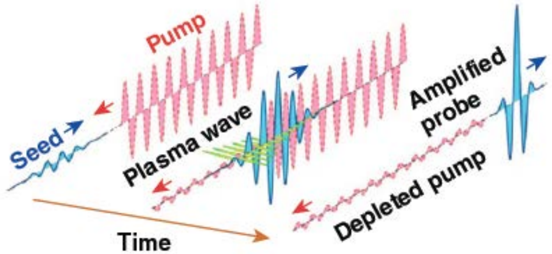
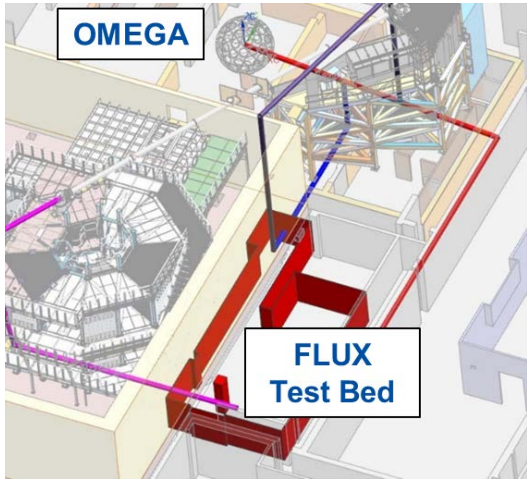
Taming Plasmas and Controlling Laser Beams for Grand Challenge Applications

Laser-Plasma Amplifiers
Raman Amplification



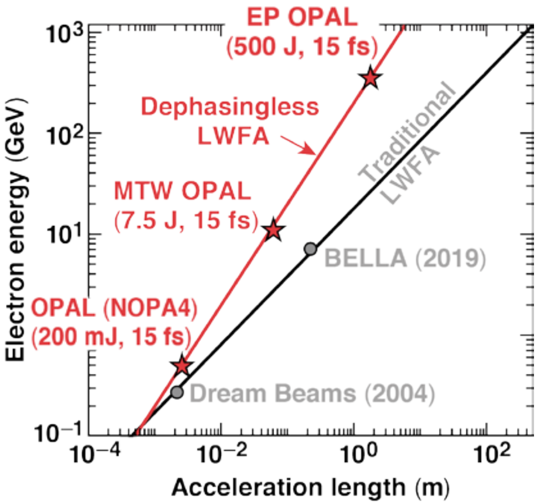
Can plasmas be used to achieve intensities above 10^{24} W/cm^2?

Laser Fusion
4th Generation ICF Lasers



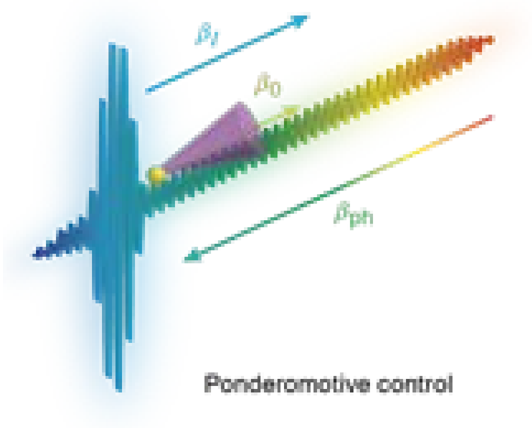
Can laser-plasma instabilities be mitigated to enable high-yield inertial confinement fusion?

Laser-Plasma Accelerators
Dephasingless Laser Wakefield Acceleration



Can manipulating light in a plasma be used to achieve the dream of a TeV electron collider?

Advanced Light Sources for HED Facilities
Nonlinear Thomson scattering with ponderomotive control



Can short-pulse lasers be used to meet the future High-Energy Density physics mission needs?

Dustin Froula
Professor of Physics
Division Director, Plasma & Ultrafast Laser Science & Engineering
Laboratory for Laser Energetics, University of Rochester

FESAC Meeting
Virtual
30 August 2021

Laser-plasma instabilities remains one of the greatest challenges to using high-power lasers for grand challenge applications

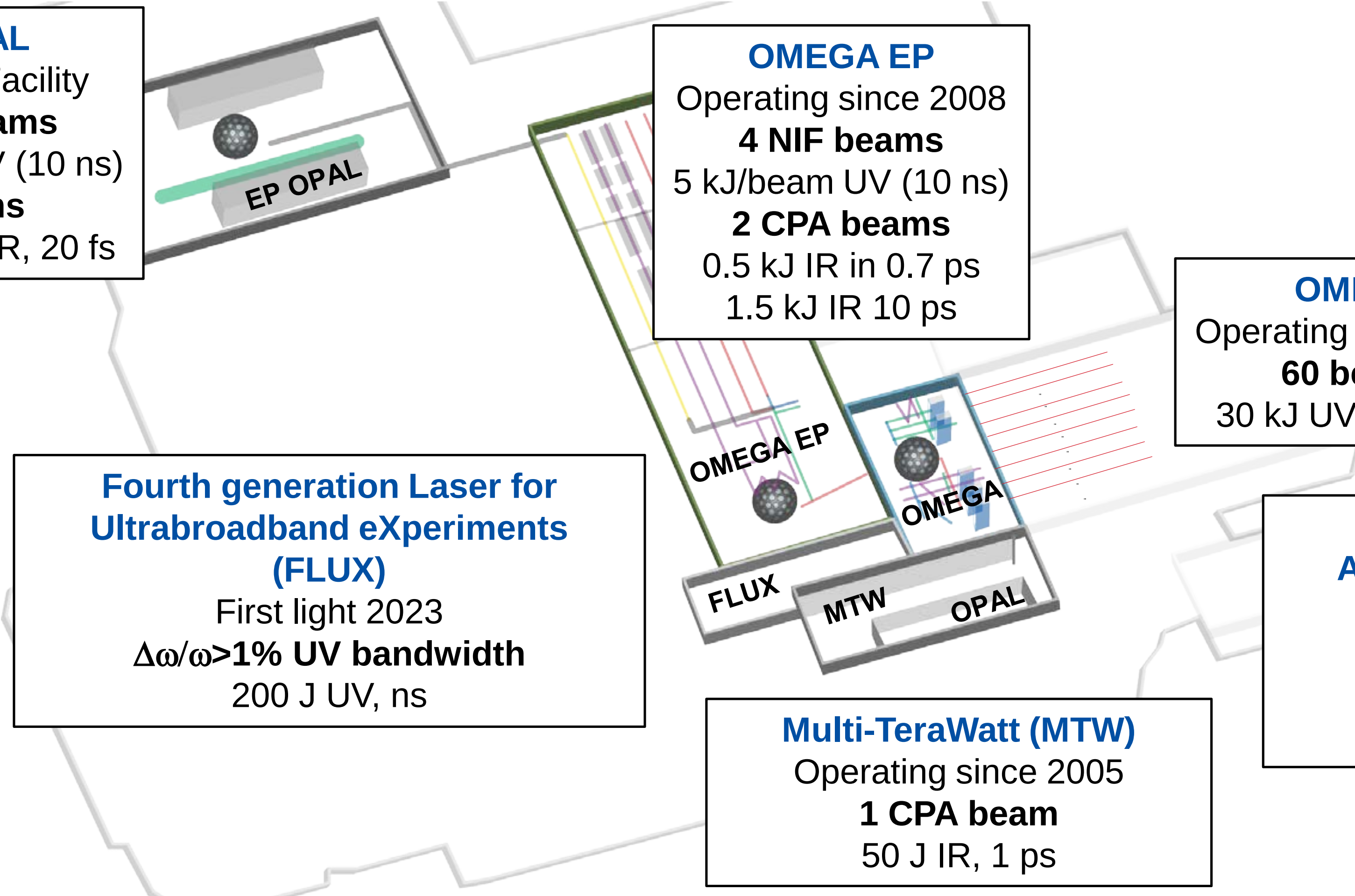
- Laser-plasma instability physics is inherently coupled to the plasma conditions and the plasma conditions are often dictated by the laser-plasma instabilities
- Thomson scattering provides a window into the electron motion with in a plasma, which has allowed the laser-plasma instability physics to be decoupled from the uncertainties in plasma conditions
  - A better understanding of the plasma physics has led to an expanded design space for applications
- Manipulating laser-light provides opportunities to mitigate laser-plasma instabilities and overcome fundamental limitations of conventional systems
  - Broadband ultraviolet glass-lasers provide a path to LPI-free 4th generation ICF drivers
  - Spatiotemporal pulse shaping has opened avenues to in laser-plasma applications

Solutions to using high-power lasers in grand challenge applications exists through understanding plasma conditions and manipulating laser light

The University of Rochester's Laboratory for Laser Energetics operates the world's largest lasers in an academic setting

UR LLE

EP OPAL
Proposed Facility
2 NIF beams
5 kJ/beam UV (10 ns)
2 beams
500 J/beam IR, 20 fs



OMEGA EP
Operating since 2008
4 NIF beams
5 kJ/beam UV (10 ns)
2 CPA beams
0.5 kJ IR in 0.7 ps
1.5 kJ IR 10 ps

OMEGA
Operating since 1995
60 beams
30 kJ UV on target

Fourth generation Laser for Ultrabroadband eXperiments (FLUX)
First light 2023
$\Delta\omega/\omega$>1% UV bandwidth
200 J UV, ns

Optical Parametric Amplifier Line (OPAL)
First light 2021
1 CPA beam
7.5 J IR, <20 fs
Contrast $>10^{10}$

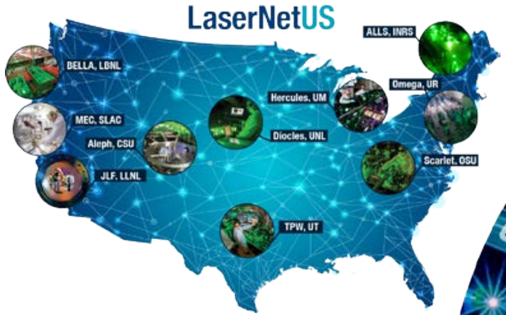
Multi-TeraWatt (MTW)
Operating since 2005
1 CPA beam
50 J IR, 1 ps

The University of Rochester lasers provide an outstanding environment of studying a wide range of plasma physics

UNIVERSITY of ROCHESTER

The community accesses the Omega Facilities through LaserNet, Laboratory Basic Sciences, National User Laser Facilities, and the NNSA laboratories

UR LLE



NNSA

LBS
LABORATORY
BASIC SCIENCE

NLUF

The Omega Lasers support a national user program where more than 60 institutions participate in 60% of the experiments

The PULSE Division is a center for innovative laser-plasma physics, impactful technology, world-class education, and engaged collaboration

PLASMA & ULTRAFAST LASER SCIENCE & ENGINEERING

UNIVERSITY OF ROCHESTER, LABORATORY FOR LASER ENERGETICS

R. Boni, S. Bucht, W. Donaldson, D. Edgell, R. Follett, D. Haberberger, J. Katz, A. Maximov, P. Nilson, J. Palastro, H. Rinderknecht, M. Romo, J. L. Shaw, D. Turnbull, K. Weichman, H. Wen

Laboratory for Laser Energetics

Current Plasma Physics Graduate Students

M. Ambat (ME, Shaw)
Z. Barfield (PAS, Froula)
P. Franke (PAS, Turnbull)
A. Hansen (PAS, Turnbull)
R. Henchen* (ME, Froula)
L. Leal (ME, Maximov)
K. McMillen (PAS, Shaw)
A. Milder (PAS, Froula)
L. Nguyen (PAS, Palastro/Yin)
S. Nwabunwanne (ECE, Donaldson)
D. Ramsey (PAS, Palastro)
T. Simson (PAS, Palastro)
M. VanDusen-Gross (PAS, Rinderknecht)
Y. Zhao (ECE, Donaldson)

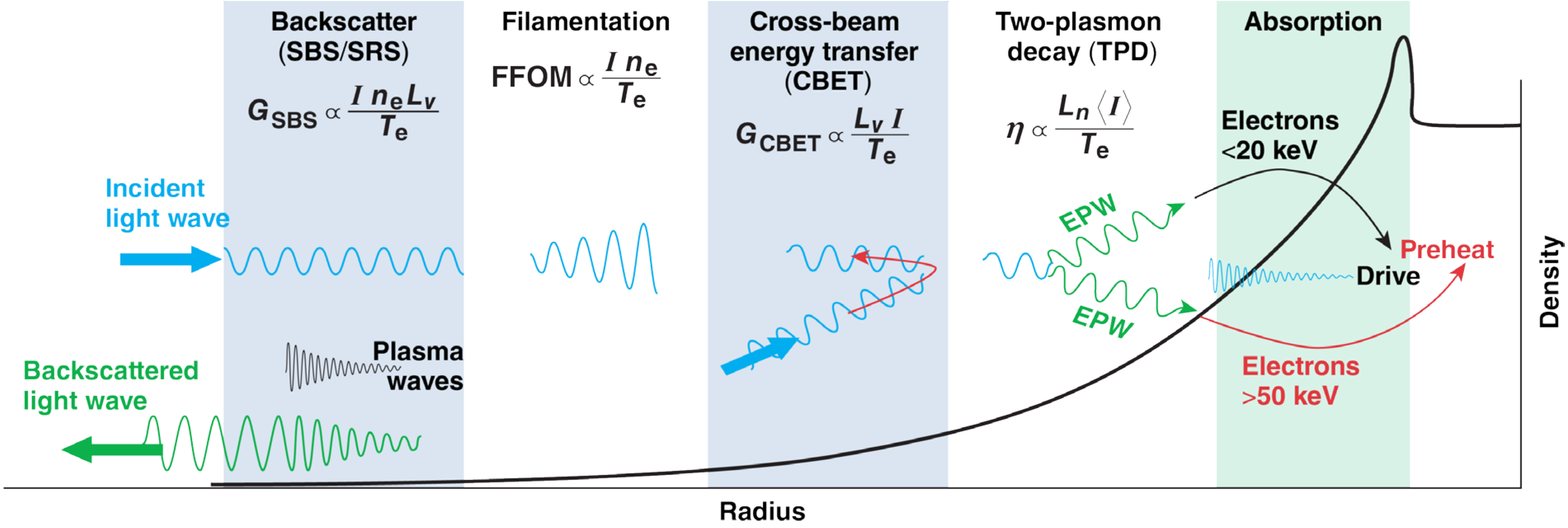
Current Undergraduate Students

K. Daub (Boni)
R. Ejaz (Boni)
T. Ha (Shaw)
J. Maltzahn (Boni)
H. Markland (Katz)

Community Collaborators

cea	S. Jolly, F. Quéré	Princeton University	N. Fisch
University Boudreaux	A. Colaitis	Berkeley Lab	C. Benedetti, E. Esarey, C. Geddes, C. Schroeder
Técnico Lisboa	B. Malaca, A. Helm, J. Vieira	University of Maryland	T.M. Antonsen Jr.
UCSD	A. Arefiev	Institute of Laser Engineering, Osaka University	Z. Li
UCLA Physics & Astronomy	F. Tsung, W. Mori	Max-Planck-Institut für Kernphysik Heidelberg	A. Di Piazza
Stony Brook University	S. Stoller, N. Vafaei-Najafabadi	Lawrence Livermore National Laboratory	M. Sherlock, L. Divol, P. Michel
University of Oxford	C. Arrowsmith, G. Gregori	Los Alamos National Laboratory	B. Albright, L. Yin
UKRI	R. Bingham	University of Alberta	W. Rozmos, J. Myatt

