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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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w22_lpi_models

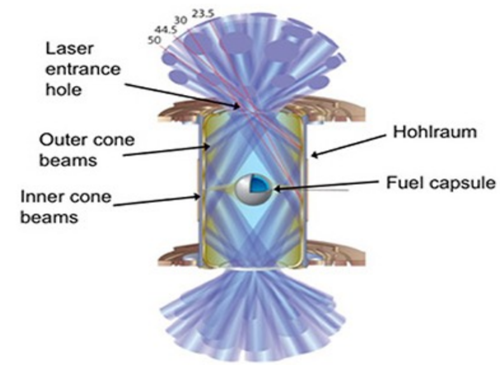
IC Report for project “Developing nonlinear laser-plasma instability models for high-fidelity, multi-physics simulation capability for ICF/HED”

LA-UR-24-xxxxx

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

- Our project has the following goals:
  - Develop physics-based nonlinear LPI models using PIC simulations
  - Couple the nonlinear LPI effects to macroscopic modeling of ICF/HED exp. through laser ray-tracing (LRT)
- We performed VPIC simulations for CBET[1] and SRS[2] for a range of plasma and laser conditions
- We developed a new automated δf-Gaussian-mixture algorithm to represent non-Maxwellian distribution functions from particle trapping and time-dependent plasma response
- We constructed nonlinear CBET and SRS models to couple to design codes
  - **CBET model**
    - **Gain**
    - **Energy deposition**
  - **SRS models**
    - **Reflectivity**
    - **Energy deposition**
    - **Hot electrons**

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

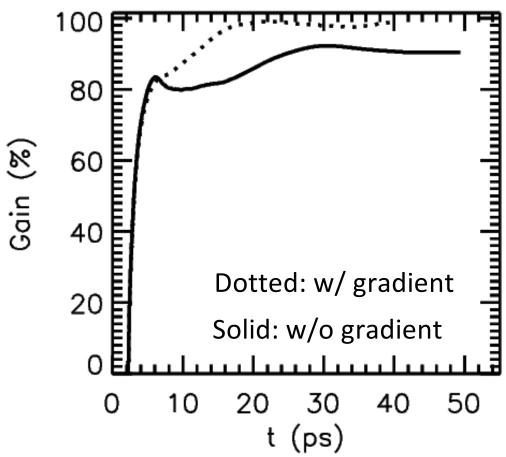
[1] Cross-beam energy transfer (CBET) is a process by which energy from overlapping laser beams is transferred between beams through the excitation of ion waves (IAW).

[2] In stimulated Raman scattering (SRS), incident laser light scatters resonantly from electron plasma waves (EPW) in the plasma.

Additional simulations have been performed with density gradient to suppress FSRS

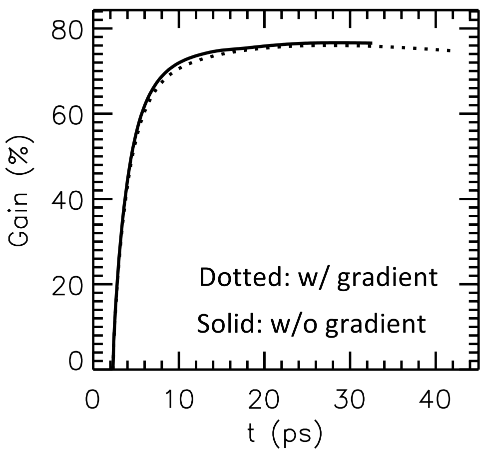
- The use of a density gradient to suppress FSRS in general leads to an increase of the CBET gain
- Two examples (2/27) are shown here

- Suppressing FSRS can lead to the seed beam gaining nearly all of the available energy in the pump beam



n_e/n_{cr}=0.04, θ=47°, $k\lambda_D$ = 0.3, T_e/T_i=4, I_{ave}=6.0x10^{14} W/cm^2

