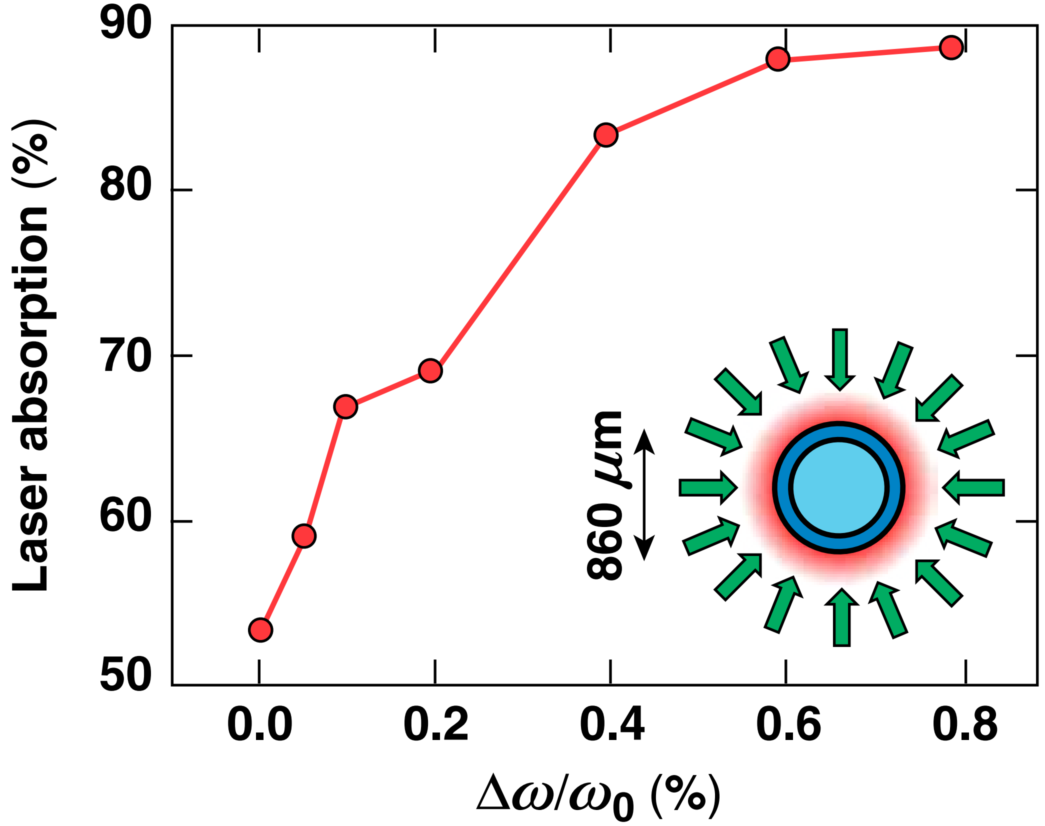
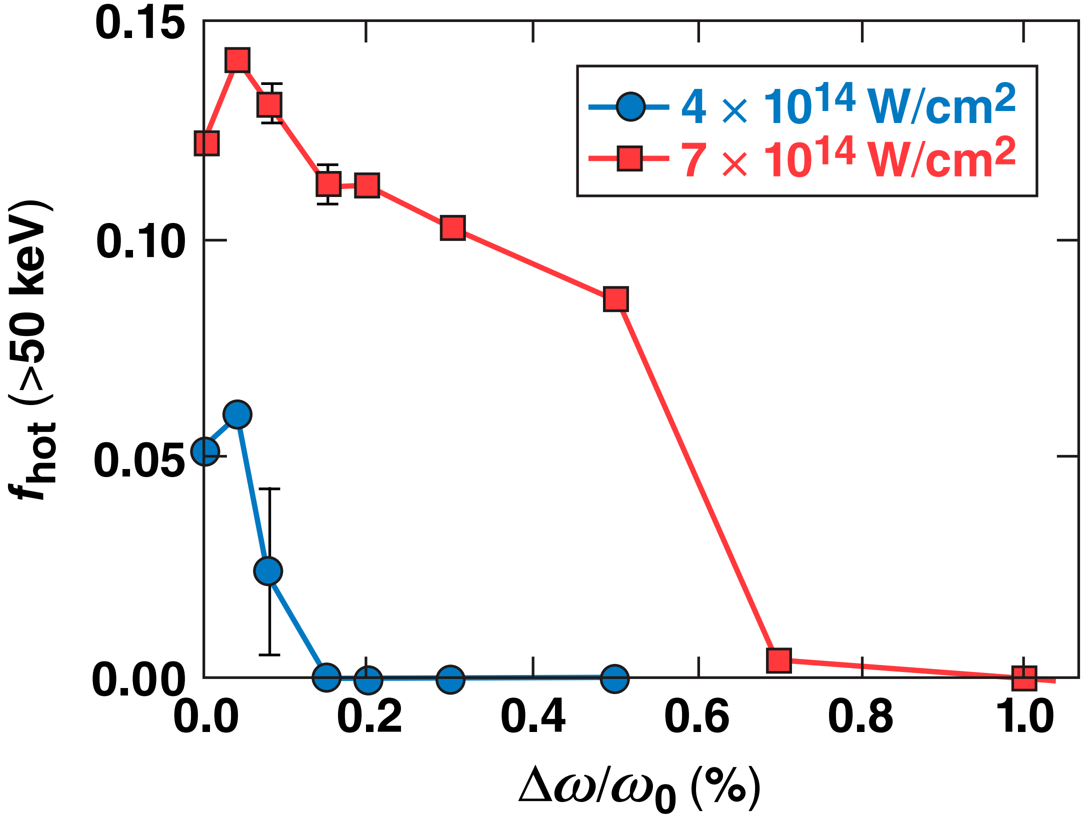
Suppressing Parametric Instabilities with Laser Frequency Detuning and Bandwidth

Cross-beam energy transfer mitigation with continuous bandwidth



Two-plasmon-decay driven hot-electron mitigation with discrete bandwidth



R. K. Follett
University of Rochester
Laboratory for Laser Energetics

60th Annual Meeting of the American
Physical Society Division of Plasma Physics
Portland, OR
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Summary

Temporal incoherence of the drive lasers suppresses cross-beam energy transfer (CBET) and two-plasmon decay (TPD)

- Laser–plasma instabilities limit the laser intensity that can be used in inertial confinement fusion (ICF) implosions
- Laser bandwidth can be used to suppress many of these instabilities and open up the implosion design space
- In direct-drive implosion experiments on OMEGA, ~0.5% to 1% bandwidth would be sufficient to suppress CBET and TPD

A future broadband laser based on optical parametric amplifiers is currently being explored at LLE.

Collaborators

**J. G. Shaw, D. H. Edgell, D. H. Froula, C. Dorrer, J. Bromage,
E. M. Campbell, E. M. Hill, T. J. Kessler, and J. P. Palastro**

University of Rochester
Laboratory for Laser Energetics

J. F. Myatt

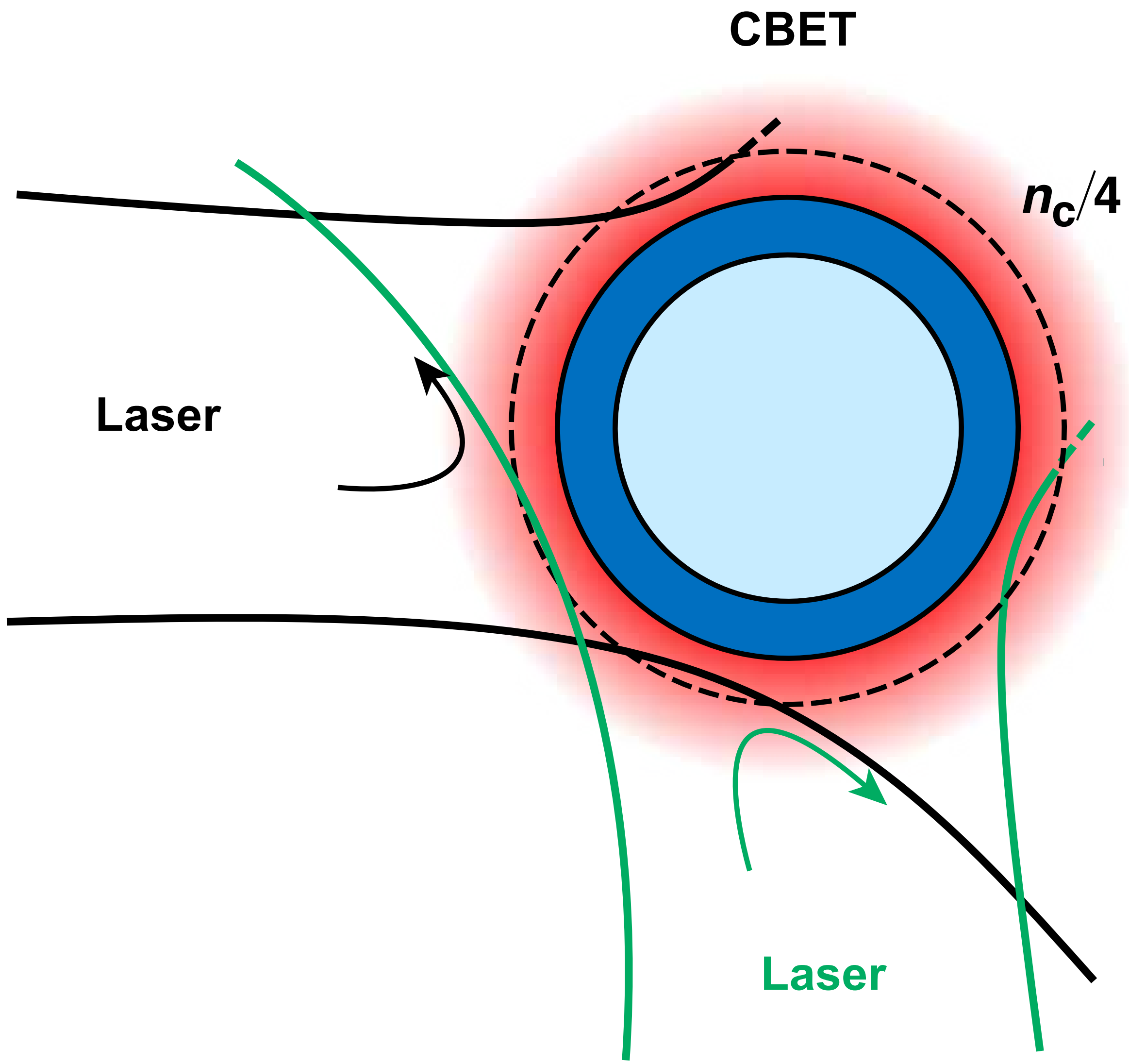
University of Alberta

J. W. Bates and J. L. Weaver

Naval Research Laboratory

Motivation

In direct-drive ICF implosions, CBET reduces the laser absorption and TPD can lead to hot-electron preheat



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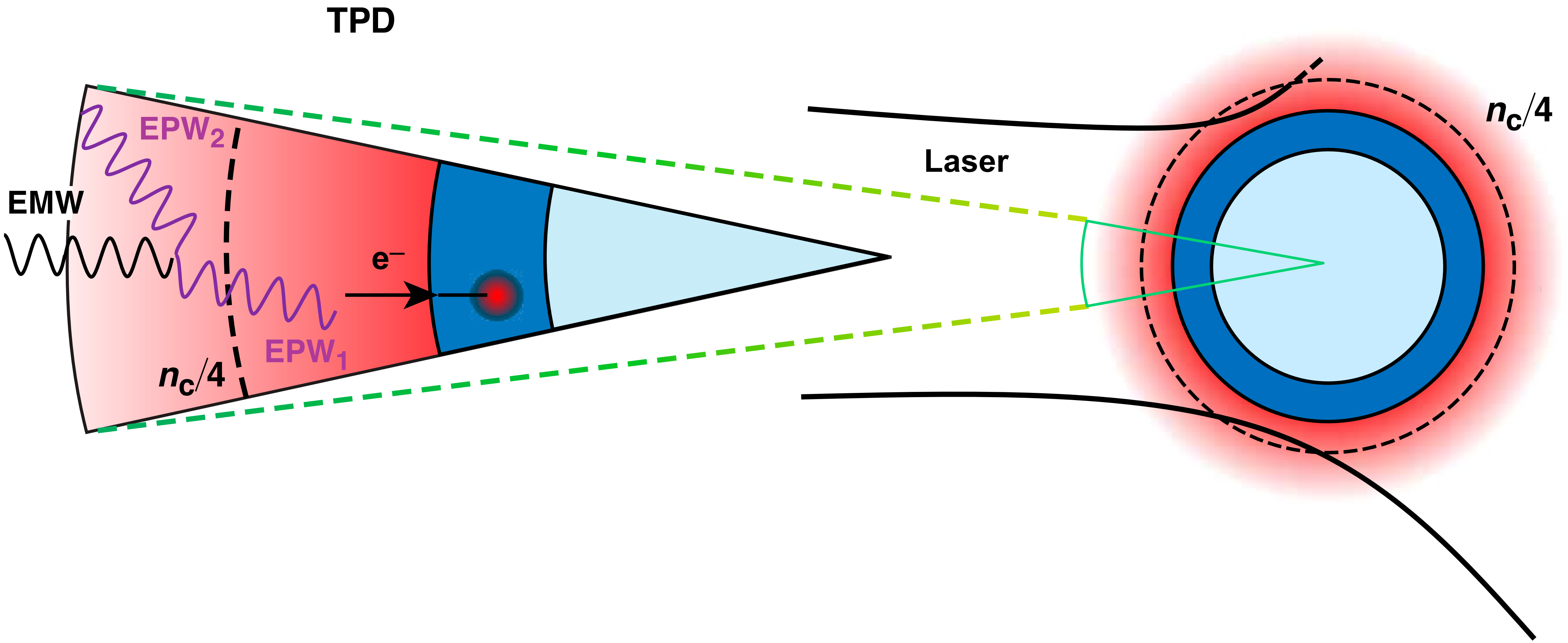
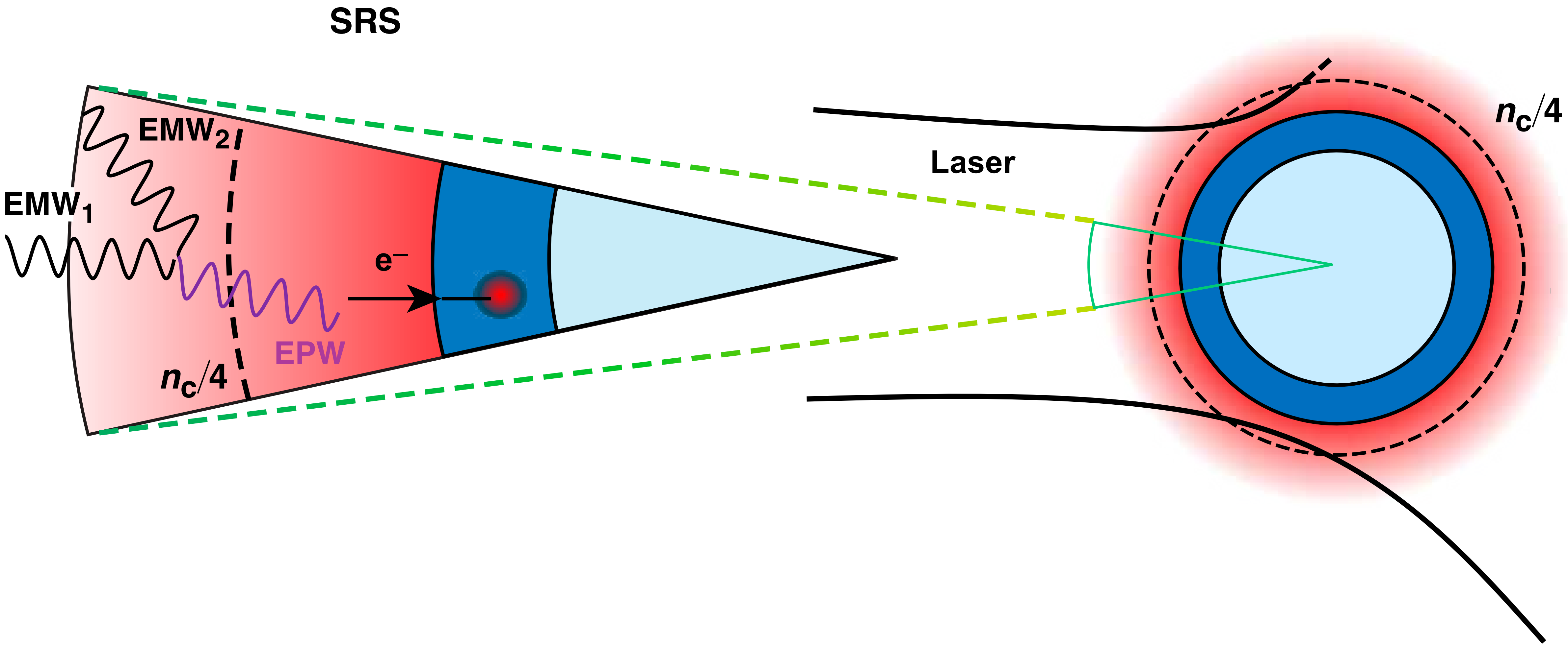


