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Title: Mitigation of cross-beam energy transfer with laser bandwidth

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Mitigation of cross-beam energy transfer with laser bandwidth

NNSA V&V/LSCI Site Visit

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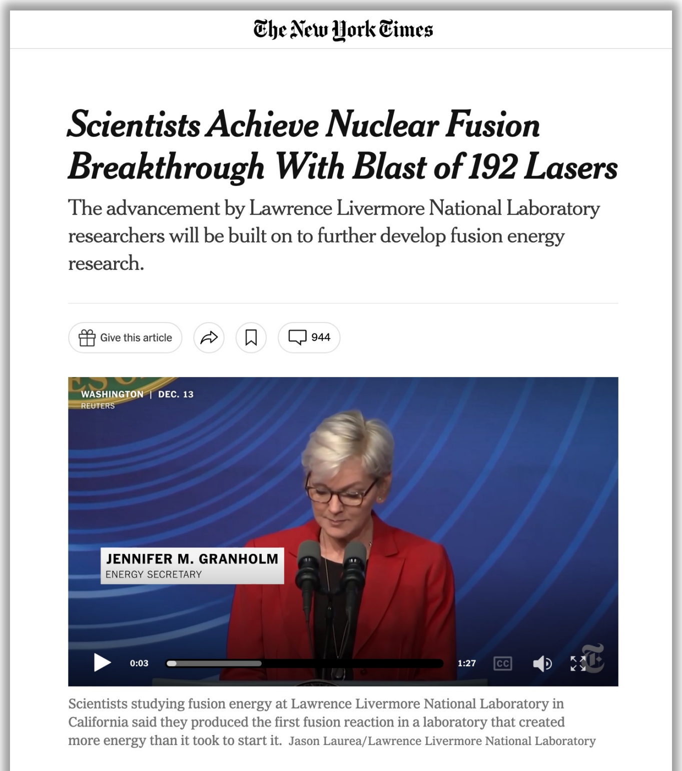
Control of laser-plasma instabilities (LPI) is critical for inertial fusion


The New York Times

Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers

The advancement by Lawrence Livermore National Laboratory researchers will be built on to further develop fusion energy research.

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WASHINGTON | DEC. 13
REUTERS

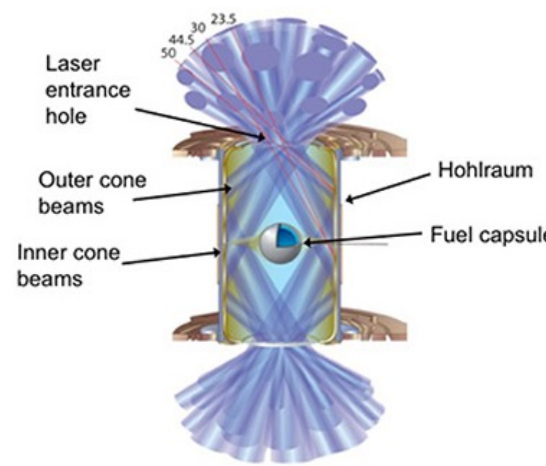
JENNIFER M. GRANHOLM
ENERGY SECRETARY

0:03 1:27

Scientists studying fusion energy at Lawrence Livermore National Laboratory in California said they produced the first fusion reaction in a laboratory that created more energy than it took to start it. Jason Laurea/Lawrence Livermore National Laboratory

- **Recent experiments on the NIF achieved ignition!**
- Future stockpile stewardship experiments on the NIF will require **increased fusion yield (up to 10 MJ)**, which will require **higher laser energy and intensity** and will have a **higher LPI risk**

Laser-driven hohlraum on the NIF



- To be successful, we need to **understand** the nonlinear behavior of LPI and **develop an improved capability** for modeling and mitigating LPI in ICF experiments

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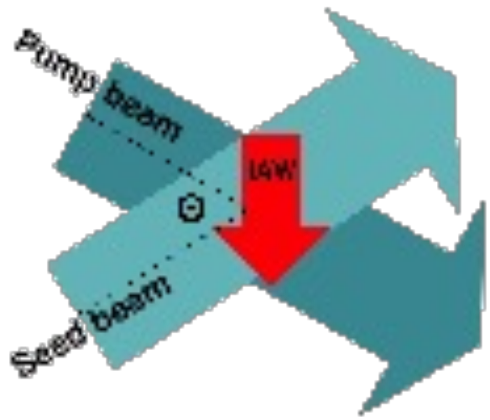
One of the most important LPI for inertial fusion experiments is cross-beam energy transfer (CBET)

