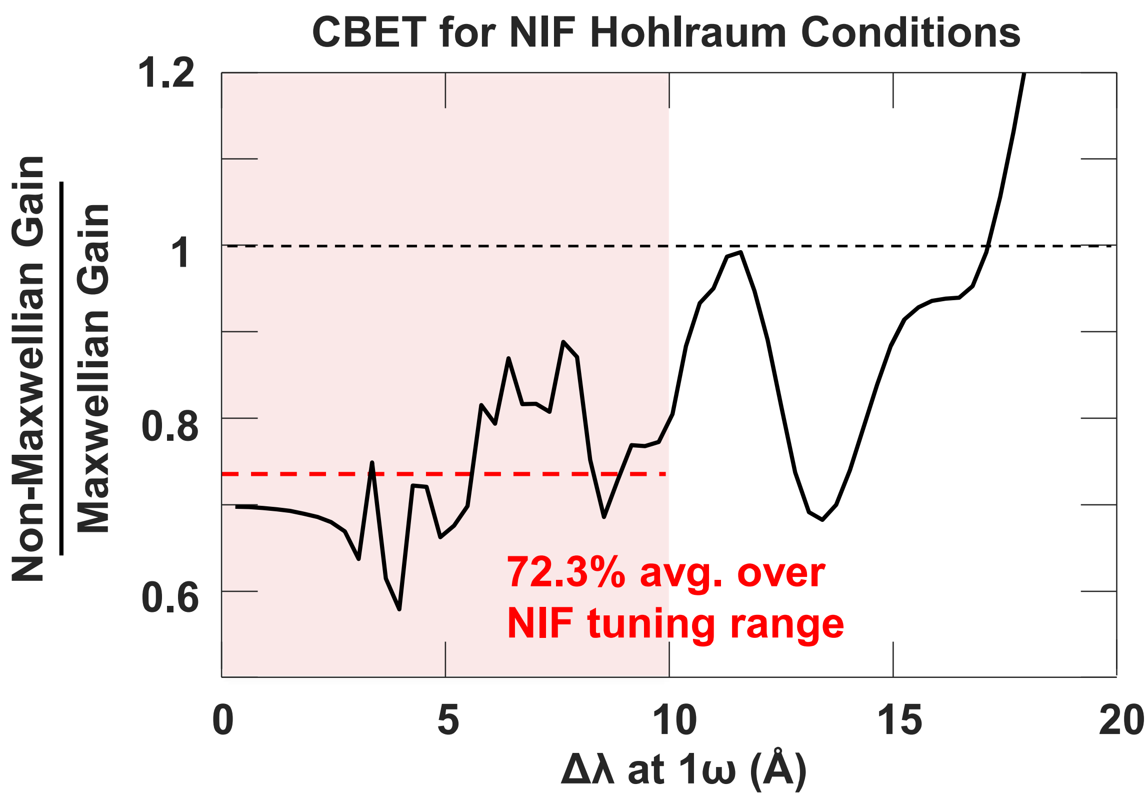
Non-Maxwellian Distribution Functions and their Impacts on Crossed-Beam Energy Transfer and Absorption



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Summary

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- But multi-beam experiments at LLE (more ICF-relevant) have shown that non-Maxwellian electro functions (EDFs) driven by laser heating can strongly impact CBET; extrapolating to NIF gives ~
  - A non-Maxwellian inline CBET model should improve the predictive capability of integrated
- Other processes are sensitive to the tails of the EDF (e.g., stimulated Raman scattering), which w with angularly resolved Thomson scattering and found not to conform to any single theory yet d
- Recent measurements are testing the effect of non-Maxwellian EDFs on absorption
- CBET is also sensitive to the *ion* distribution function and energy transfer modifies the ion distri in a way that can feed back on the CBET itself#

* P. Michel et al., PRL
D. Turnbull et al., PR
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** D. Turnbull et al, Nat.
† Under development
‡ A. Milder et al., in rev
\# A. Hansen et al., PRL

Collaborators

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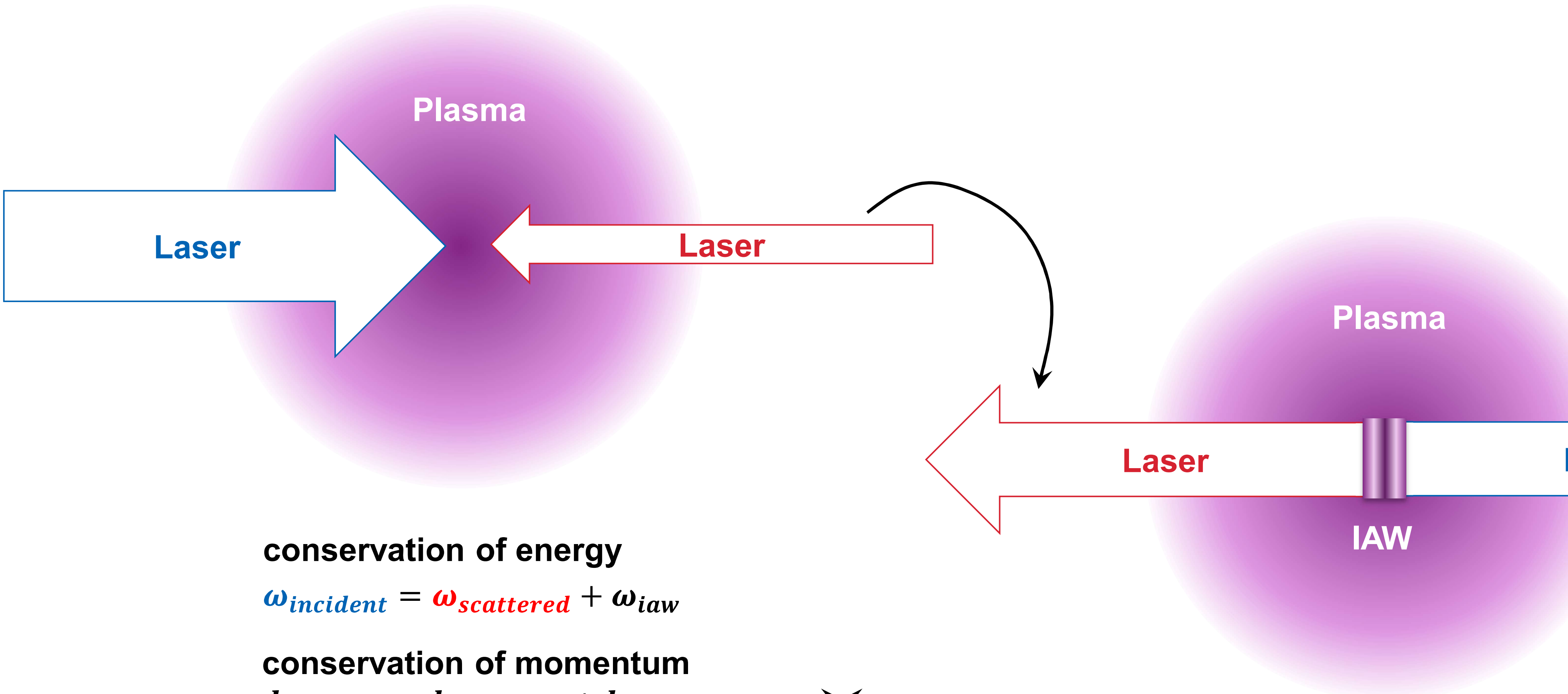
CBET is seeded stimulated Brillouin scattering (SBS)—the decay of an photon into a scattered photon and an ion acoustic wave (IAW) phonon

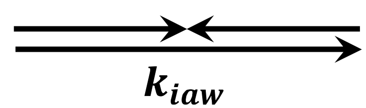


conservation of energy

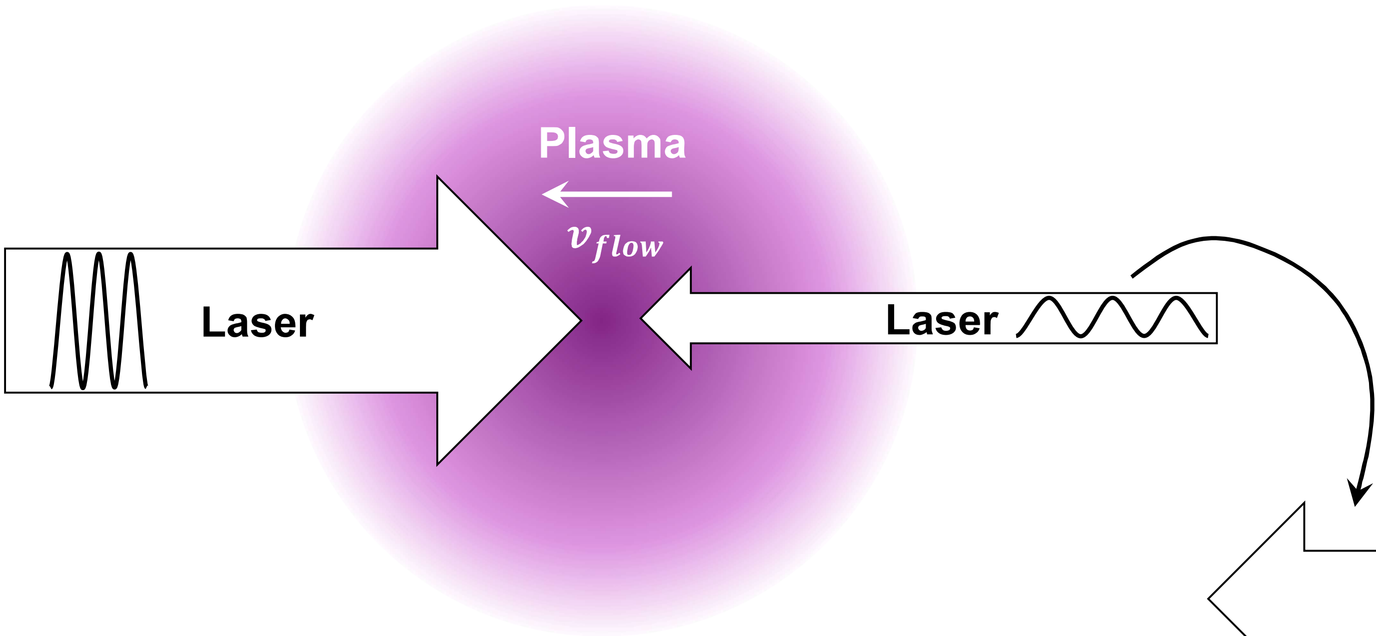
$\omega_{incident} = \omega_{scattered} + \omega_{iaw}$

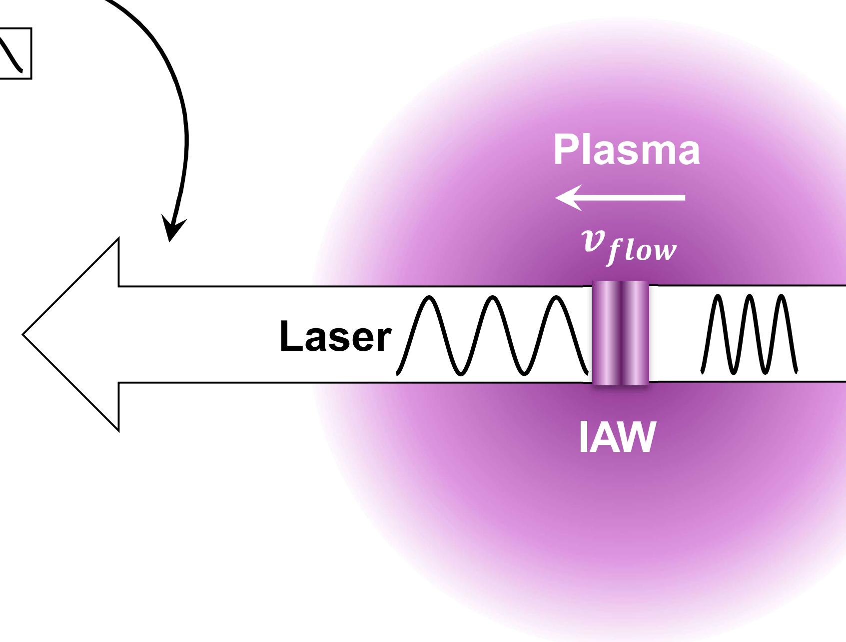
conservation of momentum

$k_{incident} = k_{scattered} + k_{iaw}$



Flows enable coupling between frequency-degenerate lasers, which ma
difficult to avoid in ICF environments





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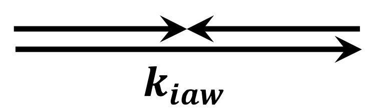
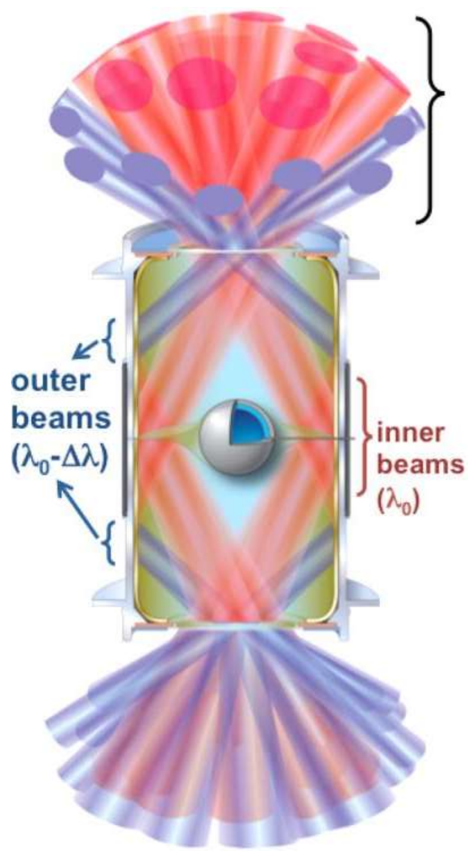
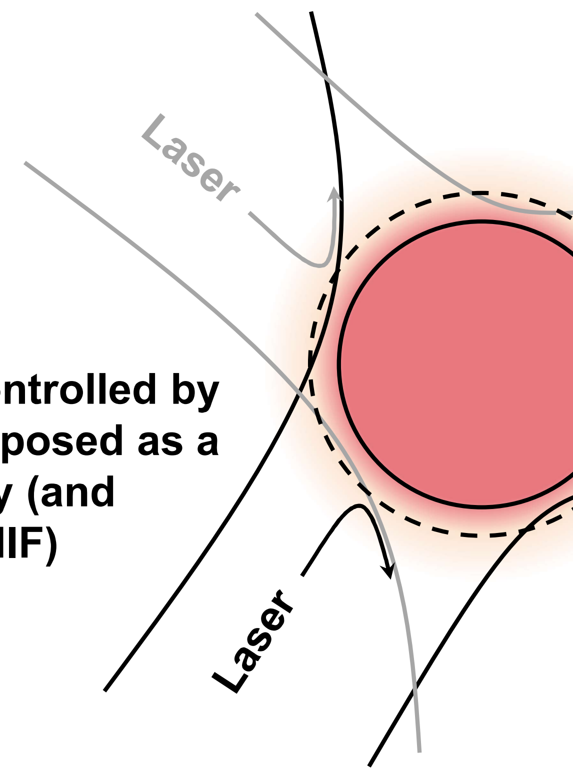


CBET is an important effect in both indirect- and direct-drive ICF



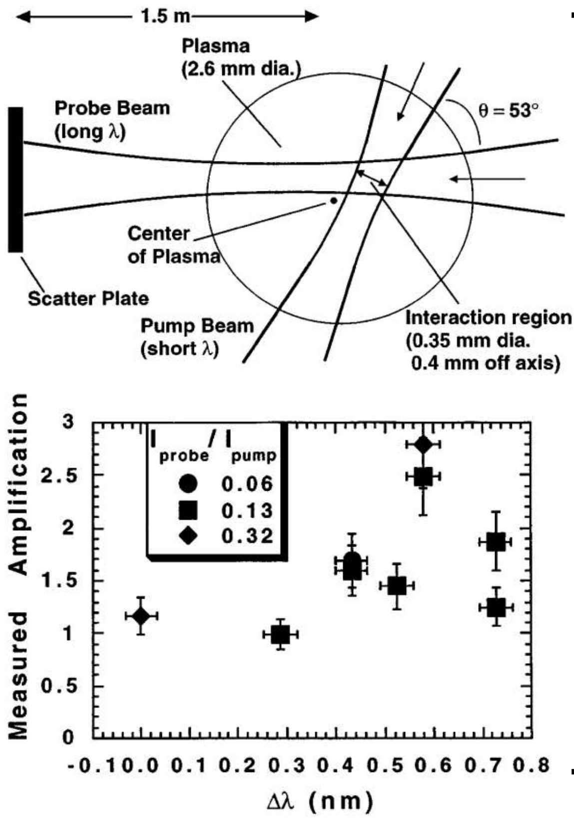
CBET primarily controlled by wavelength detuning ($\Delta\lambda$) historically, but flow is also important

CBET primarily controlled by flow, but $\Delta\lambda$ is proposed as a mitigation strategy (and demonstrated at NIF)



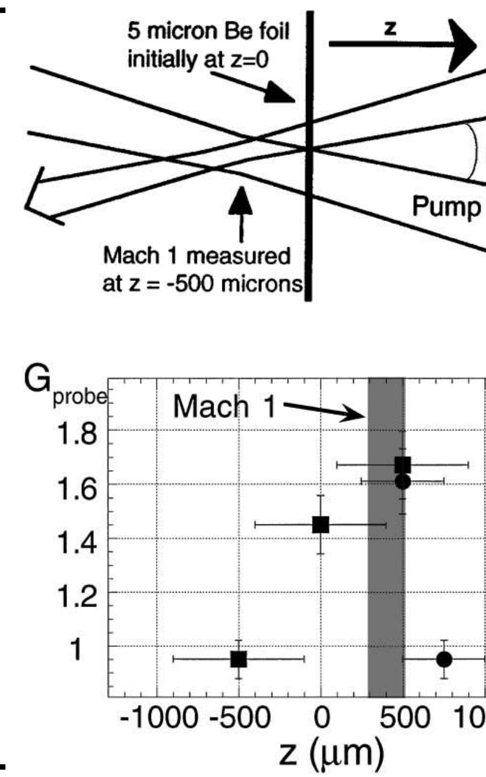
An improved understanding of CBET will impact the design of integrated ICF implosio

Early experiments observed CBET but proved difficult to calculate accu



Gas bag expts. on Nova using Δλ had anomalous peak location, gain "20x below" theory*

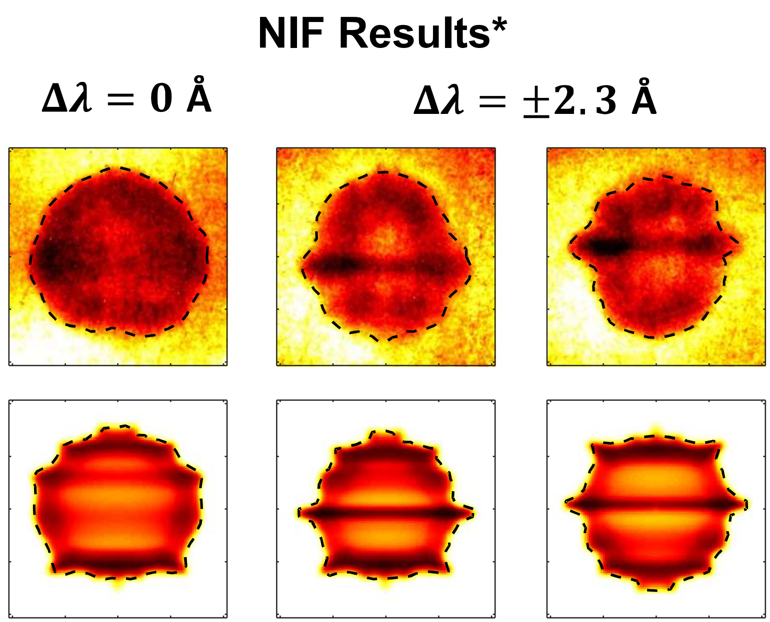
Exploding foil expts. were difficult to simulate & observed modest transfer << predicted pump depletion**

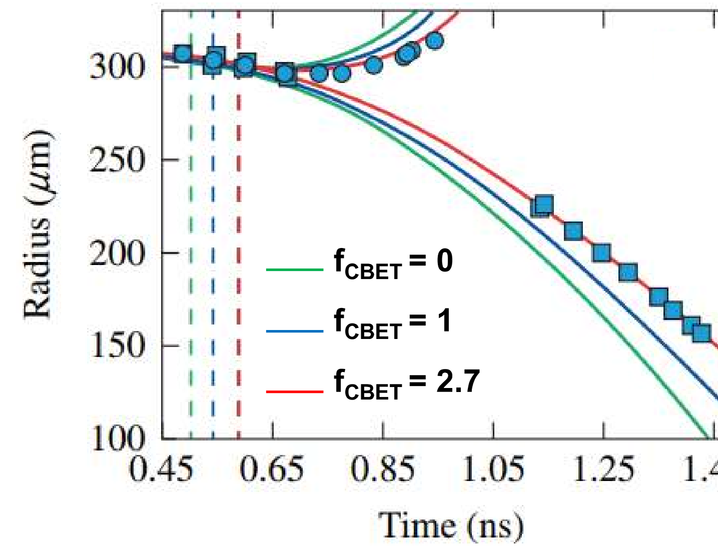


Provided proof-of-principle, but not quantitative agreement

* Kirkwood *et al.*, PRL 76, 2065 (1996).
** Wharton *et al.*, PRL 81, 2248 (1998).

Inclusion of a CBET model has been instrumental in simulating recent I implosions*, but ad hoc multipliers are still typically required**





The persistence of multipliers limits confidence in our ability to simulate CBET

* Marozas *et al.*, PRL 120, 085001 (2018)
** Davis *et al.*, PoP 23, 056306 (2016).

