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Power scaling of ultrafast laser amplifiers via coherent beam combination

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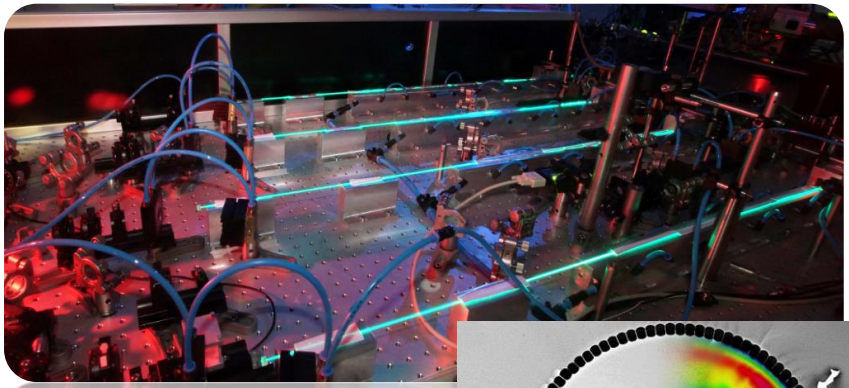
Outline

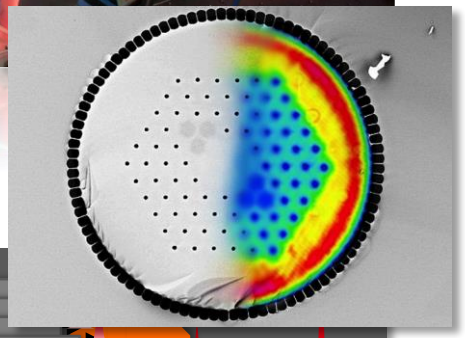
1) **Motivation**

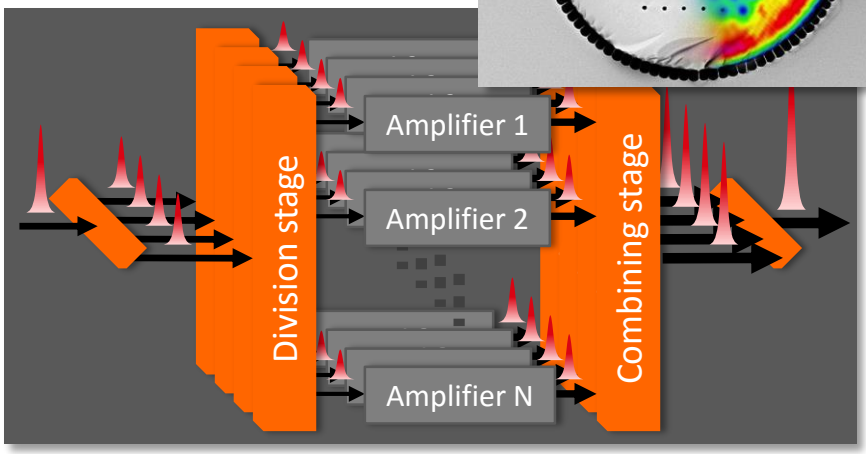
2) Power-scaling of ultrashort-pulse fiber laser systems

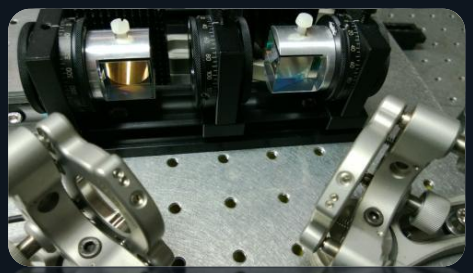
3) Power-scaling using multiplexing schemes

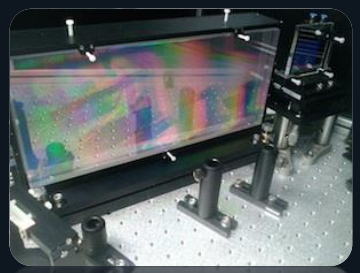
4) Summary & Outlook

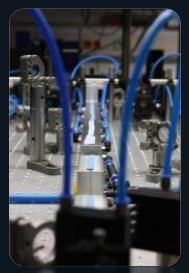












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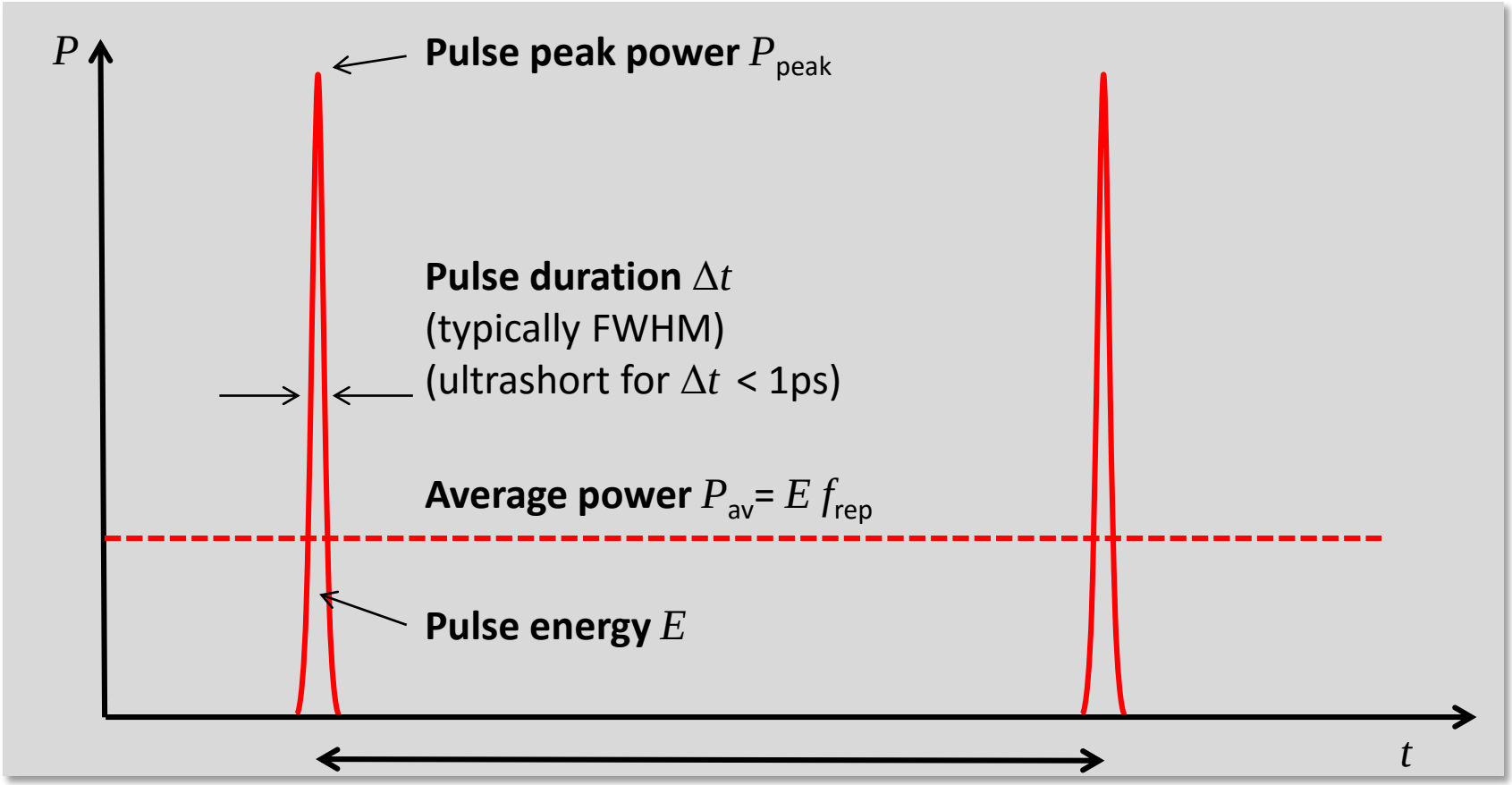

Motivation

Applications of femtosecond laser systems

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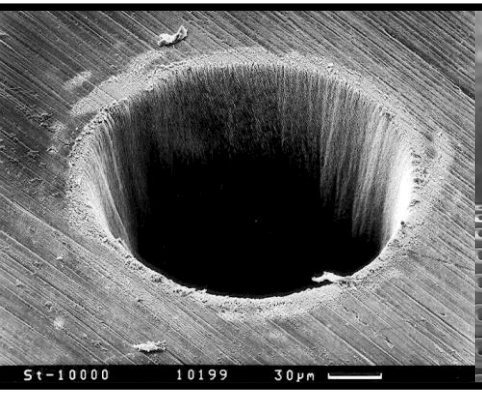
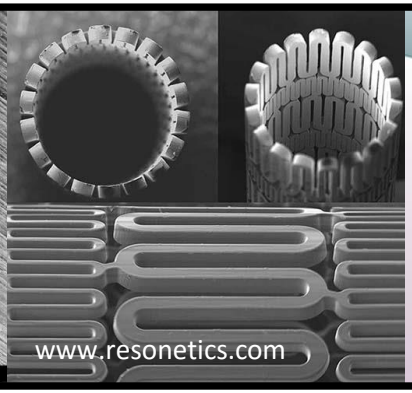
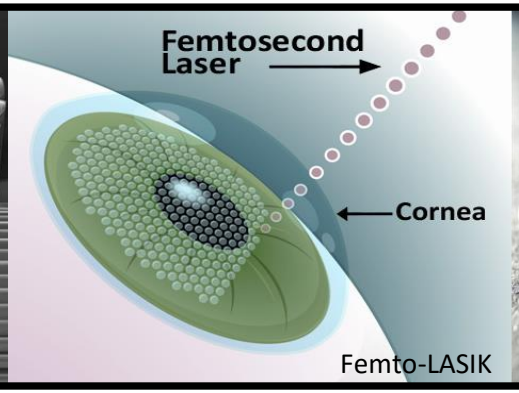
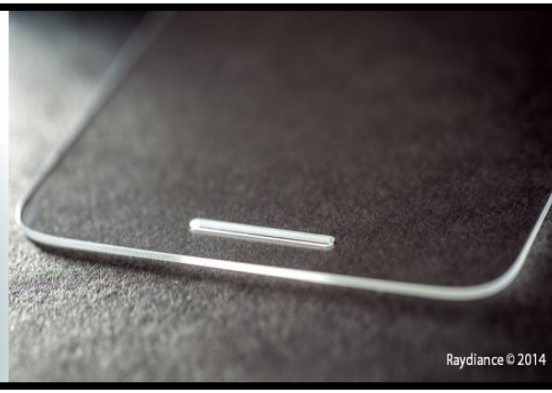
Manufacturing

