Precision high average power ultrashort pulse lasers

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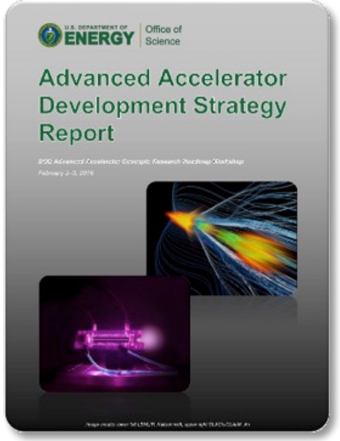
kHz-kW lasers are now realistic, key to applications and control

Laser plasma accelerator potential shown

- Order of magnitude performance increase needed for applications
- High quality particle beams: future colliders
- Compact hard photon sources
- National security applications, medical sensing/therapy, laser manufacturing
- Ion and neutron sources, remote sensing…

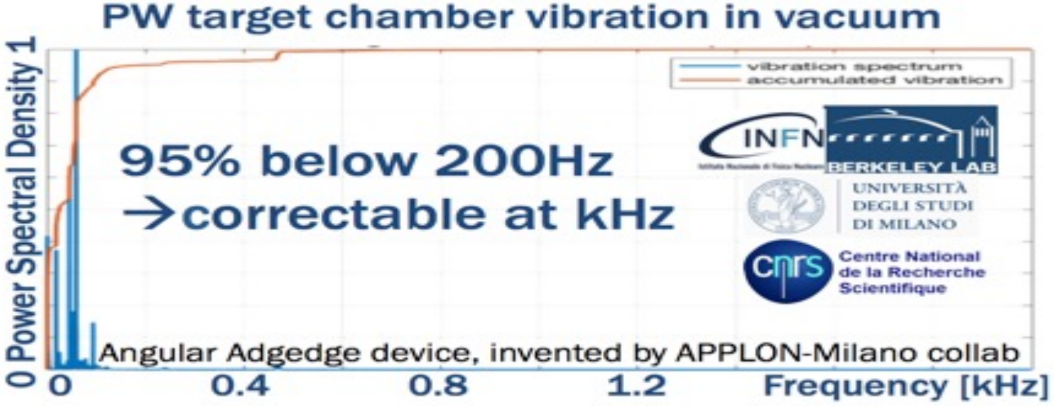


Precision laser shaping and control required for quality and efficiency

- Laser pointing: from µrad to < 0.1 µrad
- Focal spot/wave front: now at fluctuation limit
- Near field: currently not well controlled
- Pulse shape, carrier envelope phase…

kHz enables correction - ground & air motion fall off at O[100Hz]. Enabled by fiber lasers.

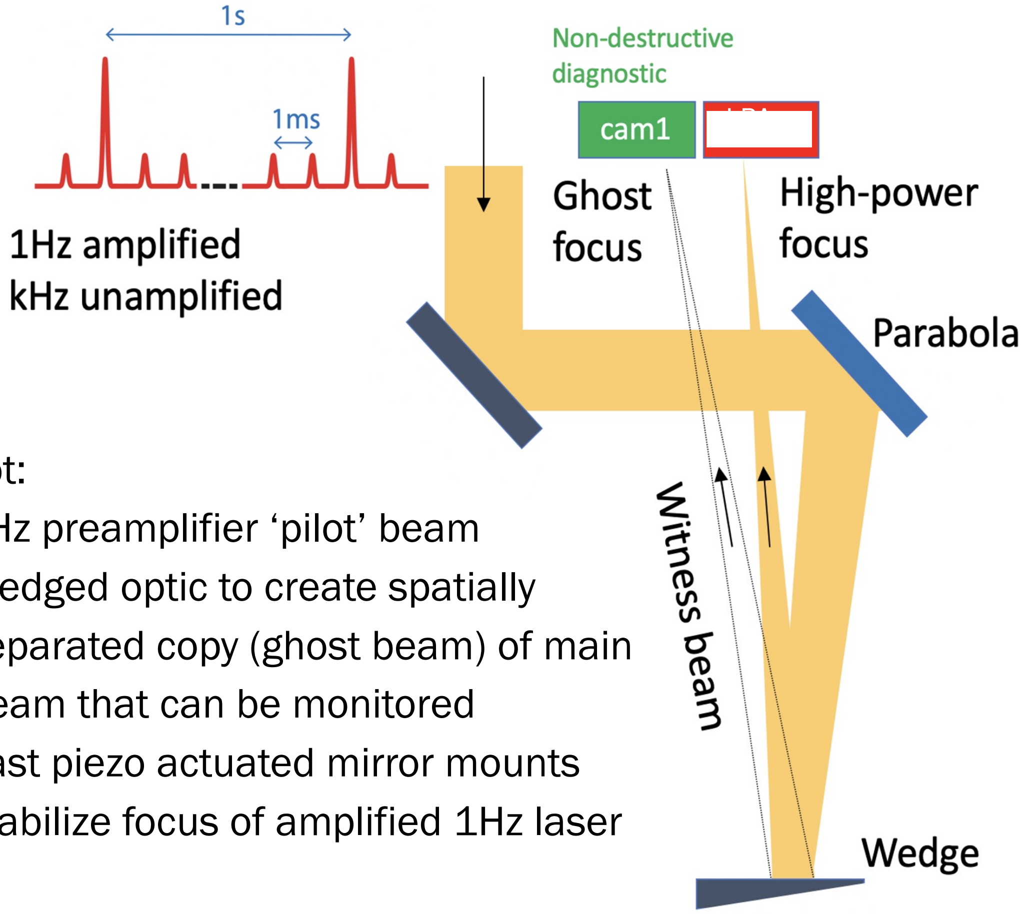
Correction at kHz >10 fold - key to LPA performance



BELLA mJ kHz: 10x reduced pointing fluctuation
Other groups: CEP, spectral phase…

Active correction using pilot beams demonstrates potential performance gain

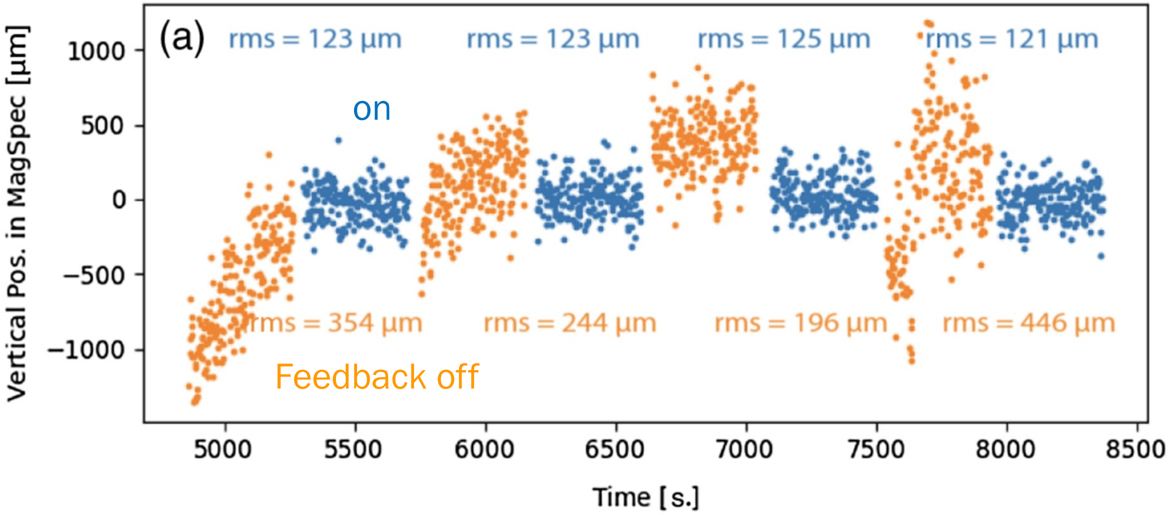
Setup



Concept:

