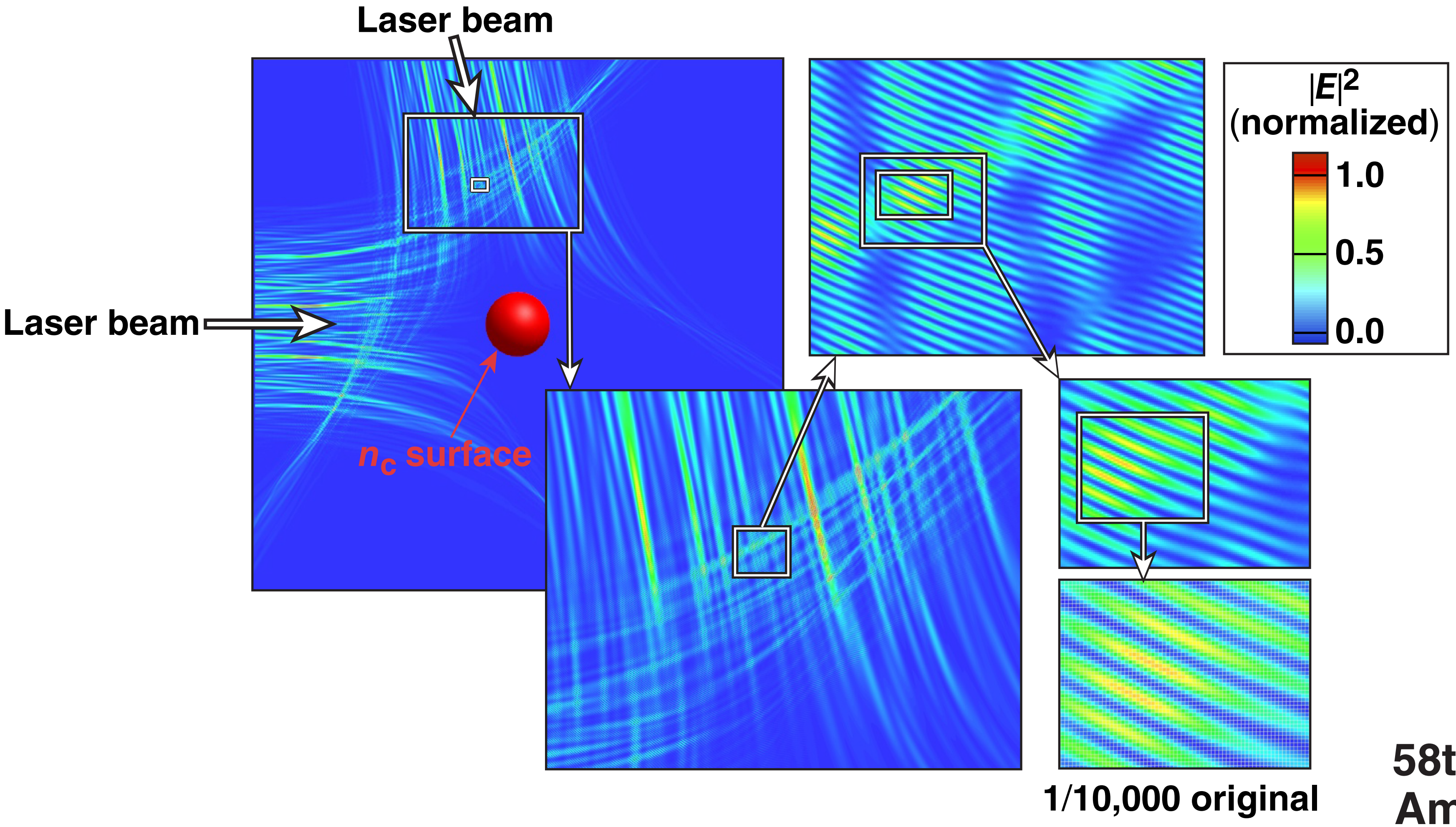
A Wave-Based Model for Cross-Beam Energy Transfer in Direct-Drive Inertial Confinement Fusion Implosions



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58th Annual Meeting of the American Physical Society Division of Plasma Physics
San Jose, CA
31 October–4 November 2016

Summary

A 3-D wave-based model has been developed to understand the physics of laser coupling in an inhomogeneous plasma

- The absorption of laser light in inertial confinement fusion experiments is significantly modified by cross-beam energy transfer (CBET)
- Detailed calculations of CBET are obtained against which existing models (implemented in radiation hydrodynamics codes) are compared
- The comparisons generally highlight the accuracy of ray-based models
- Discrepancies are found that are related to beam speckle and beam caustics
- The goal is to incorporate these findings into radiation hydrodynamics simulations by suitably adjusting the existing models

Future study will address CBET mitigation.

Collaborators

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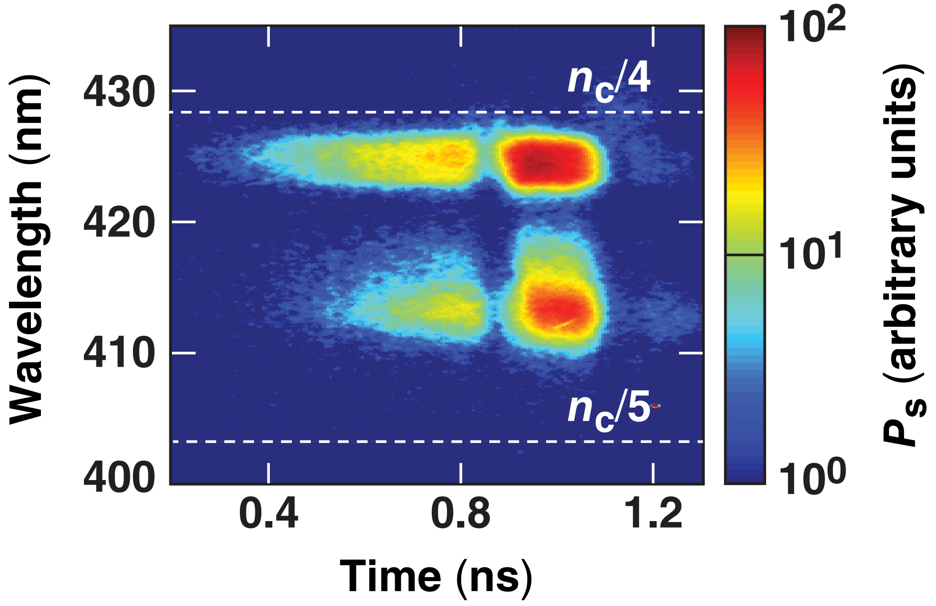
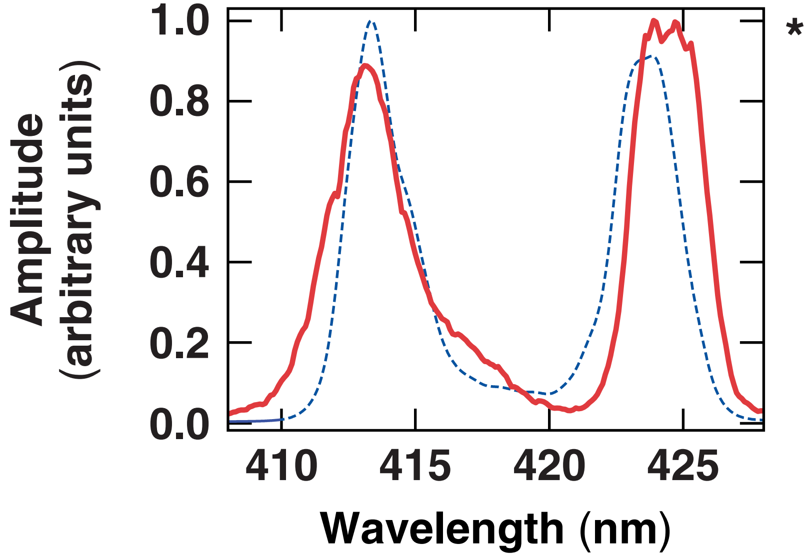
LLE code development for laser–plasma interaction physics is centered around a common environment

- *LPSE* (laser-plasma simulation environment)
  - community code [used by Naval Research Laboratory (NRL) and Lawrence Livermore National Laboratory (LLNL)]
  - common user interface, input/output (I/O), visualization tools
  - 3-D multiple-beam two-plasmon decay (TPD)
  - 3-D cross-beam energy transfer (CBET)
  - physics models can be selected according to the problem
  - extensible





*R. K. Follett *et al.*, Phys. Rev. E 91, 031104(R) (2015).

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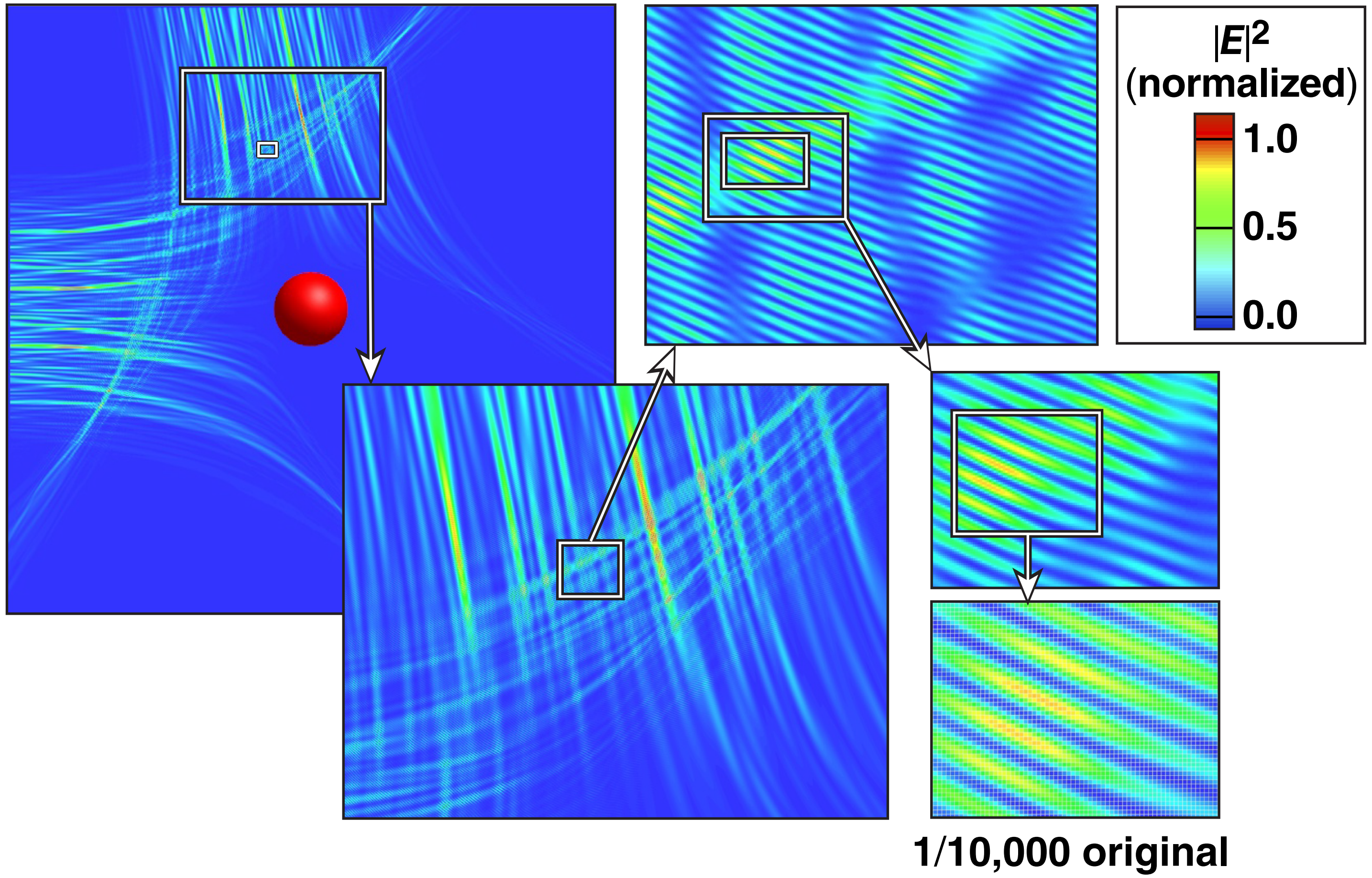


