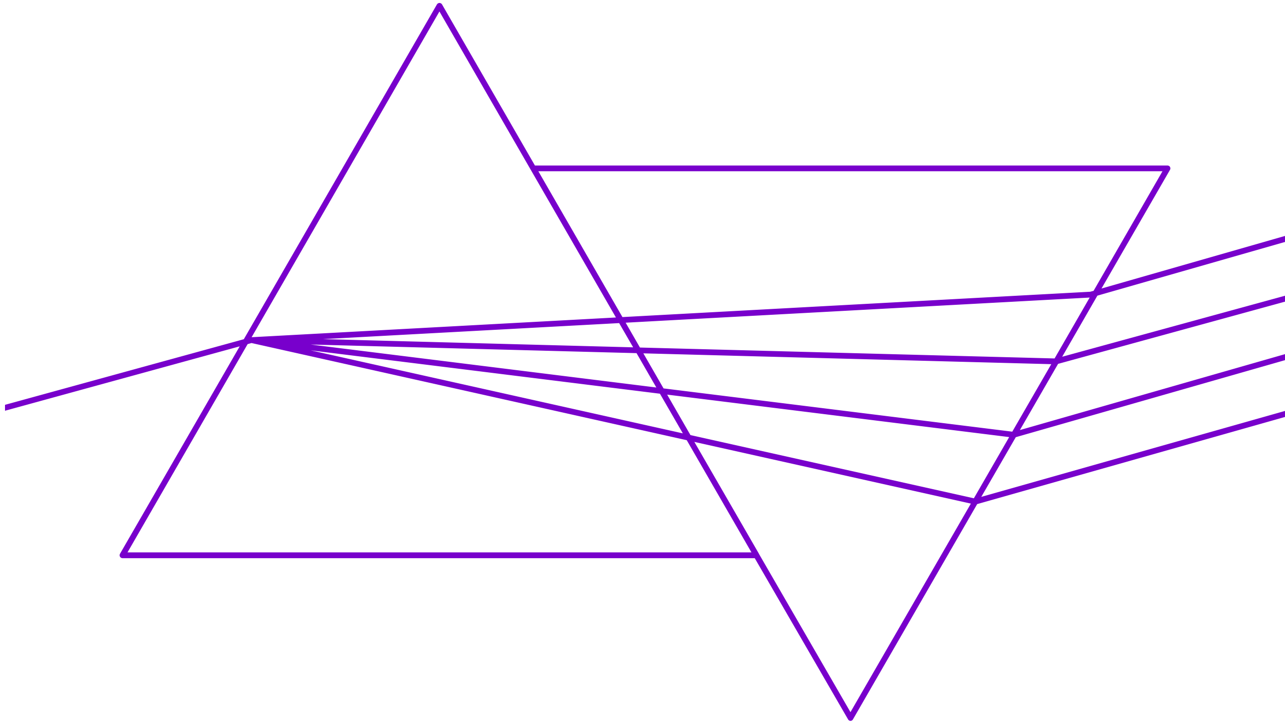
OPTICA
Advancing Optics and Photonics Worldwide

Technical Groups

Broadband OPA technology for ultrashort or incoherent laser pulses



Featuring Dr. Jonathan D. Zuegel, University of Rochester
09 March 2023

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About Our Technical Group

Our technical group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications.

Our mission is to connect the 4400+ members of our community through technical events, webinars, networking events, and social media.

Our past activities include:

- In-person/virtual Special Talk on "High Stability Fiber Lasers at 1 and 2 µm for Gravitational Wave Detectors, Sensing- and Quantum Applications" by Patrick Baer
  - At Optica's Laser Congress in Barcelona, Spain
- In-person/virtual Special Talk on "From Laser Materials to Ultrashort Pulse Lasers and Applications - An Overview of 40 years as an Optica Member" by Dr. Greg Quarles
  - At Optica's Frontiers in Optics (FiO) Conference in Rochester, NY

Feature Issue of Applied Optics

https://opg.optica.org/ao/journal/ao/feature_announce/ALSFC2022.cfm

Applied Optics

Gisele Bennett, Editor-in-Chief

Editorial Board >

FEATURE ISSUE OF *APPLIED OPTICS*

Applications of Lasers for Sensing and Free Space Communications 2022

Submission Opens: 1 January 2023

Submission Deadline: 27 March 2023

Applied Optics and the Laser Systems Technical Group welcome submissions to a feature issue on "Applications of Lasers for Sensing and Free Space Communications" in conjunction with the Applications of Lasers for Sensing and Free Space Communications (LS&C) 2022 topical meeting being held 11 - 15 December 2022 in Barcelona, Spain. Whereas meeting participants are particularly encouraged to submit their work, the feature issue is open to all contributions in related areas.

OPTICA
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Laser Systems

Connect with our Technical Group

Join our online community to stay up to date on our group’s activities. You also can share your ideas for technical group events or let us know if you’re interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/LaserSystemsTG
- On LinkedIn at www.linkedin.com/groups/6993076/
- On Facebook at www.facebook.com/groups/opticalasersystems
- Email us at TGactivities@optica.org

Today's Speaker

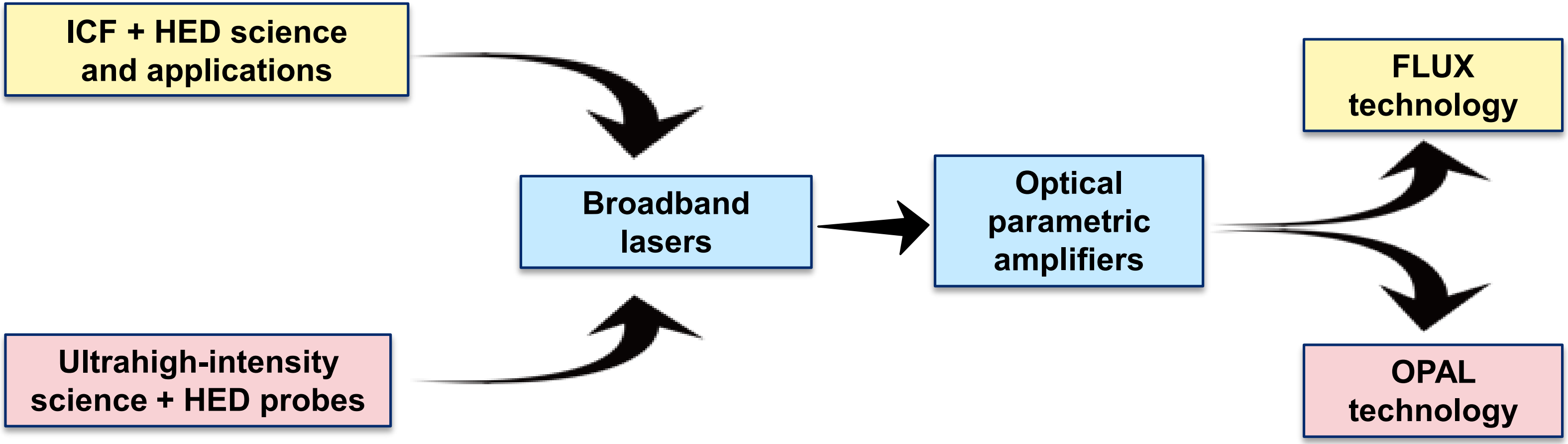
Dr. Jonathan D. Zuegel

University of Rochester

Dr. Jonathan D. Zuegel serves as the Laser and Materials Technology Division Director, and a Distinguished Scientist at the Laboratory for Laser Energetics, and a Professor of Optics at the Institute of Optics, University of Rochester. Zuegel led the Laser Development and Engineering Division from 2014 to 2019, and the Laser Technology Development Group from 2001 to 2014. Jon is a Fellow of Optica (formerly OSA) and serves/has served in numerous capacities of conferences (CLEO, ICUIL, OSA topical meetings) and international advisory committees.

Dr. Zuegel joined LLE in 1996 after receiving his Ph.D. in Optics from The Institute of Optics at the University of Rochester. He received his B.S. (1983) and Masters of Engineering (1984) in Electrical Engineering from Cornell University and served in the U.S. Navy in the Department of Energy, Division of Naval Reactors. Dr. Zuegel is author or co-author on more than 130 papers and more than 270 conference presentations.

Broadband OPA technology for ultrashort *and* incoherent laser pulses


ICF + HED science and applications

Ultrahigh-intensity science + HED probes

Broadband lasers

Optical parametric amplifiers

FLUX technology

OPAL technology

Jon Zuegel
Division Director, Laser & Materials Technology
Distinguished Scientist, and Professor of Optics
University of Rochester

Optica Laser Systems Technical Group Webinar
March 10, 2023

ICF* and HED** applications drive laser science and technology R&D at LLE

- **LLE develops laser and optical technology with broad scientific applications**
- **The MTW and MTW-OPAL lasers have served as cornerstones for laser and laser-plasma science R&D at LLE**
  - **Ultrafast lasers promise a path for implementing next-generation HED probes of burning plasmas and hydrodynamics at NNSA compression facilities**
  - **MTW-OPAL commissioning (“first light”) demonstrated 350-TW pulses ready for experiments, plus it has enabled strategic hiring and significant physics and lasers workforce development**
  - **The MTW-OPAL laser produces 0.35-PW laser pulses and prototypes technologies that can scale to tens of petawatts**
- **FLUX technology will expand laser direct-drive, inertial-confinement fusion (LDD-ICF) design space and enable higher performance implosions**
  - **The FLUX project leverages expertise developed for ultrafast lasers to provide broadband, incoherent ICF and HED laser drivers**

* Inertial Confinement Fusion
** High-Energy Density

UR/LLE designed, built, and operates the Omega Laser Facility for NNSA programmatic science and basic science research

OMEGA EP Laser System

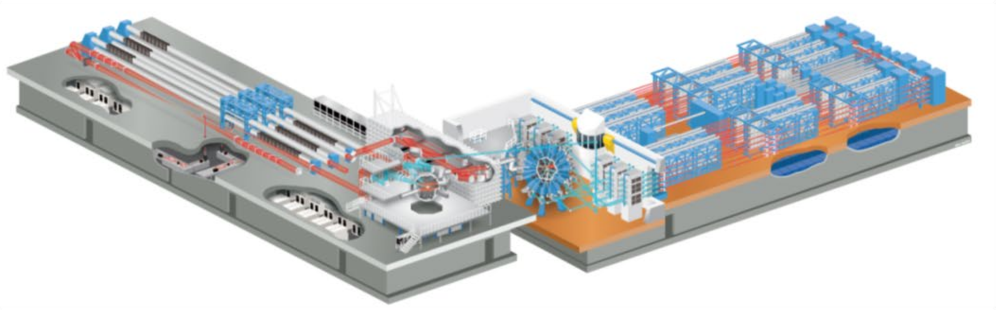
- Operating since 2008
- 4 NIF-like beamlines
- 5 kJ/beam UV (10 ns)
- 2 short-pulse IR beams:
  up to 0.5 kJ/beam in 0.7 ps
  1 kJ in 10-100 ps)
- IR beam(s) or one UV beam with wavelength tuning capability can be coupled to OMEGA
- ~600 to 800 shots/year

OMEGA Laser System

- Operating since 1995
- 60 beams
- 30 kJ UV on target
- Spherical compression and complex target configurations
- Flexible pulse shaping
- Magnetic fields (~50 Tesla)
- up to 1500 shots/year

UR/LLE

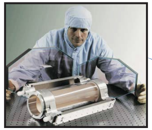
- Funded by DOE/NNSA through a cooperative agreement
- Faculty equivalent staff: 121
- Professional staff: 178
- Associated faculty: 25
- Graduate and undergraduate students: 145
  (~35 from other universities)



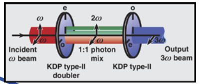
LLE supports user experiments and delivers lasers to partners

LLE continues to build on a long tradition of innovating and advancing laser and optical technologies

1978: LHG: Nd: phosphate Laser glass



1980: High-efficiency frequency tripling

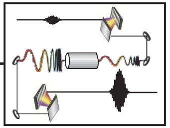


1980

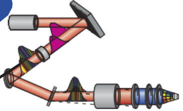
1981: 24-beam OMEGA National Laser Users' Facility

1985: OMEGA UV conversion

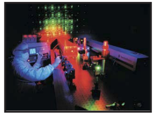
1985: Chirped-pulse amplification (CPA)



1989: Smoothing by spectral dispersion (SSD)



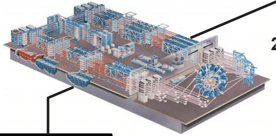
1990: High-efficiency, uniform diffractive optics

