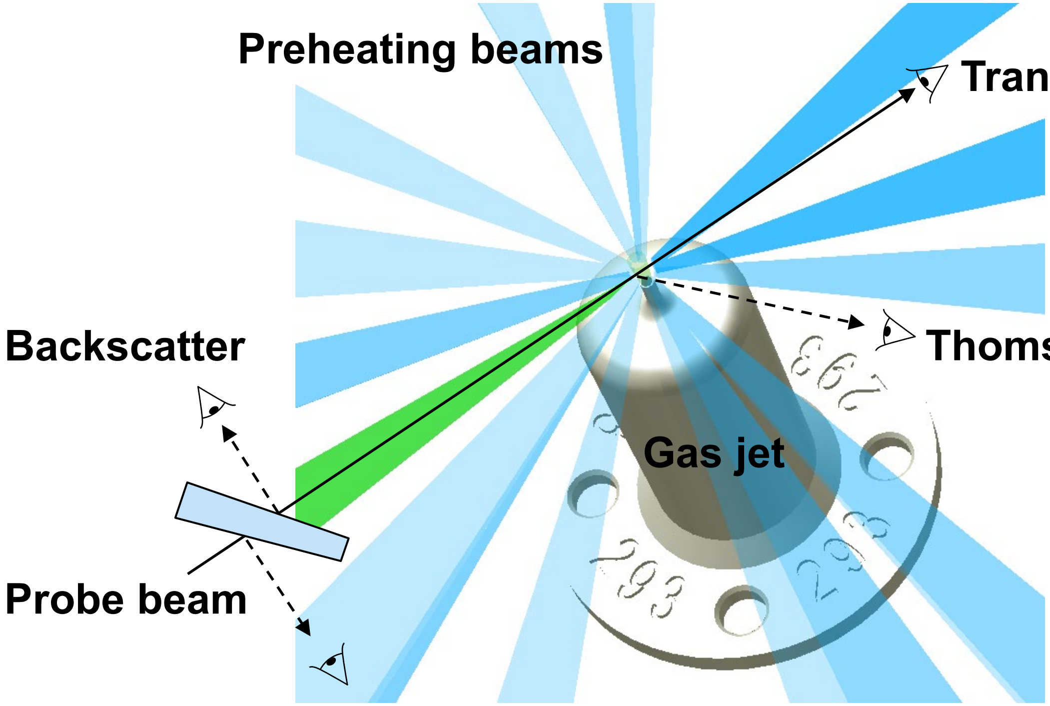
Absorption Measurements Validate the Langdon Factor and Discriminate Between Coulomb Logarithms



University of Rochester
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64th Annual Meeting of the APS DPP
Spokane, WA
17-21 October 2022

Summary

Focused absorption measurements are constraining the theory of inverse bremsstrahlung, which remains ill-defined after nearly a century

UR LLE

- The most reliable way to compute inverse bremsstrahlung absorption remains an open question
  - Is the Langdon absorption-reduction factor correct?
  - Which Coulomb logarithm to use?
- We have conducted experiments in which we measure the absorption of a 2ω probe beam that propagates through a finite-length preformed plasma while measuring its own path using imaging Thomson scattering
- While the results to date suggest that the Langdon factor *is* needed *and* that transport Coulomb logarithms can be eliminated from consideration, they cannot adequately distinguish between two remaining theories with (unfortunately) completely different physics

No single current theory provides the level of accuracy desired for predictive simulation capability

Collaborators

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Inverse bremsstrahlung laser absorption is proportional to a logarithmic factor $\ln\Lambda_{\mathrm{IB}}$ characteristic of Coulomb collisions, but there is no consensus on its definition

- **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 $\nu_{ei} = 2.91 \times 10^{-12} T_e^{-3/2} \sum_i \left(Z_i^2 n_i \ln \Lambda_{\mathrm{IB,i}}\right)$, f_{L} the Langdon factor***
- **Often framed as $\ln(b_{\max}/b_{\min})$**
- ***Why care?***

* SI units throughout talk except for temperatures in eV

We will consider some of the better-known examples to highlight some of the common sources of disagreement