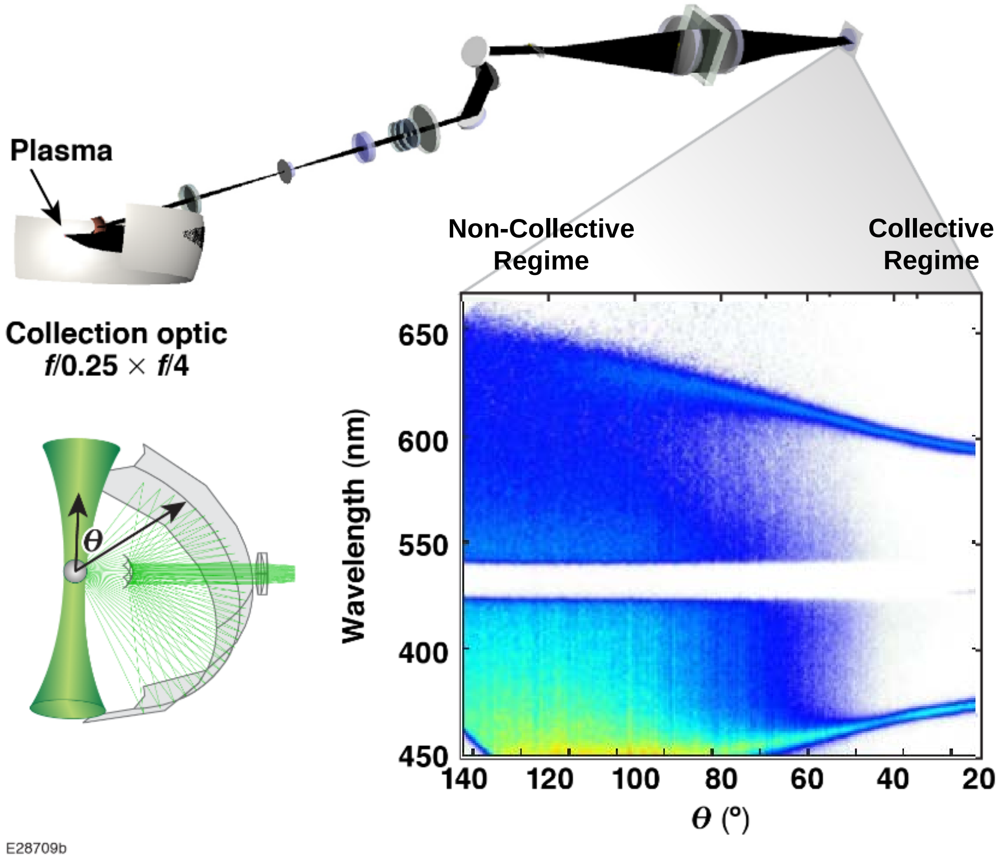
Laser-plasma instabilities remain one of the greatest challenges to using high-power lasers in grand challenge applications



E19964n

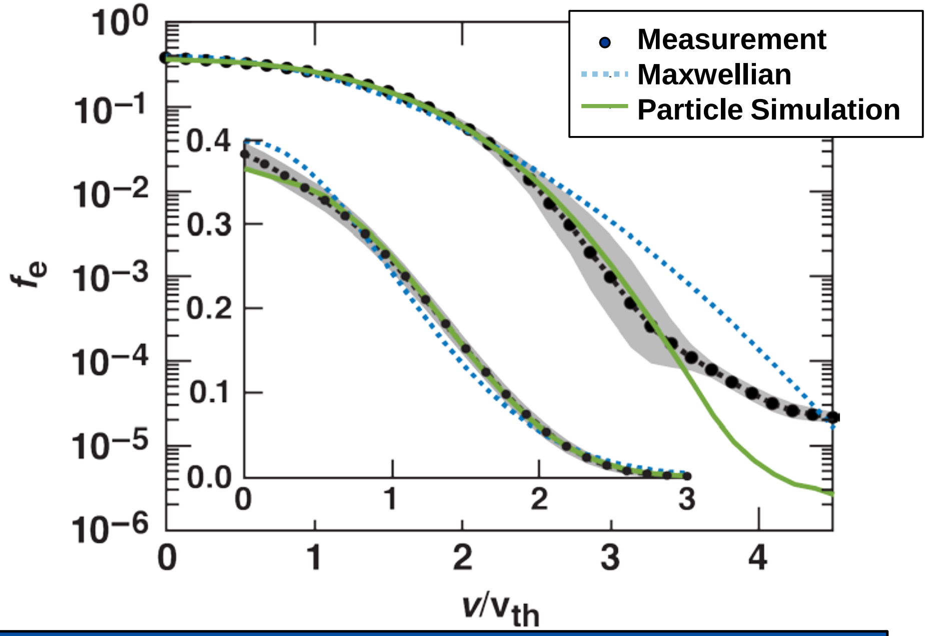
Understanding the material properties (i.e., the plasma conditions) at the macro- and microscopic levels is critical to using high-power laser beams

Thomson scattering has provided the window into the material properties of a plasma, which has enabled quantitative laser-plasma experiments



Measurements of non-Maxwellian electron distribution functions

Milder *et al.* PRL**127**, 015001 (2021)

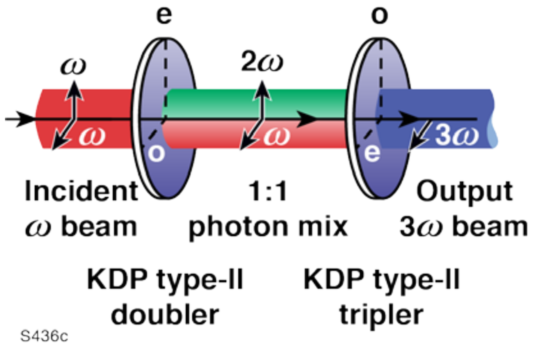


Measuring the plasma conditions is enabling the hydrodynamic uncertainties to be decoupled from the laser-plasma instability physics opening the design space for grand challenge applications

Innovative technologies that manipulate light have historically advanced laser-plasma applications

Efficient Third-Harmonic Frequency Generation

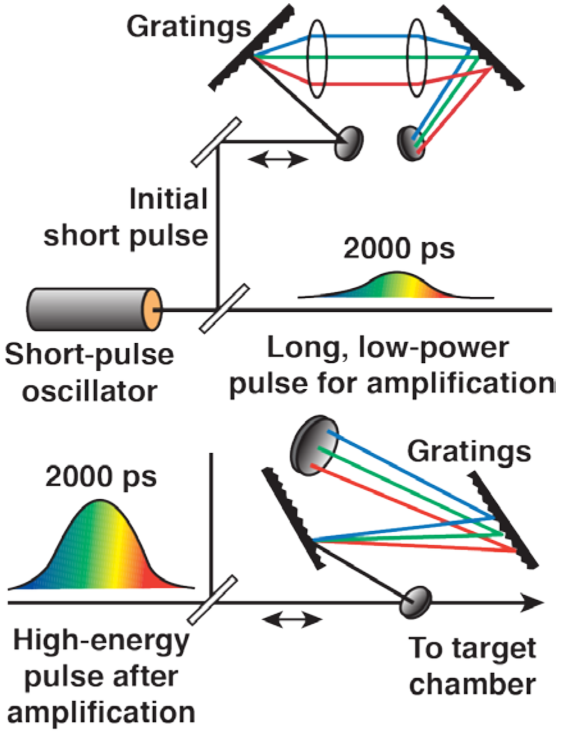
R.S. Craxton *et al.*,
Opt. Commun. **34**, 474 (1980)



Conversion efficiency of 80% enabled 2nd generation ICF drivers

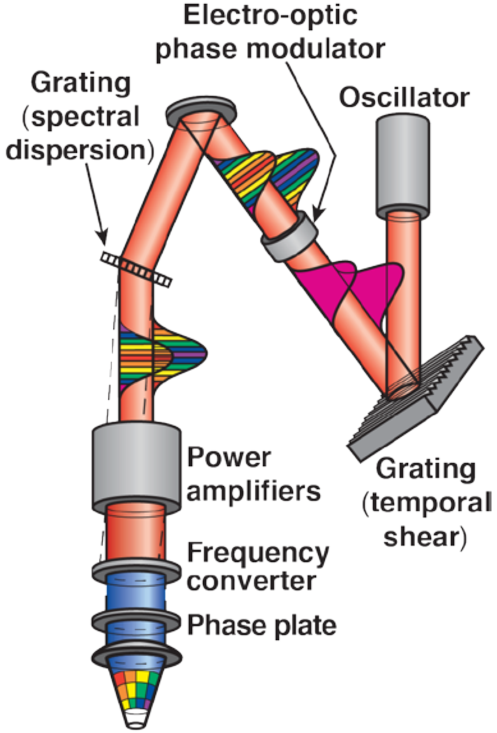
Chirped-Pulse Amplification

D. Strickland & G. Mourou
Opt. Commun. **56**, 210 (1985)



Smoothing by Spectral Dispersion

S. Skupsky *et al.*,
J. Appl. Phys. (1989)



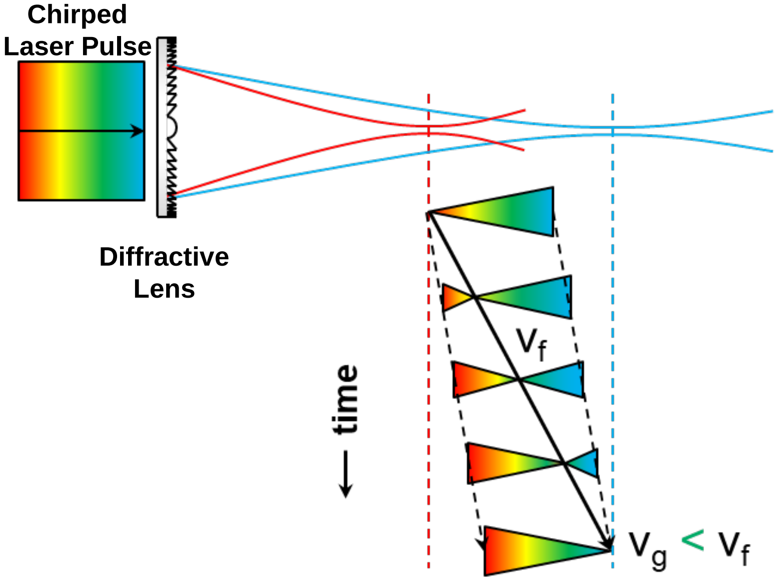
LETTERS

https://doi.org/10.1038/s41566-018-0121-8

nature photonics

Spatiotemporal control of laser intensity

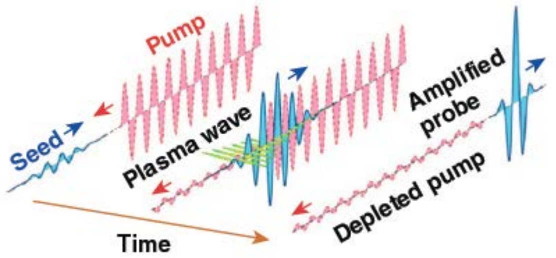
Dustin H. Froula[1,2*], David Turnbull[1], Andrew S. Davies[1,2], Terrance J. Kessler[1], Dan Haberberger[1], John P. Palastro[1], Seung-Whan Bahk[1], Ildar A. Begishev[1], Robert Boni[1], Sara Bucht[1,2], Joseph Katz[1] and Jessica L. Shaw[1]



Controlling laser beams in a plasma through innovative technologies has been at the root of laser-plasma applications from the beginning of the field

