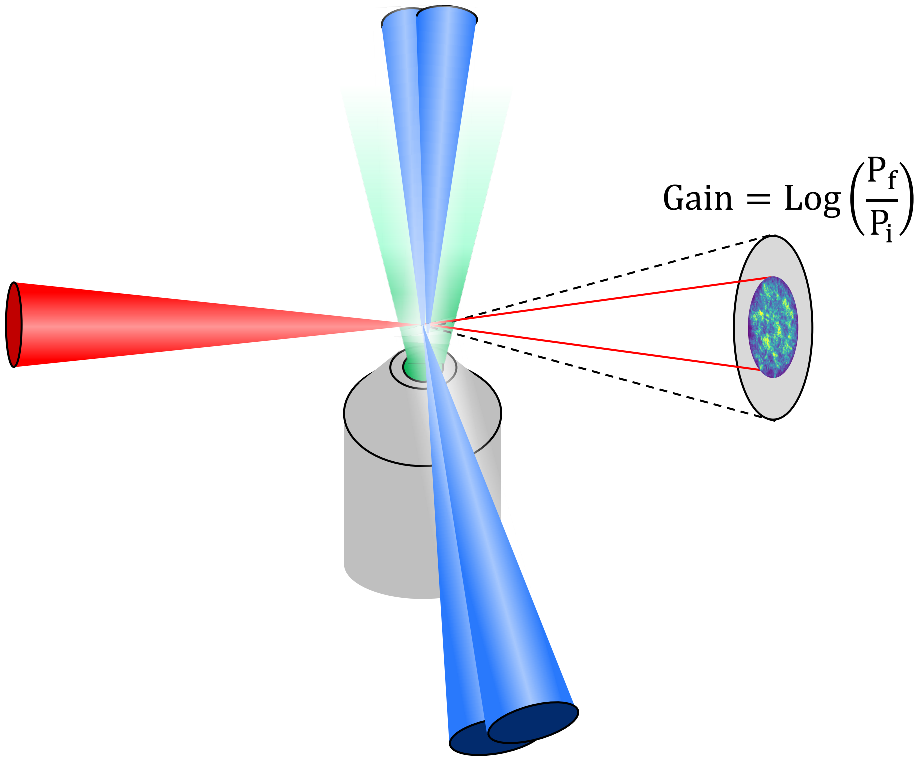
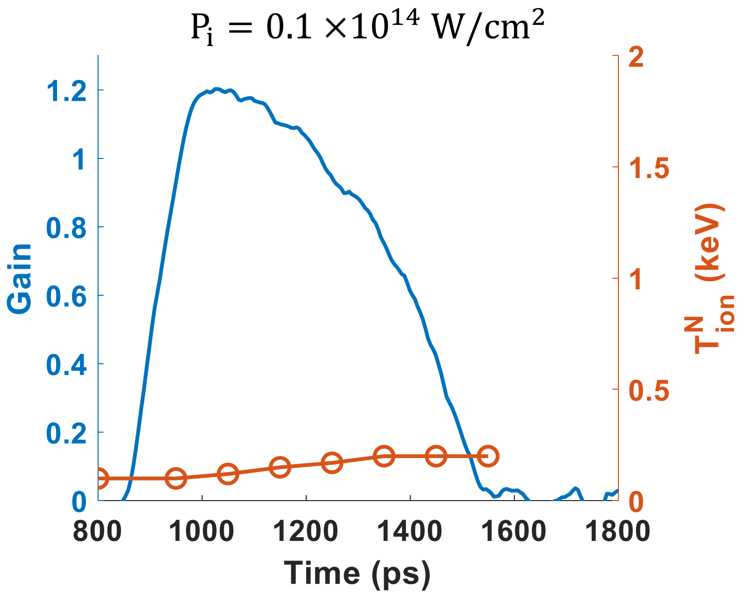
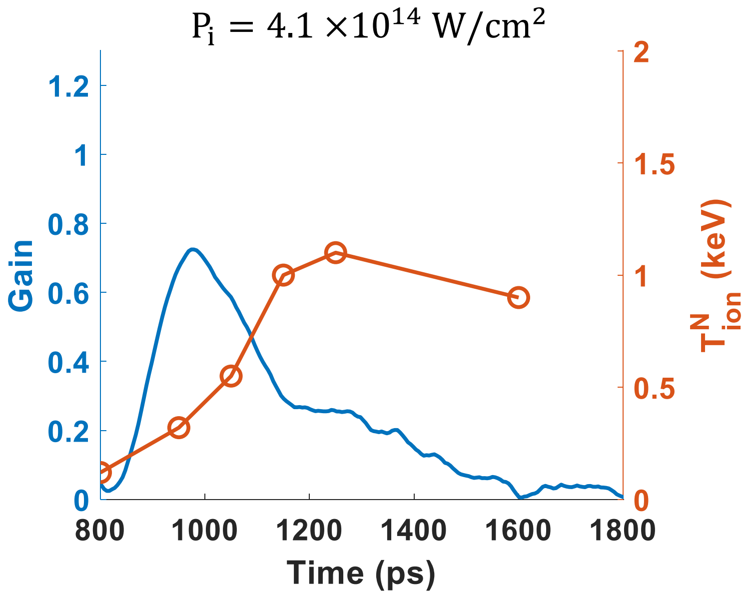
Cross-Beam Energy Transfer Saturation







A. M. Hansen
Physics Department
University of Rochester
Laboratory for Laser Energetics

62nd Annual Meeting of the APS DPP
Virtual
November 12, 2020

Summary

Crossed-beam energy transfer (CBET) saturation by ion heating was measured and found to be consistent with kinetic linear CBET theory

- Previous experiments have observed CBET saturation but have lacked the measurements to understand the CBET saturation mechanism
- Low phase velocity $(v_{ph} \approx 5\ v_{th,N})$ CBET experiments observed early (<100 ps) and late time (>100 ps) CBET saturation
  - Thomson-scattering measurements measure up to x10 increase in ion temperature
  - Linear kinetic CBET theory reproduced energy transfer experiments when including the measured ion heating
- Particle-In-Cell (PIC) simulations identify the ion heating mechanism
  - Ion trapping leads to increased ion temperature
  - Increased ion temperature limits ion wave growth and saturates CBET
- High phase velocity $(v_{ph} \approx 8\ v_{th,N})$ CBET experiments showed pump depletion and no evidence of CBET saturation
  - Thomson-scattering measured no enhanced ion heating
  - Linear kinetic CBET theory reproduced measured energy transfer when including pump depletion and measured plasma conditions

Despite all the nonlinear physics, the linear CBET model works remarkably well provided the correct plasma conditions are used

Collaborators

K. L. Nguyen, D. Turnbull, R. K. Follett, R. Huff, J. Katz, D. Mastrosimone,
A. L. Milder, J. P. Palastro, and D. H. Froula

University of Rochester
Laboratory for Laser Energetics

B. Albright, L. Yin

Los Alamos National Laboratory

Linear CBET theory predicts the transfer of energy between laser beams in a plasma

- Two beams (m, n) which are frequency mismatched (ω_m, ω_n) cross in a plasma and form a beat wave ($\mathbf{k}$, ω_k)
  - When this beat wave is resonant with the ion-acoustic mode significant amounts of energy can be transferred

$$\omega_k = k\, c_s \qquad c_s = \left(\frac{ZT_e + 3T_i}{m_i(1 + k^2\lambda_{De}^2)}\right)^{1/2}$$

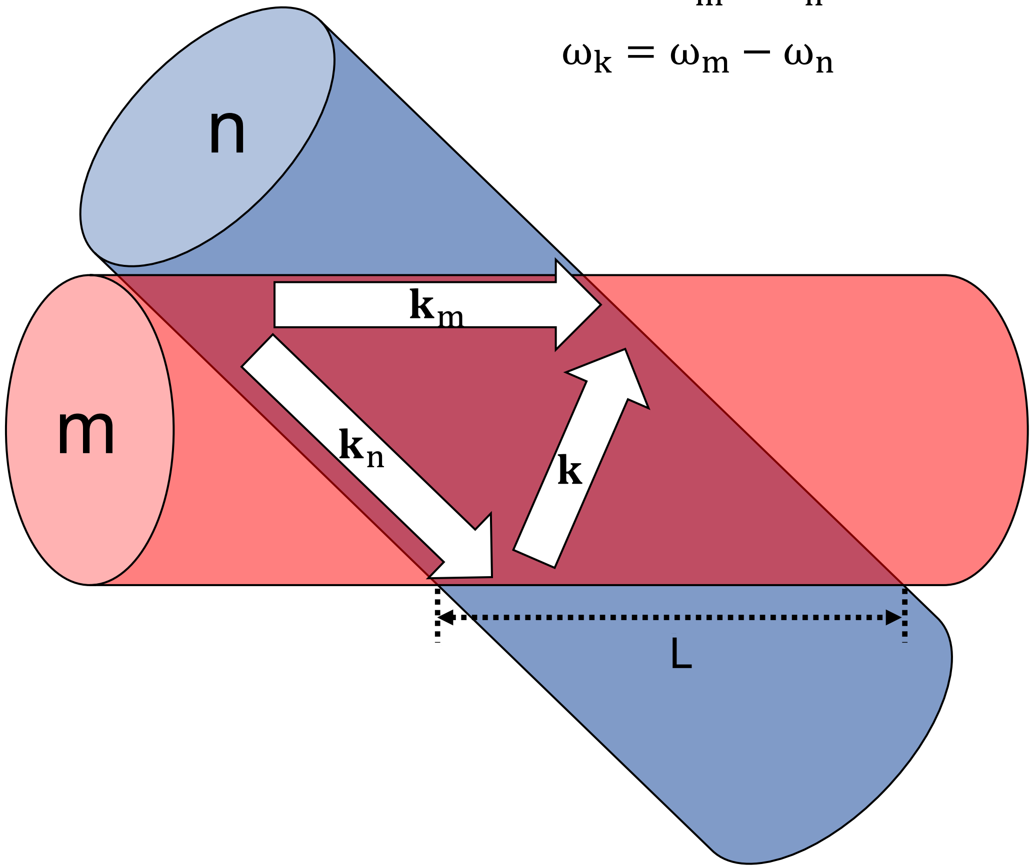
- The gain as seen by the probe beam 'm' is constant for any probe intensity
  - Amplitude of ion waves does depend on probe intensity

$$G_m = \log\left(\frac{I_{m,f}}{I_{m,0}}\right) \qquad G_m \propto I_n \frac{n_e}{T_e} L$$

$$\delta n_e / n_e \propto \sqrt{I_m I_n}$$

$$\mathbf{k} = \mathbf{k}_m - \mathbf{k}_n$$

$$\omega_k = \omega_m - \omega_n$$

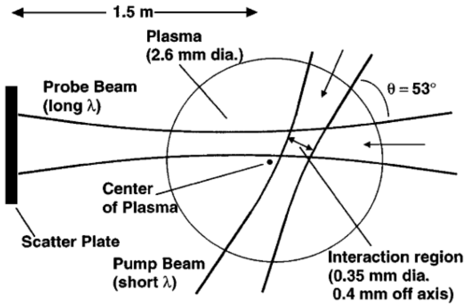


$\omega_k = \omega_m - \omega_n$

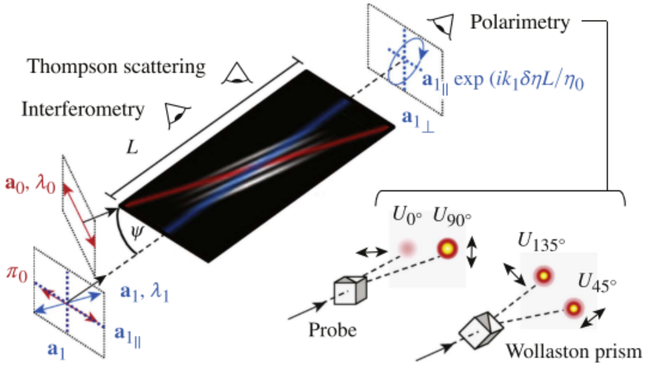
CBET saturation has been observed in past experiments but insufficient diagnostic tools have limited a physics understanding