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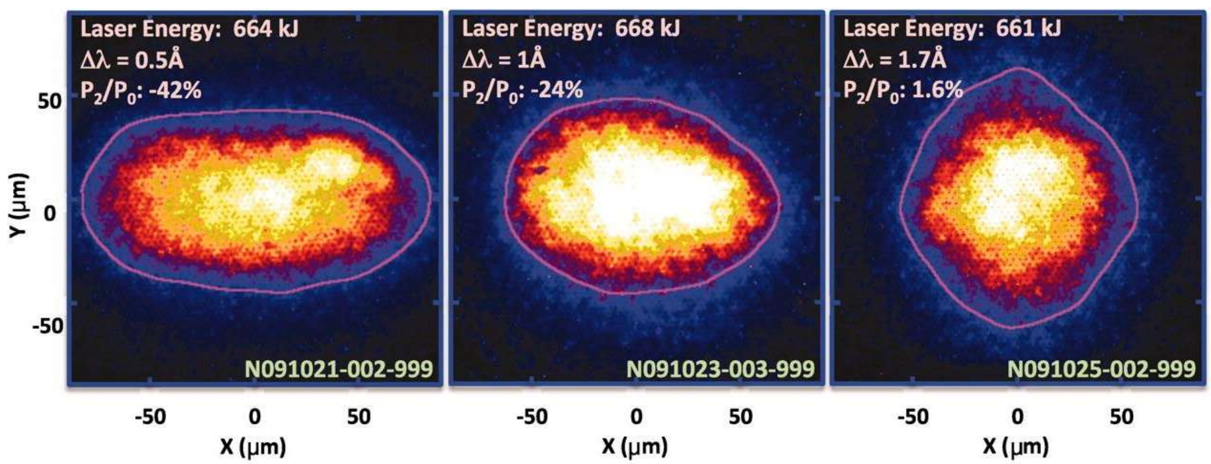
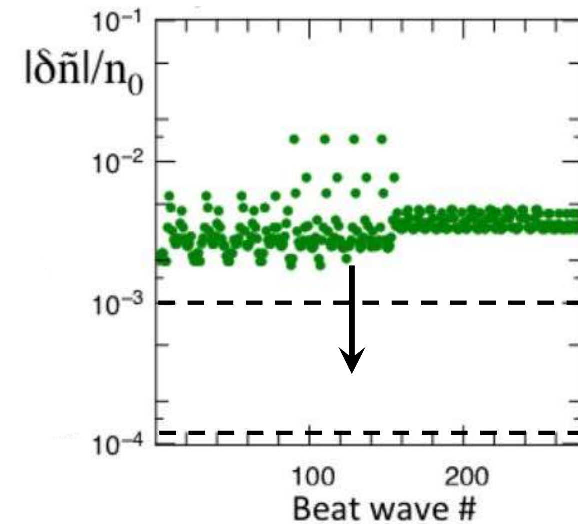
Similarly, CBET was integral to the success of early NIF ID-ICF experim
but ad hoc clamps were later added to account for apparent saturation*



Expected IAW amplitud
for each quad pairing



Inability to calculate CBET has been one factor pushing the ID-ICF program away from high hohlraums; demonstrating improved understanding could restore a larger operable desig

* Glenzer *et al*., Science 327, 1228 (2010
** Michel *et al*., PRL 109, 195004 (2012); Michel *et al*, PoP 20, 056308 (2013); Kritcher *et al*., PRE 98, 053206 (2018).

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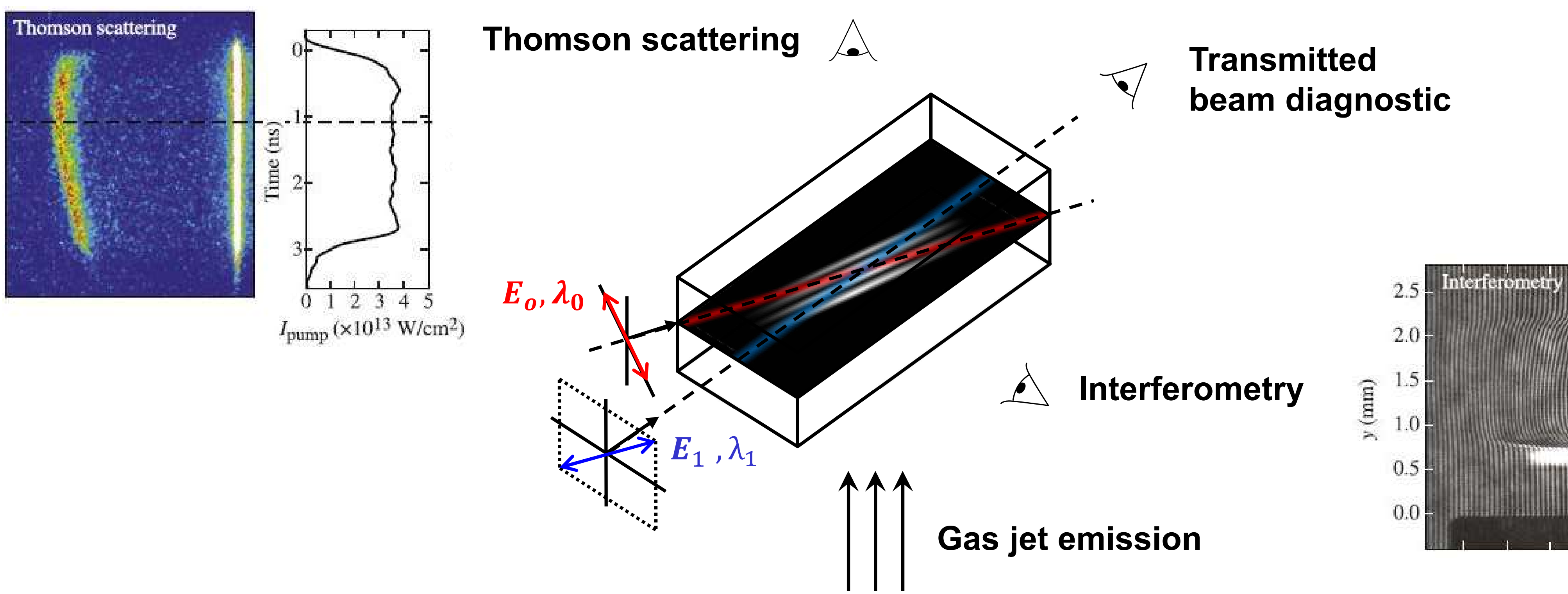
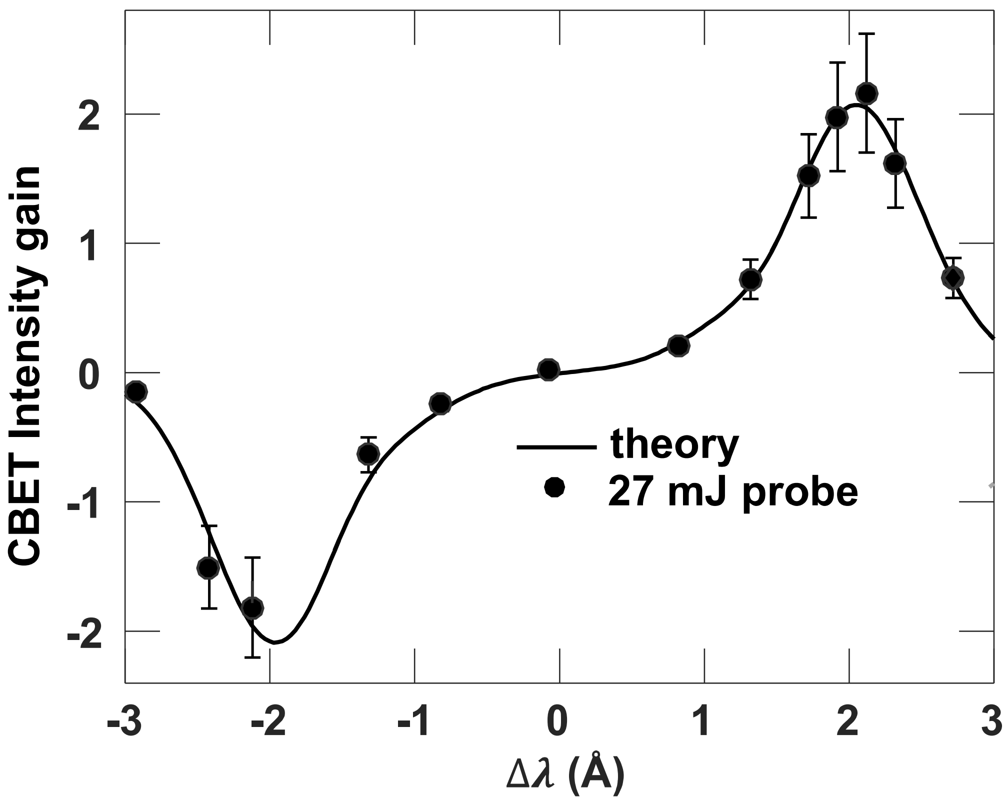
A CBET platform was first developed at LLNL's Jupiter Laser Facility to test and improve models



Using wavelength detuning and uniform, well-characterized plasmas isolates CBET physics from hydrodynamic uncertainty

The observed CBET was in reasonably good agreement with the linear theory used in ID-ICF calculations for small IAW amplitudes



Parameter	Theory input	Measured
n_e/n_c	0.0104	0.011
T_e (eV)	220	224
T_i/T_e	0.115	--
I_{pump} (W cm^{-2})	3.2e13	3.6e13
Ion comp.	30%C, 70%H	--

This represented a significant improvement over previous CBET experiments in terms of quantita

* D. Turnbull *et al.*, PRL 118, 015001 (20

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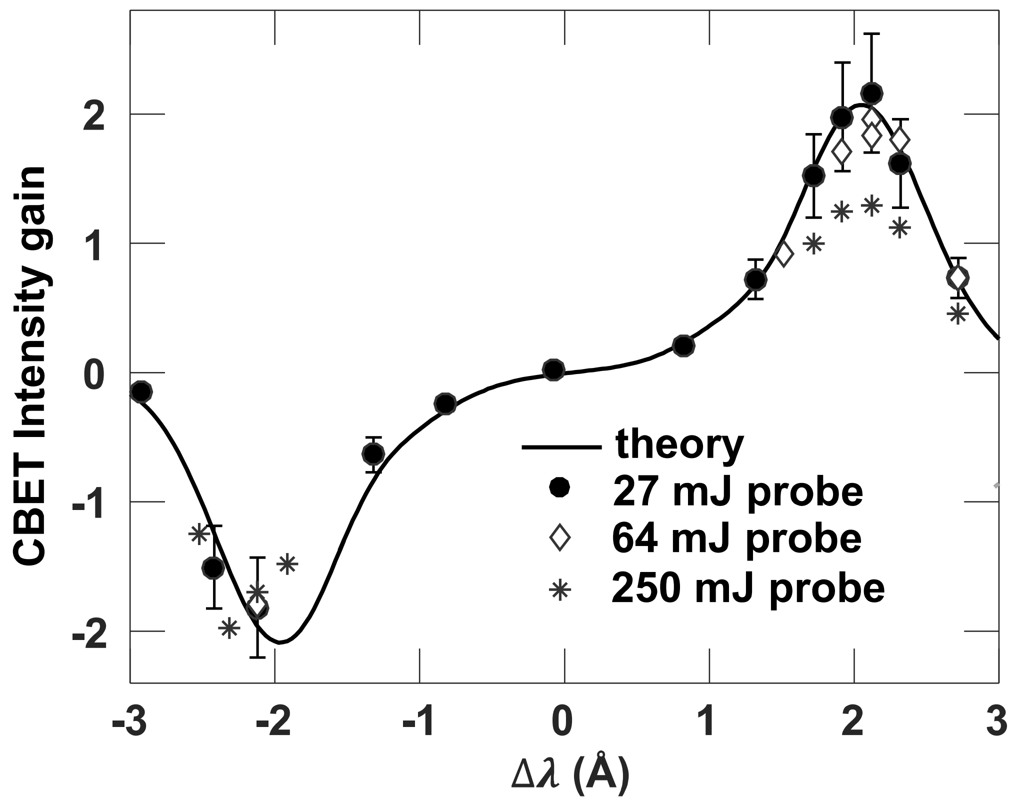
Increasing the incident probe energy led to deviation from linear theory



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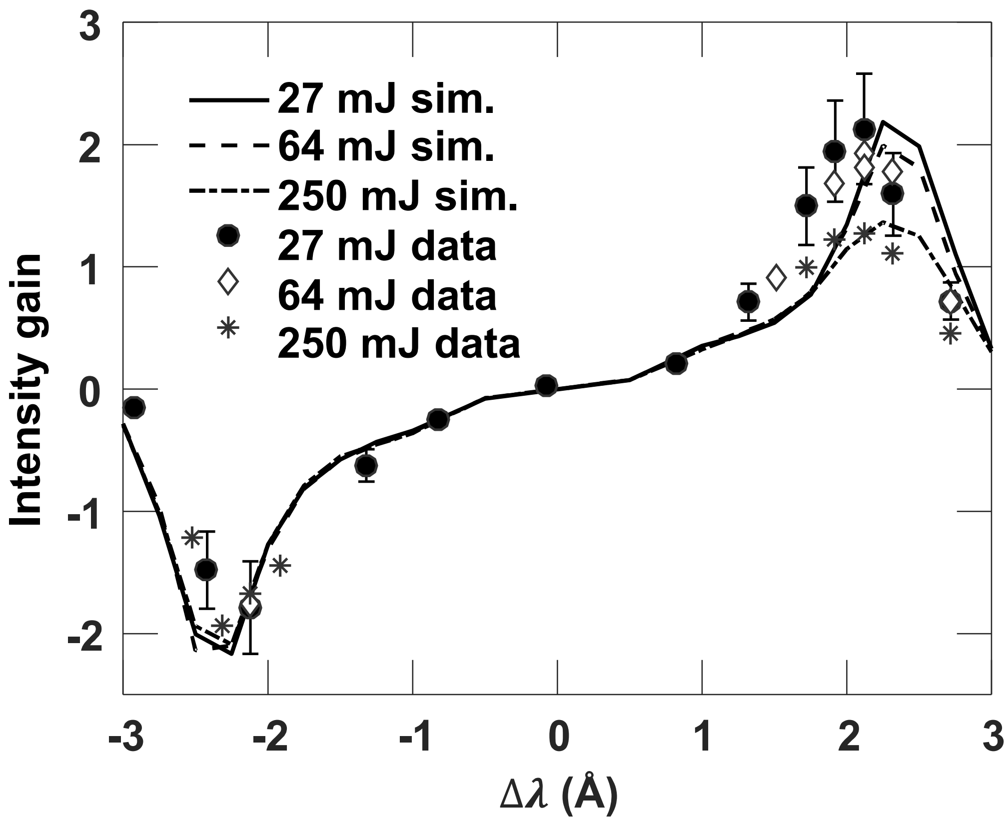
* D. Turnbull *et al.*, PPCF 60, 054017 (20

VAMPIRE* simulations reproduce a large amount of data fairly well with single clamp at the $\delta n/n = 1.5\%$ level**



This level is larger than typical IAW amplitudes in ICF experiments, suggesting saturat should not be expected (though clamps have been implemented at >10x lower levels

* A. Colaitis *et al.*, PoP 25, 033114 (2018)
** D. Turnbull *et al.*, PPCF 60, 054017 (20

Despite best CBET validation to date, knowledge gaps and questions re

- Experiments observed an anomalous peak location (same w/ Kirkwood on Nova)
- Lacked certain key measurements (e.g. T_i)
- Density, temperature, wavelength, and intensity all relatively far from ICF relevant
- Limited # of beams and geometries (multi-beam physics is particularly important for ICF)
- Limited ability to understand observed saturation

Motivation for additional experiments persists

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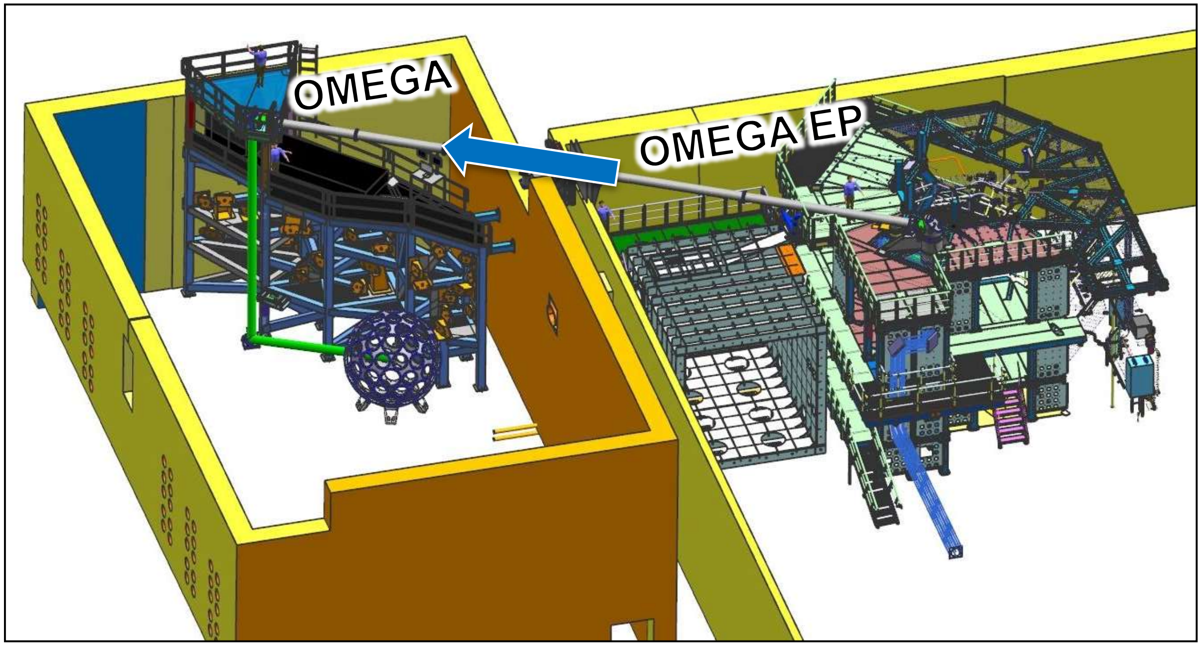
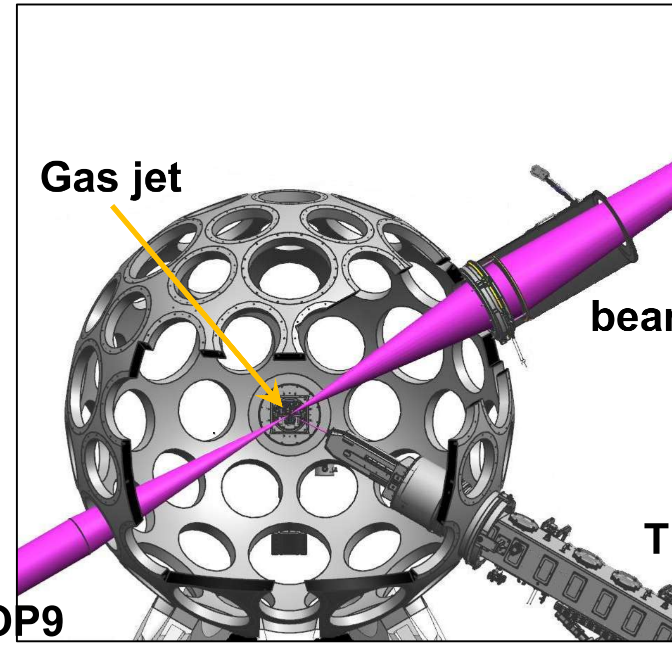
Tunable OMEGA P9 beam (TOP9; 350.2—353.4 nm) was built at LLE to d
CBET studies and develop understanding that can be scaled to ignition





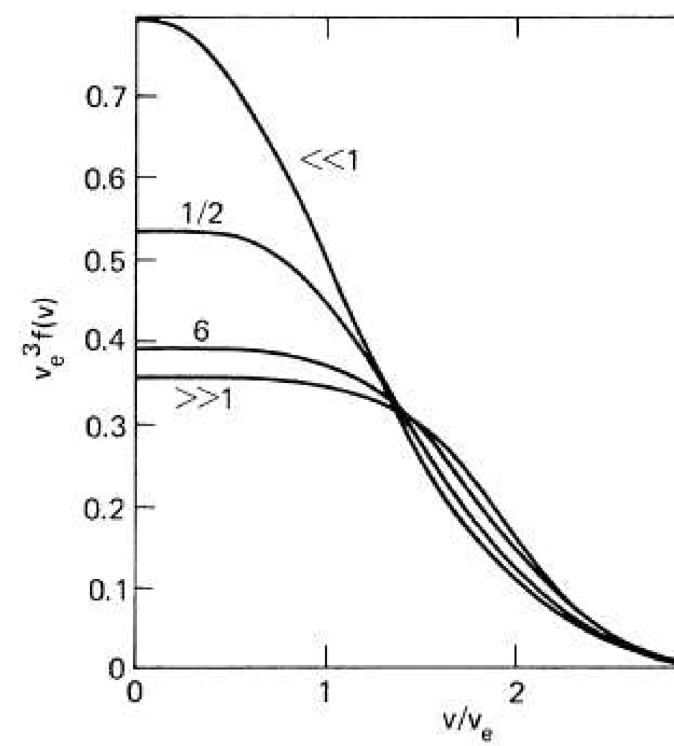
TOP9

* C. Dorrer *et al.*, Opt. Exp. 25, 26802 (20
B. Kruschwitz *et al.*, SPIE Proc. 10898

Initial TOP9 experiments studied the effect of non-Maxwellian (super-Ga electron distribution functions (EDF's) driven by inverse bremsstrahlun

- IB absorption preferentially heats low energy electrons, distorting the EDF away from a Maxwellian*
- Langdon defined $\alpha \equiv Zv_{osc}^2/v_{th}^2$
  - $\alpha \ll 1$ → Maxwellian (m=2)
  - $\alpha \gg 1$ → super-Gaussian m=5
- Matte** showed (with Fokker-Planck) that moderate heating produces intermediate super-Gaussian EDF's 2<m<5 , well-predicted by:

$$m(\alpha) = 2 + 3/(1 + 1.66/\alpha^{0.724})$$

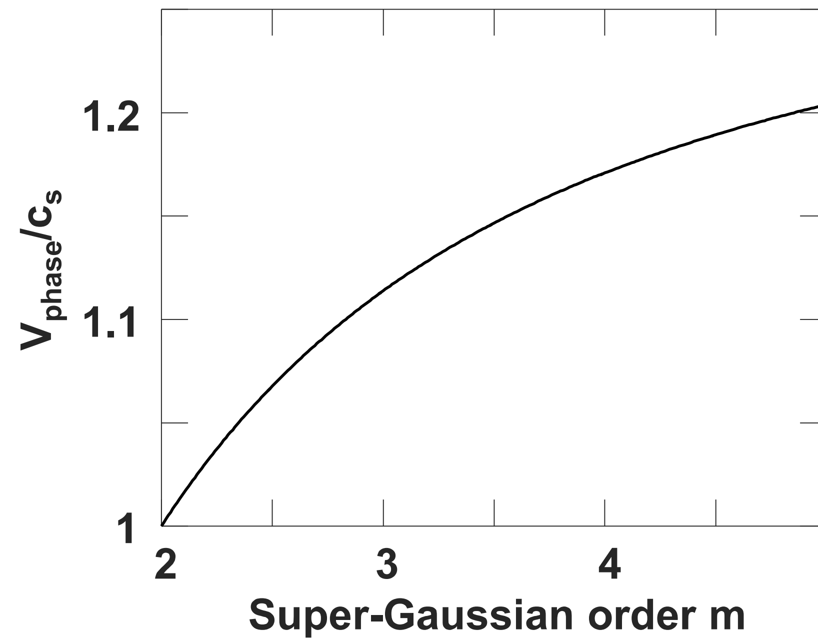


Despite potentially impacting many different processes in ICF plasmas, experimental evidence was scarce

* A B Langdon et al., PRL. 44, 576 (1980
** J-P Matte et al., PPCF 30, 1665 (1988).