Laser-Plasma Amplifiers—a path to 100 PW lasers and >10^{24} W/cm^2

Laser-Plasma Amplifiers
Raman Amplification



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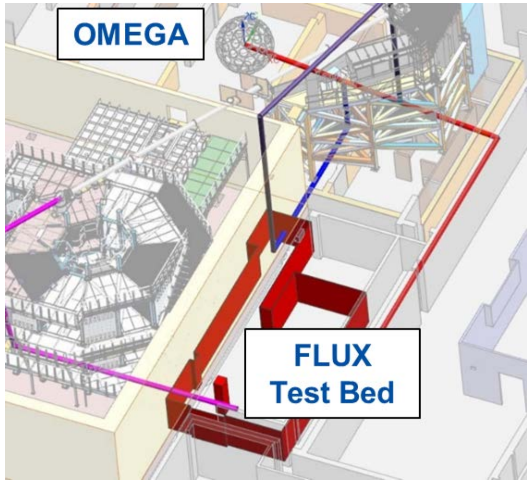
4^{th} Generation ICF Lasers



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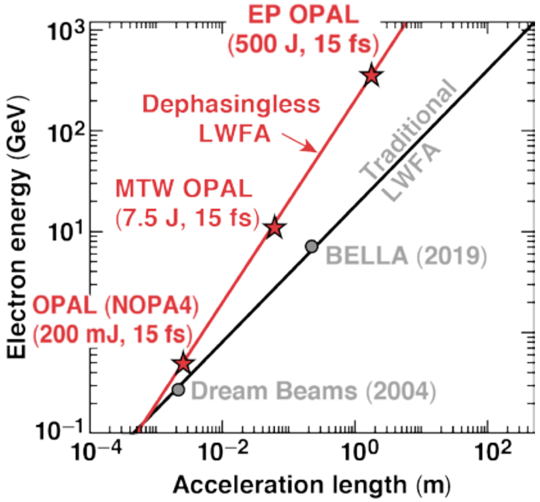
Dephasingless Laser Wakefield Acceleration



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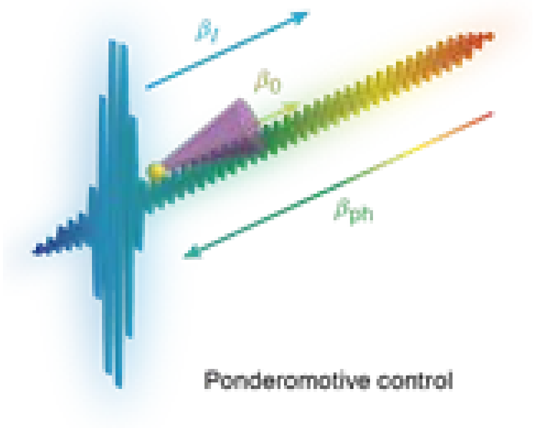
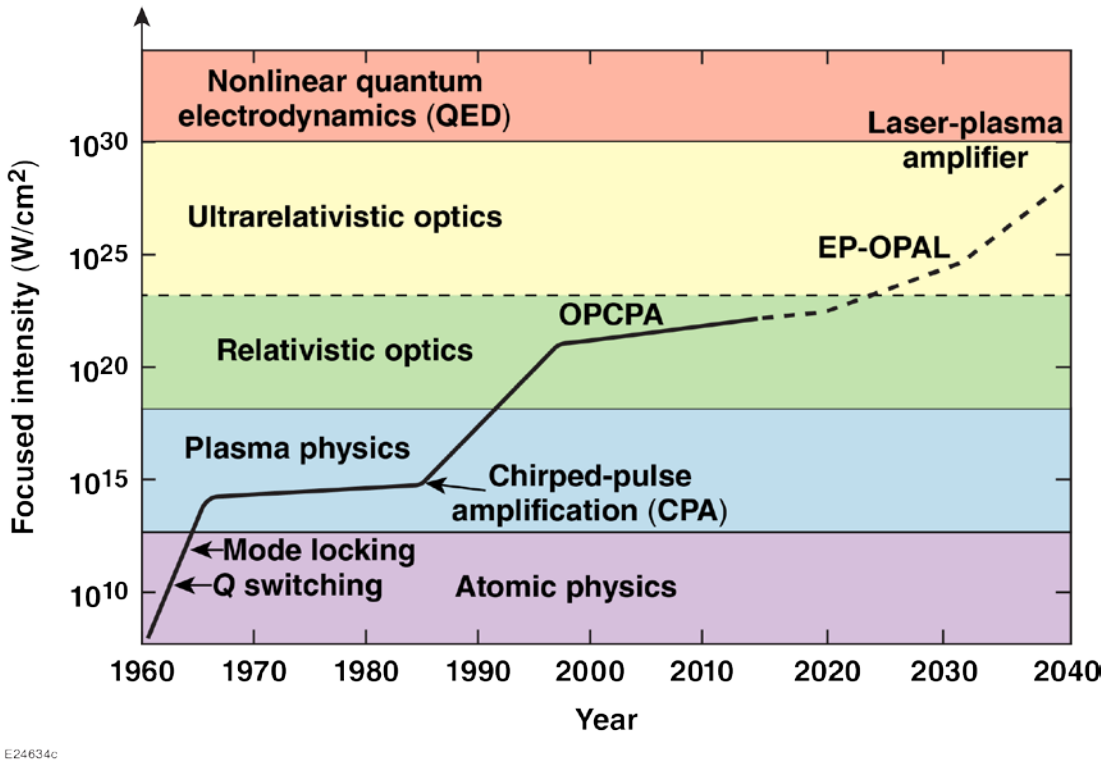
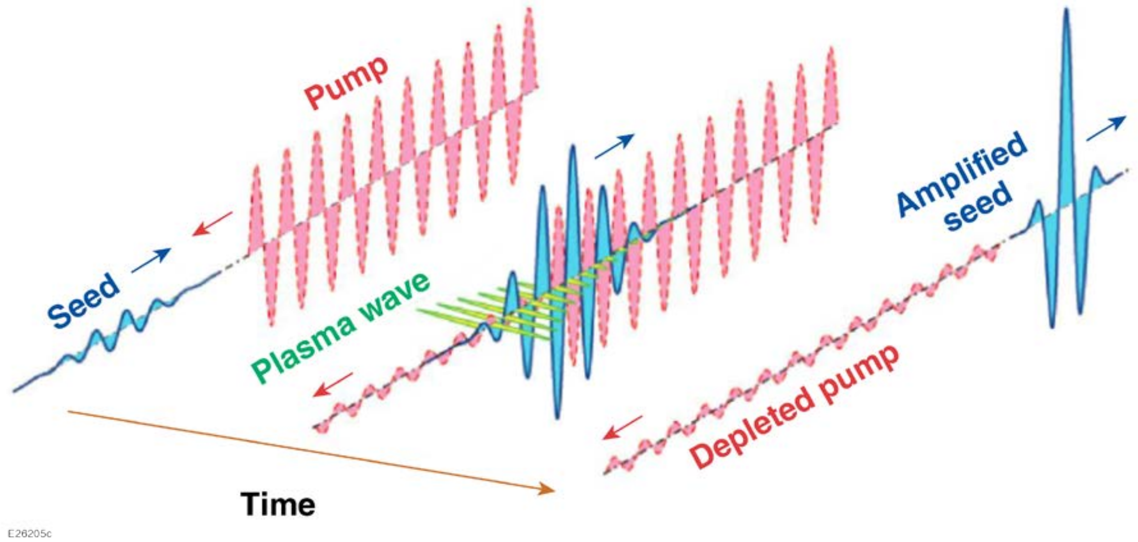
Nonlinear Thomson scattering with ponderomotive control



Can short-pulse lasers be used to meet the future High-Energy Density physics mission needs?

Laser-plasma amplification has the promise to overcome current limitations in high-power amplification

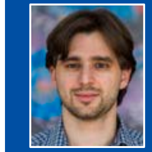




V. M. Malkin et al., Phys. Rev. Lett. **82**, 4448 (1999)

Laser-plasma amplifiers require:
(1) understanding the plasma conditions to control laser beam propagation,
(2) manipulating laser light to optimize the resonance—laser beams with the right wavelengths

Andy Davies



PHD Physics (2019)

Sara Bucht

MS Physics (2019)

UR LLE

A multi-disciplinary team has been assembled to address the plasma physics, laser science, and advanced diagnostics challenges

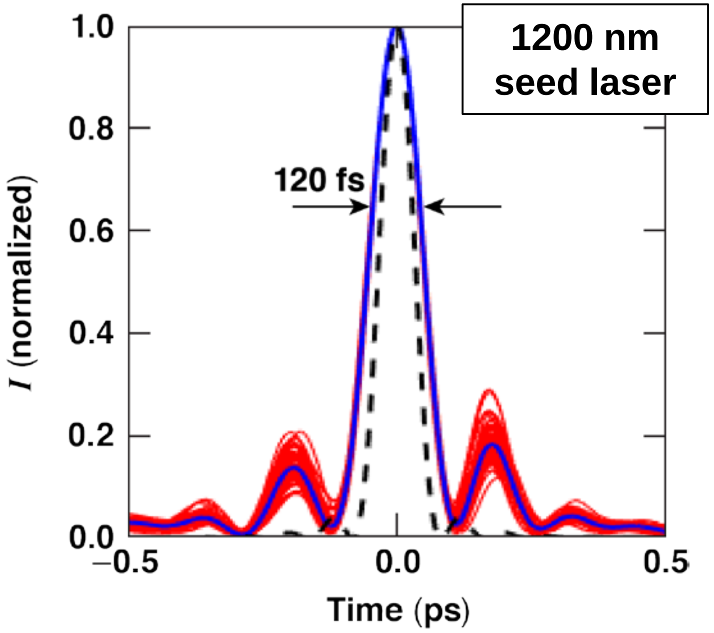
Raman Amplification Target Area

(completed January 2021)

Novel Laser Technologies

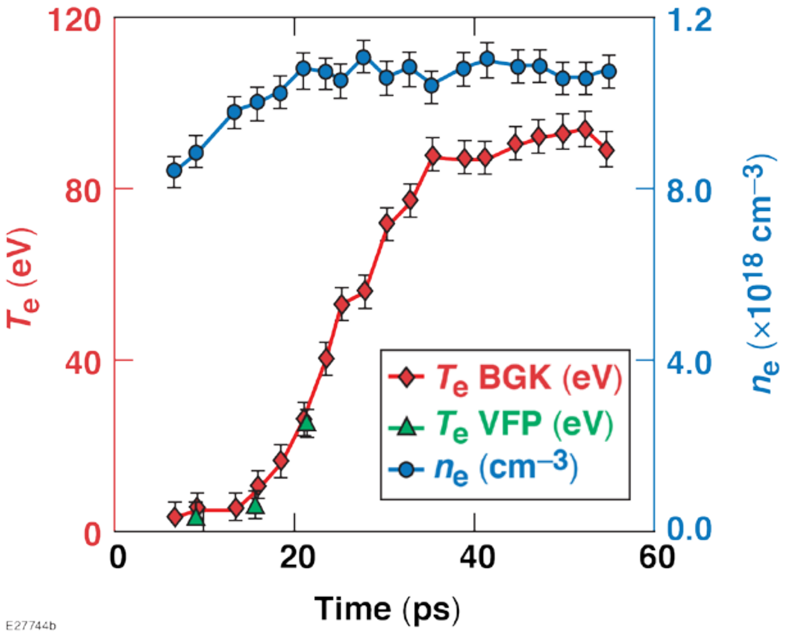
(completed April 2021)

Bucht *et al.* J.Opt.Soc.Am. B **36**, 2325 (2019)



Ultrafast Thomson scattering

Davies *et al.* PRL**122**, 155001 (2019)



Picosecond Thomson scattering measurements demonstrate the challenges in maintaining resonant plasma conditions*

DOE/FES DE-SC0016253

*A. S. Davies *et al.* PPCF **62** 015012 (2019)

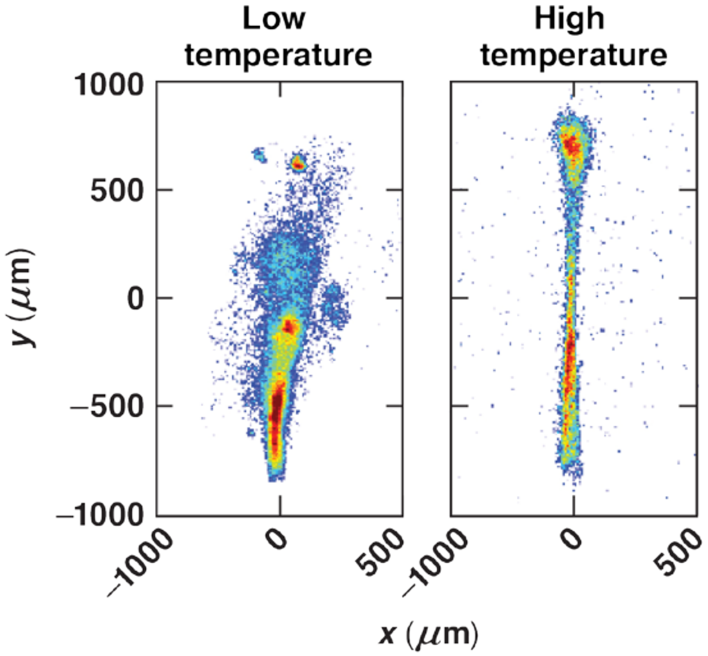
Manfred Ambat

Physics Grad. Student

Laser-Plasma Amplification—a path to 100 PW and >10^{24} W/cm^2

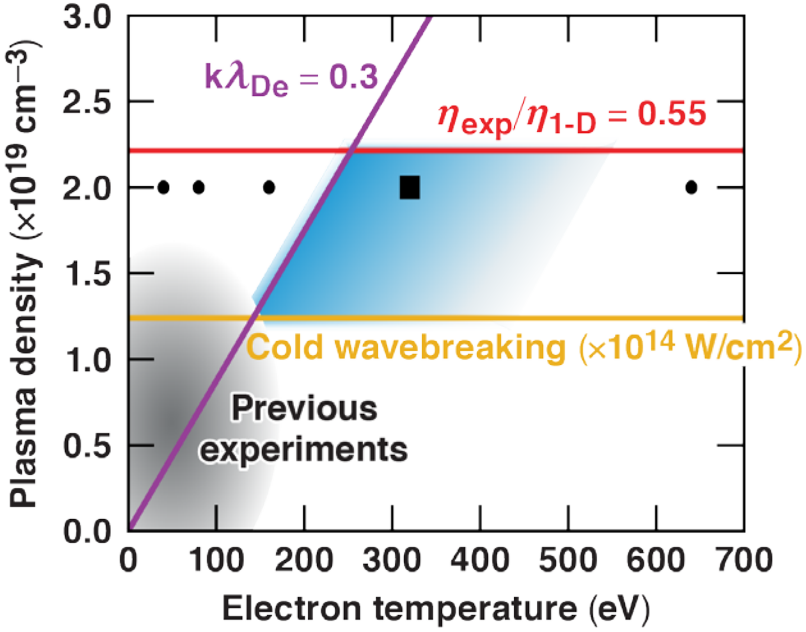
To improve laser beam propagation, a high-temperature amplifier has been proposed*