- The first 2-beam frequency mismatched CBET experiment was in a gas-bag target[1] and CBET saturation was first observed with foil targets[2,3]
  - Plasma conditions predicted using LASNEX simulations
- CBET experiments in a gas jet target demonstrated saturation at high probe intensities, but no mechanism was identified[4]
  - Plasma conditions were measured with Thomson-scattering but did not measure ion temperatures
- Recent well controlled gas jet experiments at small ion-acoustic wave amplitudes have demonstrated that when non-Maxwellian electron distribution functions are included, linear CBET theory reproduces the measured energy transfer[6]

Kirkwood[1]



Turnbull[4]

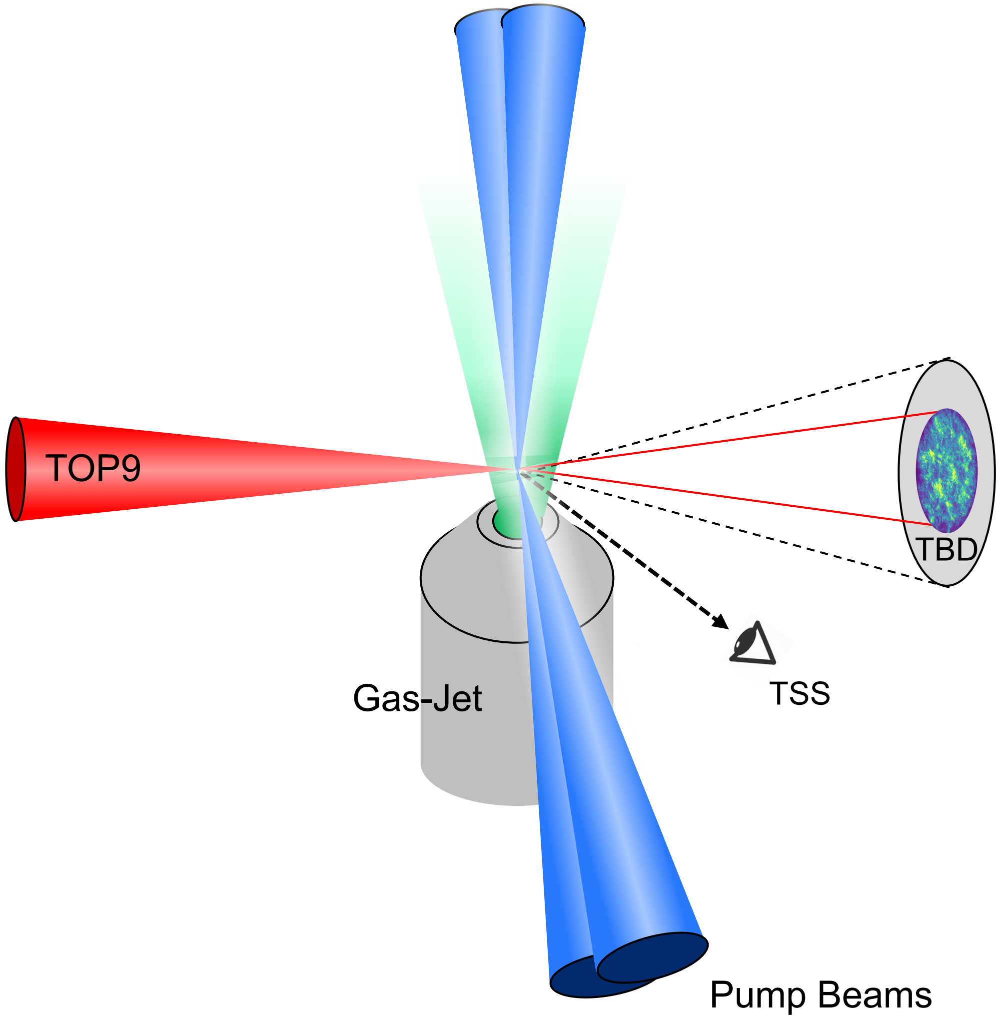


Well characterized plasma conditions are essential in validating CBET theory and understanding saturation physics

[1] R. K. Kirkwood et al. Phys. Rev. Lett. 76, 2065 (1996)
[2] R. K. Kirkwood et al. Phys. Rev. Lett. 89, 215003 (2002)
[3] R. K. Kirkwood et al. Phys. Plasmas 12, 112701 (2005)
[4] D. Turnbull et al. Phys. Rev. Lett. 118, 015001 (2017)
[5] D. Turnbull et al. Plasma Phys Control. Fusion 60, 054017 (2018)
[6] D. Turnbull et al. Nat. Physics 16, 181–185 (2020)

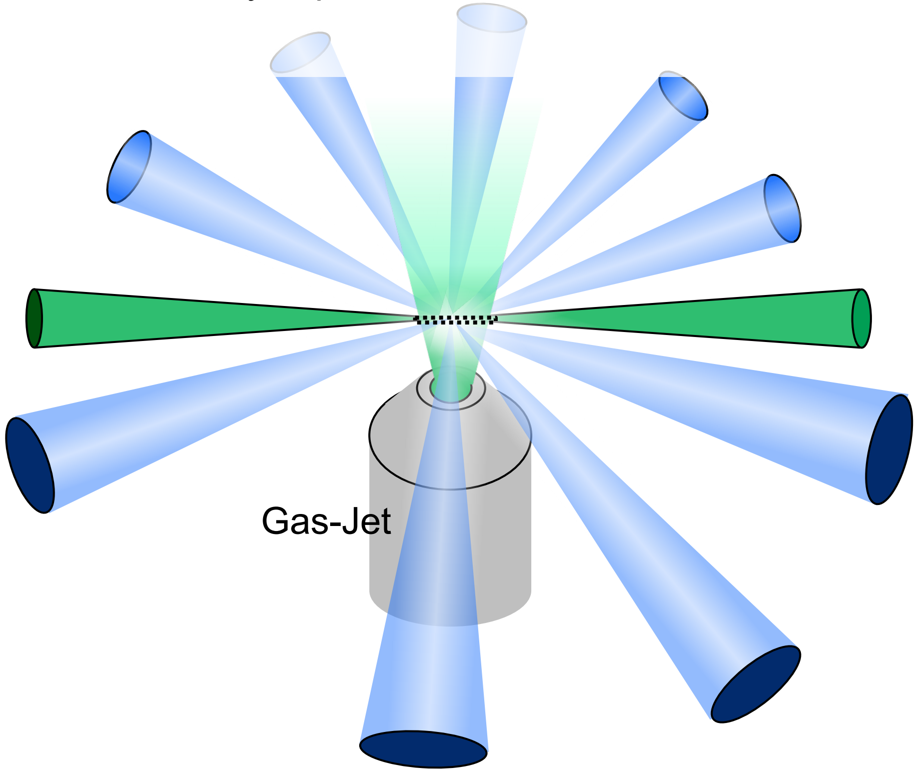
The OMEGA LPI platform enables experimental variables to be isolated by characterizing and controlling plasma conditions

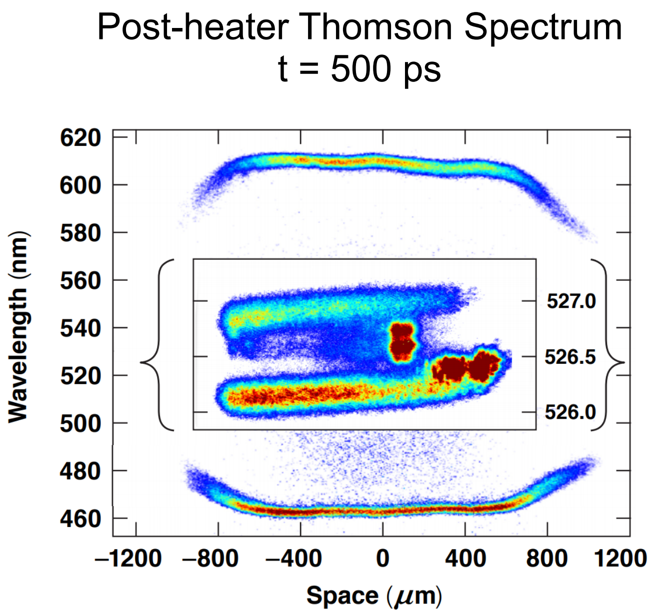
- Gas-Jet
- TOP9 Laser
- Diagnostics:
  - Transmitted Beam Diagnostic (TBD)
  - Thomson-Scattering System (TSS)
- Pump Beams

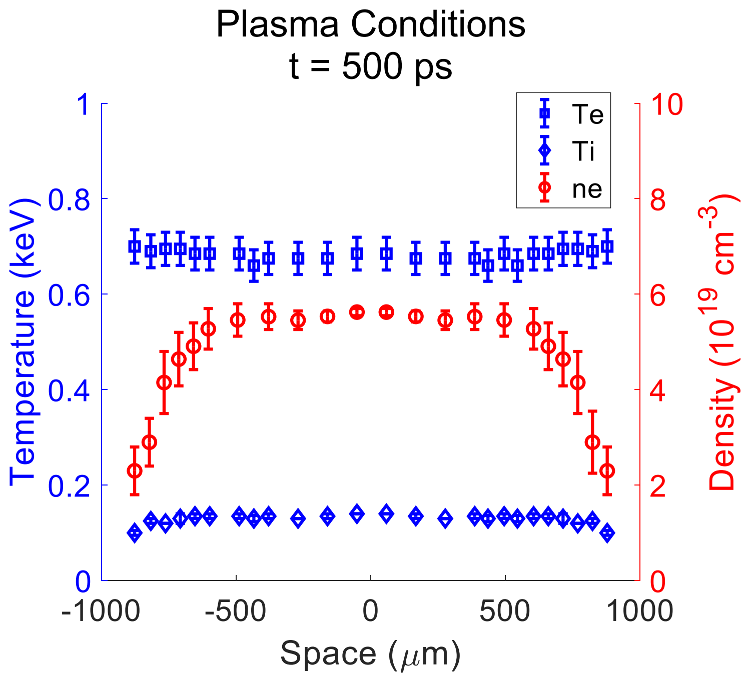


The gas-jet system produced a uniform underdense plasma target on the Omega laser system