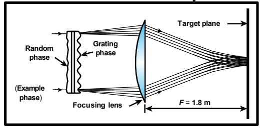


1990: Polarization smoothing

1990

1995: 60-beam OMEGA

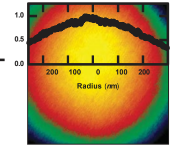




1995: Continuous distributed phase plate

1999: Commercial spin-off of magnetorheological finishing (MRF)— used for all ICF lasers

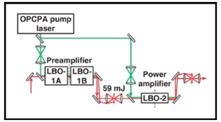
1999: THz 2-D SSD



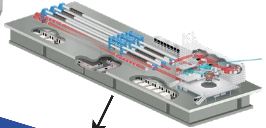
2000

2000: High-fluence NIF optic coatings

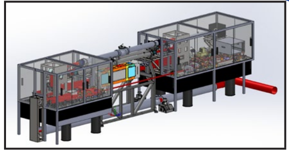
2005: Highly efficient OPCPA

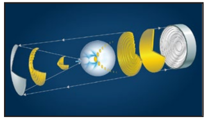


2010



2016:DCS laser





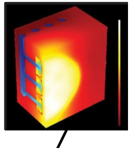
2018: Flying Focus

2020: DLWFA

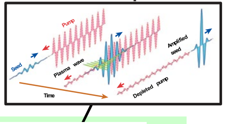
2020

2021: MTW-OPAL

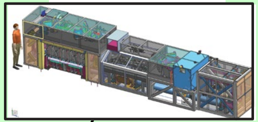
2022: HAP gratings



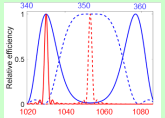
2022: Raman Amplification

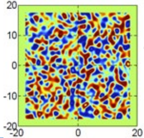


2022: AMICA laser



2023: FLUX



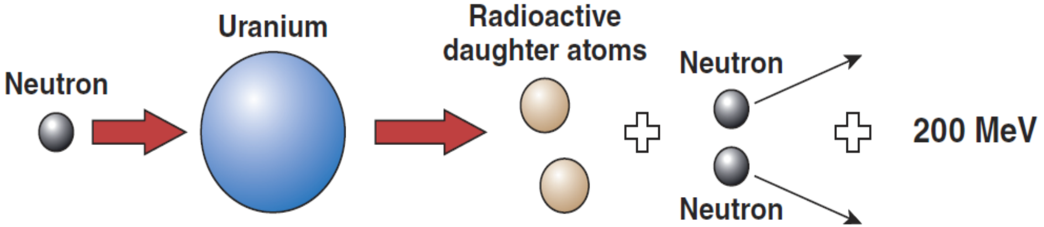


TBD: RCP polarization smoothing

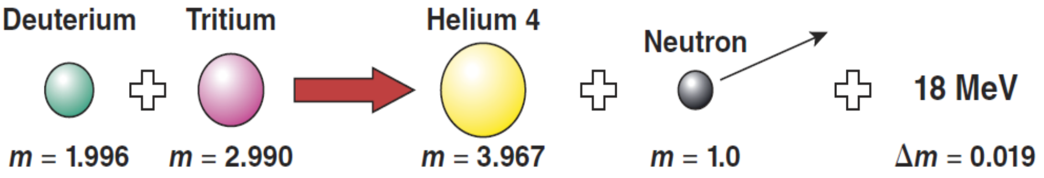
s599q

Nuclear fission and fusion release energy according to Einstein's most famous equation

Fission



Fusion



$$\boxed{E = m c^2}$$

Energy Mass Speed of light

S11b

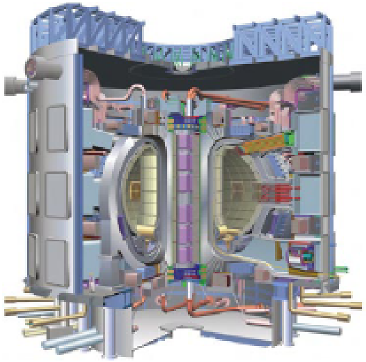
Both magnetic and inertial confinement fusion have ignition devices to prove the scientific principles of controlled fusion in the laboratory

Magnetic confinement

- Confine hot plasma with magnetic fields
- Most advanced concept is the tokamak
- ITER, a > €18 billion tokamak under construction in France is expected to produce net fusion power in 10 – 20 years
- Commonwealth Fusion Systems plans to build SPARC in Massachusetts by ~2025

Inertial confinement

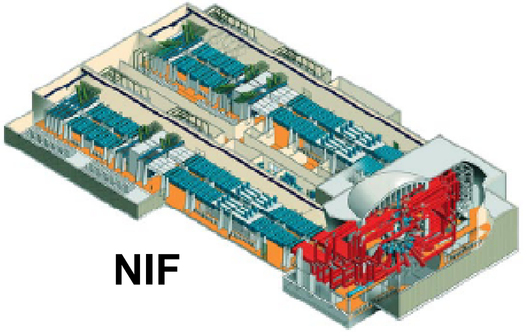
- Compresses fuel to conditions where it “fusion” burns before disassembly
- The National Ignition Facility (NIF), a $3.5B laser facility demonstrated net fusion energy in December 2022!



ITER

SPARC

Not to same scale!

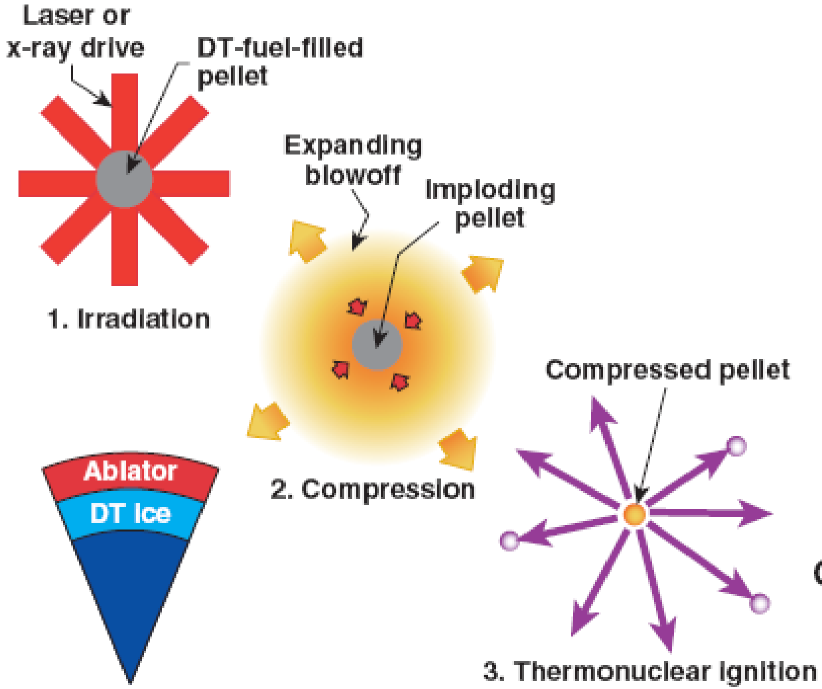


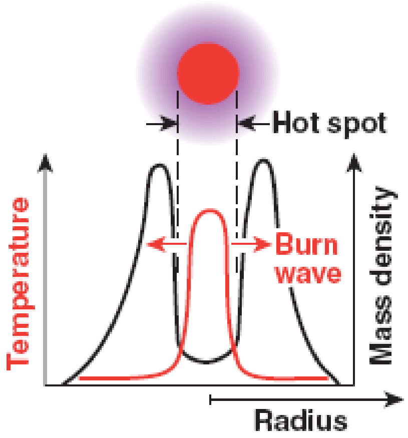
NIF

NIF Shot N221205

December 2022

Laser-induced ablation generates ultra-high pressures that compress a fusion capsule to ignition conditions



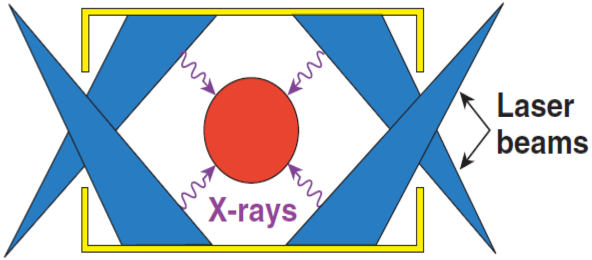


$$\text{Gain, } G = \frac{\text{Fusion energy out}}{\text{Laser energy in}}$$

"Hot-spot" ignition requires the core temperature to be at least 5 keV and the core fuel areal density to exceed ~300 mg/cm^2.

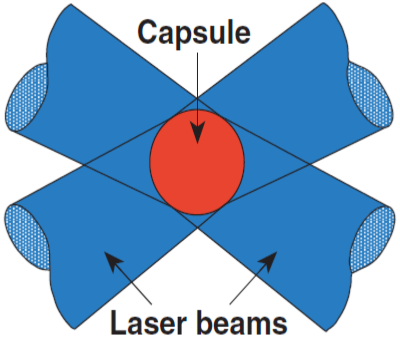
There are two main approaches to inertial confinement fusion (ICF) using lasers

X-ray (Indirect) Drive



Hohlraum using
a cylindrical high-Z case

Direct Drive



LLE globally leads in Direct Drive ICF

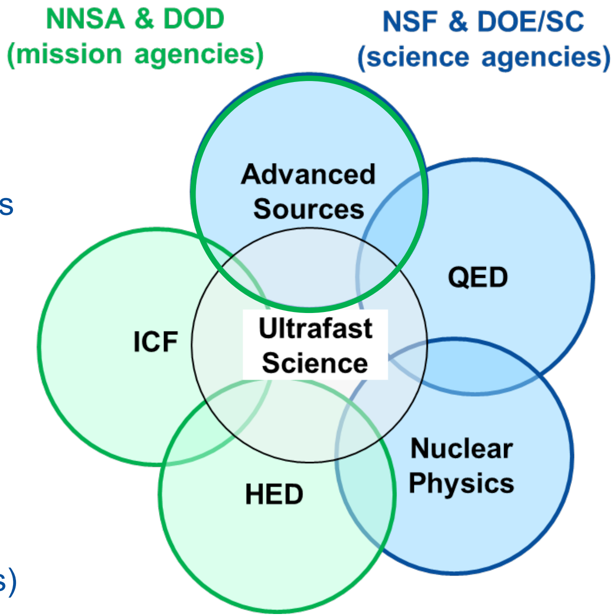
Key physics issues associated with capsule implosion are common to both direct and x-ray (indirect) drive

- Energy coupling
- Drive uniformity
- Laser-plasma instabilities
- Hydrodynamic instabilities
- Preheat
- Capsule roughness

- Direct drive couples significantly more laser energy to the target
- Indirect drive provides better driver uniformity ... so far!

Ultrafast laser science enables DOE-NNSA* missions and research topics of interest to other science agencies

- Ultrashort-pulse, high-power lasers can provide the **next generation of HED probes for burning plasmas and hydrodynamics**
  - Fast time resolution is required to probe dynamics within the inertial confinement time
  - Bright, penetrating photons enable probing extreme material conditions inaccessible by conventional laser-driven x-ray sources
  - Advanced particle sources (electrons, ions, neutrons) driven by ultrashort pulse lasers will enable understanding many physics phenomena
- **Laser-based light sources**: duration set by laser pulse length, micron-scale source size, low divergence
  - Betatron radiation – broadband 1-100 keV x-rays
  - Inverse Compton Scattering – 1 keV to 10 MeV (x-rays to gamma rays)
  - Laser-based X-ray free-electron laser (XFEL) – coherent x-rays



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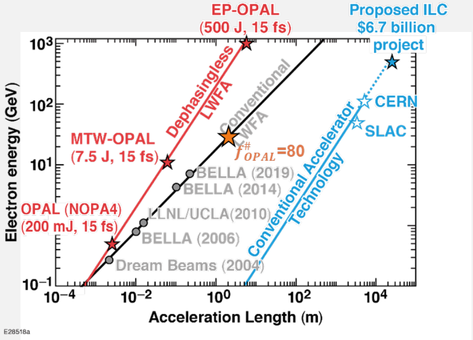
* Dept. of Energy – National Nuclear Security Administration

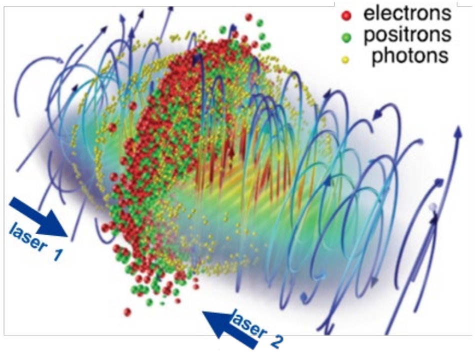
Recent scientific workshops have identified frontier science opportunities enabled by multi-petawatt lasers