- kHz preamplifier 'pilot' beam
- Wedged optic to create spatially separated copy (ghost beam) of main beam that can be monitored
- Fast piezo actuated mirror mounts stabilize focus of amplified 1Hz laser

F. Isono *et al*, High Power Laser Sci. Eng. **9**, e25 (2021)



- Measured transverse location of electron beam with/without (blue/yellow) active laser stabilization.
- RMS variation of e-beam source location reduced by factor of x4 over 1 hour
- Based on 40x magnification of e-beam optics, measured 3 um rms source location jitter over 1 hour

C. Berger *et al.* PRAB **26**, 032801 (2023)

Future: kHz main laser to enable full stabilization & control

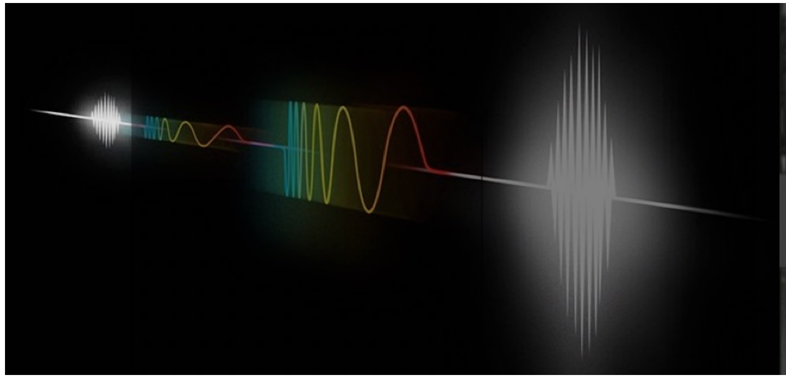
Ultrafast fiber lasers can provide high laser energy at high power and high efficiency

120 kW commercial fiber laser (CW)
with >45% wall-plug eff.
(combining ~100 fibers)

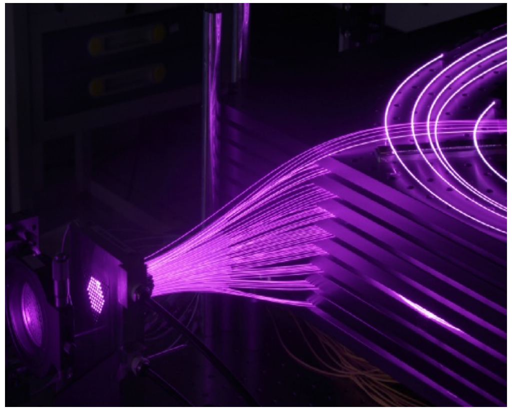
Ultrafast fiber lasers use chirped-pulse amplification technology

KUNGL. VETENSKAPS AKADEMIEN

Mourou & Strickland
2018 Nobel Prize



- Fiber laser is the most efficient high power laser to date
- Ultrafast fiber laser combining towards high laser energy, efficiency
  - Chirped-pulse amp. & pulse stacking enables high pulse energy per fiber
  - Industrial monolithic integration facilitates large-scale combining
  - Rapidly developing over the past ~15 years



Example: 61-fiber-laser combining system at Ecole Polytechnique

- I. Fsaifes et al. *Opt. Express* **28**, 20152-20161 (2020)

Coherent combining of ultrafast fiber lasers is being developed worldwide for broad applications

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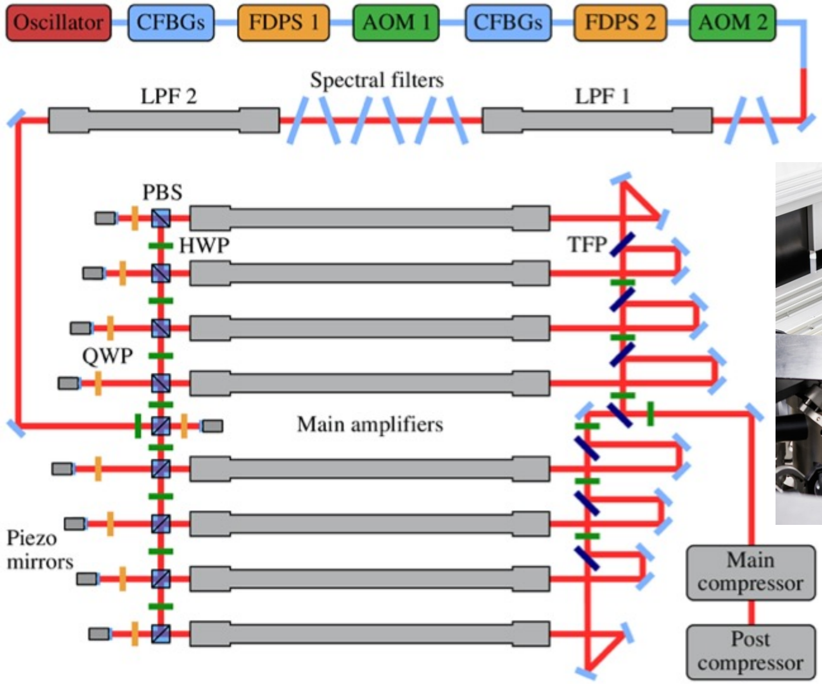
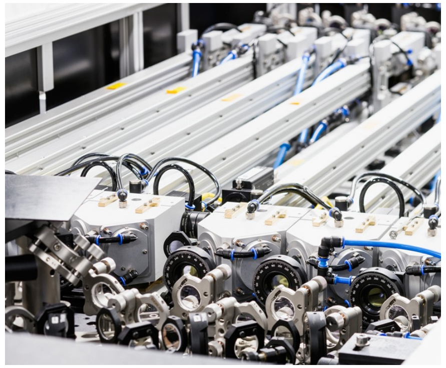
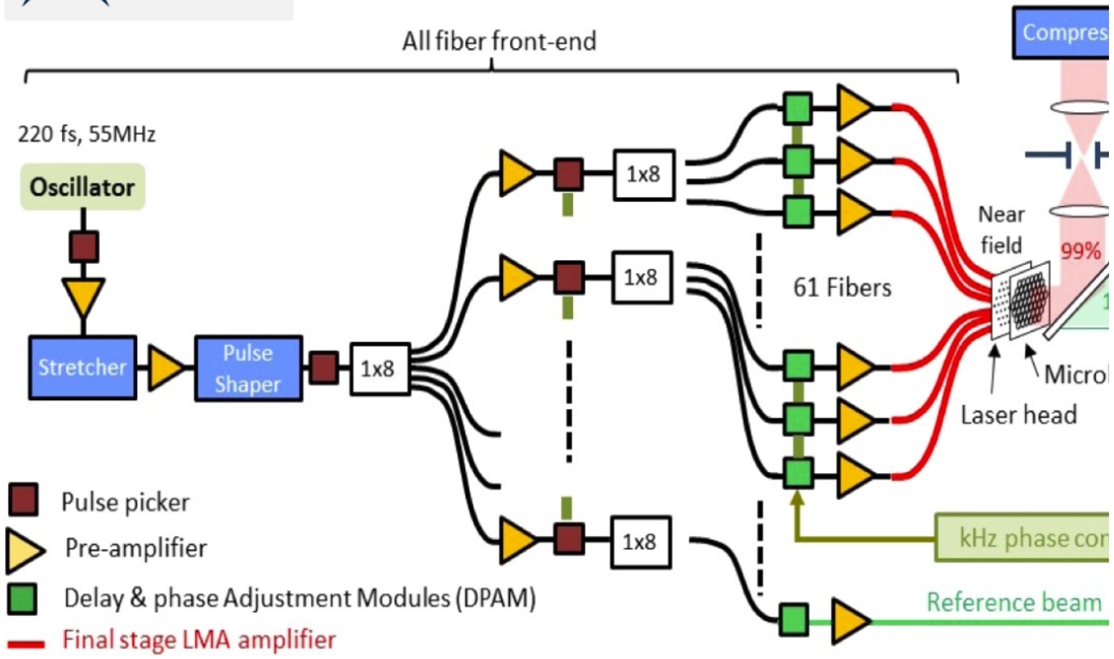




