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Potential of Fiber-based Laser Technology for Accelerators

Sven Breitkopf[1], Tino Eidam[1,2,4], Arno Klenke[1,2], Marco Kienel[1,2], Michael Müller[1], Jens Limpert[1,2,3,4], Andreas Tünnermann[1,2,3]

[1] Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena

[2] Helmholtz-Institute Jena

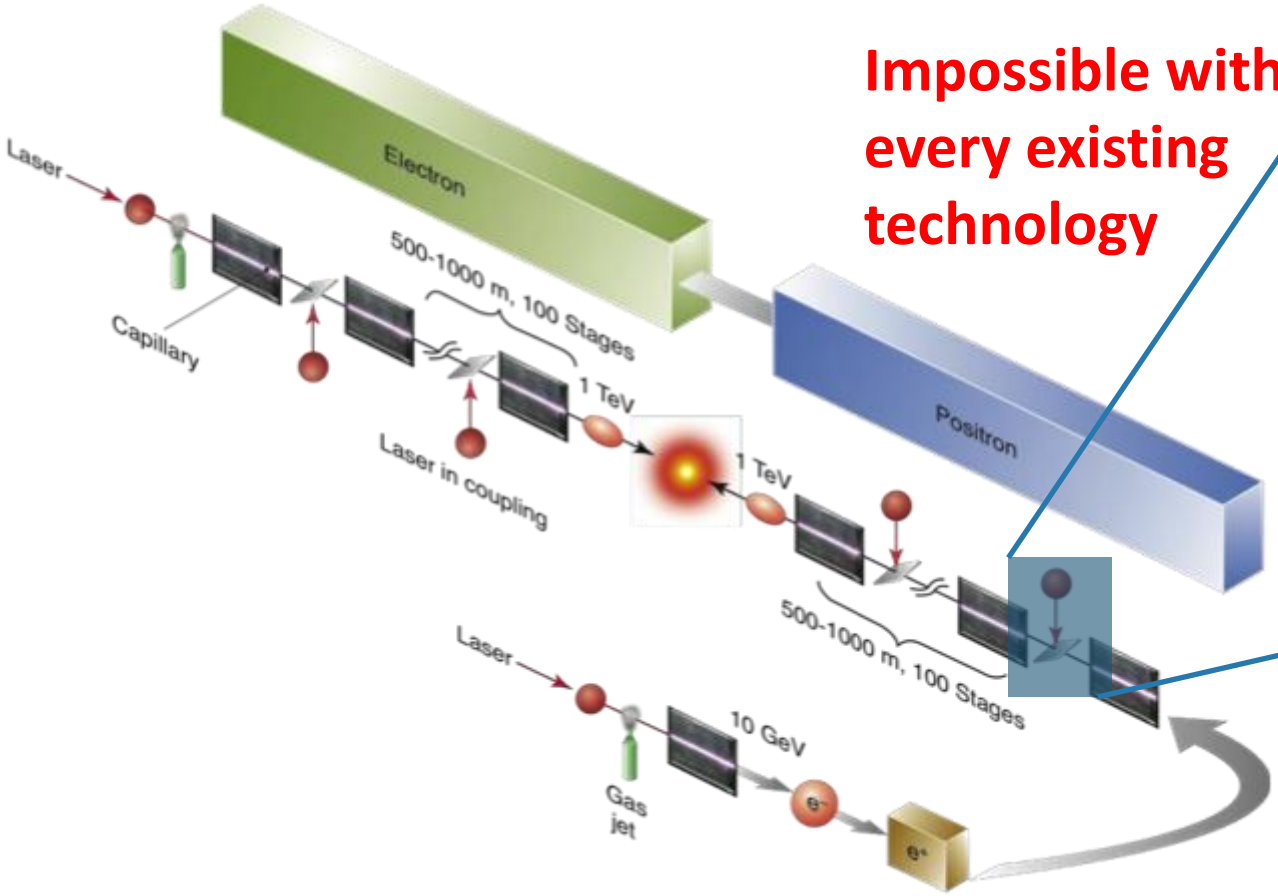
[3] Fraunhofer IOF Jena

[4] Active Fiber Systems GmbH

„A 2-TeV electron–positron collider based on laser-driven plasma-acceleration [...]“[1]

W. Leemans et. al.

Impossible with every existing technology



32 J
15 kHz
480 kW
< 300 fs
η > 20 %

[1] W. Leemans and E. Esarey, "Laser-driven plasma-wave electron accelerators," Physics Today **62**, 44 (2009).

Motivation

Laser-Wakefield Particle Acceleration

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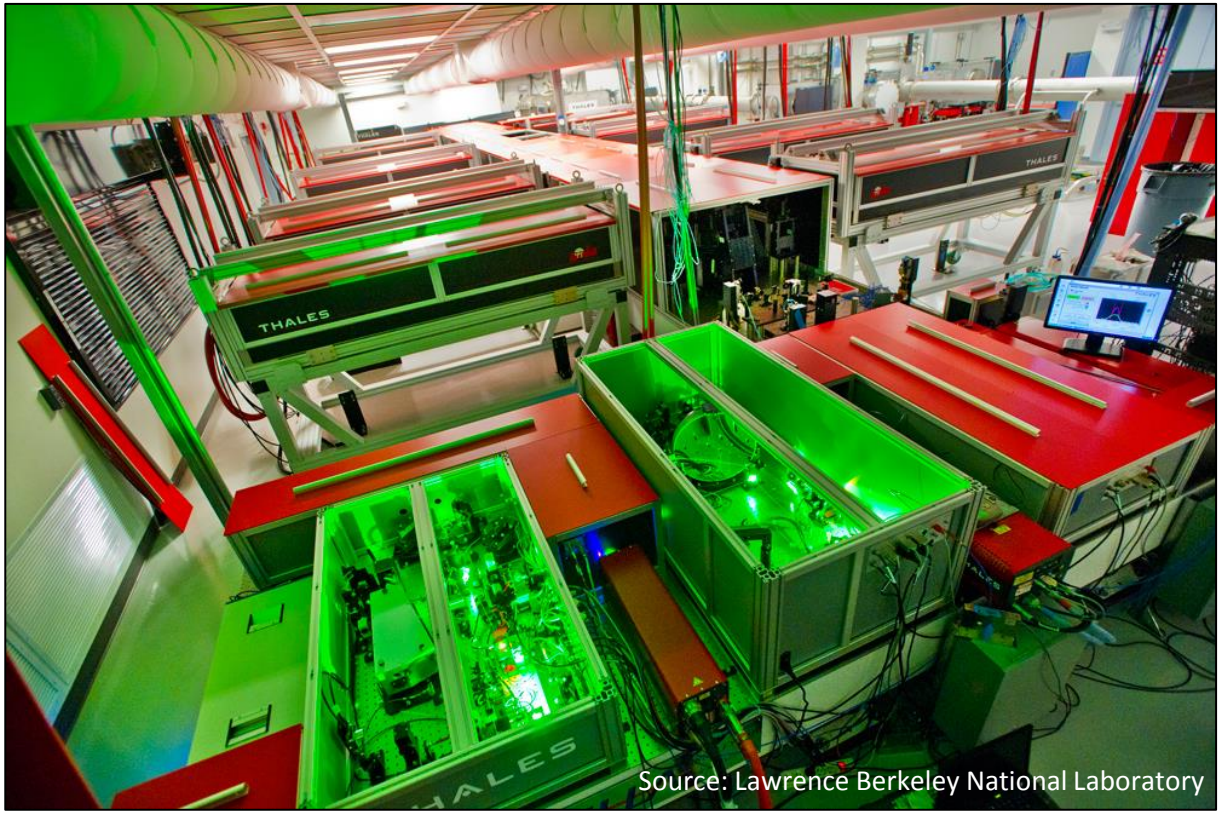

BELLA: $28M project for 10GeV accelerator

Laser system: titanium-doped sapphire, commercial system by Thales

- Pulse energy: 42J, pulse length: 40fs → Peak power > 1PW
- Repetition rate: **1Hz**
- Efficiency: 40W out for 130kW in: **0.03%**

Introduction

Simplified scheme of state of the art fs-lasers

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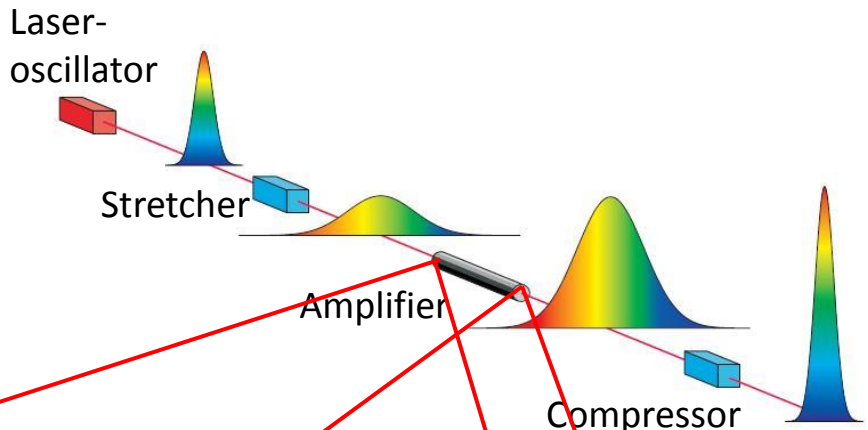

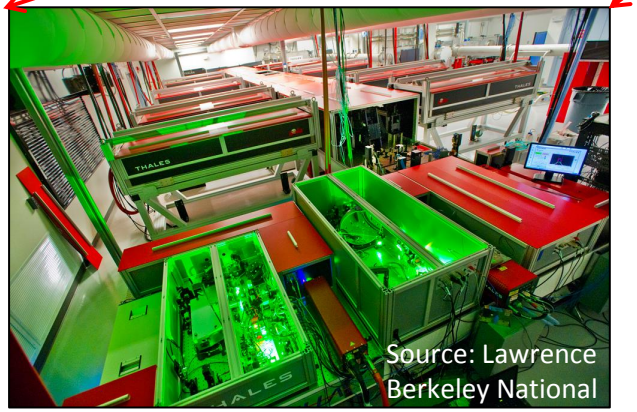

Among many other amplifier technologies!

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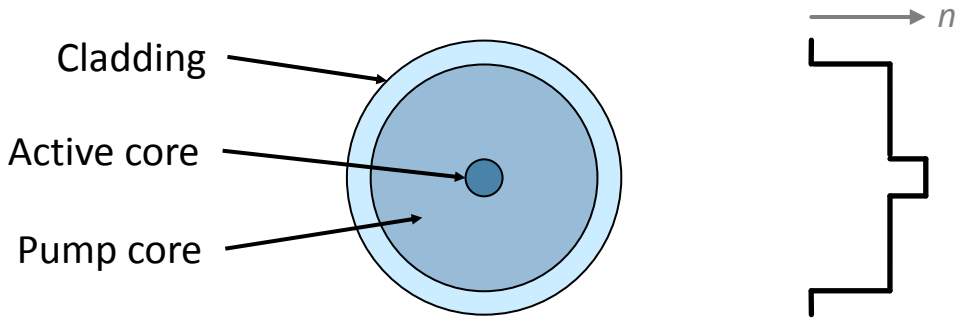
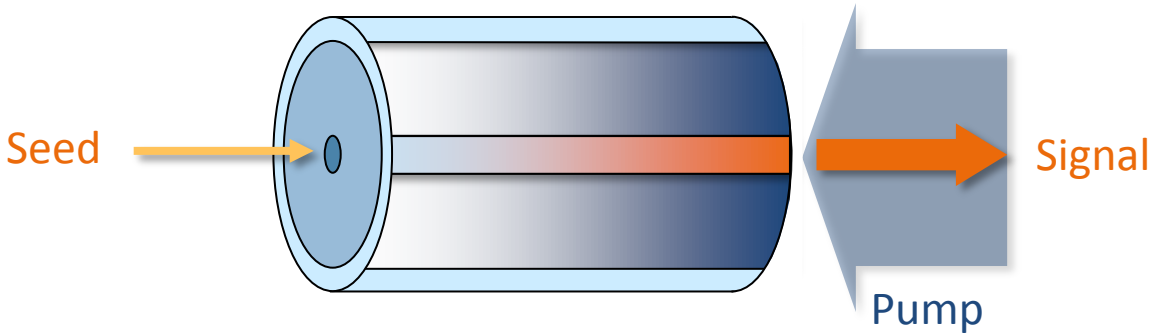
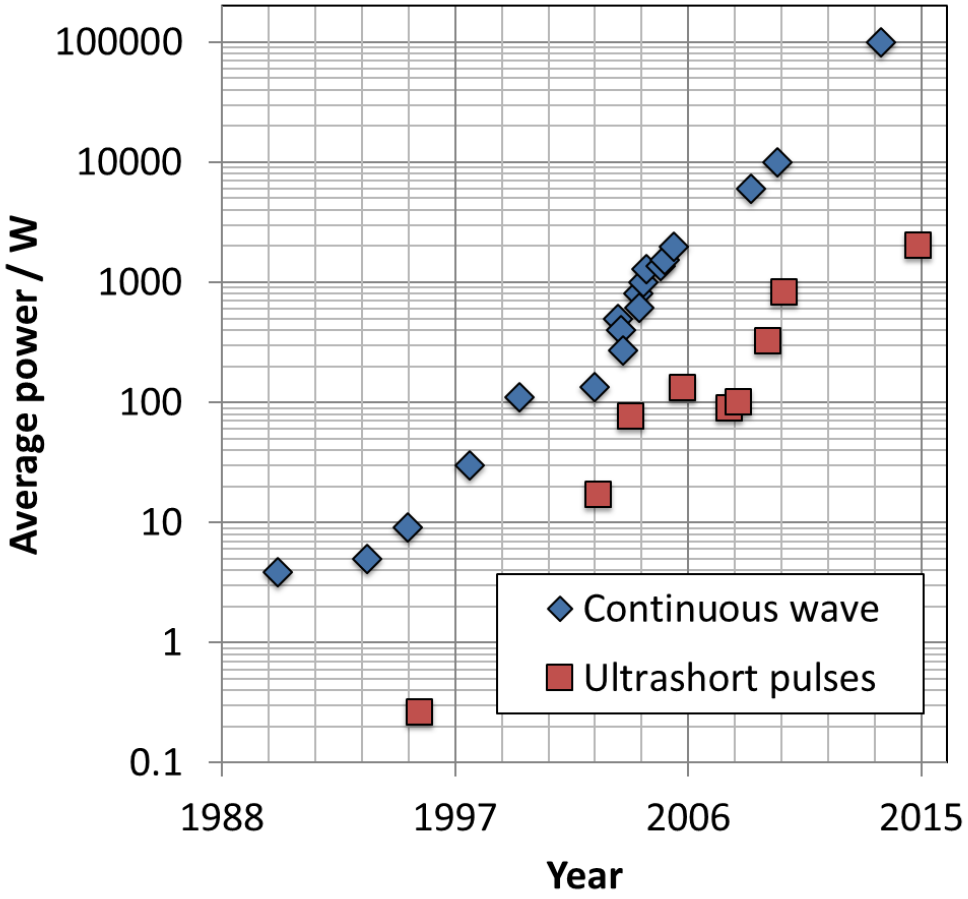
- High power fiber design: double-clad fiber



- Fiber amplifier



High average power (kW-range) with diffraction limited beam quality!



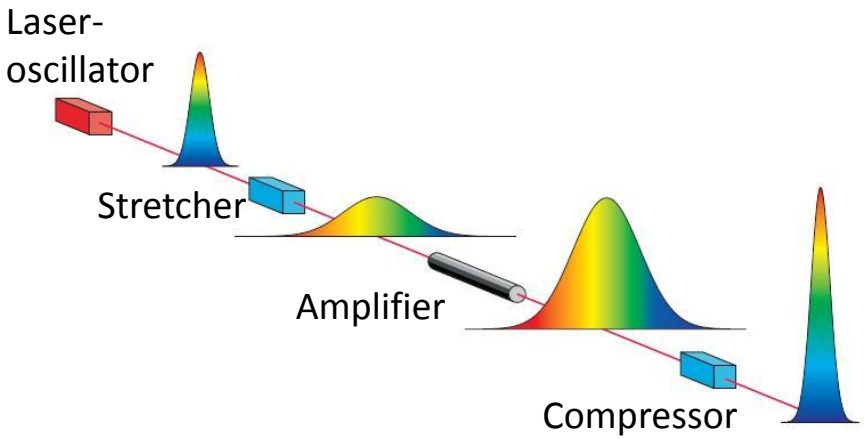
Continuous-wave fiber laser (IPG)

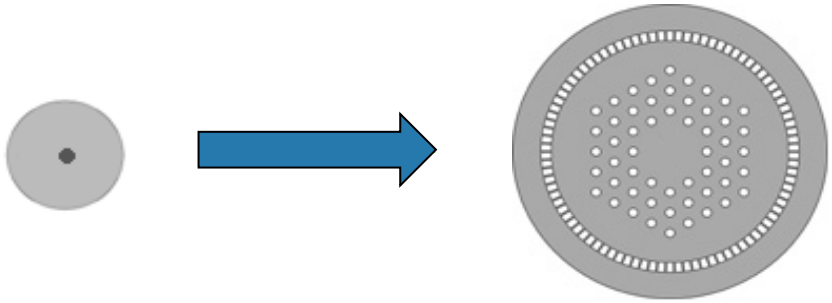
- delivering **100kW** of average power
- **>30%** wall-plug efficiency
- **compact** dimensions

High nonlinearity

Chirped-pulse amplification[1]

Mode-area scaling[2]





[1] D. Strickland and G. Mourou, “Compression of amplified chirped optical pulses,”Opt. Commun. **56**, 219–221 (1985).
[2] J. Limpert et al., “Yb-doped large-pitch fibres: effective single-mode operation based on higher-order [...],” Light Sci. Appl. **1**, 1–5 (2012).

