Inline Cross-Beam Energy Transfer and Backscatter in Hohlraum Simulations

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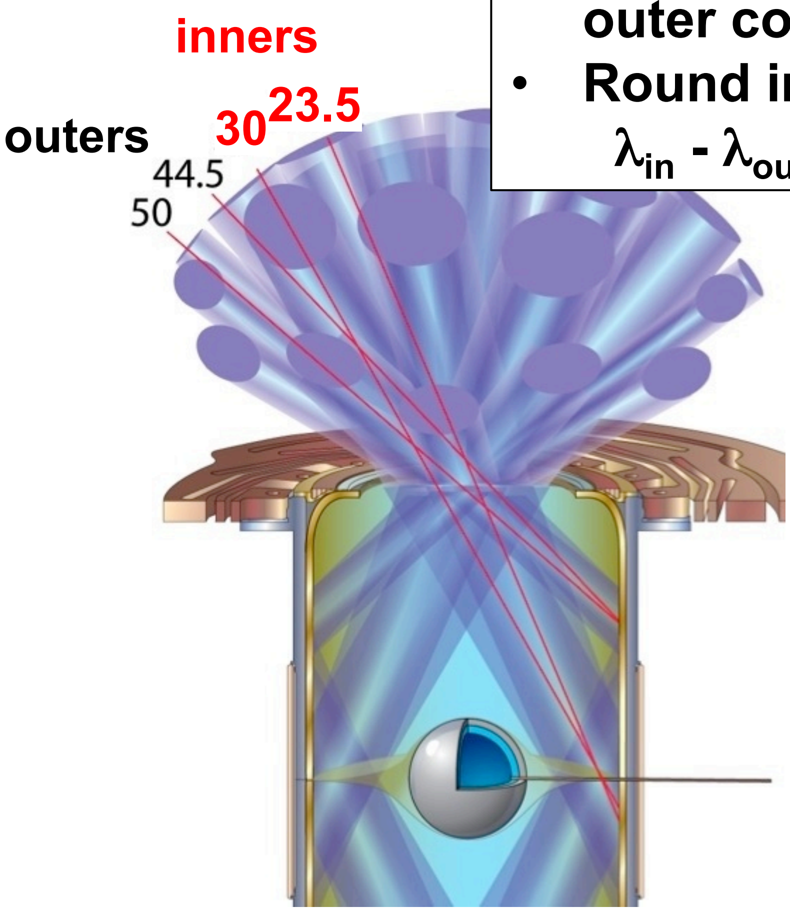
Cross-beam energy transfer (CBET) has been needed for round implosions in gas-filled hohlraums

- Transfer to beam with lower frequency in plasma rest frame
- Determined by plasma flow and laser wavelengths
- NIF has independent wavelengths for 23°, 30°, and outer cones – 3 “colors”
- Round implosions need transfer to inners:
  $\lambda_{in} - \lambda_{out}$ ~ 5-10 Å @ 1ω on cryo gas-filled shots



Hydra[1] has "Inline" model for CBET

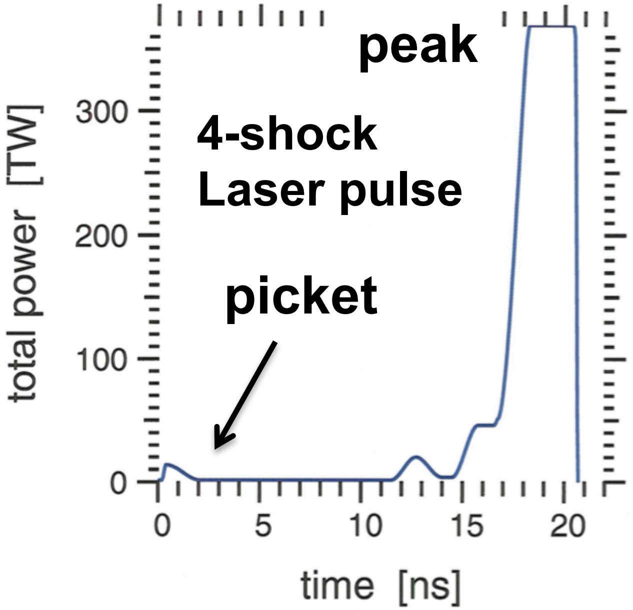
- Inline model[2] calculates CBET inside Hydra itself every cycle
- Current process uses offline script by P. Michel[3] on plasma conditions from Hydra run with no transfer. 2nd Hydra run with post-transfer powers
- Inline and script use same linear, kinetic coupled-mode equations
- Inline model advantages vs. script:
  - One Hydra run, not two
  - Includes more physics: refraction, inverse brem. absorption, spatially non-uniform transfer (along and across beam path)
  - Self-consistent ion heating by ion waves – may limit CBET[4] and reduce need for saturating CBET, under development