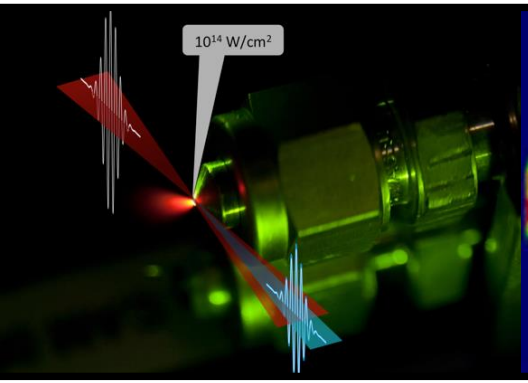


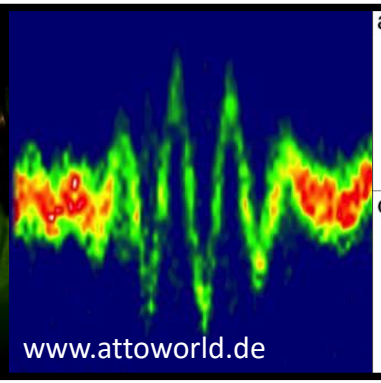


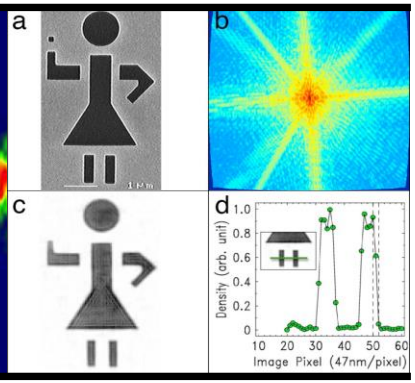




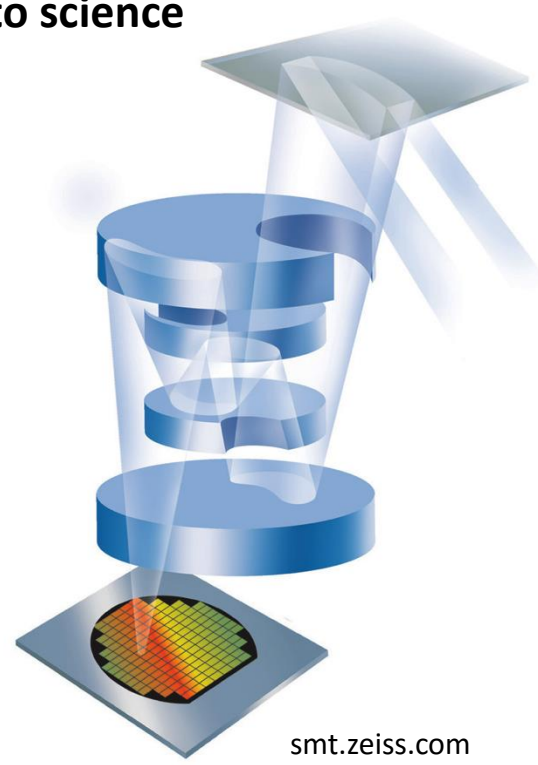
High-harmonic generation, XUV imaging, EUV lithography, FEL, Atto science







Sandberg et al., PNAS 105, 24 (2008)



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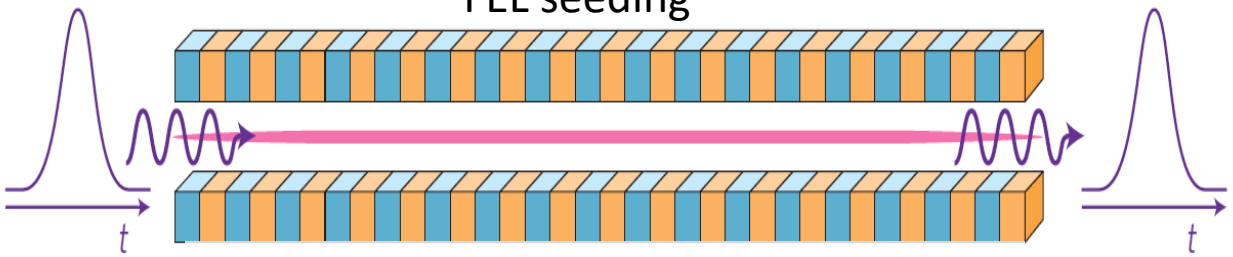
FEL seeding



P. Zeitoun et al., Nature Photonics 4, 739 - 740 (2010)

Motivation

Applications of femtosecond laser systems

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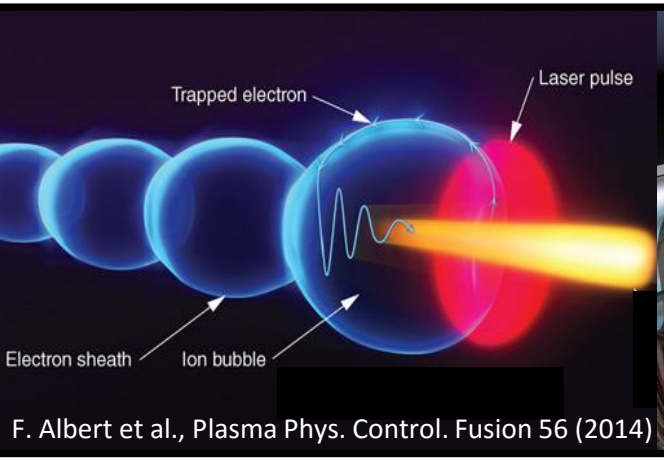
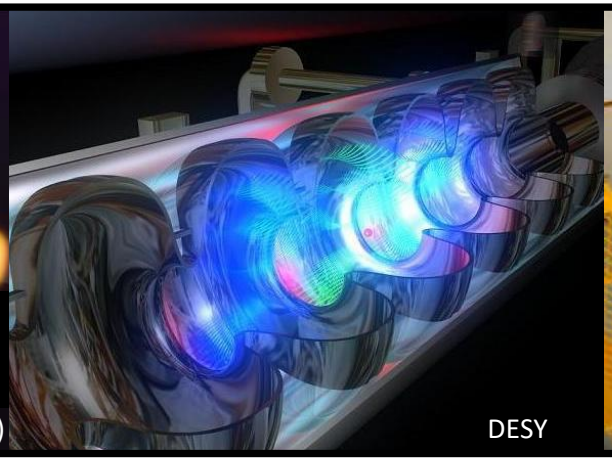
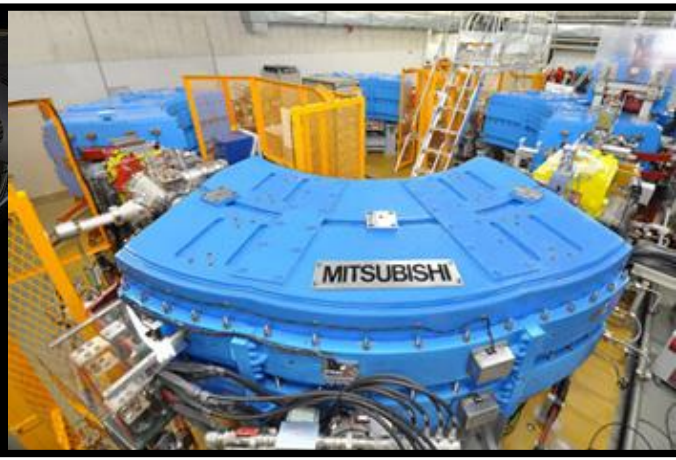
Novel laser particle accelerators, proton therapy



F. Albert et al., Plasma Phys. Control. Fusion 56 (2014)



DESY



Applications require laser systems with high pulse peak power

In conjunction with high repetition rates/high average powers

Motivation

Laser-wakefield particle acceleration

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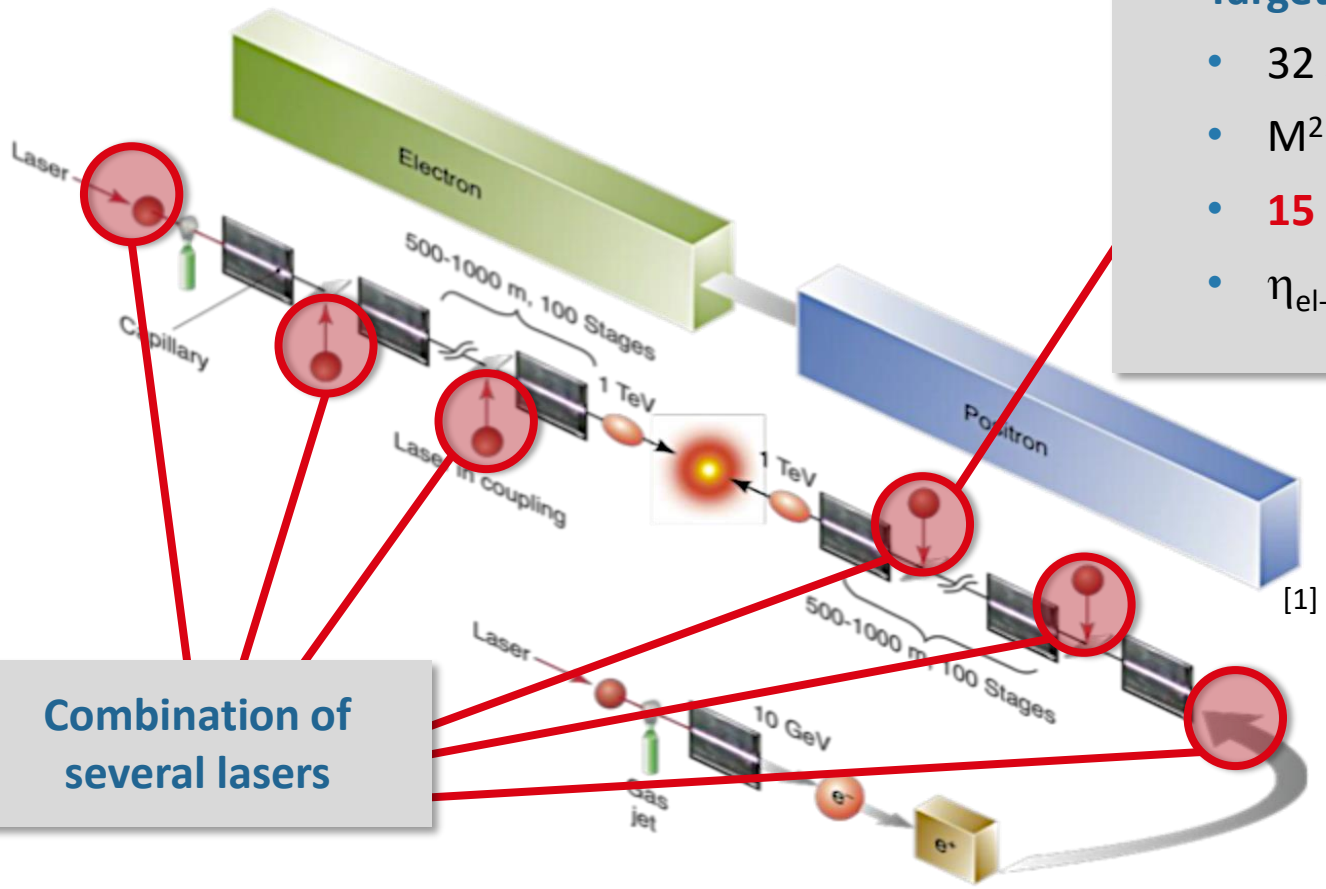

[1]

Target parameters[2]

- 32 J, <300 fs
- $M^2 = 1$
- **15 kHz** → 480 kW
- $\eta_{el\text{-}opt}$ **> 20%**

Combination of several lasers

[1] C.B. Schroeder, E. Esarey, C.G.R. Geddes, C. Benedetti und W. P. Leemans, Phys. Rev. ST Accel. Beams 13 (2010)
[2] W. Leemans, W. Chou und M. Uesaka, ICFA Beam dynamics newsletter 56 (2011)

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Motivation

Laser-wakefield particle acceleration

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Target parameters[2]

- 32 J, <300 fs
- $M^2 = 1$
- **15 kHz** → 480 kW
- $\eta_{el\text{-}opt}$ **> 20%**

There is no laser system available that can achieve these parameters!

