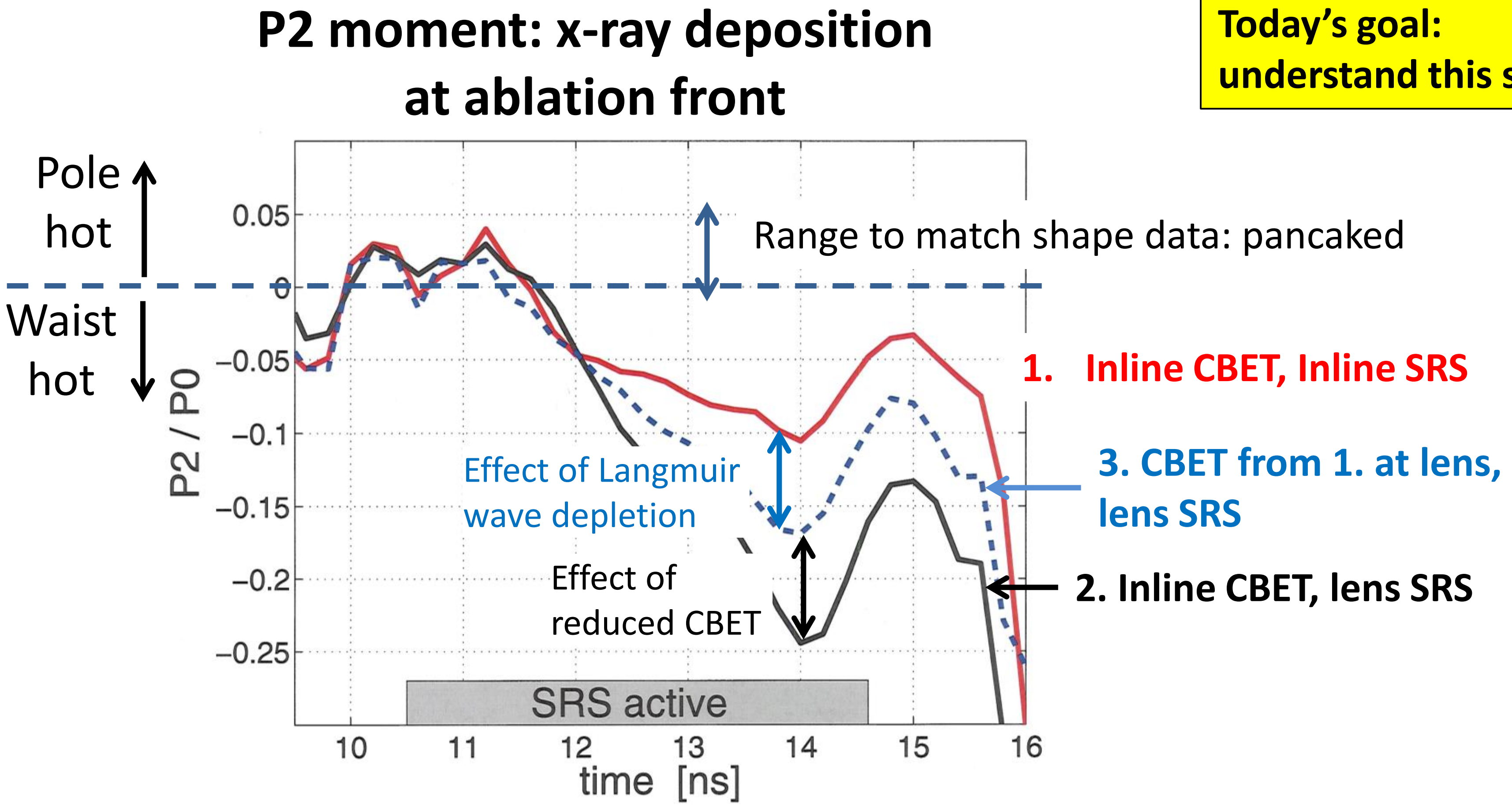
*Two curves almost overlay

Third run separates shape effect of inline SRS model: reduced CBET vs. Langmuir wave depletion



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

Today's goal: understand this slide



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- Simulated bangtime late
  - "Too much winning"

Plus inline SRS:

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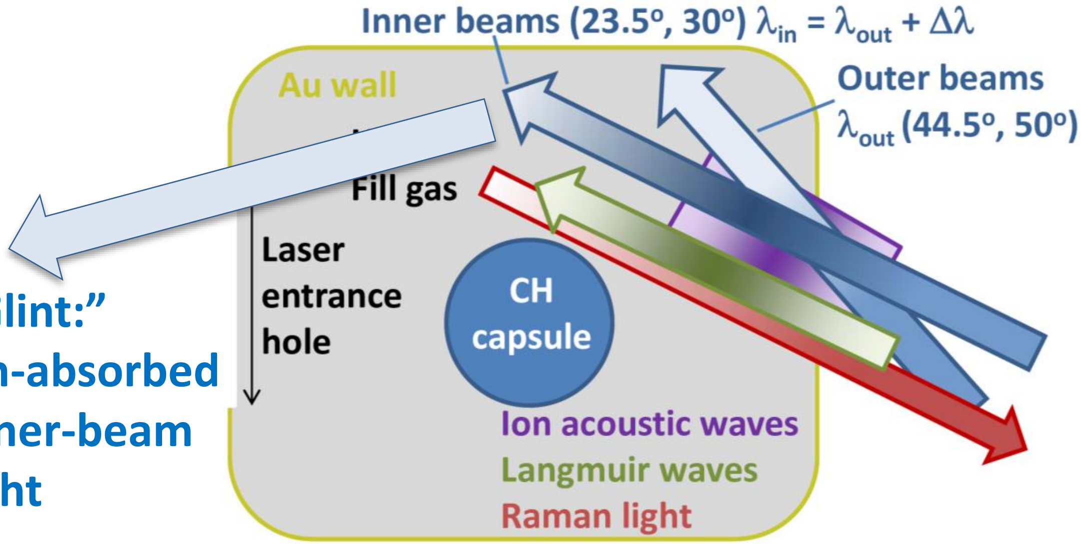
Part 3
LASNEX simulations
$\delta n_{sat} = 10^{-2}$
Two-stream flux limit

← **e- flux limit f = 0.15** →

Inner-beam "glint[1]" recently appreciated as possible significant energy loss from NIF hohlraums



"Inline" LPI models[2] in hydro codes:

- **Cross-Beam Energy Transfer (CBET)**
  - Outer → Inner + ion acoustic wave
- **Stimulated Raman scattering (SRS)**
  - Langmuir wave heating
  - SRS light absorption (minor)

Hohlraum energetics:

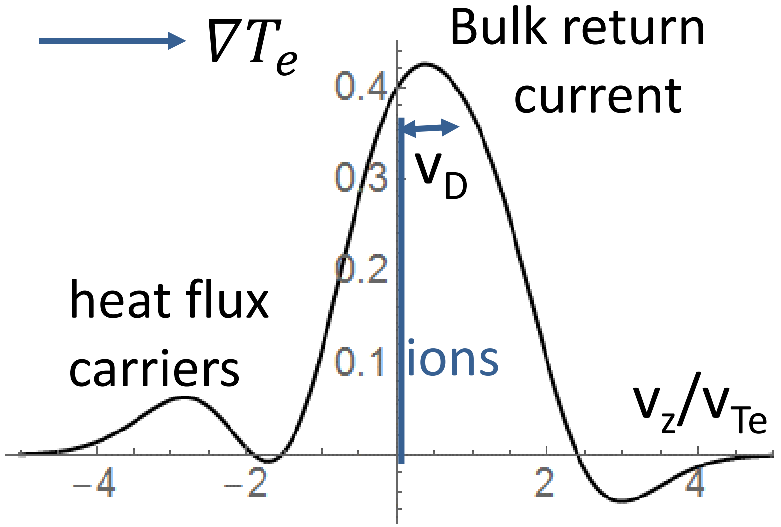
- Laser coupled to hohlraum = Incident – Backscatter – Transmitted
- Transmitted = "Glint" = (1-absorption)*(inner power after LPI)
- Inner power after LPI = Incident + CBET from outers – BS – Langmuir heating

[1] D. Turnbull, P. Michel, J. E. Ralph, L. Divol, et al., *Phys. Rev. Lett.* (2015)
[2] D. J. Strozzi, D. S. Bailey, P. Michel, L. Divol, S. M. Sepke et al., *Phys. Rev. Lett.* (2017)

Lasnex two-stream flux limit: crude return current instability model

- Spitzer-Harm heat flux carried by e- with (2-4)v_{Te}
- Zero net current → bulk electrons drift vs. ions

Electron distribution



Ion acoustic drift instability if:

- v_D > sound speed
- Growth rate exceeds ion Landau damping → ZT_e/T_i >> 1

q = e- heat flux = min($f^* n_e T_e v_{Te}$, q_{SH})

f = flux limit

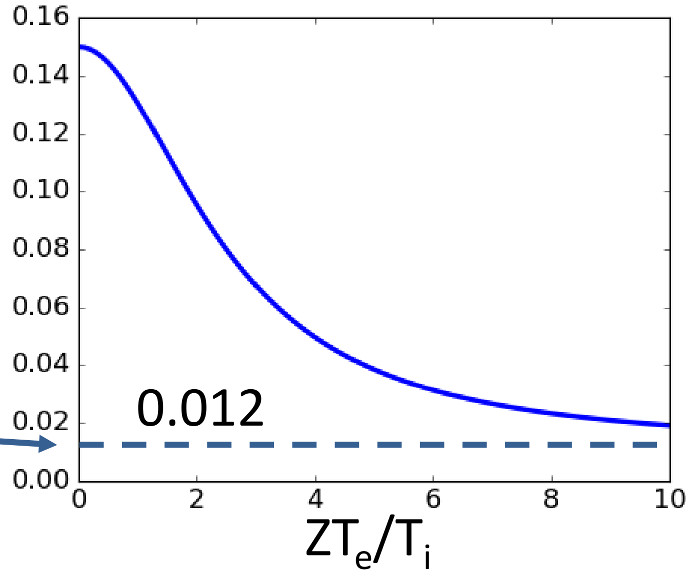
f_0 = user-specified = 0.15 here

$$f^{-1} = f_0^{-1} + \frac{a^2}{1 + a^2\left(\frac{Zm_e}{m_i}\right)^{1/2}} \quad \text{[TS]}$$

$$f = \left(\frac{Zm_e}{m_i}\right)^{1/2}, \quad a = \frac{ZT_e}{T_i} \gg 1$$

→ $q = n_e T_e c_{sound}$

f for Z/A = 0.25, e.g. Z=50 Au



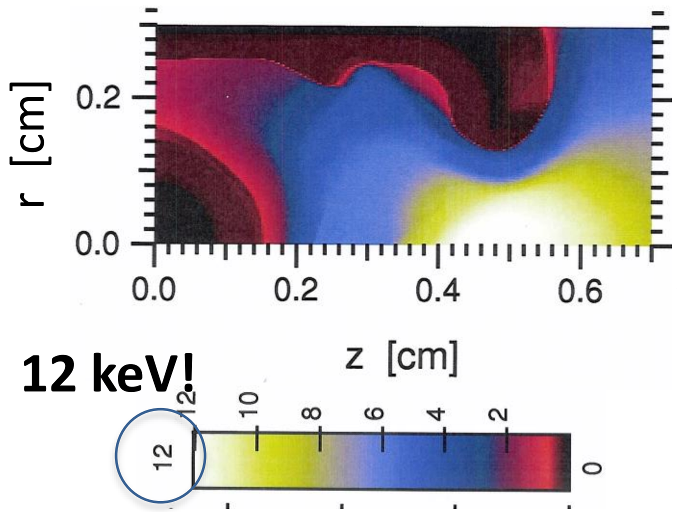
This model based on cold e- beam, realistic one for heat-flux driven return current gives higher flux limit [M. Sherlock]

Two-stream flux limit increases fill temperature – especially with Langmuir heating

Today's goal: understand this slide

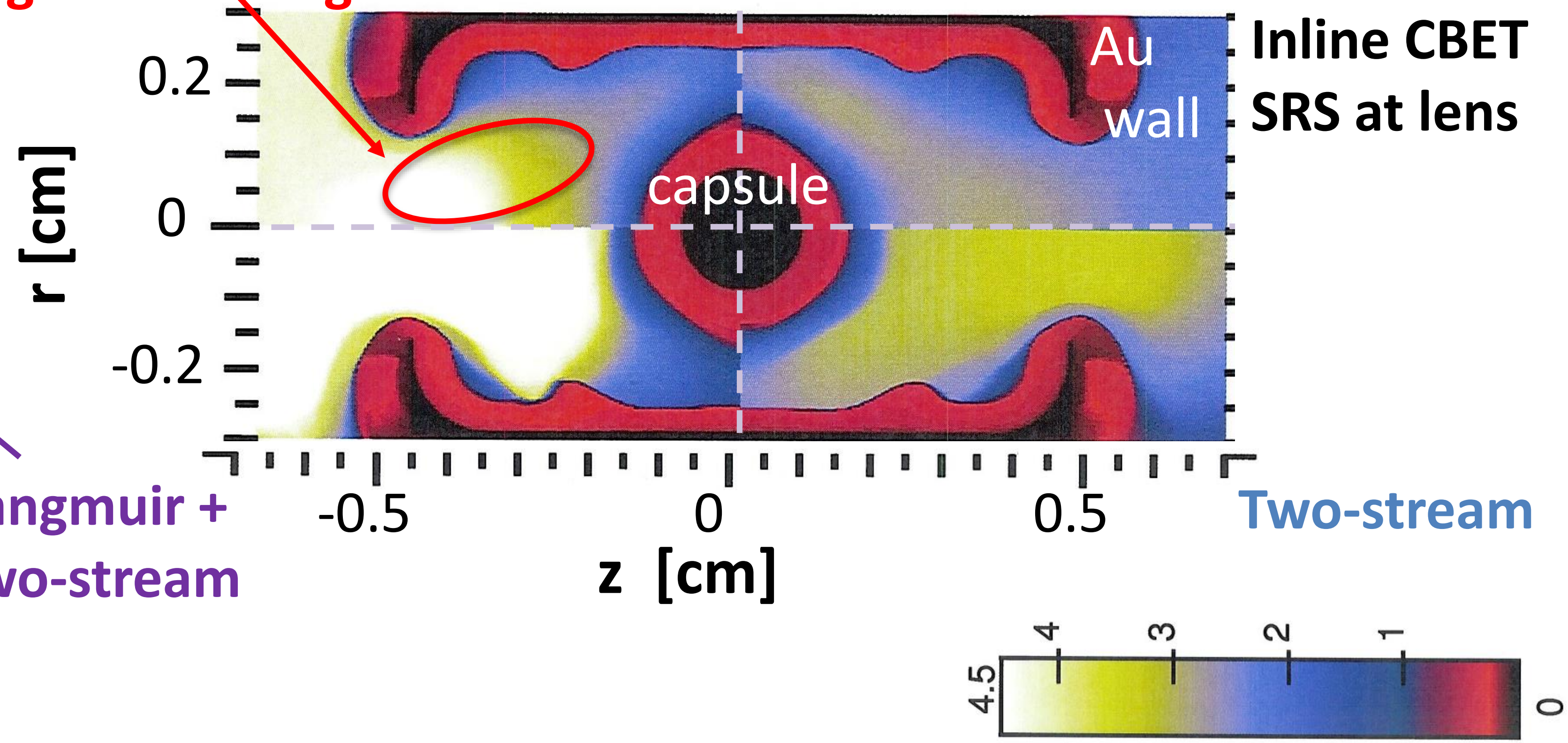
Electron temperature [keV] at 13 ns – mid peak power