- A fast valve with a supersonic nozzle releases a 1 mm-scale plume of 55% H_2 and 45% N_2 gas
- The gas-jet plume is illuminated by 9 Omega heater beams using large phase plates (~850 μm diam.)
- Uniformity in plasma conditions was confirmed using imaging Thomson scattering



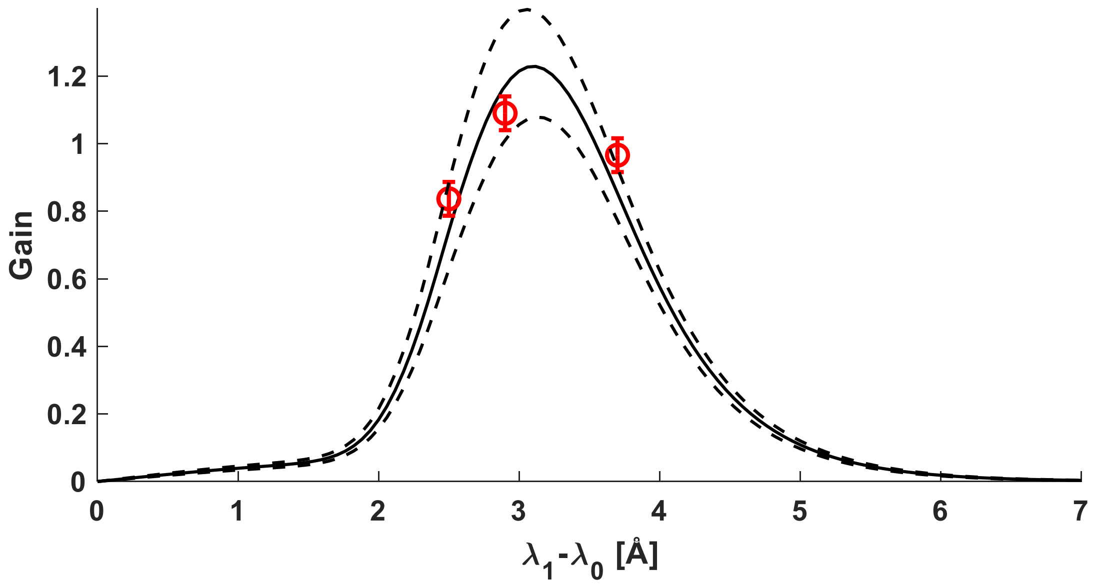


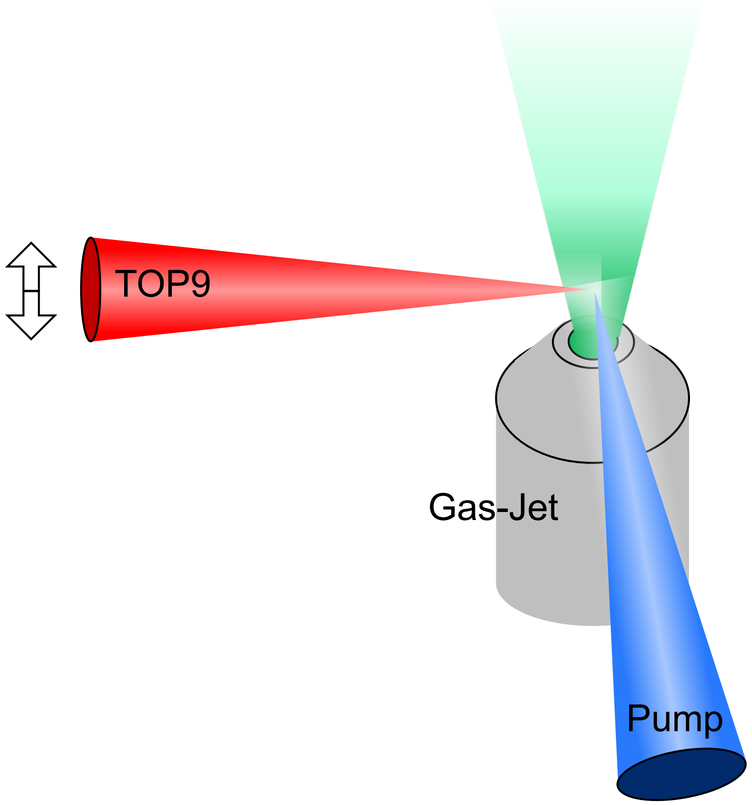


[1] A. M. Hansen et al. Rev. Sci. Instrum. **89**, 10 (2018)

The Tunable OMEGA port 9 (TOP9) laser is wavelength tunable over 3 nm to allow CBET in a quasi-stationary plasma target

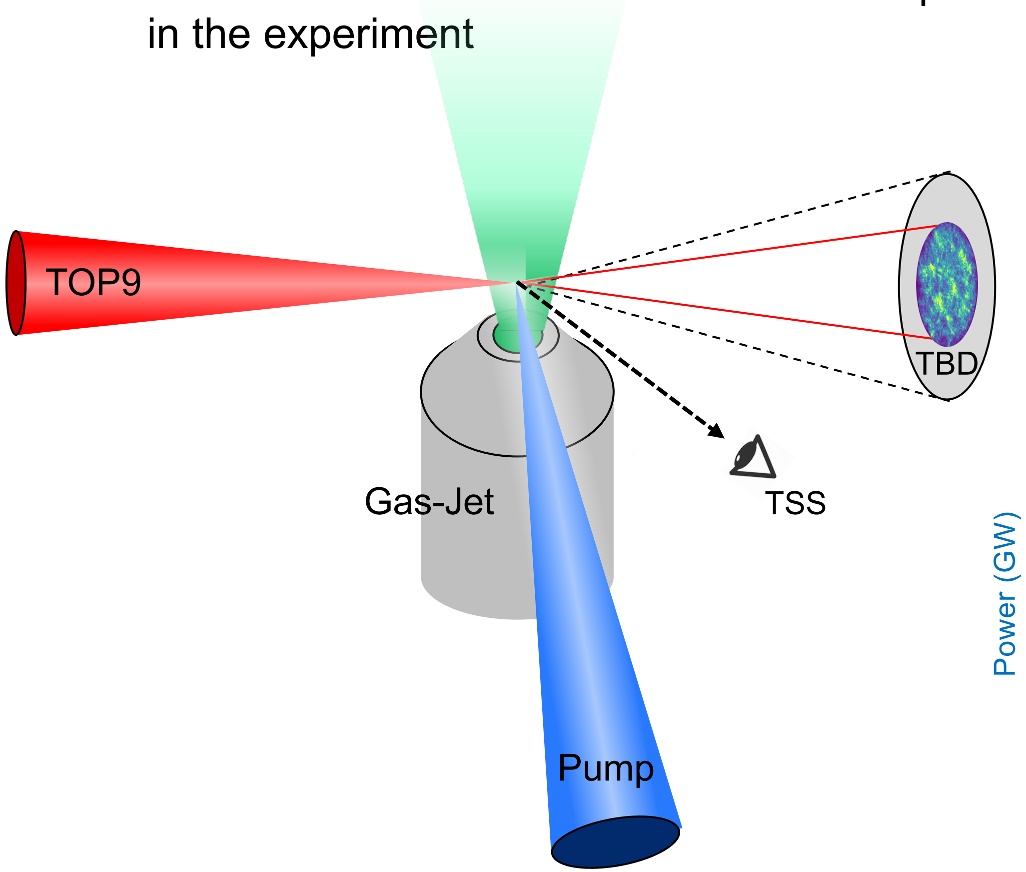
- The TOP9 beam is redshifted ~0.3 nm to resonantly beat with the unshifted pump beams in the gas-jet plasma target
- TOP9 had a small spot size (~160 μm diam.) and had linear s-polarization w.r.t crossing plane

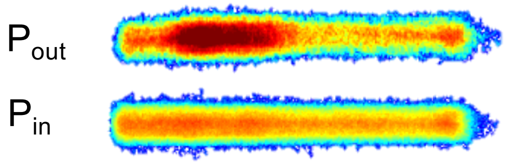


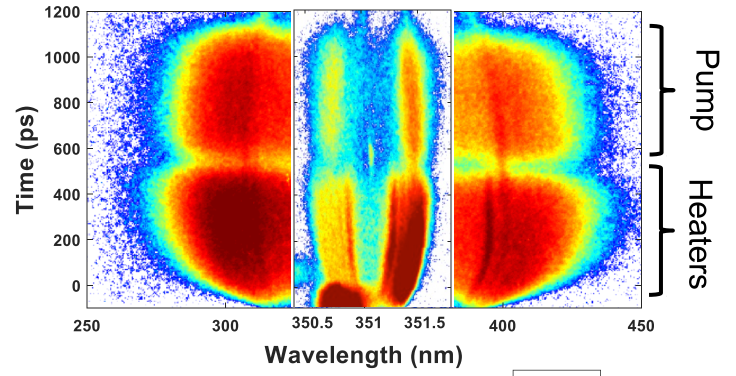


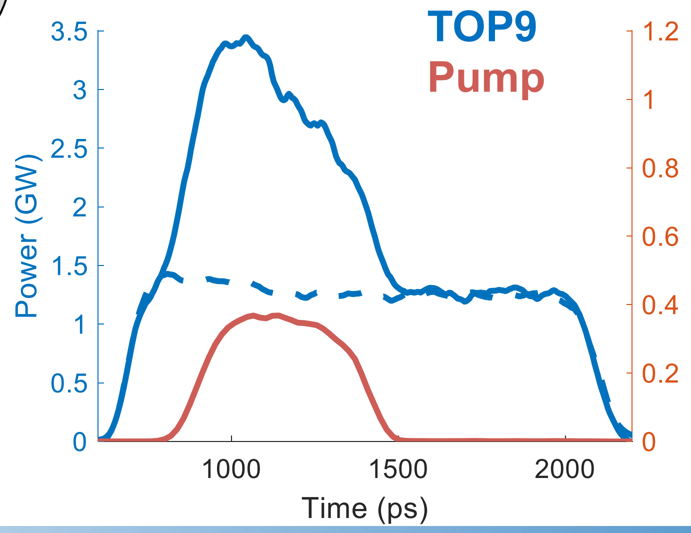
The CBET interaction was diagnosed using the transmitted beam diagnostic (TBD) and the Thomson-scattering system (TSS)