Relativistic particle beams

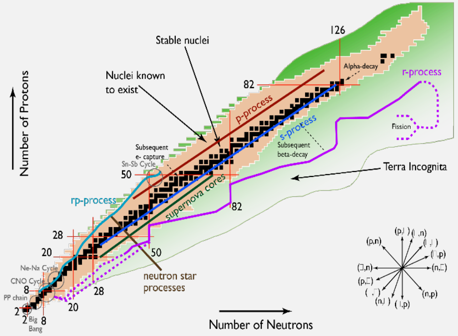


Laser Wake-Field Acceleration (LWFA)

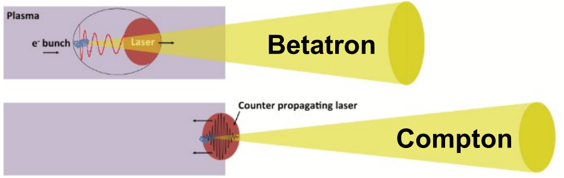
High-Field Physics & QED*



Laser-Driven Nuclear Physics

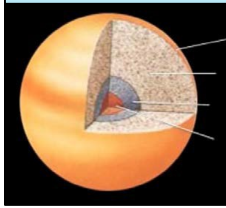


Advanced Light Sources



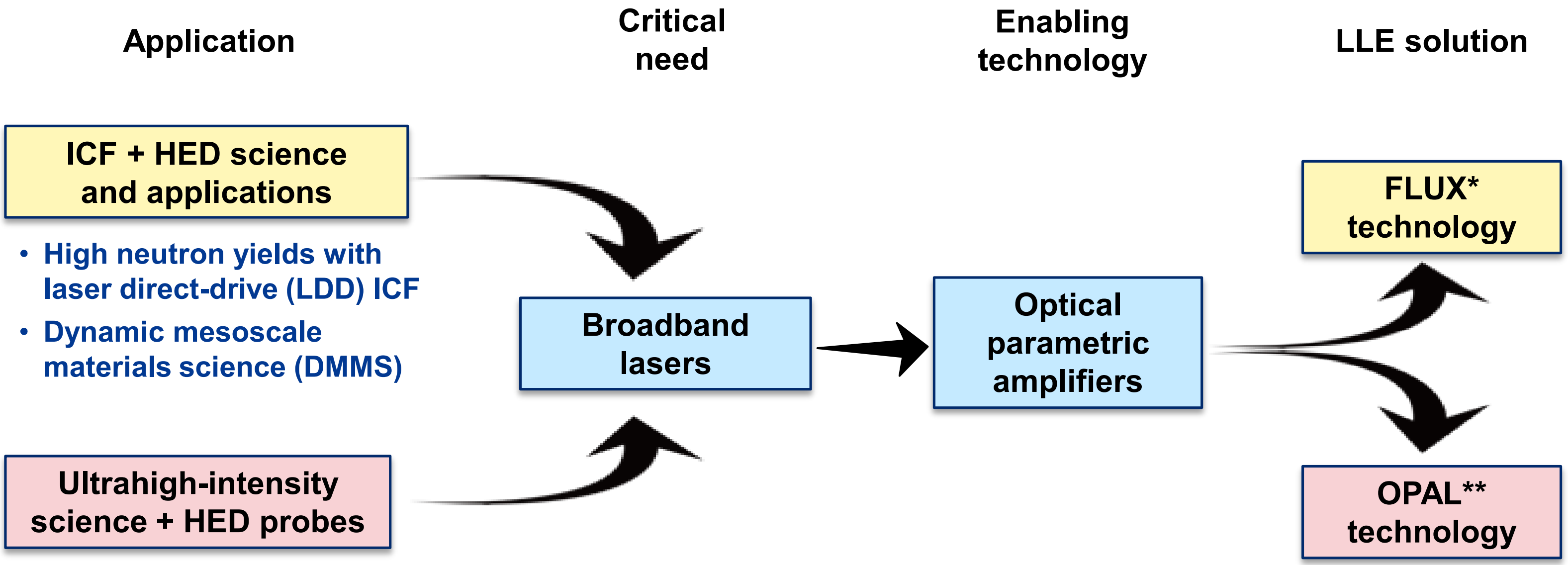
... and other sources

High-Energy-Density Science (HEDS)



Hydrogen Phase Diagram

LLE develops broadband laser technology to advance ICF and HED sciences



Application | **Critical need** | **Enabling technology** | **LLE solution**

ICF + HED science and applications

- High neutron yields with laser direct-drive (LDD) ICF
- Dynamic mesoscale materials science (DMMS)

Ultrahigh-intensity science + HED probes

- Bright and compact laser-based radiation sources

Broadband lasers

Optical parametric amplifiers

FLUX* technology

OPAL technology**

Common laser technology works for both ICF/HED *and* high-field science applications

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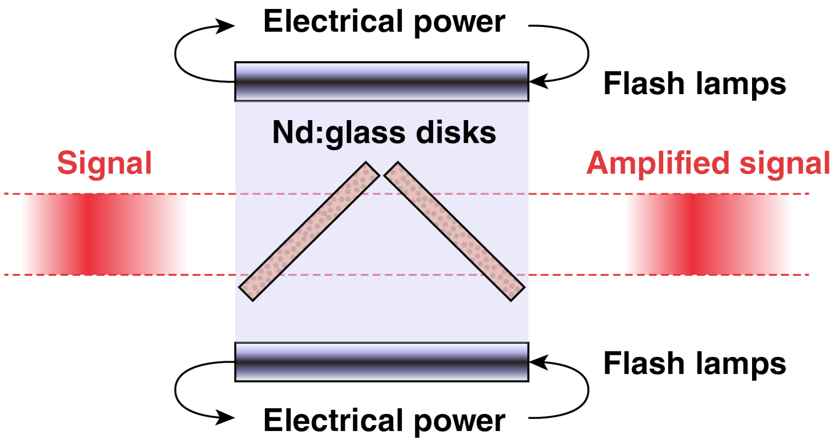
* Fourth-generation Laser for Ultra-broadband eXperiments

** Optical Parametric Amplifier Line

Ultrabroadband OPAL systems

Spectral gain narrowing limits the amplification bandwidth of laser amplifiers



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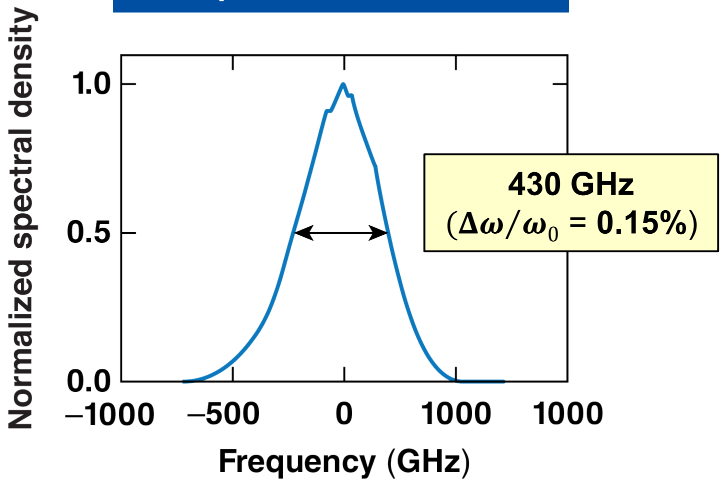
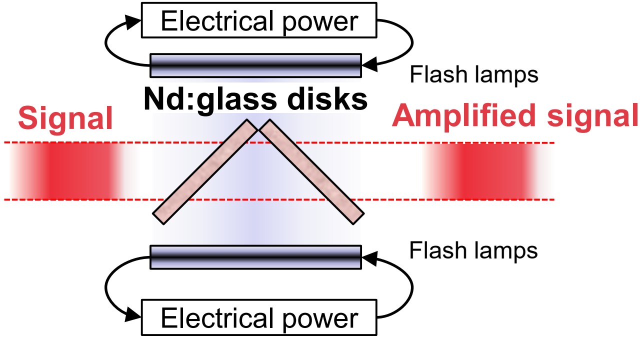
Nd:glass regenerative amplifier fluorescence



Nd:phosphate laser glass is the only solid-state laser gain material for large-aperture, high-energy amplification, but it provides insufficient bandwidth for femtosecond pulses or LPI mitigation

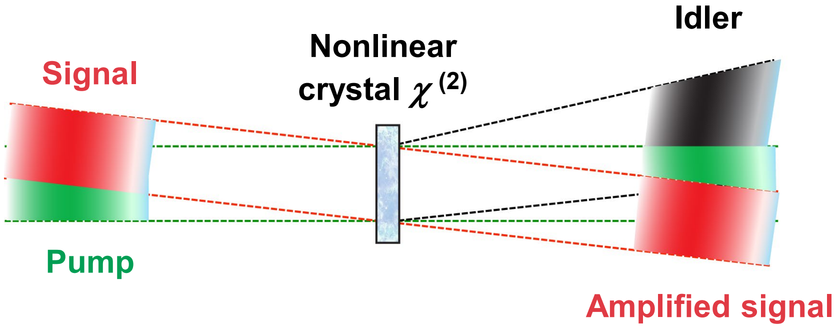
Laser and optical parametric amplifiers differ fundamentally, each possessing complementary properties

Nd:glass laser amplifier



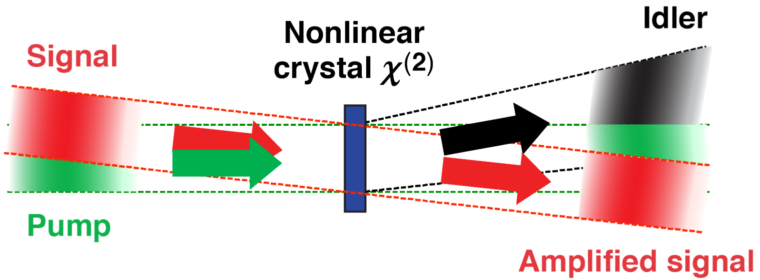
- **Neodymium ions in a glass or crystal host**
  - **— workhorse for ICF lasers**
  - **— energized electrically (flash lamps, laser diodes)**
  - **✓ High energy**
  - **✗ Narrowband (ion spectroscopy): $\Delta\omega/\omega$ < 0.3%**

Optical parametric amplifier (OPA)



- **Three-wave mixing process in nonlinear crystal**
  - **— similar to frequency-conversion (reverse of sum frequency generation)**
  - **✓ Broadband (conserves energy + momentum): $\Delta\omega/\omega$ >20%**
  - **✗ Requires laser "pump" beam**

Optical parametric amplifiers (OPAs) can have much larger bandwidths than laser amplifiers



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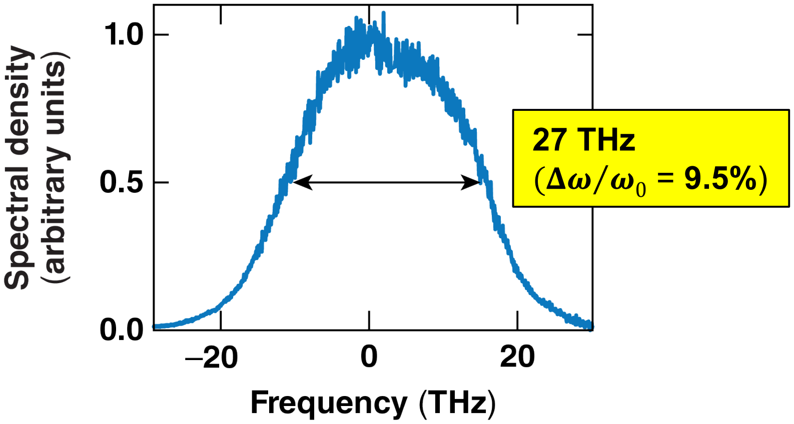
Phase mismatch $\Delta k L(\omega) = [k_s(\omega) + k_i(\omega_p - \omega) - k_p(\omega_p)]L$

LBO* OPA preamplifier



G13037

- **<u>High-efficiency energy transfer</u> from high-frequency pump to low-frequency signal (and idler)**
- **<u>Broad bandwidth</u> limited by crystal dispersion and phase-matching geometry**