- CBET gain is not sensitive to density gradient if FSRS is not strong

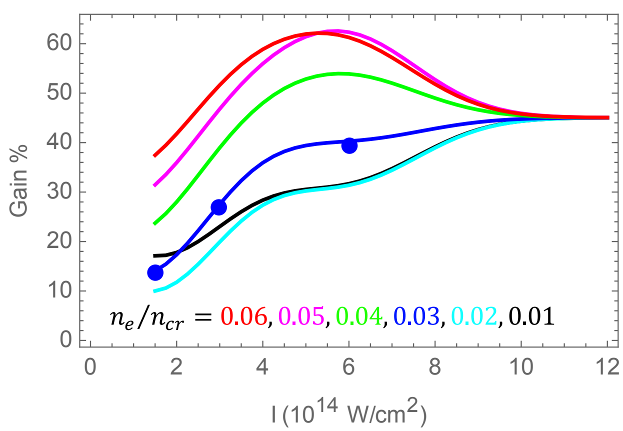


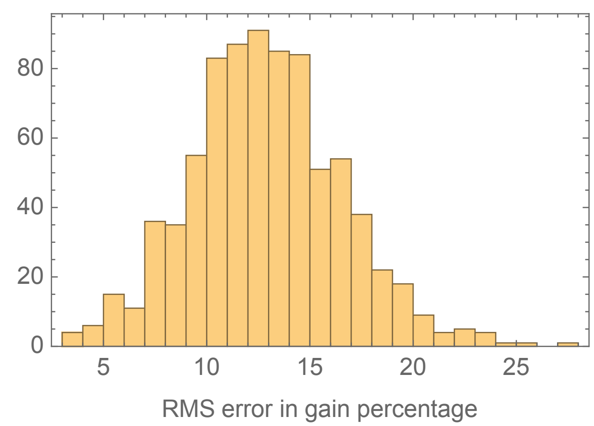
n_e/n_{cr}=0.04, θ=47°, $k\lambda_D$ = 0.3, T_e/T_i=4, I_{ave}=3.0x10^{14} W/cm^2

Construct CBET nonlinear model using Gaussian process emulator

- Another approach is to use the VPIC results to train a Gaussian process emulator
  - Economical to update – good for inline LPI models in design codes. Also, allows rapid exploration of parameter space for design studies
  - Straightforward to add to as more simulation data become available
  - Methodology allows error estimation and provides guidance of which additional simulations to perform to reduce error
  - Rule of thumb: typically, ~10 data points needed per degree of freedom (we have 5 deg. freedom – so we have a sufficient # of simulations)

- GP emulator of CBET gain % for indirect drive conditions
- We have validated the accuracy of the emulator using hold-out data (see the solid points)

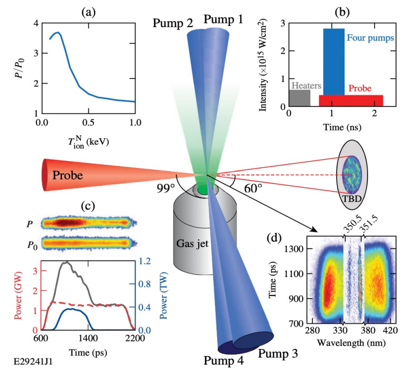


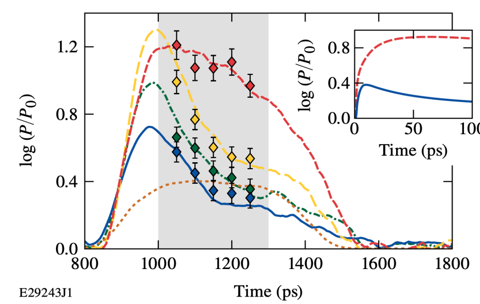


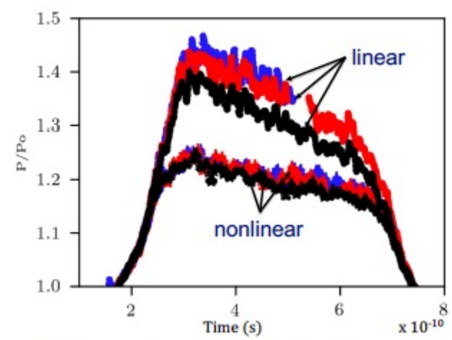
GP model error estimate using different choices of holdout data