Propagation of the pump laser is a challenge



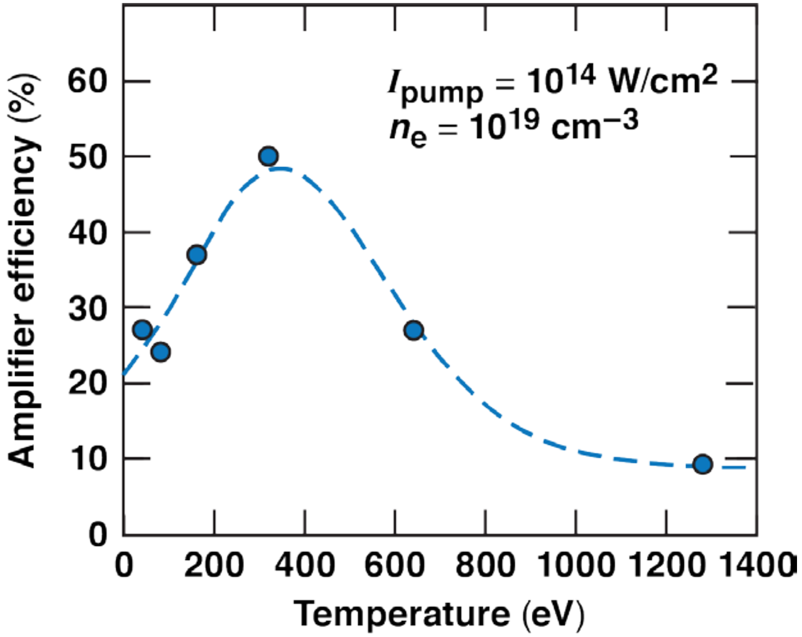
E28630

Hot Raman Amplification



E28909

Vlasov Simulations



E28833a

A proof-of-principle system scalable to high powers would demonstrate energy transfer efficiencies >30%, intensity gains >10, and output intensities >100× the pump intensity

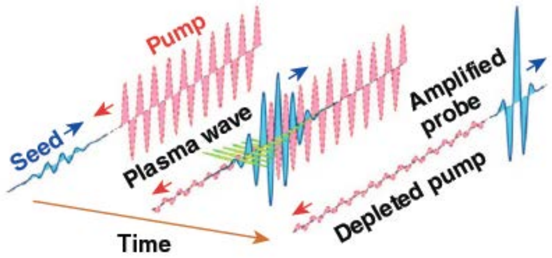
UNIVERSITY of ROCHESTER
U.S. DEPARTMENT OF ENERGY
Office of Science
DOE/FES DE-SC0016253

*D. Haberberger *et al.* Phys. Plasma **28**, 062311 (2021)

Laser Fusion—a path to high yield and clean energy

UR LLE

Laser-Plasma Amplifiers
Raman Amplification



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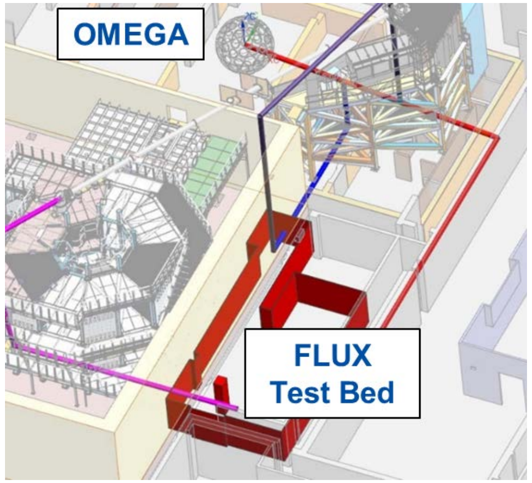
4^{th} Generation ICF Lasers



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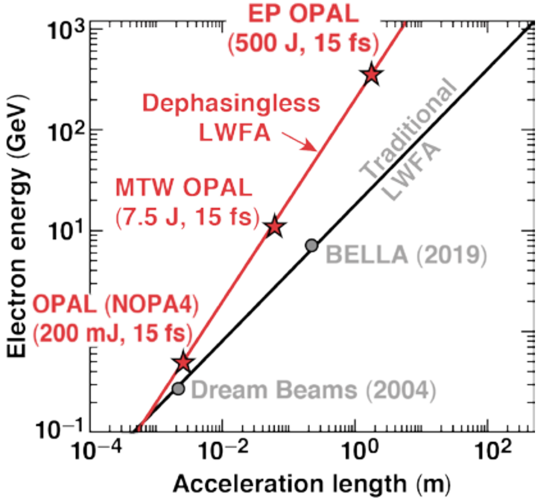

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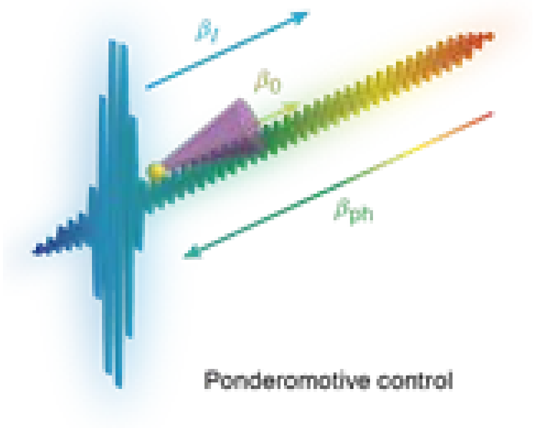
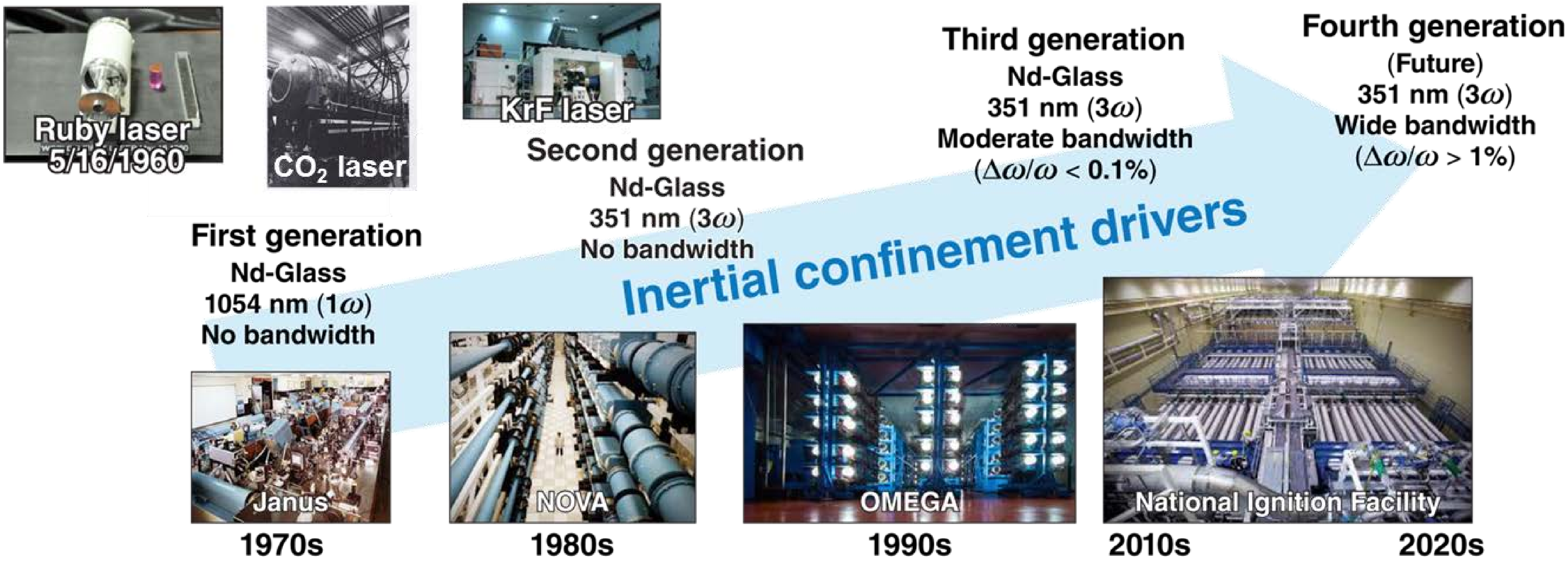


Can short-pulse lasers be used to meet the future High-Energy Density physics mission needs?

Laser-plasma instabilities set the maximum drive pressure for inertial confinement fusion and all pathways to high-yield and inertial fusion energy require LPI mitigation

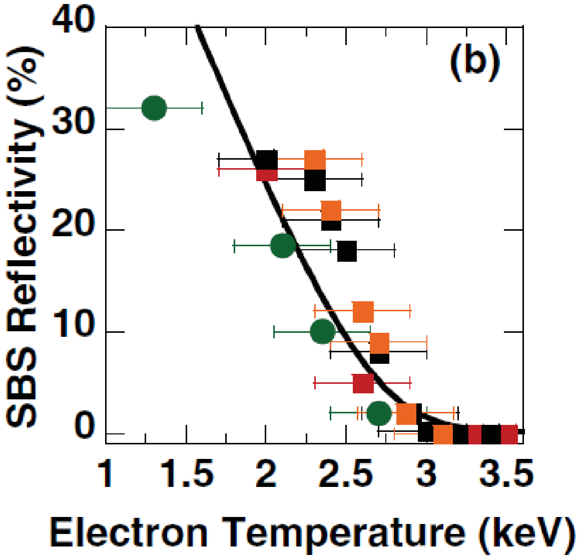


The history of ICF—a story of mitigation and control of laser-plasma instabilities through advancements in technology and improved physics understanding

A series of experiments used Thomson scattering to isolate hydrodynamic uncertainties from laser-plasma instability physics to develop predictive models for ICF designs

Indirect Drive OMEGA Experiments pre-NIF

Froula et al. PRL **98**, 085001 (2007)
Froula et al. PRL **100**, 015002 (2008)
Froula et al. PRL **103**, 045006 (2009)



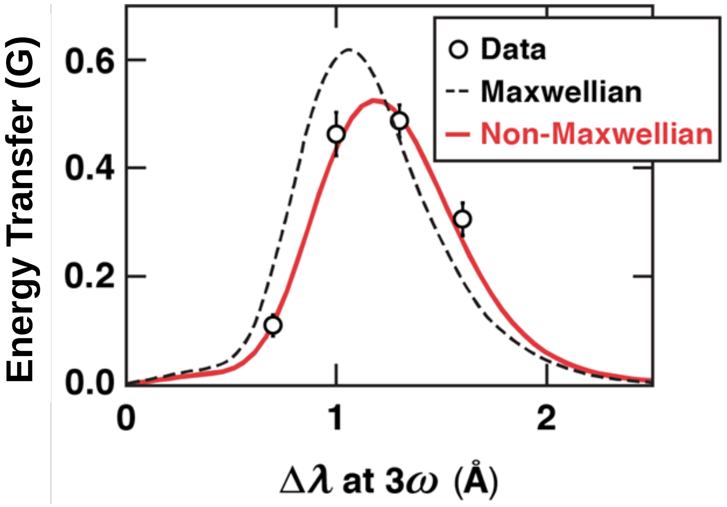
Higher temperature plasmas (>3 keV) are required for efficient laser beam propagation in hohlraums

nature physics | LETTERS

Nat. Phys. **16**(2), 181-185 (2020)

Impact of the Langdon effect on crossed-beam energy transfer

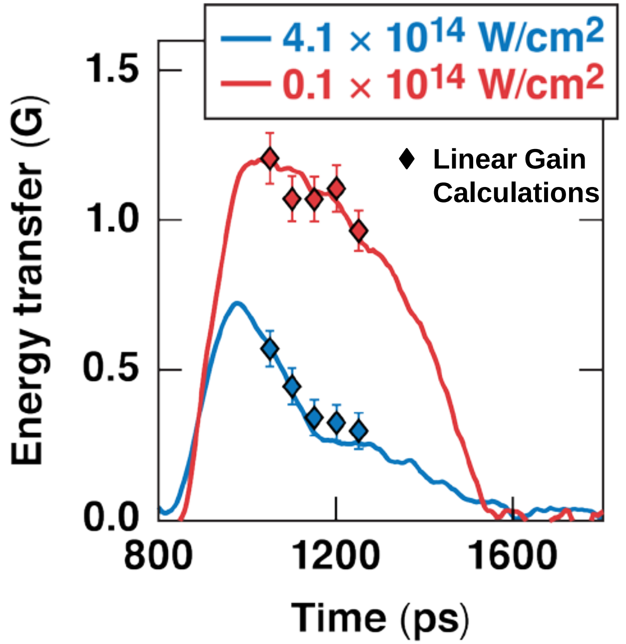
David Turnbull[1]*, Arnaud Colaïtis[2], Aaron M. Hansen[1], Avram L. Milder[1], John P. Palastro[1], Joseph Katz[1], Christophe Dorrer[1], Brian E. Kruschwitz[1], David J. Strozzi[3] and Dustin H. Froula[1]



