Inline Modeling of Cross-Beam Energy Transfer and Stimulated Raman Scattering in Radiation-Hydrodynamics Codes

Anomalous Absorption Meeting
15 June 2015

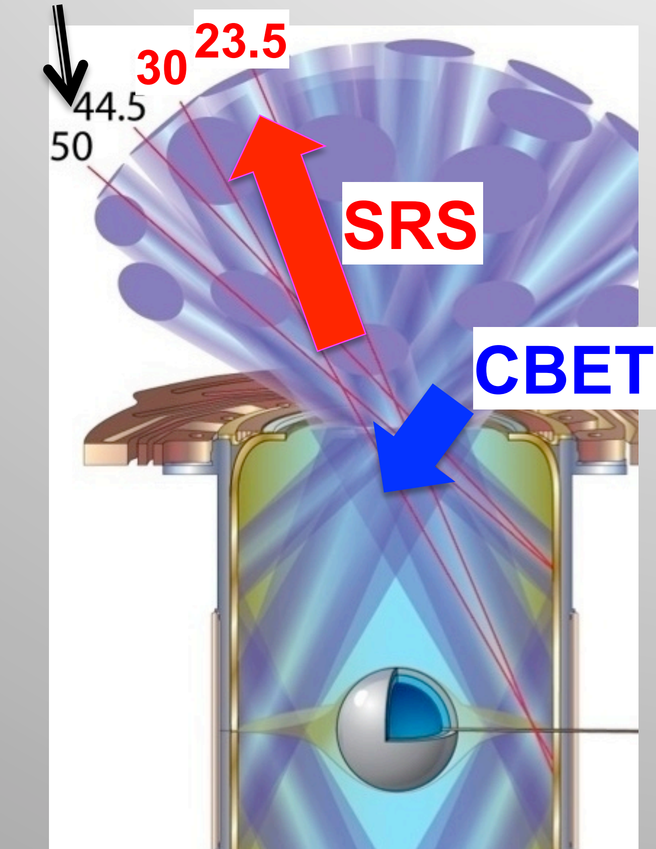
D. J. Strozzi, S. M. Sepke, G. D. Kerbel,
D. S. Bailey, P. Michel, L. Divol, C. A. Thomas

Lawrence Livermore National Laboratory

LLNL-CONF-673295
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

Cross-beam energy transfer (CBET) to inners used on NIF to control shape for hohlraum gas fill >= 0.96 mg/cm^3

Inners: Redshifted vs. outers



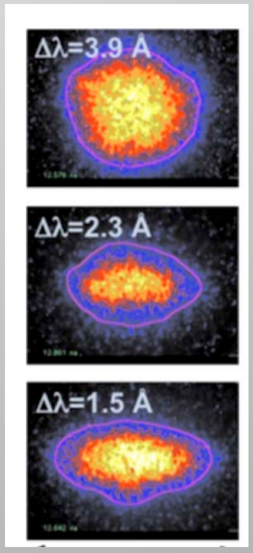
- Low- and high-foot designs
- Transfer from "pump" to "probe" beam with lower frequency in plasma frame
- 3 NIF wavelengths ("colors"): 23^o, 30^o, outers
- Stimulated Raman scattering (SRS):
  Laser photon → scattered photon + Langmuir wave

Hotspot x-ray image

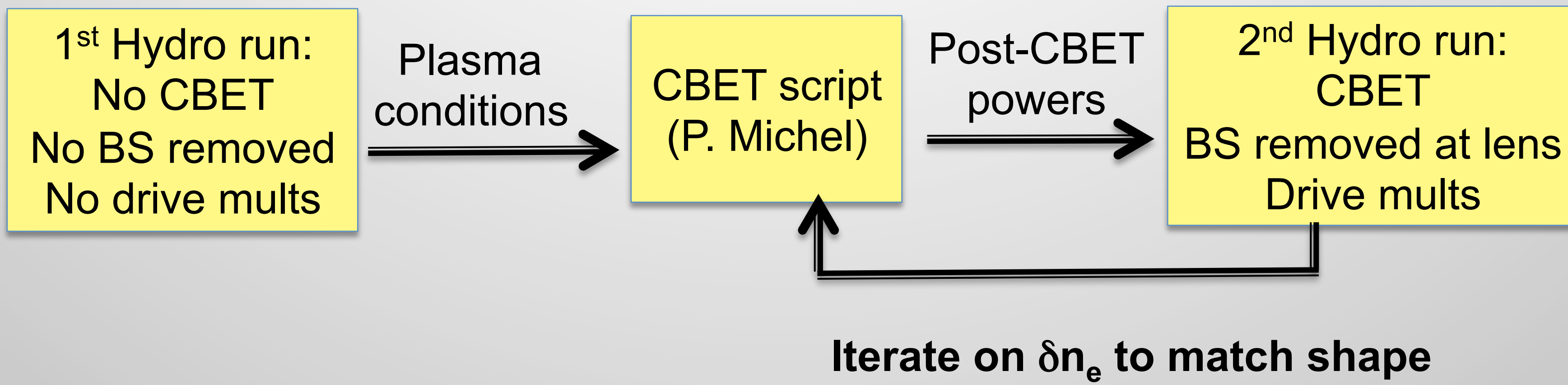
'Sausaged'

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

'Pancaked'



Current two-run "Script Process": CBET must be limited to match shape data



"The Shape Problem:"

- **More CBET to inners than matches shape data**
- **$\delta n_e/n_e$ clamp on ion wave amplitude to limit CBET**
- **Labor intensive**
- **Not predictive**

Inline models of CBET and SRS have been added to rad-hydro codes Hydra and Lasnex

Inline model: rad-hydro code calculates LPI every time step

Advantages vs. script process:

- One run, not two
- More CBET physics:
  - Refraction, inverse brem., spatially non-uniform transfer
  - Ion wave energy deposition – affects LEH temperature
- More SRS physics:
  - Pump depleted in target
  - SRS light grows in target
  - Langmuir-wave and SRS inverse brem. heating

Summary: Inline models of CBET and SRS are moving toward accurate modeling of implosion shape

Inline CBET in Hydra

- No known bugs – hats off to Scott Sepke!
- Inline CBET less than script in picket, almost as much in peak power
- See D. J. Strozzi, Anomalous 2014, APS-DPP 2014 – or discuss in person

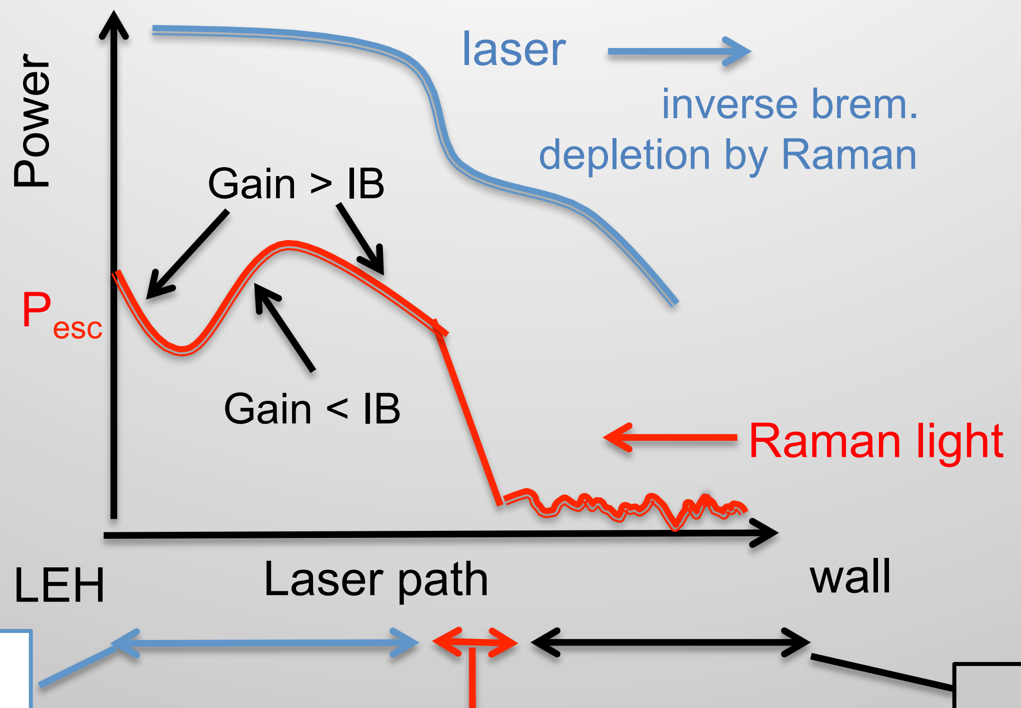
Inline CBET and SRS in Lasnex: applied to early high-foot NIF symcap

Two runs with inline CBET:

- Run A: SRS removed "at lens" = from incident laser
- Run B: inline SRS
  - SRS light grows as it propagates to LEH – gain exceeds inverse brem.

- Inline SRS vs. lens SRS:
  - LEH hotter – affects CBET
  - DRIVE: total x-ray drive and energetics same
  - SHAPE: x-ray drive stronger on pole → pancaked shape
    - Closer to data with larger δn_e clamp

SRS physical picture: resonant growth from noise, post-resonant growth and absorption