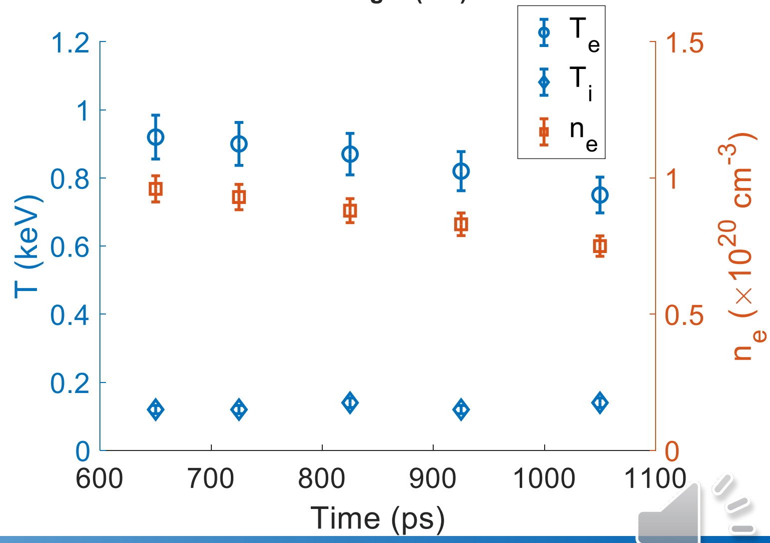
- TBD measures power in the TOP9 beam before and after the CBET interaction
- TSS measures time-resolved Thomson spectra scattered from every beam used in the experiment





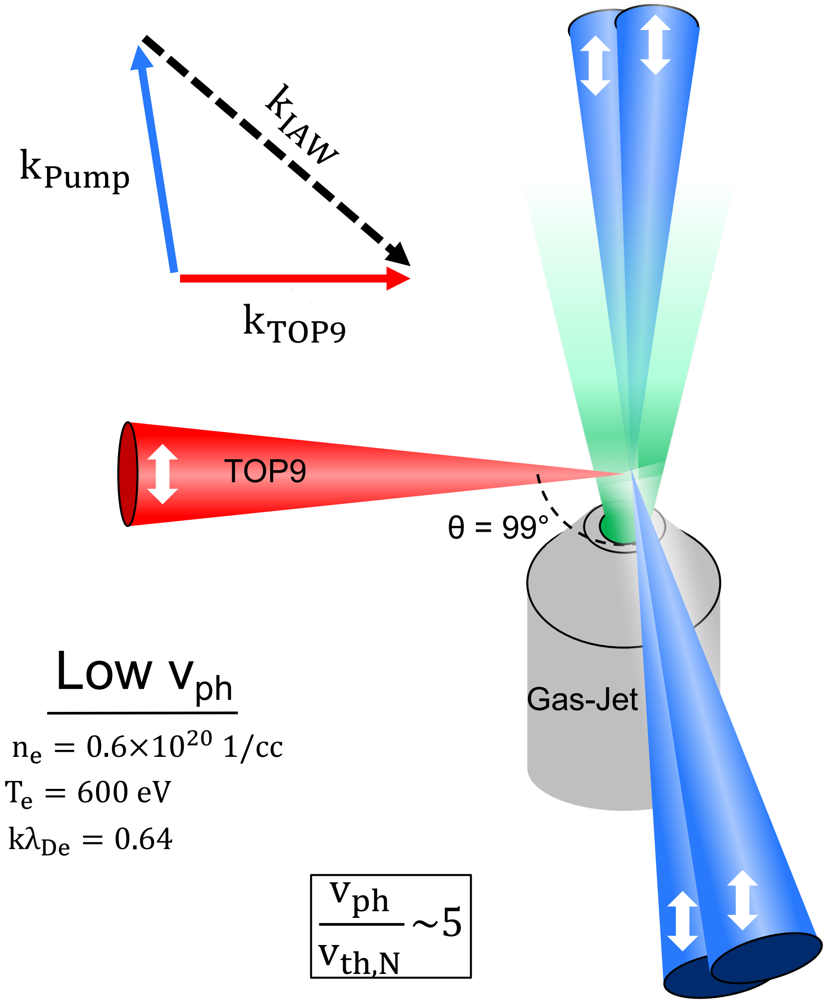






The 351 nm pump beams were used in two configurations: low- and high- phase velocity

