The Basic Research Needs Workshop on Laser Technology

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On behalf of the workshop organizing committee

21 June 2024

Outline

Summary of Basic Research Needs Workshop (BRN)

Perspectives on mid-IR development facilities (not BRN output)

Laser Technology R&D enables scientific breakthroughs

Nobel Prize in chemistry 1999

Ahmed H. Zewail for his studies of the transition states of chemical reactions using femtosecond spectroscopy"

Nobel Prize in physics 2018

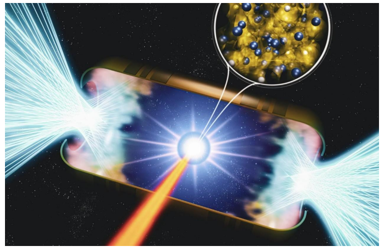
Gérard Mourou and **Donna Strickland** for "their method of generating high-intensity, ultra-short optical pulses"

Nobel Prize in physics 2023

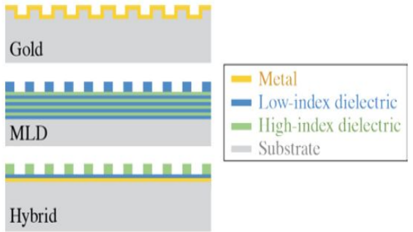
Pierre Agostini, Ferenc Krausz, Anne L'Huillier
"for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter"

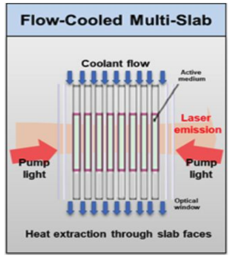
and broad science & tech…

Credit: Photo from ATF



New laser architectures emerging to carry this forward...





BRN: priority research directions & grand challenges

Workshop Charge

- Identifying areas of strong mutual **interest across participating federal agencies**
- Identifying areas of strong mutual **interest with industry, including supply chain concerns**, and ways to foster public-private partnerships to address them
- Assessing **which R&D investments** are expected to have the **highest impact**
- Identifying present and anticipated **workforce development concerns**, potential mitigation strategies
- Assessing how the proposed U.S. R&D activities **compare with global laser R&D efforts**

Outcome: Report with **Priority Research Directions**, Brochure

Panels:

Science

Technology

Crosscut

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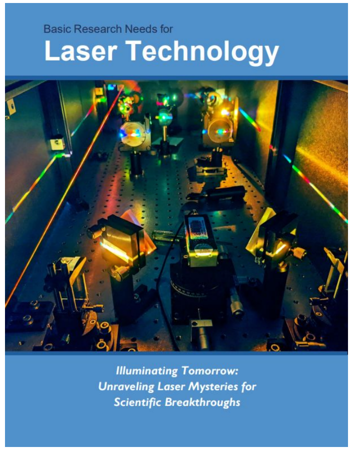
BASIC RESEARCH NEEDS WORKSHOP ON LASER TECHNOLOGY

2023 REPORT



Basic Research Needs for

Laser Technology

Illuminating Tomorrow: Unraveling Laser Mysteries for Scientific Breakthroughs

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Science Panels: Ultrafast & High-field Science; Sources

Ultrafast Science

Co-leads:
Robert Baker, Keith Nelson,
Linda Young

- Dynamics in molecules and materials
- Chemical sensing and spectroscopy
- Photochemistry
- Strong field dynamics, attosecond spectroscopy, Field-resolved spectroscopy

High-field Science

Co-leads:
Felicie Albert,
Franklin Dollar

- Quantum Electrodynamics
- Laboratory astrophysics
- Electron acceleration and light sources
- High Energy Density Science

Novel Radiation and Particle Sources

Co-leads:
Stephen Benson,
Sergio Carbajo

- Nuclear physics research
- High-brightness Electron Beams
- High Intensity Proton and Muon sources
- Novel radiation sources

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Four broad directions for future laser technology

High Repetition Rate Laser (Type I)
Up to 1 GHz
Peak power > 1 kW, average power up to 100 W
Wavelengths from NIR to MIR

Chemical sensing and spectroscopy

High-current polarized electron/positron sources

Electron dynamics

Small cross-section process studies

High Average Power Laser (Type II)
Up to 10 kHz
Peak power 50-300 TW, average power up to 100 kW
Wavelengths from VIS to MIR

Plasma-based electron accelerators

Probing exotic states

X-ray imaging and non-destructive evaluation

Proton beam manipulation

Few Cycle Laser (Type III)
Above 100 kHz
Peak power 1-10 TW, 10-100 mJ pulses
Wavelengths in MIR

Tracing molecular & material dynamics

Photochemistry

Control of molecular & material dynamics

Mapping transients with element specific resolution

High Intensity Laser (Type IV)
0.1 – 10 Hz
Peak Power 10-100 PW
Wavelengths NIR

Quantum Electrodynamics

Astrophysical phenomena

Neutron, ion, gamma, muon radiography sources

Generation of HED and WDM plasmas

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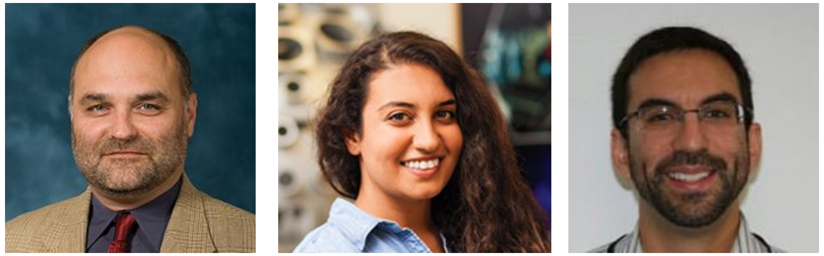
Technology Panels



High peak power and average power sources

Co-leads:
Almantas Galvanauskas, Leily Kiani,
Anthony Valenzuela

- High Peak and average power
- High peak power (PW class)
- High energy and average power lasers
- Nanosecond kJ lasers

Enabling Technologies

Co-leads:
Stavros Demos,
Douglass Schumacher

- Gain media and pumping
- Coatings, multilayer dielectric gratings, damage threshold
- Nonlinear crystals
- Beam control in laser systems
- Pulse characterization and control
- Experimental diagnostics