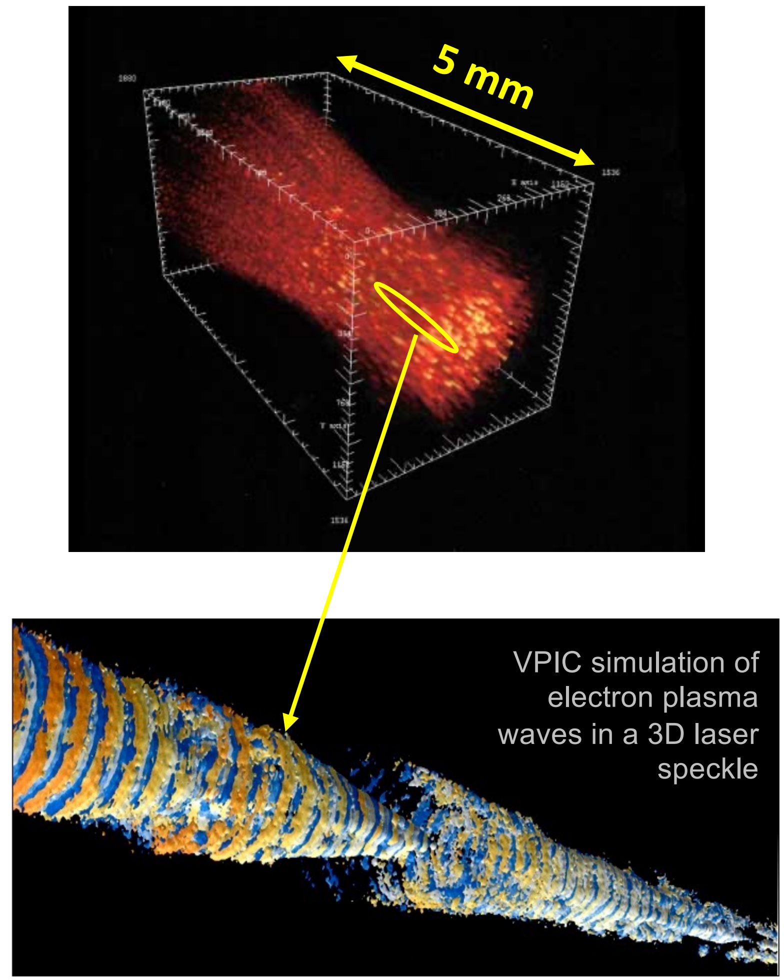
- CBET is a process by which energy from overlapping laser beams is exchanged between beams through the excitation of ion acoustic waves (IAW)
- Control of CBET is vital for maintaining implosion symmetry in ICF
- Our LSCI project used high performance computing & the **VPIC** kinetic plasma code to explore how to control CBET through the use of **laser bandwidth** (~1% of laser frequency)



https://github.com/losalamos/vpic

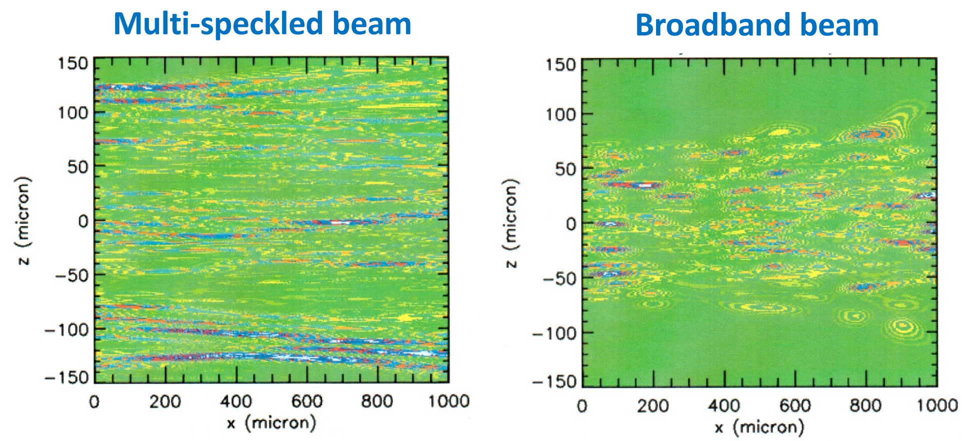
One of the challenges of modeling LPI is the inherently multiscale nature of the problem

