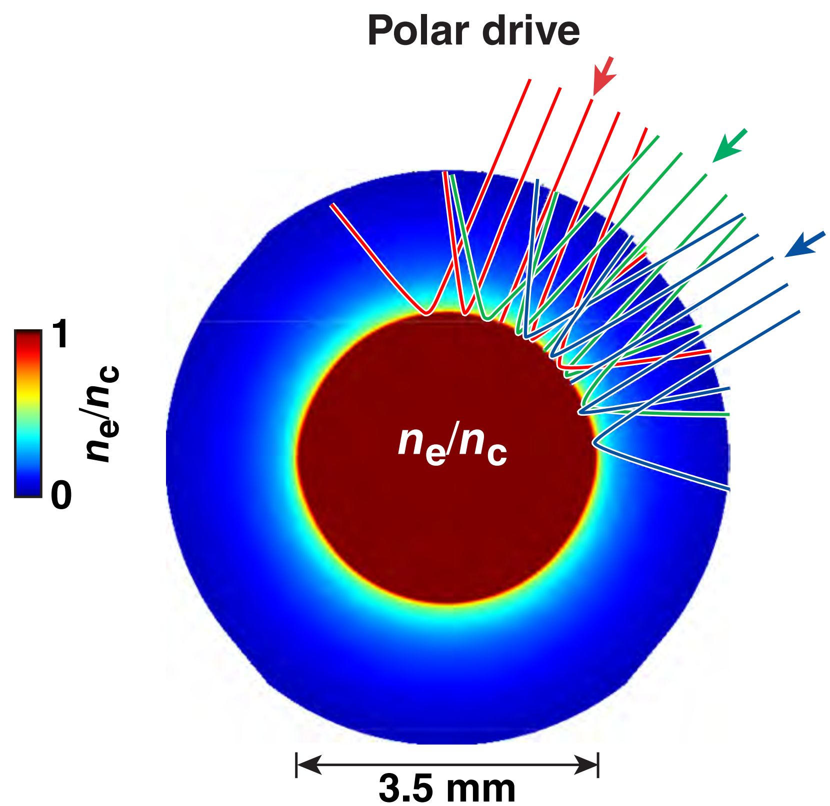
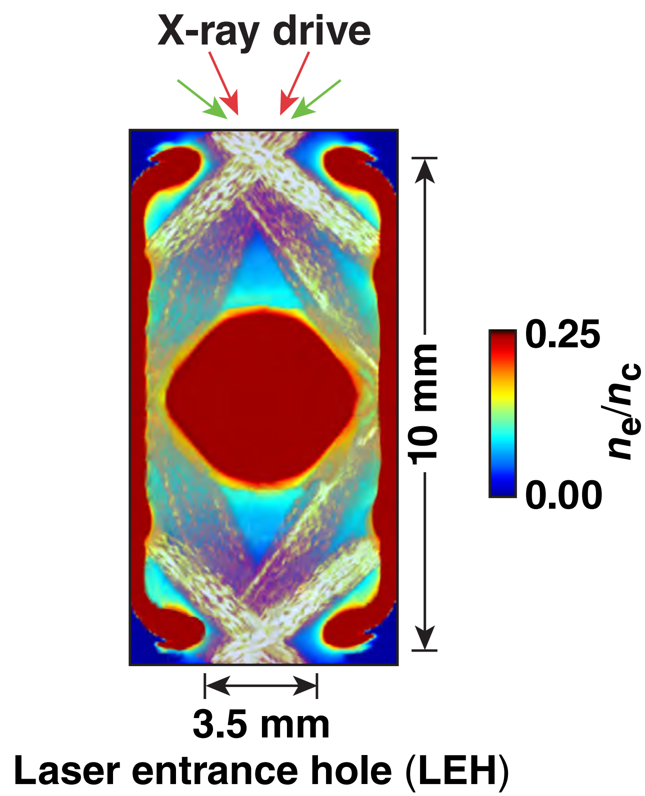
Multibeam Laser–Plasma Interactions in Inertial Confinement Fusion





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Summary

The overlapping of many laser beams in a plasma leads to cooperative laser–plasma instabilities (LPI's)

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- **Significant advances have been made toward understanding nonlinear propagation and absorption of laser light in the face of multibeam parametric instabilities**
- **Cross-beam energy transfer (CBET) has been identified in both direct- and x-ray-drive inertial confinement fusion (ICF)**
- **Multibeam two-plasmon decay is seen to be important in direct drive, while multibeam stimulated Raman scattering is implicated in x-ray drive**

Collaborators

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Outline

- Introduction
  - general concepts
  - ignition-scale interaction conditions
  - history
- Cross-beam energy transfer (CBET)
- Stimulated Raman scattering (SRS)
- Two-plasmon decay (TPD)

Laser–plasma interaction in ignition-scale plasmas is complicated by several factors

- Laser–plasma interactions involve a severe coupling of length and time scales
- Hydrodynamics ⟷ LPI
  - development of in-line models (e.g., cross-beam energy transfer)
- Kinetic codes (e.g., particle-in-cell) are still too expensive to run for realistic conditions
  - reduced models exploiting multiple time scales, e.g., harmonic decomposition,* are necessary (*pF3D*,** *Harmonhy*,† *ZAK3D*‡)
- Different codes for different scales can be patched together
- Multibeam interactions involve another level of complexity (that has usually been ignored in detailed modeling)
  - era of multibeam LPI, where 3-D geometry is important/essential

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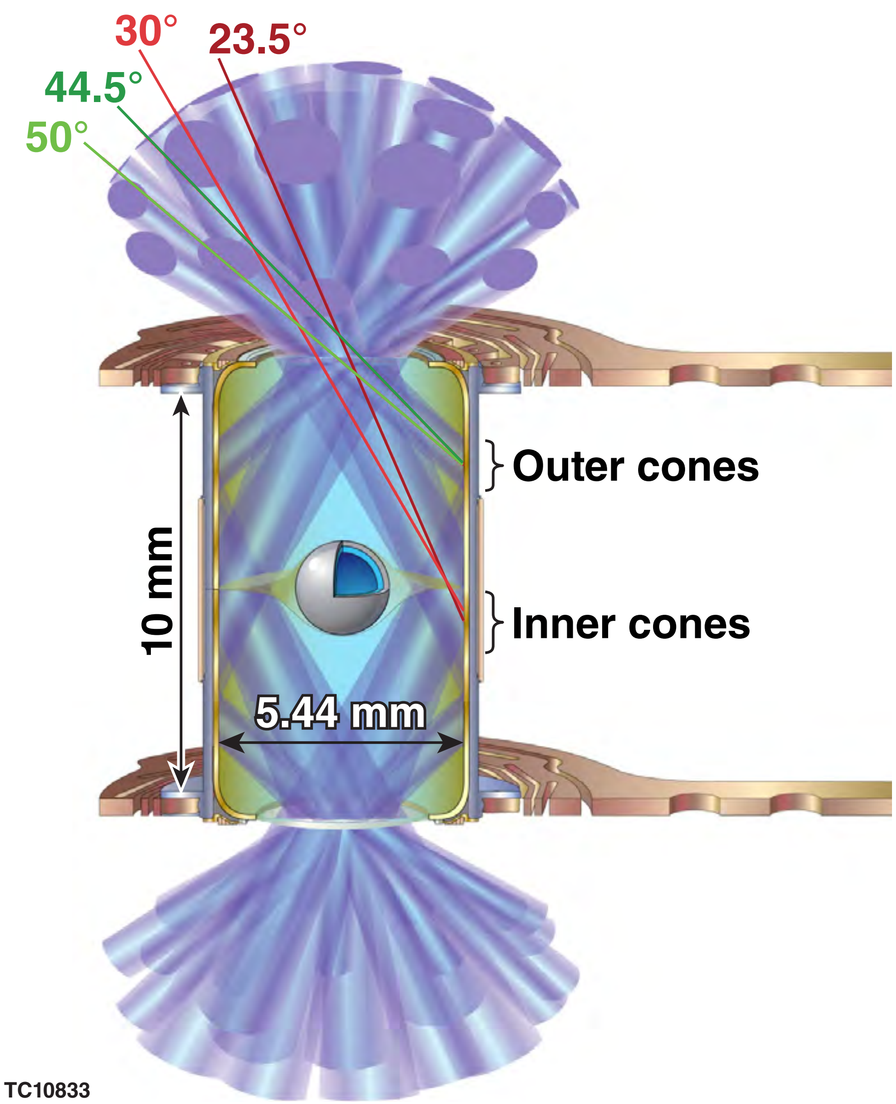
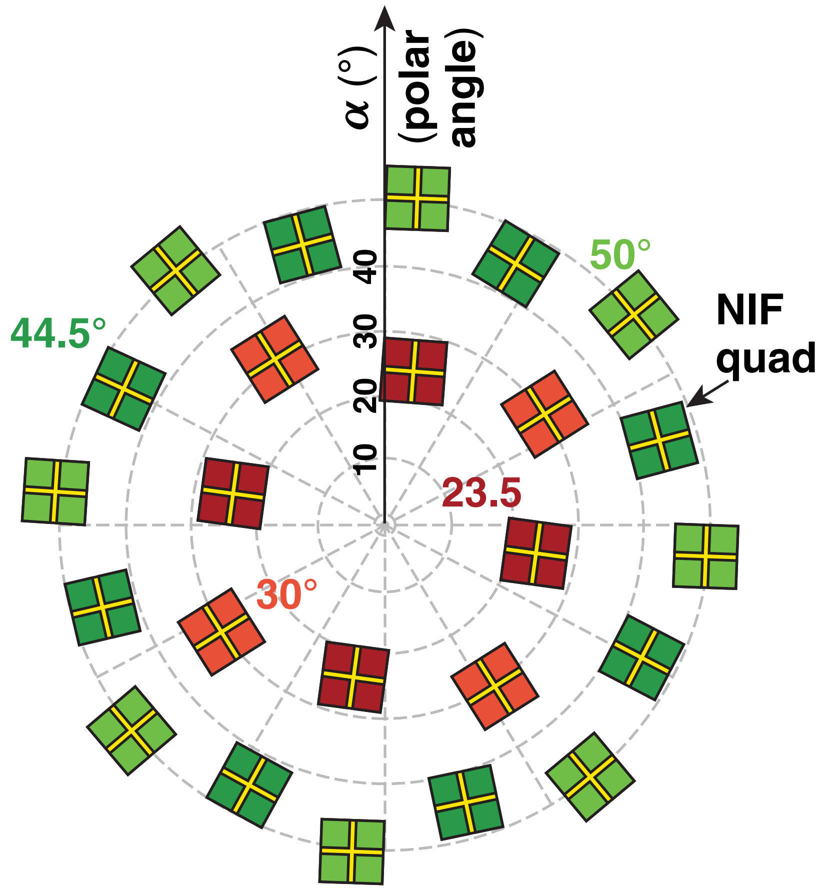
* D. Pesme *et al*., Plasma Phys. Control. Fusion 44, B53 (2002).
** R. L. Berger *et al*., Phys. Plasmas 5, 4337 (1998).
† S. Hüller *et al*., Phys. Plasmas 13, 022703 (2006).
‡ J. Zhang *et al*., presented at the 43rd Anomalous Absorption Conference, Stevenson, WA, 7–12 July 2013.

The hohlraum is the environment for the National Ignition Facility (NIF) x-ray-drive capsule





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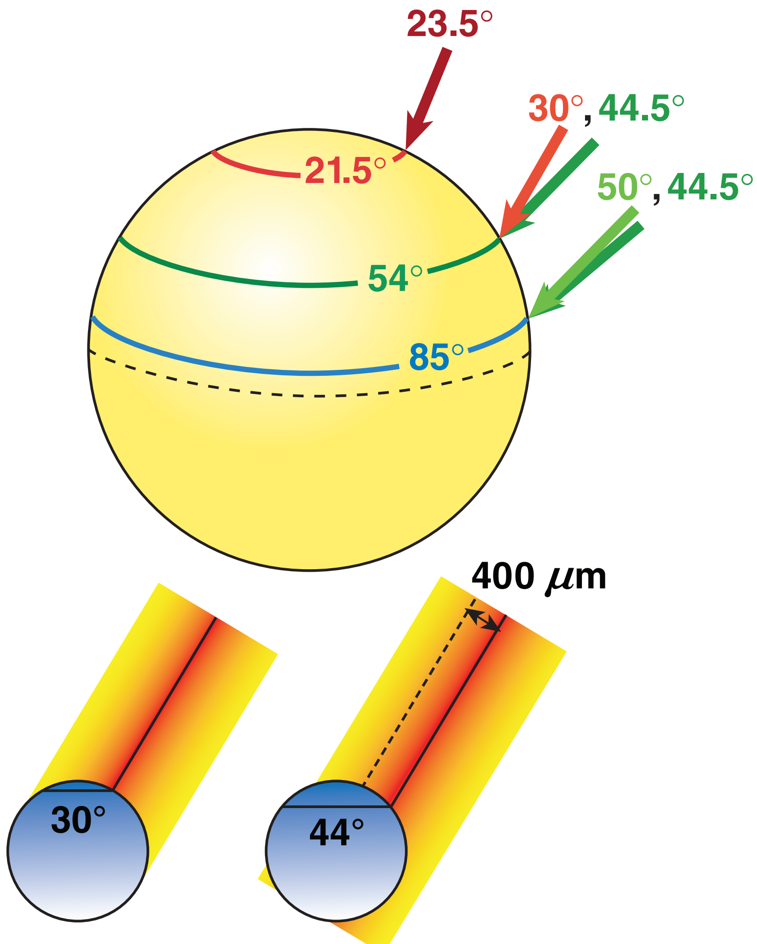
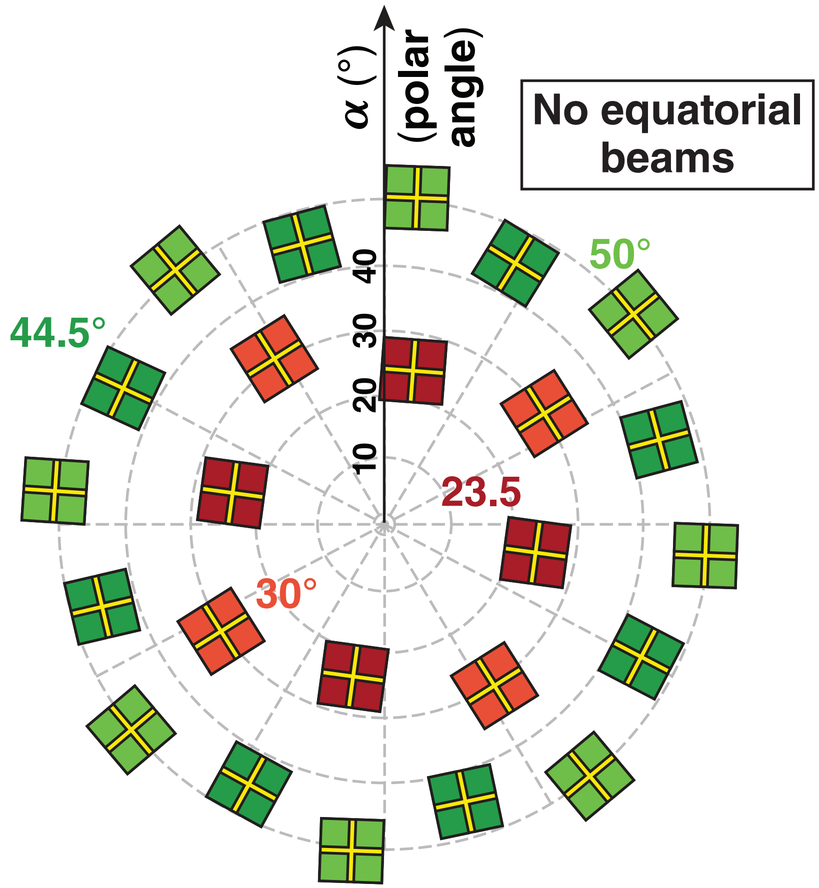
Polar Drive

Direct-drive experiments on the NIF require the nonspherically symmetric polar-drive geometry

Sufficient illumination symmetry can be obtained by a suitable repointing of the NIF beams*