[1] C.B. Schroeder, E. Esarey, C.G.R. Geddes, C. Benedetti und W. P. Leemans, Phys. Rev. ST Accel. Beams 13 (2010)
[2] W. Leemans, W. Chou und M. Uesaka, ICFA Beam dynamics newsletter 56 (2011)

Motivation

State of the art: Bulk laser

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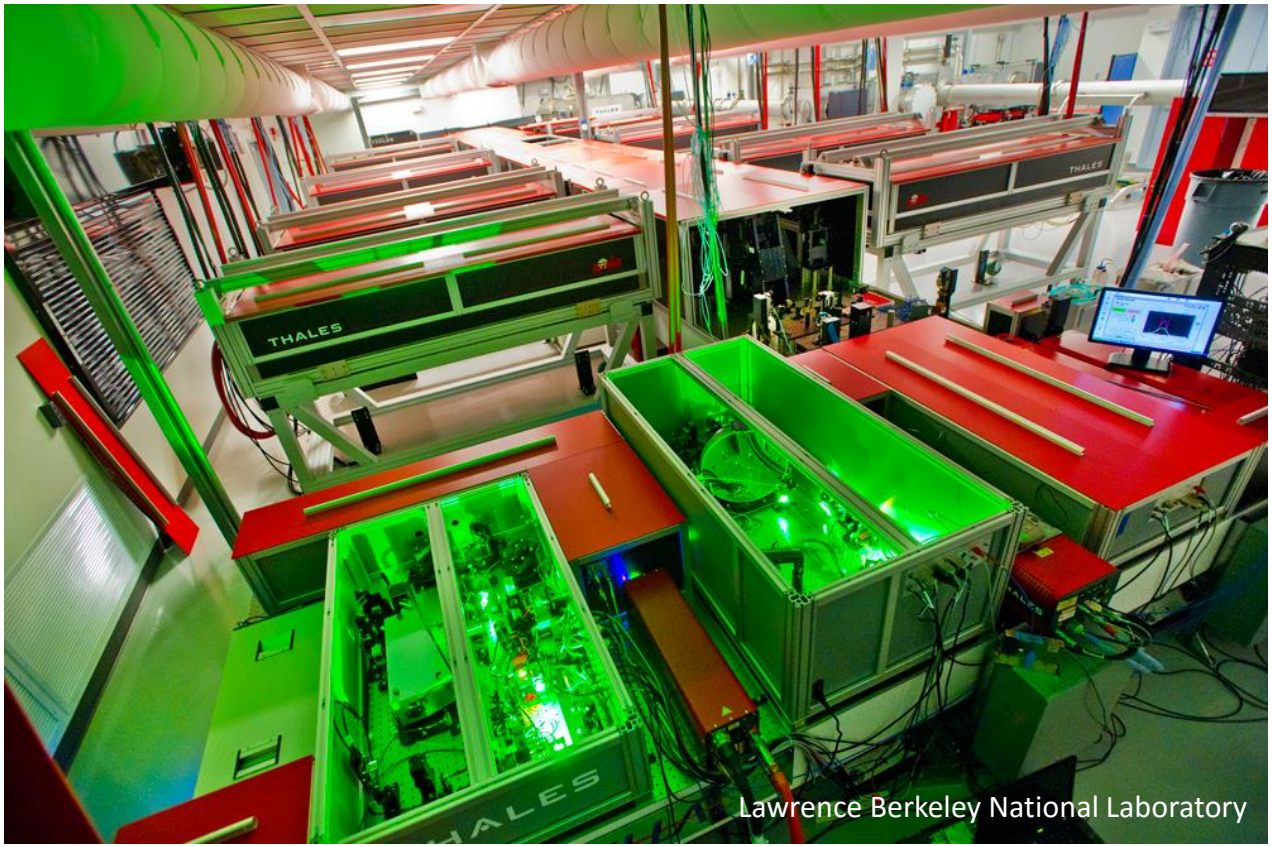

BELLA: Titanium–sapphire laser, commercially available from Thales

- Pulse energie: 42J, Pulse duration: 40fs → Pulse peak power: **>1PW**
- Repetition rate: **1Hz**
- Efficiency: 42W opt. from 130kW electr.: **0.03%**

Poor thermo-optic properties

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Motivation

Laser amplifier concepts

Fiber[1]

Thin disk [2]

Innoslab[3]

- High average power
- Excellent beam quality
- High gain
- High efficiency
- Compact design
- Robust

The performance of a single amplifiers is limited by physical effects, such as:

- Thermal effects
- Nonlinear effects
- …

Further performance scaling difficult

[1] E. Snitzer, "Proposed Fiber Cavities for Optical Masers," J. Appl. Phys. **32**, 36–39 (1961).
[2] A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, and H. Opower, Appl. Phys. B **58**, 365–372 (1994).
[3] K. Du, N. Wu, J. Xu, J. Giesekus, P. Loosen, and R. Poprawe, Opt. Lett. **23**, 370-372 (1998)

Power-scaling of ultrashort-pulse fiber laser systems

Limitations of fiber-based systems

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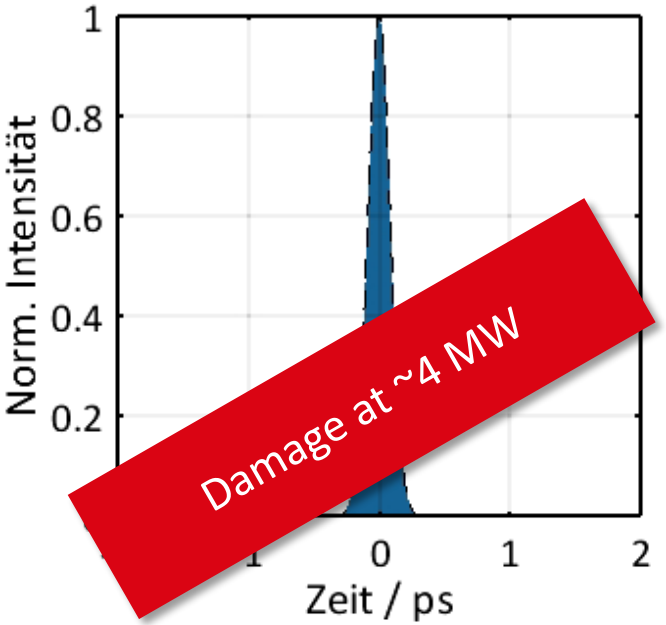

Nonlinear effects
lead to pulse distortions

➡ limit achievable peak power

Mode instabilities
lead to beam quality degradation

➡ limit achievable average power[1]

➡ **Performance-scaling concepts required**

[1] T. Eidam, C. Wirth, C. Jauregui, F. Stutzki, F. Jansen, H.-J. Otto, O. Schmidt, T. Schreiber, J. Limpert, and A. Tünnermann, *Opt. Express* **19**, 13218 (2011)

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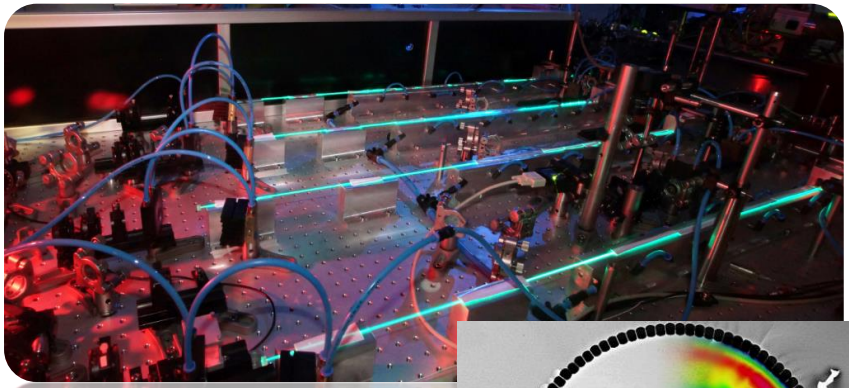
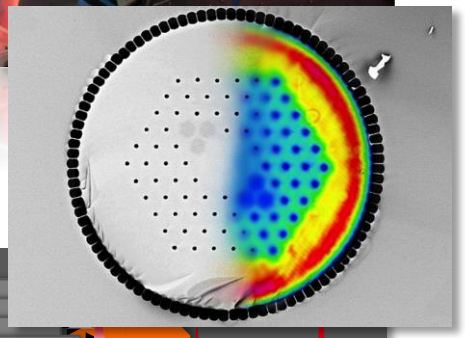
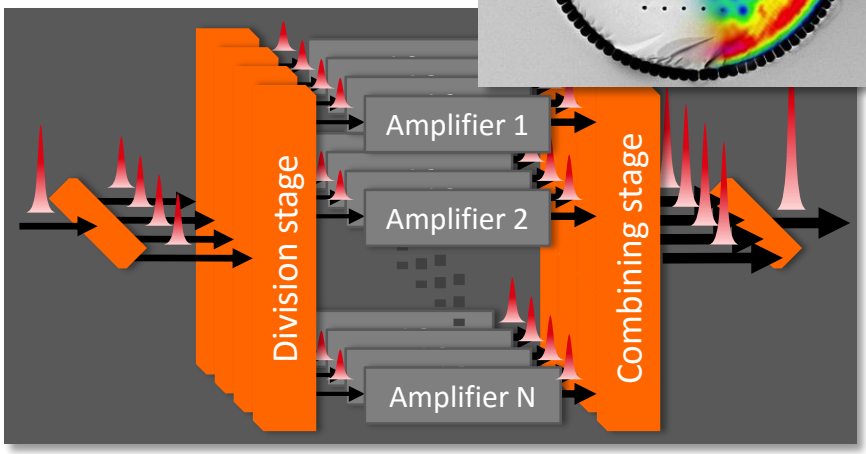
2) **Power-scaling of ultrashort-pulse fiber laser systems**

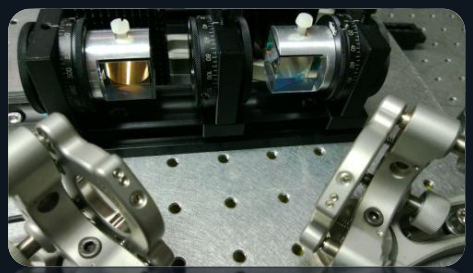
3) Power-scaling using multiplexing schemes