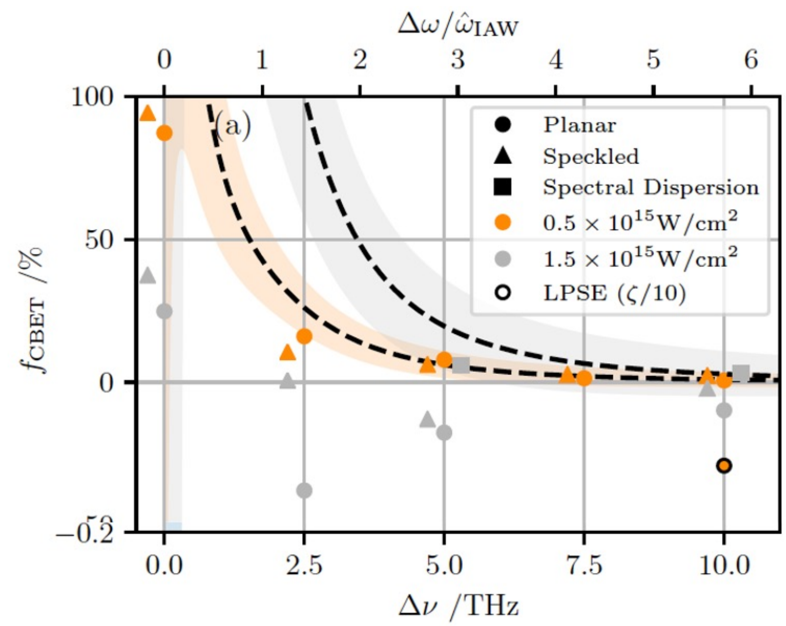
- NIF laser beams comprise thousands of individual laser speckles, or bright spots
  - Speckle width ~ 3 microns
  - Speckle length ~ 140 microns
- Capturing the behavior of LPI in speckled laser beams in hohlraums requires modeling plasmas at **extreme scales**
  - *ideal for LSCI*



Our LSCI simulations help us understand CBET and assess laser bandwidth requirements for mitigation

- Earlier (small-scale) VPIC simulations showed that 1% laser bandwidth could mitigate CBET for small laser beam diameters at 20 microns
- However it was not known whether this would hold for **more realistic, larger beam diameters** (a few 100s of microns)
- Testing this was a computationally demanding problem, requiring **at-scale simulations** with large laser beam diameters – hence the need for LSCI





Postdoc project: A. G. Seaton et al., Phys. Plasmas **29**, 042707 (2022)

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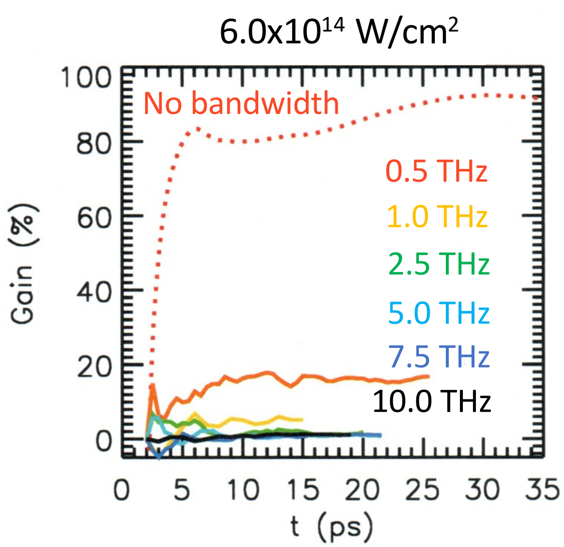
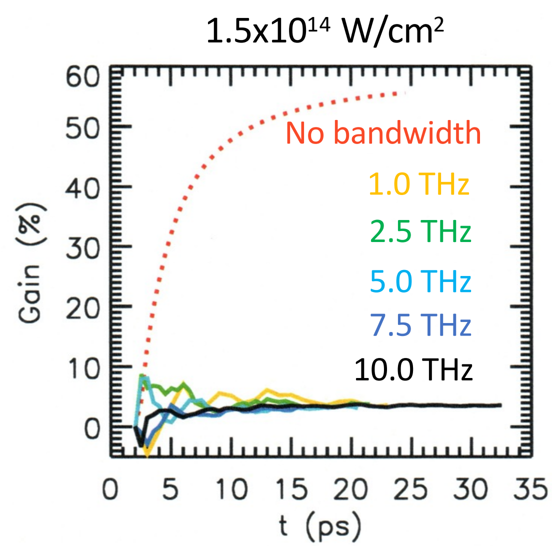
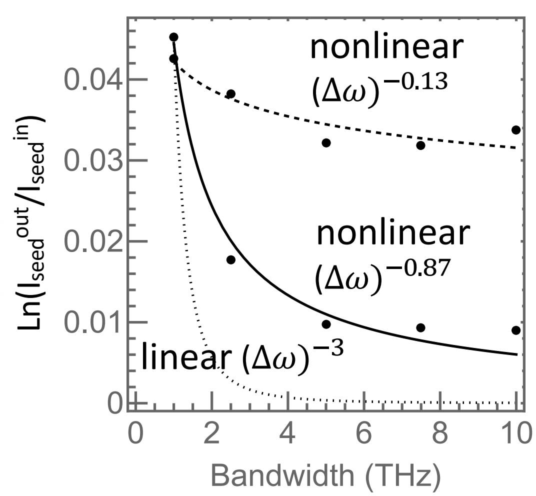
Accomplishments