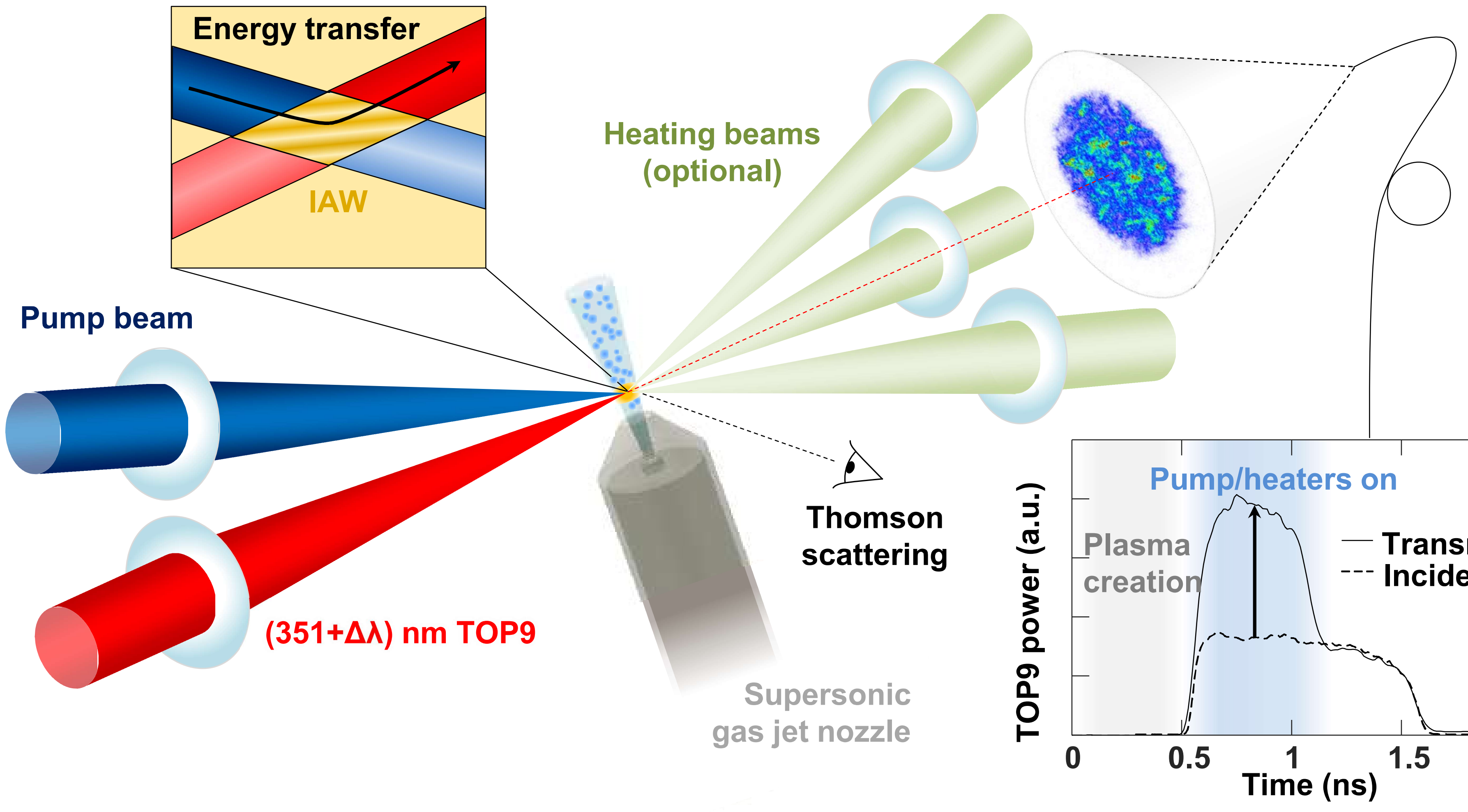
Super-Gaussian EDF's also impact the IAW's that mediate CBET*

- **The smaller # of low energy electron available to shield ion oscillations increases the frequency of IAW's, resulting in the modified dispersion relation $\omega = kc_s\left(\frac{3\Gamma^2(3/m)}{\Gamma(1/m)\Gamma(5/m)}\right)^{1/2}$**
  - **Afeyan conjectured that this might explain resonance peak anomalies in early experiments**



* B. Afeyan et al., PRL 80, 2322 (1998).

Experiments were executed as shown:



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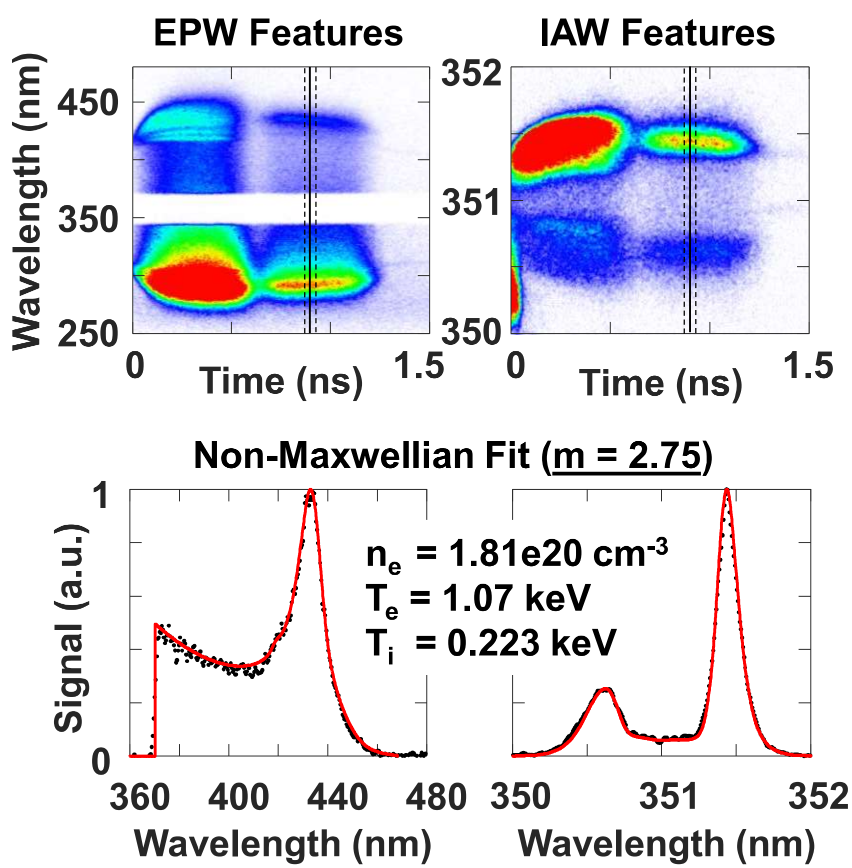
Thomson scattering clearly shows the need for a non-Maxwellian distri function; a Maxwellian assumption would give O(10's%) errors in n_e, T_e,



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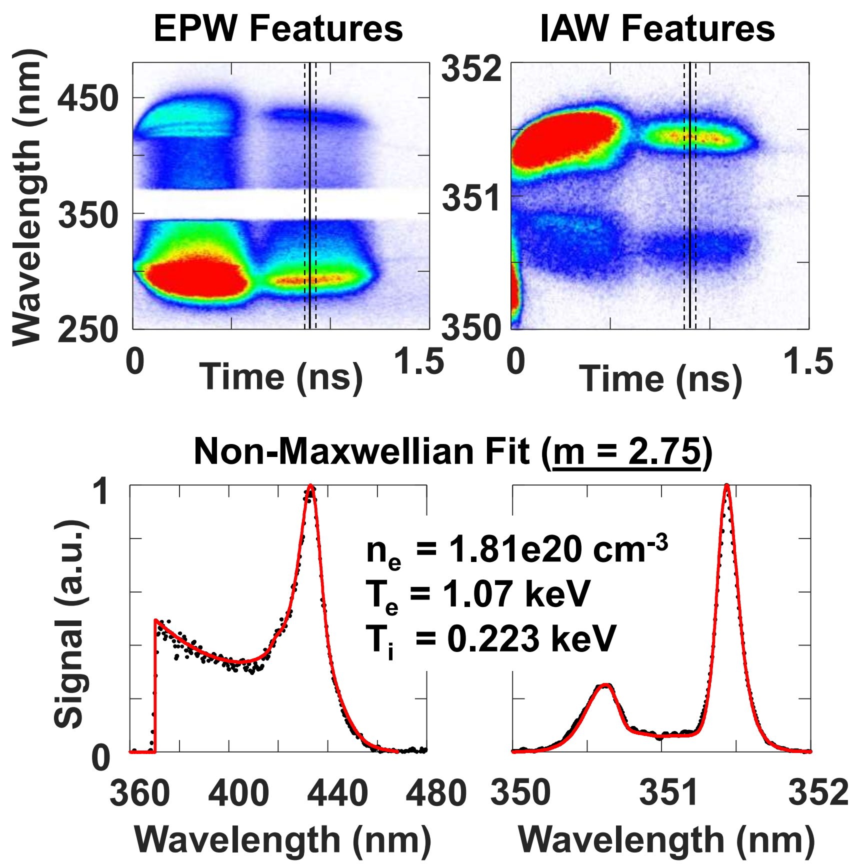

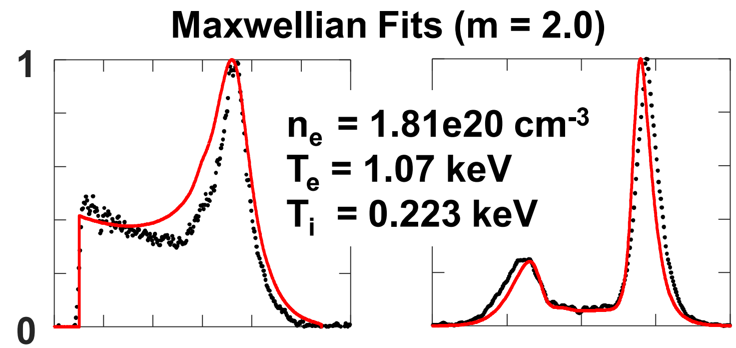

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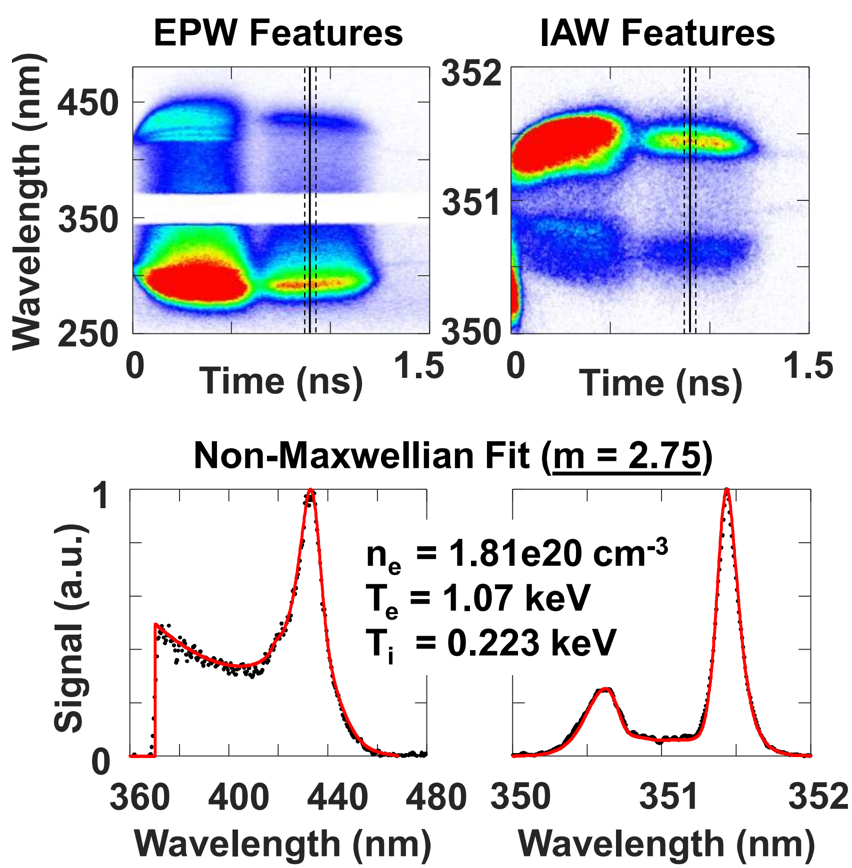

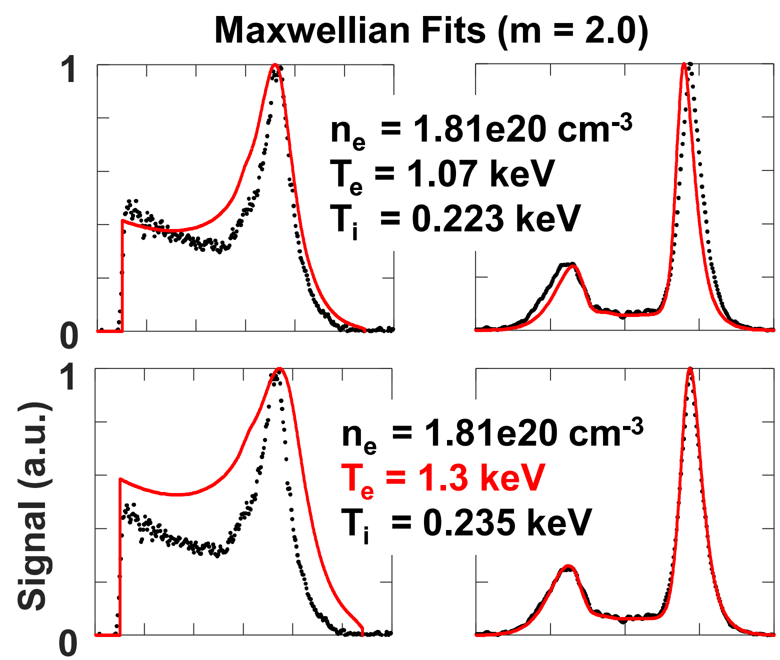

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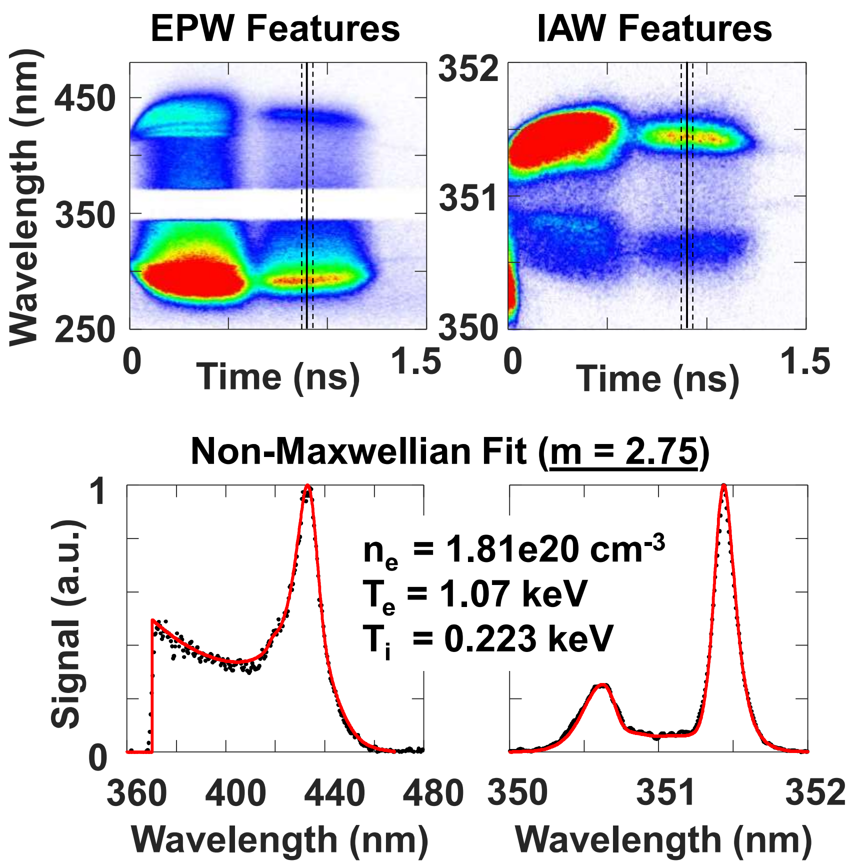

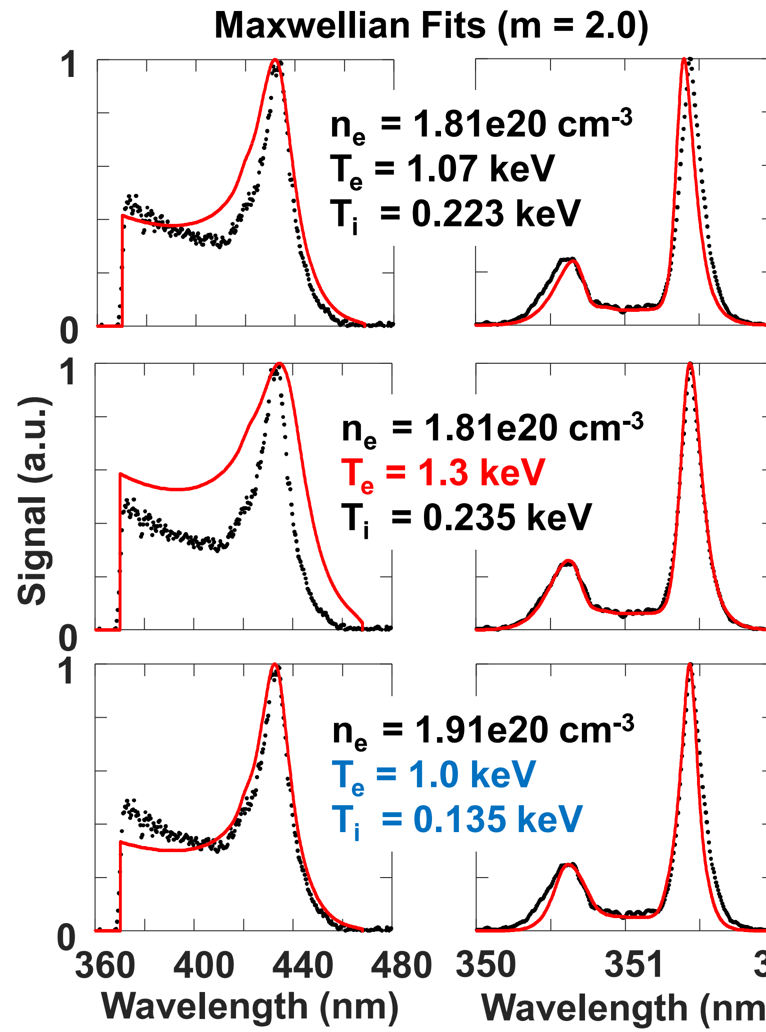

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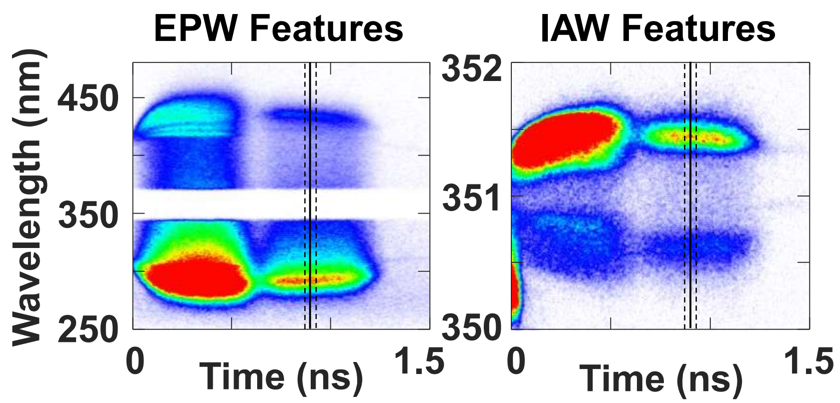

