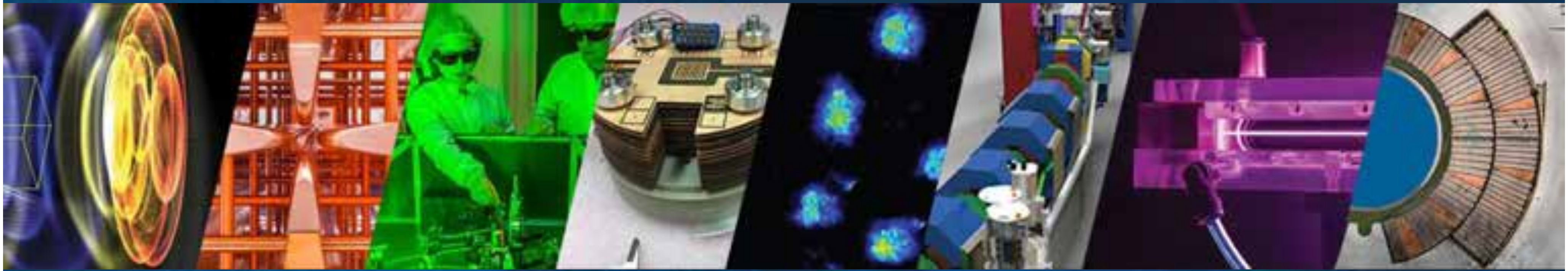
Combining fiber lasers for accelerators and broad applications

Tong Zhou, et al.

Lawrence Berkeley National Laboratory



FRIB APES (MSU)

Sept 8, 2023

BERKELEY LAB

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

U.S. DEPARTMENT OF ENERGY | Office of Science

GORDON AND BETTY MOORE FOUNDATION

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  ATAP Division: Russell Wilcox, Siyun Chen, Dan Wang, Mahek Logantha, Hao Ding, Deepak Sapkota, Qing Ji, Jeroen van Tilborg, Carl Schroeder, Eric Esarey, Cameron Geddes
  Engineering Division: Qiang Du
  Energy Technologies Area: Vassilia Zorba, Costas Grigoropoulos
  Computing Sciences Area: Juliane Mueller, Wibe de Jong

- **External Collaborators**:

  Univ. of Michigan: Almantas Galvanauskas, Lauren Cooper, Alexander Rainville, Mathew Whittlesey, et al.
  LLNL: Michael Messerly, Thomas Spinka, Leily Kiani, David Feng, et al.
  Colorado State Univ.: Jorge Rocca
  Varian: James Clayton
  Coherent: Joseph Henrich, Nigel Gallaher
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Combining fiber lasers for accelerators and broad applications

- Background
  - Accelerator applications
  - Fiber laser approach & Current LBNL effort
  - Broad applications
- Fiber laser combination approach
  - Spatial beam combining
  - Temporal pulse stacking
  - Spectral combining
- Current LBNL effort: Stepping-stone laser towards kBELLA *
  - Demo: short-pulse temporal stacking
  - Demo: short-pulse spectral combining
  - Fiber/Amplifier development
  - 200mJ demonstrator; Outlook
- Conclusion

* kBELLA is a $100M-class laser facility (3J, 1kHz, 3kW) that will secure US leadership in advanced particle accelerators and enable applications in physics, materials, security and biomedical science.

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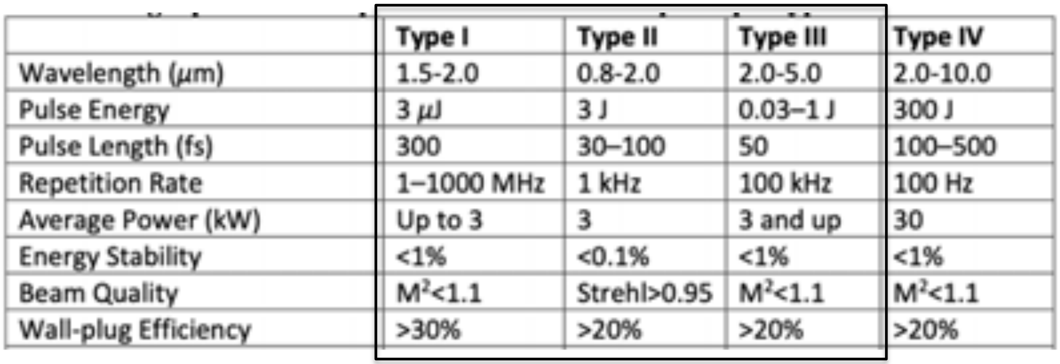
Advanced high-power laser technologies needed for broad accelerator applications

DOE Accelerator Stewardship Ultrafast Laser Technology
Program target laser parameters



	Type I	Type II	Type III	Type IV
Wavelength (μm)	1.5-2.0	0.8-2.0	2.0-5.0	2.0-10.0
Pulse Energy	3 μJ	3 J	0.03–1 J	300 J
Pulse Length (fs)	300	30–100	50	100–500
Repetition Rate	1–1000 MHz	1 kHz	100 kHz	100 Hz
Average Power (kW)	Up to 3	3	3 and up	30
Energy Stability	<1%	<0.1%	<1%	<1%
Beam Quality	$M^2<1.1$	Strehl>0.95	$M^2<1.1$	$M^2<1.1$
Wall-plug Efficiency	>30%	>20%	>20%	>20%

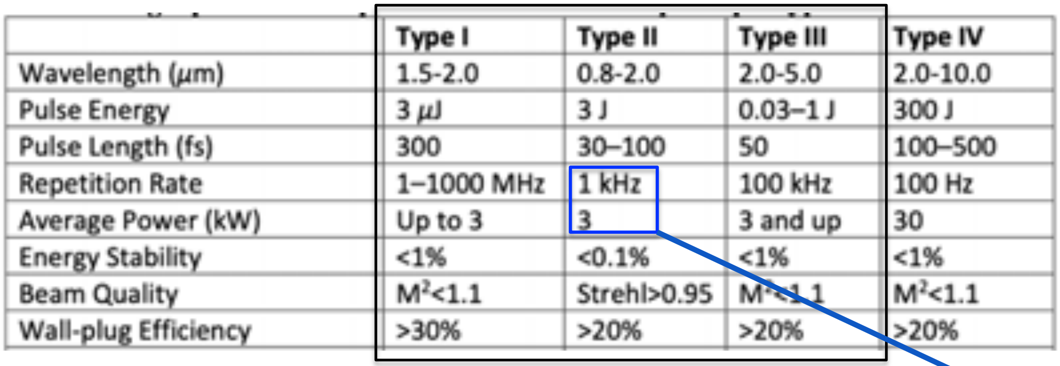
U.S. DEPARTMENT OF ENERGY

Workshop on Laser Technology for Accelerators

Ultrafast lasers for accelerator applications:
- Type I: directly laser-driven accelerators-on-a-chip
- Type II: laser plasma acceleration (LPA), Compton backscattering (x-ray)
- Type III: high rep-rate radiation, high-harmonic generation (HHG)
- Type IV: plasma-based sources of protons, ions, neutrons

Driver laser specs for >kHz plasma accelerators are most demanding

DOE Accelerator Stewardship Ultrafast Laser Technology Program target laser parameters



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ENERGY

Advanced Accelerator Development Strategy Report

REPORT OF WORKSHOP ON

Laser Technology for k-BELLA and Beyond

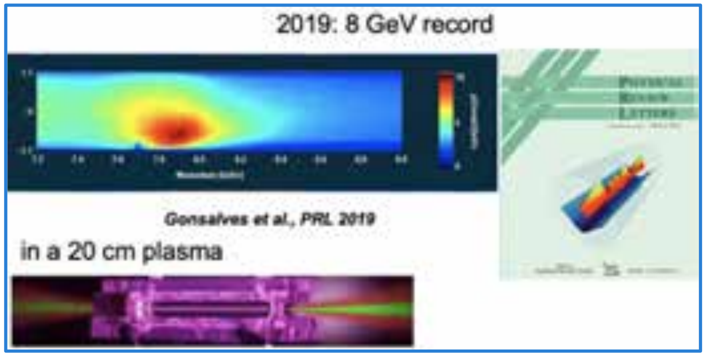
Ultrafast lasers for accelerator applications:

- Type I: directly laser-driven accelerators-on-a-chip
- Type II: **laser plasma acceleration (LPA)**, Compton backscattering (x-ray)
- Type III: high rep-rate radiation, high-harmonic generation (HHG)
- Type IV: plasma-based sources of protons, ions, neutrons

Type II laser specs extended

Laser parameter	k-BELLA	Hi rep-rate driver	Collider driver
Energy	3J	3J	6J
Pulse duration	30fs	30fs	100fs
Rep-rate	1kHz	10kHz	50kHz
Average power	3kW	30kW	300kW

LPA rep-rates need to increase beyond kHz for applications


2019: 8 GeV record

Gonsalves et al., PRL 2019

in a 20 cm plasma

Rapid progress positions LPAs as next generation compact accelerators

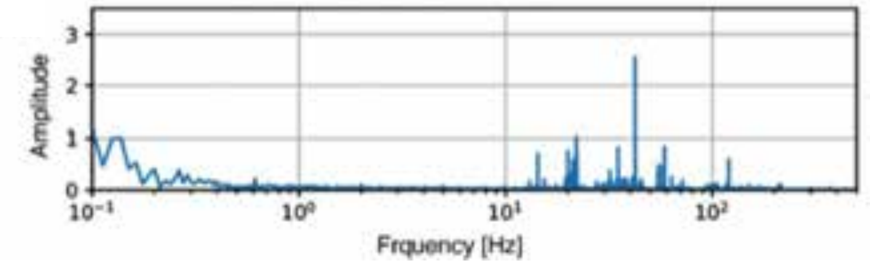
Order of magnitude improvement in LPA performance at kHz rates

- Fluctuations are faster than current LPA repetition rates (~Hz)
- Demonstrated improvements at mJ/kHz (via active feedback) [1]

kHz-Joule class will enable precision GeV-class LPA

- LPA performance, stability and control, precision staging/injection

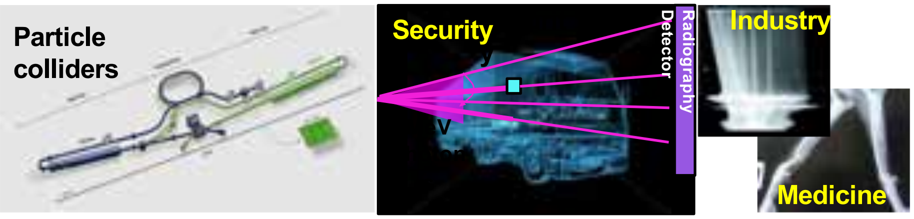
laser pointing fluctuations typically <100 Hz [1]



Enables photon sources at kHz

- Accelerator applications require >kHz rates

Key step to 50 kHz class colliders

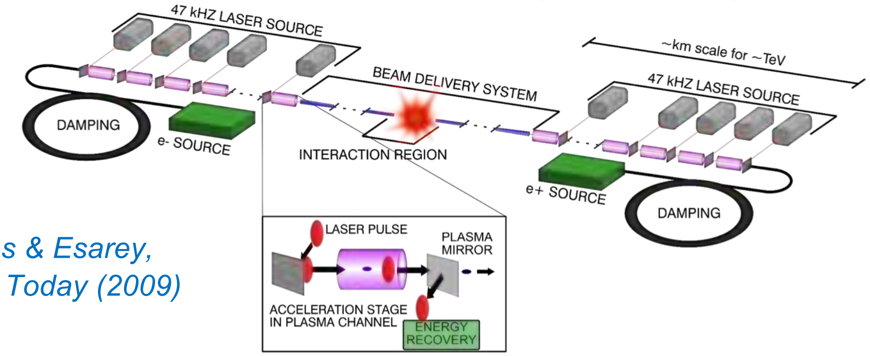


[1] F. Isono et al. *High Power Laser Science & Engineering*, 9, e10 (2021)

>kHz LPAs need new driver laser to reach power and efficiency

Laser parameter	k-BELLA	Hi rep-rate driver	Collider driver
Energy	3J	3J	6J
Pulse duration	30fs	30fs	100fs
Rep-rate	1kHz	10kHz	50kHz
Average power	3kW	30kW	300kW

Laser-Plasma Accelerator Collider (Conceptual)



Leemans & Esarey, Physics Today (2009)

Community Planning Priorities (DOE & National Academies)

- New requirements on driver lasers for >kHz LPAs
  - **High wall-plug efficiency (~10s%)**
  - **High average power capability**
- Limitation of current Ti:sapphire lasers
  - Low wall-plug efficiency & Limited thermal handling
- **Need new laser technology beyond kHz!**
  - Promising: Fiber laser, Tm:YLF bulk, Yb:YAG bulk