Langmuir + two-stream



Inline SRS:
Langmuir heating[1]

Base case:
Inline CBET
SRS at lens

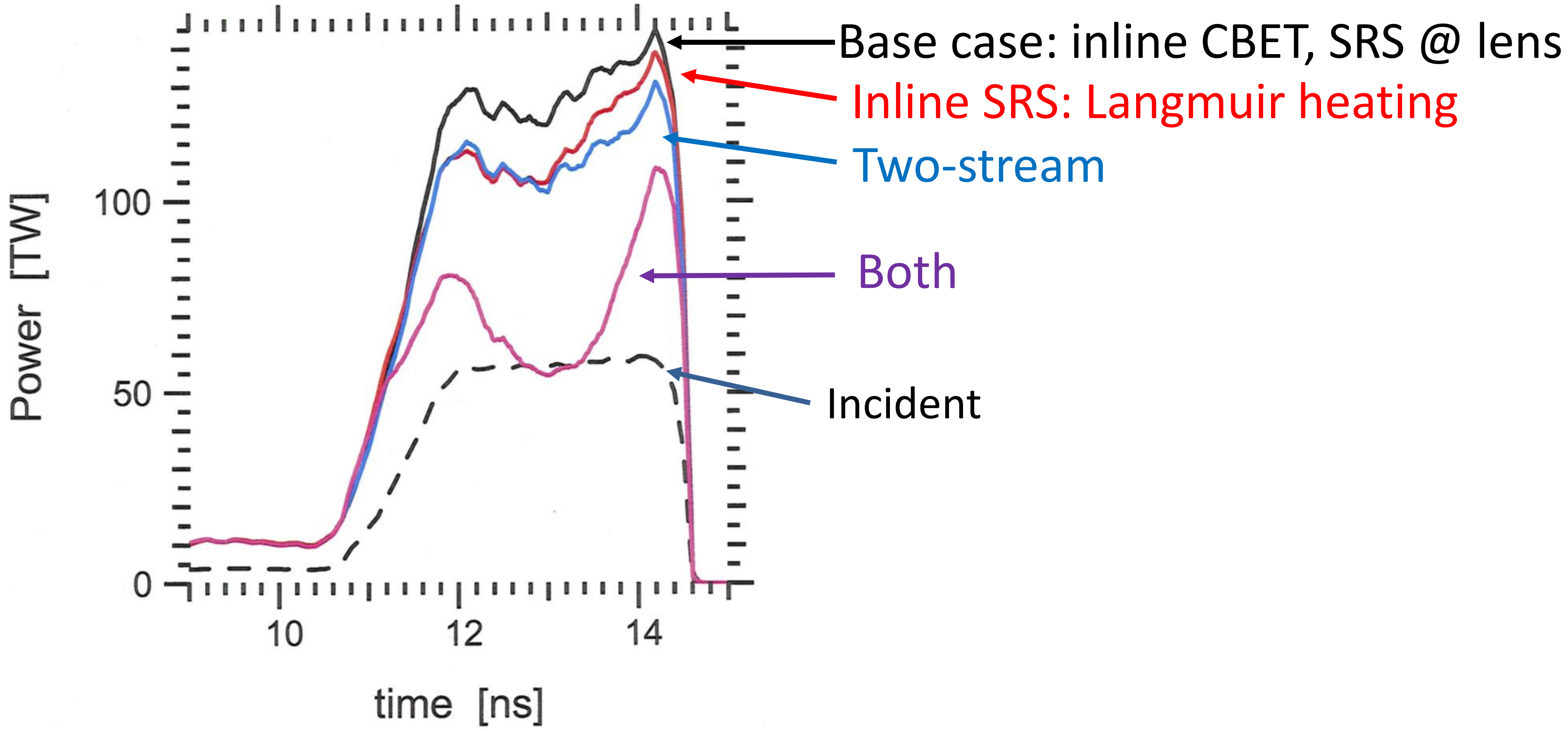


High T_e reduces CBET and laser absorption

[1]D. J. Strozzi et al., *Phys. Rev. Lett.* (2017)

Langmuir heating and two-stream both reduce CBET to inners – strong synergy

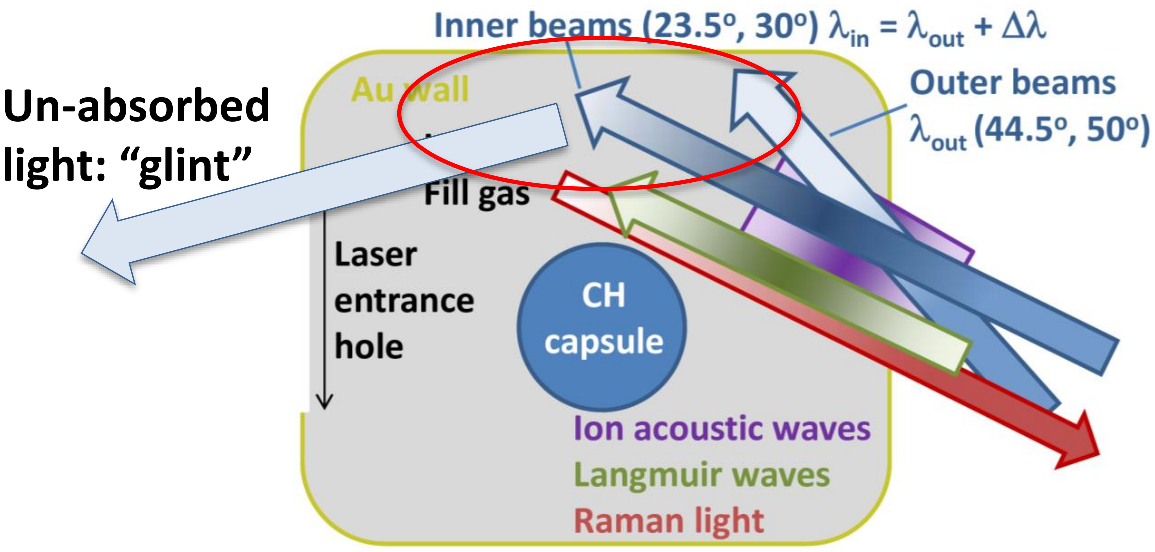
Inner-cone power:
Incident + CBET – escaping backscatter