- Achieved 32mJ, 158fs, 640W @ 16 fibers
- Achieved 10mJ, 120fs, 1kW @ 16 fibers

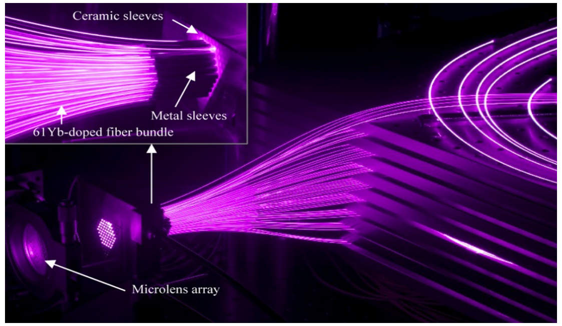
- H. Stark et al. Optics Letters 48, 3007 (2023)
- H. Stark et al. Optics Letters 46, 969 (2021)

l'X ÉCOLE POLYTECHNIQUE

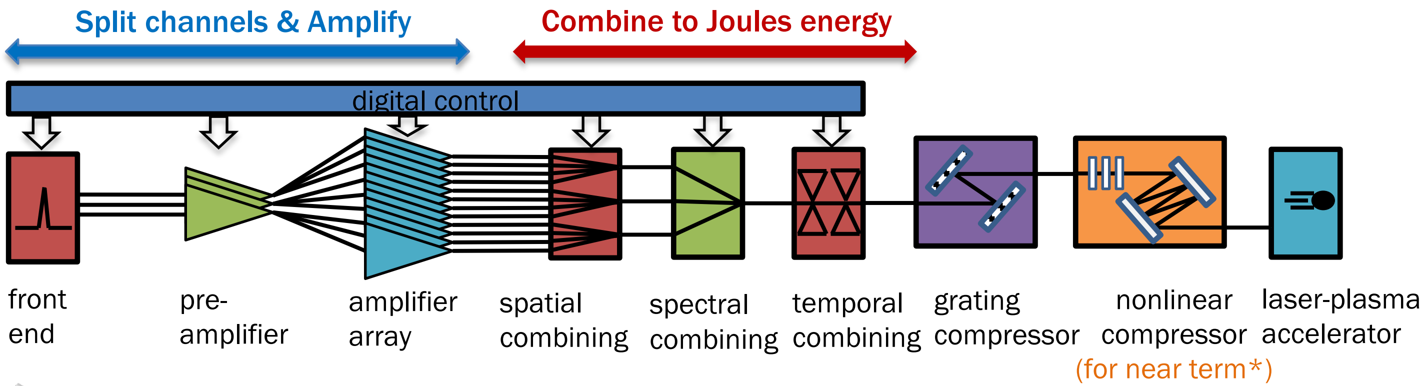


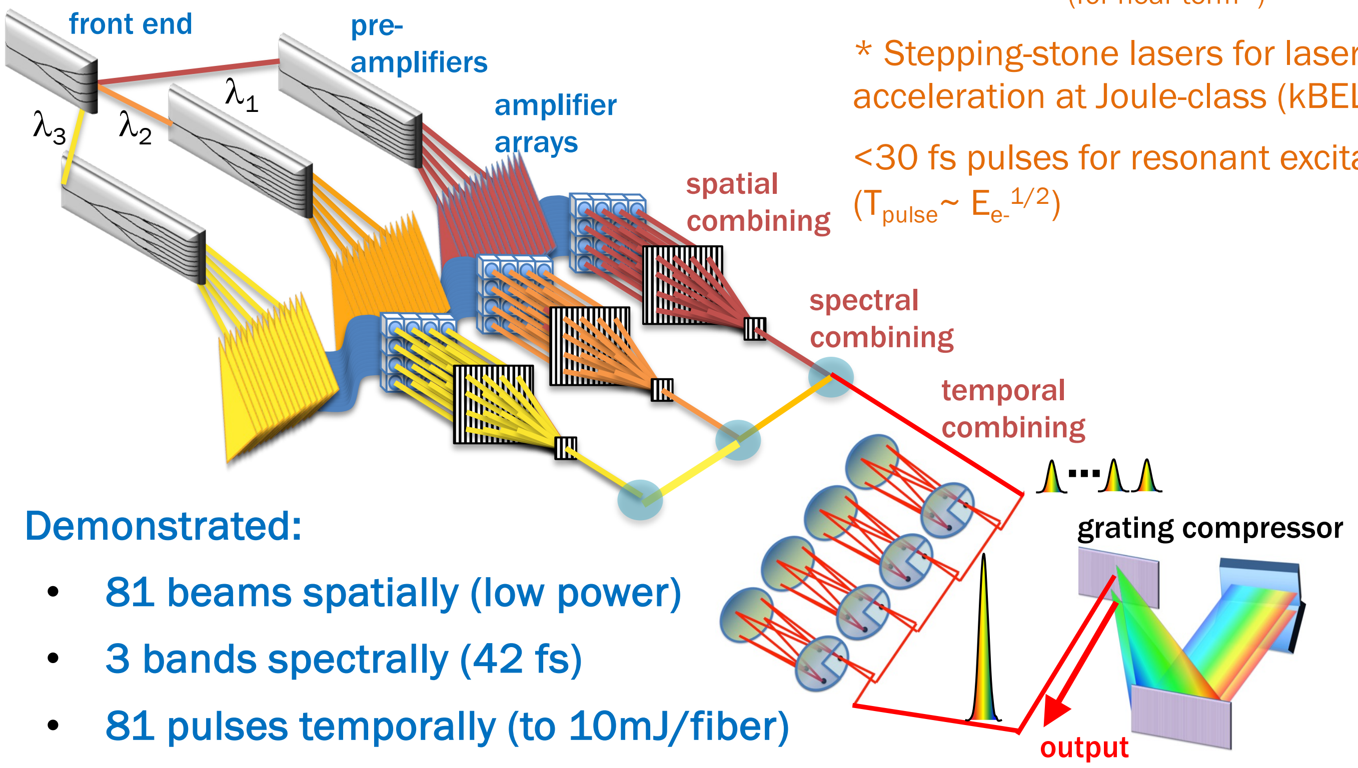
- Achieved 1kW, 257fs, @ 61 fibers

- I. Fsaifes et al. *Opt. Express* **28**, 20152-20161 (2020)