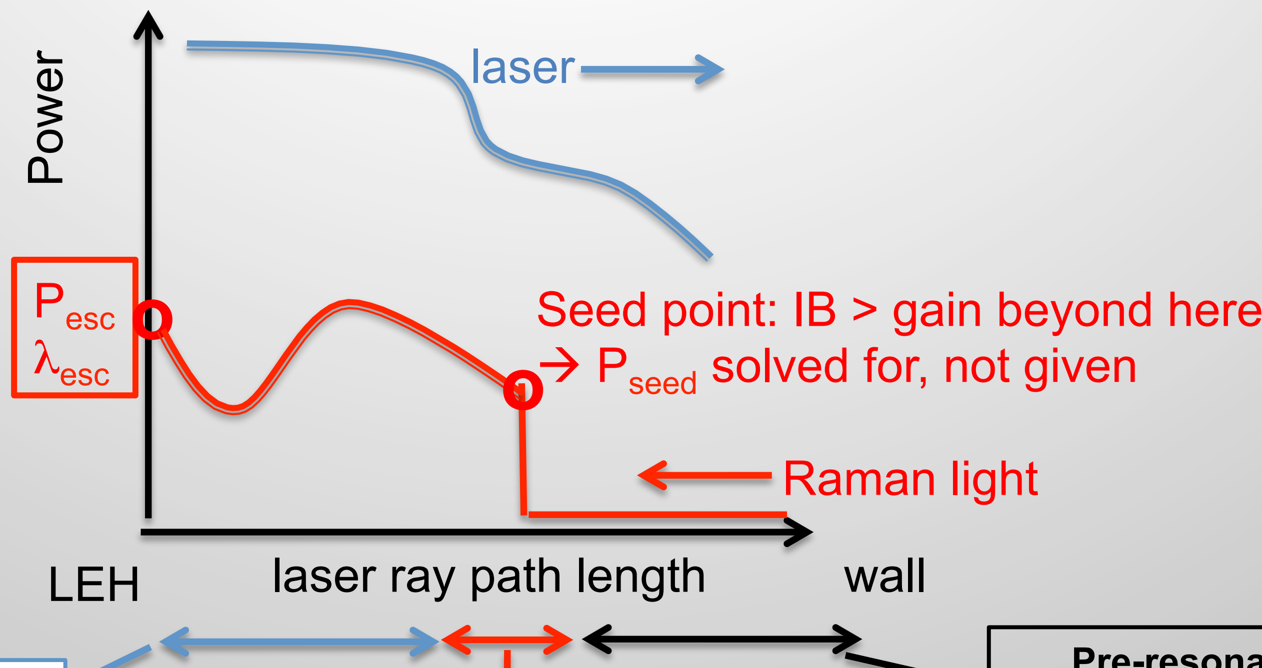
Post-resonance
- Non-resonant growth, inv. brem.
- 1D linear gain should suffice

Resonance
- Raman grows from noise to finite level
- Length ~ speckle length
- Most exponentiation
- One $\{n_e, T_e\}$ → Raman wavelength
- "Fun physics:" speckles, kinetics, pF3D, PIC

Pre-resonance
Thermal Raman noise: brem., Thomson

Inline SRS model: 1D coupled-mode equations in post-resonant region

User gives SRS power, wavelength



Post-resonance
1D plane-wave coupled-mode equations solved until turning point reached

Resonance
$P_{SRS} = P_{seed}$ = finite seed power

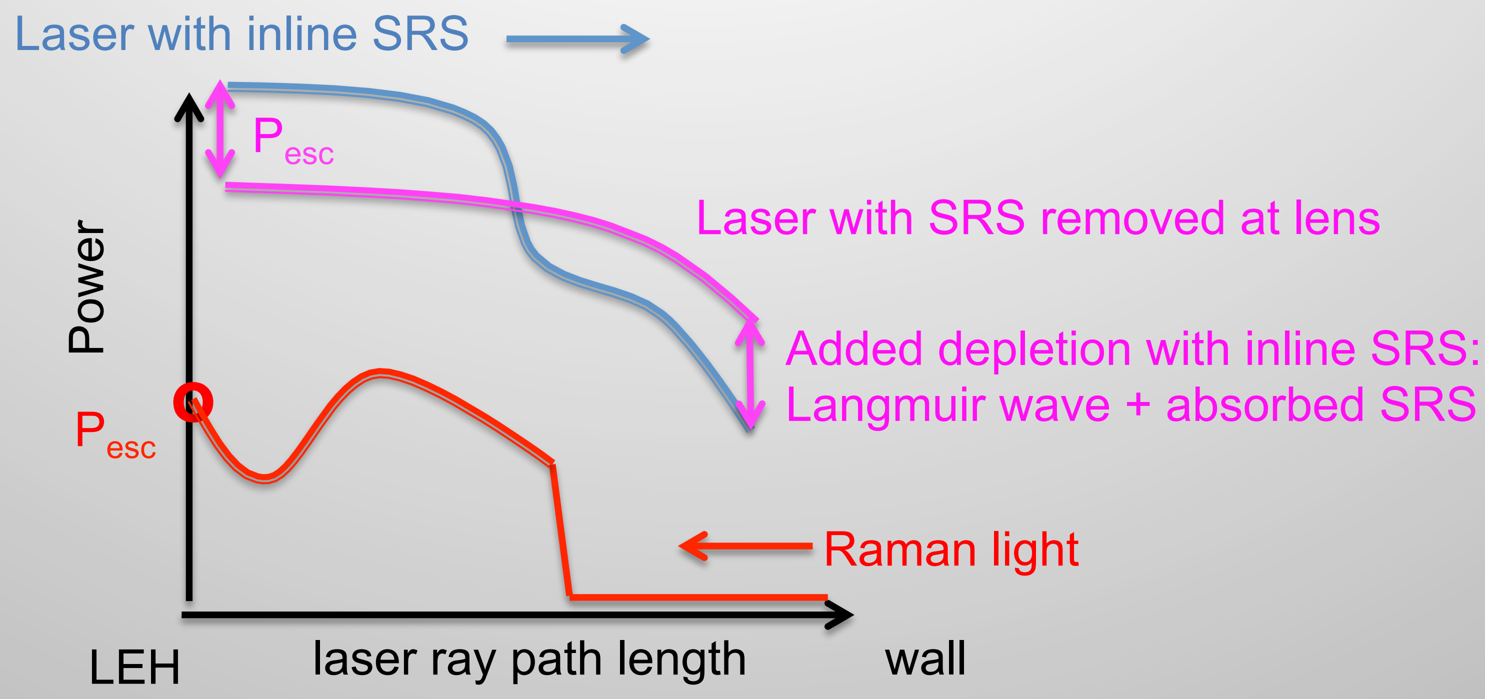
Pre-resonance
$P_{SRS} = 0$

$$\partial_z I_0 = -\kappa_0 I_0 - \omega_0 K I_0 I_1 \qquad \text{pump laser}$$

$$-\partial_z I_1 = -\kappa_1 I_1 + \omega_1 K I_0 I_1 \qquad \text{scattered light}$$

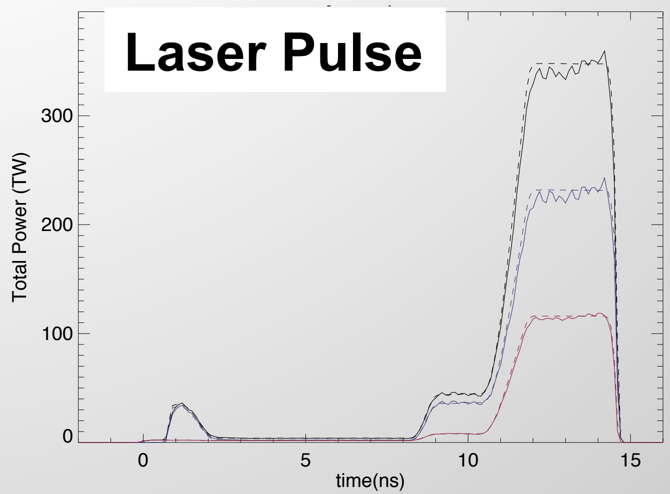
$$p_{EPW} = (\omega_0 - \omega_1) K I_0 I_1 \qquad \text{Langmuir wave power}$$

Inline SRS has more pump depletion than SRS removed at lens

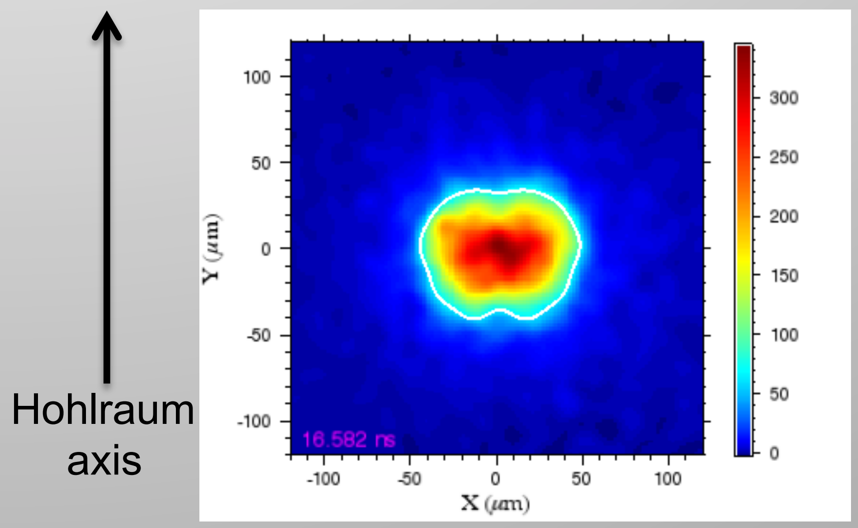


NIF shot N121130: early high-foot symcap

- Laser
  - E_{laser} = 1274 kJ P_{laser} = 350 TW
  - $(\lambda_{23}, \lambda_{30}) - \lambda_{out}$ = (8.5, 7.3) Ang.
  - Large CBET to inners: tune P2 shape
  - "3-color" CBET to 23's: tune azimuthal M4 shape
- Hohlraum: Au, "575 size"
  - Fill: 1.45 mg/cc He, current high-foot 1.6 mg/cc
- Capsule: CH, D-He3 gas fill – no DT layer
- Results
  - ~16% laser energy backscattered
    - — Mostly inner SRS
  - Bangtime: 16.6 ns
  - Hotspot pancaked: pole-high x-ray drive