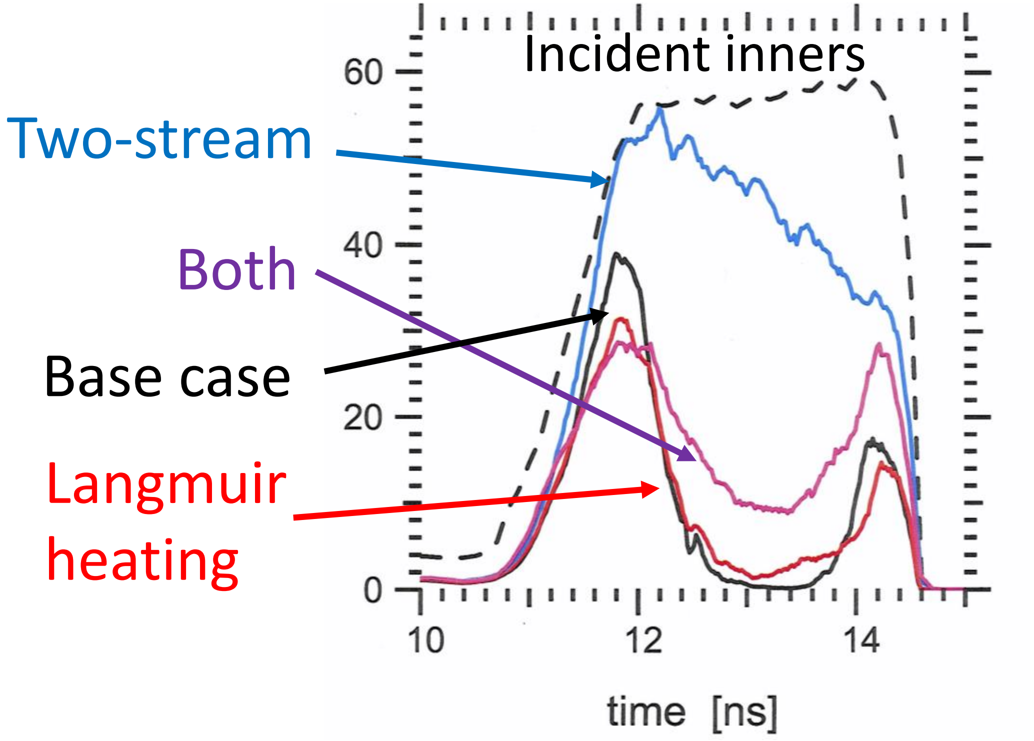
Two-stream flux limit reduces laser absorption, enhances glint

Enhanced Glint

Hotter → less inverse brem. absorption



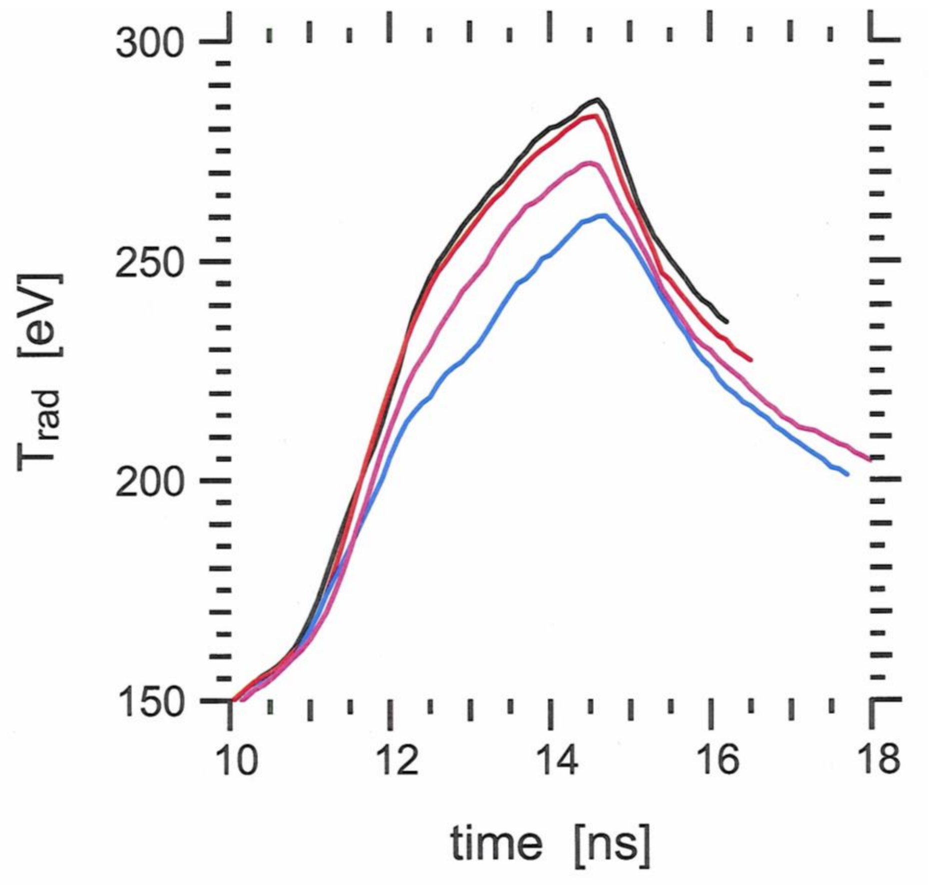
Glint: escaping laser power [TW]