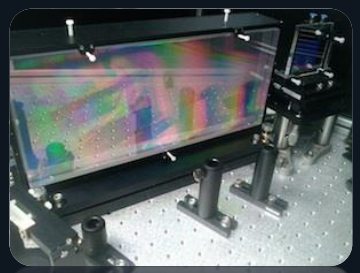
4) Summary & Outlook

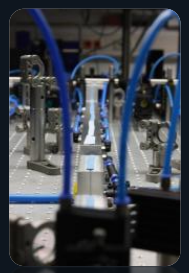












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Power-scaling of ultrashort-pulse fiber laser systems

Scaling possibilities

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Nonlinear effects

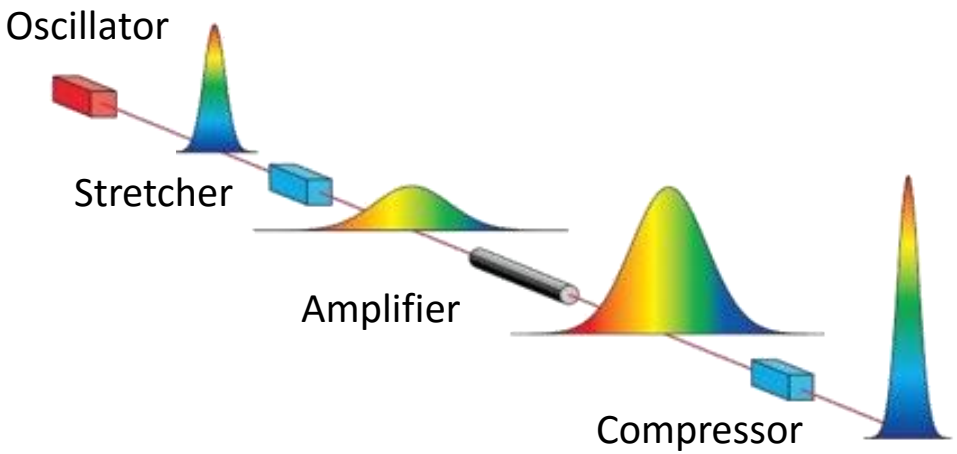
B-integral[1]

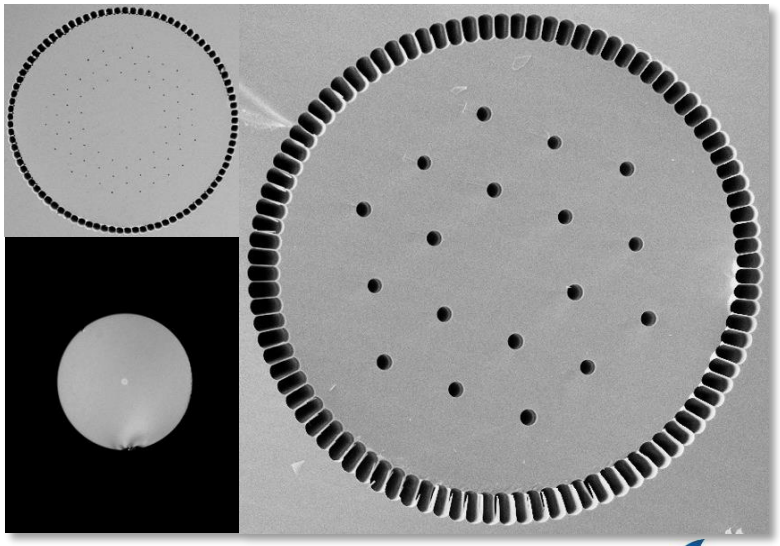
Measure of the accumulated nonlinear phase during propagation

$$B = \frac{\omega n_2}{c A_{\text{eff}}} \int_0^L \hat{P}(z)\,\mathrm{d}z$$

Chirped-pulse amplification[2]

Scaling of the mode-field area[3]





[1] G. P. Agrawal, *Nonlinear Fiber Optics*. Academic Press, 3. Ed. (2001)
[2] D. Strickland and G. Mourou, *Opt. Comm.* **56** (1985)
[3] F. Stutzki, F. Jansen, T. Eidam, A. Steinmetz, C. Jauregui, J. Limpert, and A. Tünnermann, *Opt. Lett.* **36** (2011)

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Power-scaling of ultrashort-pulse fiber laser systems

Typical setup of femtosecond high-power/energy fiber laser system

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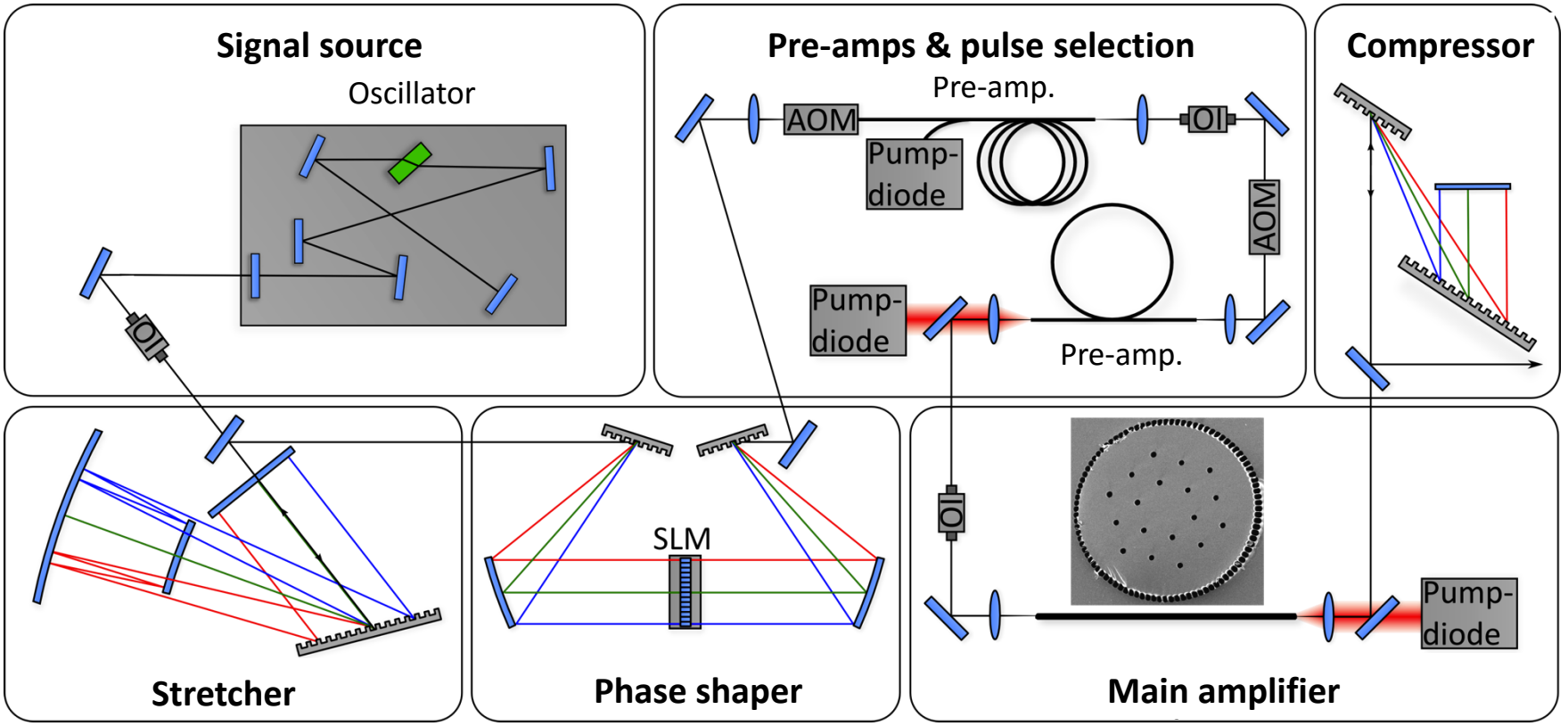

- Phase shaping using *spatial light modulator* (SLM)
- Pulse selection using *acousto-optic modulators* (AOM)

Maximum average power:	830 W[1]
Maximum pulse energy:	2.2 mJ[2]
	(P_{peak} = 3.8 GW)

[1] T. Eidam, S. Hanf, E. Seise, T. V. Andersen, T. Gabler, C. Wirth, T. Schreiber, J. Limpert, and A. Tünnermann, *Opt. Lett.* **35**, 94 (2010)
[2] T. Eidam, J. Rothhardt, F. Stutzki, F. Jansen, S. Hädrich, H. Carstens, C. Jauregui, J. Limpert, and A. Tünnermann, *Opt. Express* **19**, 255 (2011)

Power-scaling of ultrashort-pulse fiber laser systems

Performance evolution of fiber-based sources

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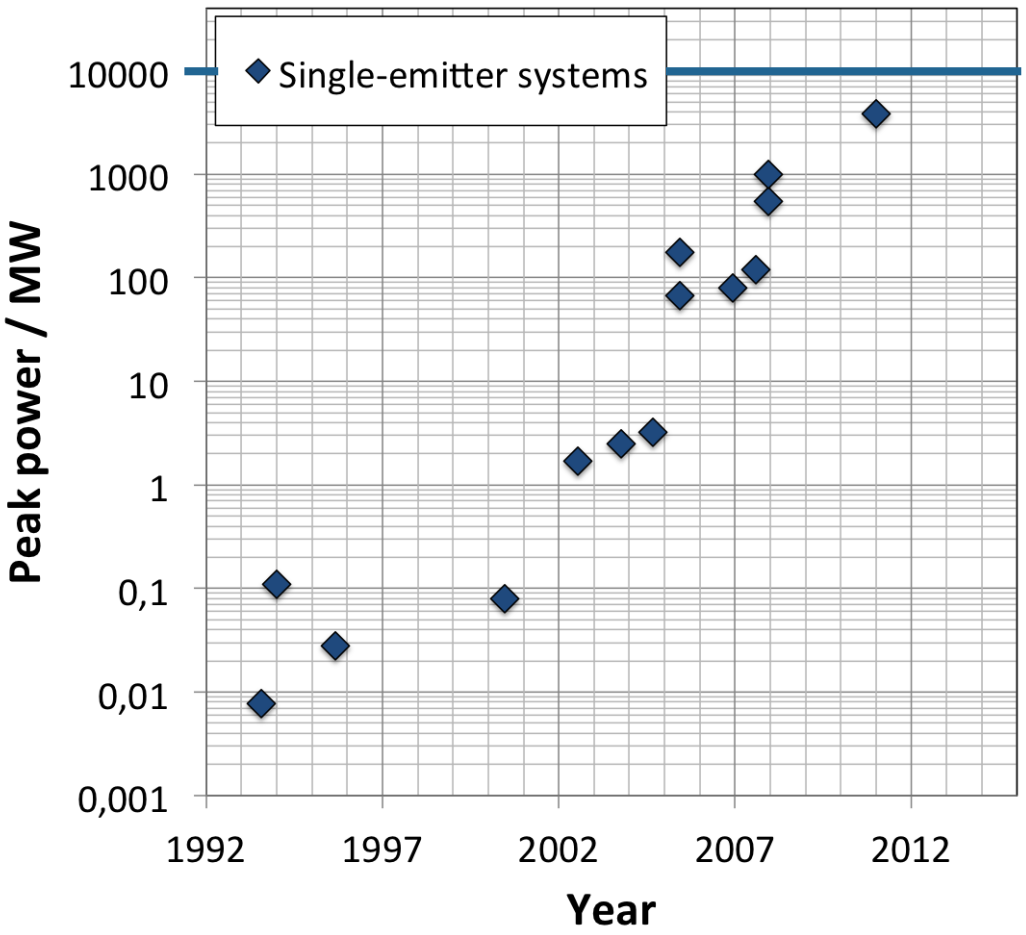
Peak-power of fiber-based sources

