Advanced solid state lasers are merging with accelerators

IPAC 2012, New Orleans Louisiana

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Institute Jena

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seit 1558

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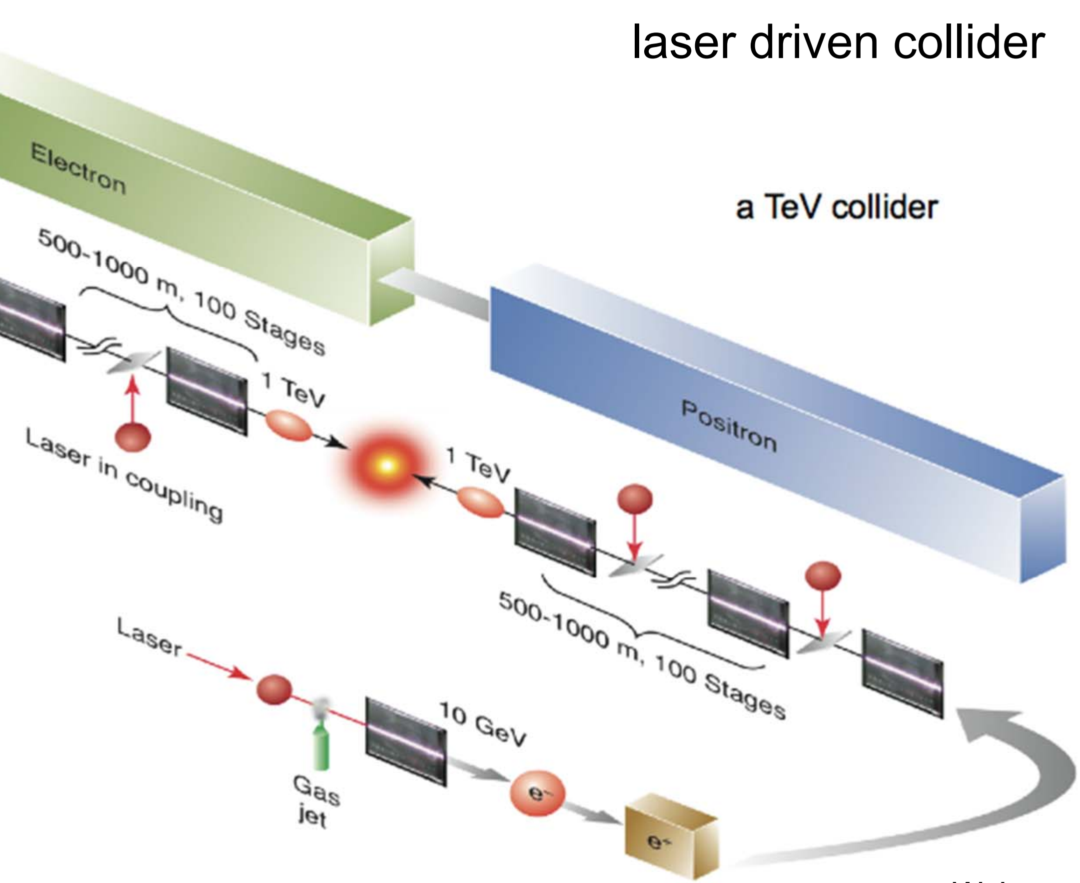
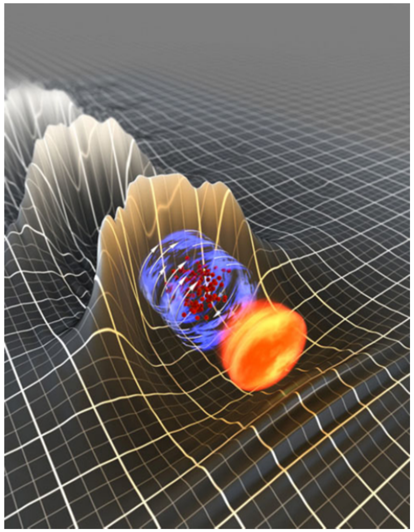
Laser particle acceleration

laser driven collider



W. Leemans et al.



M. Kaluza et al.

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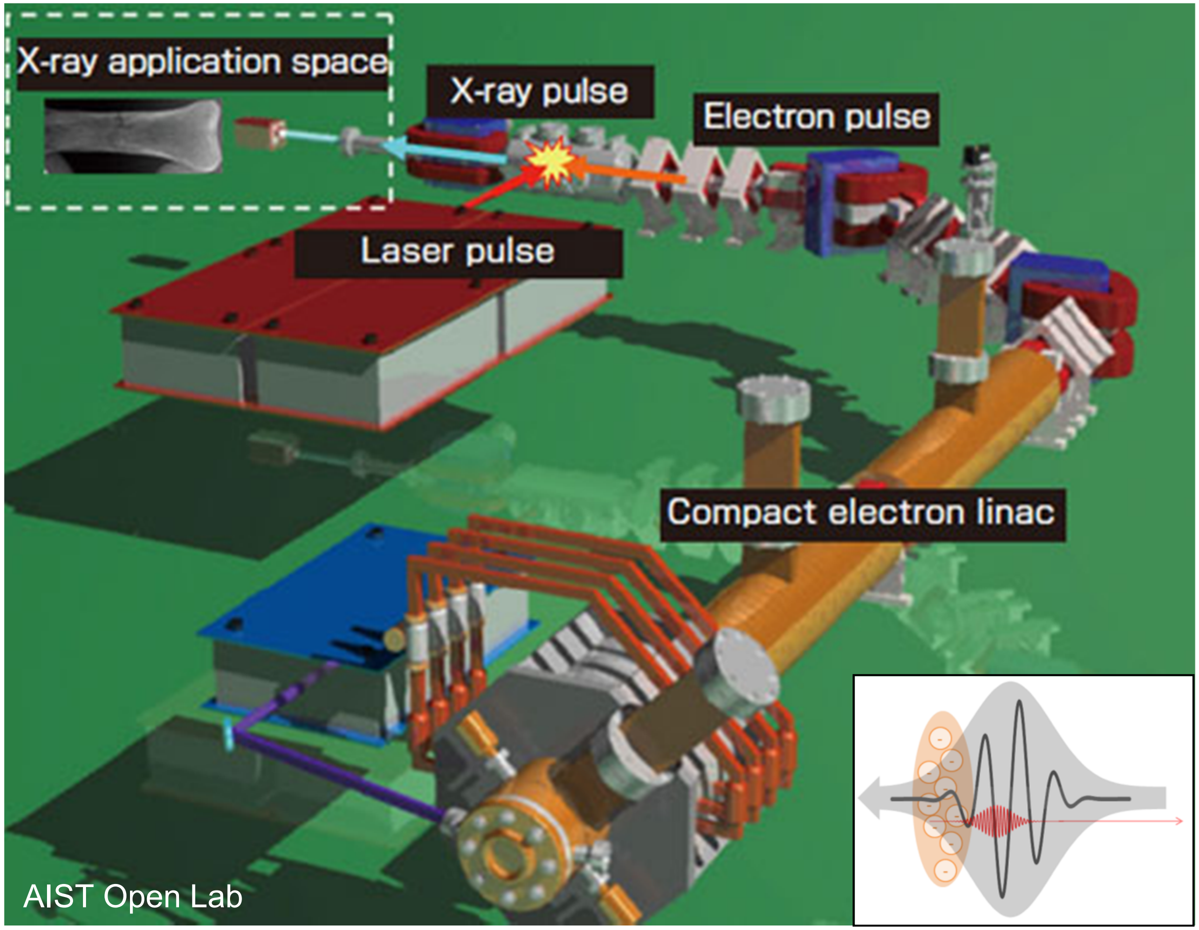
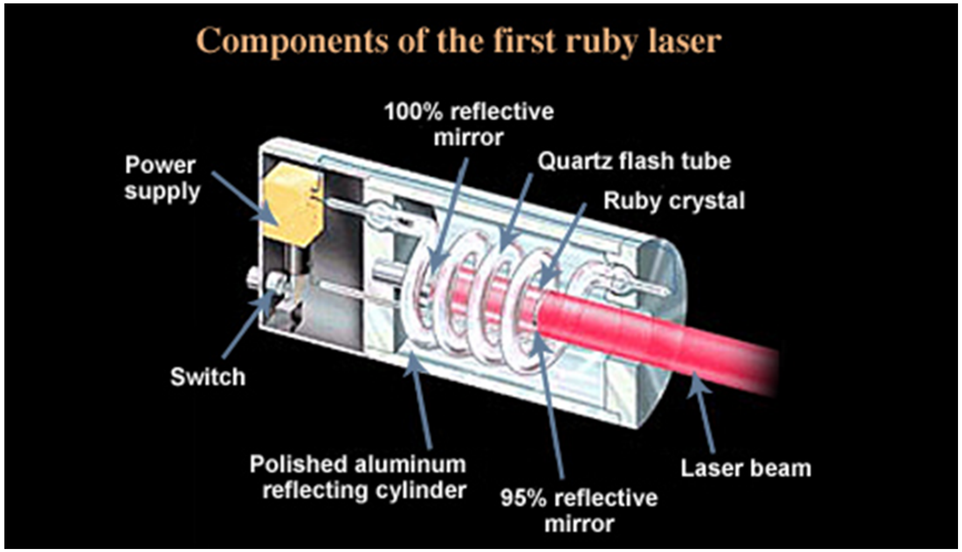
Laser Compton scattering



