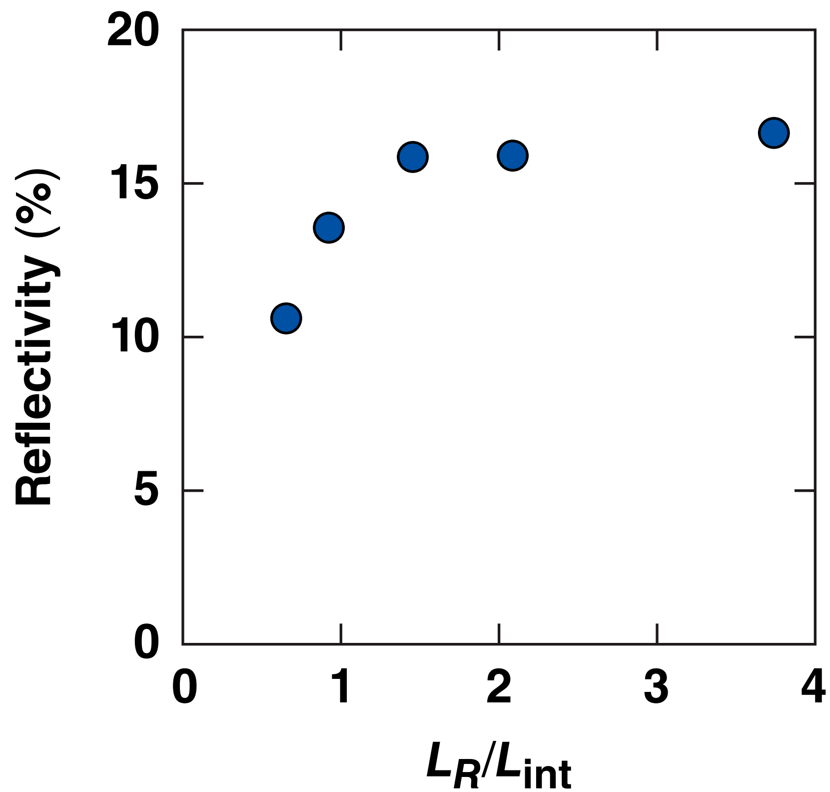
Nonlinear Interaction Between Multiple Incoherent Laser Beams in the Plasmas of Direct-Drive ICF



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In the plasmas of direct-drive inertial confinement fusion (ICF), the scattering of light is determined by the interaction of multiple incoherent beams via common ion waves

- When driven by incoherent laser beams
  - the scattered-light direction is determined by the laser speckle structure
  - the scaling of reflectivity with intensity is determined by the interaction in high-intensity speckles
- The reflectivity depends strongly on the ratio between the laser coherence length and the interaction length
- Multiple crossing laser beams can drive common ion waves and scatter off them, increasing the overall reflectivity

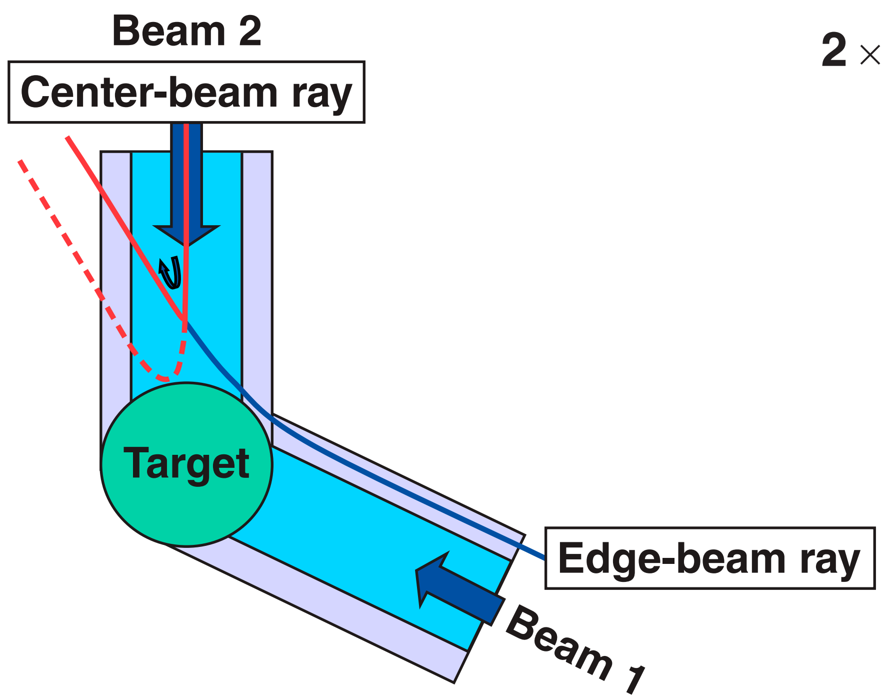
Outline

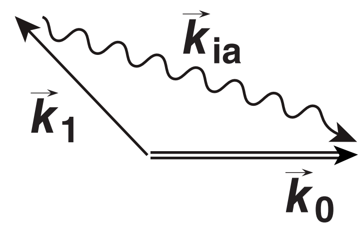
- Motivation from hydrodynamic modeling and experimental results
- Numerical modeling of nonlinear interaction between crossing laser beams
- Scaling of the reflectivity with the laser intensity
- Common ion-acoustic waves driven by multiple laser beams

In large-scale hydrodynamic simulations, cross-beam energy transfer is shown* to significantly influence the laser absorption

- For direct-drive ICF plasmas, the interaction between rays is

$$\frac{dI_1}{d\ell} = I_1 I_0 \underbrace{\frac{\omega_0^2}{2c^2 n_c}\mathrm{Re}\left\{\frac{n_e k_{ia}^2 c_{ia}^2}{2\nu_i \omega_{ia} + i\left[(\omega_{ia} + k_{ia} v_0)^2 - k_{ia}^2 c_{ia}^2\right]} \times \frac{1}{2k_{0x}}\right\}}_{2 \times \mathrm{Re}\, g(\vec{k}_{ia})}$$