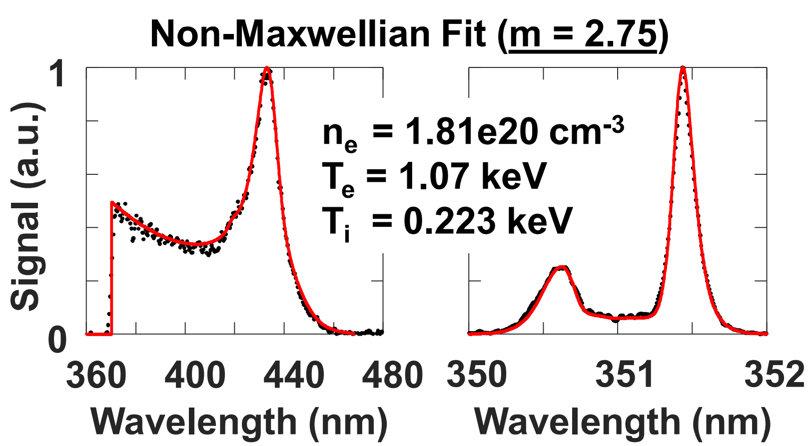

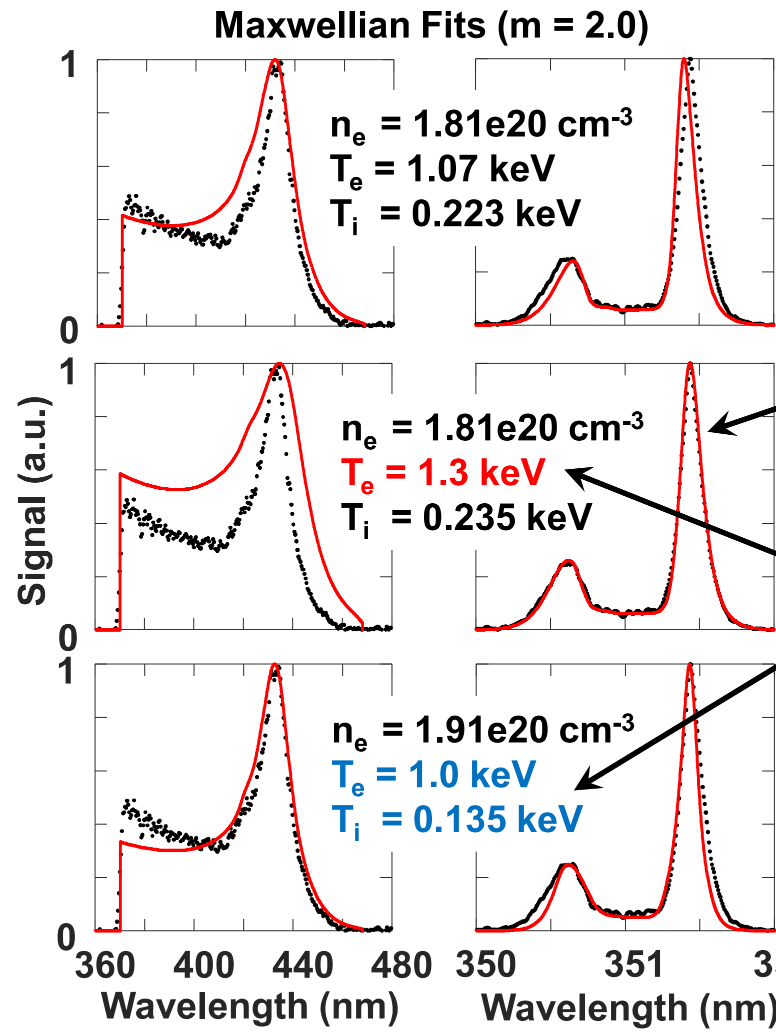

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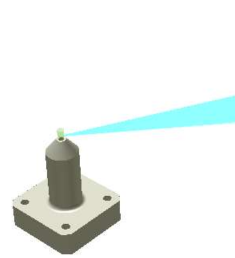
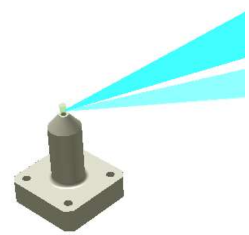
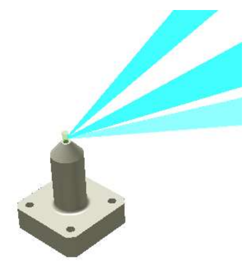
* D. T
** J. Z
† A. M

Intensity scaling showed a clear increase in the super-Gaussian expon
non-Maxwellian EDF* in agreement with existing theory**

	1 beam	2 beams	3 beams
I (10^{14} W cm^{-2})	5.1	10.2	15.3
T_e (keV)	0.84	0.98	1.07
α	0.17	0.3	0.41
$m_{observed}$	**2.4**	**2.65**	**2.75**
$m_{calculated}$	**2.43**	**2.6**	**2.72**

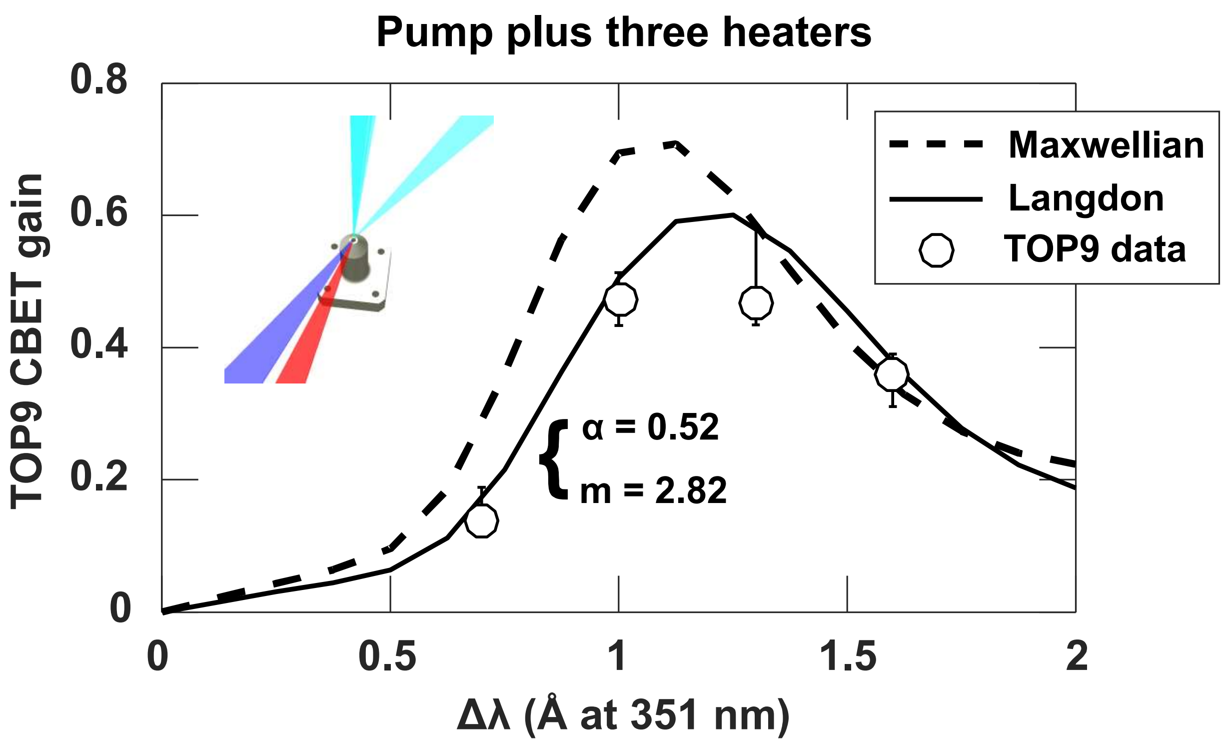
$$m(\alpha) = 2 + \frac{3}{1+\frac{1.66}{\alpha^{0.724}}} \quad **$$

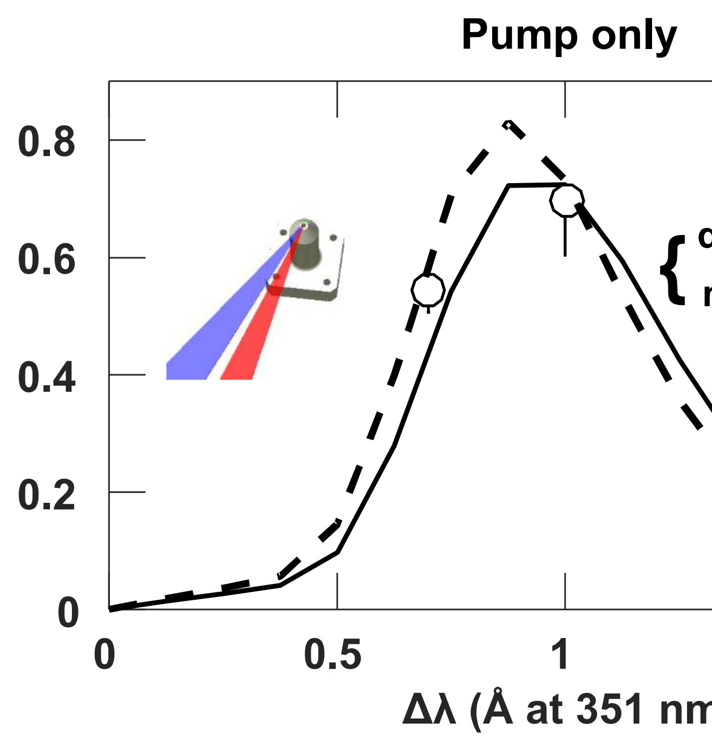




This confirms that the formula can actually be used in simulations to convert intensity to

* D. Turnbull et al, Nat. Phys. 16, 181 (20
** J-P Matte *et al.*, PPCF 30, 1665 (1988).

The CBET data confirmed the impact of the non-Maxwellian electrons o that was evident in the Thomson scattering data





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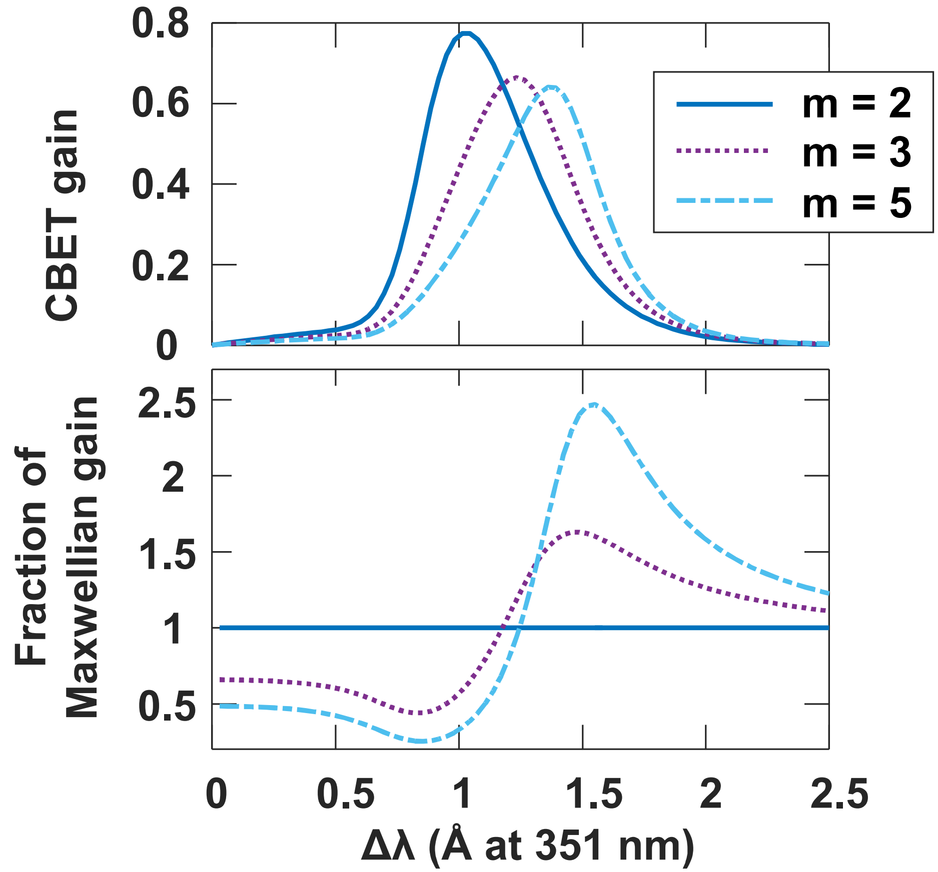
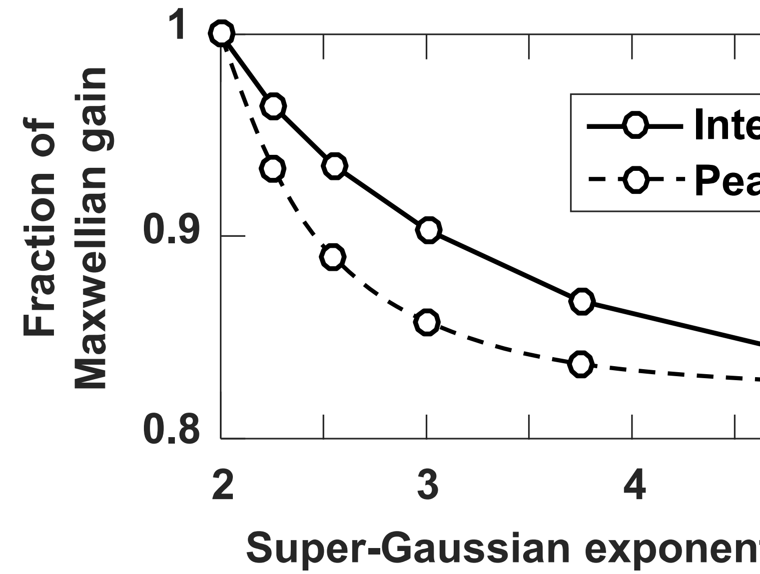
The impact of the super-Gaussian distribution on IAW's is primarily a re shift concern in strongly damped plasmas

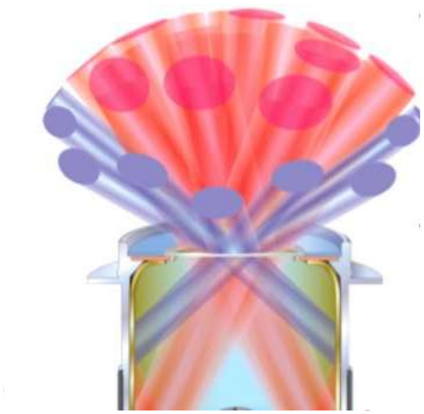




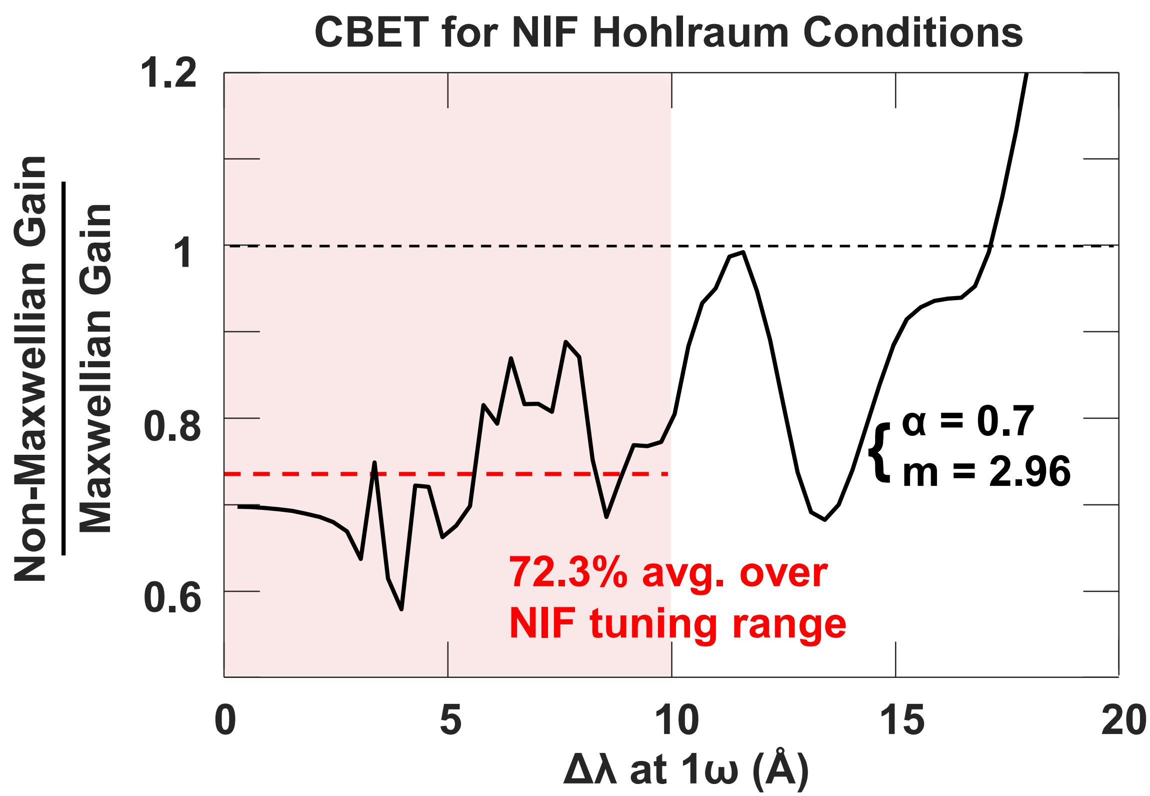
This most strongly affects situatio CBET doesn't integrate over a flow (ID-ICF), but also modifies detu requirements for CBET mitigation i

* D. Turnbull et al, Nat. Phys. 16, 181 (20

A calculation for typical NIF conditions suggests that non-Maxwellian E lowers CBET gain by 10s of % over relevant tuning range



$\alpha \equiv Z v_{osc}^2 / v_{th}^2$



Calculation
- T_e = 2.8 k
- T_i = 0.8 k
- Z = 2, A =
- n_e = 0.03
- 384 TW F
- Beam-by pointing

Implementing the non-Maxwellian model will improve prediction of CBET's space- and dependence in ID-ICF, and it will reduce (and may eliminate) the need for a saturation c

* D. Turnbull et al, Nat. Phys. 16, 181 (20

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- Recent measurements are testing the effect of non-Maxwellian EDFs on absorption
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† Under development
‡ **A. Milder et al., in rev**
\# A. Hansen et al., PRL

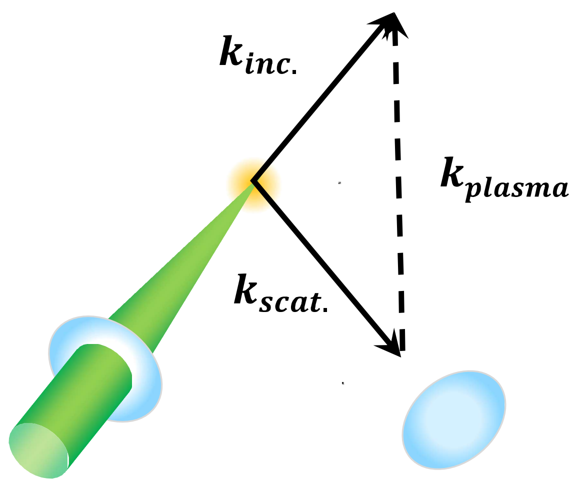
CBET is determined by bulk electrons, but many processes are sensitiv tails of the EDF

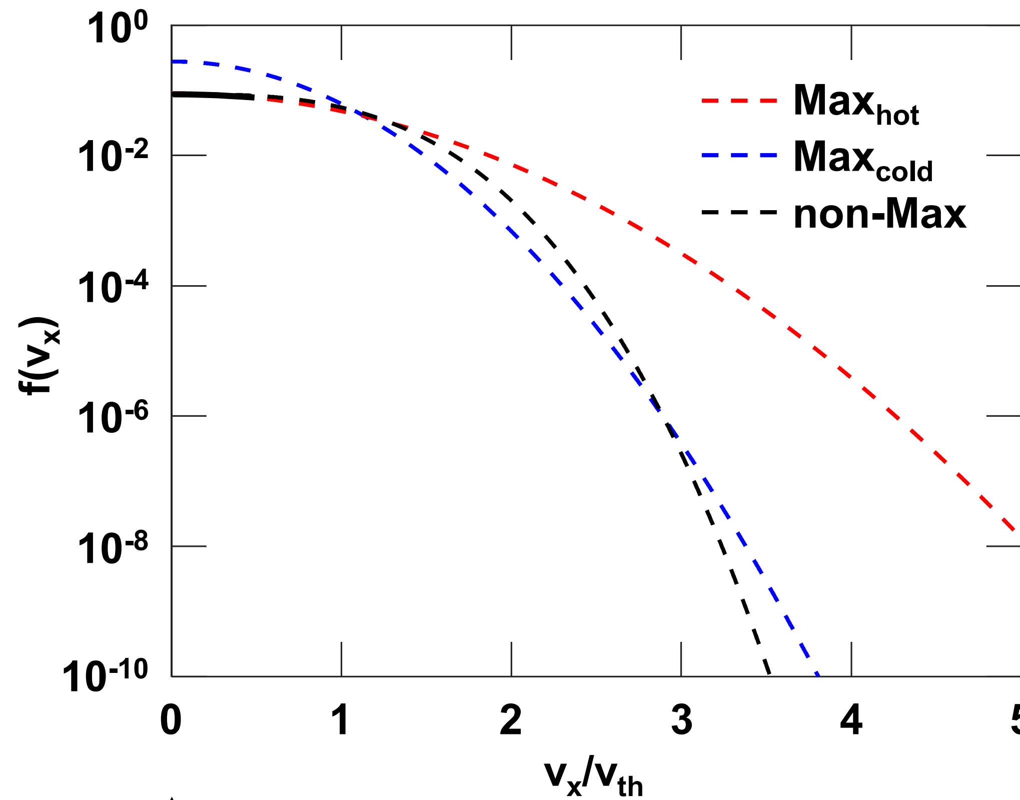
- Subsequent simulation work consistently validated Matte's formula for bulk electrons
- But some have argued that tails are likely more Maxwellian than the pure super-Gaussian distri various reasons (e.g., transport*, neglected e-e collisional term**)
- Processes affected by tails of the EDF include x-ray emission†, electron plasma wave instabilit heat transport§, etc.