Large-Mode-Area Fibers

Large-Pitch Fibers

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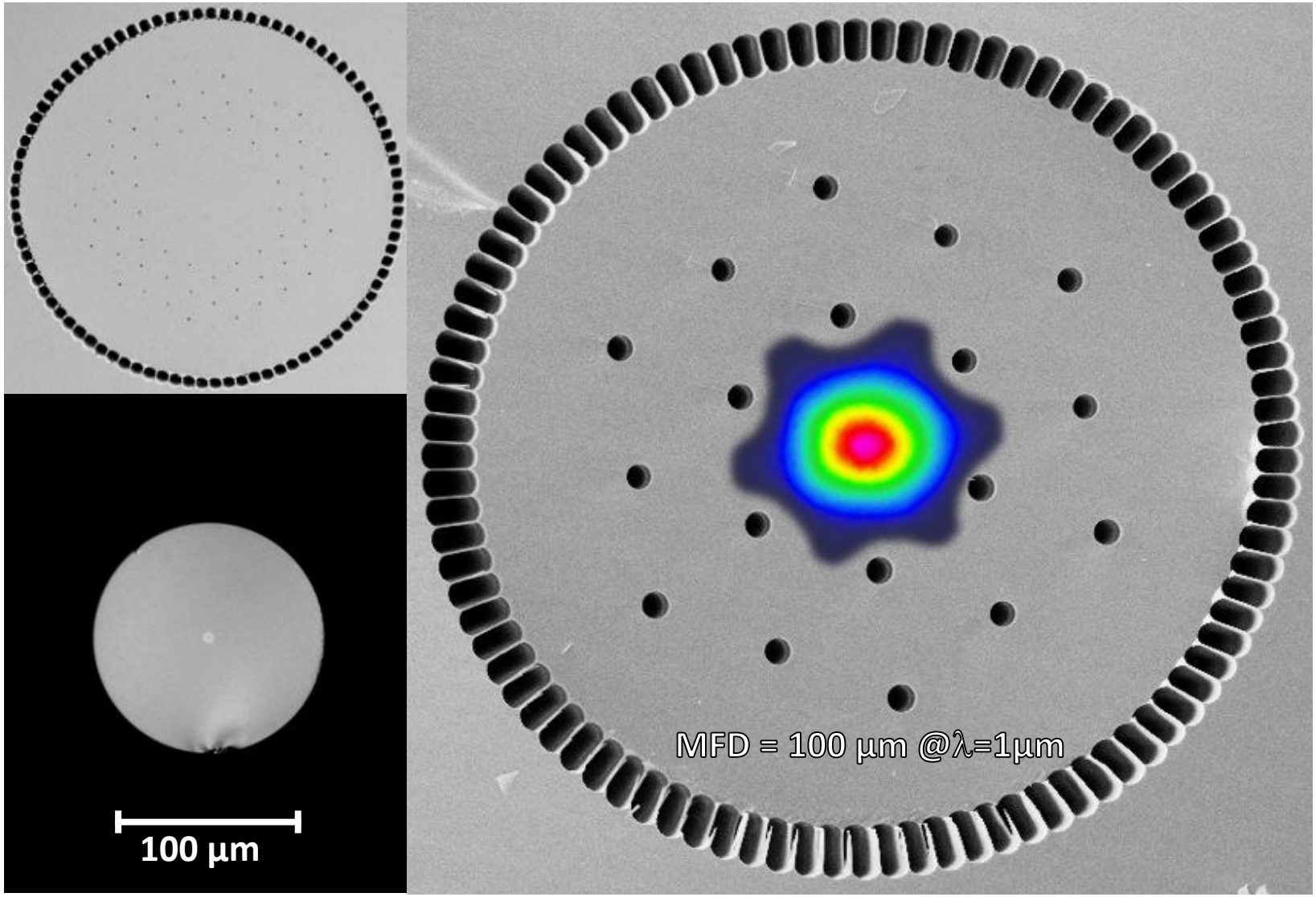

[1] T. Eidam et al., “Fiber chirped-pulse amplification system emitting 3.8 GW peak power,” Opt. Express **19**, 255–60 (2011).
[2] H.-J. Otto et al., “2 kW average power from a pulsed Yb-doped rod-type fiber amplifier,” Opt. Lett. **39**, 6446–9 (2014).
[3] F. Stutzki et al., “26 mJ, 130 W Q-switched fiber-laser system with near-diffraction-limited beam quality,” Opt. Lett. **37**, 1073–1075 (2012).

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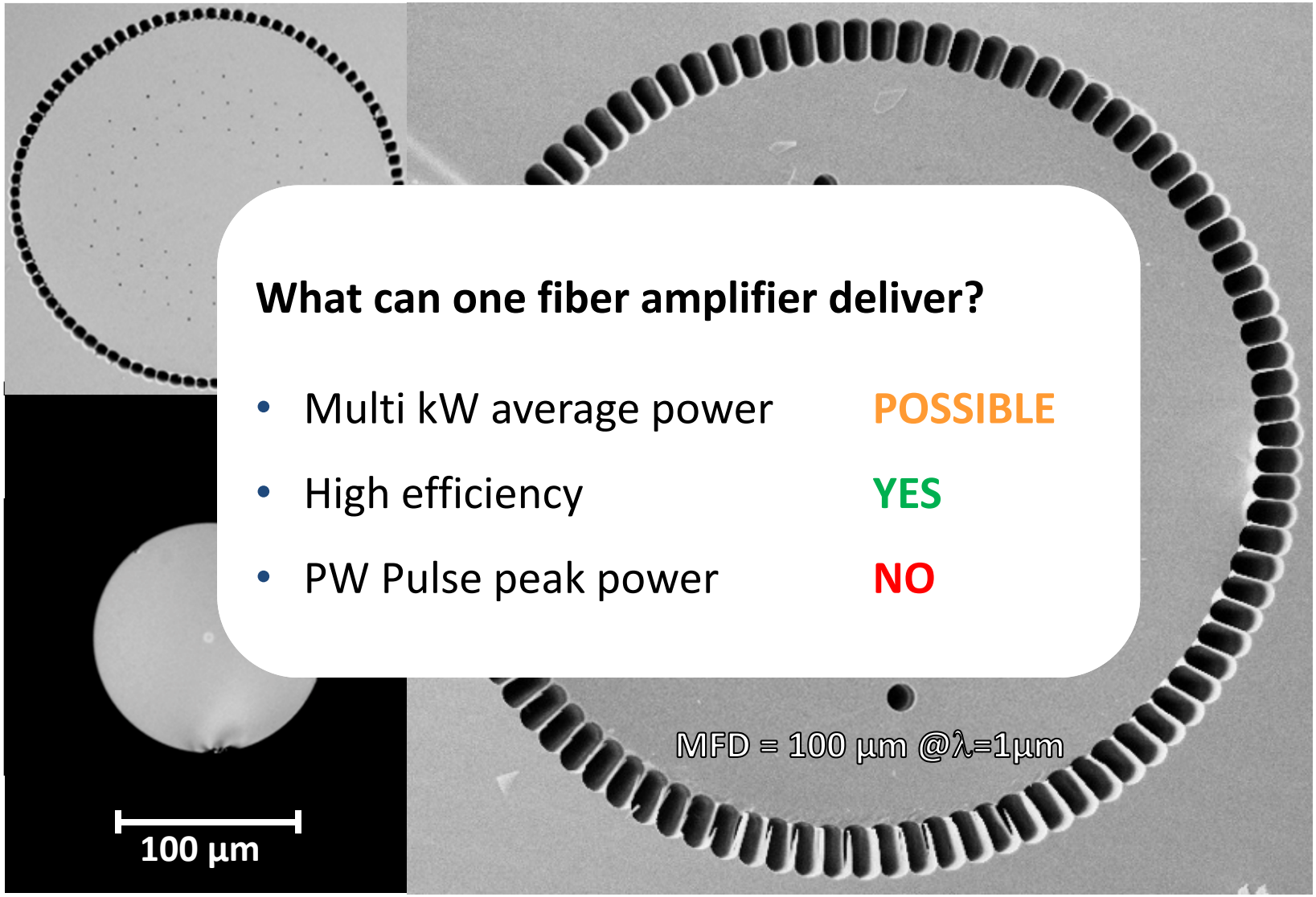

What can one fiber amplifier deliver?

- Multi kW average power **POSSIBLE**
- High efficiency **YES**
- PW Pulse peak power **NO**

[1] T. Eidam et al., "Fiber chirped-pulse amplification system emitting 3.8 GW peak power," Opt. Express **19**, 255–60 (2011).
[2] H.-J. Otto et al., "2 kW average power from a pulsed Yb-doped rod-type fiber amplifier," Opt. Lett. **39**, 6446–9 (2014).
[3] F. Stutzki et al., "26 mJ, 130 W Q-switched fiber-laser system with near-diffraction-limited beam quality," Opt. Lett. **37**, 1073–1075 (2012).

Large-Mode-Area Fibers

Evolution of Peak Power

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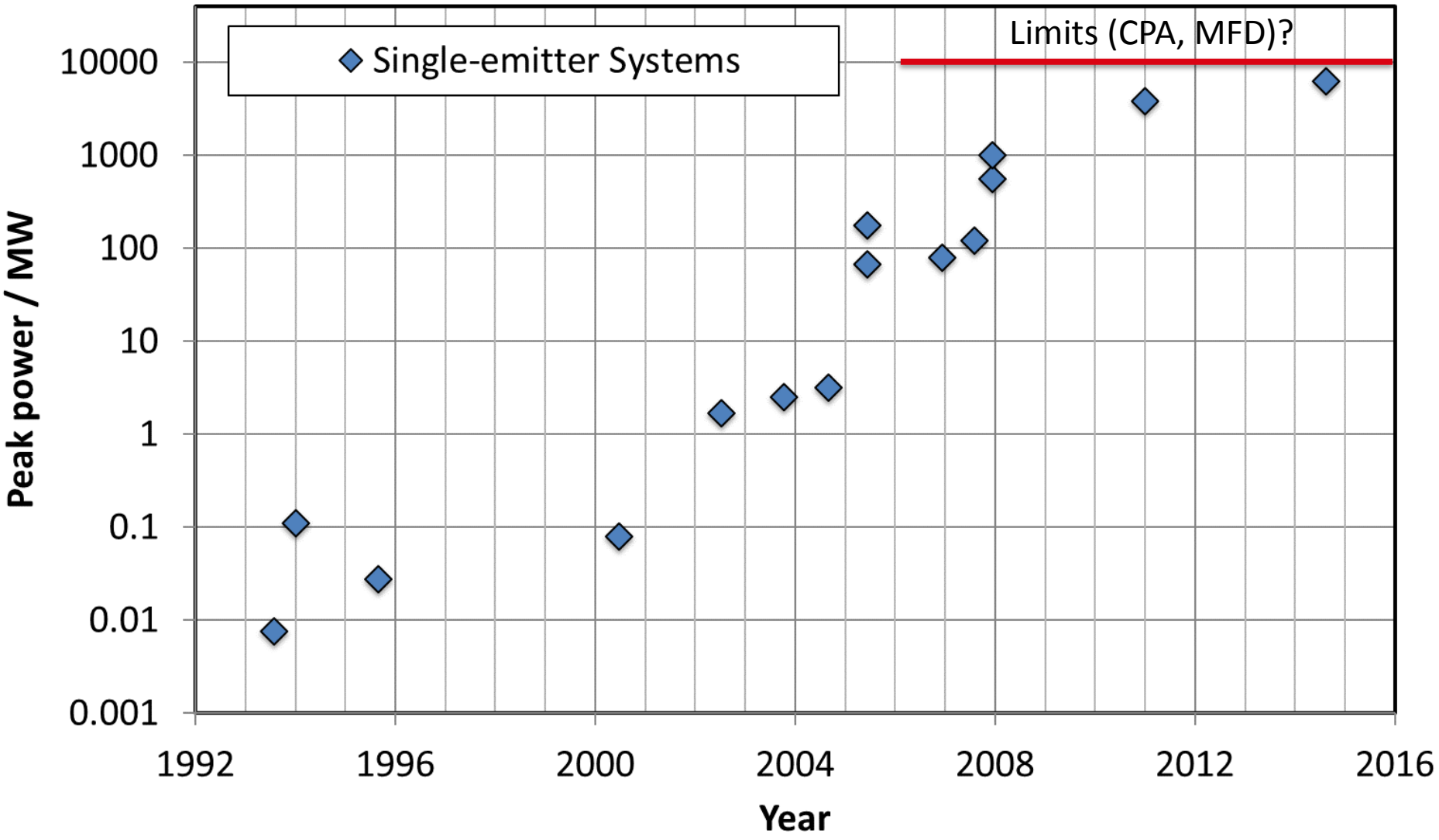

Coherent Combination

Parallelisation of the Problem

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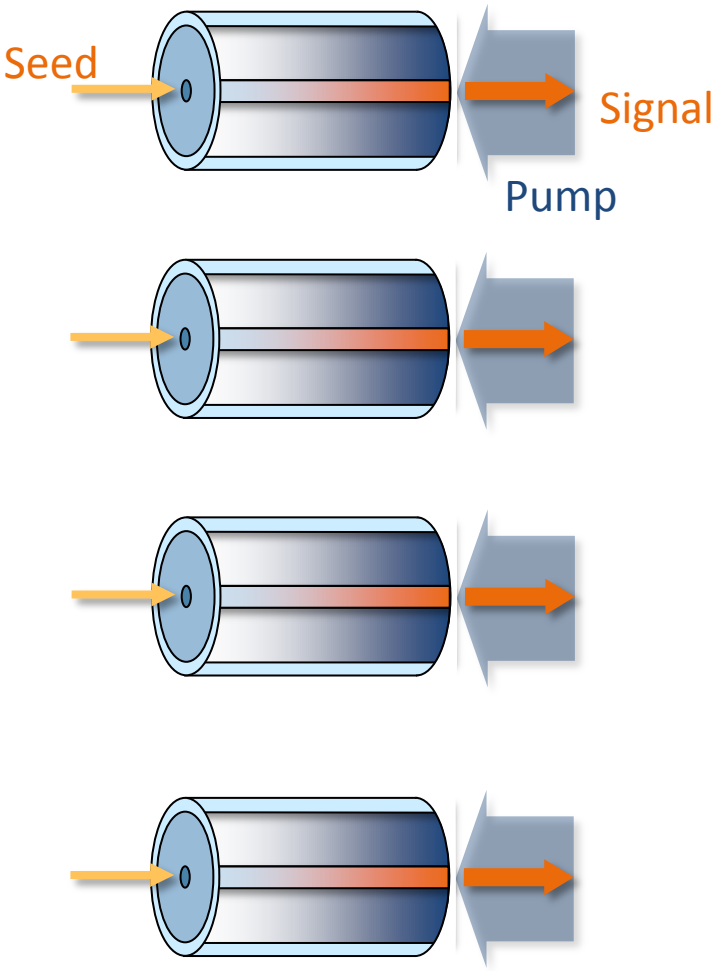

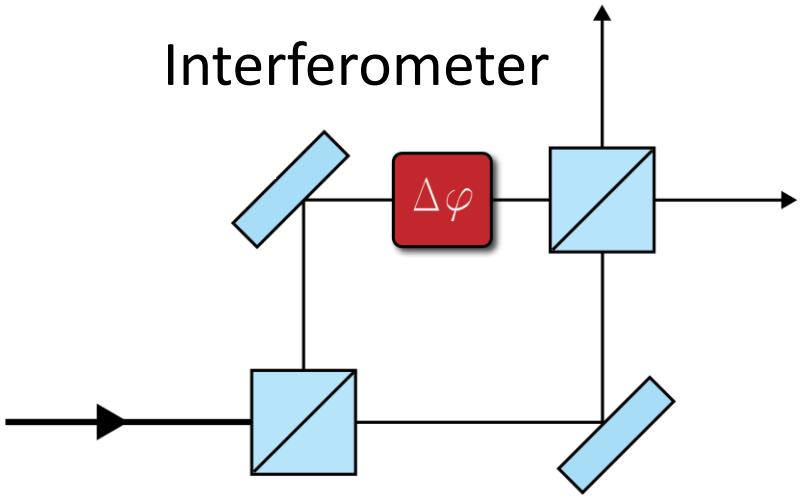

Scalable technology that could put PW peak powers and multi kW average powers in reach