The CBET package required several key technical challenges to be solved

- Solving the time-enveloped electromagnetic (EM) vector wave equation in 3-D is expensive in plasma of useful size
- An efficient algorithm was implemented [Yee-like from finite-difference time-domain (FDTD) EM]*
- The boundary conditions are complicated (and in 3-D)
  - arbitrary incident fields
  - all scattered light must exit cleanly (no reflections)
- The boundary conditions work very well using
  - total field/scattered-field formulation**
  - perfectly matched layer (PML)†
- The solver is practical to run in 3-D
  - 1000 Intel cores are okay, could scale to 10,000 s (testing at Oak Ridge)

*P. B. Visscher, Computers in Phys. 5, 596 (1991).
**D. E. Merewether, R. Fisher, and F. W. Smith, IEEE Trans. Nucl. Sci. 27, 1829 (1980).
†A. Nissen and G. Kreiss, Commun. Comput. Phys. 9, 147 (2011).

TC13068

CBET involves the exchange of energy between laser beams mediated by ion waves; a problem occuring across inertial confinement fusion (ICF) platforms*

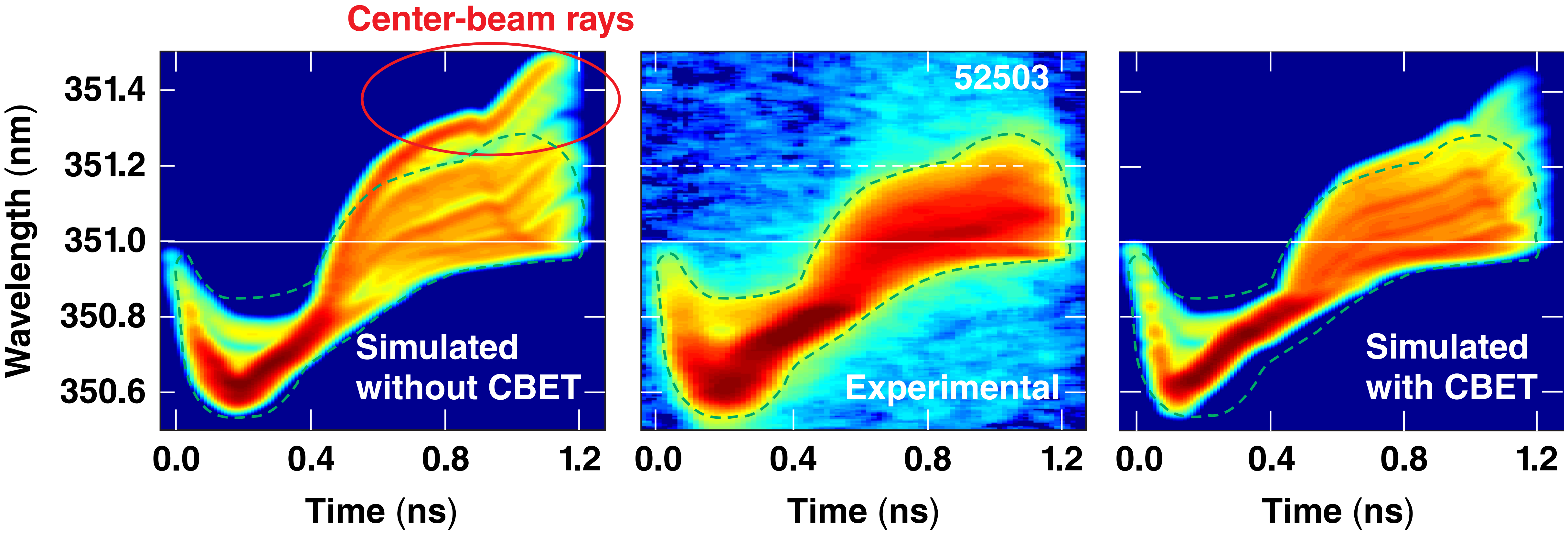
- Indirect drive
  - symmetry adjustment between the inner and outer cones
  - refraction not important in CBET region
  - forward-scattering geometry; high single-beam intensities
- Direct drive
  - has a dramatic impact on absorption in OMEGA designs
  - observed in NIF implosions (polar-drive configuration)
  - refraction essential; EM wave cutoff at the critical density in the CBET region; moderate single-beam intensities
- Ubiquitous wherever multiple coherent laser beams cross in plasma
  - e.g., magnetized liner inertial fusion (MagLIF)

*APS-DPP presentations on CBET: M. Hohenberger *et al.*, UO9.00009; R. K. Follett *et al.*, UO9.00010; D. H. Edgell *et al.*, UO9.00011; P. B. Radha *et al.*, NO5.00005; J. A. Marozas *et al.*, NO5.00009; R. Trines *et al.*, UO9.00012; T. Chapman *et al.*, UO9.00013; J. Bates *et al.*, NP10.00081; J. Weaver *et al.*, NP10.00082, this conference.

Cross-beam energy transfer was discovered several years ago on OMEGA because of inconsistencies in observations of scattered light

UR LLE

- Radiation–hydrodynamics simulation assuming collisional absorption of laser-light predicted features that were not observed*

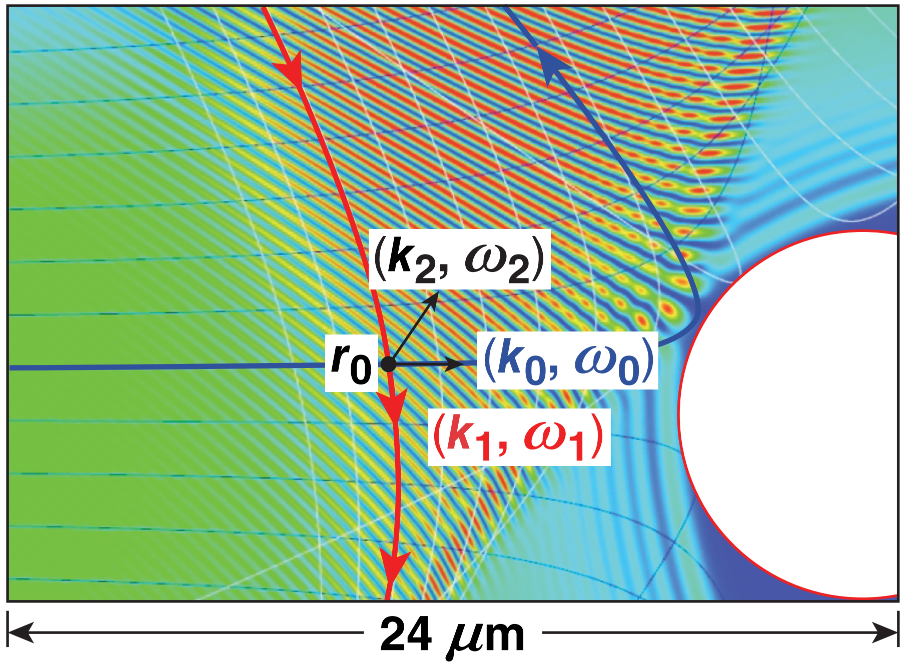


*D. H. Edgell *et al*., Bull. Am. Phys. Soc. 52, 195 (2007).

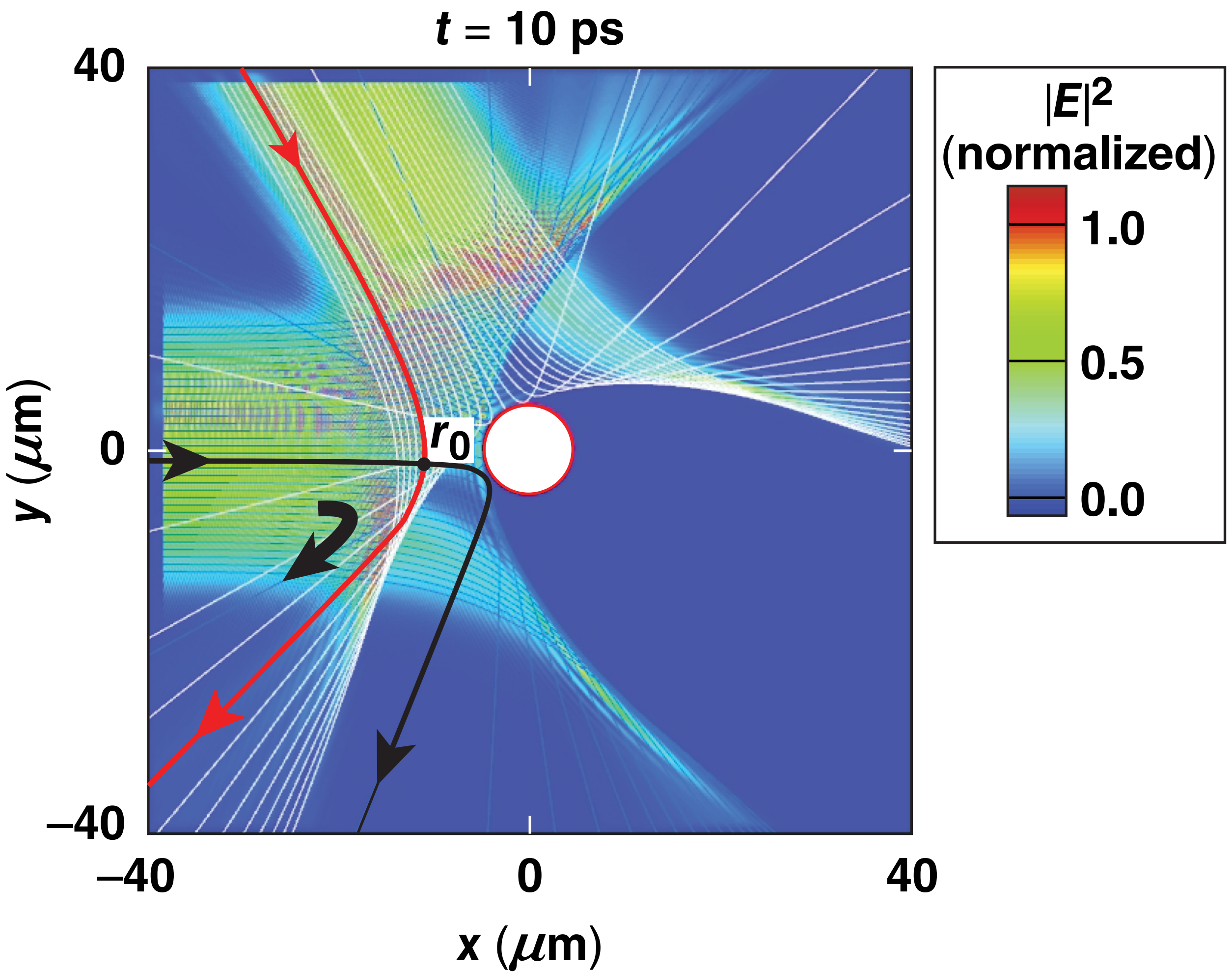
E19972g

Reflected/refracted light provides a strong seed for stimulated Brillouin scattering (SBS) backscatter; large gains are not required for a significant nonlinear reflectivity

