Inline Modeling of Cross-Beam Energy Transfer and Backscatter in Hohlraums

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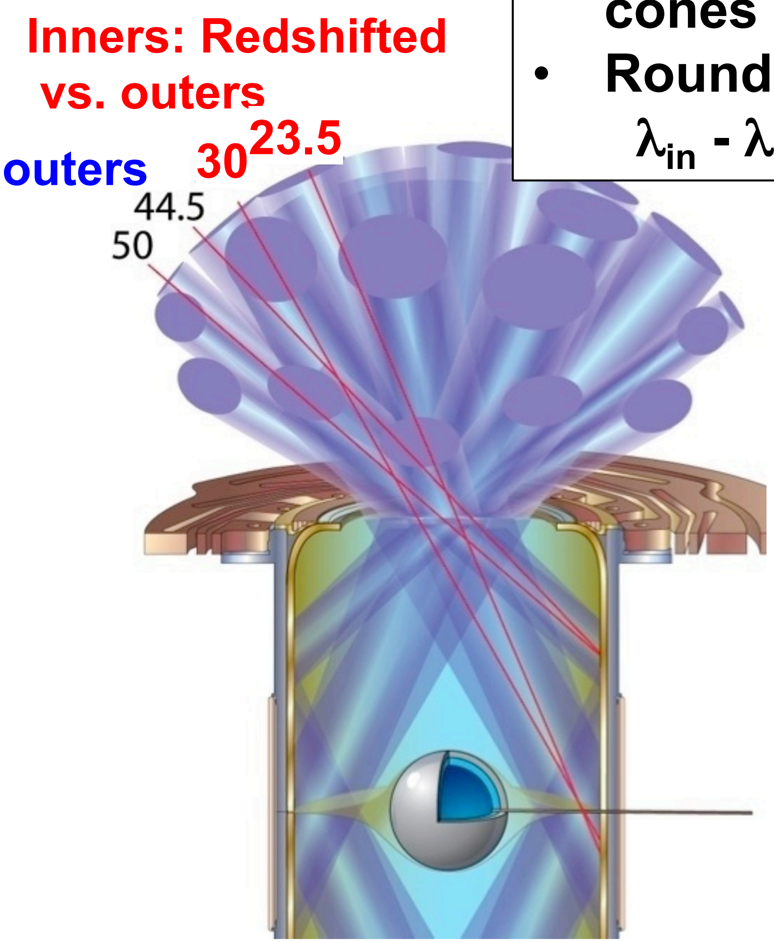
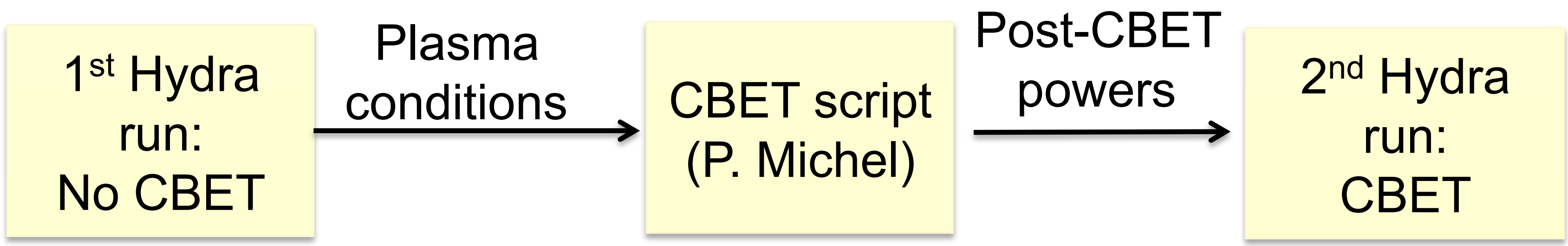
Cross-beam energy transfer (CBET) is needed for round implosions in gas-filled hohlraums

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



Summary: Hydra[1] inline CBET model is applied to gas-filled NIF hohlraums with large transfer

- Script process:
  - Straight rays, no inverse brem. absorption, used to date for NIF designs
  - Gives more CBET than experiments -> δn saturation clamp



- Inline model[2]: Hydra calculates CBET every time step
  - — Same linear, kinetic coupled-mode equations as script
- Inline model advantages vs. script:
  - — One Hydra run, not two
  - — More physics: refraction, inverse brem. absorption, spatially non-uniform transfer
  - — Ion wave energy and momentum deposition:

    May limit CBET[4], reduce need for δn saturation clamp

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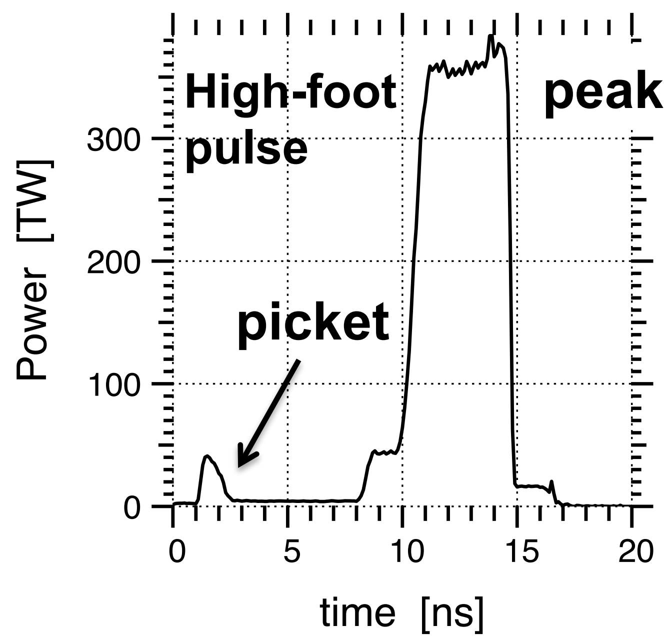
[1] M. M. Marinak et al., PoP 2001; [2] M. M. Marinak et al., APS-DPP 2012
[3] P. Michel et al., PoP 2010; [4] P. Michel et al., PRL 2012

Physics results

- **Early-time picket:**
  - — **Inline model agrees with script, once inners burn through LEH plasma**
  - — **Before, plasma dense and cold, inverse brem. (neglected by CBET script) matters**

- **Peak power:**
  - — **Inline model converges to script result – with enough numerical rays**
  - — **Inline ion-wave energy deposition heats LEH ions, little effect on transfer**

NIF shot N131118:
Laser Power vs. Time



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

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

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

beams 0 and 1

Laser polarization angles random and uncorrelated
CBET w/ polarized beams: P. Michel, talk PO4.13 Wed. PM