EMW: electromagnetic wave
EPW: electron plasma wave

Motivation

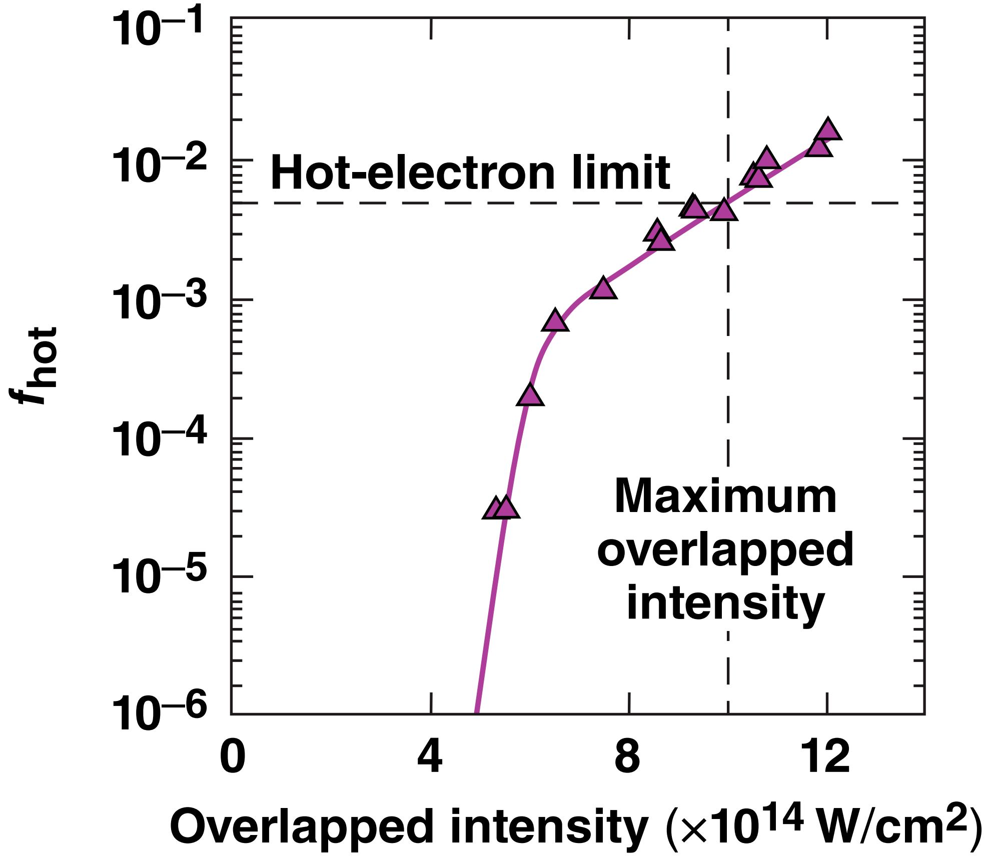
In direct-drive ICF implosions, CBET reduces the laser absorption and TPD can lead to hot-electron preheat



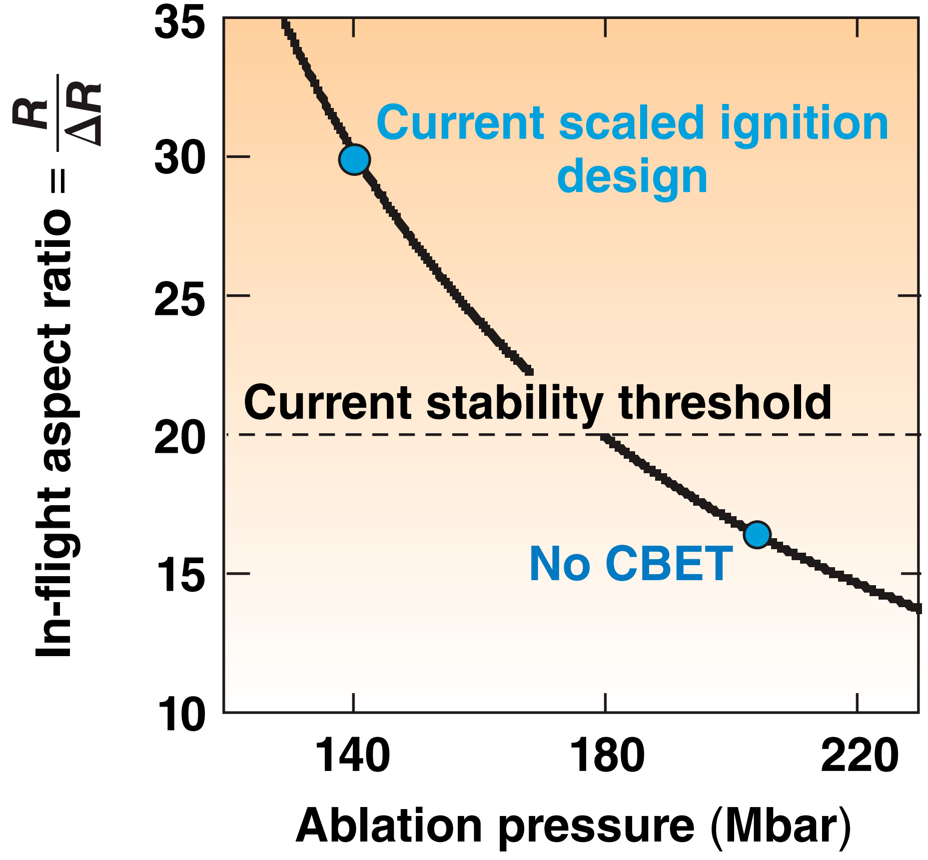
SRS: stimulated Raman scattering

Motivation

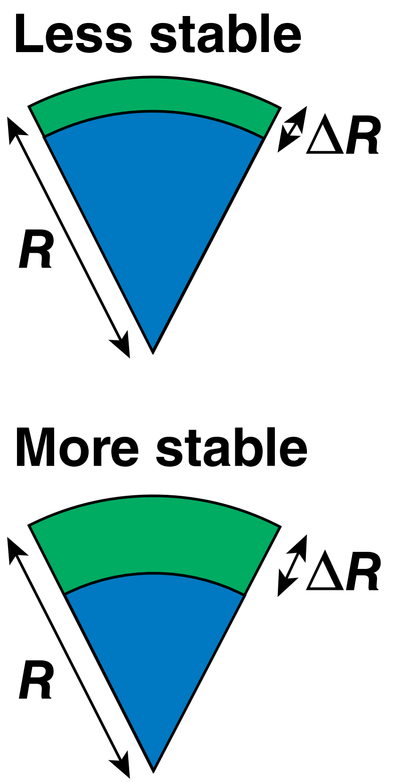
Laser–plasma instabilities define the maximum laser intensity for direct-drive experiments



Hot-electron production on OMEGA



Direct drive (constant hot-spot pressure)



CBET reduces the ablation pressure for direct-drive ICF by ~50%.

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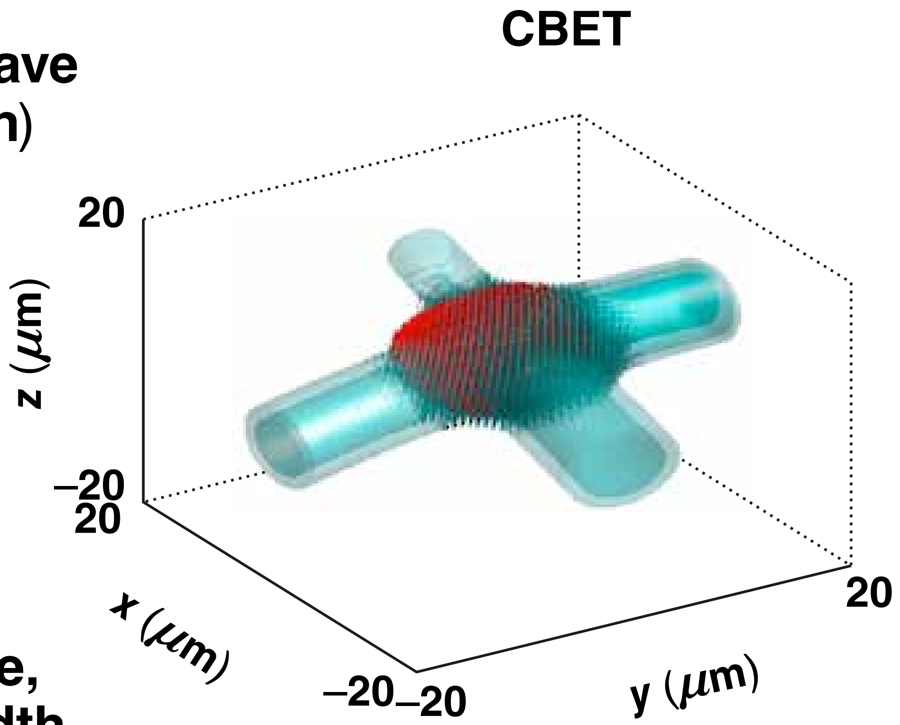
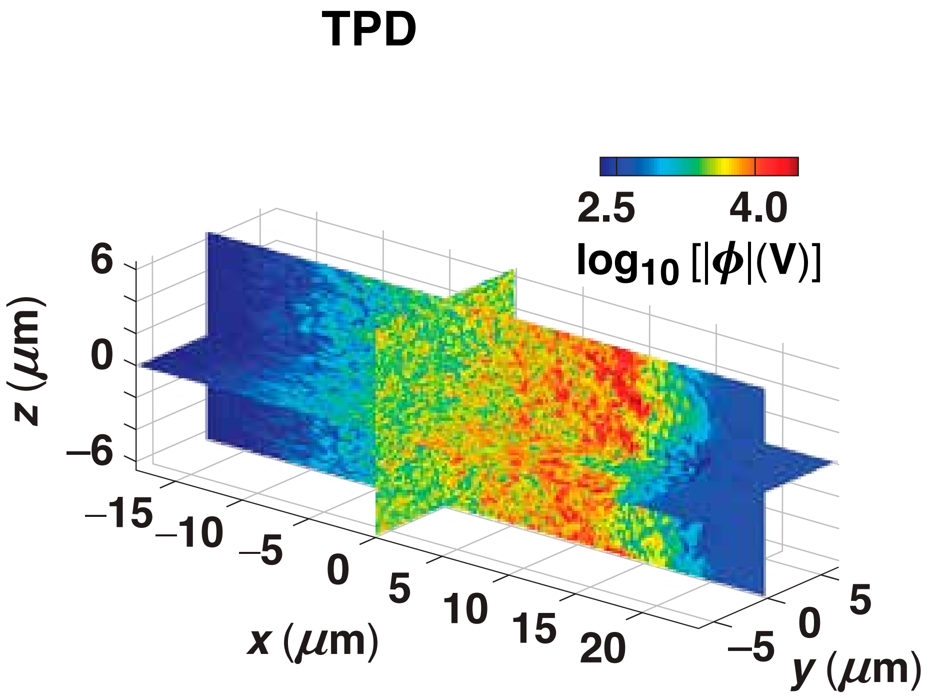
*IFAR: in-flight aspect ratio