[1]Hydra is main radiation-hydrodynamics code for NIF: M. M. Marinak et al., PoP 2010
[2] M. M. Marinak et al., APS-DPP 2012
[3] P. Michel et al., PoP 2010
[4] P. Michel et al., PRL 2012

Physics results: Inline model gives less CBET during picket than script, same CBET during peak power

- Early-time picket:
  - — Inline model gives less transfer than script and re-emit shot data
  - — Plasma is dense and cold, so inverse brem. (neglected by script) could be important
  - — indicates Hydra plasma conditions likely not correct

- Peak power:
  - — Inline requires enough rays per quad to converge – adequately resolve intensity on Hydra mesh
  - — Somewhat slower run due to more rays and CBET calculations
  - — Converged inline result agrees with script



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

$$\frac{dI_1}{dz} = \frac{\pi r_e}{2\omega_0 m_e c^2}\frac{k^2}{k_0 k_1}\left[1+\cos^2(\psi)\right]\mathrm{Im}(K)*\min\left[I_0 I_1, a\,\delta n_{\max}\sqrt{I_0 I_1}\right]$$

beams 0 and 1

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

Polarization angles ϕ_0, ϕ_1 random and uncorrelated
CBET w/ polarized beams: P. Michel, this Friday,

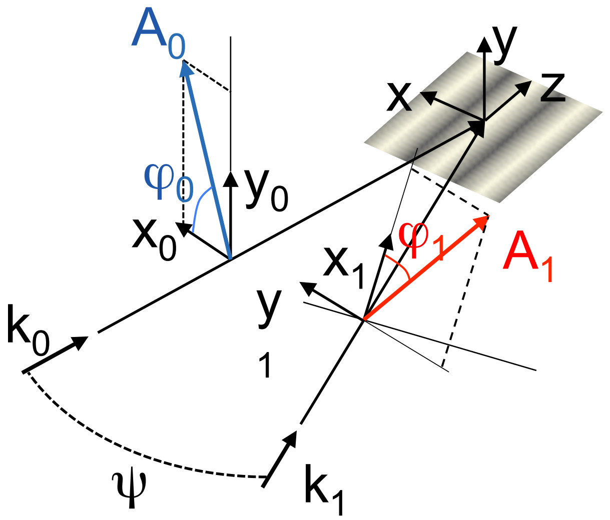
Strongly damped ion waves, saturation clamp δn_{max}:

$$\delta n \propto \min\left[\sqrt{I_0 I_1}, \delta n_{\max}\right]$$ **Ion wave amplitude**

$$k_i = \frac{\omega_i}{c}\left[1-\frac{n_e}{n_{crit}}\right]^{1/2}$$ **Accounts for electric field swelling**

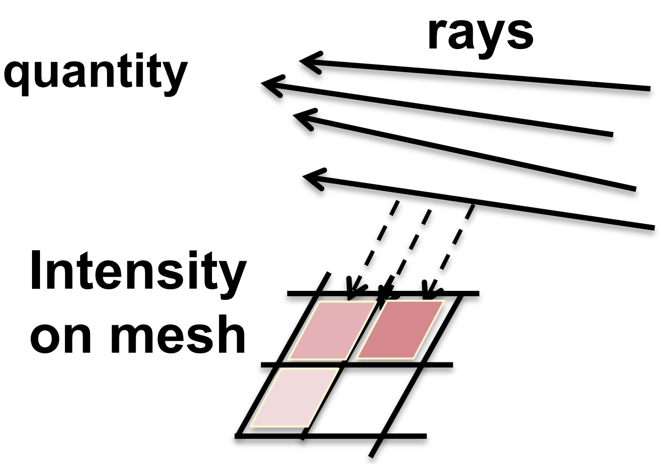
$$I_i \propto \frac{v_{gi}}{c}E_i^2$$

$$K = \frac{\chi_e(1+\chi_i)}{1+\chi_e+\chi_i}$$ **Uses kinetic Z-function at ion wave** $(\omega,\mathbf{k}) = (\omega_0-\omega_1, \mathbf{k}_0-\mathbf{k}_1)$



CBET along HYDRA ray found using zonal intensity: sum of all rays in a zone

In HYDRA, rays carry power, intensity is a *zonal* quantity



Transfer is done along rays, based on zonal intensity. Manley-Rowe is not exactly satisfied, so iterate until it is to desired tolerance

Numerical Iteration:

- Trace rays, doing inv. brem. absorption, and CBET after first step
- Update zonal intensities