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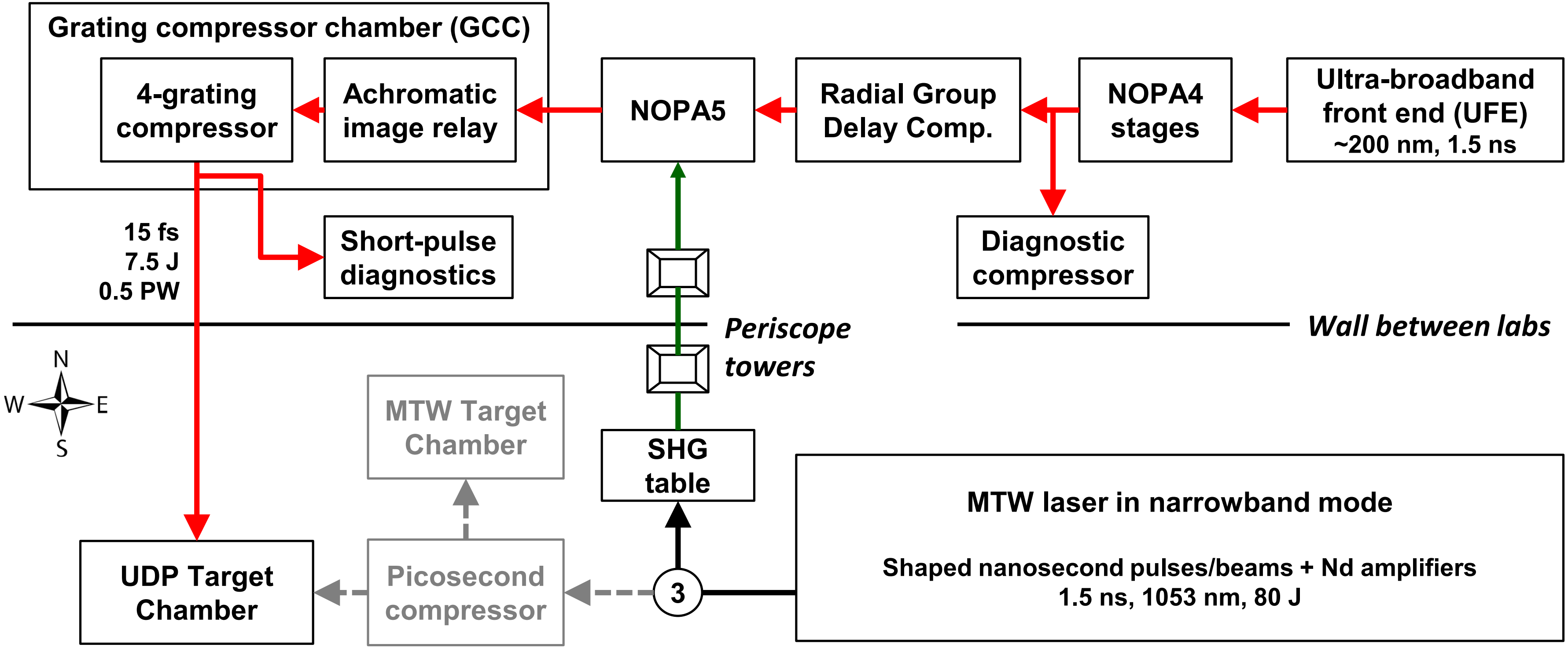
* LBO: lithium triborate

MTW-OPAL has two main parts: the broadband all-OPCPA portion, and the MTW system for pumping the final NOPA (#5)



Grating compressor chamber (GCC)

4-grating compressor

Achromatic image relay

NOPA5

Radial Group Delay Comp.

NOPA4 stages

Ultra-broadband front end (UFE)
~200 nm, 1.5 ns

15 fs
7.5 J
0.5 PW

Short-pulse diagnostics

Diagnostic compressor

Periscope towers

Wall between labs

N
W
E
S

MTW Target Chamber

SHG table

UDP Target Chamber

Picosecond compressor

3

MTW laser in narrowband mode

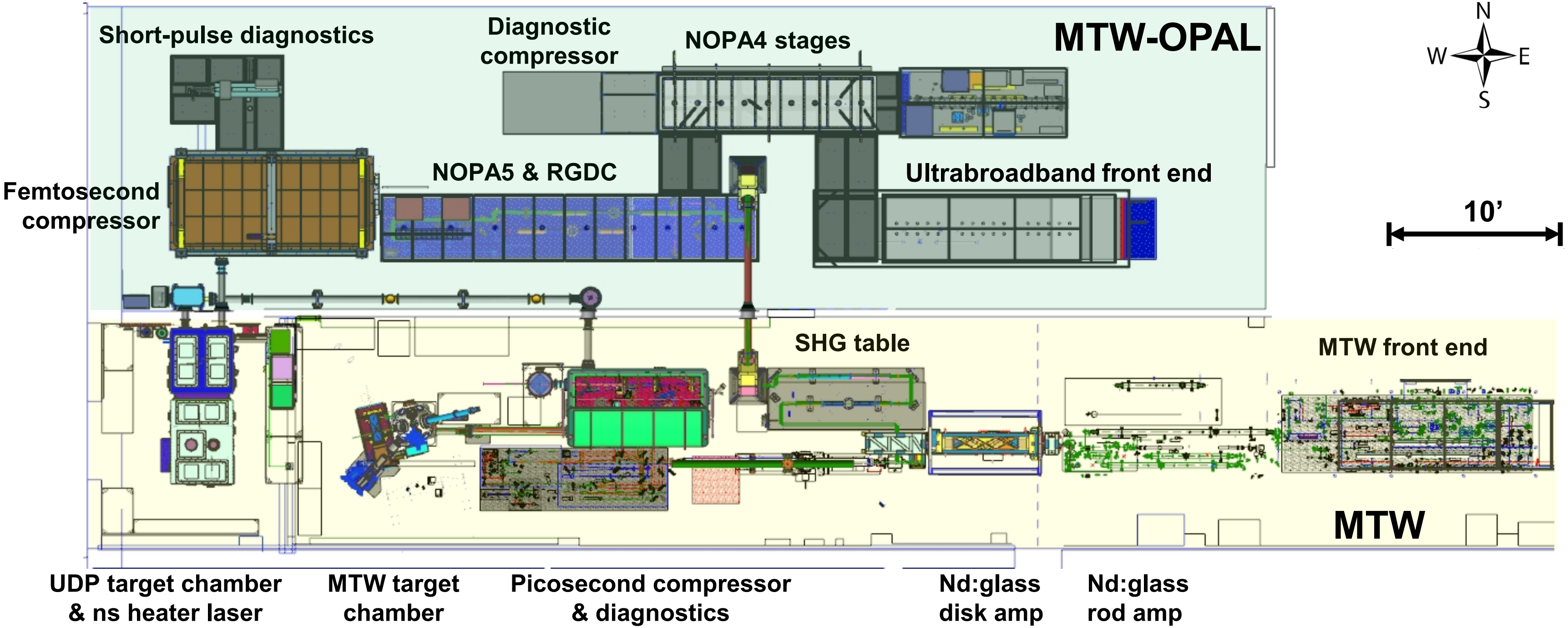
Shaped nanosecond pulses/beams + Nd amplifiers
1.5 ns, 1053 nm, 80 J

UDP: Under-dense plasma

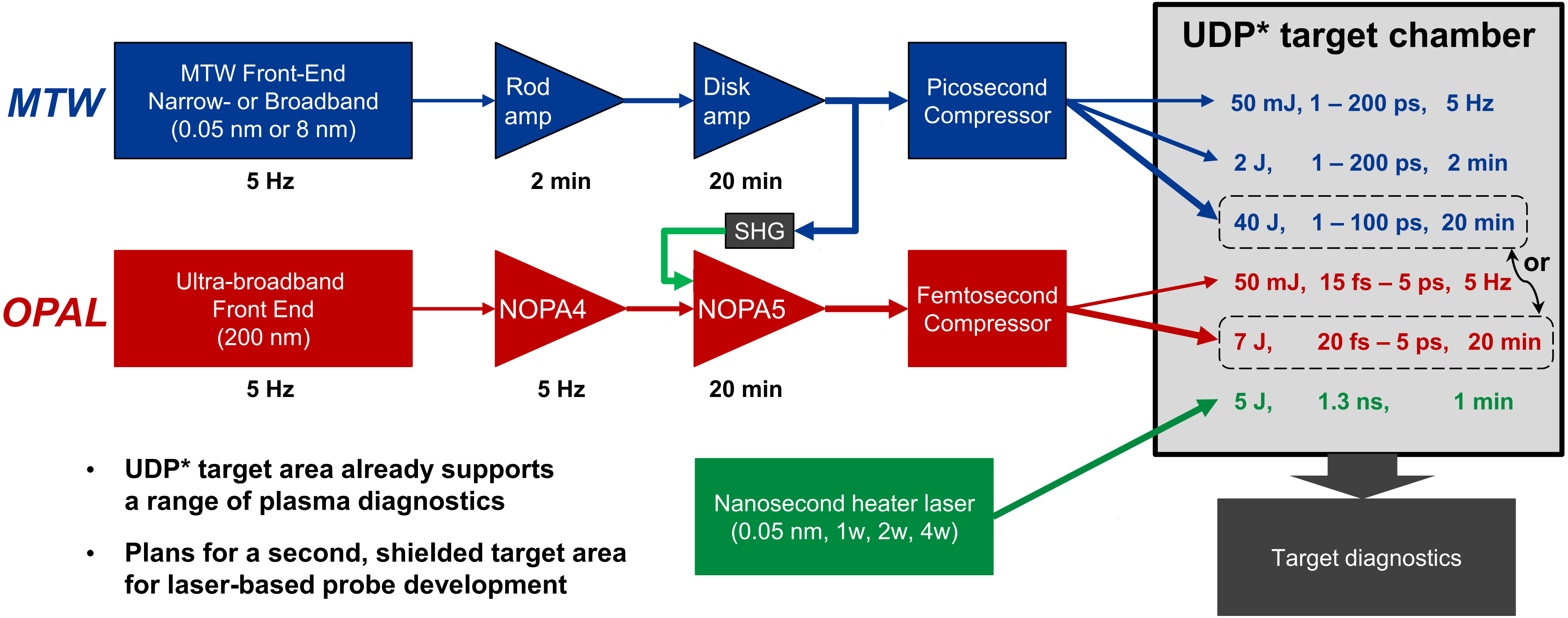
🟩 527 nm	🟥 830 - 1010 nm	▬ 1053 nm

SHG: second harmonic generation

The MTW and MTW-OPAL lasers support laser, diagnostic, and physics research and development by staff, students and external users



A joint target area support experiments with three lasers (ns, ps, fs) in a variety of configurations with existing and new target diagnostics



MTW

MTW Front-End
Narrow- or Broadband
(0.05 nm or 8 nm)
5 Hz

Rod amp
2 min

Disk amp
20 min

Picosecond Compressor

SHG

OPAL

Ultra-broadband
Front End
(200 nm)
5 Hz

NOPA4
5 Hz

NOPA5
20 min

Femtosecond Compressor

Nanosecond heater laser
(0.05 nm, 1w, 2w, 4w)

UDP* target chamber

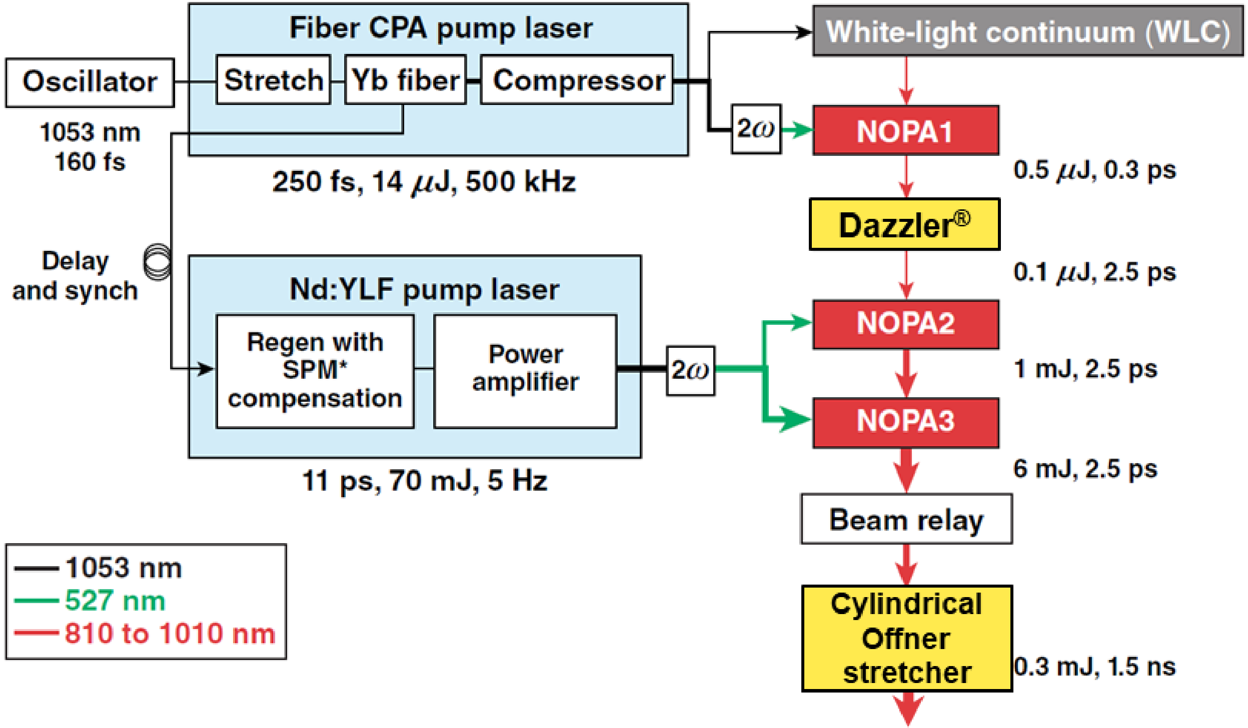
50 mJ, 1 – 200 ps, 5 Hz
2 J, 1 – 200 ps, 2 min
40 J, 1 – 100 ps, 20 min
or
50 mJ, 15 fs – 5 ps, 5 Hz
7 J, 20 fs – 5 ps, 20 min
5 J, 1.3 ns, 1 min