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

$$K = \frac{\chi_e(1+\chi_i)}{1+\chi_e+\chi_i}$$

- **Strongly damped ion waves**
- **Saturation clamp δn_{max}**

Uses kinetic Z-function at ion wave $(\omega,\mathbf{k}) = (\omega_0-\omega_1, \mathbf{k}_0-\mathbf{k}_1)$

Ion-wave momentum and energy deposition:

P. Michel et al., PRL 2012

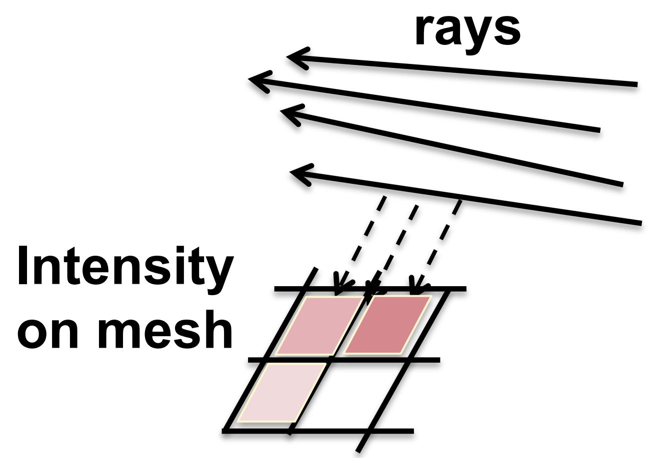
$$m_i\frac{d\langle\vec{v}_i\rangle}{dt} = -\alpha\vec{k}$$

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

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

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

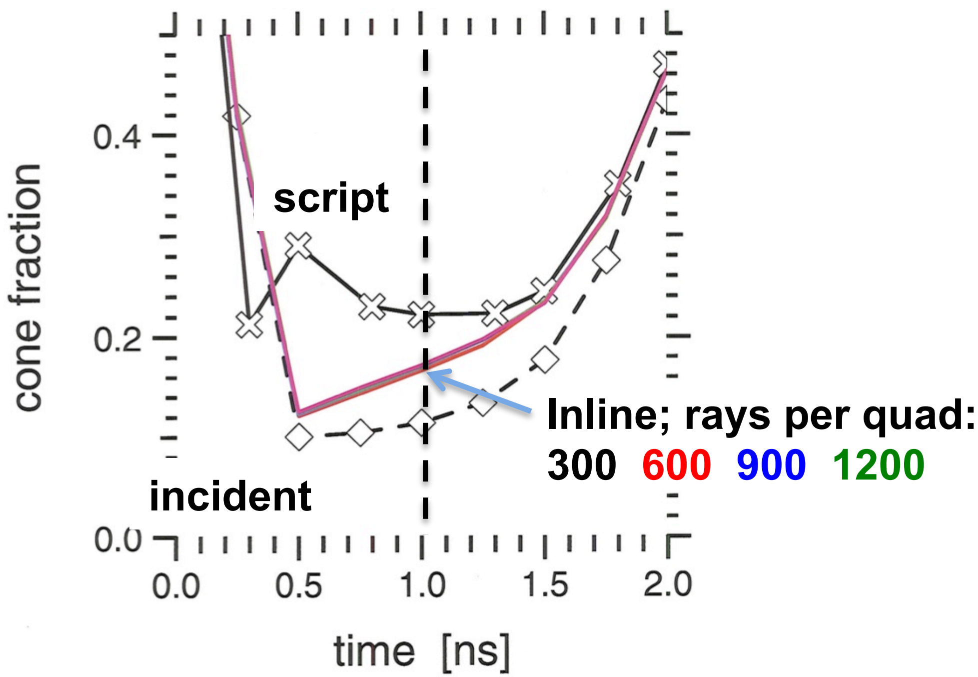
In HYDRA, rays carry power, intensity is a *zonal* quantity



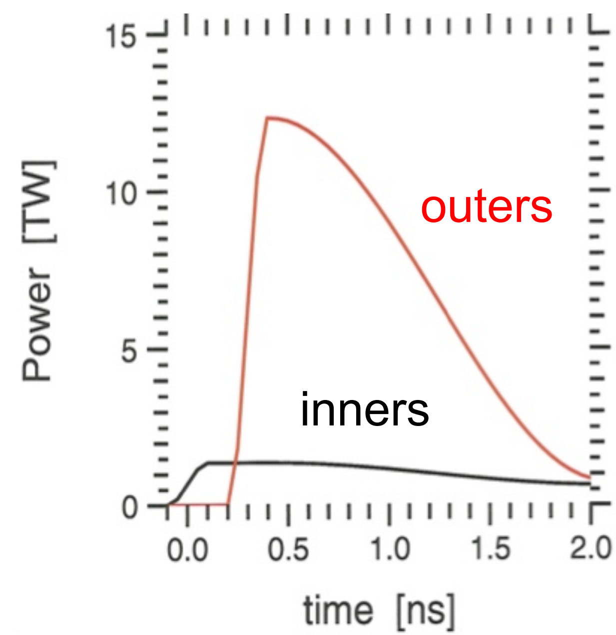
- Transfer is done along rays, based on zonal intensity
- Enough numerical rays needed to resolve intensity
- Manley-Rowe not exactly satisfied
- Numerically iterate until CBET power loss < tolerance * incident power

Picket: inline model gives less transfer than script

Picket cone fraction vs. time



Laser picket power vs. time



Before 1 ns:

- **Inline model gives less transfer**
- **Inners absorbed in dense, cold LEH plasma**
- **X-ray flux symmetry on capsule similar**

Afer 1 ns:

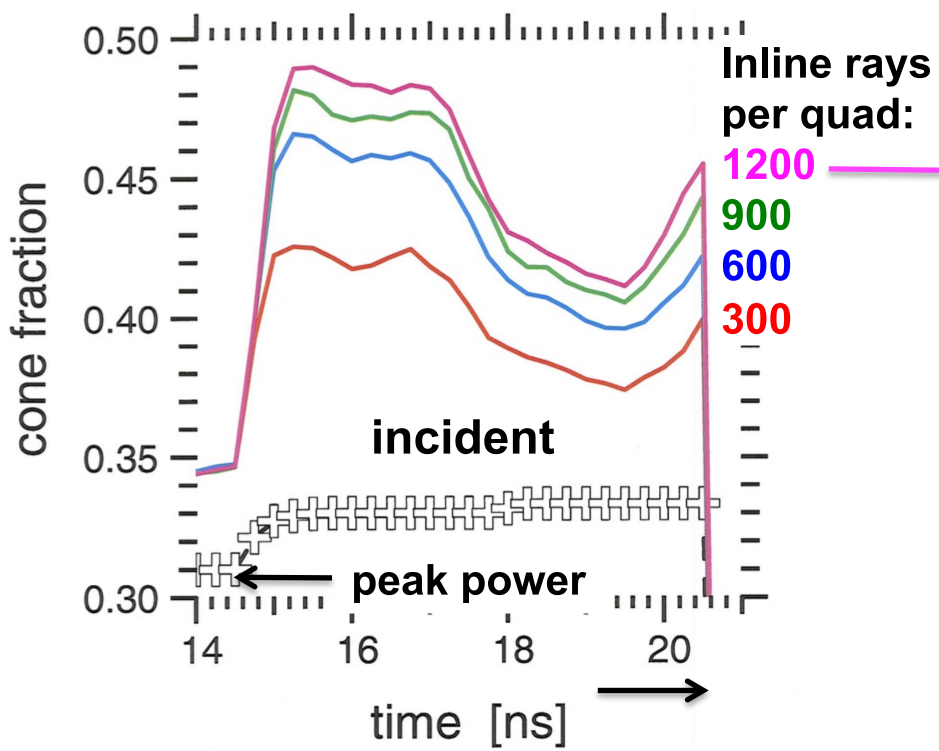
- **Inners propagate through LEH**
- **Script and inline model agree**

- **Generic low-foot pulse**
- **Moderate CBET:**
  $\lambda_{in} - \lambda_{out}$ = 3.5 Å
- **Saturation clamp $\delta n_e/n_e = 6*10^{-4}$**

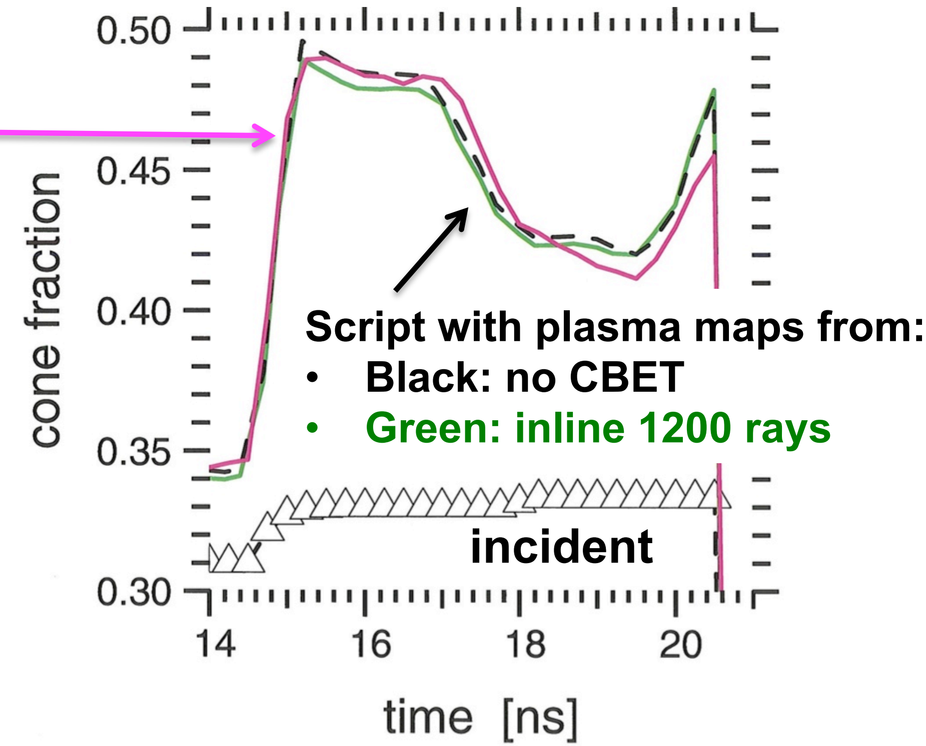
Cone fraction = Inner / total power

Peak power: inline CBET converges to script results with more numerical rays: intensity better resolved

Peak power cone fraction vs time



Inline cone fraction converges to script

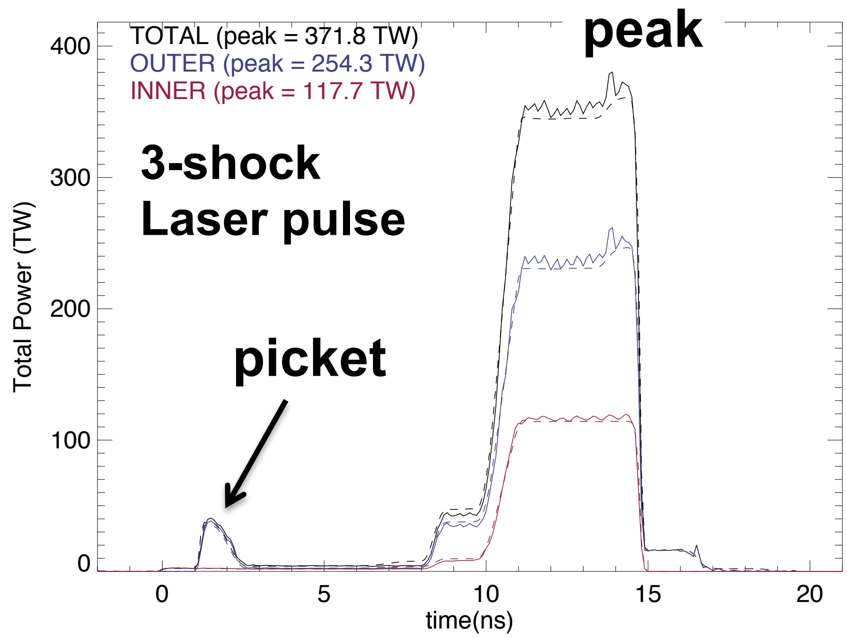


- Generic low-foot pulse
- Moderate CBET:
  $\lambda_{in} - \lambda_{out}$ = 3.5 Å
- Saturation clamp $\delta n_e/n_e = 6*10^{-4}$