- Until power lost due to CBET < tolerance * incident power

Details of model as run for this talk

- **Exponential model with Manley-Rowe cap:**

$$\frac{dI_1}{dz} = GI_1 \quad G \propto I_0 \quad \longrightarrow \quad P_{ray,1}(\mathrm{end}) = P_{ray,1}(\mathrm{begin})\exp[G]$$

Beam 1, unsaturated case

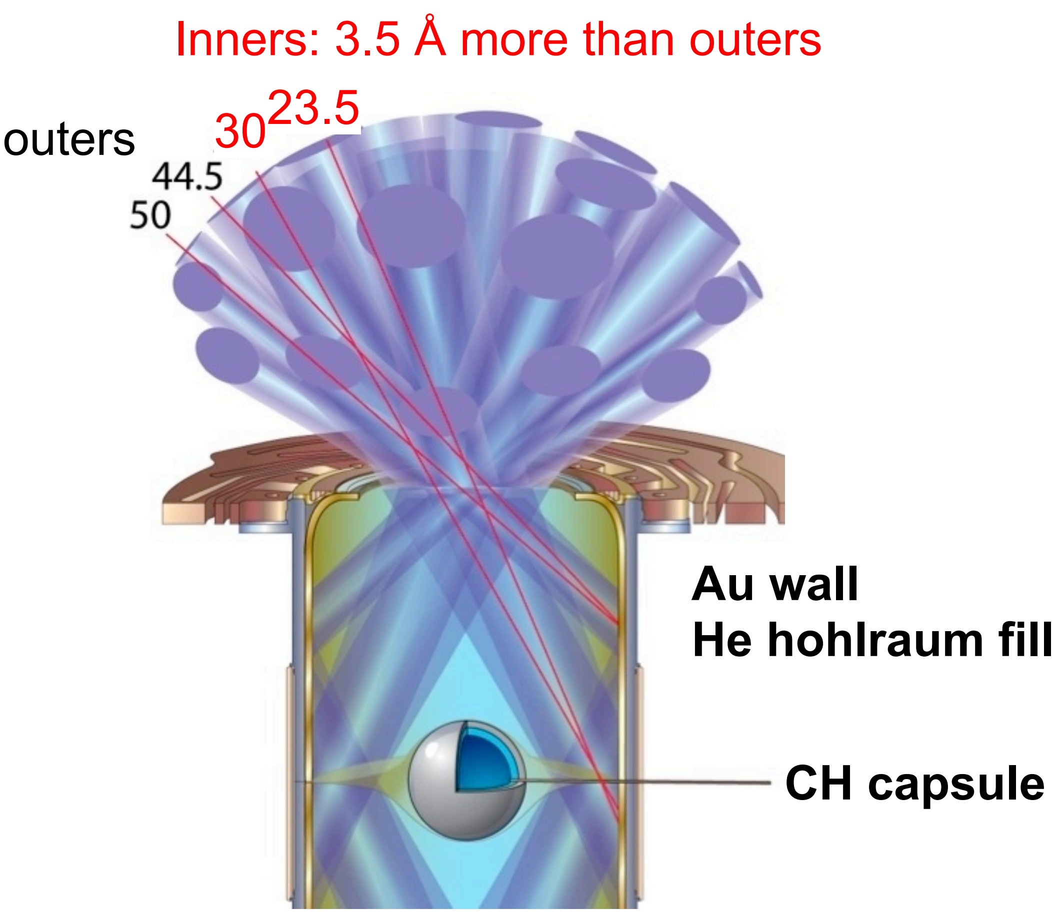
  — **Intensity of other beam updated separately: pump depletion occurs over numerical iterations**

  — **Manley-Rowe cap: ray can't gain more power than available from all beams transferring to it**

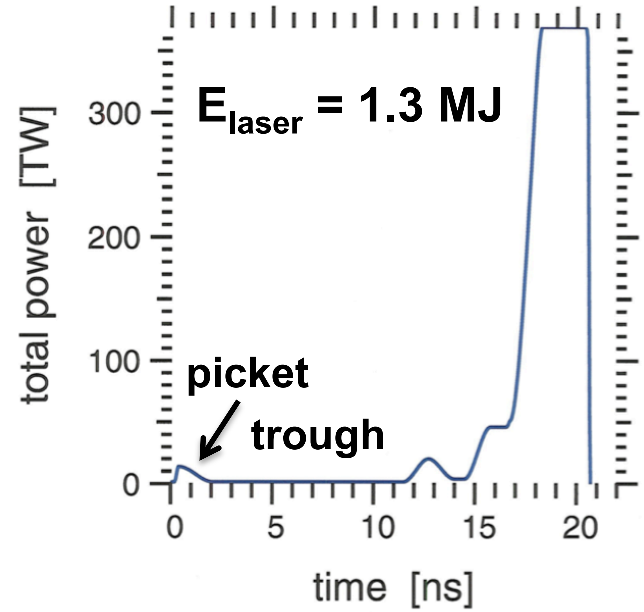
- **Beam k vector found by intensity-weighting rays in a zone: can change from value at lens due to refraction**