- L. Kiani, T. Zhou, et al. “High average power ultrafast laser technologies for driving future advanced accelerators”, *Journal of Instrumentation* (2023)

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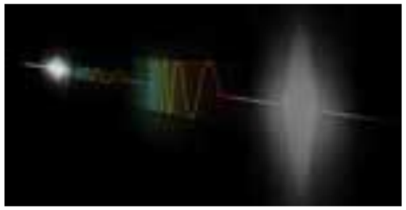
Ultrafast fiber lasers can provide high power & energy at high efficiency

- **Fiber laser: most efficient high power laser & industrial maturity**
- **Chirped-pulse amplification & combining enables high energy**
- **Coherent combined fiber lasers rapidly developing worldwide**

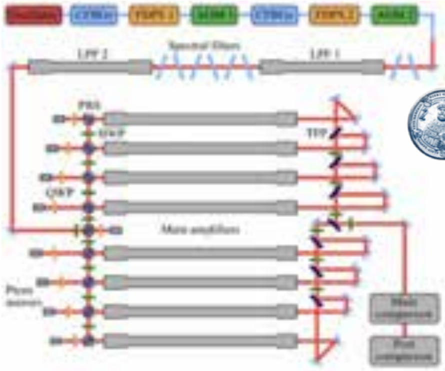
Commercial fiber laser from IPG Photonics (120 kW CW, WPE>45%)



Chirped-pulse amplification, 2018 Nobel Prize (Mourou & Strickland)

Example: 61-fiber-laser combining system (1kW, >250fs)

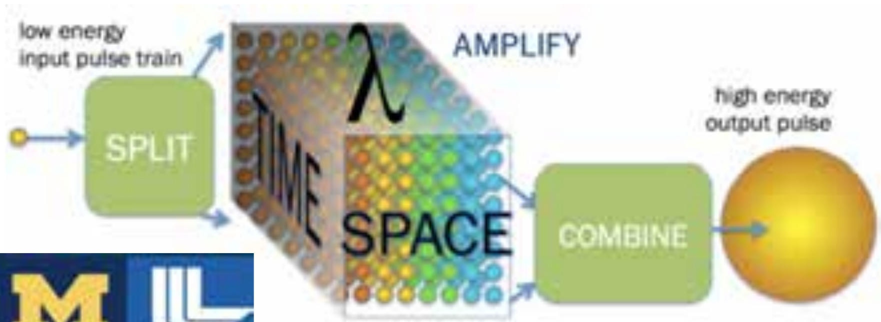
Fsaifes et al. *Opt. Express* 28, 20152 (2020)



32mJ, 158fs, 640W combining 16 fibers
10mJ, 120fs, 1kW combining 16 fibers

H. Stark et al. Optics Letters 48, 3007 (2023)
Stark et al. *Optics Letters* 46, 969 (2021)

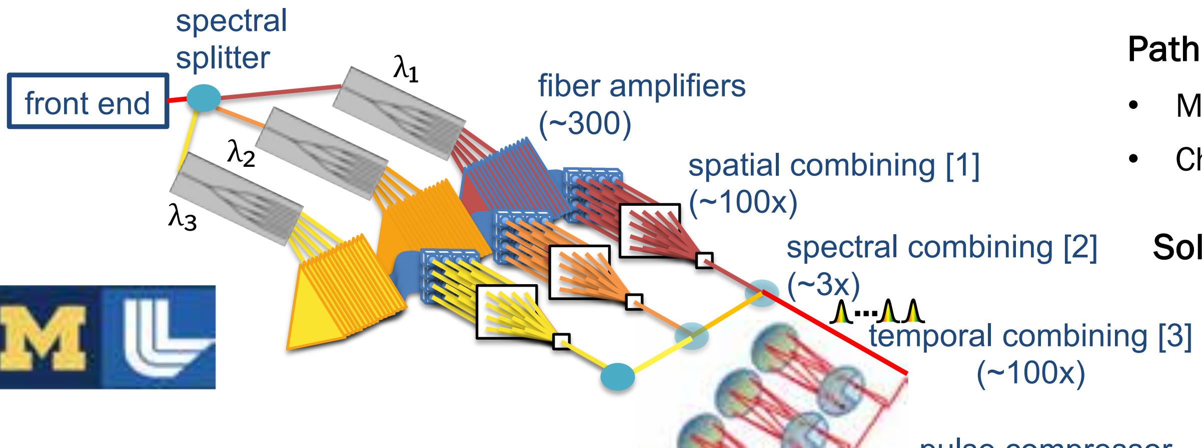
- **LBNL/UM/LLNL research breakthroughs enabled fiber laser combination path towards >kHz LPA drivers**

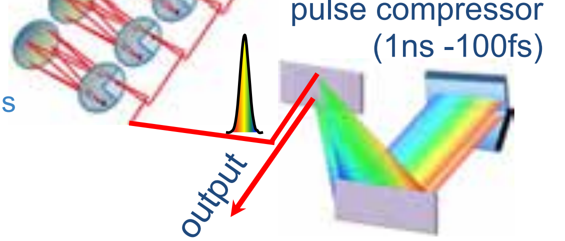


Laser parameter	Funded, ongoing	k-BELLA	Hi rep-rate driver	Collider driver
Energy	0.2 J	3J	3J	6J
Pulse duration	30fs	30fs	30fs	100fs
Rep-rate	5 kHz	1kHz	10kHz	50kHz
Average power	1kW	3kW	30kW	300kW

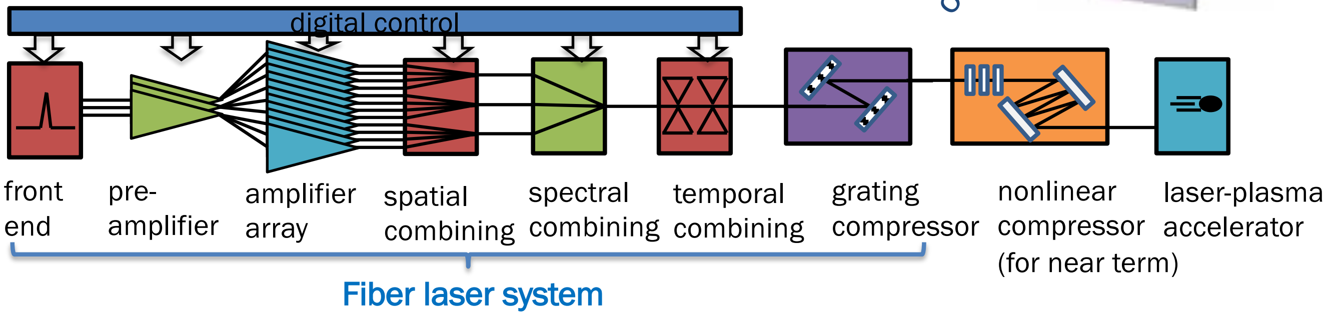
Funded by DOE Accelerator Stewardship, DOE ECRP, Moore Foundation

Multidimensional fiber laser combination is a path to drive future LPAs





Cited in DOE & National Academies & Community Planning



Path: Coherent combining of fiber lasers

- Most efficient, high power, monolithic integration
- Challenge: <1mJ per fiber and >100fs

Solution: Combine pulses in space, in color, & in time

- Combine 100’s fibers for Joules, 100’s kW, 100 kHz (in 3 spectral bands and in 100-pulse burst)
- Combine 3 spectral bands for 30 fs
- Combine 100 pulses in a burst to a single pulse

[1] T. Zhou et al. *Optics Letters* 21, 4422 (2017)
[2] S. Chen et al. *Optics Express* 31, 12717 (2023)
[3] T. Zhou et al. *Optics Express* 23, 7442 (2015)

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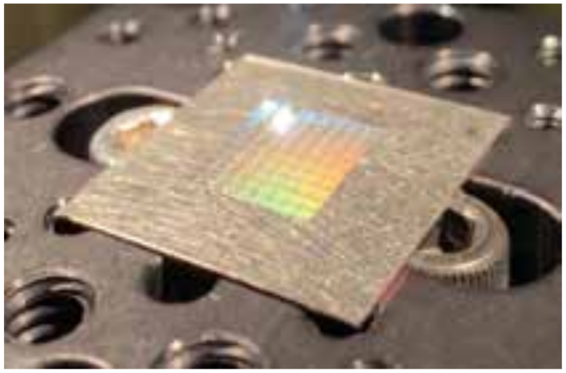
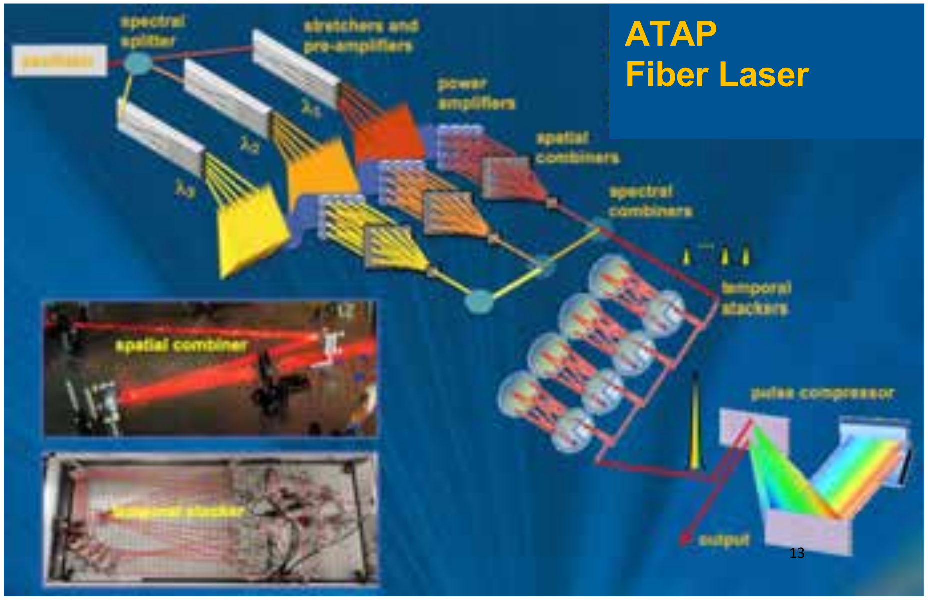
LBNL Multi-Area LDRD: Vassilia Zorba (ETA), Tong Zhou (PSA), Wibe de Jong (CSA)

Self-Driving Labs for Accelerated Photonics Materials Discovery & Scale-up

Approach: Close the materials discovery feedback loop

- Scale-up discovery & manufacture speed and volume with new lasers
  - ***Speed***: High repetition rate lasers
    - Implement **switchable** repetition rates and pulse energies: Enable **fast switching of operation modes**
  - ***Volume:*** High pulse energy lasers
    - Develop **beam mode shaping** methods to improve **homogeneity and quality** of the fabricated surface features





ATAP Fiber Laser

(1) Enable a new area of laser processing, materials discovery, transformative manufacturing.
(2) Extend strategic high average & peak power laser development towards broad application capabilities.

Feasibility of fiber lasers for laser fusion

Challenge/Opportunity

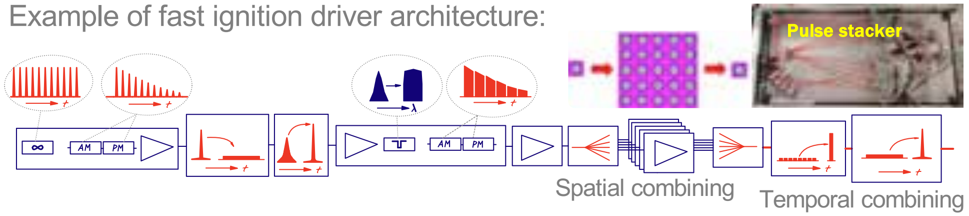
- ➢ Fusion laser driver needs high wall-plug efficiency and high-power capability
- ➢ Fiber lasers are the most efficient high power laser demonstrated so far
- ➢ Combined fiber laser arrays are scalable in pulse energy and average power

Commercial (IPG)100kW CW fiber laser with 35% WPE integrating ~10^2 channels

Approach

- Incoherent/Coherent combining of many fiber laser channels to reach the pulse energies needed for inertial fusion/fast ignition
- Advances in specialty large-core fiber amplifiers could enable ~100mJ per fiber (for fast ignition), and ~1J per multicore fiber (for inertial fusion)
- Laser drivers would require 10^4 – 10^5 parallel channels, which could be feasible due to fiber compatibility with monolithic integration

Example of fast ignition driver architecture:



Timeliness

Why now?