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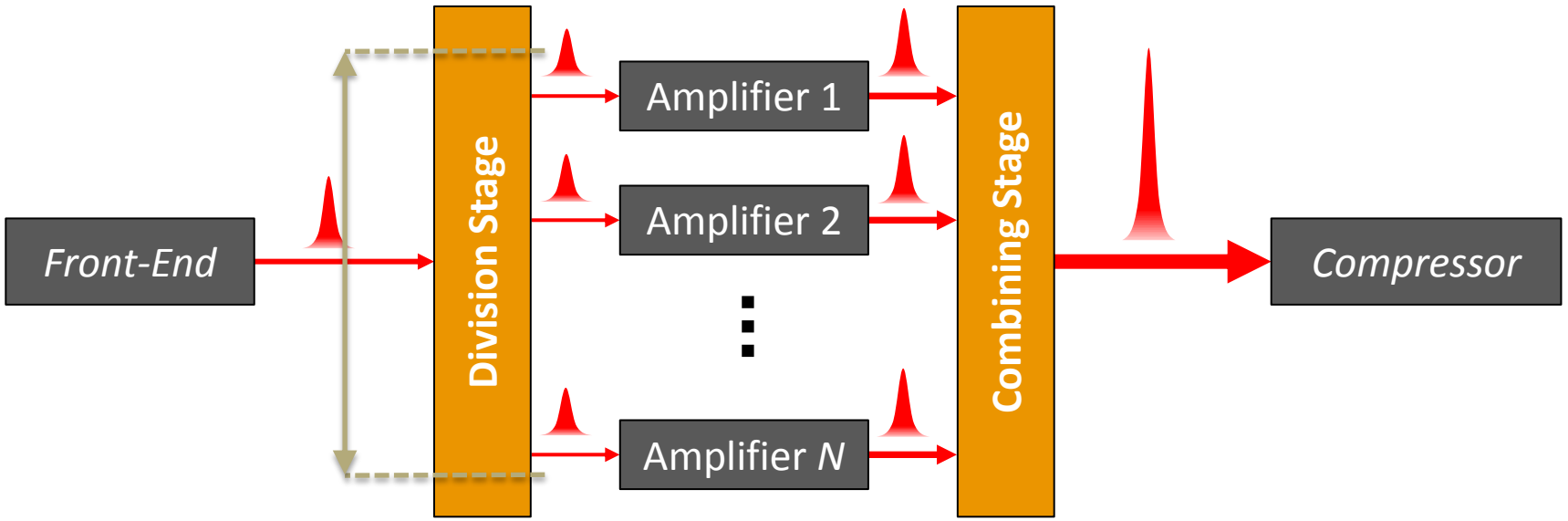
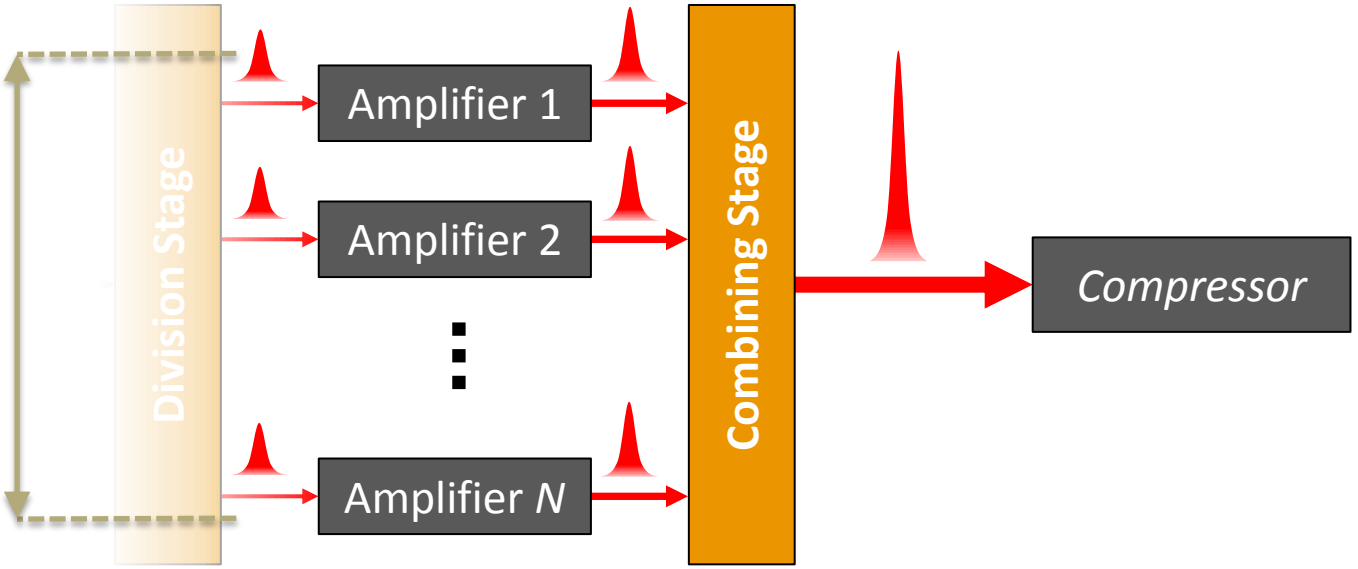
“Amplifying Interferometer”



- Use ***N*** amplifiers and combine the spatially separated pulses
- Best case: Improvement of the pulse energy and average power by a factor of ***N***

“Amplifying Interferometer”

Artificial scaling
of mode area



Use ***N*** amplifiers and combine the spatially separated pulses

Best case: Improvement of the pulse energy and average power by a factor of ***N***

Coherent Addition of Ultrashort Pulses

Spatial beam combination

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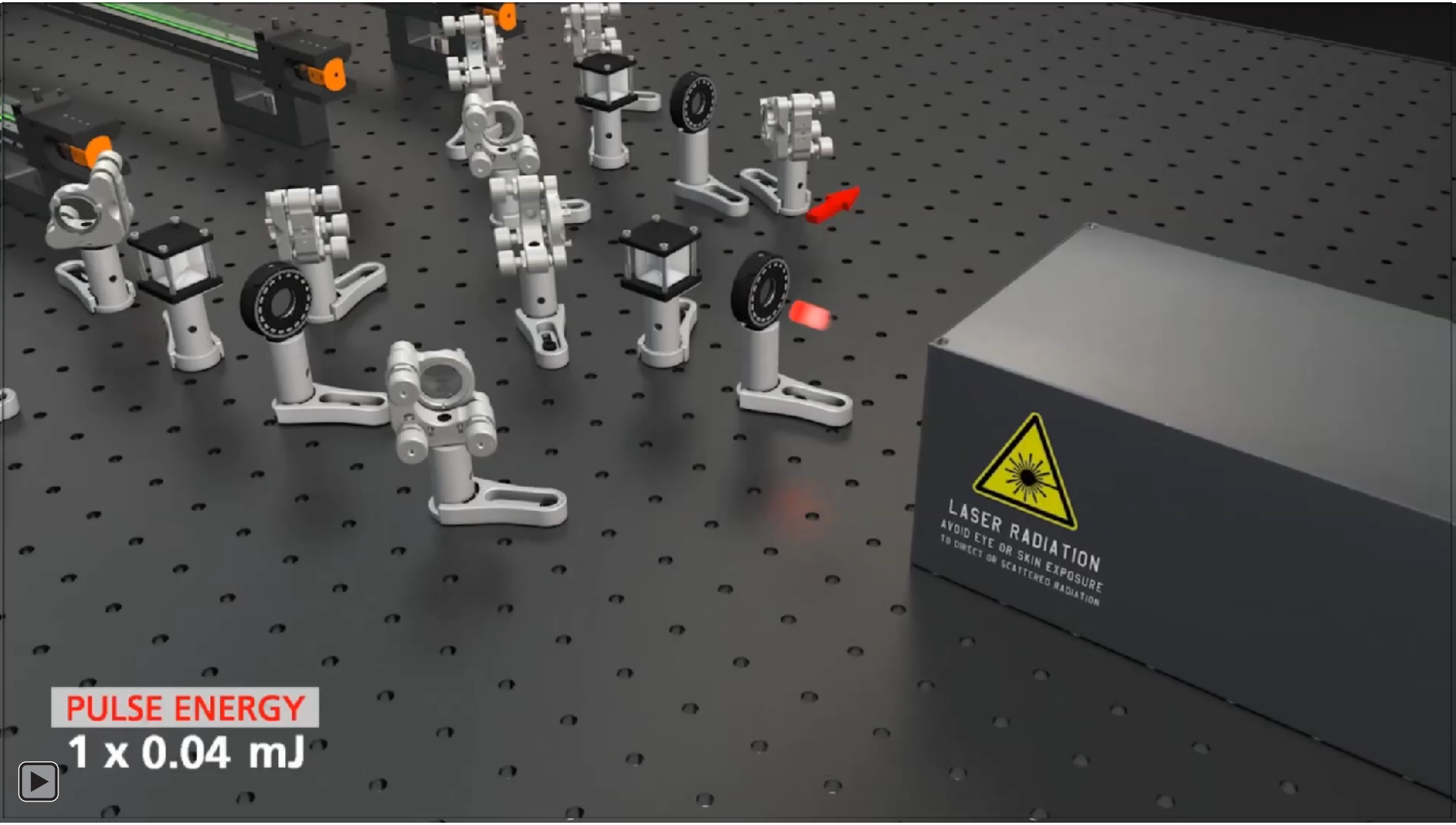

[1] A. Klenke, S. Breitkopf, M. Kienel, T. Gottschall, T. Eidam, S. Hädrich, J. Rothhardt, J. Limpert, and A. Tünnermann, "530 W, 1.3 mJ, four-channel coherently combined femtosecond fiber chirped-pulse amplification system," Opt. Lett. 38, 2283-2285 (2013)

Coherent Combination

4-Channel Fiber-CPA System

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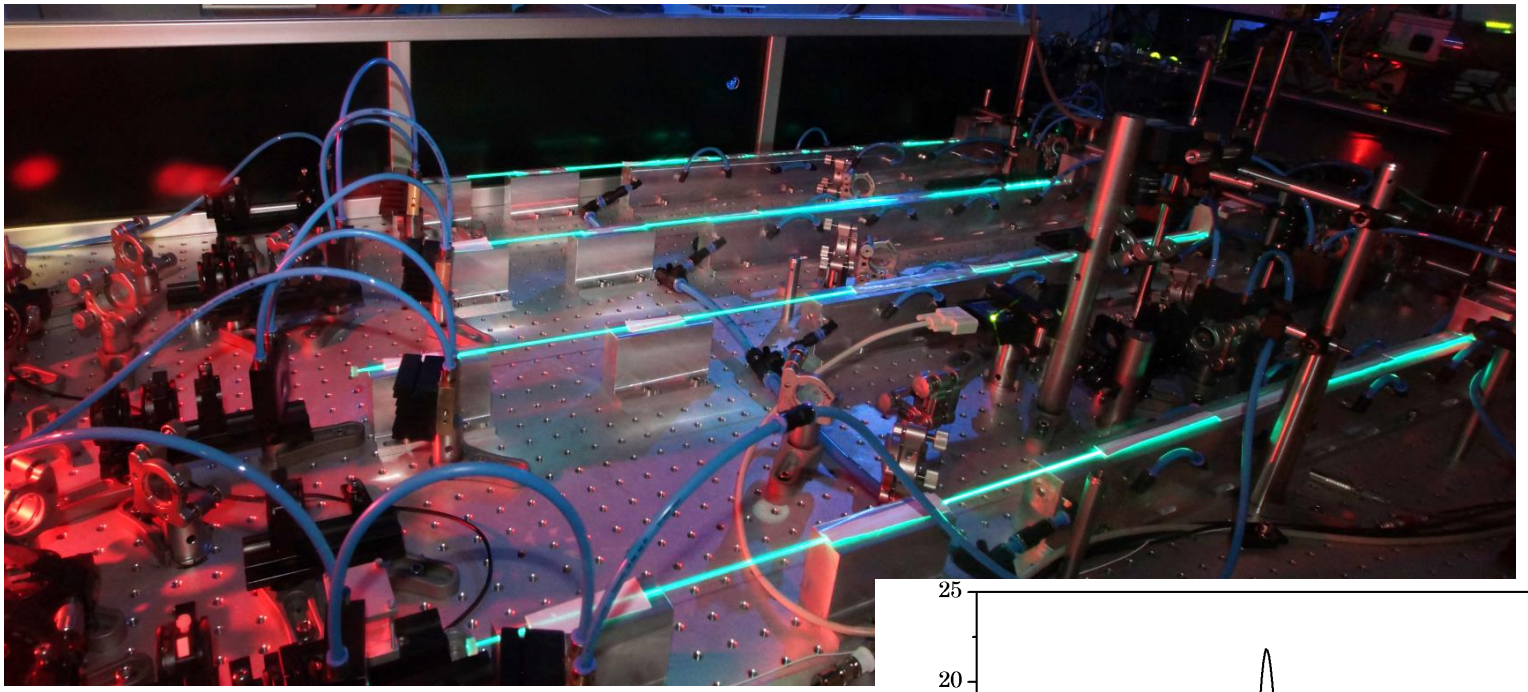
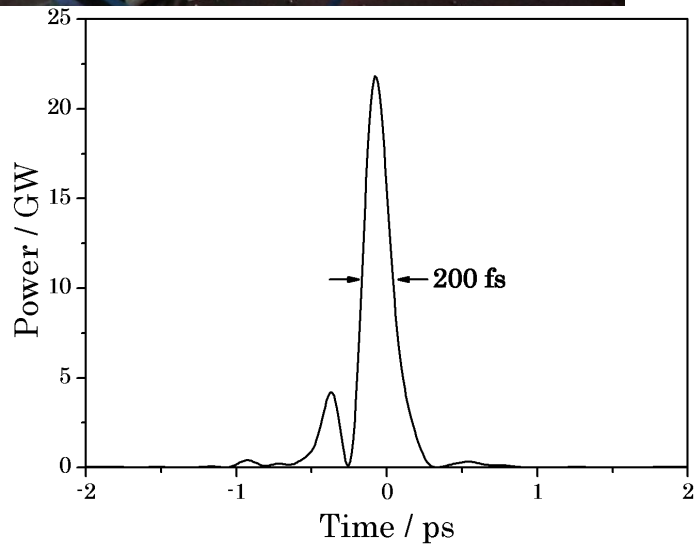


- 5.7mJ pulse energy
- 200fs pulse duration
- 22GW peak power
- 88% combining efficiency
- $M^2 = 1.25$



[1] A. Klenke, S. Hädrich, T. Eidam, J. Rothhardt, M. Kienel, S. Demmler, T. Gottschall, J. Limpert, and A. Tünnermann, “22 GW peak-power fiber chirped-pulse-amplification system”, submitted to OL

Coherent Combination

Evolution of Peak Power

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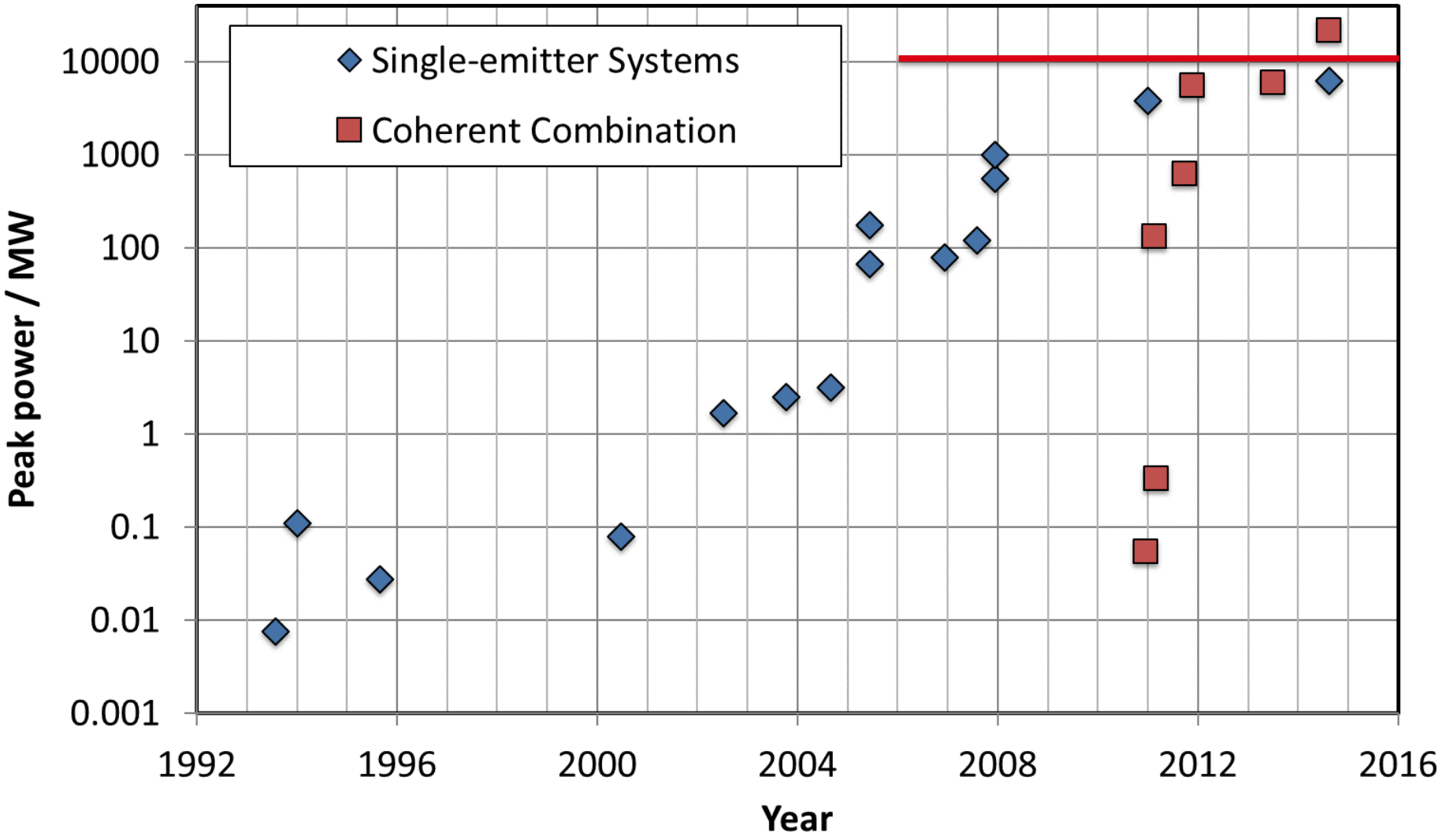