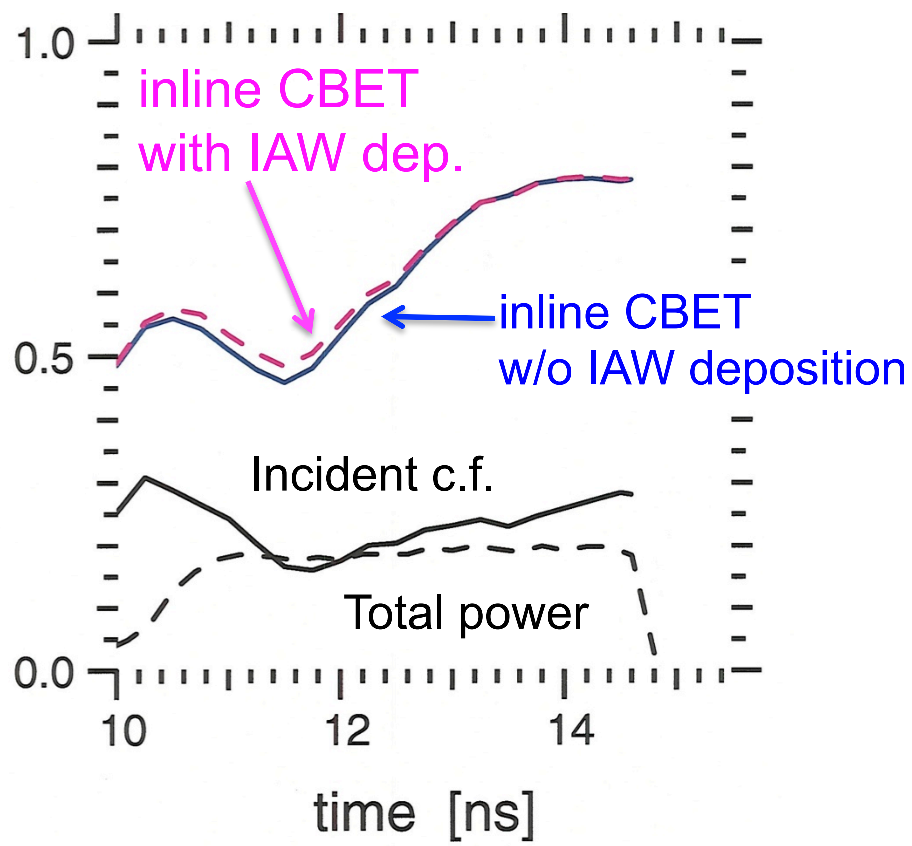
- Magenta and green curves agree:
  Script and inline model give same transfer on same plasma maps
- Black and green curves agree:
  Script gives same transfer on plasma maps with and without CBET:
  no need to iterate script

Peak power: inline ion-wave energy deposition has little effect on transfer

N131118: high-foot 2D ConA
E_{laser} = 1.71 MJ
$(\lambda_{23}, \lambda_{30}) - \lambda_{out}) = (8.2, 7.5)$ Å @ 1ω
CH capsule, He gas fill
Saturation clamp $\delta n_e/n_e = 10^{-3}$



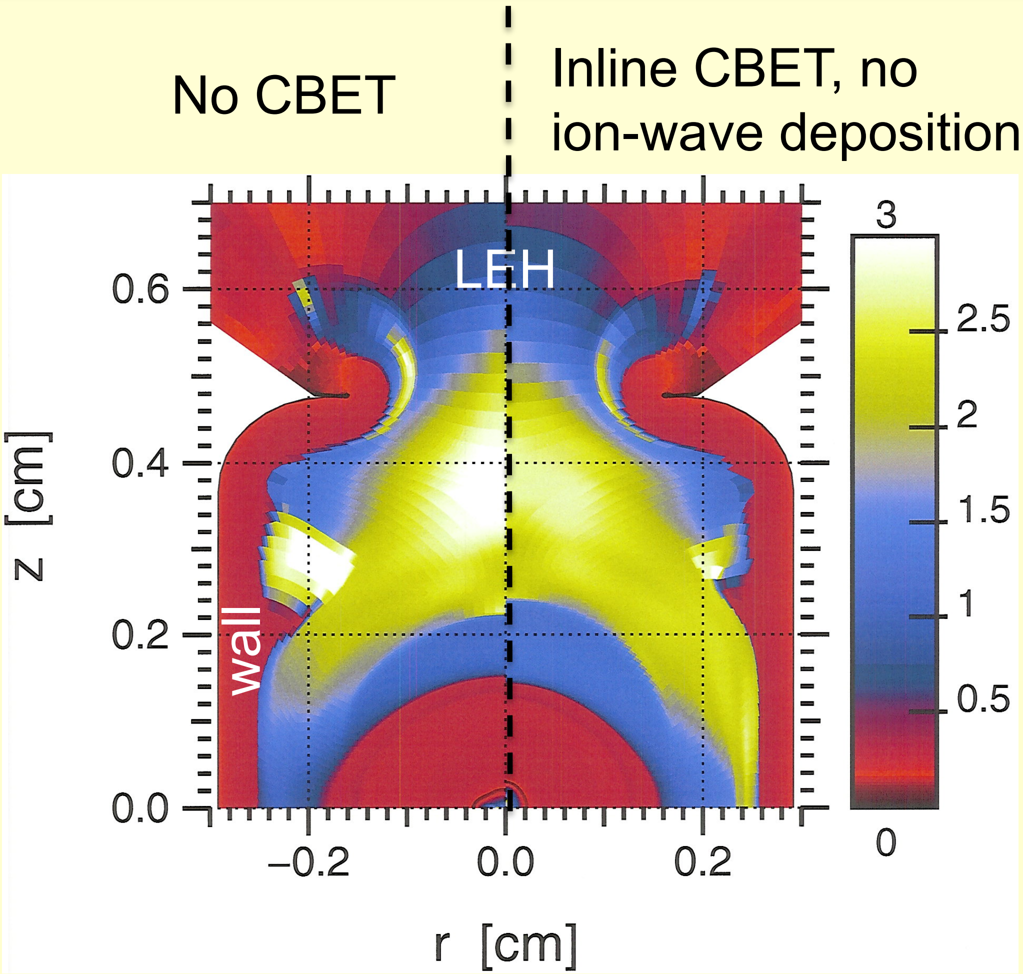
Cone fraction:
inner / total power

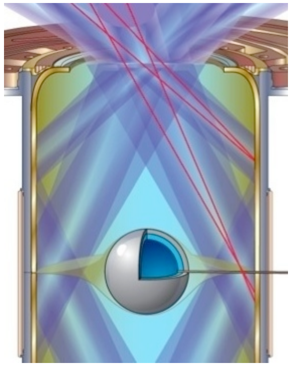


Peak power: CBET without ion deposition changes ion temperature via cone fraction