- **Numerically iterate, max of 10 times, til power lost due to CBET (Manley-Rowe violation) < 10^{-4} * incident power**

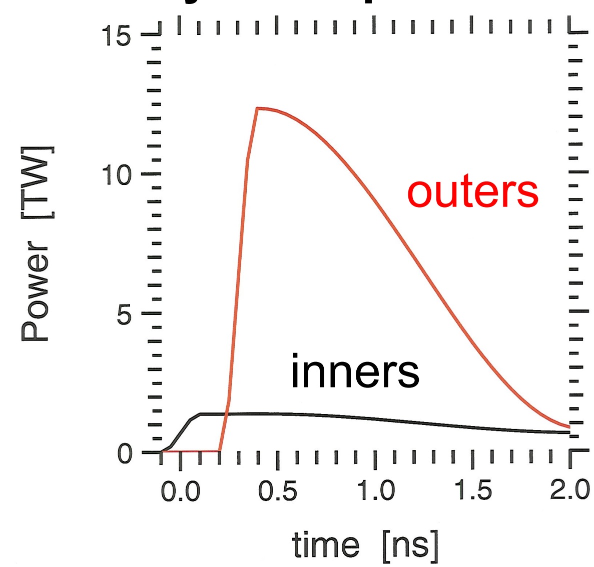
Test case: generic low-foot (4-shock), plastic capsule design



Incident laser power



Early-time "picket"

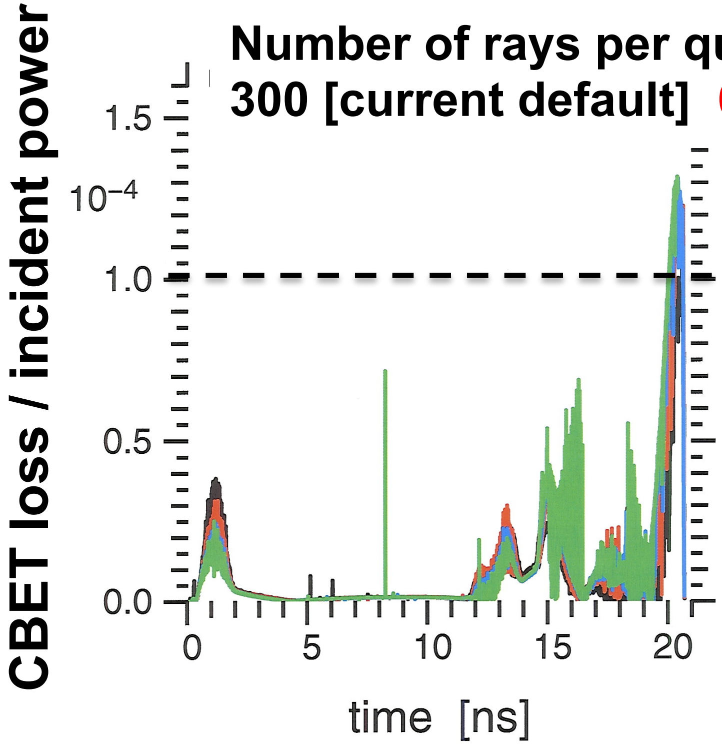


- **Wavelengths give moderate transfer from outers to inners:**
  $\lambda_{23} = \lambda_{30} = \lambda_{out}$ + 3.5 Ang. @ 1ω
- **$\delta n/n_0$ saturation clamp = $6*10^{-4}$**
- **No backscatter removed or drive multipliers**

The 4 C's of coding

- Correctness – are the desired equations being solved?
  - — Yes: comparisons with Python coupled-mode solutions (S. Sepke)
- Crash? Model runs without crashing
- Conservation – is power error acceptable? Yes
- Convergence – do physical answers like flux moments and capsule shape change with numerics, e.g. zoning, rays?