Target diagnostics

- **UDP* target area already supports a range of plasma diagnostics**
- **Plans for a second, shielded target area for laser-based probe development**

*** UDP – Under Dense Plasma**

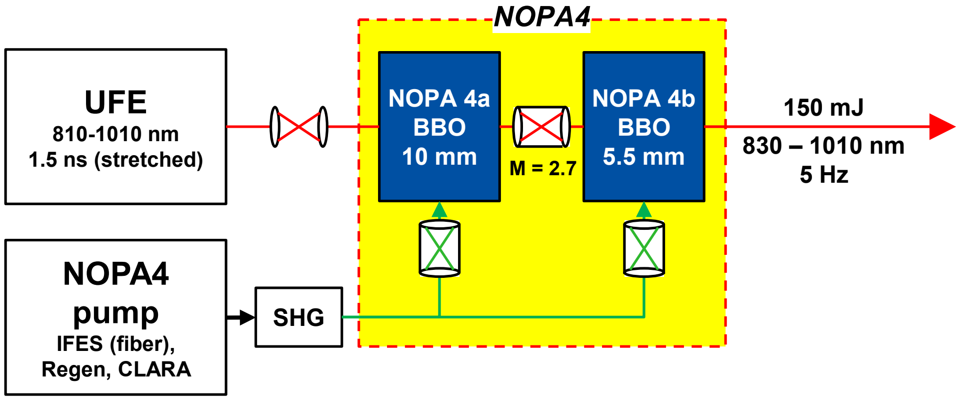
The UFE[†] uses white-light continuum generation and three NOPA stages to produce a stretched pulse compressible to <15 fs with high contrast



[†] UFE – Ultrabroadband Front End

* SPM – self-phase modulation

NOPA4 boosts the energy of the stretched pulses to 150 mJ



NOPA4

UFE
810-1010 nm
1.5 ns (stretched)

NOPA4 pump
IFES (fiber),
Regen, CLARA

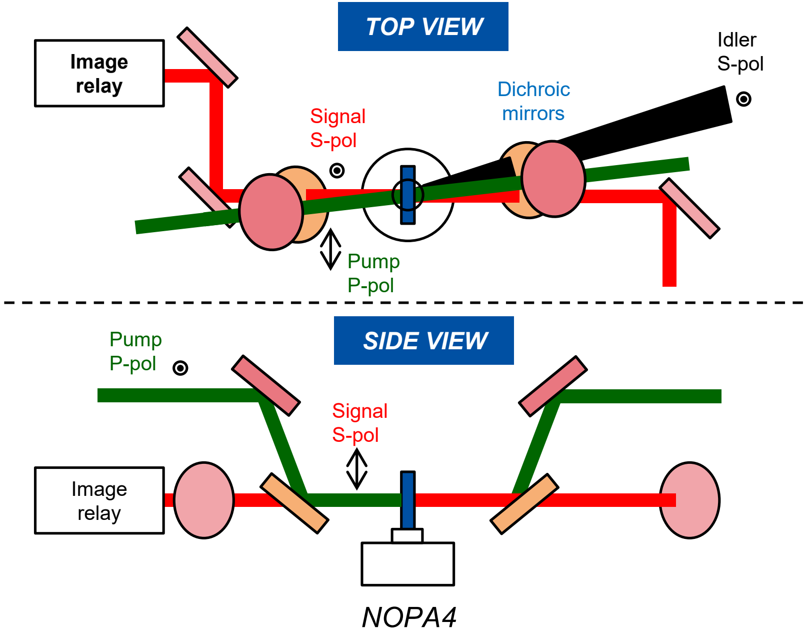
SHG

NOPA 4a
BBO
10 mm

M = 2.7

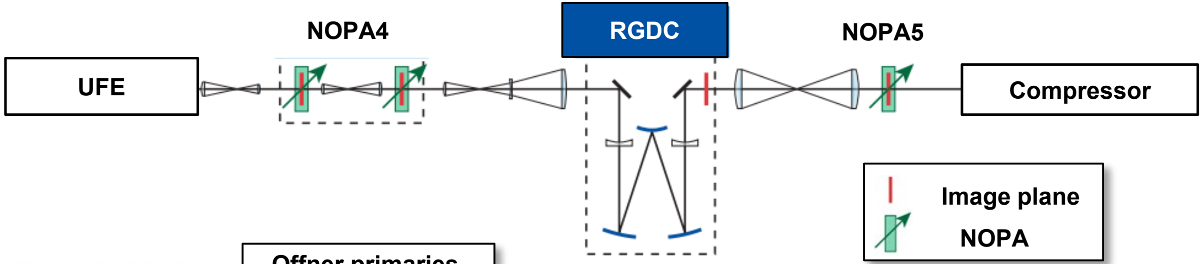
NOPA 4b
BBO
5.5 mm

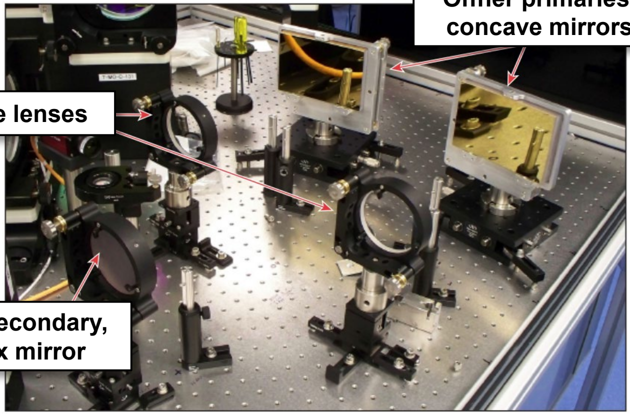
150 mJ
830 – 1010 nm
5 Hz



- **Use dichroic mirrors for pump-seed beam combination**
  - **Reflect the pump (526.5 nm)**
  - **Transmit the signal and idler**
- **Architecture can be scaled up for additional amplifier stages with larger beams**

The ultra-broadband transport system uses a novel radial group-delay compensator (RGDC) to accommodate the lens-based image relays

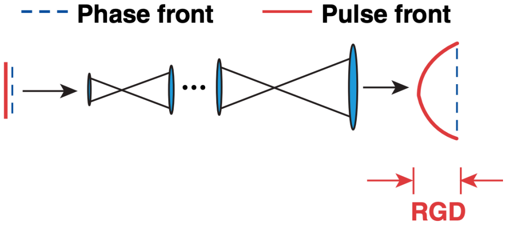


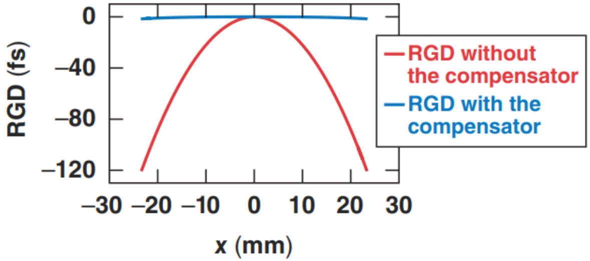


Offner primaries, concave mirrors

Negative lenses

Offner secondary, convex mirror





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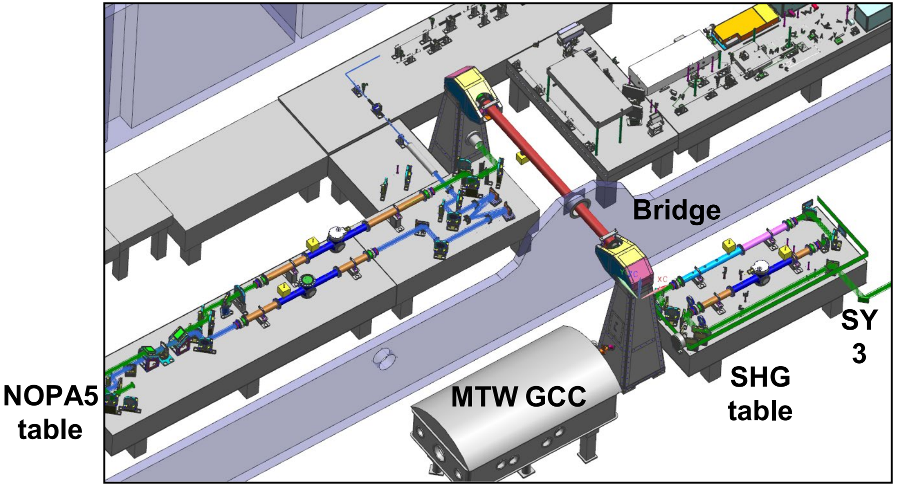
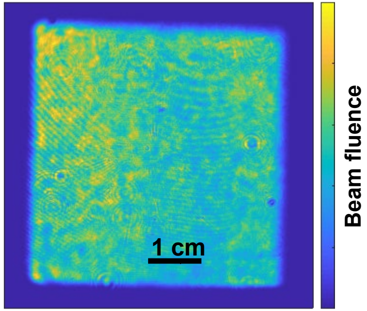
* S.-W. Bahk *et al.* Opt. Lett., 39, 1081 (2014)

The MTW laser delivers narrowband 527-nm pulses (2ω) for pumping the final MTW-OPAL amplifier (NOPA5) with up to 50 J of energy in a 1.5-ns pulse

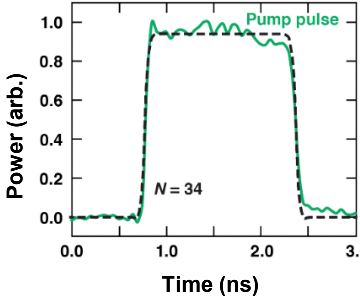
- A series of three switchyards redirects the MTW OPCPA pump laser towards NOPA5
- MTW adaptive pulse and beam shaping systems optimize uniformity in space and time



NOPA5 pump near field



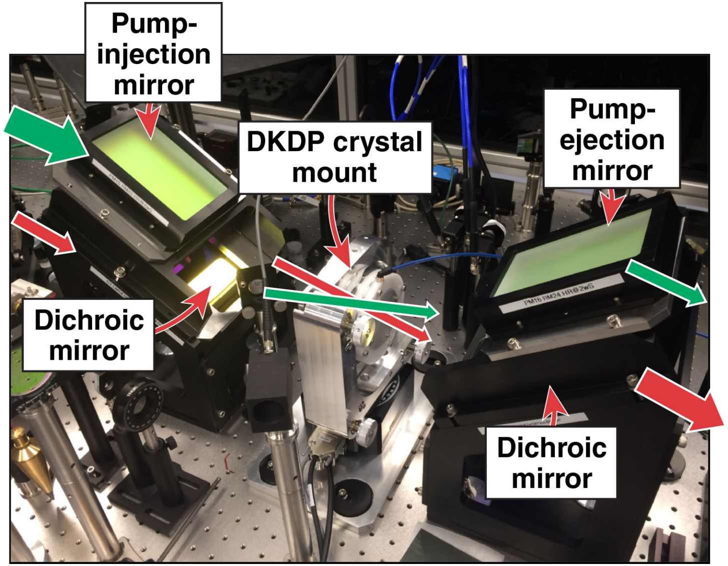
NOPA5 pump pulse



Flat beams and flat pulses maximize NOPA5 pump-to-signal efficiency (up to 40%)

The NOPA5 amplifier produces >10-J pulses with bandwidth that supports sub-20-fs compressed pulse widths

- NOPA5 employs highly deuterated DKDP (≥70%)
- Higher deuteration values are preferred
  - broader gain bandwidth (up to 810 to 1010 nm)
  - less idler absorption
- Pump and seed beams are combined and separated using dichroic mirrors



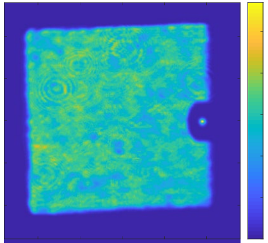
G11860d

The 70% deuteration level of current NOPA5 crystals limit bandwidth; full-aperture crystals with 95% deuteration have been delivered