Modified Dawson-Oberman*: $ln\,\Lambda_{IB} = ln\left(\frac{2}{e^{\gamma}}\frac{v_T/\omega}{\max\left(\frac{Z^*e}{4\pi\epsilon_0 T_e},\frac{\hbar}{2\sqrt{m_e T_e e}}\right)}\right)$, **with** $v_T = \sqrt{\frac{T_e e}{m_e}}$, $\gamma = 0.577$

Lee-More**: $ln\,\Lambda_{\mathrm{Tr}} = ln\left(\frac{\lambda_{\mathrm{D},ei}}{\max\left(\frac{Z^*e}{12\pi\epsilon_0 T_e},\frac{\hbar}{2\sqrt{3m_e T_e e}}\right)}\right)$, **with** $\lambda_{\mathrm{D},ei} = \sqrt{\frac{\epsilon_0 T_e T_i}{n_e e(Z^* T_e + T_i)}}$

Dimonte-Daligault †: $ln\,\Lambda_{\mathrm{Tr}} = ln\left(1 + 0.7\frac{\lambda_{\mathrm{D},e}}{Z^*e/(4\pi\epsilon_0 T_e)}\right)$, **with** $\lambda_{\mathrm{D},e} = \sqrt{\frac{\epsilon_0 T_e}{n_e e}}$

Devriendt-Poujade‡: $ln\,\Lambda_{IB} = 0.55 * ln\left(1 + 0.7\frac{\lambda_{\mathrm{D},e}}{Z^*e/(4\pi\epsilon_0 T_e)}\right)$

Key questions:

1) $b_{\max}$: $v_{\mathrm{T}}/\omega_{\mathrm{P}} \equiv \lambda_{\mathrm{D,e}}$ **versus** v_{T}/ω?
2) **Ion contribution to Debye shielding?**
3) **Correct numerical factors?**
4) **Classical and quantum limits?**
5) **Validity for non-Maxwellian electron distribution functions?**

Classical →

* J. Dawson & C. Oberman, Phys. Fluids 5, 517 (1962);
J. M. Dawson, Phys. Fluids 7, 981 (1964);
T. W. Johnston & J. M. Dawson, Phys. Fluids 16, 722 (1973);
NRL Plasma formulary;