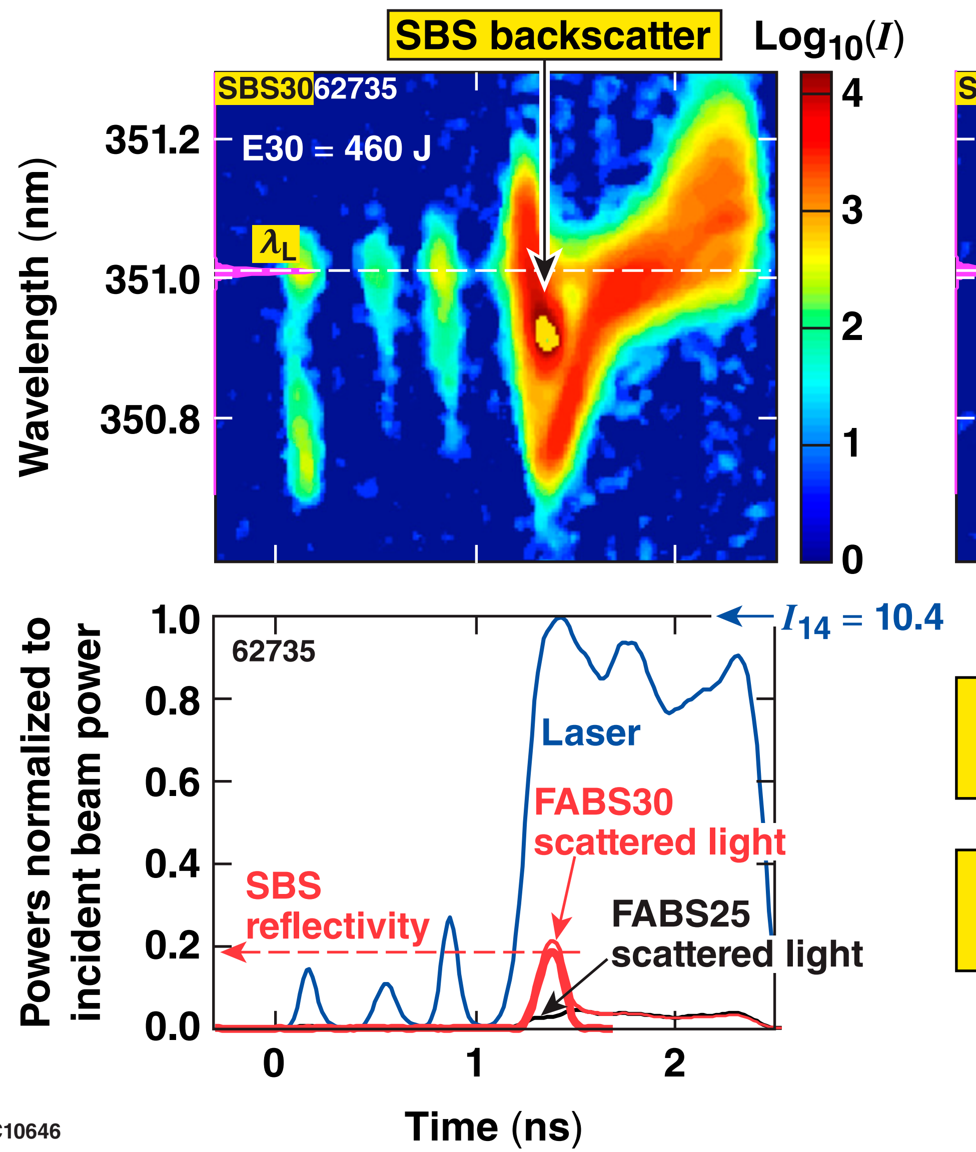


- Cross-beam energy transfer reduces the energy of incoming center-beam light and increases the energy of outgoing edge-beam light

E19905u

*I. V. Igumenshchev *et al.*, Phys. Plasmas 19, 056314(2012).

Stimulated Brillouin scattering (SBS) backscatter is clearly visible in implosion shots with a fast rising main pulse



SBS increases when the velocity profile has a shelf.

Low level of scattered light is observed between the FABS.