- Commercial high power multi-modular fiber laser systems
- Recent advances in high energy generation with specialty large core fiber technologies
- Recent advances in coherent combining of ultrashort pulse fiber lasers

R&D goals (e.g. 5 years):

- Large core specialty fiber based integrated amplifier array technology with 0.1-1J per channel
- Pulsed pumping for 30-40% wall-plug efficiency at low rep-rate (~10Hz)
- Specifically for fast ignition: Coherent control of large numbers of fiber channels, and high fidelity temporal pulse stacking

Impact

A pathway to efficient fusion driver laser technology for future IFE plants

- A. Galvanauskas, T. Zhou, et al. White paper to *IFE Science & Technology Community Strategic Planning Workshop*, 2022

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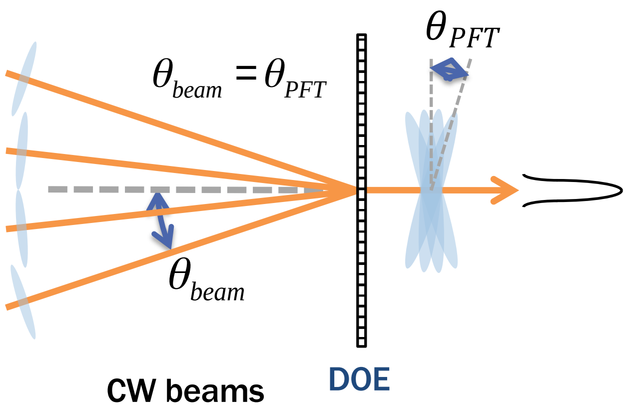
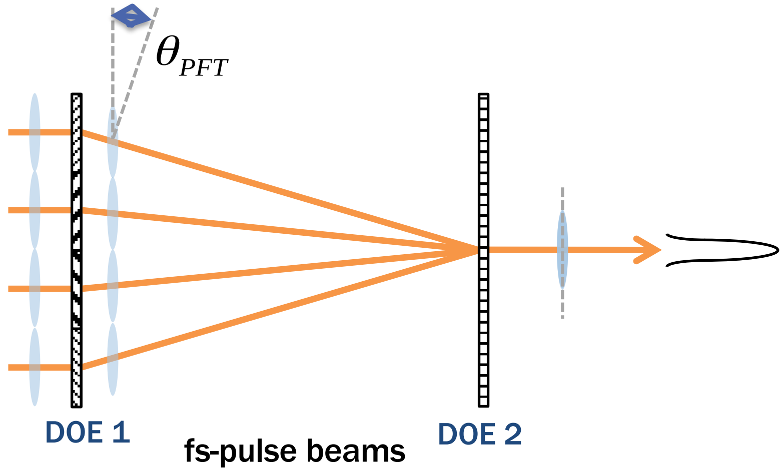
Many short-pulse laser beams can be added using two diffractive elements

- Many CW lasers can be combined with >90% efficiency on one diffractive optical element (DOE)
- Short pulses (broadband) don’t combine well due to pulse front tilt (angular dispersion)
- Adding a compensation DOE (DOE 1) solves the problem for short pulses



Uncompensated pulse front tilt



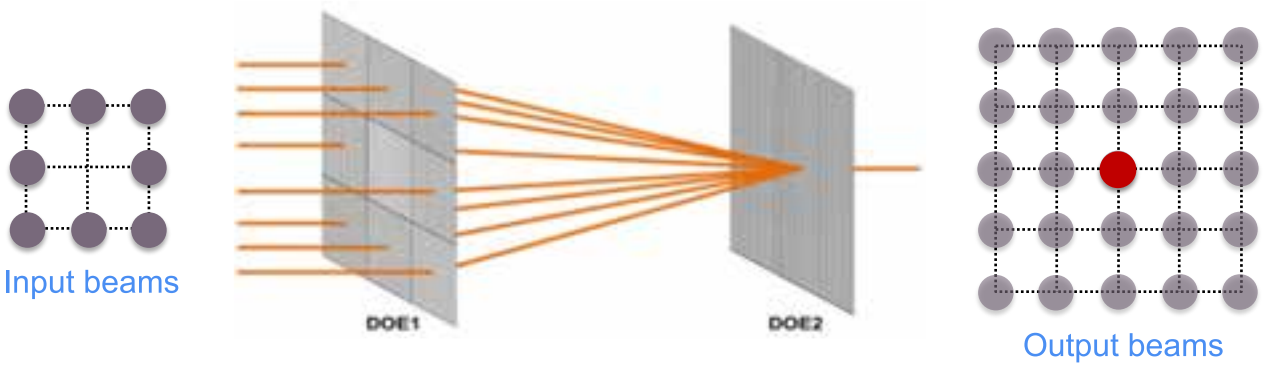
Pulse front tilt compensated

Proof-of-principle: 4 fiber-amplified, 120fs pulse beams are combined in a 1×4 array with close to theoretical limit efficiency

T. Zhou, T. Sano, R. Wilcox, Optics Letters 42, 4422 (2017).

2-D combination is essential for combining large beam arrays

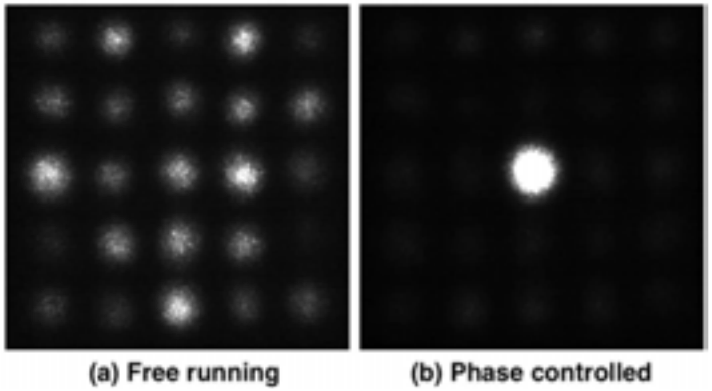
- Example: 8 fiber-amplified, 120-fs beams combined in a 3×3 array



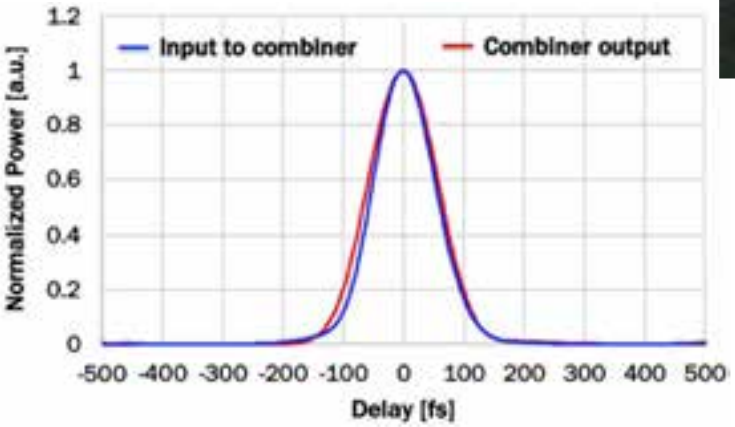
- DOEs manufactured using a scalable digitized surface-writing process
- Each input beam produces a square 8–beam array after DOE2, all these arrays partially overlap to form a 5×5 output array
- All input beams combined into one beam when pulse delay & phase matched

Experiment demonstration: 2-D diffractive combination of 8 ultrashort-pulse beams

- Combined/compressed pulse preserves 120fs transform limited pulse width
- 89.5% of output power is in central beam
  - Close to limit: DOE2 splitting efficiency is measured to be 90.7%
    - Limited by the discontinuous-surface DOE2



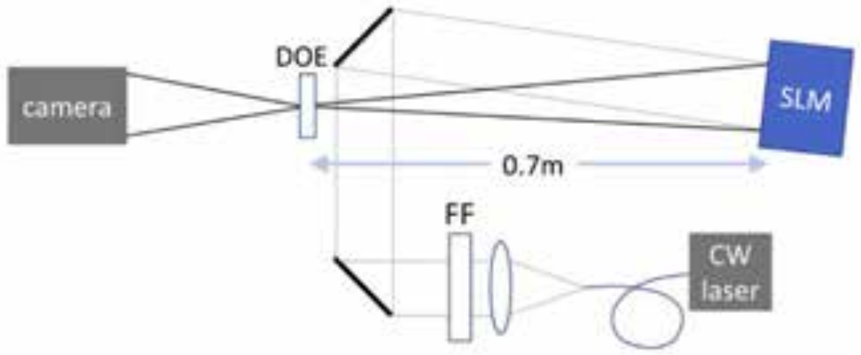
Output beam array from a camera



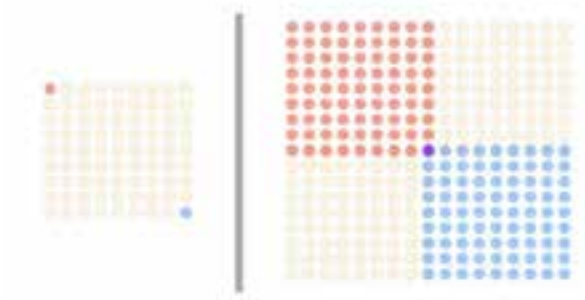
Input and output pulses,
compressed and diagnosed by a FROG

Tong Zhou, et al. Opt. Lett. 43, 3269-3272 (2018)

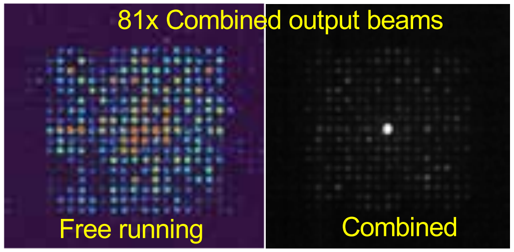
81-beam diffractive combining demo with free space CW laser

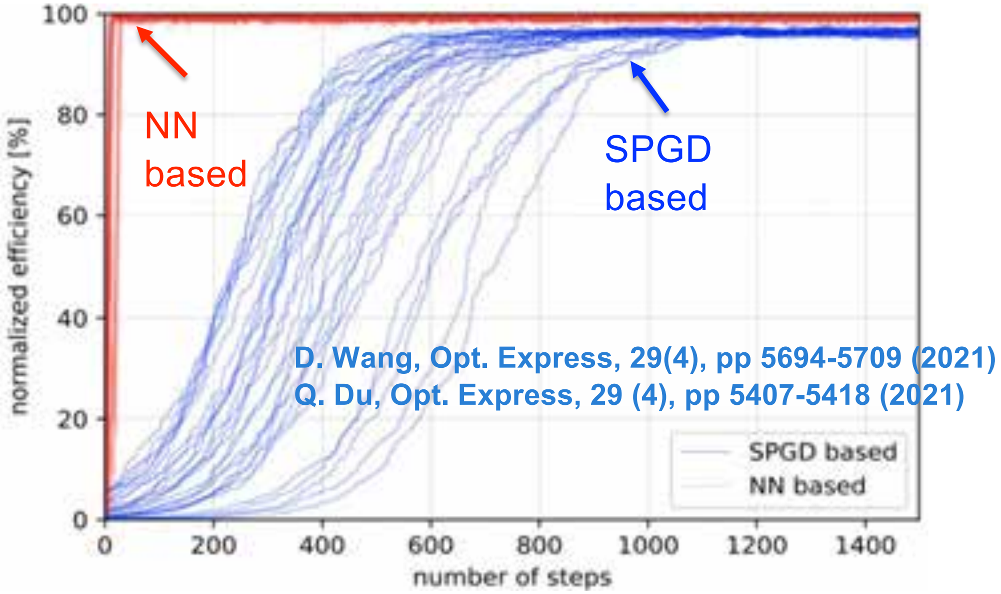


Simulation: 81 beams combining:



81 input beams 9 by 9 DOE 17 by 17 output





D. Wang, Opt. Express, 29(4), pp 5694-5709 (2021)
Q. Du, Opt. Express, 29 (4), pp 5407-5418 (2021)

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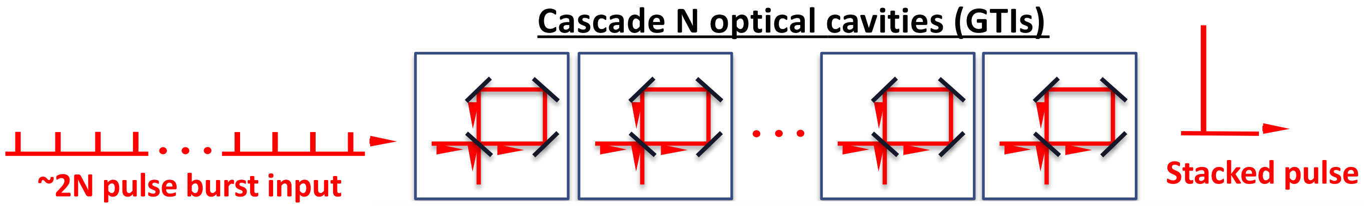
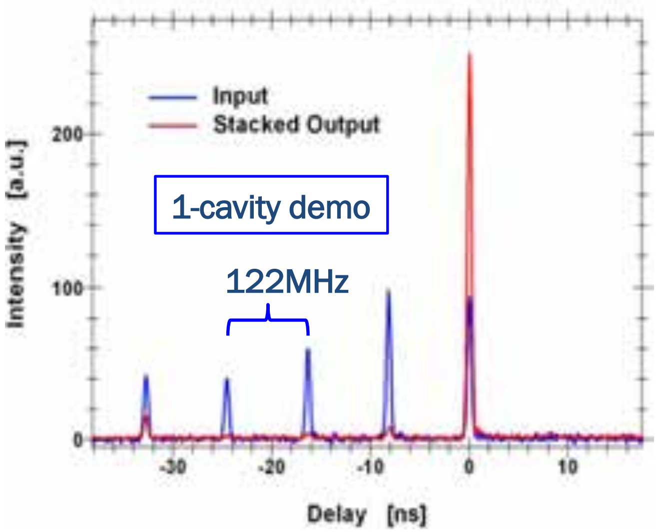
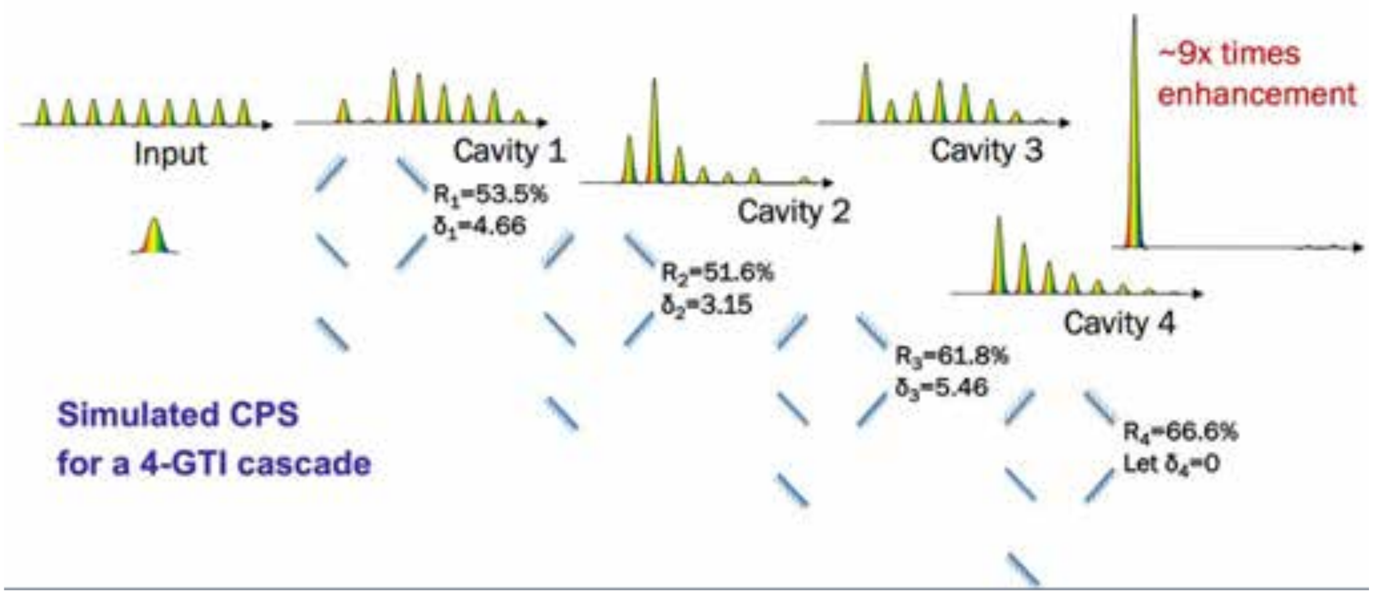
Multiple optical cavities can be cascaded to stack many pulses


Cascade N optical cavities (GTIs)

~2N pulse burst input

Stacked pulse

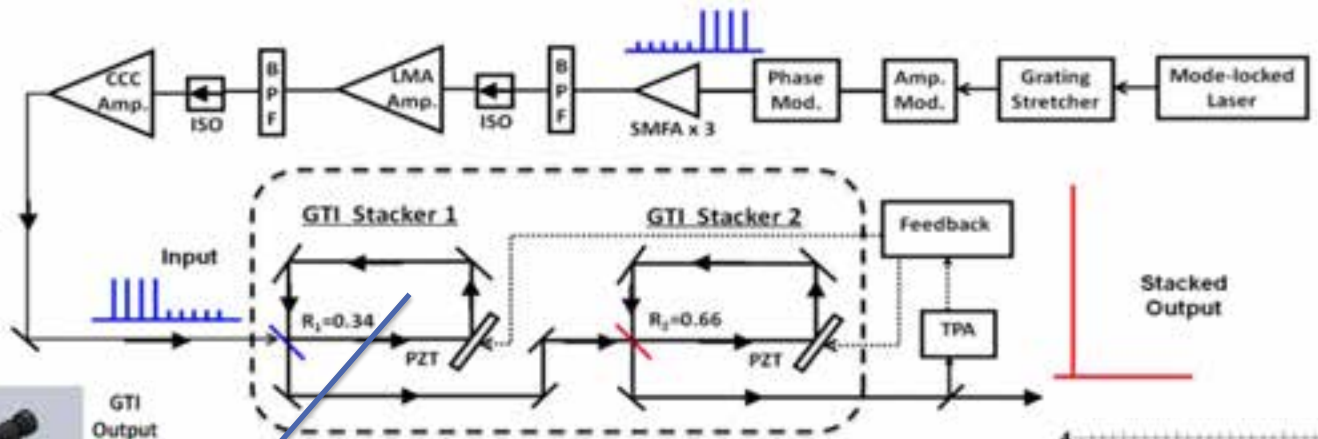


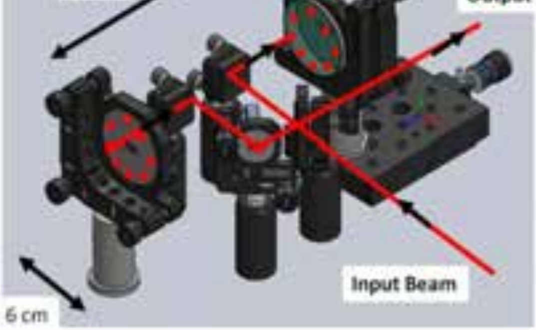


Tong Zhou, et al. ASSL 2014, AW4A.7

Tong Zhou, et al. Opt. Express 23, 7442-7462 (2015)

First demonstration of cascaded coherent pulse stacking

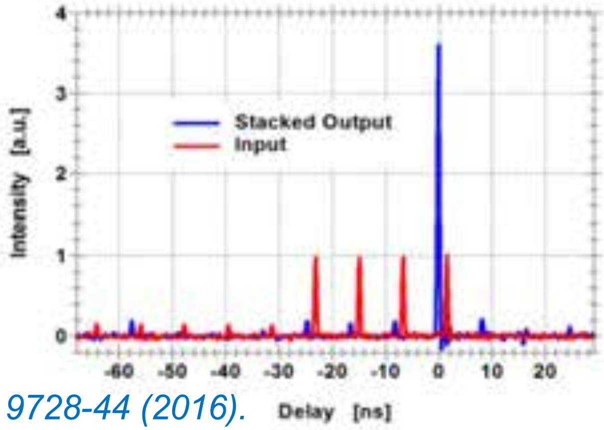




Self-relaying long path cells greatly improve compactness

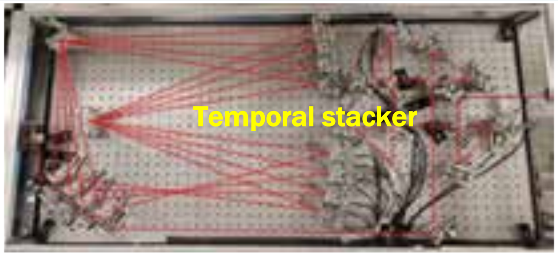
Input/Stacked pulses:

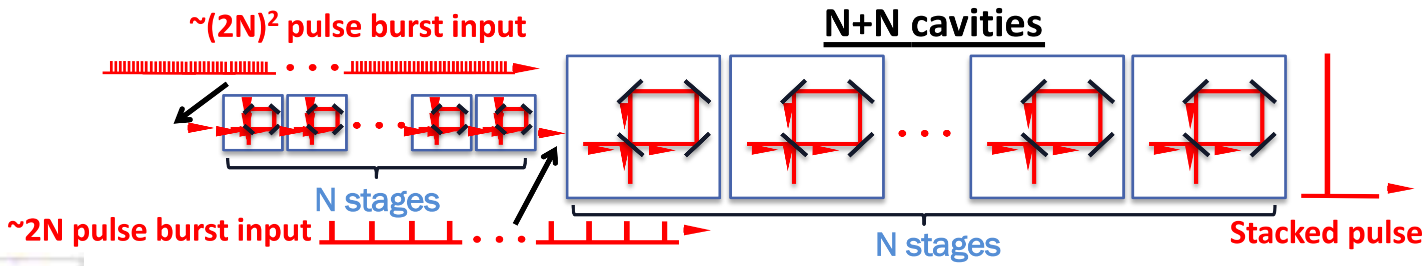
- 122MHz pulse rep-rate
- 3.64 enhancement (theoretical maximum 4.38)
- Stacking error due to Herriott cell mirrors



Tong Zhou, et al. Photonics West, paper 9728-44 (2016).

Multiple cavity-cascades can be multiplexed to stack large numbers of pulses





~(2N)^2 pulse burst input

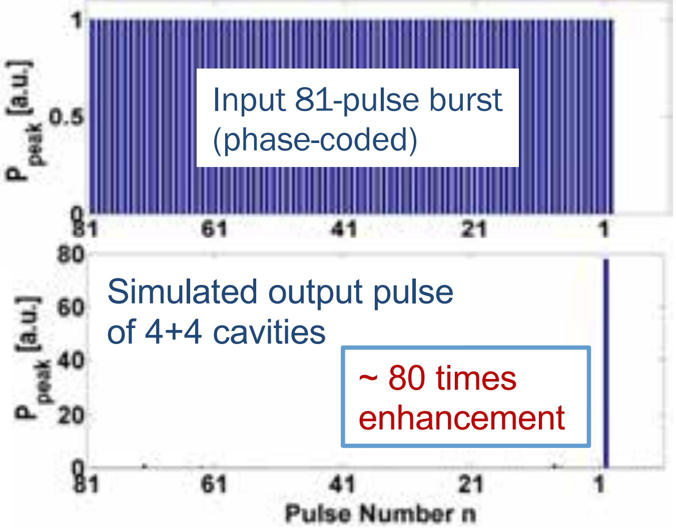
N+N cavities

N stages

~2N pulse burst input

N stages

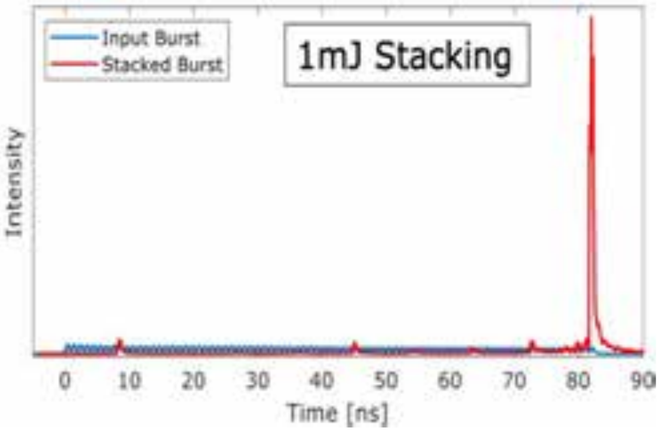
Stacked pulse

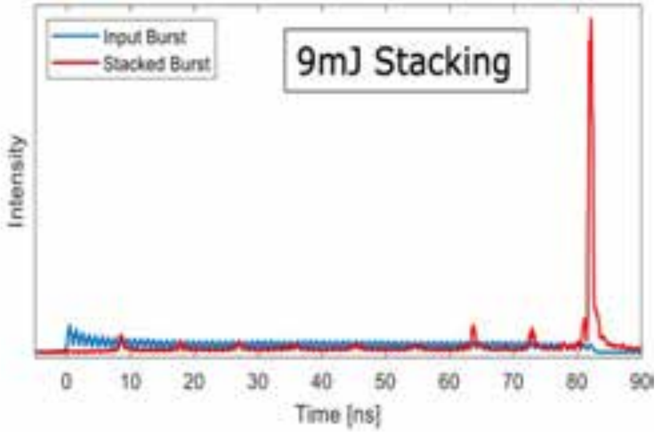


Input 81-pulse burst (phase-coded)

Simulated output pulse of 4+4 cavities

~ 80 times enhancement

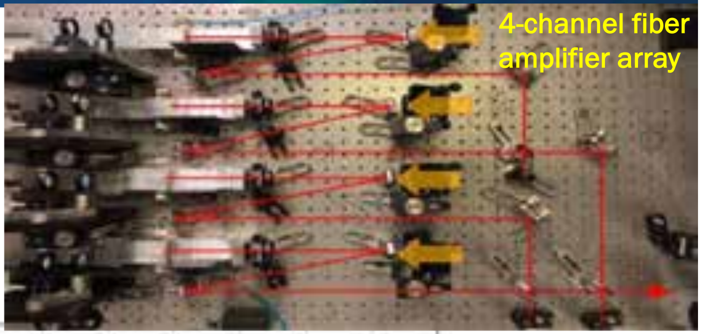




Tong Zhou, et al. Opt. Express 23, 7442-7462 (2015)

Alexander Rainville, et al. AAC 2022.
Alexander Rainville, et al. CLEO 2023.

