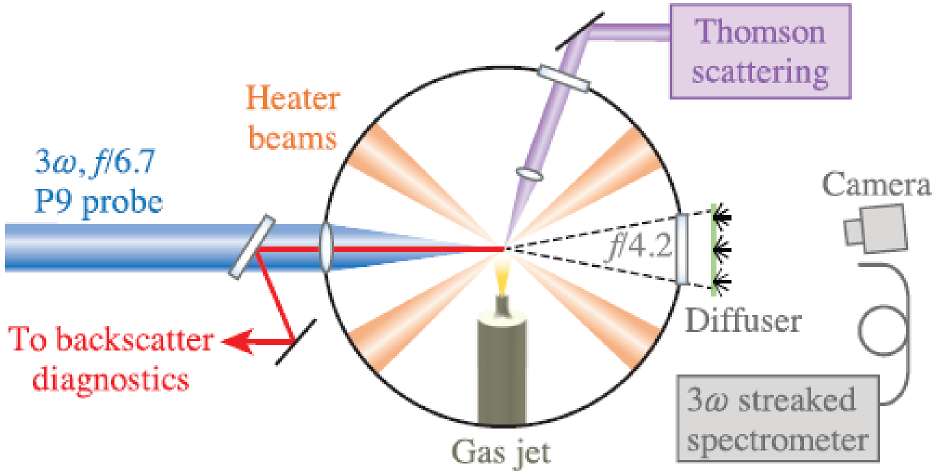
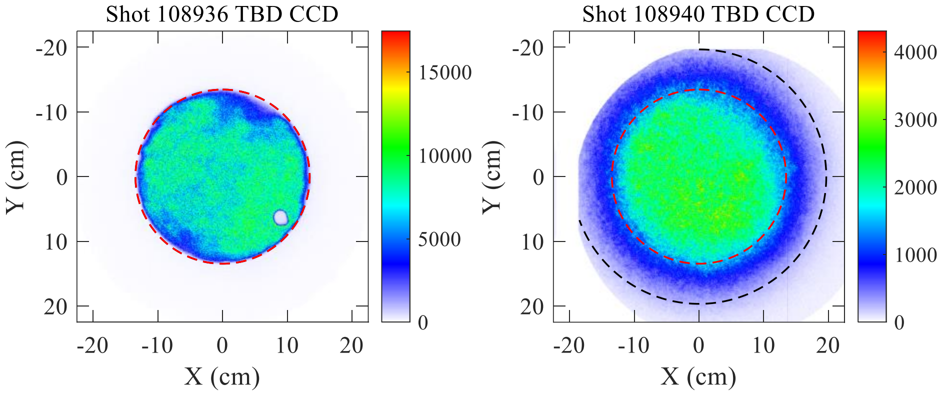
Understanding Laser Propagation in Plasma: Absorption and Beam Spray





David Turnbull
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LLNL HEDS Seminar Series
Virtual
24 August 2023

Summary

Recent work suggests the need for revise our understanding of several key aspects of laser beam propagation

- **Laser coupling to HED targets is still not calculated reliably in many rad-hydro codes (*not* a crossed-beam energy transfer problem)**
- **What about inverse bremsstrahlung absorption?**
  - **Experiments precisely measured transmission of a probe beam that propagated through plasma while measuring its own path using imaging Thomson scattering***
  - **To match data, it is necessary to account for: (i) the Langdon effect; (ii) laser-frequency (rather than plasma-frequency) dependence in the Coulomb logarithm; and (iii) a correction due to ion screening**
  - **Preliminary calculations suggest this revised model will substantially alter the code predictions**
- **What about stability to beam spray?**
  - **Intensity threshold for beam spray can be significantly lower than suggested by common metric****
  - **Most recent data also shows insensitivity to SSD, contrary to expectation based on literature**

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* D. Turnbull *et al.*, Phys. Rev. Lett. 130, 145103 (2023).

** D. Turnbull *et al.*, Phys. Rev. Lett. 129, 025001 (2022).

Collaborators

A. Colaïtis, D. H. Edgell, R. K. Follett, D. H. Froula, J. Katz, K. R. McMillen,
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A. L. Milder

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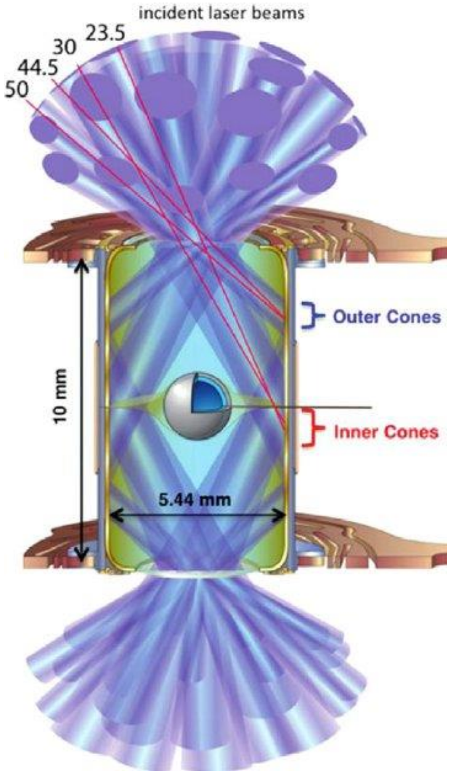
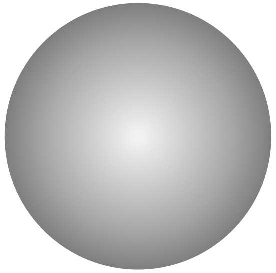
Motivation

The modeling of laser coupling to inertial confinement fusion targets is known to be imperfect

Indirect Drive

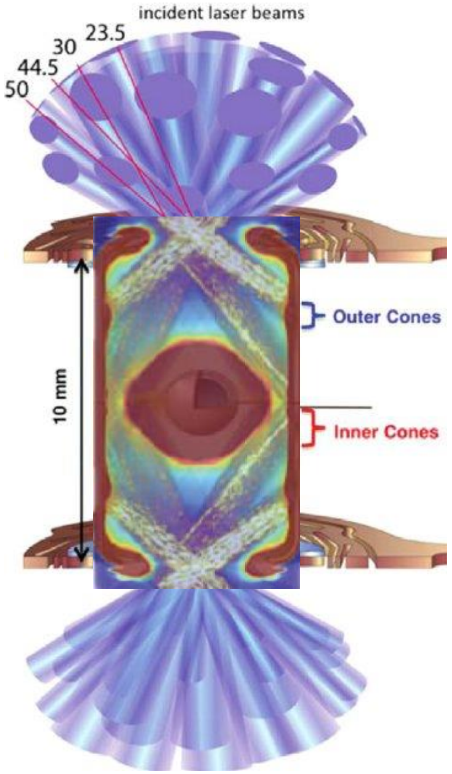


Direct Drive



The modeling of laser coupling to inertial confinement fusion targets is known to be imperfect

Indirect Drive



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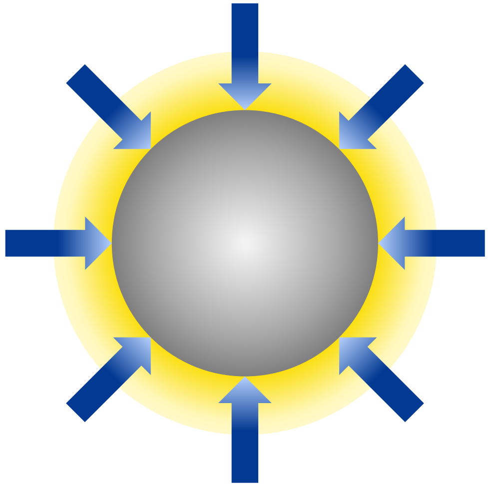

The modeling of laser coupling to inertial confinement fusion targets is known to be imperfect

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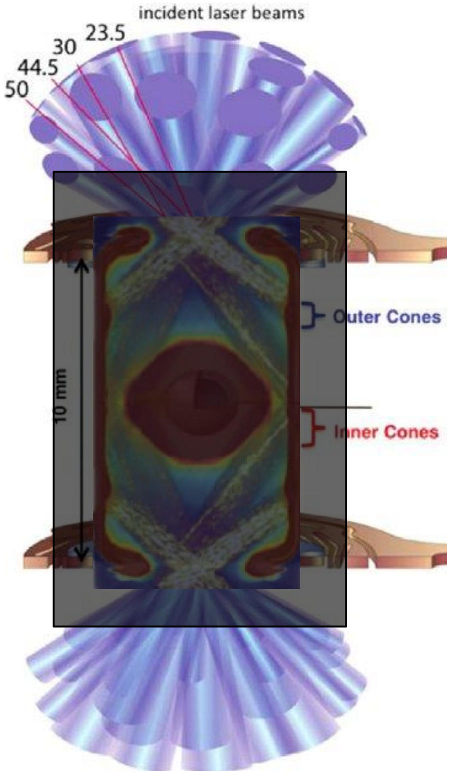

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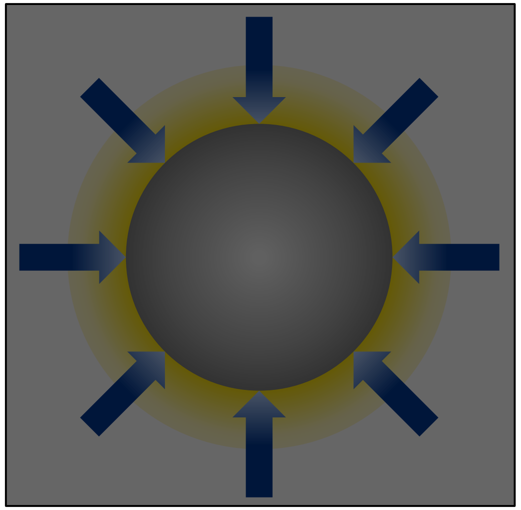
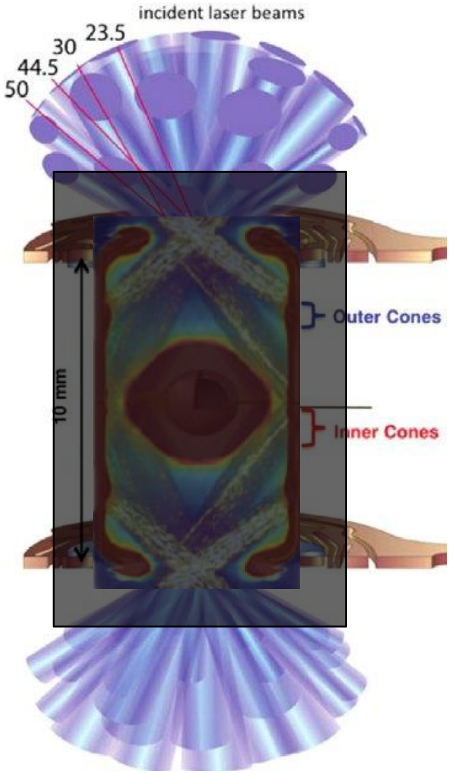


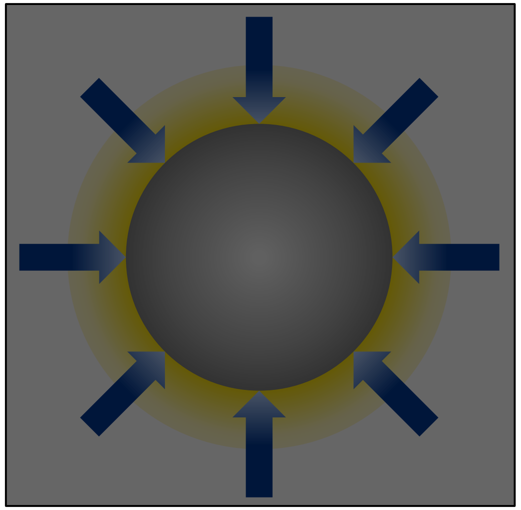
The modeling of laser coupling to inertial confinement fusion targets is known to be imperfect