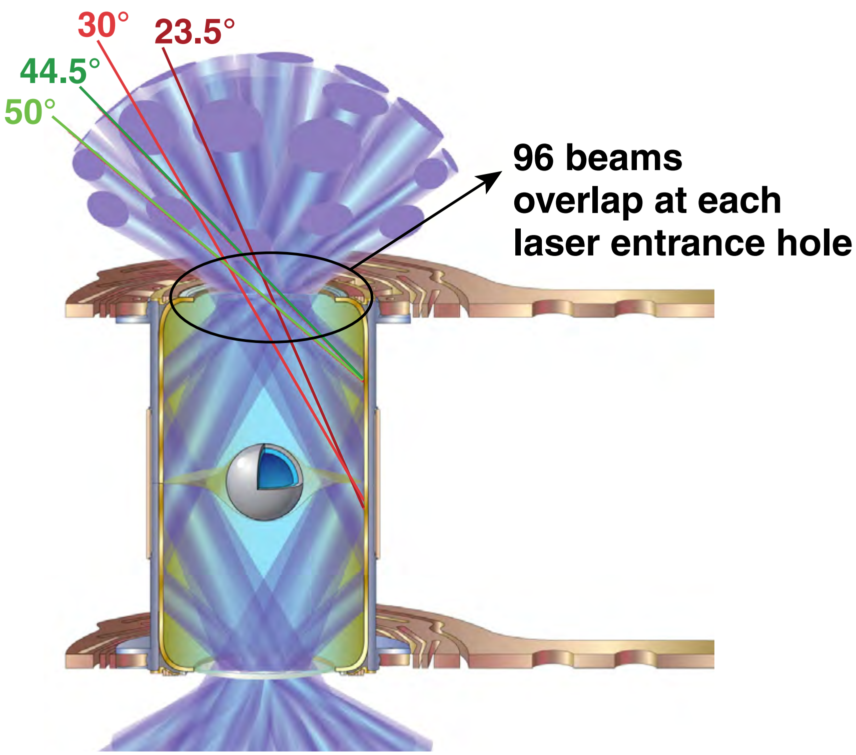




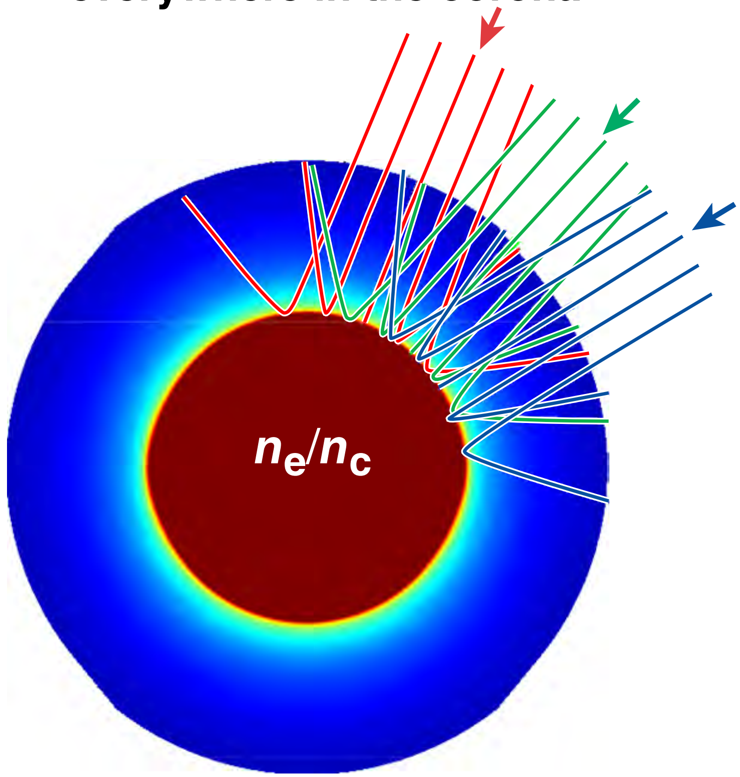
TC10832

*S. Skupsky *et al.*, Phys. Plasmas 11, 2763 (2004).

In both x-ray and direct-drive approaches to ICF, multiple intense laser beams overlap in plasma



Multiple beams overlap everywhere in the corona



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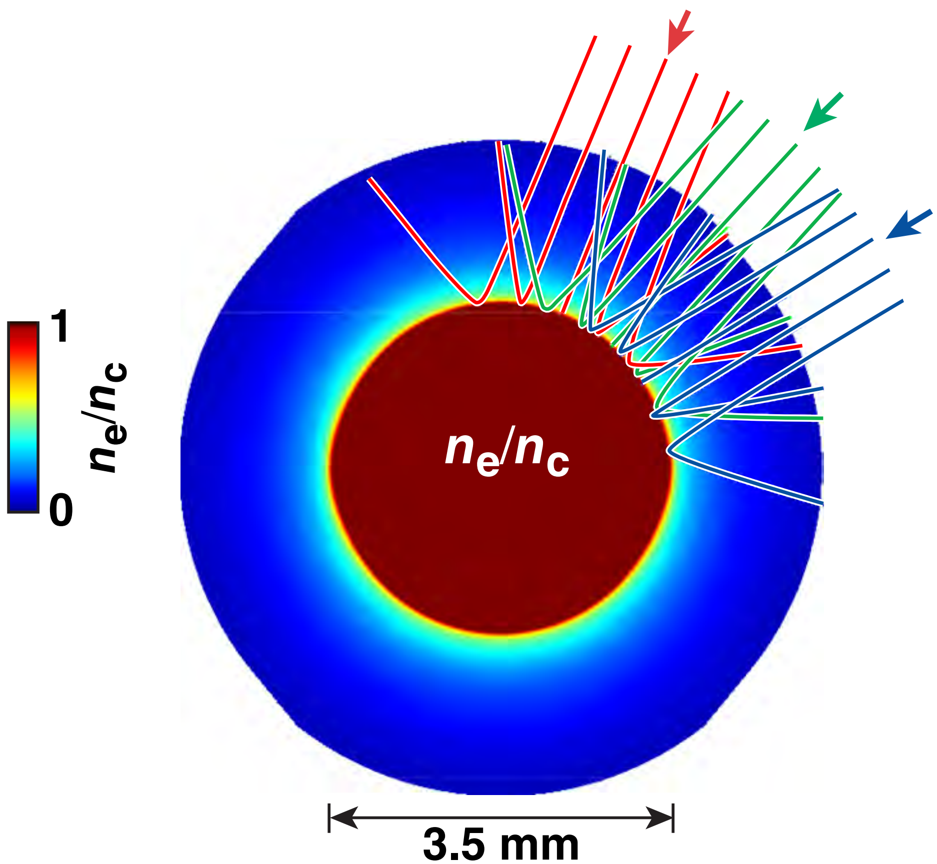
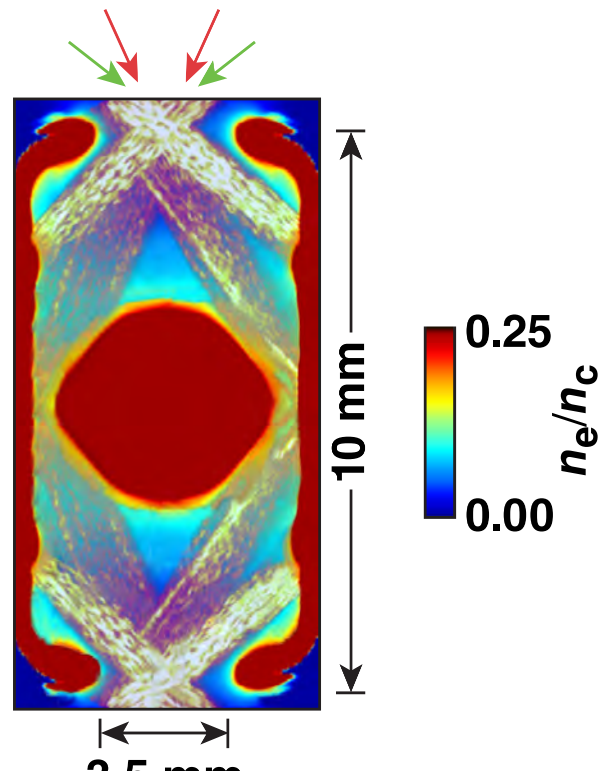
There are differences in interaction conditions between x-ray drive and polar drive (PD)

I_{single} ~ 10^{14} W/cm^2
Scale lengths ~ 0.5 mm
Small LPI gains



I_{single} ~ 10^{15} W/cm^2 (tightest focus at LEH)
Scale lengths ~ mm's
Large LPI gains



Laser entrance hole (LEH)

Hohlraum figure from P. Michel *et al*., Phys. Rev. Lett. 102, 025004 (2009).

Ignition designs do not generally exceed single-beam laser–plasma instability thresholds

- Unmagnetized plasmas support electromagnetic (EM) waves, electron plasma waves (EPW's), and ion-acoustic waves (IAW's)
- Three-wave parametric instabilities are the most important:

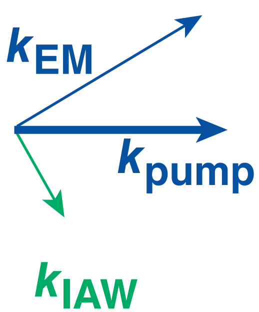
$$L_{pump} A_{pump} = i\Gamma A_1 A_2$$

$$L_1 A_1 = i\Gamma A_{pump} A_2^*$$

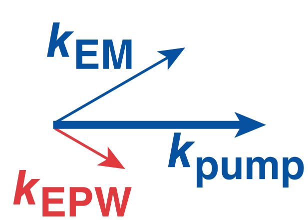
$$L_2 A_2 = i\Gamma A_{pump} A_1^*$$

Type	SBS	SRS	TPD
A_1	EM	EM	EPW
A_2	IAW	EPW	EPW

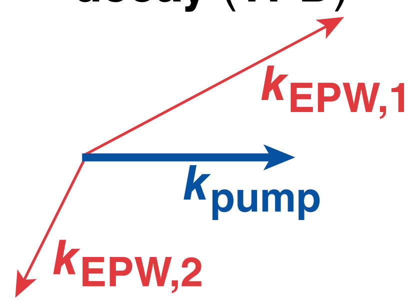
Simulated Brillouin scattering (SBS)



Simulated Raman scattering (SRS)



Two-plasmon decay (TPD)



Parametric instability occurs when wave-number and frequency-matching conditions are satisfied

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- The essential features (absolute/convective) were determined long ago for a single-plane EM pump

$$\omega_{\text{pump}} = \omega_1 + \omega_2$$

$$\vec{k}_{\text{pump}} = \vec{k}_1 + \vec{k}_2$$

The dispersion relations define ω in terms of k for waves of each type e.g., $\omega_{\text{IAW}} = \pm c_s \left| k_{\text{IAW}} \right| + v_f \cdot \vec{k}_{\text{IAW}}$

- The presence of plasma inhomogenity was also understood, and often leads to a convective instability

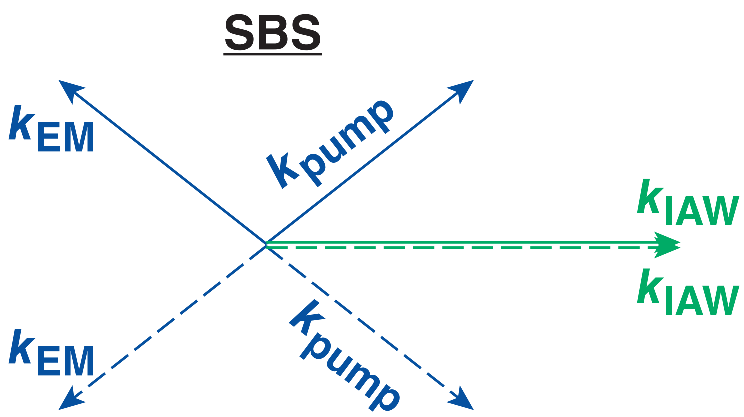
$$A_1 = A_{1,\text{seed}} \exp(G), \text{ where } G = \frac{2\pi\Gamma^2}{\left|\kappa' V_1 V_2\right|}{}^*$$

The gain (G) depends on the temporal growth rate (Γ) squared, the group velocities of the daughter waves (V_1, V_2), and the spatial rate of change of phase mismatch $\kappa' \cong 1/L$

*M. N. Rosenbluth *et al*., Phys. Rev. Lett. 29, 565 (1972).

There are several ways multiple beams can cooperate to produce instability

- Daughter waves can be shared between decays occuring in different beams*



Growth rates (or gains) depend on combined intensities.

- The instability can be seeded, or "induced," (A_{seed} enhanced) because one of the daughter waves is present in the laser drive or has been produced as a result of the other decays†

*D. F. DuBois, B. Bezzeridels, and H. A. Rose, Phys. Fluids B4, 241 (1992).
†W. L. Kruer *et al*., Phys. Plasmas 3, 382 (1996).

TC10982

Cross-beam (or multibeam) LPI work started over 20 years ago

- **Theoretical/numerical examples:**
  - Randall *et al.* 1979, 1981 (LLNL); DuBois *et al*., (LANL) 1992; Kruer *et al*. 1996 (LLNL); Elissev *et al*., 1996 (U. Alberta/Canada); McKinstrie *et al*., 1996, 1997 (LLE); Rose and Ghosal, 1998 (LANL); Cohen *et al*., 1998 (LLNL); Williams *et al*., 2004 (LLNL); Hittinger *et al*., 2005 (LLNL)

- **Experimental examples:**
  - Kirkwood *et al*. 1996 (Nova/LLNL); Baldis *et al*. 1996 (LULI/France); Lal *et al*. 1997 (CO_2/UCLA); Fernándaz *et al*. 1998 (Trident/LANL); Wharton *et al*. 1998 (Nova/LLNL); Labaune *et al*. 1999, 2000 (LULI/France); Kirkwood *et al*. 2002 (OMEGA/LLNL); Seka *et al*. 2002 (OMEGA/LLE); Stoeckl *et al*. 2003 (OMEGA/LLE)

- **The investigation for igniton-relevant conditions has only just begun**

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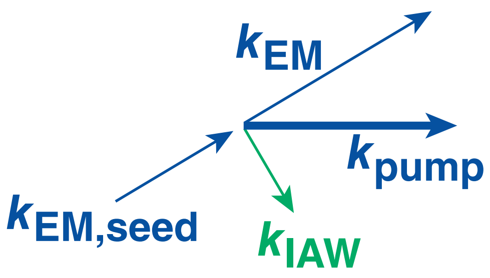
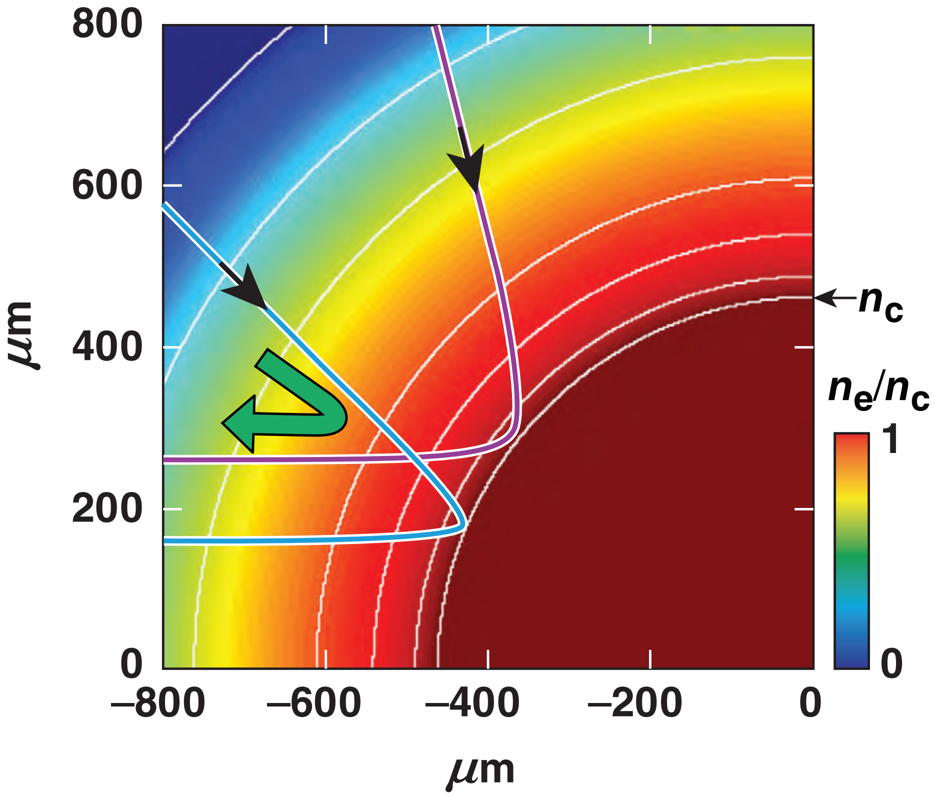


Cross-Beam Energy Transfer

EM-seeded SBS (cross-beam energy transfer) reduces absorption and drive in directly driven targets

- **Unlike x-ray drive, the presence of supersonic plasma flow enables the process to be resonant***
- **Three-wave SBS equations are computed (pairwise) for each beam crossing using a generalization of Randall *et al*.* and are implemented in-line in 1-D *LILAC***



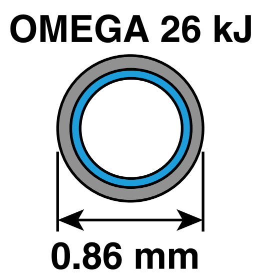
Because the EM seed amplitude is large, small gains affect the absorbed energy.