NonMaxwelliean distribution functions shift the CBET resonances used to tune symmetry in hohlraum experiments on the NIF

Cross-Beam Energy Transfer Saturation

Hansen PRL **126**, 075002 (2021)



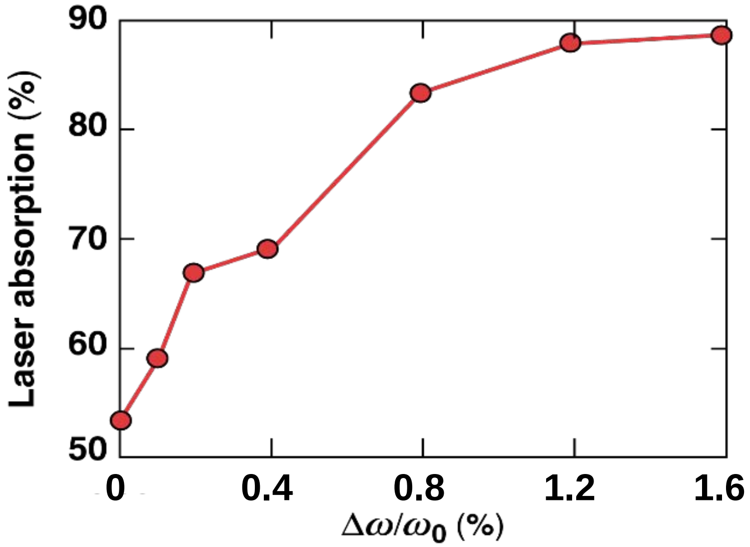
Experiments demonstrate linear CBET models used in integrated ICF simulations are robust

Russ Follett
PHD Physics (2015)

To expand the ICF design space for high-yield implosions, LPI must be mitigated to enable higher intensities to be coupled to the capsules—high-bandwidth lasers provide the path

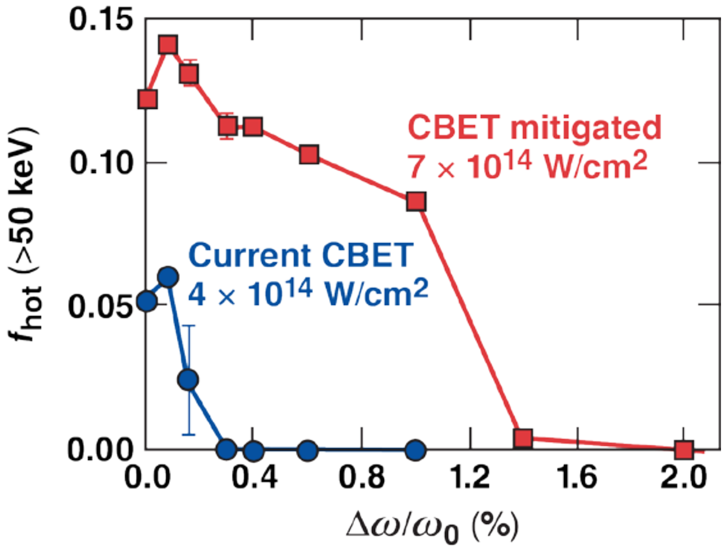
Cross-Beam Energy Transfer (Increased Drive Pressure)

Follett *et al.*, PRL **120**, 135005 (2018)

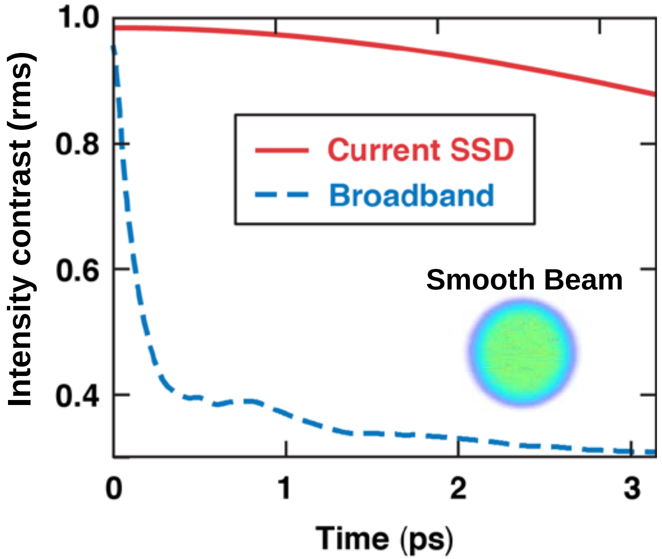


Hot-Electron Mitigation ($n_{cr}/4$ ignition intensities)

Follett *et al.*, Phys. Plasmas **26**, 062111 (2019)



Imprint Mitigation (<1-ps asymptotic smoothing)



SSD: Smoothing by Spectral Dispersion

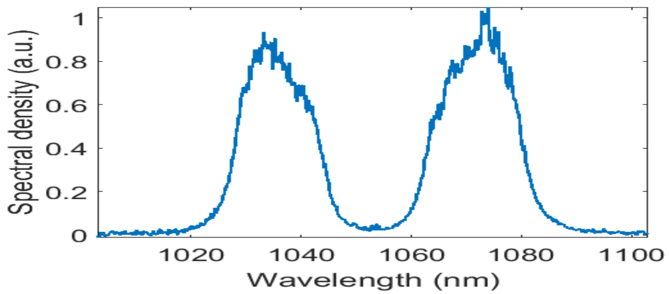
Laser bandwidth $\Delta\omega/\omega$>1.5% is predicted to mitigate hot electron generation, increase the laser absorption, and eliminate imprint, which will enable a robust ICF implosion

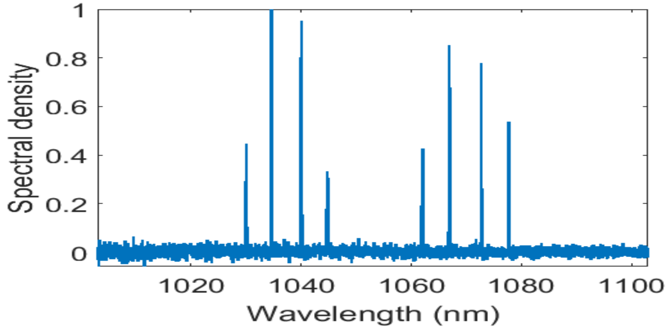
*R. Follett *et al.*, Phys. Plasmas **28**, 032103 (2021)

The Fourth generation Laser for Ultrabroadband eXperiments (FLUX) is under construction and will use the OMEGA LPI Platform to validate bandwidth modeling

UR LLE

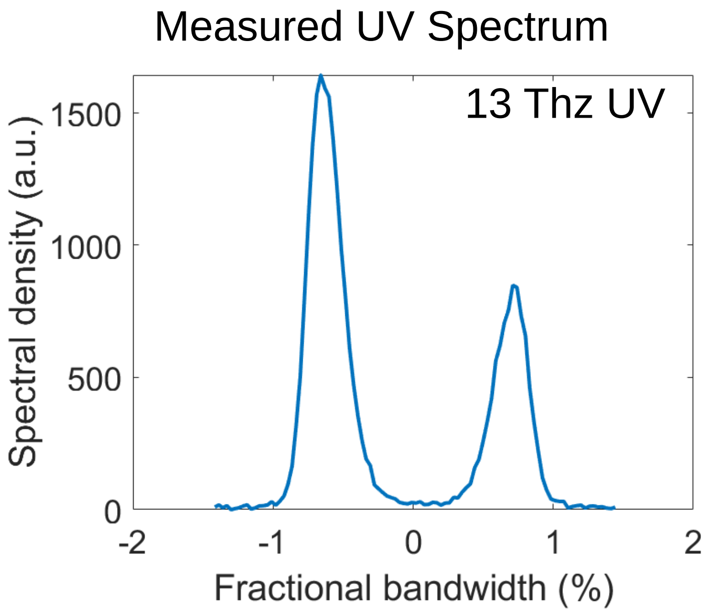
Ultrabroad Band Laser* (concept demonstration)





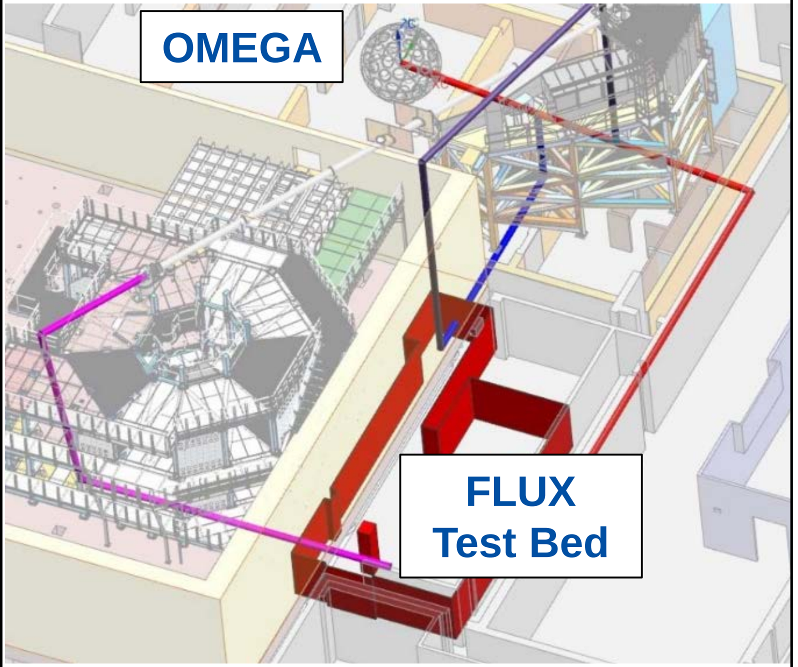
A colinear OPA was used to amplify broad bandwidth long-pulse laser beam

Demonstrated Broadband UV Frequency Conversion**



Novel concept demonstrates efficient broad band ($\Delta\omega/\omega$>1.5%) UV frequency tripling

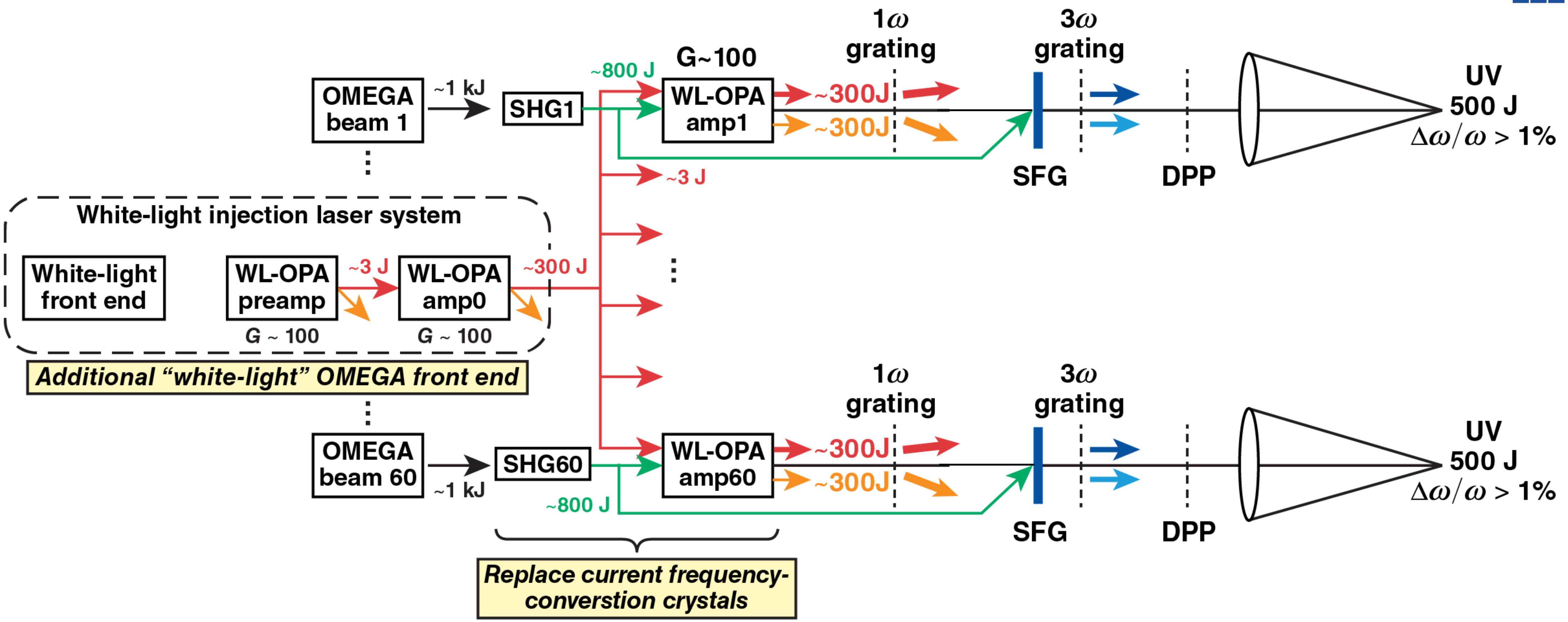
The FLUX laser will feed the OMEGA LPI Platform



FLUX experiments will validate LPI modeling with bandwidth

*C. Dorrer *et al.*, Opt. Express **28**, 451 (2020)
C. Dorrer *et al.*, Opt. Express **29, 16135 (2021)