The ability to measure the electron distribution function without assuming its functional form would be extremely useful

* S. Brunner and E. Valeo, PoP 9, 923 (2
** E. Fourkal *et al.*, PoP 8, 550 (2001).
† J-P Matte *et al.*, PPCF 30, 1665 (1988).
‡ B. Afeyan *et al.*, PRL 80, 2322 (1998).
§ C. Ridgers *et al.*, PoP 15, 092311 (2008

Thomson scattering with additional collection angles could help to fill i electron distribution function





IAW feature

ω/k_{iaw}

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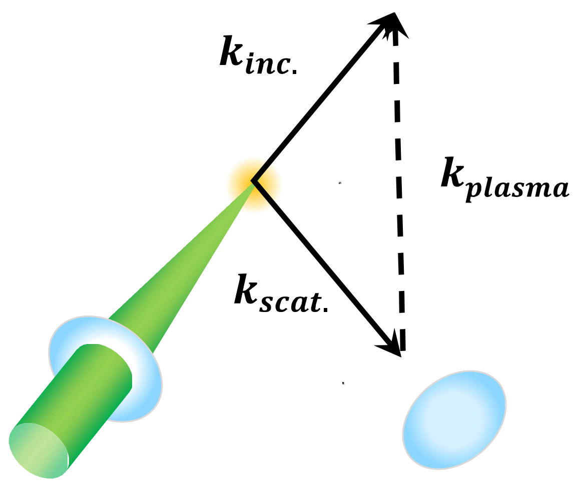

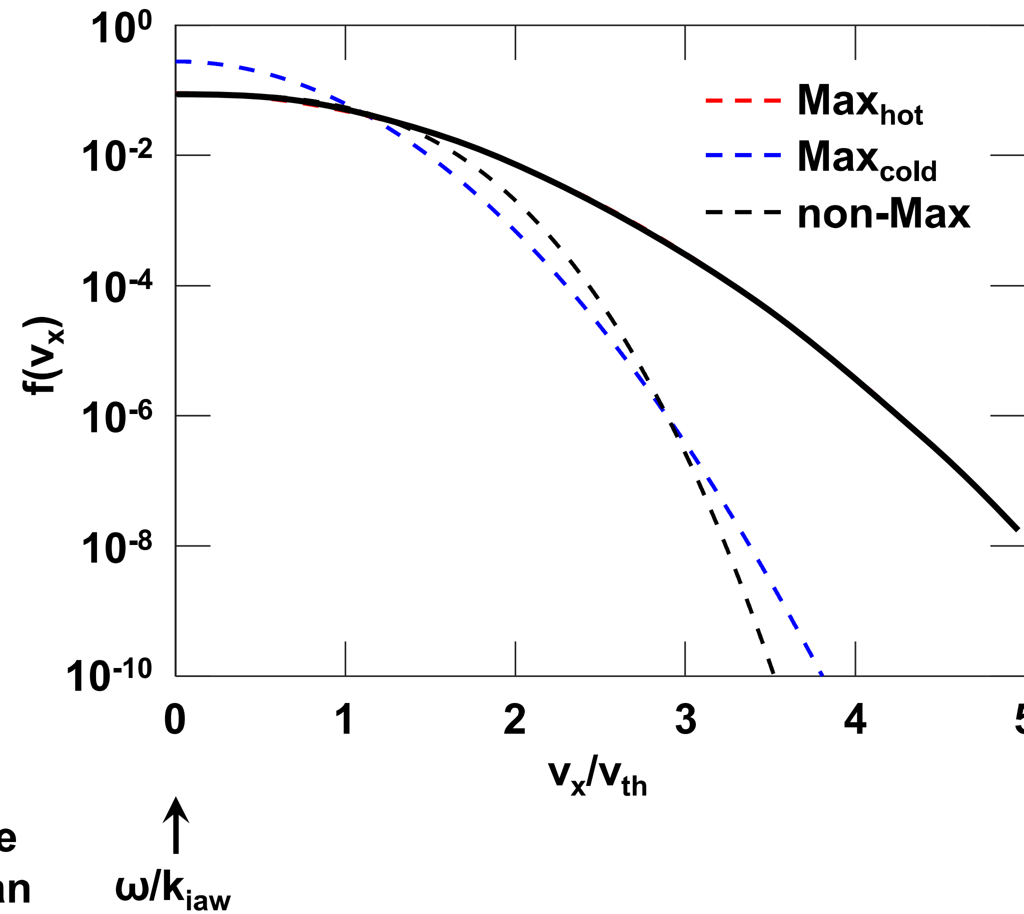

IAW feature
+ Maxwellian

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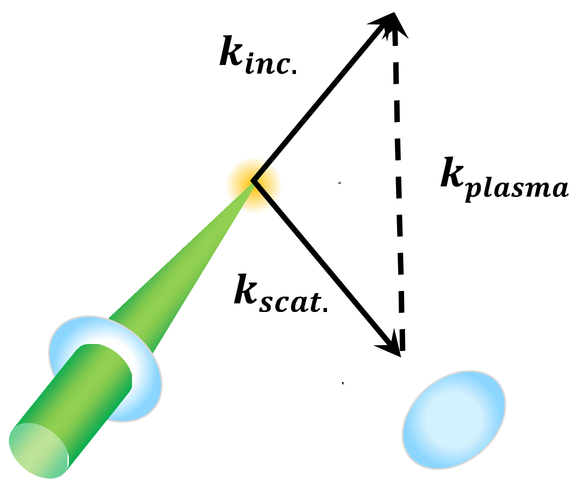

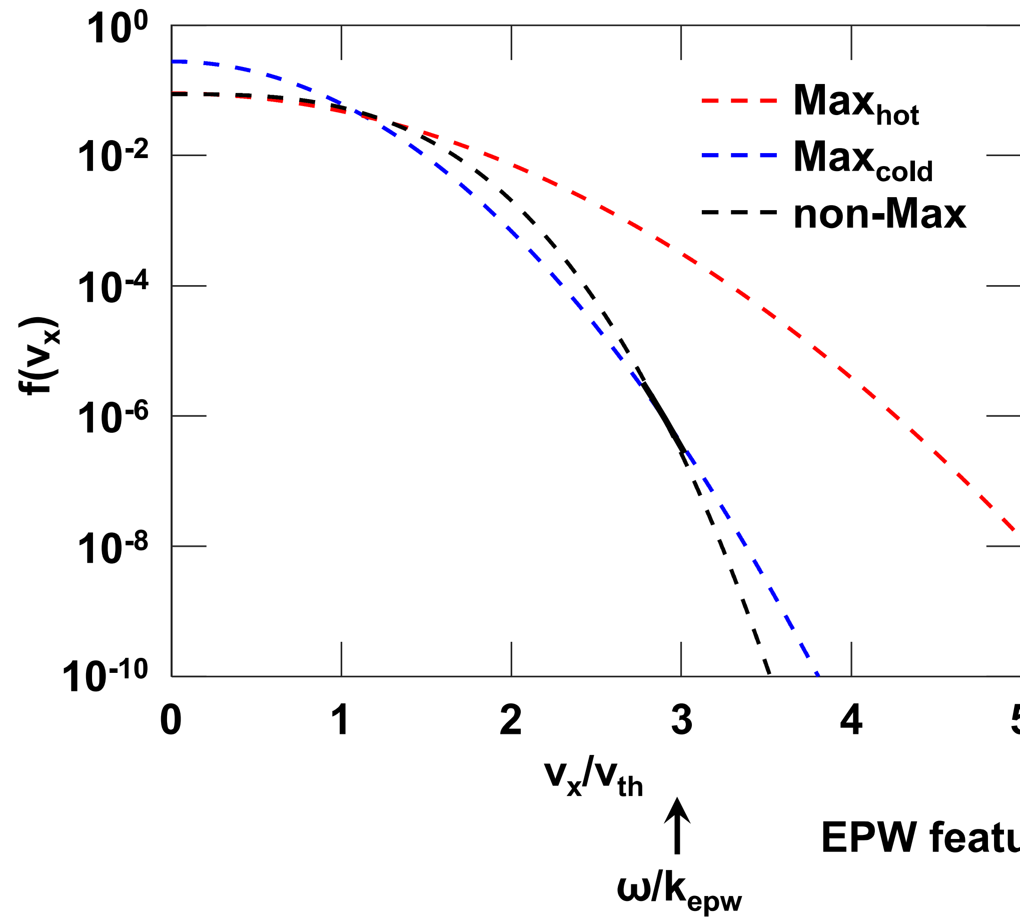

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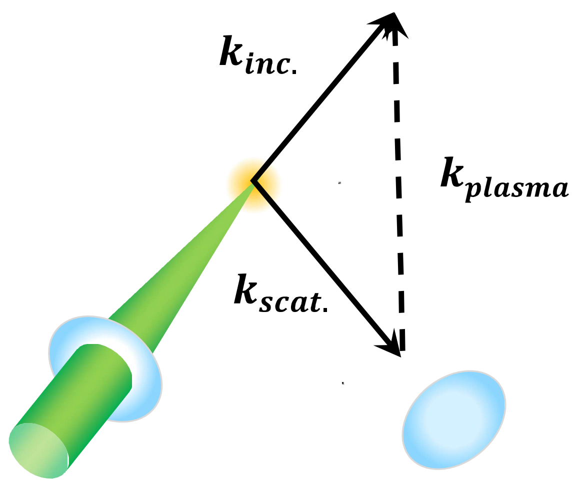

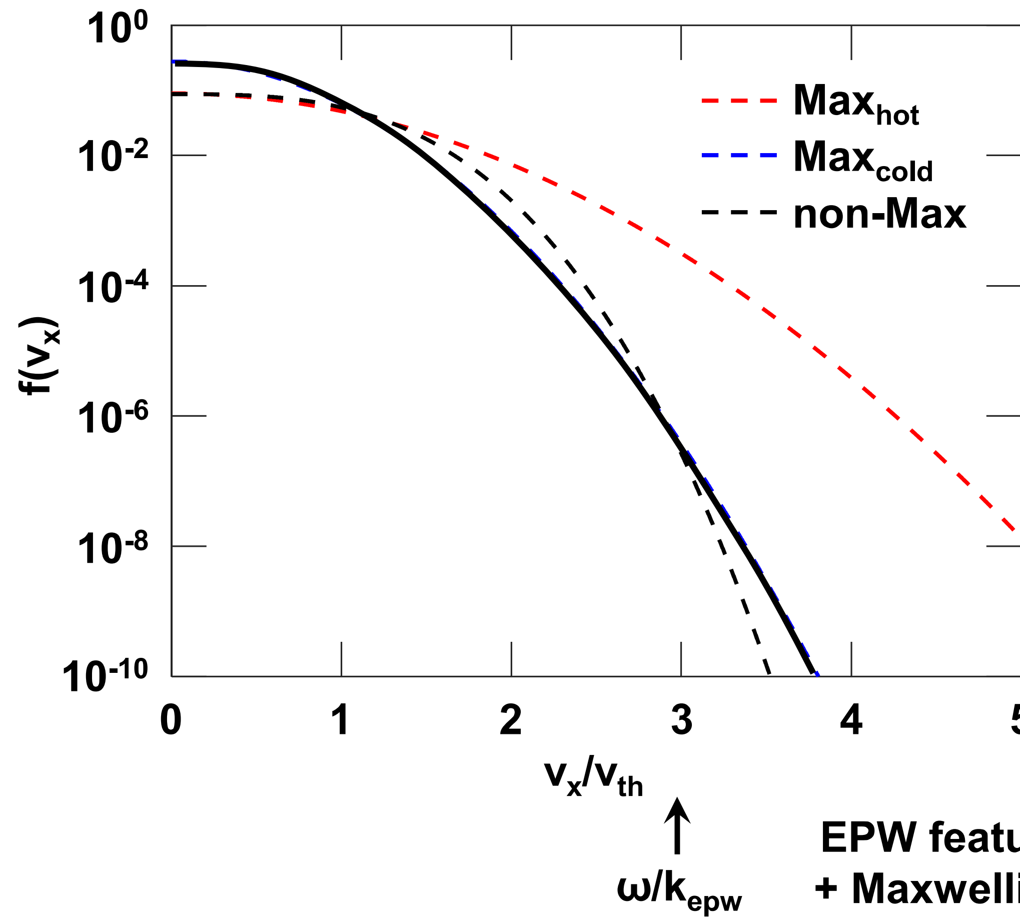

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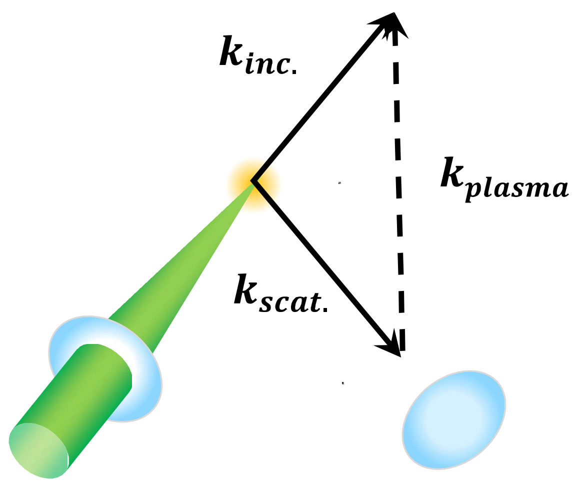

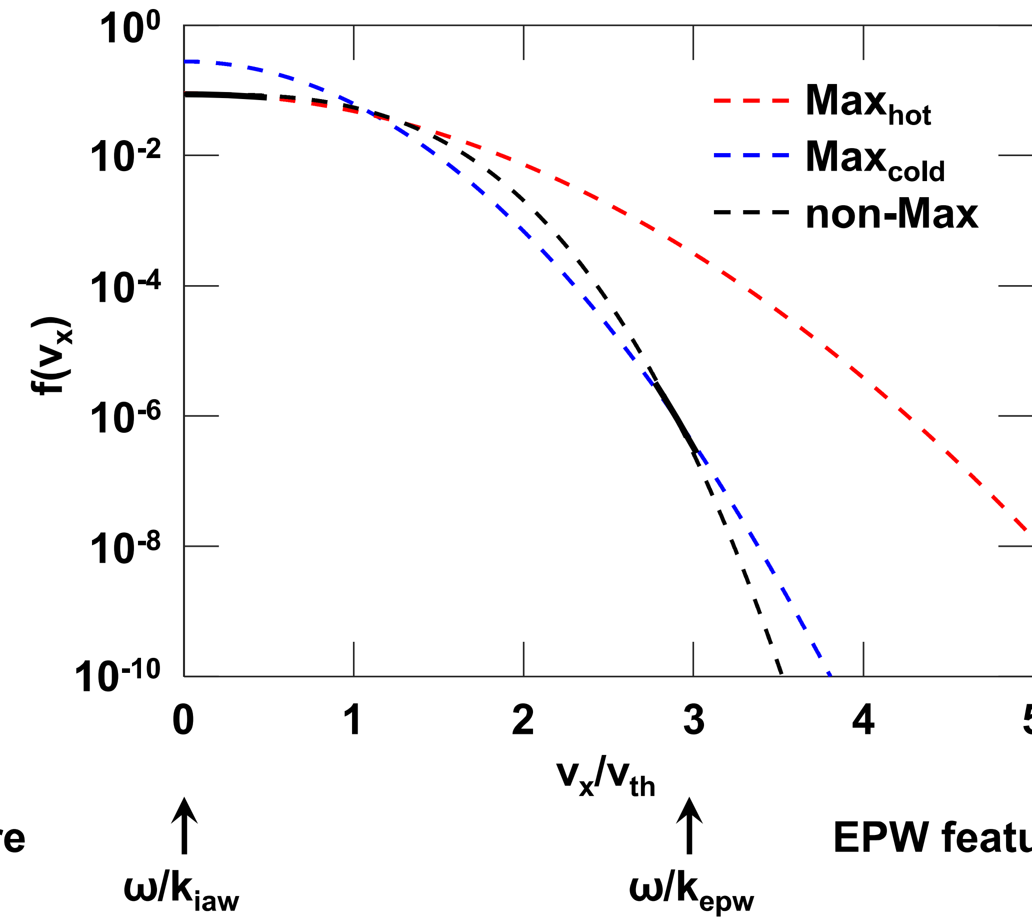

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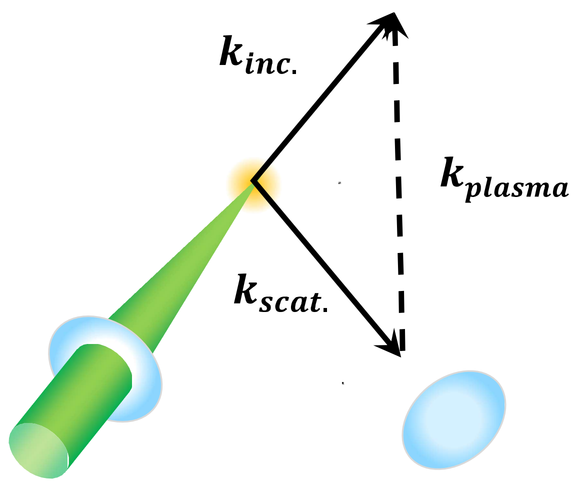

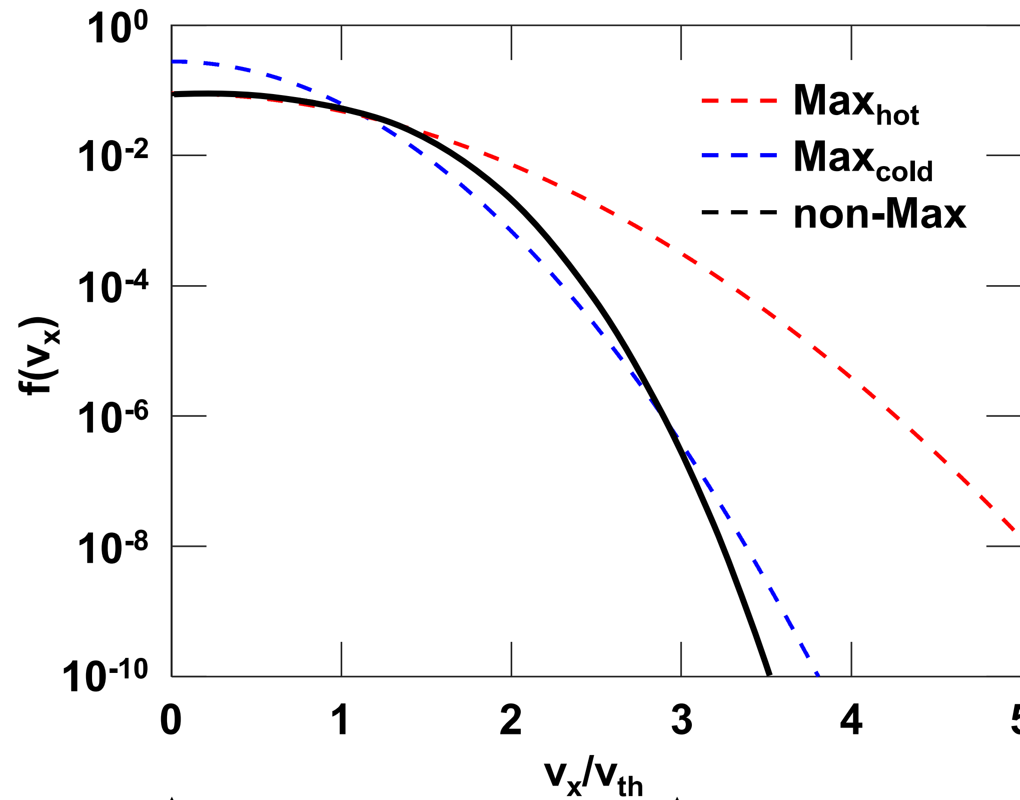

IAW feature
+ super-Gaussian

EPW featu
+ super-Gaus

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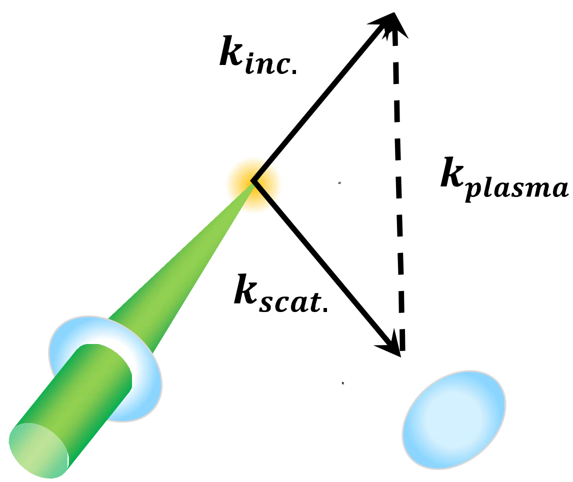