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

LPSE **(laser–plasma simulation environment)**

- **Solves 3-D time-enveloped vector wave equations (no paraxial approximation)**
- **Two-plasmon decay[1,2]**
- **Cross-beam energy transfer[3–6]**
- **Stimulated Raman scattering (SRS)**
- **Quasilinear Landau damping and hot-electron production [7,8]**
- **Arbitrary beam injection with speckle, polarization smoothing, and bandwidth**





***LPSE* is a community code (LLE, NRL, University of Alberta, and RAL).**

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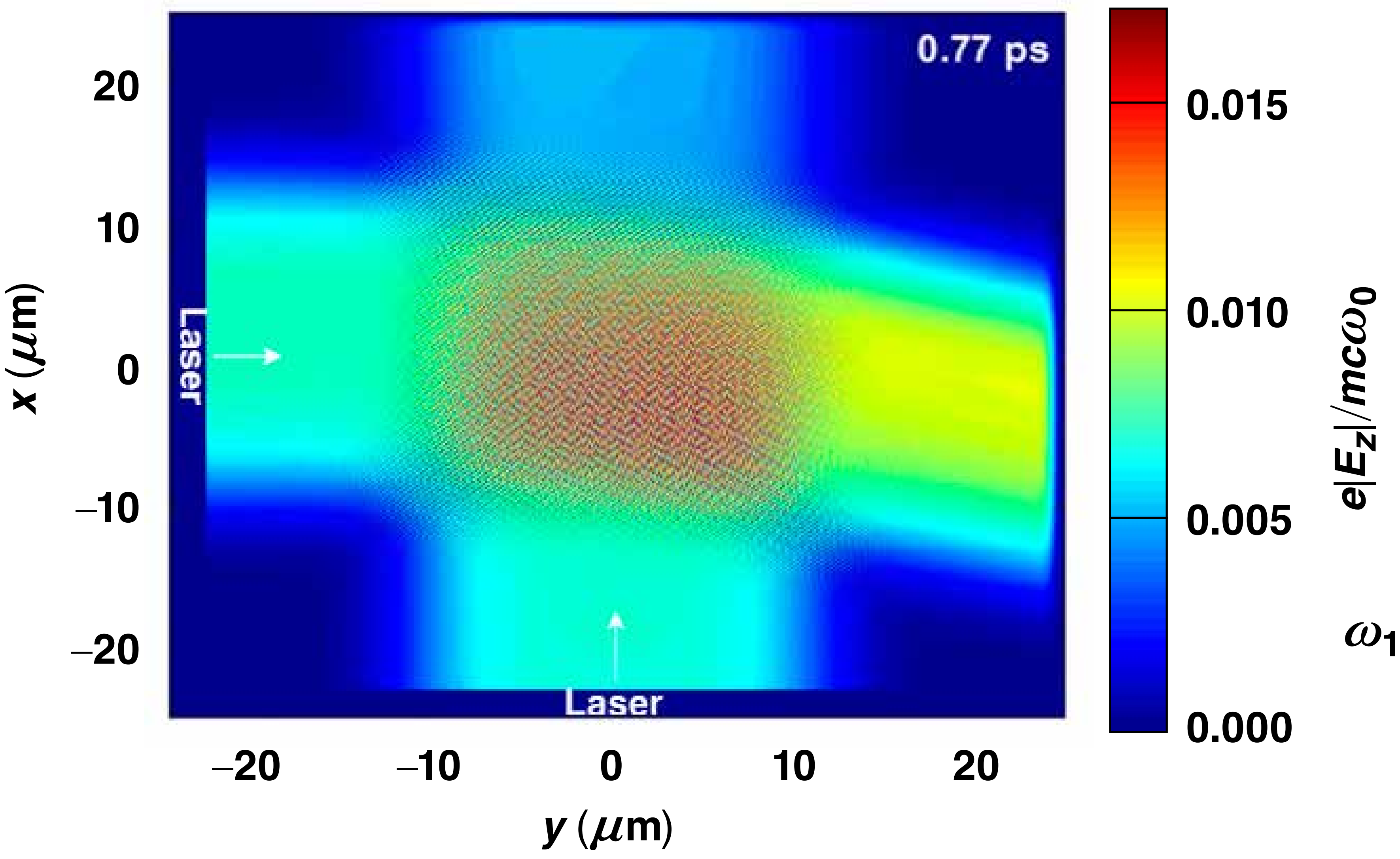
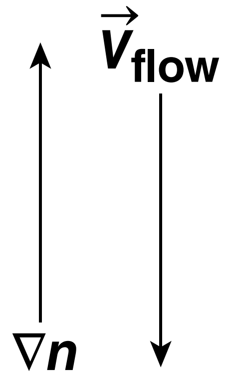
[1] R. K. Follett *et al.*, Phys. Rev. E 91, 031104 (2015).
[2] R. K. Follett *et al.*, Phys. Plasmas 24, 102134 (2017).
[3] J. F. Myatt *et al.*, Phys. Plasmas 24, 056308 (2017).
[4] R. K. Follett *et al.*, Phys. Plasmas 24, 103128 (2017).
[5] J. W. Bates *et al.*, Phys. Rev. E 97, 061202 (2018).
[6] R. K. Follett *et al.*, Phys. Rev. E 98, 043202 (2018)
[7] R. K. Follett *et al.*, Phys. Rev. Lett. 116, 155002 (2016).
[8] R. K. Follett *et al.*, Phys. Rev. Lett. 120, 135005 (2018).

E27879

Cross-beam energy transfer is the exchange of energy between two electromagnetic (EM) waves mediated by a ponderomotively driven ion-acoustic wave (IAW)

Two-beam *LPSE* CBET simulation



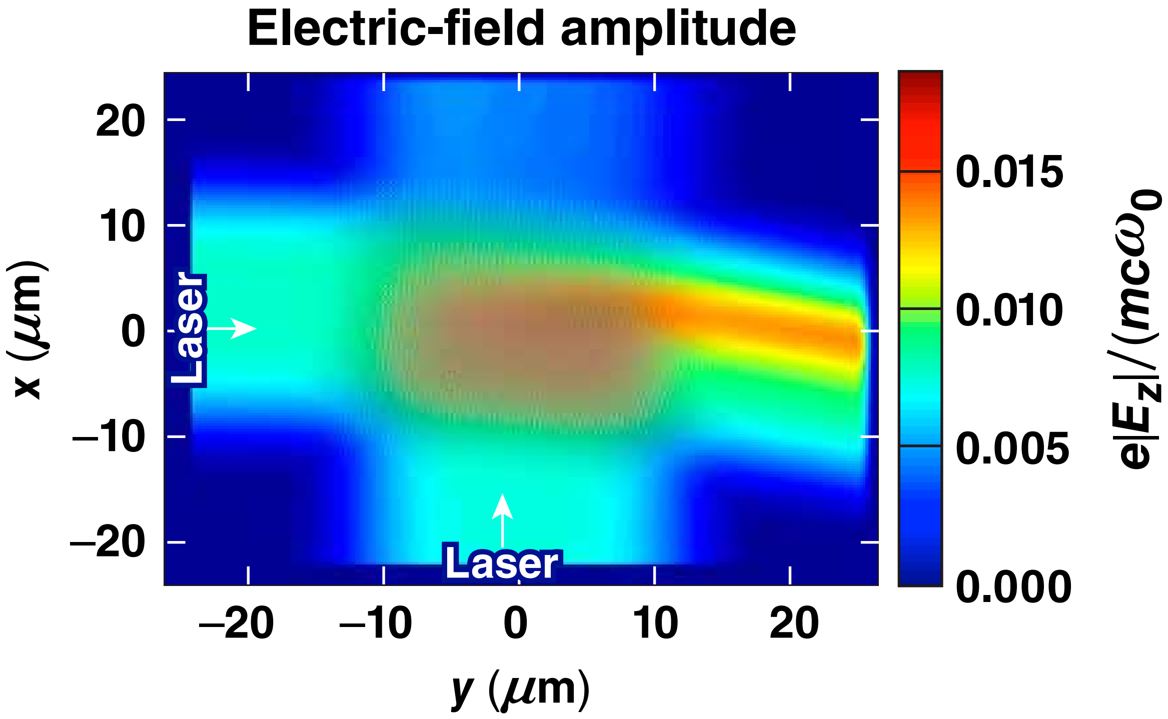


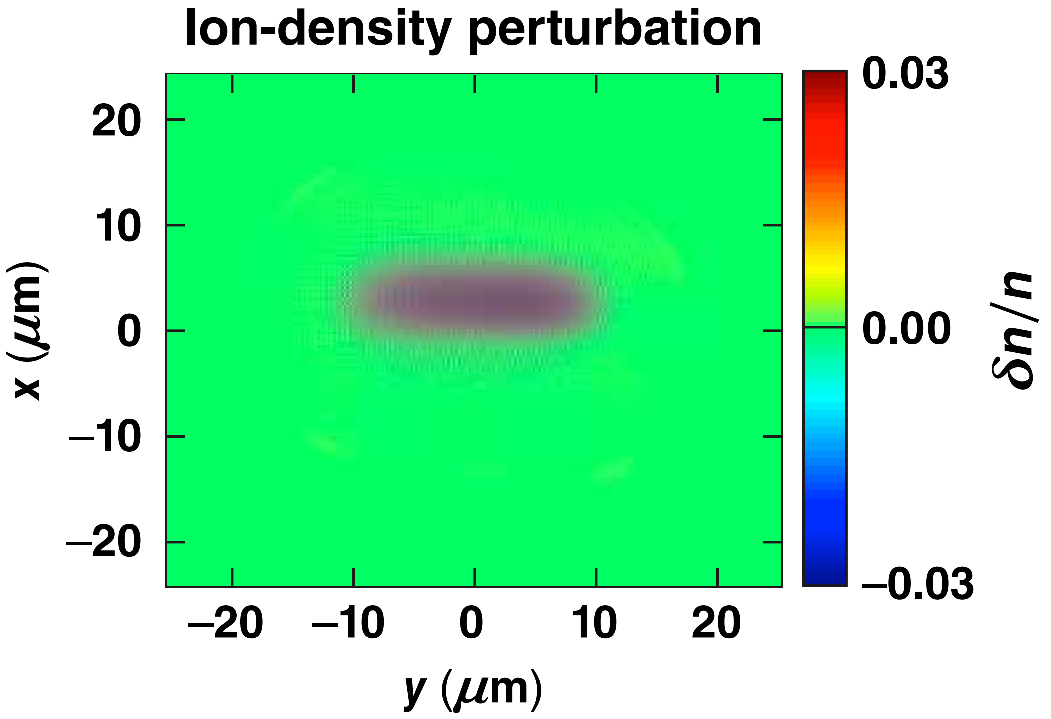
Resonance condition:

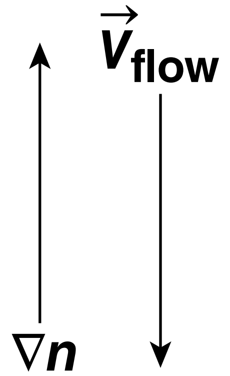
$$\omega_1 - \omega_2 - \omega_{\text{IAW}} = (\vec{k}_1 - \vec{k}_2) \cdot \vec{V}_{\text{flow}}$$

E27881

Cross-beam energy transfer is the exchange of energy between two electromagnetic waves mediated by a ponderomotively driven ion-acoustic wave