L. Suter: similar enhanced glint with low flux limit f=0.02-0.03, and amplified glint

Two-stream flux limit: enhanced glint reduces total drive

Radiation temperature on capsule

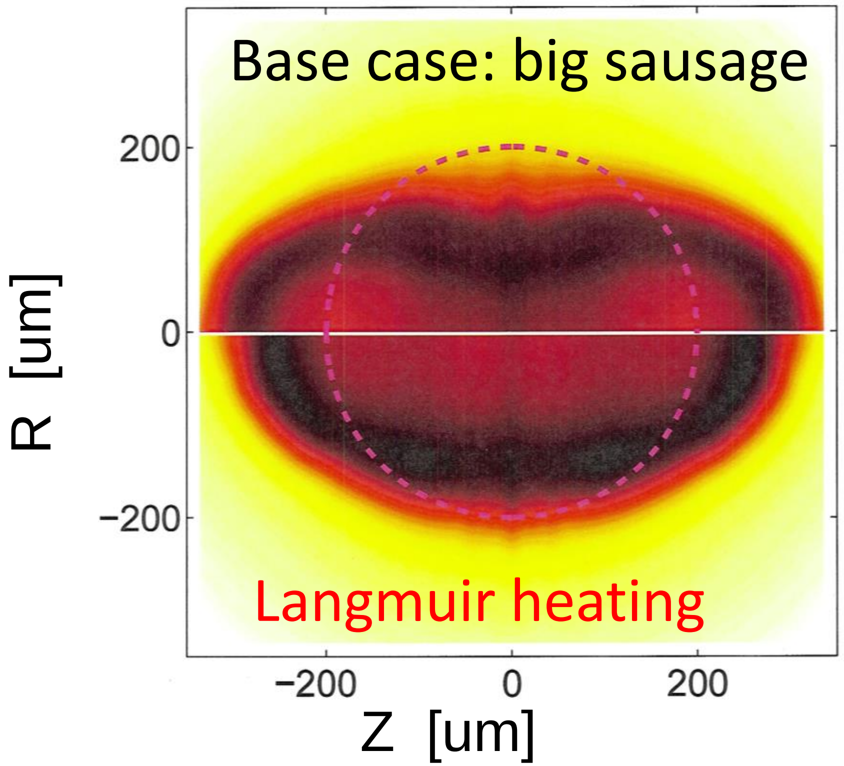


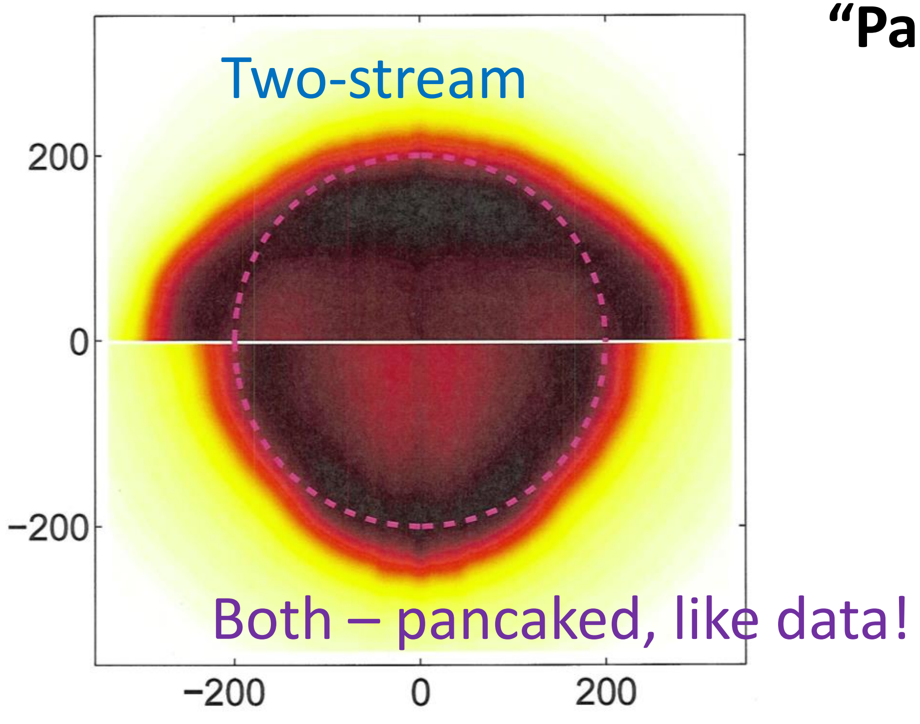
x-ray bangtime: experiment – simulated [ps]

Base case:	+650	
Langmuir heating:	+510	
Both:	+10	matches experiment!
Two-stream:	-450	

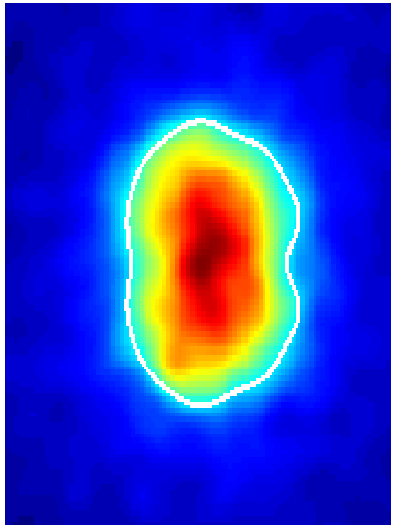
Capsule shape combines CBET, Langmuir heating, and glint

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

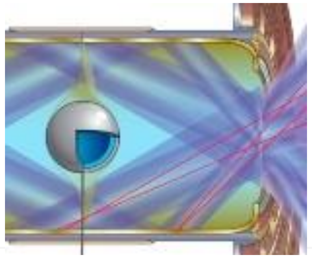




Measured x-ray self emission: "Pancaked", P_2/P_0 = -0.12



Hohlraum axis



Summary: Inline CBET and SRS improve shape modeling, plus low flux limit may explain drive and shape

Inline CBET reduced 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 further reduces waist x-ray drive

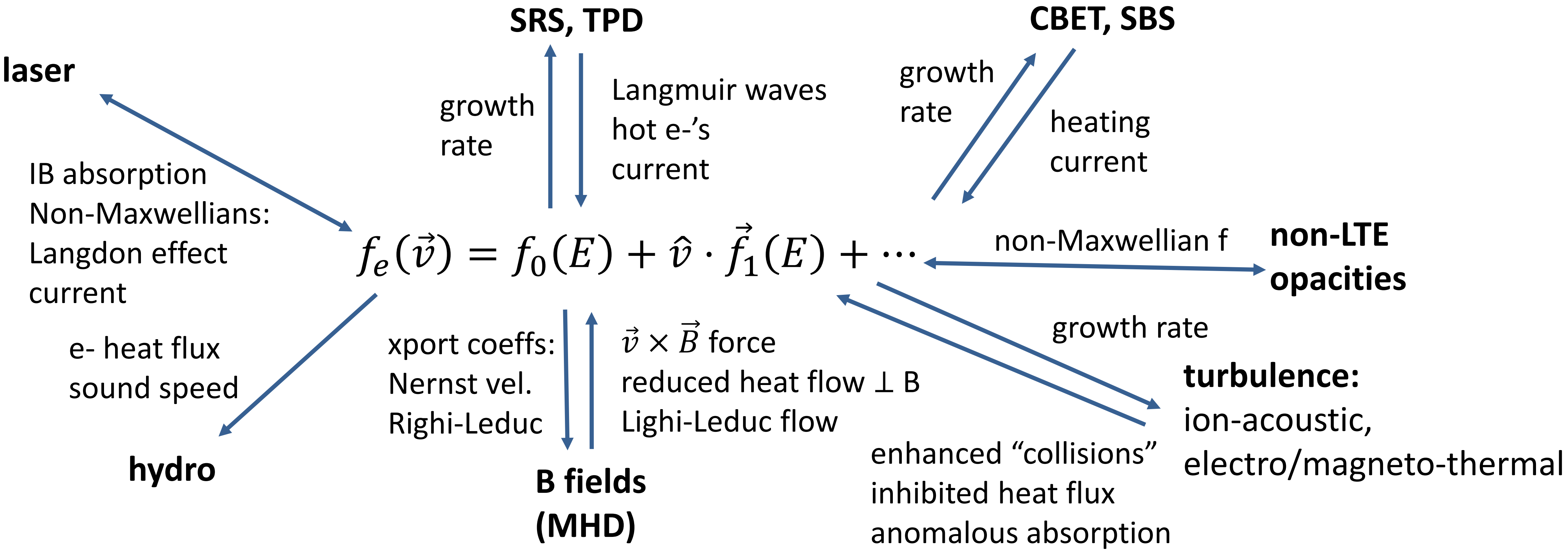
- Langmuir waves driven just inside entrance - far from inner-beam spots
- LEH hotter → less CBET
- Net effect is less sausaging drive, same total x-ray drive
- Little absorption of SRS light

Low (two-stream) flux limit

- "Just right" amount of CBET and inner-beam glint

Inline models change plasma conditions in entrance hole, especially with low flux limit

Future model improvements: consistent electron distribution



As complex as needed but not more so:

- No 3D PIC – need reasonable computing time
- A few spherical harmonics? → like multigroup diffusion
- Expand about Maxwellian: reduce to collisional fluid when valid
- Nonlocal Schurtz, Lasnex suprathermal models of this type
- Extensions needed to incorporate all effects