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

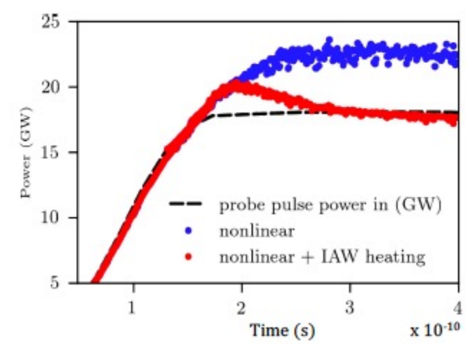
- Integrate LRT into ICF design codes
  - Use LLE's state-of-the-art Mazinisin LRT code [Marozas et al., Phys. Plasmas 25:056314 (2018)]
  - Use LANL-developed methodology for coupling Mazinisin to design codes via separate laser mesh [Haines et al., Comput. Fluids 201:104478 (2020)]
- Update Mazinisin to include new LPI models
  - Nonlinear CBET saturation model implemented
  - Tested using Top9 experimental data
  - Begin implementing the nonlinear SRS model
- Validate LPI coupling through modeling of ICF experiments







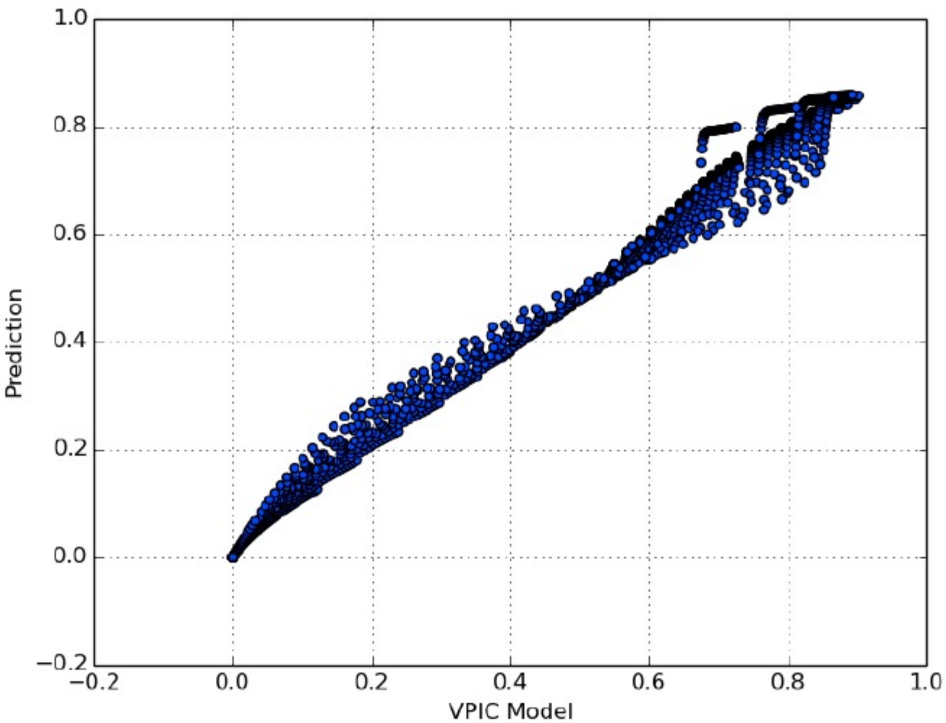
The power transferred into to the probe beam for three different initial intensities



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).

Knowing energy lost to the plasma and to scattered light, we seek to construct a sub-grid SRS module for ICF codes