*C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluids 24, 1474 (1981);
K. B. Wharton *et al.*, Phys. Rev. Lett. 81 2248 (1998);
B. I. Cohen *et al.*, Phys. Plasmas 5 3408 (1998);
H. A. Rose and S. Ghosal, Phys. Plasmas 5 1461 (1998).

E17994d

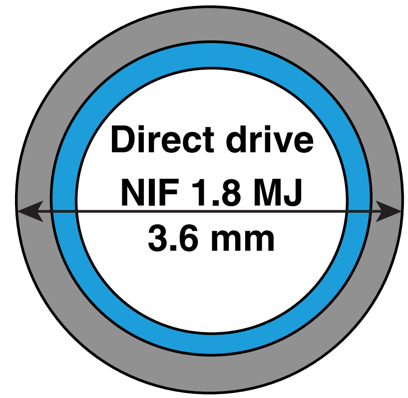
In-line CBET models have been developed and tested on OMEGA

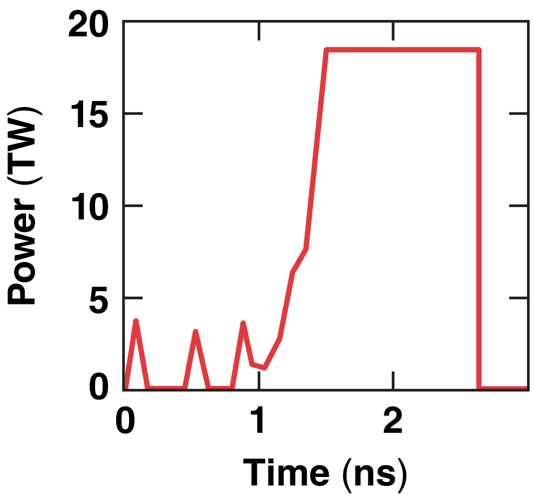
- OMEGA implosions are designed to be hydrodynamically equivalent to those on the NIF

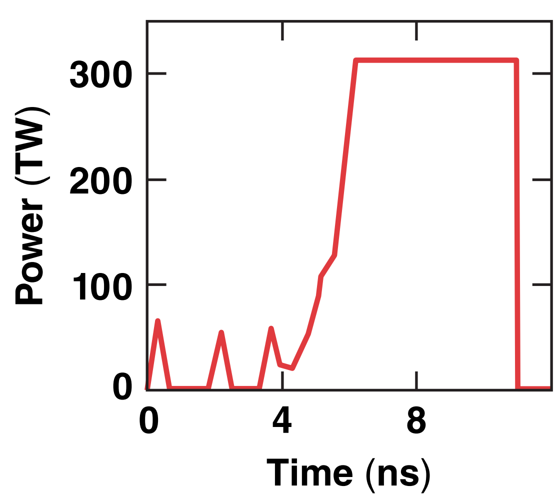


Hydrodynamic scaling

Capsule radius ~ $E_L^{1/3}$
Laser power ~ $E_L^{2/3}$
Pulse length ~ $E_L^{1/3}$





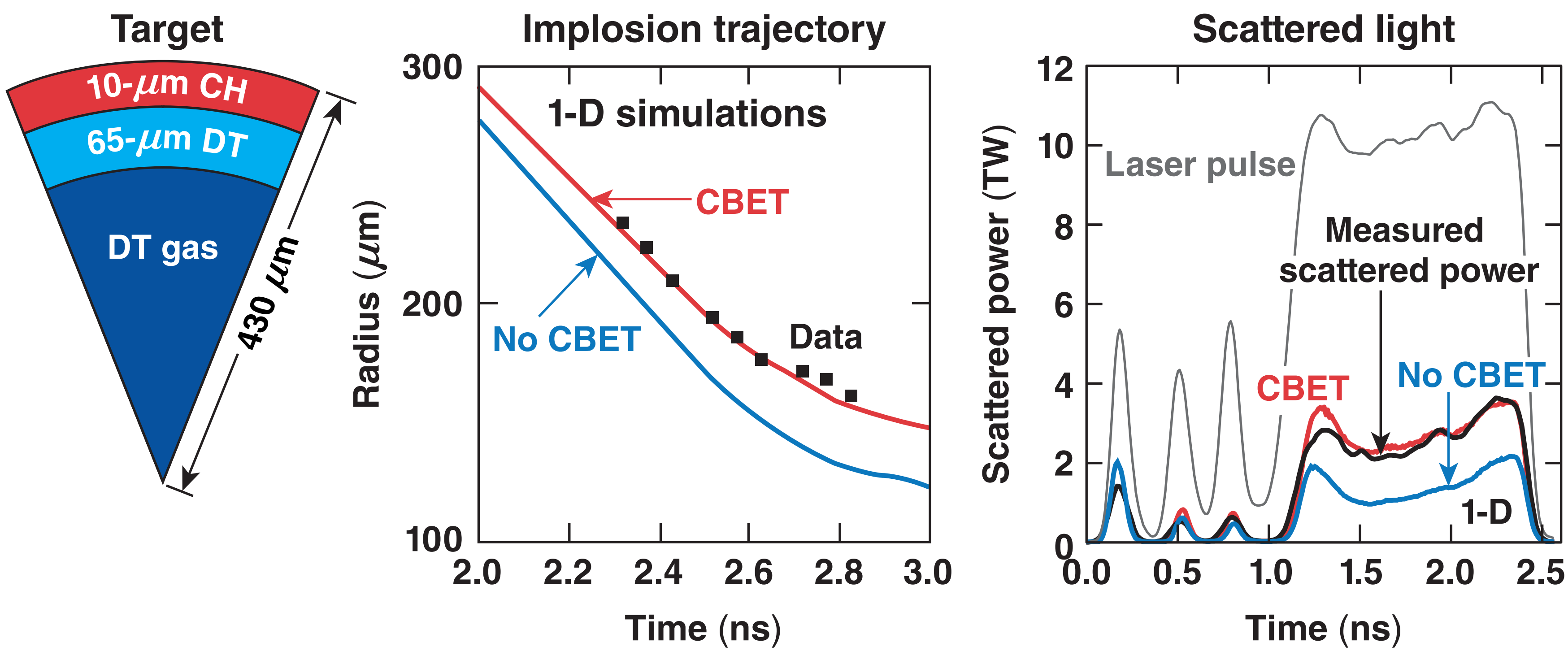


TC10267e

R. Nora, GI3.00002, this conference (invited).

Direct-drive simulations that include nonlocal heat transport and CBET match the experimental observables on OMEGA*

- Spherically symmetric direct drive



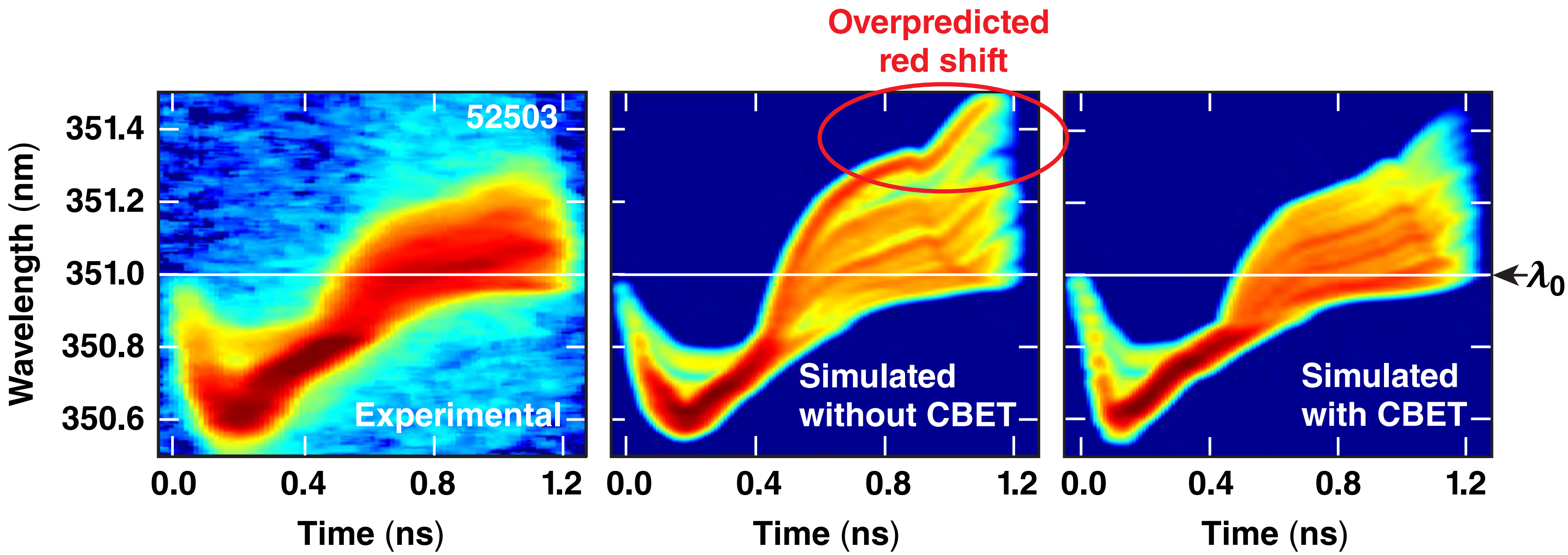
Good agreement with experiments is achieved with no free parameters (small power transferred).

*I. V. Igumenshchev *et al*., Phys. Plasmas 19, 056314 (2012); D. H. Froula *et al*., Phys. Rev. Lett. 108, 125003 (2012).

E21315h

CBET was inferred on OMEGA by a detailed spectroscopic analysis of the time-resolved reflected light*

- The time rate of change of an optical path for a given ray trajectory results in a frequency shift** that can be calculated in the simulation



- The best agreement is found when the CBET model is implemented together with nonlocal thermal transport

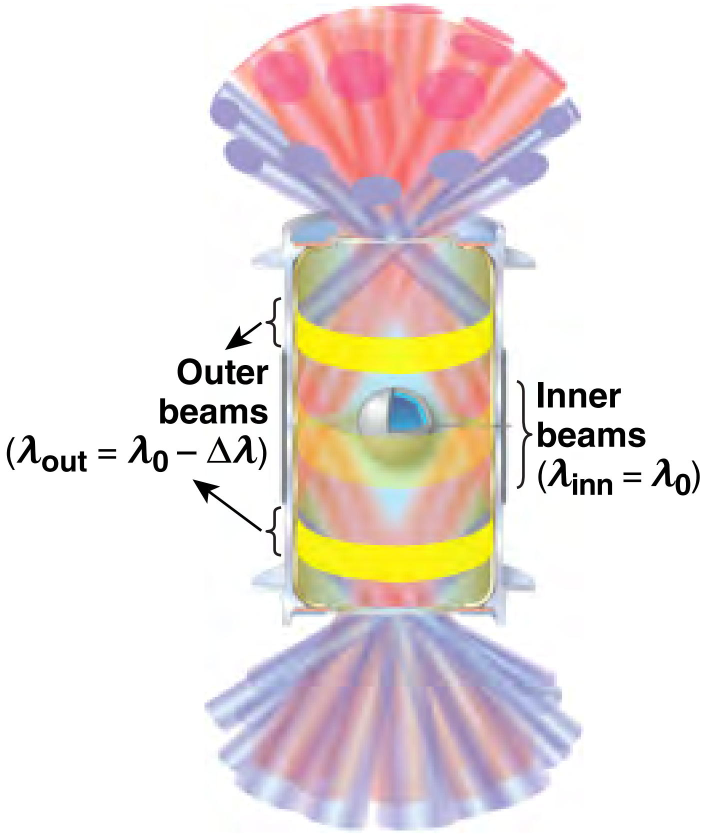
* W. Seka *et al*., Phys. Plasmas 15, 056312 (2008); I. V. Igumenshchev et al., Phys. Plasmas 19, 056314 (2012); D. H. Edgell *et al*., Bull. Am. Phys. Soc. 52, 195 (2007); *ibid*. 53, 168 (2008); *ibid*. 54, 145 (2009).

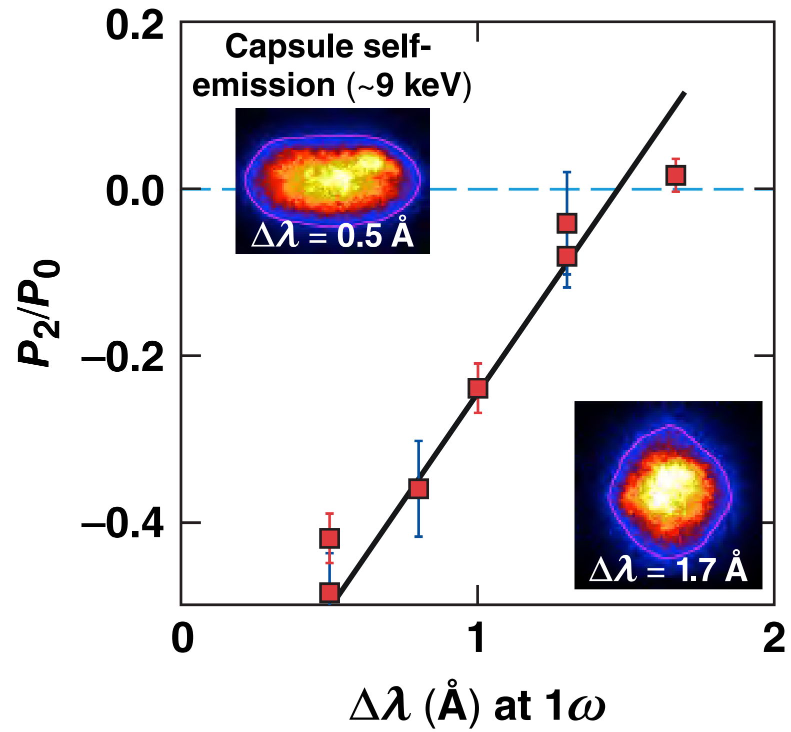
** T. Dewandre, J. R. Albritton, and E. A. Williams, Phys. Fluids 24, 528 (1981).