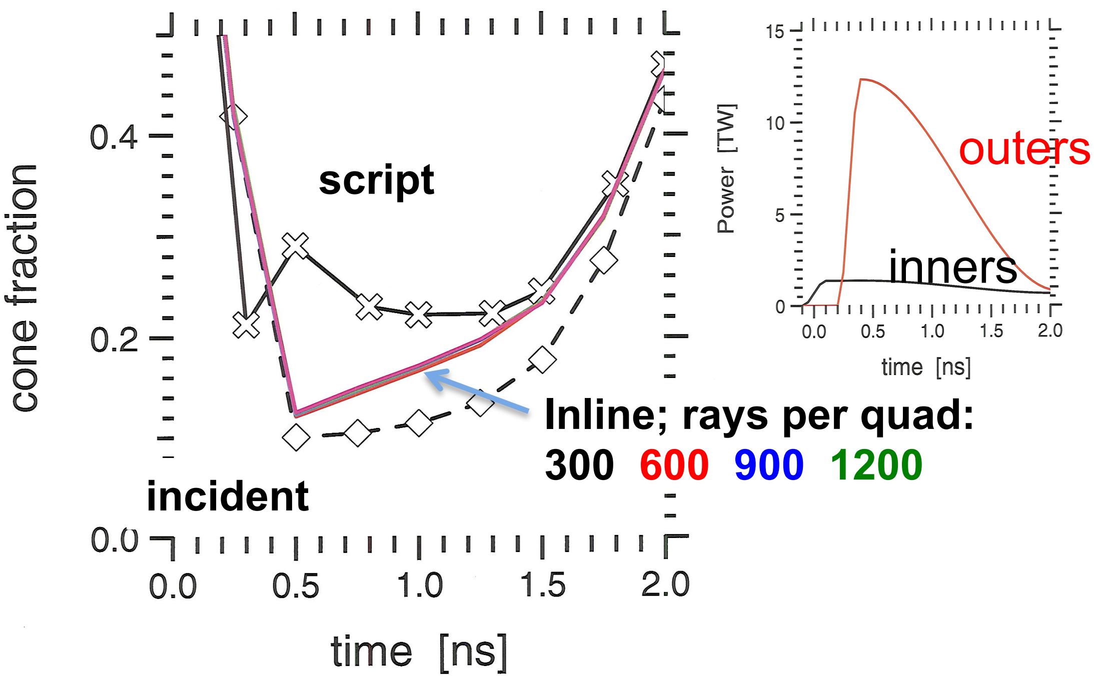
Number of rays per quad:
300 [current default] 600 900 1200



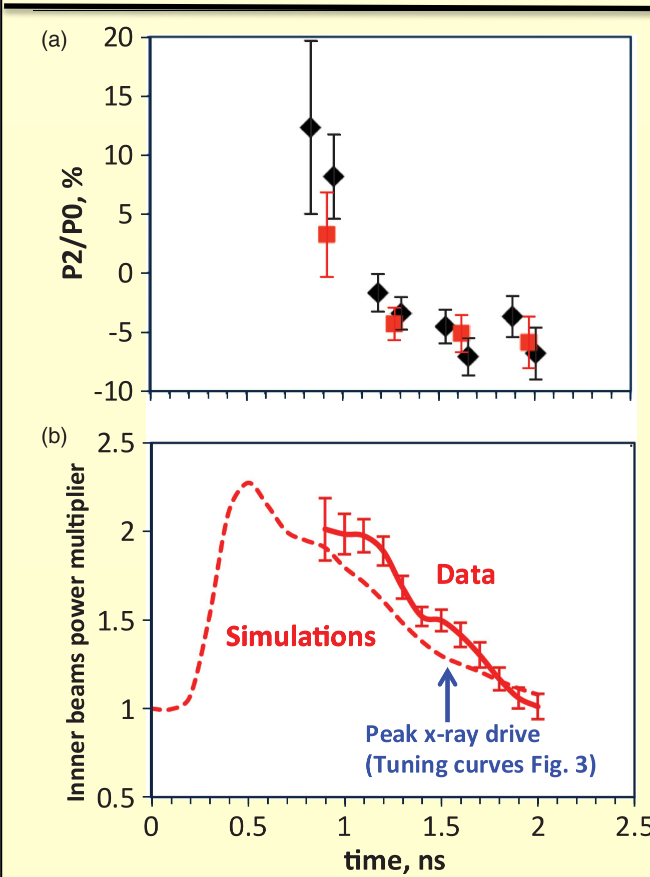
Specified tolerance of 10^{-4} almost always achieved, with <= 10 iterations

Picket: inline model gives less transfer than script – or re-emit data

Cone fraction = Inner / total power



Script gives slightly less transfer than Re-emit shot data[1]