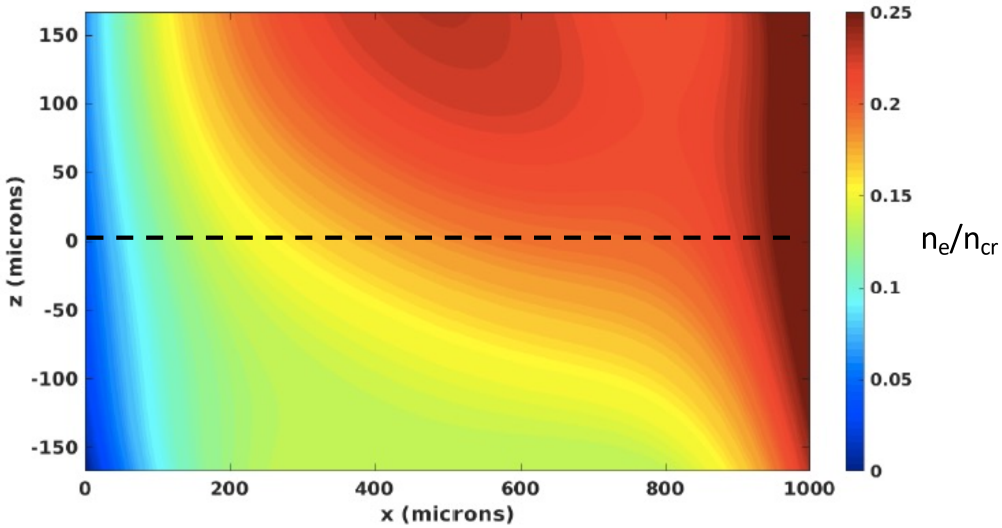
$$\frac{dI_{14}}{I_{14}} = fa_1(k_{epw}\lambda_D)^{-4} f_s f_L f_H (1 + f_m \frac{\omega_{epw}}{\omega_s}) e^{\lambda/L_g(s)} \frac{(I_{14}/I_{ref})^{\alpha}}{1 + (I_{14}/I_{ref})^{\alpha}} ds$$

$$\gamma = \frac{k_{eps} v_{osc}}{4} \frac{\omega_{pe}}{\sqrt{\omega_s \omega_{epw}}}$$

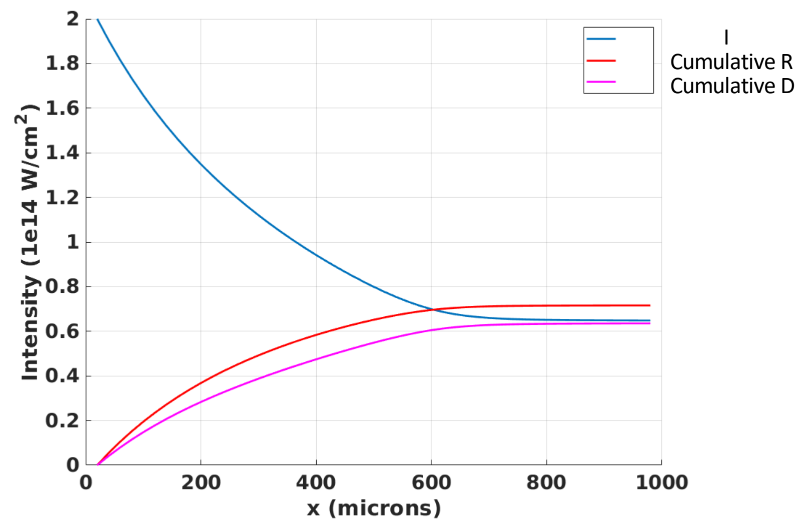
$$L_g = \frac{\omega_s / k_s}{\gamma}$$

- We fit the free parameters to a large sample of points from the VPIC model.
- Points in the intensity range (0.1-7)x10^{14} W/cm^2 and densities of 0.06n_{cr}-0.20n_{cr} are used, spanning the parameter space used for the study.
- We integrate the rays for 500 micron path length to match the settings of the VPIC simulations.

We can test the SRS model by looking at a realistic density profile from a rad-hydro simulation of a hohlraum



Yin et al. Phys. Plasmas 21, 092707 (2014)



- We integrate the ansatz along lineouts (z=0 example shown) to test the reflectivity over longer path lengths.

Breakdown of Energy Between Reflected and Deposited

$$dR = dI_{14}\frac{1}{1+f_m(\omega_{epw}/\omega_s)}$$

$$dD = dI_{14}\frac{f_m(\omega_{epw}/\omega_s)}{1+f_m(\omega_{epw}/\omega_s)}$$

Summary

- Using suites of 2D large-scale multi-speckled kinetic simulations of LPI employing the LANL VPIC code, we have developed nonlinear models of both CBET[1] and SRS[2] that span a 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 the LANL xRAGE and Hyperion codes
  - allows for nonlinear feedback of effects of LPI to the hydrodynamics
- This first-of-a-kind capability eliminates the use of *ad hoc* saturation clamps on wave amplitudes to reduce LPI in linear models in rad-hydro codes

[1] L. Yin et al., Phys. Plasmas **30**, 042706 (2023)
[2] D. J. Stark et al., Phys. Plasmas **30**, 042714 (2023)
[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).