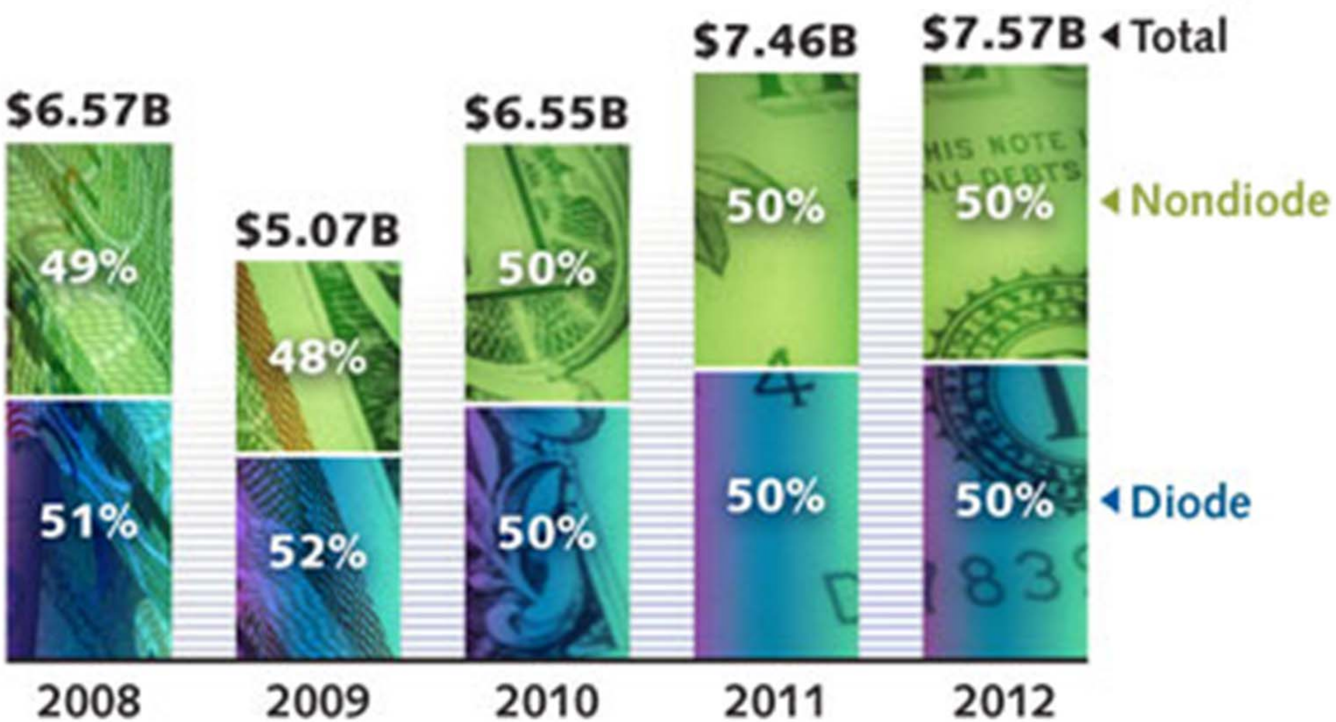
Compton x-ray source

Laser technology – more than 50 years of innovations

Theodore Maiman

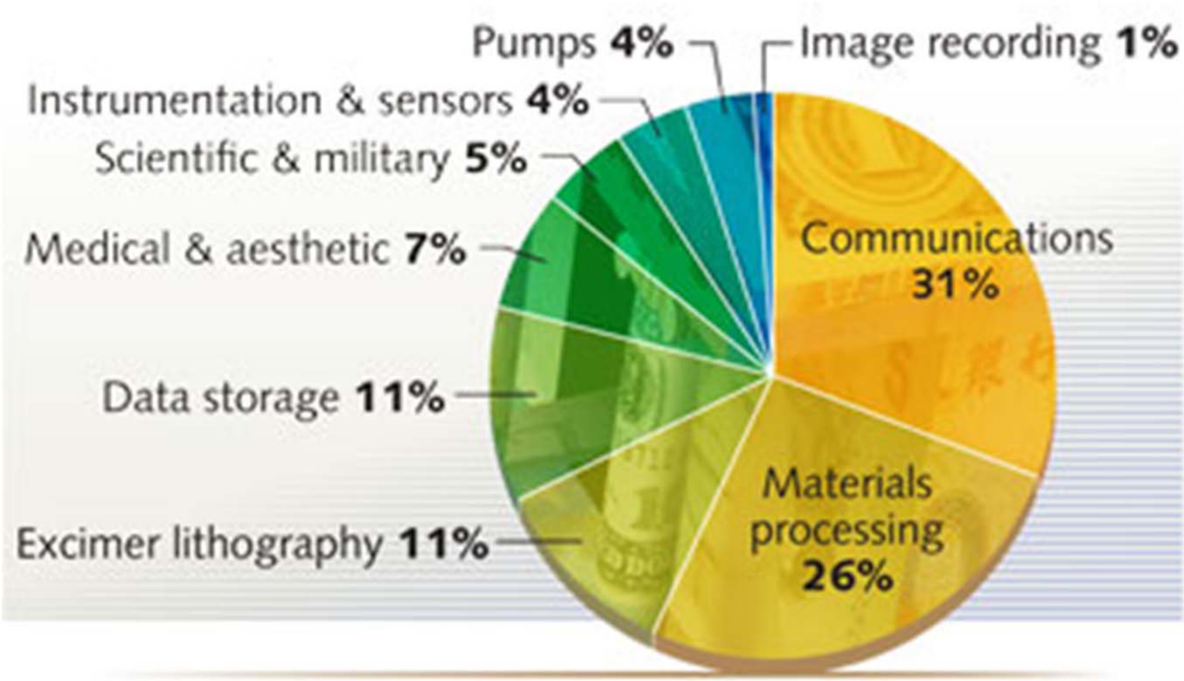


Worldwide commercial laser revenues 2011



Laser Focus World

Laser revenues by application 2011



Laser Focus World

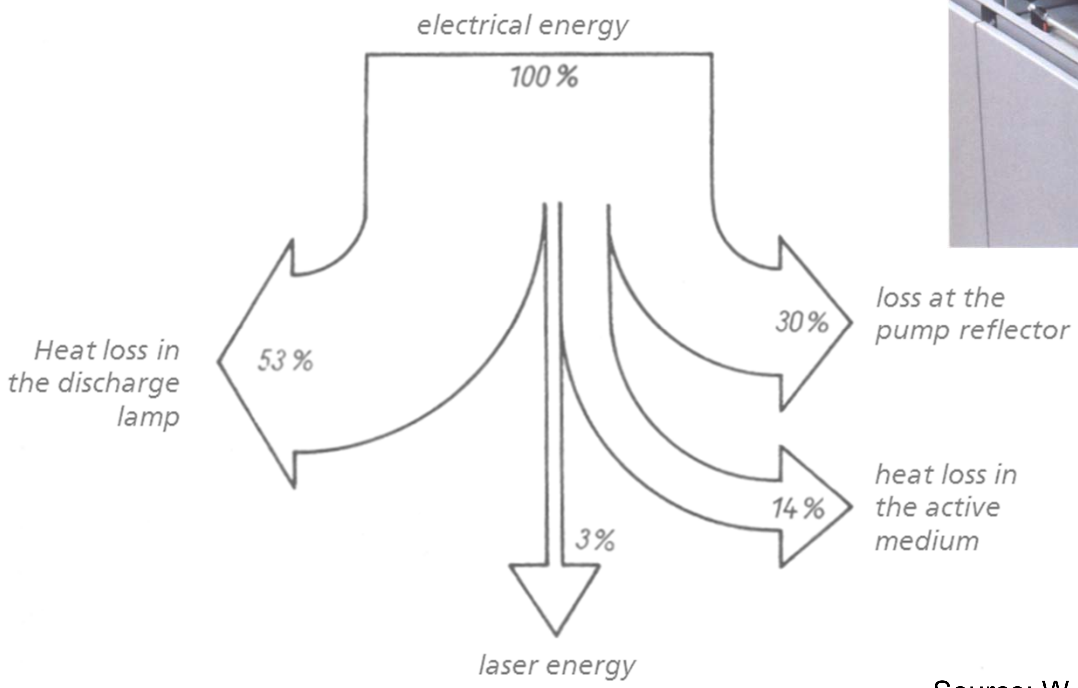
High power solid state lasers in materials processing