Fiber Combination Provides a Route to Very Efficient, High Average Power Ultrafast Lasers





* Stepping-stone lasers for laser-plasma acceleration at Joule-class (kBELLA):

<30 fs pulses for resonant excitation ($T_{pulse} \sim E_{e-}^{1/2}$)

Demonstrated:

- 81 beams spatially (low power)
- 3 bands spectrally (42 fs)
- 81 pulses temporally (to 10mJ/fiber)

Path to Joules at 30-100fs

- Efficiency circa 30%
- Rates of 10-100 kHz

Path: Coherent addition of fiber lasers

- Most efficient, potential monolithic integration

Challenge: Fibers < mJ each, typically > 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

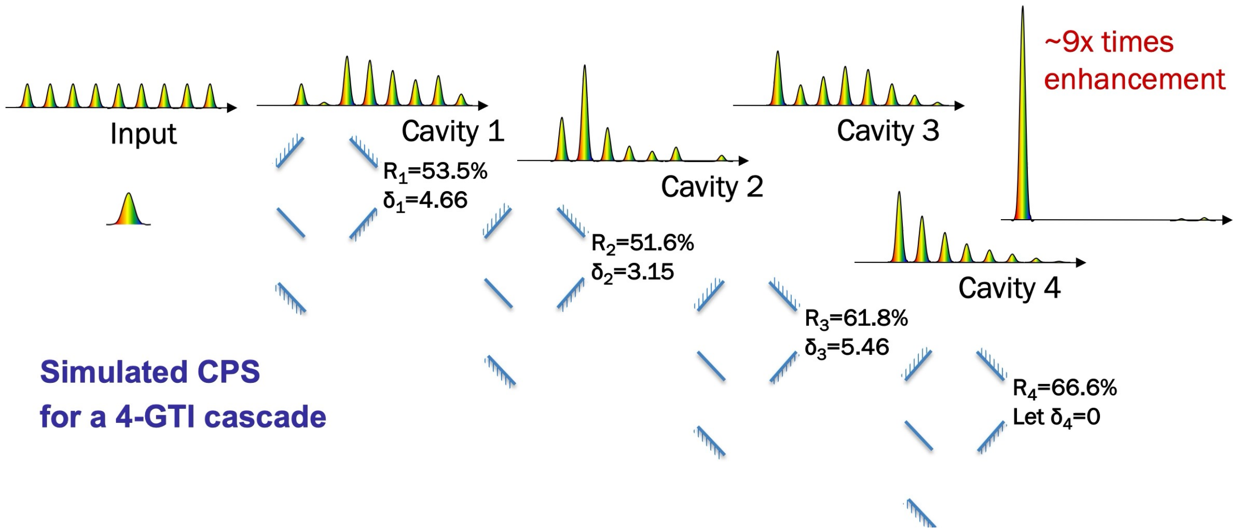
Related: Fraunhofer, U. Jena, XCAN

Industry: nLight, Optical Engines, Coherent…

Novel temporal pulse stacking and spatial combining enable fiber lasers to achieve high energy

- Coherent pulse stacking: cascaded optical cavities to stack many pulses in time
- Full energy extraction of fiber amplifier (e.g. stacking 81 pulses to >10mJ with 4+4 cavities)

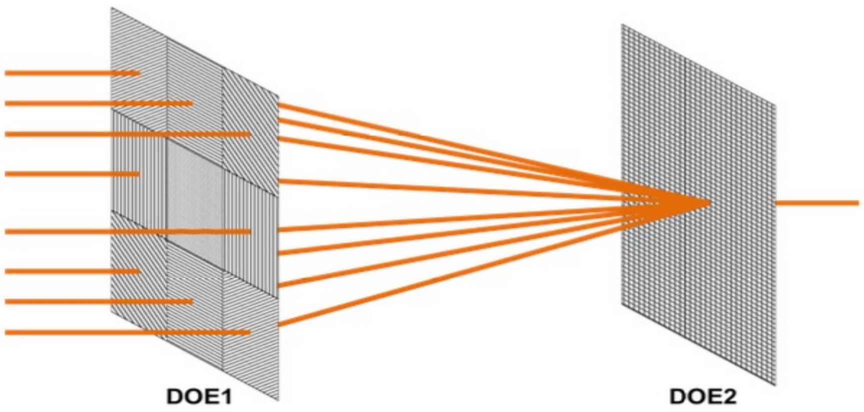
Example: 9 laser pulses stacked to 1 pulse using 4 optical cavities



- Tong Zhou, John Ruppe, Cheng Zhu, I-Ning Hu, John Nees, and Almantas Galvanauskas, Opt. Express 23, 7442-7462 (2015)

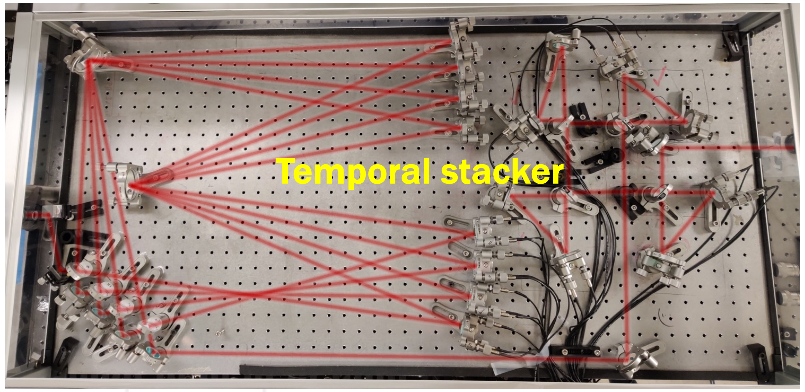
- Diffractive beam combining of ultrashort-pulse beams: two optics correct tilt
- Filled aperture for beam quality
- Scalable, compact, stable

Example: 8 laser beams combined to 1 beam using two diffractive optical elements (DOE)



- Tong Zhou, Qiang Du, Tyler Sano, Russell Wilcox, and Wim Leemans, Opt. Lett. 43, 3269-3272 (2018)

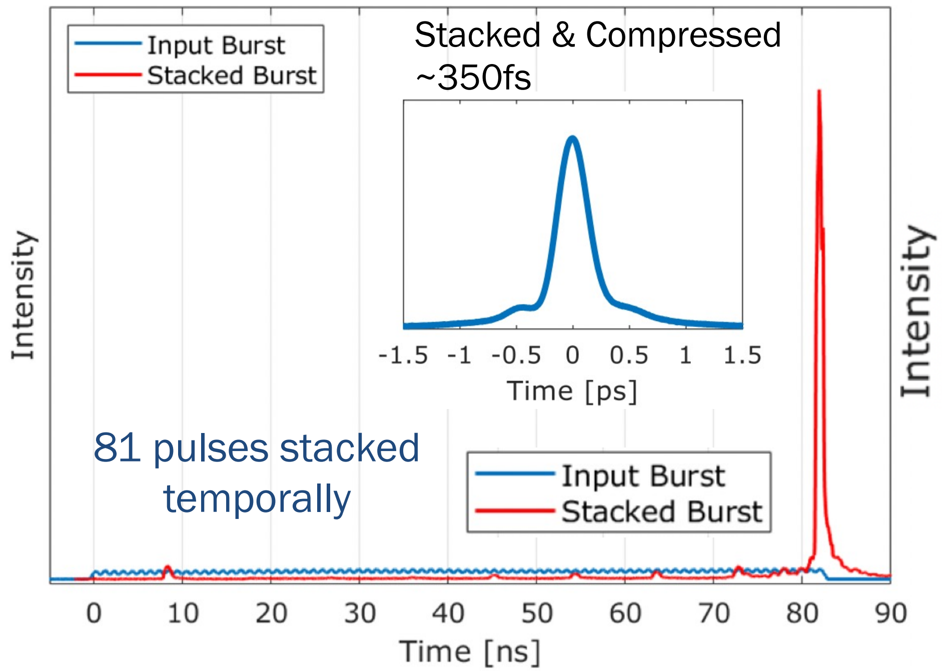
Breakthrough in coherent pulse stacking will lead to practical fiber arrays for multi-J energies