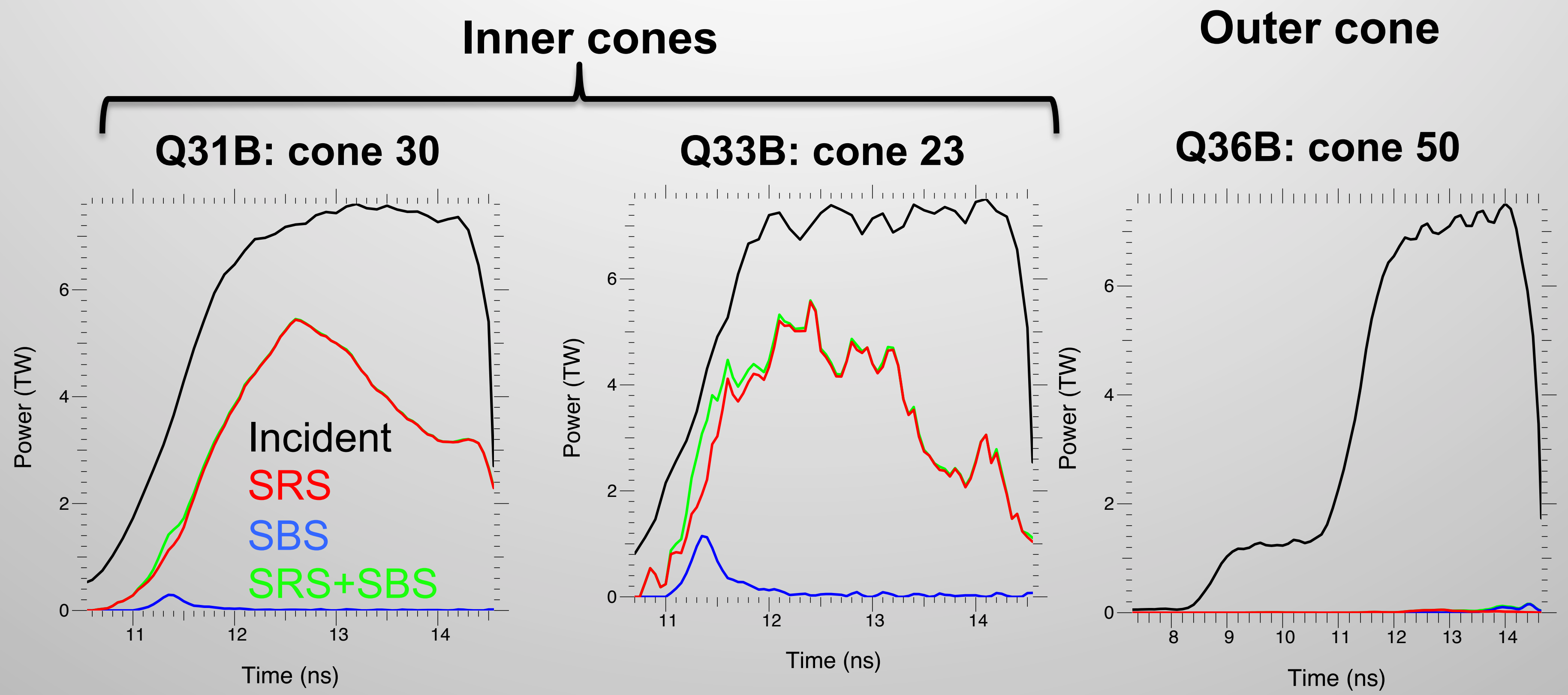


Hotspot x-ray image at bangtime: "Pancaked", P_2/P_0 = -0.12



Inline SRS: user specifies power and wavelength of escaping SRS light

NIF shot N121130

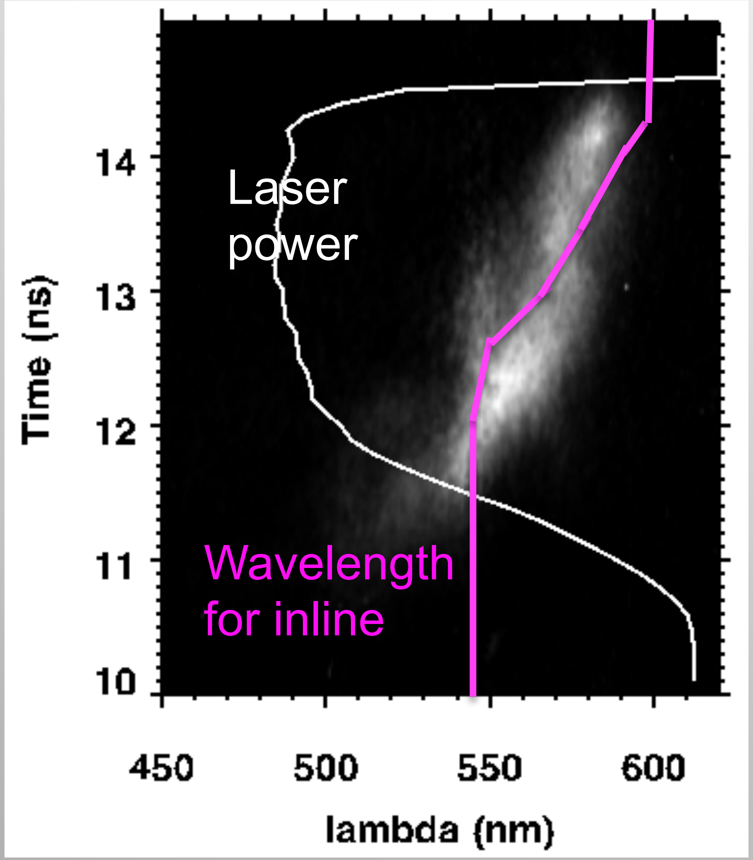


Inline SRS: user specifies power and wavelength of escaping SRS light

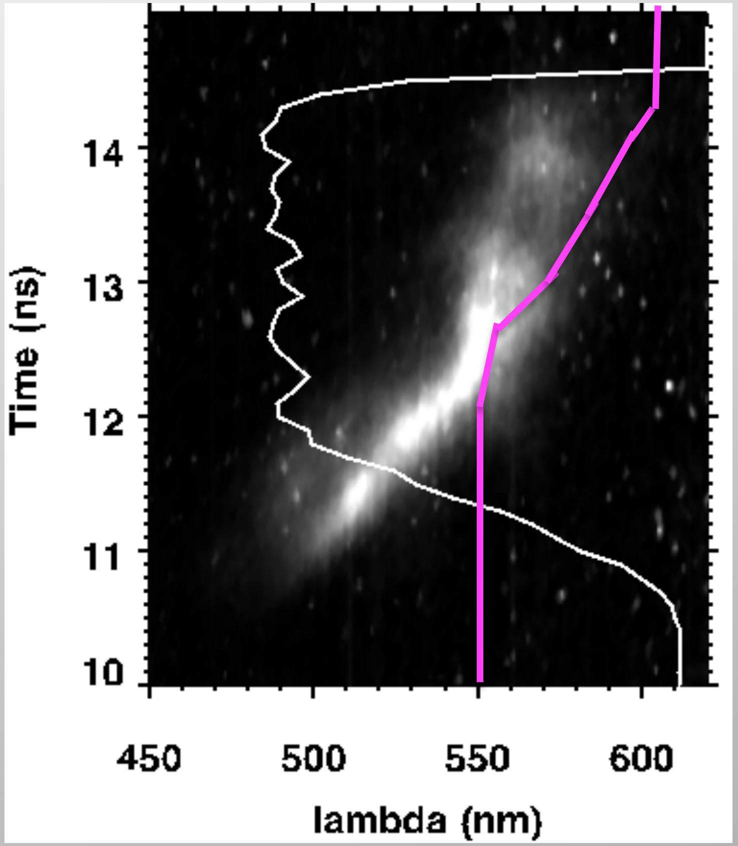
NIF shot N121130

Chose wavelength close to cone 30 measured value, used same for cone 23

SRS – cone 30



SRS – cone 23



Lasnex inline CBET and SRS modeling of N121130

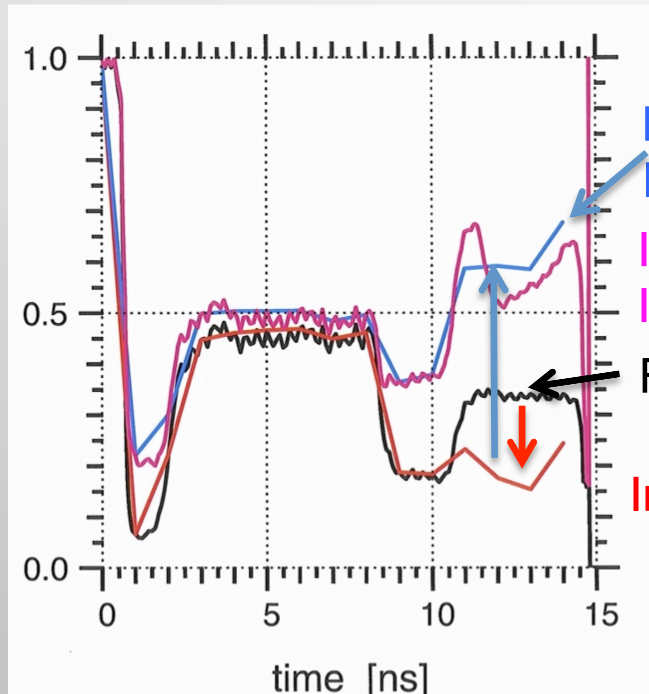
Three runs by C. Thomas, all with:

- Lagrange mesh management: better match x-ray and capsule drive data
- High-flux model: DCA opacities, f=0.15 flux limit
- CBET saturation clamp $\delta n_e/n_e = 10^{-3}$

- Run A: Traditional two-step “CBET script process”
- Run B: Lens SRS + Inline CBET
- Run C: Inline SRS + Inline CBET

Lasnex inline SRS and lens SRS give similar cone fraction – neglecting Langmuir-wave heating

Cone fraction = Inner / total power



Lens-SRS:
Incident – escaping SRS + CBET

Inline-SRS:
Incident – escaping SRS + CBET

Full incident laser

Incident – escaping SRS

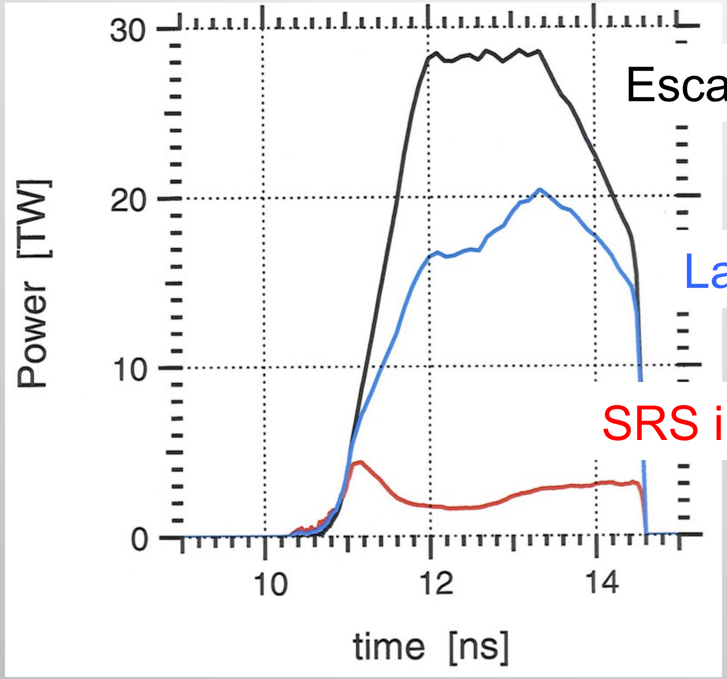
Laser Pulse

Inline SRS

- Langmuir-wave heating, SRS inv. brem. further deplete inner beam at wall
- Reduces equatorial x-ray drive on capsule