$$v_{ph} = \left(\frac{ZT_e + 3T_i}{m_i(1 + k^2\lambda_{De}^2)}\right)^{1/2}$$



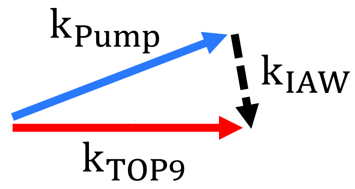
Low v_{ph}

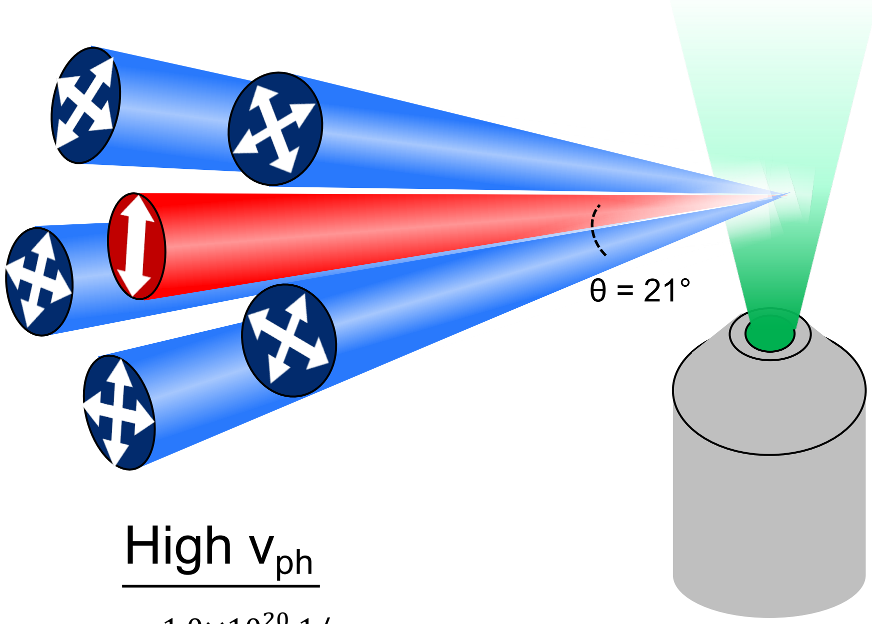
$n_e = 0.6\times10^{20}$ 1/cc

$T_e = 600$ eV

$k\lambda_{De} = 0.64$

$$\frac{v_{ph}}{v_{th,N}} \sim 5$$





High v_{ph}

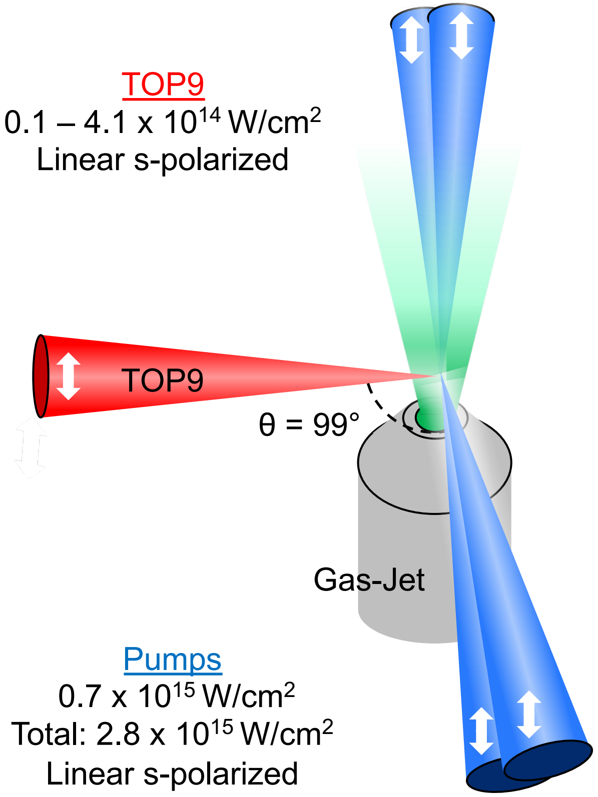
$n_e = 1.0\times10^{20}$ 1/cc

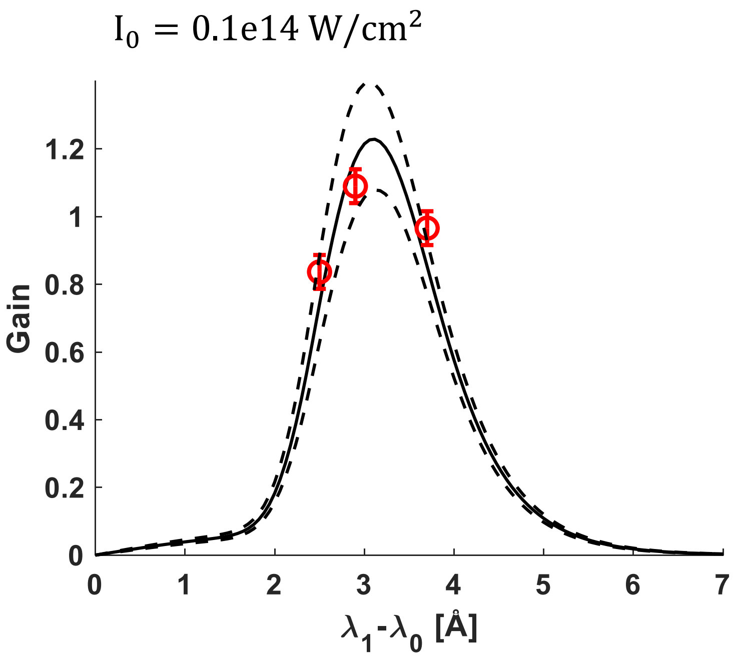
$T_e = 850$ eV

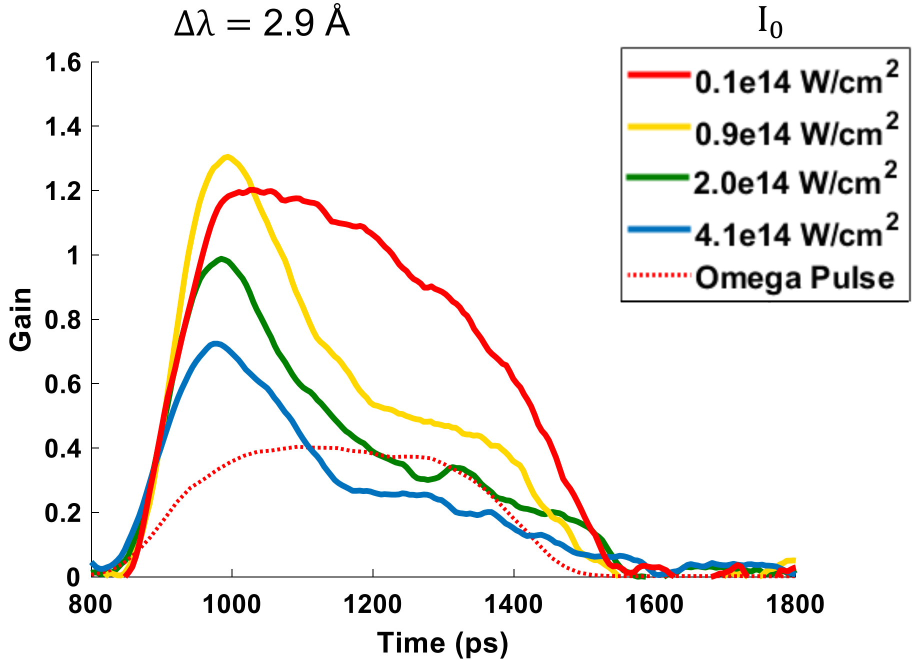
$k\lambda_{De} = 0.14$

$$\frac{v_{ph}}{v_{th,N}} \sim 9$$

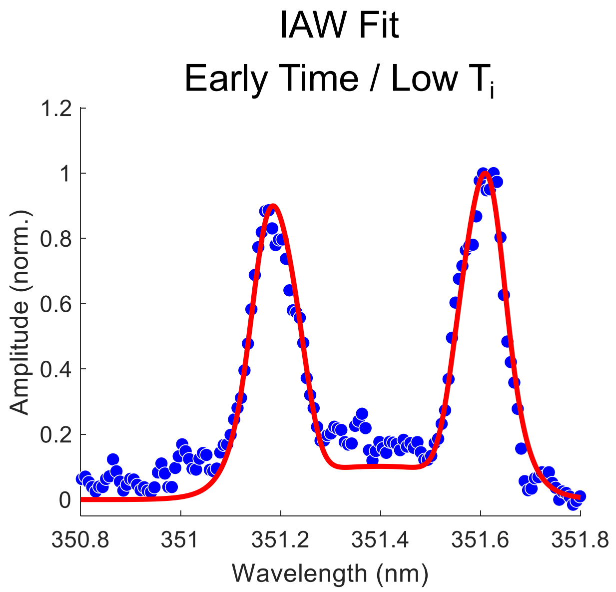
Low phase velocity CBET experiments demonstrated diminishing gains with increasing TOP9 intensity and time-dependent saturation effects

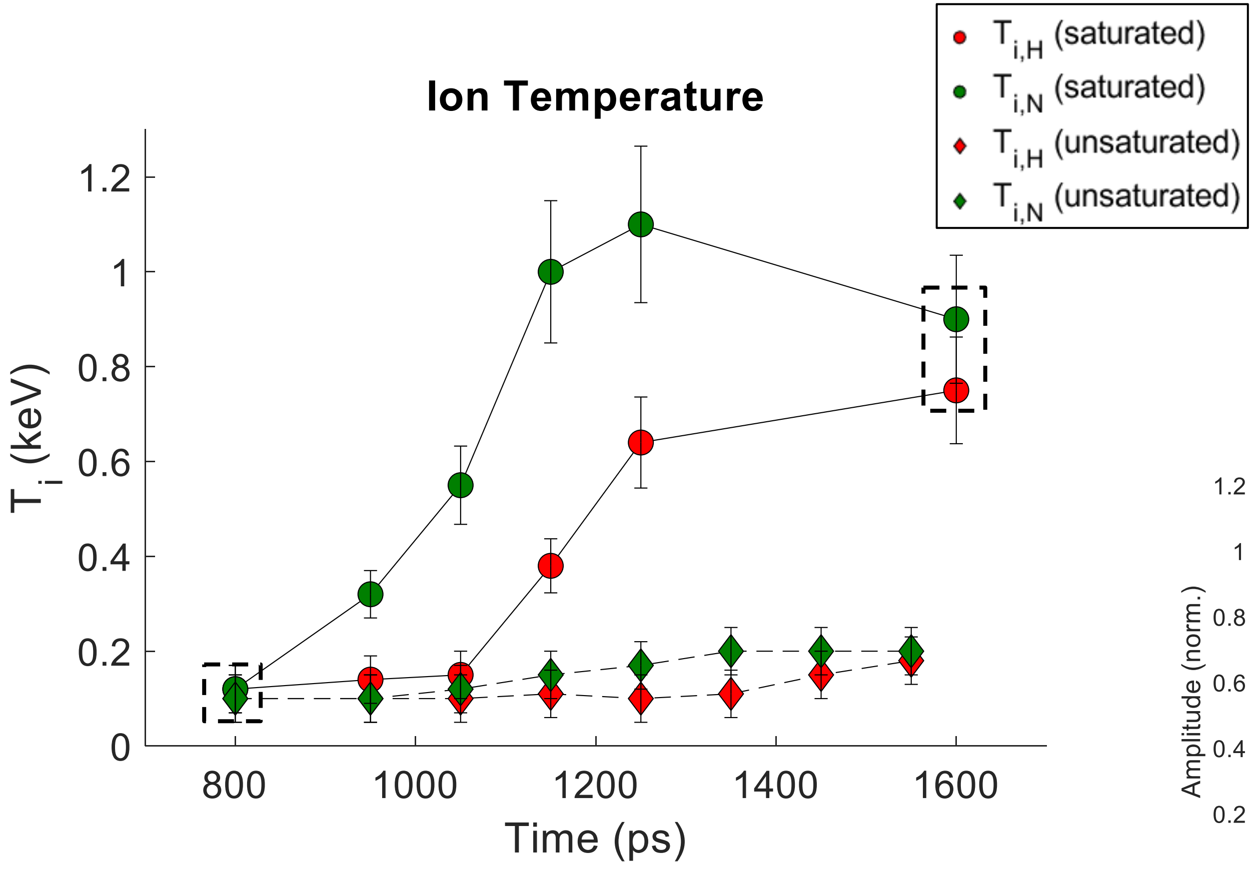


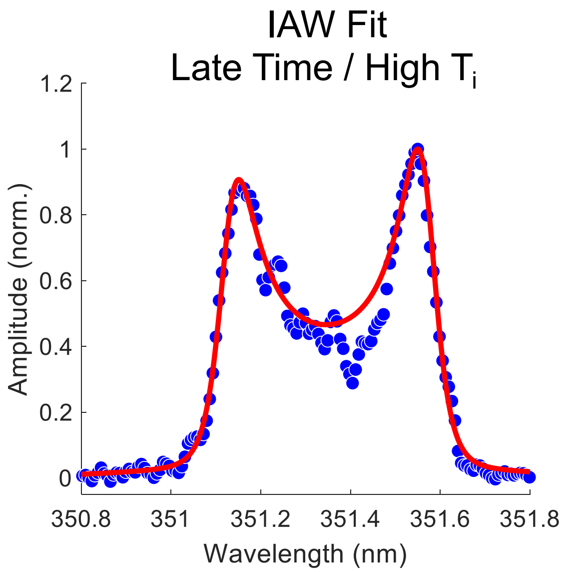




Thomson fits of the ion-acoustic wave feature indicates significant ion heating during the CBET interaction

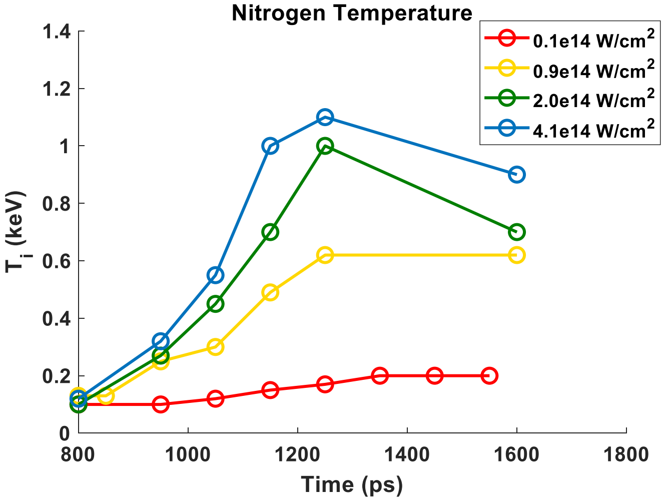


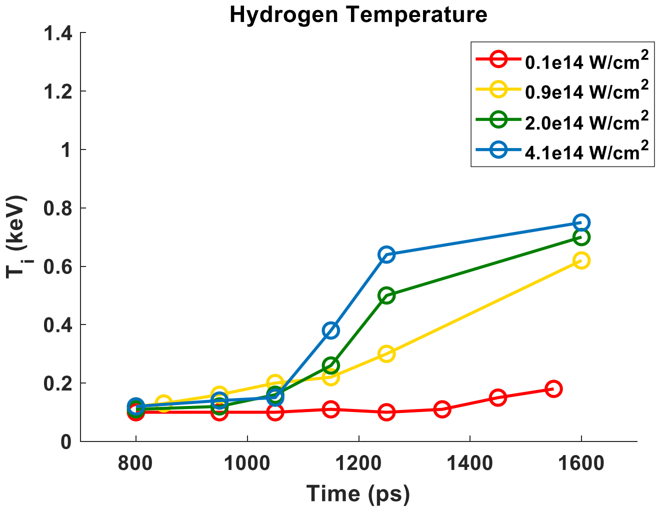


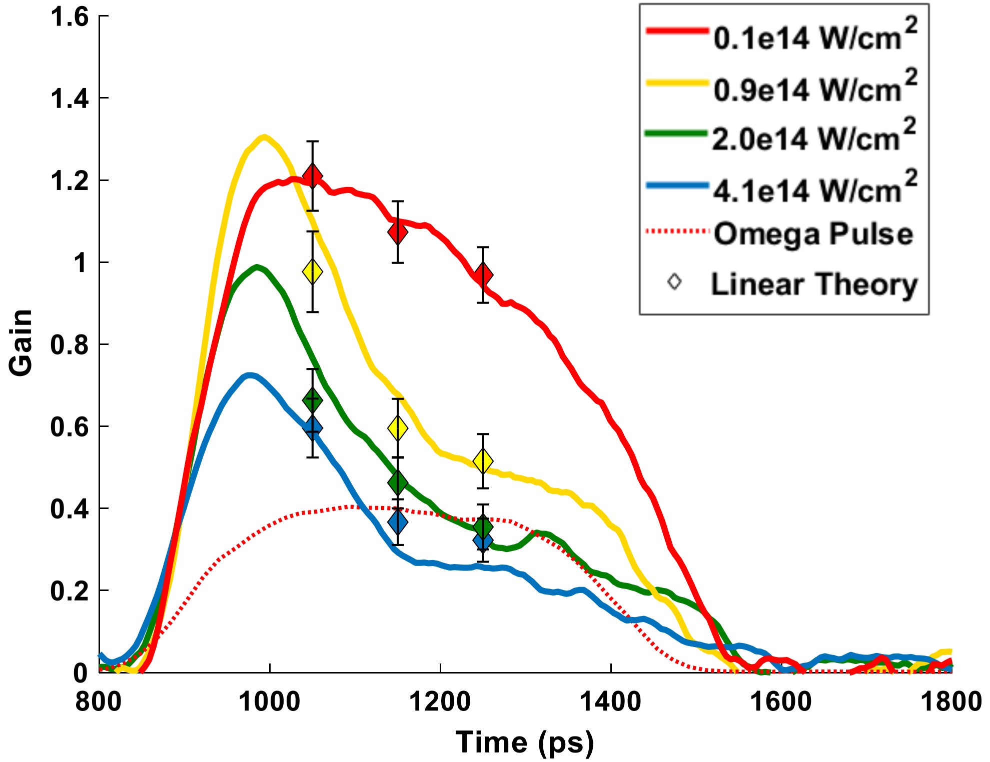


Both ion species experience rapid heating when the CBET interaction is saturating