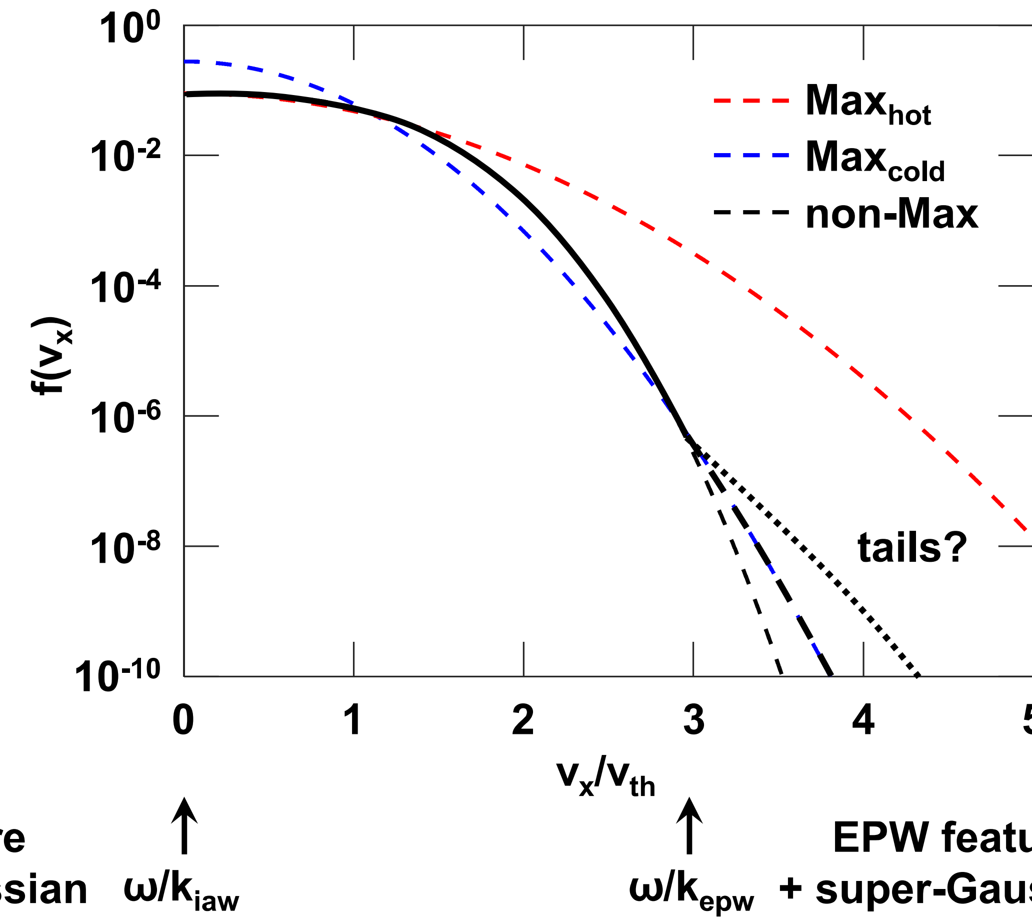

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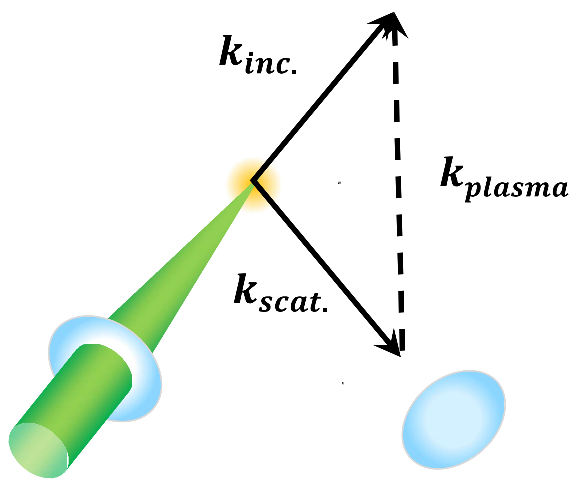

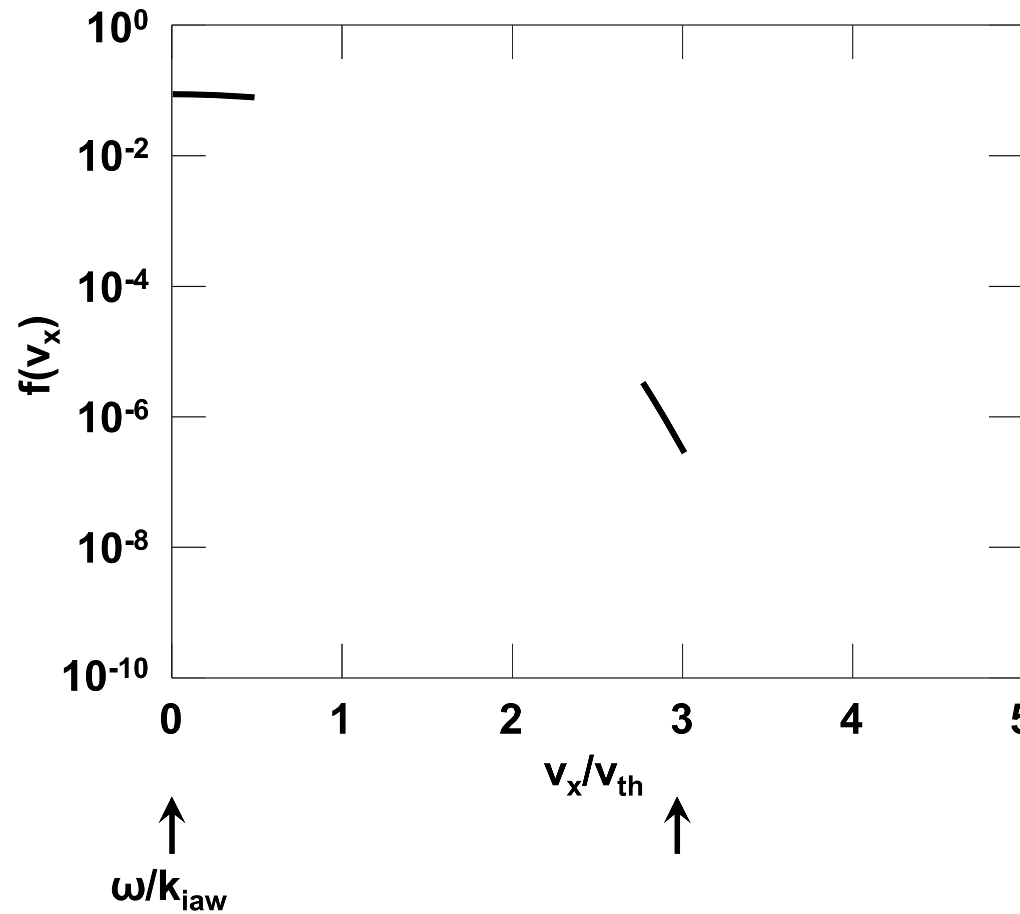

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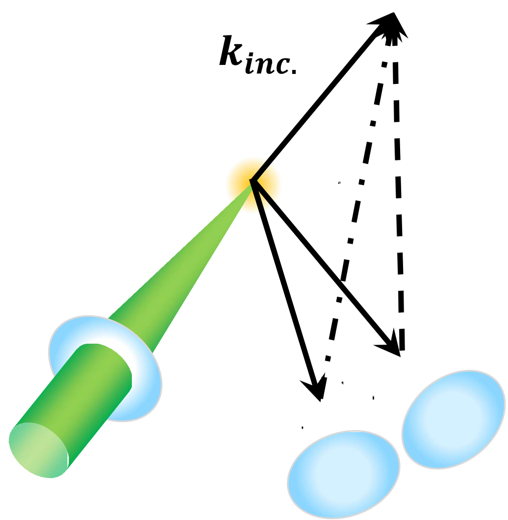

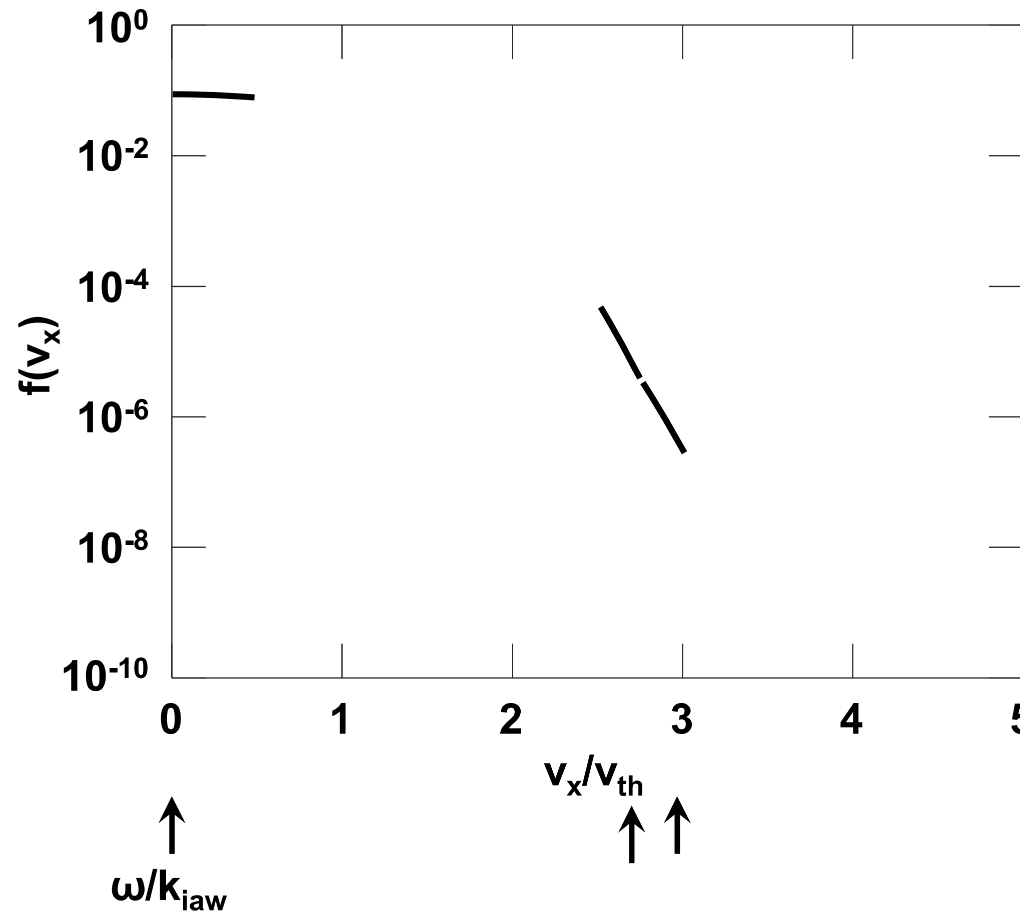

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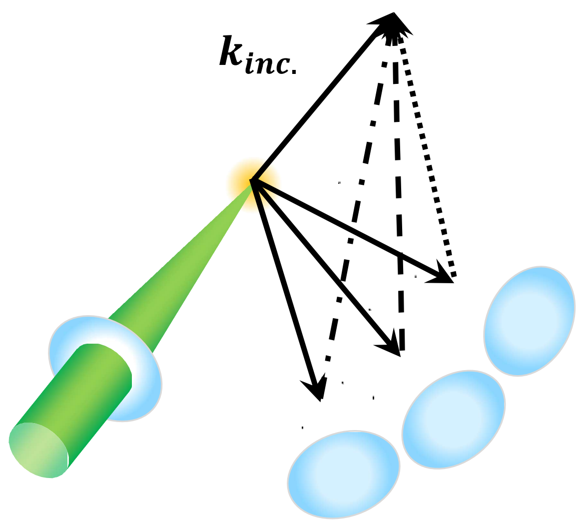

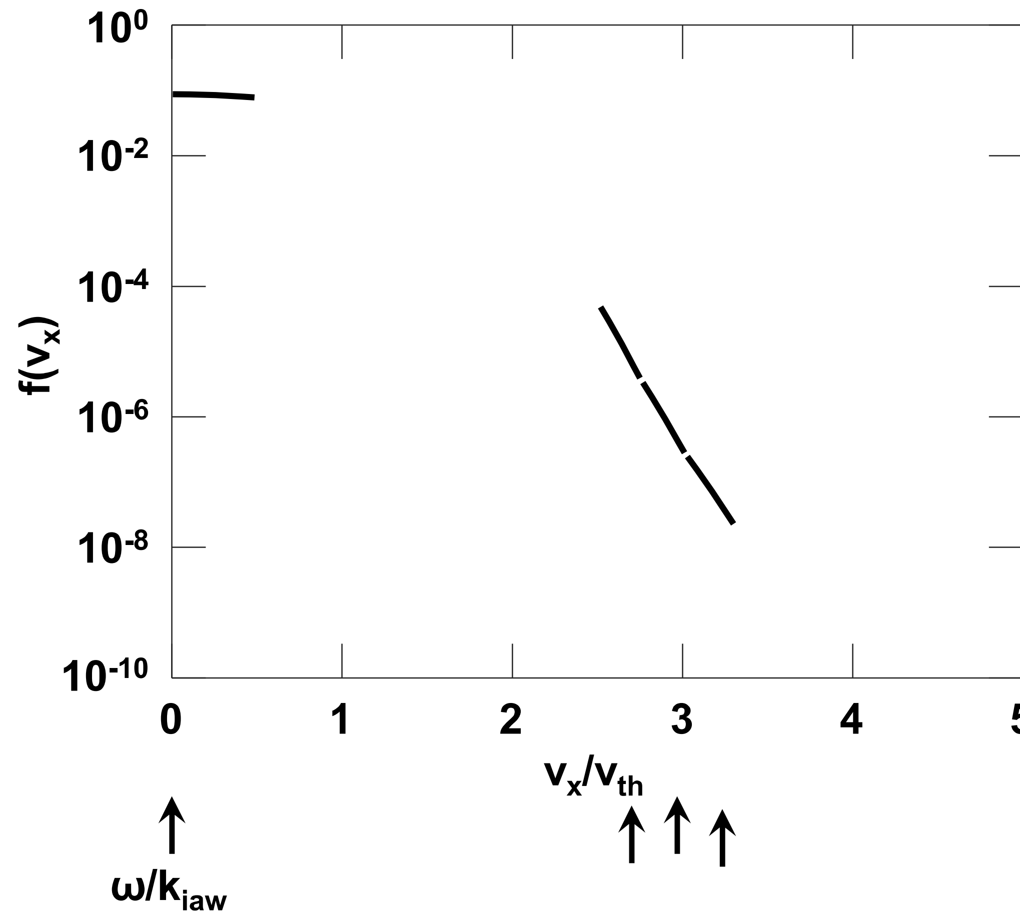

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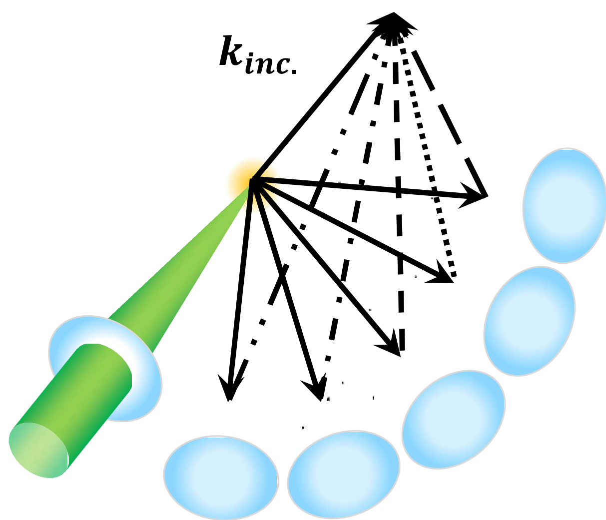
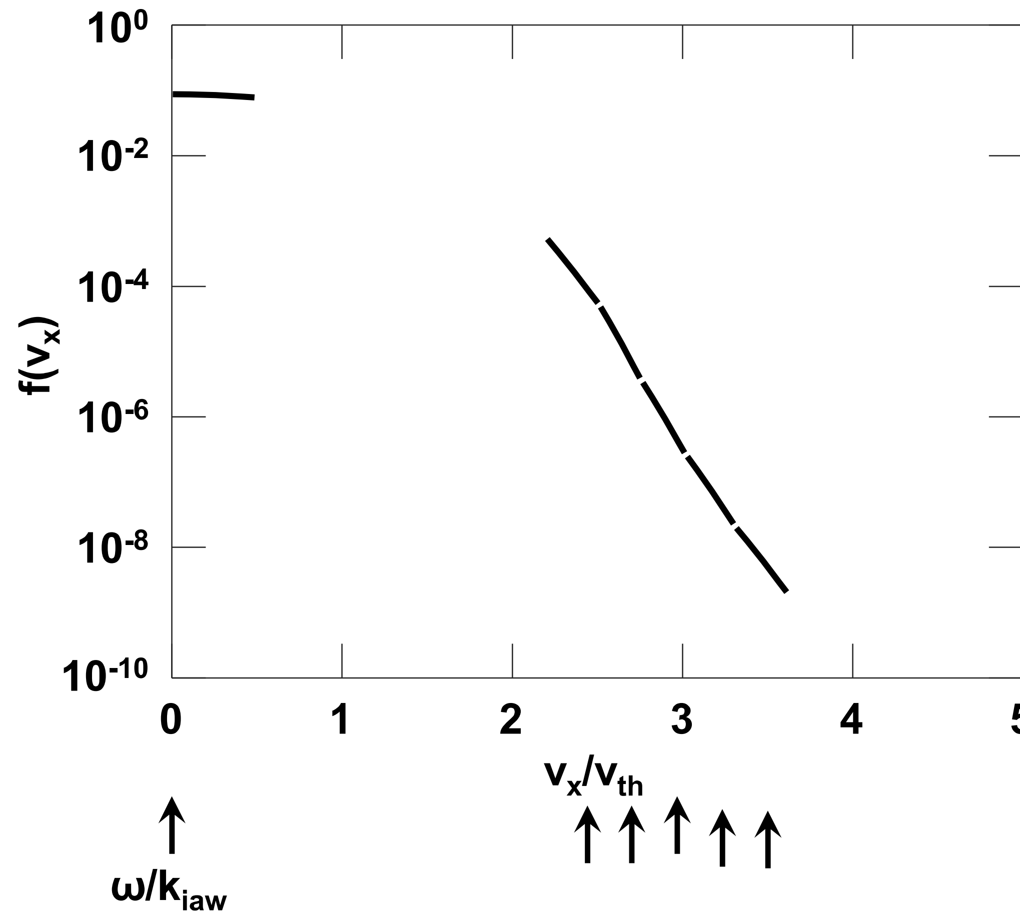
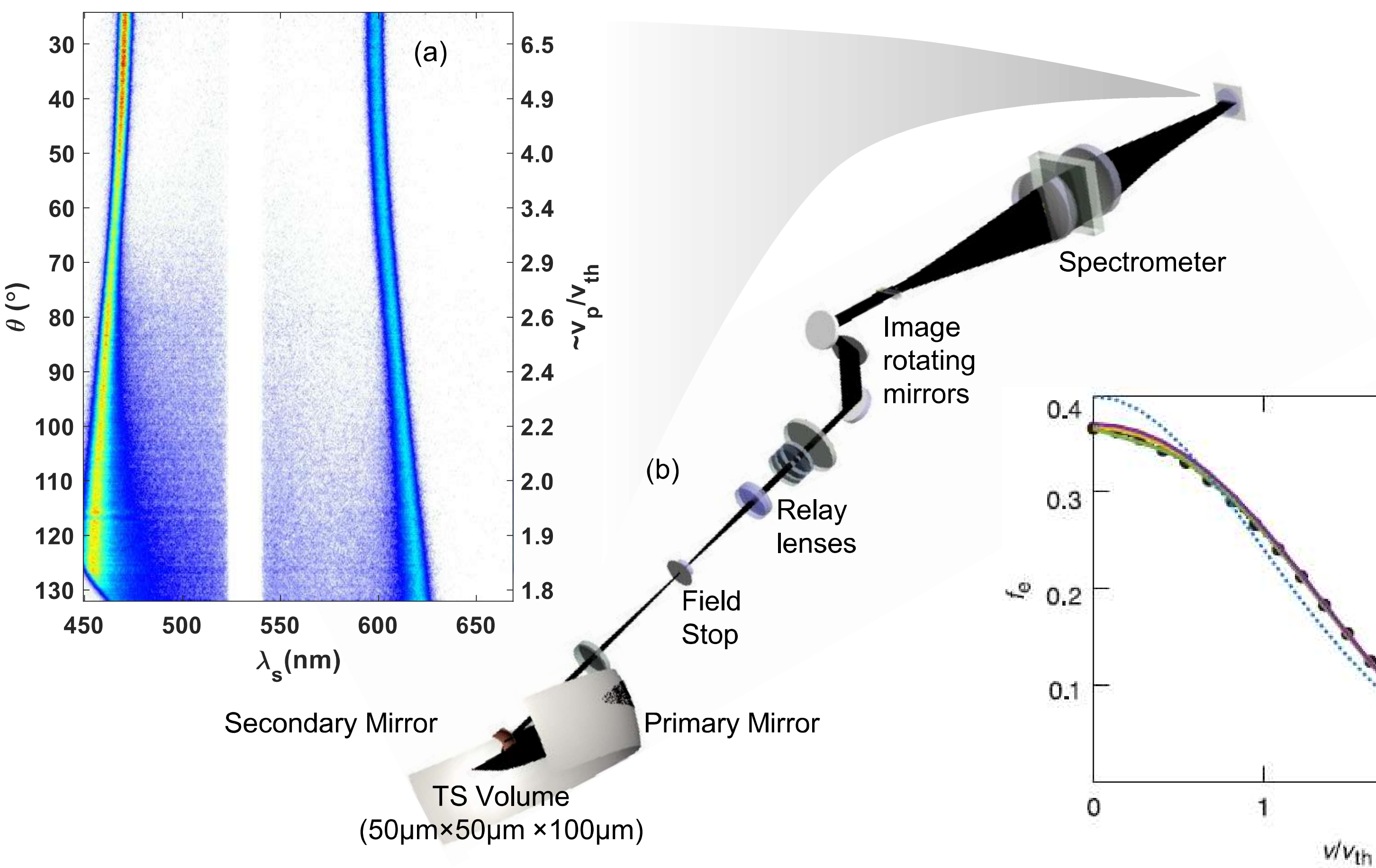
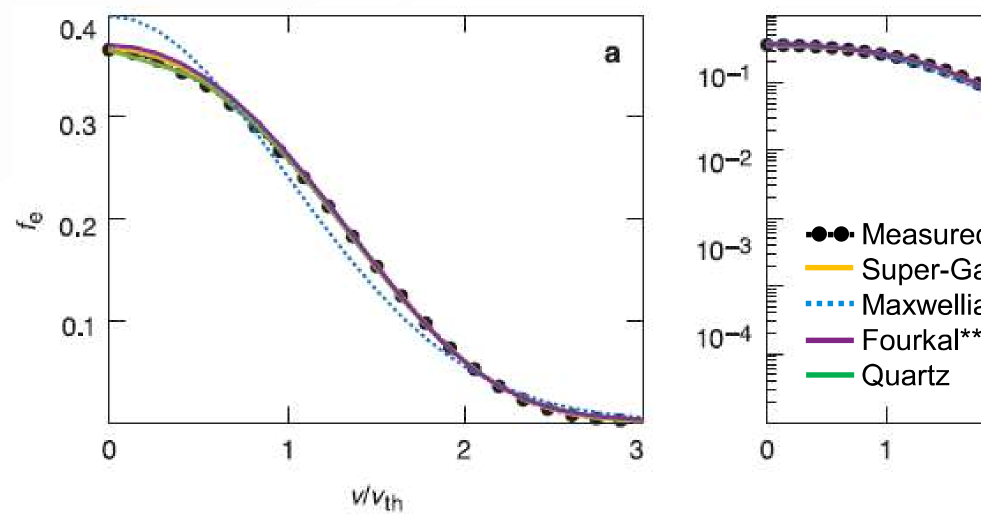