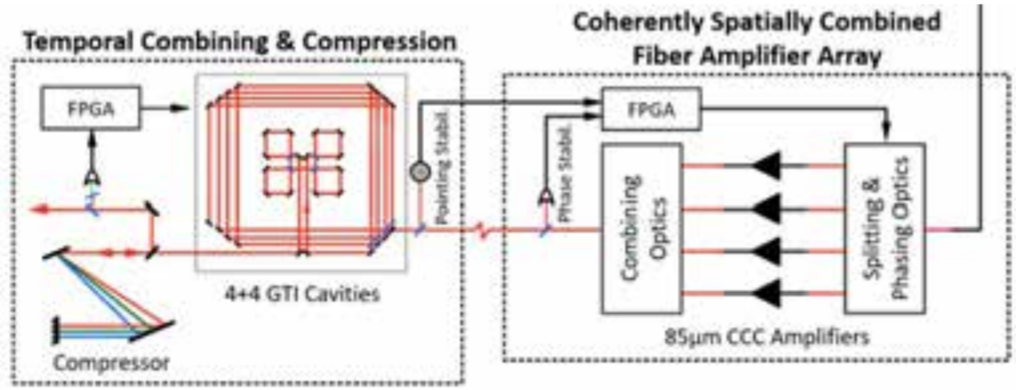
High-energy spatial & temporal combination of ultrafast fiber lasers have been demonstrated

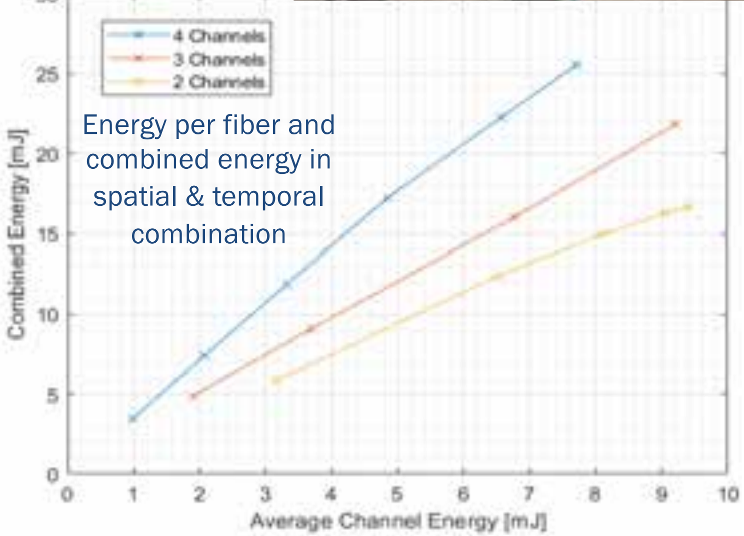


Spatial & temporal combination for power/energy scaling

- 4 beams combined, stacked & compressed to ~25mJ with ~7mJ/fiber

  - A. Rainville et al, CLEO 2023, paper SF3H.6
  - M. Whittlesey et al, SPIE Photonics West 2022, paper 11981-27





Energy per fiber and combined energy in spatial & temporal combination

Combining fiber lasers for accelerators and broad applications

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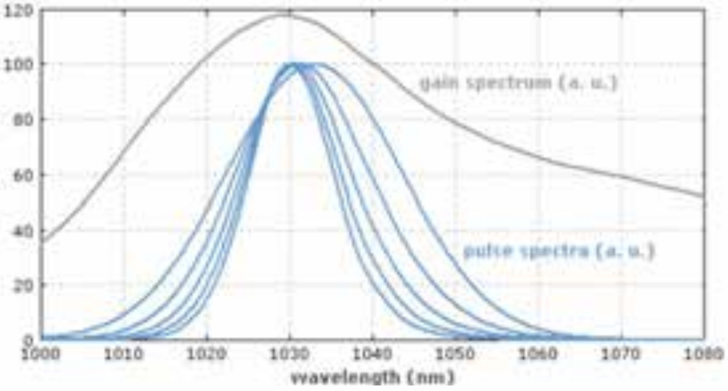
Gain narrowing effect limits short-pulse durations of current fiber lasers; Spectral combining multiple fiber amplifier channels can solve the problem

Pulse duration from high-energy Yb fiber amplifiers limited to >300 fs (without compensation):

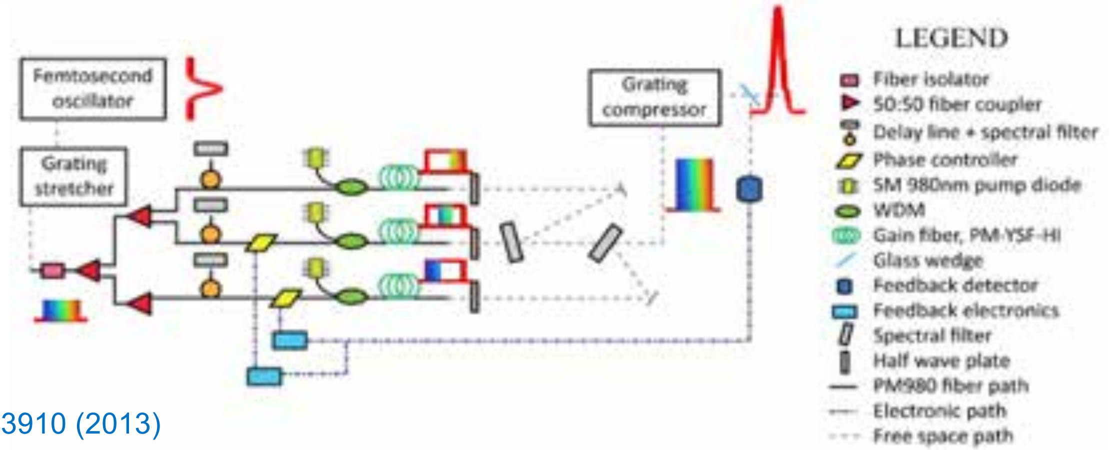
- Gain narrowing and saturation
- High-order dispersions



Simulated seed and amplified (10-40 dB) spectra from an Yb fiber amplifier

(from *rp-photonics*)

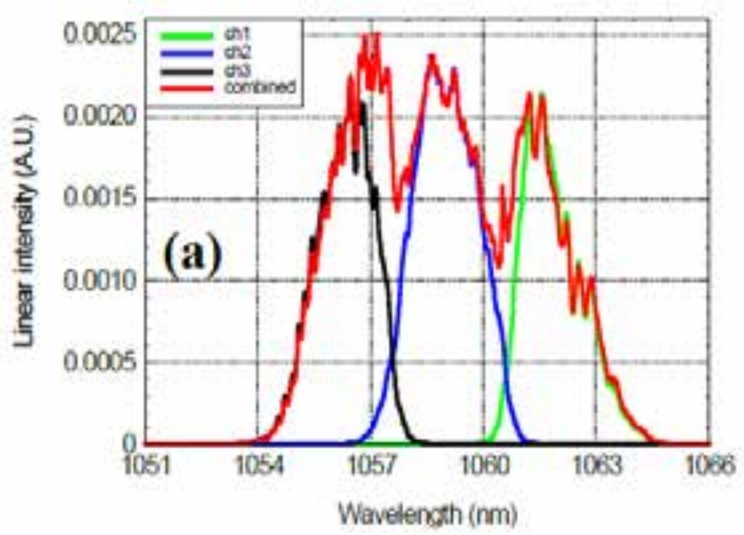
First demonstration of spectral combining of fiber lasers at 1um wavelength in 2013



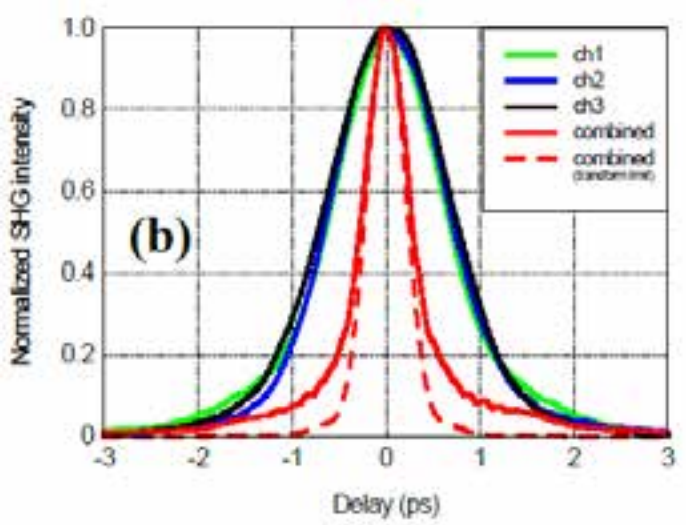
Wei-zung Chang, Tong Zhou, et al., Opt. Express 21, 3897-3910 (2013)

Coherent spectral combining results

Measured spectrum of the individual-channel and combined signals:



Normalized autocorrelation traces for the individual-channel and combined signals:



Wei-zung Chang, Tong Zhou, et al., Opt. Express 21, 3897-3910 (2013)

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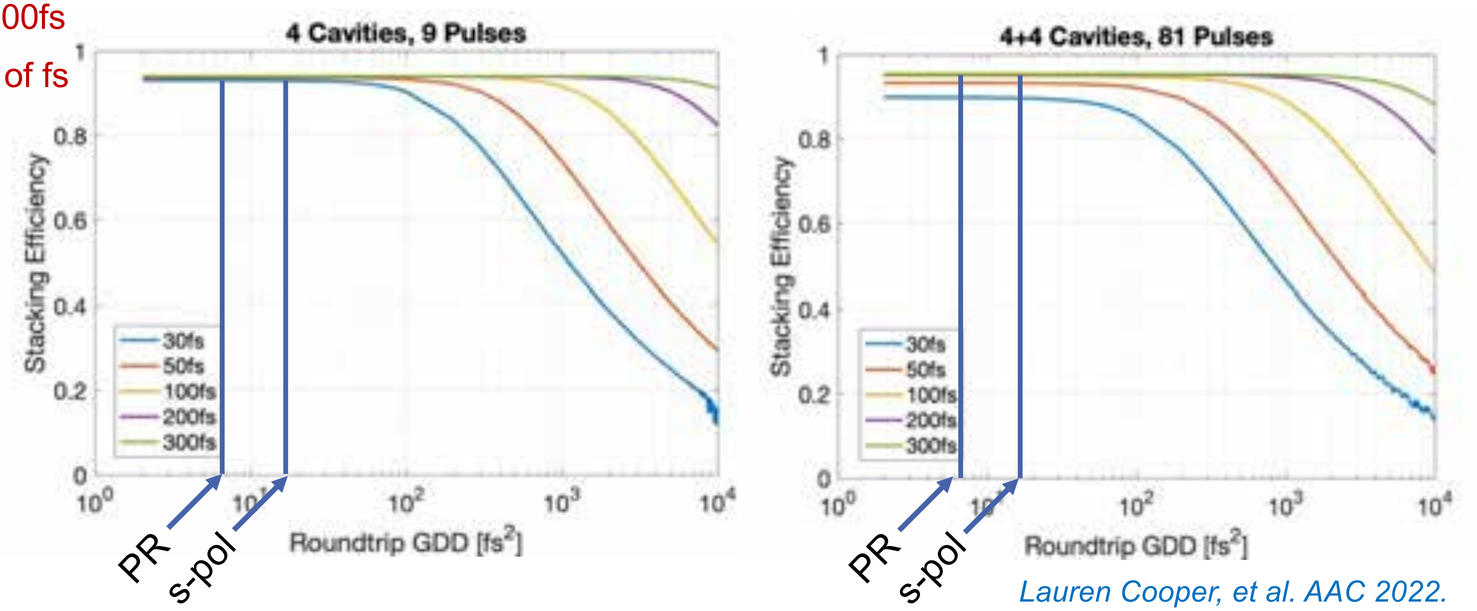
Coherent Temporal Stacking of tens-of-fs Laser Pulses