TC10646

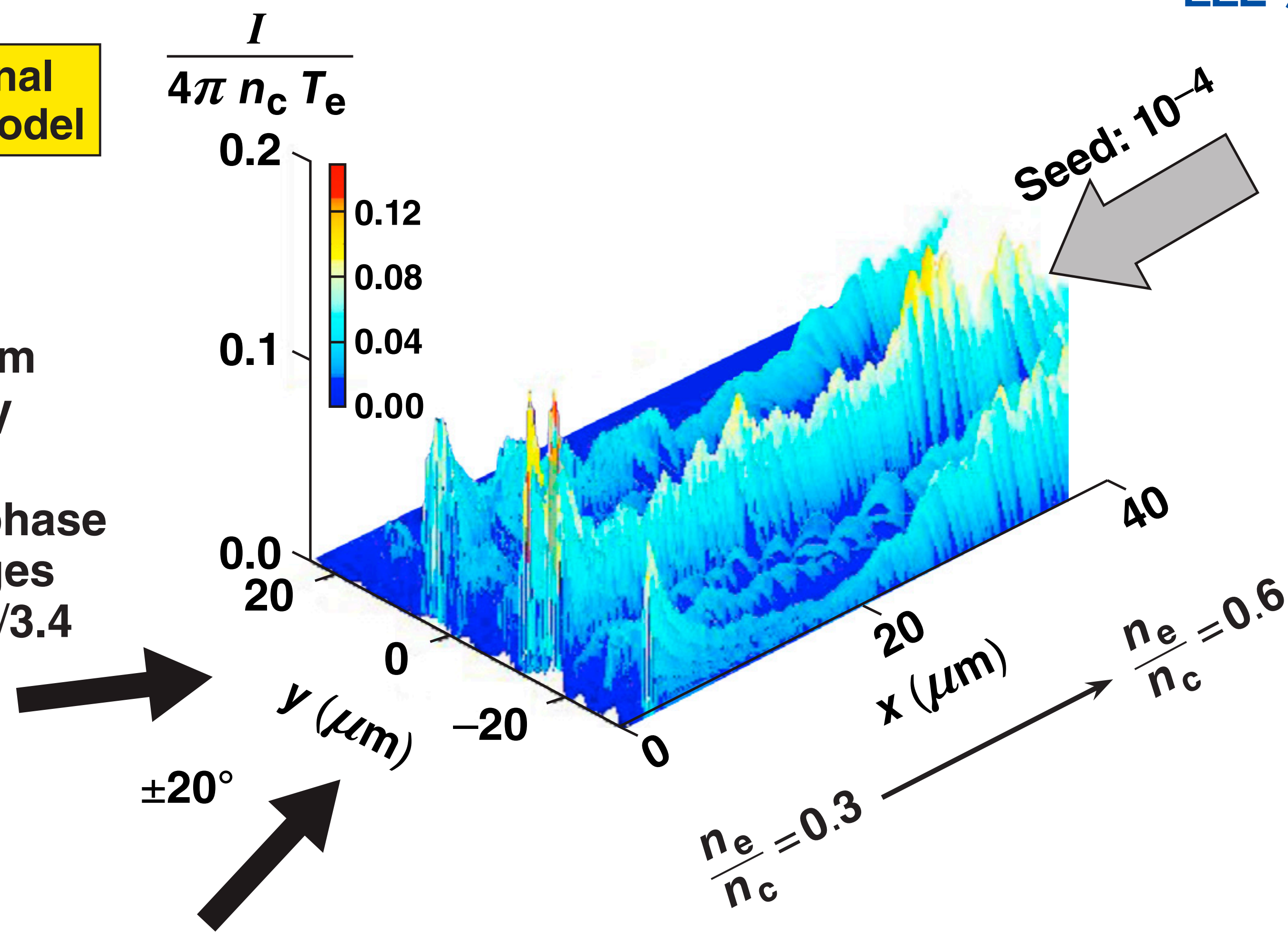
The nonlinear propagation of crossing laser beams has been modeled in the region of moderate plasma density, about 0.3 n_c to 0.6 n_c

UR LLE

Two-dimensional nonparaxial model

L_n = 140 μm
T_e = 2 keV

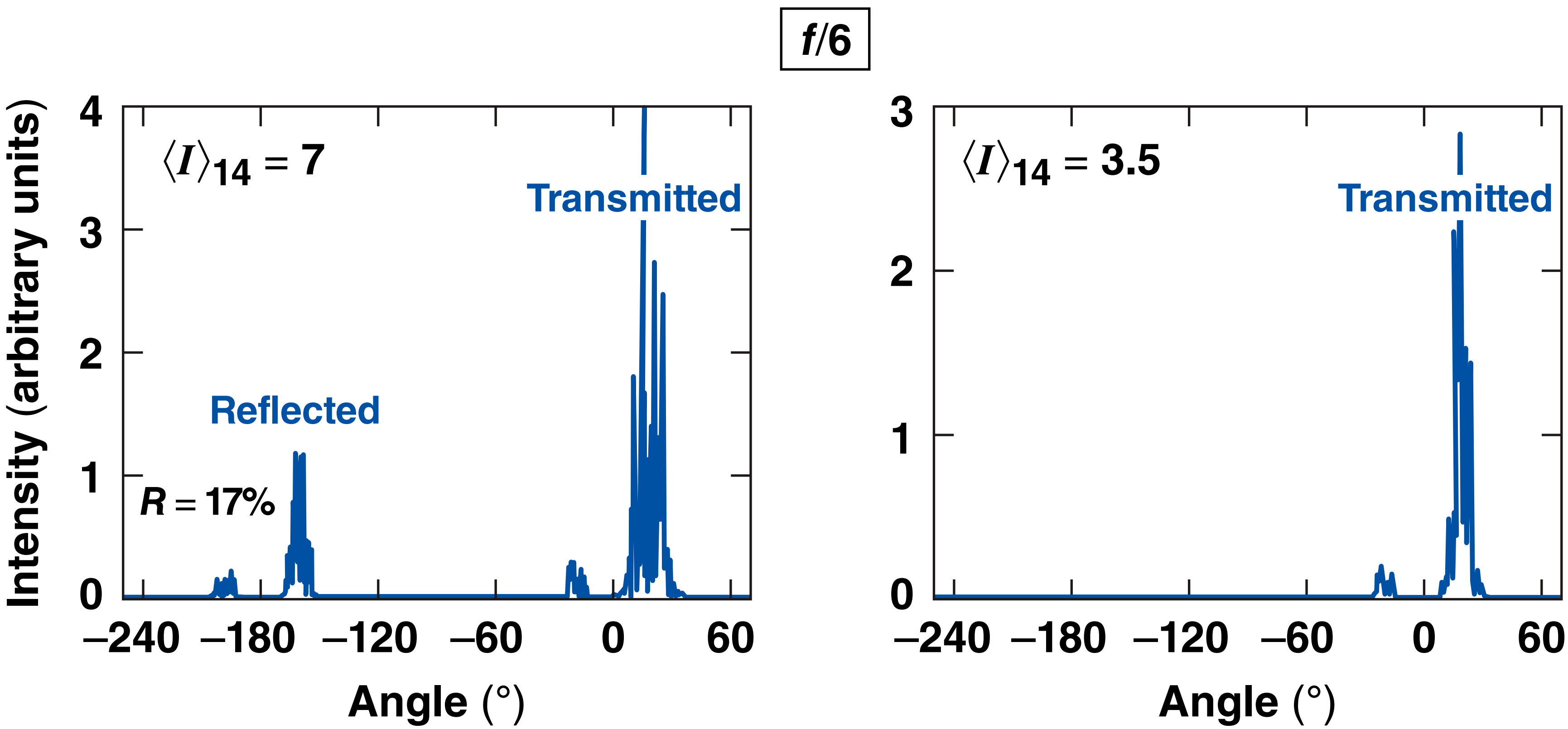
Distributed phase plate *f* changes from *f*/15 to *f*/3.4