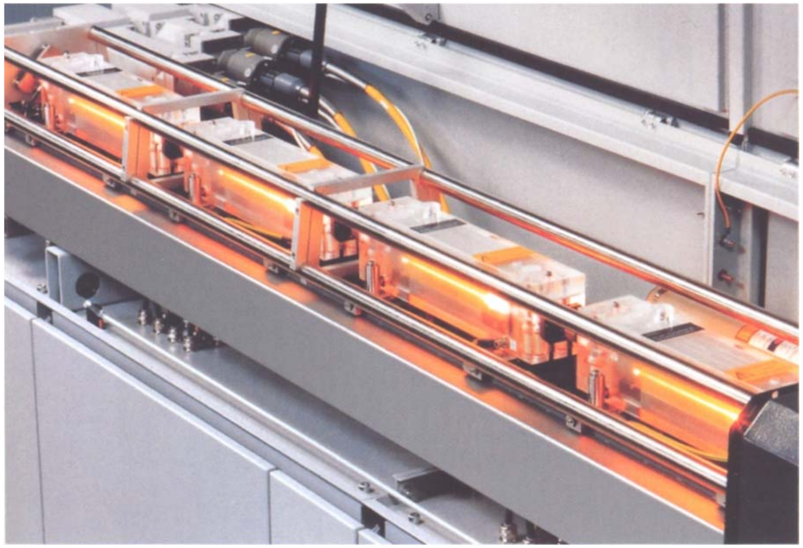
joining

removal cutting

The laser markets survived »the big one« — the global economic recession of 2008/2009 — and recovered nearly all their losses by the close of 2010. By all measures, 2010 and early 2011 were more favorable for laser manufacturers than anyone could have predicted… *Laser Focus World*

Energy balance of high-power solid state laser (year 2000)