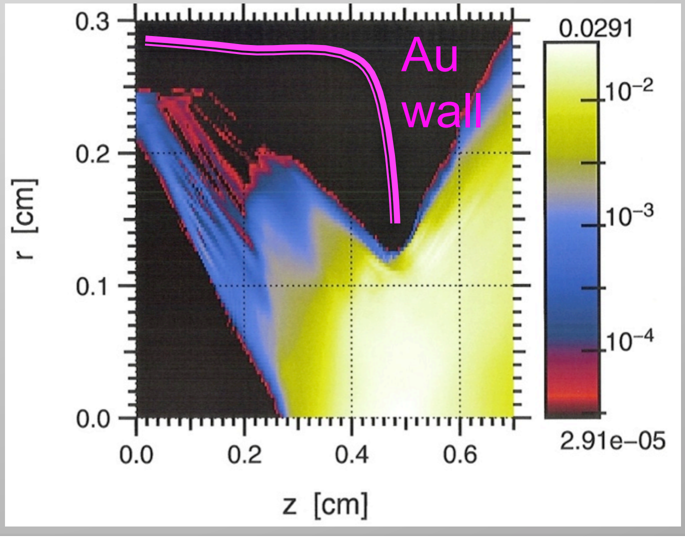
Lasnex inline SRS energetics: inverse brem. of SRS light not energetically significant

Inner cone SRS: 23's + 30's



"Script" process and removing SRS at lens neglect Langmuir wave and SRS IB heating

SRS light intensity [a.u.]



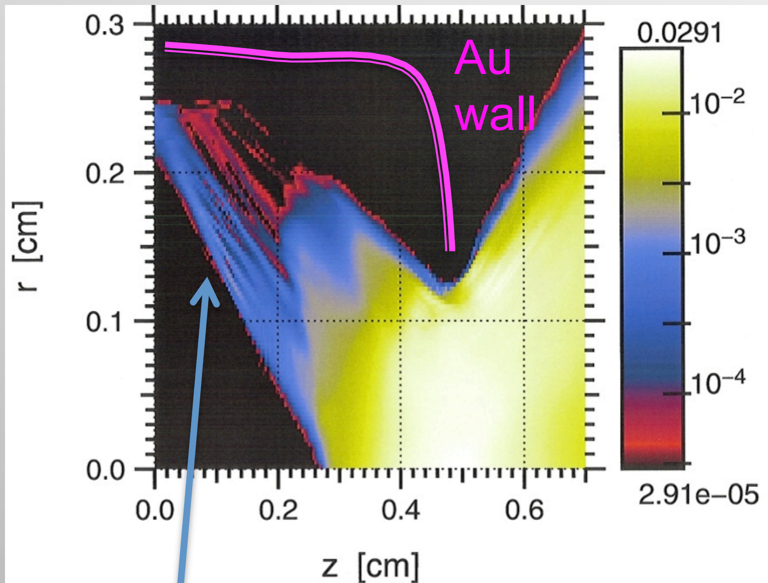
Manley-Rowe for Langmuir waves:

$$P_{Langmuir} = \frac{\omega_{las} - \omega_{srs}}{\omega_{srs}} * \left[P_{srs}^{esc} + P_{srs}^{IB} \right]$$

Inline SRS: gain exceeds absorption as it propagates, most heating just inside LEH

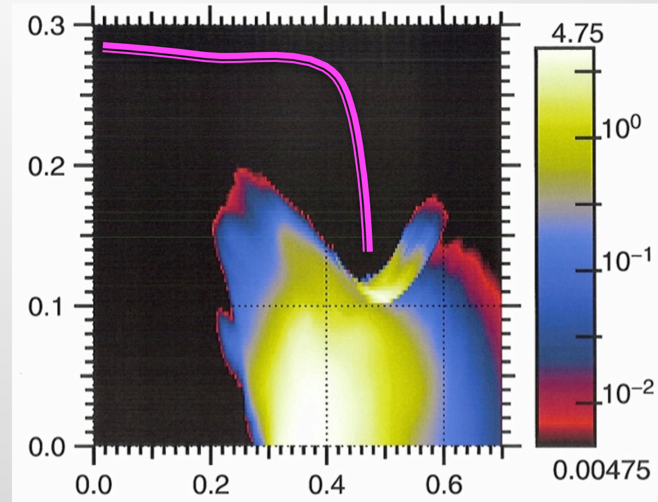
t = 13 ns

SRS light intensity [a.u.]

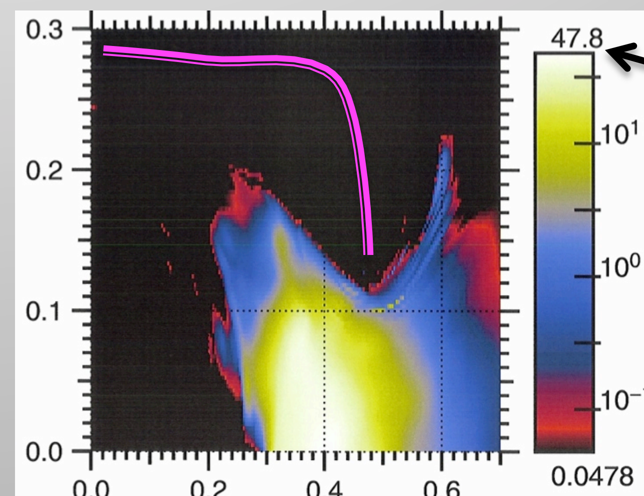


* Small azimuthal volume with high intensity: little power

SRS inv. brem. heating [Mbar/ns]

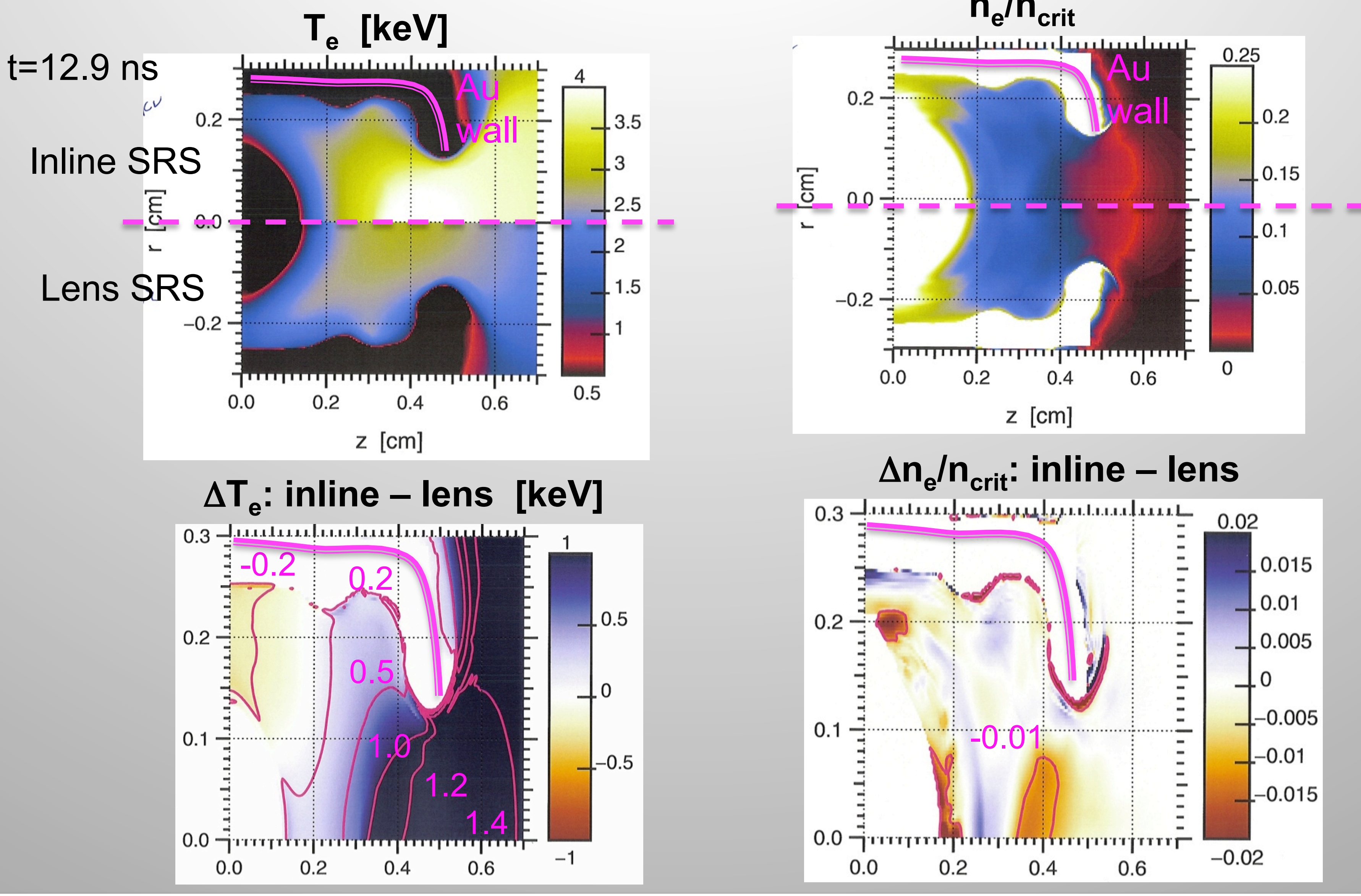


Langmuir wave heating [Mbar/ns]



scale 10x SRS IB

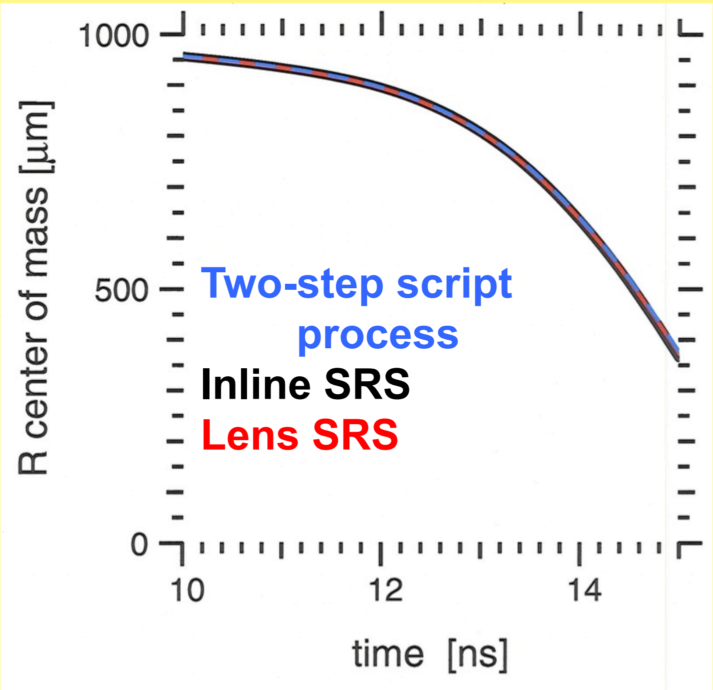
Inline SRS: hotter and less dense LEH than lens SRS