Coherent Combination

Two-stage hollow core compression

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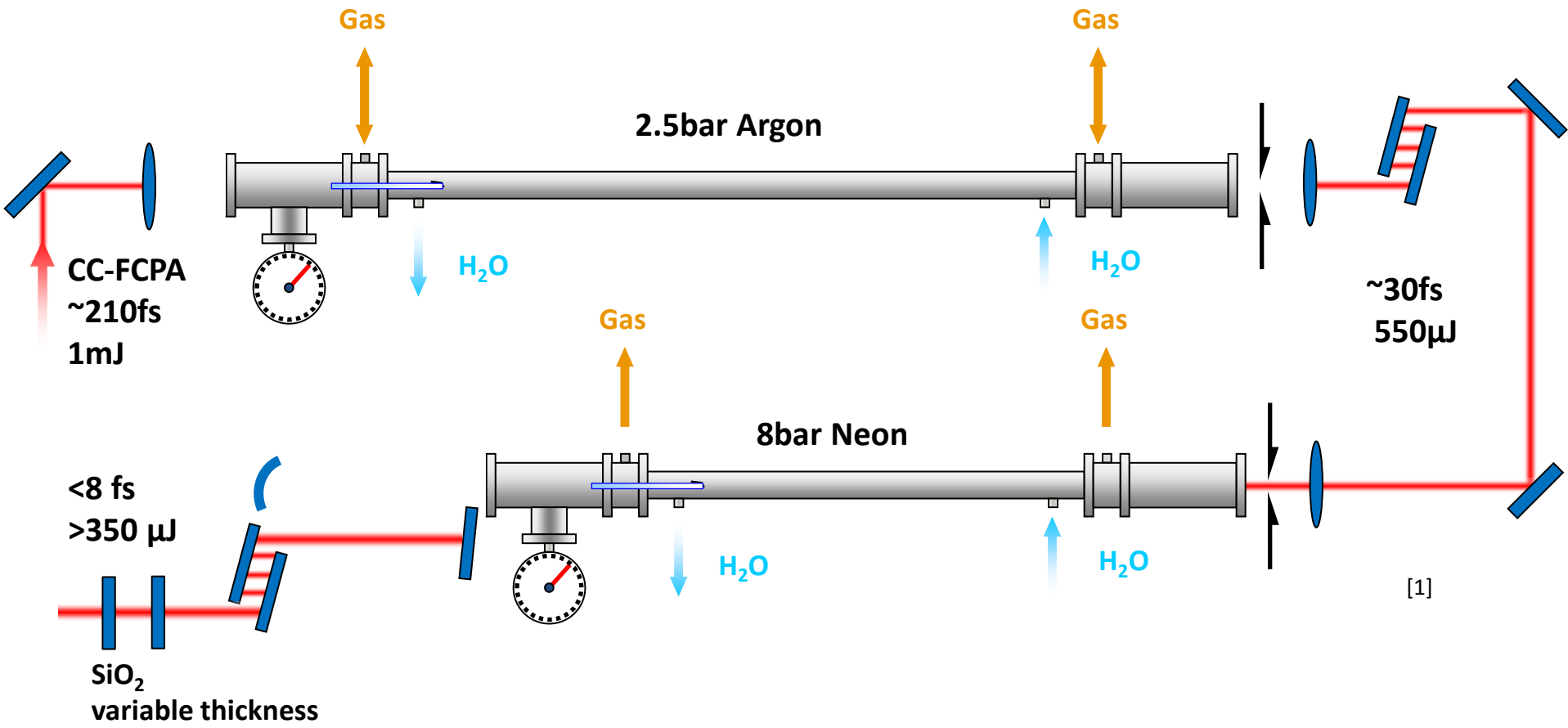

[1]

[1] J. Rothhardt et al., „53 W average power few-cycle fiber laser system generating soft x rays up to the water [...],” Opt. Lett. **39**, 5224 (2014)
[2] M. Nisoli et al. "Compression of high-energy laser pulses below 5 fs," Opt. Lett. **22**, 522-524 (1997)

Coherent Combination

Two-stage hollow core compression

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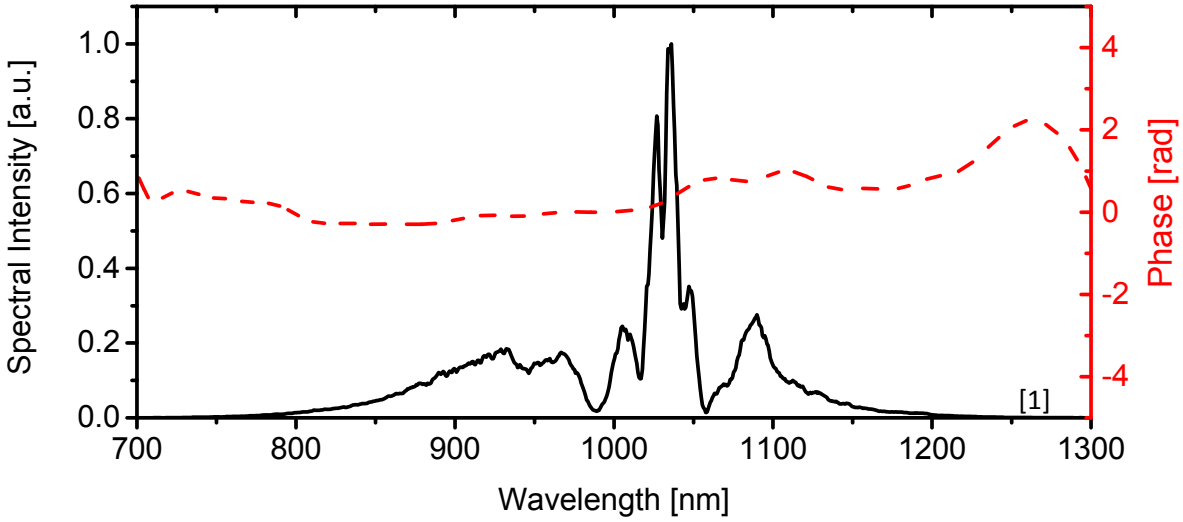
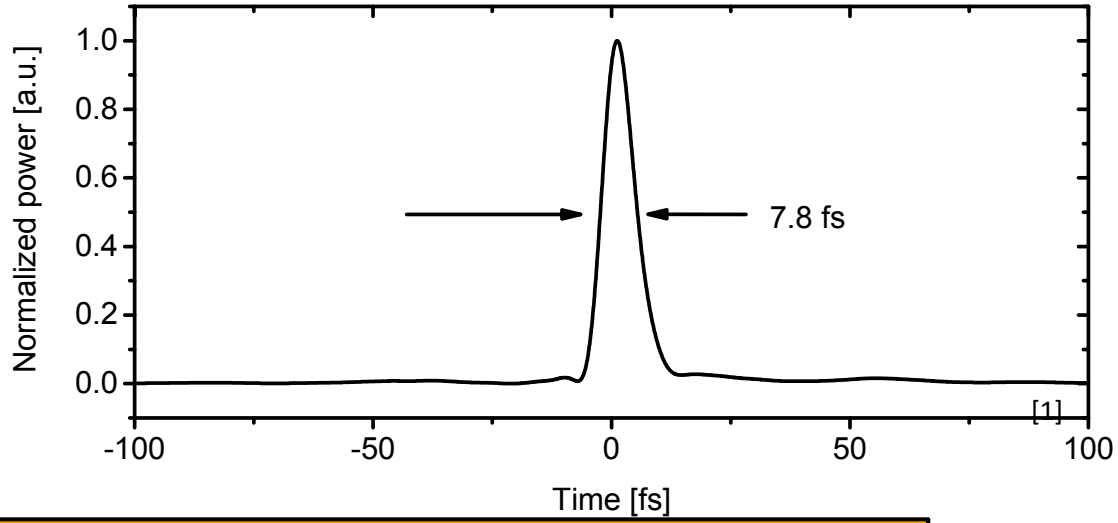
- **350µJ** pulse energy
- **Sub-8fs** pulse duration
- **>25GW** peak power
- **150kHz** repetition rate
- **53W** average power
- **Excellent beam quality**

- Scaling to

  >>100W average power,

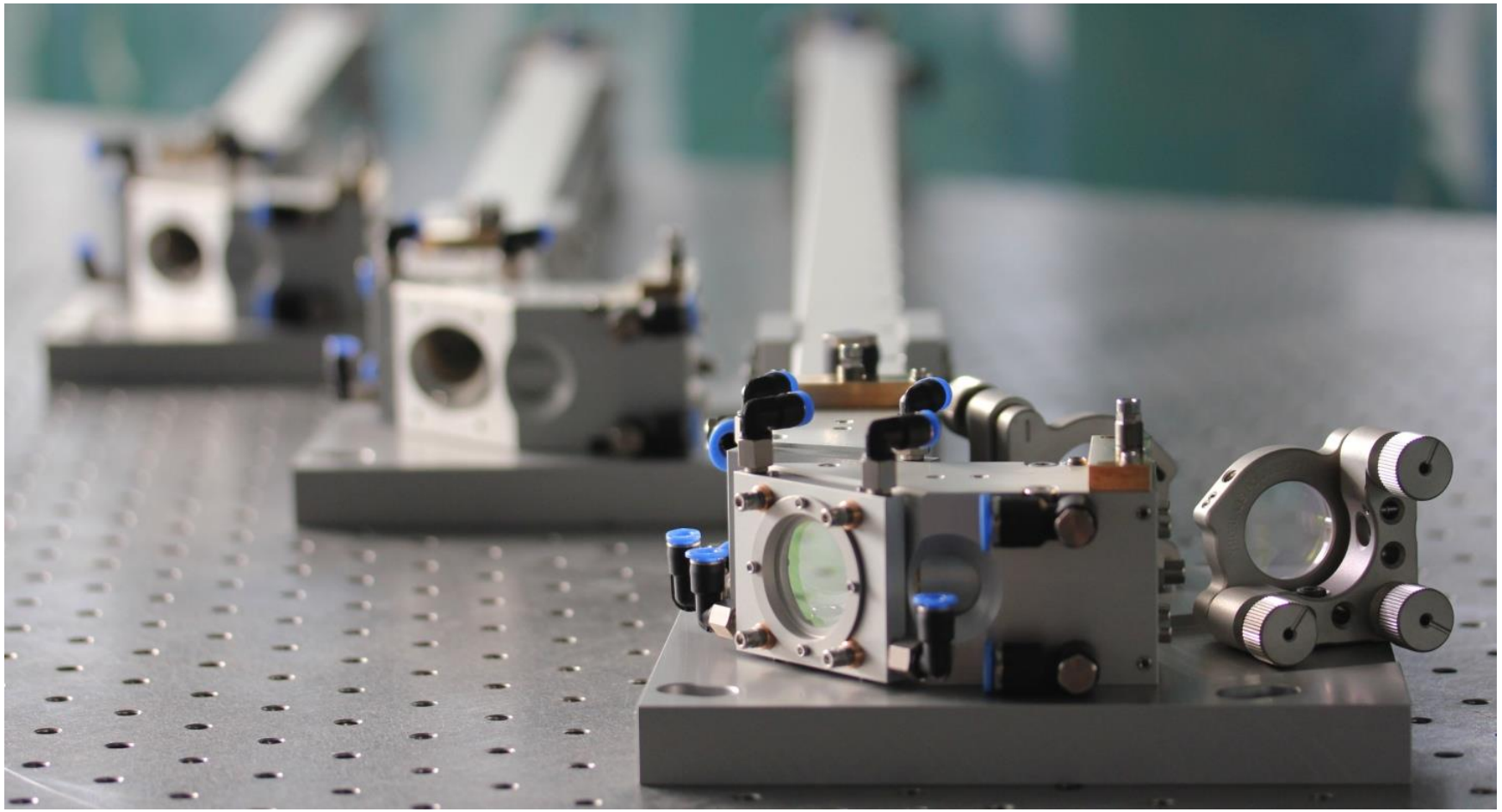
  multi-mJ few-cycle pulses





The most powerful energetic few-cycle laser in the world !

[1] J. Rothhardt et al., „53 W average power few-cycle fiber laser system generating soft x rays up to the water [...],” Opt. Lett. **39**, 5224 (2014).



Short, non-bendable, rod-type fibers

Coherent Combination

Rod-type fiber amplifier modules

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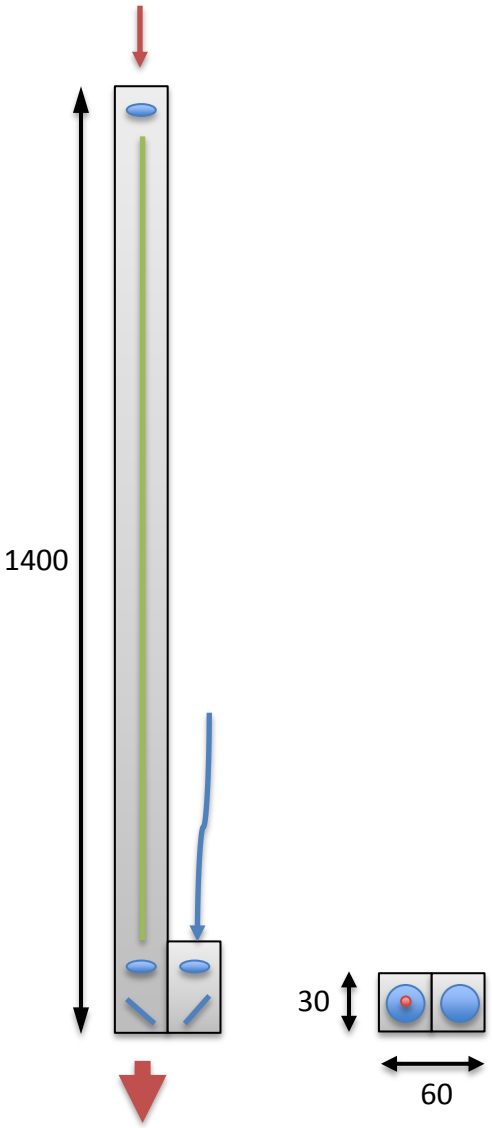

Coherent Combination

Rod-type fiber amplifier modules

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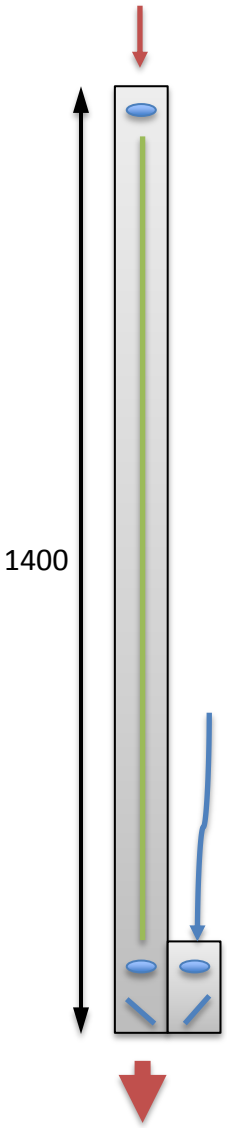
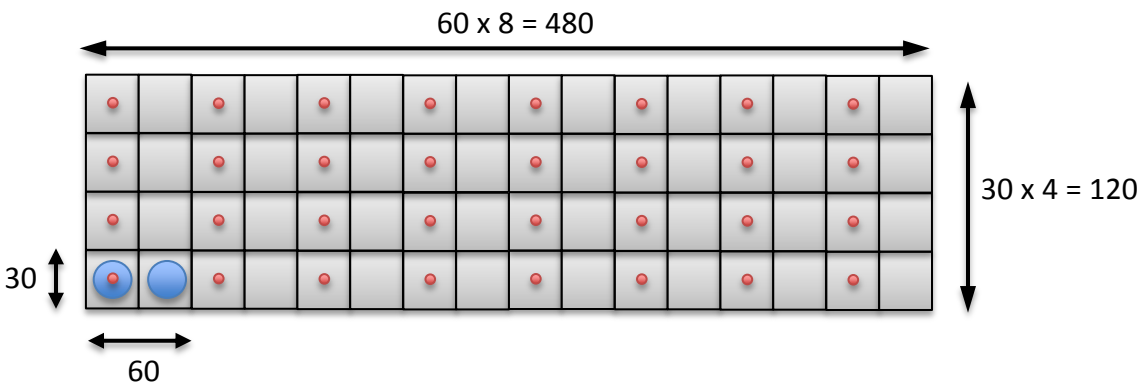


0.08 m³ for 1J at 15kHz = 15 kW



Coherent Combination

Rod-type fiber amplifier modules

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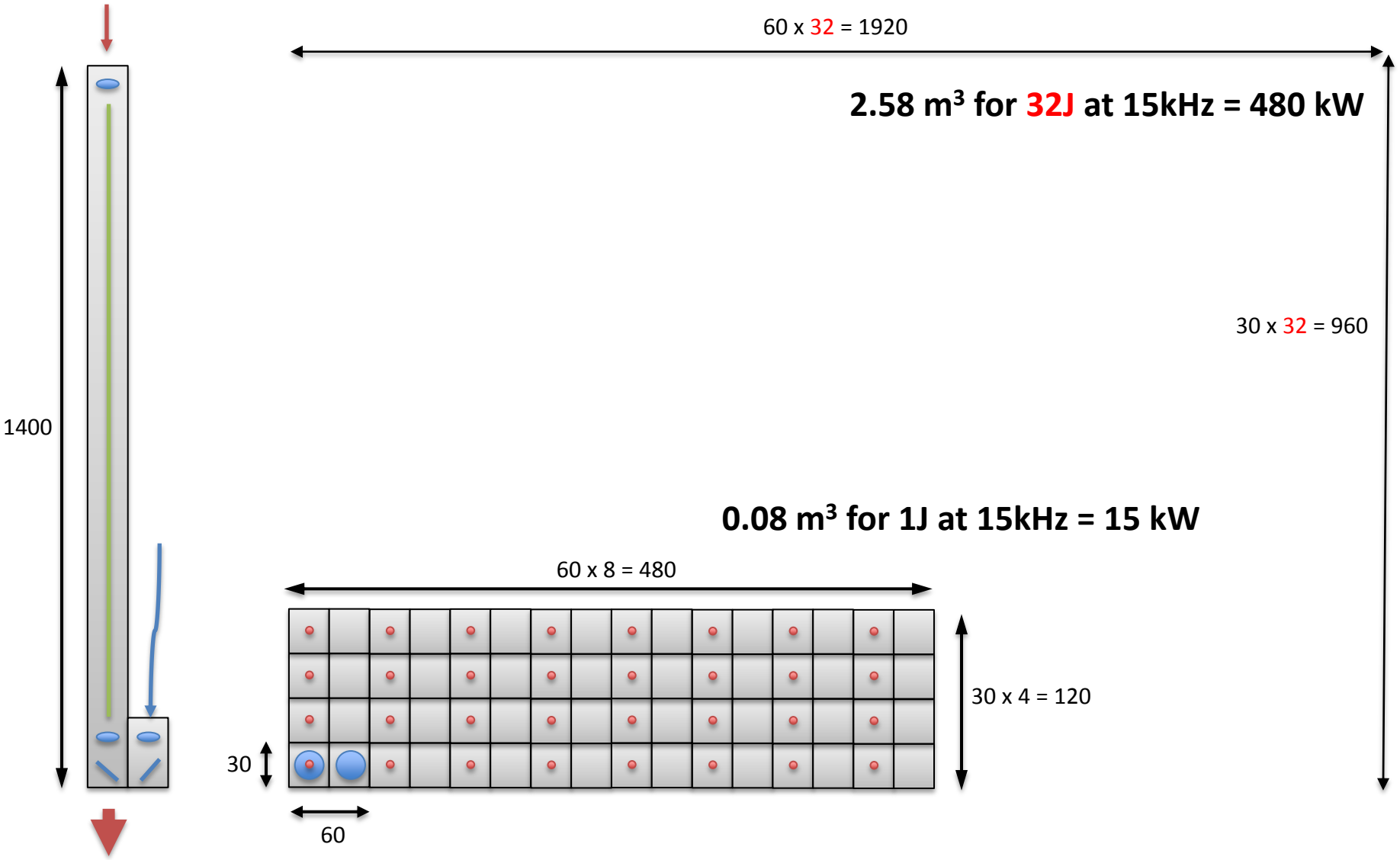