- *LPSE* simulations illustrate the effect



$$\omega_0 = \omega_1 + \omega_2$$
$$\vec{k}_{pump} = \vec{k}_1 + \vec{k}_2$$



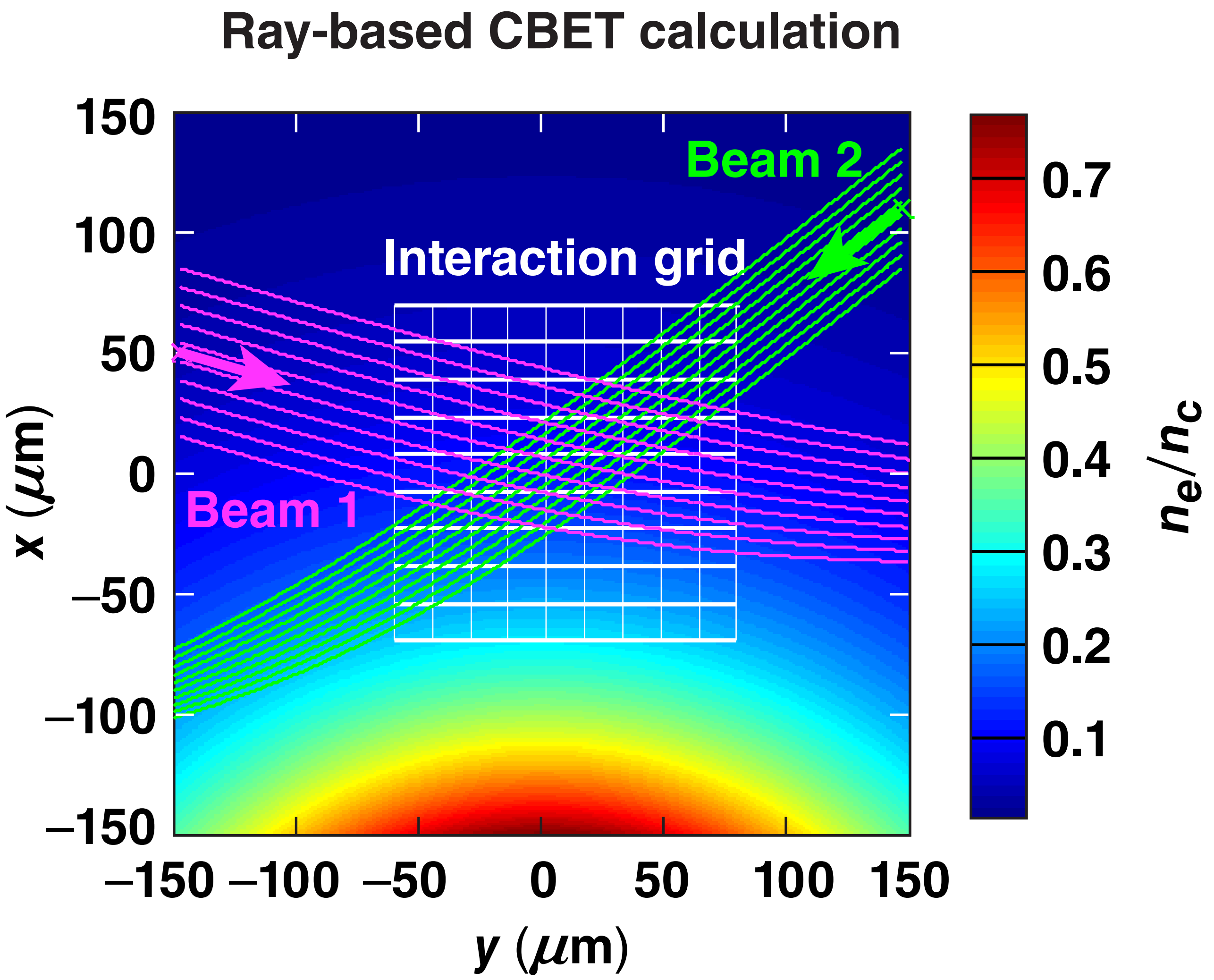
Energy is transferred from the beam with highest frequency to the lower-frequency beam in the frame where the plasma is at rest.

TC12773a

The impact of CBET on direct-drive designs is currently accounted for using ray-based (geometric optics) models

- Such models are attractive because laser-energy deposition is already computed using ray tracing
  - with CBET, energy is exchanged "between rays" by computing pairwise interactions [Igumenshchev (*LILAC*); Marozas (*DRACO*)]
- Similar approaches have been used in laser indirect drive
  - D. J. Y. Marion *et al.*, Phys. Plasmas 23, 052705 (2016).
  - P. Michel *et al.*, Phys. Plasmas 20, 056308 (2013).
    P. Michel *et al.*, Phys. Rev. Lett. 113, 205001 (2014).
- Attempts have even been made to go beyond geometric optics using thick ray modeling that transports electric-field amplitude along rays
  - A. Colaïtis *et al.*, Phys. Rev. E 91, 013102 (2015); *ibid.* 89, 033101 (2014).

Ray-based CBET models calculate CBET by considering pairwise interactions between rays* on a fixed grid



$$\frac{dI_i}{d\ell} = -\sum_j I_i \times L_{ij}^{-1}$$

$$L_{ij}^{-1} = 5.88 \times 10^{-2} \frac{I_j \lambda_{0,\mu m}}{T_e\left(1+3T_i/ZT_e\right)} \frac{n_e}{n_c} \frac{\omega_s}{\nu_i} P(\eta_{ij})$$

$$P(\eta) = \frac{\nu_i^2 \eta}{\left(\eta^2-1\right)^2 + \nu_i^2 \eta^2} \qquad \eta_{ij} = \frac{\omega_j - \omega_i - \left(k_j - k_i\right)\cdot u}{\omega_s}$$

*C. J. Randall, J. R. Albritton, and J. J. Thomson, Phys. Fluids 24, 1474 (1981).

TC13071

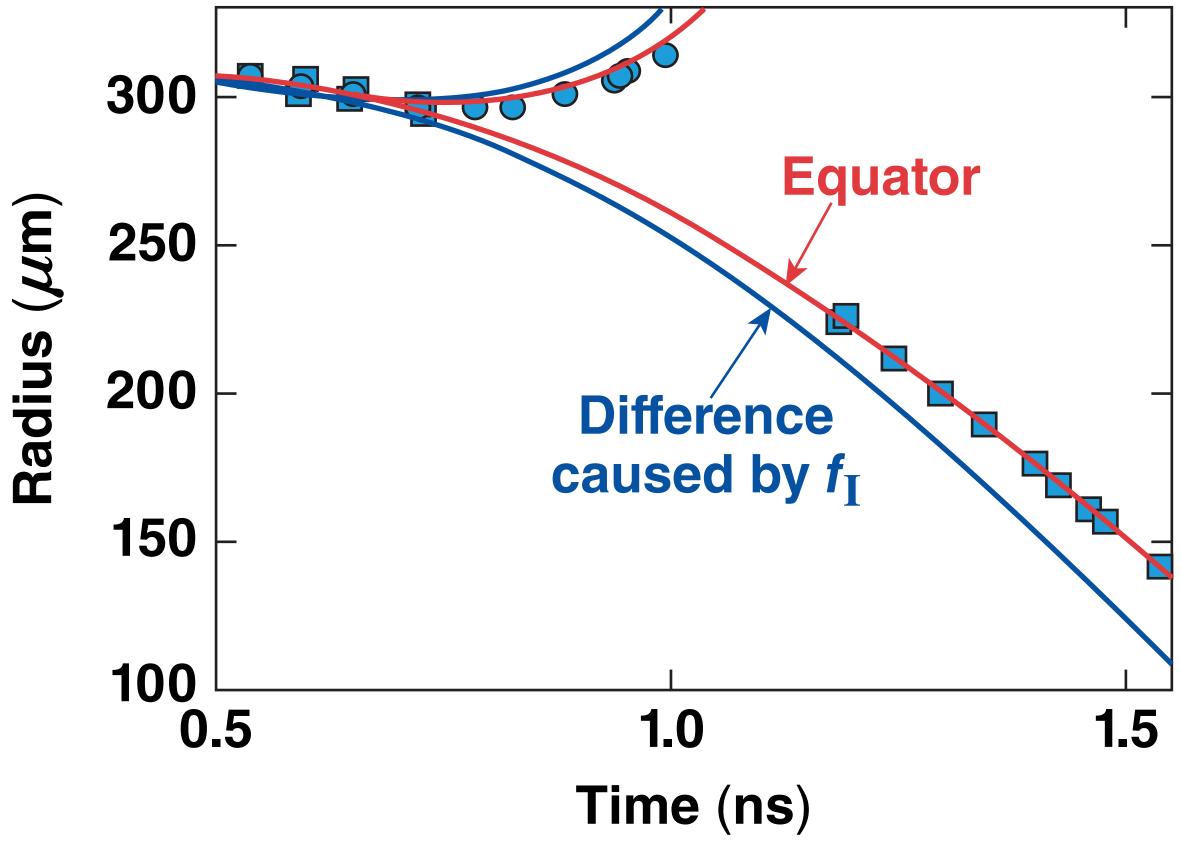
Several approximations are required to make the ray-based CBET model practical to implement in radiation–hydrodynamics codes

- Linearity of the plasma response to the ponderomotive force [i.e., small ion-acoustic wave (IAW) amplitudes ($\delta n/n \ll 1$)]
  - strong damping approximation
- Local plane-wave approximation for each crossing beam
  - i.e., all wave fields are assumed to be "eikonal," having a single well-defined wave vector and frequency
- Steady-state convective gain for the three-wave process is assumed
- Coupling constant is polarization averaged; otherwise, polarization must be tracked*

*D. T. Turnbull *et al.*, CO5.00013, and D. T. Michel *et al.*, TO5.00006, this conference.

"Multipliers" are required to obtain the best quantitative agreement between CBET models and experiment

- It is not currently known if such multipliers are required because of inaccuracies in the ray-based CBET model or caused by other effects



Full-wave solutions of CBET are required to assess the accuracy of ray-based models.

TC13073

*A. K. Davis *et al.*, Phys. Plasmas 23, 056306 (2016).