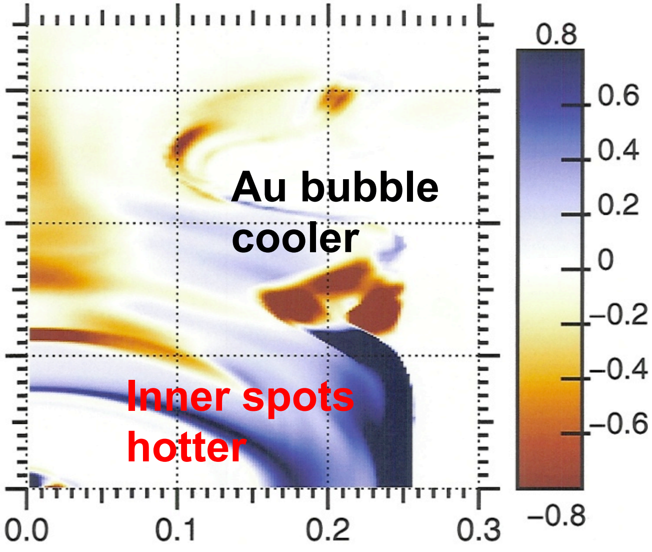
High-foot shot N131118

T_{ion} [keV] @ 14 ns:
late peak power





T_{ion} [keV]
CBET – No CBET

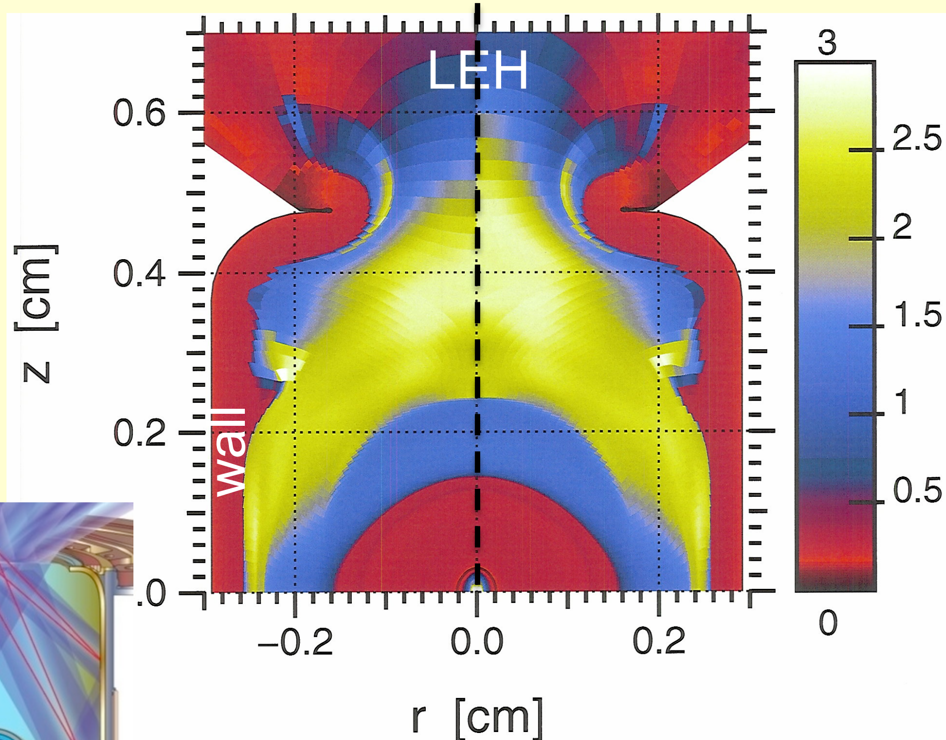


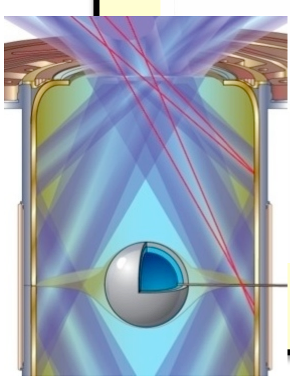
Peak power: CBET with ion-wave deposition heats LEH ions – little effect on transfer

High-foot shot N131118

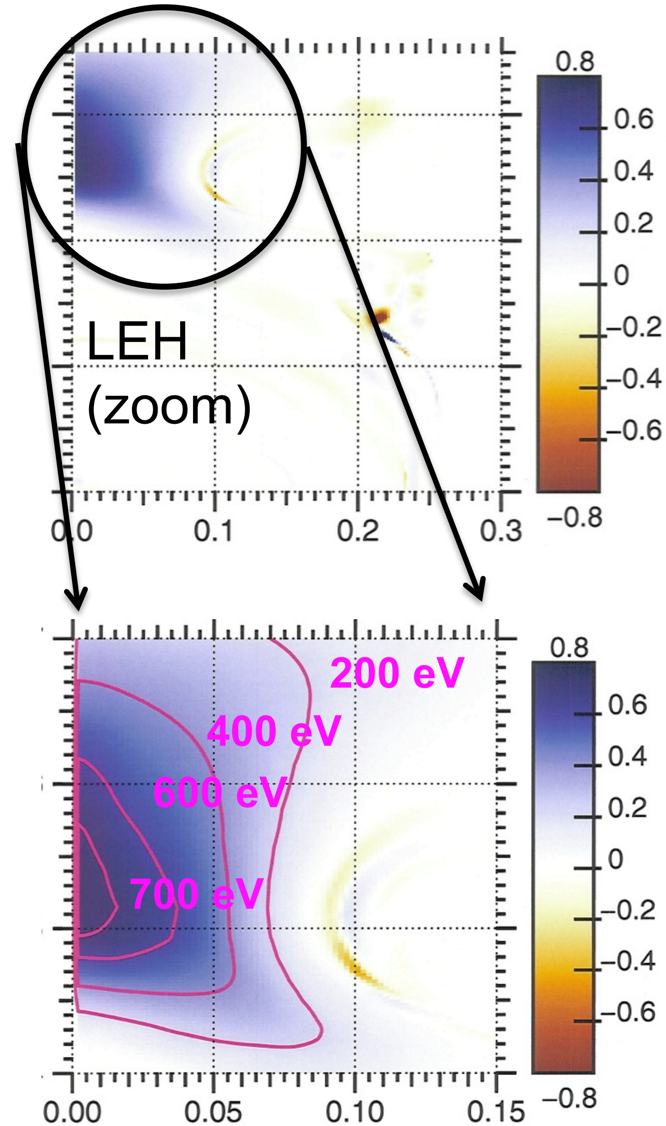
Inline CBET T_{ion} [keV] @ 14 ns: late peak power