A successful technology demonstration (FLUX) will lead to a design for an upgraded OMEGA (i.e., using existing 1ω laser driver) with ultra-wide bandwidth UV tripling



E28484

A conceptual layout for a "OMEGA FLUX-60" leverages the existing infrared laser system, target area, and diagnostics

Laser-Plasma Accelerators—a path to TeV electron accelerators

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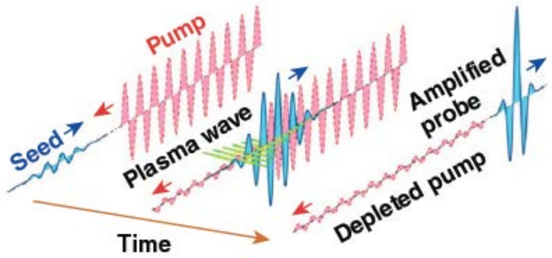
Raman Amplification



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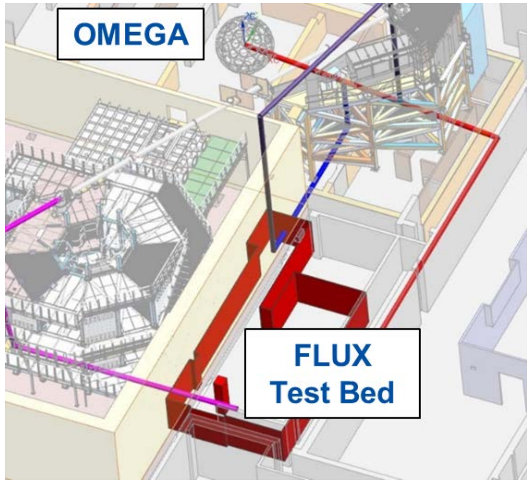
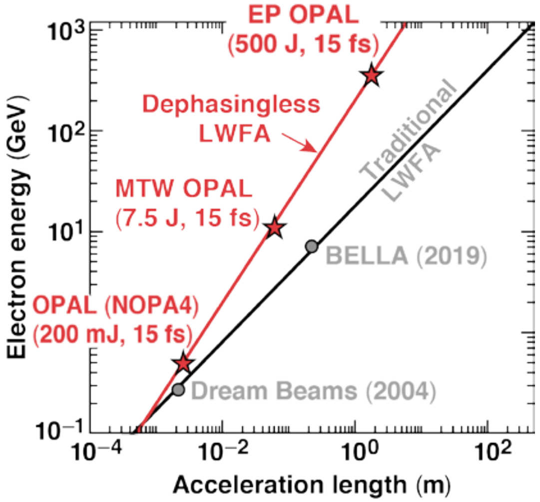
Laser Fusion
4th Generation ICF Lasers



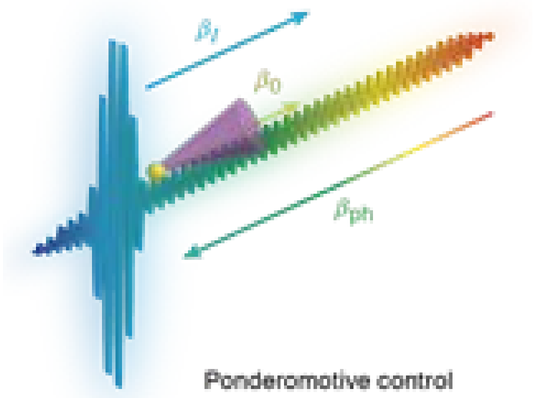
Can laser-plasma instabilities be mitigated to enable inertial confinement fusion?

Laser-Plasma Accelerators
Dephasingless Laser Wakefield Acceleration



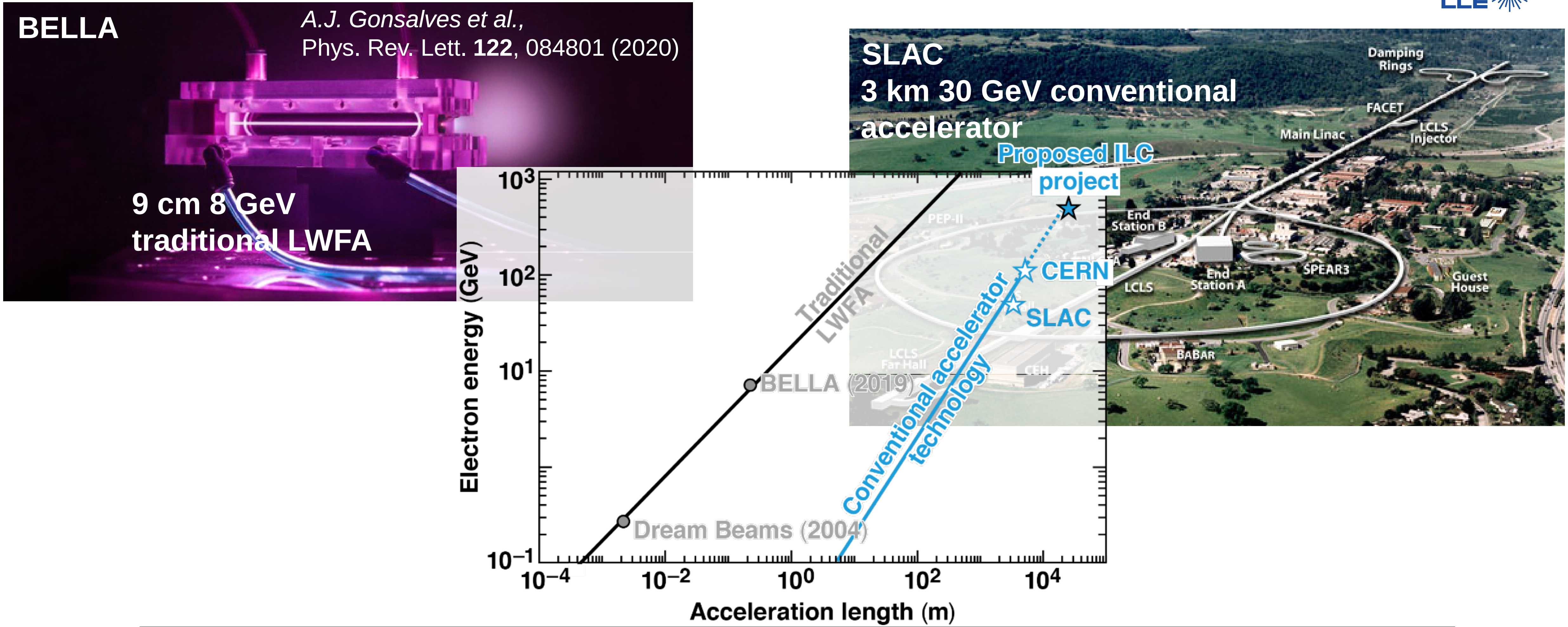
Can manipulating light in a plasma be used to achieve the dream of a TeV electron collider?

Advanced Light Sources for HED Facilities
Nonlinear Thomson scattering with ponderomotive control



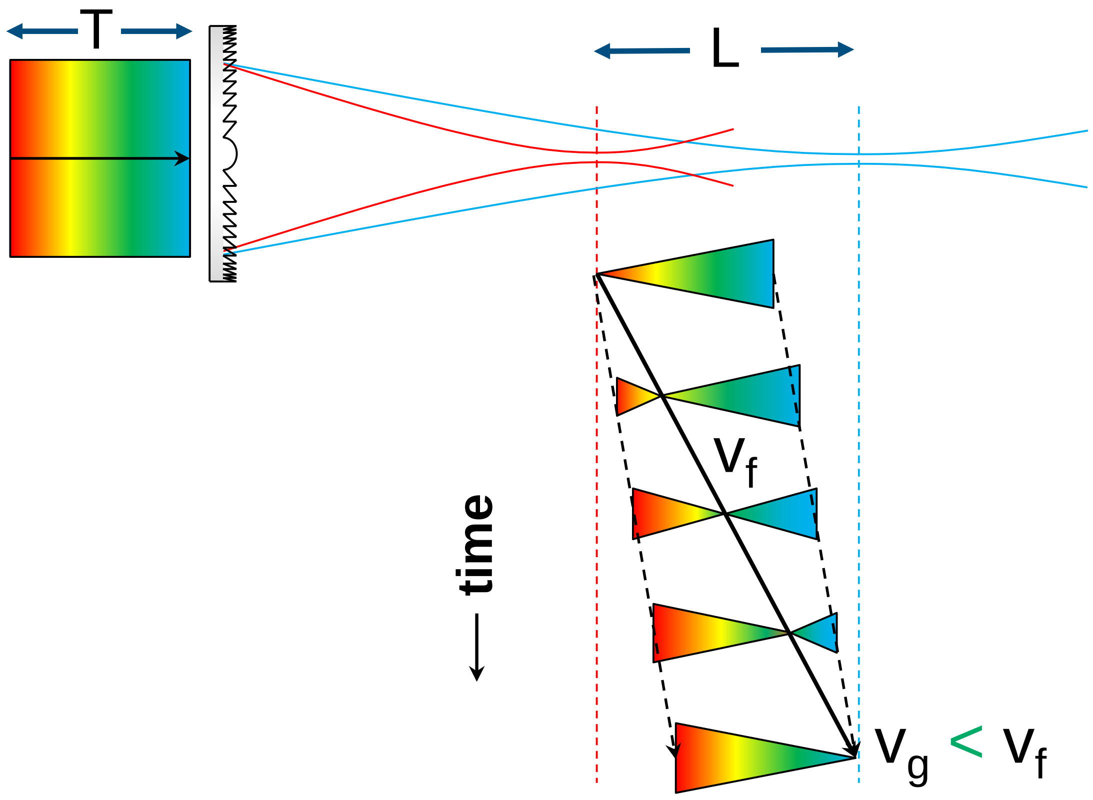
Can short-pulse lasers be used to meet the future High-Energy Density physics mission needs?

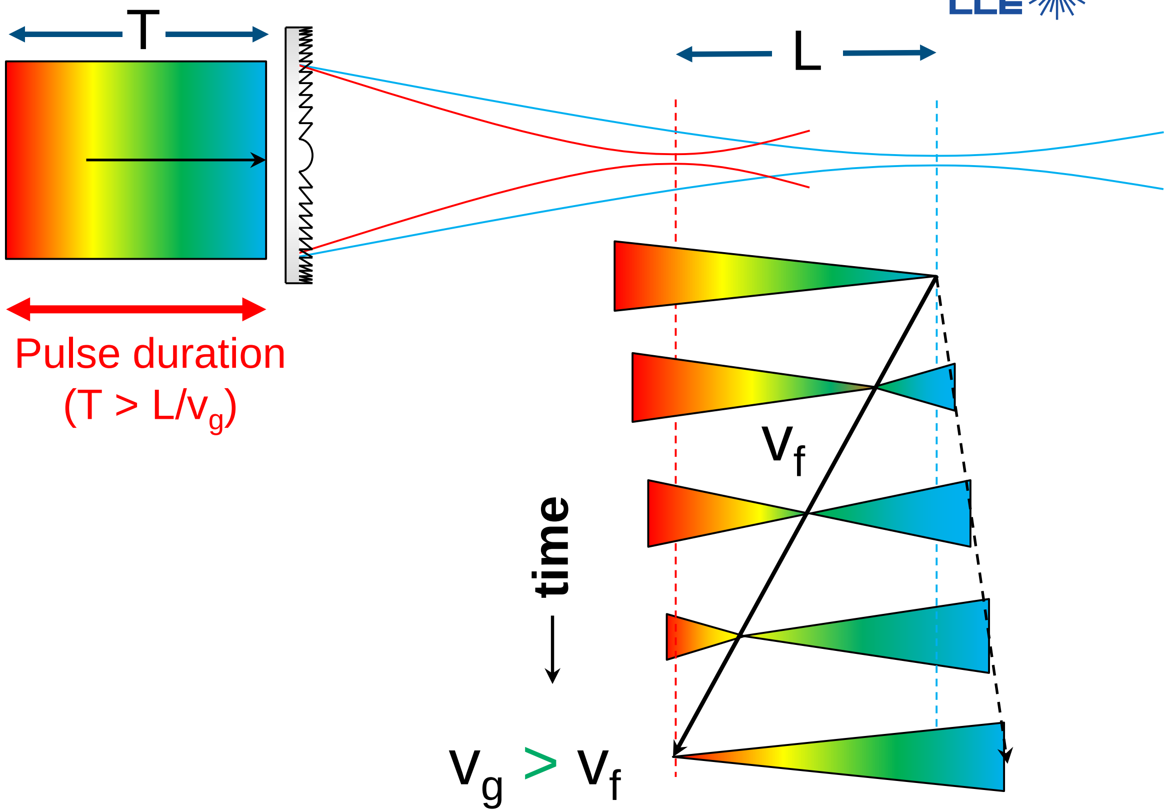
Laser wakefield accelerators provide a promise to the next generation of High-Energy Physics electron drivers



Spatiotemporal pulse shaping provides controllable velocity intensity peaks that can be sustained for long distances, which opens new ways to optimize laser wakefield accelerators