Accounting for increased ion temperatures in the high-intensity TOP9 shots brings linear CBET theory into agreement with measured gain data



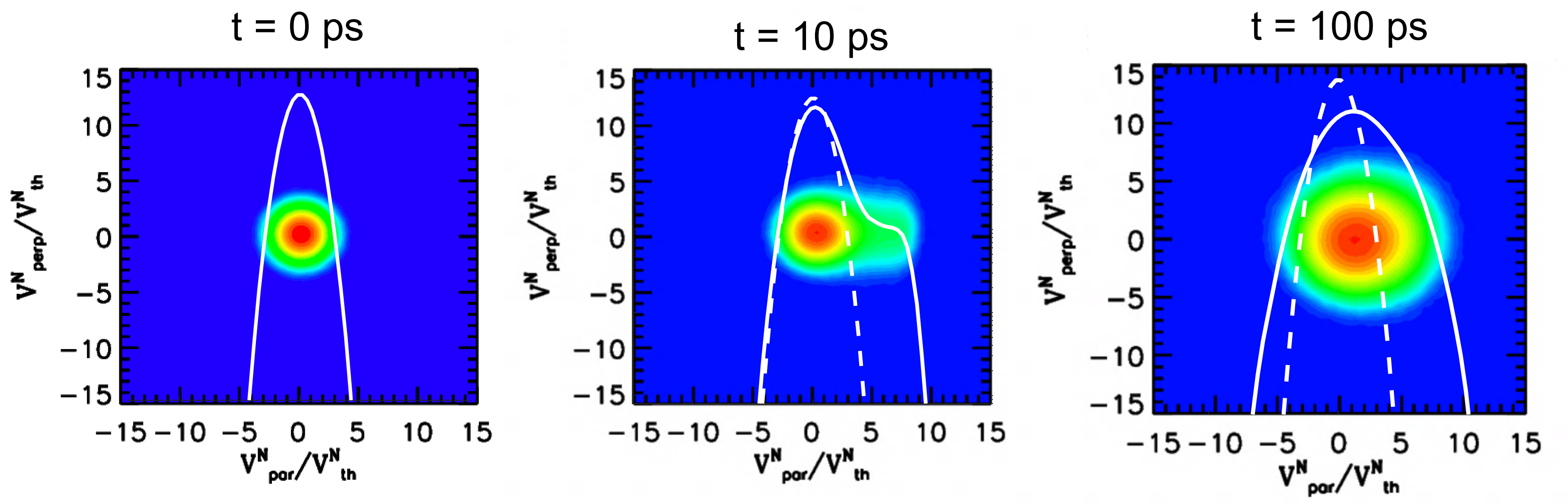




Linear CBET Theory agrees with measured gains when ion heating is accounted for

PIC simulations demonstrate ion trapping and heating effects on experiment relevant time scales

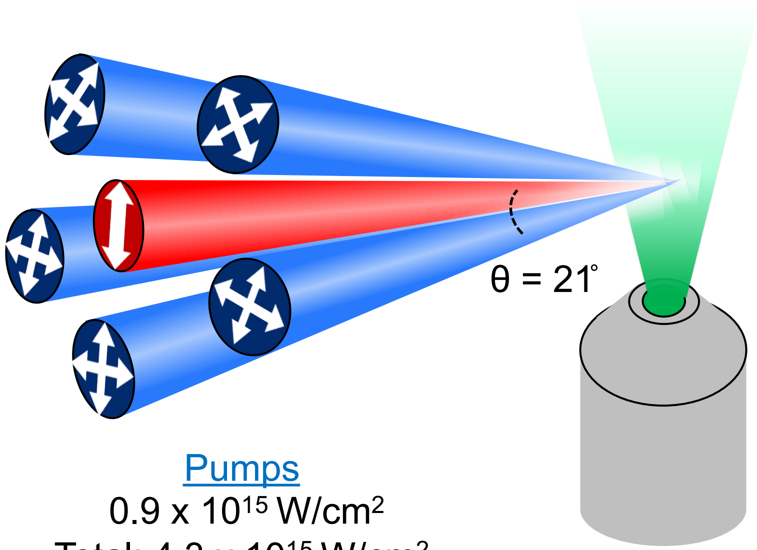
- Single-pump, low phase velocity ($\theta = 99°$) configuration using VPIC
- Early time (~10 ps) PIC ion distributions show trapping along the driven IAW k-vector
- Late time (~100 ps) PIC shows anisotropic heating of the ion distribution



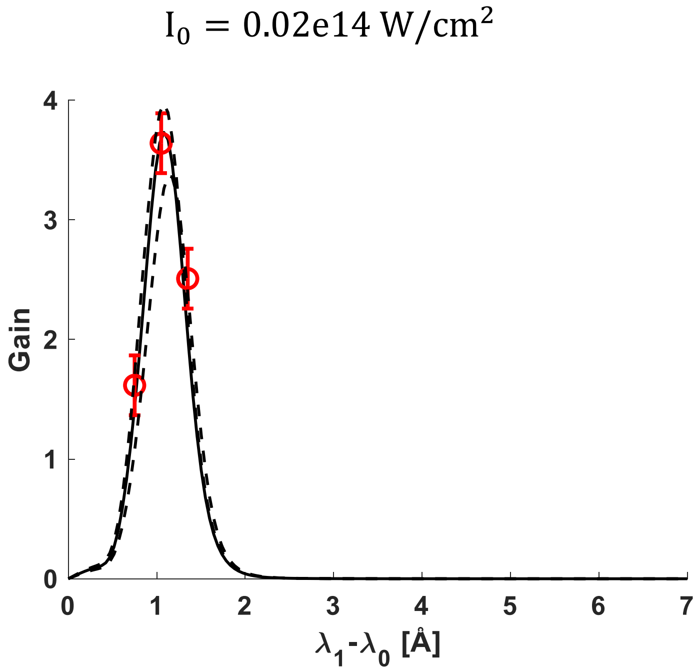
* L. Nguyen talk to follow

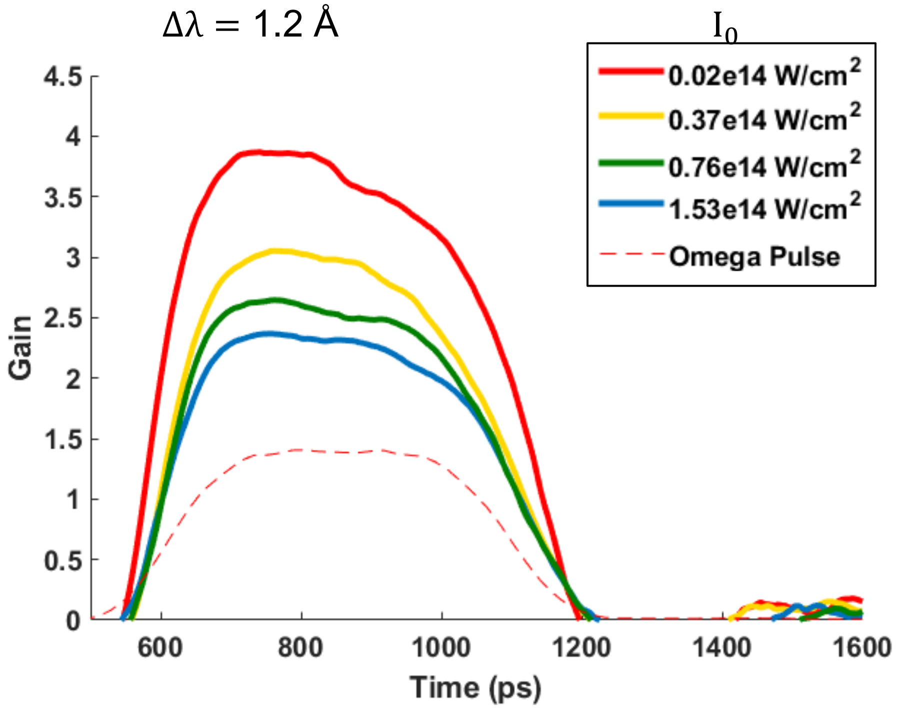
High phase velocity CBET experiments demonstrated diminishing gain with increasing TOP9 beam intensity

TOP9
0.02 -- 1.5 x 10^{14} W/cm^2
Linear Polarized

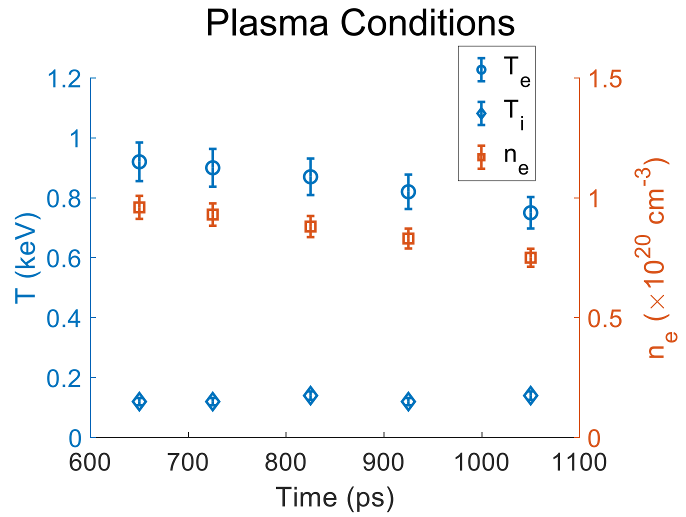


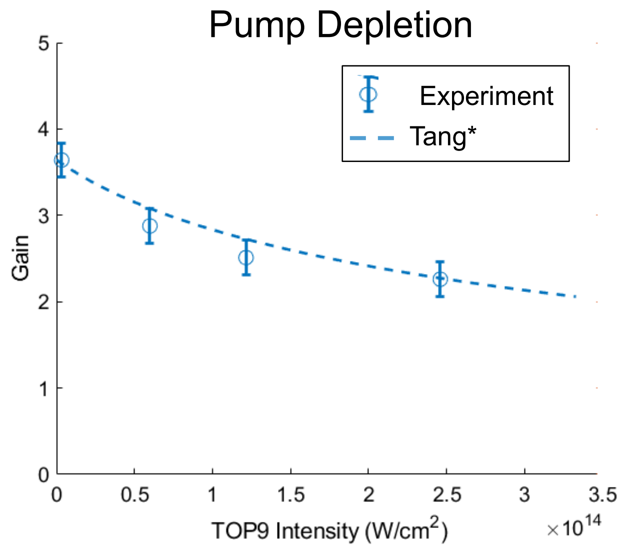
Pumps
0.9 x 10^{15} W/cm^2
Total: 4.3 x 10^{15} W/cm^2
Polarization Smoothed