Indirect Drive



- "Cone-fraction multipliers"
- "Drive multipliers"
- "Saturation clamps"

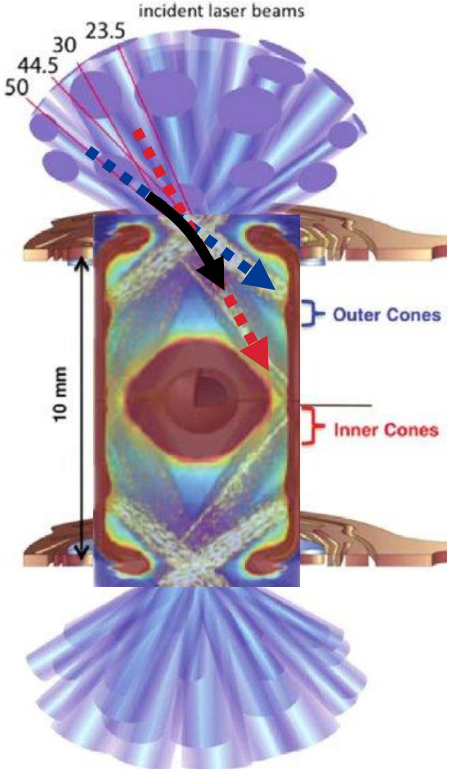
Direct Drive



- "CBET multipliers"

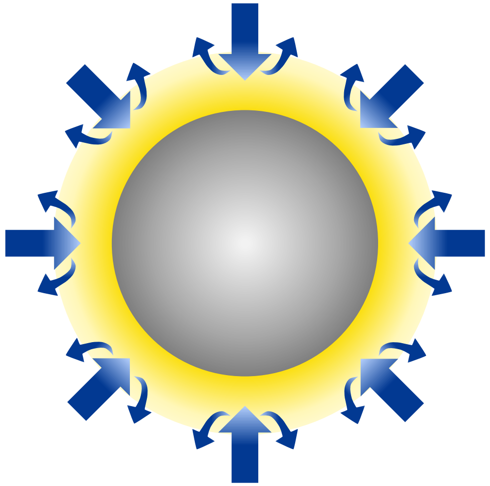
The modeling of laser coupling to inertial confinement fusion targets is known to be imperfect

Indirect Drive



- **“Cone-fraction multipliers”**
- **“Drive multipliers”**
- **“Saturation clamps”**

Direct Drive



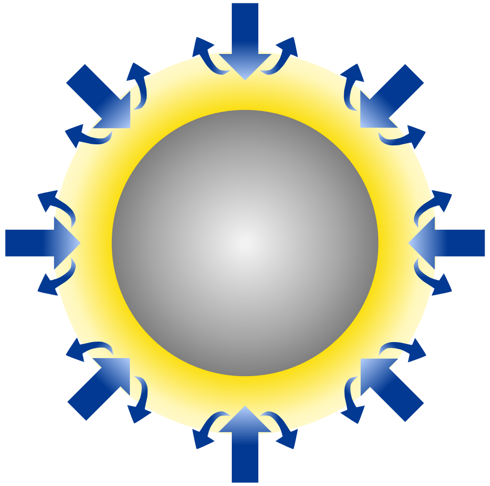
- **“CBET multipliers”**

Crossed-beam energy transfer (CBET) has long been a favorite scapegoat, but we believe the linear kinetic CBET model works well for typical conditions (see my 2021 HEDS seminar if necessary)

Absorption

If CBET models are adequate, why did we need to add a CBET multiplier? Let's scrutinize the more dominant process—inverse bremsstrahlung (IB) absorption

- **Inverse bremsstrahlung laser absorption is proportional to the "Coulomb logarithm" [often framed as $\ln(b_{\max}/b_{\min})$], but no consensus on its definition**
- **Also typically assumed to be impacted by the Langdon factor f_{L}*, not validated**
- **Absorption rate $\kappa = \nu_{\mathrm{ei}} \frac{n_{\mathrm{e}}/n_{\mathrm{c}}}{c\sqrt{1-n_{\mathrm{e}}/n_{\mathrm{c}}}} f_{\mathrm{L}}$, with $\nu_{ei} = 2.91 \times 10^{-12} T_e^{-3/2} \sum_i \left(Z_i^2 n_i \ln \Lambda_{\mathrm{IB,i}}\right)$**



Inverse bremsstrahlung is by far the most important mechanism coupling laser energy to ICF targets!

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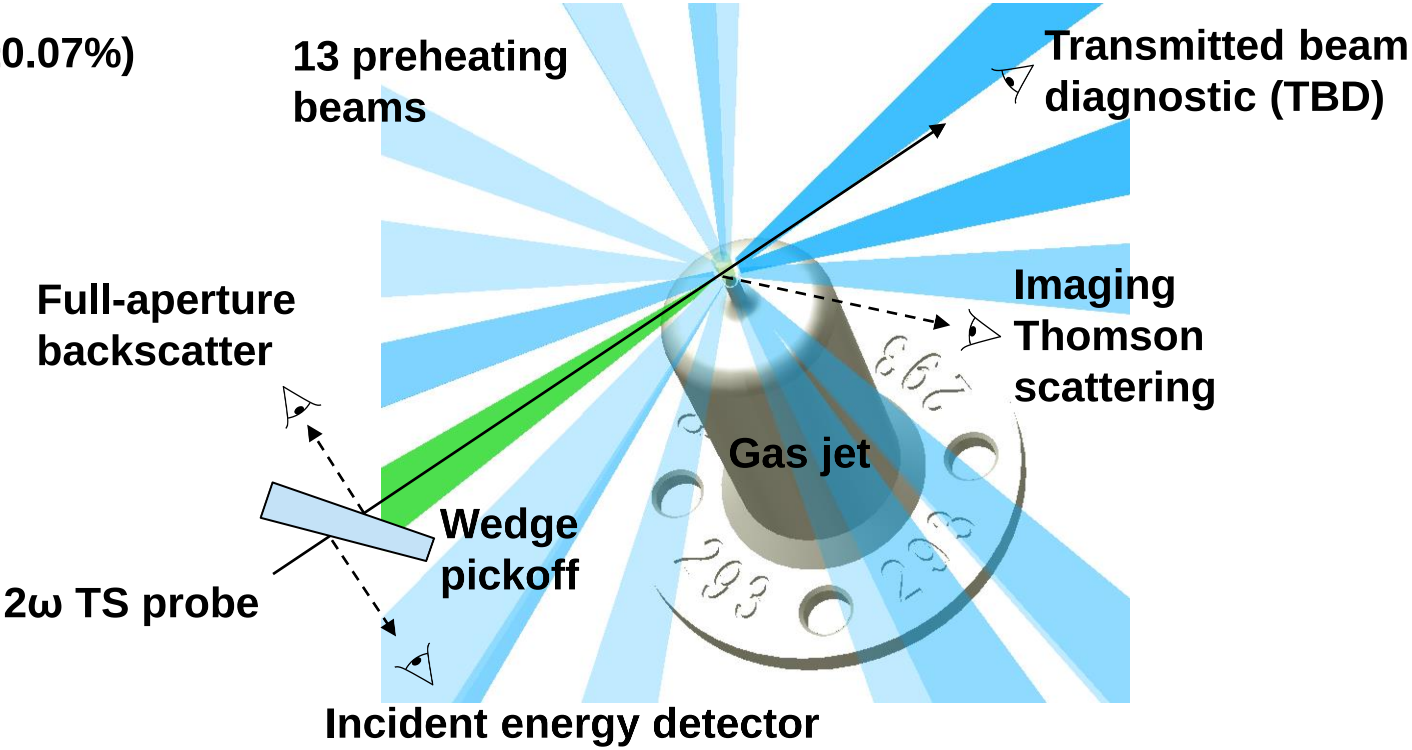
* A. B. Langdon, Phys. Rev. Lett. 44, 576 (1980).

We have executed a number of campaigns over the last several years focused on measuring absorption through well-characterized underdense plasmas

- **(1) Preform ~spherically-symmetric plasma**
- **(2) Measure plasma conditions along probe path**
- **(3) Precisely measure transmission (±0.07%)**
- ***Avoid competing instabilities****



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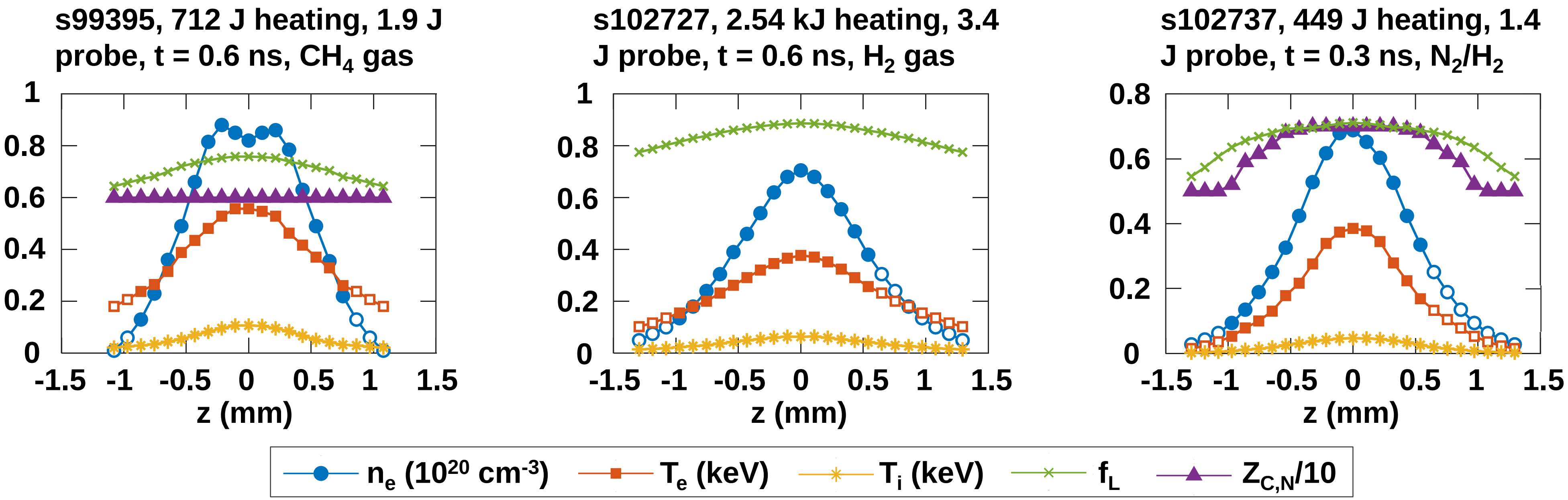
* e.g., filamentation, return-current instability, SBS, SRS

We emphasized measuring the full probe path through the plasma



s99395, 712 J heating, 1.9 J probe, t = 0.6 ns, CH_4 gas

s102727, 2.54 kJ heating, 3.4 J probe, t = 0.6 ns, H_2 gas

s102737, 449 J heating, 1.4 J probe, t = 0.3 ns, N_2/H_2

The absorption calculations are therefore highly constrained

To make predictions to compare with data, we considered several well-known Coulomb logarithm theories

Brems., binary collisions

- Sommerfeld*: complicated $f(v, \omega, Z)$
- Oster**: $ln\left(\left(\frac{2}{e^{\gamma}}\right)^{5/2} \frac{v_T/\omega}{\max\left(\frac{Z^* e}{4\pi\epsilon_0 T_e}, \frac{\hbar}{1.68\sqrt{m_e T_e e}}\right)}\right)$, with $v_T = \sqrt{\frac{T_e e}{m_e}}$, $\gamma = 0.577$

Transport

- Lee-More†: $ln\left(\frac{\lambda_{\mathrm{D},ei}}{\max\left(\frac{Z^* e}{12\pi\epsilon_0 T_e}, \frac{\hbar}{2\sqrt{3 m_e T_e e}}\right)}\right)$, with $\lambda_{\mathrm{D},ei} = \sqrt{\frac{\epsilon_0 T_e T_i}{n_e e(Z^* T_e + T_i)}}$
- Dimonte-Daligault ‡: $ln\left(1 + 0.7\frac{\lambda_{\mathrm{D},e}}{Z^* e/(4\pi\epsilon_0 T_e)}\right)$, with $\lambda_{\mathrm{D},e} = \sqrt{\frac{\epsilon_0 T_e}{n_e e}}$

Key questions:

1) $\mathbf{b_{max}}$: $\mathrm{v_T}/\omega_\mathrm{P} \equiv \lambda_{\mathrm{D,e}}$ versus $\mathrm{v_T}/\omega$?
2) Ion contribution to Debye shielding?
3) Correct numerical factors?
4) Classical and quantum limits?

