#### Cross-beam energy transfer saturation by ion trapping-induced detuning



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CBET can saturate through resonance detuning as a result of trapped-ion modifications to the ion distribution functions

- Experiments on the OMEGA LPI platform (TOP9) have provided the first measurements of CBET saturation by ion heating\*
- Collisional VPIC simulations indicate that the saturation mechanism depends on the phase velocity of the driven ion-acoustic wave (IAW)\*\*
  - For small IAW phase velocity, rapid thermalization causes a blueshift in the resonant IAW frequency
  - For large IAW phase velocity, persistent trapping-induced tails in the ion distribution functions redshift the resonance IAW frequency
- Preliminary simulations for OMEGA relevant parameters reveal that pump depletion saturates CBET at densities above quarter critical



Summary

Cross-beam energy transfer (CBET) is the exchange of energy between two laser beams mediated by their mutually driven ion acoustic wave (IAW)



TC16129

Linear CBET theory predicts maximum energy transfer when the detuning frequency of the laser beams is equal to the Doppler-shifted frequency of the IAW



#### CBET plays a critical role in laser-based inertial confinement fusion



Direct drive: CBET scatters laser light
away from the target, reducing absorption



• Indirect drive: CBET can be used to tune the symmetry of the implosion

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### CBET saturation has been observed in past experiments but insufficient diagnostic tools have limited physics understanding



 At resonance, measurements of the power transmitted in the probe beam show a decrease in the amplification as the probe intensity increases\* L

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 Linear theory agreed with CBET amplification measurements for weaker probe energies, but a clear deviation is observed at the highest probe energy

# Previous computational studies have revealed that stochastic ion heating can saturate CBET



TC16131

An ensemble of IAWs driven by many overlapping laser beams stochastically heats the ions, which increases the ion sound speed and detunes the CBET resonance\*













• Gas-Jet produces a highly uniform plasma, characterized by Thomson scattering



TC15126





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• TOP9 Laser can be tuned over 3 nm to map out the CBET resonance







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- TOP9 Laser can be tuned over 3 nm to map out the CBET resonance
- Transmitted beam diagnostic (TBD) measures the energy transfer



The time-dependent CBET gain was measured for two different configurations: (1) Near perpendicular/small IAW  $v_p$ 





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### The time-dependent CBET gain was measured for two different configurations: (1) Near perpendicular/small IAW $v_p$



The increase in ion temperature detunes the resonant IAW frequency, leading to CBET saturation



The time-dependent CBET gain was measured for two different configurations: (2) Near co-propagating/large IAW  $v_p$ 





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A. Hansen. et al., Phys. Rev. Lett. (2021) 16

The time-dependent CBET gain was measured for two different configurations: (2) Near co-propagating/large IAW  $v_p$ 



CBET saturates due to pump depletion



Collisional VPIC simulations were performed to understand the underlying physics of CBET saturation for the two configurations: (1) Small IAW  $v_p$ 



The large crossing angle and low plasma density result in a "small" IAW phase velocity ( $v_p \approx 0.54 c_s$ )

Here, 
$$c_s = \sqrt{\frac{\overline{Z}T_e + 3T_i}{\overline{M_i}}}$$
 is the sound speed





#### On the fast-time scale, CBET saturates due to transverse breakup of the ion-acoustic wave



Transverse breakup of the IAW is caused by the • trapped particle modulational instability (TPMI)\*

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#### On the fast-time scale, CBET saturates due to transverse breakup of the ion-acoustic wave



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- Transverse breakup of the IAW is caused by the trapped particle modulational instability (TPMI)\*
- The breakup allows for rapid dissipation of IAW energy, which limits the amplitude of the IAWs and inhibits energy transfer

#### Over longer time scales, ion-ion collisions rapidly thermalize the trappinginduced modifications to the ion distribution function



- The IAW traps many more H ions than N ions
- Nevertheless, the N temperature increases by a factor of 3.2, while the H temperature only increases by a factor of 1.6
- Rapid H-N collisions allow the H ions to quickly transfer energy to the N ions, while the slower N-H collisions inhibit the N ions from giving energy to H ions



#### The rapid thermalization causes the resonant IAW frequency to blueshift



TC16137

The gain drops over time as the resonant frequency continues to blueshift



Collisional VPIC simulations were performed to understand the underlying physics of CBET saturation for the two configurations:(1) Large IAW  $v_{\rm p}$ 





 $I_{seed} = 5.0e14 \text{ W/cm}^2$ 

result in a "large" IAW phase velocity ( $v_p \approx 0.85 c_s$ )

Here, 
$$c_s = \sqrt{\frac{\overline{Z}T_e + 3T_i}{\overline{M_i}}}$$
 is the sound speed



# On the fast-time scale, CBET saturate due to transverse breakup of the ion-acoustic wave





#### On the fast-time scale, CBET saturate due to transverse breakup of the ion-acoustic wave



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### Over longer time scale, the larger velocity of trapped ions weakens the collisionality and slows thermalization



- The H and N temperatures increase nearly in unison by a factor of ~2.0
- The energy exchange rates between the H and N are nearly equal (v<sub>ε</sub><sup>HN</sup> ≈ v<sub>ε</sub><sup>NH</sup>)
- The weak collisionality allows the trapping induced modifications to the distribution functions to persist over longer time scales



The persistent trapping-induced tails in the ion distribution functions result in a small redshift to the resonance IAW frequency



TC16139

Redshifting of the resonant frequency causes a slight drop in the gain over the interaction time



### Collisional VPIC simulations are now being performed to model CBET in conditions relevant to OMEGA implosions





#### Near 30% critical density, CBET coupling is maximized in a nearperpendicular beam geometry



TC16140



X

### CBET gain saturates due to pump depletion near 30% critical density and no significant ion heating is observed



The lower intensities and higher temperatures result in smaller amplitude IAWs, which reduces ion trapping and increases in the ion temperature



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CBET can saturate through resonance detuning when trapped-ion modifications to the ion distribution functions detune the resonance



- Experiments on the OMEGA LPI platform (TOP9) have provided the first measurements of CBET saturation by ion heating\*
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  - For small IAW phase velocity, rapid thermalization causes a blueshift in the resonant IAW frequency
  - For large IAW phase velocity, persistent trapping-induced tails in the ion distribution functions redshift the resonance IAW frequency
- Preliminary simulations for OMEGA relevant parameters reveal that the nonlinear evolution of CBET depends on the plasma density



#### For OMEGA conditions, CBET coupling is maximized near 30% critical density