Extending the pulse duration, produces a counter-propagating intensity pulse



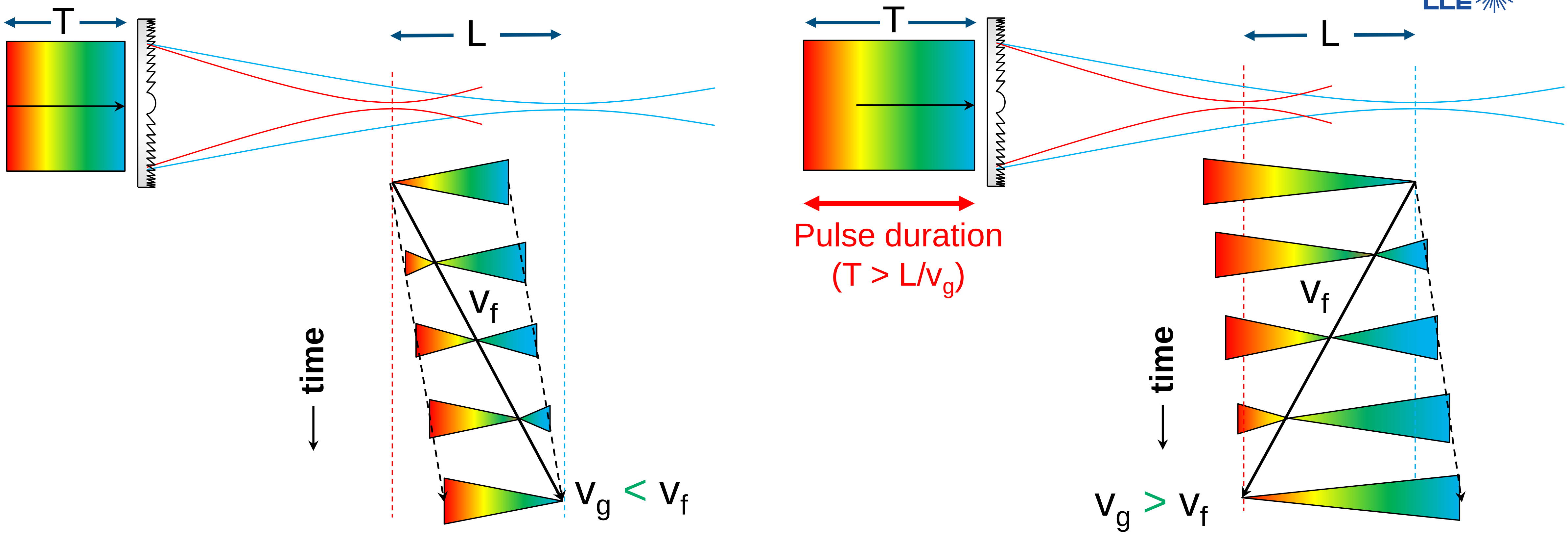


The intensity peak is propagating faster than the group velocity of light

The intensity peak is counter propagating

D. Froula *et al.* Nat. Photonics (2018)

Extending the pulse duration, produces a counter-propagating intensity pulse

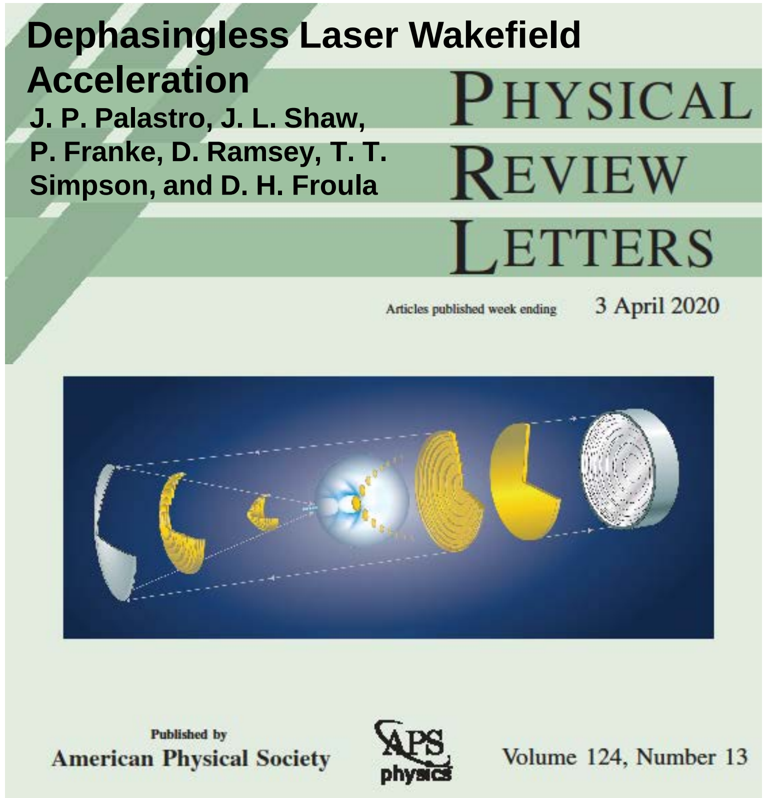


The chromatic focusing creates an extended focal range, while the chirp sets the time at which each frequency comes to its focus providing control over the velocity of the intensity peak

D. Froula *et al.* Nat. Photonics (2018)

Phil Franke
Physics Grad. Student

Flying focus opens a novel way to optimize laser wakefield accelerators by controlling the velocity of the intensity and extending the interaction length



Dephasingless Laser Wakefield Acceleration
J. P. Palastro, J. L. Shaw, P. Franke, D. Ramsey, T. T. Simpson, and D. H. Froula

PHYSICAL REVIEW LETTERS

Articles published week ending 3 April 2020

Published by American Physical Society

APS physics

Volume 124, Number 13

Standard LWFA: Acceleration length is limited by dephasing
DLWFA: Acceleration length is set by laser power

$$a_0 \equiv 0.855\sqrt{I\lambda^2} \propto \sqrt{P/L}$$

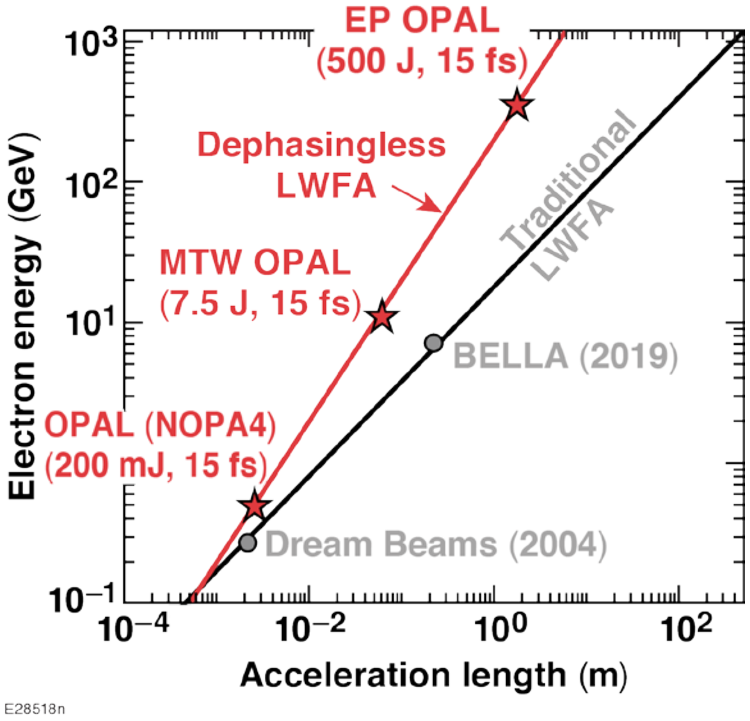
Standard LWFA: Density sets the laser's pulse duration
DLWFA: Density is set by the laser's pulse duration

$$c\tau \sim \lambda_p \propto \frac{1}{\sqrt{n_e}}$$

Standard LWFA: Electron energy gain requires lower densities requiring longer laser pulses
DLWFA: Energy gain requires shorter laser pulses

$$\Delta E = qE_{LWF}L \propto \sqrt{n_e}a_0^2 L \propto \sqrt{n_e}\frac{E_{laser}}{\tau}$$

$$\Delta E \propto \frac{E_{laser}}{\tau^2}$$



Spatiotemporal pulse shaping provides the opportunity to accelerate electrons to TeV energies in few-meter single-stage plasma without the need for a guiding structure

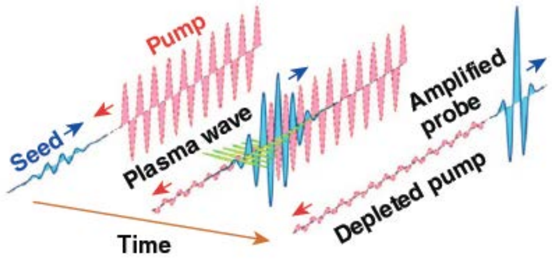
DOE/FES DE-SC00215057

*J.P. Palastro *et al.* Phys. Rev. Lett. (2020) **C. Caizergues *et al.* Nat. Photonics (2020)

Advanced Light Sources—a path to light sources with short-pulse lasers

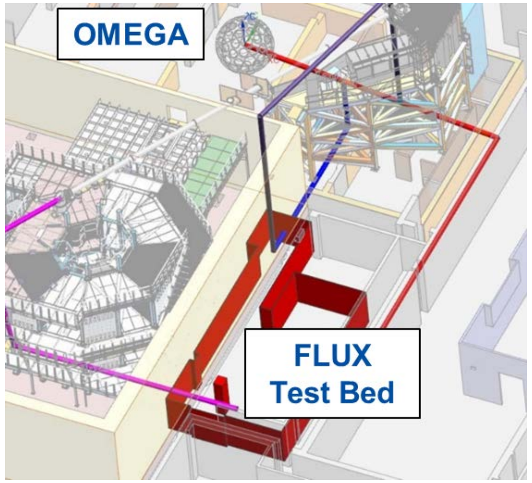
UR LLE

Laser-Plasma Amplifiers
Raman Amplification



Can plasmas be used to achieve intensities above 10^{24} W/cm^2?

Laser Fusion
4^{th} Generation ICF Lasers



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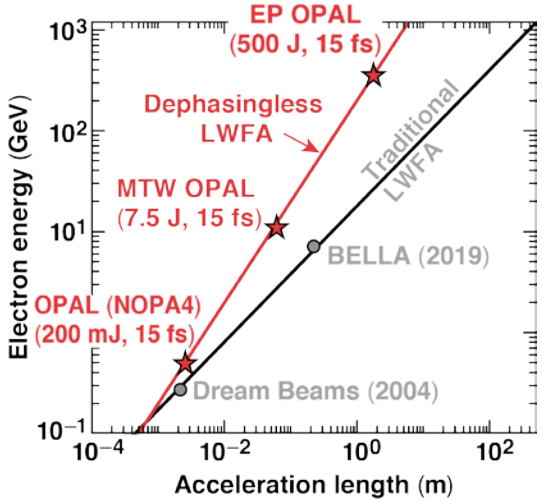

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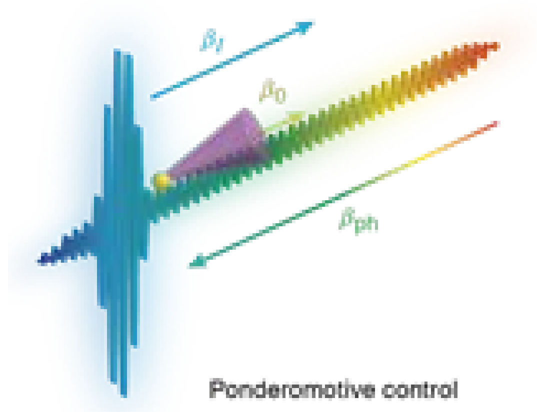
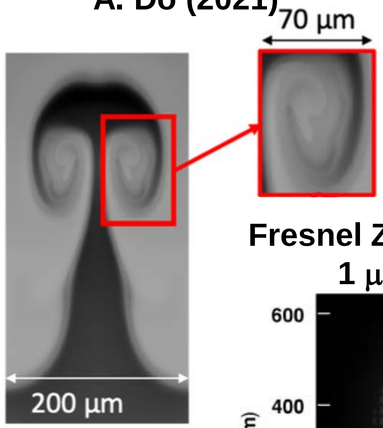


Can short-pulse lasers be used to meet the future High-Energy Density physics mission needs?