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* A. Sommerfeld & A. W. Maue, Annalen der Physik 415, 589-596 (1935);
W. J. Karzas & R. Latter, Astrophysical Journal Supplement 6, 167 (1961);
J. Pradler & L. Semmelrock, The Astrophysical Journal 922:57 (2021).

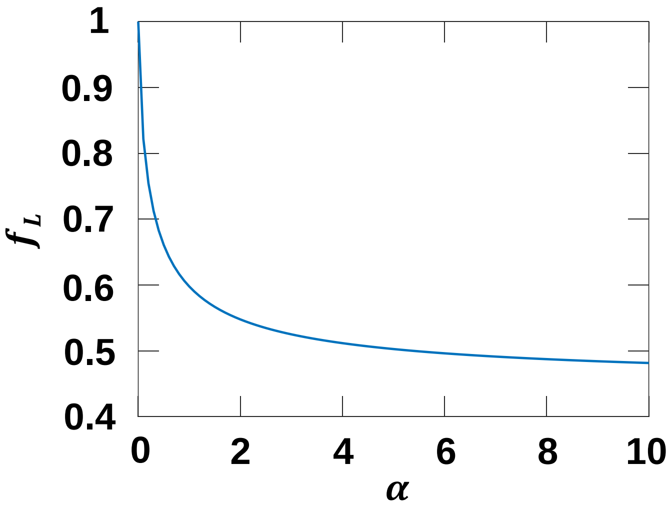
** L. Oster, Rev. Mod. Phys. 33, 525 (1961);
G. Bekefi, "Radiation Processes in Plasmas," (1966);
S. Skupsky, Phys. Rev. A 36, 5701-5712 (1987);
R. E. Kidder, Proc. Int. Sch. Phys. Enrico Fermi, Phys. HED (1971);
As shown, merges classical and q.m. results in a form resembling: T. W. Johnston & J. M. Dawson, Phys. Fluids 16, 722 (1973) [also NRL formulary]

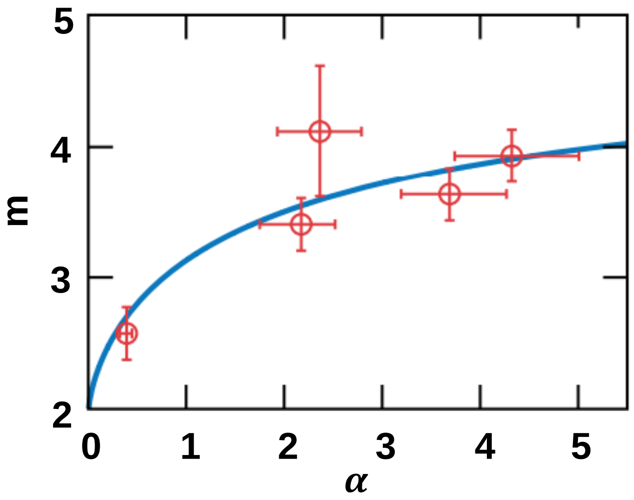
† Y. T. Lee & R. M. More, Phys. Fluids 27, 1273 (1984).

‡ G. Dimonte J. Daligault, Phys. Rev. Lett. 101, 135001 (2008).

Coulomb logarithms typically assume Maxwellians, but separately Langdon found that laser heating produces non-Maxwellians that reduce absorption

- **Langdon absorption-reduction factor:** $\boldsymbol{f_L = 1 - \frac{0.553}{\left[1+(0.27/\alpha)^{0.75}\right]}}$, **with** $\boldsymbol{\alpha = \frac{Zv_{osc}^2}{v_{th}^2}}$
- **From Fokker-Planck**, electron distribution functions (EDFs) span** $\boldsymbol{2 < m < 5}$: $\boldsymbol{m(\alpha) = 2 + \frac{3}{1+1.66/\alpha^{0.724}}}$
  - **"consistent with** $\boldsymbol{f_L}$ **to within 1% for any** $\boldsymbol{\alpha}$**"**
- **Thomson-scattering data have validated** $\boldsymbol{m(\alpha)}$**†, but not yet** $\boldsymbol{f_L}$





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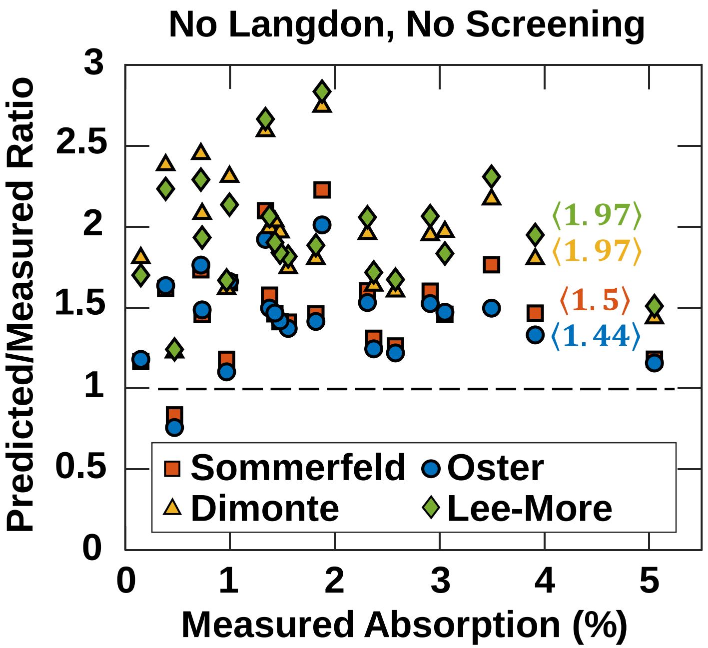
* A B Langdon, Phys. Rev. Lett. 44, 576 (1980).

** J-P Matte *et al.*, Plas. Phys. & Cont. Fus. 30, 1665 (1988).

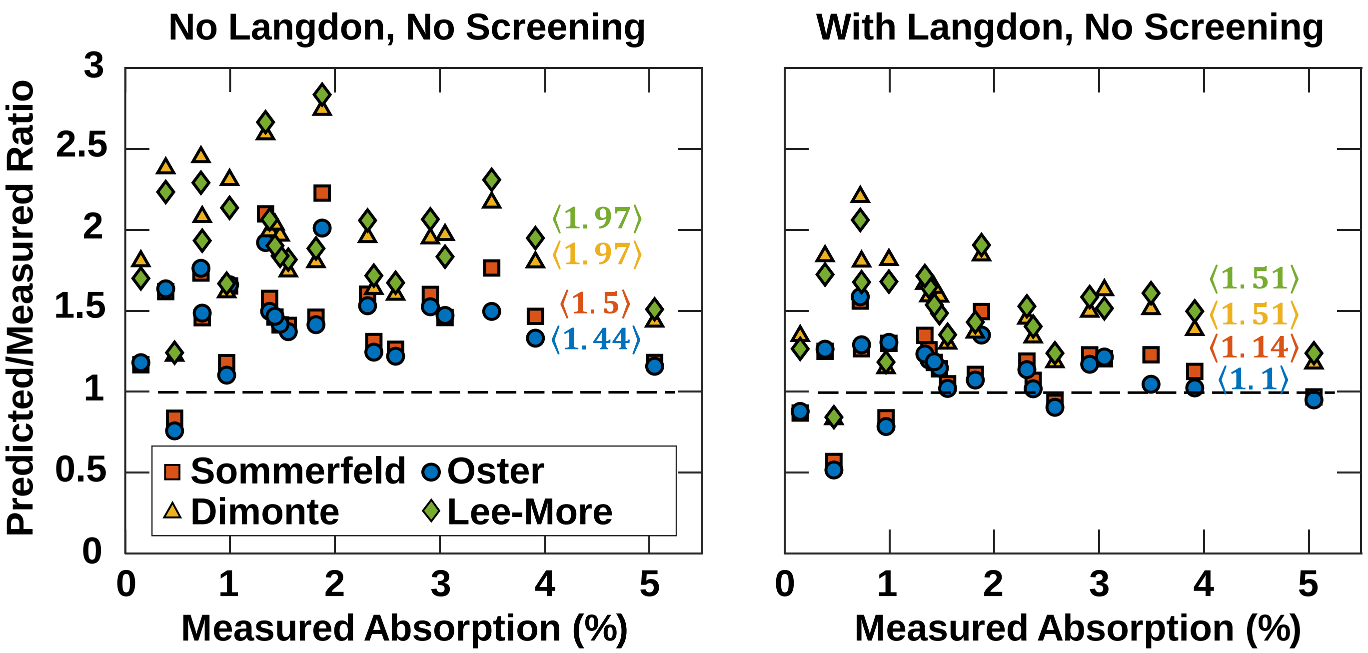
† D. Turnbull *et al.*, Nature Physics 16, 181 (2020);
A. L. Milder *et al.*, Phys. Rev. Lett. 127, 015001 (2021).

The measurements were precise enough to discriminate between various theories, with several key takeaways



(1) Without the Langdon effect, all models overestimate absorption

The measurements were precise enough to discriminate between various theories, with several key takeaways



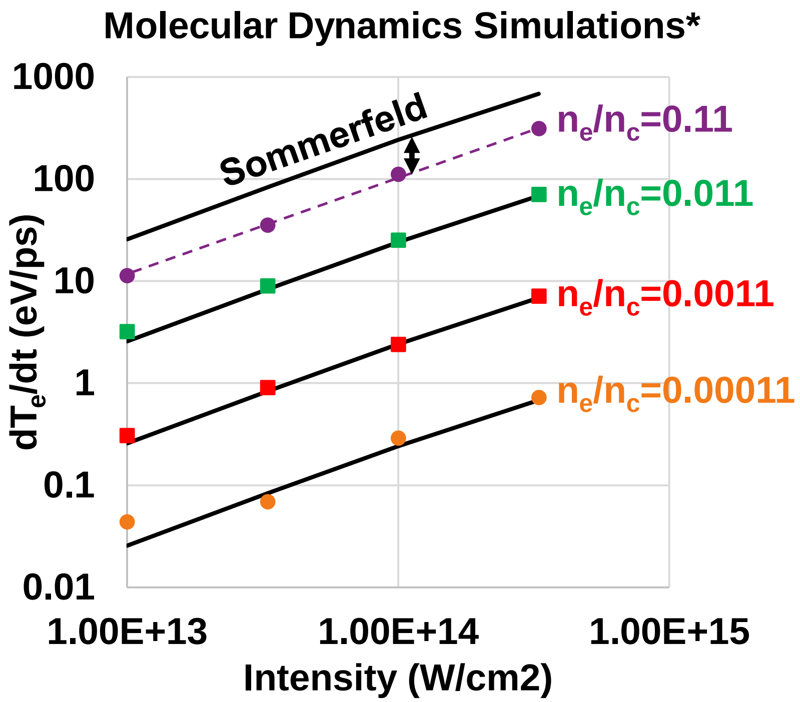
(1) Without the Langdon effect, all models overestimate absorption