Without ion-wave deposition | With ion-wave deposition





T_{ion} [keV]
IAW dep – No IAW dep



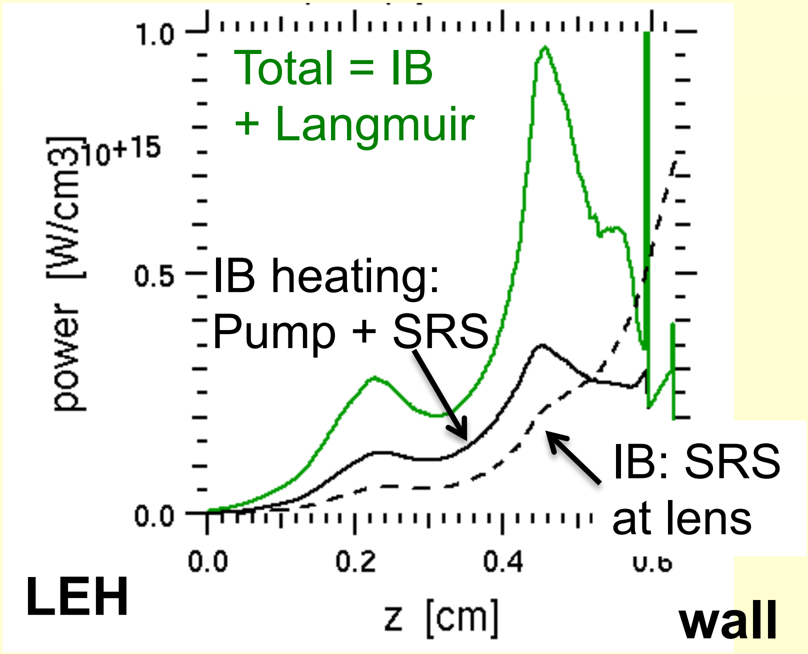
Hydra inline CBET model works, being extended to include Raman backscatter

- Picket: Inline model agrees with script once inners burn through LEH
- Peak power:
  - — Inline model agrees with script, with enough numerical rays
  - — Inline ion-wave energy deposition has little effect on transfer

- Backscatter also heats LEH, impairs inner-beam propagation more than reducing incident laser power

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

Teaser: inline SRS on 1D profile



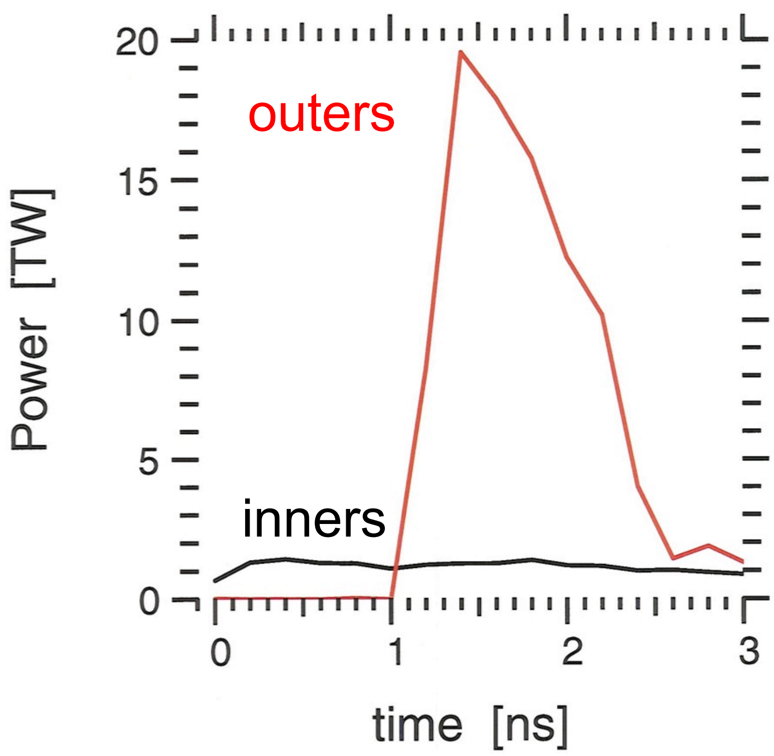

NIF

- BACKUP
- BELOW
- HERE

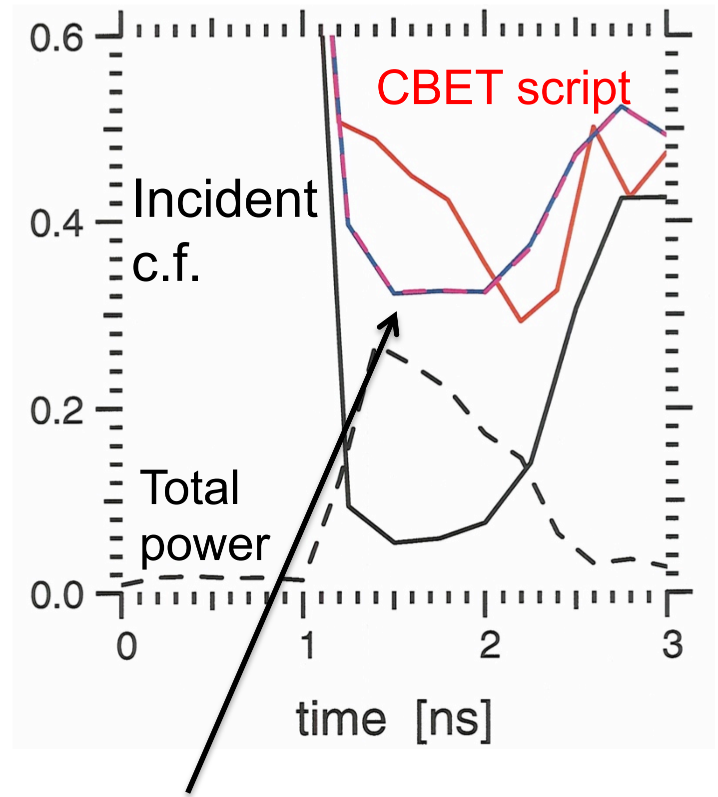
Picket: script and inline models both give large CBET, differ in details