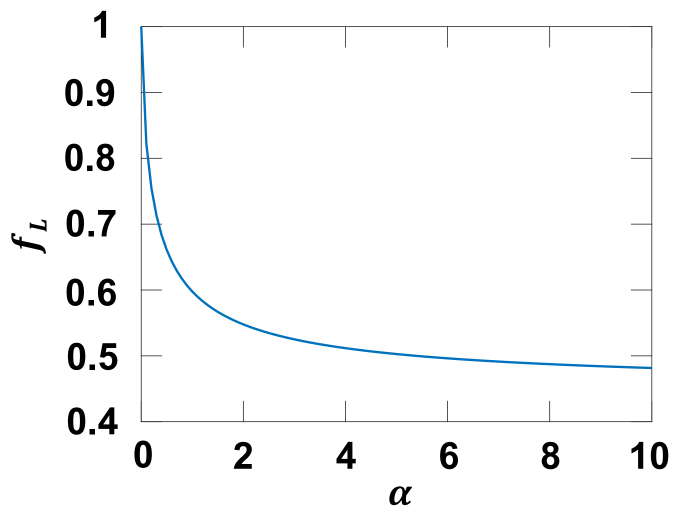
Q. M. ←

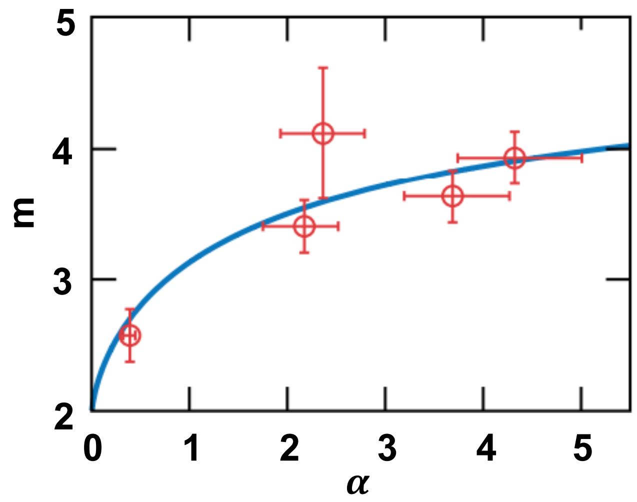
L. Oster, Rev. Mod. Phys. 33, 525 (1961);
S. Skupsky, Phys. Rev. A 36, 5701-5712 (1987);
R. E. Kidder, Proc. Int. Sch. Phys. Enrico Fermi, Phys. HED (1971).

** Y. T. Lee & R. M. More, Phys. Fluids 27, 1273 (1984).
† G. Dimonte J. Daligault, Phys. Rev. Lett. 101, 135001 (2008).
‡ R. Devriendt O. Poujade, Phys. Plasmas 29, 073301 (2022).