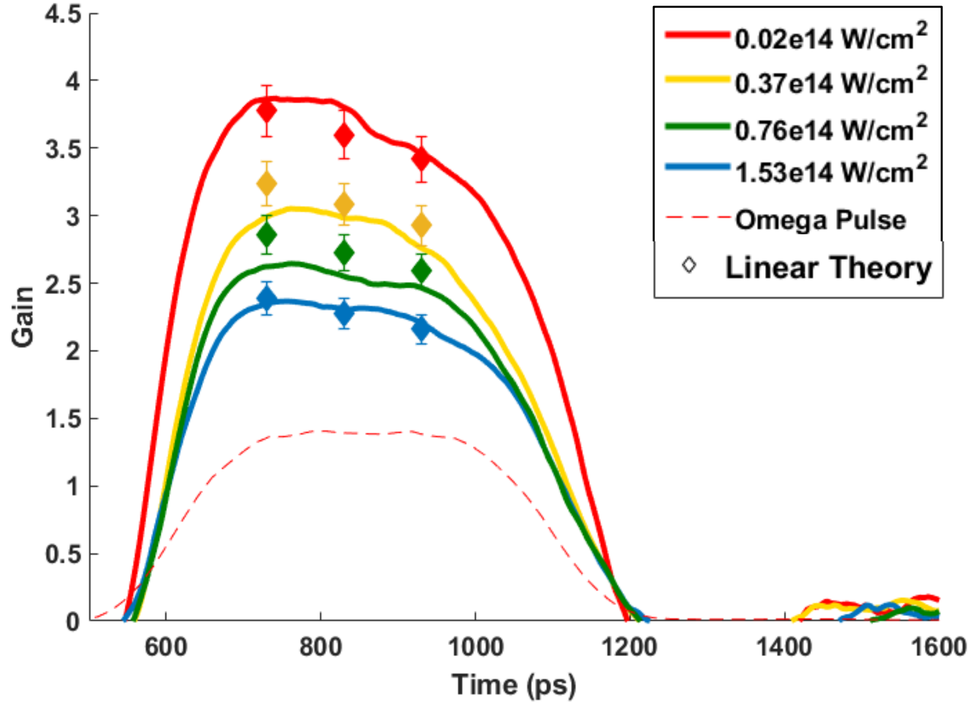




Time-resolved plasma conditions and pump depletion effects account for the measured time-resolved gain







Minimal ion heating was observed for the high phase velocity configuration

* C. L. Tang, J. Appl. Phys. 37, 2945 (1966)

Relatively low velocity trapped ions mainly heated the CBET volume for low phase velocity CBET experiments

$$\lambda_{mfp} \propto \frac{v^4}{n_e}$$

Low v_{ph}

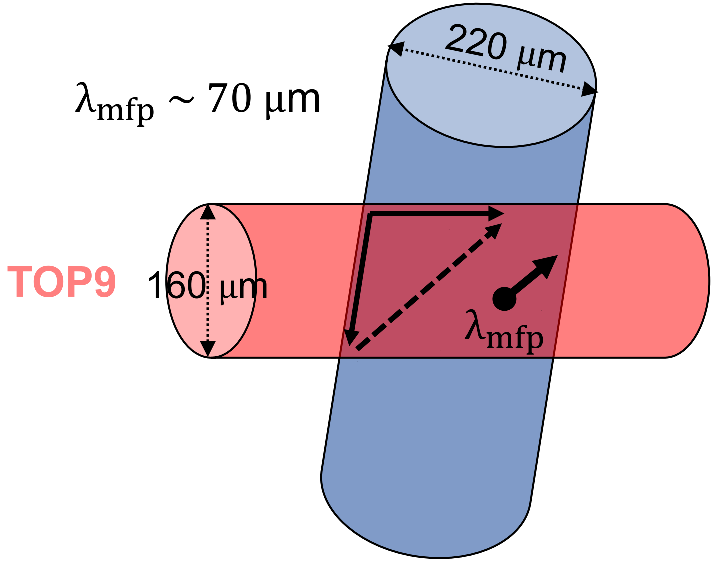
$n_e = 0.6\times10^{20}\ 1/cc$

$T_e = 600$ eV

$k\lambda_{De} = 0.64$

$\boxed{\frac{v_{ph}}{v_{th,N}} \sim 5}$

$\lambda_{mfp} \sim 70\ \mu m$



High v_{ph}

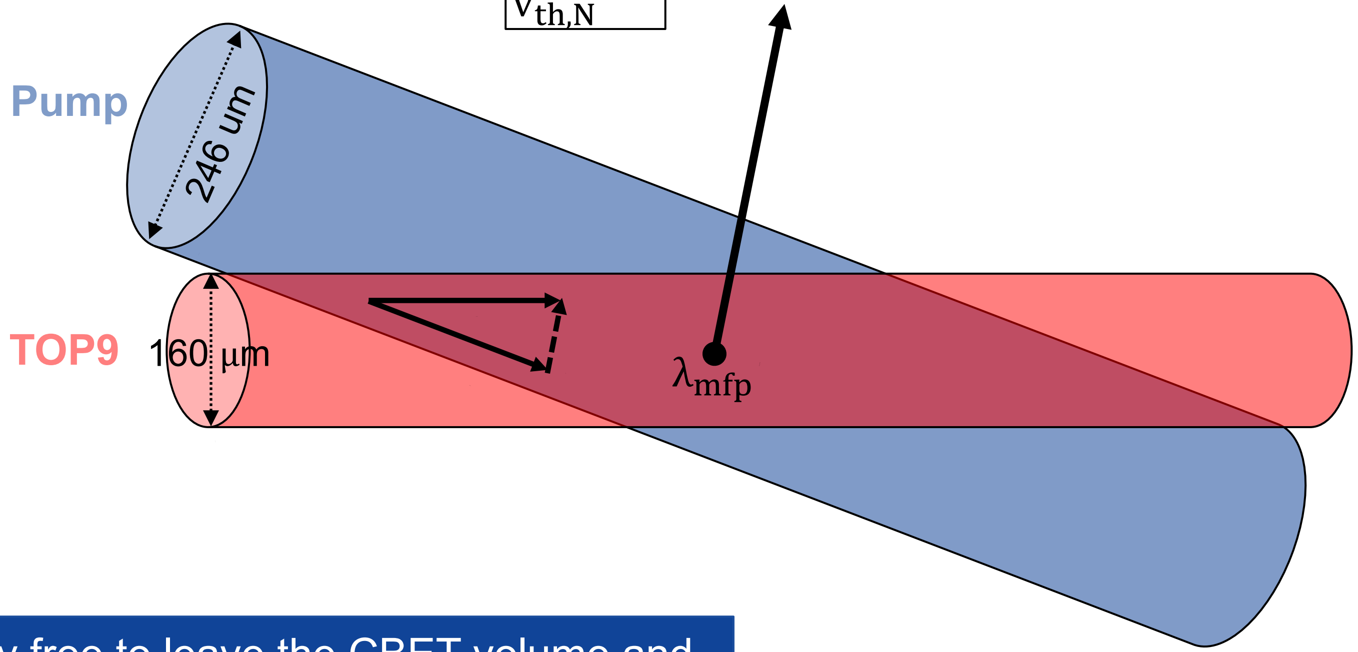
$n_e = 1.0\times10^{20}\ 1/cc$

$T_e = 850$ eV

$k\lambda_{De} = 0.14$

$\boxed{\frac{v_{ph}}{v_{th,N}} \sim 9}$

$\lambda_{mfp} \sim 370\ \mu m$



Trapped ions were mostly free to leave the CBET volume and heat the surrounding plasma in high phase velocity experiments

Crossed-beam energy transfer (CBET) saturation by ion heating was measured and found to be consistent with kinetic linear CBET theory

- Previous experiments have observed CBET saturation but have lacked the measurements to understand the CBET saturation mechanism
- Low phase velocity $(v_{ph} \approx 5\, v_{th,N})$ CBET experiments observed early (<100 ps) and late time (>100 ps) CBET saturation
  - Thomson-scattering measurements measure up to x10 increase in ion temperature
  - Linear kinetic CBET theory reproduced energy transfer experiments when including the measured ion heating
- Particle-In-Cell (PIC) simulations identify the ion heating mechanism
  - Ion trapping leads to increased ion temperature
  - Increased ion temperature limits ion wave growth and saturates CBET
- High phase velocity $(v_{ph} \approx 8\, v_{th,N})$ CBET experiments showed pump depletion and no evidence of CBET saturation
  - Thomson-scattering measured no enhanced ion heating
  - Linear kinetic CBET theory reproduced measured energy transfer when including pump depletion and measured plasma conditions

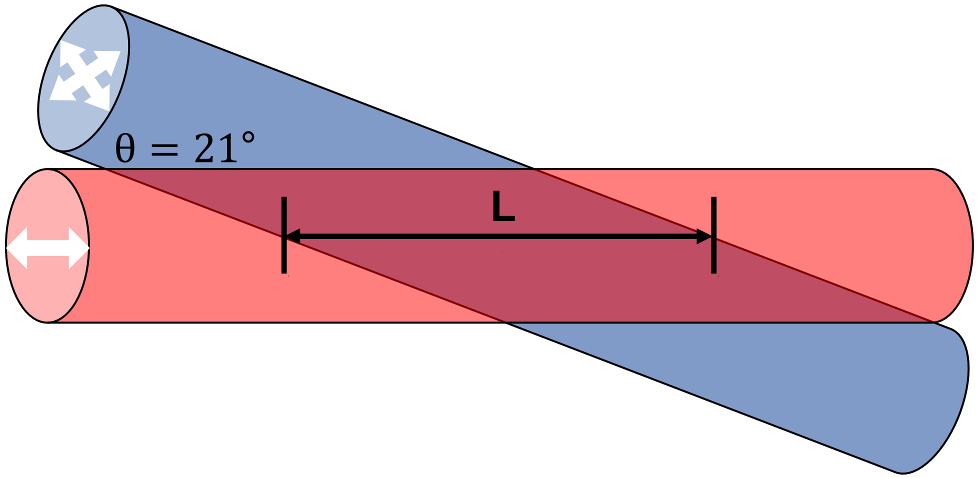
These results highlight the importance of coupling laser-plasma instability physics into hydrodynamic models to accurately predict the plasma conditions

Extra Slides

Beam geometry and plasma density were modified in a low-gain campaign to minimize pump-depletion effects