Coherent Combination

Splitting and combination elements

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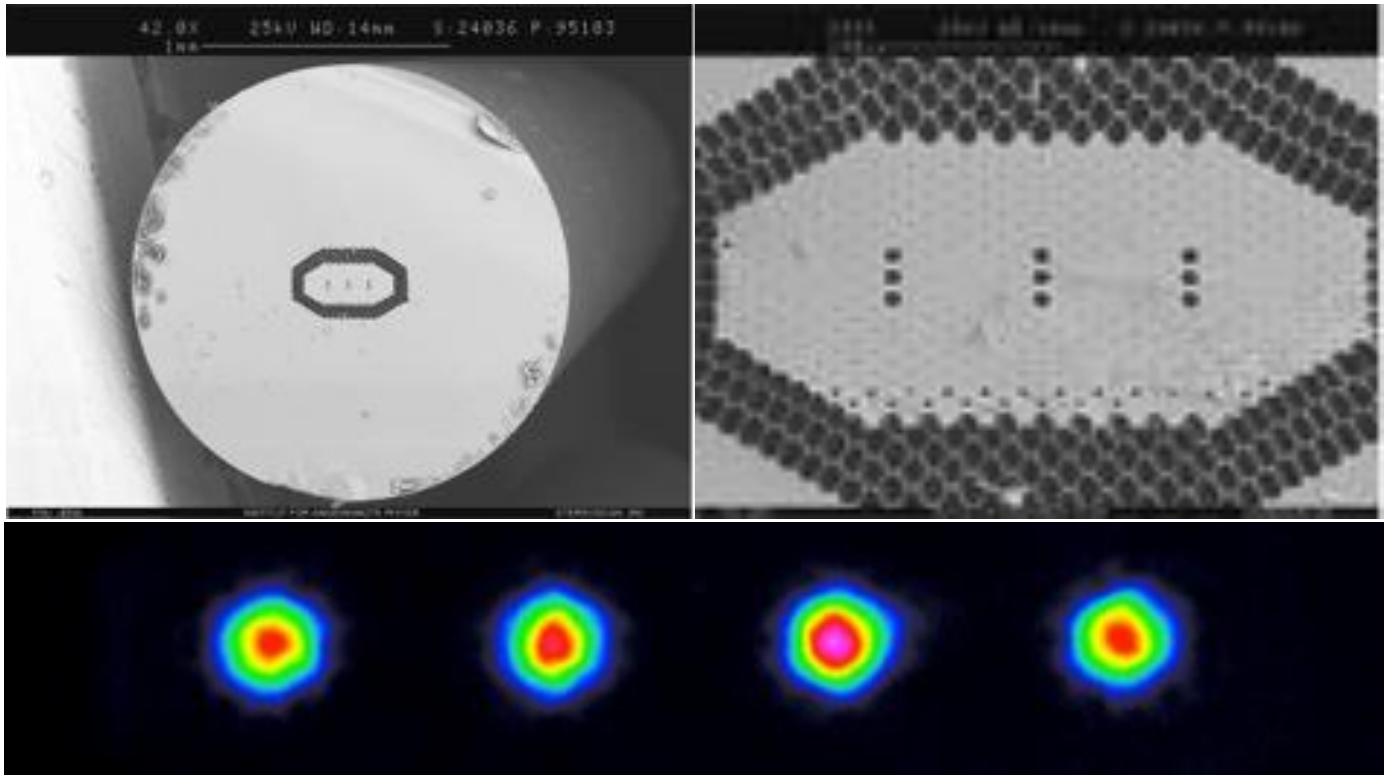
- Multi-core photonic-crystal fibers
- Shielded interferometer → no active stabilization required
- Multi-core arrangement realizes mode area scaling



Coherent Combination

Overview of possible Methods

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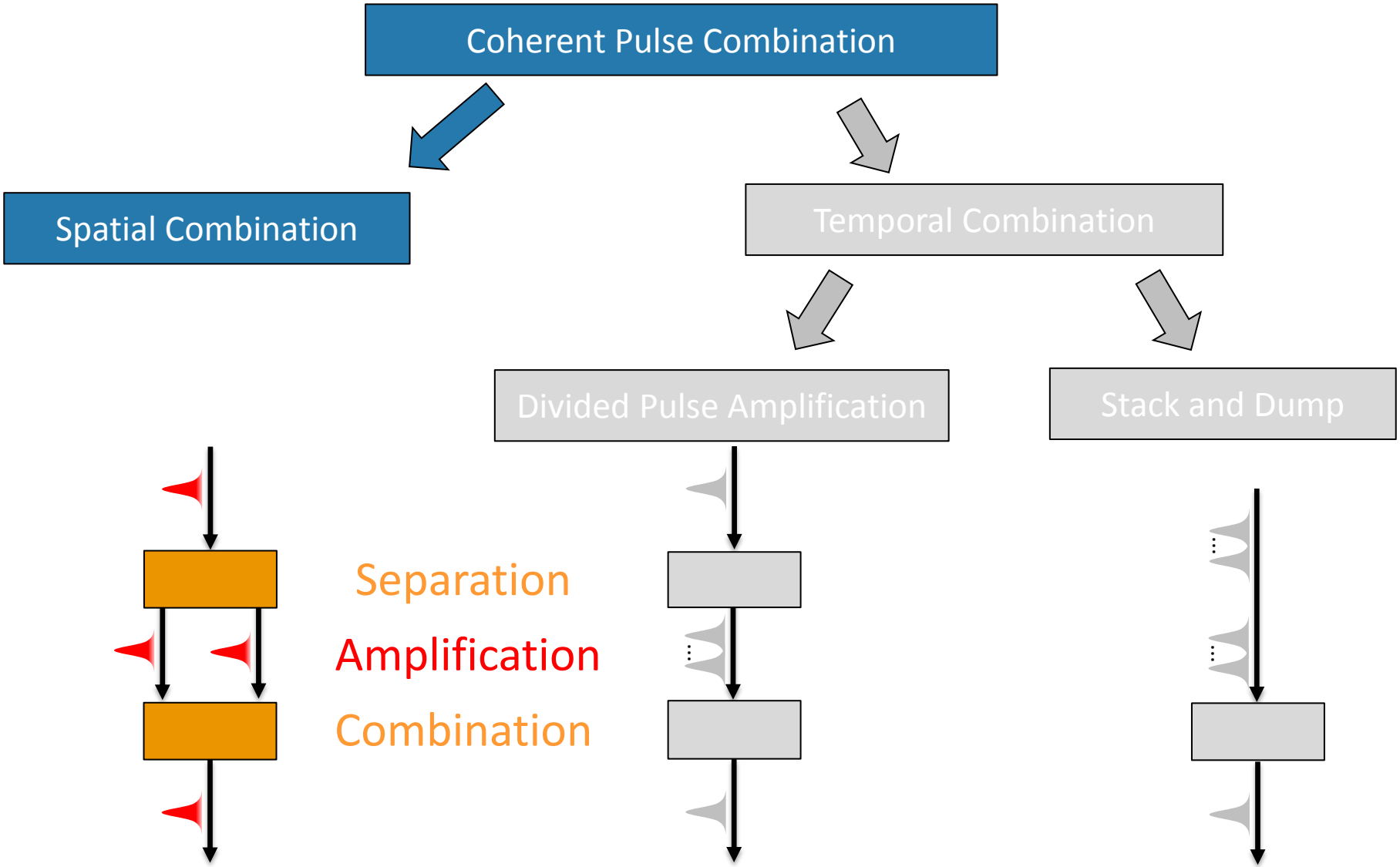

Coherent Combination

Overview of possible Methods

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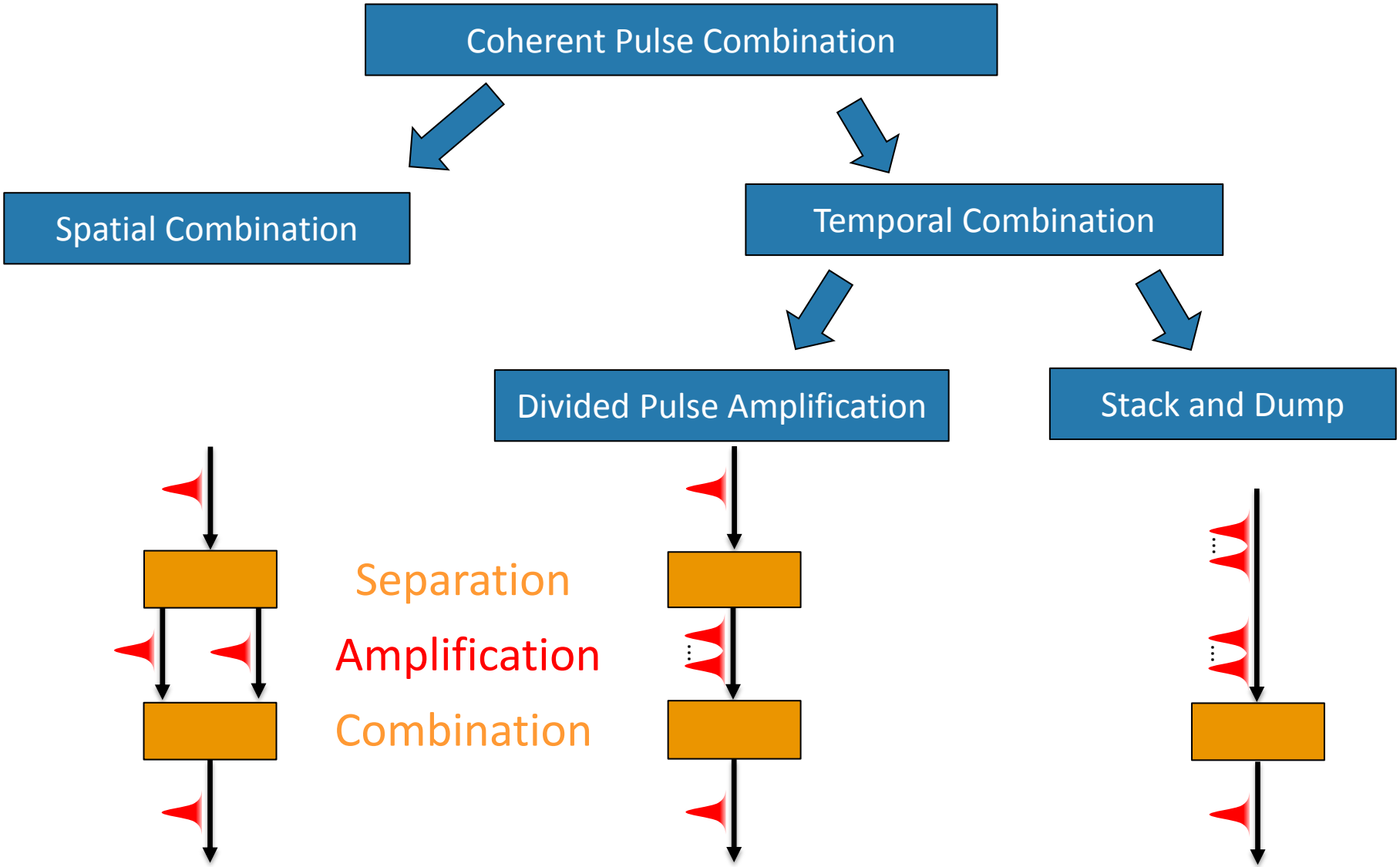
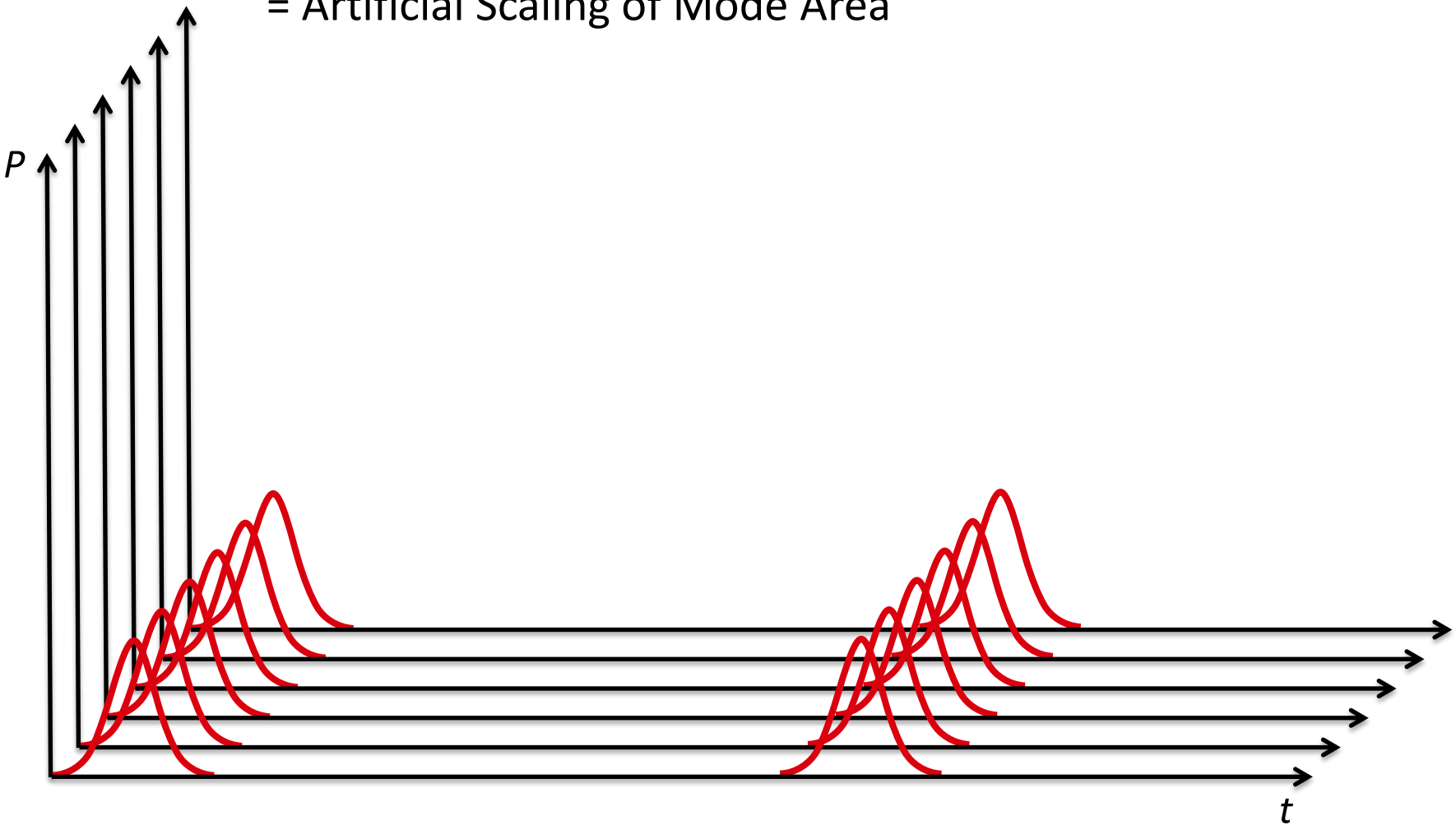