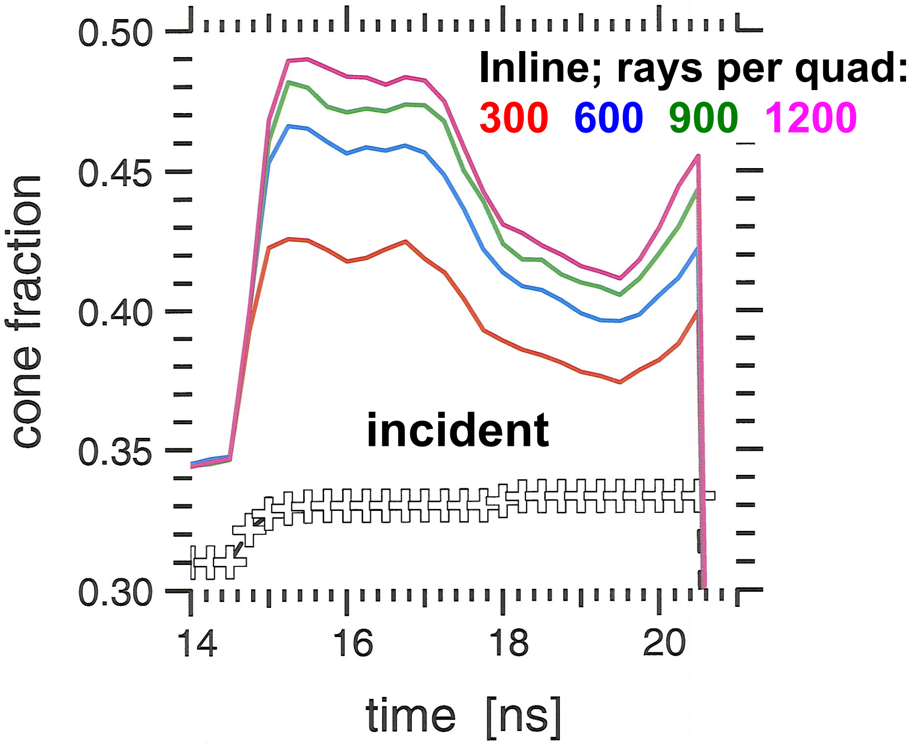


- **Inline model has more physics than script e.g. inverse brem: matters in picket (dense, cold plasma)**
- **Poor agreement of inline with script (and thus data) indicates plasma conditions not right in picket**

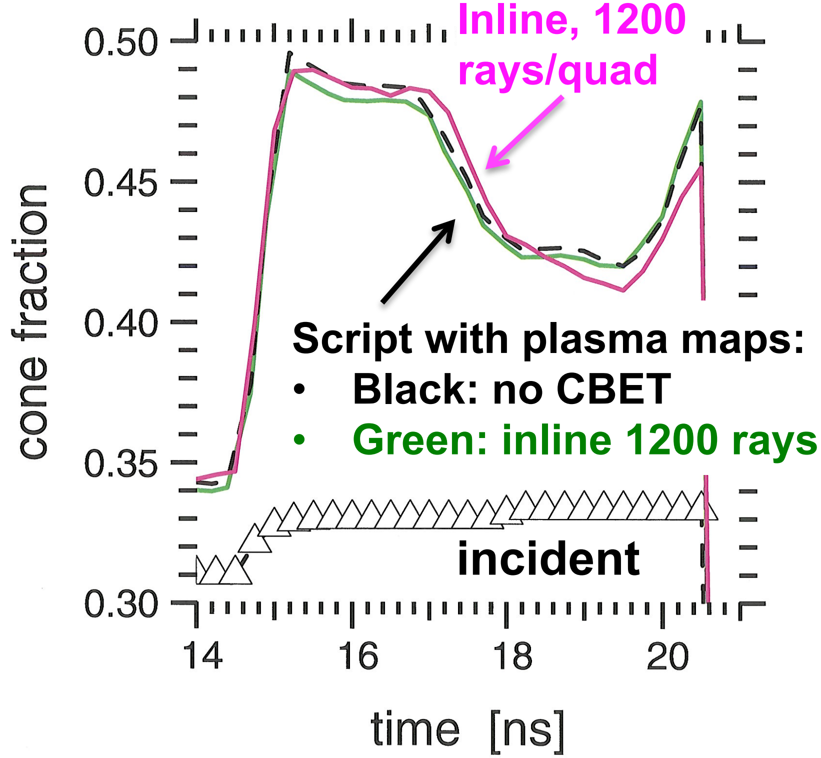
[1]E. L. Dewald, J. L. Milovich et al., PRL 2013

