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Title: IC Report for project “Developing nonlinear laser-plasma instability models for high-fidelity, multi-physics simulation capability for ICF/HED”

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IC Report for project "Developing nonlinear laser-plasma instability models for high-fidelity, multi-physics simulation capability for ICF/HED"

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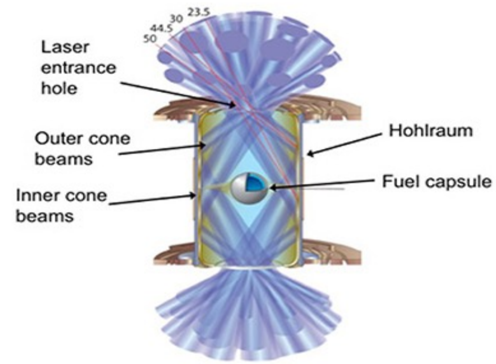
Modeling nonlinear effects of laser plasma instabilities (LPI) is critically important for ICF/HED experiments

- Technical goals:
  - Develop physics-based nonlinear LPI models
  - Couple the nonlinear LPI effects to macroscopic modeling of ICF/HED exp.
- Achieving these goals requires
  - Large-scale kinetic simulations
  - New machine learning algorithms for accurate characterization of plasma non-Maxwellian distributions
- We performed VPIC simulations for SRS[1] and CBET[2] for a range of plasma and laser conditions
- We developed a new δf-Gaussian-mixture algorithm to represent non-Maxwellian distribution functions from particle trapping and time-dependent plasma response
- We developed preliminary nonlinear SRS and CBET models to couple to laser ray-tracing/Mazinisin and AMP
  - SRS models
    - Reflectivity
    - Energy deposition
    - Hot electrons
  - CBET model
    - Gain
    - Energy deposition

LPI scatter laser light out of the hohlraum and impede the efficient coupling of laser energy to the fuel capsule

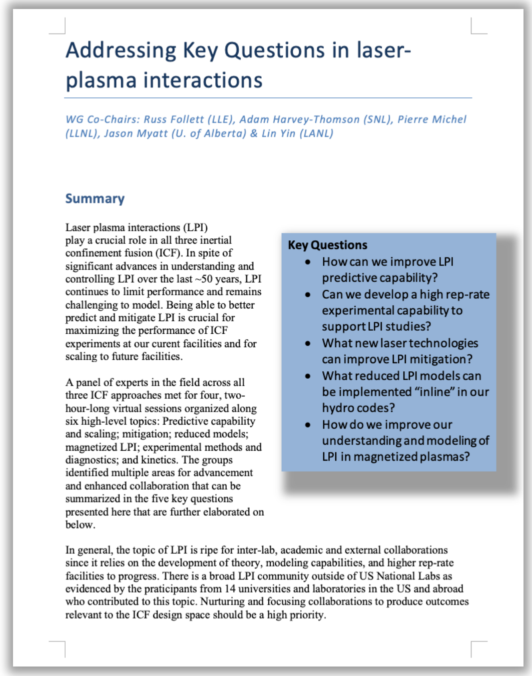


Laser-driven hohlraum on the NIF

[1] In stimulated Raman scattering (SRS), incident laser light scatters resonantly from electron plasma waves (EPW) in the plasma.
[2] Cross-beam energy transfer (CBET) is a process by which energy from overlapping laser beams is transferred between beams through the excitation of ion waves (IAW).

The LPI team succeeded in developing first-ever physics-based nonlinear LPI models for SRS and CBET

- Using suites of 2D large-scale multi-speckled kinetic simulations of LPI employing the LANL VPIC plasma code, the LPI team developed nonlinear models of both SRS[1] and CBET[2] that span the range of laser and plasma conditions relevant to ICF hohlraums
- These new models are being implemented[3] into the LLE Mazinisin laser ray-trace package used in XRAGE and Hyperion
  - allows for nonlinear feedback of effects of LPI to the hydrodynamics
- This first-of-a-kind capability of LANL LDRD investment in this project has a lasting impact on ICF
  - Necessary for development of Hyperion capability
  - Eliminate the use of *ad hoc* saturation clamps on wave amplitudes to reduced LPI in linear models in rad-hydro codes
  - Answers an LPI “grand challenge” called out by the ICF community in the 2021 ICF Fall Workshop



Addressing Key Questions in laser-plasma interactions

WG Co-Chairs: Russ Follett (LLE), Adam Harvey-Thomson (SNL), Pierre Michel (LLNL), Jason Myatt (U. of Alberta) & Lin Yin (LANL)

Summary

Laser plasma interactions (LPI) play a crucial role in all three inertial confinement fusion (ICF). In spite of significant advances in understanding and controlling LPI over the last ~50 years, LPI continues to limit performance and remains challenging to model. Being able to better predict and mitigate LPI is crucial for maximizing the performance of ICF experiments at our curent facilities and for scaling to future facilities.