Extensions to new wavelength ranges and new light sources

Co-leads:
Michael Chini,
Jeffrey Moses

- Pulsed laser sources at UV, mid-IR and THz
- Non-linear optical systems for wavelength extension
- Control of wavefront shape, spatio-temporal shape, polarization
- Frequency combs and dual comb sources
- Field-controlled multi-color or hyperspectral high-power sources

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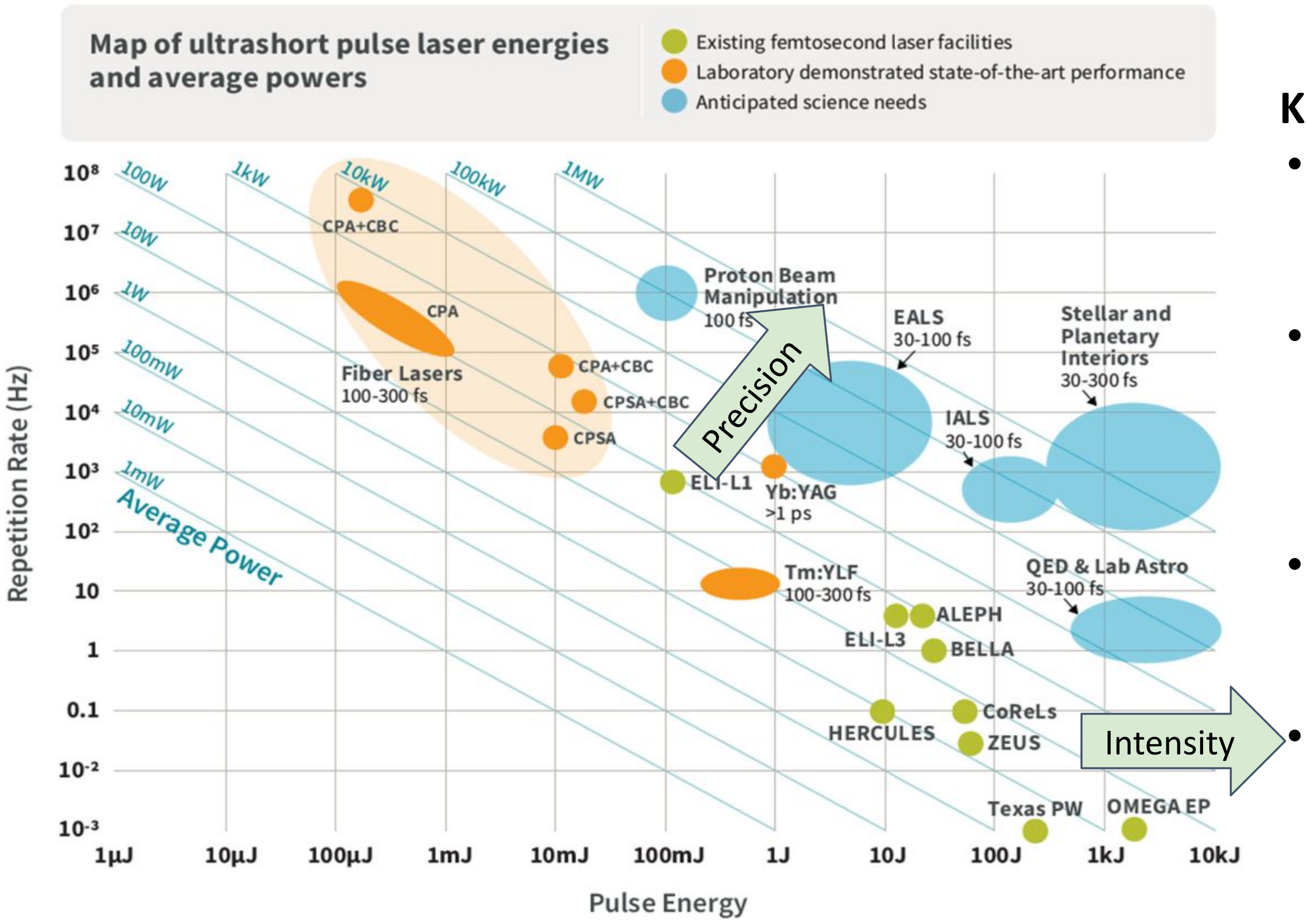
Priority Research Direction (PRD) Defined

High-level statement defining an R&D area that has high potential for producing transformative scientific breakthroughs.

- It is **broadly applicable** – its successful completion will impact as many areas of science (and technology) as reasonably possible
- It is **durable** – it will not be mooted by R&D in the next 2-3 years, but could be achieved in 5-10 years

PRD 1: Revolutionize Laser Power, Energy, Precision Control



Map of ultrashort pulse laser energies and average powers

Key Questions:

- *How do we extend laser performance to address ultra-intense science needs in the next decade?*
- *How might ultra-intense laser performance be extended to create and probe extreme conditions that represent the frontiers of science needs in the next decade?*
- *What laser architectures enable high repetition rate operations?*
- *How could ultra high peak power lasers also be scaled to extreme repetition rates?*

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Transformative opportunities in rate and energy

Motivation:

- Study of extreme physical states of matter in the universe
- New regimes of energetic particle generation
- Propel fundamental science
- Unlock high- impact applications in medicine, advanced materials, beyond
- Requires transformative advances in energy, intensity, pulse rate, control

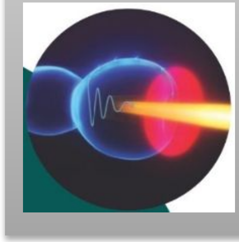
Opportunity

- New materials and architectures
- Contrast enhancement
- Coherent combination of many channels at sub-wavelength precision
- Direct diode pumped gain media
- Adaptive feedback control enabling pulse shaping & stability
- Post-compression

Overcome previous limits, open new science areas

100 TW and beyond, at kHz and beyond

Laser wakefield accelerators, radiation sources, THz, Optical Parametric Amplifier pumps (PRD2)

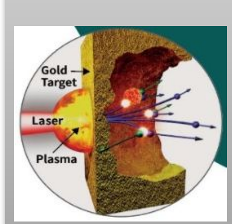


Innovations in:

- Coherent combination of many Yb or Tm fibers
- YAG,YLF bulk laser pumping, heat extraction, post compression
- Active feedback stabilization and precision shaping
- Combine high efficiency and multi-J pulse energy

Beyond 10 PW lasers

High field science, QED, ion acceleration, light sources

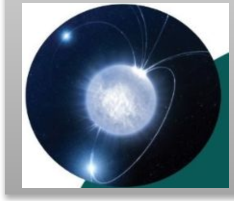


Innovations in:

- Optical Parametric Amplifiers for highest intensities
- Optic and grating aperture
- Extreme temporal contrast > 10^{12}, cooling for rate
- Coherent combination of apertures, spectral bands

Nanosecond kJ systems with shaping, rate

Matter at extreme high energy densities, pump lasers



Innovations in:

- Energy scaling of cooled, diode pumped systems
- Precision spatial smoothing, temporal shaping

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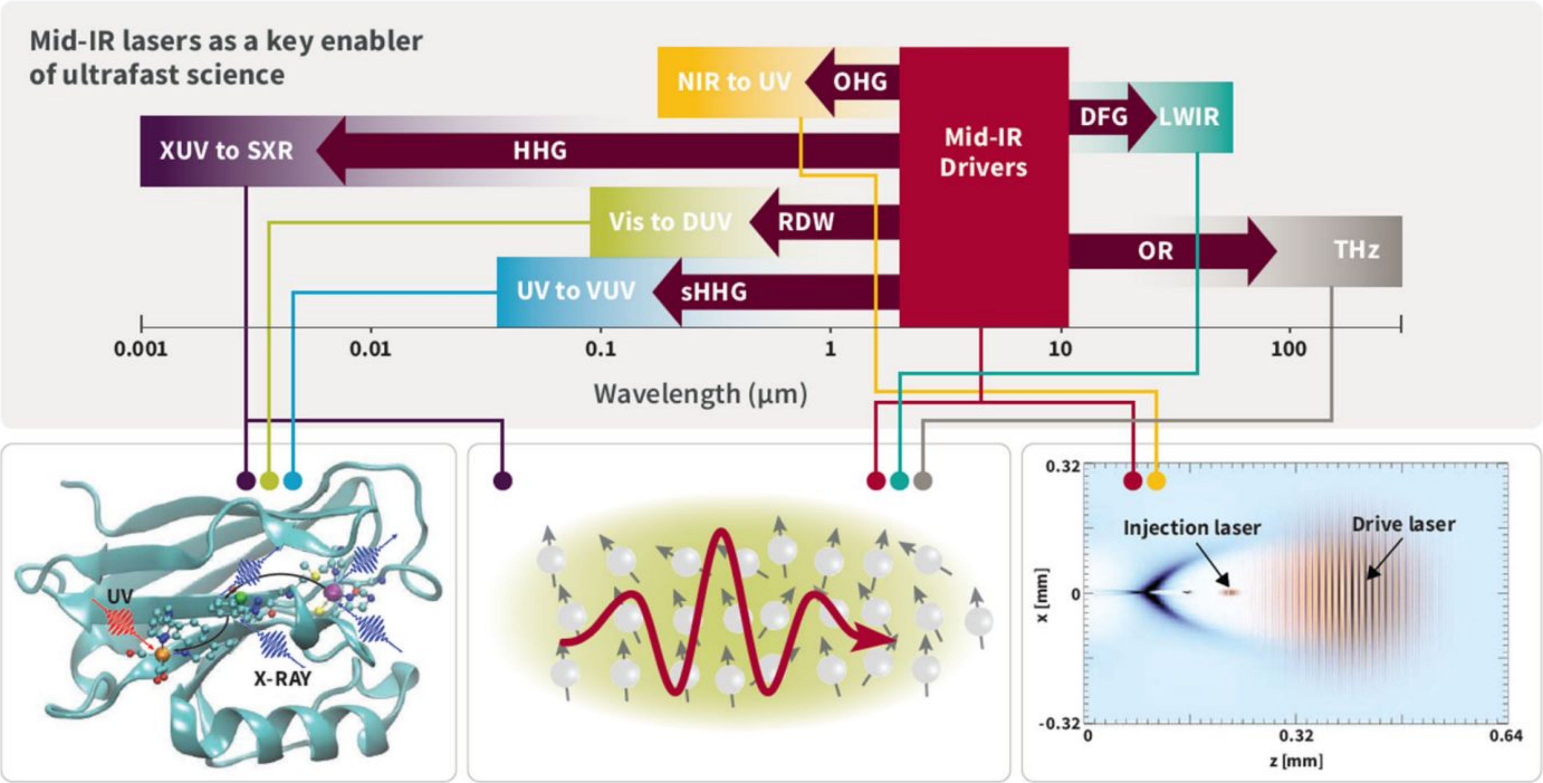
PRD 2: Transform Mid-IR Sources for Science from THz to X-Rays

Key Questions:

- *Can we **create the new laser technologies** needed to meet the significant demands for **high average and peak power mid-infrared science**, and for driving secondary sources with extreme spectral coverage?*
- *How do we **overcome the current limitations** in mid-IR laser intensity to take full advantage of ponderomotive* λ^2 *scaling?*
- *What are the ideal wavelengths, **platforms, and architectures** for nonlinear conversion from the mid-IR to generate transformative sources in hard-to-access spectral ranges?*



The mid-IR laser as optimal starting point for frequency conversion across the electromagnetic spectrum