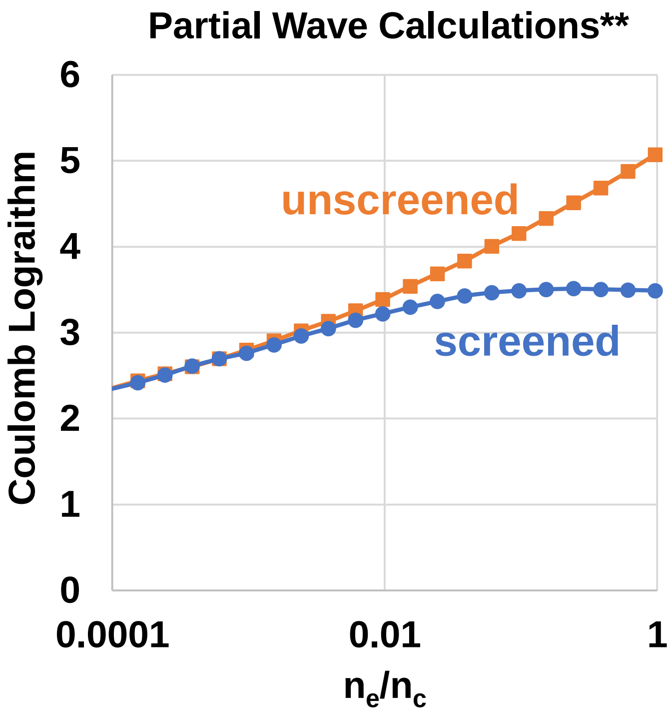
(2) With the Langdon effect, brems. models approach data; transport models still off by >50%

(3) Simpler brems. formula (Oster) close enough for real plasmas

(4) Final ~10% overprediction implies screening is important

The few existing simulation/theory approaches that accounted for ion screening also point to it becoming important for densities ≥0.01n_c


Molecular Dynamics Simulations*


Partial Wave Calculations**

Screening Correction from Rozsnyai †

$$f_{sc} = \frac{\ln\left(\frac{2T_e e}{\hbar\omega}\frac{y}{\sqrt{1+y^2}}\right) - \frac{0.5}{1+y^2}}{\ln\left(\frac{2T_e e}{\hbar\omega}\right)}, \text{ with } y = \frac{l_{sc}}{b_{max}}$$

For densities we care about, we need to account for ion screening

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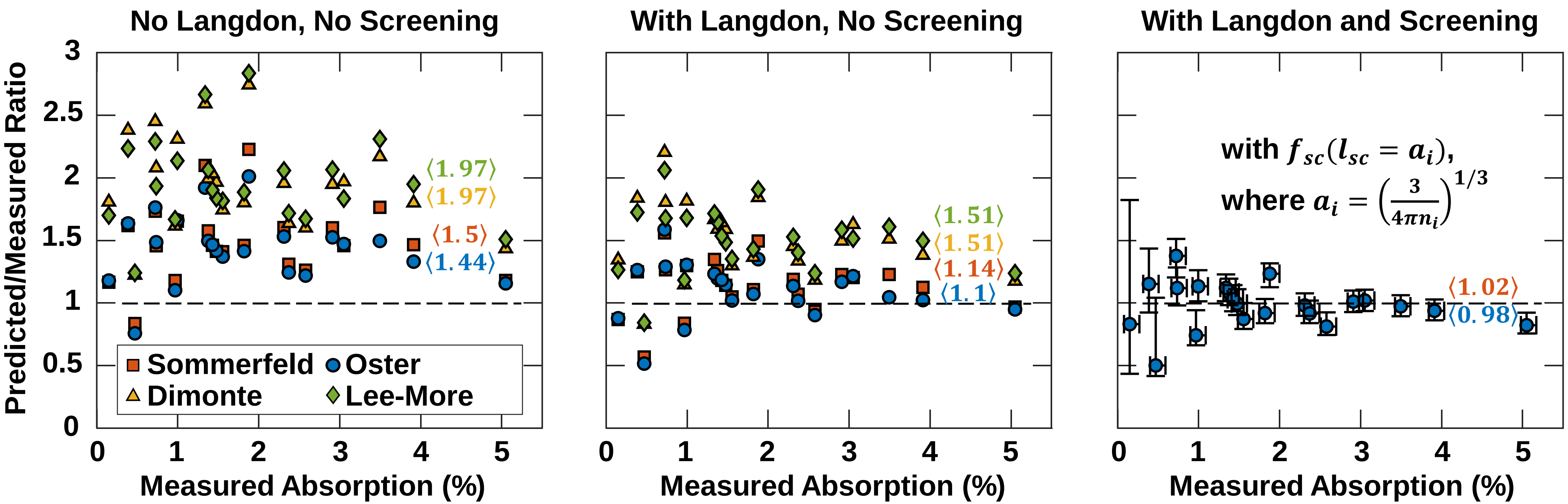
* R. Devriendt O. Poujade, Phys. Plasmas 29, 073301 (2022).

** G. S. J. Armstrong *et al*., High Energy Density Physics 10, 61-69 (2014).

† B. F. Rozsnyai, J. Quant. Spect. Rad. Trans. 22, 337-343 (1979).

Using the Langdon factor, bremsstrahlung Coulomb logarithms, and a screening correction, we are able to match the data well



with $f_{sc}(l_{sc} = a_i)$,

where $a_i = \left(\frac{3}{4\pi n_i}\right)^{1/3}$

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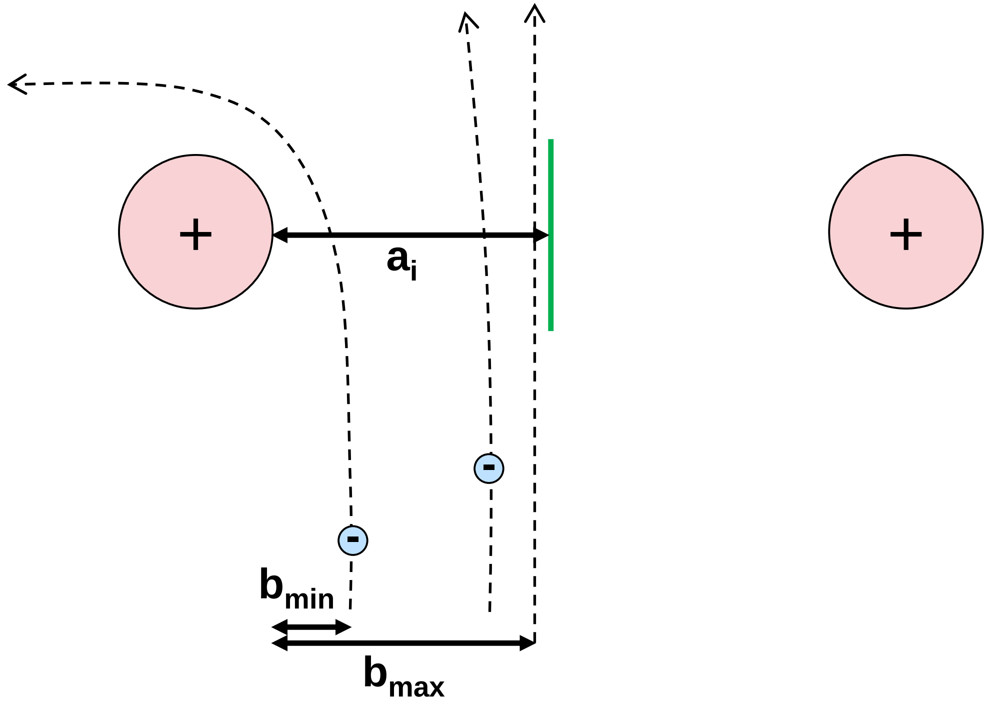
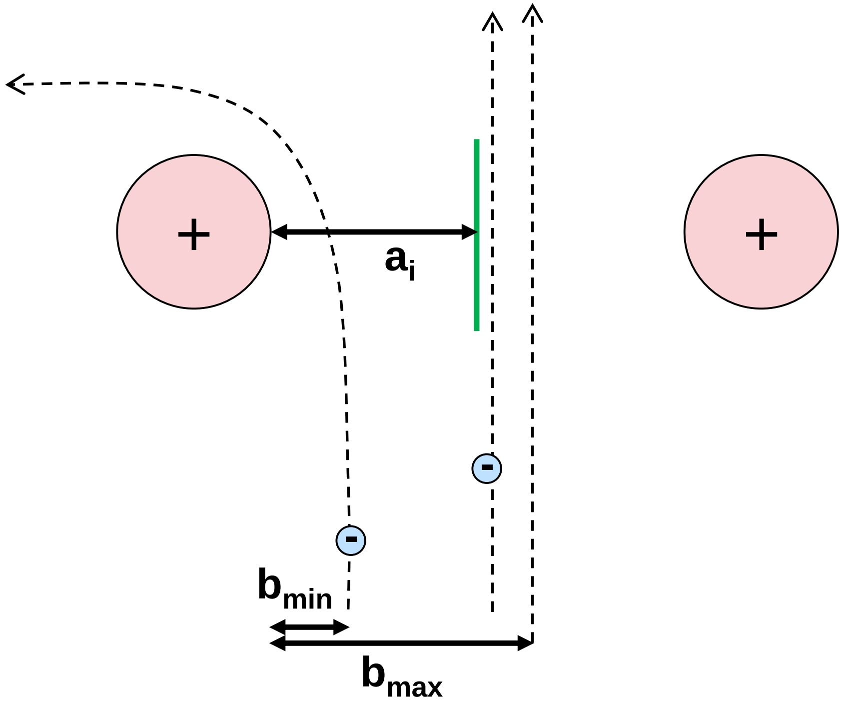
* D. Turnbull et al., Physical Review Letters 130, 145103 (2023).

Is the Wigner-Seitz radius a_i (mean inter-ionic distance) a valid screening length?