Coherent pulse stacking is the key enabler of the fiber laser combination approach for >kHz LPAs

- 100x reduction in fiber array size
- Only been demonstrated with >300fs
- Critical to demonstrate with tens of fs (needed for LPA drivers)

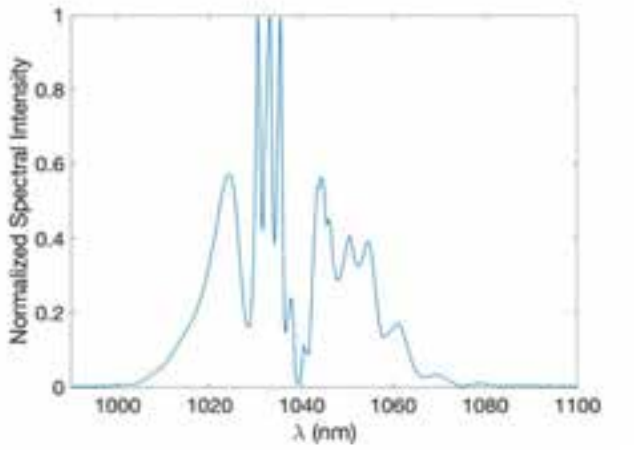
- Pulse stacking uses optical cavities → Broadband pulses accrue different dispersions upon stacking → Dispersions affect pulse stacking efficiency
- Simulation shows: With off-the-shelf, low-dispersion mirrors, efficient stacking of 81 pulses can be achieved with pulse lengths down to 30fs

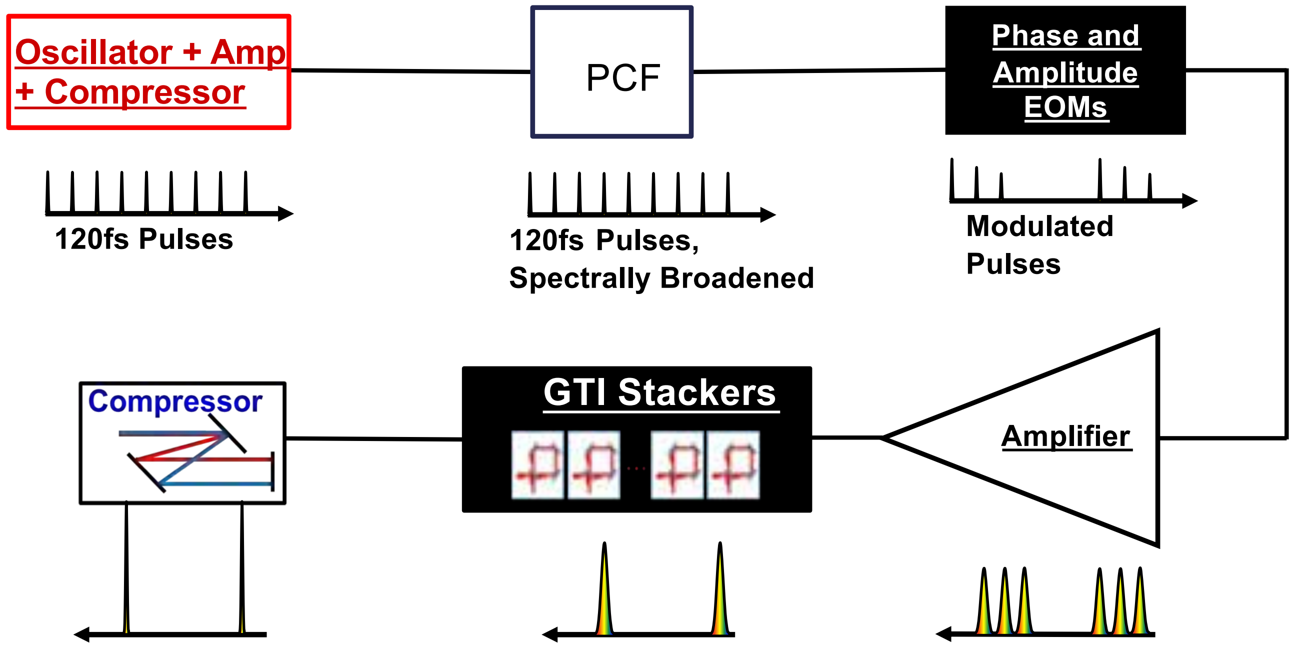


Lauren Cooper, et al. AAC 2022.

Setup of Broadband Stacking

Using PCF with 10mW input pulse energy, we obtained spectra corresponding to <50fs transform limited pulse duration:




Oscillator + Amp + Compressor

120fs Pulses

PCF

120fs Pulses, Spectrally Broadened

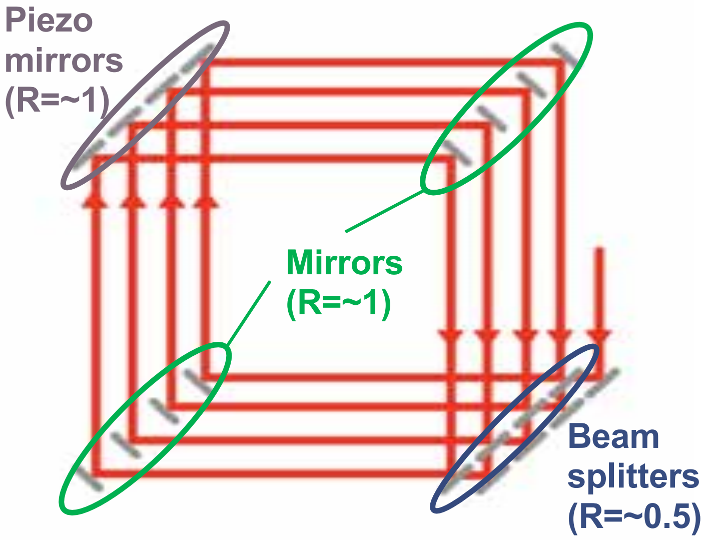
Phase and Amplitude EOMs

Modulated Pulses

Amplifier

GTI Stackers

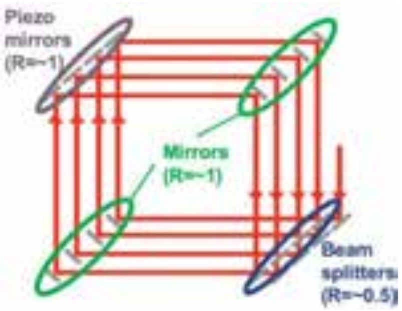
Compressor

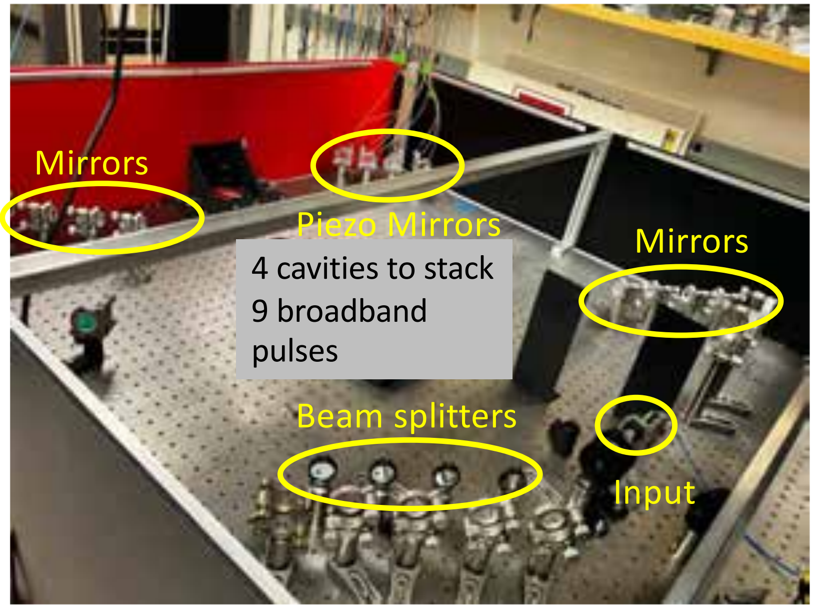

Piezo mirrors (R=~1)

Mirrors (R=~1)

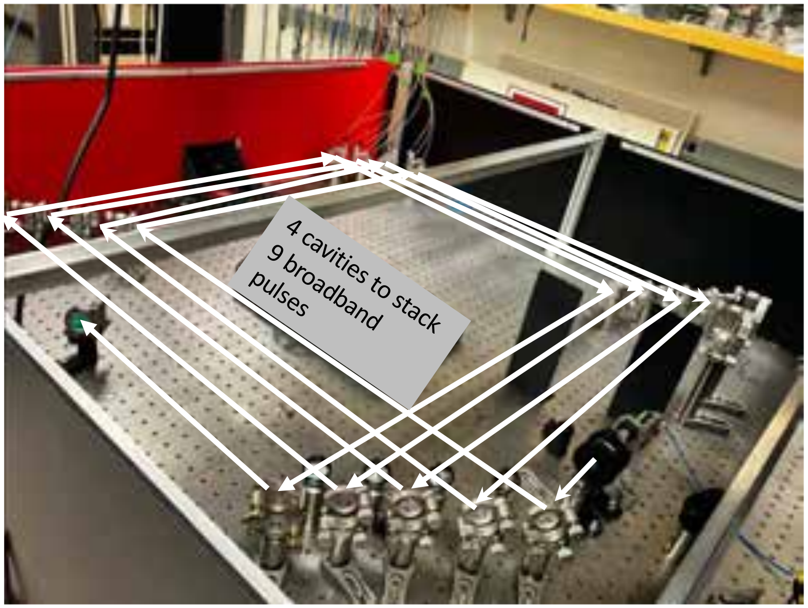
Beam splitters (R=~0.5)