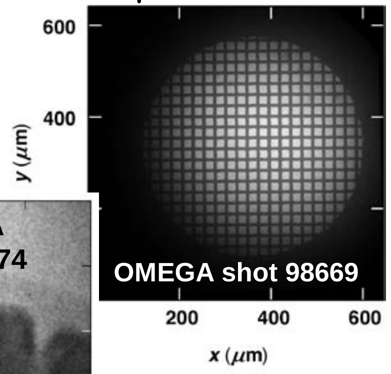
Short-pulse laser could drive future light sources that have the potential to be compact and provide unique capabilities for high-energy density facilities

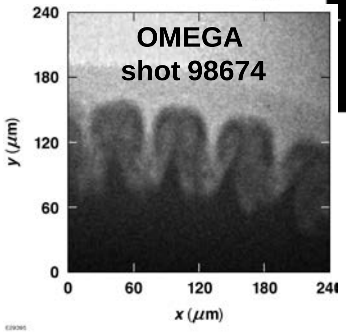
UR LLE

HYDRA Simulations
A. Do (2021)



Fresnel Zone Plate Imaging
1 μm resolution





P. Nilson (LLE)

Novel advancements using spatiotemporal pulse shaping

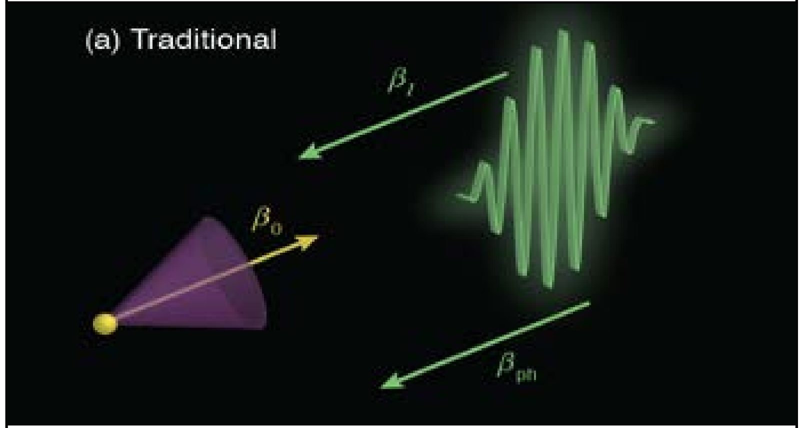
Howard *et al.* PRL **123**, 124801 (2019)
Ramsey *et al.* PRE **102**, 043207 (2020)
Palastro *et al.* in preparation

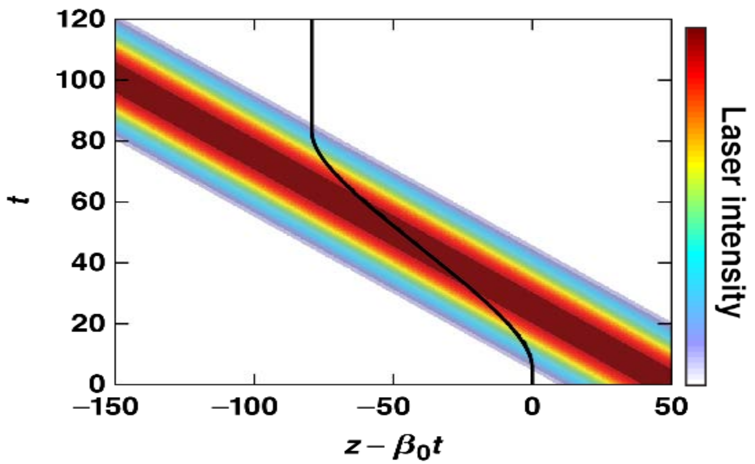
- **Photon acceleration (UV probe)**
- **Nonlinear Thomson (“Compton”) scattering (x-rays probe)**
- **Harmonic generation (XUV probe)**
- **Cherenkov (THz probe)**

Improved sources for High-Energy Density measurements with ultrashort pulse lasers will provide time resolution for access to novel physics

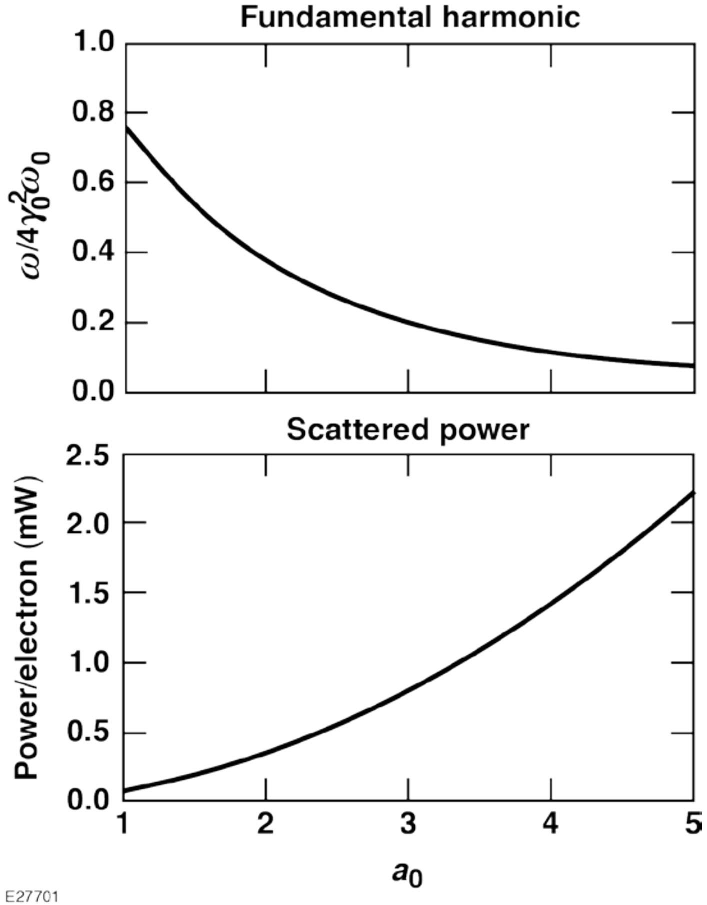
Nonlinear Thomson "Compton" scattering has the potential to produce high-energy photons beams from high-power lasers

Nonlinear Thomson scattering

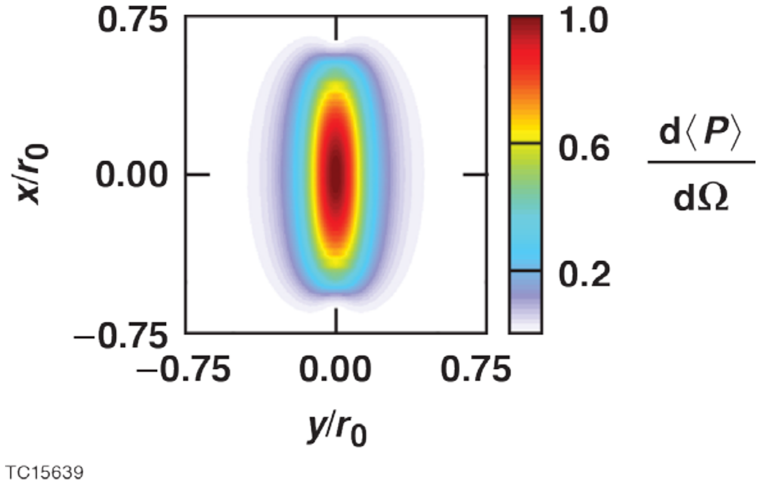




Poor scaling with laser intensity



Poor emittance scaling with laser intensity



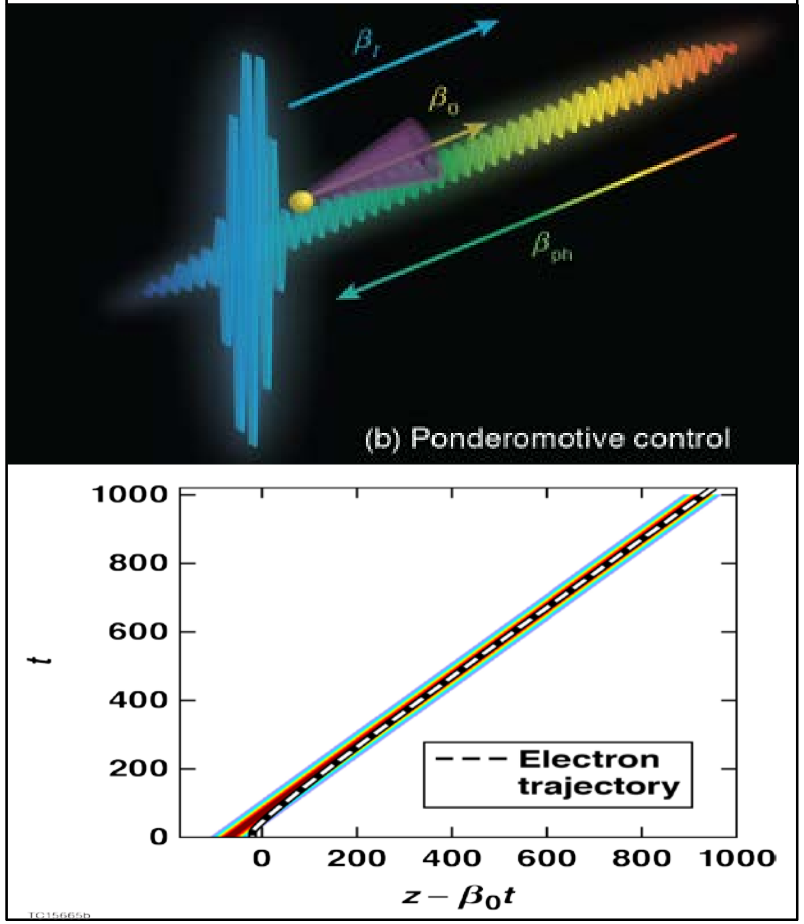
Traditional Nonlinear Thomson scattering scales poorly with increased laser intensity significantly limiting the on-target flux

Dillon Ramsey

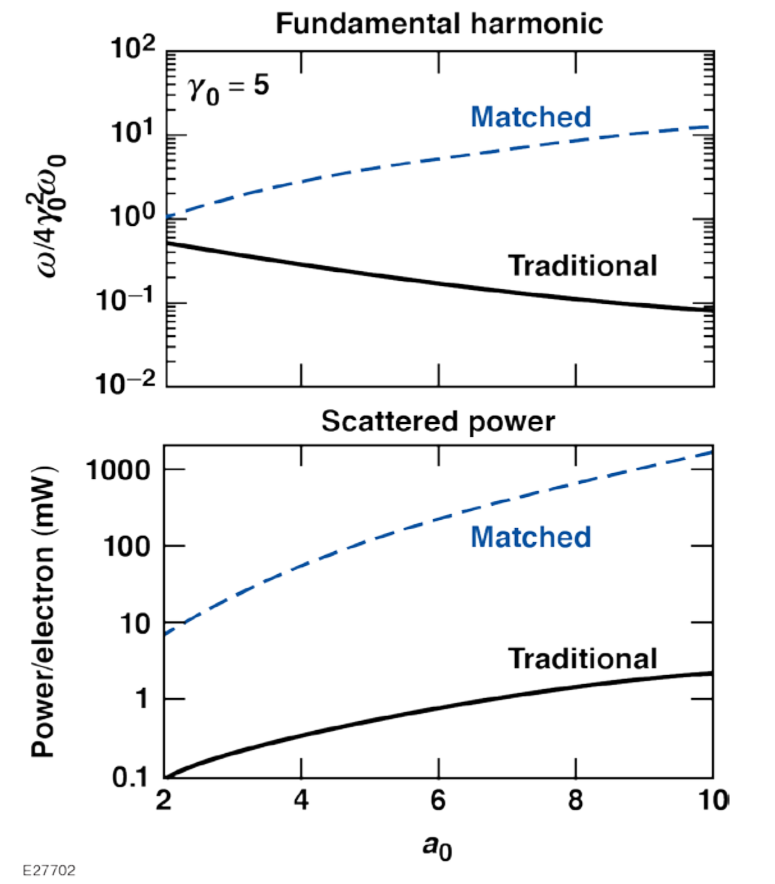
Physics Grad. Student

Spatiotemporal pulse shaping can control the ponderomotive force significantly improving the power scattered, the scattered photon energies, and the scattered emittance

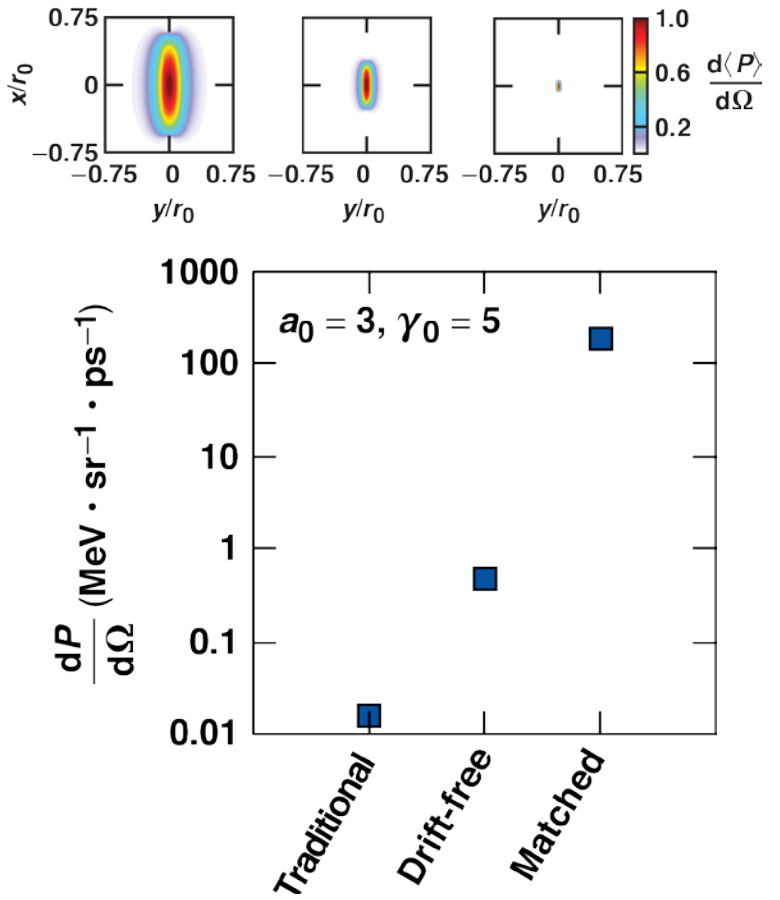
Nonlinear Thomson scattering with ponderomotive control*



Scattered power and frequency



Scattered Emittance



UNIVERSITY of ROCHESTER

*D. Ramsey *et al.*, In Review (2021)

Laser-plasma instabilities remains one of the greatest challenges to using high-power lasers for grand challenge applications

- Laser-plasma instability physics is inherently coupled to the plasma conditions and the plasma conditions are often dictated by the laser-plasma instabilities
- Thomson scattering provides a window into the electron motion with in a plasma, which has allowed the laser-plasma instability physics to be decoupled from the uncertainties in plasma conditions
  - A better understanding of the plasma physics has led to an expanded design space for applications
- Manipulating laser-light provides opportunities to mitigate laser-plasma instabilities and overcome fundamental limitations of conventional systems
  - Broadband ultraviolet glass-lasers provide a path to LPI-free 4th generation ICF drivers
  - Spatiotemporal pulse shaping has opened avenues to novel physics

Solutions to using high-power lasers in grand challenge applications exists through understanding plasma conditions and manipulating laser light