When $b_{max} < ai$, no ion screening occurs

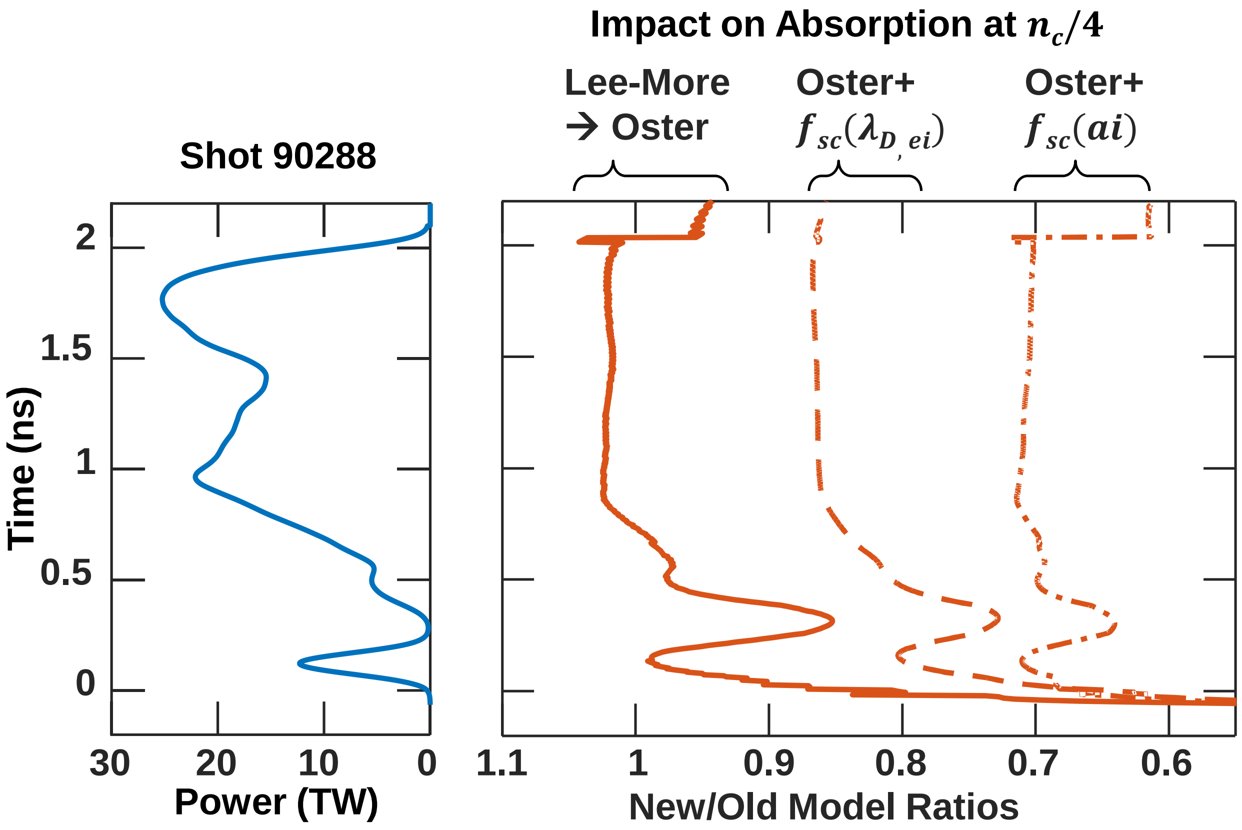


When $b_{max} \geq ai$, electrons interact with multiple ions simultaneously, effectively reducing absorption



We’re not sure, and the data don’t strongly constrain it in the low-density gas jet experiments. We are currently varying f_{sc} in simulations to see what best matches implosion data.

Radiation-hydrodynamics codes at LLE (LILAC, DRACO) were using Lee-More, so we expect substantial implications for direct-drive ICF



The model suggested by the gas-jet experiments predicts IB absorption could be up to ~30% less efficient in direct-drive

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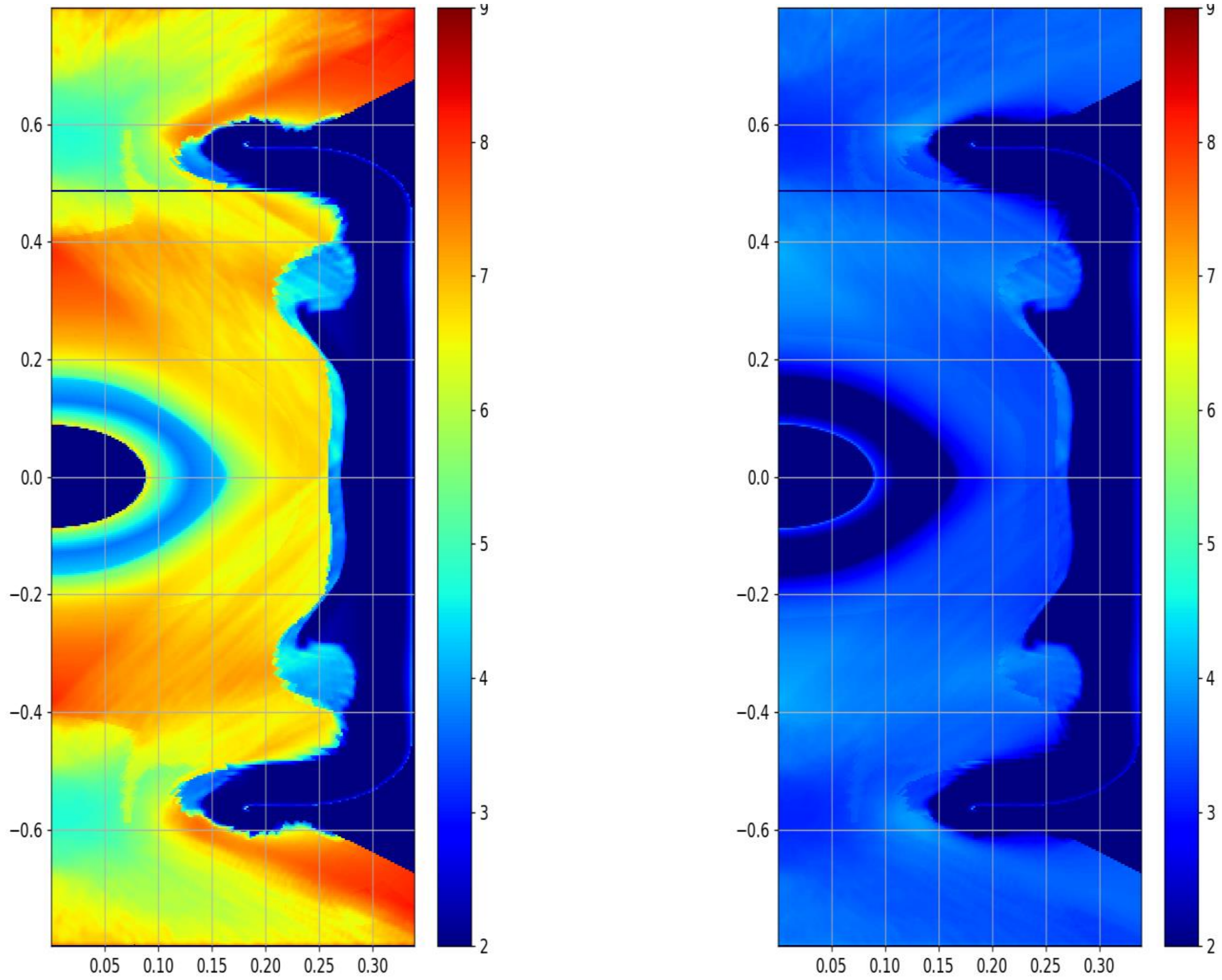
* D. Turnbull et al., Physical Review Letters 130, 145103 (2023).

Codes at LLNL (HYDRA, LASNEX) were likewise using Lee-More, and there too it appears likely to be a substantial lever on plasma conditions and drive*

Coulomb Logarithm



Lee-More + Langdon

Sommerfeld + New Langdon + Screening

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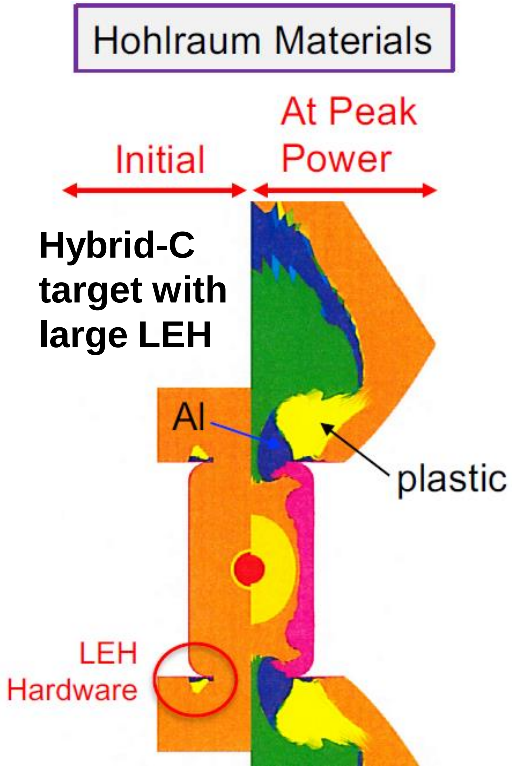
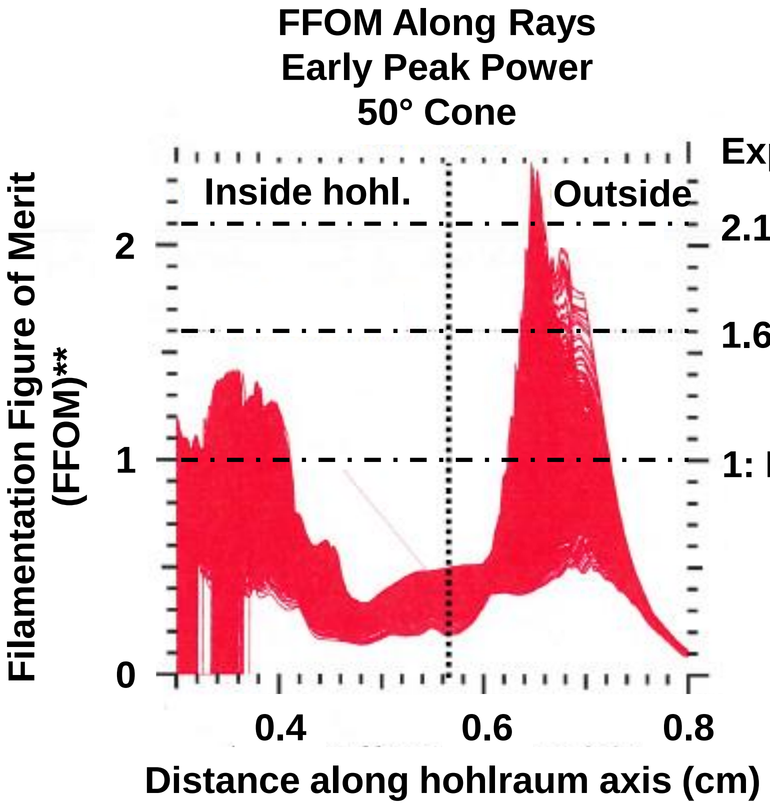
* courtesy of M. Sherlock

Beam Spray

Questions were recently raised about the possible influence of “filamentation”, or beam spray, in certain hohlraum platforms*



Hybrid-C target with large LEH



Expected thresholds:**

2.1: DPP + PS + Smoothing by Spectral Dispersion (SSD)

1.6: DPP + Polarization smoothing (PS)

1: Distributed Phase Plate (DPP) only

Q: How is the beam impacted when in proximity to the FFOM threshold?

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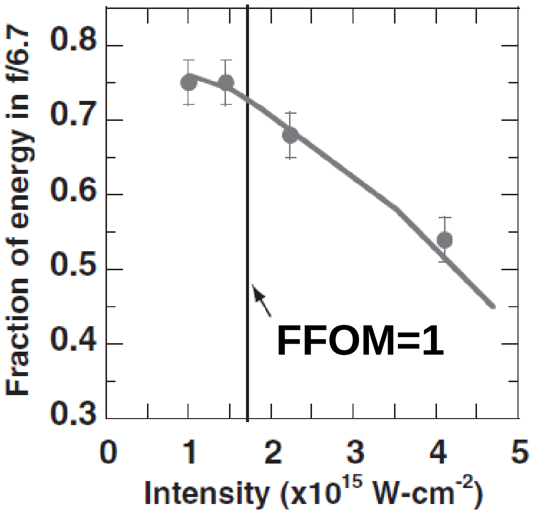
* Hinkel, MacLaren, Rosen *et al.*, Hohlraum Physics Working Group, 2020 ICF Workshop.