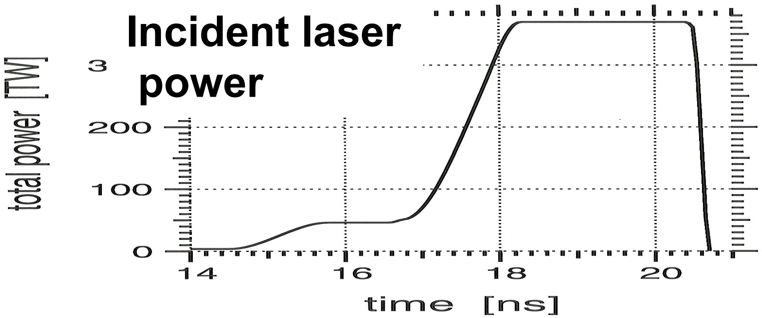
Peak power: inline CBET increases with more rays: intensity better resolved, plasma conditions similar

Cone fraction = Inner / total power



Cone fraction: Inline converges to script result

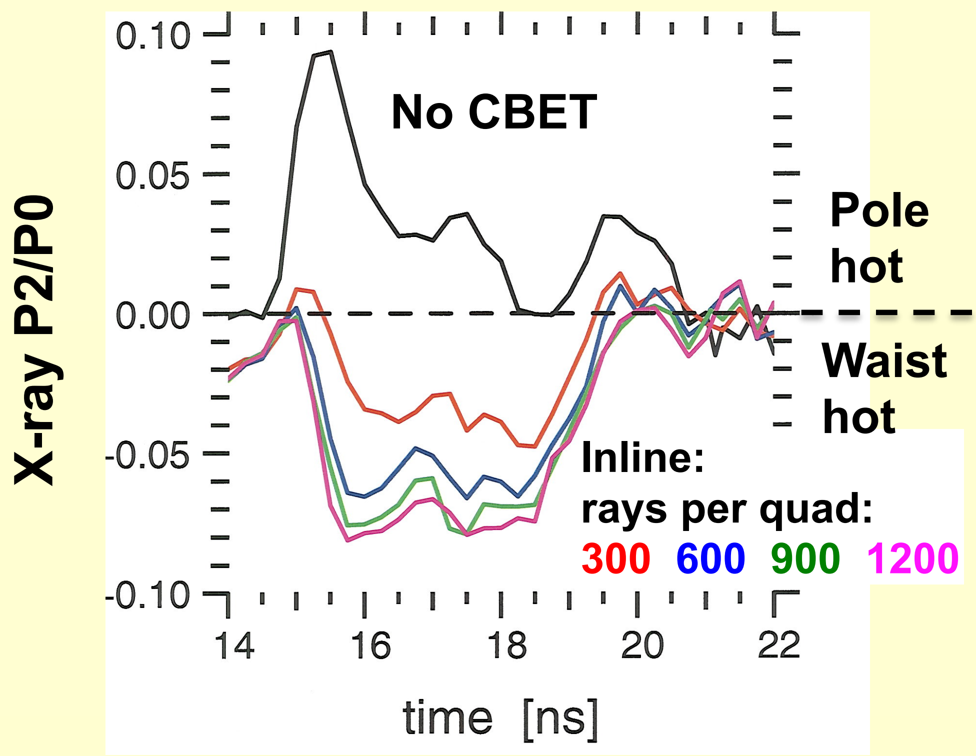




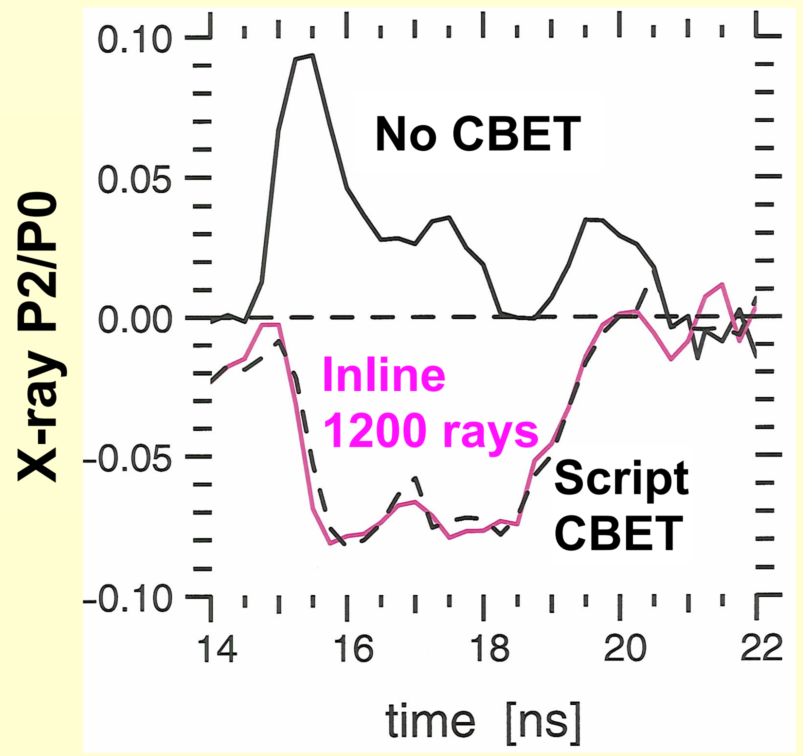
- Script gives same transfer using plasma maps with or without transfer
- Indicates plasma conditions aren't changing with number of rays
- Hydra zonal intensity better resolved