This physics occurs in all ICF approaches:

- **Direct**
- **Indirect**
- **Magnetic (MagLIF)**

BACKUP BELOW

Physics beyond 1D energetics is limiting NIF fusion yield

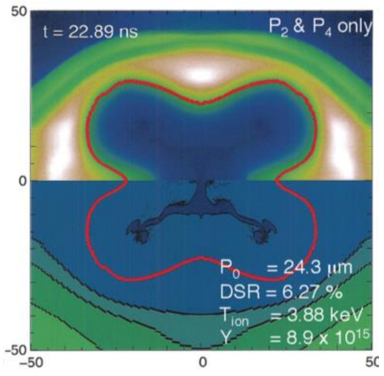
- Several designs have experimentally shown implosion velocities adequate for much higher yields than measured
  - HDC, low foot, high foot - even with backscatter and drive multipliers

Yield deficit due to 2D and 3D effects

- **Low-mode shape → fix the hohlraum**
- **Fix the tent**

Low-mode asymmetry: this talk

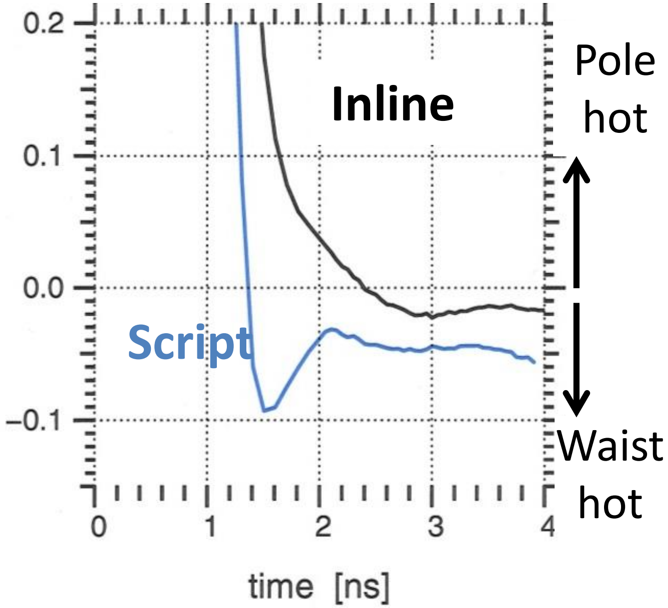
- Asymmetric x-ray drive
- Implosion shape
- Time-dependent symmetry swings:
  - Non-stagnating flow, residual KE



D. Clark, PoP 2015

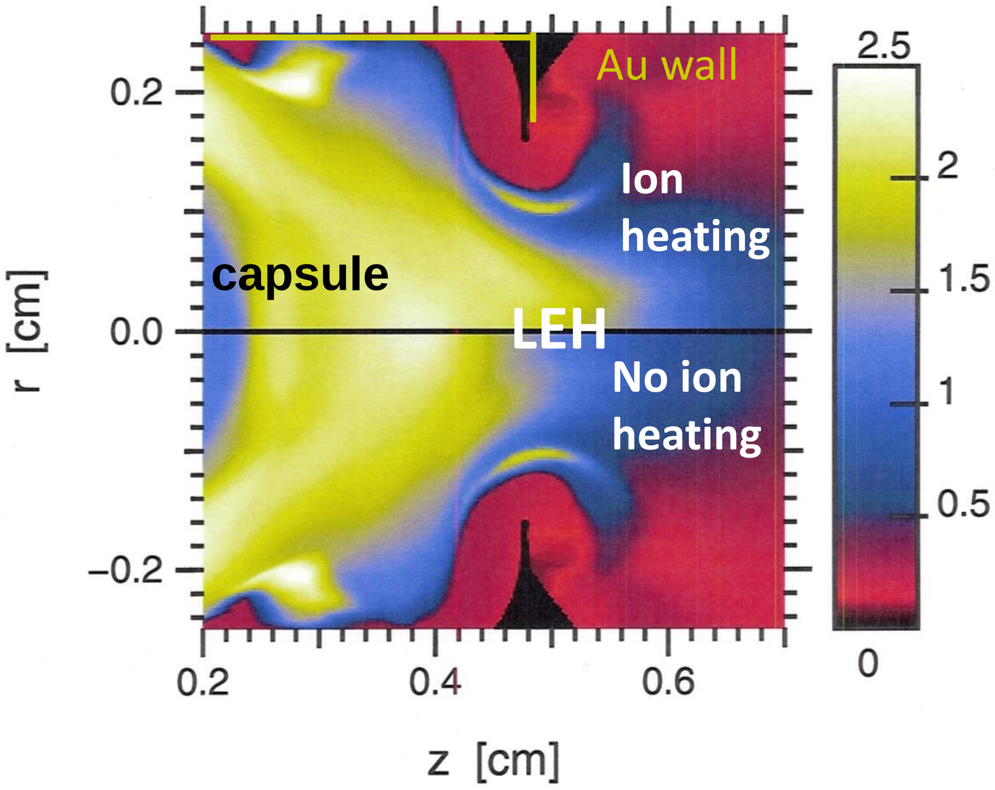
Hydra inline CBET picket

x-ray flux P2/P0 moment at ablation front

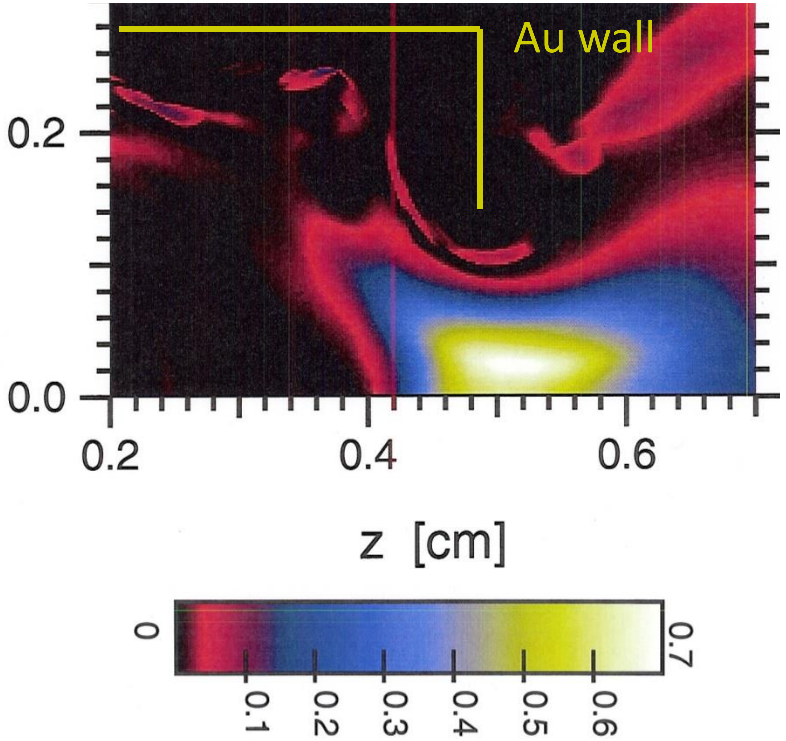


Inline CBET: Ion-wave heating increases ion temperature ~ 700 eV in entrance hole