Key Questions
- How can we improve LPI predictive capability?
- Can we develop a high rep-rate experimental capability to support LPI studies?
- What new laser technologies can improve LPI mitigation?
- What reduced LPI models can be implemented “inline” in our hydro codes?
- How do we improve our understanding and modeling of LPI in magnetized plasmas?

A panel of experts in the field across all three ICF approaches met for four, two-hour-long virtual sessions organized along six high-level topics: Predictive capability and scaling; mitigation; reduced models; magnetized LPI; experimental methods and diagnostics; and kinetics. The groups identified multiple areas for advancement and enhanced collaboration that can be summarized in the five key questions presented here that are further elaborated on below.

In general, the topic of LPI is ripe for inter-lab, academic and external collaborations since it relies on the development of theory, modeling capabilities, and higher rep-rate facilities to progress. There is a broad LPI community outside of US National Labs as evidenced by the praticipants from 14 universities and laboratories in the US and abroad who contributed to this topic. Nurturing and focusing collaborations to produce outcomes relevant to the ICF design space should be a high priority.

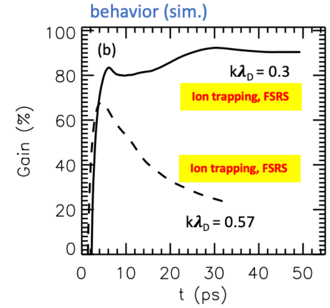
Excerpt from the 2021 ICF (“San Ramon”) Fall Workshop

[1] D. J. Stark et al., "Nonlinear Models for Coupling the Effects of Stimulated Raman Scattering to Inertial Confinement Fusion Codes," Phys. Plasmas, submitted (2022)
[2] L. Yin et al., "Time-dependent saturation and physics-based nonlinear model of cross-beam energy transfer," Phys. Plasmas, submitted (2022)
[3] L. Green et al., "Coupling Nonlinear CBET effects to radiation-hydrodynamic modeling of ICF/HED experiments via laser ray tracing" APS-DPP presentation (2022).

CBET Model Accomplishments

- The nonlinear saturation of CBET has been explored using large-scale particle-in-cell simulations for a range of densities, angles, temperatures, beam diameters, and intensities
- Simulations show time-dependent gain
- CBET saturation levels depend on several nonlinear effects
  - ion-trapping-induced detuning, IAW self-focusing, secondary instabilities (FSRS, BSBS), and pump depletion
- An automated method has been developed using Gaussian mixtures to represent non-Maxwellian distribution functions from ion trapping and time-dependent plasma response
- We constructed nonlinear CBET models
  - CBET gain
  - Ion heating via Landau damping of IAWs

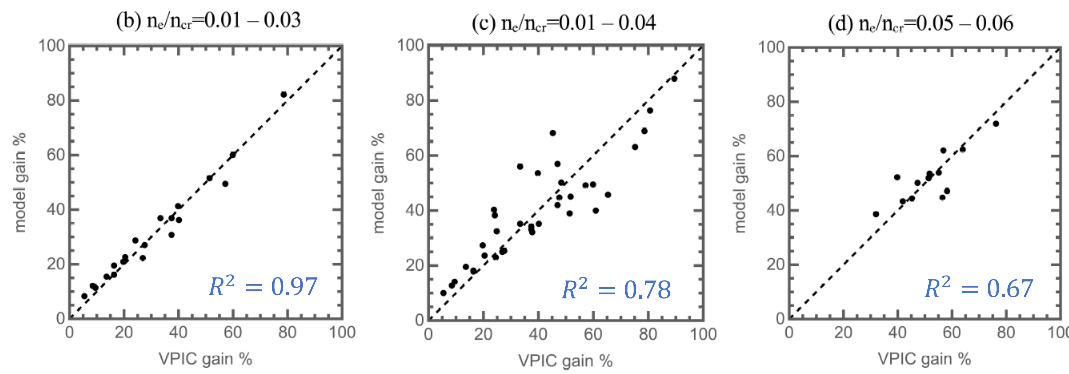
Time-dependent, nonlinear behavior (sim.)