TC9444b

The threshold for the backscattering driven by crossing laser beams has been found at moderate laser intensities

- The intensities of the two driving beams differ by a factor of 10

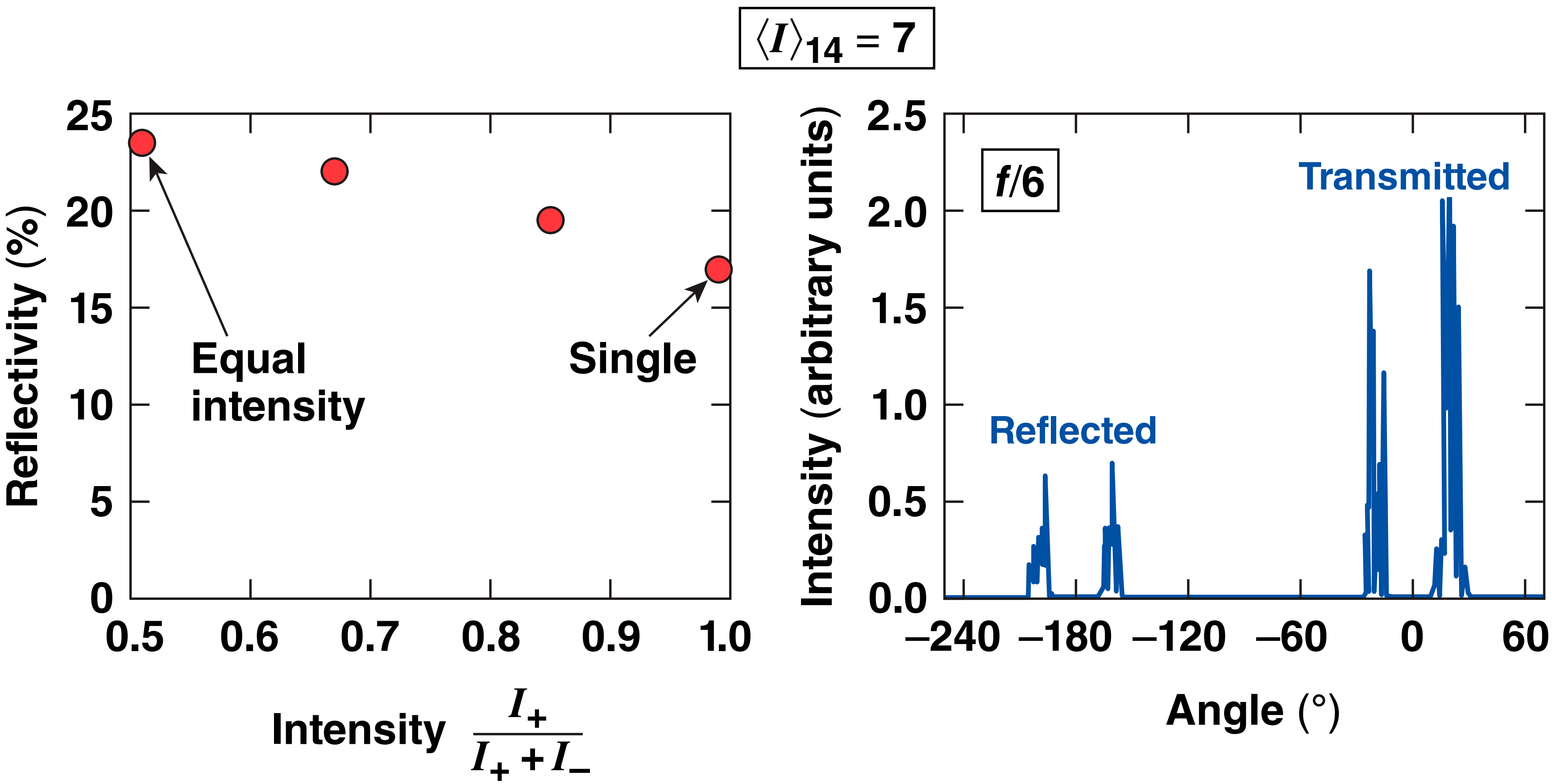


$$G_{SBS} = 0.24 \langle I \rangle_{14} \left(\frac{I_{max}}{\langle I \rangle} \right)$$

Interaction takes place mostly in high intensity hot spots.

TC9445c

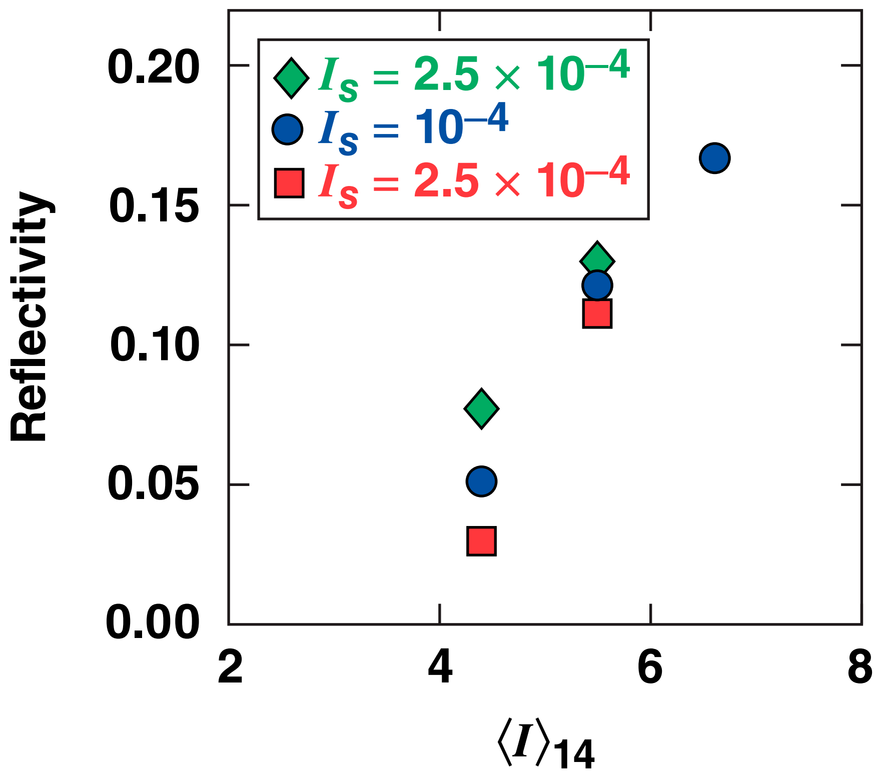
The reflectivity has a moderate dependence on the distribution of intensity between the driving laser beams