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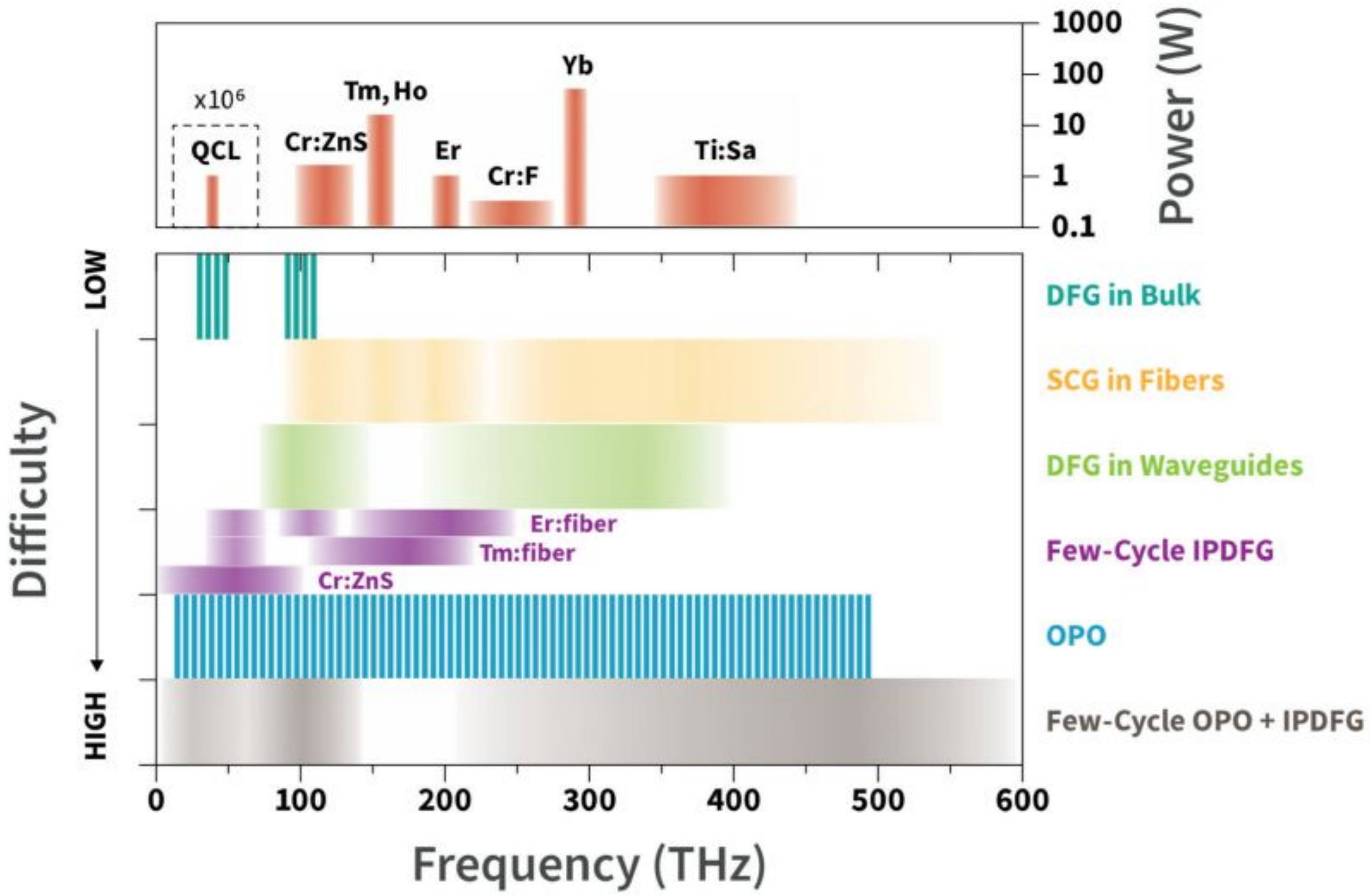
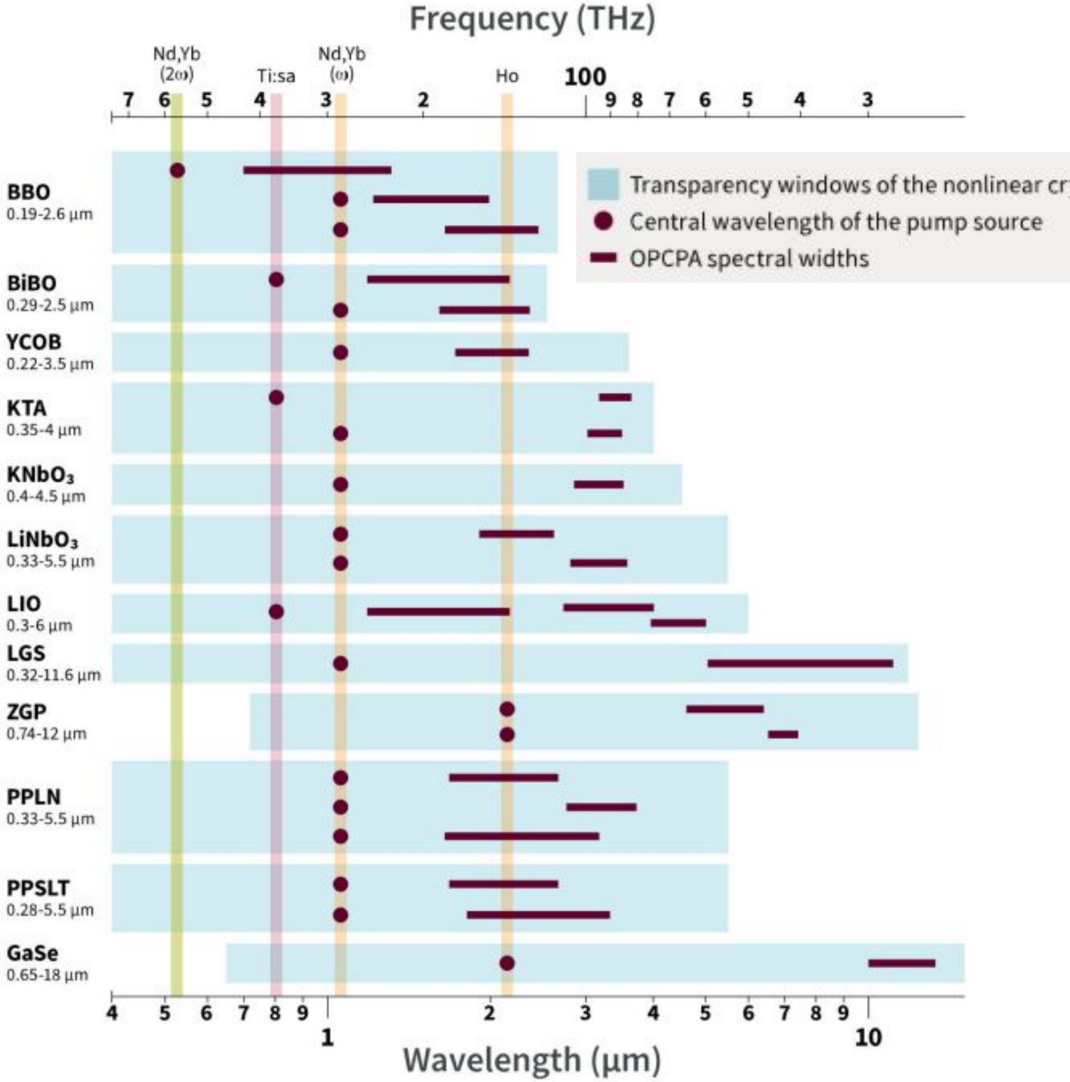
Existing platforms in the mid-IR are limited