Peak power: x-ray flux moments on capsule behave like cone fraction, inline converges to script

X-ray P2 on capsule: converged with 900-1200 rays per quad



X-ray P2 on capsule: inline converges to script



- 2D ConA shots and hot-spot self-emission measure capsule P2/P0 to < 5%
- P2/P0 <~ 2% in peak required for ignition (A. Kritcher)

Hydra Inline CBET works, being extended to include CBET ion heating, and Raman backscatter

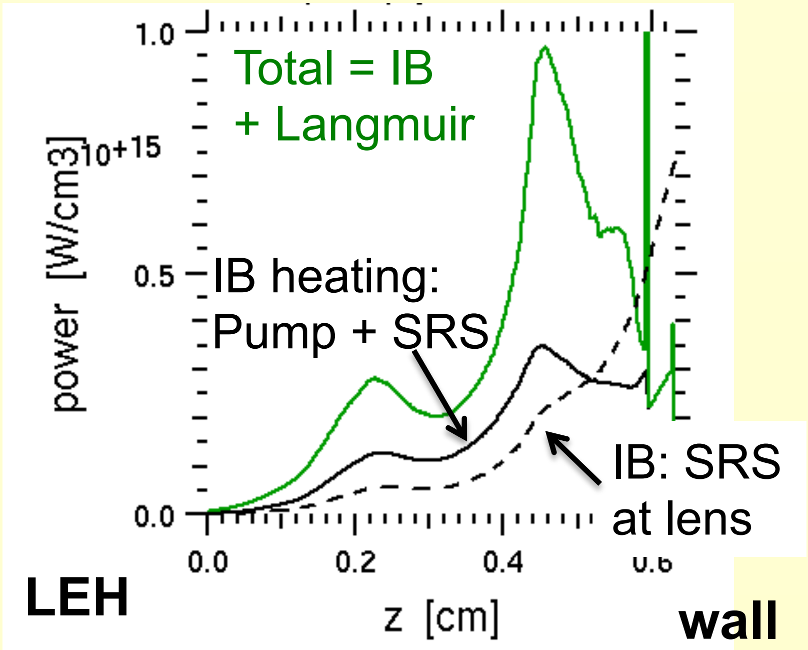
- **Inline model of CBET implemented in Hydra:**
  - **— Picket: less transfer to inners than script or re-emit data**
  - **— Peak power: converges to script result with enough rays**

- **Ion heating by CBET should reduce CBET and need for δn_{max} saturation clamp**

- **Inline backscatter will also heat LEH, and impair inner-beam propagation more than removing escaping backscatter at lens**

- **Similar inline models under development in Lasnex (D. Bailey)**

Teaser: inline SRS on 1D profile




NIF

The inline Hydra model includes effects beyond the offline script

CBET script method (P. Michel):

- Hydra "pre-transfer" run: no CBET, no backscatter, no drive multipliers
- CBET script run on pre-transfer plasma conditions
- Hydra "post-transfer" run with incident cone powers modified according to script

Additional physics in inline CBET model:

- Inverse brem. absorption
- Ray refraction
- Spatially non-uniform transfer: both along beam propagation direction and transverse to it
- Momentum and energy deposition by CBET-driven ion waves, may limit CBET[1]: under development

- Inline model only uses a single Hydra run, with increased computer resources for laser propagation

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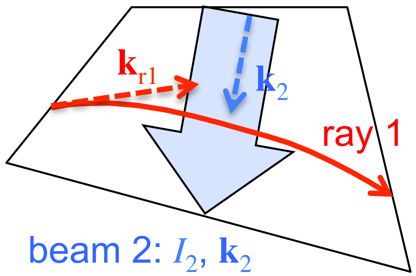
[1] P. Michel et al., PRL 109, 195004 (2012)



$$I = \sum_{r=1}^{Nrays} P_r \frac{s_r}{\Delta V}, \quad P_r = \frac{1}{s_r}\int_0^{s_r} ds' P(s')$$

s_r = distance of ray through zone