A ‘first light’ campaign commissioned MTW-OPAL with 350-TW pulses that now can propagate to the under-dense plasma target chamber

High-quality beams for maximum throughput

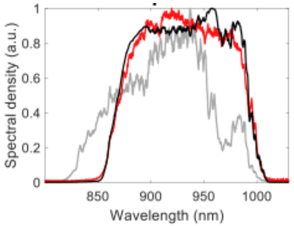
NOPA5 beam



11 J, 1.4:1 (peak-mean)

Broadband output from all-OPCPA system

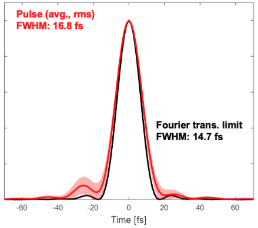
NOPA5 spectrum



140 nm (FW10%)

Compressed pulses near Fourier transform limit (FTL)

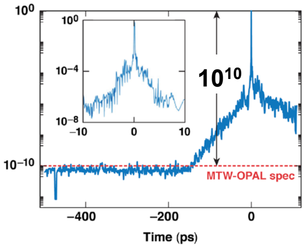
NOPA4 pulse



Pre-shot: 1.14 x FTL
On-shot: 1.23 x FTL

High temporal contrast
(currently diagnostic limited)

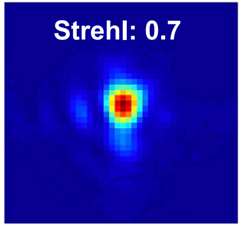
Pre-shot contrast



> 10^{10} at -150 ps

High-quality focus
(sub-beam, no adaptive optics)

OAP focus (70-mm beam)

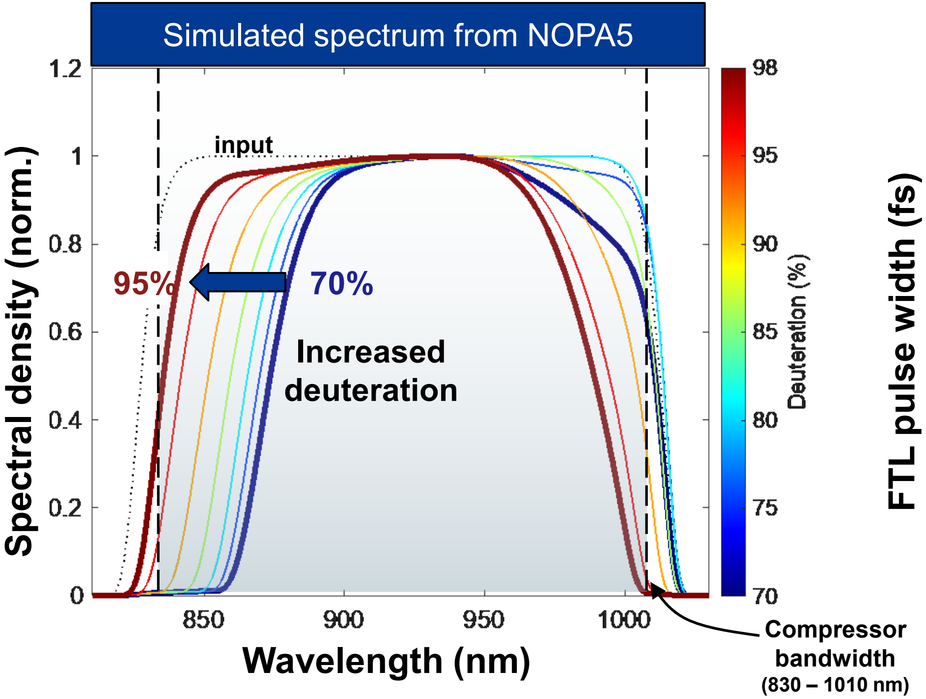


Strehl: 0.92 (expected w/ deformable mirror)

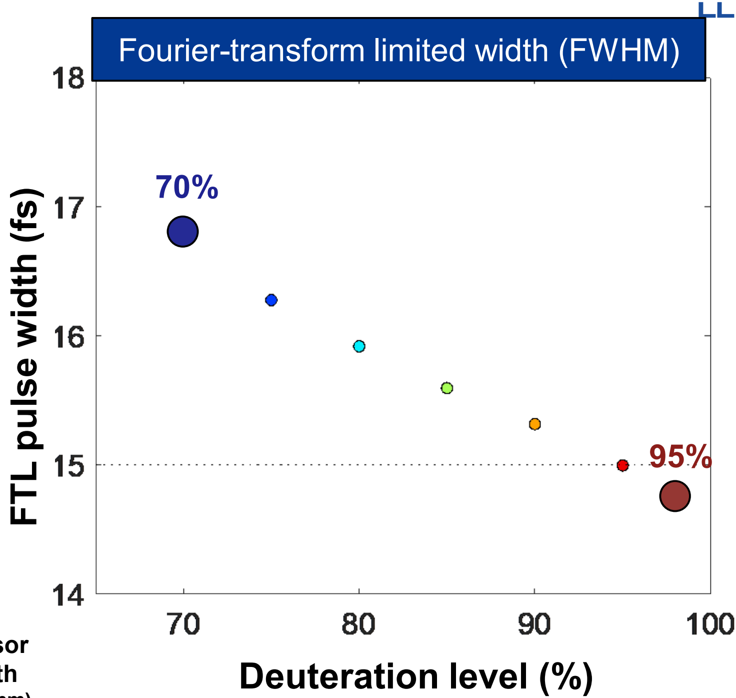
- **Mid-scale demonstrates technology scalable to femtosecond-kilojoule pulses**
- **On-going improvements to “back-end” with new NOPA5 crystal, double-plasma mirrors, and adaptive optics**

HPLSE, Vol. 9, e63 (2021);
DOI: https://doi.org/10.1017/hpl.2021.45

Simulations show that DKDP crystals with higher deuteration will increase NOPA5 bandwidth enabling shorter pulses



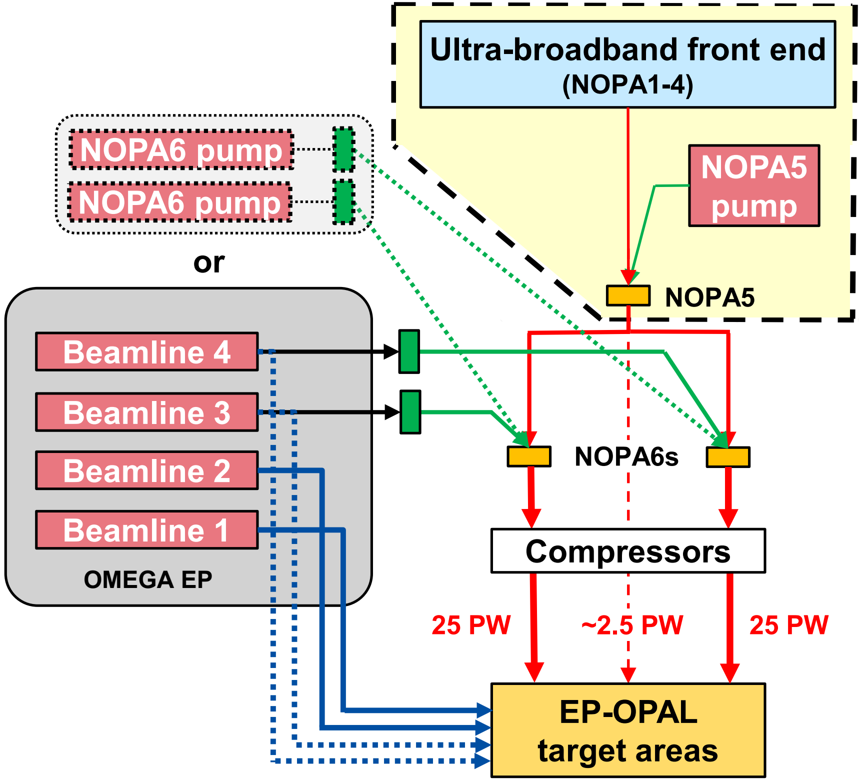
Simulated spectrum from NOPA5

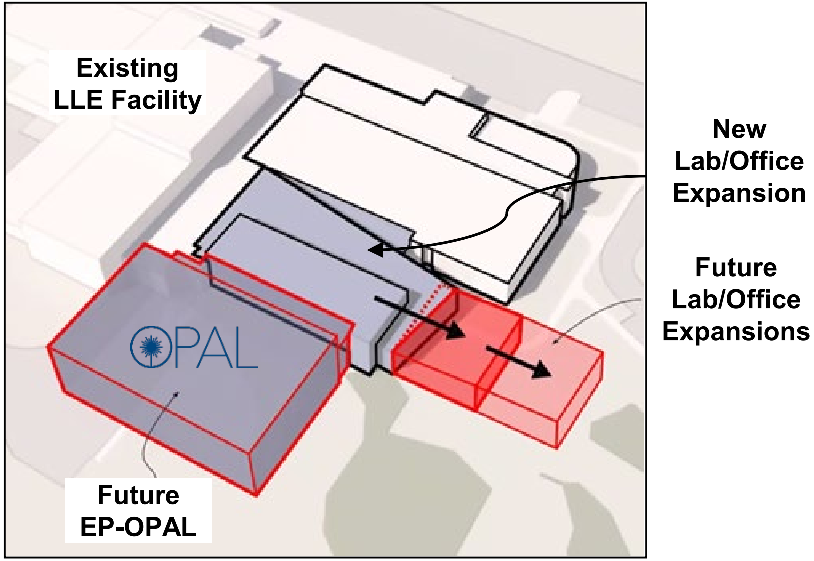


Fourier-transform limited width (FWHM)

Higher deuteration crystals (>90%) can fully utilize the bandwidth of NOPA4 and the compressor

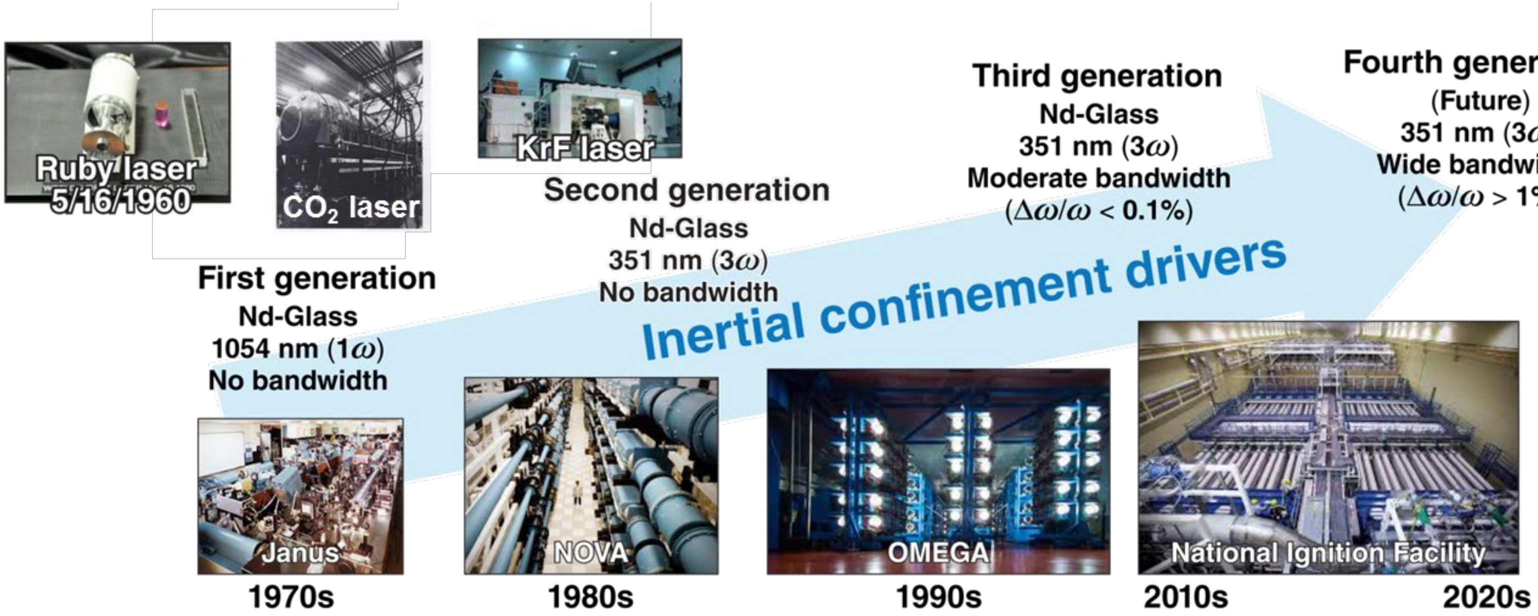
LLE has submitted a preliminary proposal to NSF for EP-OPAL and expect to be invited to submit a full proposal due by May 5