T_{ion} [keV]:
two runs with inline CBET



T_{ion} difference [keV]:
with heating - without



Time 14 ns: late peak power

Inline CBET: ion heating can have small effect on CBET

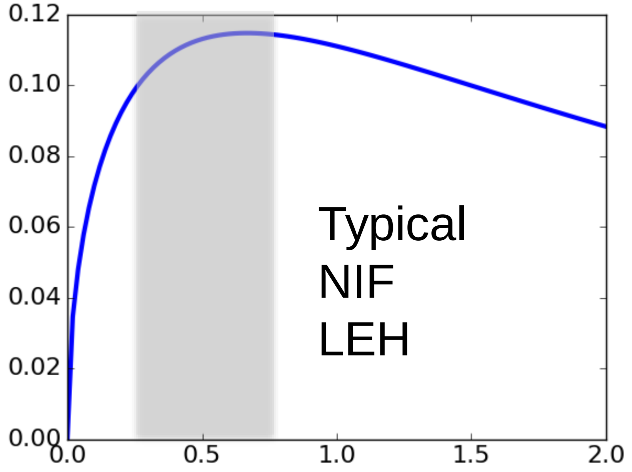
Off-resonance CBET gain rate: P. Michel et al., Phys. Plasmas 2013

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

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

Ion heating can slightly increase
CBET gain before it gradually drops

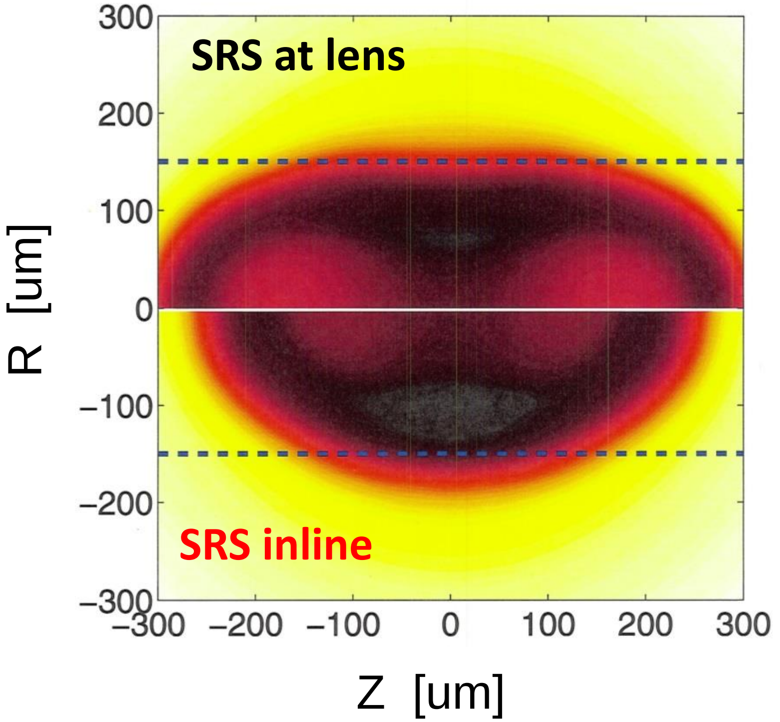
Gain rate (Z=2)



T_i / T_e

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

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



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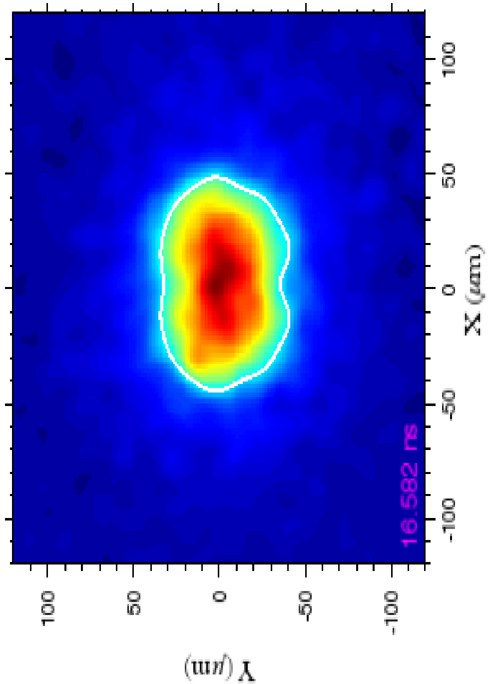
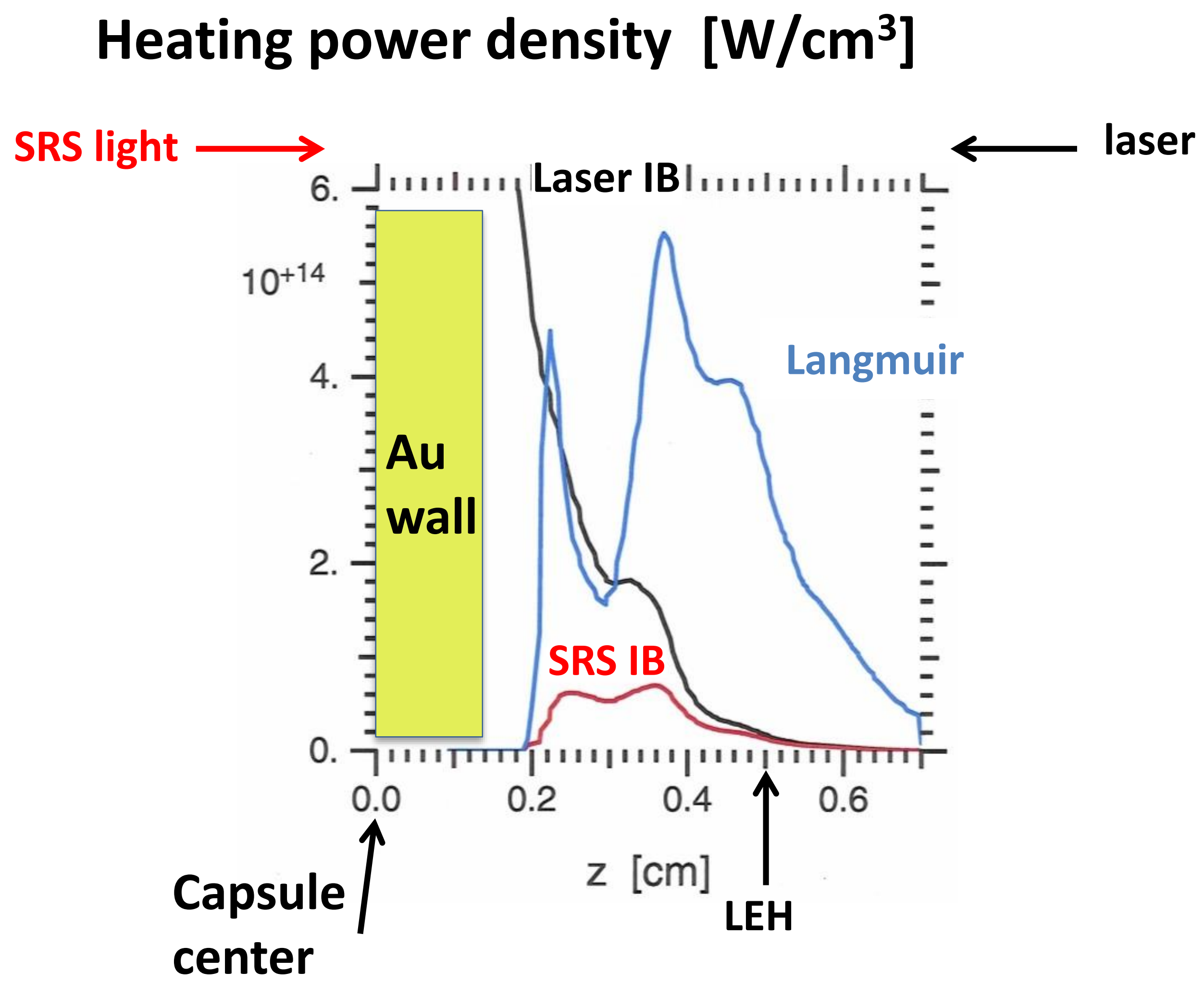
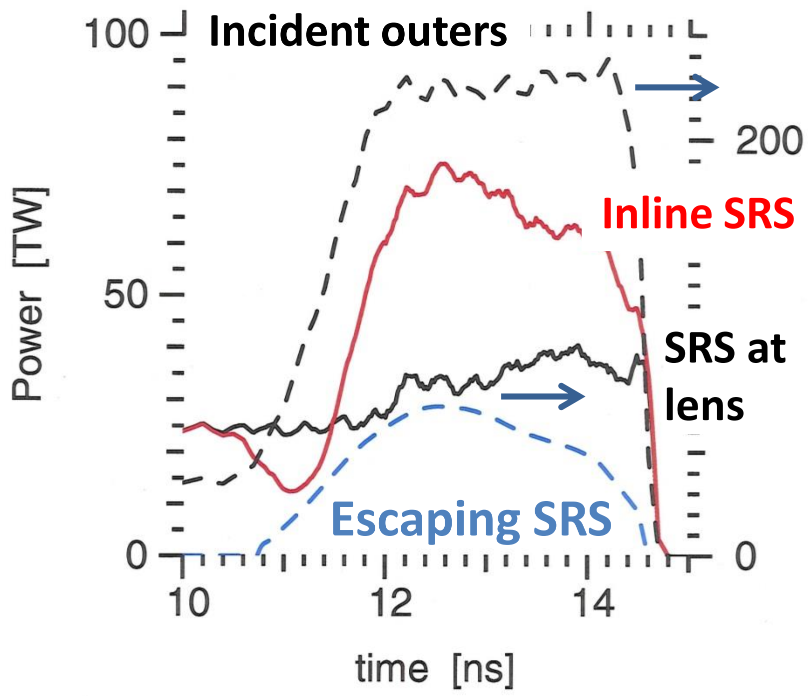