Theoretical limit for 80µm core fiber at 1030nm, 10nm FWHM bandwidth ~10GW[1]



- Further scaling of the mode-field diameter limited by production tolerances of the respective fiber design
- Stretched pulse duration limited by grating size

Additional performance-scaling concepts required

[1] D. Schimpf, J. Limpert, and A. Tünnermann, J. Opt. Soc. Am. B **27**, 2051-2060 (2010)

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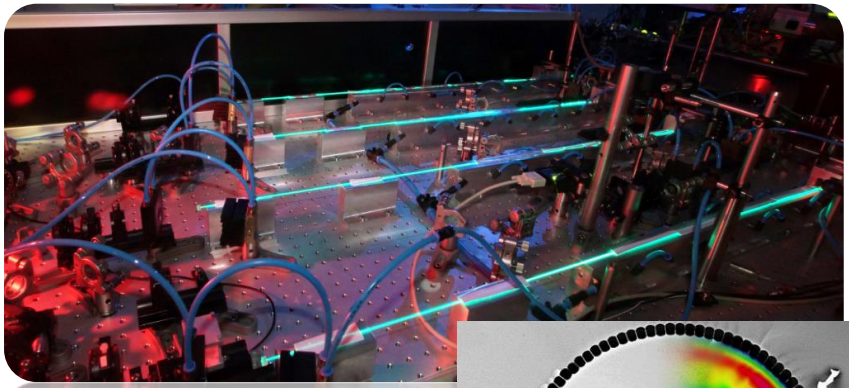

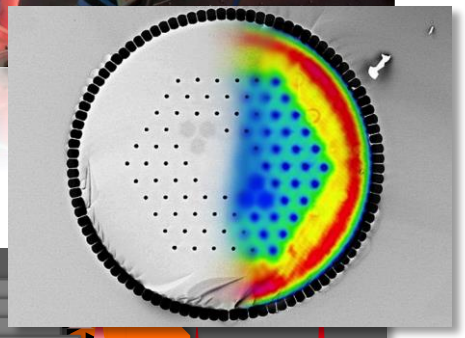

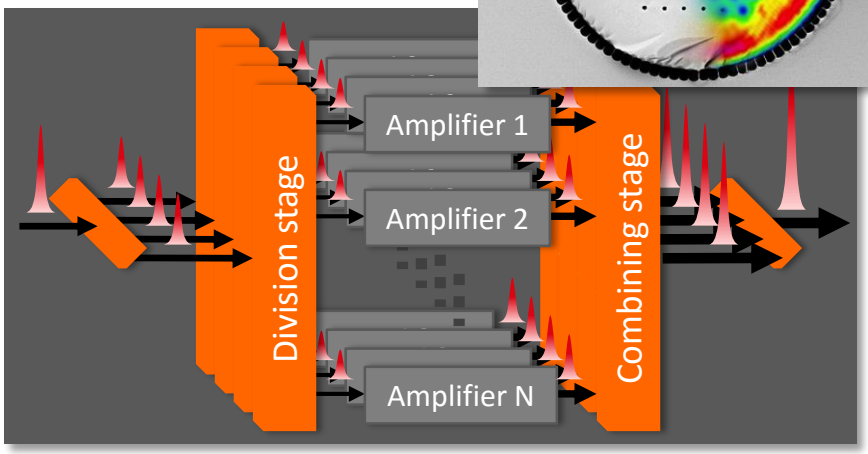

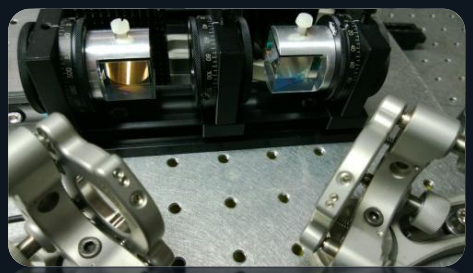

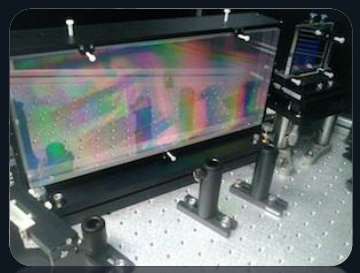

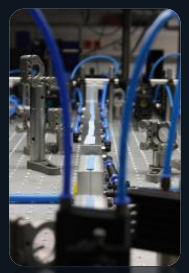

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Power-scaling using multiplexing schemes

Spatial and temporal multiplexing

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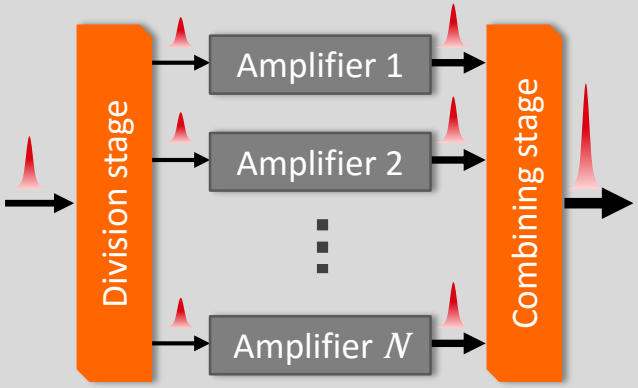
Spatial multiplexing

Coherent beam combining[1]



- ***N*-times scaling**
  (of the peak and average power)

Artificial scaling
of mode area

Temporal multiplexing

Divided-pulse amplification (DPA)[2,3,4]

- ***M*-times scaling**
  (of the peak power)

Artificial scaling
of stretched pulse duration

[1] Fan, T.Y., *IEEE JSTQE* **11**, 567 (2005)
[2] S. Szatmari and P. Simon, *Opt. Communication* **98**, 193 (1993)
[3] S. Zhou, F. W. Wise, and D. G. Ouzounov, *Opt. Lett*. **32**, 871 (2007)
[4] S. Podleska, German Patent DE102006060703 (2006)

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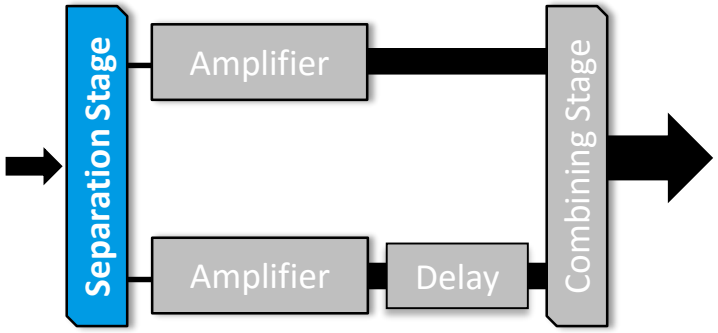
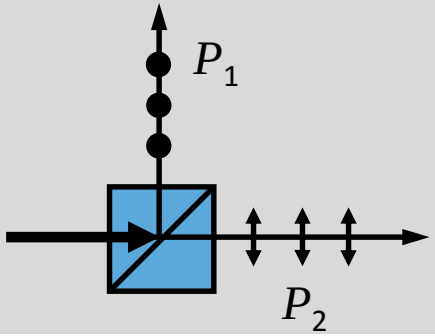
Mutual coherence of the laser pulses from the channels

Single seed source



Beam division by (polarizing) beam splitters



Spatial multiplexing

Requirements for successful coherent combination of fs pulses

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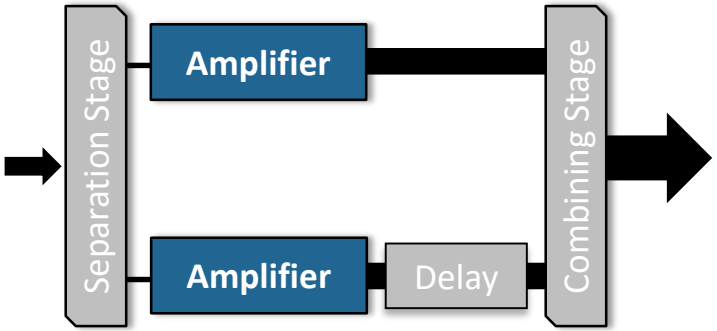
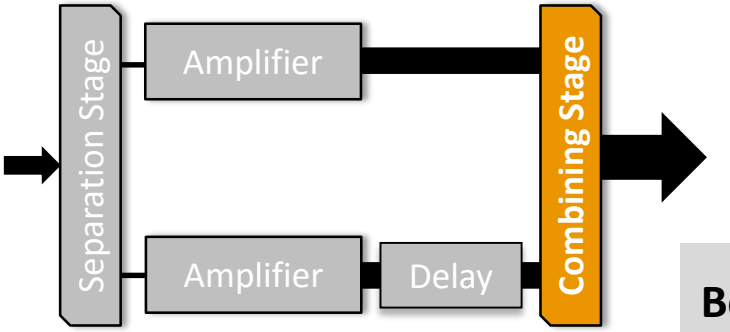
Mutual coherence of the laser pulses from the channels

Single seed source

Amplification properties should be matched

Spectral intensity and phase of the pulses
Spatial intensity and phase of the beams