Incoherent broadband laser systems

The FLUX* program is a multi-year effort to demonstrate broadband laser driver technology to mitigate LPI** and improve irradiation uniformity



First generation
Nd-Glass
1054 nm (1ω)
No bandwidth

Second generation
Nd-Glass
351 nm (3ω)
No bandwidth

Third generation
Nd-Glass
351 nm (3ω)
Moderate bandwidth
($\Delta\omega/\omega < 0.1\%$)

Fourth generation
(Future)
351 nm (3ω)
Wide bandwidth
($\Delta\omega/\omega > 1\%$)

---

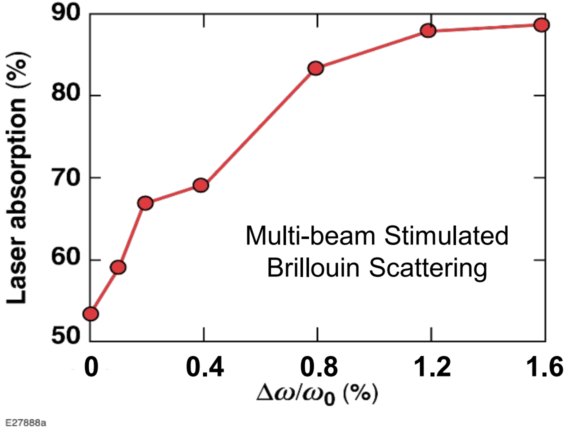
* Fourth-generation Laser for Ultra-broadband Experiments

** Laser Plasma Instabilities

Broad-bandwidth, laser direct-drive (LDD) can mitigate laser-plasma instabilities (LPI) and couple higher intensities to ICF capsules, plus reduce laser imprint

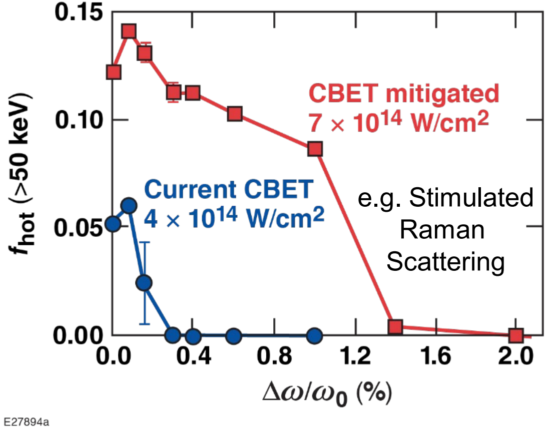
Cross-Beam Energy Transfer (Increased Drive Pressure)

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

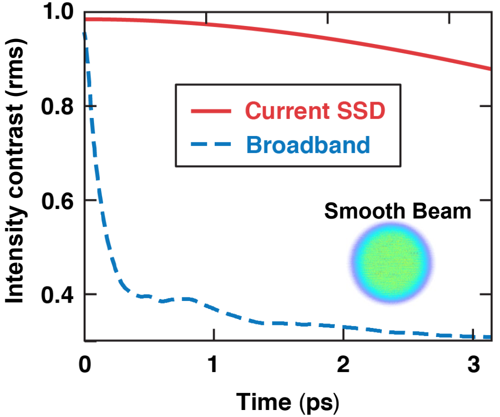


Hot-Electron Mitigation (n_{cr} / 4 ignition intensities)

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



Imprint Mitigation (ps asymptotic smoothing)

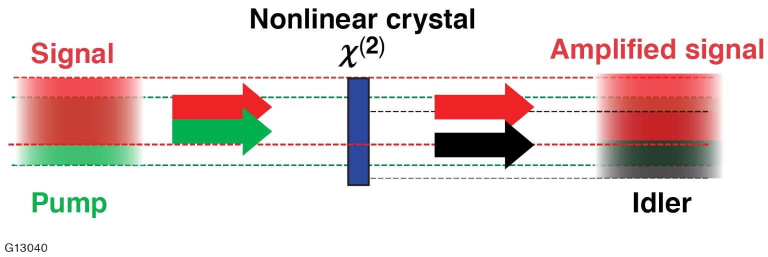


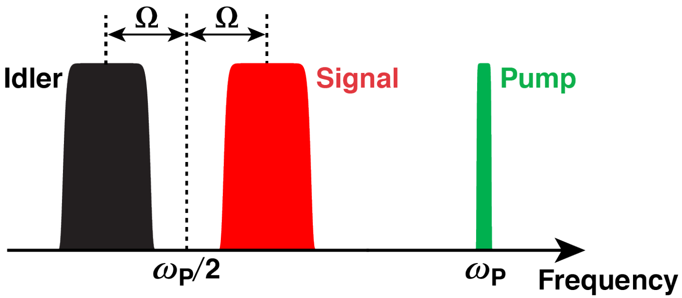
SSD: Smoothing by Spectral Dispersion

Simulations predict laser bandwidth $\Delta\omega/\omega$ > 1.5% will enable robust LDD-ICF implosions

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

Operation close to spectral degeneracy and a collinear configuration for the last OPA increase the available energy and bandwidth

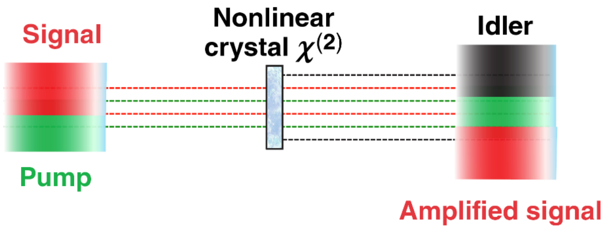




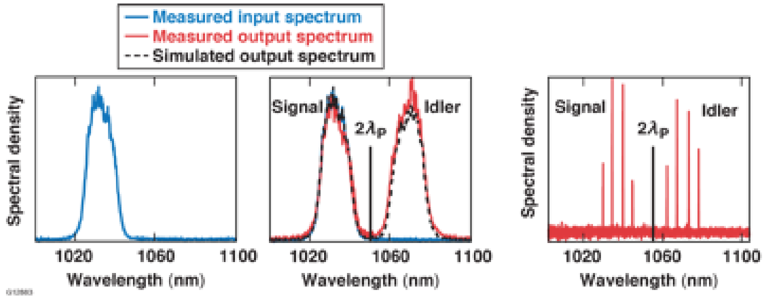
- Type-I collinear interaction
  - co-polarized, co-propagating signal and idler
  - output energy ~2× signal energy
  - larger output bandwidth
- Seeding with pump, signal, and idler from the previous stage can lead to detrimental effects
  - collinear configuration only used in last OPA

FLUX* implements novel nonlinear optical schemes to deliver broadband, incoherent UV laser illumination

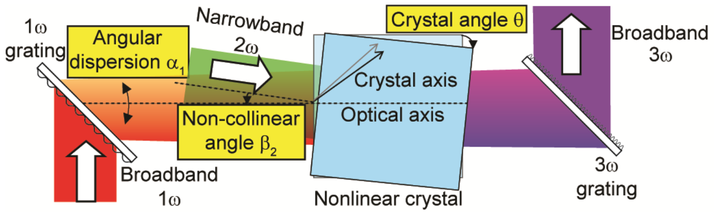
Collinear Optical Parametric Amplifier (COPA) near degeneracy



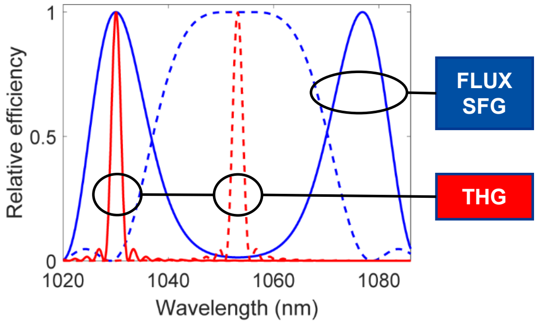
Bandwidth and spectral shaping



Sum Frequency Generation (SFG) boosts broadband IR signal and idler beams to UV



Simulated SFG + THG outputs



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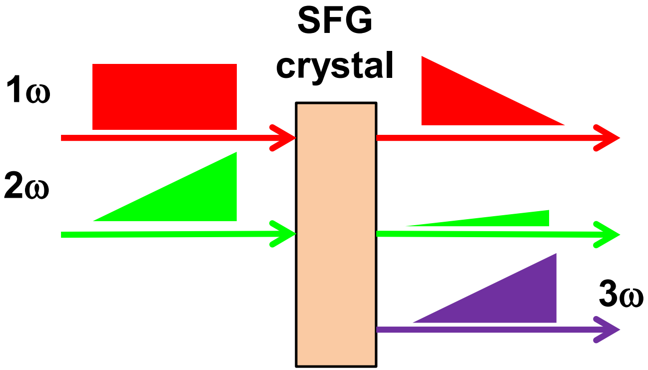
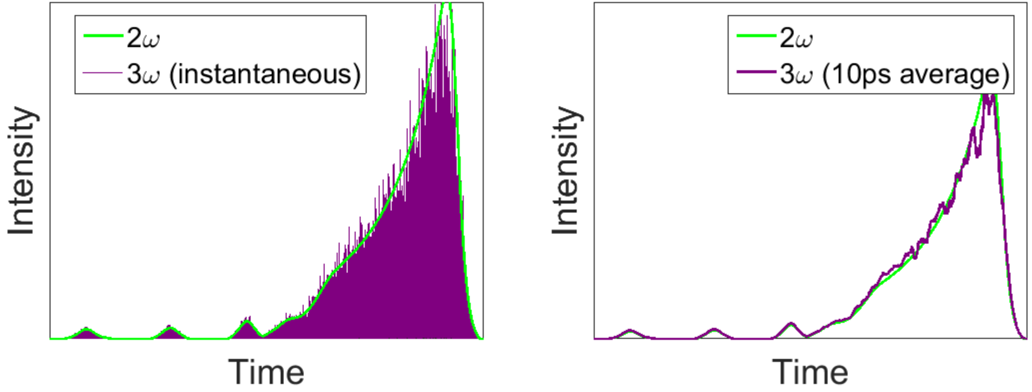
* Fourth-generation Laser for Ultra-broadband eXperiments

Temporally shaping the narrowband 2ω pump pulse used for Sum Frequency Generation provides pulse shaping at 3ω

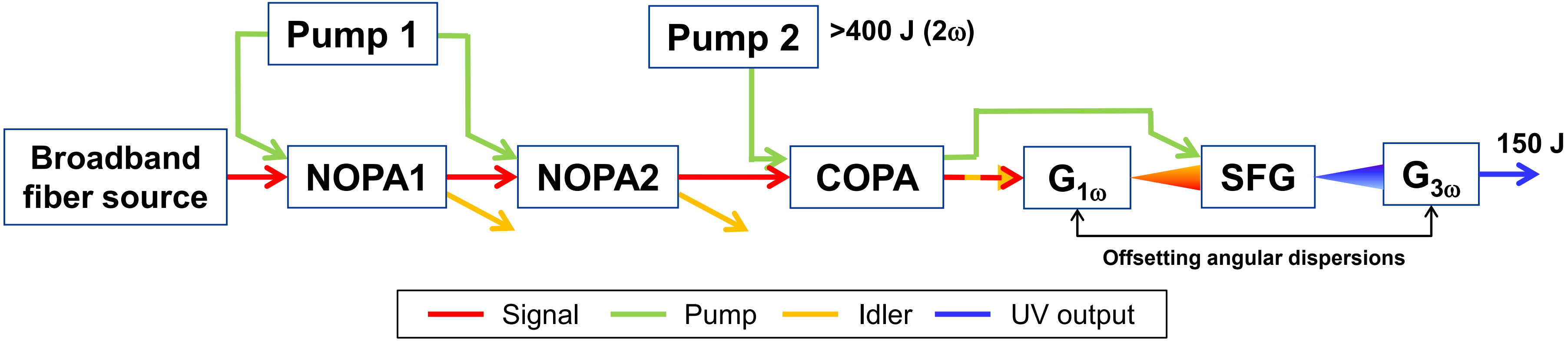


Simulated FLUX performance



- 3ω output intensity approximately linear relative to 2ω input intensity
- High-dynamic-range pulse shaping in SFG is easier than for conventional tripling schemes currently implemented in high-energy laser systems

FLUX* implements novel nonlinear optical schemes to deliver broadband, incoherent UV laser illumination