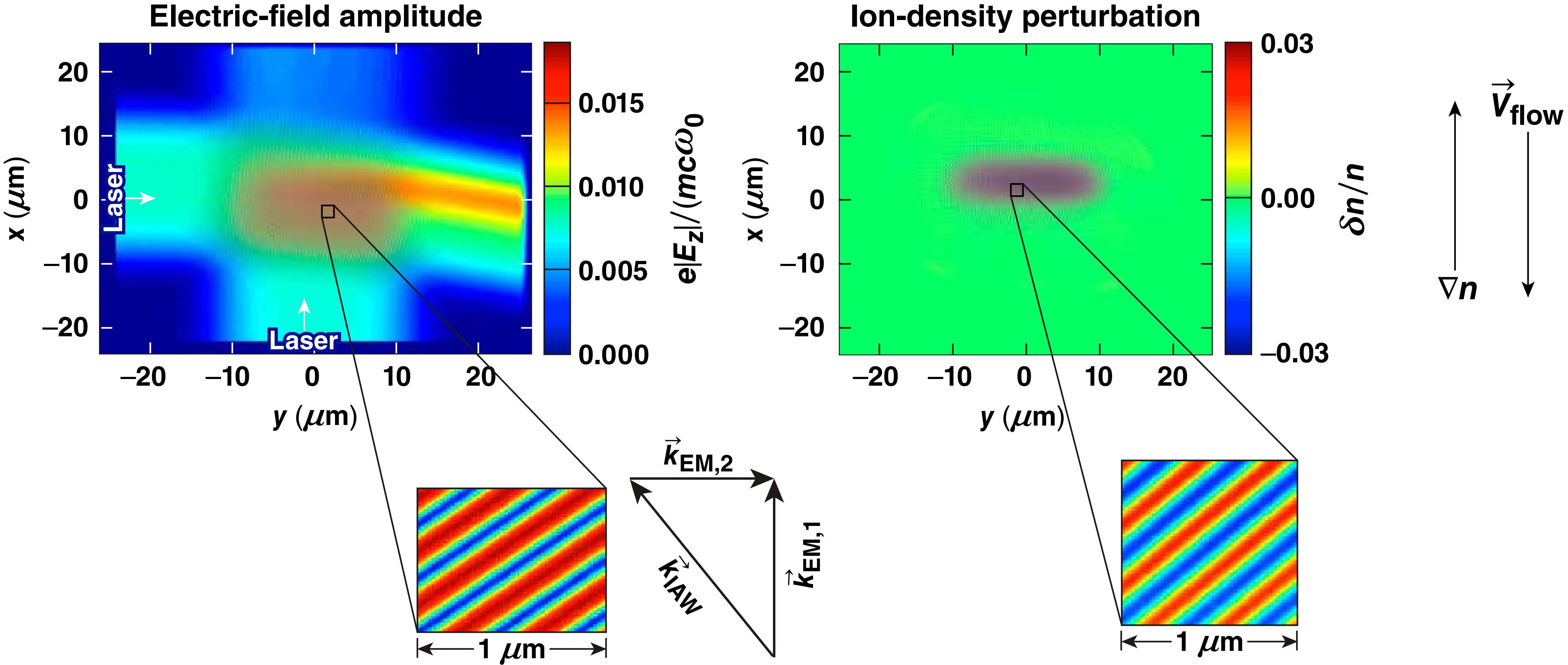

Electric-field amplitude


Ion-density perturbation



E27882

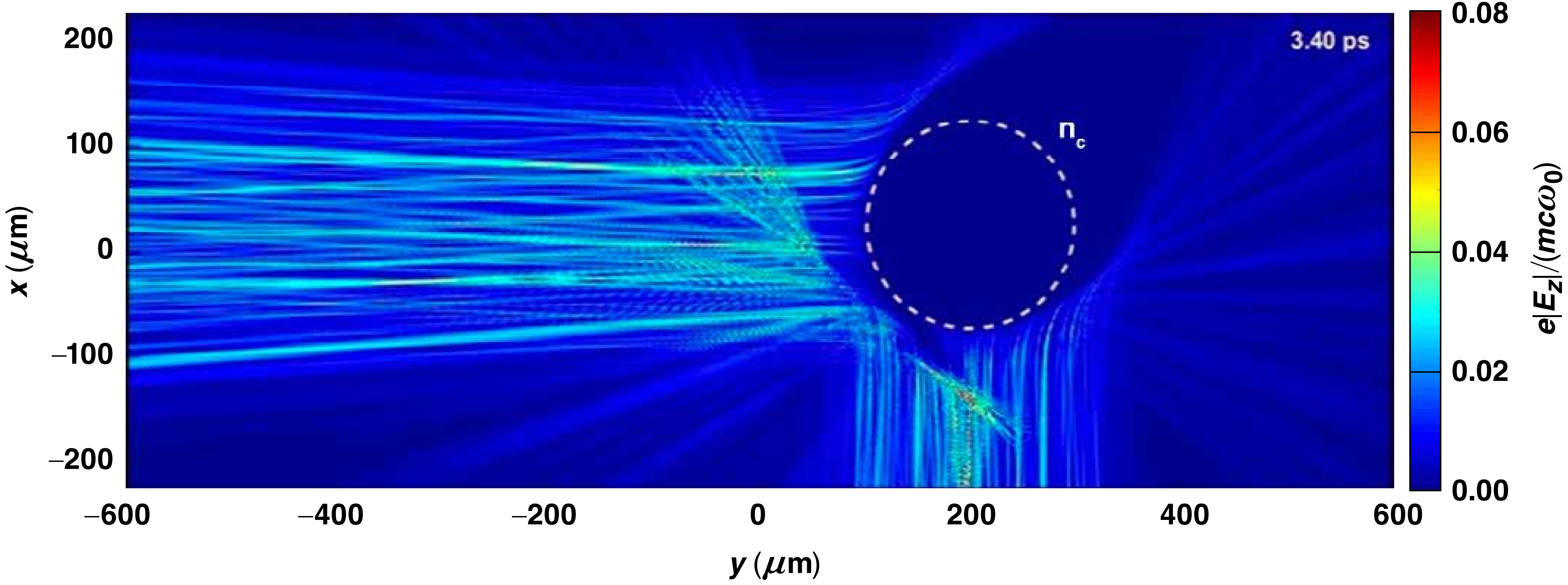
Cross-beam energy transfer is the exchange of energy between two electromagnetic waves mediated by a ponderomotively driven ion-acoustic wave



E25598c

In direct-drive ICF, CBET scatters light out of the incoming beams and reduces the absorption of the drive lasers

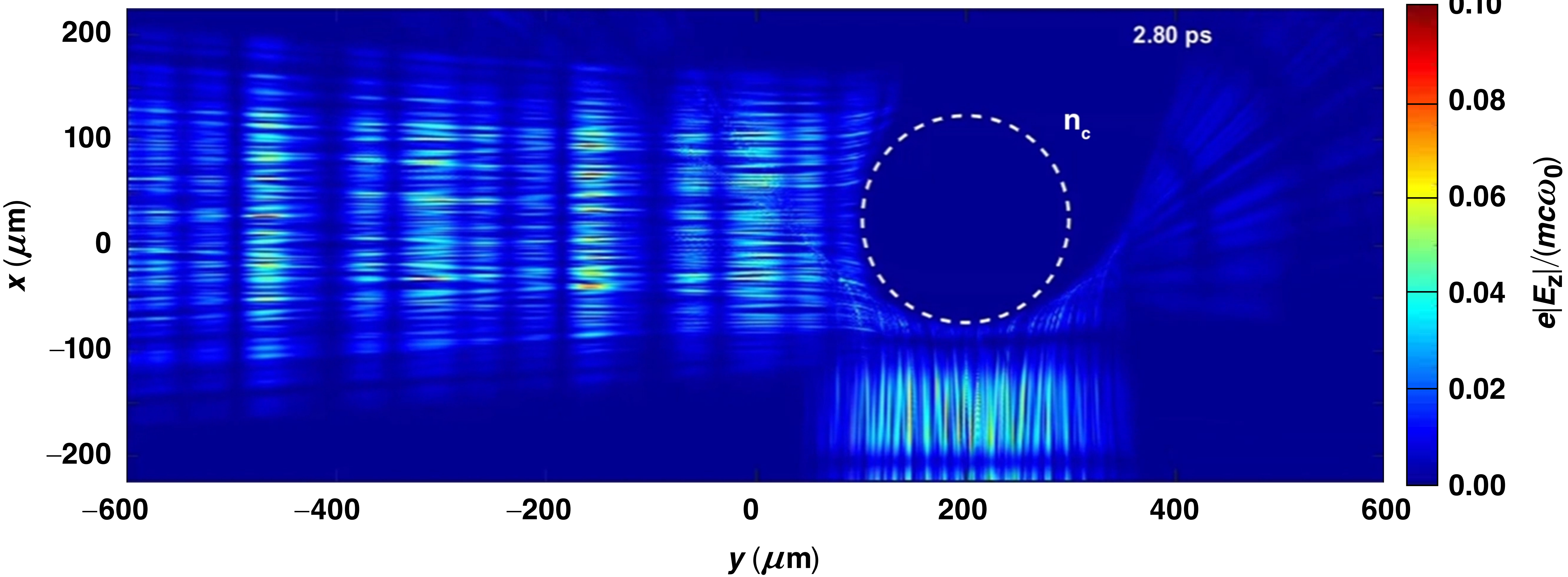
Electric field of lasers incident on an ICF target (64% absorption)



E27883

Laser bandwidth can be used to mitigate CBET and increase laser absorption

Electric field of lasers incident on an ICF target with 1% bandwidth (90% absorption)

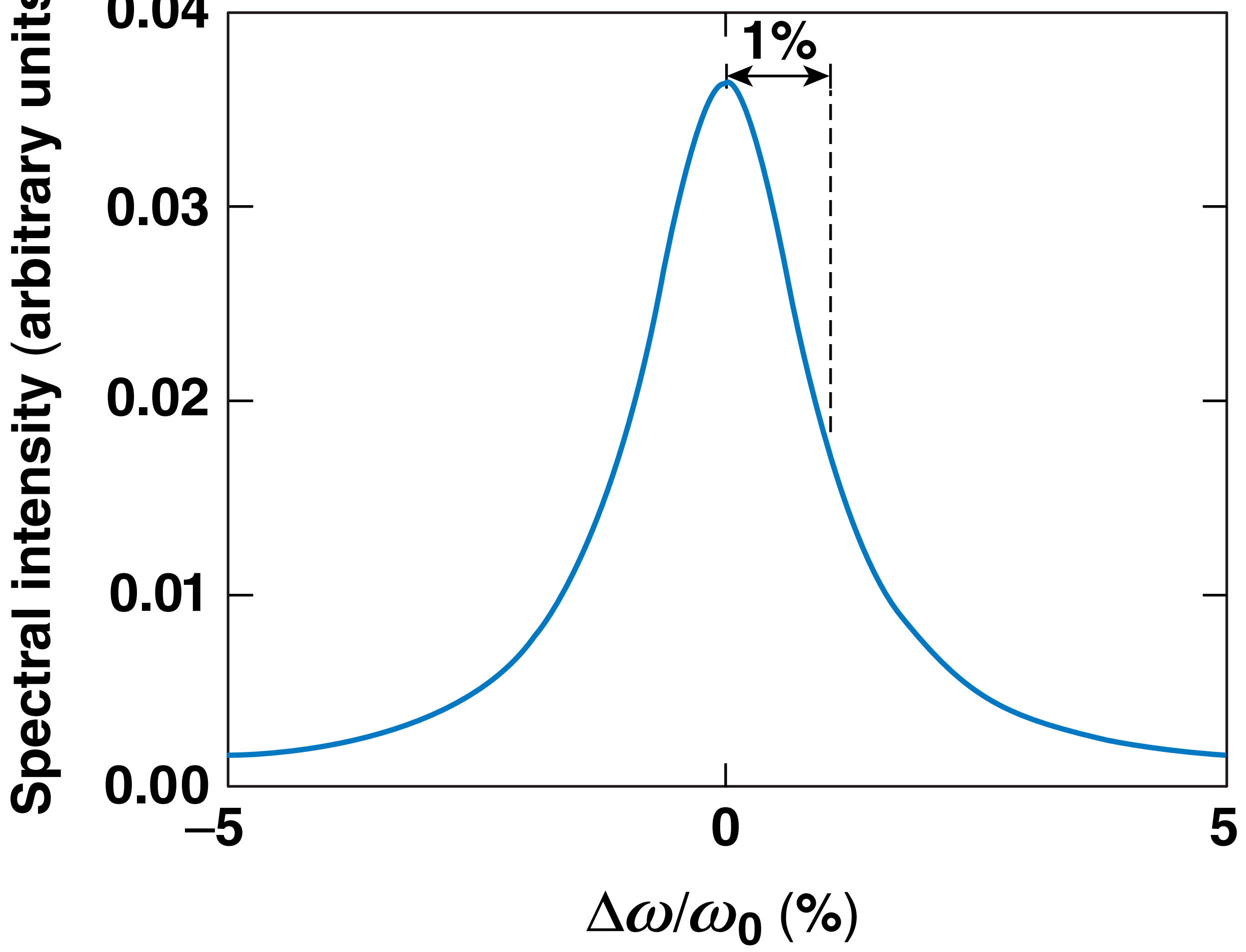


E27884

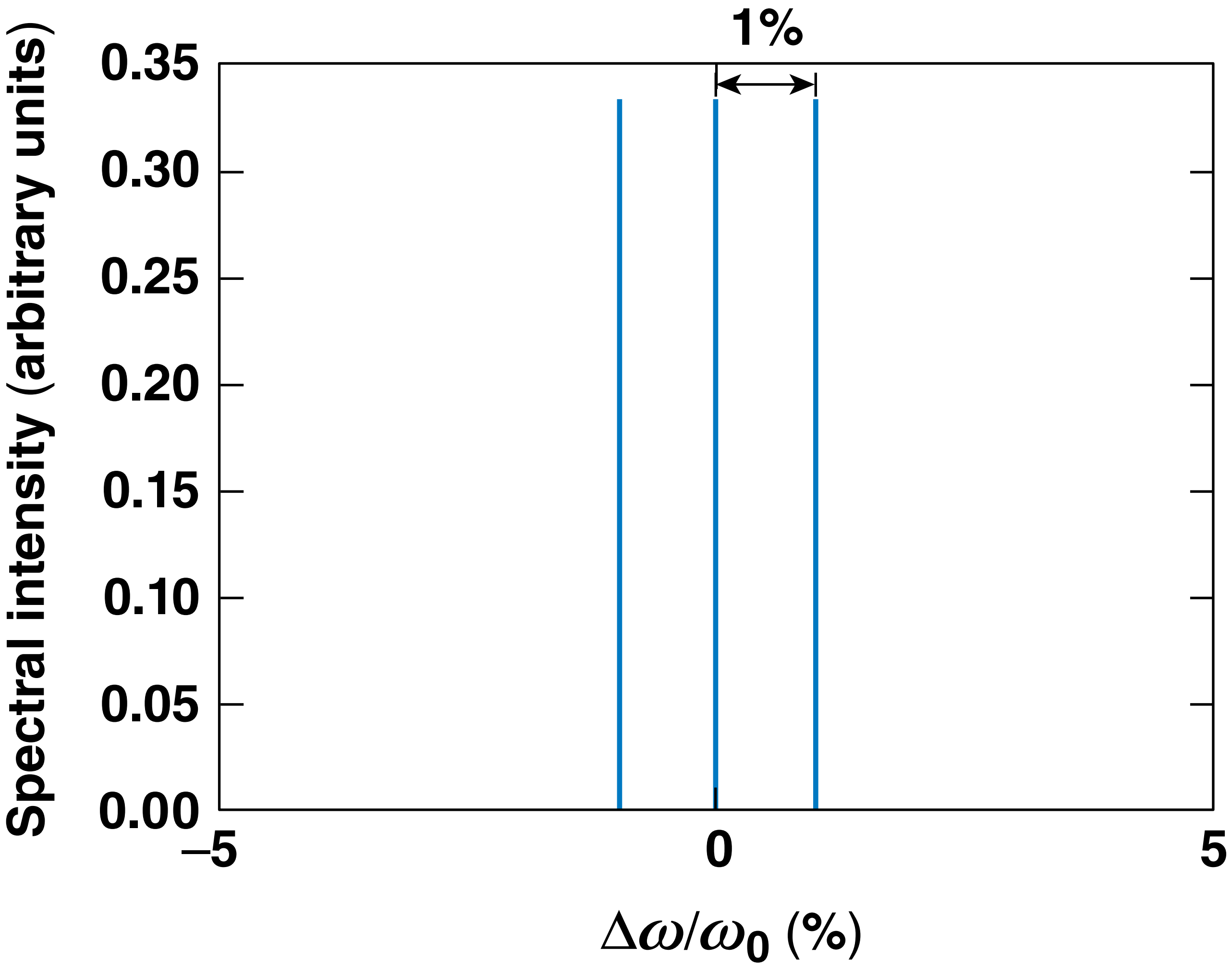
Temporal incoherence can be introduced in the form of continuous or discrete bandwidth