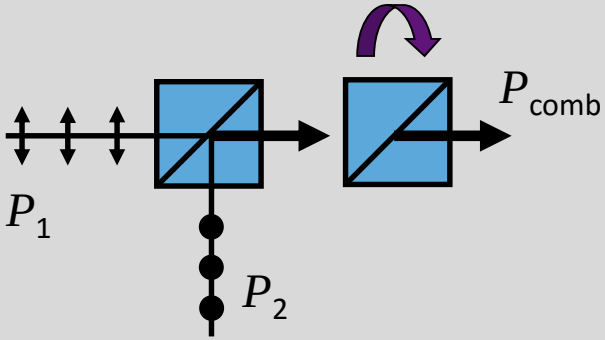




Combining the beams

Spatial overlap of the beams from the channels

Beam combination by (polarizing) beam splitters



Combining efficiency

$$\eta_{\mathrm{comb}} = \frac{P_{\mathrm{comb}}}{P_1 + P_2}$$

Spatial multiplexing

Requirements for successful coherent combination of fs pulses

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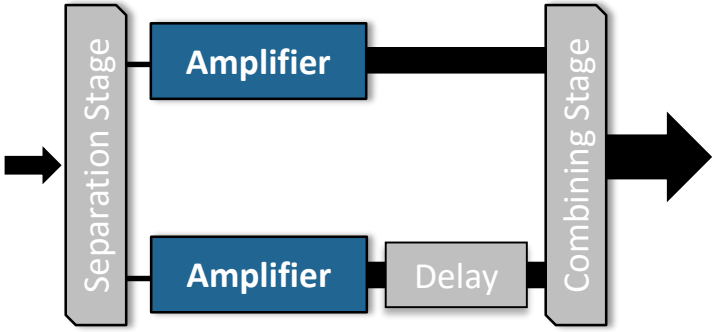
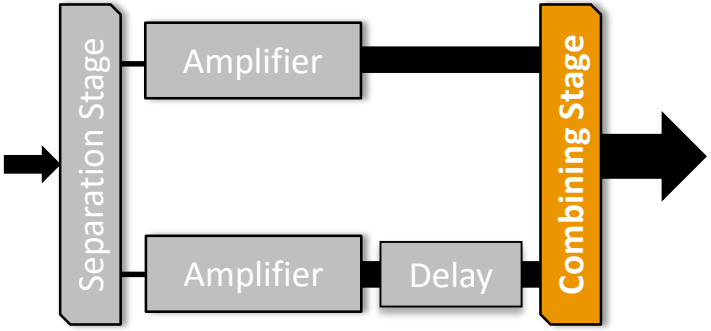
Mutual coherence of the laser pulses from the channels

Single seed source

Amplification properties should be matched

Spectral intensity and phase of the pulses
Spatial intensity and phase of the beams



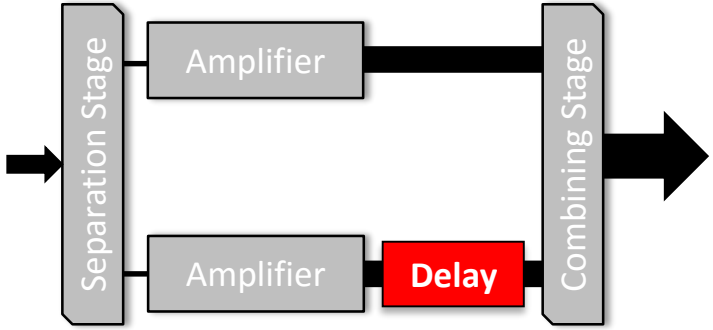


Combining the beams

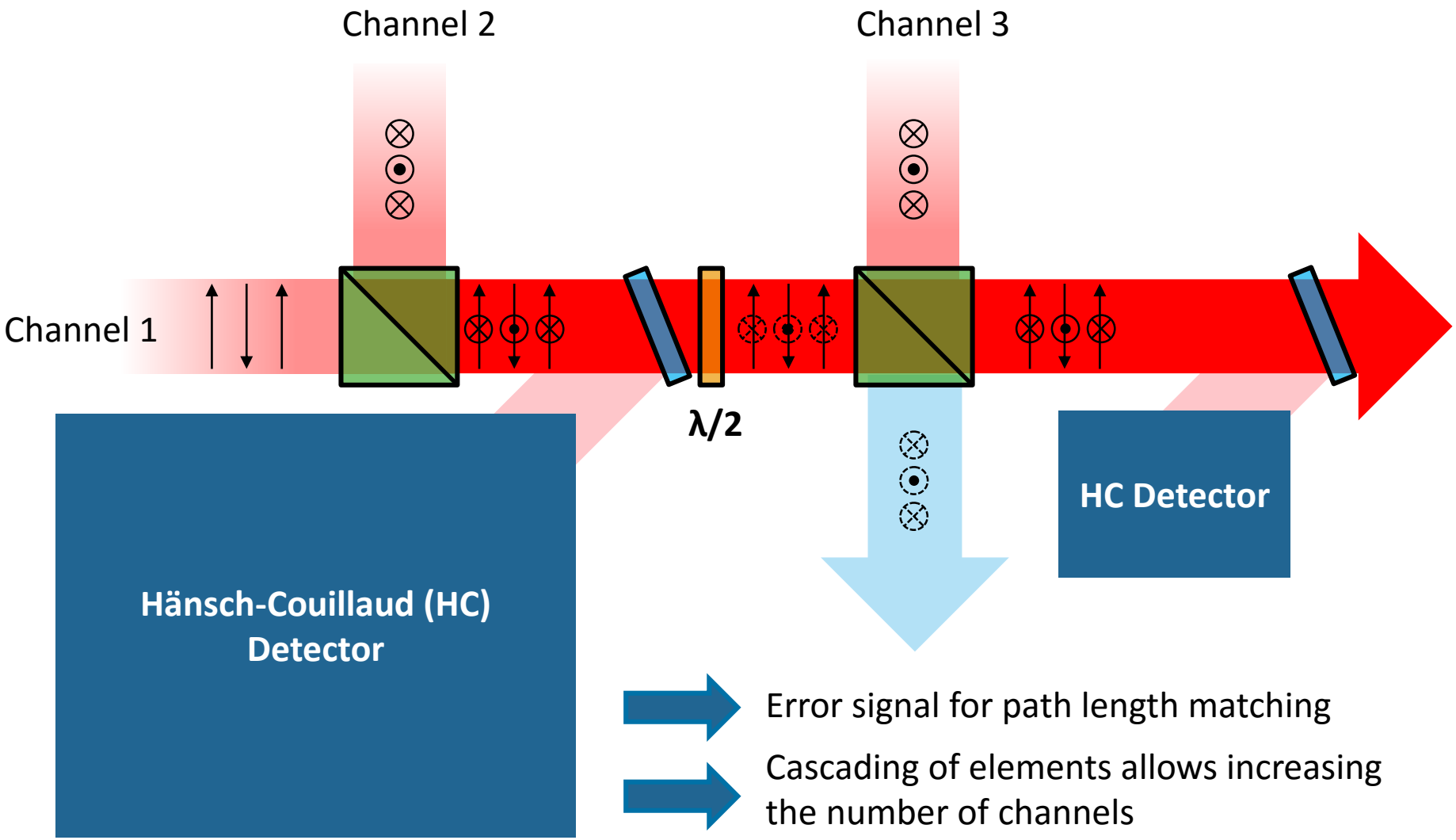
Spatial overlap of the beams from the channels

The setup is a Mach-Zehnder type interferometer

Active stabilization mechanism required
E.g. with piezo actuators



Polarization beam combining



[1] T.W. Hänsch, B. Couillaud, *Opt. Commun.* **35** 441 (1980)

Spatial multiplexing

High-power 4-channel setup

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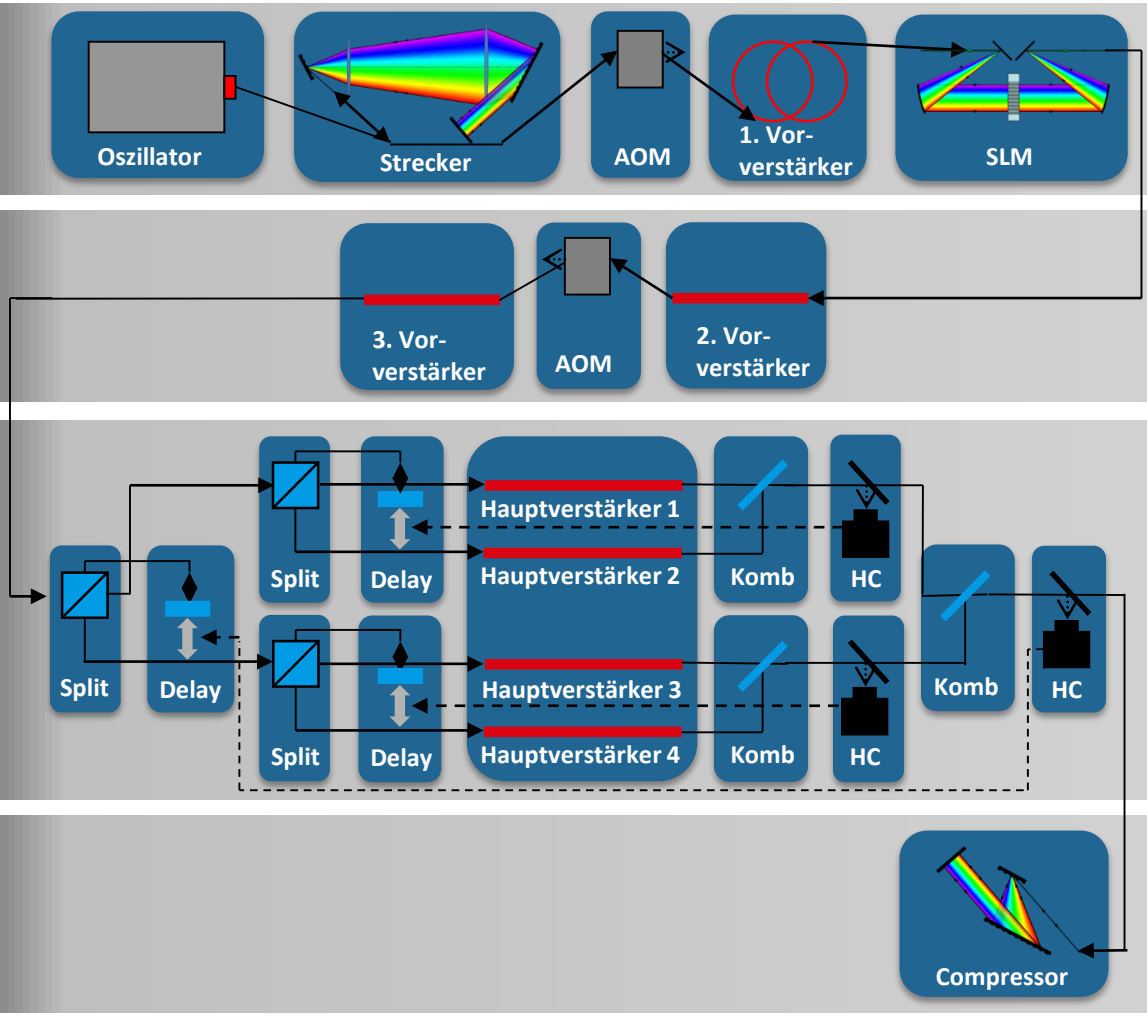

- Grating stretcher 1.5ns-2ns stretched pulse duration
- 3 preamplifiers
- 2 acousto-optic modulators to set repetition rate
- 4x large-pitch main amplifier fibers[1]
- Division and combination with polarizing beam splitters
- Optical path length matching via piezo-driven mirrors
- Grating compressor

[1] J. Limpert, F. Stutzki, F. Jansen, H.-J. Otto, T. Eidam, C. Jauregui, and A. Tünnermann, *Light Sci. Appl.* **1**, e8 (2012)