NIF High-foot Shot N131118

Incident power: Inners burn through window to avoid hot electrons

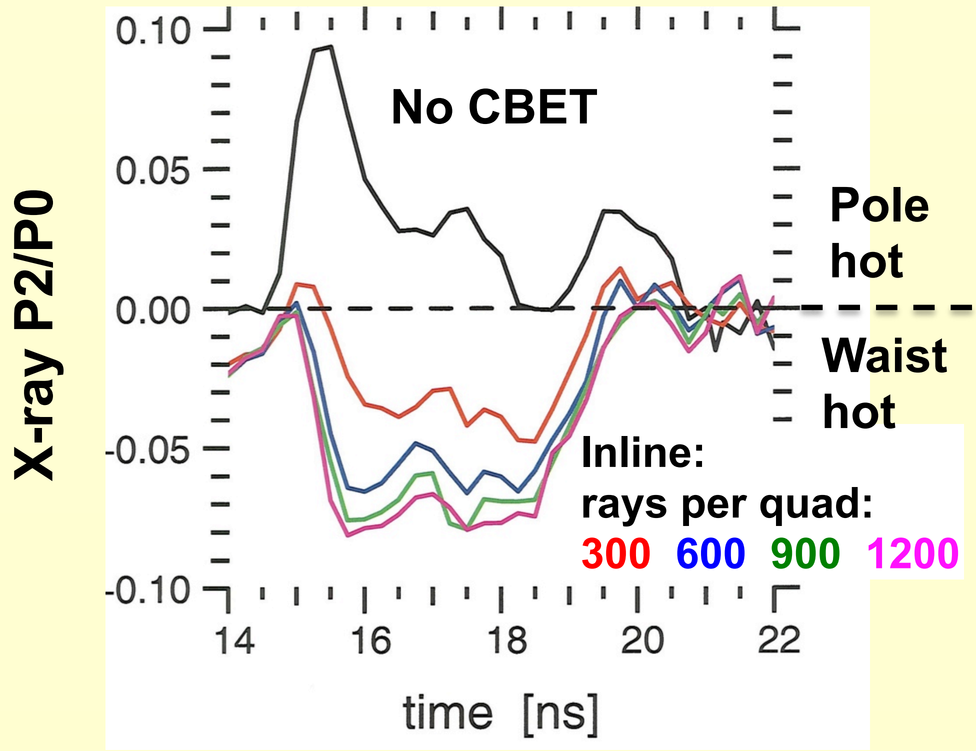


Cone fraction: inner / total power

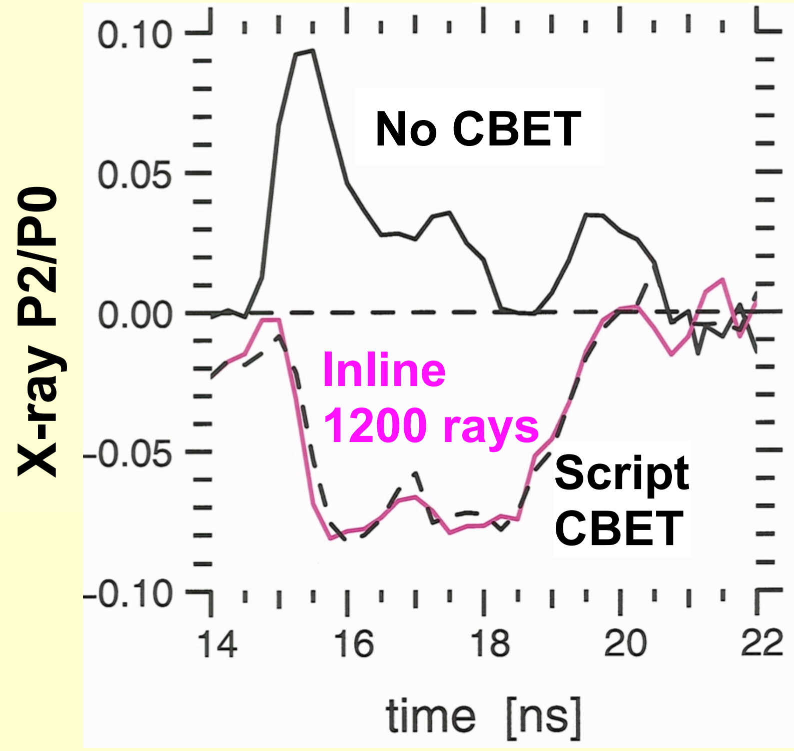


Peak power: x-ray flux moments on capsule behave like cone fraction, inline converges to script

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)

Details of model as run for this talk

- Exponential model with Manley-Rowe cap:

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

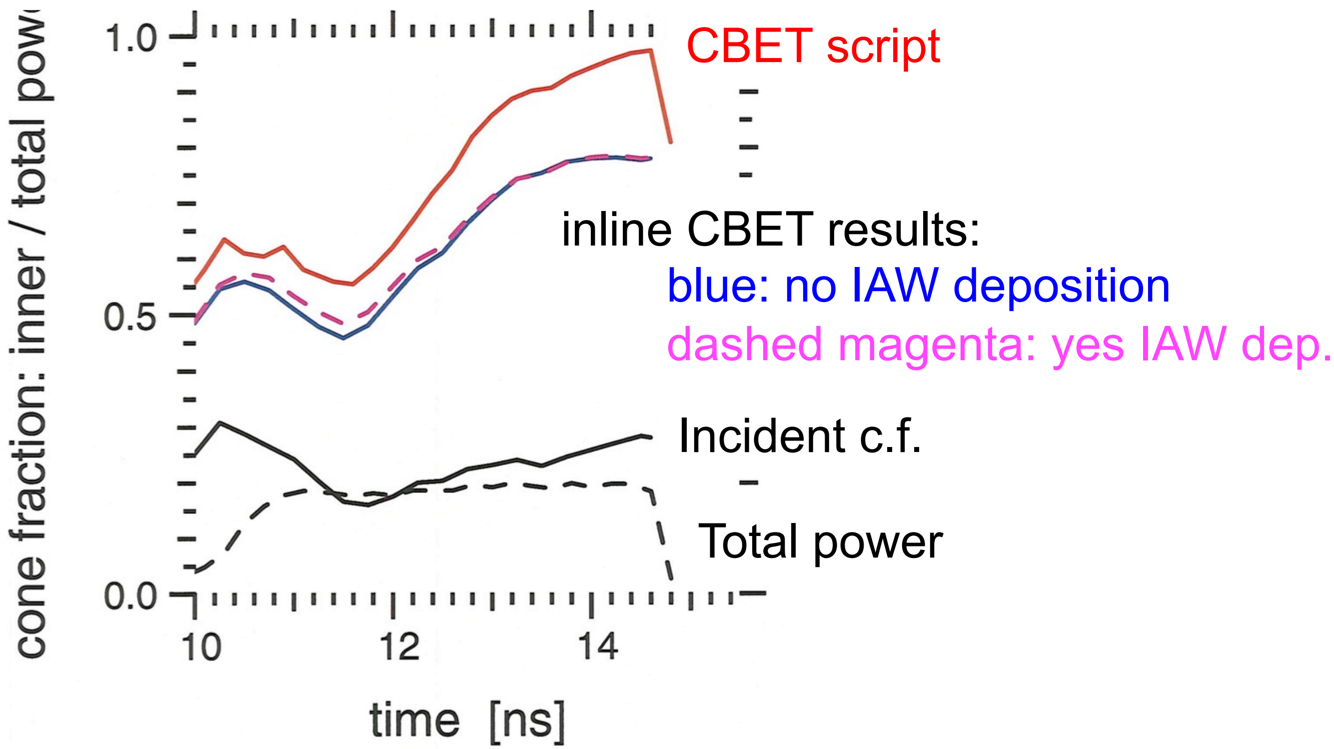
Beam 1, unsaturated case

  - 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

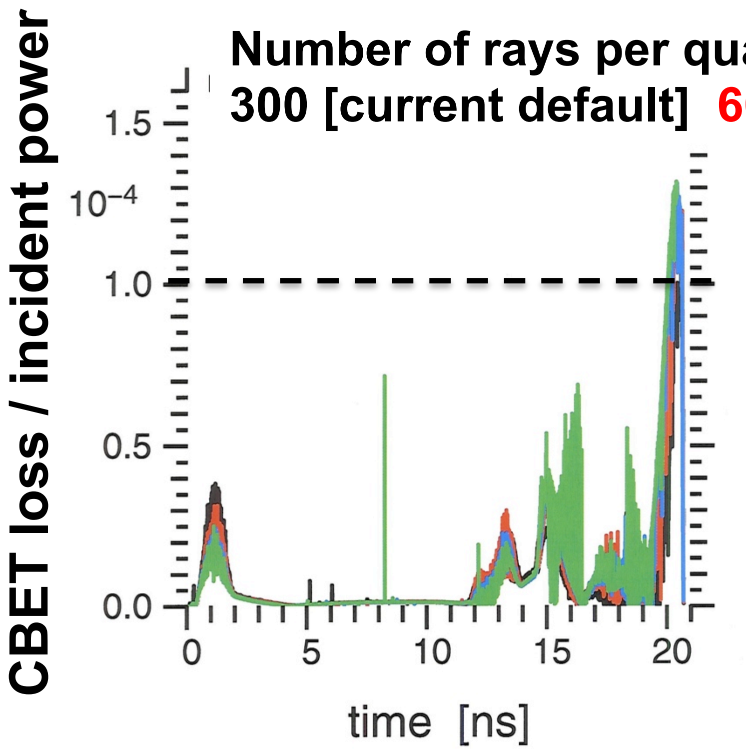
- Numerically iterate, max of 10 times, til power lost due to CBET (Manley-Rowe violation) < 10^{-4} * incident power

Cone fraction: inner / total power



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?**



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

The inline Hydra model includes effects beyond the offline script

CBET script method (P. Michel):

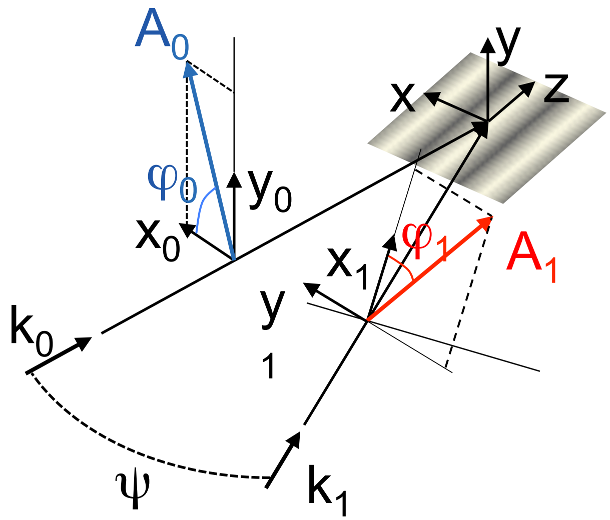
- Hydra "pre-transfer" run: no CBET, no backscatter, no drive multipliers
- CBET script run on pre-transfer plasma conditions
- Hydra "post-transfer" run with incident cone powers modified according to script

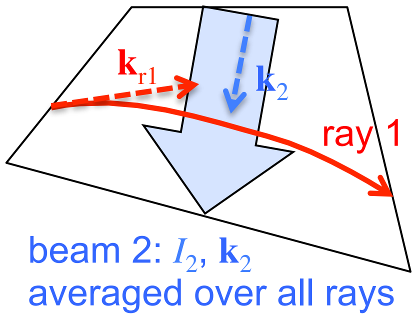
Additional physics in inline CBET model:

- 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

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





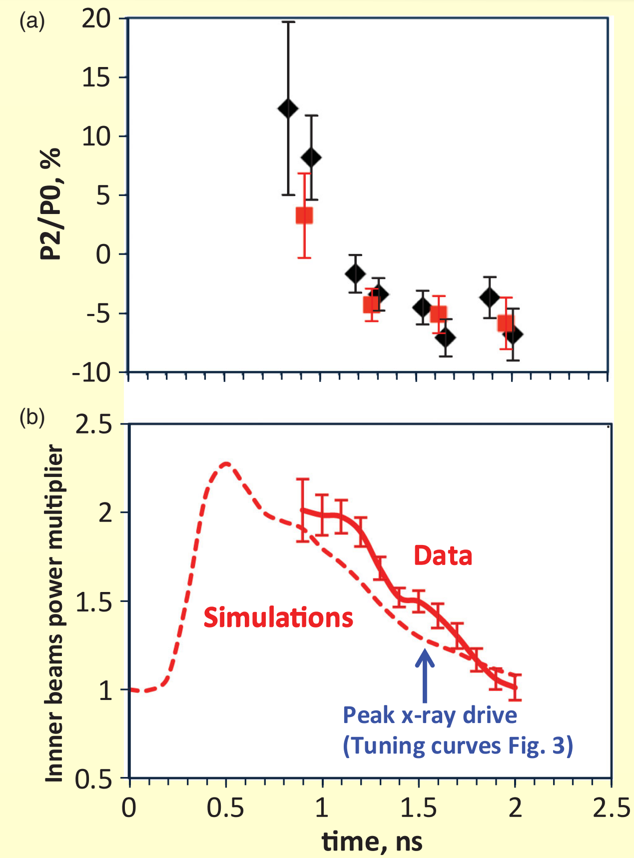
$$I = \sum_{r=1}^{Nrays} P_r \frac{s_r}{\Delta V}\,, \quad P_r = \frac{1}{s_r}\int_0^{s_r} ds' P(s')$$

s_r = distance of ray through zone

Coupling coeff from formula page:

$$\frac{\pi r_e}{2\omega_0 m_e c^2}\frac{k^2}{k_0 k_1}\left[1+\cos^2(\psi)\right]\mathrm{Im}(K)$$

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



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