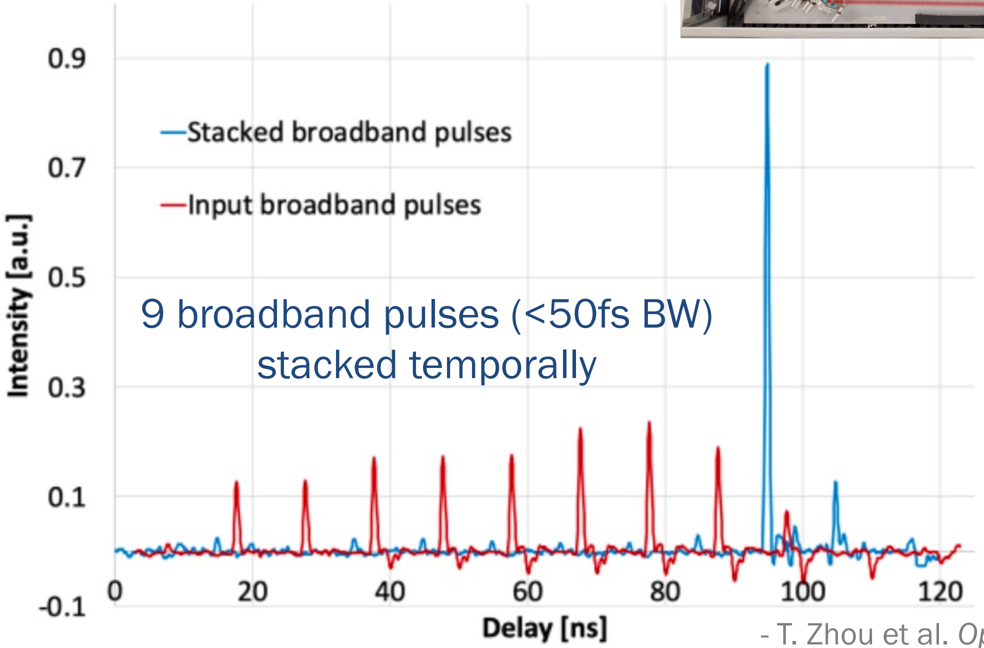


Time-domain coherent pulse stacking: full extraction of stored energy
→ ~100 times reduced fiber array size

>1J potential at ~100 fiber amplifier channels

- Stacked 81 pulses to ~10mJ with 8 cavities (~350fs)
- Broadband stacking showed CPS supports ~30fs





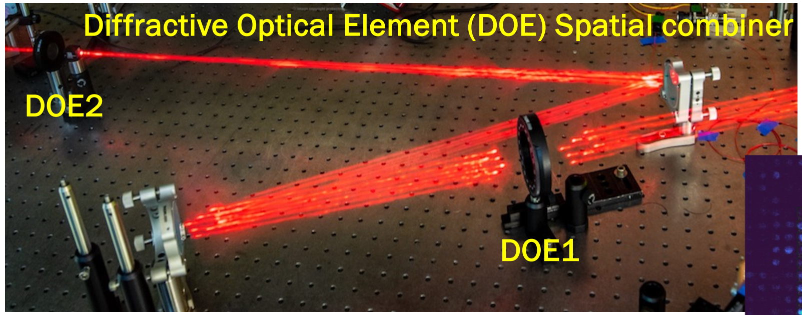
- T. Zhou et al. *Optics Express* **23**, 7442-7462 (2015)
- H. Pei et al. *Laser Congress* 2017
- M. Whittlesey et al. *AAC Workshop* 2022
- L. Cooper et al. *CLEO* 2023

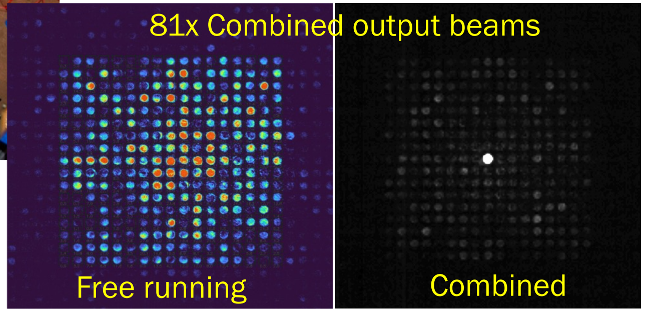
Large-scale beam combination and high-energy spatio-temporal combination of ultrafast fiber lasers have been demonstrated

Spatial beam combination

- 100’s beams can be combined spatially to 1 beam with two diffractive optics
- Combined eight, 100fs beams with 90% efficiency
- **Combined 81 beams** (low power)

- T. Zhou et al. *Optics Letters* **42**, 4422-4425 (2017)
- T. Zhou et al. *Optics Letters* **43**, 3269-3272 (2018)
- Q. Du et al. *Optics Express* **29**, 5407-5418 (2021)