E19972f

In x-ray-drive experiments on the NIF, P_2 symmetry is tuned by CBET (by adjusting $\Delta\lambda = \lambda_{inn} - \lambda_{out}$)

No CBET → oblate implosions caused by impaired inner beams propagating



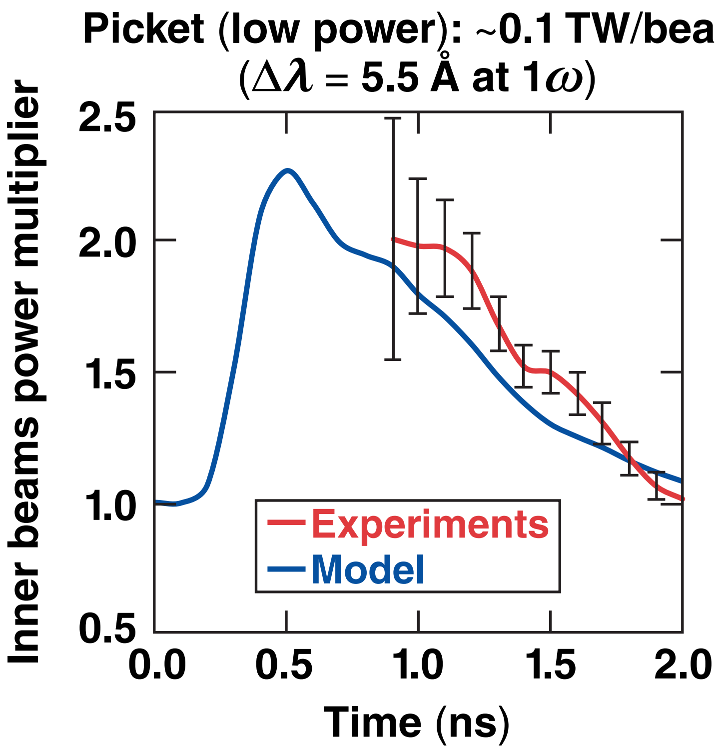


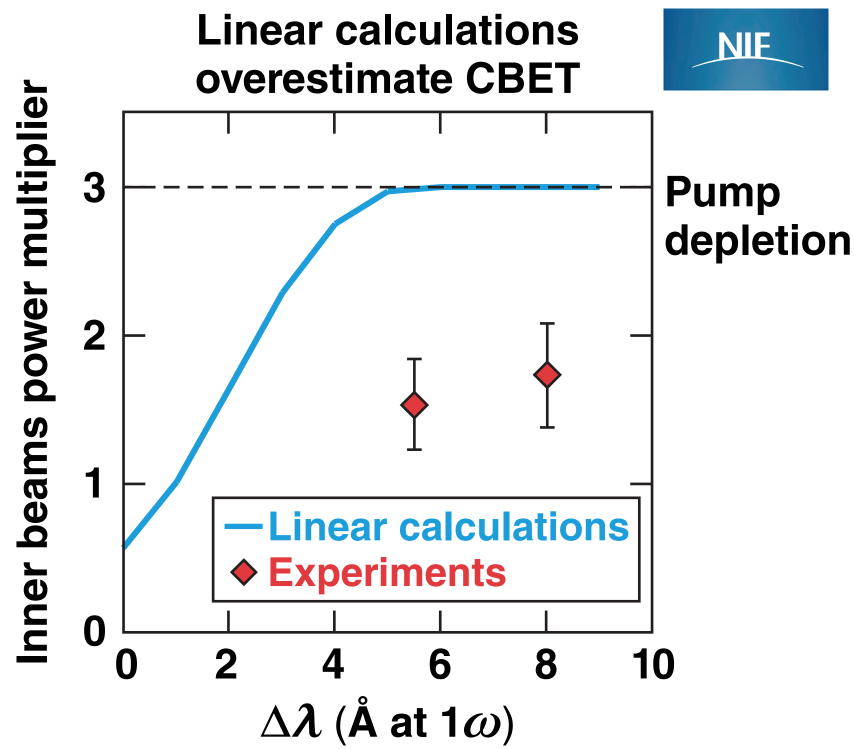
- More energy is tranferred to the inner beams as $\Delta\lambda$ increases because the induced SBS process becomes closer to resonance

P. Michel *et al*., Phys. Plasmas 17, 056305 (2010); S. H. Glenzer *et al*., Science 327, 1228 (2010).

TC10846

In x-ray drive, calculations based on linear kinetic models work well at small power transfers but not at large ones



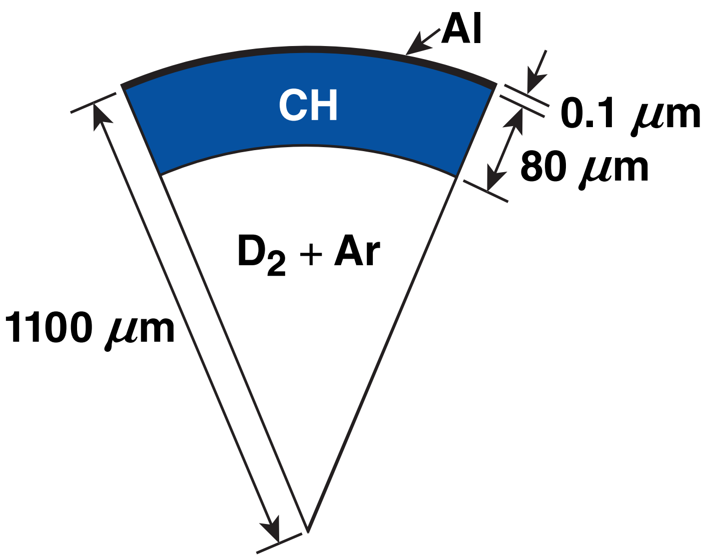


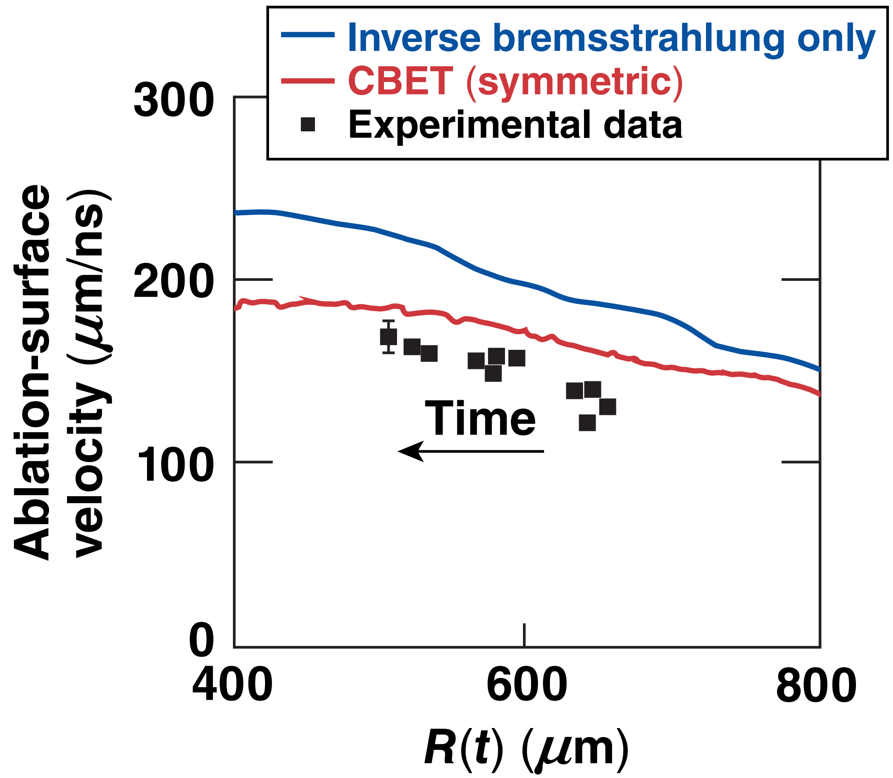
- The same linear kinetic response for CBET is used at LLNL, LLE, and CEA
- LLNL's CBET model includes an arbitrary saturation parameter because gains are larger in x-ray drive, although recent work on quasilinear ion heating may remove the need*
- Such models may be suitable for in-line implementation

*P. Michel, *et al.*, Phys. Rev. Lett. 109, 195004 (2012); E. A. Williams *et al.*, Phys. Plasmas 11, 231 (2004).

As expected, early NIF (PD) experiments show a reduction in ablation-surface velocity

N130731 $I \sim 8 \times 10^{14}$ W/cm^2





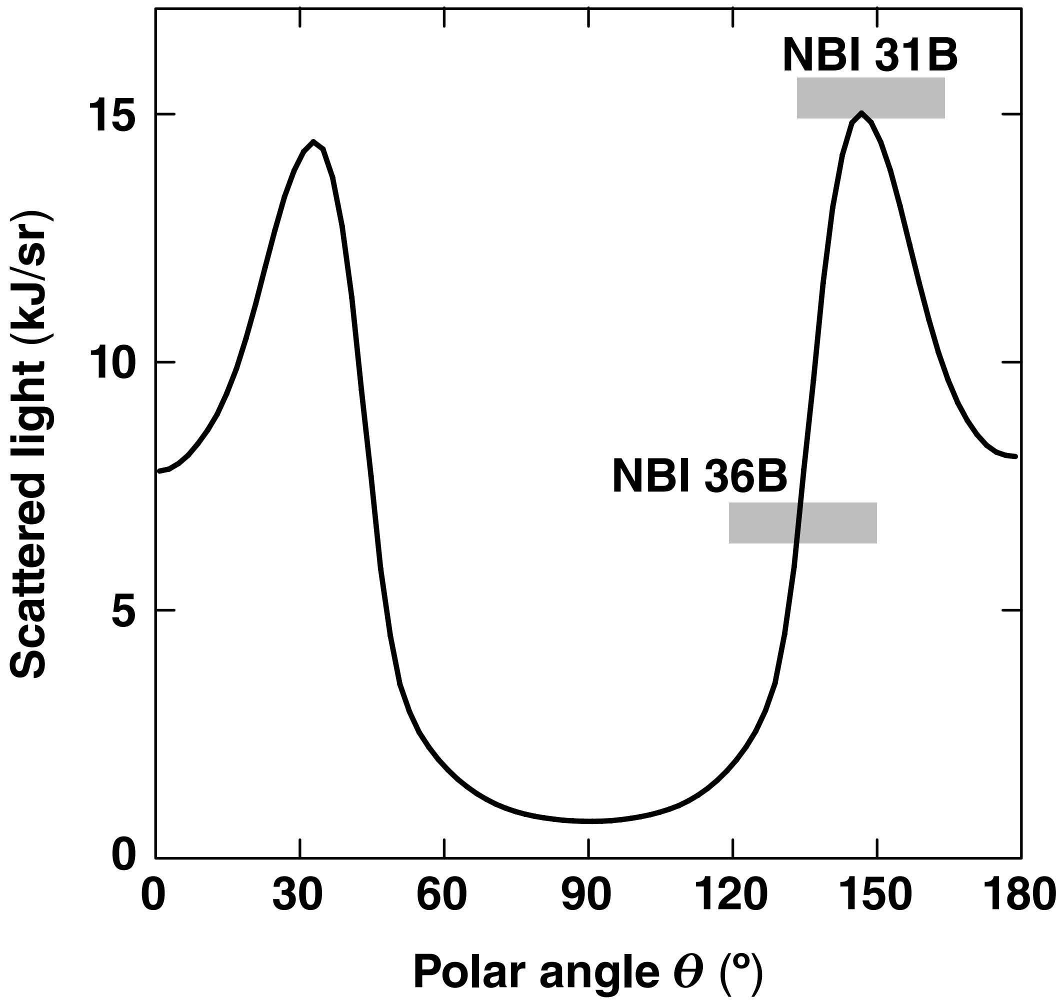
- Implementing a CBET model is more computationally expensive for PD because of the reduced symmetry and complex ray trajectories, although much progress has been made*

*J. A. Marozas *et al.*, CO7.00004, this conference.

TC10699b

The predicted scattered light is strongly anisotropic

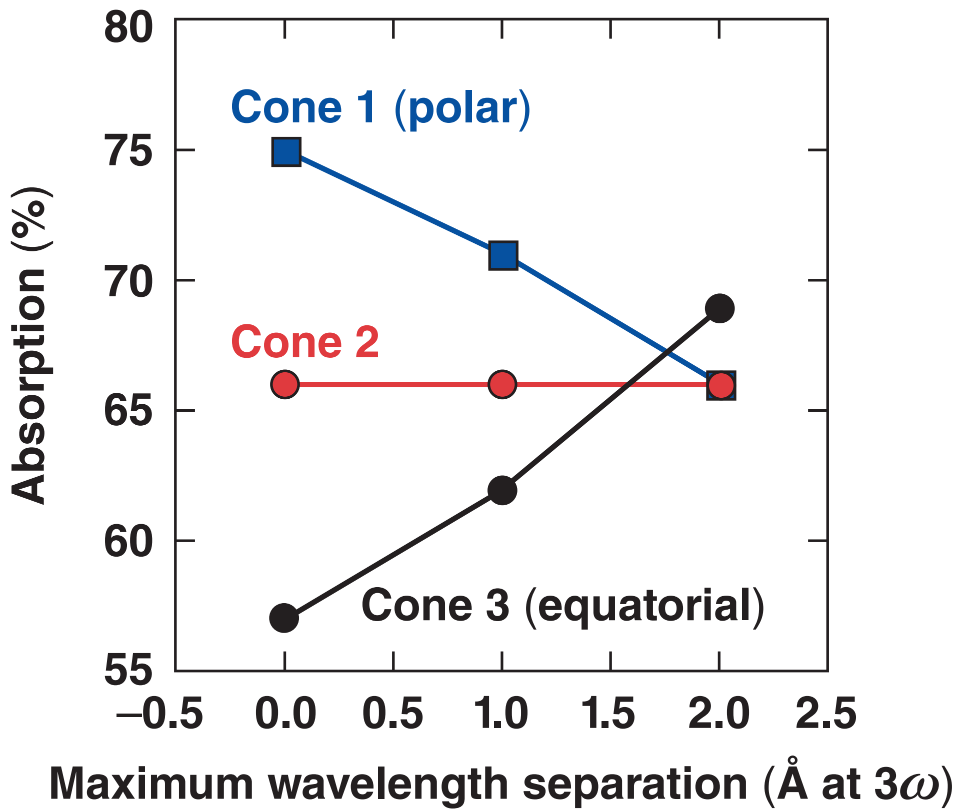
- The cumulative scattered light is concentrated in a narrow range of angles θ sampled by the two near-backscatter imaging (NBI) plates



TC11042

Preliminary calculations indicate that shifting the wavelength between polar-drive cones could significantly alter the energy exchange*†

- The process is similar to $\Delta\lambda$ in x-ray drive, but more complicated because of the number of possible resonances



- The ring structure of PD allows similar beams to be wavelength shifted as a group
- Preliminary calculations suggest wavelength shifting can balance the rings or steer power to the equator
- $\Delta\lambda$ ~ 5Å (at 3ω) can mitigate CBET*
- Will be tested on the NIF

*I. V. Igumenshchev *et al*., Phys. Plasmas 19, 056314 (2012);
†D. H. Edgell *et al*., presented at the 43rd Anomalous Absorption Conference, Stevenson, WA, 7–12 July 2013.

E21282a

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- **Stimulated Raman scattering (SRS)**
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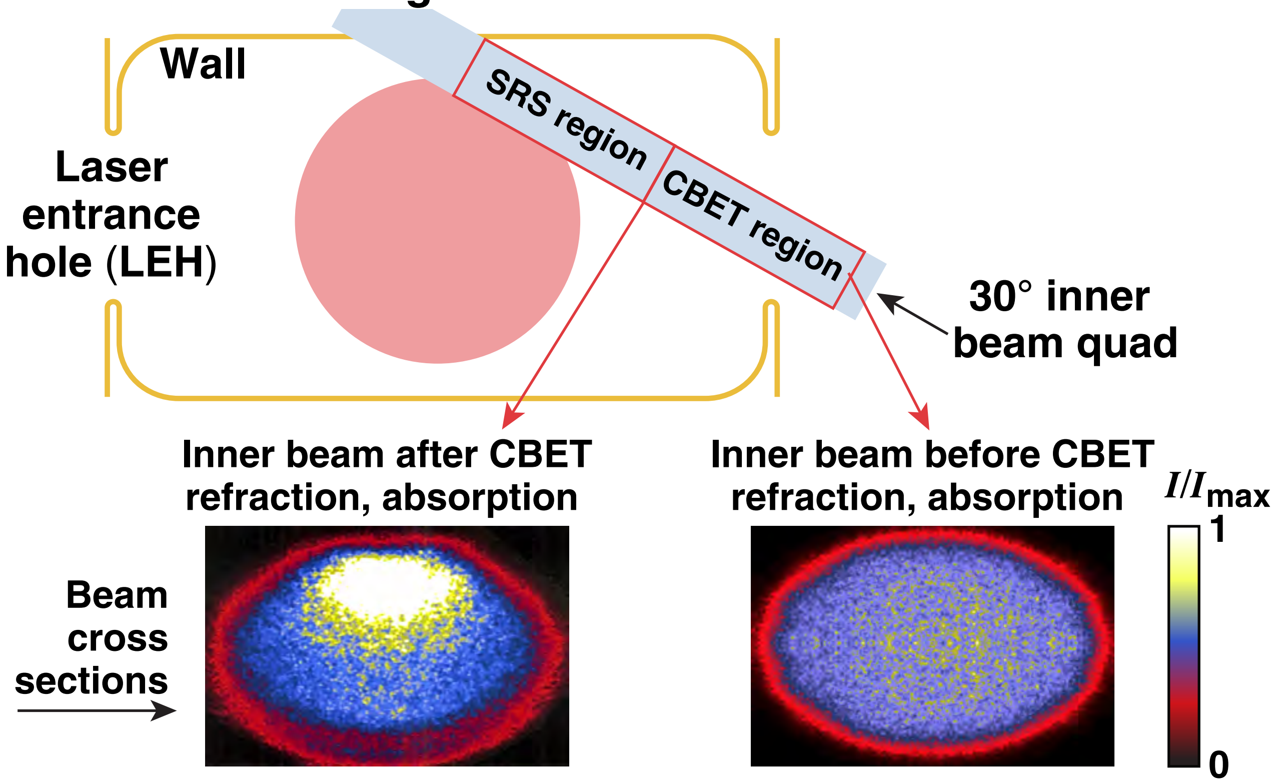
CBET results in a modified laser-intensity distribution downstream of the interaction region in x-ray drive

- In x-ray drive, stimulated Raman scattering (SRS) occurs downstream of the CBET region
- Codes must be pieced together (separation in scales)

Schematic of ignition hohlraum*

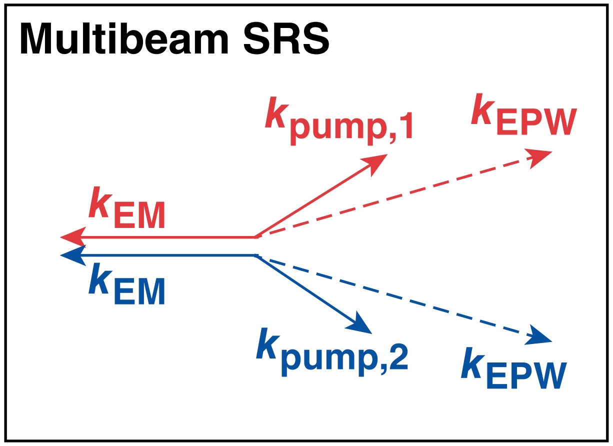


TC10851

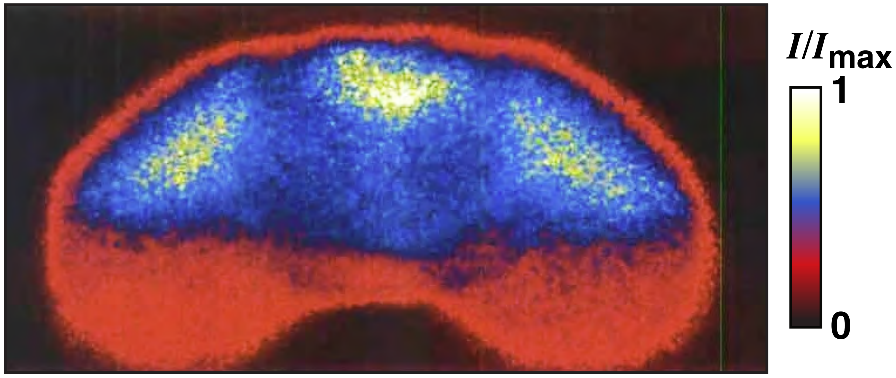
*D. E. Hinkel, presented at the HEDP Summer School, Columbus, OH, 15–19 July 2013.