Total x-ray drive same for inline and lens SRS, stronger on pole with inline SRS

DRIVE

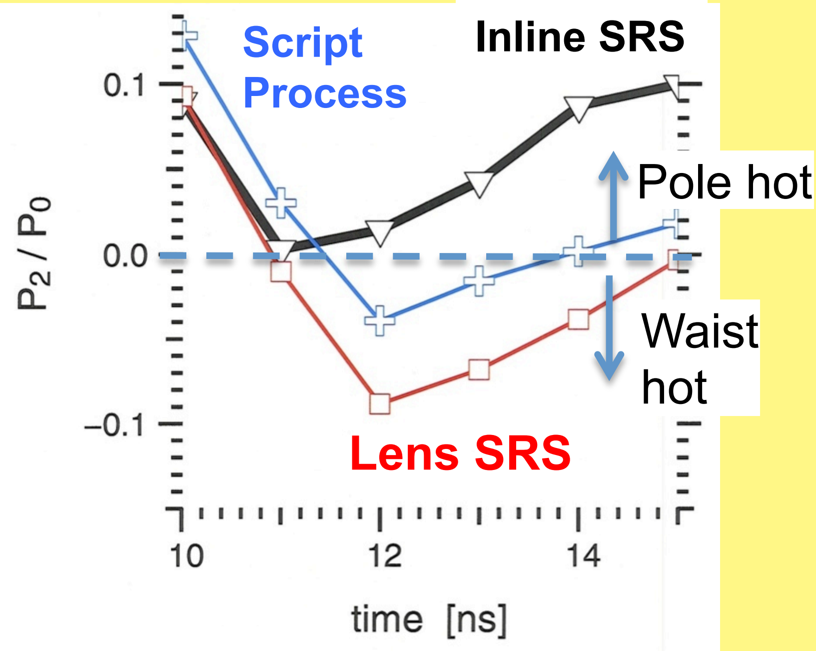
Capsule center of mass: Total x-ray drive the same



Your eyesight is fine –
3 curves indistinguishable

SHAPE

P_2 moment of x-ray power deposition at ablation front



P_2(hot spot) ~ P_2(x-ray)*cnvg. ratio

Time-integrated:
P_2(x-ray)/P_0 < 1% for ignition

Conclusions and future work

Inline CBET and SRS in Lasnex:

- Most Langmuir-wave and SRS inverse brem. just inside LEH
- Langmuir-wave heating dominates over SRS inverse brem.

Compared to SRS removed at lens:

- DRIVE: Same total x-ray drive and capsule energetics
- SHAPE: X-ray drive pole-hot with inline SRS – inner beams depleted
    - Closer to experimental data

Future:

- Super-thermal package for hot electrons – local deposition to fluid T_e (shown here) overstates LEH heating
- Replace CBET δn_e clamp with physical nonlinearity:
    - trapping, two-ion wave decay, wave-breaking
- Match capsule shape without dialing clamp

Ultimate goal: predictive model for drive and shape

BACKUP BELOW

Inline CBET model: coupled-mode equations for unpolarized beams: NIF quad-to-quad transfer

Steady state, strong damping limit:

$$\frac{dI_1}{dz} = g * \min\left[I_0 I_1, a\,\delta n_{\max}\sqrt{I_0 I_1}\right] \qquad g = \text{coupling coeff}$$

$$\frac{dI_0}{dz} = -\frac{\omega_0}{\omega_1}\frac{dI_1}{dz} \qquad \text{Manley-Rowe}$$

beams 0 and 1

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

Ion wave amplitude, clamp δn_{max}

Ion-wave momentum and heat deposition:

$$m_i \frac{d\langle \vec{v}_i \rangle}{dt} = \alpha \vec{k}$$

$$\frac{dT_i}{dt} = \frac{2}{3}\left(\omega - \vec{k} \bullet \langle \vec{v}_i \rangle\right)\alpha$$

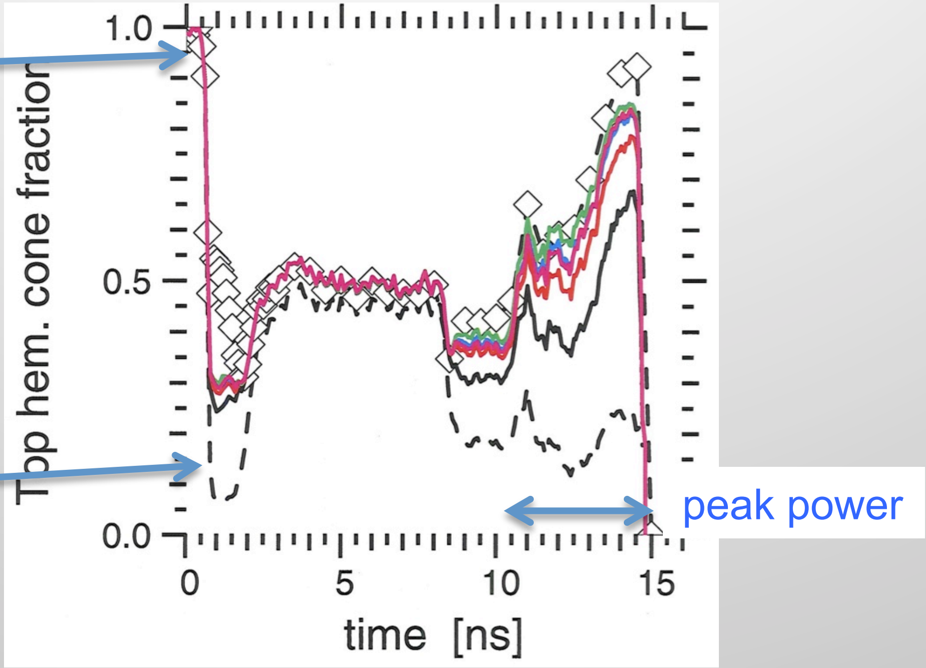
$$\alpha \equiv \frac{|E_k|^2 \operatorname{Im}\chi_i}{8\pi n_i}$$

P. Michel et al., PRL 2012

Laser cone fraction: N121130

Diamonds: script on 600 ray plasma maps

Dashed: incident (BS removed)

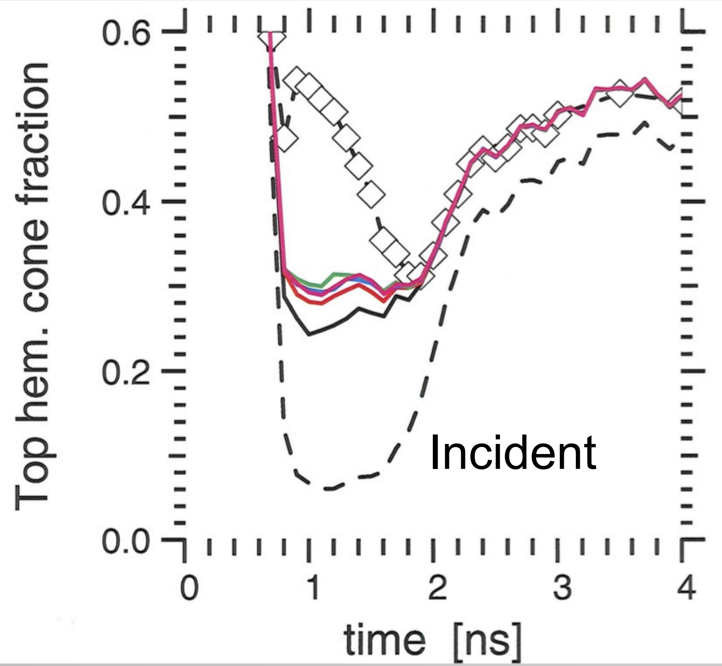


Rays per quad: 300 (nominal UBT) 600, 900, 900 no pond / heat*, 1200

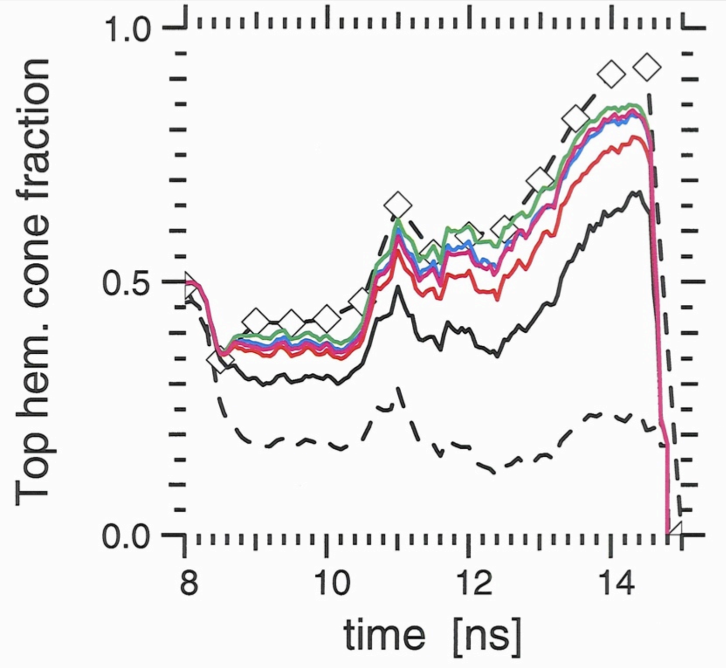
- No ponderomotive force = momentum deposition by lasers (of any kind, not just CBET), and no CBET ion heating.
- Enough rays needed to resolve quad intensity on Hydra mesh