In *LPSE*, the time-enveloped Maxwell's equations are solved numerically in 3-D coupled to a linearized plasma response

- Maxwell's equations (for time envelope) $\tilde{E} = \Re\left[E(x,t)\exp(-i\omega_0 t)\right]$

$$\frac{2i\omega_0}{c^2}\frac{\partial}{\partial t}E + \nabla^2 E - \nabla(\nabla \cdot E) + \frac{\omega_0^2}{c^2}\epsilon(\omega_0;x,t)E = 0$$

- Plasma response

$$[\partial_t + U_0(x)\cdot\nabla]\left(\frac{\delta n}{n_0}\right) = -w$$

$$[\partial_t + U_0(x)\cdot\nabla]w = -\nabla^2\left[c_s^2\left(\frac{\delta n}{n_0}\right) + \alpha|E|^2\right]$$

$$\epsilon(\omega_0;x,t) = 1 - \frac{\omega_{pe}^2(x,t)}{\omega_0(\omega_0 + i\nu_{ei})}$$

$$\omega_{pe}^2 = \frac{4\pi e^2 n_e(x,t)}{m_e}$$

$$n_e \equiv n_0(x) + \delta n(x,t)$$

$$w \equiv \nabla \cdot \delta v$$

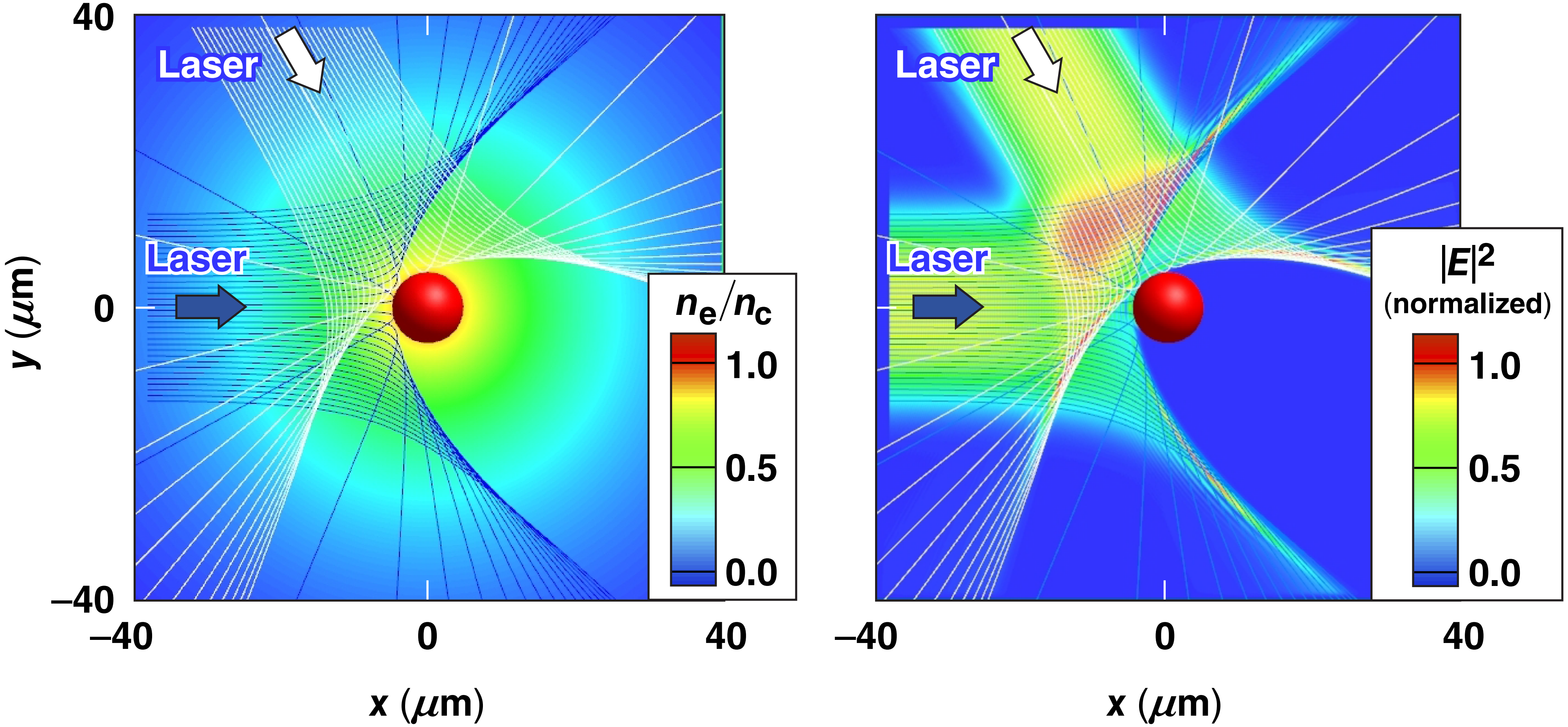
TC13074

The *LPSE*-CBET model makes few approximations

- The plasma profile is prescribed, which assumes a separation of scales between the laser–plasma interaction (LPI) and the hydrodynamics
  - currently not self-consistent with hydrodynamics since CBET is assumed to be much faster than hydrodynamic evolution
- Linear plasma response (verified *a posteriori*)
  - fluid approximation retains full-time dependence (no steady-state approximation)
- Linearization is performed about a spatially varying background plasma
  - gradients and temporal dependence is assumed weak compared with IAW wave vectors and frequencies
- The fluid approximation is assumed for the low-frequency plasma response

The laser-beam propagation is computed in a realistic scattering geometry; an arbitrary number of beams can be injected from any boundary

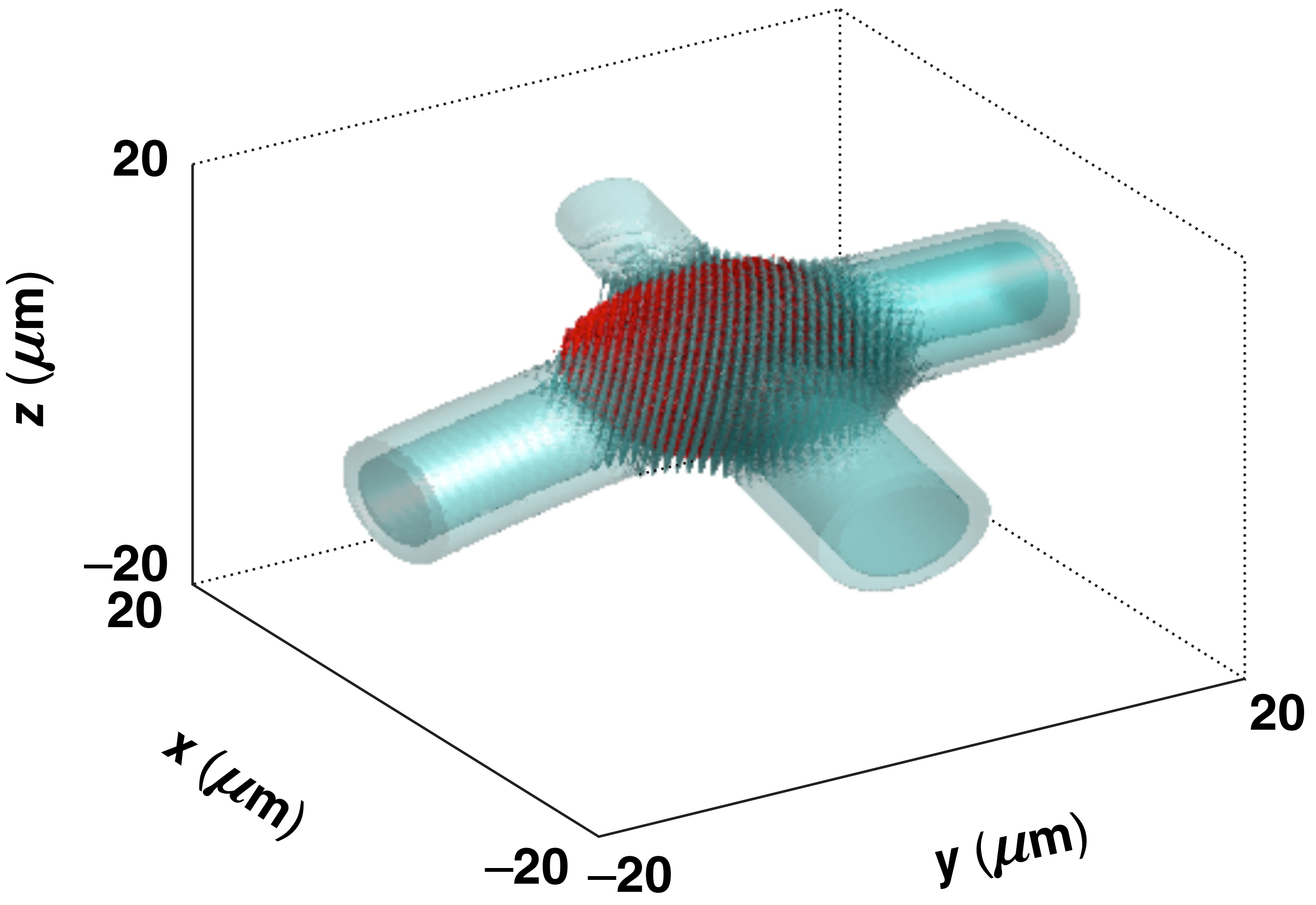
- **Absent nonlinearity, the geometric optics approximation is well-justified based on the long plasma scale length**



TC12768a

These equations are tractable in three spatial dimensions

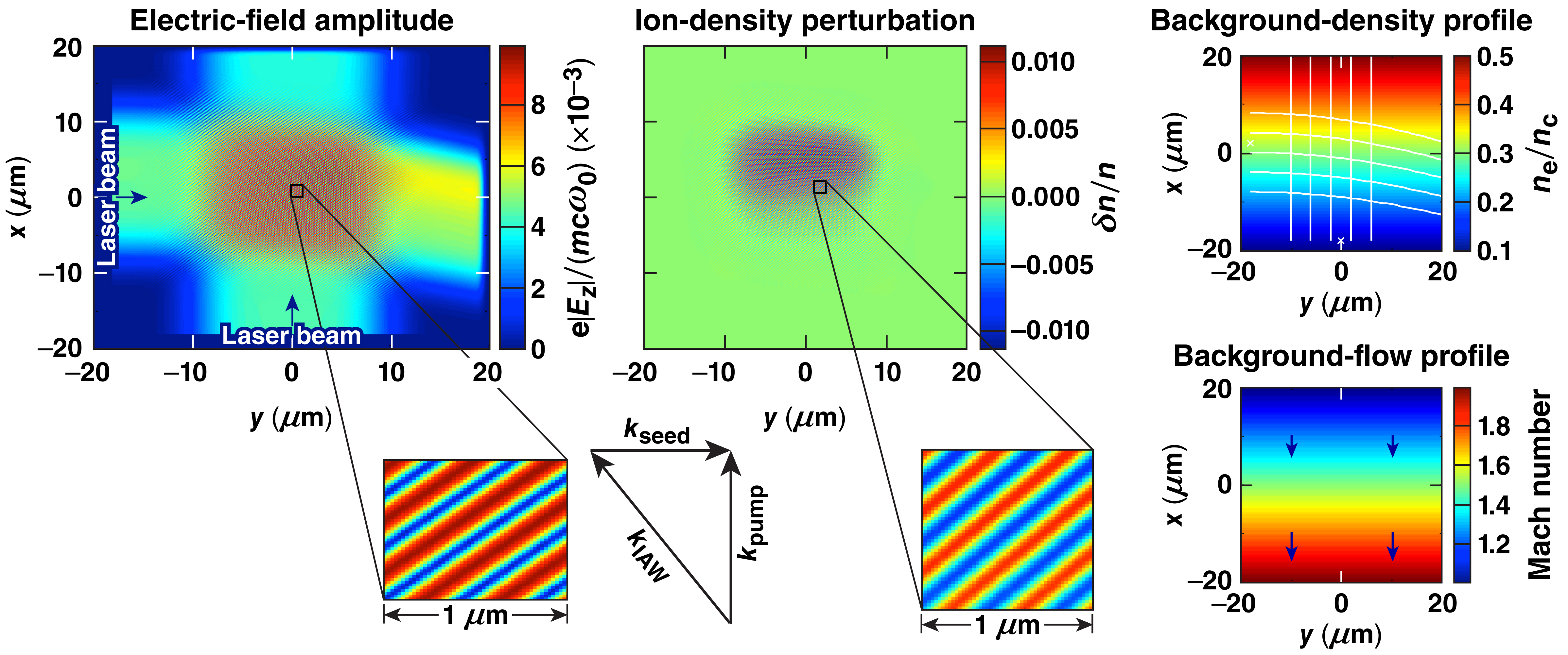
- The goal is to produce a practical model that reproduces the 3-D microphysics for inclusion in radiation–hydrodynamics codes