Source: W. Brunner, K. Junge: Lasertechnik - Eine Einführung

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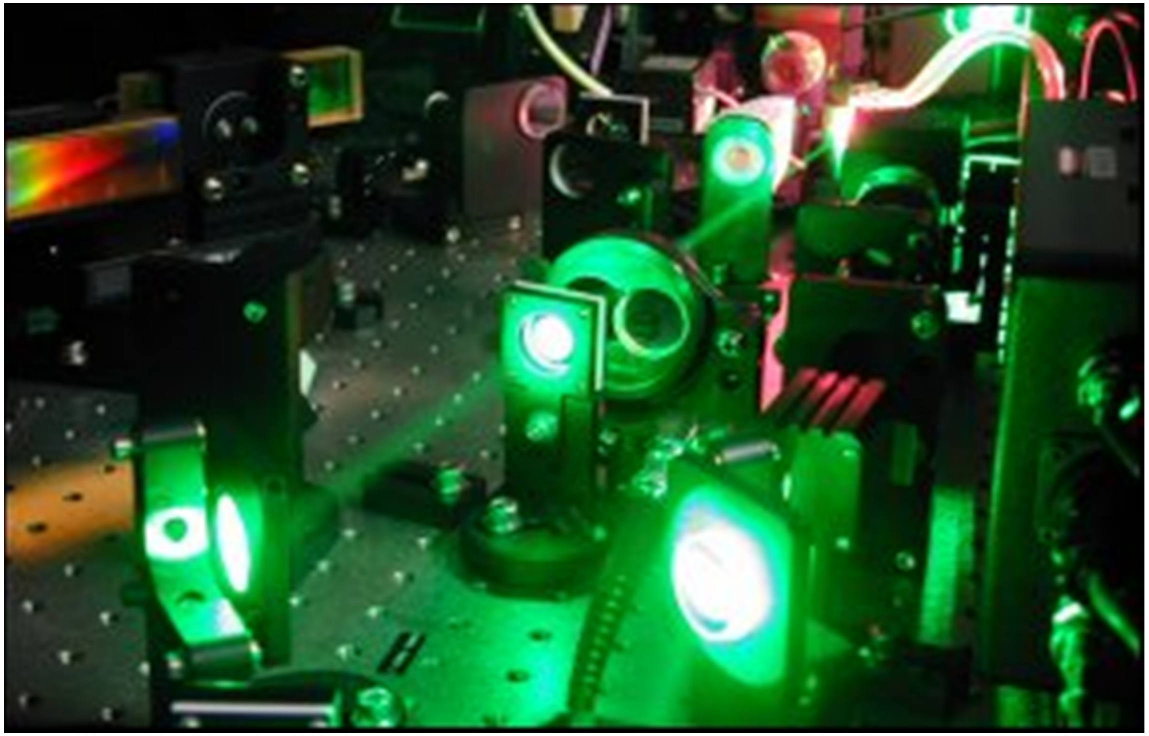
Ultrafast Ti:sapphire laser systems



PW-Laser

E_{pulse}= 30 J @ τ_{pulse}= 30 fs

1 kHz repetition rate

→ P_{av}= 30 kW (optical)

→ P_{av}>> 1 MW (electrical)

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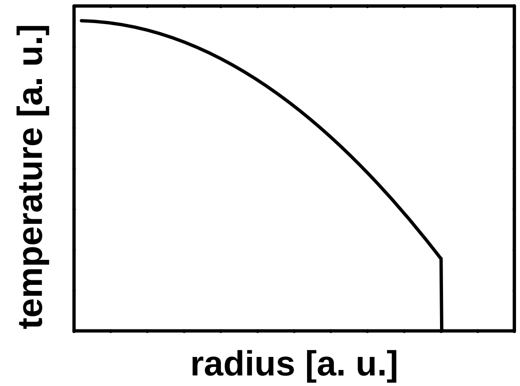
Thermal effects in rod lasers

heating of the rod
heat dissipation via the surface



- ➔ **parabolic temperature profile**
- ➔ **thermo-optical effects**

$$f = \frac{KA}{P_a}\left(\frac{1}{2}\frac{dn}{dT} + \alpha C_{r,\phi} n_0^3 + \frac{\alpha r_0 (n_0 - 1)}{L}\right)^{-1}$$

temperature depending refractive index changing

stress induced refractive index changing

temperature depending surface effects

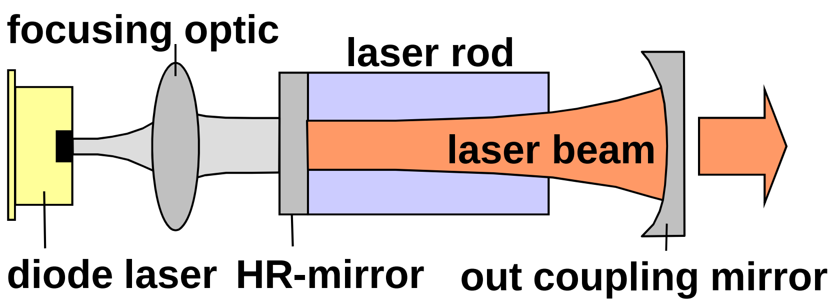
➔ **poor beam quality at high output powers**