LLNL *pF3D** calculations demonstrate that multiple inner beam quads share a reflected light wave

- *pf3D* is a massively parallel, paraxial fluid-based LPI code*
- Experimental observables are matched when the multibeam interaction is taken into account**



Input: cross sections of three inner quads after CBET



With three interacting quads, the simulated reflectivity approaches the measurement**

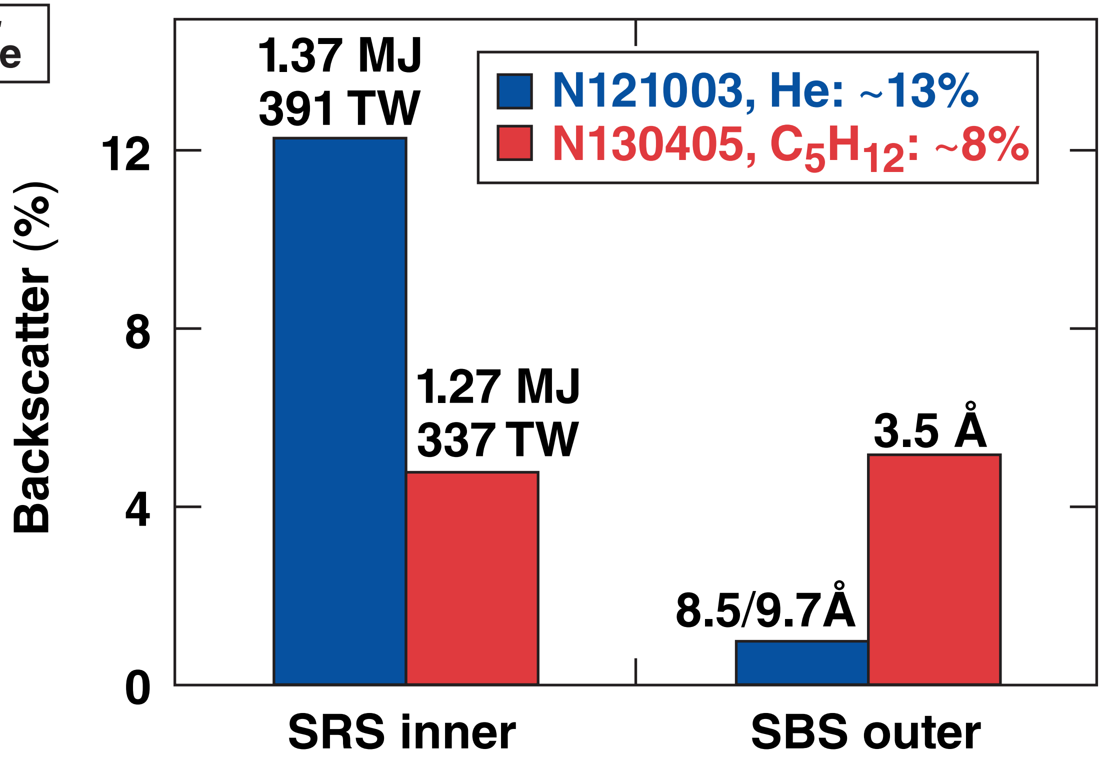
Shot	Energy (MJ)	Time (ns)	30° SRS measurement (TW)	Three-quad *pF3D* prediction (TW)
N091204	1.05	19	1.3	1.0

* R. L. Berger *et al*., Phys. Plasmas 5, 4337 (1998).
** D. E. Hinkel *et al*., Phys. Plasmas 18, 056312 (2011);
D. E. Hinkel, presented at the HEDP Summer School, Columbus, OH, 15–19 July 2013.

Higher plasma temperatures reduce LPI and require a smaller $\Delta\lambda$

- High-Z gas-filled hohlraums show good performance while using less cross-beam transfer*

$G \sim I n_e / T_e$



- Mid-Z ablators have been designed for PD implosions

TC10848

*D. E. Hinkel, presented at the HEDP Summer School, Columbus, OH, 15–19 July 2013.

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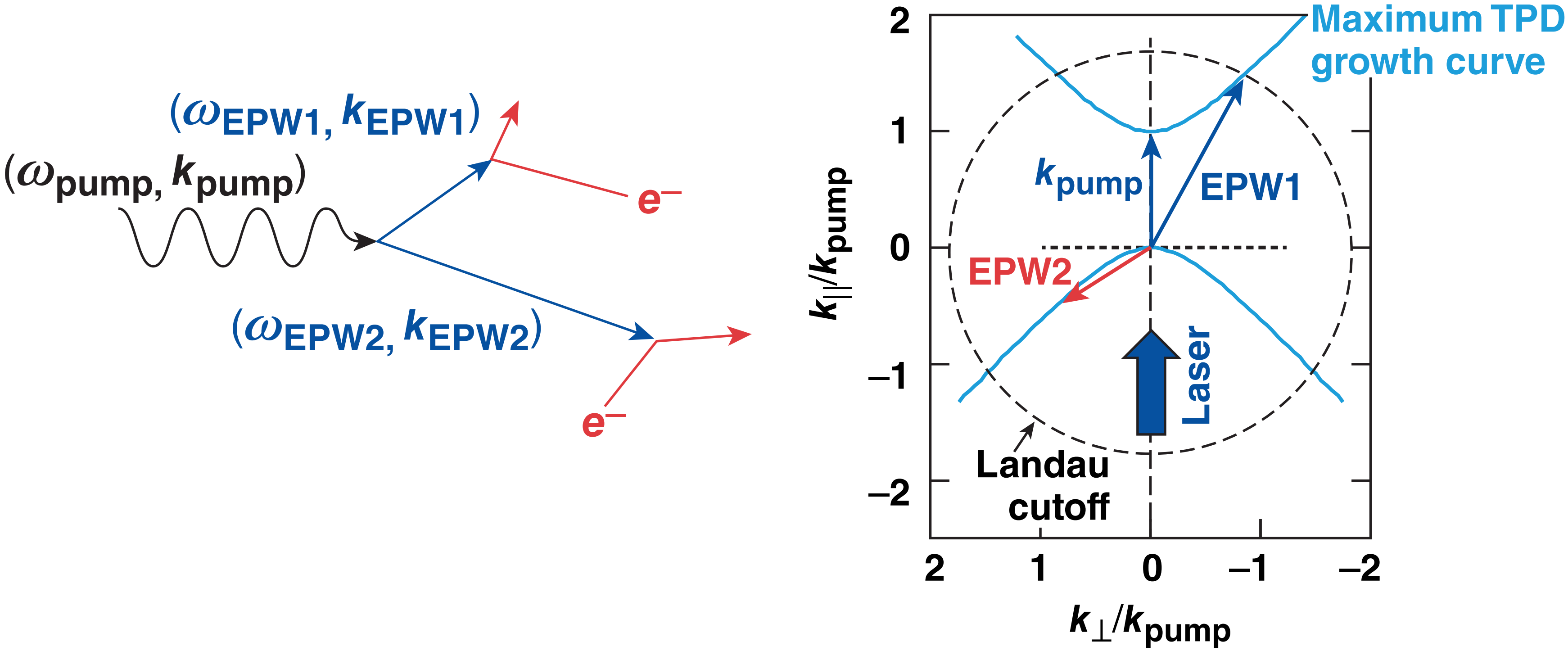
In polar-drive, two-plasmon decay occurs at $n_c/4$, potentially in competition with CBET

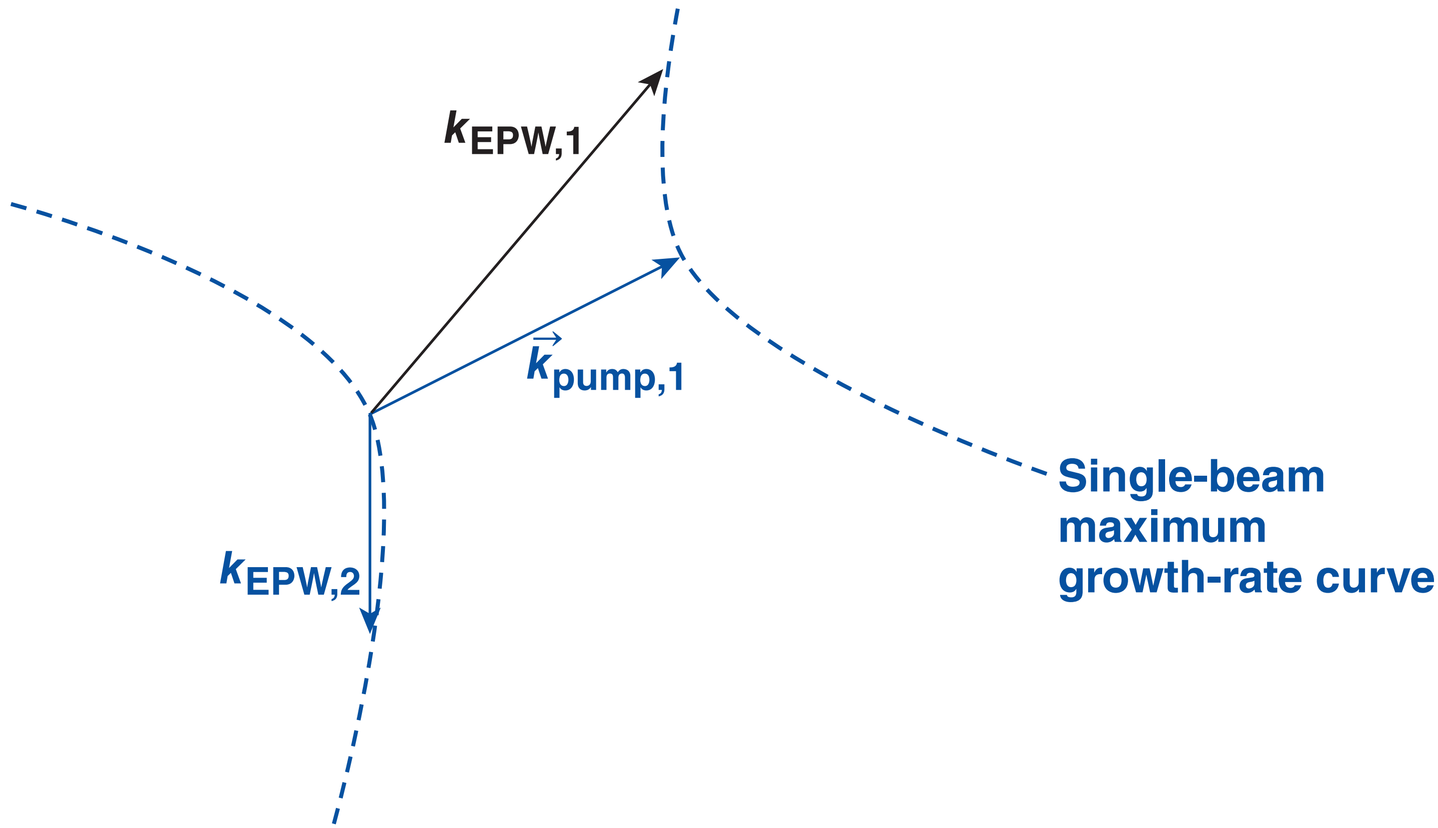
- Laser energy is transferred to plasma waves



- Hot electrons are produced by linear wave–particle interactions (Landau damping) and nonlinear kinetic processes
- Important because of potential loss of drive and preheat (0.1% tolerable)

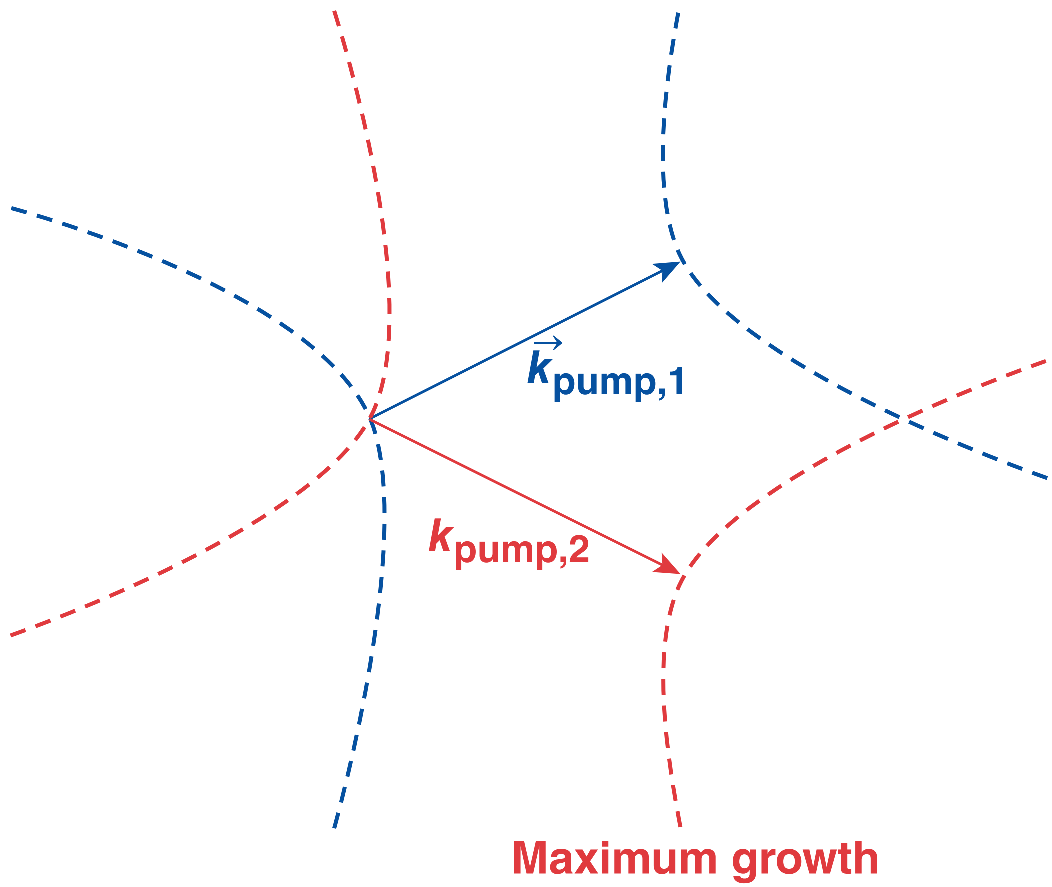
TC10853

Laser beams can cooperate to drive TPD most strongly where the single-beam maximum growth-rate curves overlap