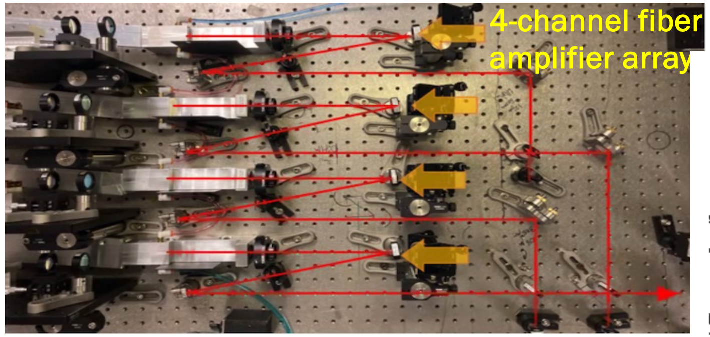


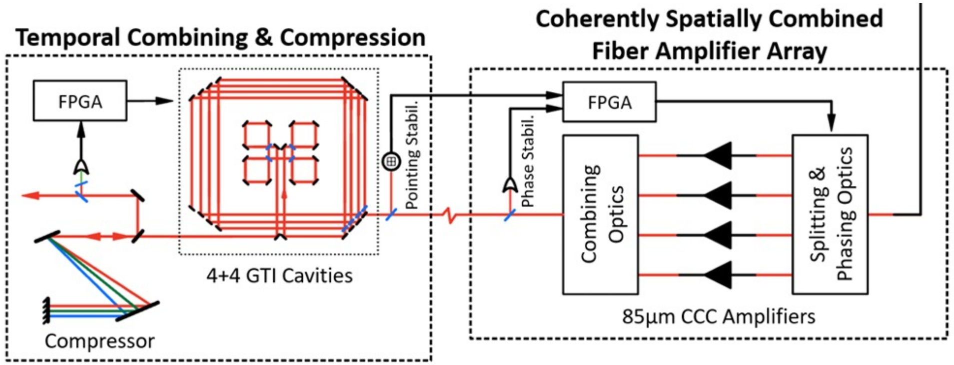


Spatial & temporal combination for power/energy

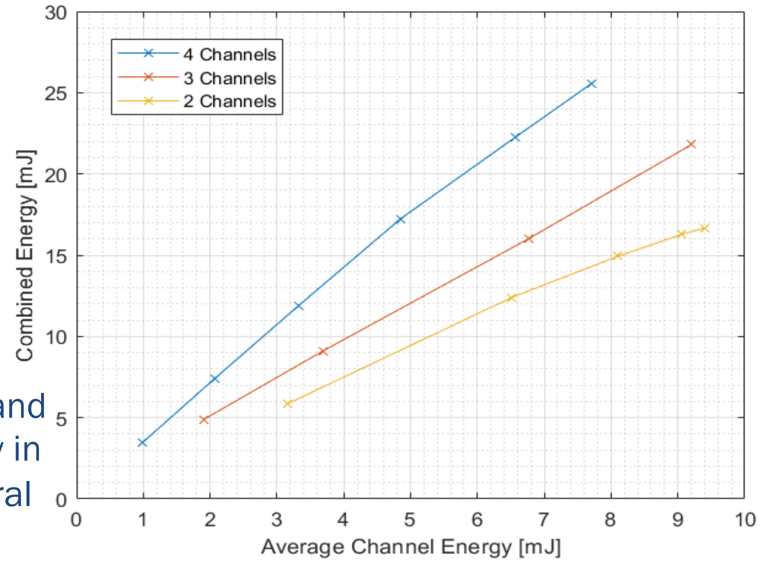
- 4 beams combined, stacked & compressed to ~25mJ with ~7mJ/fiber

- 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



Demonstration of record short pulse from Yb:fiber combination systems paves 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

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

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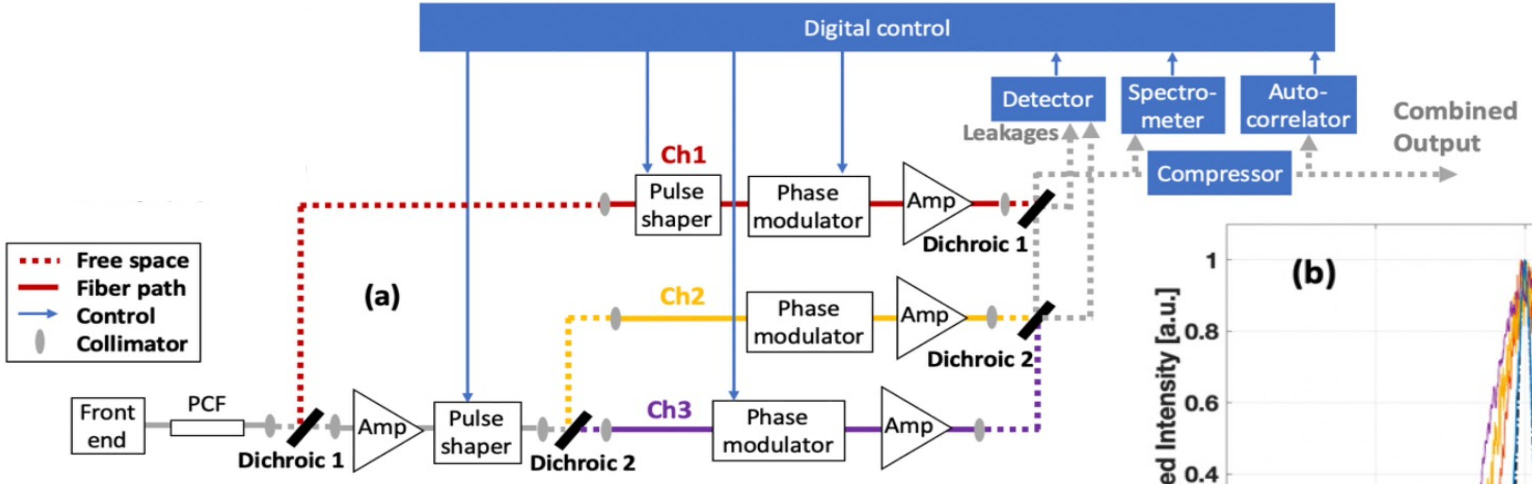
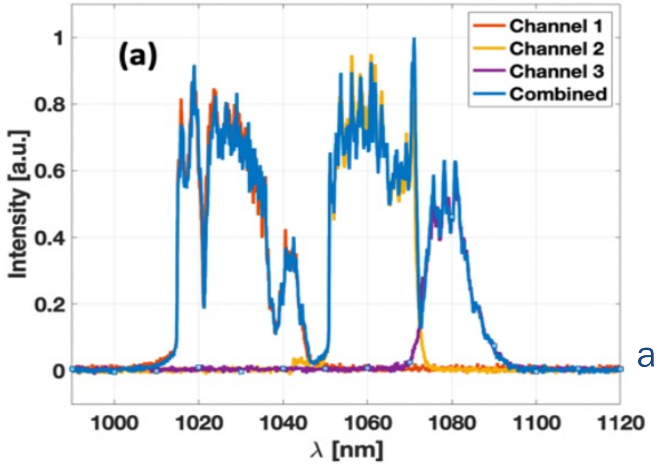
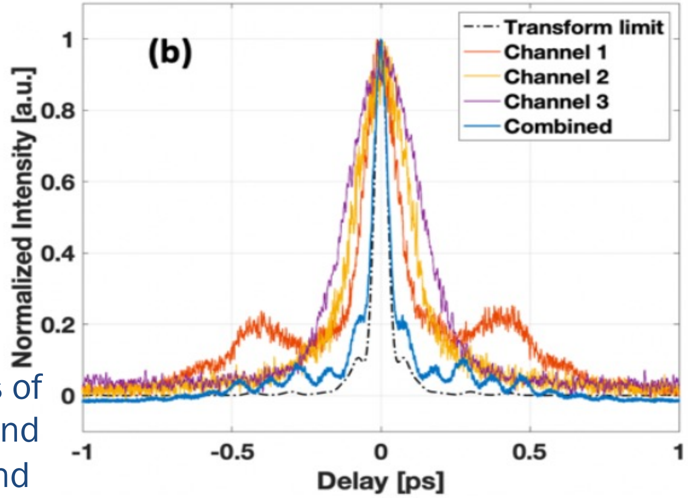




Spectra from each band and the combined spectrum (gap due to frontend broadening – now solved)