Setup of Broadband Stacking





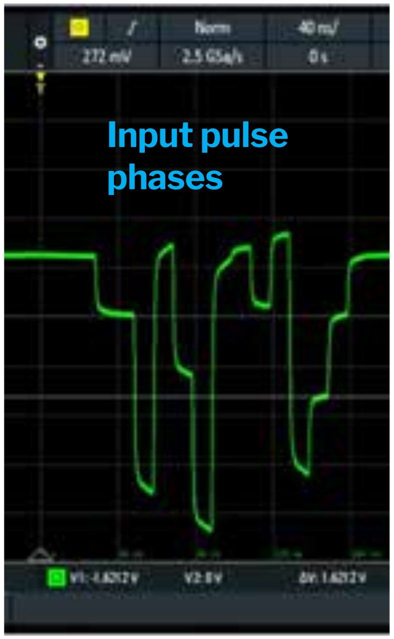
4 cavities to stack
9 broadband
pulses

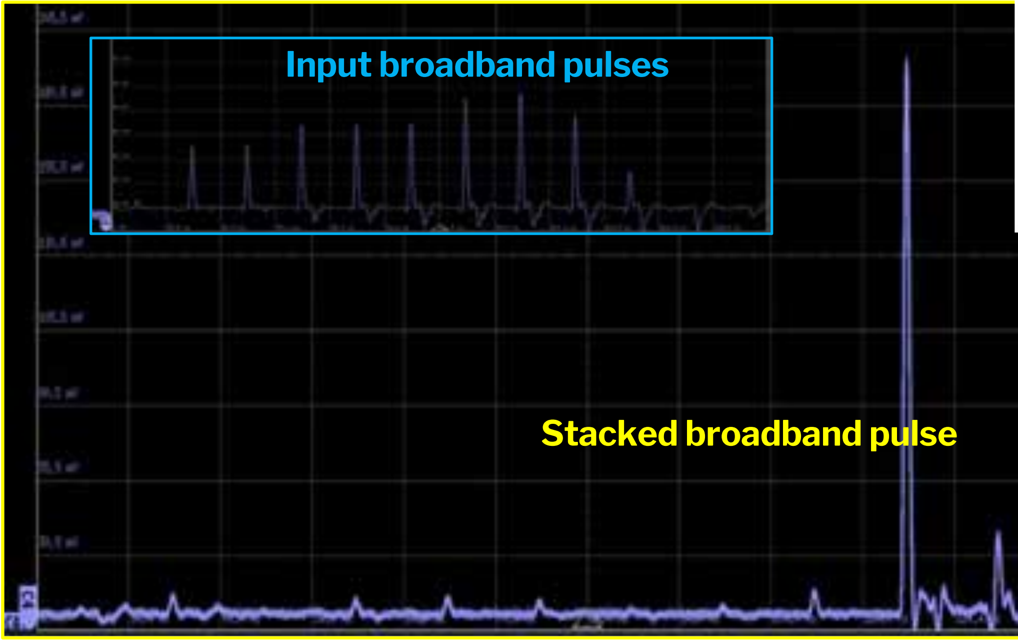


4 cavities to stack
9 broadband
pulses

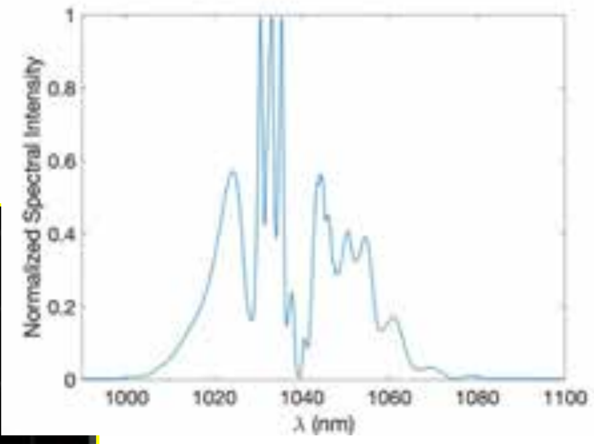
4 Cavity Broadband Stacking Results

- **Experiment**
  - <50fs bandwidth pulses were stacked in a 4-cavity, 9-pulse stacking setup
  - High efficiency stacking was demonstrated with 30:1 pre-pulse contrast


Input pulse phases


Input broadband pulses

Stacked broadband pulse



Lauren Cooper, et al. AAC 2022.
Lauren Cooper, et al. CLEO 2023.

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Prior art on generating short pulses from Yb:fiber systems & Challenges

Shortest pulse from a single fiber amplifier channel

- 130fs, 250μJ
- Pulse shaping (intensity & phase)

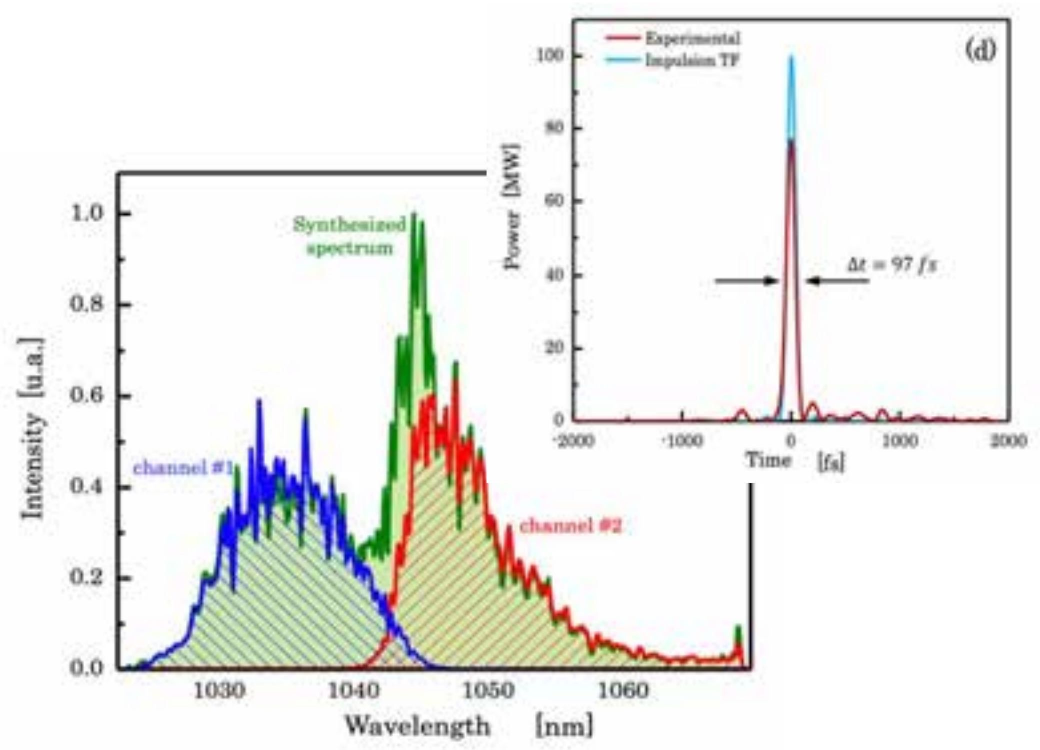
L. Lavenu, et al. Opt. Express 25, 7530-7537 (2017).

Shortest pulse from spectrally combined Yb:fiber systems

- ~100fs, 10μJ, combining 2 channels [1]
- One pulse shaper (phase) before splitting

But LPA drivers require pulse durations as short as 30fs

- Critical to demo spectral combining to 30-50 fs
- Need ~100nm bandwidth, while current high-resolution pulse shapers only cover <50nm

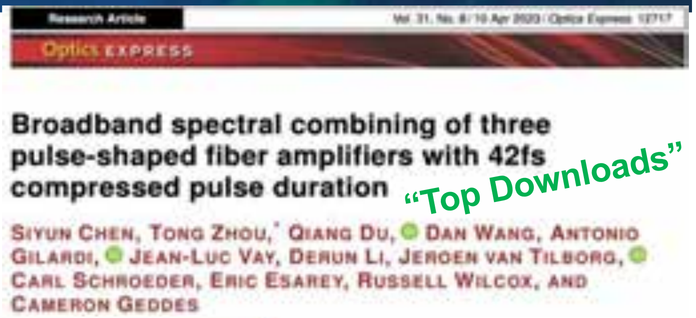


[1] *F. Guichard, et al. Proc. SPIE 9728, Fiber Lasers XIII: Technology, Systems, and Applications (2016).*

Demonstration of record short pulse from Yb:fiber combination systems paved way to high-energy multi-dimensionally combined systems

Demonstrated record short pulse (42fs) from Yb:fiber combination systems

- Combining 3 spectral bands over 80nm, covering Yb3+ gain window
- Coherently-spectrally synthesize pulse shaping achieves full-band spectral intensity/phase control



Research Article

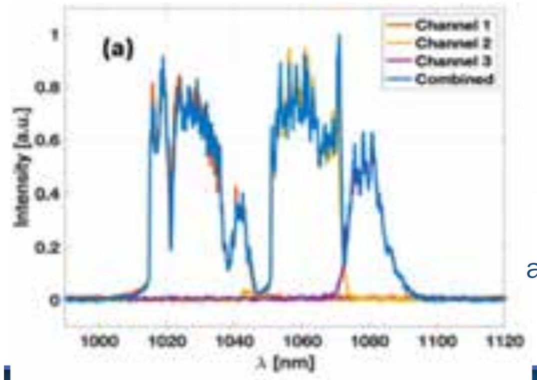
Vol. 31, No. 8 / 10 Apr 2023 / Optics Express 12717

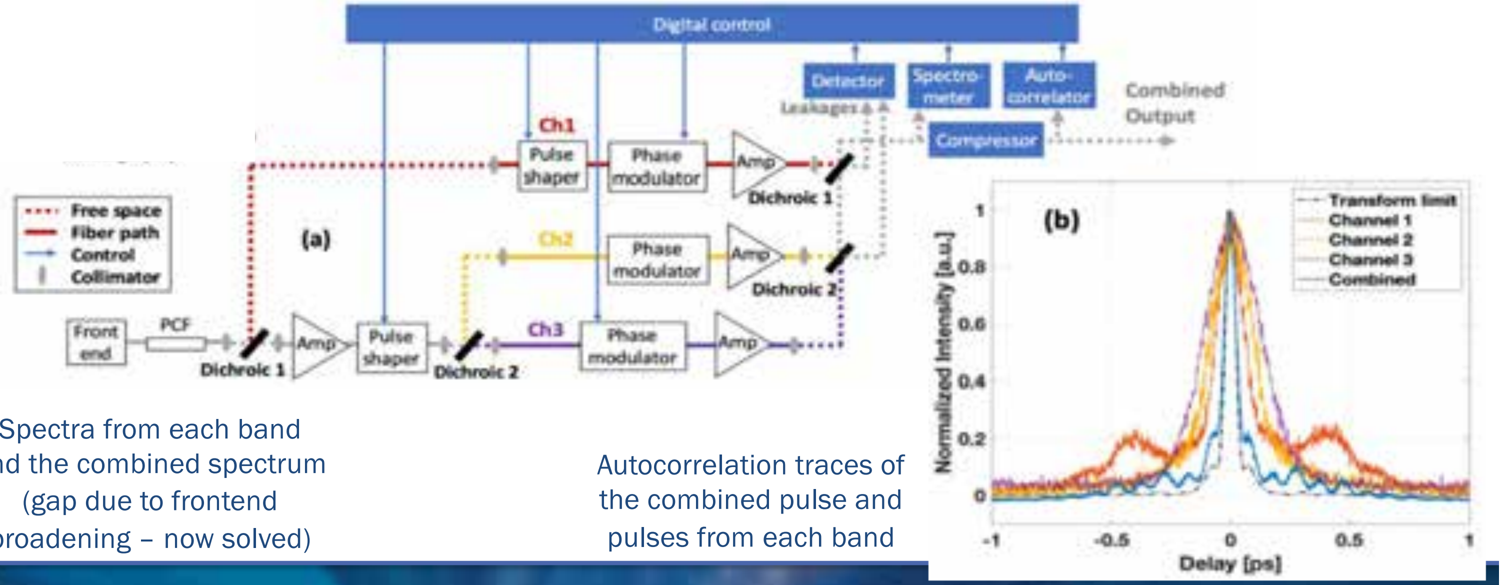
Optics EXPRESS

Broadband spectral combining of three pulse-shaped fiber amplifiers with 42fs compressed pulse duration

SIYUN CHEN, TONG ZHOU,* QIANG DU, DAN WANG, ANTONIO GILARDI, JEAN-LUC VAY, DERUN LI, JEROEN VAN TILBORG, CARL SCHROEDER, ERIC ESAREY, RUSSELL WILCOX, AND CAMERON GEDDES

“Top Downloads”





Spectra from each band and the combined spectrum (gap due to frontend broadening – now solved)