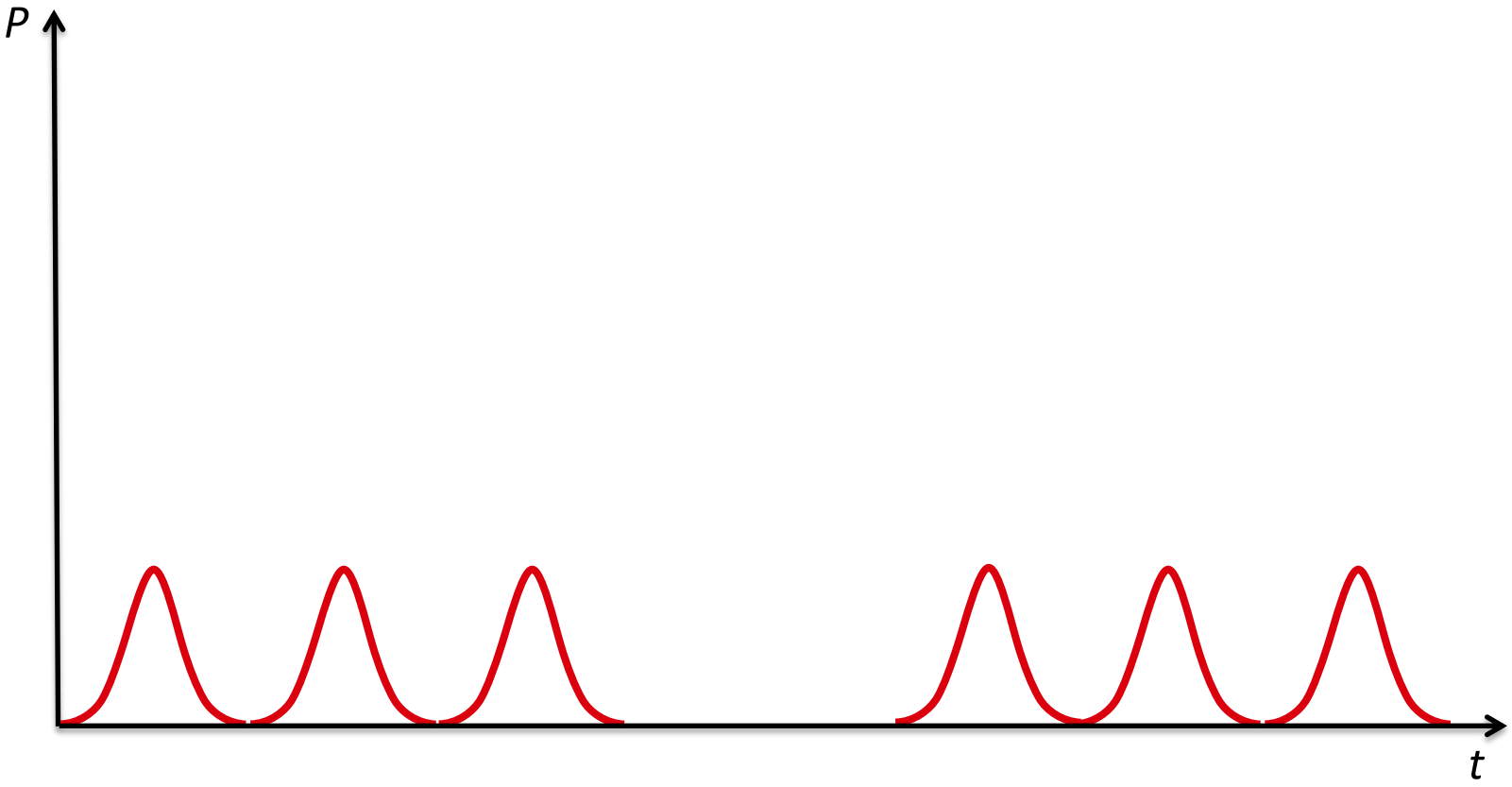
Coherent Combination

Spatially seperated amplification

= Artificial Scaling of Mode Area



= Artificial Scaling of Pulse-Duration



Coherent Combination

Overview of possible Methods

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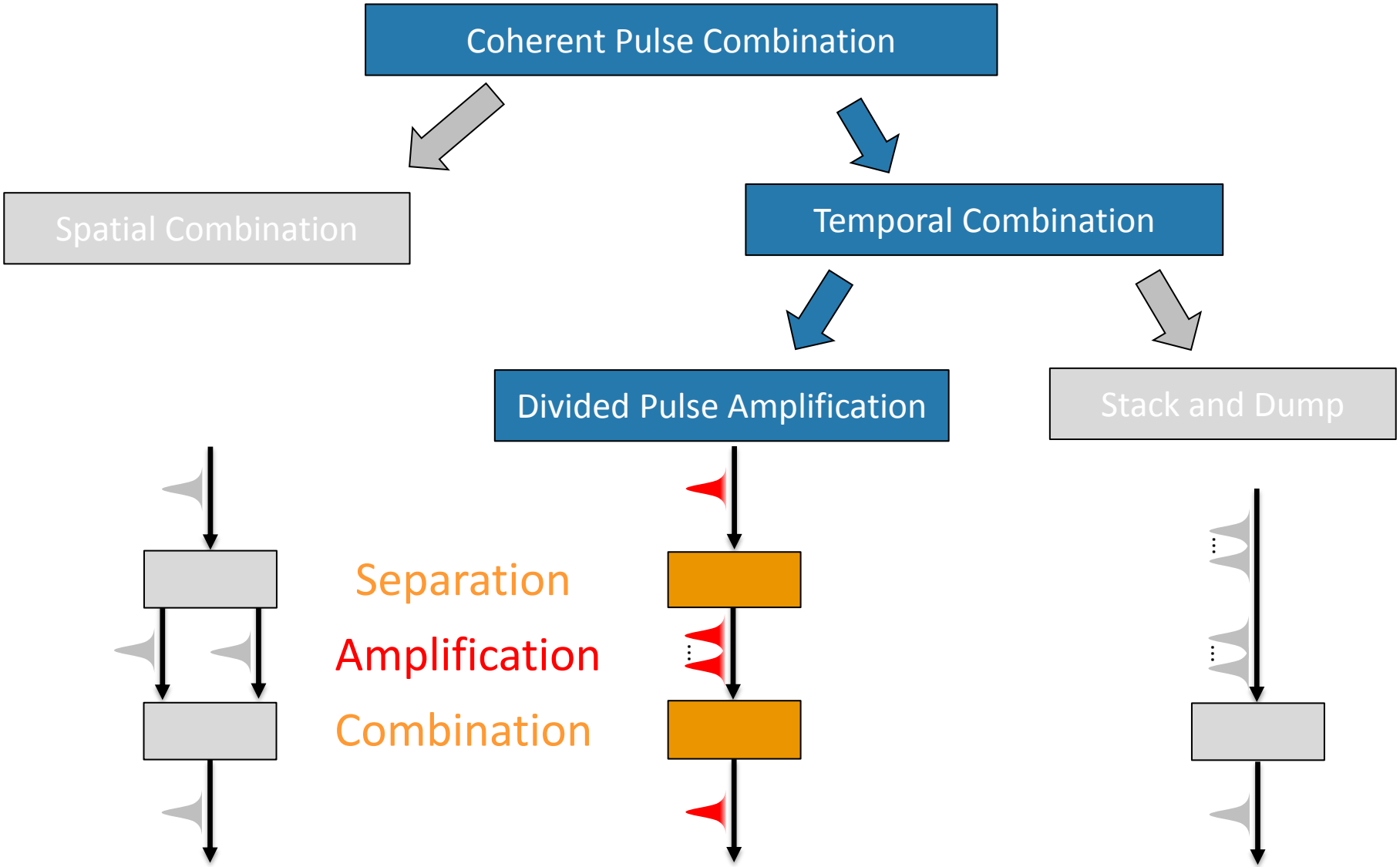

Coherent Combination

Temporal Pulse Stacking

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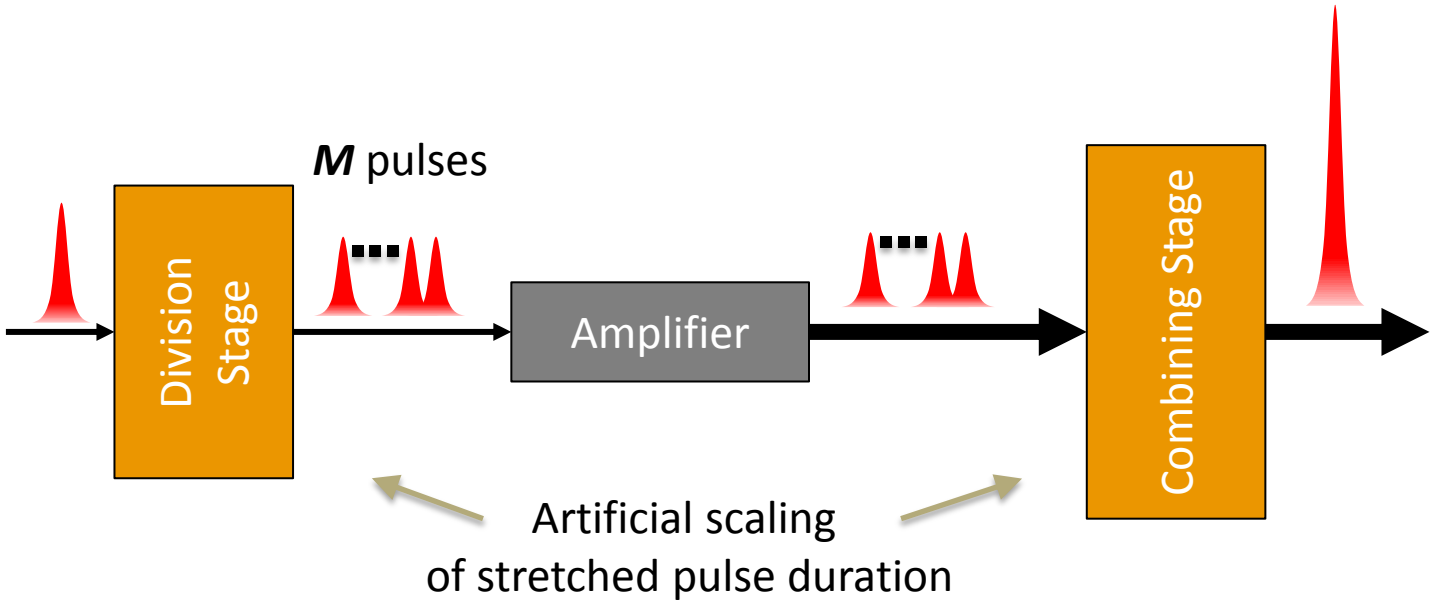

- Use ***M*** pulse replicas and combine the temporally separated pulses
- Best case: Improvement of the pulse energy and peak power by a factor of ***M***

Coherent Combination

Divided-Pulse Amplification of Chirped Pulses (DPA-CPA)

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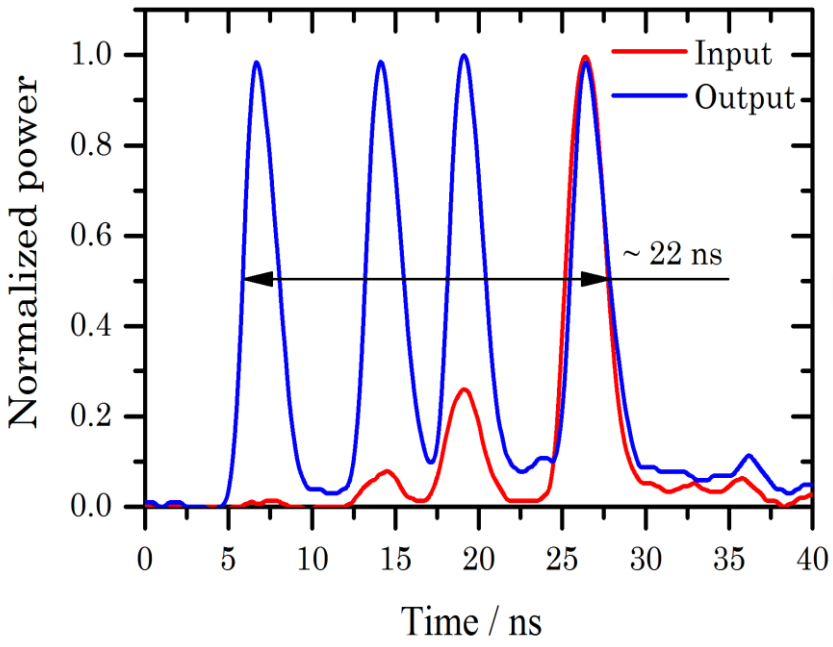
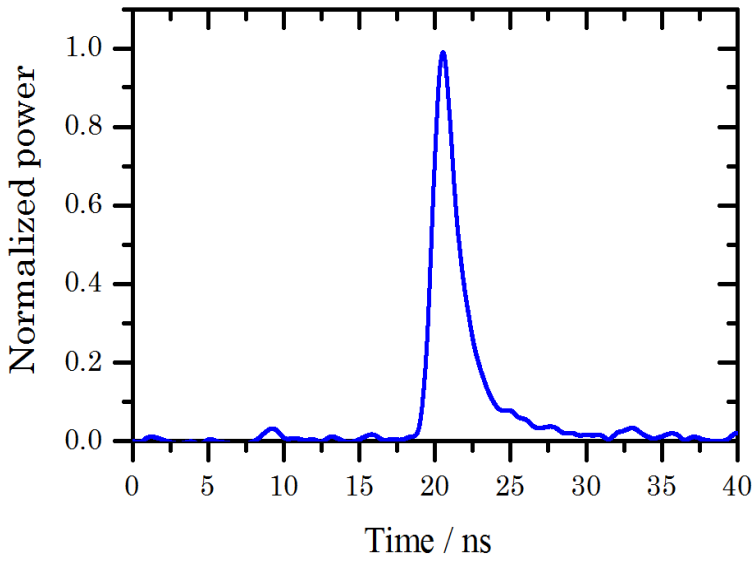
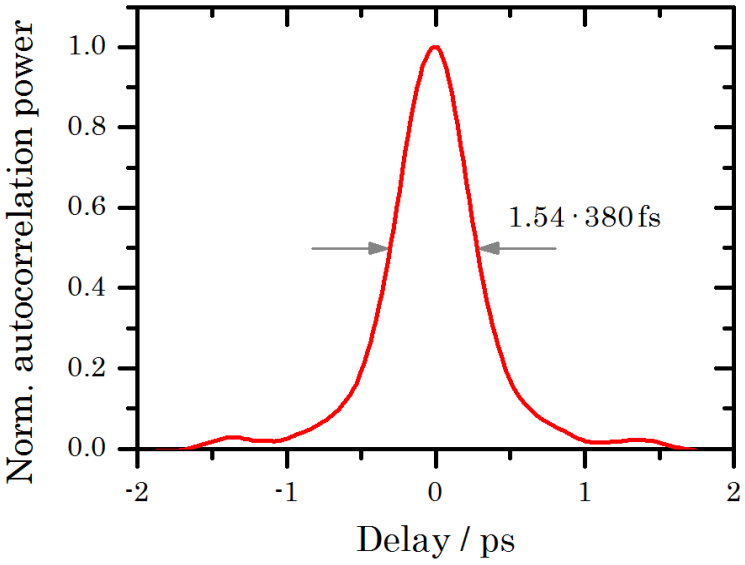