Frequency combs (gain materials for mid-IR to THz)



Crystal based conversion



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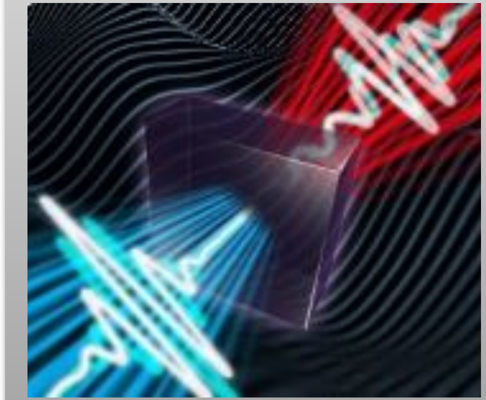
Transformative opportunities with mid-IR sources

Motivation:

Mid-IR sources are a **key enabling technology to address societal challenges** related to renewable energy and sustainable chemical synthesis, efficient electronic materials, for information storage and processing, and radiolytic applications to nuclear waste remediation and medicine.

Challenges:



- Complexity, cost, and instability
- Need new concepts and new gain materials
- Explore different platforms: frequency comb, fiber, and semiconductor sources
- Stable and waveform-controllable front ends for next-generation amplifiers

Reduced complexity and increased efficiency

Attosecond X-ray science; high-field THz science

Innovations in:

- Highly stable broadband mid-IR seed lasers
- Scaling of Tm-, Ho-, Cr-, and Fe-doped laser amplifiers to high pulse energy and average power and of CO2
- OPCPA architectures based on longer-wavelength pumps
- Development of tunable few-cycle parametric sources

Scaling peak and average power in mid-IR CPA

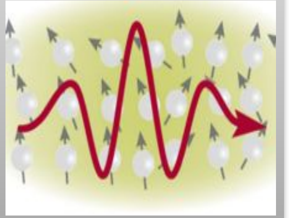
High field science, QED, ion acceleration, light sources

Innovations in:

- LWFA will require lasers with J-level pulse energies
- Repetition rate scaling >10 kHz
- Increase in peak power through nonlinear compression

Waveform-controlled sources mid-IR to THz

Molecular fingerprinting for healthcare, energy, and defense



Innovations in:

- Combs over entire fingerprint range of 1–100 THz
- Power scaling for sensitivity and nonlinear spectroscopy

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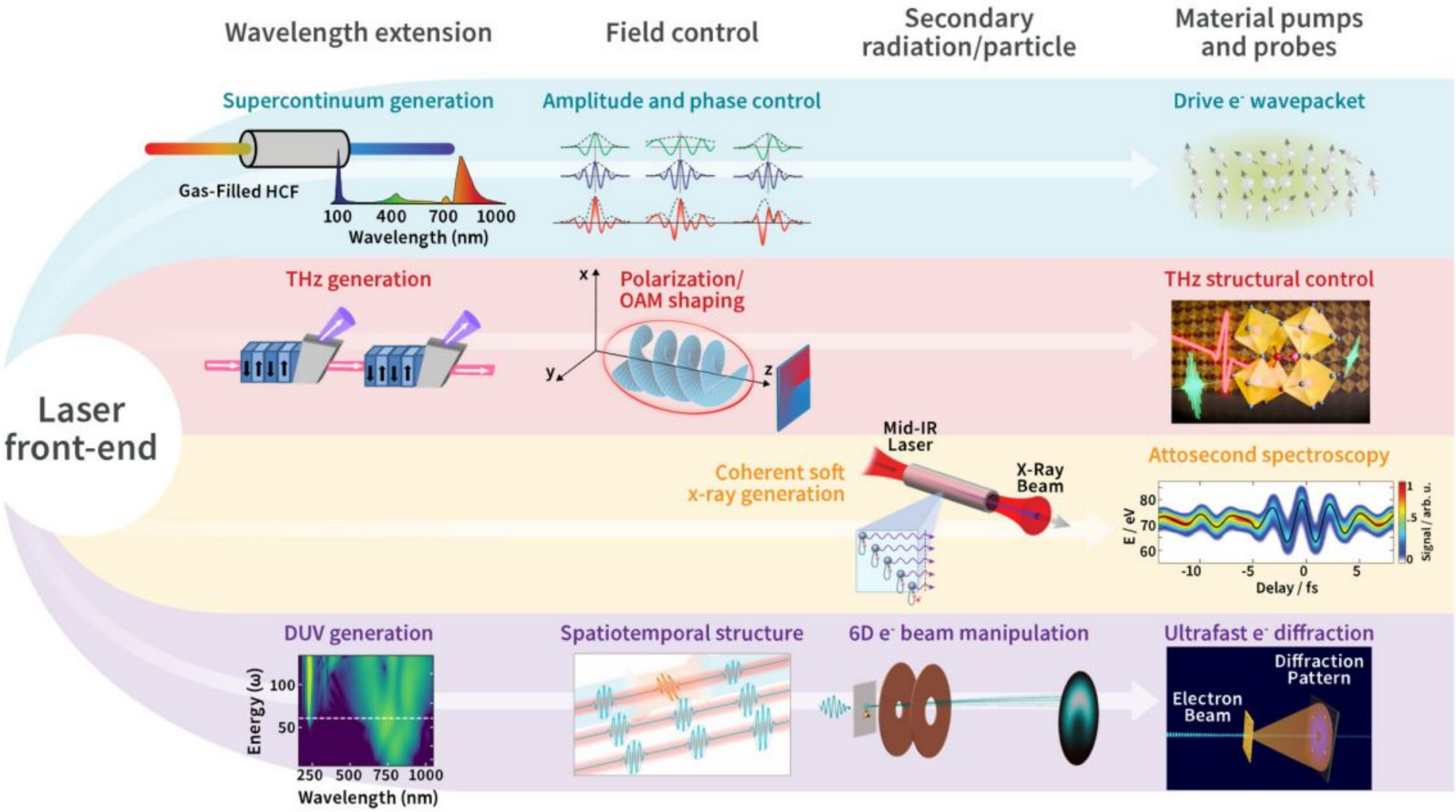
PRD 3: Revolutionize Frequency Conversion and Field Control