Ion heating model

$$P_{ion} \approx f\left(I_{ave}, k\lambda_D, \frac{ZT_e}{T_i}, \frac{n_e}{n_{cr}}, L\right) P_{IAW}^{MR}$$

$$P_{\rm ion}/P_{\rm IAW}^{\rm MR} = 0.79\, I_{14}{}^{0.58}(k\lambda_D)^{-0.84}L^{0.98}(n_e/n_{\rm cr})^{2.58}(ZT_e/T_i)^{0.30}$$



$$\text{gain\%} = 4.165\, I_{14}{}^{0.45}(k\lambda_D)^{0.37}L^{0.82}(n_e/n_{\rm cr})^{1.43}(ZT_e/T_i)^{1.16}$$

Nonlinear CBET model

$$\text{gain\%} = 3.227\, I_{14}{}^{0.48}(k\lambda_D)^{-0.39}L^{0.32}(n_e/n_{\rm cr})^{0.64}(ZT_e/T_i)^{0.97}$$

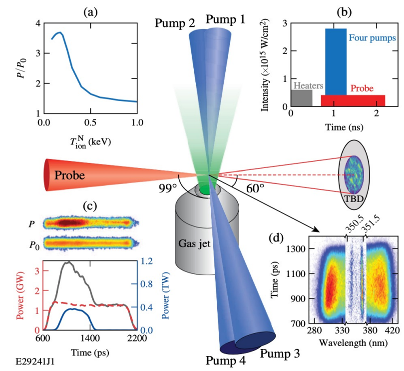
$$\text{gain\%} = 1.18 \times 10^4\, I_{14}{}^{-0.22}(k\lambda_D)^{-2.06}L^{-2.25}(n_e/n_{\rm cr})^{-1.87}(ZT_e/T_i)^{0.48}$$

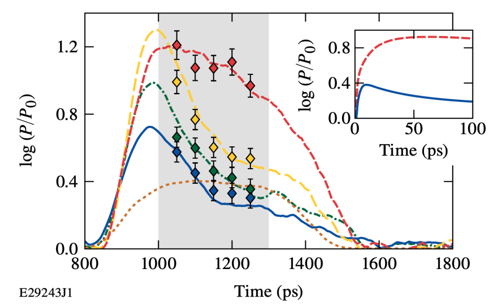
Yin et al., "Time-dependent saturation and physics-based nonlinear model of cross-beam energy transfer" Phys. Plasmas, in press (2023)

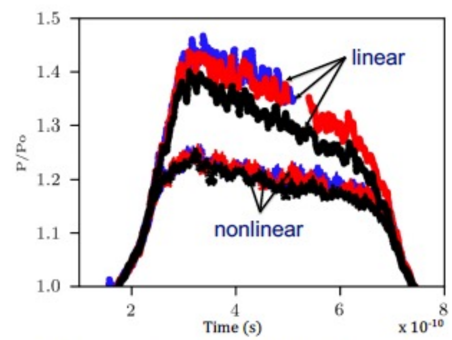
Nonlinear LPI models are being implemented in laser ray-tracing (LRT) package

Goals:

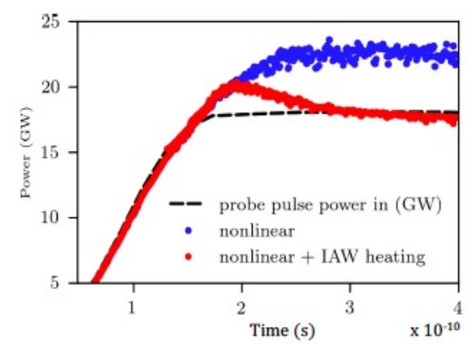
- Integrate LRT into Hyperion
  - Use LLE's state-of-the-art Mazinisin LRT code [Marozas et al., Phys. Plasmas 25:056314 (2018)]
  - Use LANL-developed methodology for coupling Mazinisin to Hyperion using separate laser mesh [Haines et al., Comput. Fluids 201:104478 (2020)]
  - Validate coupling using established laser test problems for ray trajectories and inverse bremsstrahlung deposition (in progress)
- Update Mazinisin to include new LPI models
  - Nonlinear CBET saturation model implemented
  - Tested using Top9 experimental data
  - Begin implementing the nonlinear SRS model







The power transferred into to the probe beam for three different initial intensities