TC13076

The ray-based approach to CBET has been directly compared with the full-wave solution as solved by *LPSE*

- Smooth, coherent beams,* eikonal wave fields

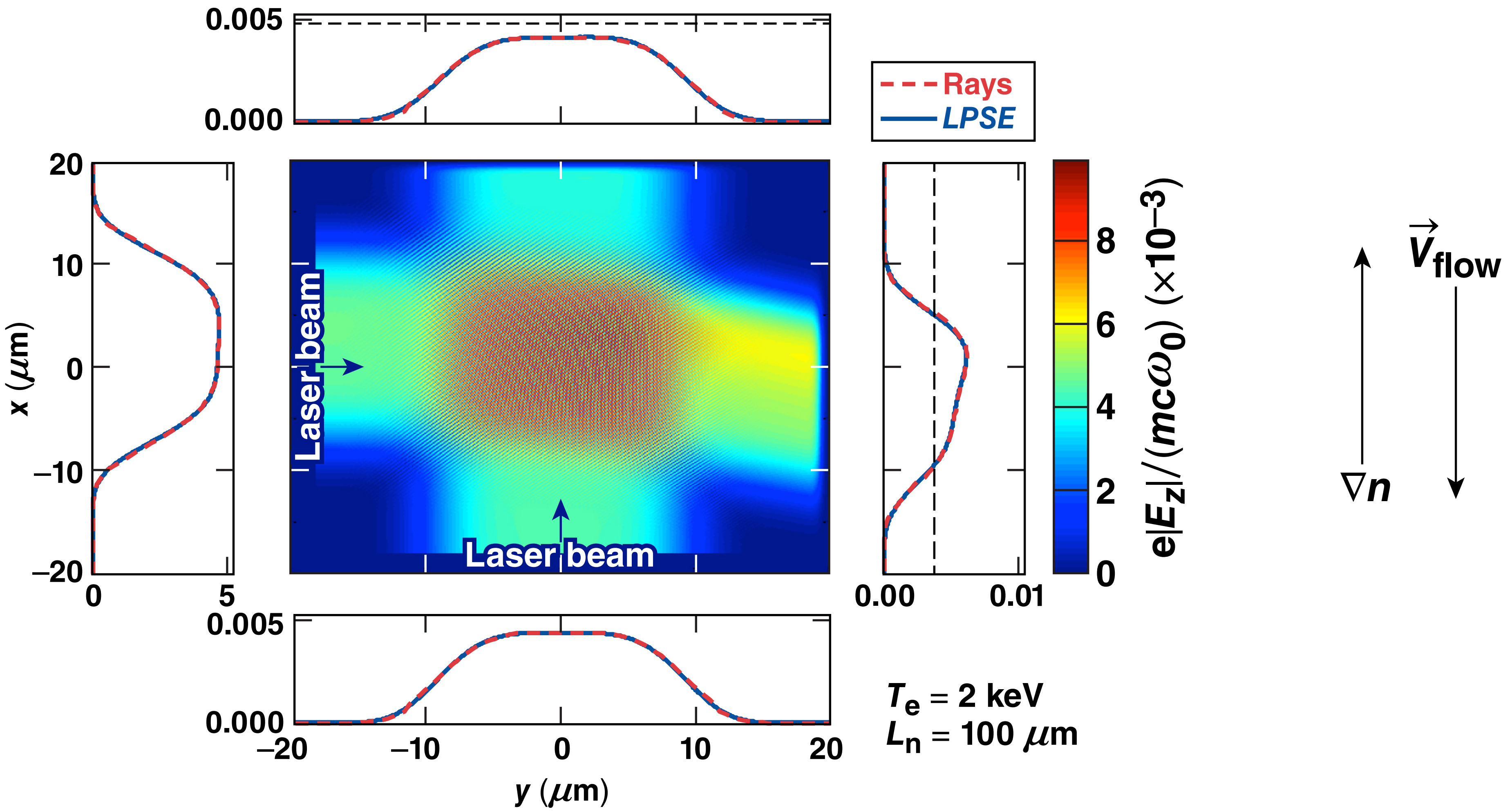


*Each beam is described locally by a single wave vector and frequency

E25598a

When the assumptions underlying the ray-based model are satisfied, the agreement with *LPSE* is astonishing

- **Smooth, coherent beams,* eikonal wave fields**



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E25599b

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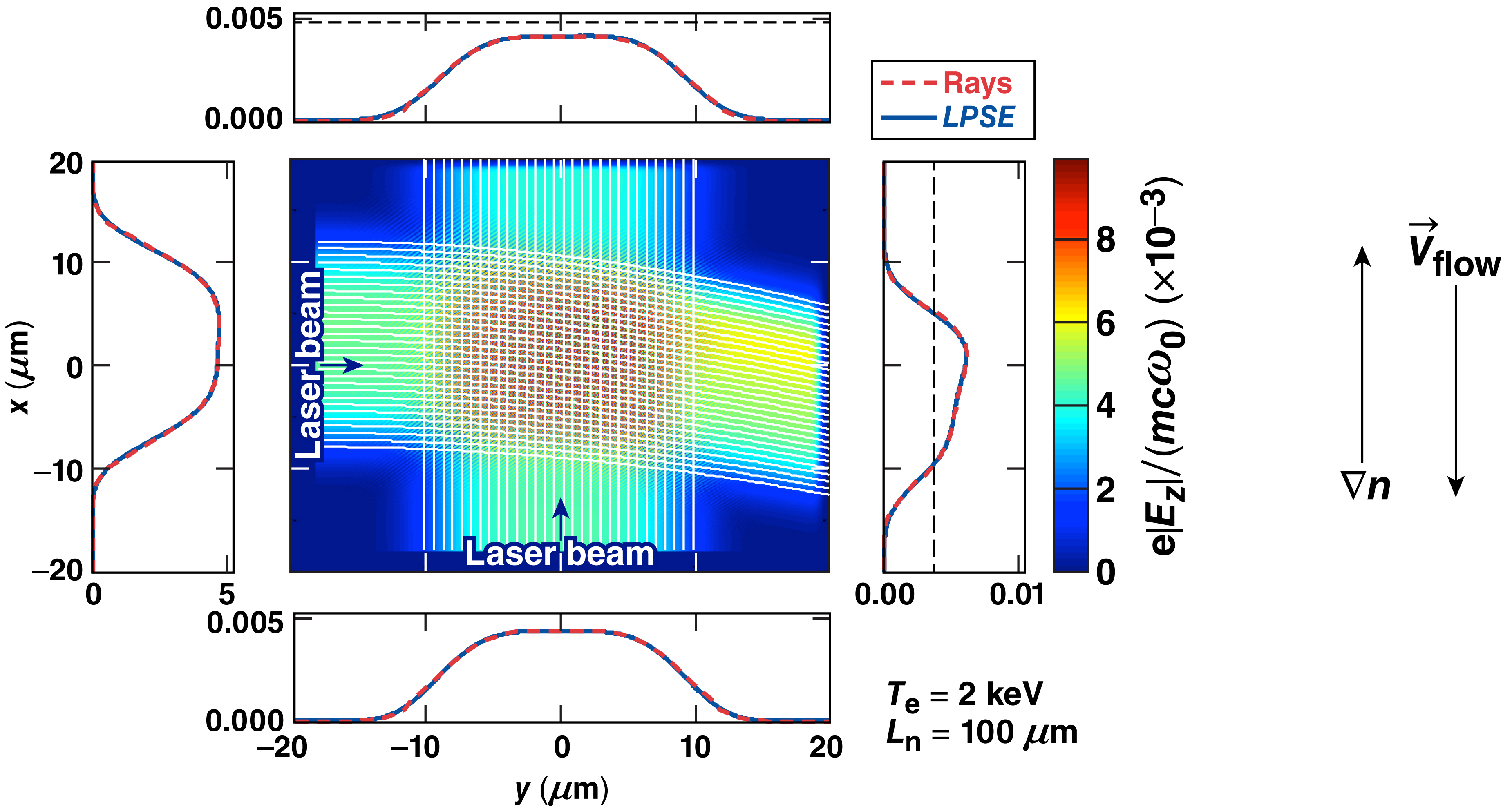
- Smooth, coherent beams,* eikonal wave fields