Our LSCI study concluded that 1% laser bandwidth is sufficient to mitigate CBET under realistic ICF conditions

- Our LSCI simulation results showed that 10 THz bandwidth (~1% of the laser bandwidth) is able to reduce CBET gain from **~80% to 1%** (!) for larger diameter laser beams for several of the highest risk plasma conditions for ICF
- However, the nonlinear gain reduces with increasing bandwidth more slowly than linear theory prediction
- **This result has important implications for possible future facility upgrades for the NIF**







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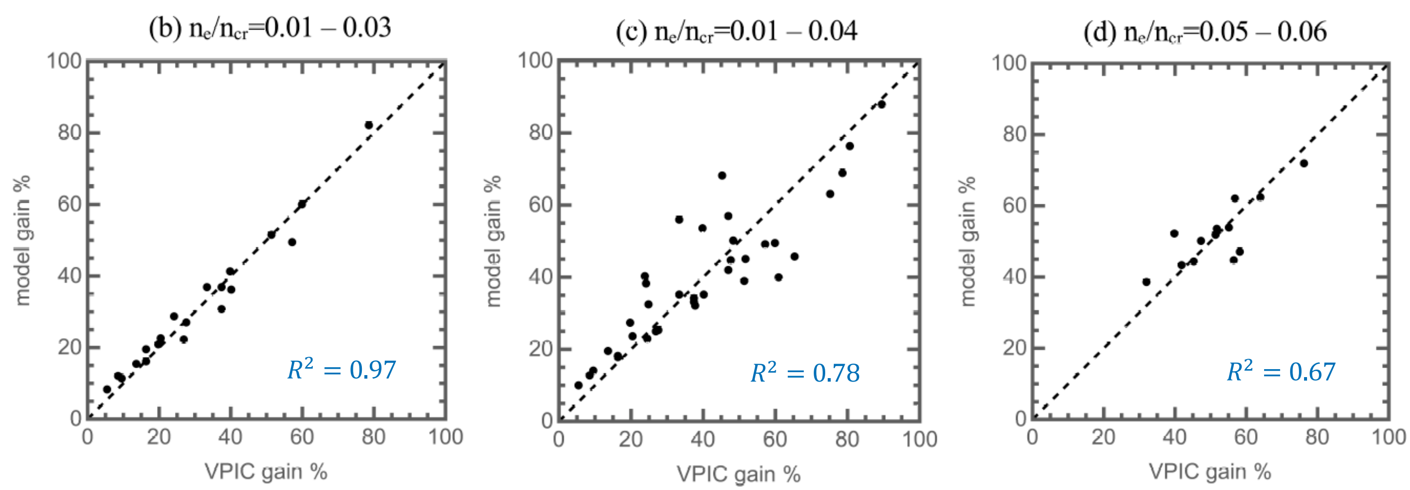
Our VPIC LSCI simulations are having wider impact

- We are applying the VPIC modeling capability used for our LSCI project to improve the modeling of LPI in our ASC ICF design code
- We have run an ensemble of VPIC simulations of CBET over a wide range of laser and plasma conditions relevant to ICF experiments on the NIF and used the results to develop an **inline nonlinear CBET model** that is **being implemented in the LANL xRAGE ASC code**



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

Nonlinear CBET model

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

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

Summary

- What was accomplished and delivered in this effort? What specific capabilities were exercised or developed? Mitigation of cross-beam energy transfer (CBET) is a critical requirement for laser-driven inertial confinement fusion (ICF) ignition. In this LSCI study, the nonlinear behavior of CBET was explored using large-scale 2D VPIC kinetic plasma simulations for a range of plasma densities and temperatures, as well as laser crossing angles, beam diameters, and intensities.
- What have we learned about the physics of the problem or the computational challenges in exercising the platform? Was that the intended outcome or were the results learned as an outcome? These results are encouraging, providing evidence in support of the use of laser bandwidth to mitigate the deleterious effects of CBET. As this is a possible upgrade option for HED facilities such as the NIF, the results obtained from this LSCI study could be of very high impact for the NNSA Complex.
- Describe the level of maturity of the capabilities at completion: The simulation/modeling capability as well as diagnostic and analysis techniques were mature at completion of this project. A large, though not comprehensive portion of relevant parameter space was explored. These results informed the development of an inline reduced LPI model being implemented in the LANL xRAGE ASC code.
- What future work should be considered and be sure to identify whether or not it in the next FY IP: Further evaluation of design space and refined options for mitigation of LPI through laser conditioning would be valuable. These studies should be included in the FY23 OES ICF Implementation Plan.
- Lessons learned, i.e., describe how the results specifically reinforce or redirect your platform and code strategies: No major “lessons learned” to report, aside from refinement and optimization of our workflow for the Trinity KNL platform for production problems of this type.