The hot-spot structure determines the direction of scattered light.

TC9798

The dependence of reflectivity on the seed level indicates the saturation of scattering in high-intensity laser speckles



- Changing the seed level by a factor of 2.5 (increasing and decreasing)
  - leads to significant changes in the reflectivity in the linear regime
  - leads to small changes in reflectivity in the saturated regime

TC10633

The nonlinear interaction in intense laser speckles determines the scaling of reflectivity with intensity

Reflectivity

$$\frac{d\langle R\rangle}{dx} \sim U_m^3 e^{-U_m},$$

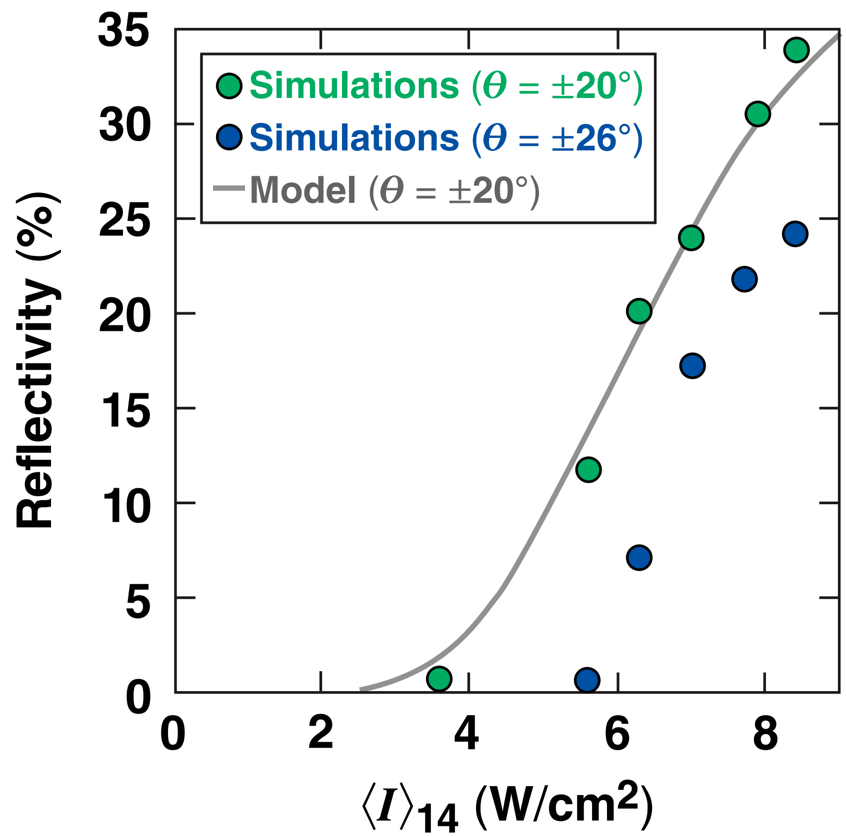
where

$$U_m \equiv \frac{I_m}{\langle I\rangle}$$

for the saturation R_{sat}*