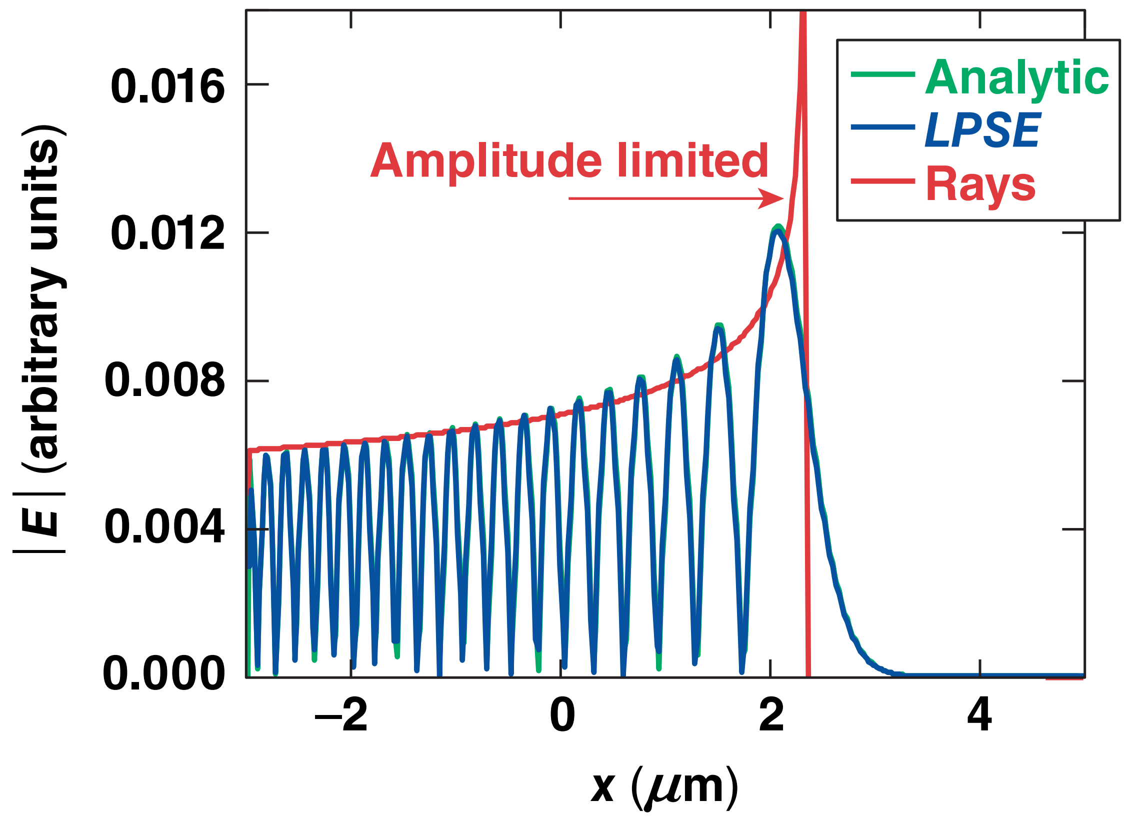
T_e = 2 keV
L_n = 100 μm

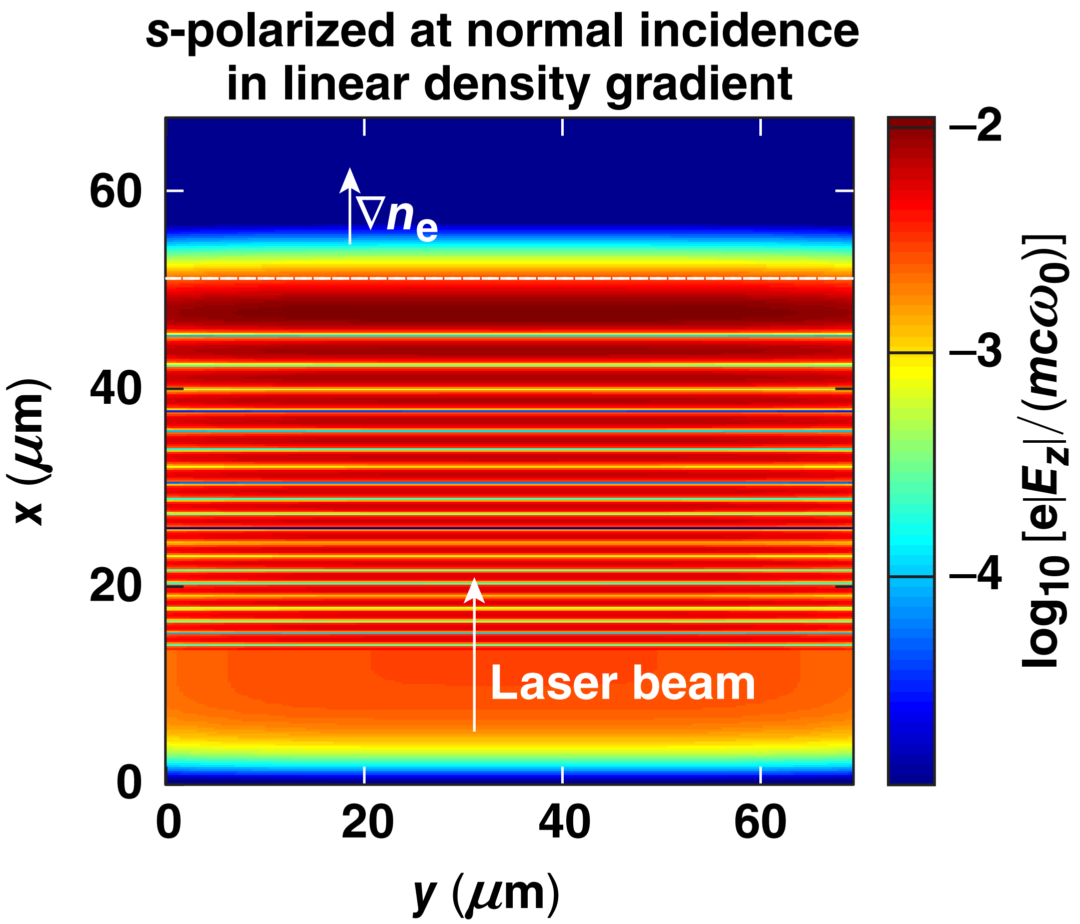
*Each beam is described locally by a single wave vector and frequency

E25599b

Problems are encountered when reconstructing the electromagnetic wave amplitude from rays at caustics

- Wave equations can exhibit caustics,* where the eikonal solution is not valid (its envelope blows up)
- Envelope is limited by the maximum of the Airy function in the ray model



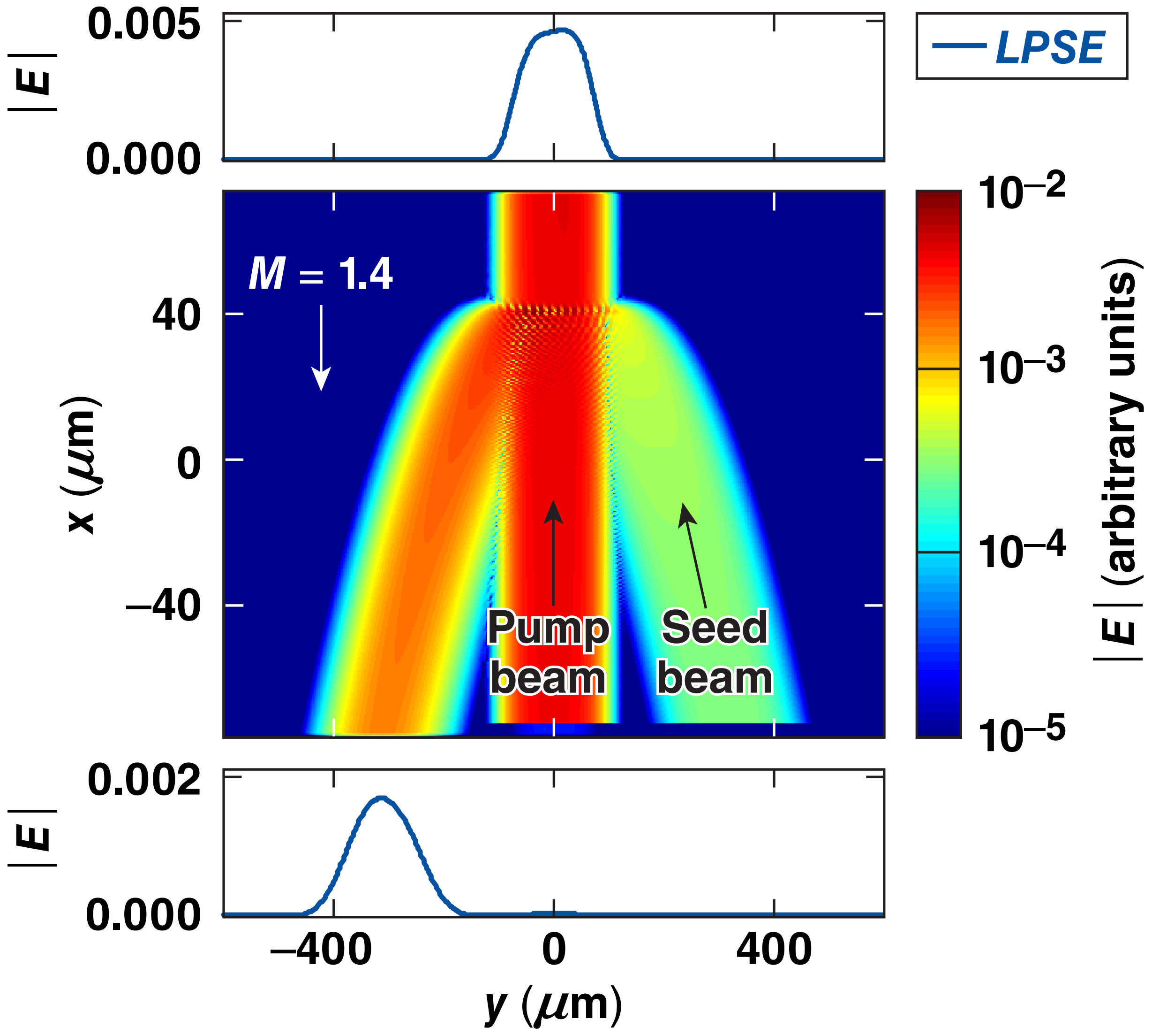


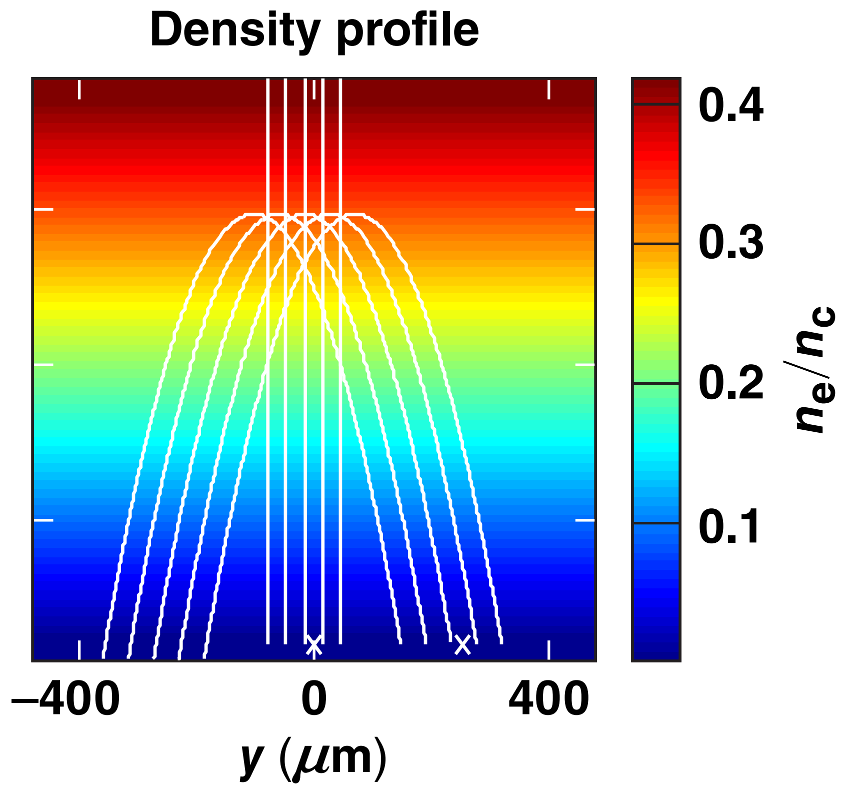
*I. B. Bernstein and L. Friedland, in *Handbook of Plasma Physics*, edited by M. N. Rosenbluth and R. A. Sagdeev, *Basic Plasma Physics I*, edited by A. A. Galeev and R. N. Sudan (North-Holland, Amsterdam, 1983), Vol. 1, Chap. 2.5, pp. 368-418.