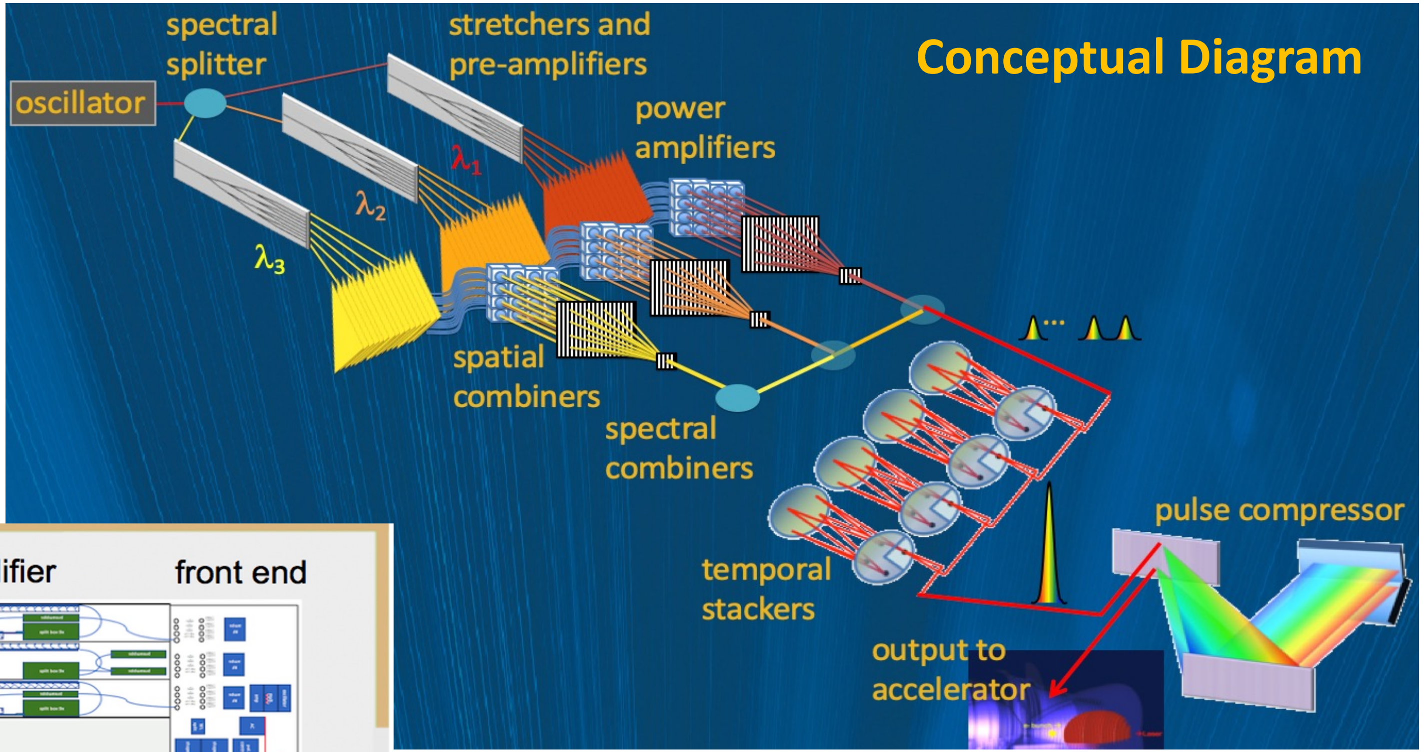
Autocorrelation traces of the combined pulse and pulses from each band

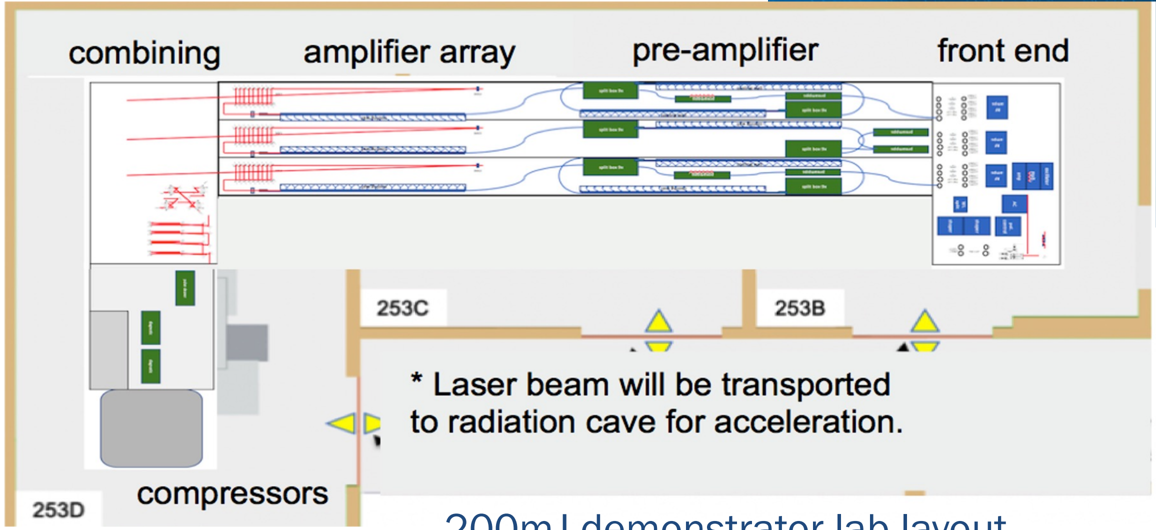
BERKELEY LAB ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP GORDON AND BETTY MOORE FOUNDATION U.S. DEPARTMENT OF ENERGY Office of Science

200mJ demonstrator system under construction

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 towards 3J, 3kW class and future laser-plasma collider stages (6J, 300kW)