$$R_{sat} = \varepsilon\, e^{\langle G_{SBS}\rangle U_m}$$

ε – seed

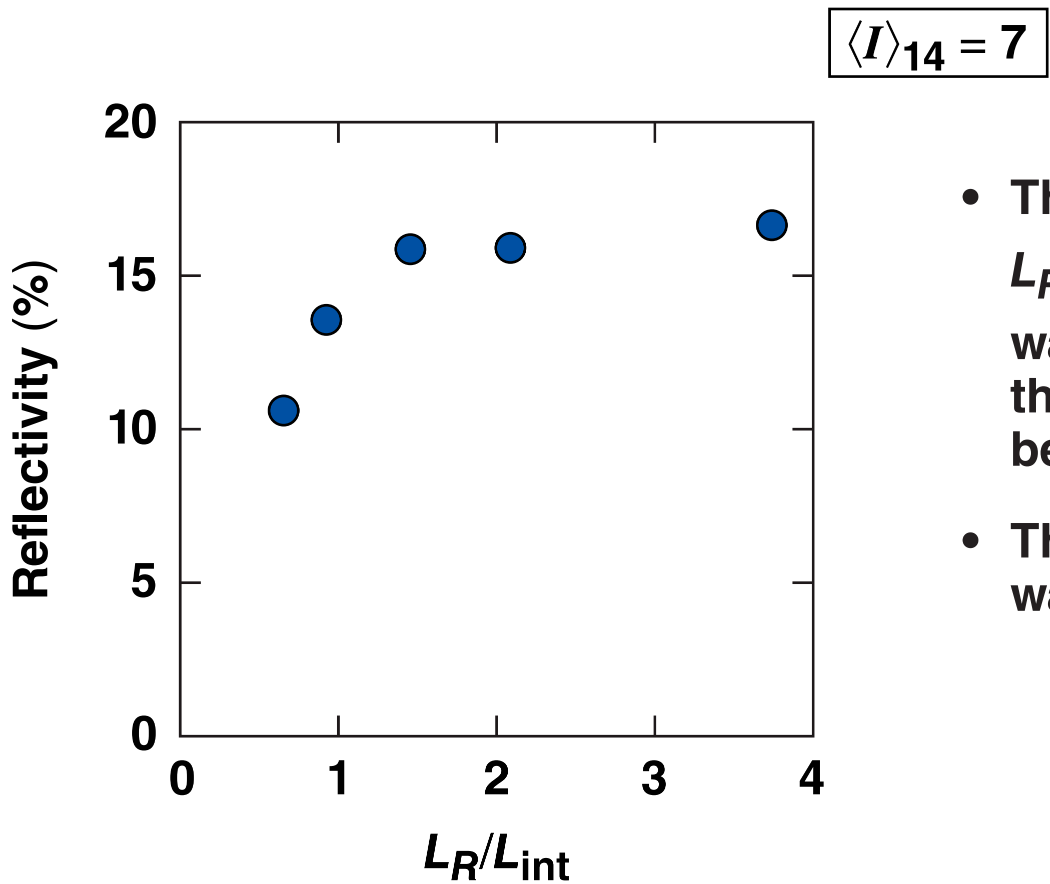


Coupling via common grating is weaker for larger θ

*H. A. Rose and D. F. DuBois, Phys. Rev. Lett. 72, 2883 (1994).

TC9446c

The reflectivity is determined by the ratio of the coherence length to the interaction length



- The coherence length
  $L_R = 2\pi \cdot f^2 \lambda_0$
  was changed by changing the *f* number of incident laser beams from $f = 8$ to $f = 3.4$
- The interaction length L_{int} was not changed

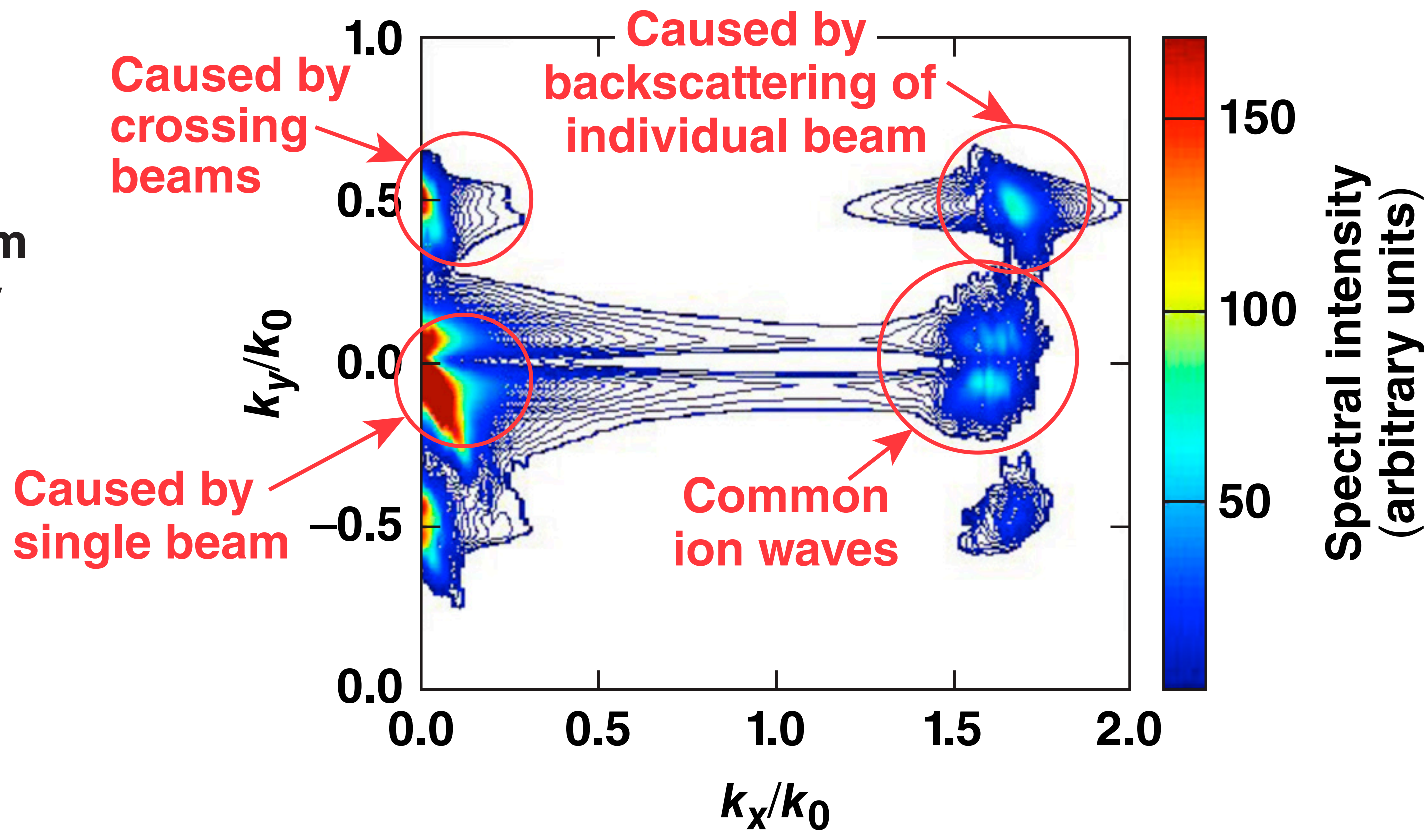
The interaction of incoherent crossing laser beams with plasmas produces a broad spectrum of low-frequency density perturbations