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

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

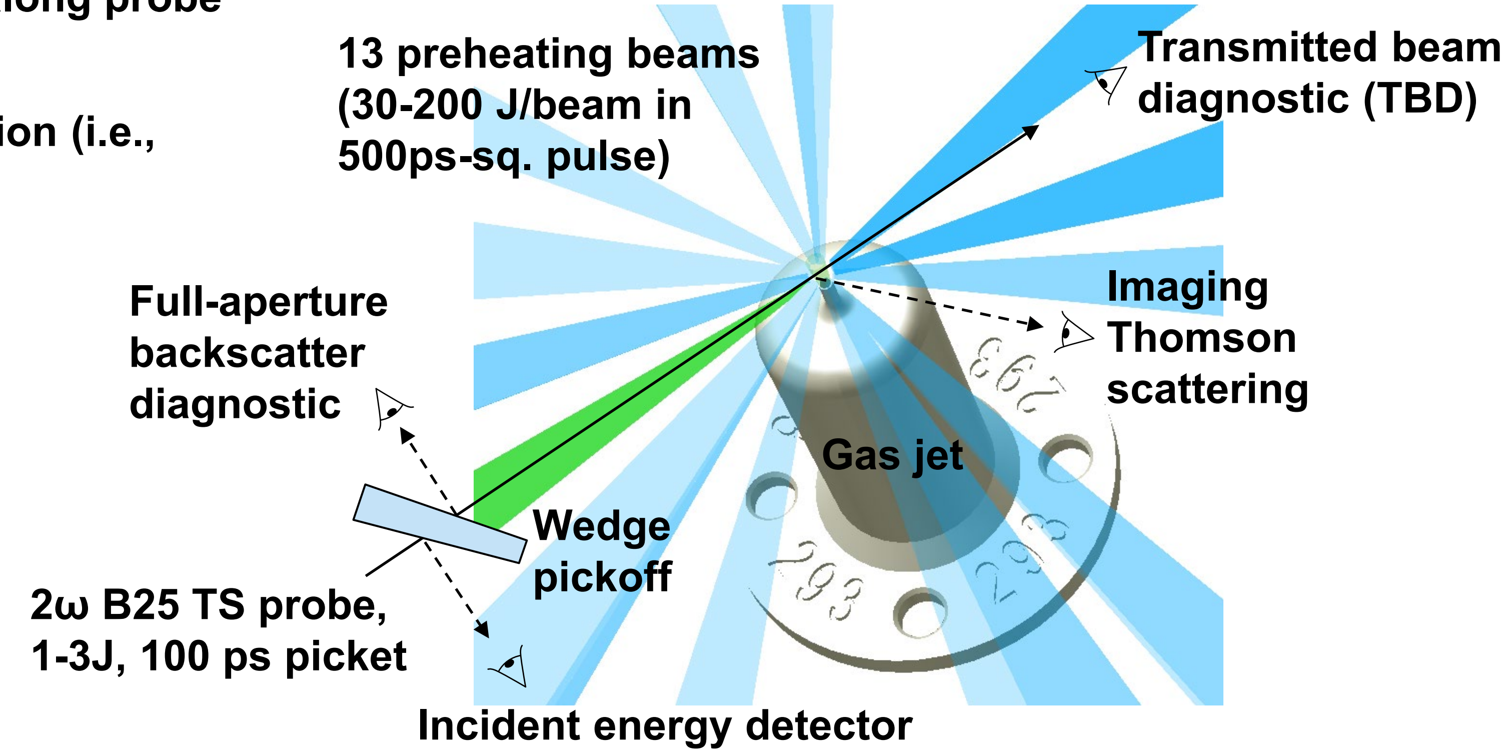




* A B Langdon, Phys. Rev. Lett. 44, 576 (1980).
** J-P Matte *et al.*, Plas. Phys. & Cont. Fus. 30, 1665 (1988).
† D. Turnbull *et al.*, Nature Physics 16, 181 (2020);
A. L. Milder *et al.*, Phys. Rev. Lett. 127, 015001 (2021).

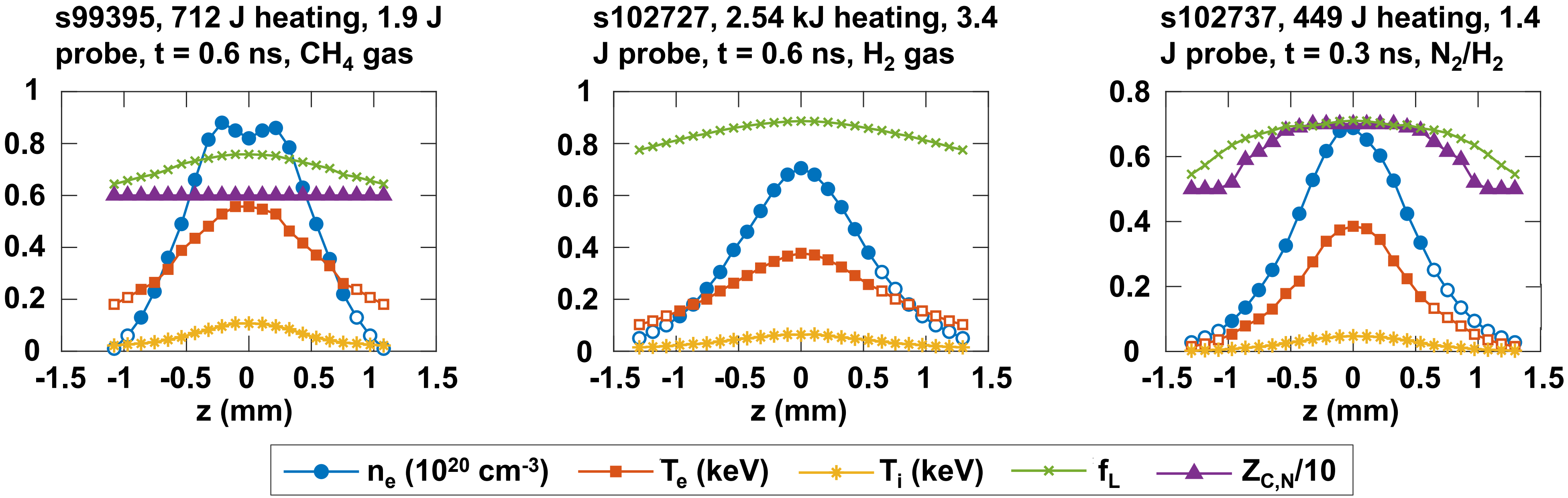
We have executed a number of campaigns over the last several years focused on measuring absorption through well-characterized underdense plasmas

- (1) Preform ~spherically-symmetric plasma
- (2) Measure plasma conditions along probe path
- (3) Precisely measure transmission (i.e., absorption), to within ±0.05%
- *Avoid competing instabilities**