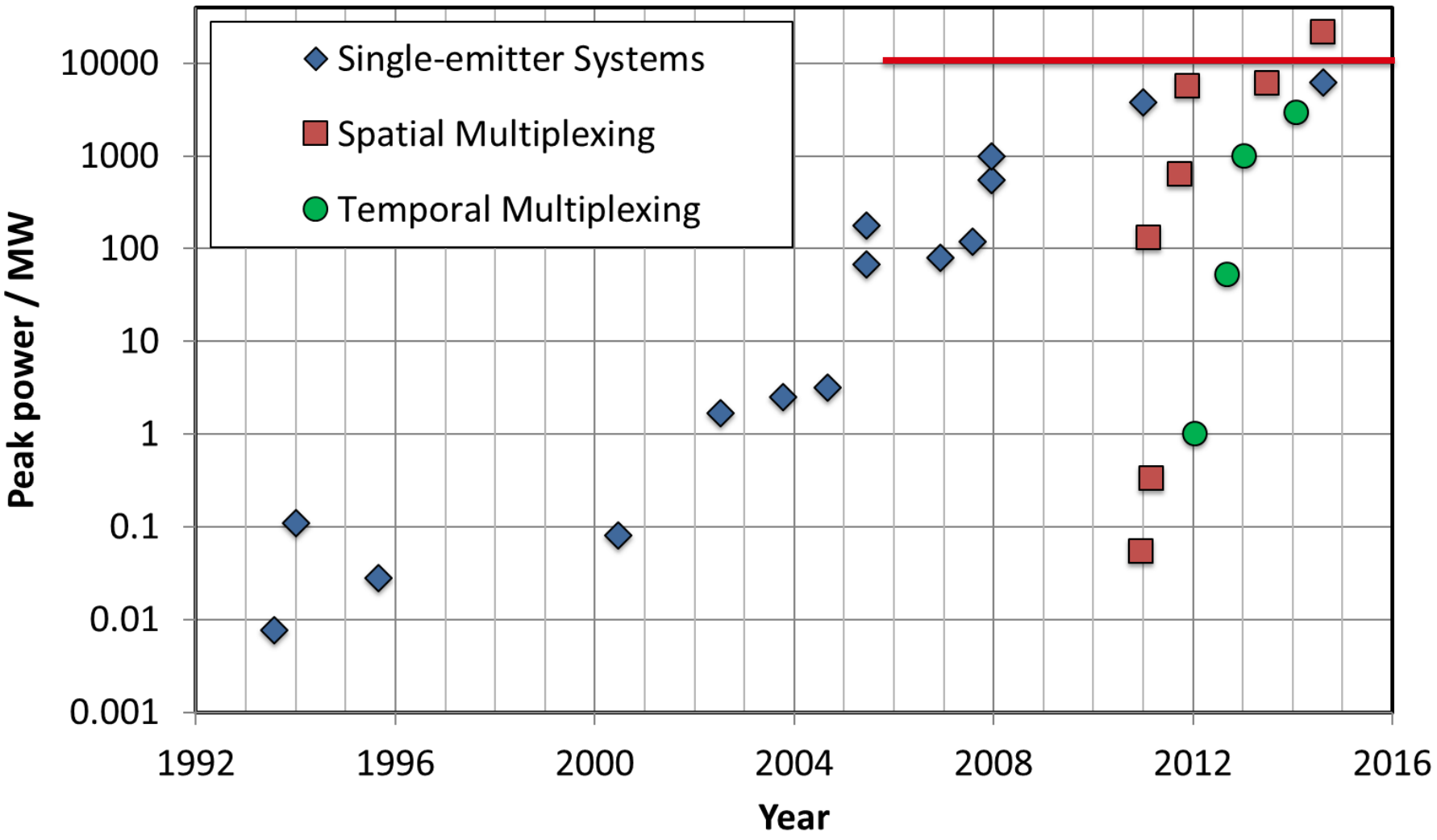




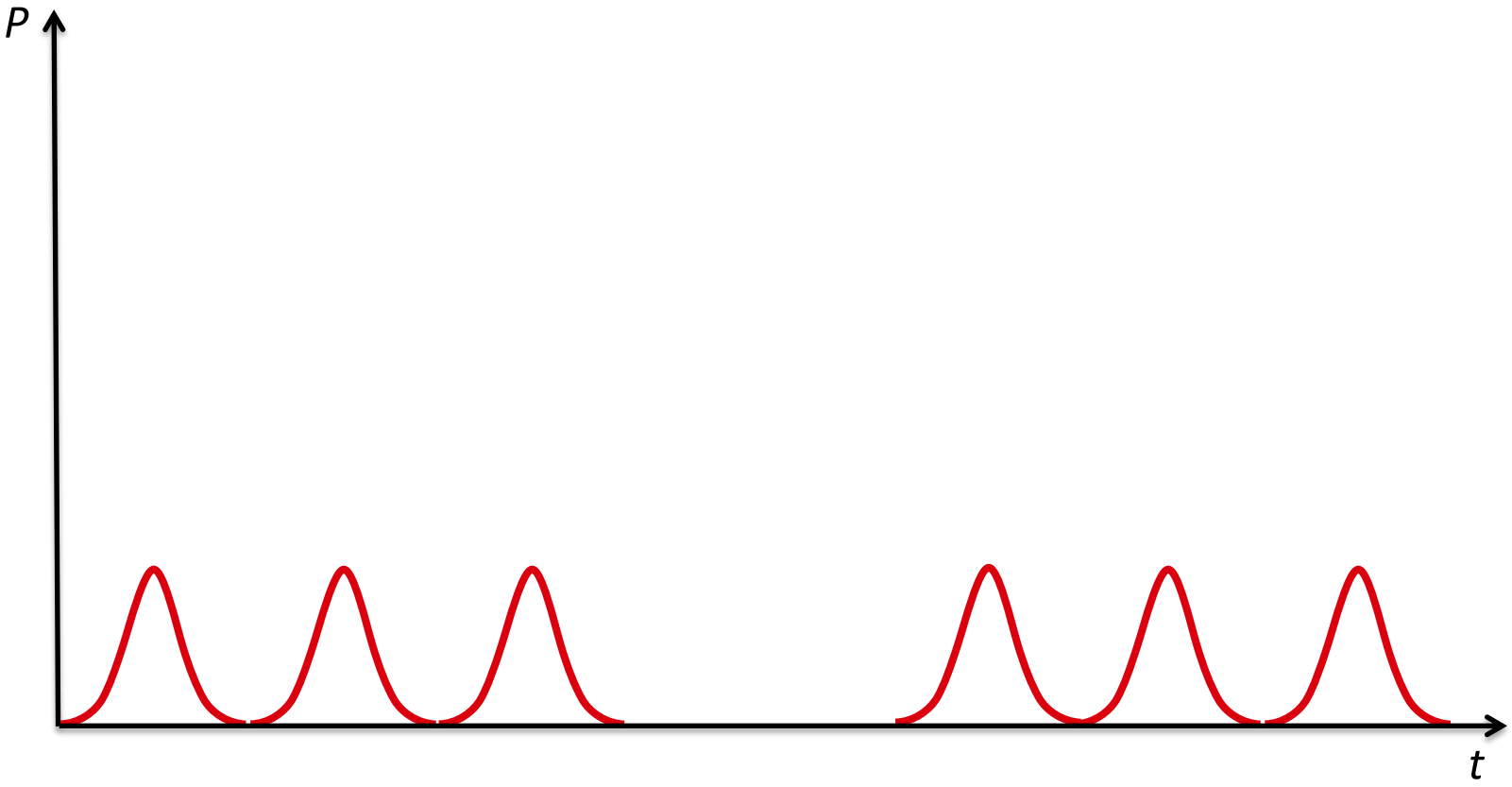
- Compensation of saturation
- Compression to 380fs
  → 2.9GW peak power

[1] M. Kienel, A. Klenke, T. Eidam, S. Hädrich, J. Limpert, and A. Tünnermann, "Energy scaling of femtosecond amplifiers using actively controlled divided-pulse amplification.," Opt. Lett. 39, 1049–52 (2014).

Conclusion & Outlook



= Artificial Scaling of Pulse-Duration



Coherent Combination

Spatially and temporally seperated amplification

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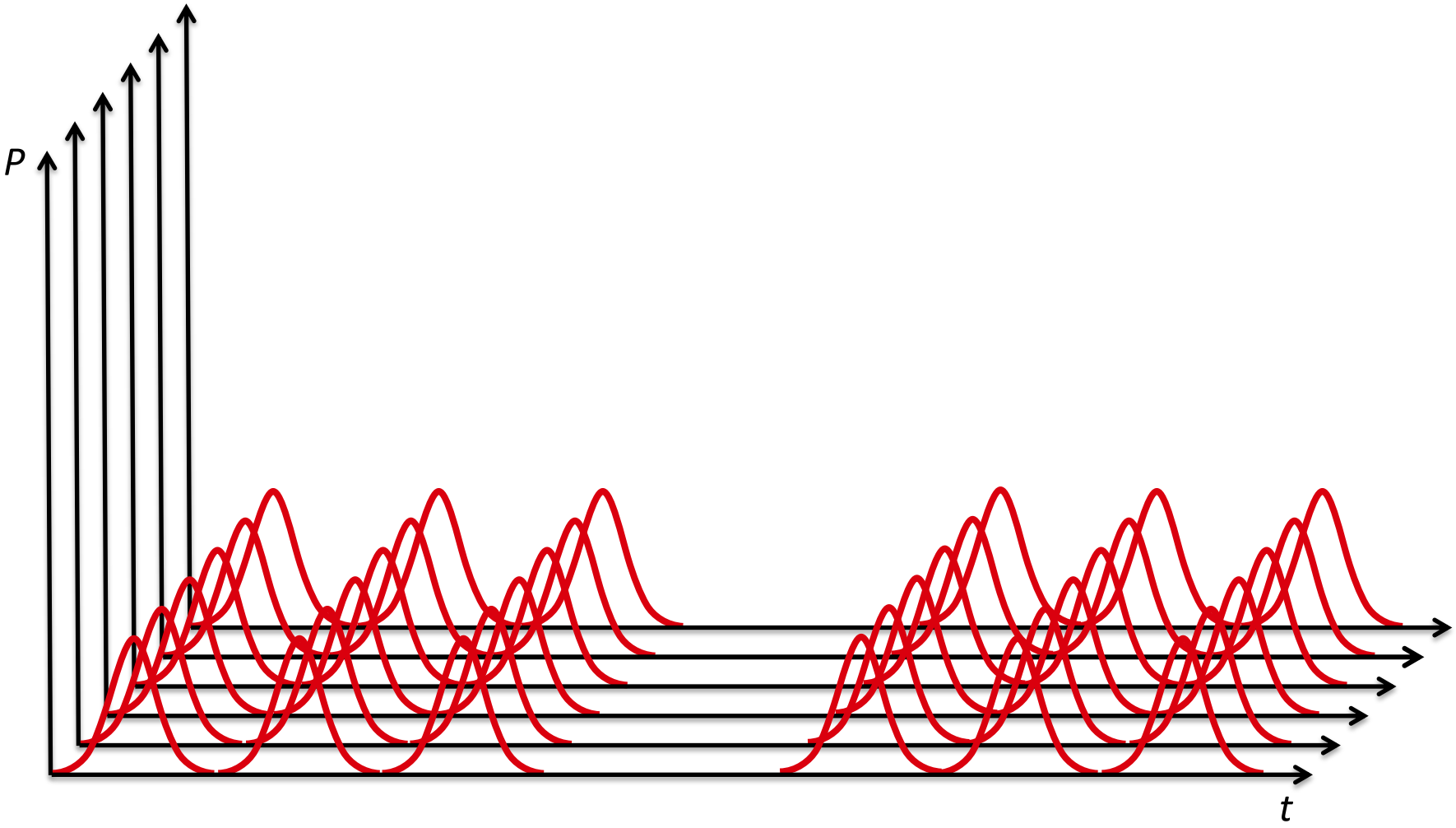

Coherent Combination

Multidimensional approach (Spatially separated and DPA)

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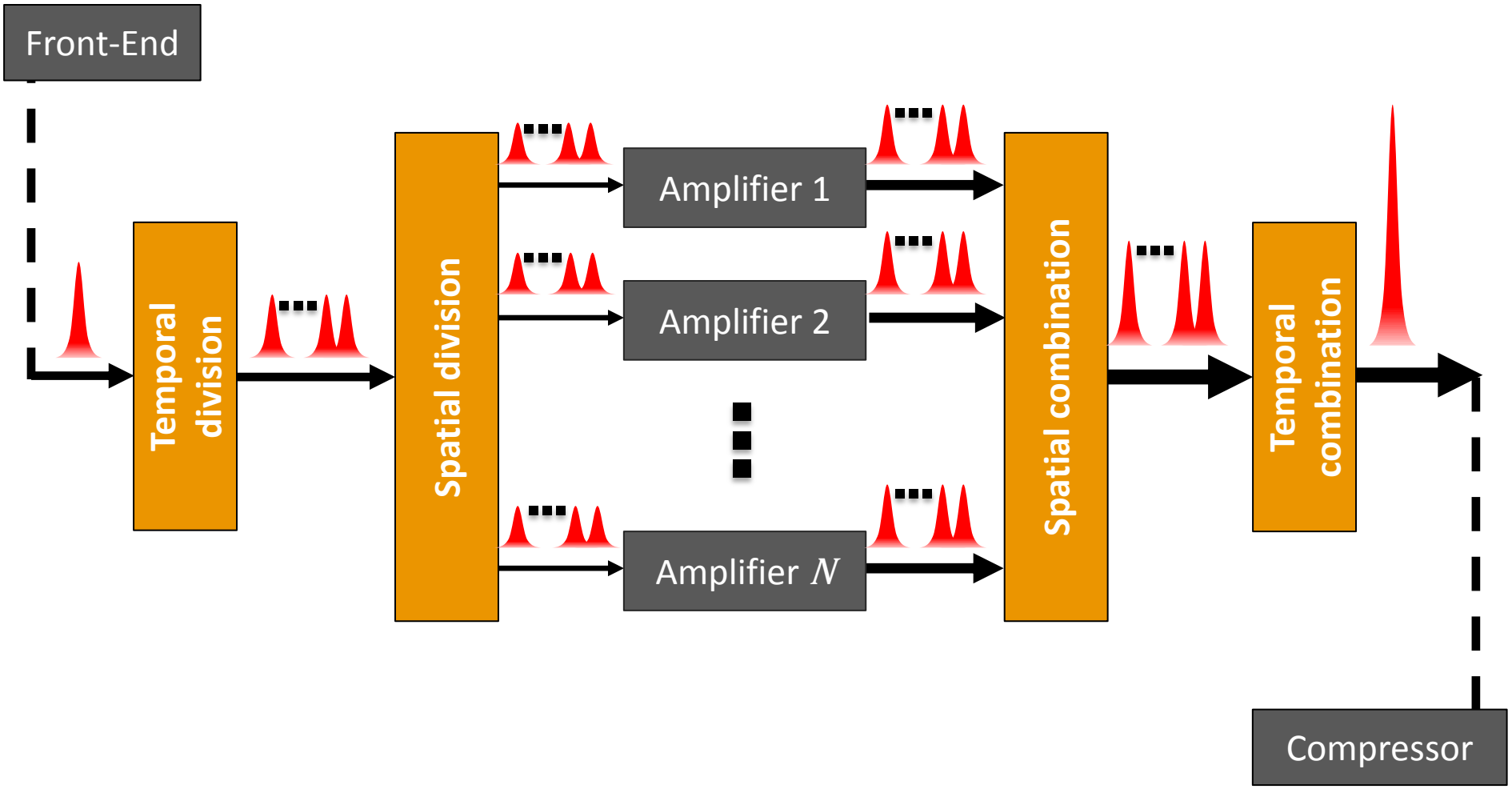

[1] M. Kienel et al., „Energy scaling of femtosecond amplifiers using actively controlled divided-pulse [...],” Opt. Lett. **39**, 1049–52 (2014).
[2] Y. Zaouter et al., „Femtosecond fiber chirped- and divided-pulse amplification system,” Opt. Lett. **38**, 106 (2013).

Coherent Combination

Multidimensional approach (Spatially separated and DPA)

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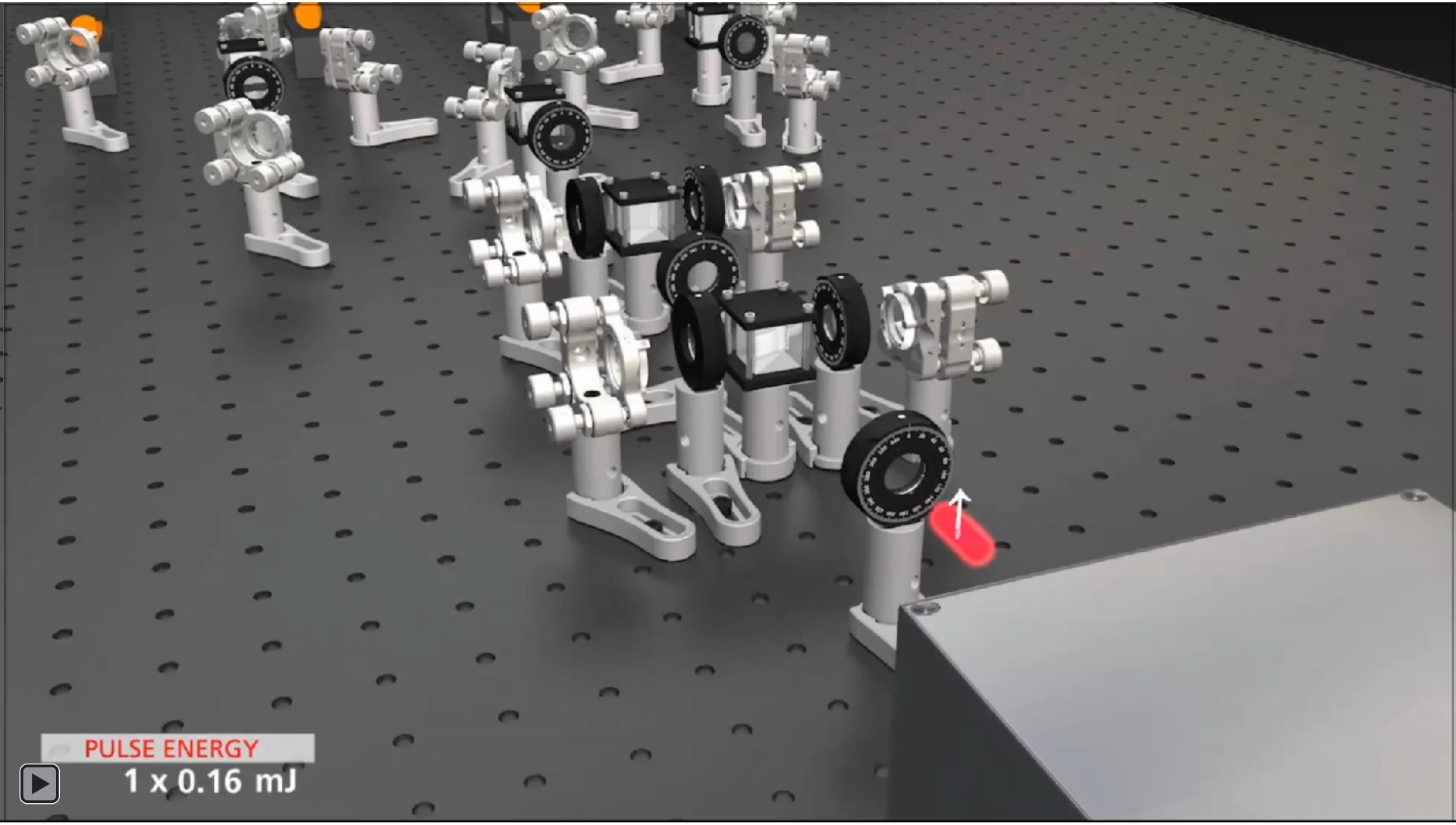

[1] M. Kienel, M. Müller, A. Klenke, T. Eidam, J. Limpert, and A. Tünnermann, "Multidimensional coherent pulse addition of ultrashort laser pulses.," Opt. Lett. 40, 522–5 (2015).