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Spatial multiplexing

Experimental results

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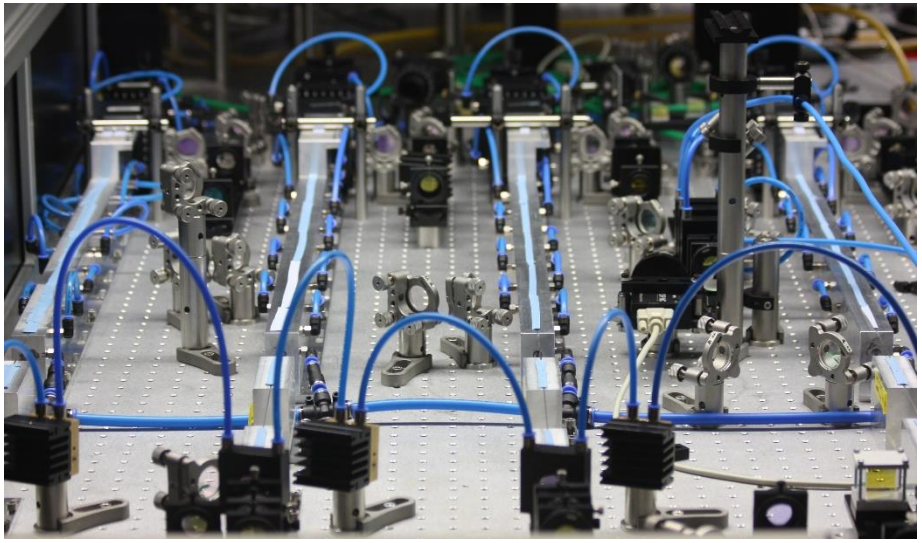
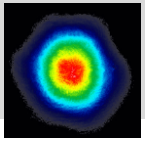
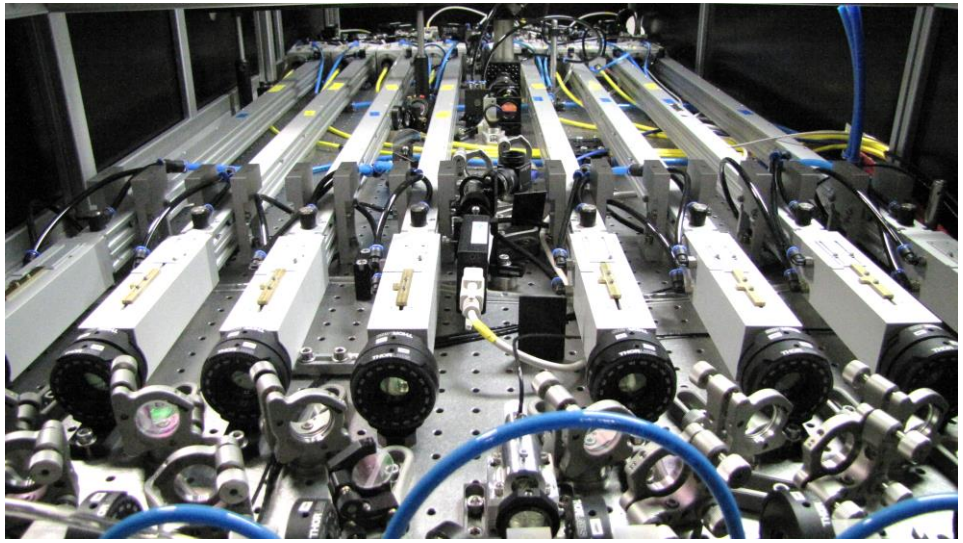
4-channel setup



- **fs** pulse duration
- **>40kHz** repetition rate
- **230W/5.7mJ** ave. power/pulse energy[1] (**22GW** peak power)
- **530W/1.3mJ** ave. power/pulse energy[2]
- **~90%** combination efficiency
- **$M^2 < 1.3$**



8-channel setup



- **fs** pulse duration
- **>100kHz** repetition rate
- **1kW/1mJ** ave. power/pulse energy[3]
- **870W/3.3mJ** ave. power/pulse energy[3]
- **~90%** combination efficiency
- **$M^2 < 1.2$**

[1] A. Klenke, S. Hädrich, T. Eidam, J. Rothhardt, M. Kienel, S. Demmler, T. Gottschall, J. Limpert, and A. Tünnermann, *Opt. Lett.* **39**, 6875 (2014)
[2] A. Klenke, S. Breitkopf, M. Kienel, T. Gottschall, T. Eidam, S. Hädrich, J. Rothhardt, J. Limpert, and A. Tünnermann, *Opt. Lett.* **38**, 2283 (2013)
[3] M. Müller, M. Kienel, A. Klenke, T. Gottschall, E. Shestaev, M. Plötner, J. Limpert, and A. Tünnermann, *Opt. Lett.* **41**, 3439 (2016)

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Spatial multiplexing

Experimental results

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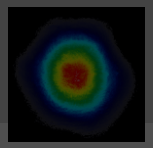
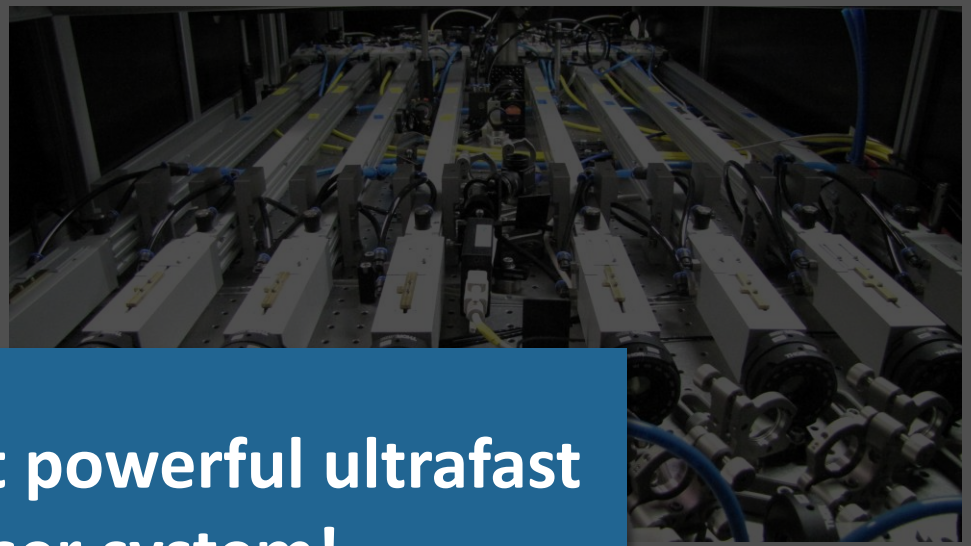
4-channel setup

- **fs** pulse duration
- **>40kHz** repetition rate
- **230W/5.7mJ** ave. power/pulse energy[1] (**22GW** peak power)
- **530W/1.3mJ** ave. power/pulse energy[2]
- **~90%** combination efficiency
- **$M^2 < 1.3$**



8-channel setup



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- **870W/3.3mJ** ave. power/pulse energy[3]
- **~90%** combination efficiency
- **$M^2 < 1.2$**

The world most powerful ultrafast fiber-laser system!

[1] A. Klenke, S. Hädrich, T. Eidam, J. Rothhardt, M. Kienel, S. Demmler, T. Gottschall, J. Limpert, and A. Tünnermann, *Opt. Lett.* **39**, 6875 (2014)
[2] A. Klenke, S. Breitkopf, M. Kienel, T. Gottschall, T. Eidam, S. Hädrich, J. Rothhardt, J. Limpert, and A. Tünnermann, *Opt. Lett.* **38**, 2283 (2013)
[3] M. Müller, M. Kienel, A. Klenke, T. Gottschall, E. Shestaev, M. Plötner, J. Limpert, and A. Tünnermann, *Opt. Lett.* **41**, 3439 (2016)

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Power-scaling of ultrashort-pulse fiber laser systems

Spatial multiplexing

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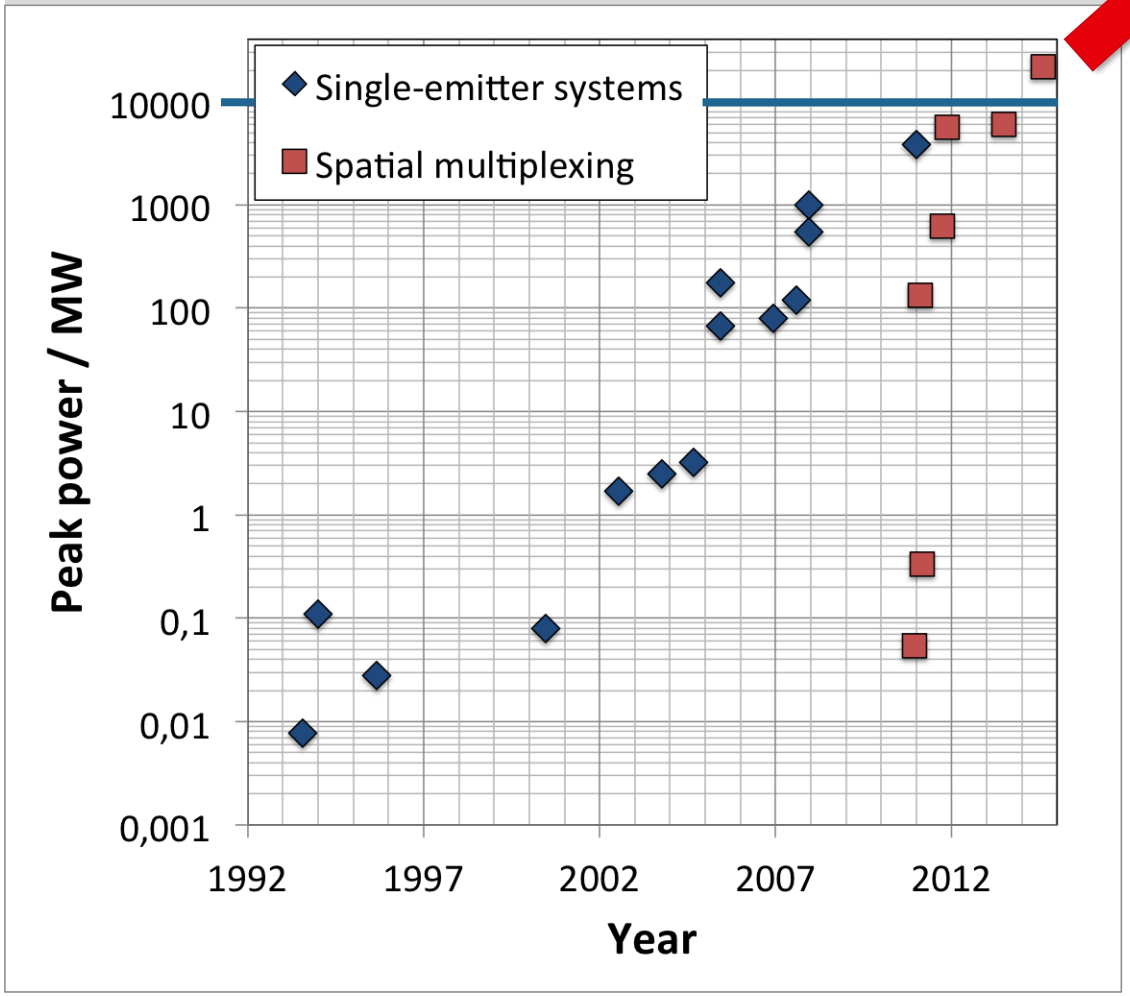
Peak-power of fiber-based sources