$\boxed{\langle I \rangle_{14} = 8}$

$L_n = 140\ \mu m$
$T_e = 2$ keV

$\boxed{f/6}$

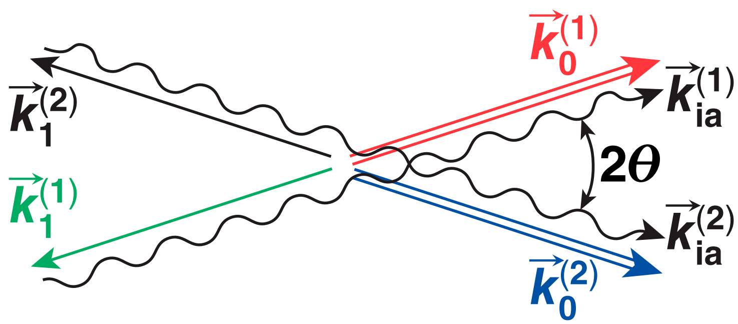
Spectrum of density perturbations



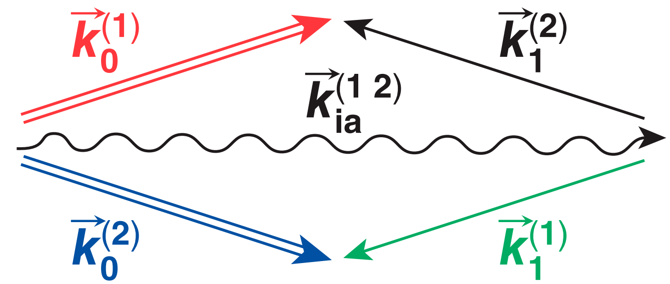
Laser beams can share density perturbations.

Crossing laser beams can scatter off common ion waves driven by multiple beams

Backscattering of individual beams



Scattering off common ion waves

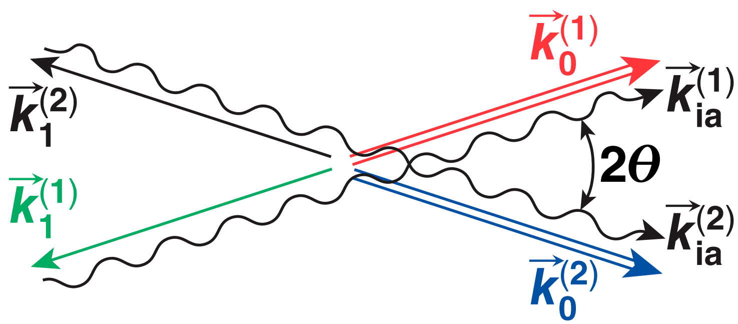


$$\frac{dE_1^{(1)}}{d\ell_1} = g\left[\vec{k}_{ia}^{(1\,2)}\right]\underbrace{\left[E_1^{(1)}E_0^{(2)*} + E_1^{(2)}E_0^{(1)*}\right]}E_0^{(2)} + g\left[\vec{k}_{ia}^{(1)}\right]\underbrace{\left|E_0^{(1)}\right|^2 E_1^{(1)}}$$

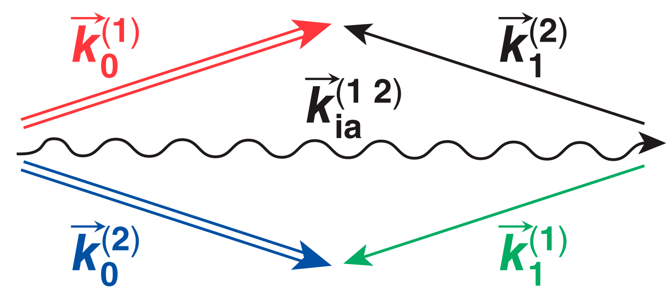
$$\frac{dE_1^{(2)}}{d\ell_2} = g\left[\vec{k}_{ia}^{(1\,2)}\right]\underbrace{\left[E_1^{(1)}E_0^{(2)*} + E_1^{(2)}E_0^{(1)*}\right]}_{\text{common grating}}E_0^{(1)} + g\left[\vec{k}_{ia}^{(2)}\right]\underbrace{\left|E_0^{(2)}\right|^2 E_1^{(2)}}_{\text{backscattering}}$$

Scattering is possible in the direction opposite to the weaker beam.

Resonant conditions for common ion waves depend on the angle between driving laser beams



$\vec{k}_{ia}^{(1)} = 2\vec{k}_0^{(1)}$ $\vec{k}_{ia}^{(2)} = 2\vec{k}_0^{(2)}$



$\vec{k}_{ia}^{(1,2)} = \vec{k}_0^{(1)} + \vec{k}_0^{(2)}$

$$g\left[\vec{k}_{ia}\right] = \frac{\omega_0^2}{16\pi n_c^2 T_e c^2} \times \frac{n_e k_{ia}^2 c_{ia}^2}{2\nu_i \omega_{ia} + i\left[\left(\omega_{ia} + \vec{k}_{ia}\vec{v}_0\right)^2 - k_{ia}^2 c_{ia}^2\right]} \times \frac{1}{2k_{0x}}$$

The difference in the resonance width in $g\left[\vec{k}_{ia}^{(c)}\right]$ versus $g\left[\vec{k}_{ia}^{(1)}\right]$ and $g\left[\vec{k}_{ia}^{(2)}\right]$ is ~$(\sin\theta)^2$, comparable to width caused by damping and inhomogeneity

TC10381a

The scattered-light gain can be significantly increased because of scattering off common ion waves

$$A_1 = E_1^{(1)} E_0^{(1)} \qquad A_2 = E_1^{(2)} E_0^{(2)}$$

$$\frac{dA_1}{d\ell_1} = \left\{ g\left[\vec{k}_0^{(1)} + \vec{k}_0^{(2)}\right] \cdot \left| E_0^{(2)} \right|^2 + g\left[2\vec{k}_0^{(1)}\right] \cdot \left| E_0^{(1)} \right|^2 \right\} A_1 + g\left[\vec{k}_0^{(1)} + \vec{k}_0^{(2)}\right] \cdot \left| E_0^{(1)} \right|^2 \cdot A_2$$