** E. L. Dewald *et al.*, PPCF 44, B405 (2005).

Various figures of merit have been proposed for predicting the onset of beam spray

- **The filamentation figure of merit (FFOM) was determined from pF3D* simulations accounting for ponderomotive filamentation****
  - $FFOM = I_{13}\lambda^2 \frac{n_e}{n_c}\frac{3}{T_e}\left(\frac{f\#}{8}\right)^2 > 1$ **(DPP only)**
  - **Claimed to have been validated experimentally† →**
- **The generalized, or Grech, figure of merit (GFOM), was based on a statistical model of forward stimulated Brillouin scattering (FSBS)‡**
  - $GFOM = 0.1\gamma_T \left(\frac{\omega}{\nu}\right)_{IAW} I_{13}\lambda^2 \frac{n_e}{n_c}\frac{3}{T_e}\left(\frac{f\#}{8}\right)^2 > 1$**, with thermal enhancement factor** $\gamma_T = 1 + 1.76 Z_{eff}^{5/7}(\rho_0/\lambda_{ei})$, ρ_0 **the transverse speckle width, and** λ_{ei} **the e-i m.f.p.**
  - ***Also* claimed consistency with experiment† using** $\gamma_T = 1.6$ **and** $\left(\frac{\nu}{\omega}\right)_{IAW} = 0.15$
  - **FSBS as dominant mechanism was consistent with other prior literature^**



†

Experiments had not been performed to break the degeneracy between the FFOM and GFOM

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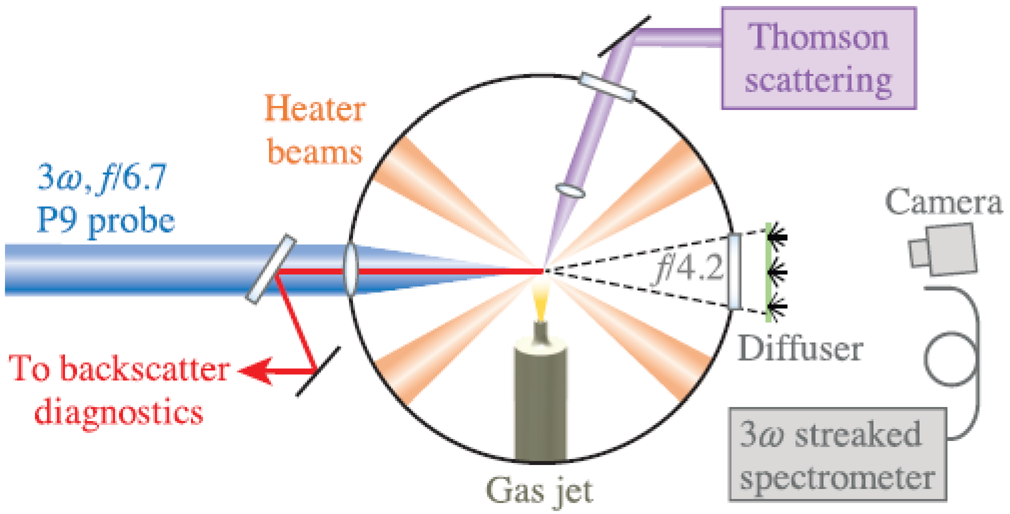
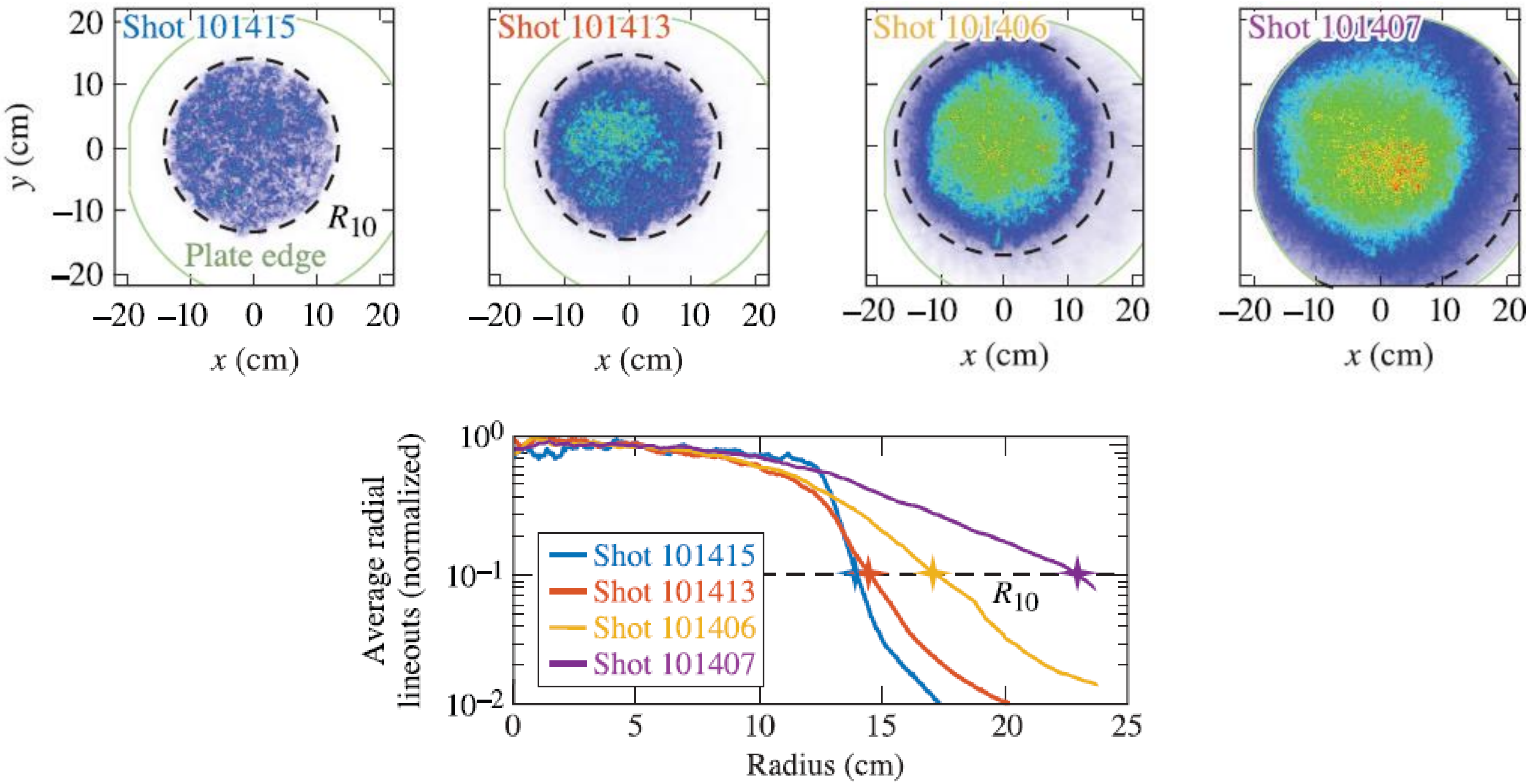
* R. L. Berger *et al*., Phys. Fluids B 5, 2243 (1993).
** E. L. Dewald *et al*., Plas. Phys. & Cont. Fus. 44, B405 (2005);
† D. H. Froula *et al*., Phys. Rev. Lett. 98, 085001 (2007).
‡ M. Grech *et al*., Phys. Rev. Lett. 102, 155001 (2009).
^ V. V. Elisseev *et al*., Phys. Plasmas 4, 4333(1997);
A. J. Schmitt & B. B. Afeyan, Phys. Plasmas 5, 503 (1998);
A. V. Maximov *et al*., Phys. Plasmas 8, 1319 (2001).

Experiments were performed using the LPI platform at OMEGA to study beam spray in more detail



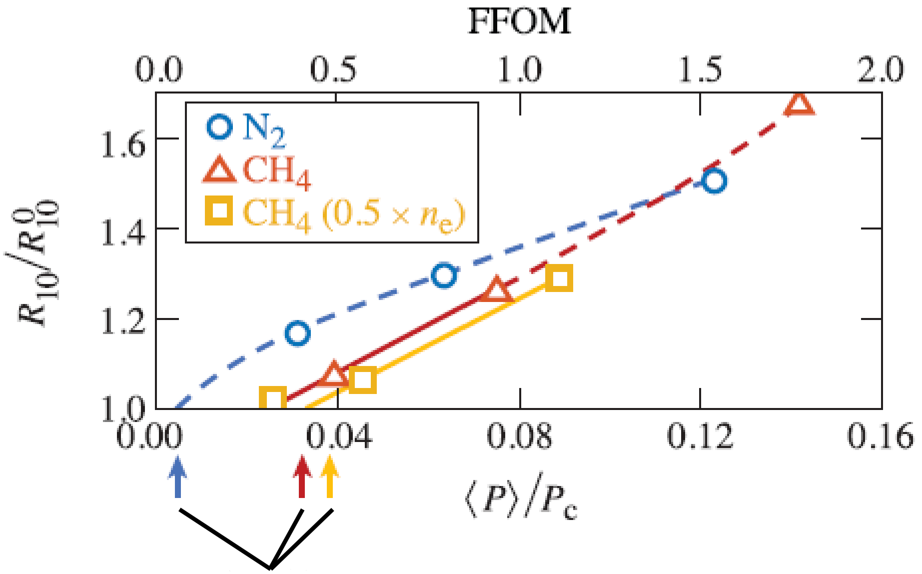
Ω#	Gas	$\langle I_{14}\rangle$	n_e (10^{20} cm^{-3})	T_e (keV)	$\left(\frac{\nu}{\omega}\right)_{IAW}$	Trans. (%)	SBS (%)	SRS (%)	Abs. (%)	Total (%)
101415	CH_4	3.8	2.26	0.75	0.1-0.5	93.6	< 0.2	0.0	5.9	99.7
101413	CH_4	7.7	2.05	0.79	0.1-0.5	95.7	< 0.2	0.0	4.2	100.2
101414	CH_4	17	2.02	0.89	0.1-0.5	93.1	3.1	0.8	3.2	100.2
101408	CH_4	3.8	4.15	0.92	0.1-0.5	74.6	0.7	0.1	15.2	90.7
101406	CH_4	7.8	4.04	0.95	0.1-0.5	65.1	1.0	2.8	12.9	81.9
101407	CH_4	16	3.86	1.01	0.1-0.5	56.0	5.3	4.5	10.0	75.8
101404	N_2	3.9	3.96	1.13	0.02	66.6	4.3	0.0	16.9	87.9
101402	N_2	8.1	3.91	1.13	0.02	55.4	21.7	0.0	15.1	92.2
101403	N_2	17	3.98	1.23	0.02	40.1	37.2	0.0	12.9	90.2

Beam spray was quantified by finding the radial location with signal nearest 10% of a central value from an average radial lineout



The data are consistent with thresholds predicted by the GFOM, which are ~2 to 15x lower than would be expected from the FFOM