W. Koechner „Solid-State Laser Engineering“, Springer, 1999

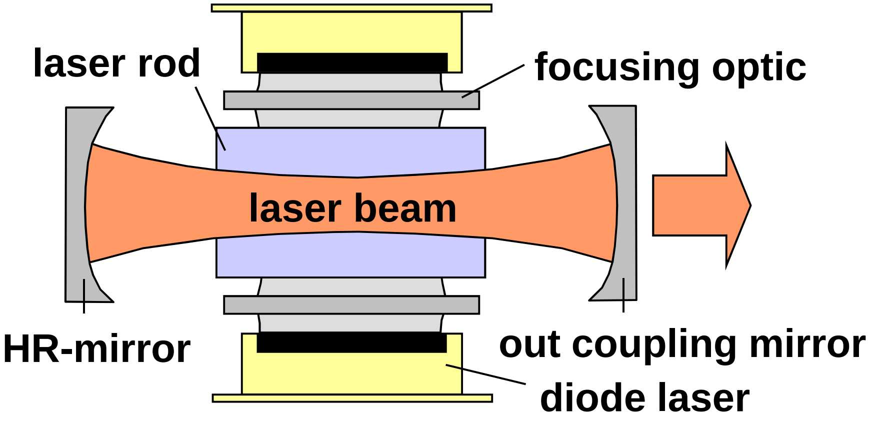
All-solid state lasers

the canonical approaches

end pumped laser rod

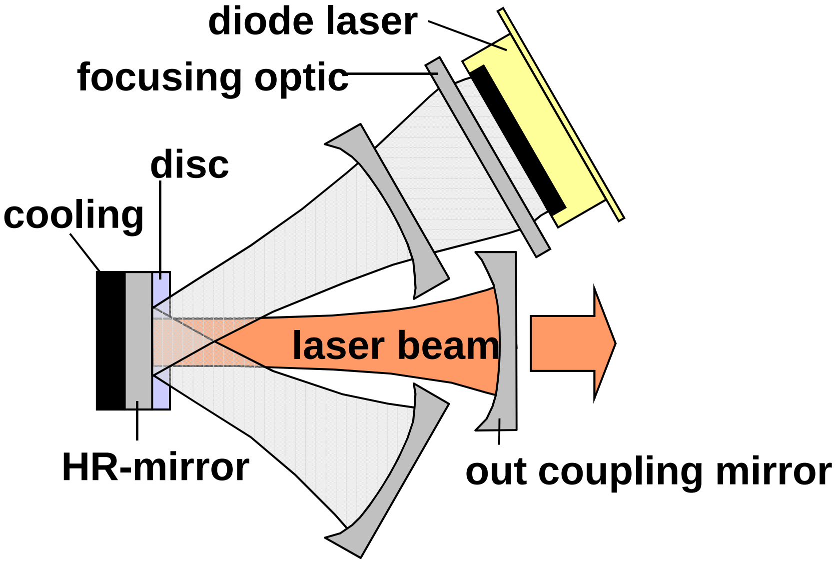


side pumped laser rod

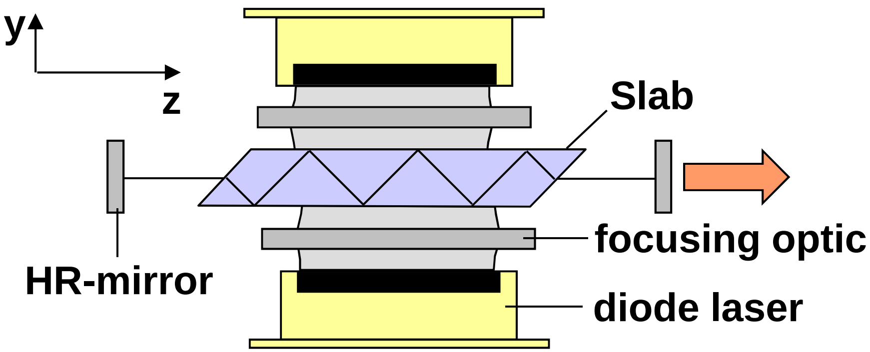


Advanced all-solid state laser concepts

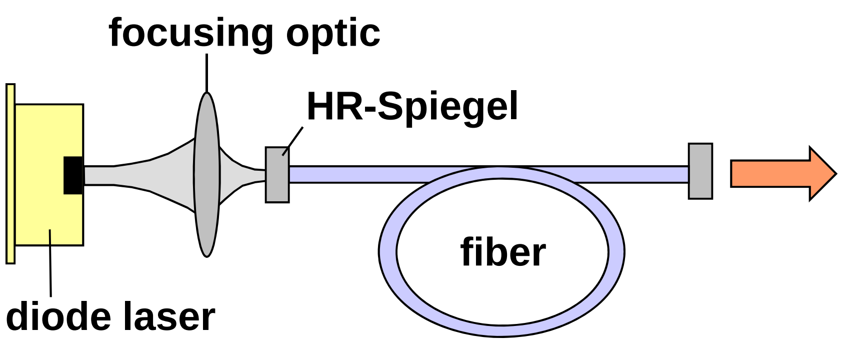
disc laser



slab laser



fiber laser



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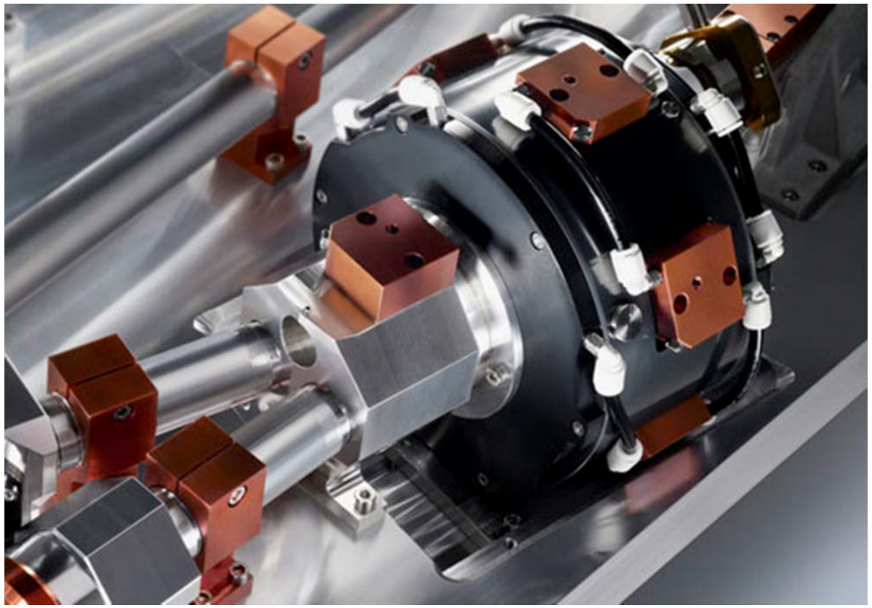
Thin disc laser



TruDisk 5302 Trumpf

kW Ytterbium Thin Disc Laser System

output power 4000 W

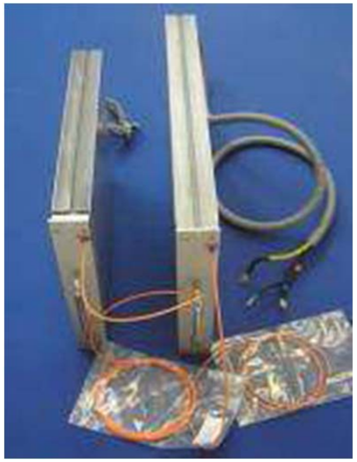
emission wavelength 1030 nm

beam quality 8 mm*mrad

wall-plug efficiency ≈ 30%

TRUMPF

Fiber laser



YLS-XXXX IPG

kW Ytterbium Fiber Laser System

output power 500 W - 4 kW

emission wavelength 1070 - 1080 nm

beam quality: 0.36 mm x mrad (single mode)