Key Questions:

- *Can we advance **laser light manipulation** with bandwidth efficiently extended from deep ultraviolet to THz ranges, employing all ranges simultaneously and with **exquisite control** of field structure?*
- *Can we **synchronize** these sources to secondary radiation and particle beams?*
- *Is it possible to simultaneously **greatly reduce the complexity of laser systems**, making them accessible, affordable, stable, and robust?*



Enabling **transformative studies of material physics** through wavelength extension, field control, and secondary radiation and particle generation

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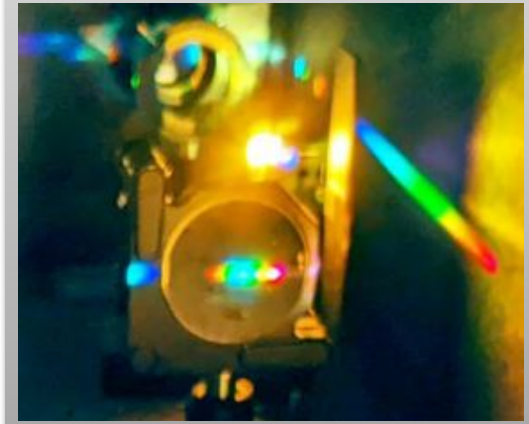
Transformative opportunities with freq. conv. & field control

Motivation:

Ultrafast, synchronized sources promise **groundbreaking insights** into **molecular charge and energy dynamics**, revolutionizing photochemistry, photocatalysis, and photovoltaics. Stronger THz/IR fields will enable discoveries of hidden material phases, supporting applications from **ultralow-power electronics to medical imaging**.

Challenges:



- Cost and complexity limit accessibility
- advance frequency conversion and field control technology
- more efficient, flexible, and simpler approaches
- tunable, tailored laser pulses across UV-to-visible range

Frequency extension in fibers and gases, efficient NLO

Access to selective excitations and probes of molecules and materials

Innovations in:

- Reducing complexity and improving robustness
- Up- and down-conversion methods (e.g. four-wave mixing, dispersive wave)
- Spectral broadening in fibers and Herriot cells
- Surpassing the limitation of the quantum defect

Field-control across the spectrum, synchronization

Control of dynamics in molecules and materials; field-resolved spectroscopy

Innovations in:

- Ultrawide shaping methods at up to extreme powers
- Generating OAM and other complex field structure
- Solutions for shaping X-ray beams via optical methods

Integration and driving technology democratization

Remove barriers to practical development and research timelines

Innovations in:

- Fully integrated and accurate modeling, along with data-driven approaches
- Optimizing system architecture, reducing complexity, and enhancing stability and field control capabilities

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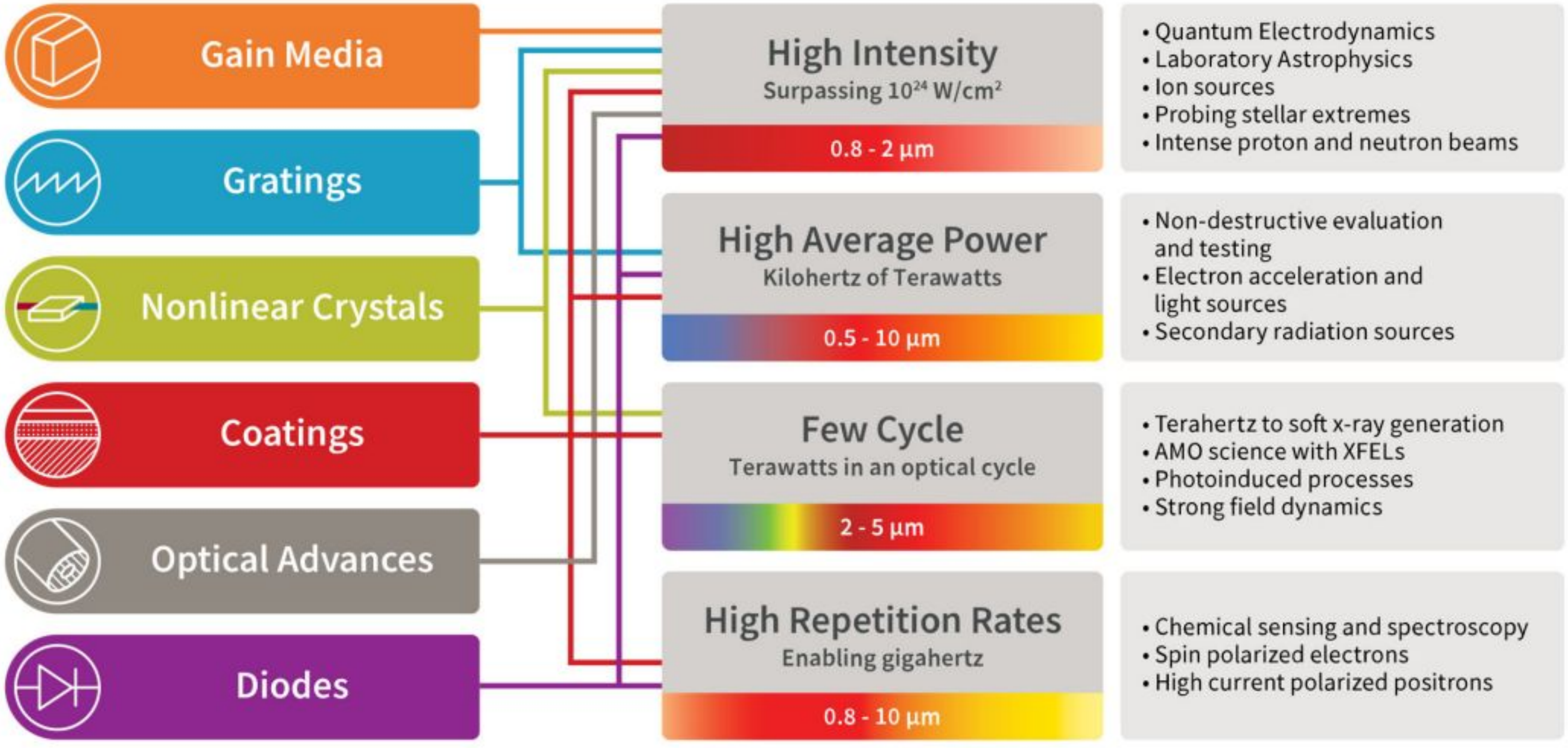
PRD 4: Reinvent materials and optics for intense laser science