Coherent Combination

Overview of possible Methods

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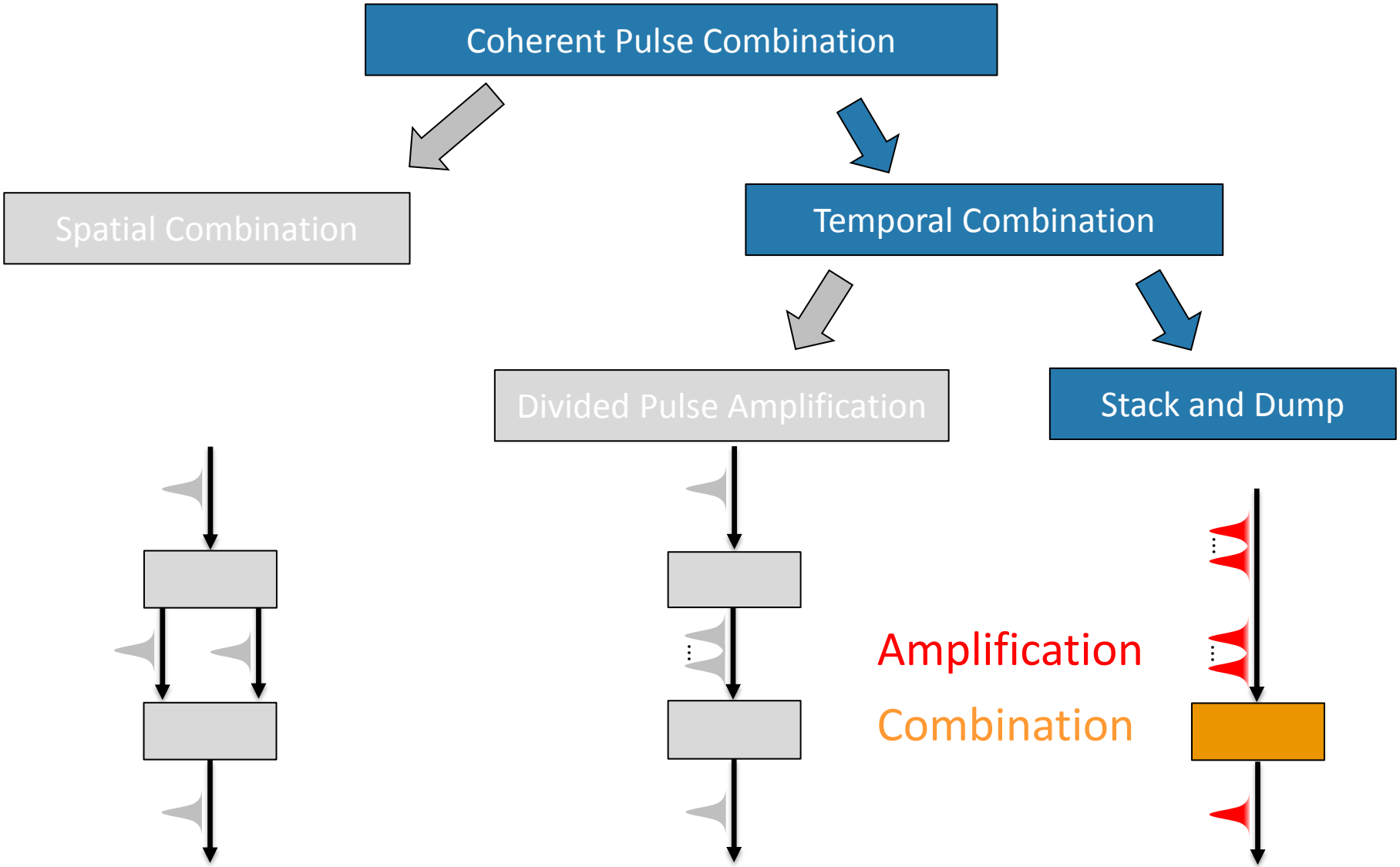

Stack and Dump

Enhancement Cavities for Pulse Stacking

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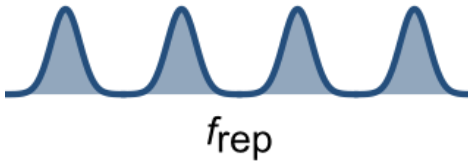
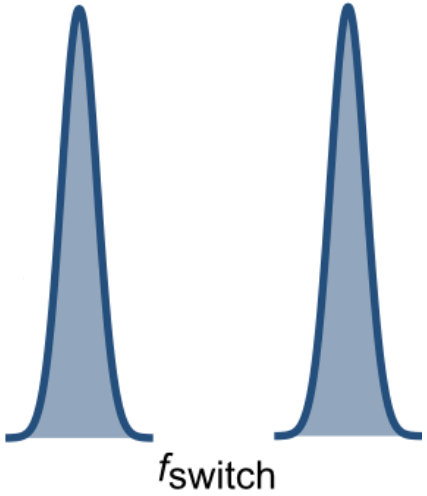
Input pulse train



Output pulse train



→ capable of 800kW average power[2]

[1] S. Breitkopf, T. Eidam, A. Klenke, L. von Grafenstein, H. Carstens, S. Holzberger, E. Fill, T. Schreiber, F. Krausz, A. Tünnermann, I. Pupeza, and J. Limpert, "A concept for multi-terawatt fibre lasers based on coherent pulse stacking in passive cavities," Light Sci. Appl. e211, doi:10.1038/lsa.2014.92 (2014).

[2] H. Carstens, N. Lilienfein, S. Holzberger, C. Jocher, T. Eidam, J. Limpert, a Tünnermann, J. Weitenberg, D. C. Yost, a Alghamdi, Z. Alahmed, a Azzeer, a Apolonski, E. Fill, F. Krausz, and I. Pupeza, "Megawatt-scale average-power ultrashort pulses in an enhancement cavity.," Opt. Lett. 39, 2595–8 (2014).

Stack and Dump

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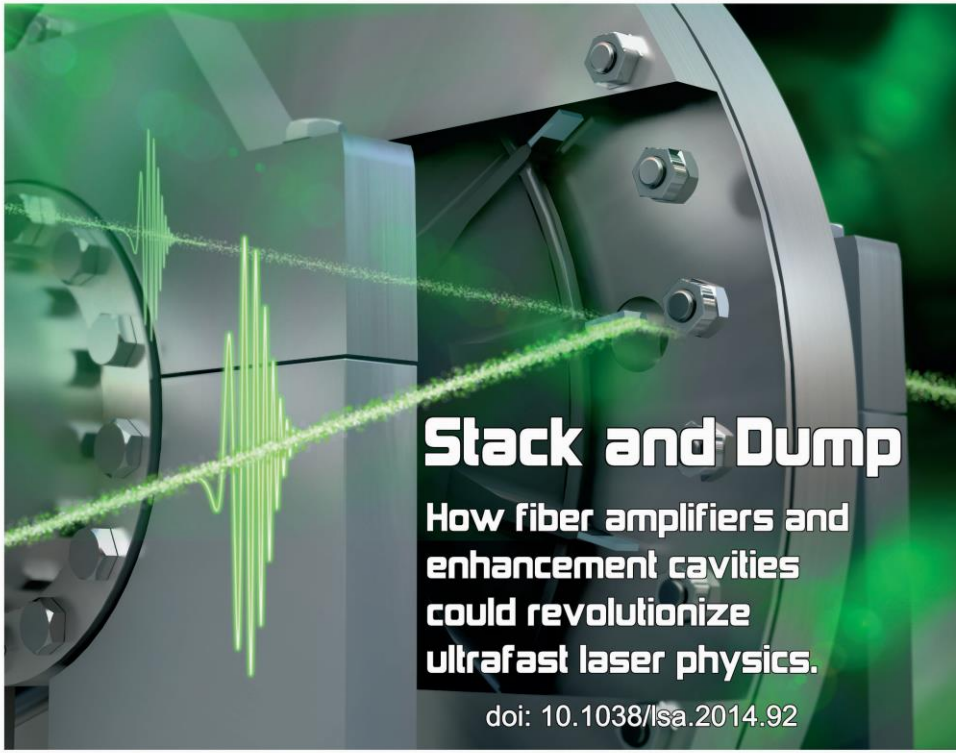

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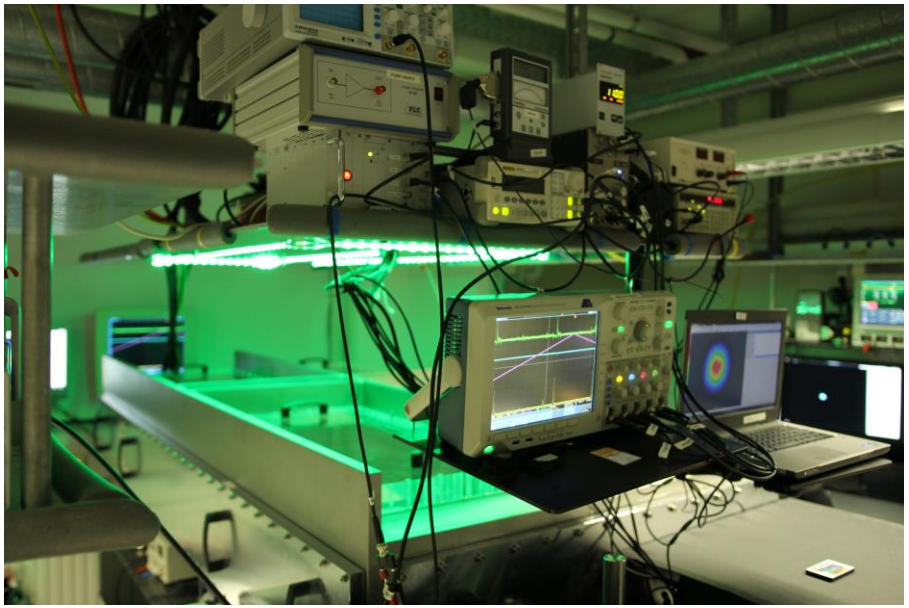
ORIGINAL ARTICLE

A concept for multiterawatt fibre lasers based on coherent pulse stacking in passive cavities

Sven Breitkopf[1], Tino Eidam[1,2], Arno Klenke[1,2], Lorenz von Grafenstein[1], Henning Carstens[3,4], Simon Holzberger[3,4], Ernst Fill[3,4], Thomas Schreiber[5], Ferenc Krausz[3,4], Andreas Tünnermann[1,2,5], Ioachim Pupeza[3,4] and Jens Limpert[1,2,5]

Since the advent of femtosecond lasers, performance improvements have constantly impacted on existing applications and enabled novel applications. However, one performance feature bearing the potential of a quantum leap for high-field applications is still not available: the simultaneous emission of extremely high peak and average powers. Emerging applications such as laser particle acceleration require exactly this performance regime and, therefore, challenge laser technology at large. On the one hand, canonical bulk systems can provide pulse peak powers in the multi-terawatt to petawatt range, while on the other hand, advanced solid-state-laser concepts such as the thin disk, slab or fibre are well known for their high efficiency and their ability to emit high average powers in the kilowatt range with excellent beam quality. In this contribution, a compact laser system capable of simultaneously providing high peak and average powers with high wall-plug efficiency is proposed and analysed. The concept is based on the temporal



Conclusion & Outlook

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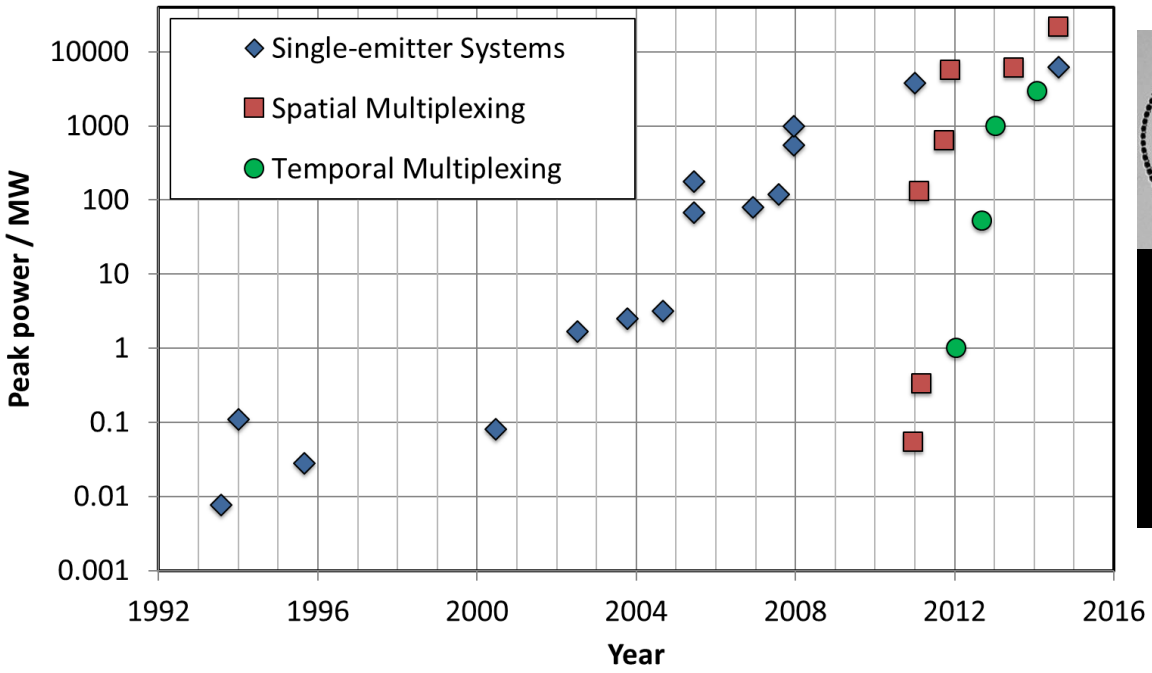
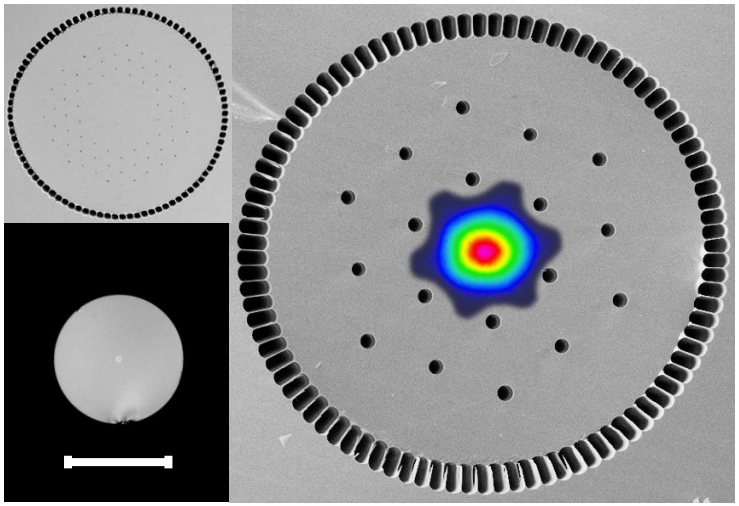
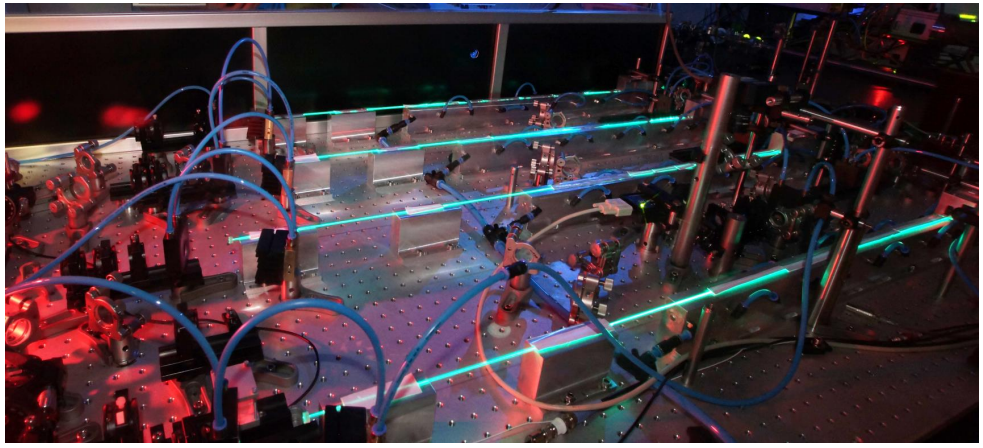




- 3 orders of magnitude peak power increase within the last 10 years
- Coherent Combination schemes have the potential to accelerate this progress



Conclusion & Outlook

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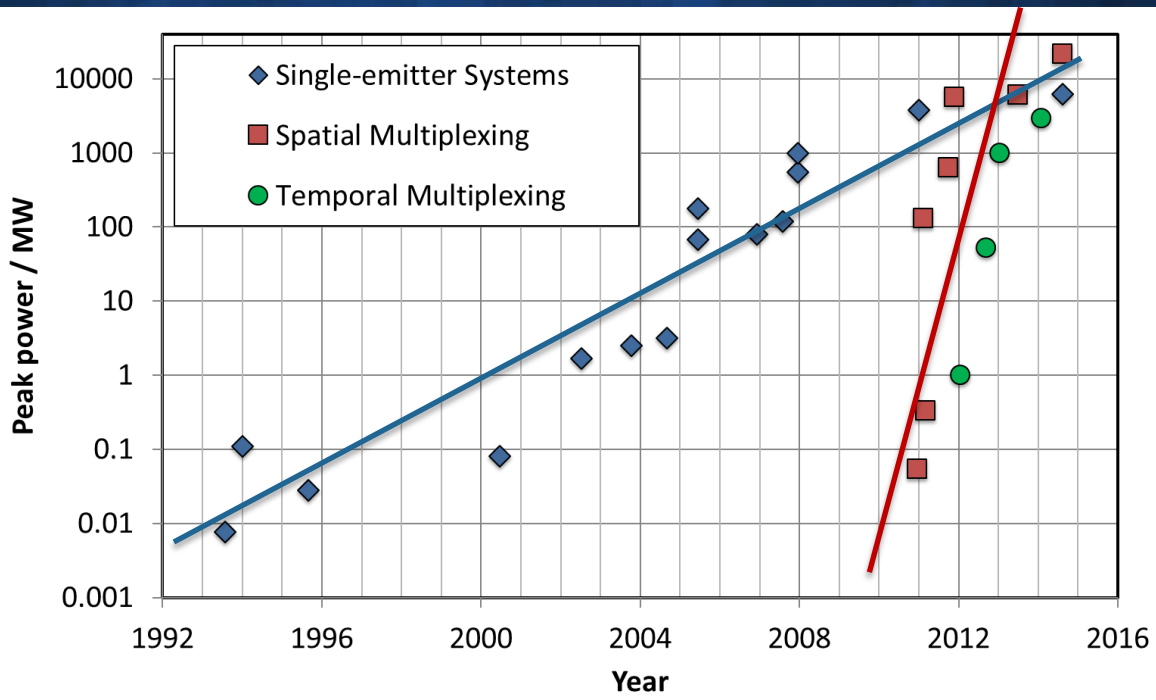
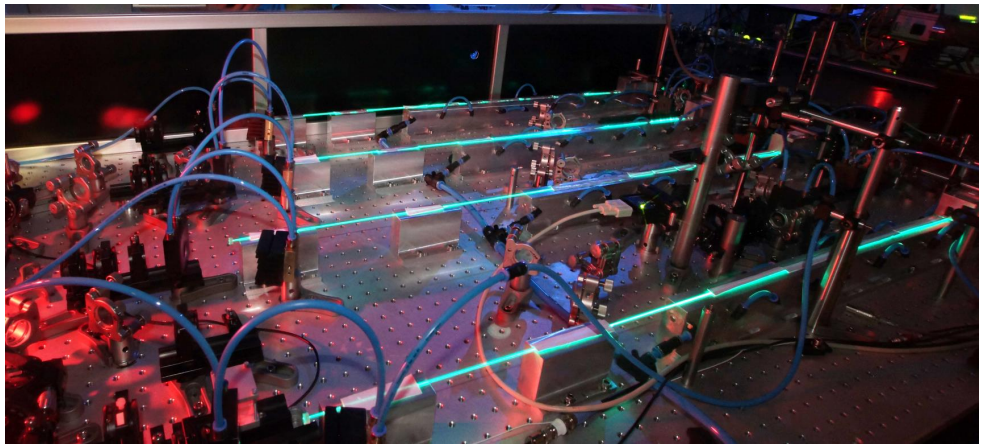


Limited by phycics

Limited by size and money

- 3 orders of magnitude peak power increase within the last 10 years
- Coherent Combination schemes have the potential to accelerate this progress
- **New field of applications for fiber lasers**



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