Laser cone fraction: picket and peak

Picket: script gives more CBET, neglects inv. brem. absorption

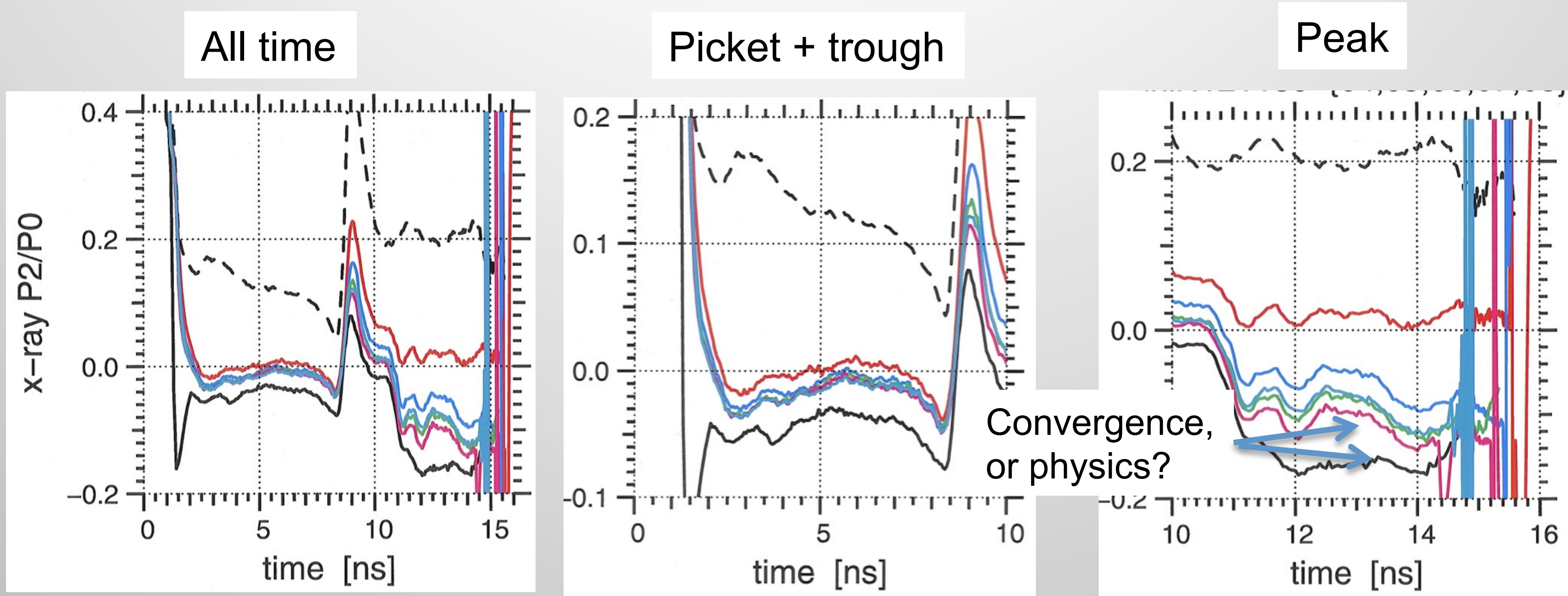


Peak: inline converges to script, with enough rays



- Diamond: script on 600 ray plasma maps
- Rays per quad: 300 (nominal UBT), 600, 900, 900 no pond / heat, 1200

X-ray flux P2 moment at ablation front: script consistently above inline CBET

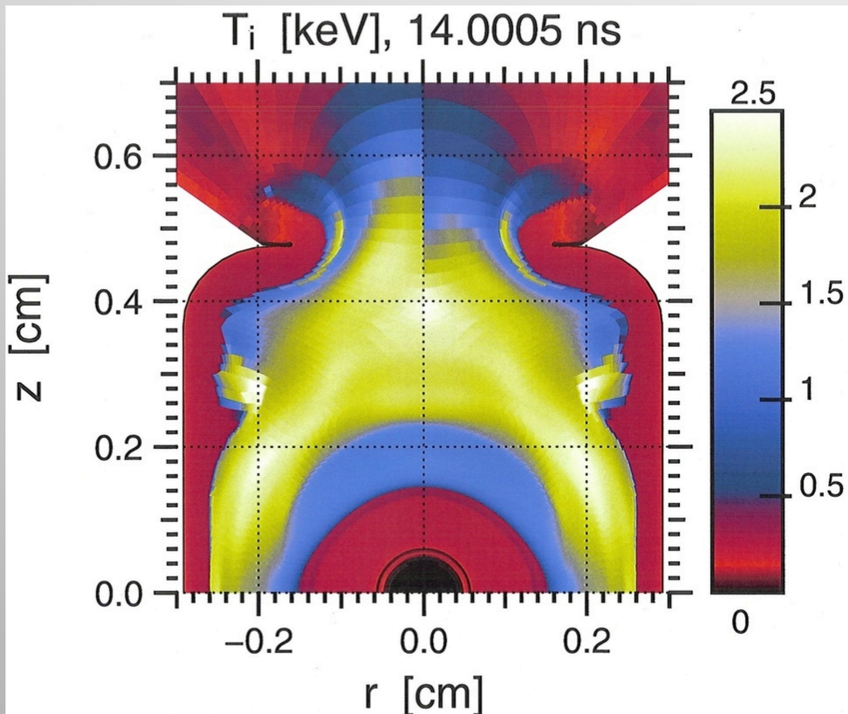


- Black dashed: BS removed at lens, no CBET
- Black solid: two-step process: pre-CBET, script, post-CBET w/ BS removed
- Rays per quad: 300 (nominal UBT), 600, 900, 900 no pond / heat, 1200
- Two 900-ray cases almost the same: ion-wave deposition doesn't affect CBET

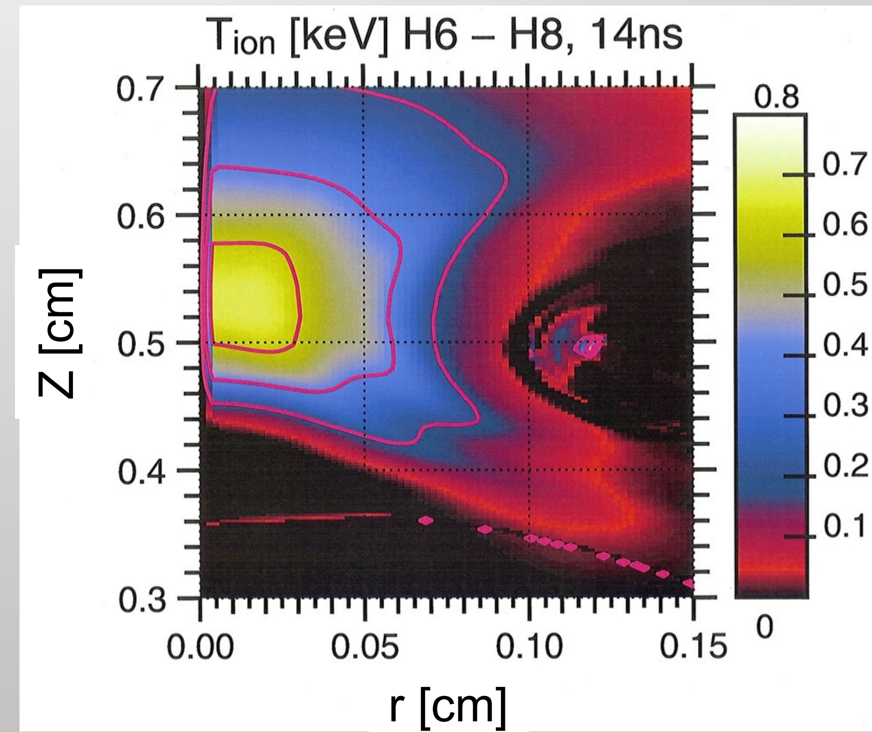
Ions hotter in LEH with CBET ion-wave deposition

N121130 at 14.0 ns – end of peak power

Left: Ion heating + pond. Forces
Right: both off



With deposition – without:
Zoom on LEH

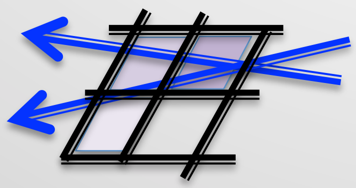


Contours at 200, 400, 600 eV

CBET difference insignificant

CBET model uses *zonal* intensities to update ray *power*

Rays carry power, intensity is *zonal* quantity



CBET ray power change in zone, unsaturated case:

$$\frac{dI_1}{dz} = gI_0 I_1 \quad \longrightarrow$$

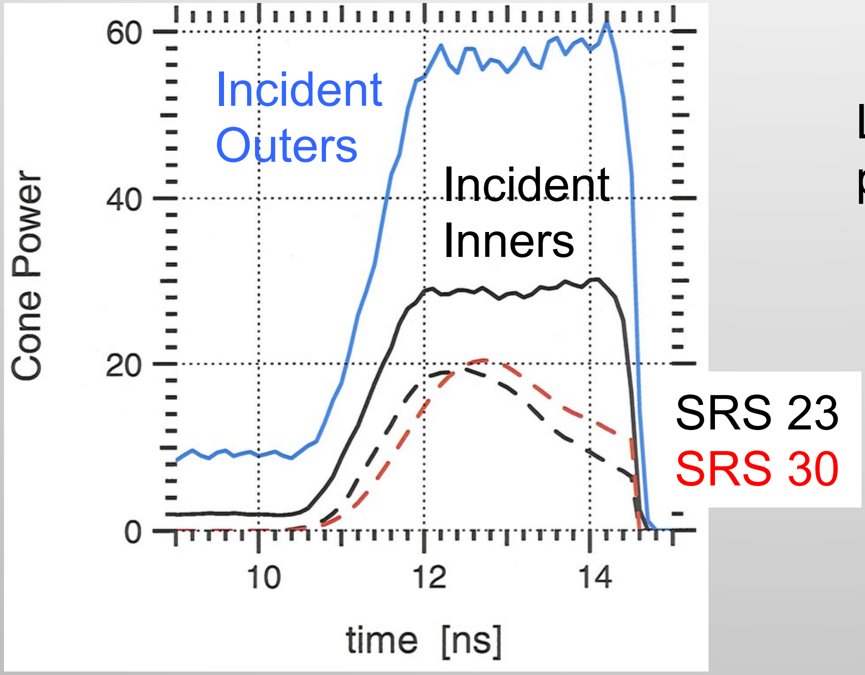
$$P_{ray,1}(\text{end}) = P_{ray,1}(\text{begin})\exp[gI_0\Delta z]$$