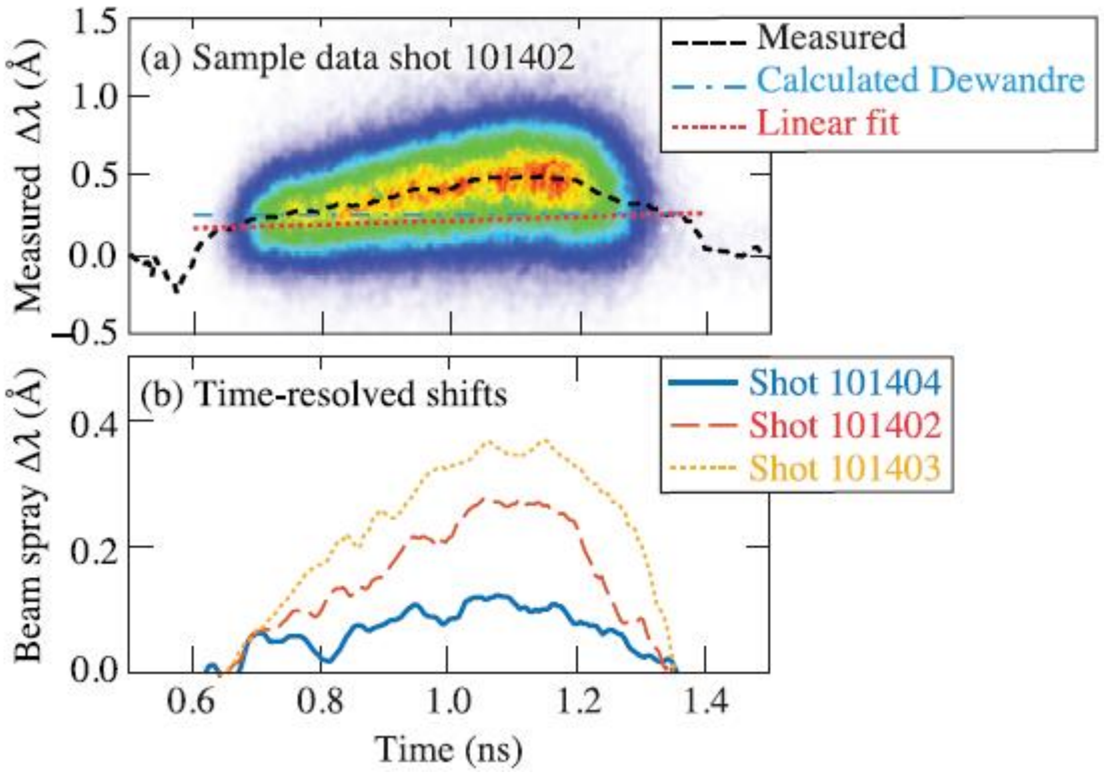
- Lower threshold in N_2 compared to CH_4, primarily due to weak ion-acoustic wave damping ($\frac{\nu}{\omega} = 0.02$) but also larger thermal enhancement factor ($\gamma_T = 3.1$)
  - Concavity suggests saturation from pump depletion
- Beam spray in CH turns on at higher intensity ($\frac{\nu}{\omega} \approx 0.1$)
- ~10% difference between CH datasets is consistent with their thermal enhancement factors ($\gamma_T = 2.3$ versus 2.1)



GFOM=1

Transmitted-beam spectra were redshifted, confirming that FSBS is the dominant beam-spray mechanism

- **Redshifts resulted from both the "Dewandre" shift* (dn/dt) and the classical FSBS shift**
- **Isolating the FSBS shift, the time-resolved data indicate that beam spray grows for ~100s of ps****
  - **SBS expected to reach steady state in $\boldsymbol{\tau} \approx \frac{\mathbf{1}}{\nu_{IAW}}$, and $\nu_{IAW} \propto \boldsymbol{\omega}_{IAW} \approx \boldsymbol{k c_s}$, so large $\boldsymbol{\tau}$ implies small k (scattering angles <1°)**
  - **In turn, the total spray must result from multiple FSBS events †**



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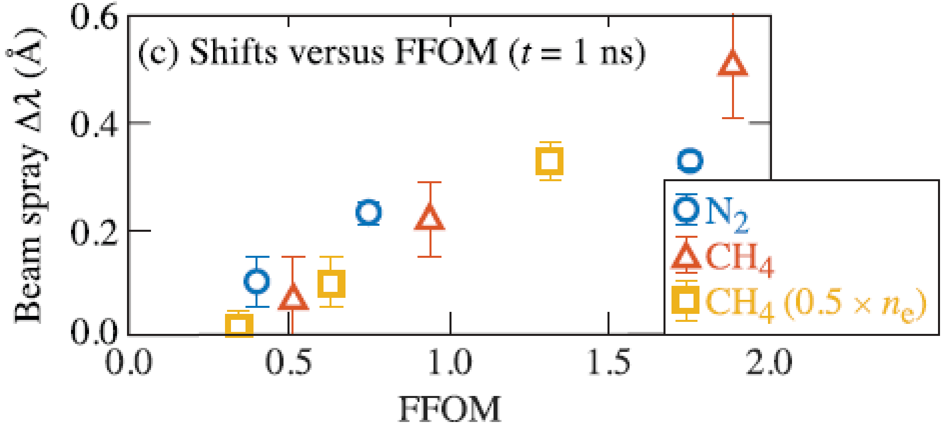
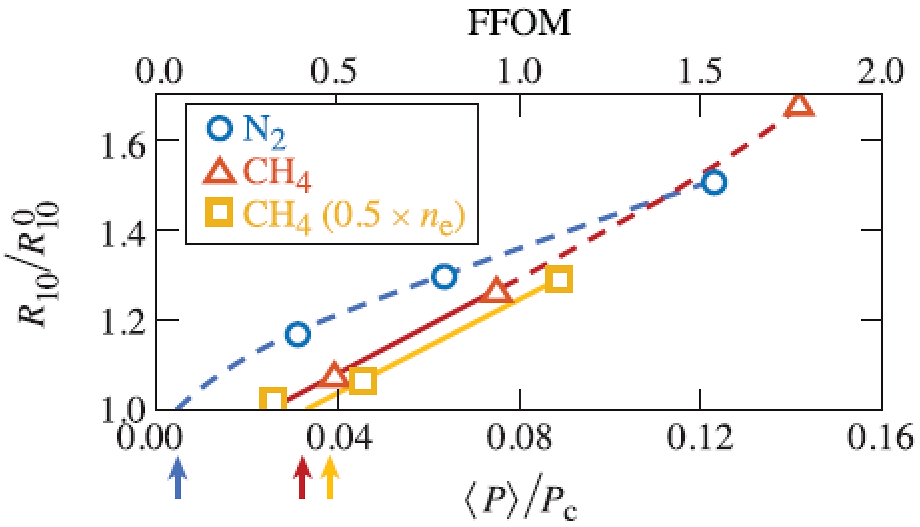
* T. Dewandre *et al.*, Phys. Fluids 24, 528 (1981).
** A. V. Maximov *et al.*, Phys. Plasmas 8, 1319 (2001);
M. Grech *et al.*, Phys. Rev. Lett. 102, 155001 (2009).
† A. J. Schmitt & B. B. Afeyan, Phys. Plasmas 5, 503 (1998);
A. V. Maximov *et al.*, Phys. Plasmas 8, 1319 (2001).

The FSBS frequency shifts scale with the amount of spray, as expected

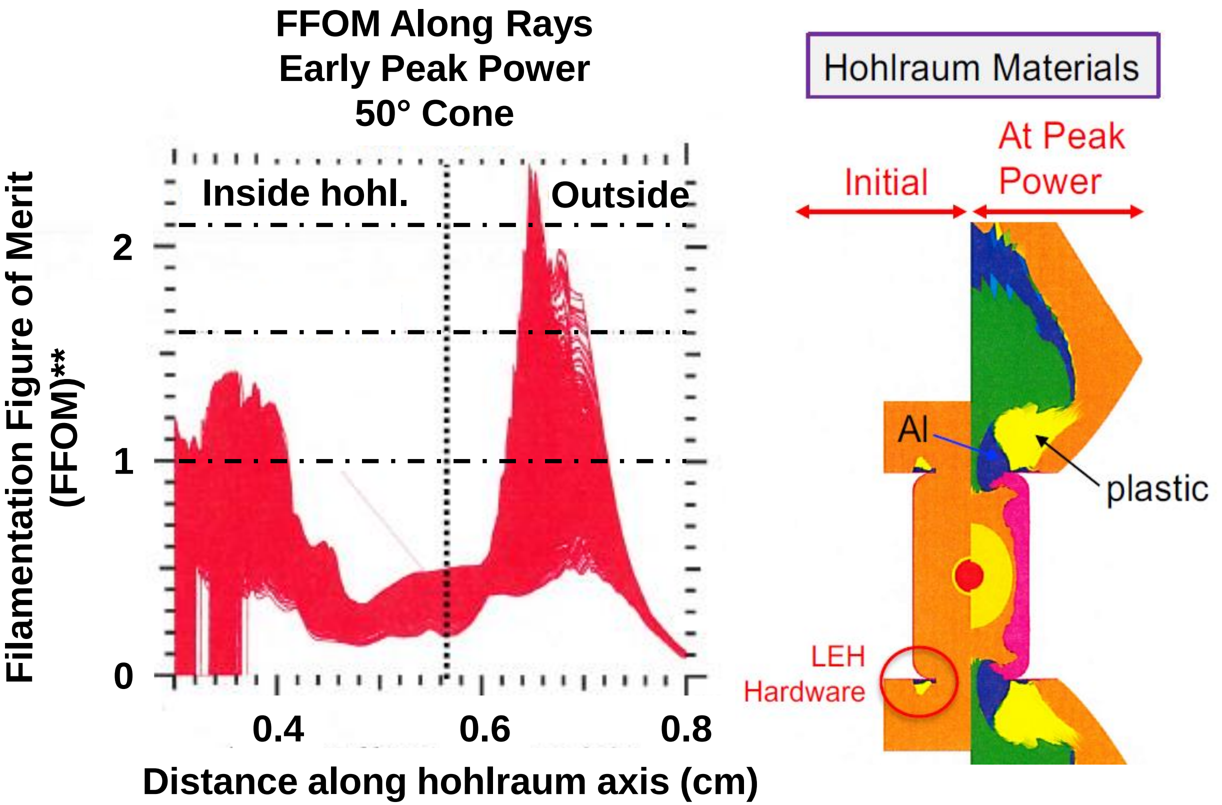




As the amount of spray increased, so too did the FSBS frequency shifts, further confirming the mechanism

Returning to the motivation*, beam spray could affect propagation, but the frequency shifts may be most concerning in terms of impacting symmetry

- For high-Z, the beam spray threshold is *very* low; however, spray is not explosive around FFOM~1
- On the other hand, the frequency shifts are substantial (~0.5 Å at 3ω, or ~1.5 Å at 1ω), and modern hohlraums are very sensitive to wavelength detuning (~20 to 50 µm-P2/Å at 1ω)**
  - Loss of symmetry control due to interplay with CBET may be greatest risk



Be wary of beam propagation in high-Z (i.e., $ZT_e/T_i \geq\approx 10$)—most codes will fail!

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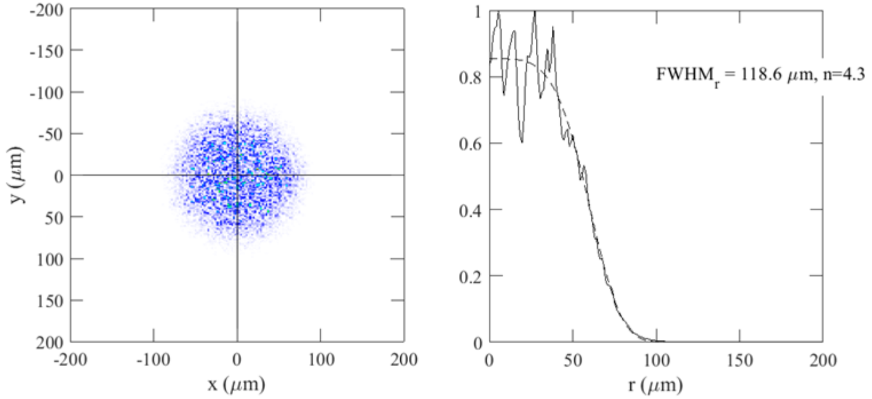
* Hinkel, MacLaren, Rosen *et al*., Hohlraum Physics Working Group, 2020 ICF Workshop.
** A. L. Kritcher *et al*., Phys. Rev. E 98, 053206 (2018);
L. A. Pickworth *et al*., Phys. Plasmas 27, 102702 (2020);
A. L. Kritcher *et al*., Phys. Plasmas 28, 072706 (2021);
A. B. Zylstra *et al*., Phys. Rev. Lett. 126, 025001 (2021);
J. S. Ross *et al*., arXiv:2111.04640 (2021).