TC13087

Discrepancies have been found between the current ray-based model and *LPSE* when caustics are present

- The beam with 50° incidence angle turns at $n_e = 0.32\ n_c$





TC13088

Discrepancies have been found between the current ray-based model and *LPSE* when caustics are present

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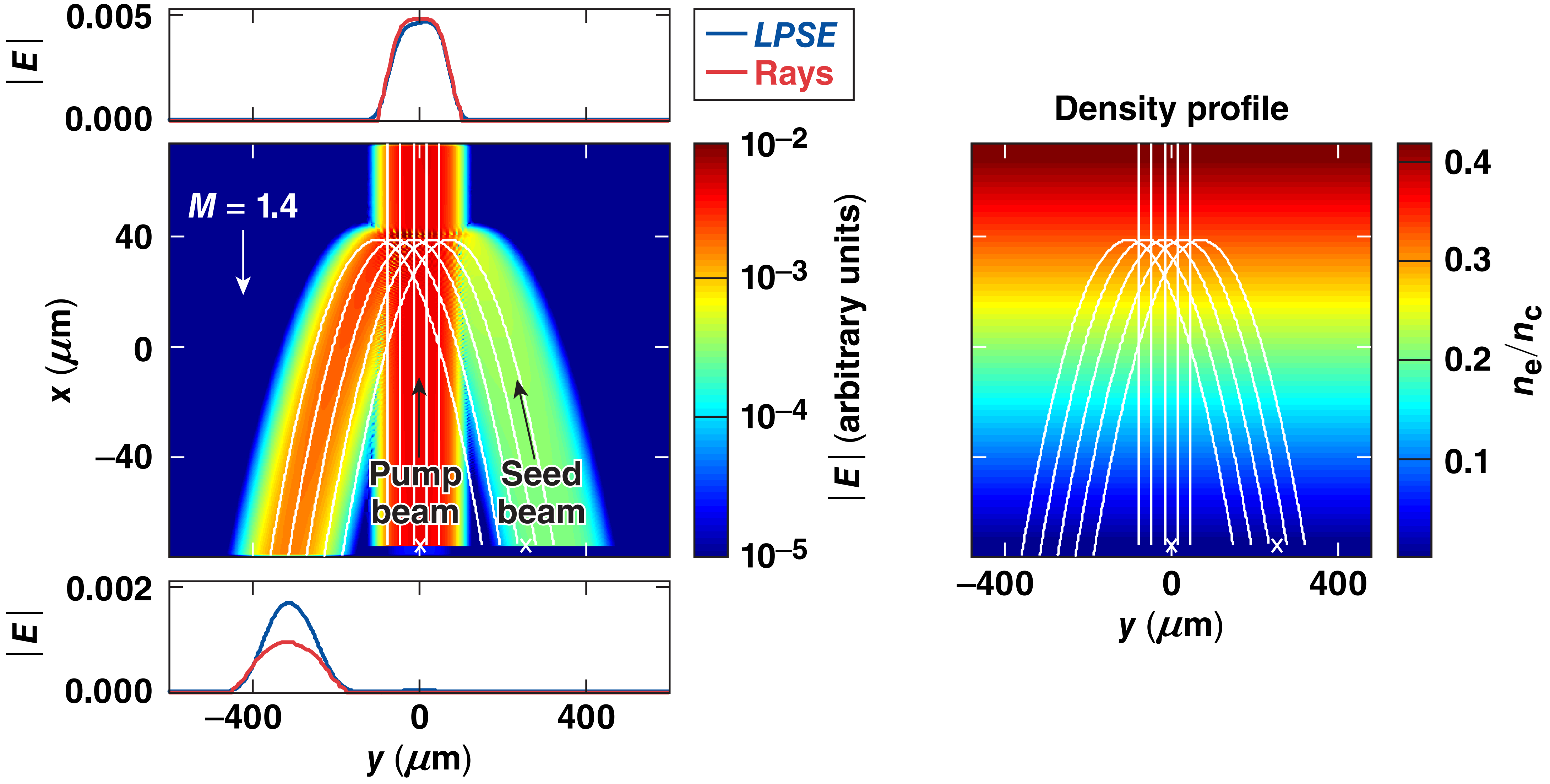
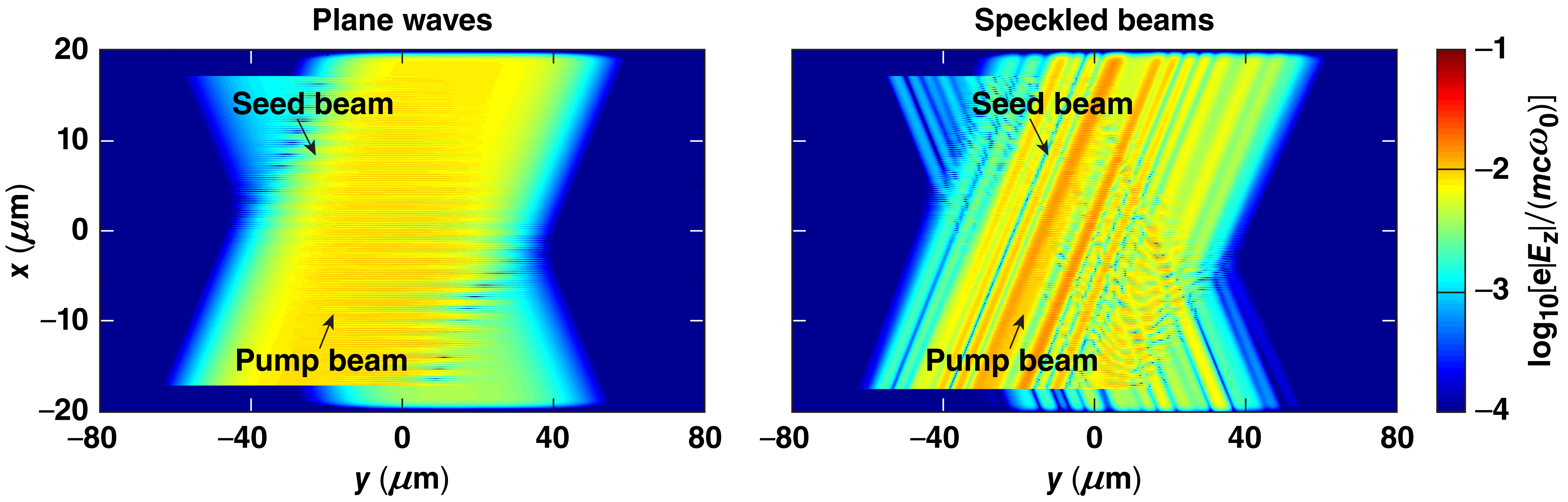


TC13088a

The impact of laser speckle on CBET is another area of investigation

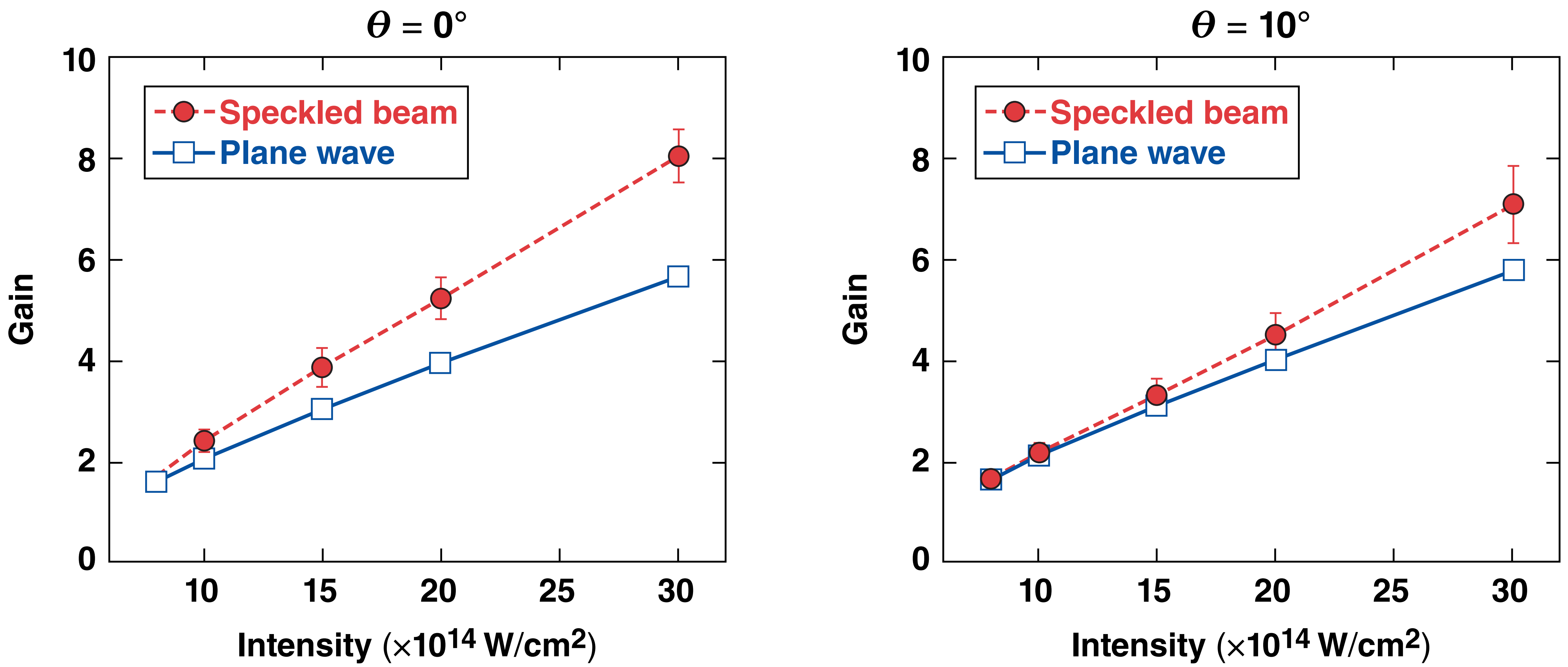
- See R. K. Follett's talk, UO9.00010, this conference
- Ray-based models typically use average intensities
- A speckled beam could, in principle, be described by rays, because it can be locally described by the sum of multiple-plane waves*



*H. A. Rose and S. Ghosal, Phys. Plasmas 5, 1461 (1998).