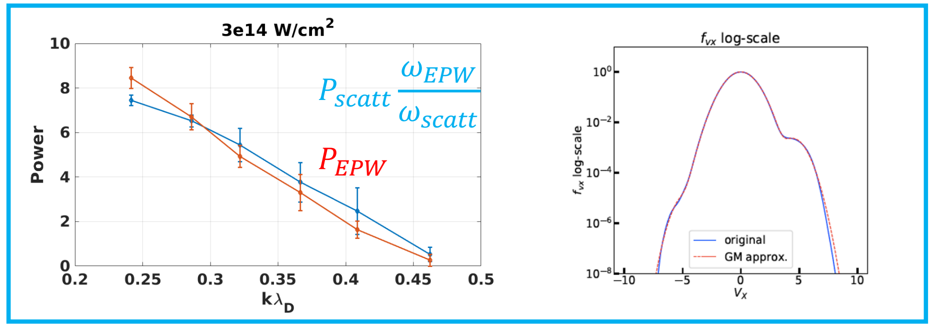


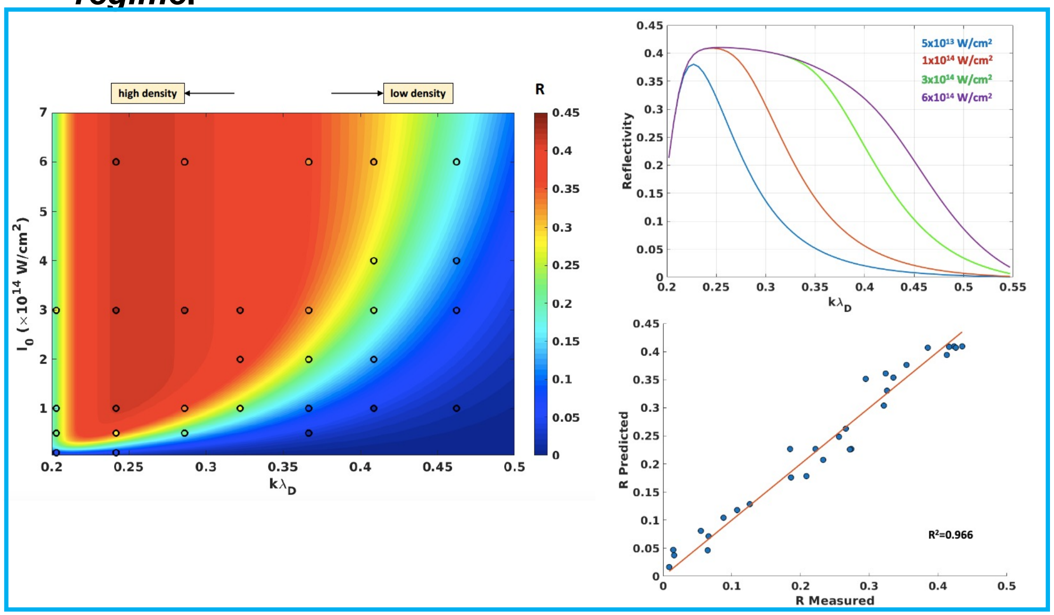
Power of the probe beam at exit, relative to input pulse power of probe beam, with and without IAW heating

Green et al., "Coupling Nonlinear CBET effects to radiation-hydrodynamic modeling of ICF/HED experiments via laser ray tracing" APS-DPP presentation (2022).

SRS Model Accomplishments

- **We performed large-scale multi-speckled stimulated Raman scattering (SRS) simulations in a broad scan of density and intensity parameter space to develop nonlinear models for laser ray-trace packages.**
- **We identified different scattering regimes: the *key trapping-dominated regime* with $(k\lambda_D)^{-4}$ scaling, the *strong damping regime* at high $k\lambda_D$, and the *Langmuir decay instability (LDI) regime*.**





- **Reflectivity model:** We fit reflectivity with correction terms to the key trapping-dominated scaling.

$$a_1 I_{ave}^{3/4}(k\lambda_D)^{-4} = \chi \qquad R = \chi \underbrace{f_s f_L f_H}$$