Continuous bandwidth (Lorentzian)

$$I(\omega) \propto \frac{1}{\omega^2 + \Delta\omega^2}$$

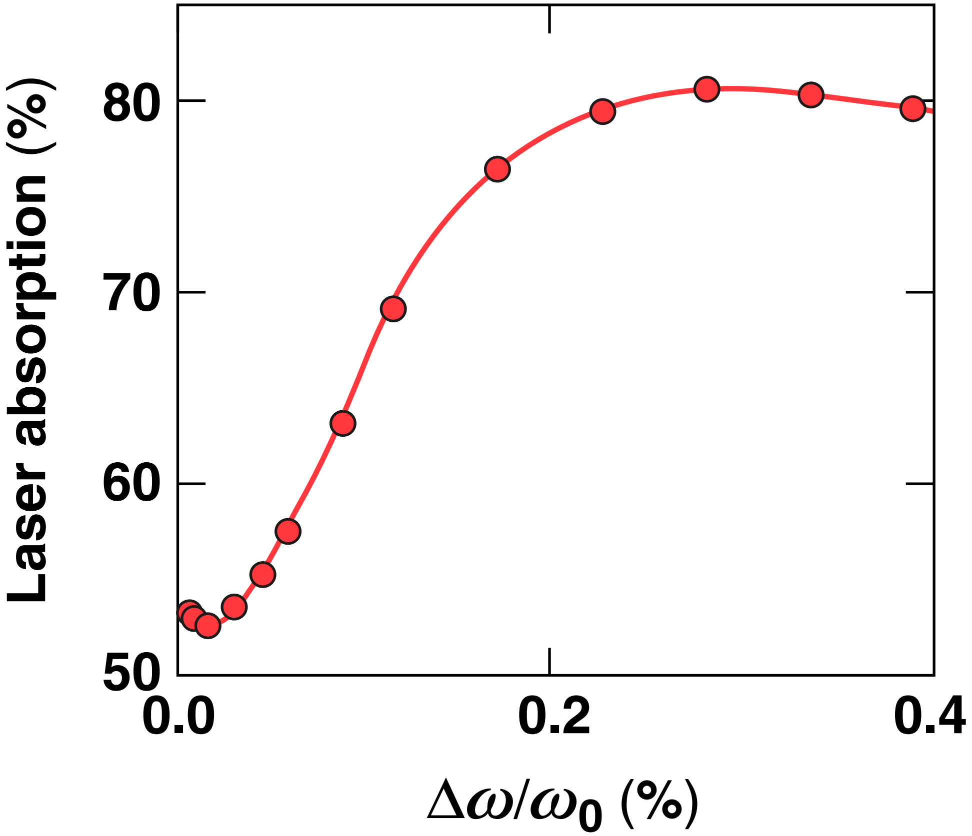


Discrete bandwidth

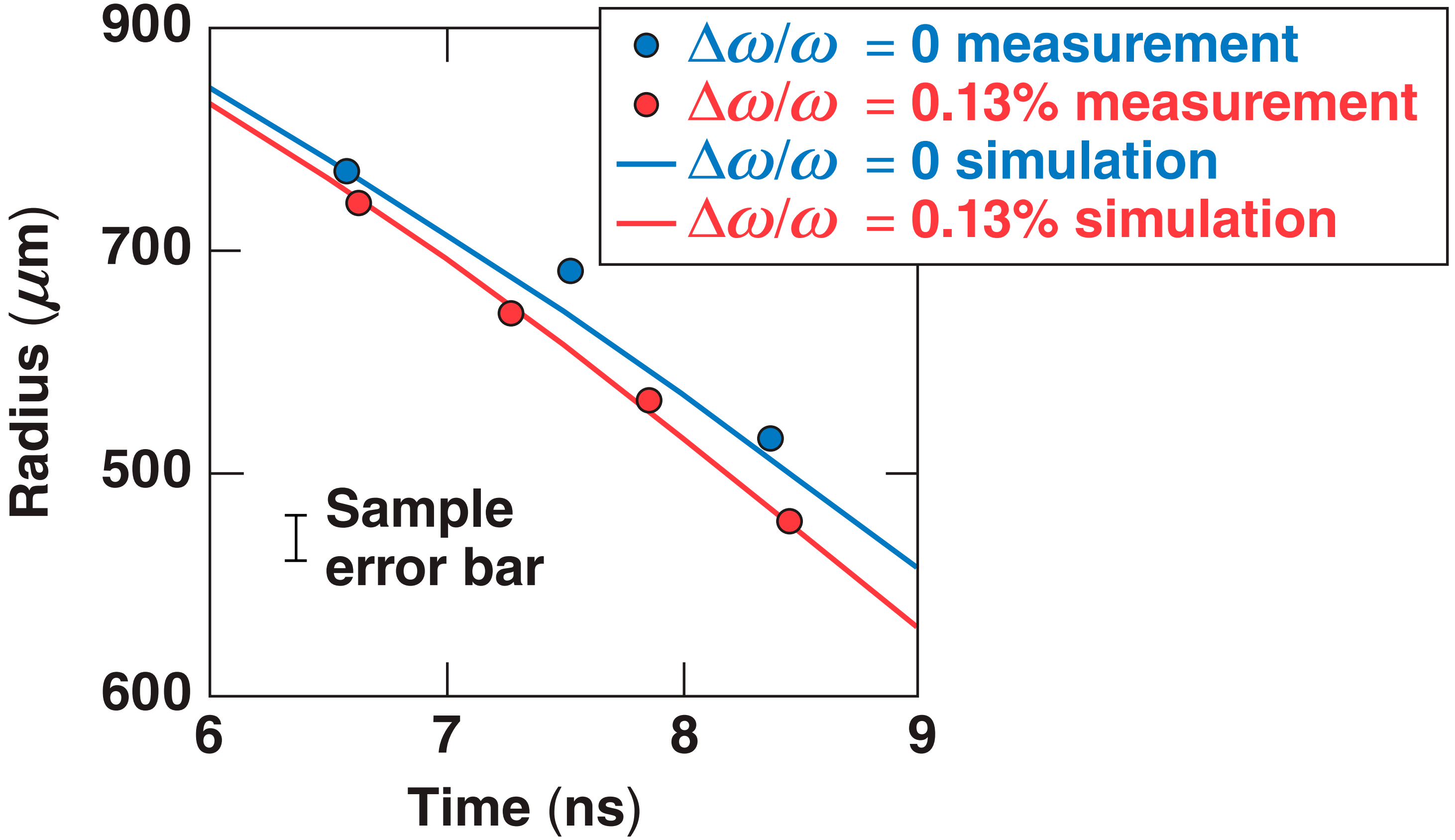


E27885

Discrete bandwidth (~0.3%) can be used to increase the laser absorption by ~50% in OMEGA implosions by mitigating CBET



CBET mitigation on OMEGA using discrete bandwidth (three colors)*



CBET mitigation using NIF polar drive with $\Delta\omega/\omega$ = 0.13% (two colors with $\Delta\lambda$ = 4.6 Å)**

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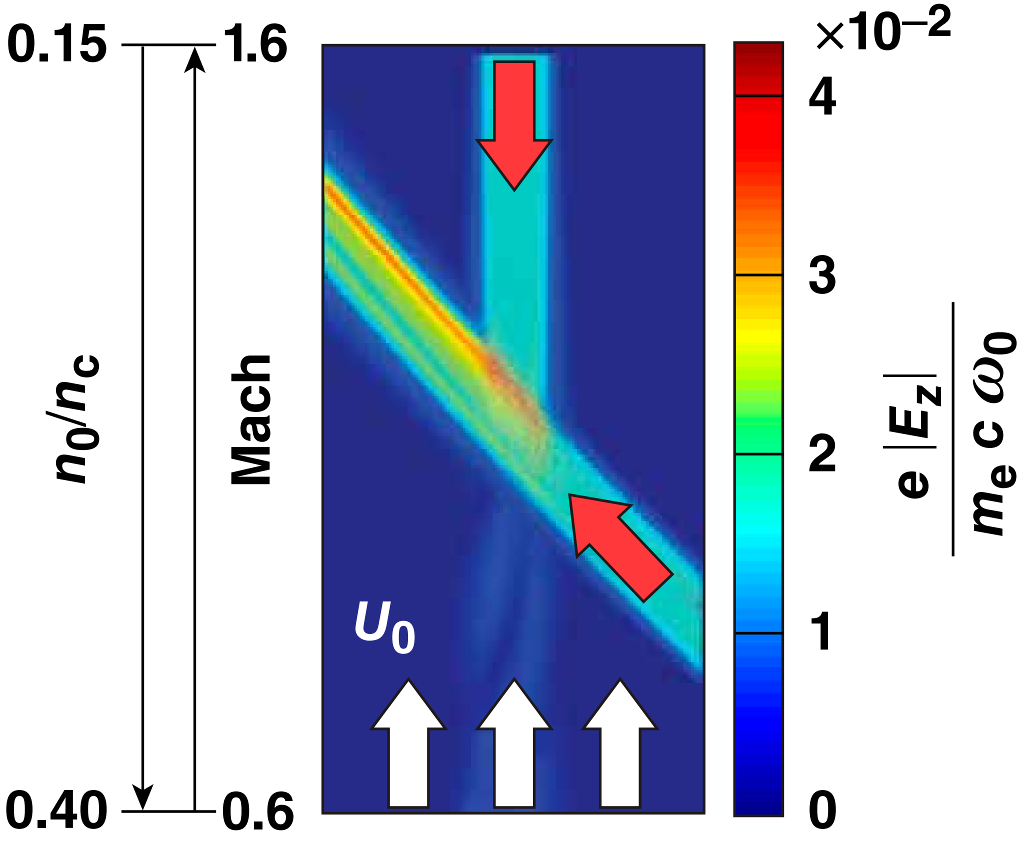
*D. H. Edgell *et al.*, Phys. Plasmas 24, 062706 (2017).

**J. A. Marozas *et al.*, Phys. Rev. Lett. 120, 085001 (2018).

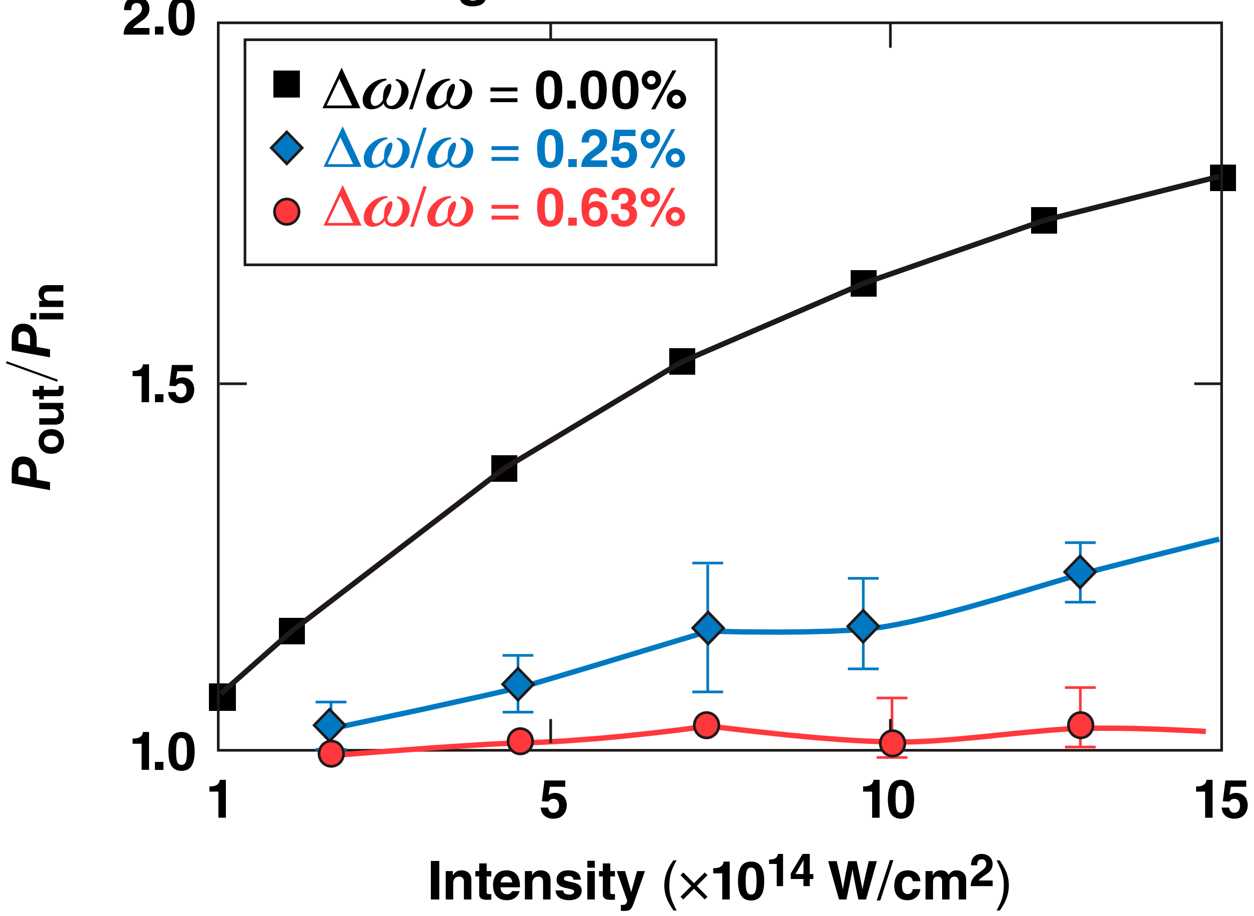
LPSE simulations show that ~0.6% of continuous bandwidth can suppress CBET in a planar two-beam configuration

Simulation geometry*

(T_e = 3 keV, T_i = 1 keV, $L_n \approx$ 200 μm)