Key questions:

- *What are the most significant improvements to materials and optics needed for next generation ultra-high intensity and high average power laser technologies?*
- *What can be discovered to expand the spectral range of ultrafast lasers toward the Mid IR and UV?*
- *What new concepts can be exploited to innovate materials and optics for intense laser science?*



Gain Media

Gratings

Nonlinear Crystals

Coatings

Optical Advances

Diodes

High Intensity
Surpassing 10^{24} W/cm^2
0.8 - 2 µm

- Quantum Electrodynamics
- Laboratory Astrophysics
- Ion sources
- Probing stellar extremes
- Intense proton and neutron beams

High Average Power
Kilohertz of Terawatts
0.5 - 10 µm

- Non-destructive evaluation and testing
- Electron acceleration and light sources
- Secondary radiation sources

Few Cycle
Terawatts in an optical cycle
2 - 5 µm

- Terahertz to soft x-ray generation
- AMO science with XFELs
- Photoinduced processes
- Strong field dynamics

High Repetition Rates
Enabling gigahertz
0.8 - 10 µm

- Chemical sensing and spectroscopy
- Spin polarized electrons
- High current polarized positrons

Where the challenges are:

Gain material

- Large aperture; improved thermo-mechanical properties for high average power (T)
- Laser gain material for direct pumping with large bandwidth (S)
- Laser gain materials for mid-infrared beyond 2 µm (S+T)

FIBER LASERS: SiO_2 fibers are a superior platform. Beam combining to reach multi-Joule level very challenging

Non-linear crystals

For OPO, up and down-conversion of laser fundamental to UV and mid-IR

- Large aperture for high peak and average power (T)
- Improved thermal and mechanical properties (T)
- Novel platforms (S+T)

(S+T): Science and Technology

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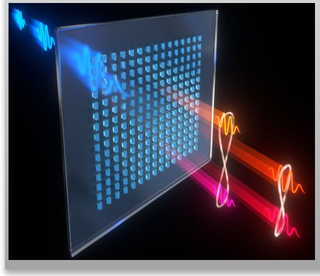
Multilayer dielectric coatings and gratings

MLD in optics and gratings - are prone to laser damage at large fluence and repetition rates

Innovations in:

- Materials with controlled structural, thermo-mechanical and optical properties (S)
- Novel concepts: self-healing, impervious to surface contamination (S+T)
- Gratings: good coatings, large aperture (T)



Emerging innovations in optics

- Gas and plasma optics for higher damage threshold optics (S+T)
- Metasurface technologies – for wavefront and polarization control (T)

Laser diodes for pumping ultrashort pulse lasers

- Well developed at NIR, lacking in mid-IR (T)
- Innovation in fabrication of diodes stacks to increase production, reduce cost and shorten lead times (T)

Crosscut Issues and Findings

- **Workforce Development**
  - “**Engagement**” rather than “Outreach”
  - **Five distinct workforce development opportunities at different junctures of career paths** in laser technology: pre-college, technician pathways, undergrad training for industry, undergrad training for research/academia, and early career/graduate student training.
- **Domestic and International Strengths**
  - Science and technology can advance internationally in a friendly and cooperative while also competitive manner through international “**co-opetition**,” but articulating principles and criteria to inform compete/collaborate decisions proves challenging since multiple factors play against each other.
- **Supply Chain Issues and Public Private Partnerships**
  - Challenges encompass extended lead times, production delays, and quality control issues for critical laser-specific components. Attracting suppliers for low-volume or high-risk commodities is challenging, as is obtaining other essential materials for laser system development
  - Engage industry and research labs to cooperate in making laser technologies more available, affordable, robust

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Lead: Jonathan Zuegel, U. Rochester, LLE

Summary – a few key points

- Advancing **laser technologies is key to scientific discovery** in multiple areas:
  (a) **High-repetition rate laser (Type I):** Chemical sensing, electron dynamics, high-current polarized electron/positron sources, small cross-section process studies

  (b) **High average power laser (Type II):** Plasma-based electron accelerators, probing exotic states, proton beam manipulation, x-ray imaging and non-destructive evaluation

  (c) **Few-cycle laser (Type III):** Tracing and control of molecular and material dynamics, photochemistry, mapping transients with element specific resolution

  (d) **High intensity laser (Type IV):** Quantum electrodynamics, astrophysical phenomena, netron, ion, gamma, muon radiography sources, generation of high-energy density (HED) and warm-dense matter (WDM) plasmas

- Material and other science advances are key to ultrafast laser technologies

- BRN identifies critical needs and provides suggestions for incentivizing technology advances

- For the U.S. to keep its leadership in laser technologies new strategies have to be explored:
  PPP, multi-institutional efforts, strengthen U.S. supplies, etc.