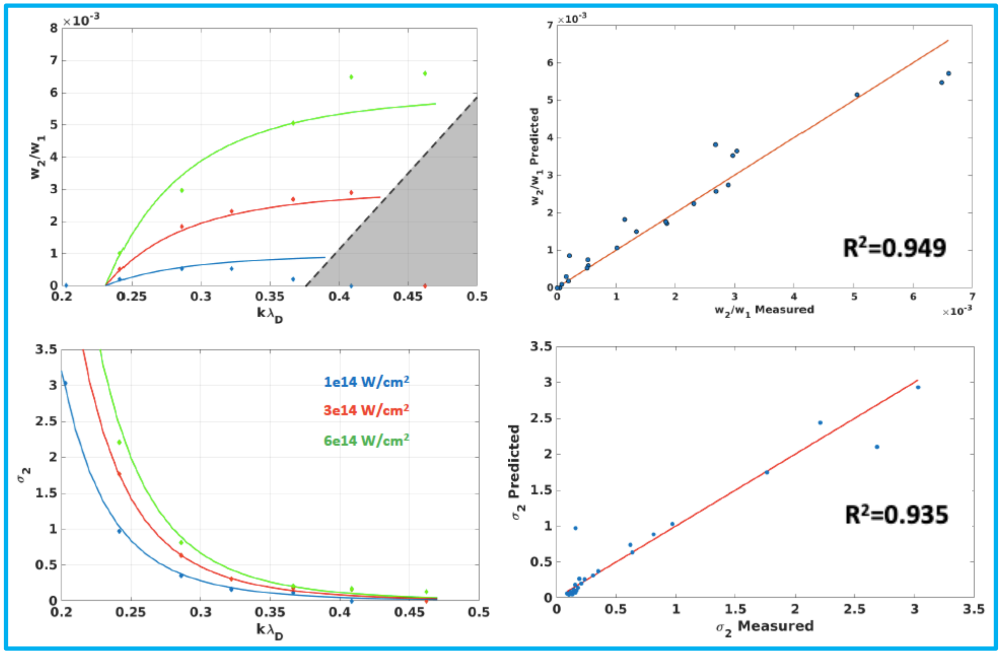
Base scaling — Correction factors

- **Power deposition model:** We observed approximate fulfillment of the Manley-Rowe relations, and we incorporated a small correction factor when secondary LPI throws off the energy balance.
- **Hot-electron model:** We developed Gaussian fits for the dominant trapped electron population using the δf-Gaussian-mixture algorithm.

Stark et al., "Nonlinear Models for Coupling the Effects of Stimulated Raman Scattering to Inertial Confinement Fusion Codes" Phys. Plasmas, in press (2023)

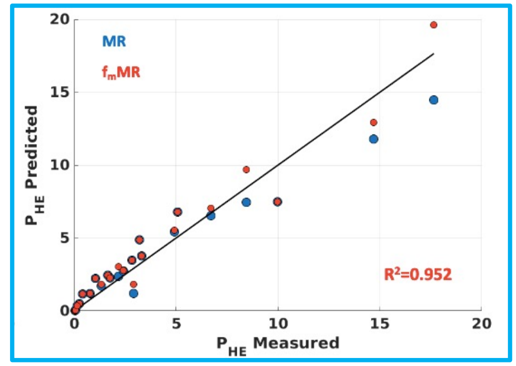
Nonlinear hot electron model is being implemented in Hyperion

Hot Electron Gaussian (for particle sourcing)



Hot electron weight $w_2 = aI_0(k\lambda_D)^{-4} + bI_{ave}$

Hot electron variance $\sigma_2 = aI_{ave}^b(k\lambda_D)^{-6}$



Hot Electron Power Deposition

$$f_m = 1 + e^{-a(k\lambda_D)^4 + bI_{ave}}$$ **M-R correction factor**

$$P_{HE} = f_m R P_0 \frac{\omega_{EPW}}{\omega_s}$$ **Power deposition into hot electrons**

Hot electron source is constructed by δf-Gaussian-mixture algorithm for particle sourcing (left) and Manley-Rowe for power deposition (right).

Summary

- We've achieved our year 1-2 technical goals:
  - ✓ Perform large-scale kinetic simulations of SRS and CBET a range of plasma and laser conditions
  - ✓ Develop a new δf-Gaussian-mixture algorithm to represent non-Maxwellian distribution functions from particle trapping and time-dependent plasma response
  - ✓ Develop physics-based nonlinear LPI models for coupling to LRT/ Mazinisin and AMP
  - ✓ Updated Mazinisin to include nonlinear CBET models
  - ✓ Begin refinement of nonlinear LPI models & CBET model implementation in Mazinisin
- Research plan to the 3rd year:
  - Begin SRS model implementation in Mazinisin
  - Perform additional simulations to improve confidence in model scaling laws
  - Refine nonlinear models
  - Complete the integration of LPI models into multi-physics codes

New GM-δf

$$f(v) = \sum_{k=1}^{K} w_k G_k(v; \mu_k, \Sigma_k)$$

weight: w_k; Gaussian: G_k; mean: μ_k; variance: Σ_k

Nonlinear SRS reflectivity model

SRS energy deposition model

SRS hot electron model

Nonlinear CBET model

CBET energy deposition model