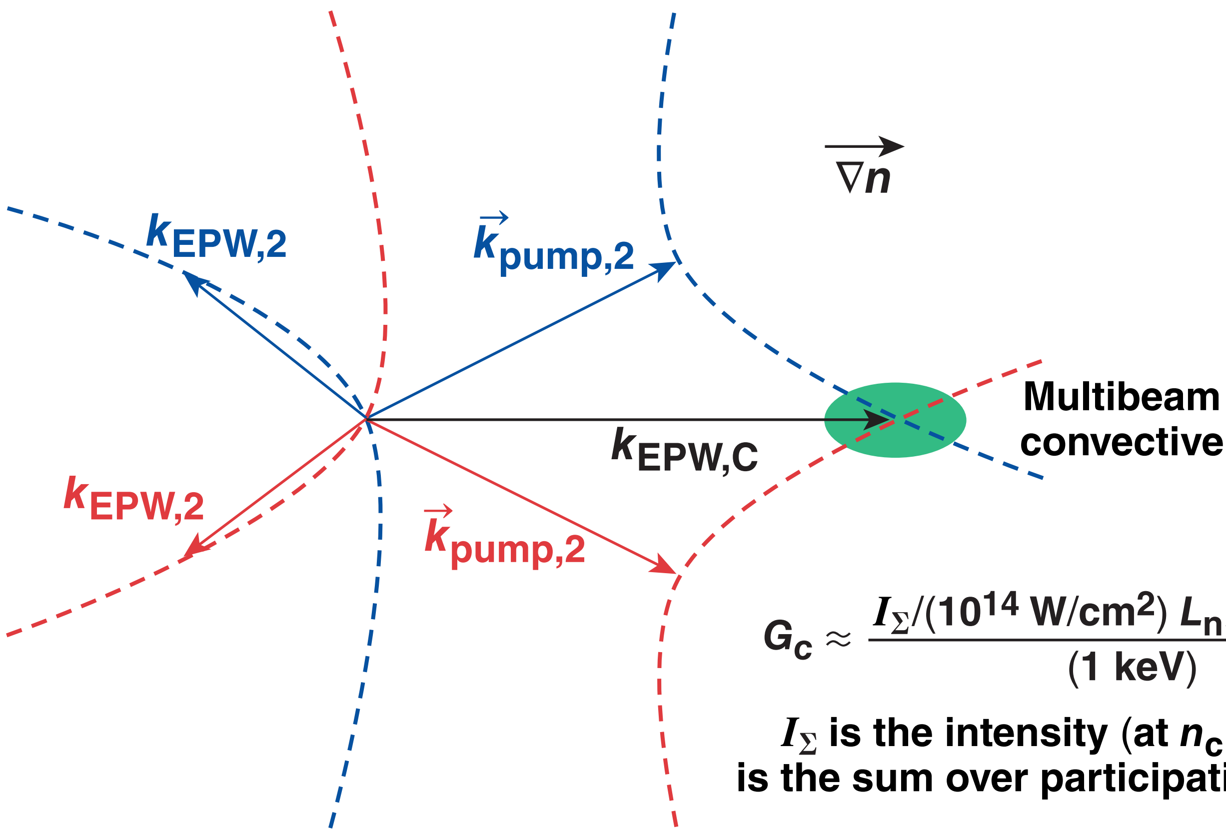
TC10984

Laser beams can cooperate to drive TPD most strongly where the single-beam maximum growth-rate curves overlap



TC10984a

Multibeam convective gains have been calculated for TPD*

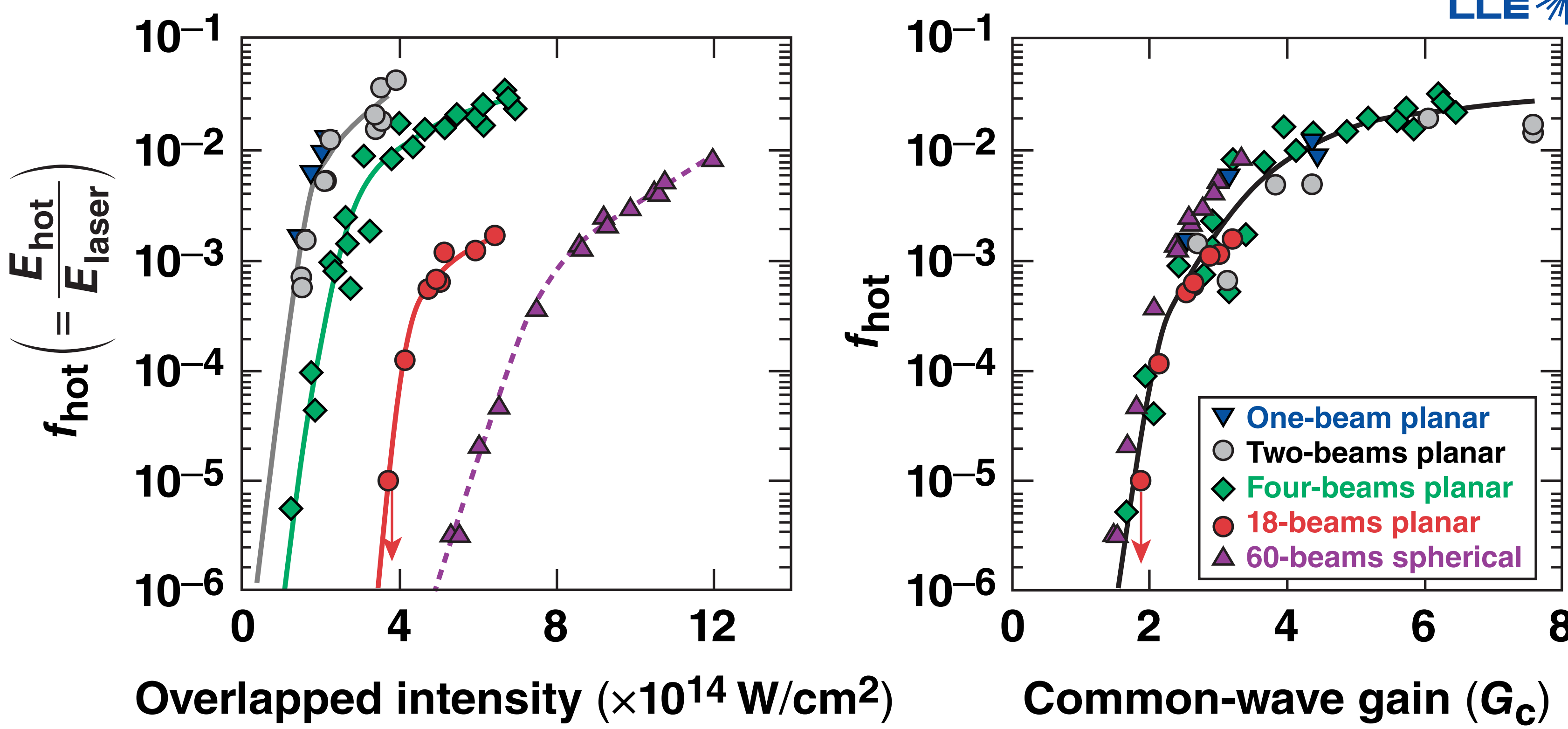


$$G_c \approx \frac{I_\Sigma/(10^{14}\ \mathrm{W/cm^2})\ L_n/(100\ \mu\mathrm{m})}{(1\ \mathrm{keV})}$$

I_Σ is the intensity (at $n_c/4$) that is the sum over participating beams

*D. T. Michel *et al.*, Phys. Plasmas 20, 055703 (2013); D. T. Michel *et al.*, Phys. Rev. Lett. 109, 055007 (2012).

Different OMEGA and OMEGA EP experiments are reconciled when shared convective TPD waves are considered*

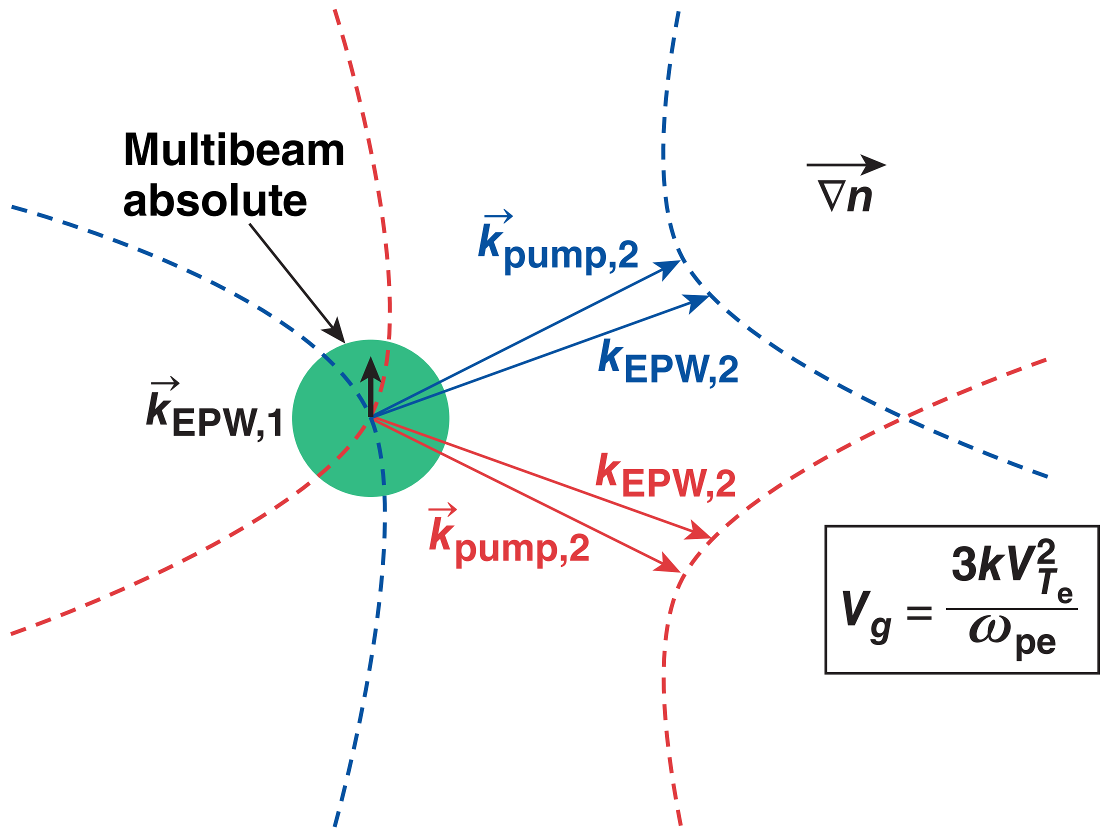


- Saturation is seen below the nominal convective threshold ($G \lesssim 2\pi$)
- This might be related to the presence of absolute instability†

*D. T. Michel *et al.*, Phys. Plasmas 20, 055703 (2013);
D. T. Michel *et al.*, Phys. Rev. Lett. 109, 155007 (2012).
†R. W. Short *et al.*, BO4.00009, this conference.

E21699g

The possibility of an absolute form of multibeam TPD has only recently been identified*

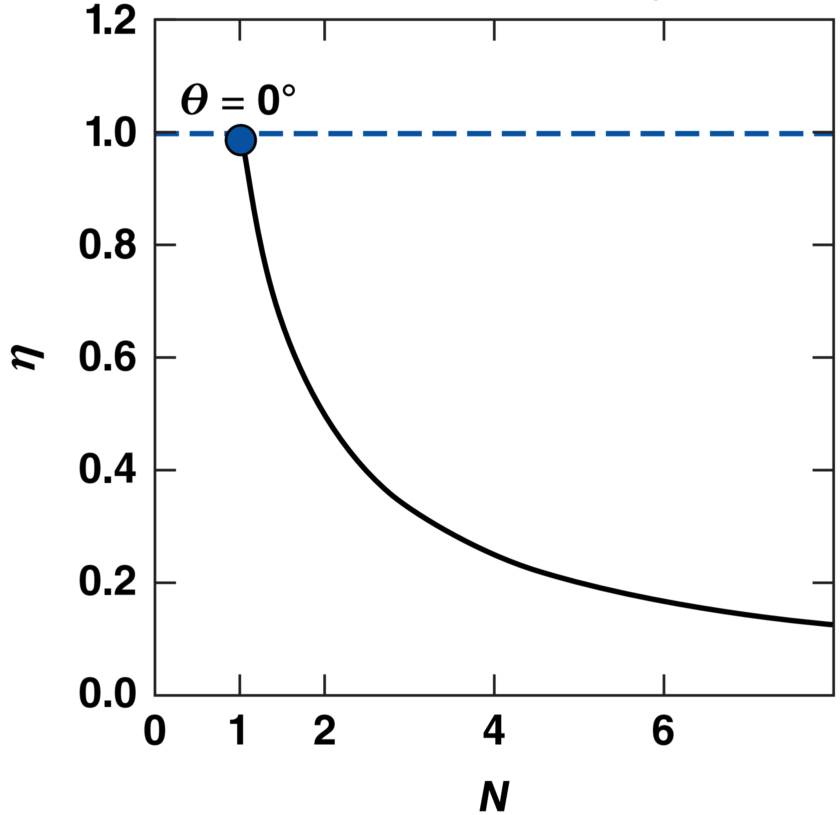


- The determination of an absolute versus convective form of instability in inhomogeneous plasma is a classic problem (solved a long time ago for plane EM waves†)

*R. W. Short *et al.*, BO4.00009, this conference.
†A. Simon *et al.*, Phys. Fluids 26, 3107 (1983).

The absolute thresholds for different numbers of beams and beam configurations have been computed*

$\theta = 27°$, $L_n = 150\ \mu m$, $T_e = 2$ keV



Independent beams:† (normal incidence)

$$\eta \equiv \frac{I_s}{(I_s)_{thr}} = \frac{I_s L_{\mu m}}{230\, T_{e,keV}}$$

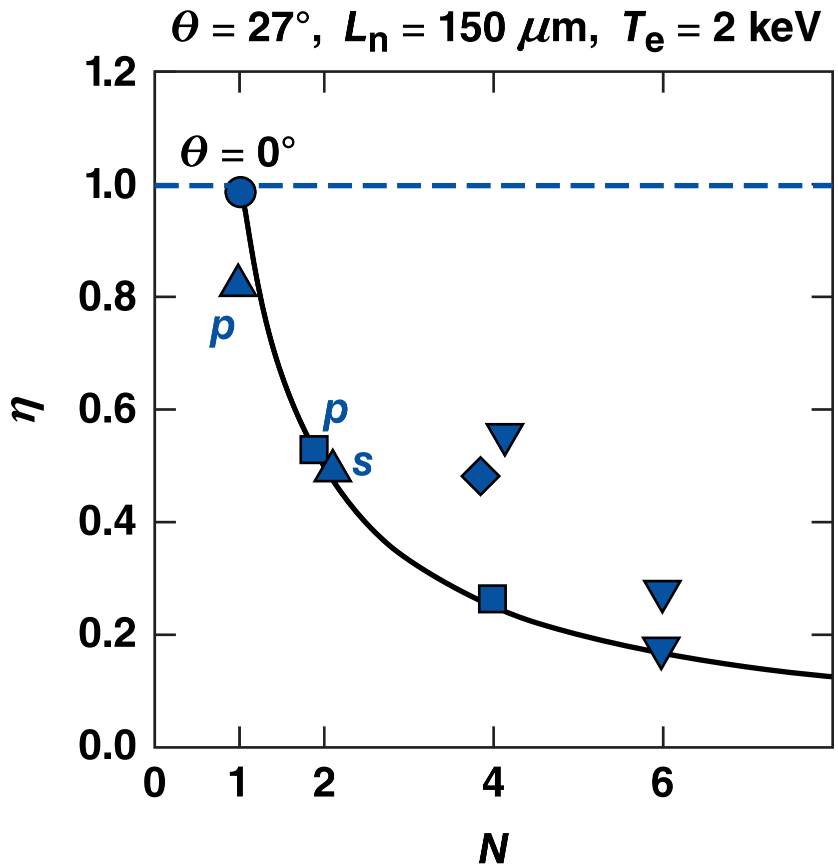
Perfect cooperation:

$$\eta_{MB} = \frac{I_{tot} L_{\mu m}}{230\, T_{e,keV}};\ I_{tot} = N I_s$$

*R. W. Short *et al*., BO4.00009, this conference;
J. Zhang *et al*., presented at the 43rd Anomalous Absorption Conference, Stevenson, WA, 7–12 July 2013.
†A. Simon *et al*., Phys. Fluids 26, 3107 (1983).