The angularly resolved Thomson scattering instrument allows for conti
collection over ~120° in scattering angle (A. Milder Ph.D. project under



Tails of the EDF were obse
from the bulk super-Gauss
not well-matched by any s



This promises to be a powerful diagnostic technique for the measurement of arbitrary EDF's

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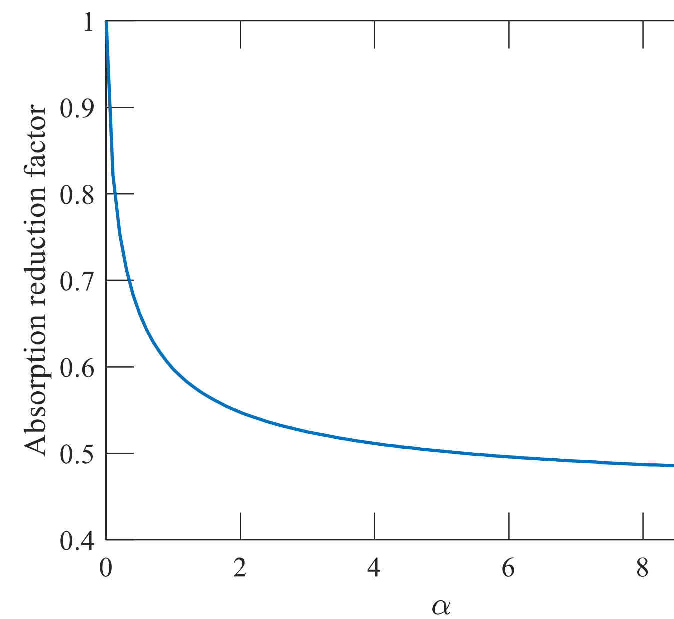
The key result in Langdon's seminal paper actually pertained to absorp specifically a widely used reduction factor

- Concluded that the impact of the lower number of electrons f(v~0) in the laser-heated non-Maxwellian EDFs actually reduces the absorption by a factor (where α is the Langdon parameter):

$$f_L = 1 - \frac{0.553}{[1 + (0.27/\alpha)^{0.75}]}$$

- This factor is widely used in rad-hydro codes to modify the inverse bremsstrahlung absorption coefficient

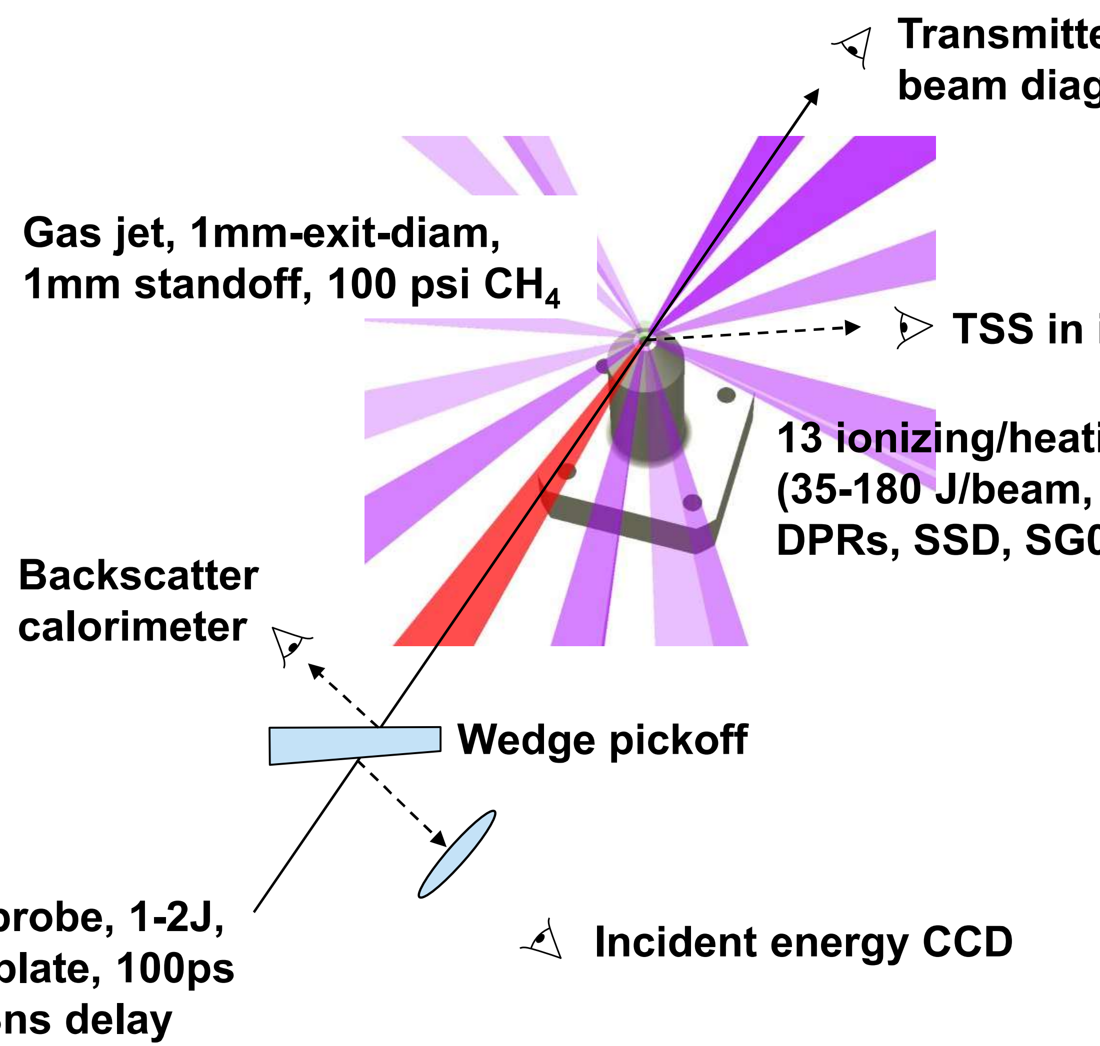


To our knowledge, this conclusion remained largely untested

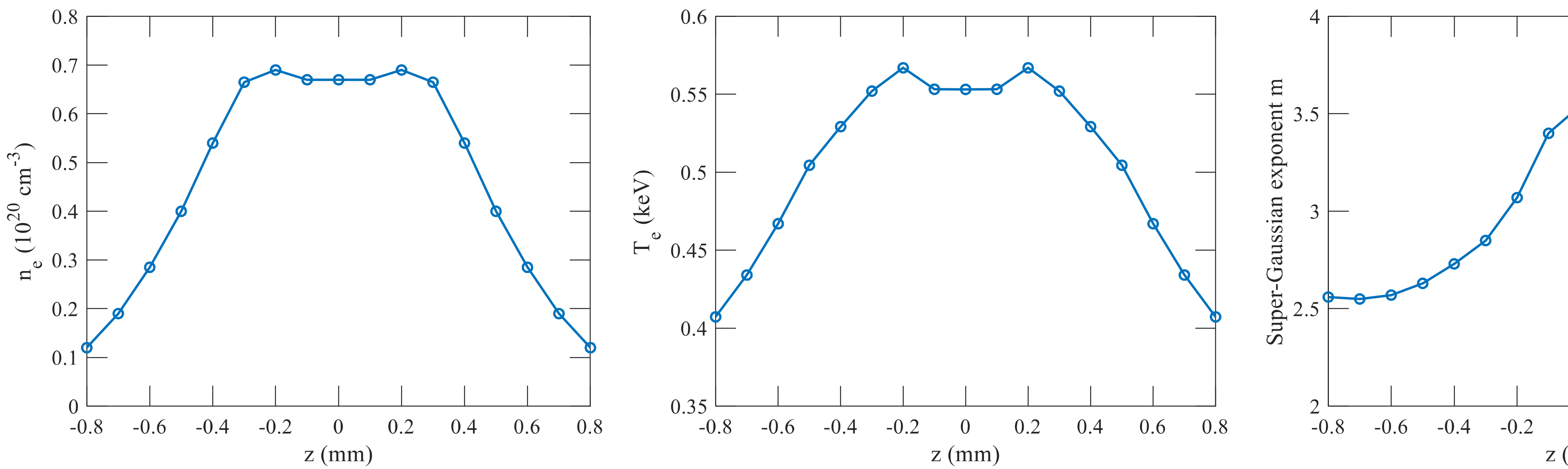
* A B Langdon, PRL. 44, 576 (1980).

Additional recent experiments at LLE (1/14/21) have aimed to measure absorpti… spatially resolving plasma conditions along the entire probe path

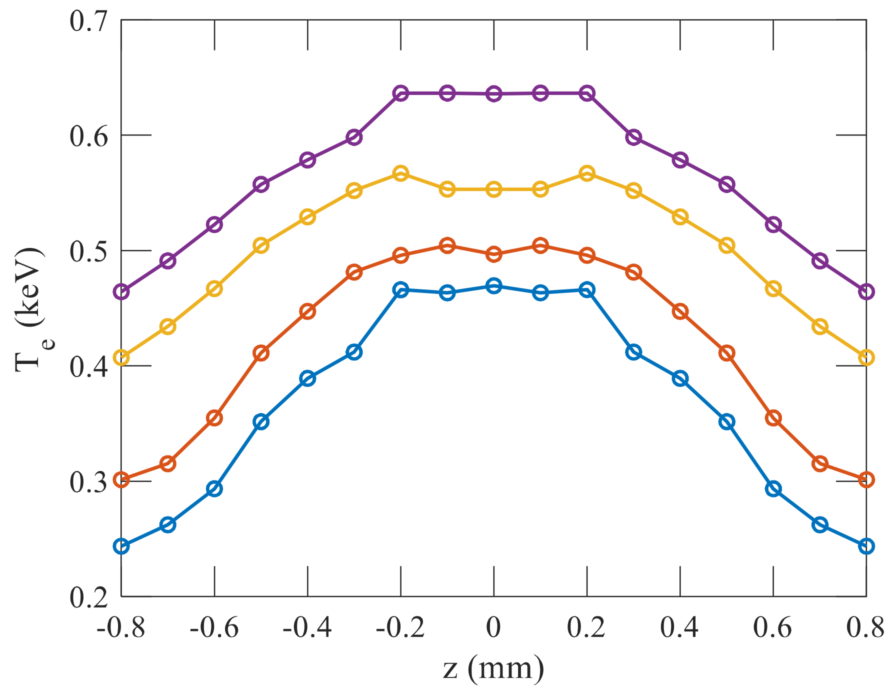
- Requirements:
  - Measure n_e, T_e, T_i along entire probe path through plasma
  - Measure absorption with ±0.1% accuracy (achieved ±0.2%)
  - Avoid competing instabilities (SBS/SRS, return-current instability, beat waves impacting Thomson, filamentation)

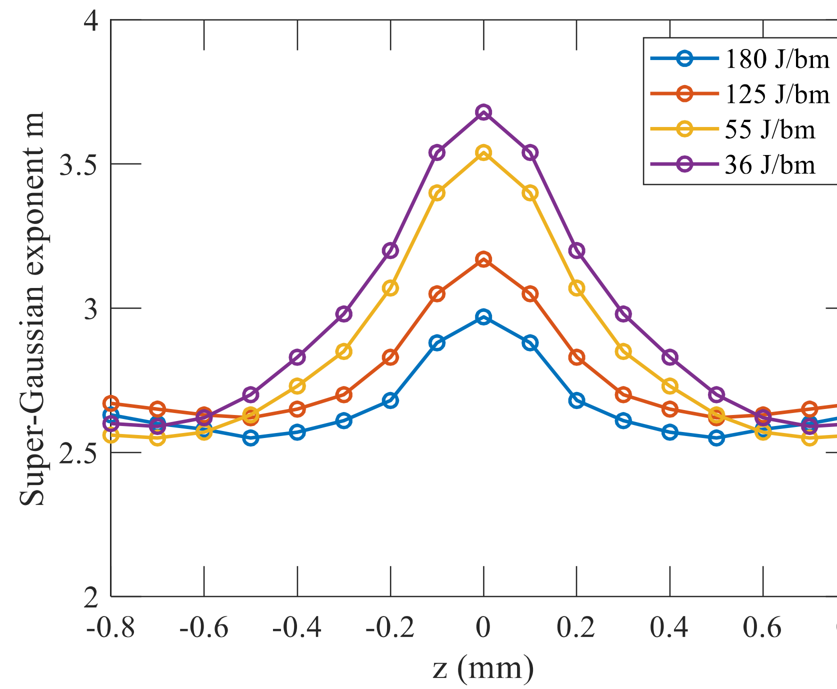


Nearly the entire probe path through the plasma was captured within th
Thomson scattering field of view, providing a tight constraint on absorp

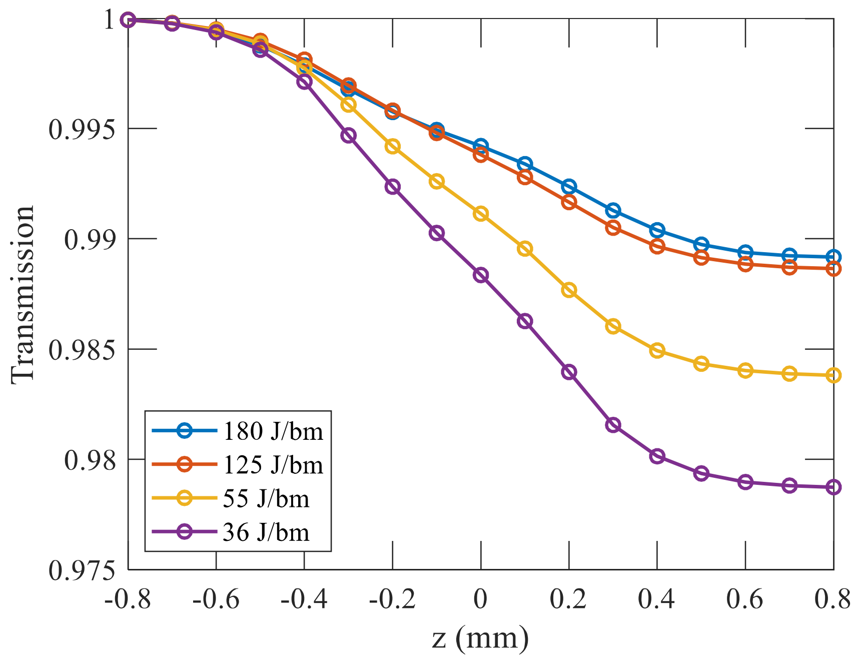


With ~constant density, heater-beam energies were varied to access dif temperatures and super-Gaussian exponents (hence also the Langdon





The expected path-integrated absorption is then calculated using the m plasma conditions (n_e, T_e, and m)



$exp(-\int \kappa \, dl)$, with $\kappa = \frac{\nu_{ei}}{v_g}\frac{\omega_p^2}{\omega^2} f_L = \nu_{ei} \frac{n_e/n_c}{c\sqrt{1-n_e/n_c}} f_L$,

$\nu_{ei} = 2.91 \times 10^{-6} Z^* n_e T_e^{-3/2} ln\Lambda$, $Z^* = \frac{\langle Z^2 \rangle}{\langle Z \rangle}$, and $ln\Lambda^*$

Absorbing region was almost entirely contained within Thomson FOV, providing strong constraint on modeling

* NRL formulary, from Johnston & Daws

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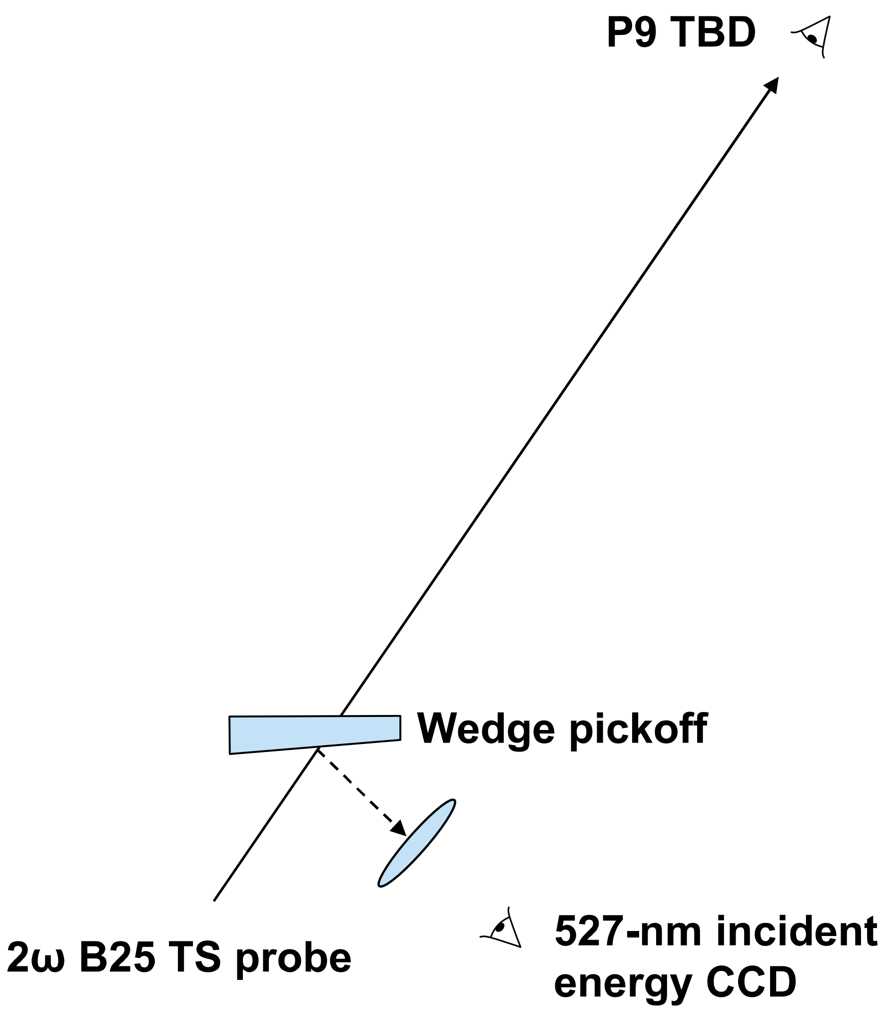
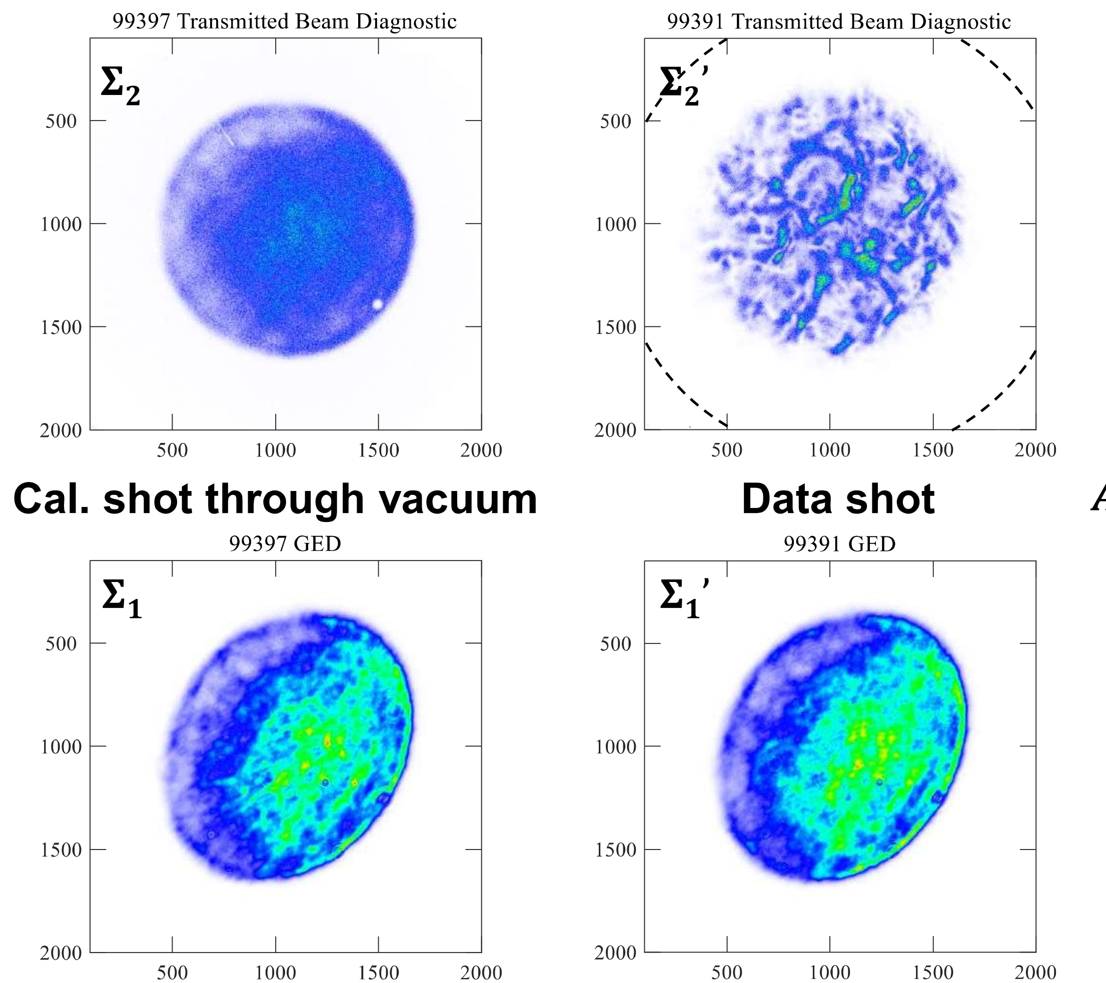
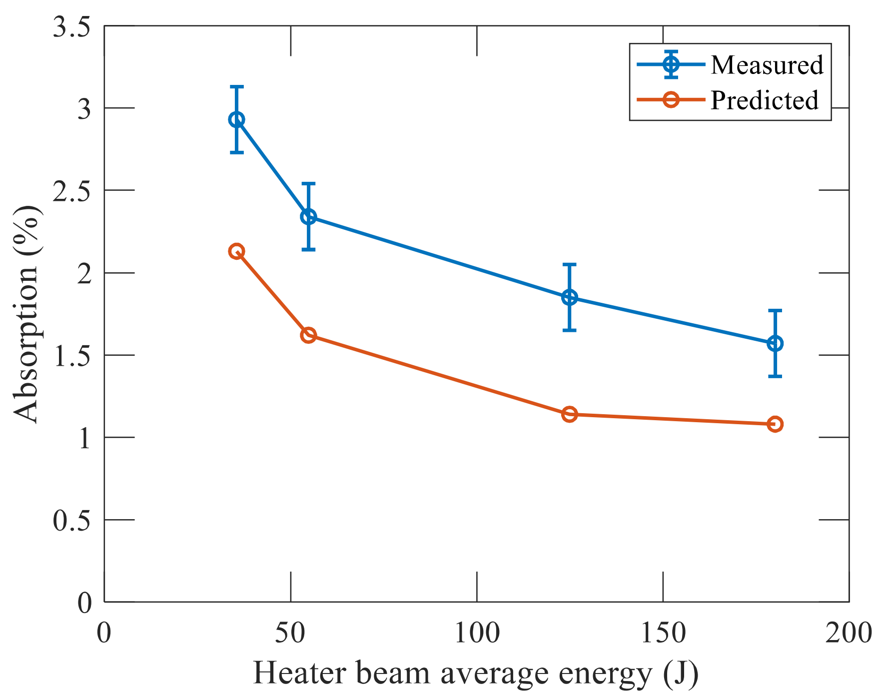
Absorption measurements were enabled by cal. shots through vacuum (+/-0.2% based on 2 shots) and greater-than-full aperture transmitted beam collection





Measured absorption was ~50% higher than predicted at all heating lev



- Many possible explanations have been c
  - Backscatter
  - Filamentation
  - Langdon factor
  - Direct speckle-to-ion heating
  - Anomalous scattering
  - Stochastic speckle heating
  - Log lambda?
  - Other?