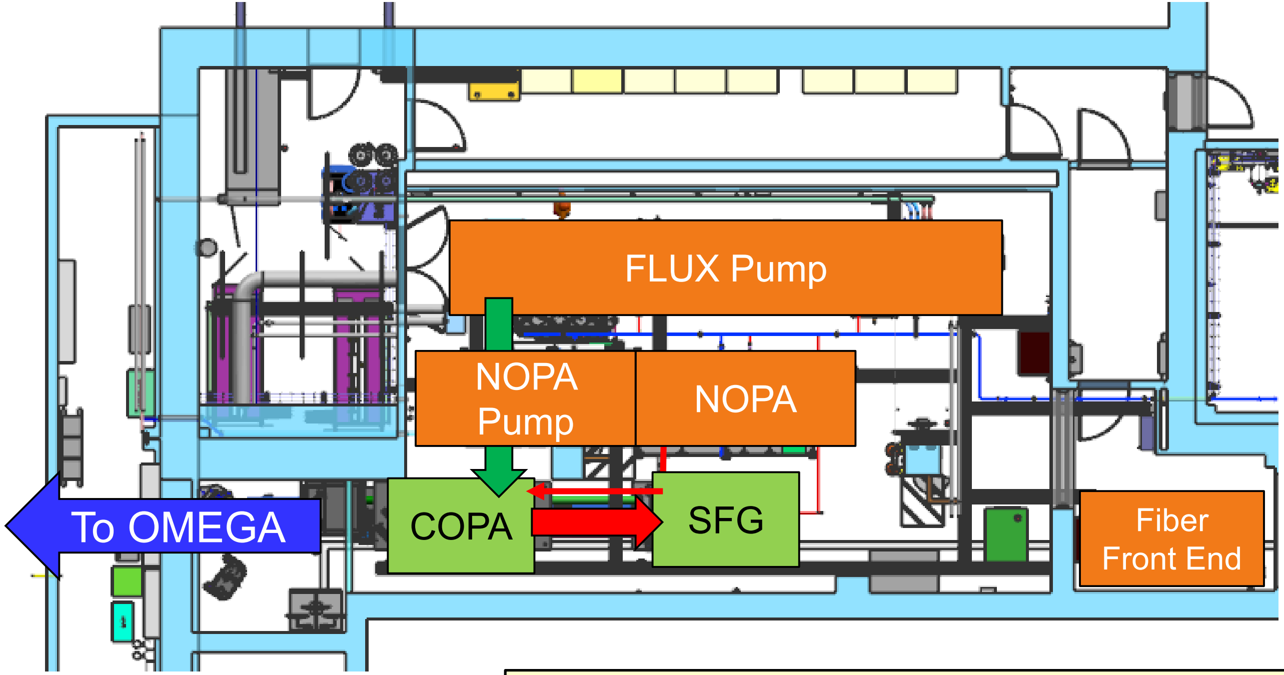


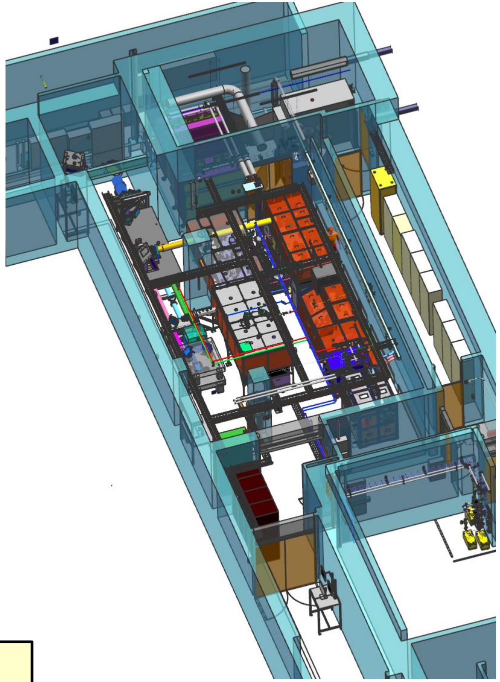
- Remove idler waves after NOPA** stages to avoid coherent reconversion of signal/idler waves
- Keep signal and idler waves after the COPA** stage for energy efficiency and broader bandwidth
- Sum-frequency generation (SFG) with the 2ω pump beam shifts the COPA output to ultraviolet (UV)*
  - 1ω gratings phase matches the SFG process and a matched 3ω grating sets dispersion for focal spot beam smoothing

** NOPA/COPA – noncollinear/collinear optical parametric amplifier

* C. Dorrer et. al., "Broadband sum-frequency generation of spectrally incoherent pulses", Optics Express, Vol. 29, Issue 11

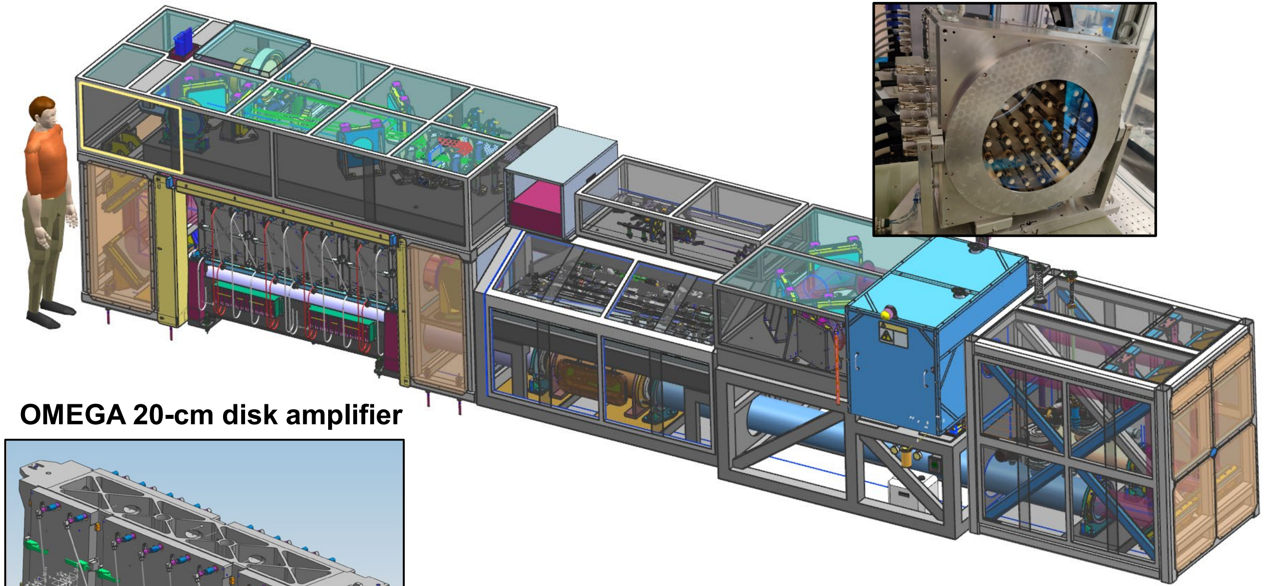
Design reviews for most FLUX subsystems have been completed, NOPA system commissioning is underway, and FLUX pump laser construction has started





FLUX-P9 transport design review scheduled May 25

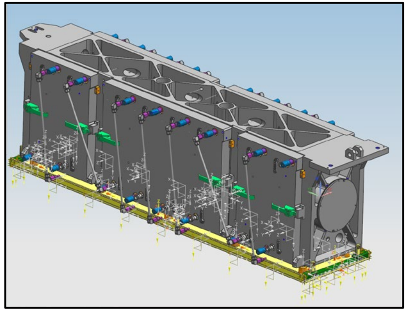
A major design element of the FLUX system is the Active Multi-pass Imaging Cavity Amplifier (AMICA) which integrates a complete beamline into a flexible package that can serve multiple programs



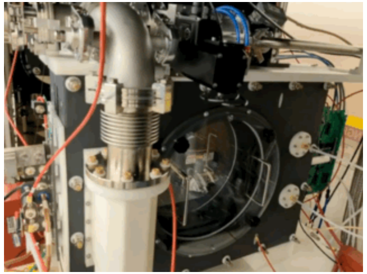
Deformable Mirror

AMICA-based FLUX pump laser	AMICA+ laser *plus* booster amp
600 J (1ω) 400 J (2ω)	~2 kJ (1ω) ~1.5 kJ (2ω)
2× 1.5 ns	30 ns
narrowband	Multi-FM SSD

OMEGA 20-cm disk amplifier



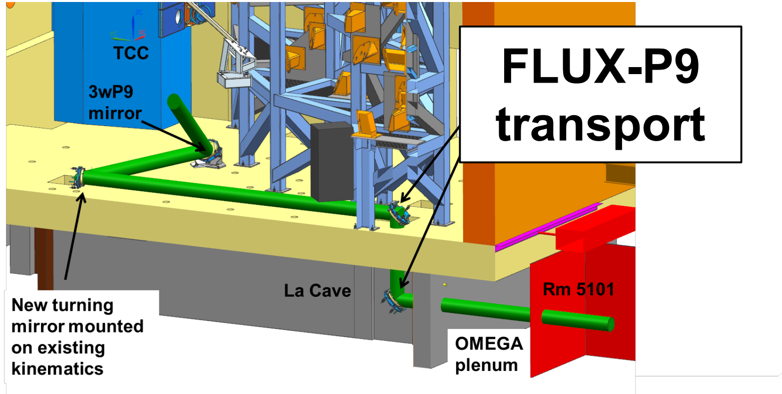
LLE midscale PEPC



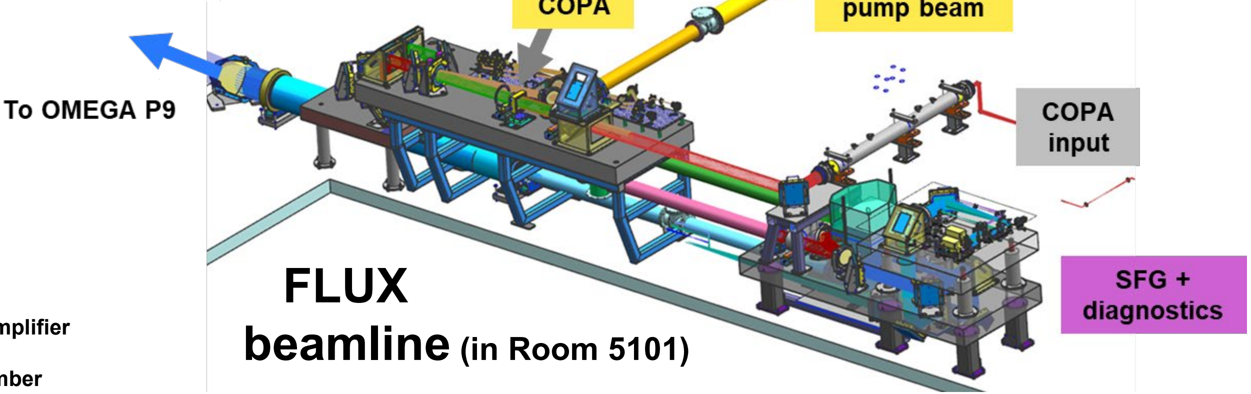
The FLUX Pump design leverages technology proven on OMEGA-60 and OMEGA-EP: 20-cm OMEGA Amplifier, Plasma Electrode Pockels Cell (PEPC), Deformable Mirror

SSD: Smoothing by Spectral Dispersion

The FLUX* beamline and beam transport will deliver broadband, incoherent laser pulses to the OMEGA target chamber for experiments



Physics requirement	Specification
Central wavelength	351 nm (3ω)
Fractional bandwidth $\Delta\omega/\omega_0$	0 to 1.5%
Pulse duration/shape	1.5 ns/flat in time
Energy	150 J
On-target power	0.1 TW
Far-field size	Focusable to 100 μm (with distributed phase plates)
On-target intensity	10^{15} W/cm^2



FLUX beamline (in Room 5101)

COPA – collinear optical parametric amplifier
SFG – sum frequency generation
P9 – P9 port of OMEGA target chamber

* Fourth-generation Laser for Ultra-broadband eXperiments

ICF* and HED** applications drive laser science and technology R&D at LLE

- **LLE develops laser and optical technology with broad scientific applications**
- **The MTW and MTW-OPAL lasers have served as cornerstones for laser <u>and</u> laser-plasma science R&D at LLE**
  - Ultrafast lasers promise a path for implementing next-generation HED probes of burning plasmas and hydrodynamics at NNSA compression facilities
  - MTW-OPAL commissioning ("first light") demonstrated 350-TW pulses ready for experiments, plus it has enabled strategic hiring and significant physics and lasers workforce development
  - The MTW-OPAL laser produces 0.35-PW laser pulses and prototypes technologies that can scale to tens of petawatts
- **FLUX technology will expand laser direct-drive, inertial-confinement fusion (LDD-ICF) design space and enable higher performance implosions**
  - The FLUX project leverages expertise developed for ultrafast lasers to provide broadband, incoherent ICF and HED laser drivers

* Inertial Confinement Fusion
** High-Energy Density