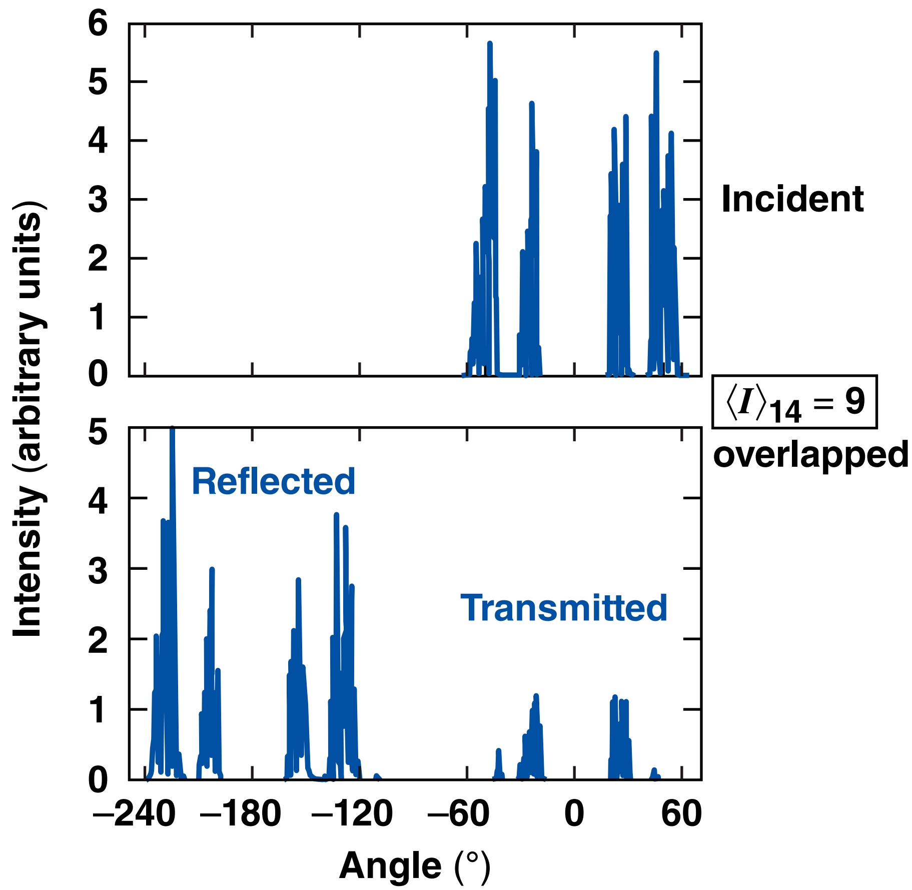
$$\frac{dA_2}{d\ell_2} = \left\{ g\left[\vec{k}_0^{(1)} + \vec{k}_0^{(2)}\right] \cdot \left| E_0^{(1)} \right|^2 + g\left[2\vec{k}_0^{(2)}\right] \cdot \left| E_0^{(2)} \right|^2 \right\} A_2 + g\left[\vec{k}_0^{(1)} + \vec{k}_0^{(2)}\right] \cdot \left| E_0^{(2)} \right|^2 \cdot A_1$$

$$\text{if } g\left[\vec{k}_0^{(1)} \cdot \vec{k}_0^{(2)}\right] \approx g\left[2\vec{k}_0^{(1)}\right] \approx g\left[2\vec{k}_0^{(2)}\right] = \bar{g}$$

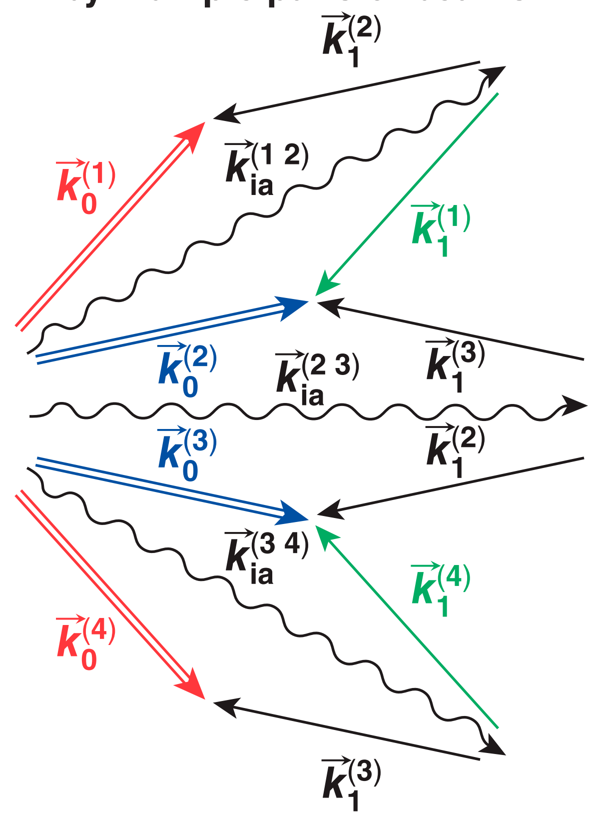
$$G \sim \bar{g}\left[\left| E_0^{(1)} \right|^2 + \left| E_0^{(2)} \right|^2 + \sqrt{\left| E_0^{(1)} \right|^2 \left| E_0^{(2)} \right|^2} \right]$$

- For a constant overlapped intensity of two laser beams, the gain can reach maximum when the beam intensities are equal

The interaction between multiple obliquely incident beams at moderate densities increases the backscatter as the result of sharing multiple common ion waves



Common ion waves driven by multiple pairs of beams



Scattering of inner beams is stronger (for same-intensity driving beams) $\frac{|A_{1,4}|}{|A_{2,3}|} \approx 0.41$

TC9450b

Summary/Conclusions

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