Analysis is ongoing, and this campaign will be continued next year

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# A. Hansen et al., PRL

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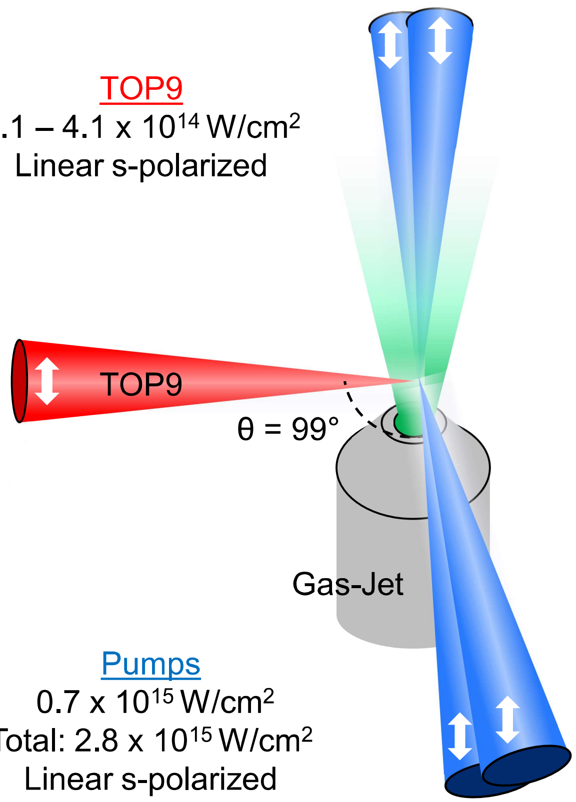
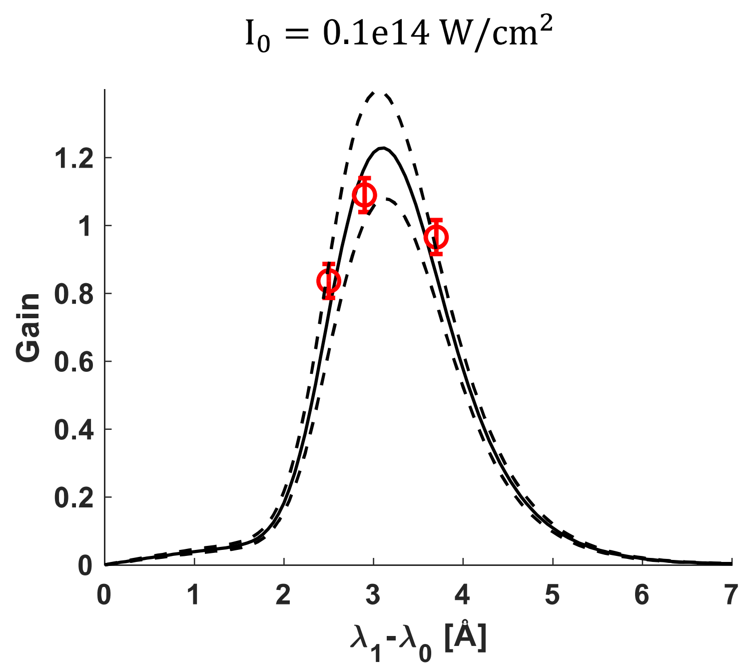
A. Hansen* has recently observed CBET saturation using the TOP9 LPI with implications for ID- and DD-ICF

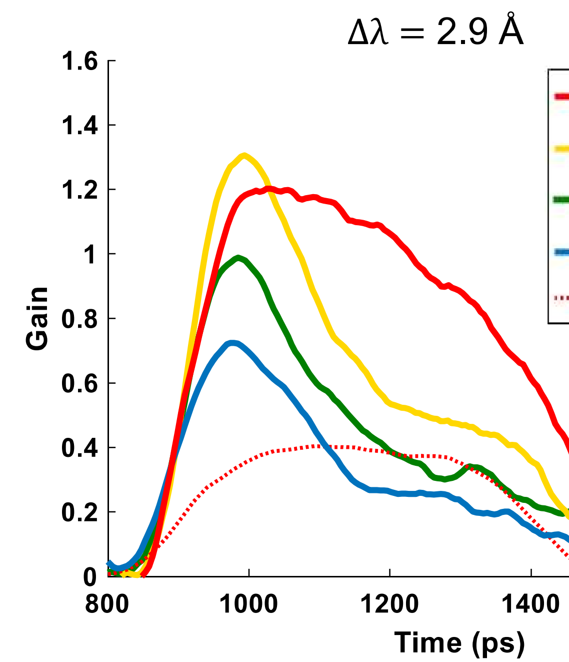
TOP9
$0.1 - 4.1 \times 10^{14}$ W/cm^2
Linear s-polarized

Pumps
0.7×10^{15} W/cm^2
Total: 2.8×10^{15} W/cm^2
Linear s-polarized





(1) At low TOP9 intensity (small plasma waves), map resonance



(2) On resonance, increase (larger plasma waves) & lo

The campaign was in the spirit of the earlier JLF experiments, but with greater precision and diagnostic access

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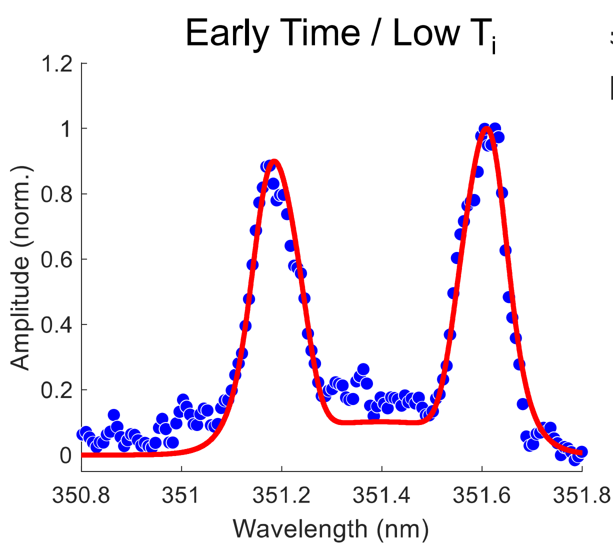
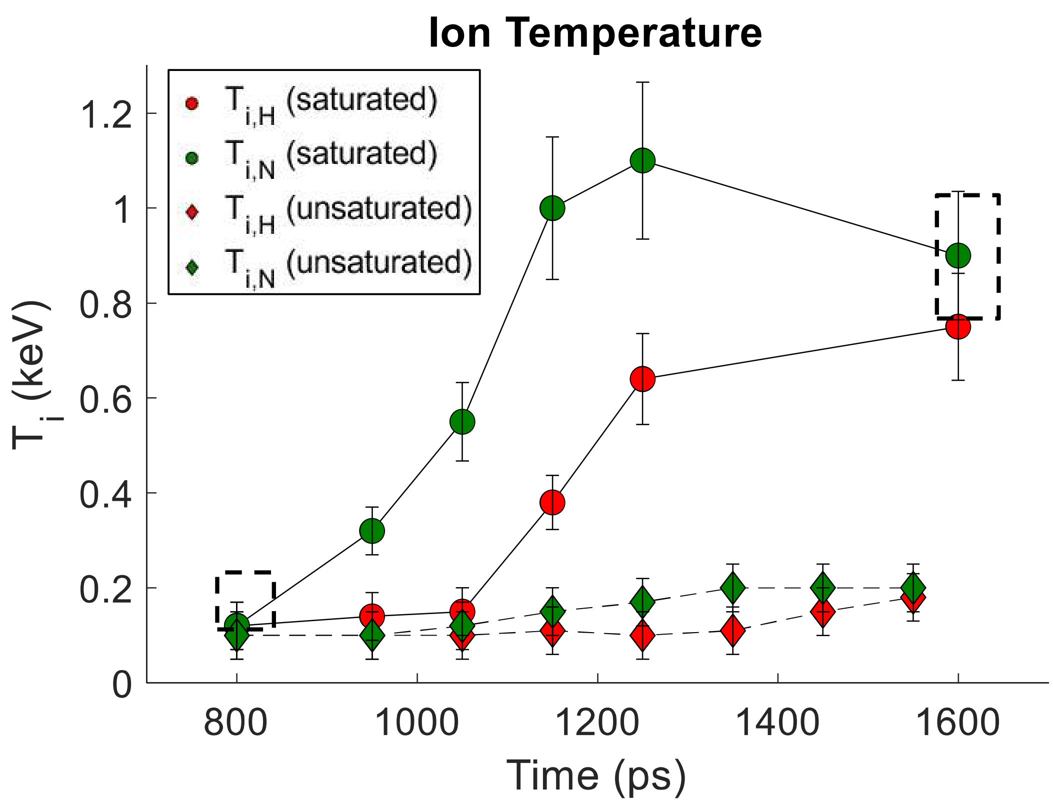
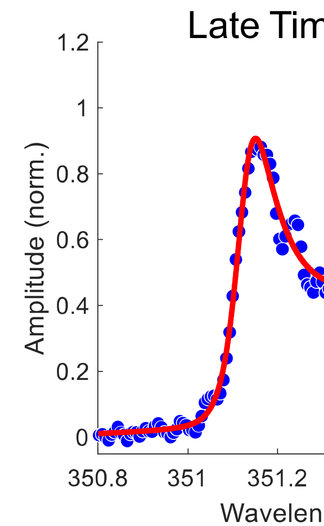
Thomson-scattering ion-acoustic wave features (not used at JLF) indica significant ion heating during the CBET interaction

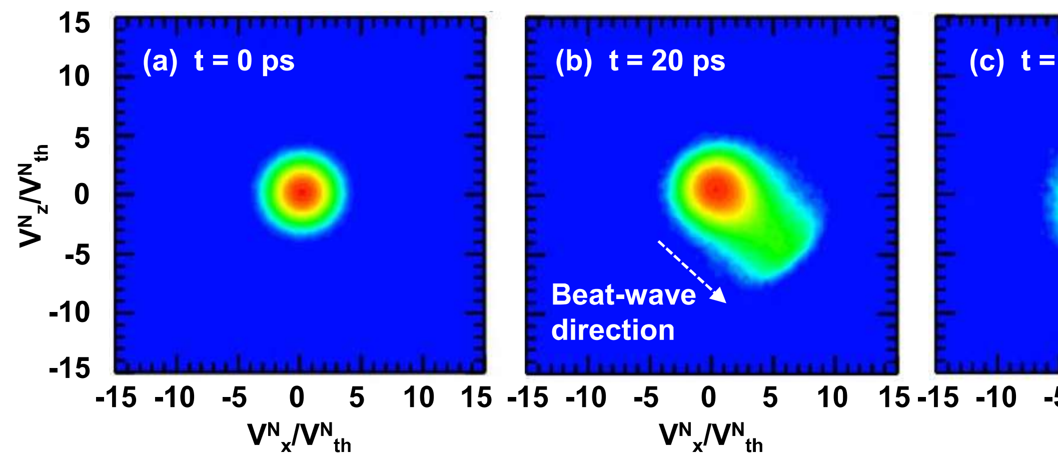






VPIC simulations (LLE-LANL collaboration*) capture the physics of ion (here showing a simpler example of a single-pump interaction)

- On O(10) ps time scales, ions are trapped in the driven wave, forming a hot tail in the ion distribution function
- By ~100 ps, ion-ion collisions have driven the distribution towards a hotter Maxwellian
- Predicted ion heating broadly consistent with Manley-Rowe
  - energetics of expt. are striking: plasma heated by ~2kJ, pumps transferred ~16J to probe, so ~16 *mJ* goes into plasma waves → <u>10x</u> increase in T_i



* by K. L. Nguyen and L. Yin

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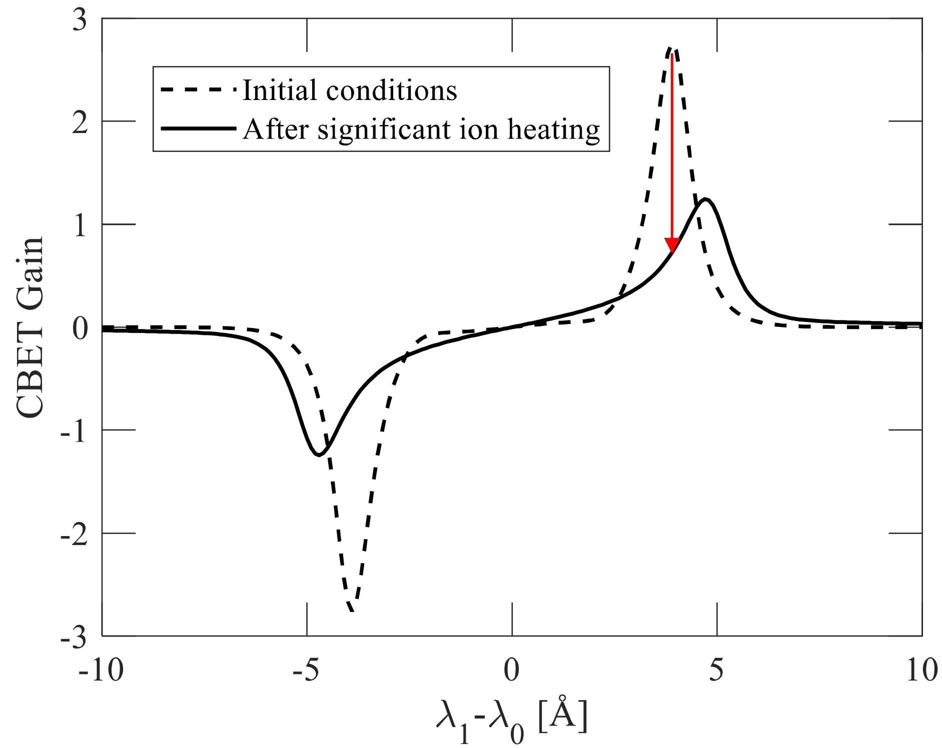
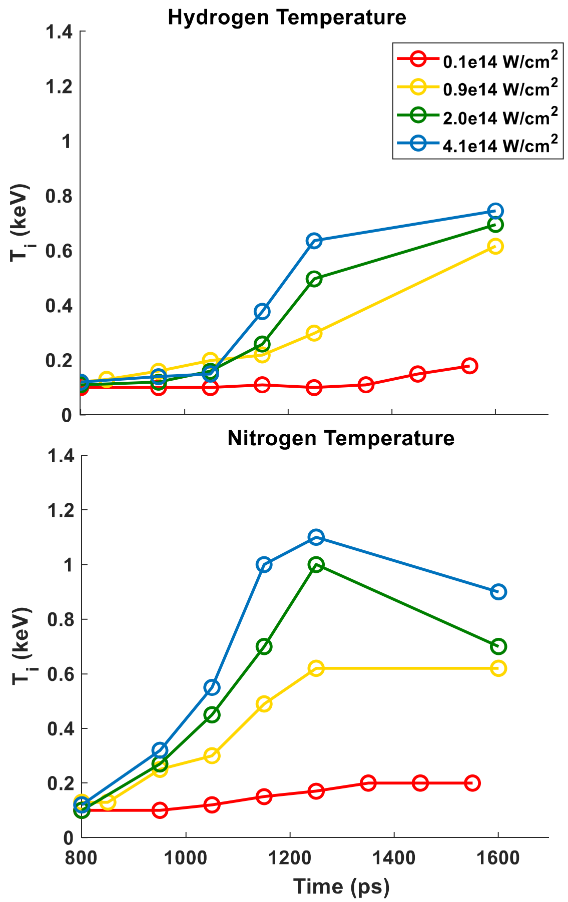
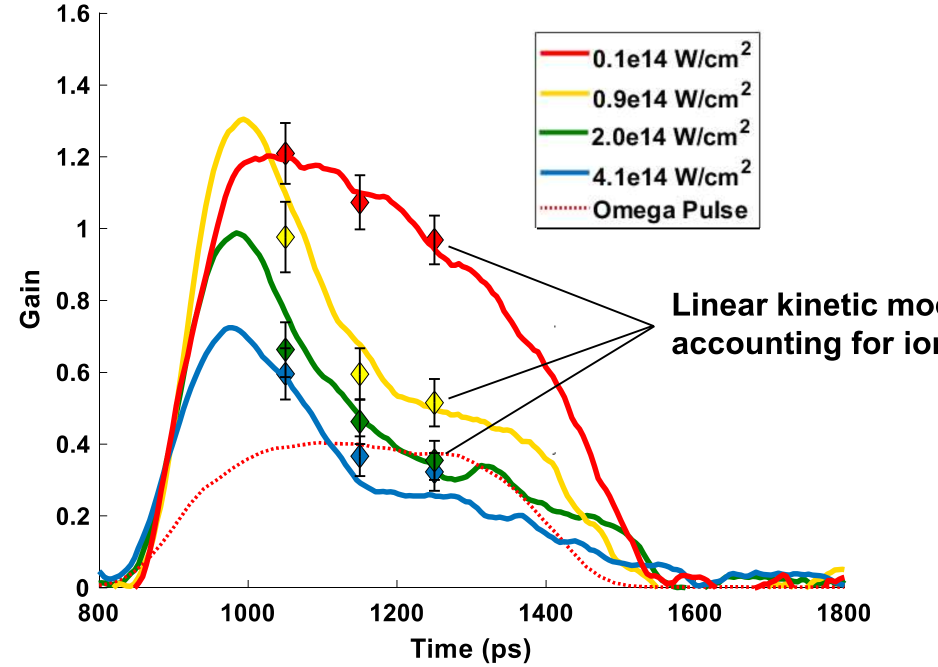
The ion heating in the experiment shifted the resonance frequency and the ion Landau damping, both acting to reduce the energy transfer



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



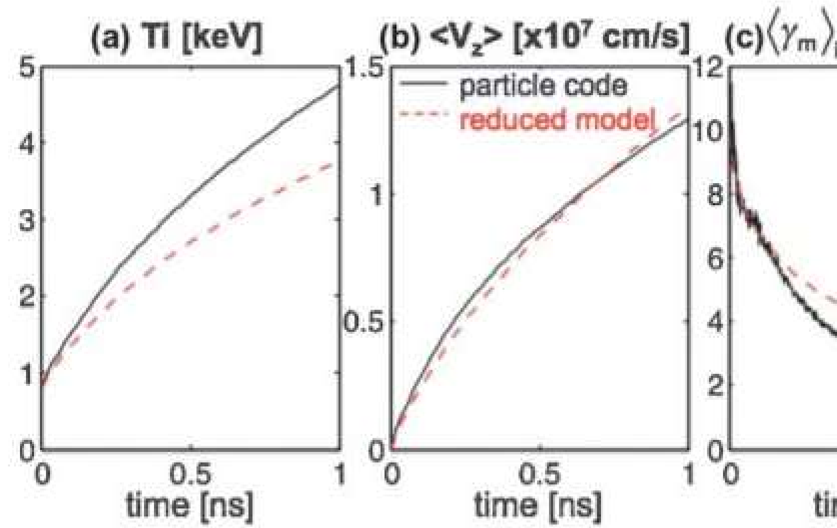


Linear kinetic model remains valid (no need for typical saturation clamps!) but hydro feedback on plasma conditions needs to be taken into account

* A.

This ion heating mechanism has implications for both indirect-drive an drive ICF

- Ion heating was considered for indirect-drive in the early 2010s and found to be important*
  - LEH ion heating rates of ~4keV/ns (huge)
  - Aaron's results are essentially the first experimental validation
- In direct-drive, where flow is more important than wavelength detuning, there is a redistribution in the total energy of the ions from flow energy to heat, meaning CBET will stagnate the ablated coronal plasma
  - This is not currently modeled, and assessing the impact is future work but could significantly change coronal plasma conditions and CBET



* P. Michel *et al.*, PRL (2012); P. Michel *et*

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