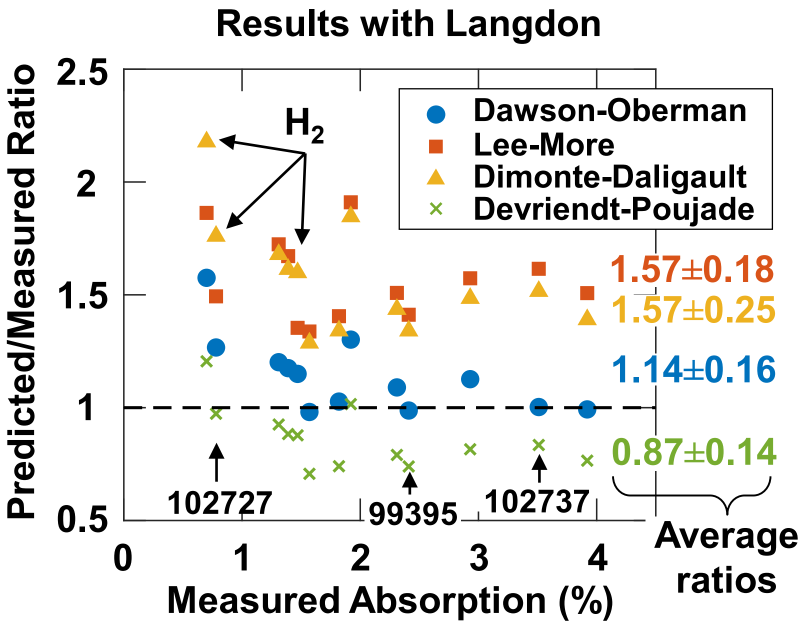
* e.g., filamentation, return-current instability, SBS, SRS

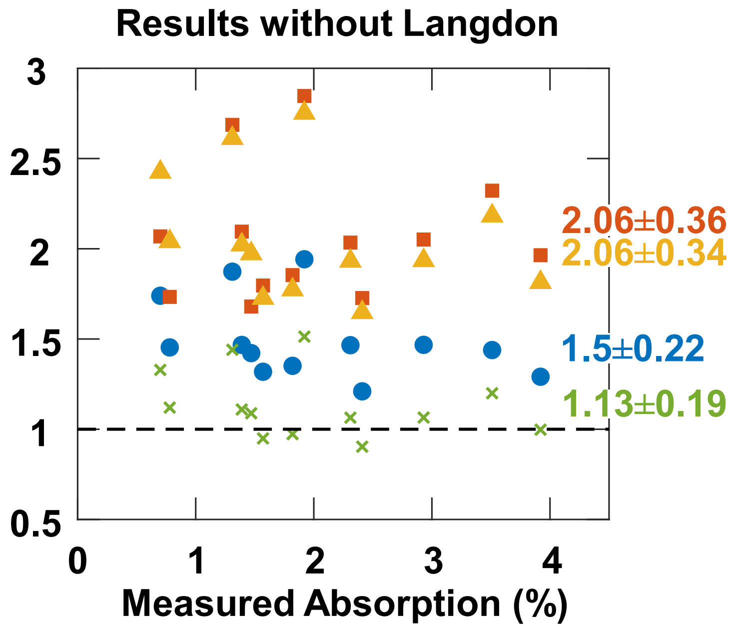
Special emphasis was placed on measuring (or at least reasonably extrapolating) the full probe path through the plasma



The absorption calculations are thus highly constrained

Results suggest the Langdon factor is needed and that transport Coulomb logarithms can be eliminated, but no theory matches all data to within 10%