TC10985

The absolute thresholds for different numbers of beams and beam configurations have been computed*



Independent beams:† (normal incidence)

$$\eta \equiv \frac{I_s}{(I_s)_{thr}} = \frac{I_s L_{\mu m}}{230\, T_{e,keV}}$$

Perfect cooperation:

$$\eta_{MB} = \frac{I_{tot} L_{\mu m}}{230\, T_{e,keV}};\ I_{tot} = N I_s$$

The absolute threshold is lower than the convective threshold in most cases; the regime of linear convective growth is restricted.

*R. W. Short *et al.*, BO4.00009, this conference;
J. Zhang *et al.*, presented at the 43rd Anomalous Absorption Conference, Stevenson, WA, 7–12 July 2013.
†A. Simon *et al.*, Phys. Fluids 26, 3107 (1983).

Several approaches are being used to predict multibeam TPD

UR LLE

- **Linear convective gain calculations assume a common plasma wave**
- **Particle-in-cell (PIC) calculations are being used to provide insight into the mechanisms of hot-electron production and saturation**
  - ***OSIRIS*,[1] *RPIC*[2]**
  - **3-D calculations are difficult, but the 3-D geometry is essential[3,4]**
- **An extended Zakharov model[5] provides a practical middle ground that addresses the multiscale problem by harmonic decomposition**
  - ***ZAK3D* contains linear instability of multiple beams in three dimensions[4]**
  - **it incorporates the important nonlinearities that lead to saturation**
  - **kinetic effects are included in the quasilinear approximation (*QZAK* computes hot-electron production[6])**

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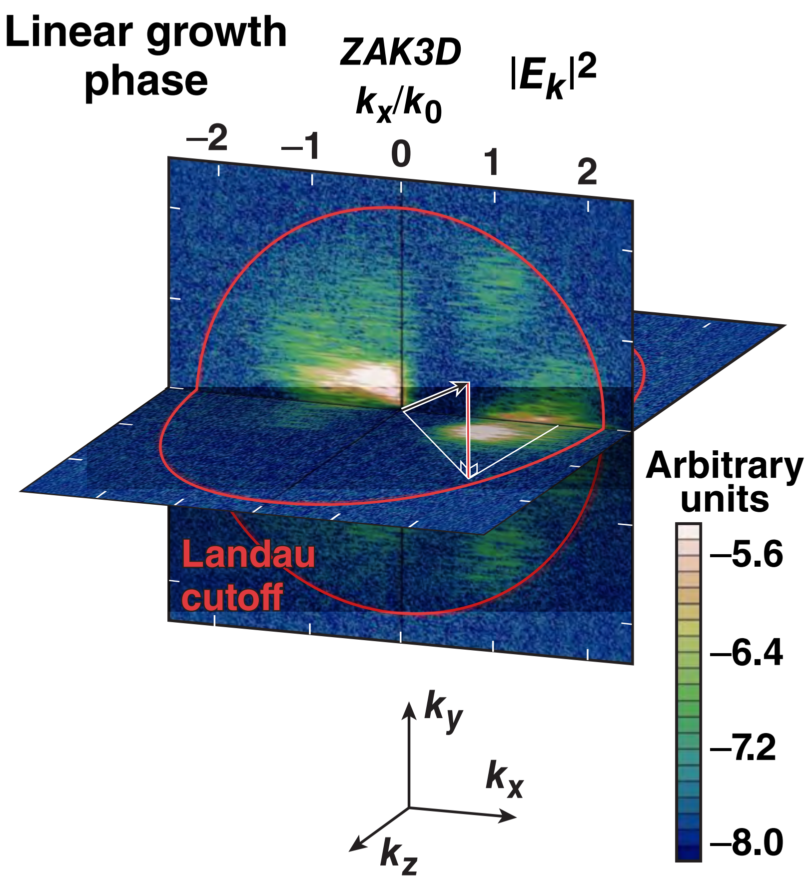
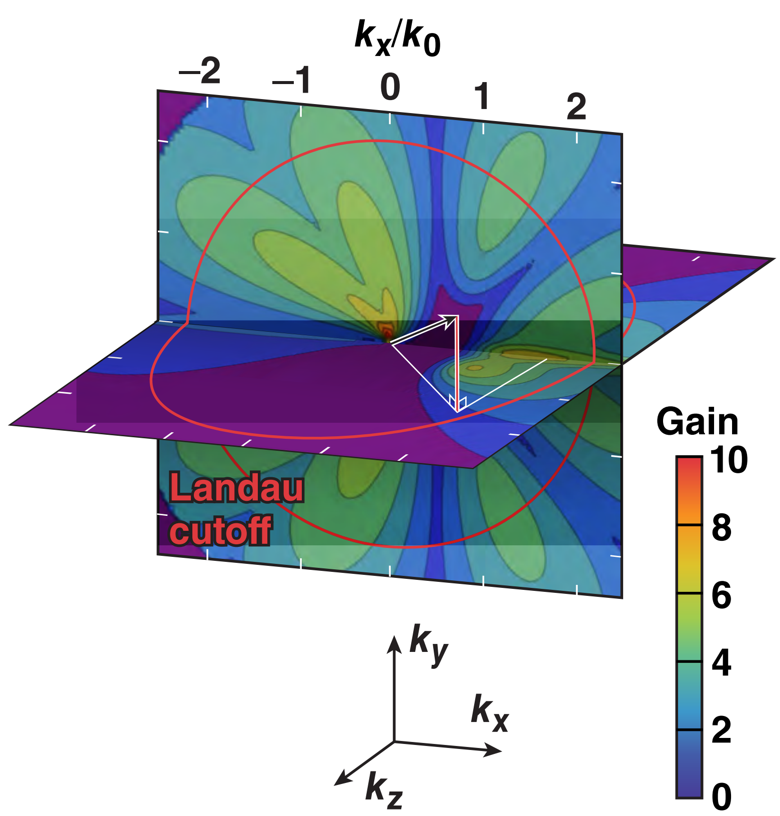
1 R. Yan *et al*., Phys. Rev. Lett. 108, 175002 (2012).
2 H. X. Vu *et al*., Phys. Plasmas 19, 102703 (2012).
3 H. Wen *et al*., BO4.00005, this conference.
4 J. Zhang *et al*., presented at the 54th Annual Meeting of the APS Division of Plasma Physics, Providence, RI, 29 October–2 November 2012.
5 D. F. DuBois, D. A. Russell, and H. A. Rose, Phys. Rev. Lett. 74, 3983 (1995); D. A. Russell *et al*., Phys. Rev. Lett. 86, 428 (2001).
6 J. F. Myatt *et al*., Phys. Plasmas 20, 052705 (2013).

Comparison between *ZAK3D* and convective gain for four beams with parallel polarization shows consistency for large wave numbers



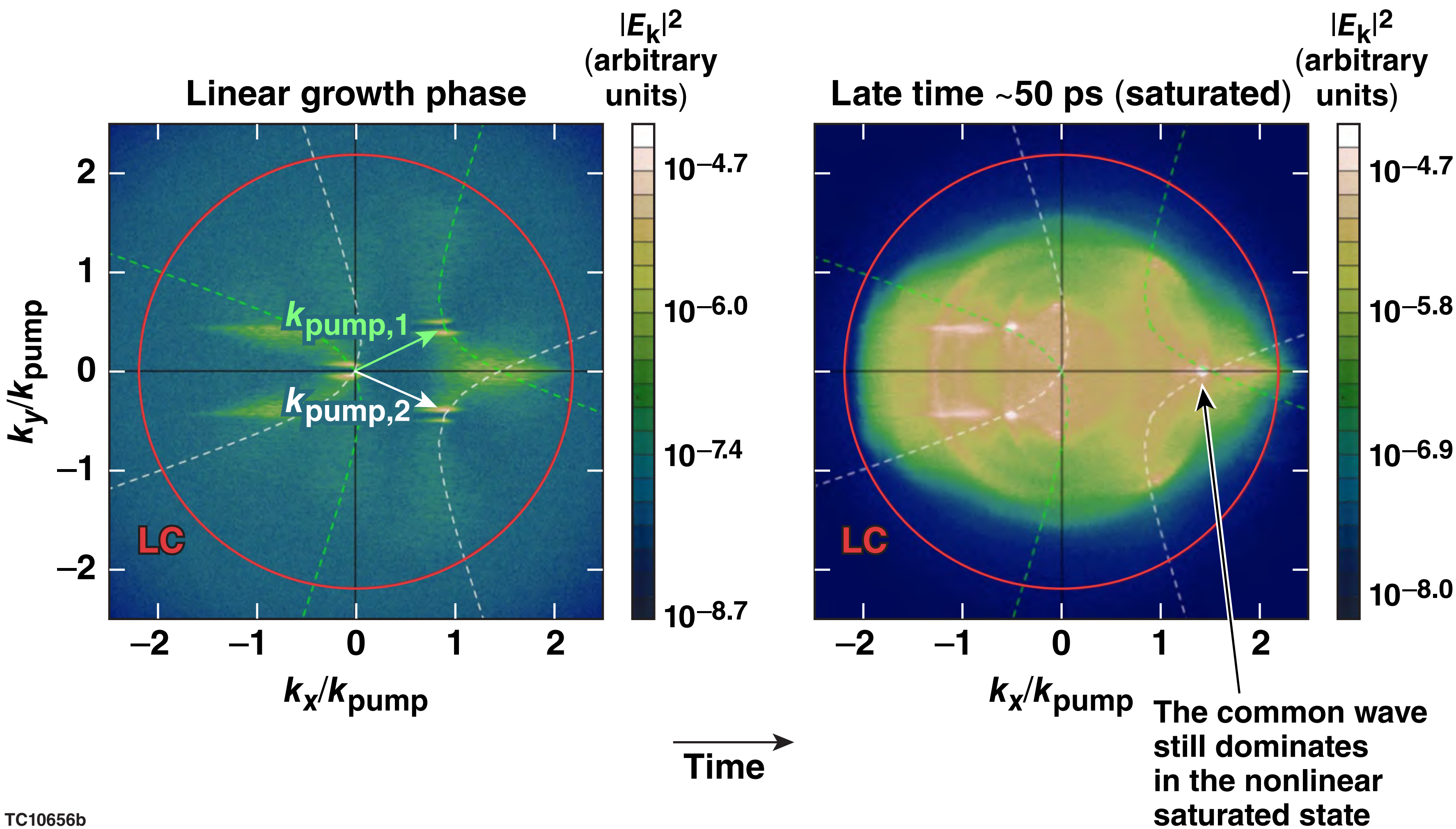


The presence of absolute instability requires a treatment of nonlinear saturation.

TC10854

TPD is always a nonlinear problem because of the small domain of linear convective growth, even when driven by multiple beams

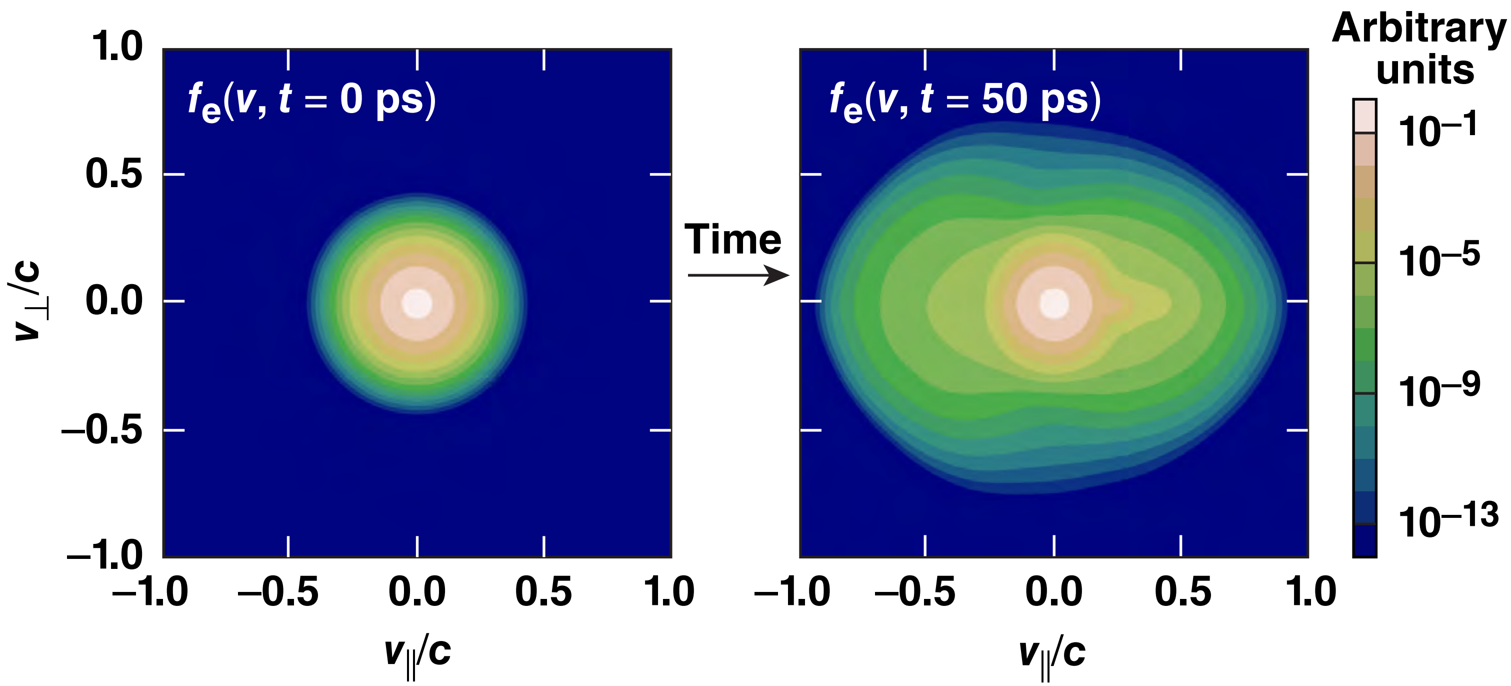
- Two beams, *p*-polarized, $I_{14} = 1.2$, $L_n = 660\ \mu m$, and $\theta = 27°$



TC10656b

Quasilinear evolution of the hot-electron distribution function appears to be valid because of the broad EPW spectrum

- **Acceleration of electrons is a stochastic process modeled by the diffusion equation** $\frac{\partial \langle f_e \rangle}{\partial t} + \frac{\partial}{\partial \vec{v}} \cdot \left(D_{QL}(\vec{v},t) \cdot \frac{\partial \langle f_e \rangle}{\partial \vec{v}} \right) = \sigma(\langle f_e \rangle - f_M)$
- ***QZAK*** **(an extension of** ***ZAK3D*****) calculations predict a broad divergence angle for hot electrons***

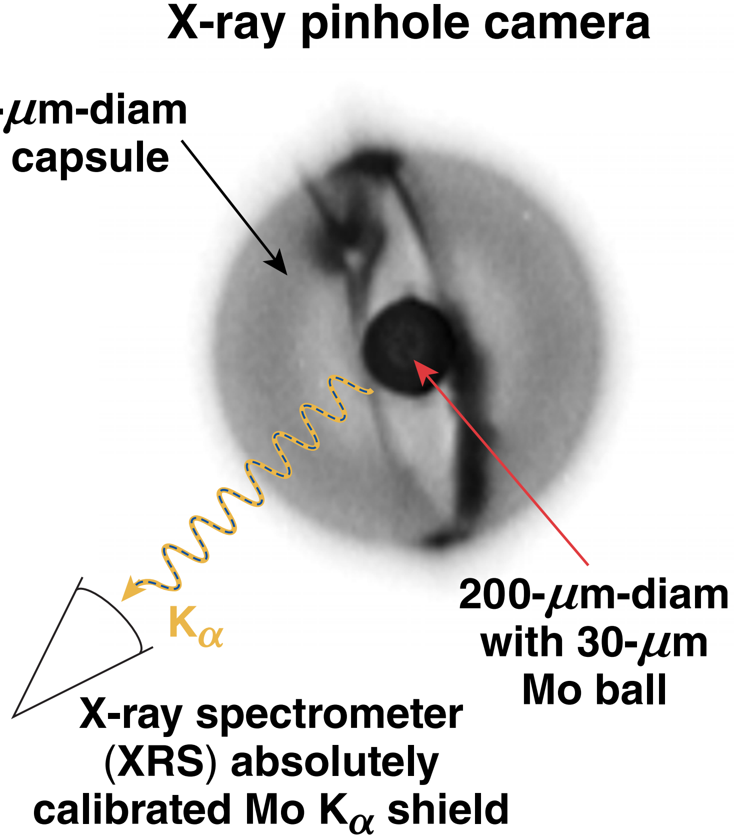


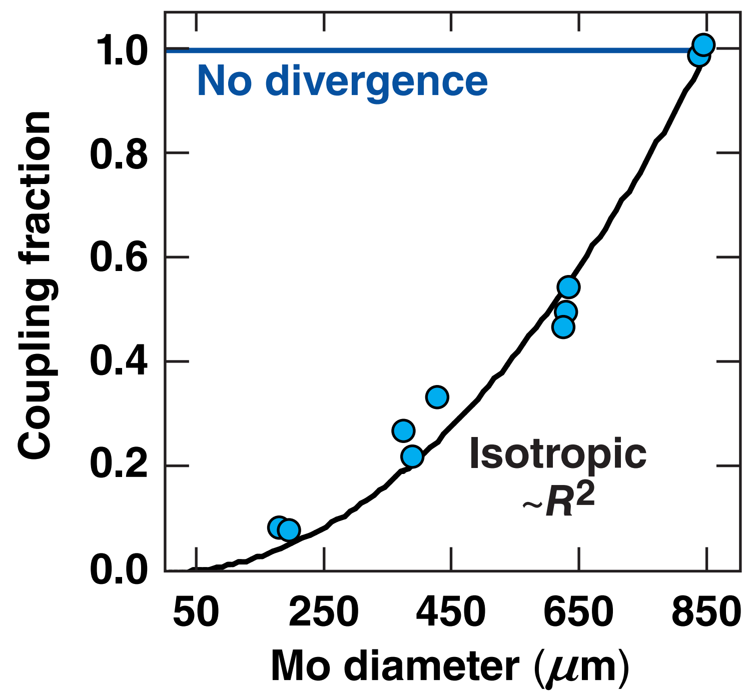
*J. F. Myatt *et al*., Phys. Plasmas 20, 052705 (2013).