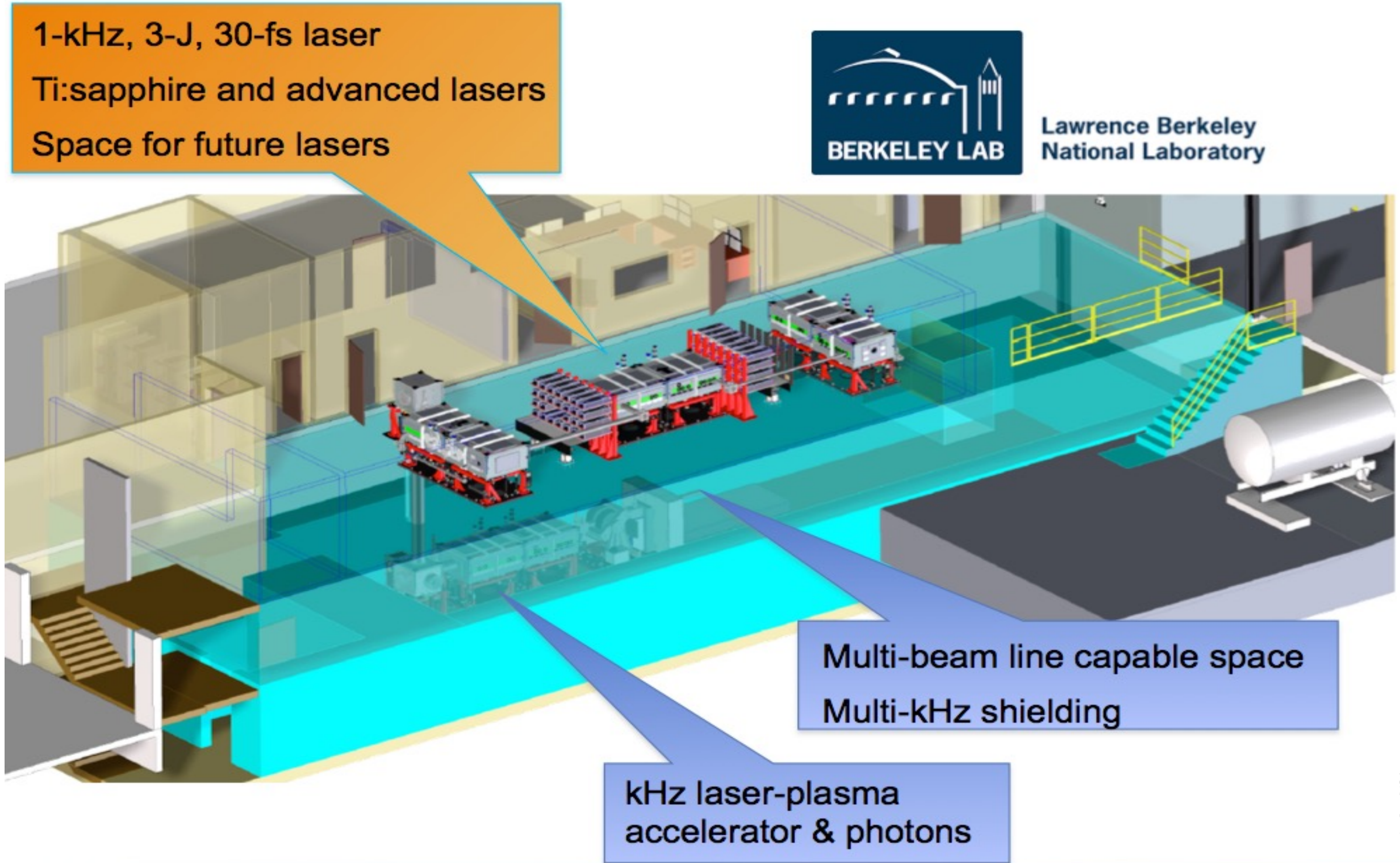


200mJ demonstrator lab layout

kBELLA Initiative Under Development for kHz, Joule-class LPA

High priority in community and funding agency plans for precision LPA

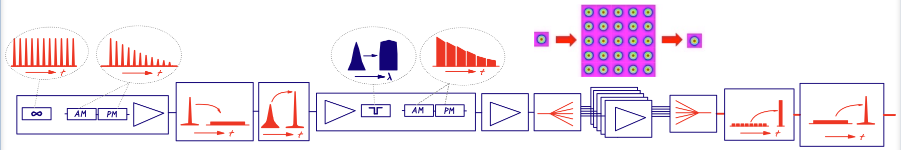
- Fiber, Yb and Tm:YLF offer paths to high efficiency
- Facility supporting multiple lasers for immediate experiments and long term development
- Key step on collider roadmap and enables photon sources and precision HEDS



Coherently combined fiber laser power and energy scaling demonstrations, and systems development

Table-top demonstration of fiber laser based 1kW/1TW system

- Coherent pulse stacking amplification (temporal combining)
- Spatial coherent combining



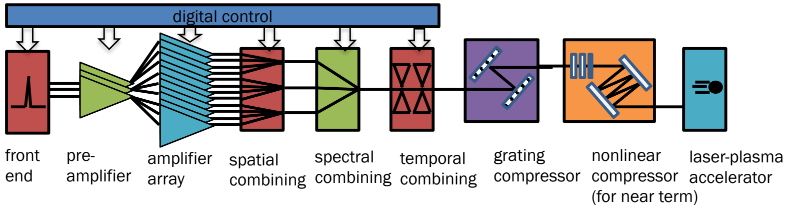
Demonstration of 10-channel coherently combined fiber laser system producing ~100mJ, ~50-100fs, at 1 – 10 kHz & ~kW average power

System-level high power demonstration, which integrates:

- Coherent pulse stacking and spatial coherent combining
- Gain-narrowing & energy saturation compensation
- Dispersion control
- Embedded control systems and efficient control algorithms

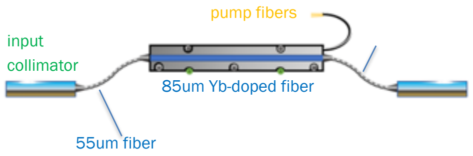
Laboratory demonstration of spectrally-combined 30fs/kW system

- Monolithic integration & modular engineering of fiber amplifiers
- Kilowatt thermal management for laser and combining stability



Demonstration of 30-channel coherently combined fiber laser system producing ~200mJ, ~30fs, at 1 – 10 kHz & ~kW average power

Design of modularized monolithic fiber amplifier



DOE Stewardship → Moore's Foundation → kBELLA 300MeV → kBELLA 1GeV → Collider drivers

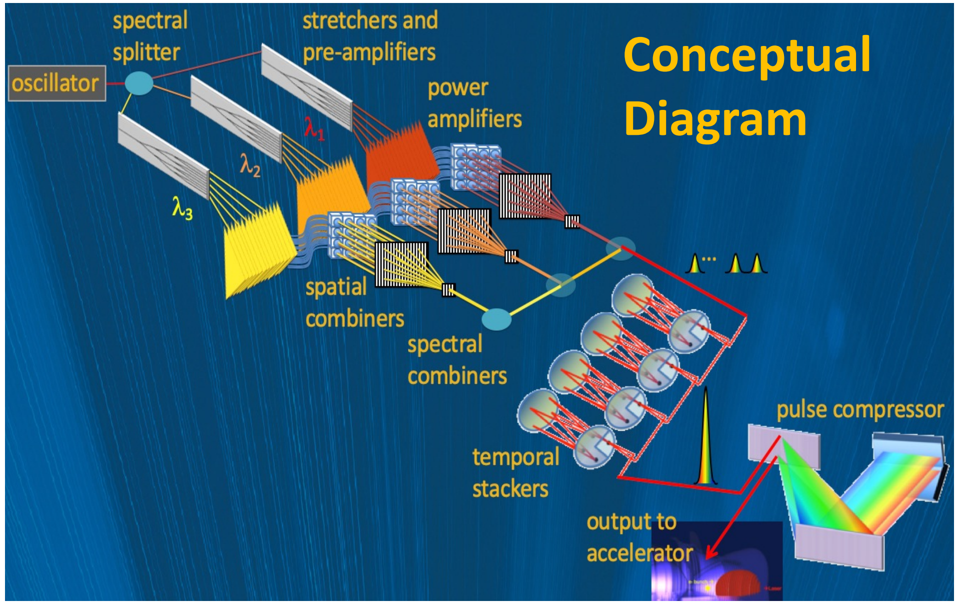
System engineering

Project Type	R&D	R&D	Facility	Facility	Facility
Energy [Joule]	0.1 J	0.2 J	0.5 J	3 J	10 J
Duration [fs]	100 fs	30-50 fs	15 fs (Nonlinear Compression)	30 fs	30-100 fs

- Enable kBELLA using advanced laser technologies, stepping stone towards collider drivers

Summary: Relativistic Ultrafast Lasers Enable Transformative Applications

- Ultrafast lasers enable unique capabilities
  - Compact accelerators, remote sensing and novel photon and particle sources
  - Applications across science, industry, medicine and security



- Fiber laser combining making rapid progress
  - Key elements demonstrated at 10's of mJ
  - Channel count for Joule class demonstrated
  - 200 mJ demonstrator in progress
  - Highly efficiency, meeting application needs
  - Potential for monolithic integration, robustness

- kHz enables crucial discovery science via active feedback precision
  - Towards future particle colliders and applications
  - Laser R&D is preparing for project implementation