wall-plug efficiency > 30%

IPG PHOTONICS

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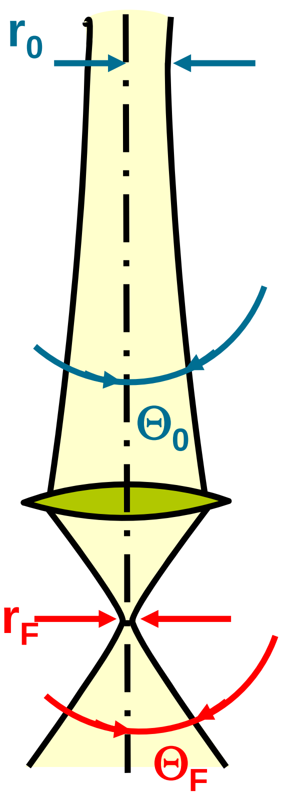
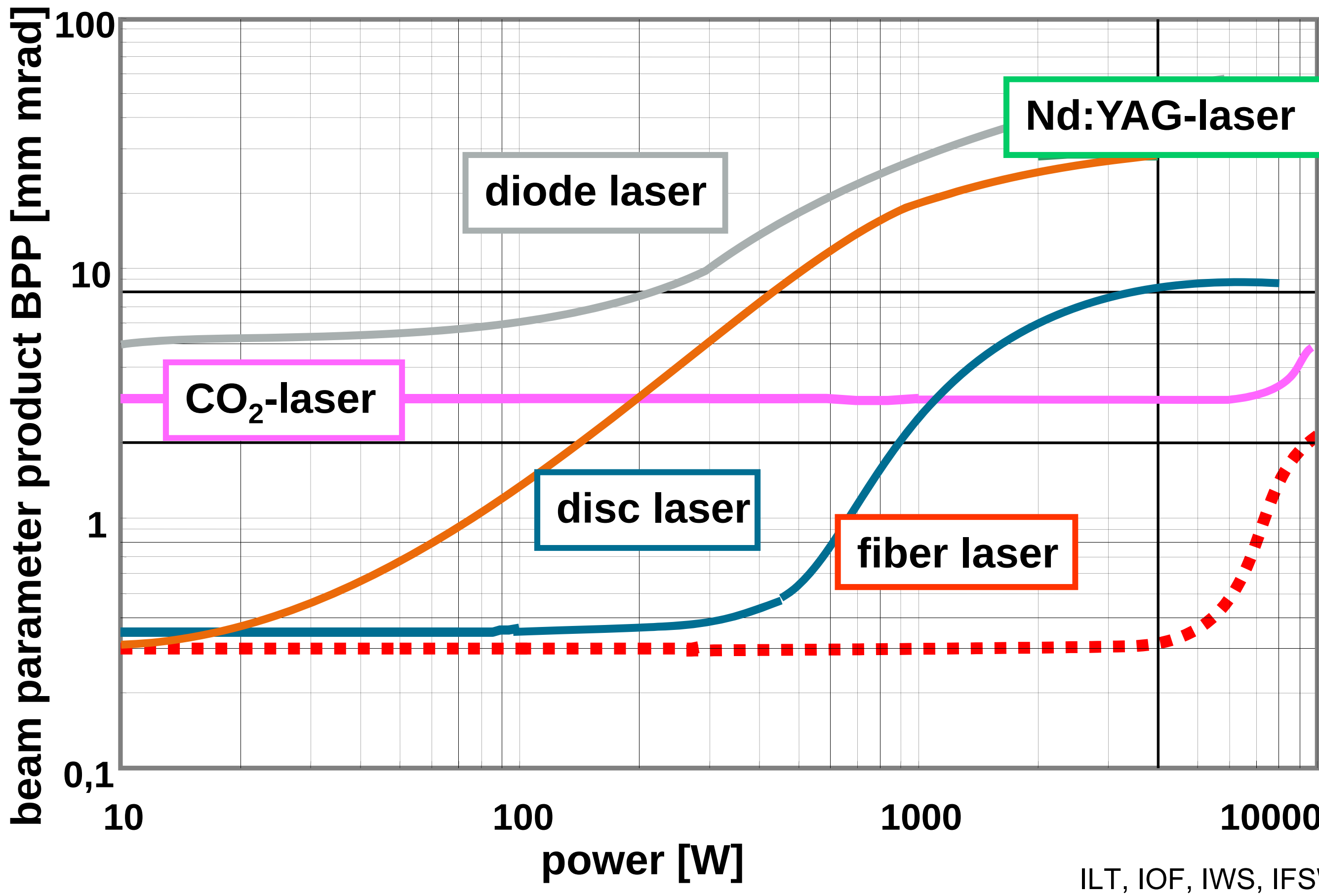
High power lasers: beam quality and output power

BPP = **r Θ**

$r_0 \Theta_0 = r_F \Theta_F$





ILT, IOF, IWS, IFSW

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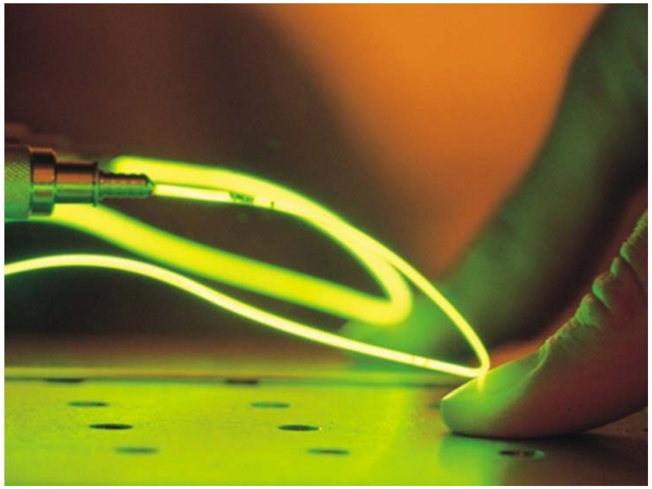
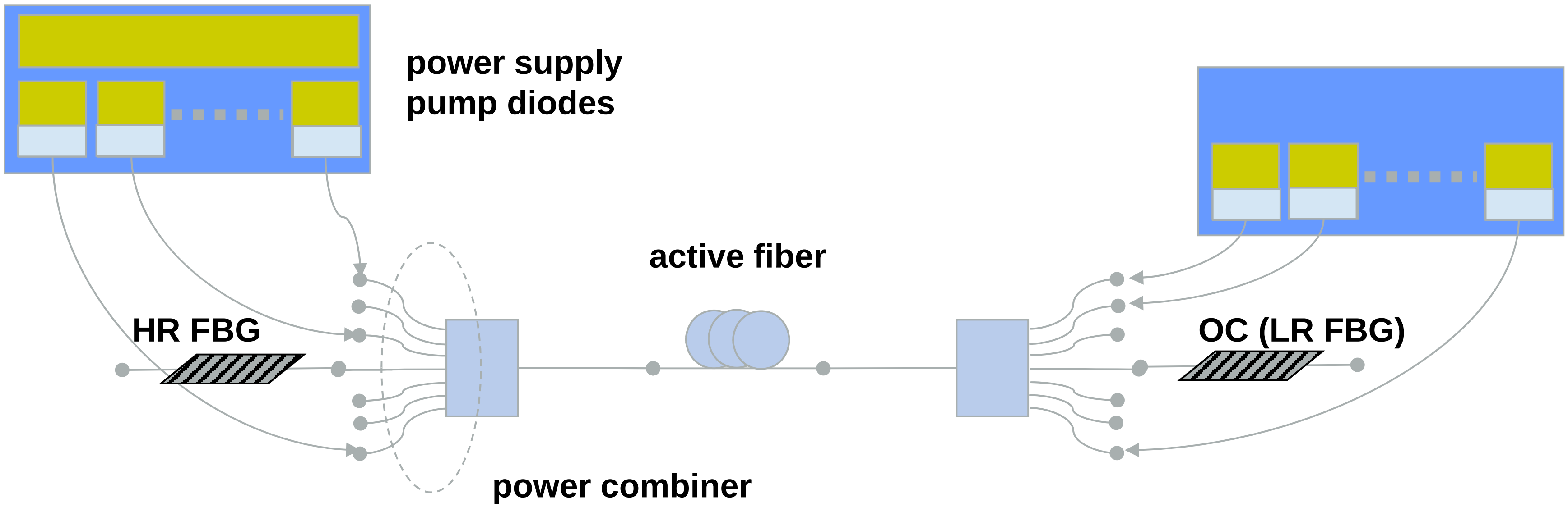
Outline