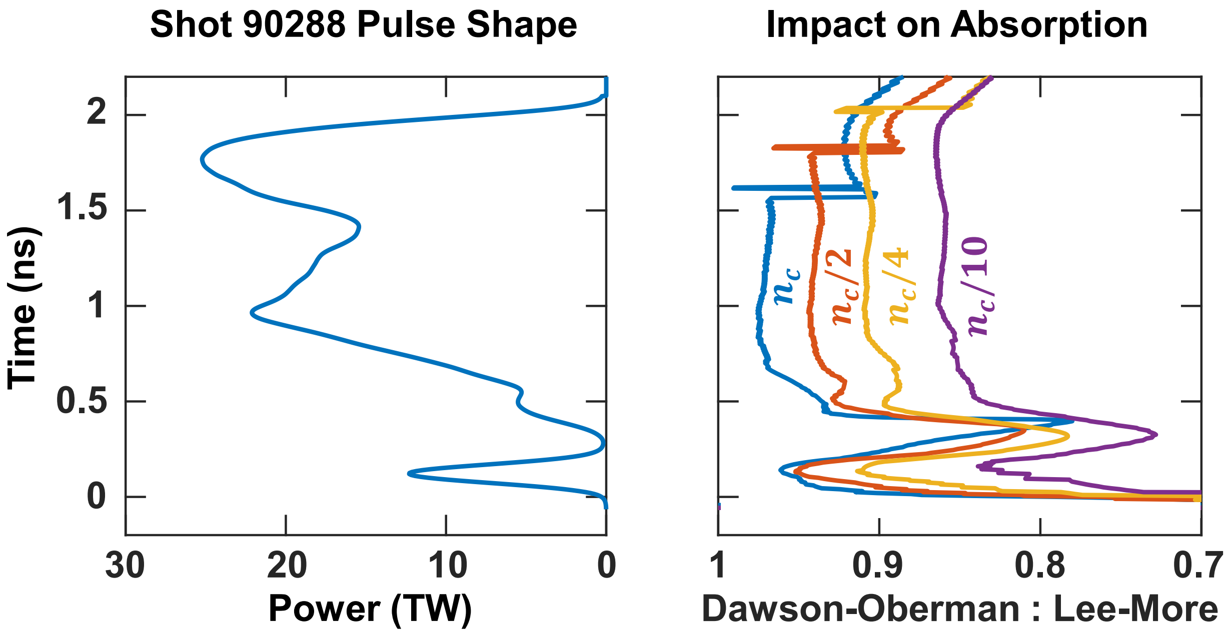




- All predictions overestimate absorption without f_L
- With f_L, transport Coulomb logarithms can still be eliminated
- D.-O. does well for classical absorption, less well for quantum-mechanical
- But D.-P. also brackets the data with and without f_L

A 4th (!) shot day in November will be dedicated to obtaining more data in H_2 (testing q.-m. limit) and to performing density scans (to break the degeneracy between D.-O. and D.-P.)

Radiation-hydrodynamics codes at LLE (LILAC, DRACO) and LLNL (HYDRA, LASNEX) were using Lee-More, so we expect substantial implications for ICF



The intention is to substitute an improved model once further experiments discriminate between the remaining contenders