Inline SRS model: Langmuir wave heating dominates in low Z



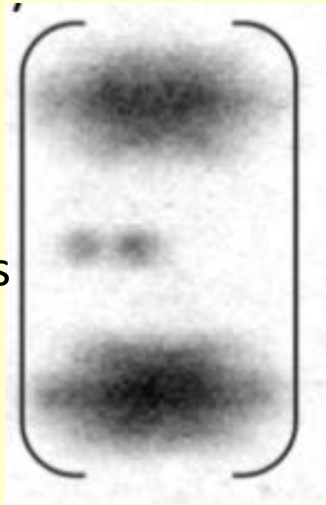
Post-CBET outer beam power



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

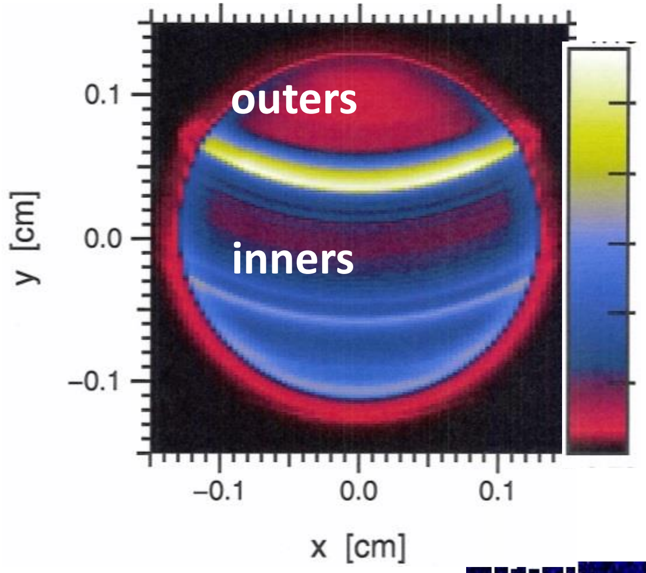
N130315

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

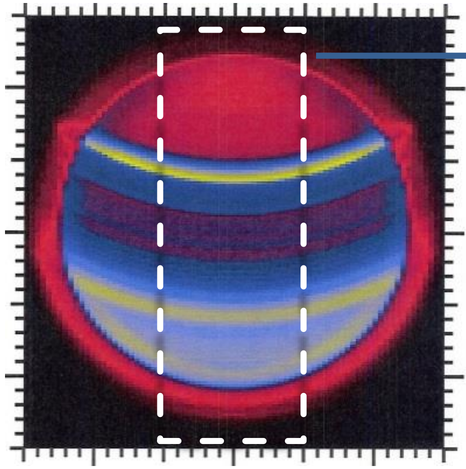
"Microdot" platform
- M. Barrios, N. Izumi
- Mid-Z patches on target surfaces
- Spectroscopy → T_e

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

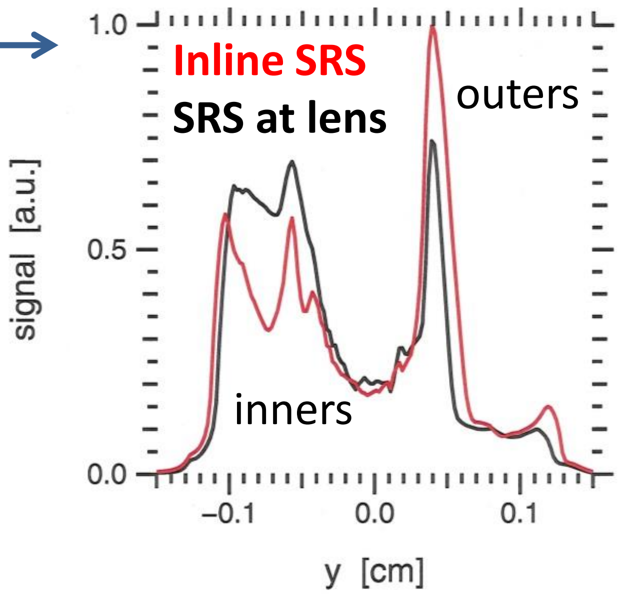
Inline SRS



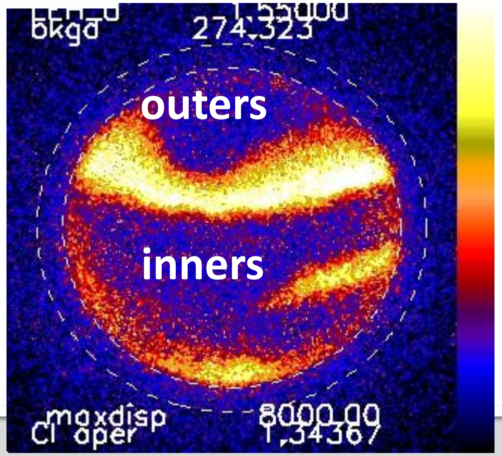
SRS at Lens



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

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