E25600a

Initial studies with *f*/6 beams show discrepancies in the energy transfer when the crossing angle is less than 15° to 20° (from backscatter)

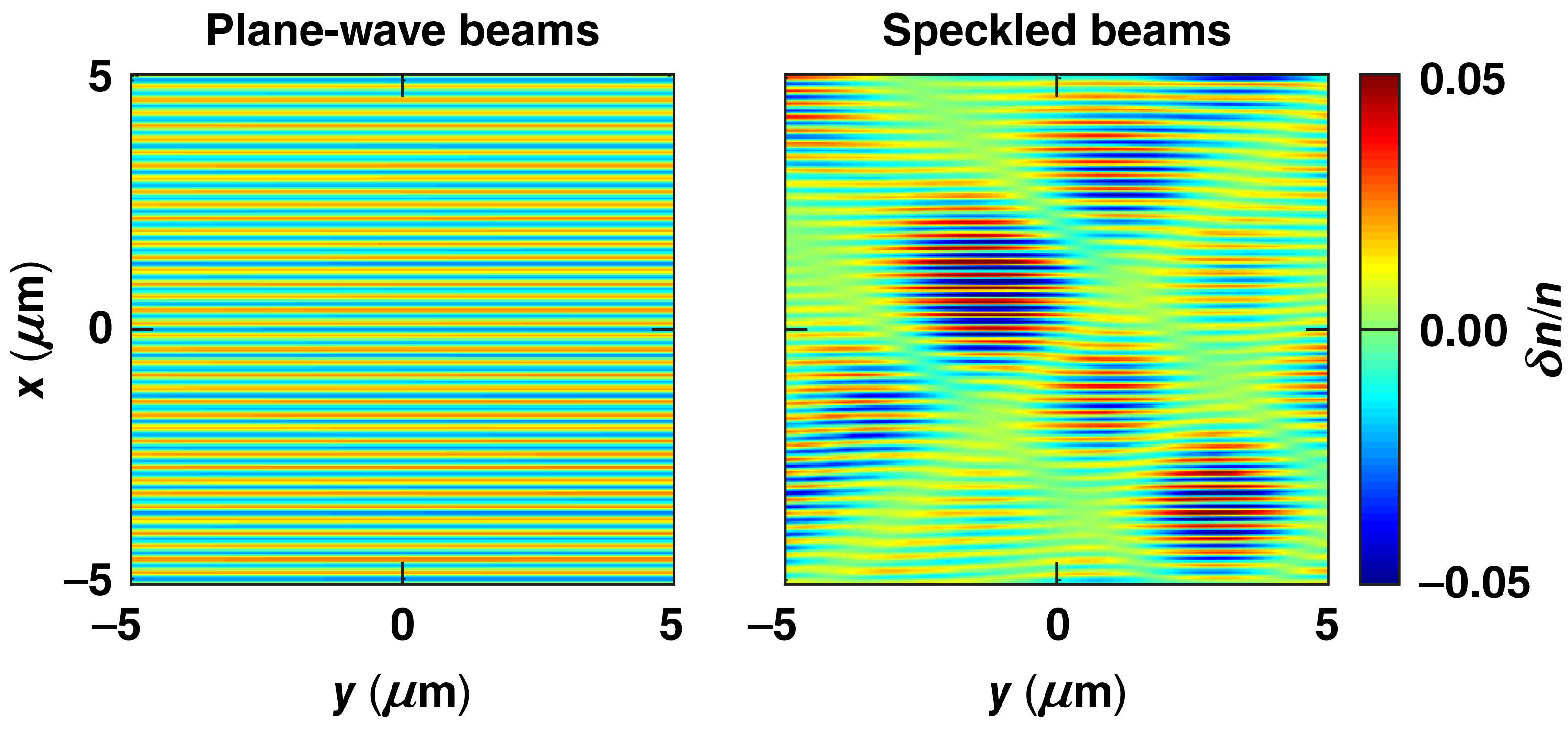


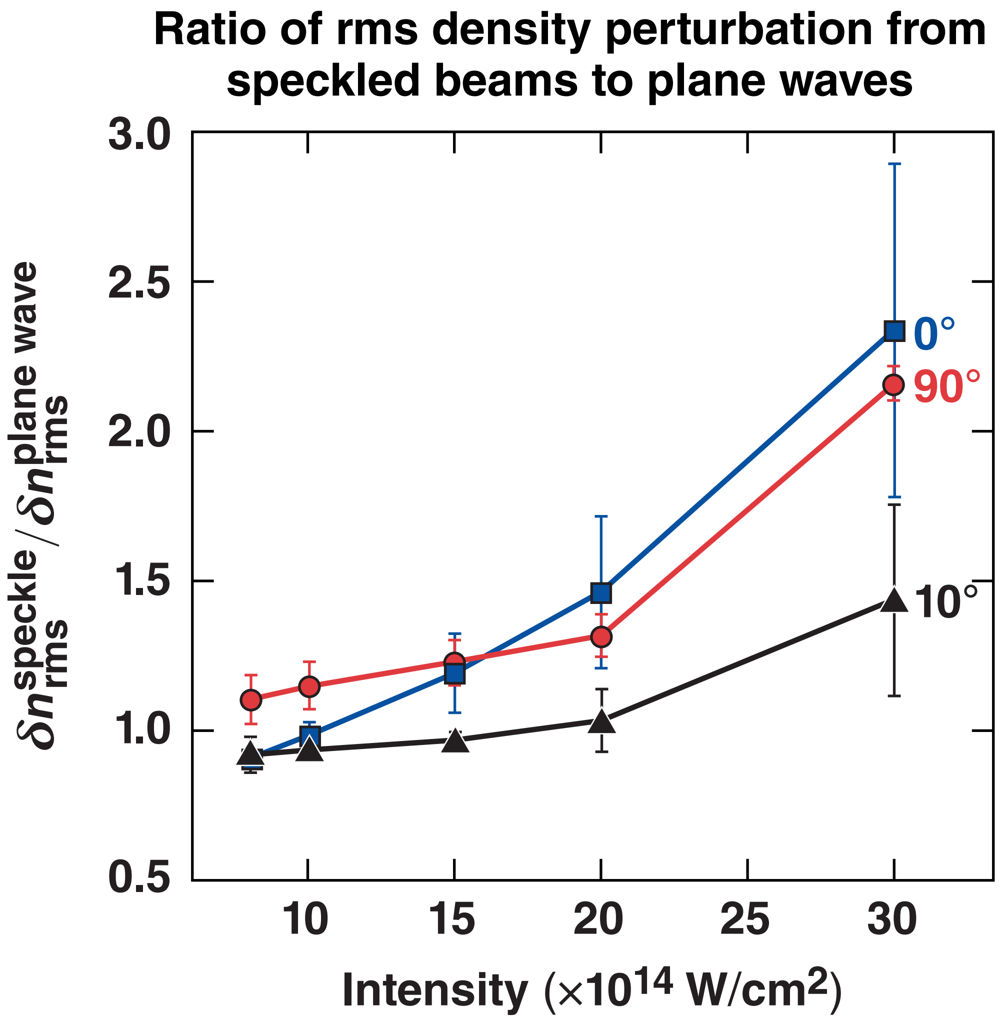
The discrepancies will be included in a "correction table" for use in radiation–hydrodynamics simulations.

TC13089

Additionally, larger amplitude-density perturbations are generated than for plane waves for the same transferred power

- The linear response approximation for IAW's appears to be valid for direct-drive parameters
- Ray-based predictions $\delta n/n \sim 10^{-4}$





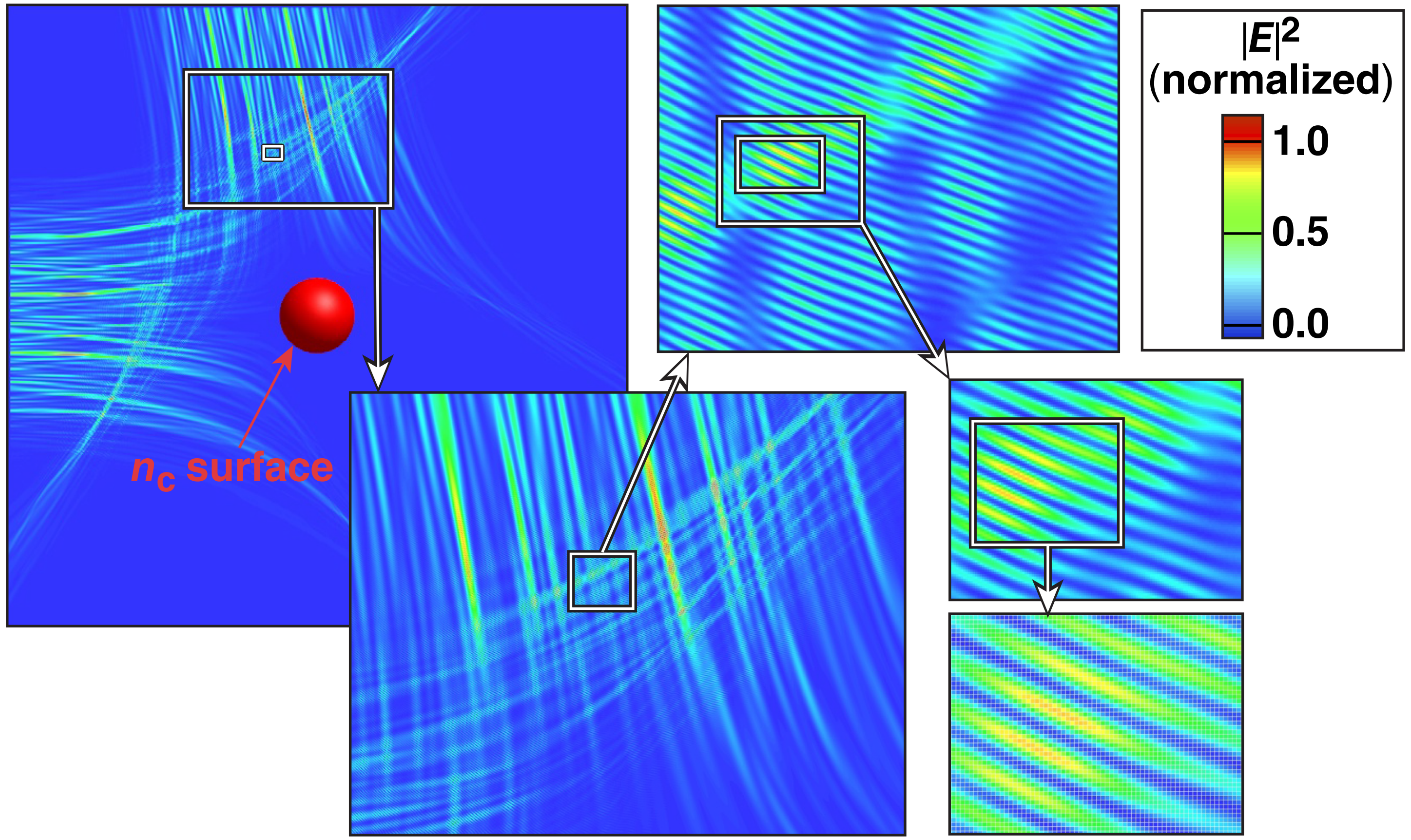
E25602a

Future plans for *LPSE* include the investigation of CBET mitigation and TPD/CBET interaction

- Wavelength detuning
  - see M. Hohenberger *et al.,* U09.00009, this conference
- Laser bandwidth
  - see J. Bates *et al.*, "Preliminary numerical investigation of bandwidth effects on CBET using the *LPSE*-CBET code", NP10.00081, this conference
- *LPSE* is able to model both TPD and CBET
  - the two effects are expected to interact as CBET modifies the laser intensity at the quarter-critical surface

In the near future it may be possible to carry out wave-based CBET in 3-D for OMEGA-scale plasmas

- Could full-wave solutions on a sub-volume be connected to ray tracing elsewhere?
- Quantum mechanical Schrödinger equation connected to semi-classical solutions*



*E. Kieri, G. Kreiss, and O. Runborg, Adv. Appl. Math. Mech. 7, 687 (2015).

TC12778b

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