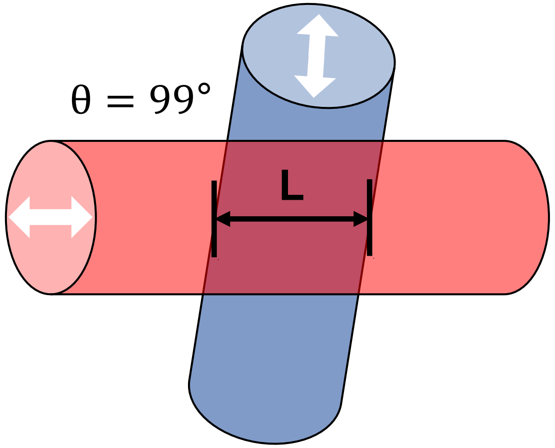
High-gain Campaign

- Nearly co-propagating crossing
- High density ($n_e = 1.0 \times 10^{20}$ 1/cc)
- Polarization smoothed & s-polarized beams



Low-gain Campaign

- Nearly perpendicular crossing
- Low density ($n_e = 0.6 \times 10^{20}$ 1/cc)
- Aligned s-polarization



$$\frac{L_{99°}}{L_{21°}} = 0.36$$

$$\frac{n_{e,99°}}{n_{e,21°}} = 0.6$$

$$G \propto n_e L$$

$$\boxed{\frac{G_{99°}}{G_{21°}} \approx 0.25}$$

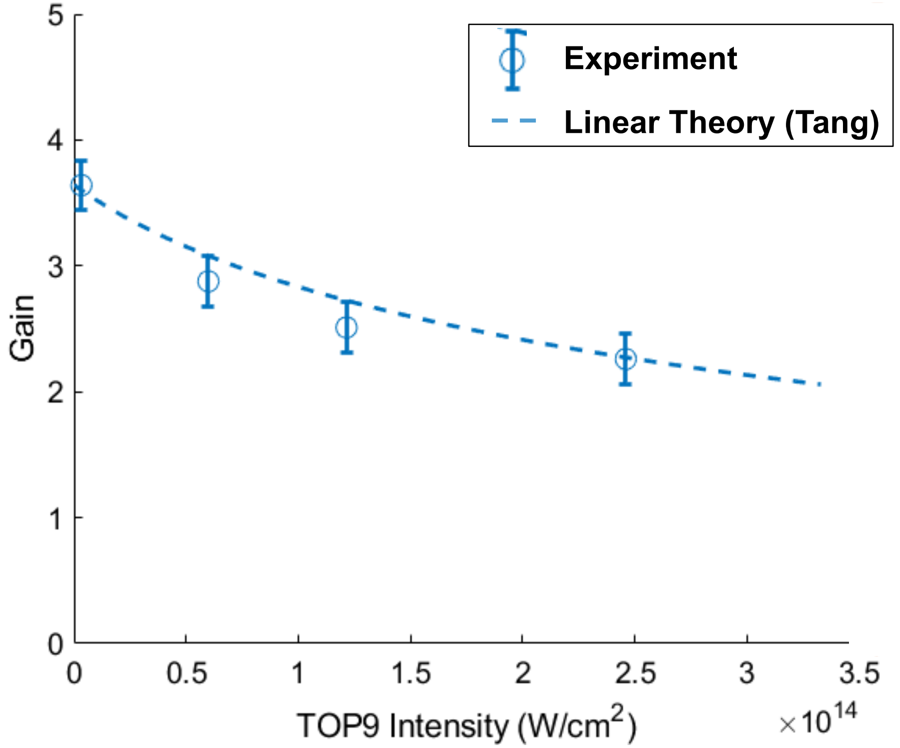
Pump depletion limited the effective pump beam intensity which diminished gains as the TOP9 intensity was increased

- Gain in the TOP9 beam is proportional to the available pump intensity

$$G \propto I_{pump} \qquad \frac{I_{probe}}{I_{probe,0}} = \exp(G)$$

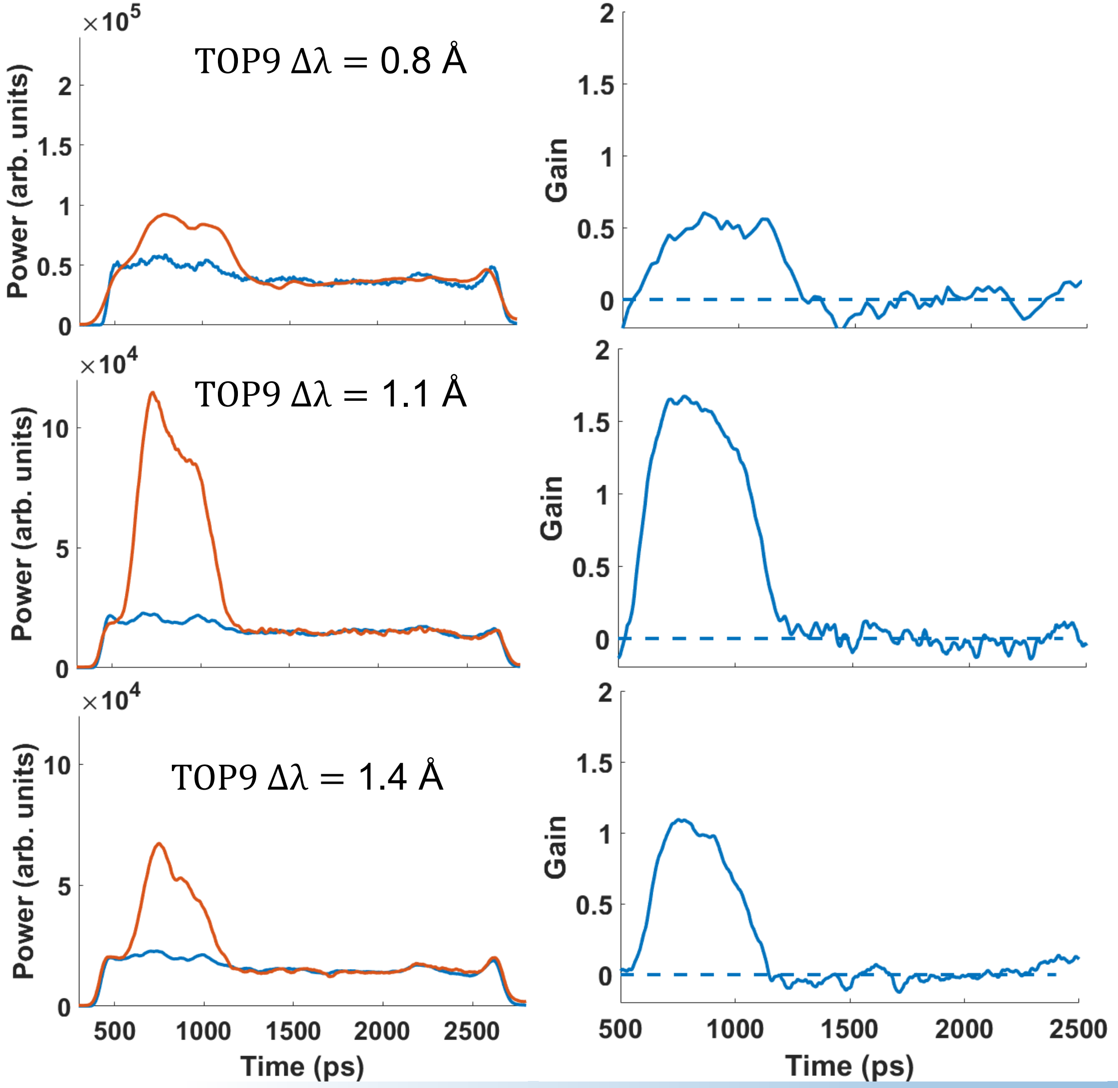
- The impact of pump depletion on the effective gain is calculated using the Tang formula*

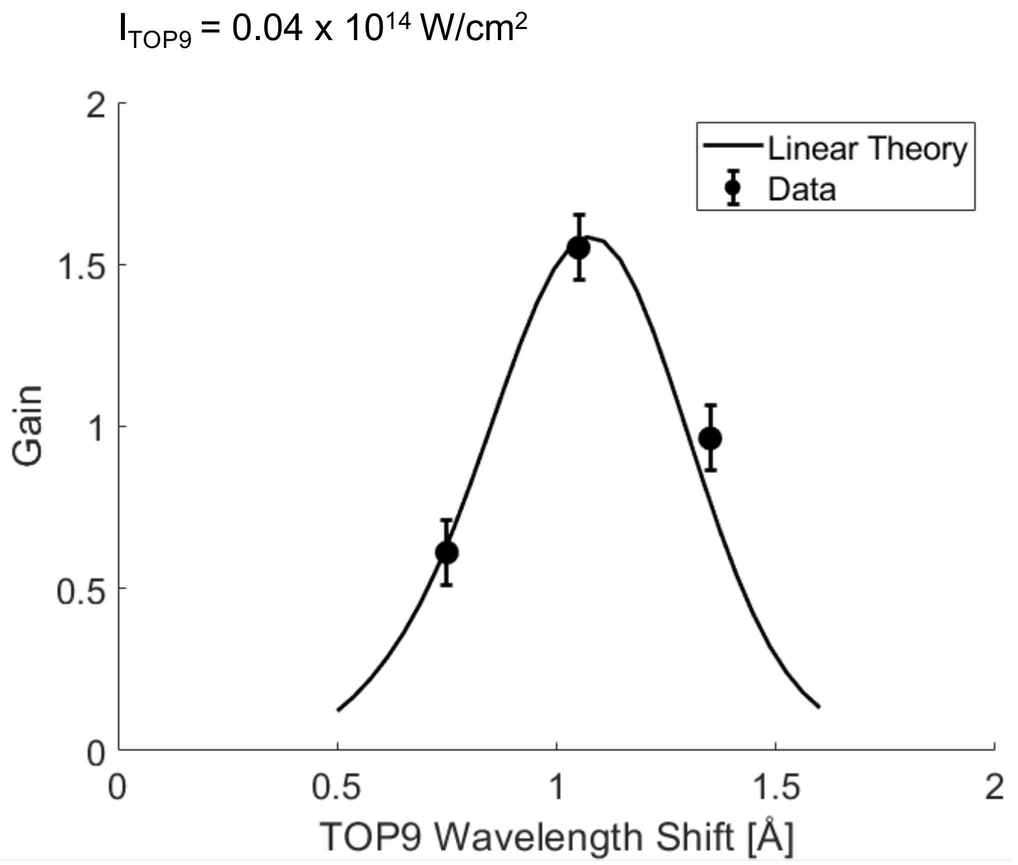
$$\exp(G) \rightarrow \frac{(1+\beta)\exp(G\,(1+\beta))}{1+\beta\exp(G\,(1+\beta))} \qquad \beta = \frac{I_{probe}}{I_{pump}}$$



* C. L. Tang, J. Appl. Phys. 37, 2945 (1966)

Gain in the TOP9 beam was measured while varying the wavelength detuning and holding intensity constant





Energy transfer experiments agree with linear CBET theory when measured plasma conditions are used