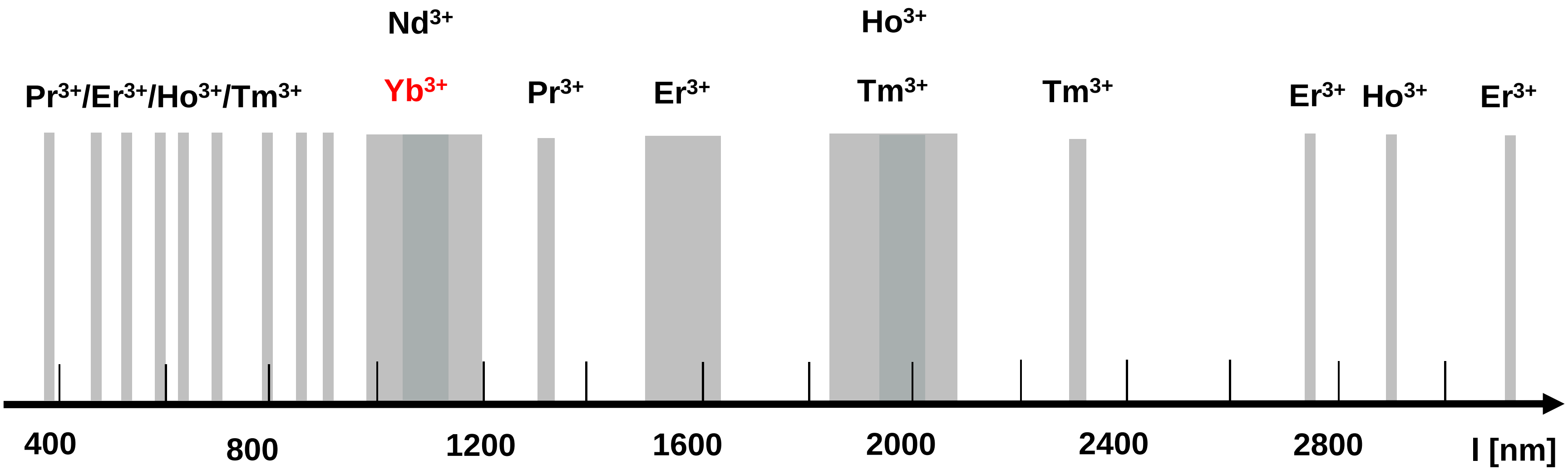
- fiber lasers – basic principles
- advanced fiber designs
- high power ultrafast fiber laser
- conclusion



Fiber laser: basic principle



Fiber laser: emission wavelength

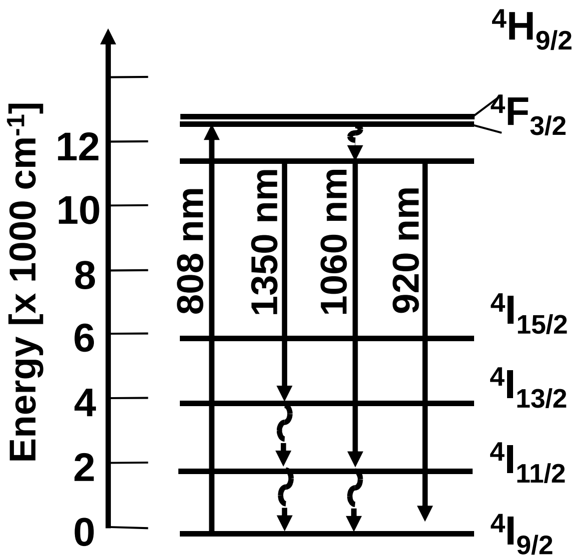


first demonstration of a fiber laser: in the early sixties !

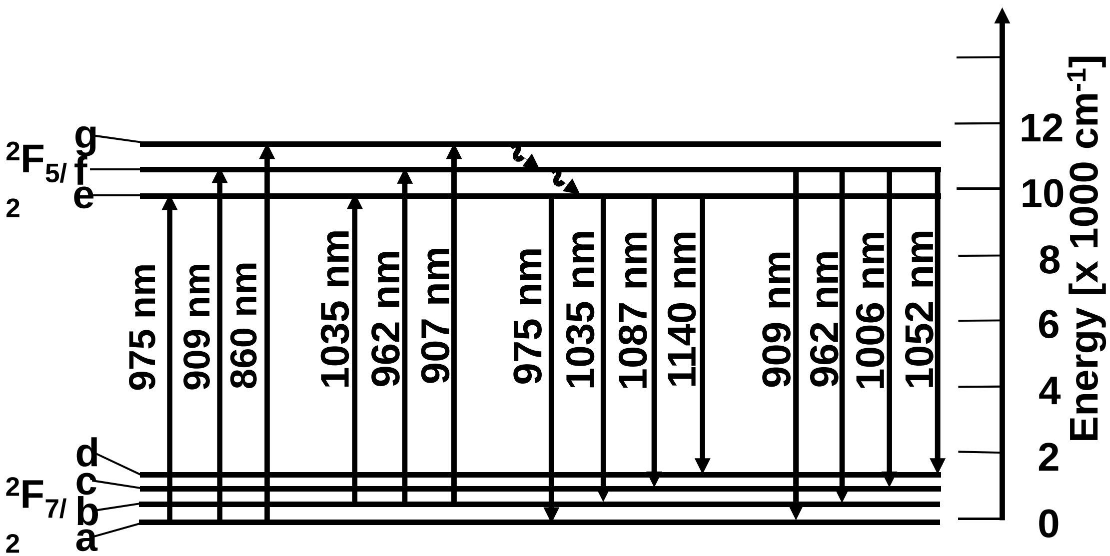
E. Snitzer, “Neodymium glass laser,” Proc. of the Third International conference on Solid Lasers, Paris, page 999 (1963)
C.J. Koester and E.Snitzer, “Amplification in a fiber laser,” Appl. Opt. 3, 10, 1182 (1964)