- **Transfer along rays, with zonal intensity**
- **Enough numerical rays needed to resolve intensity**

Inline model: intensities on 3D mesh

- **"3D wedge run:" effectively 2D plasma conditions**
- **Inline model: additional azimuthal coordinate for intensities**
- **Hohlraums use 2.5° wedge → 144 azimuthal zones**
- **Each quad has 3D (x,y,z) intensity – need more rays than 2D (r,z) intensity**

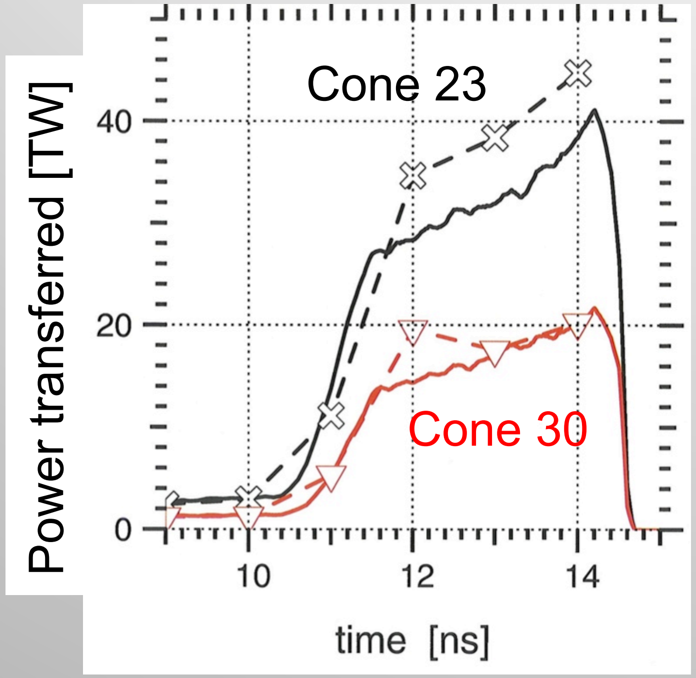
N121130: Large inner SRS, other backscatter small



Lens SRS run: much lower incident power to CBET region

Less CBET to inners with inline SRS – especially relative to incident

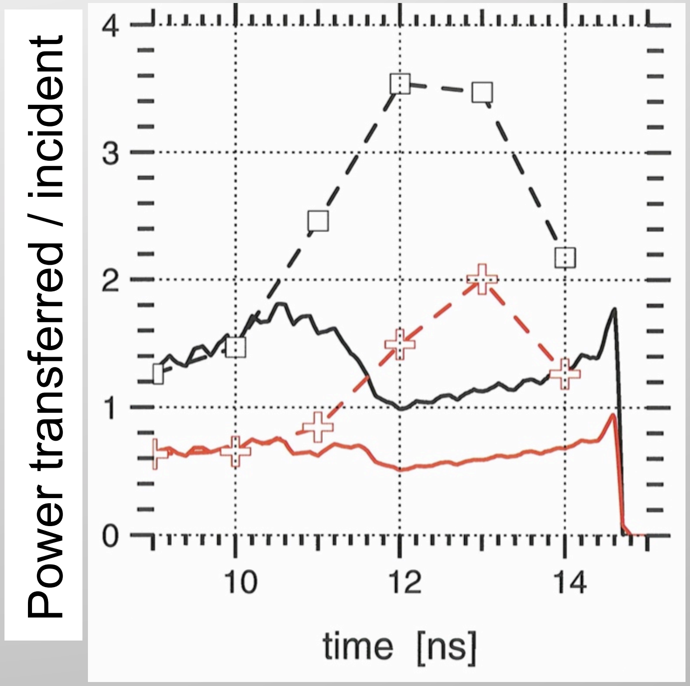
Absolute power transferred to inners: depends on incident power



- - - - - Lens SRS

——— Inline SRS

Relative increase in inner power: depends only on plasma conditions if no pump depletion



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

$$\rightarrow \quad I_{in}^{post} = I_{in}^{inc} \exp[g I_{out} L]$$

Outline: Inline Hydra CBET model results on high-foot shot N121130

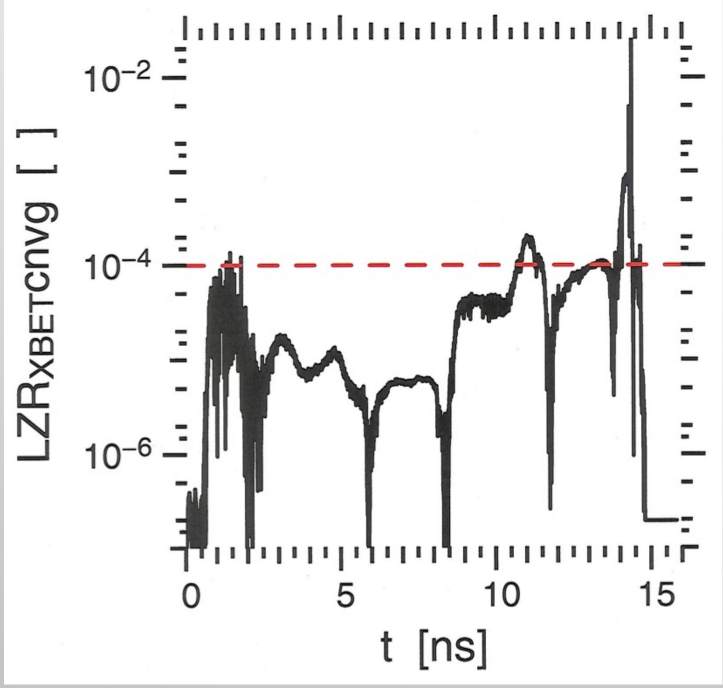
- Model runs with ***NO*** known bugs – hats off to Scott!
- Physics results similar to what we found previously on hi-foot shot N131118 (D. Strozzi, APS-DPP 2014, AX WIP Jan. 2015)
- With saturation clamp $\delta n_e/n = 10^{-3}$, script CBET >= inline model
  - Picket: inline gives less CBET than script, which neglects inv. brem.
  - Peak power: inline converging toward script, with enough numerical rays
  - Inline ion-wave momentum and heat deposition makes LEH ions hotter, has little effect on CBET
- All inline runs had measured backscatter removed at lens
  - Inline SRS needed to consistently handle backscatter – in the works

Inline Hydra runs for N121130

- Laser power: Measured backscatter removed at lens, no drive multipliers
  - Purpose is to study inline CBET model, and compare with script
  - Not a consistent post-shot simulation – requires inline SRS package
- Two-sided (+ and – z): inline CBET ***CAN NOT*** be run with z-symmetry plane! E.g. no one-sided hohlraum runs.
- CBET saturation clamp $\delta n/n = 10^{-3}$: larger than what is needed for script to agree with shape data during peak power
- Other CBET settings:
- `LZR_XBET_klocal` = 1: use intensity-weighted k-vector in each zone
- `LZR_XBET_align` = 0: should not be used with klocal
- `LZR_XBET_istate` = 1: use post-CBET intensity as initial guess for next cycle
- `LZR_XBET_iter_lite` = 2: save coupling data in all active zones after 2 iterations
- `LZR_XBET_cnvg_tol` = 1E-4: iterate til fractional power lost due to CBET is below this
- `LZR_XBET_niter_mx` = 10: max. allowed iterations
- `ray_power_flr` = 1E-4: remove rays when they reach this fraction of initial power
- `bm_reseed` = 1: roll dice for rays every cycle

Numerical error in CBET package is almost always below requested 10^{-4}

LZR_XBET_cnvg = power error in CBET package / incident power



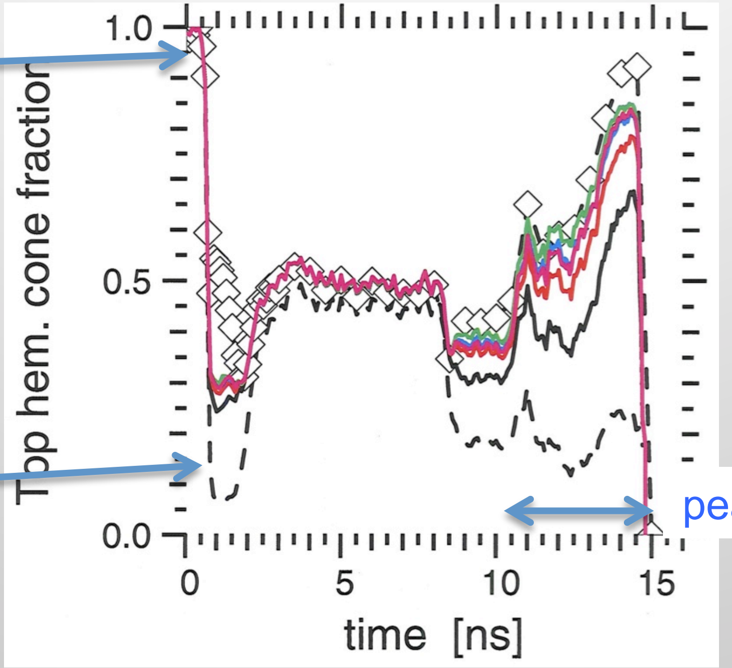
LZR_XBET_cnvg_tol = 10^{-4}
Requested tolerance

- CBT package does not exactly satisfy Manley-Rowe, i.e. net energy lost by lasers should be energy into ion waves, but isn't
- Other errors in laser package generally larger than CBET error

Laser cone fraction: N121130, top hemisphere

Diamonds: script on 600 ray plasma maps

Dashed: incident (BS removed)