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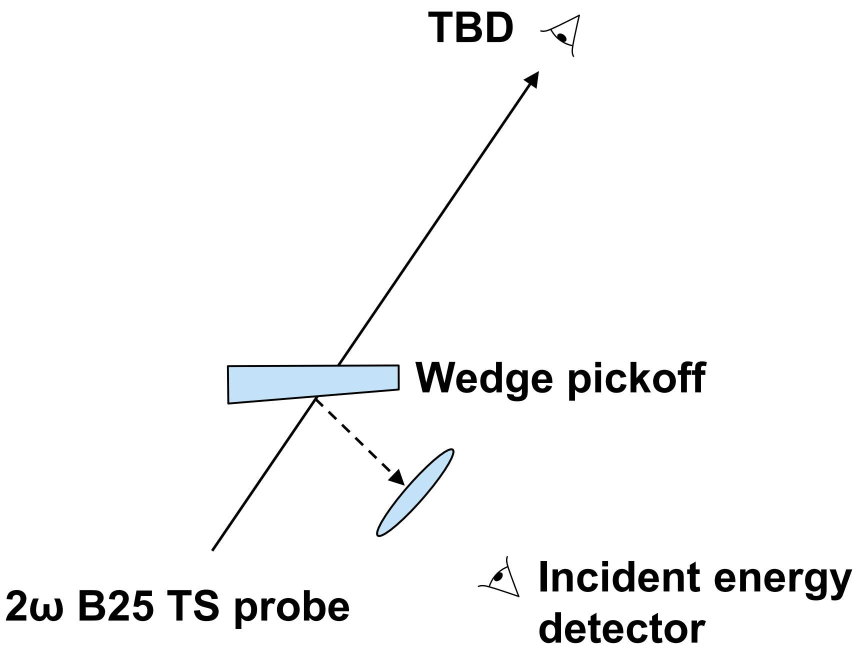
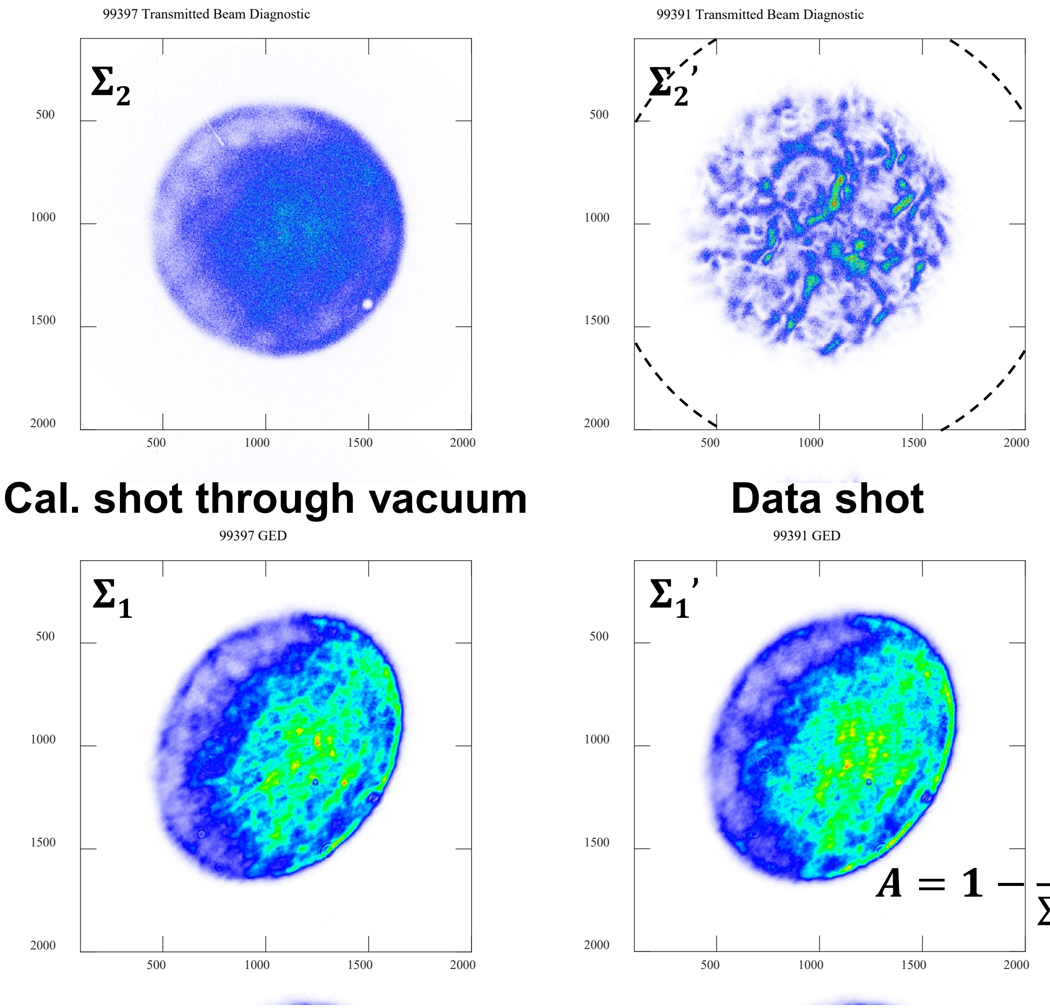
Absorption measurements are enabled by calibration shots through vacuum and >full-aperture transmitted beam collection



- **Estimated uncertainty in absorption is ±0.05%**



$$A = 1 - \frac{\Sigma_2'}{\Sigma_1'(\Sigma_2/\Sigma_1)}$$

There were two primary configurations, with the predominant campaign variables being heater beam energy, gas composition, and probe timing