LPSE simulations of CBET mitigation using continuous bandwidth*



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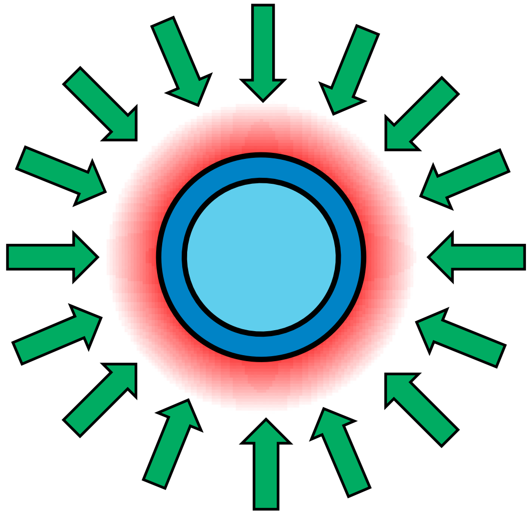
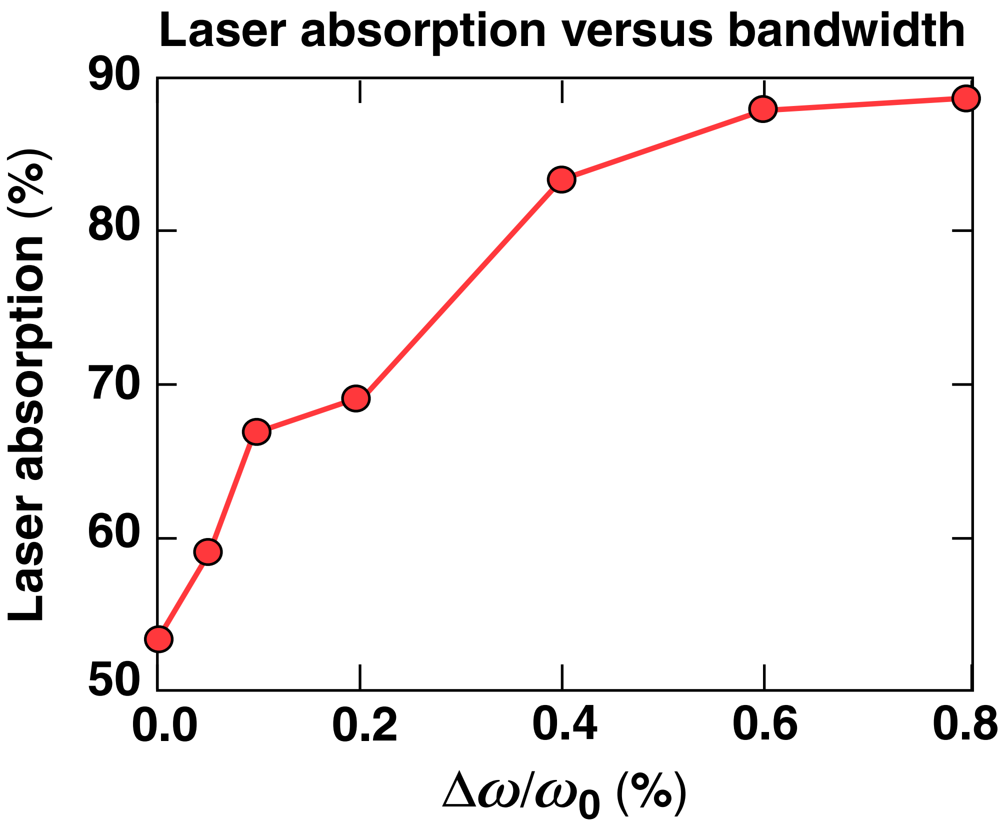
*J. W. Bates *et al.*, Phys. Rev. E 97, 061202 (2018);
J. Bates *et al.*, JO6.00006, this conference.

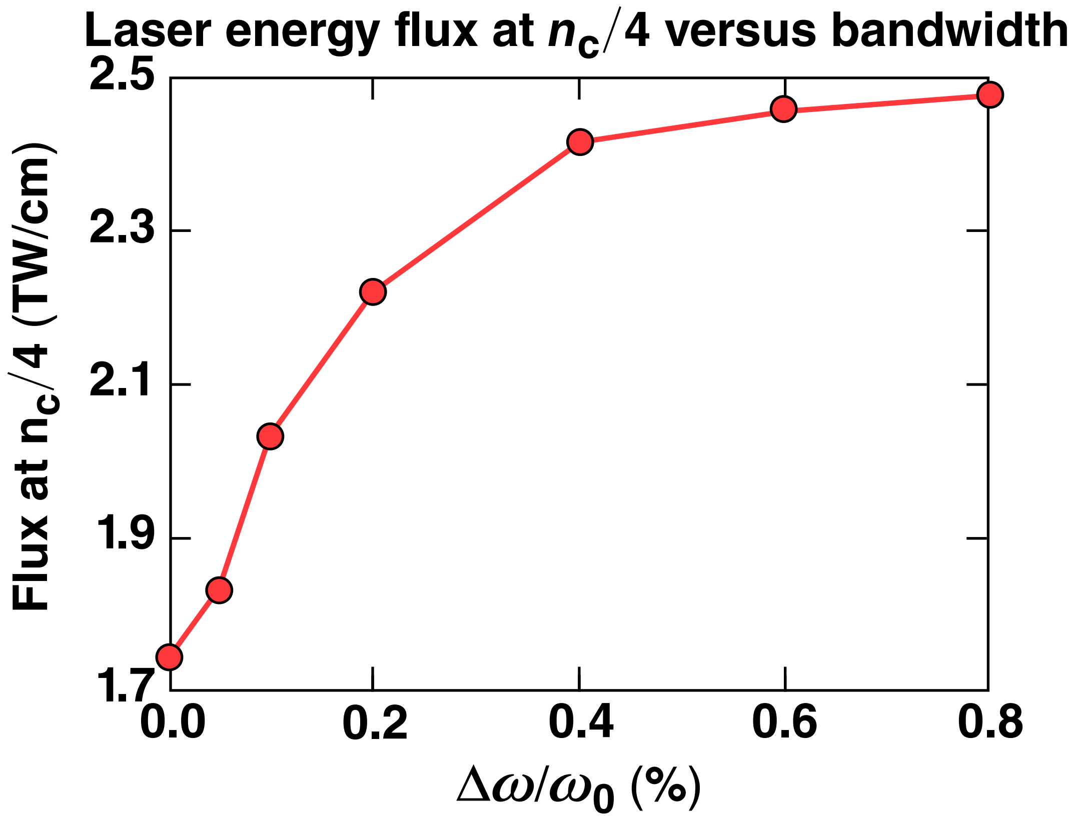
A bandwidth of ~0.6% is required to eliminate CBET in 2-D *LPSE* simulations of 16 beams incident on an azimuthally symmetric plasma profile

16-beam configuration
($I_{\text{single beam}} = 10^{14}$ W/cm^2)
(Plasma profiles taken from *LILAC* simulations of OMEGA implosion)





Laser absorption versus bandwidth

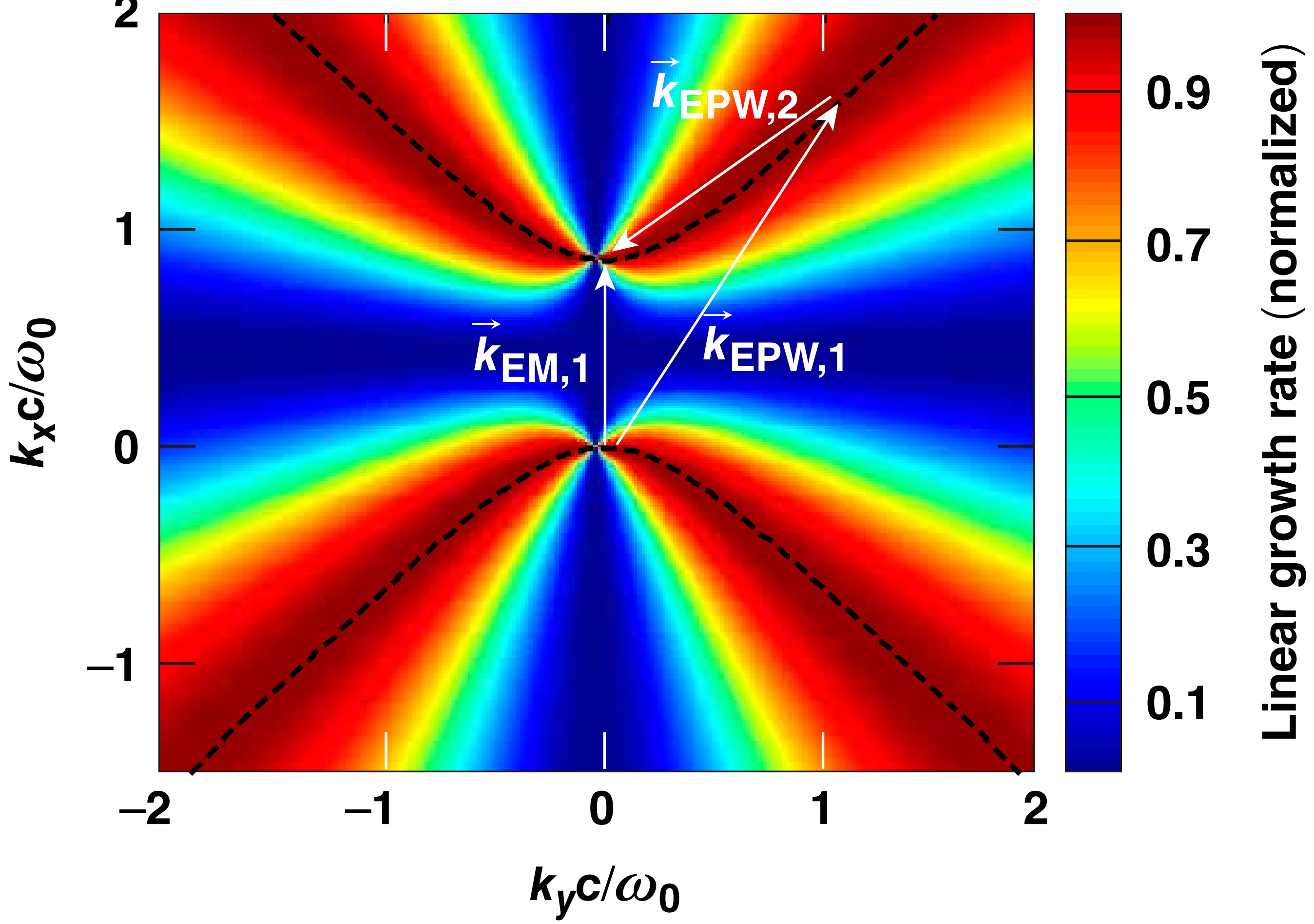


Laser energy flux at $n_c/4$ versus bandwidth

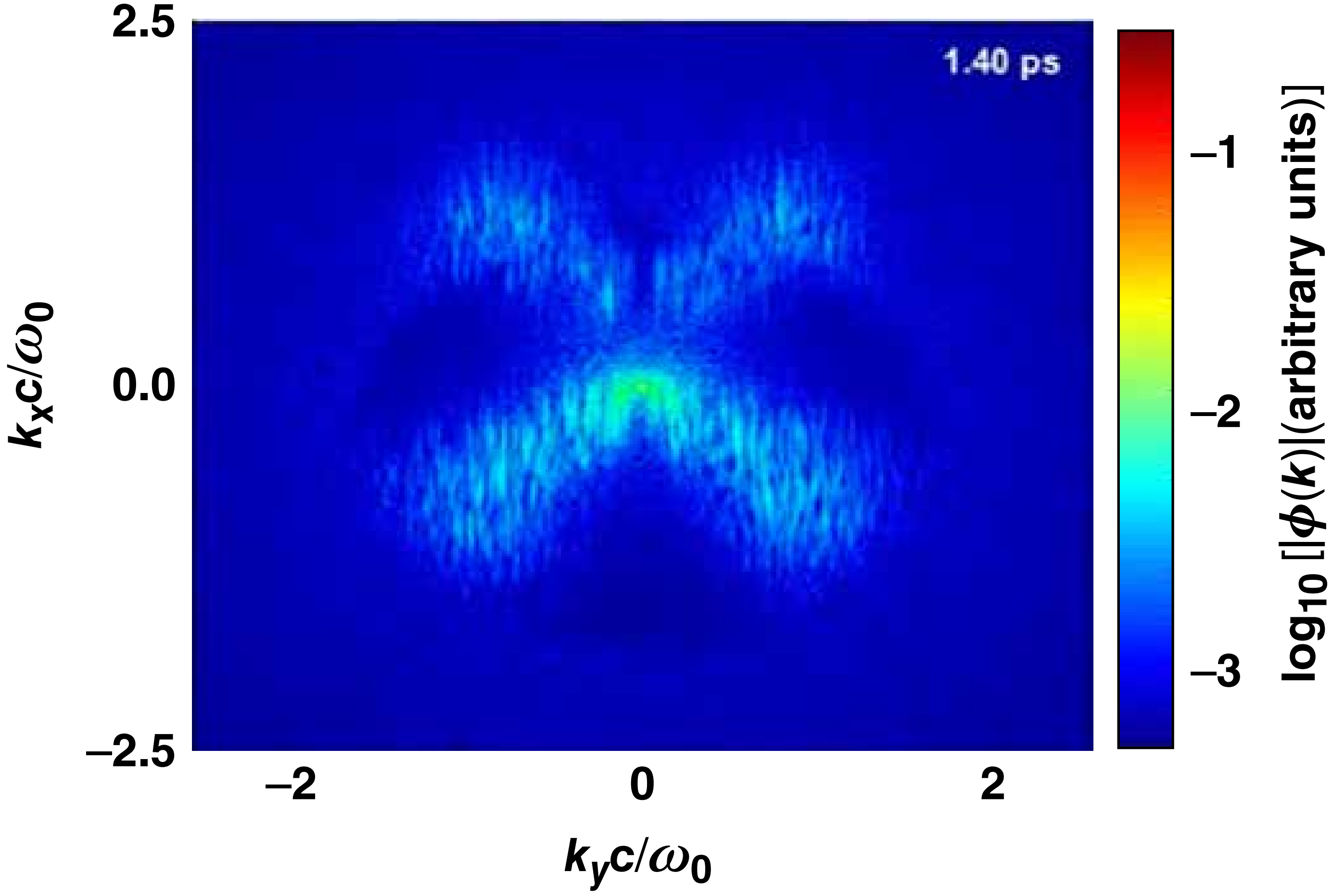
Increasing the laser intensity at $n_c/4$ by mitigating CBET could result in increased hot-electron production from TPD and SRS.