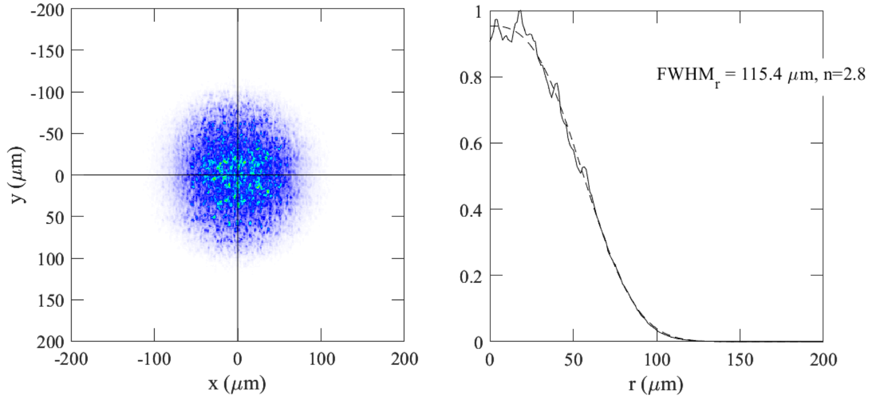
This platform was revisited last month to examine the effect of smoothing by spectral dispersion (SSD)

- **<u>Purpose/goal:</u>**
  - **Repeat scans from SRSPlatform-21C but with *<u>partial</u>* SSD**
- **<u>Specific deliverable(s) of this campaign:</u>**
  - **Get intermediate-bandwidth curves for scalings of spray/SBS/SRS**
- **<u>What would we do with results:</u>**
  - **Be able to show impact of <u>current</u> levels of bandwidth (from SSD) in order to show in the future that benefits from FLUX are more dramatic**

Far-field beam profile without SSD



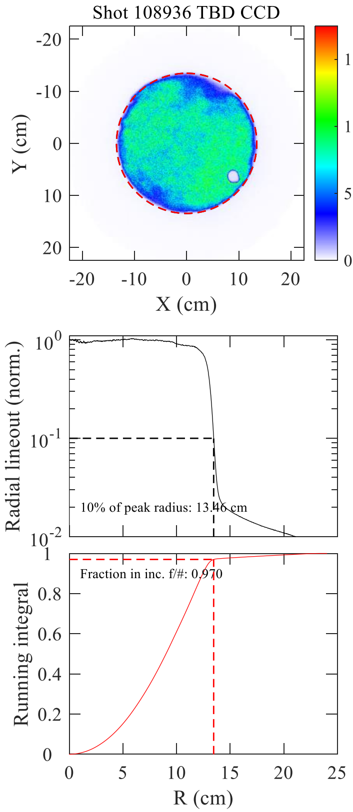
Beam profile with 1.0x1.0 Å SSD



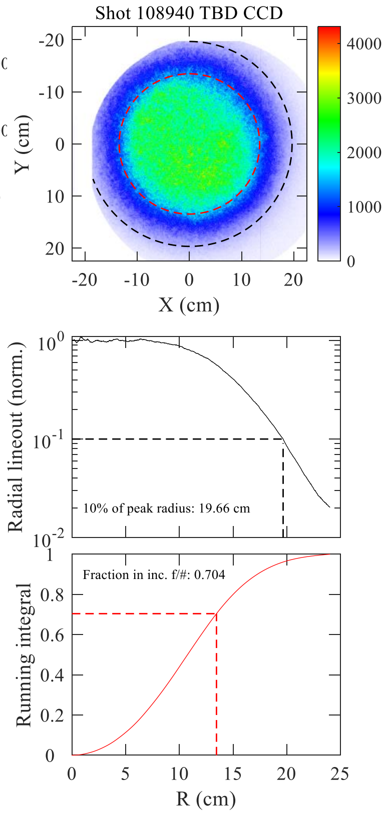
Coherence time reduced to ~6ps while minimizing the spatial profile alteration

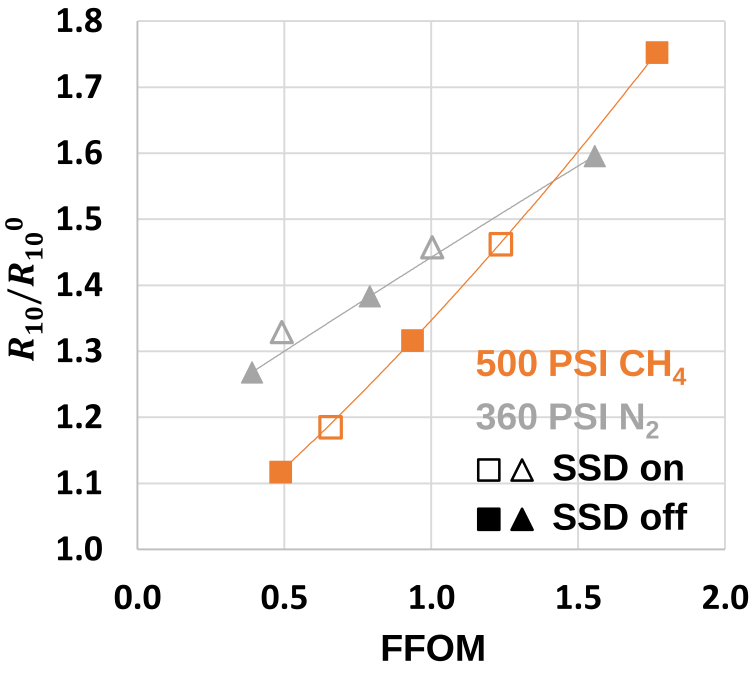
SSD appears to have had little to no effect on beam spray (if anything, it was slightly worse in N_2), which is contrary to existing literature*

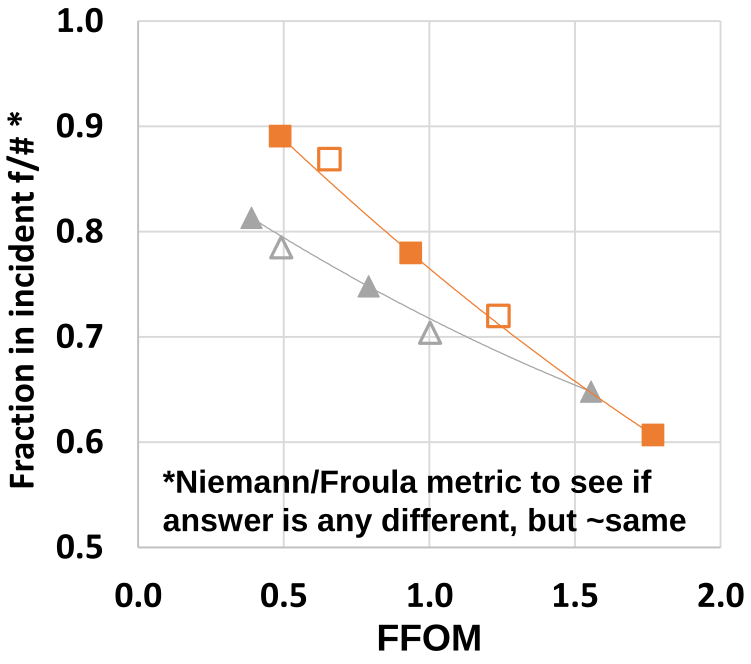
Vacuum profile



65.1 J, N_2, w/ SSD







*Niemann/Froula metric to see if answer is any different, but ~same

Leading hypothesis is that the bandwidth seeds FSBS in this regime, but it is under investigation

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* A. J. Schmitt & B. B. Afeyan, Phys. Plasmas 5, 503 (1998);
E. L. Dewald *et al*., Plas. Phys. & Cont. Fus. 44, B405 (2005);
C. Niemann *et al*., Phys. Rev. Lett. 94, 085005 (2005);
D. H. Froula *et al*., Meeting of the APS DPP (2006)
S. H. Glenzer *et al*., Nat. Phys. 3, 716-719 (2007).

Summary/Conclusions

Recent work suggests the need for revise our understanding of several key aspects of laser beam propagation

- **Laser coupling to HED targets is still not calculated reliably in many rad-hydro codes (*not* a crossed-beam energy transfer problem)**
- **What about inverse bremsstrahlung absorption?**
  - **Experiments precisely measured transmission of a probe beam that propagated through plasma while measuring its own path using imaging Thomson scattering***
  - **To match data, it is necessary to account for: (i) the Langdon effect; (ii) laser-frequency (rather than plasma-frequency) dependence in the Coulomb logarithm; and (iii) a correction due to ion screening**
  - **Preliminary calculations suggest this revised model will substantially alter the code predictions**
- **What about stability to beam spray?**
  - **Intensity threshold for beam spray can be significantly lower than suggested by common metric****
  - **Most recent data also shows insensitivity to SSD, contrary to expectation based on literature**

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* D. Turnbull *et al.*, Phys. Rev. Lett. 130, 145103 (2023).
** D. Turnbull *et al.*, Phys. Rev. Lett. 129, 025001 (2022).

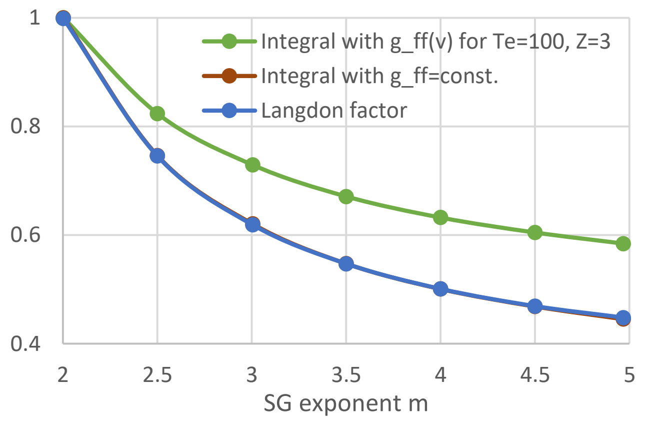
EXTRA

Note the inconsistency—we should really be calculating $\ln \Lambda$ for a super-Gaussian rather than Maxwellian, but this drives predictions further from data

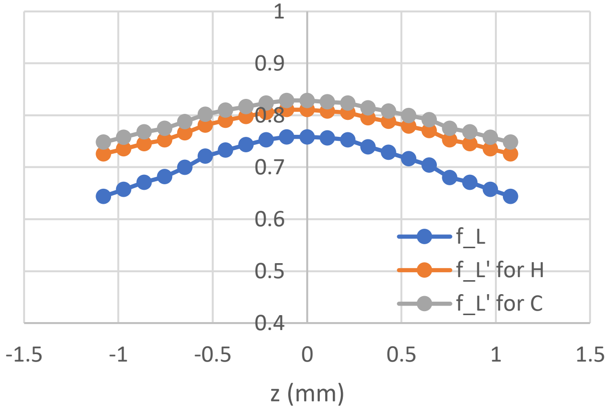
- **The Langdon factor is just $f_{SG}(v=0)/f_{max.}(v=0)$, ignoring velocity dependence of Gaunt factors**
- **Coulomb logarithms in literature typically assume Maxwellians when thermally averaging over an electron distribution function**
- **Revised Langdon factor accounting for velocity-dependent $g_{ff}(v)$ is $f_L' = \frac{m}{2}\frac{v_{m=2}}{v_m^{m-1}}\frac{c_m}{c_{m=2}}\frac{\int_0^\infty g_{ff}(v)\exp(-(v/v_m)^m)v^{m-1}dv}{\int_0^\infty g_{ff}(v)\exp(-(v/v_{m=2})^2)vdv}$, for $f(v) = c_m \exp\left(-\left(\frac{v}{v_m}\right)^m\right)$, with $v_m = \frac{3T_e e}{m_e}\frac{\Gamma(3/m)}{\Gamma(5/m)}$ and $c_m = \frac{n_e}{4\pi}\frac{m}{\Gamma(3/m)v_m^3}$**
  - **$g_{ff}(v)$ comes, again, from Pradler***

For our conditions, this reduces the Langdon effect about ~28% (when used, this increases predicted absorption, moving it further from data…)

General test case



Ex. Impact on our data



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* J. Pradler & L. Semmelrock, Astro. J. 922:57 (2021).