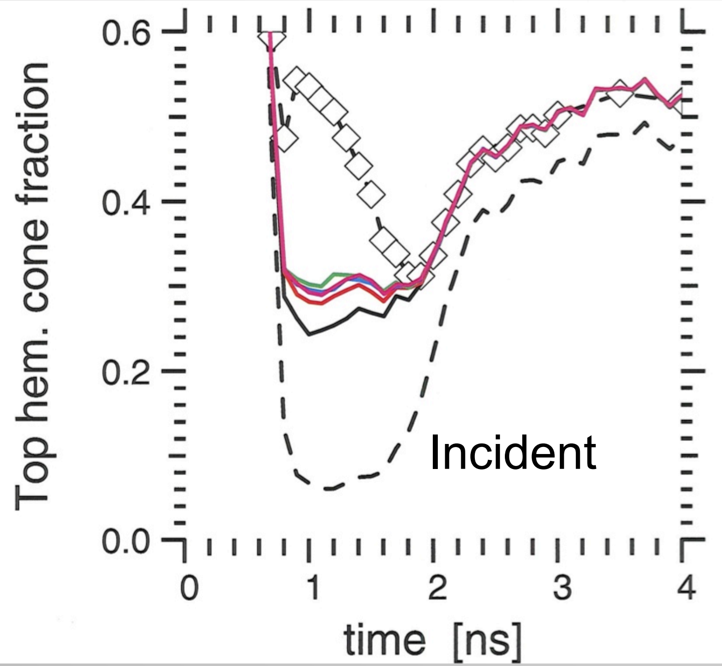
peak power

Rays per quad: 300 (nominal UBT) 600, 900, 900 no pond / heat*, 1200

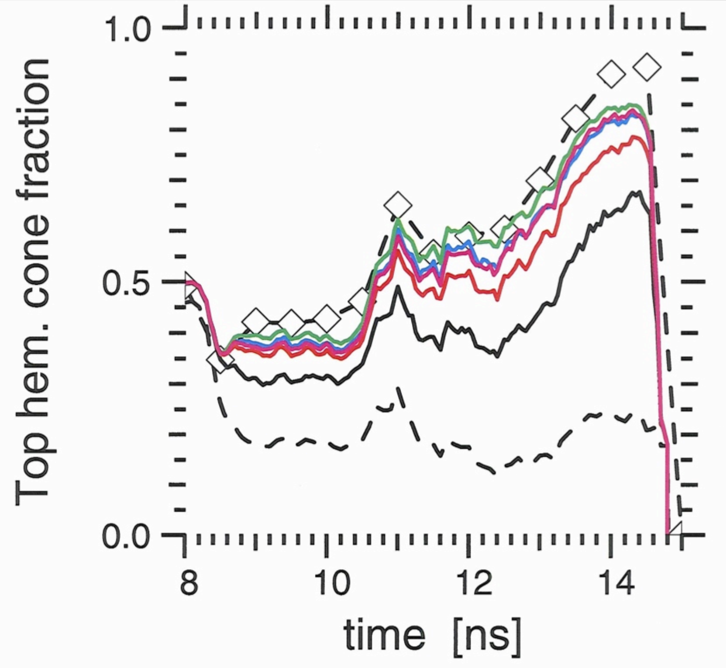
- No ponderomotive force = momentum deposition by lasers (of any kind, not just CBET), and no CBET ion heating.
- Enough rays needed to resolve quad intensity on Hydra mesh
- Different rays on inners and outers may reduce total number

Laser cone fraction: picket and peak

Picket: script gives more CBET, neglects inv. brem. absorption



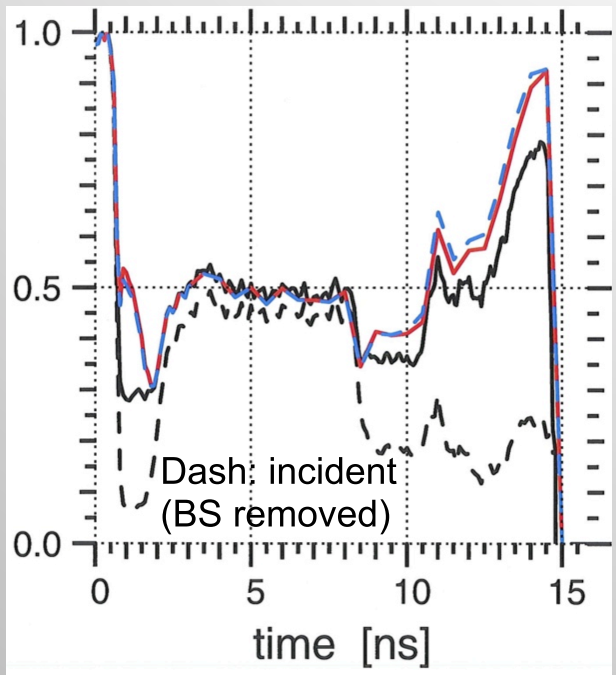
Peak: inline converges to script, with enough rays



- Diamond: script on 600 ray plasma maps
- Rays per quad: 300 (nominal UBT), 600, 900, 900 no pond / heat, 1200

Laser cone fraction: CBET has little effect on script calculation of CBET: no need to iterate

Top hem. cone fraction

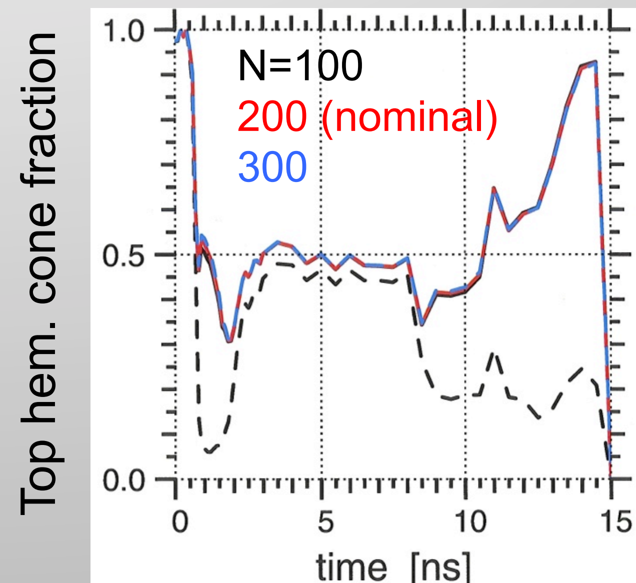


Script on no-CBET plasma maps

Script on inline 600-ray plasma maps

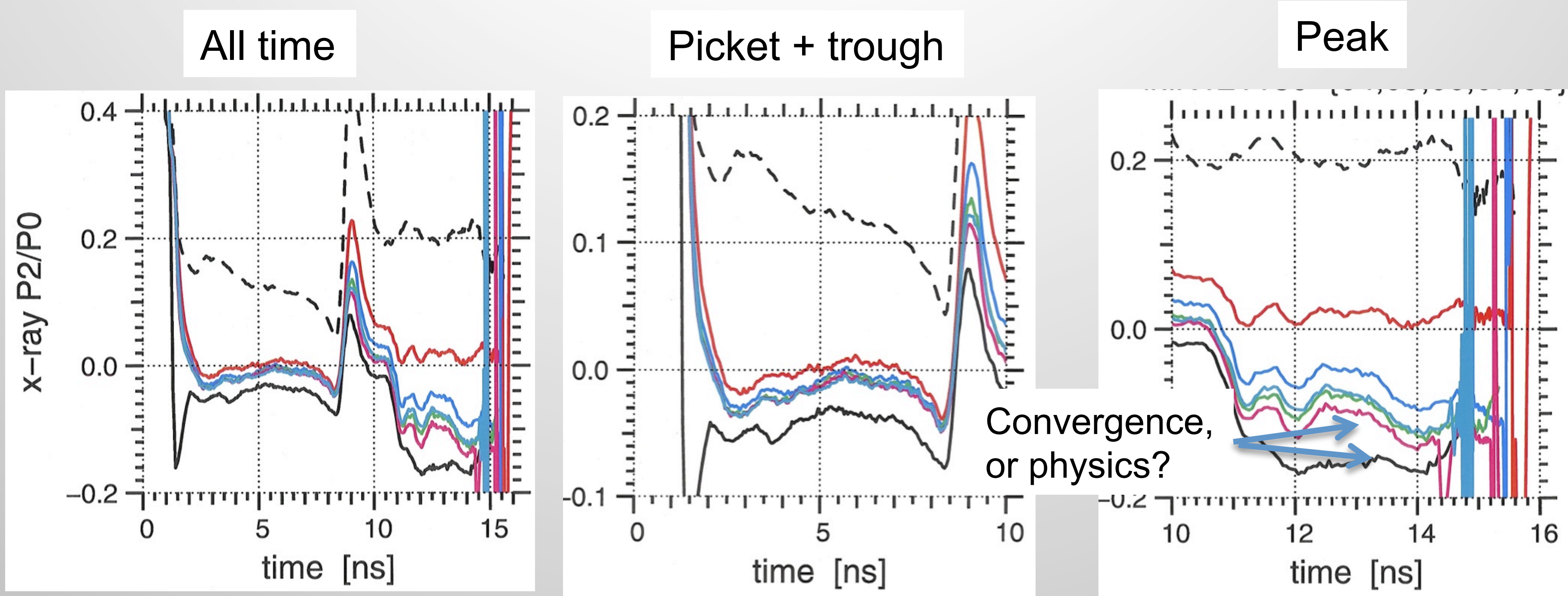
Inline, 600 rays (1200 rays approaches script)

Script converged for
N := Nx=Ny=Nz=100



Yes, there really are 3 curves. Your eyesight is fine.

X-ray flux P2 moment at ablation front: script consistently above inline CBET

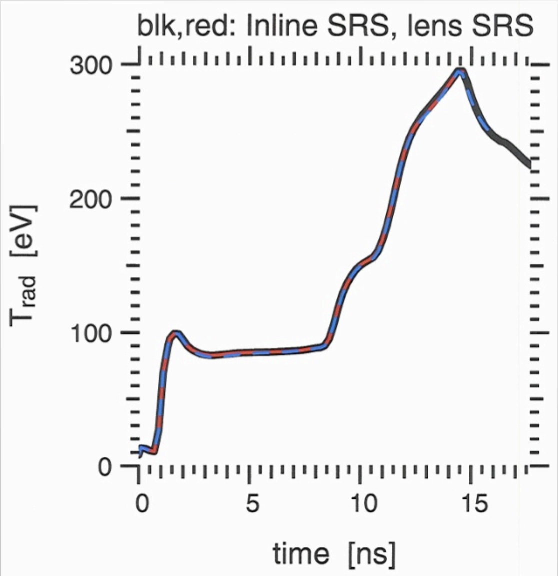


- Black dashed: BS removed at lens, no CBET
- Black solid: two-step process: pre-CBET, script, post-CBET w/ BS removed
- Rays per quad: 300 (nominal UBT), 600, 900, 900 no pond / heat, 1200
- Two 900-ray cases almost the same: ion-wave deposition doesn't affect CBET

- 900 rays looks adequate to end of trough, 1200 may not be enough for peak

Inline vs. lens SRS: total x-ray drive same, stronger on pole with inline

T_{rad}



Script two-step