Two-plasmon decay is the resonant decay of an incident photon into two electron plasma waves that occurs near quarter-critical densities

Single-beam two-plasmon–decay growth rate



EPW *k* spectrum for a plane-wave drive beam ($I = 3 \times 10^{14}$ W/cm^2, L_n = 162.5 μm, T_e = 2 keV)



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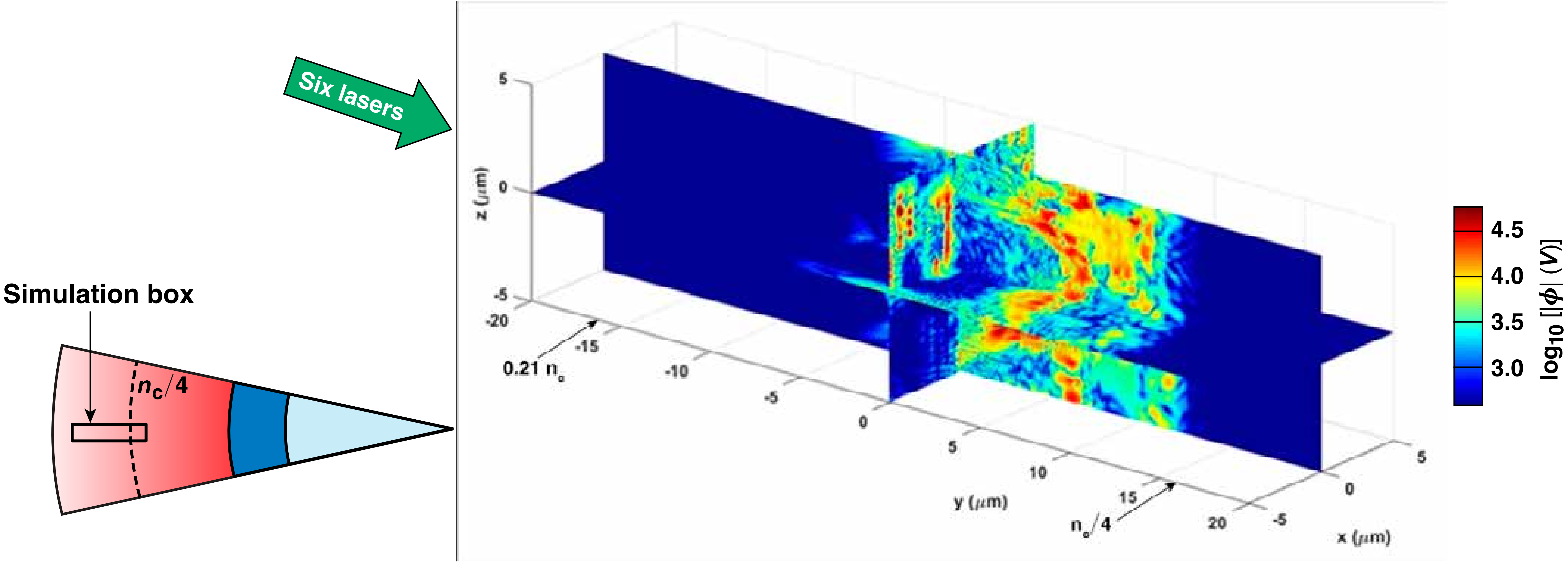
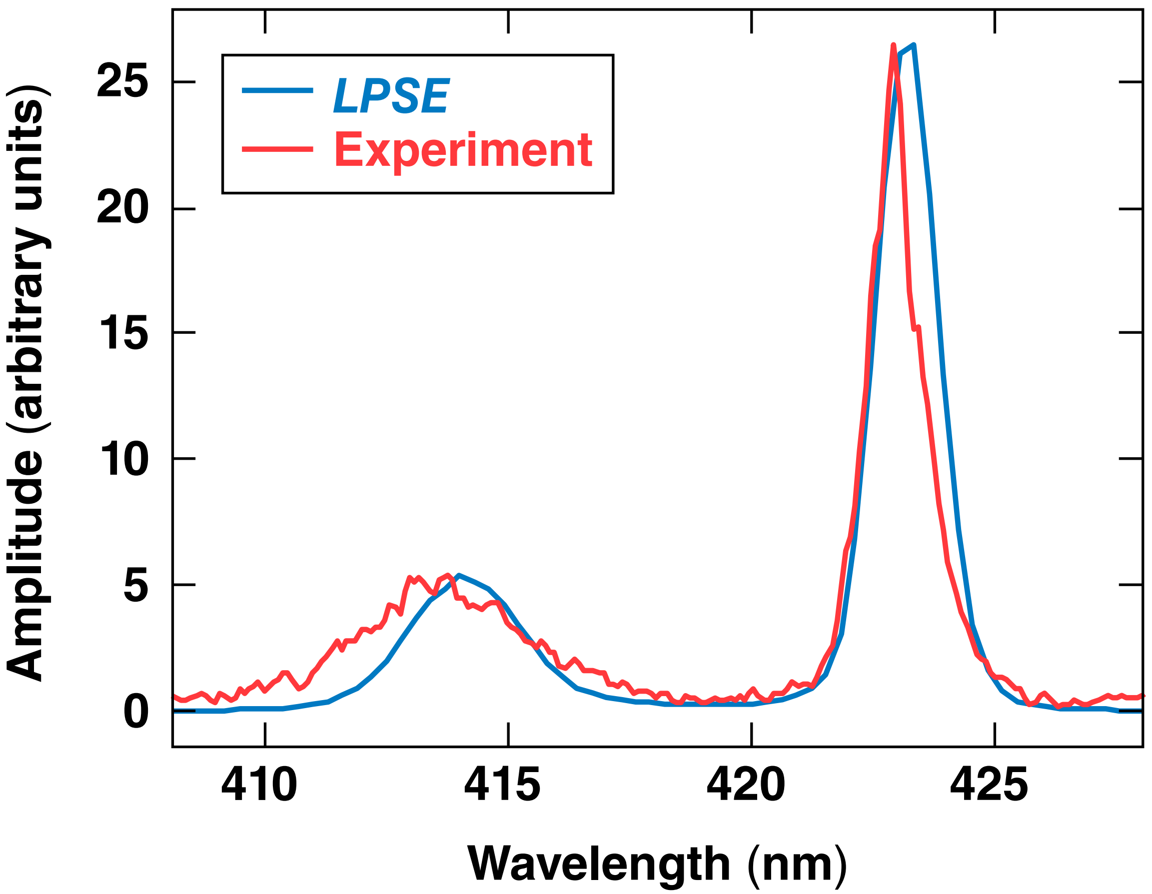
The coupling between TPD-driven EPW's and IAW's results in a turbulent spectrum of driven waves

***LPSE* simulated EPW's using the OMEGA beam geometry**

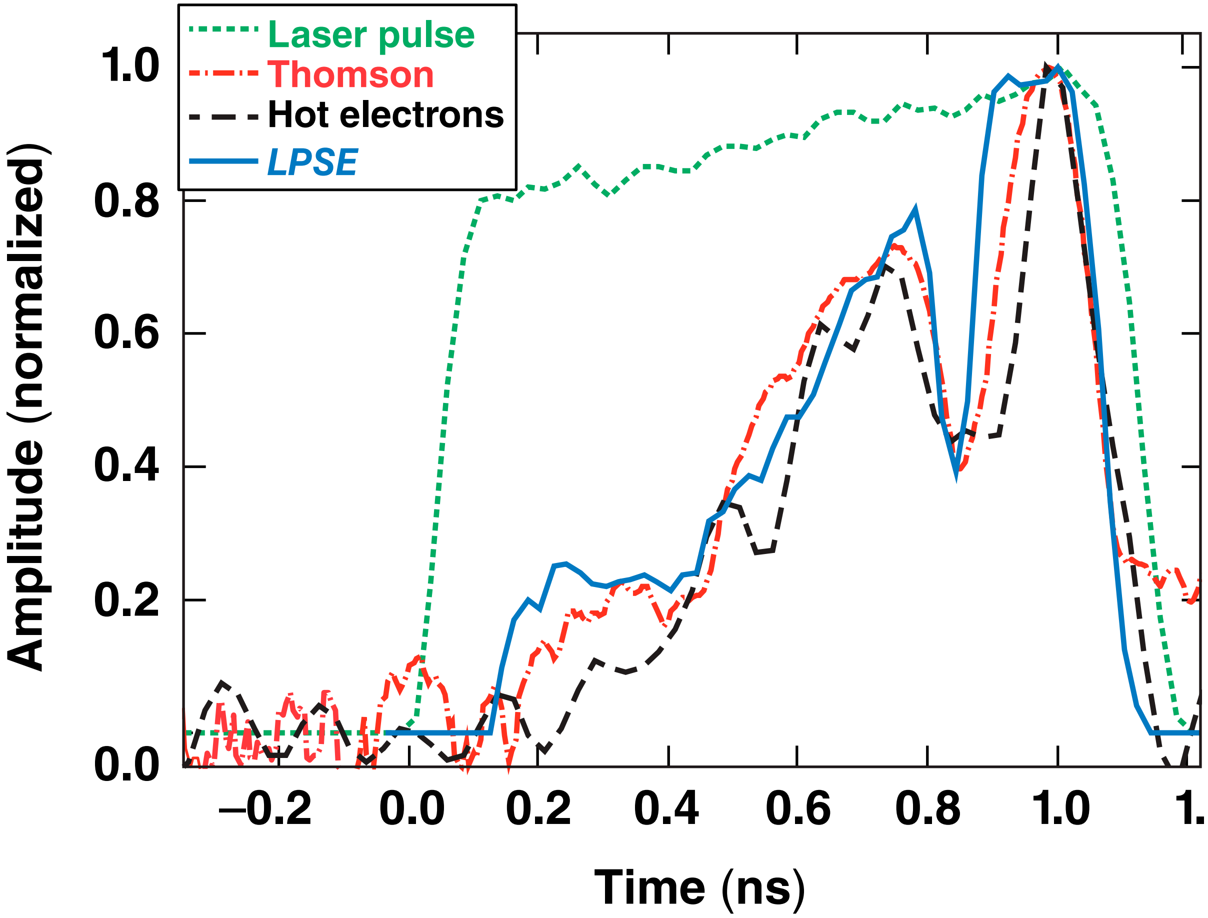


LPSE simulations show excellent agreement with Thomson-scattering and hot-electron measurements from OMEGA experiments

Comparison with Thomson-scattering spectrum*



Time history of TPD signatures**



E27892

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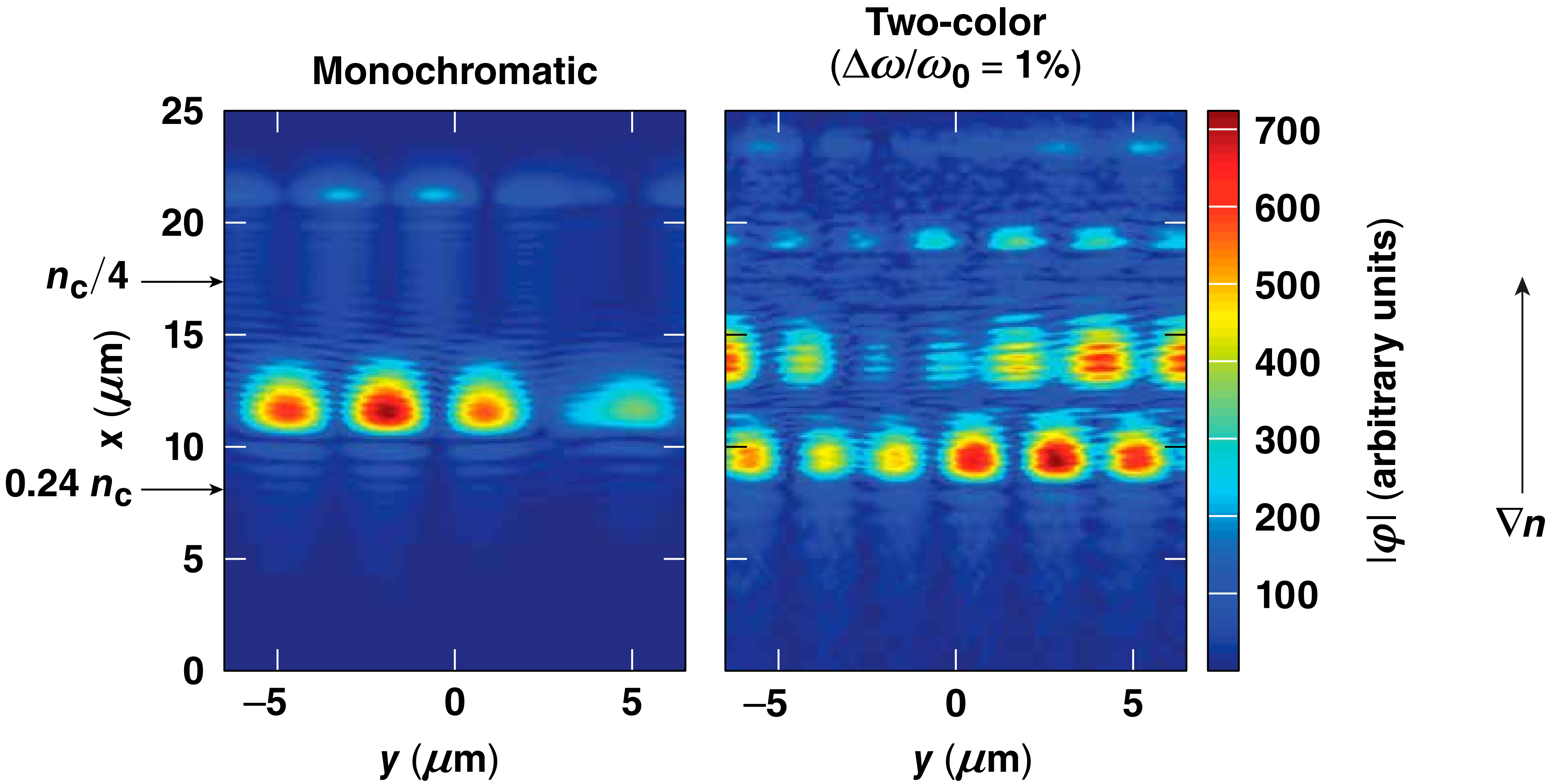
*R. K. Follett *et al.*, Phys. Rev. E 91, 031104(R) (2015).