Theoretical limit for 80µm core fiber at 1030nm, 10nm FWHM bandwidth ~10GW[1]



[1] D. Schimpf, J. Limpert, and A. Tünnermann, *J. Opt. Soc. Am. B* **27**, 2051 (2010)

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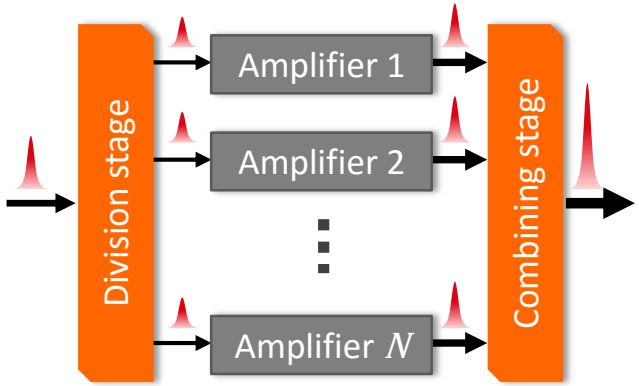
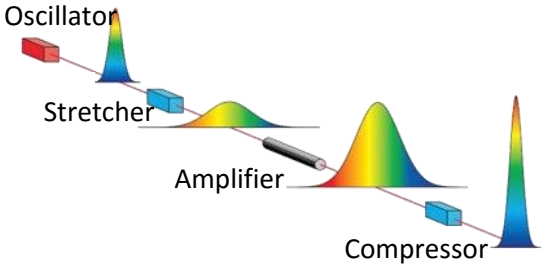
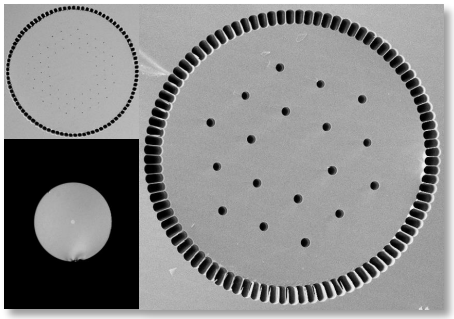
Summary

Power-scaling concepts

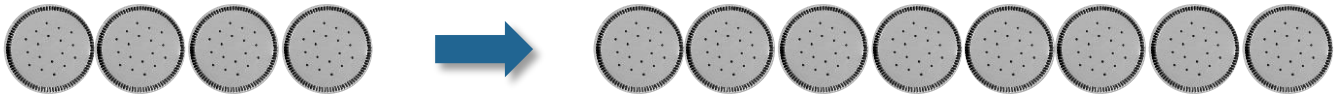






Multiplexing as power-scaling concept

4-channel and 8-channel ultrafast fiber-laser systems



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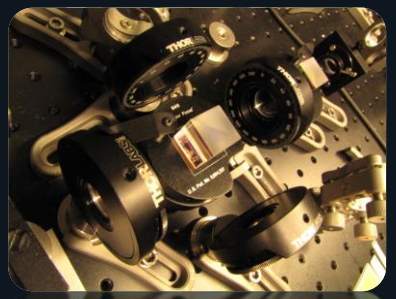
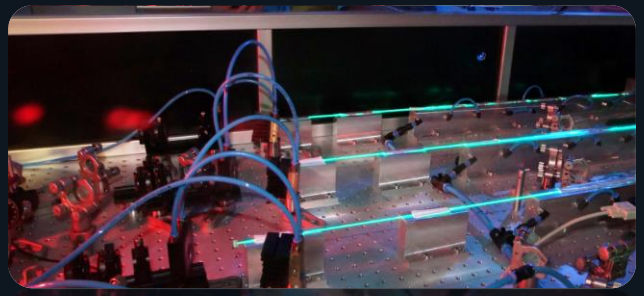
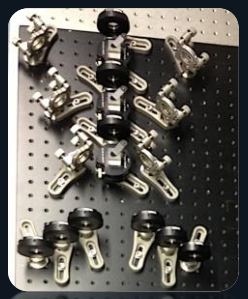
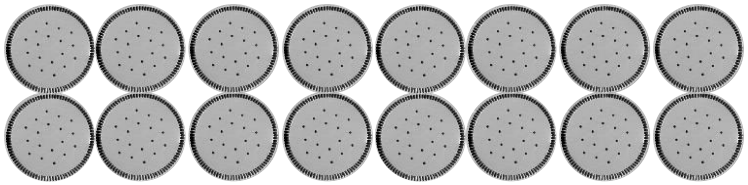


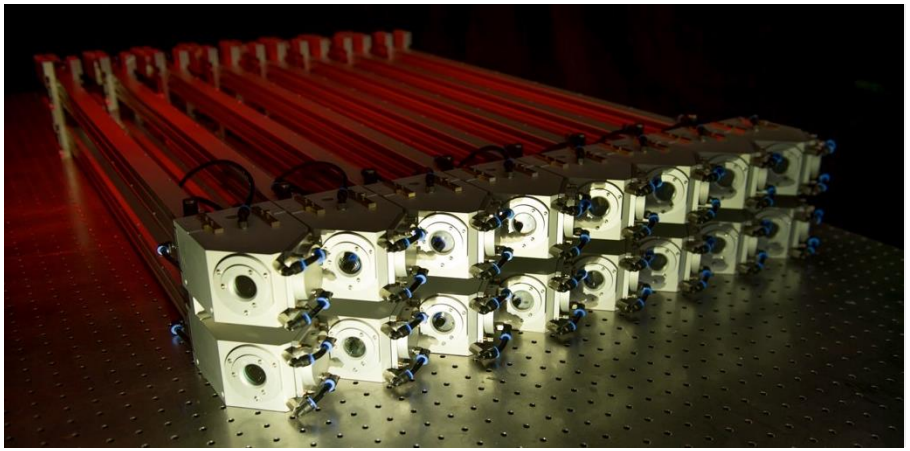




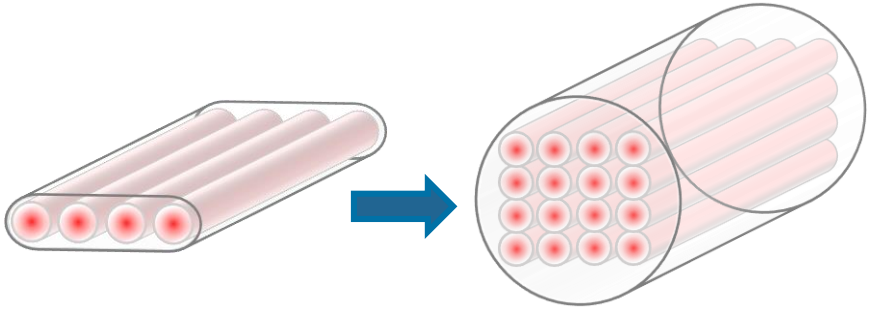
Outlook

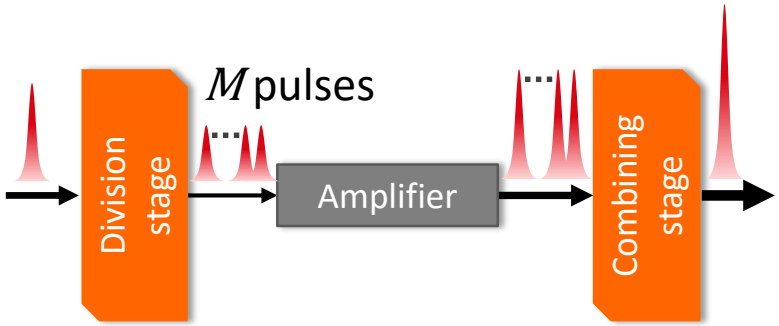
Scaling to 16 channels





Integrated design
Multicore fibers





Additional temporal multiplexing

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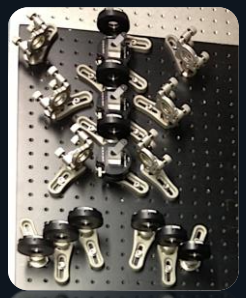
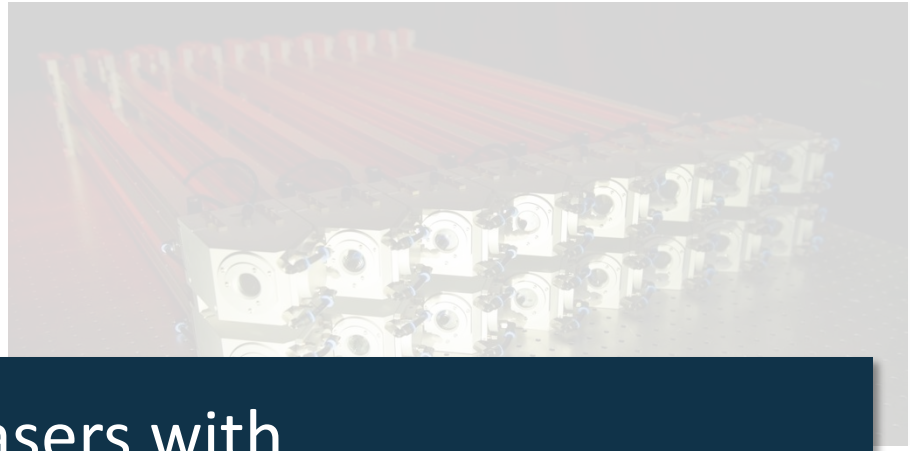


Outlook

Scaling to 16 channels



Fiber lasers with
TW-class peak powers and **multi-kW average powers**

Additional temporal multiplexing

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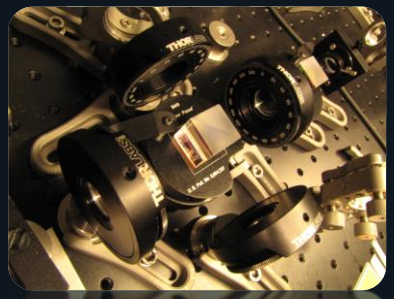

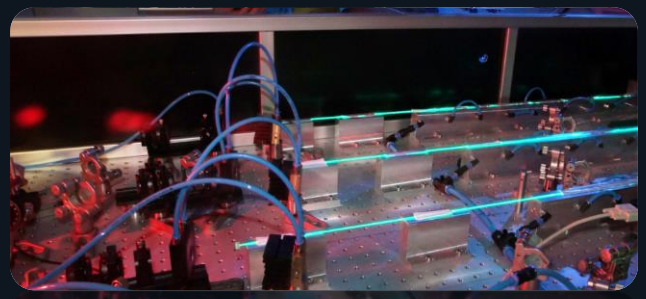

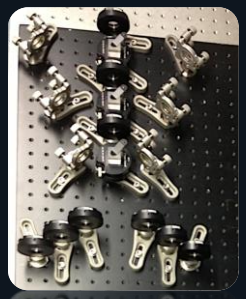

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