- **Increasing workforce is paramount**: technicians, engineers, scientists

Outline

Summary of Basic Research Needs Workshop

Perspectives on mid-IR development facilities (not BRN output)

MWIR lasers require development for science

Most of the laser categories involve MWIR (2 to >10µm) - strong impact

mJ’s of MIR OPA including long wavelength sources with Ho, Cr:ZnSe, Fe:ZnSe…

Tunable few-cycle parametric sources

New approaches to generating broadband mid-IR seed lasers

Stable, waveform-controlled sources spanning the mid-IR to THz

Precision diagnostics beyond NIR

Efficient pumping and energy extraction at scale and rate

Optics and coatings at large aperture

MWIR lasers require development for science

Scaling of Tm-, Er-, Ho-, Cr-, and Fe-doped laser amplifiers to high pulse energy and average power

Advancing peak power of C02 lasers

- Elevating the seed energy from the 10-µJ to the 10-mJ range using MIR OPAs
- Optical pumping - e.g. 2.8-micron, Er:Y3Sc2Ga3O12 or 4.3-micron, Fe:ZnSe

Peak power scaling ≥ 10-TW level: Energy scaling, nonlinear compression…

Strong synergy with ATF programs

Development Facility Could Expedite R&D

Analog to LaserNetUS, BeamNetUS providing advanced capability to broad science base in laser R&D to share expertise and expedite progress

Common diagnostics and metrology

Optics, chambers, and laser capabilities

Gain media and optical elements for testing

Space for experiments: clean, safety certified, high capacity power and utilities

Support for high power development

Advanced sources in MIR and LWIR supporting development

- Pump, seed
- Range of wavelengths

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Broaden and democratize advanced R&D

Share:
    R&D capabilities
    Facility infrastructure
    Laser science and engineering expertise
    Training

Advocacy & engagement in design is needed with science champions:
    Laser science/ R&D
    Potential users and industry
    Application scientists in chemistry, materials etc.

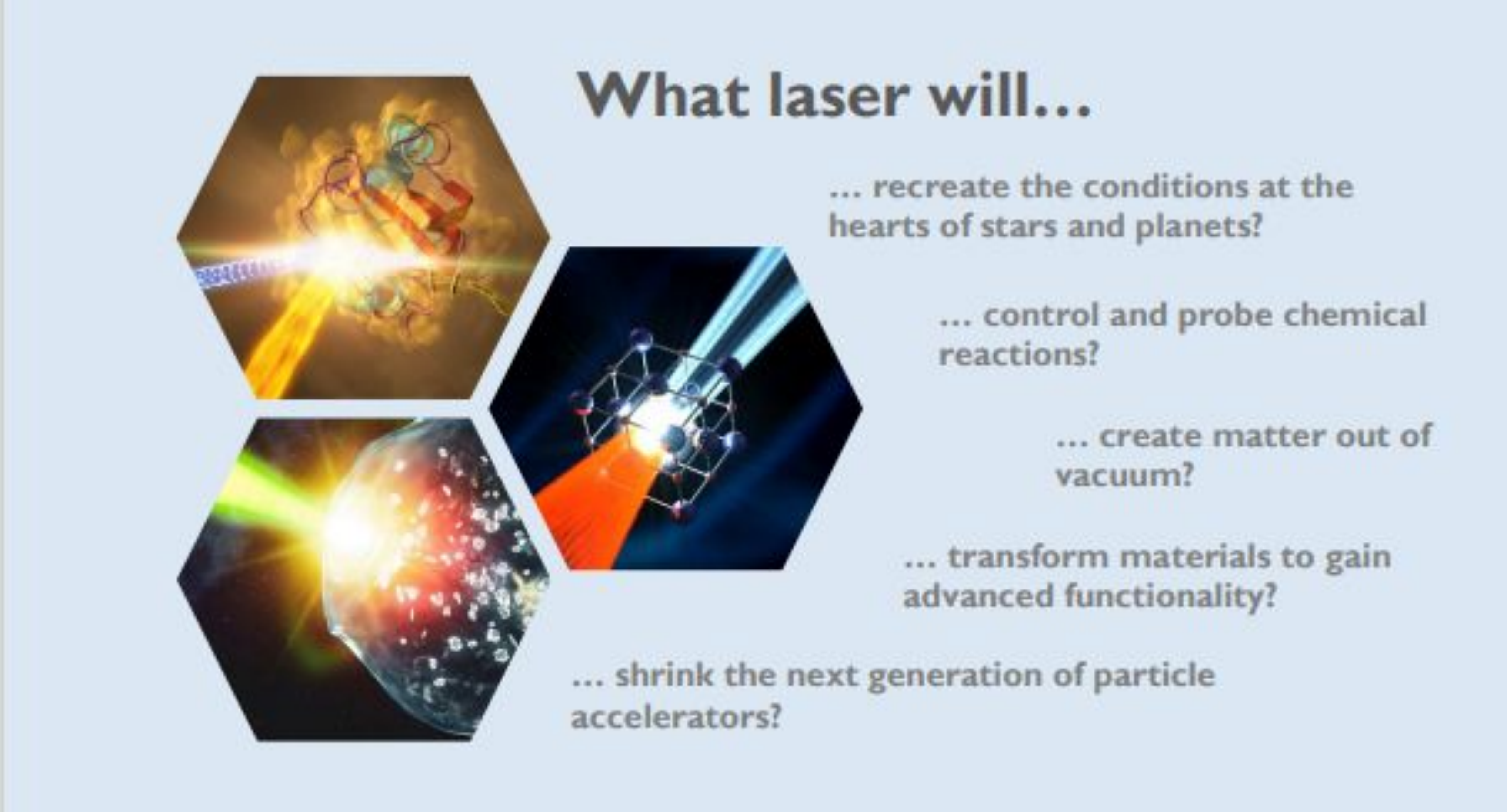
Leverage unique facility capabilities - e.g. high power lasers & facility, engineering

Thank you!

- Questions, comments, other forms of feedback?
- Discussion?

Thanks to:
Eric Colby
Slava Lukin
Quentin Saulter

& Christine Clarke
Roark Marsh



What laser will…

… recreate the conditions at the hearts of stars and planets?

… control and probe chemical reactions?

… create matter out of vacuum?

… transform materials to gain advanced functionality?

… shrink the next generation of particle accelerators?

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