**R. K. Follett *et al.*, Phys. Plasmas 24, 102134 (2017).

Discrete bandwidth leads to spatial separation of the absolutely unstable modes, increasing the instability threshold*



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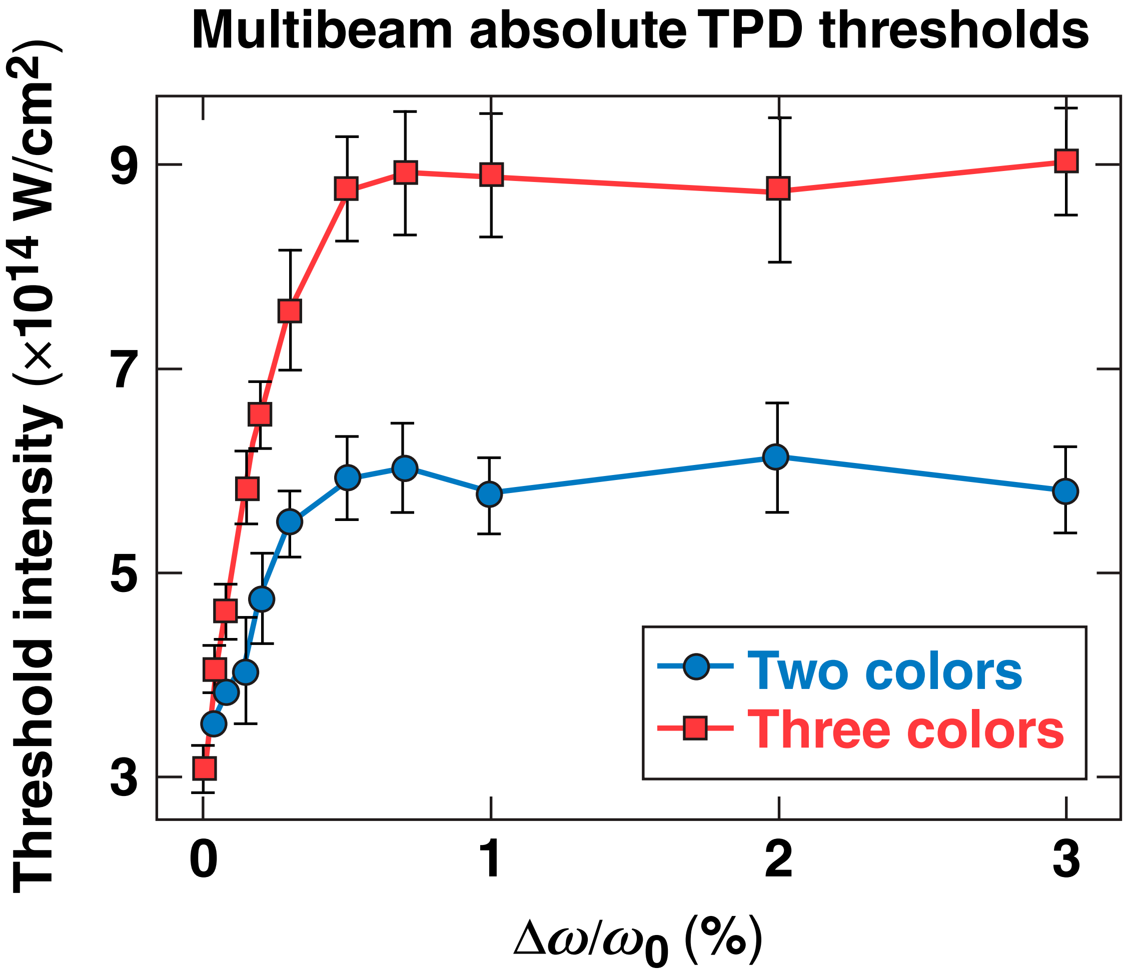
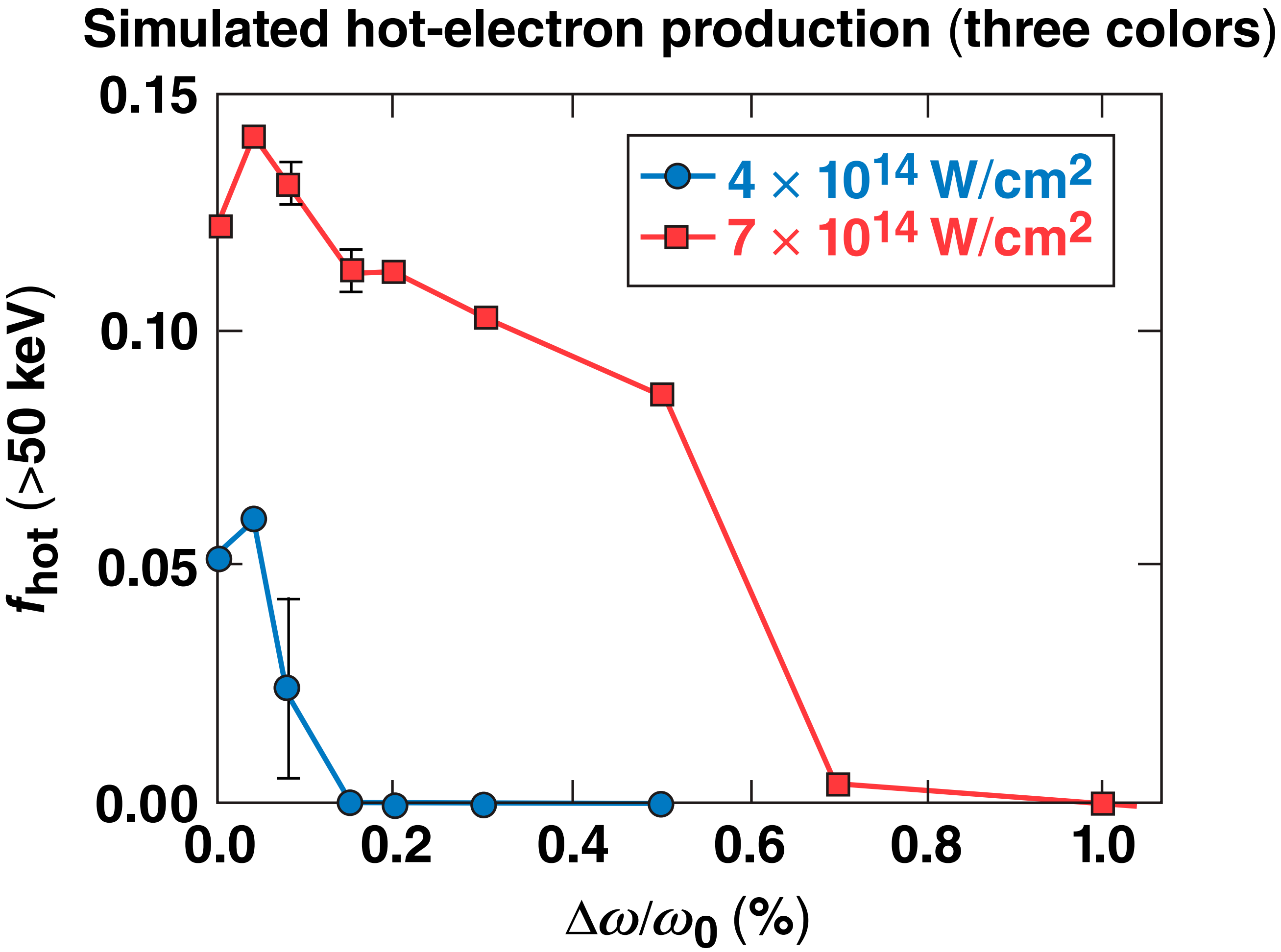
*R. K. Follett *et al.*, Phys. Rev. Lett. 120, 135005 (2018).

E27893

Discrete bandwidth with $\Delta\omega/\omega_0 \approx 0.6\%$ is sufficient to suppress hot-electron generation at conditions relevant to OMEGA experiments

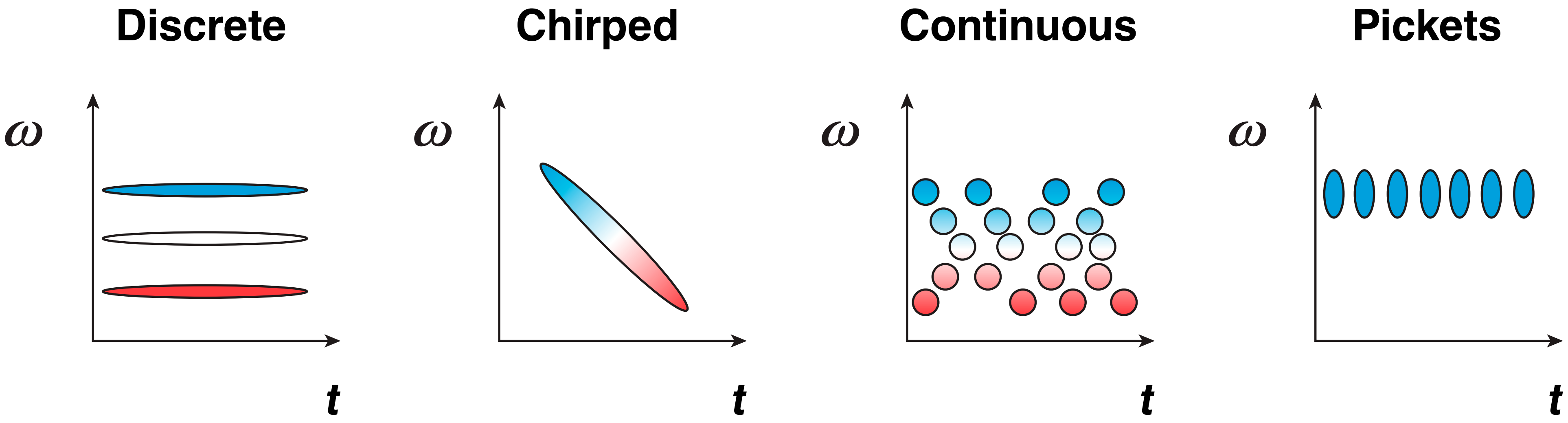




E27894

A broadband laser based on optical parametric amplifiers is currently being explored at LLE

Potential bandwidth formats

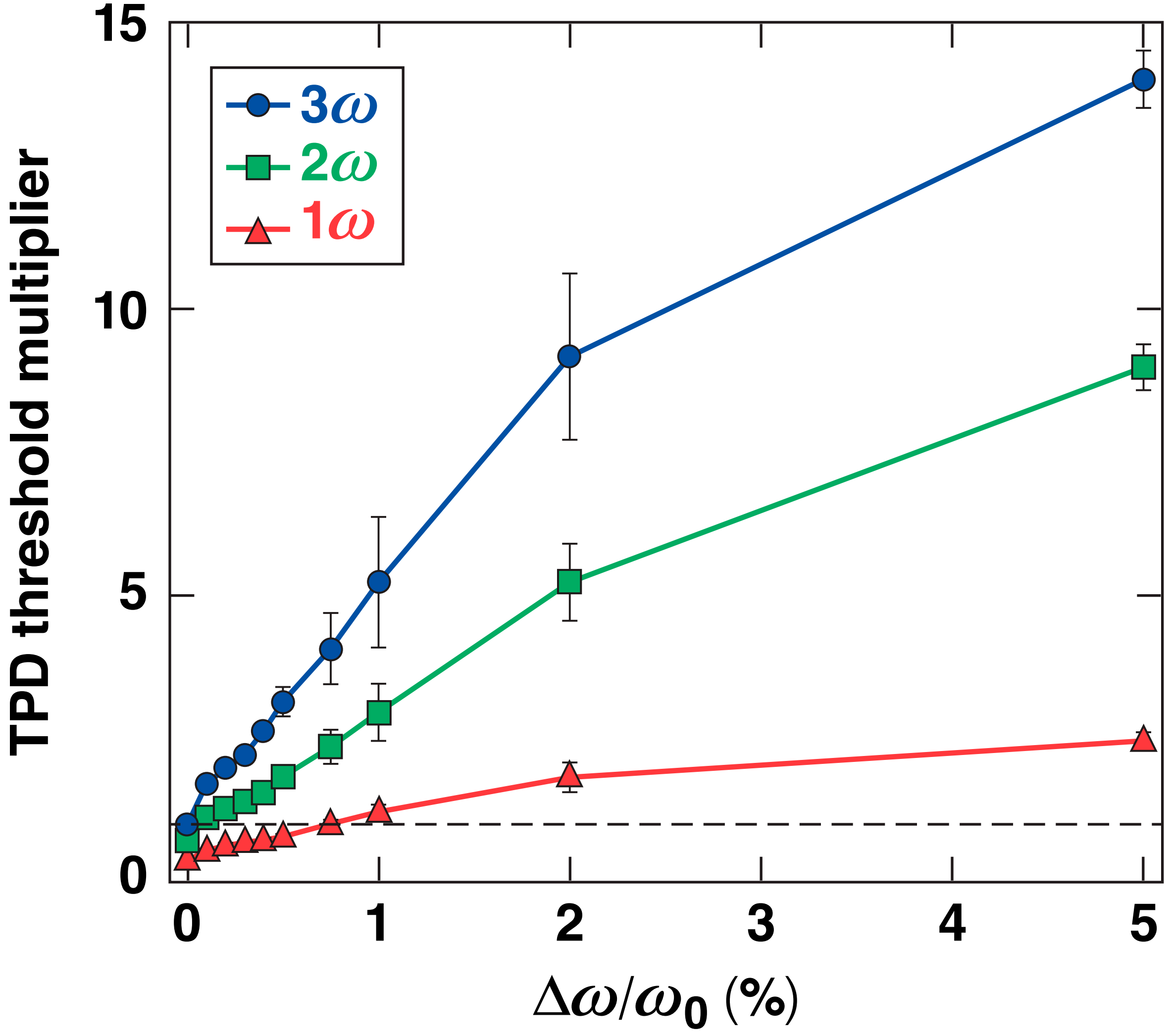


- **Introducing bandwidth to suppress LPI can be accomplished in several different forms**
  - multiple carrier wavelengths
  - temporal chirping
  - incoherent “spead spectrum”
  - picket waveforms

LPI: laser–plasma instability

The use of sufficiently large bandwidth beams opens up the possibility for higher-intensity or longer wavelength beams

LPSE-simulated TPD threshold as a function of Lorentzian bandwidth



E27896

Summary/Conclusions

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- Laser bandwidth can be used to suppress many of these instabilities and open up the implosion design space
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