TC9801c

Experimentally, TPD hot electrons are inferred to be emitted isotropically

- This can reduce the fraction of TPD hot electrons that contribute to preheat





E21184g

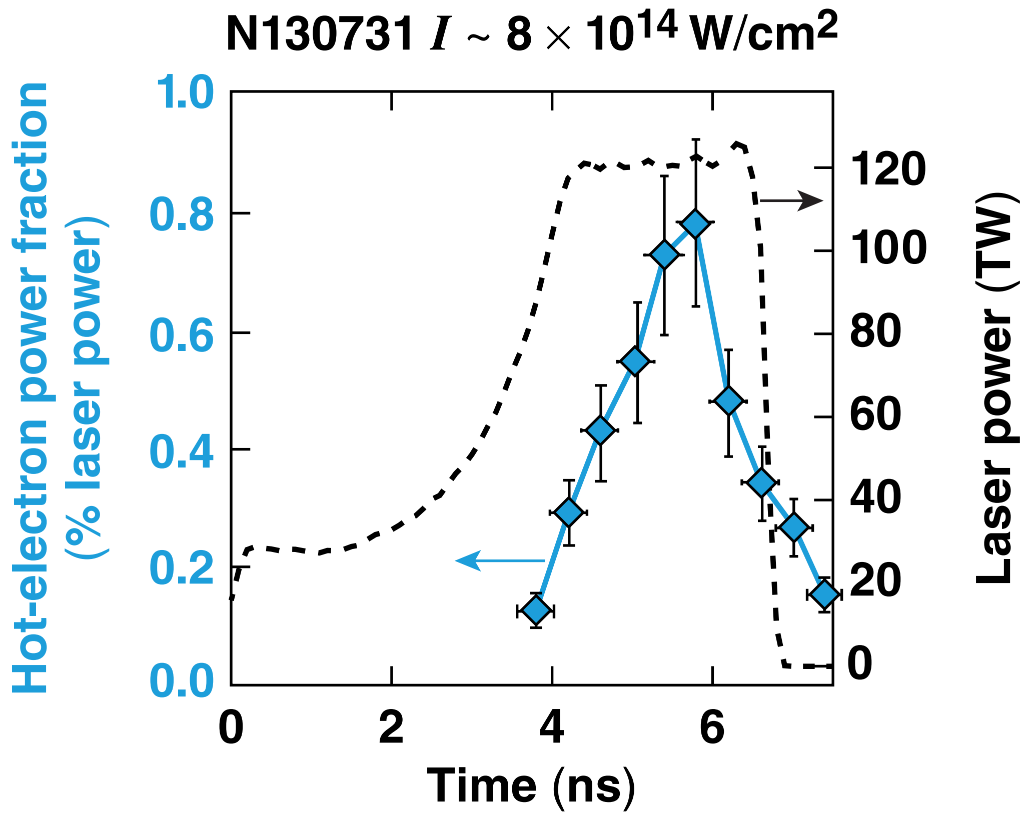
B. Yaakobi *et al*., Phys. Plasmas 20, 092706 (2013).

The extrapolation of experimental OMEGA/OMEGA EP multibeam TPD results to the NIF is not straightforward—experiments are necessary

- The linear dependence of the gain or scale length comes from linear theory, but TPD is always nonlinear because of absolute instability
- Experimentally, there are significant differences between OMEGA/OMEGA EP and the NIF (besides density scale length)
  - NIF has 2× higher electron temperature (λ_D larger by $\sqrt{2}$)
  - PD NIF has lower beam symmetry than OMEGA
  - EPW and IAW collisional effects differ between OMEGA and the NIF
- LLE is investigating a model that accounts for these effects (*ZAK3D*)*
- Ignition-scale experiments are being performed on the NIF

*J. Zhang *et al.*, BO4.00006, this conference.

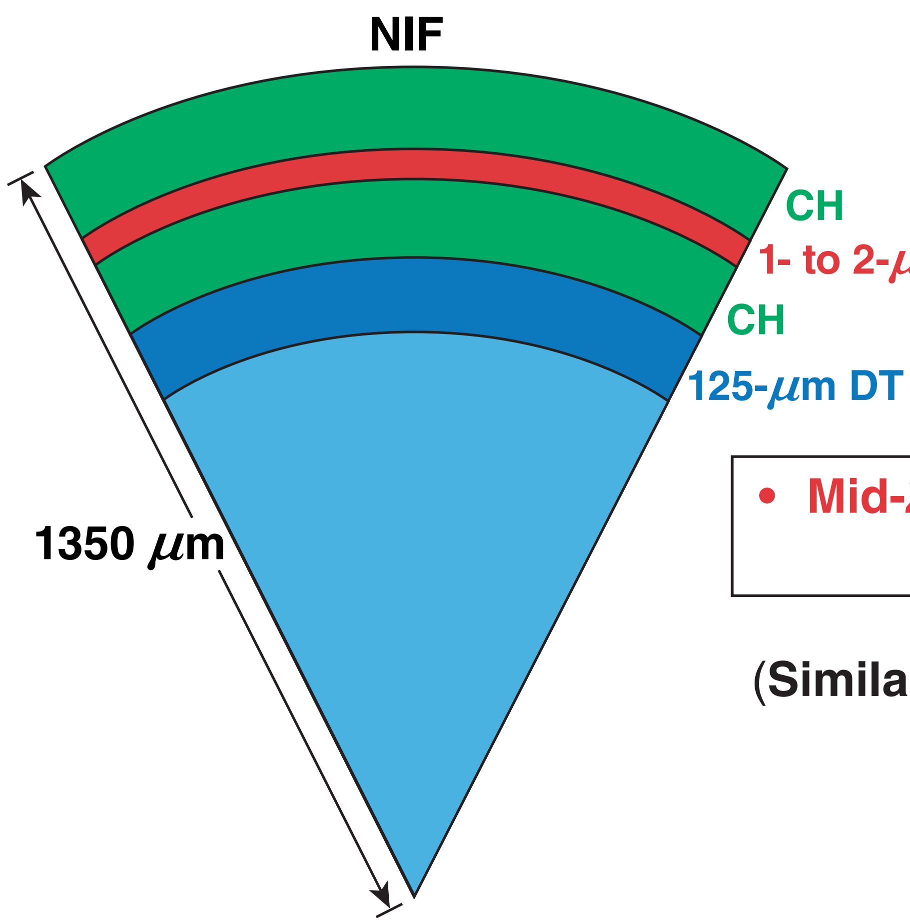
The first measurements of >50-keV electrons for PD on the NIF indicate a tolerable level of preheat



- The energy of electrons above 50 keV is 1600 J or ~0.3% of the laser energy (T_{hot} ~ 45 keV)
- Ignition designs can tolerate up to ~0.4% of laser energy in hot electrons, corresponding to 0.1% preheat because of divergence

E22373c

Multilayer targets promise to reduce the deleterious effect of multibeam LPI



- Mid-Z layer: Reduces LPI at quarter-critical surface

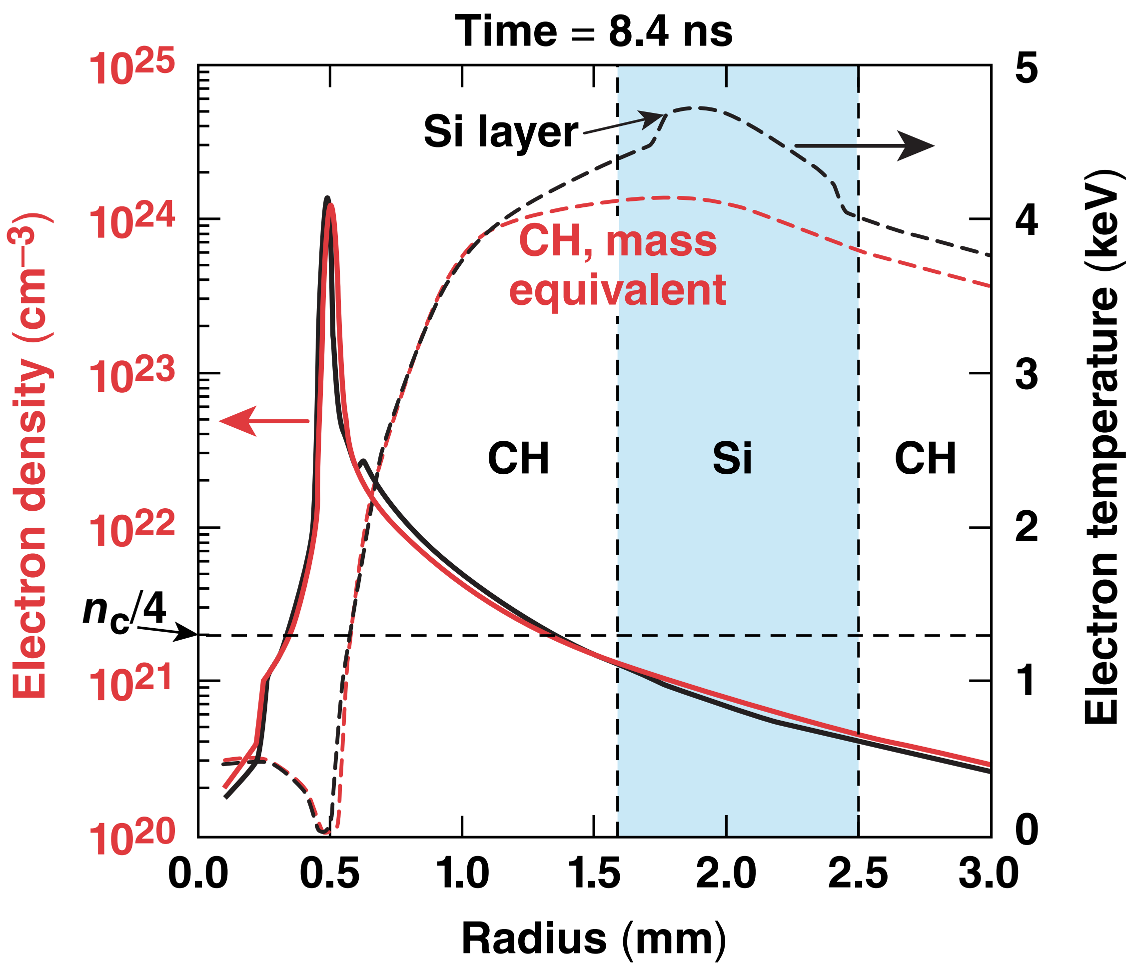
(Similar to x-ray drive higher-Z fill gas)

TC10544d

The higher predicted electron temperature in the corona of the multilayer design has a mitigating effect*

UR LLE

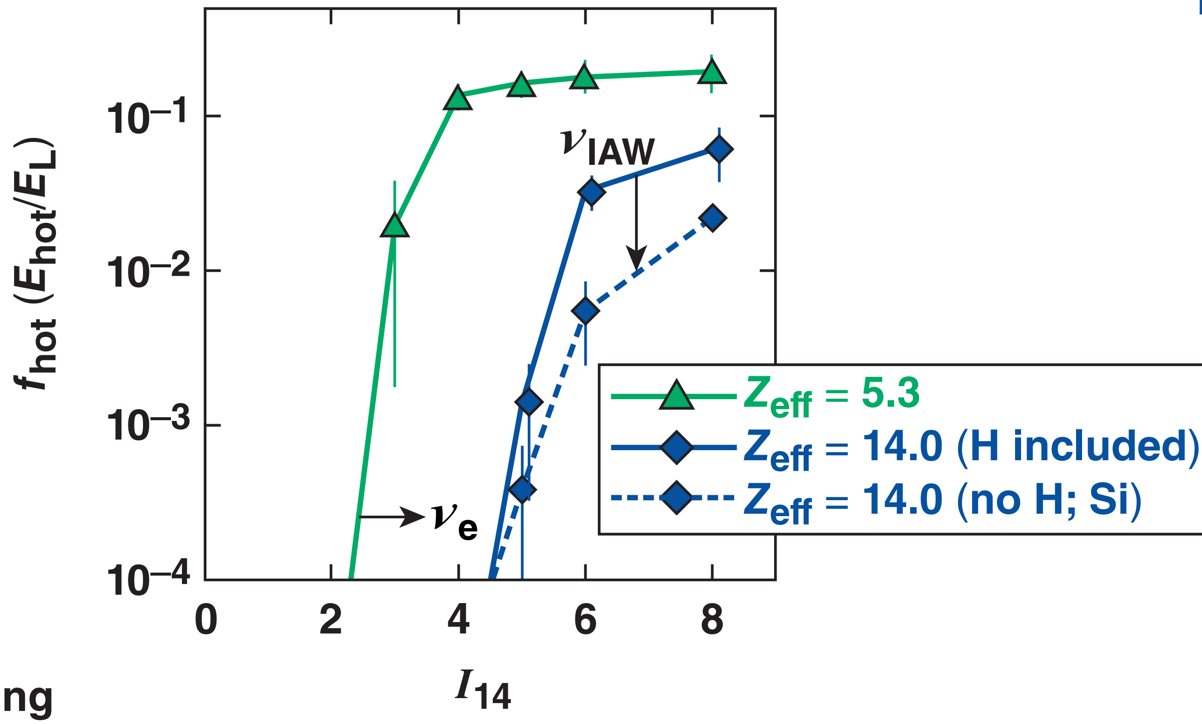
- Increased plasma collisionality also plays a role†



*V. N. Goncharov, GI3.00001, this conference (invited).
†M. Lafon *et al.*, UO4.00010, this conference;

TC10545b

Nonlinear *ZAK3D*/*QZAK* simulations suggest there may be extra mitigating effects of mid-Z layers



- Ion-wave damping
  - saturated EPW intensity and hot-electron production depends on ν_{IAW}* (a nonlinear effect, similar to that observed for SRS)**
- Collisional damping
  - for NIF-scale lengths, the LW collisional damping can become important* (increases linear threshold, linear and nonlinear*,† LPI effect)

V. A. Smalyuk *et al*., Phys. Rev. Lett. 104, 165002 (2010).
* J. F. Myatt *et al*., Phys. Plasmas 20, 052705 (2013); M. Lafon *et al*., UO4.00010, this conference.
** J. C. Fernández *et al*., Phys. Rev. Lett. 77, 2702 (1996); Kirkwood *et al*., Phys. Rev. Lett. 77, 2706 (1996).
† R. Yan *et al*., Phys. Rev. Lett. 108, 175002 (2012).

Summary/Conclusions

The overlapping of many laser beams in a plasma leads to cooperative laser–plasma instabilities (LPI's)

- Significant advances have been made toward understanding nonlinear propagation and absorption of laser light in the face of multibeam parametric instabilities
- Cross-beam energy transfer (CBET) has been identified in both direct- and x-ray-drive inertial confinement fusion (ICF)
- Multibeam two-plasmon decay is seen to be important in direct drive, while multibeam stimulated Raman scattering is implicated in x-ray drive