Autocorrelation traces of the combined pulse and pulses from each band

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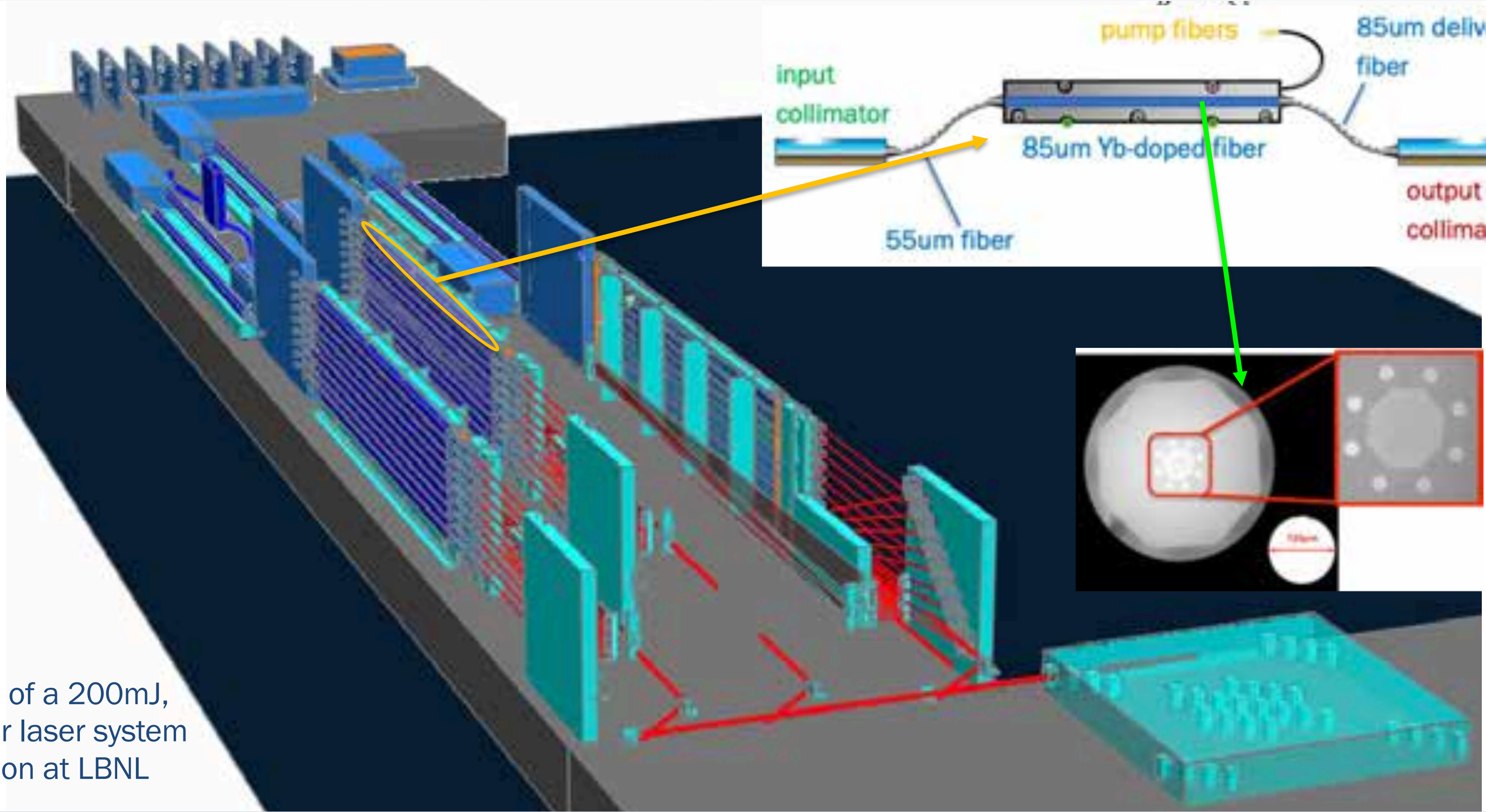
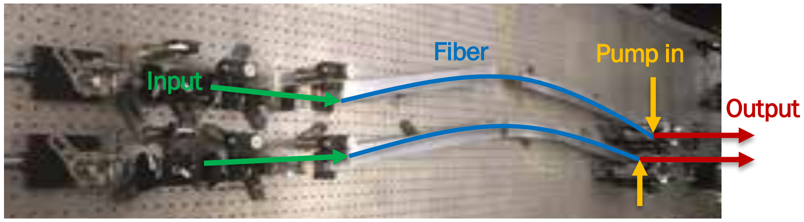
Fibers/Amplifiers are the backbone of high energy fiber lasers



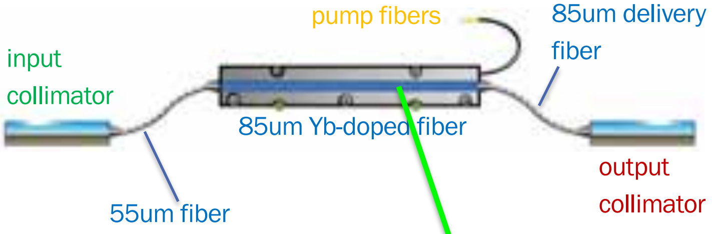
Layout design of a 200mJ, 5kHz, 1kW fiber laser system in construction at LBNL

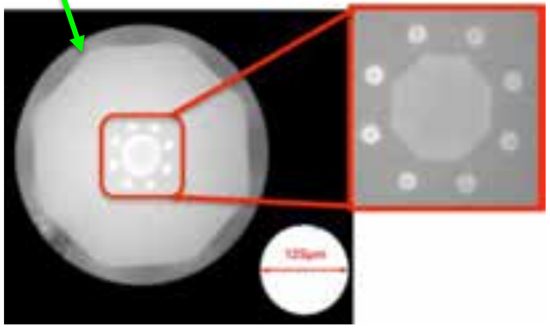
Significant progress in developing and manufacturing fiber and amp modules

High power fiber amplifier to be monolithically modularized (currently free-space coupling in and out of fiber)



Design of modularized monolithic fiber amplifier





- Fabricated record large-mode passive fiber (LBNL/UM/nLight)
- Active fiber in progress
- Designed record large-mode integrated fiber amplifier module (LBNL/UM/Optical Engines)
- Amp module prototype in progress

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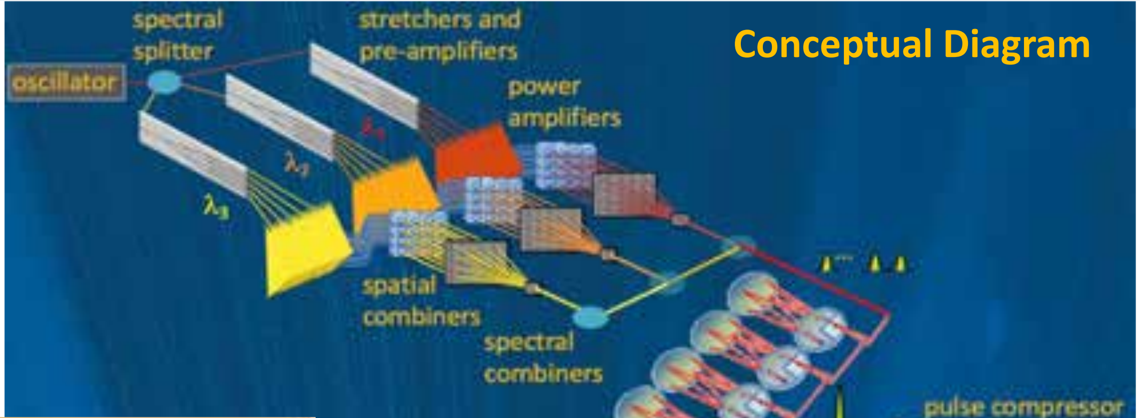
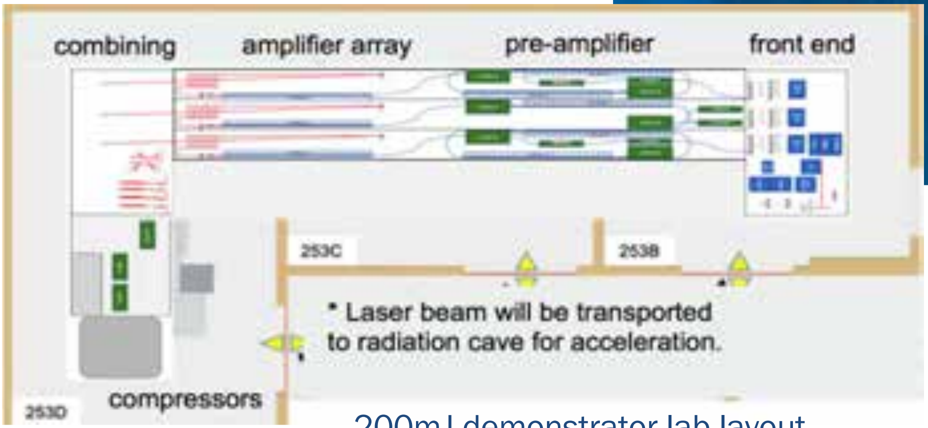
200mJ demonstrator system under construction at LBNL

Short-term (<3 yrs): 0.2J pulse energy, 30-50fs pulse duration, 5kHz rep-rate, 1kW avg. power

- ~30 integrated high power fiber amplifier modules
- Demo key capability of energy/power scalability and short pulse approach
- Demo high rep-rates precision feedback control
- Key step to a kBELLA facility (3J, 3kW) and future laser-plasma collider stages (6J, 300kW)

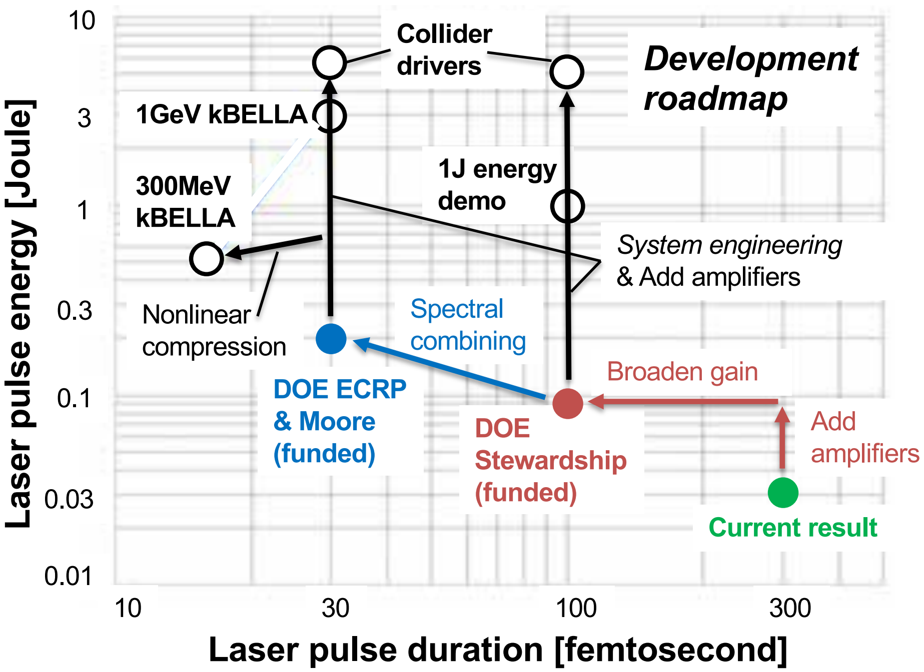

Conceptual Diagram



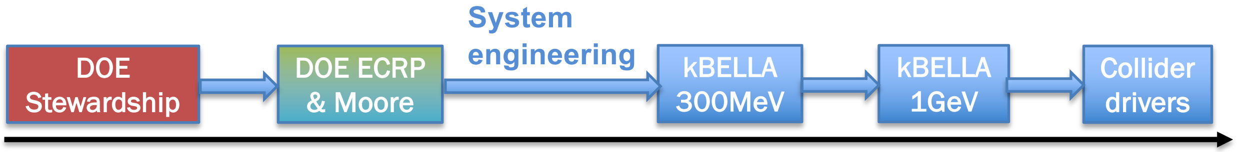
* Laser beam will be transported to radiation cave for acceleration.

200mJ demonstrator lab layout

Fiber-laser accelerator driver development roadmap: from short-term R&D to long-term facilities



- Short-term goal (3-5 yrs): Achieve technical readiness for building fiber laser driver facilities
  - o Laser specs: 0.2J, 30-50fs, 5kHz, 1kW
  - o Solid circles in the left roadmap are short-term R&D milestones (funded)
- Mid-term goal (<10 yrs): Build and operate accelerator facilities driven by fiber lasers, e.g. kBELLA
  - o Laser specs: 3J, 30fs, 40kHz, 120kW
  - o Stepping stone towards collider drivers
- Long-term goal (>10 yrs): Build and operate collider driver facilities
  - o Laser specs: 5J, 30/100fs, 40kHz, 200kW



	DOE Stewardship	DOE ECRP & Moore	kBELLA 300MeV	kBELLA 1GeV	Collider drivers
Project Type	R&D (funded)	R&D (funded)	Facility	Facility	Facility
Energy	0.1 J	0.2 J	0.5 J	3 J	5 J
Duration	100 fs	30-50 fs	15 fs	30 fs	30/100 fs

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Conclusion

- Advanced high-power laser technologies are needed for broad accelerator applications; Fiber laser combination approach is promising for driving >kHz plasma accelerators and broad applications.
- Our fiber laser combination approach integrates novel laser methods:
  - Diffractive ultrashort-pulse beam combining (in space)
  - Coherent pulse stacking (in time)
  - Coherent spectral combining (in spectrum)
- Current grants will build a 200mJ/30fs/1kW fiber laser, a stepping stone for kBELLA facility and beyond
  - We demonstrated coherent pulse stacking of <50fs pulses (>6x shorter than prior art)
  - We demonstrated spectral combining to 42fs pulses (>2x shorter than prior art)
  - We designed the key fibers/amplifiers (being fabricated)
  - The 200mJ demonstrator will demo P/E scalability, pulse duration, fiber amp modules, feedback control
- We have a fiber laser development roadmap: from short-term R&D to long-term accelerator facilities.

Thank you!

Look forward to potential collaborations!

- R&D
- Accelerator Science and Engineering Traineeship (ASET) program
- DOE Office of Science Graduate Student Research (SCGSR) program
- and more...