Solid state laser materials

Nd



Yb



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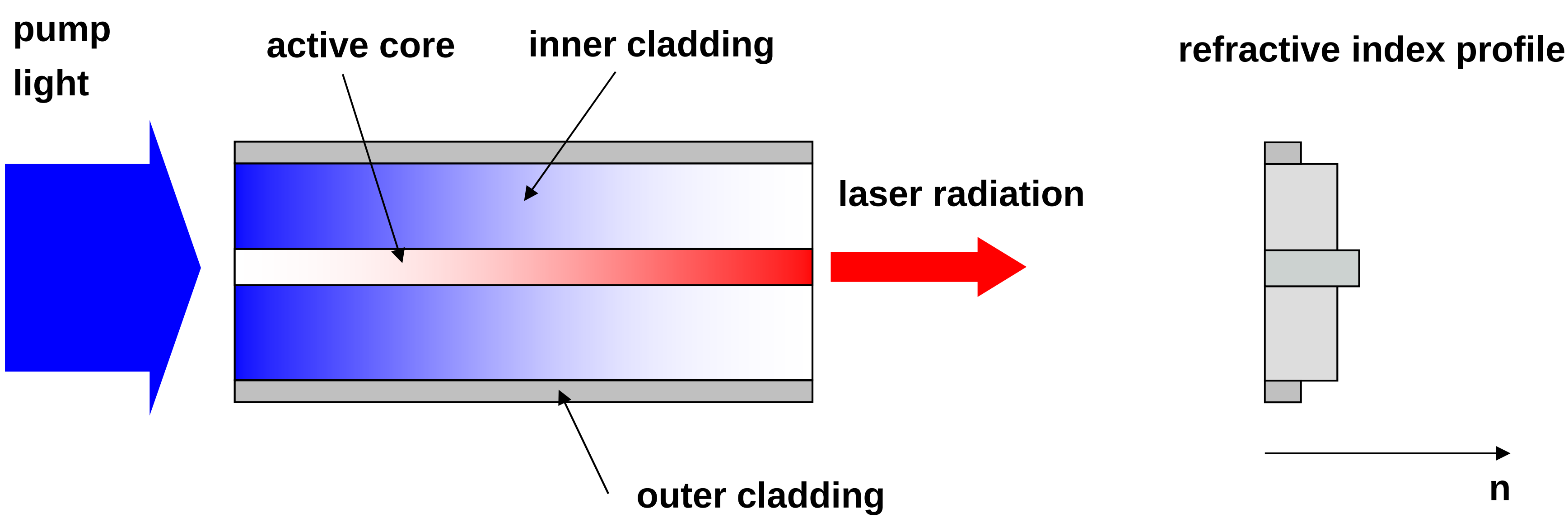
Double-clad fiber laser



highly efficient brightness conversion using the laser process

$$Brightness = \frac{P}{M_x^2 \cdot M_y^2 \cdot \lambda^2}$$

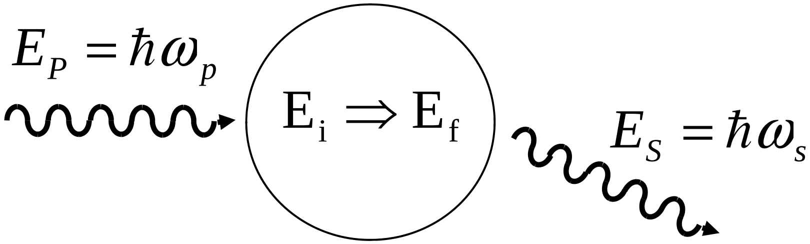
example: IC 400 µm/NA = 0.4 (M^2 ~ 260)

brightness improvement by factor ~70000

E. Snitzer, H. Po, F. Hakimi, R. Tumminelli, and B.C. McCollum, “Double-clad, offset core Nd fiber laser,” in Optical Fiber Sensors, Vol.2 of 1988 OSA Technical Digest Series (1988), postdeadline paper PD5

Power scaling limitation – nonlinearity (SRS)

inelastic scattering process of photons on optical phonons



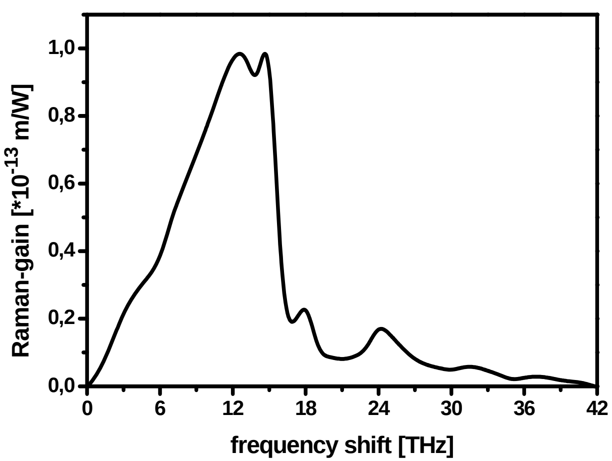
$$P_{SRS} \approx 16 \cdot \frac{A_{eff}}{L_{eff}\, g_R}$$

g_R = Raman-gain coefficient,
A_{eff} = eff. area
L_{eff} = effective interaction length

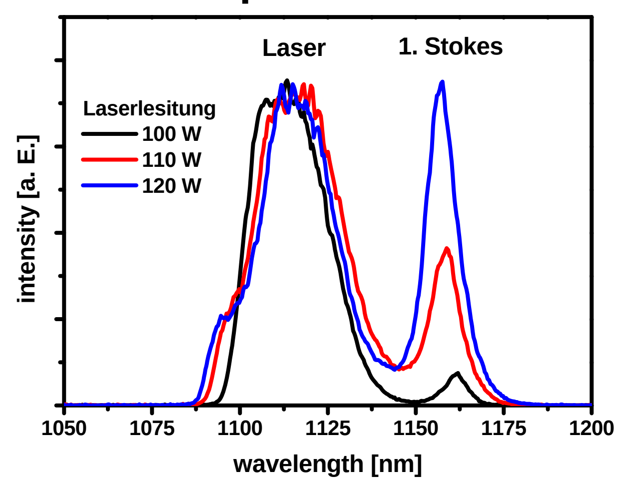
$$\omega_S \approx \omega_p - 13\,THz$$ **in silica**

G.P. Agrawal „Nonlinear fiber optics“, Academic Press, 1995

Raman-gain coefficient



Raman-spectrum



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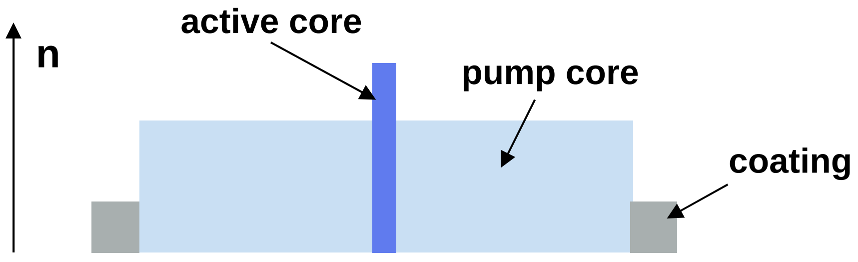
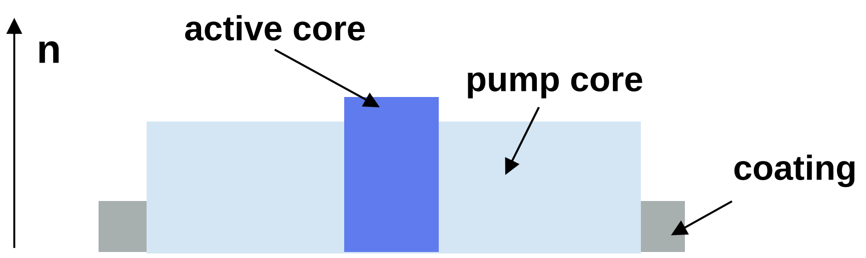
Low-NA large-mode-area fiber design

double-clad single-mode fiber



core ∅ <10 µm
core NA = 0.1 – 0.2
absorption length > 20 m

double-clad large-mode-area fiber



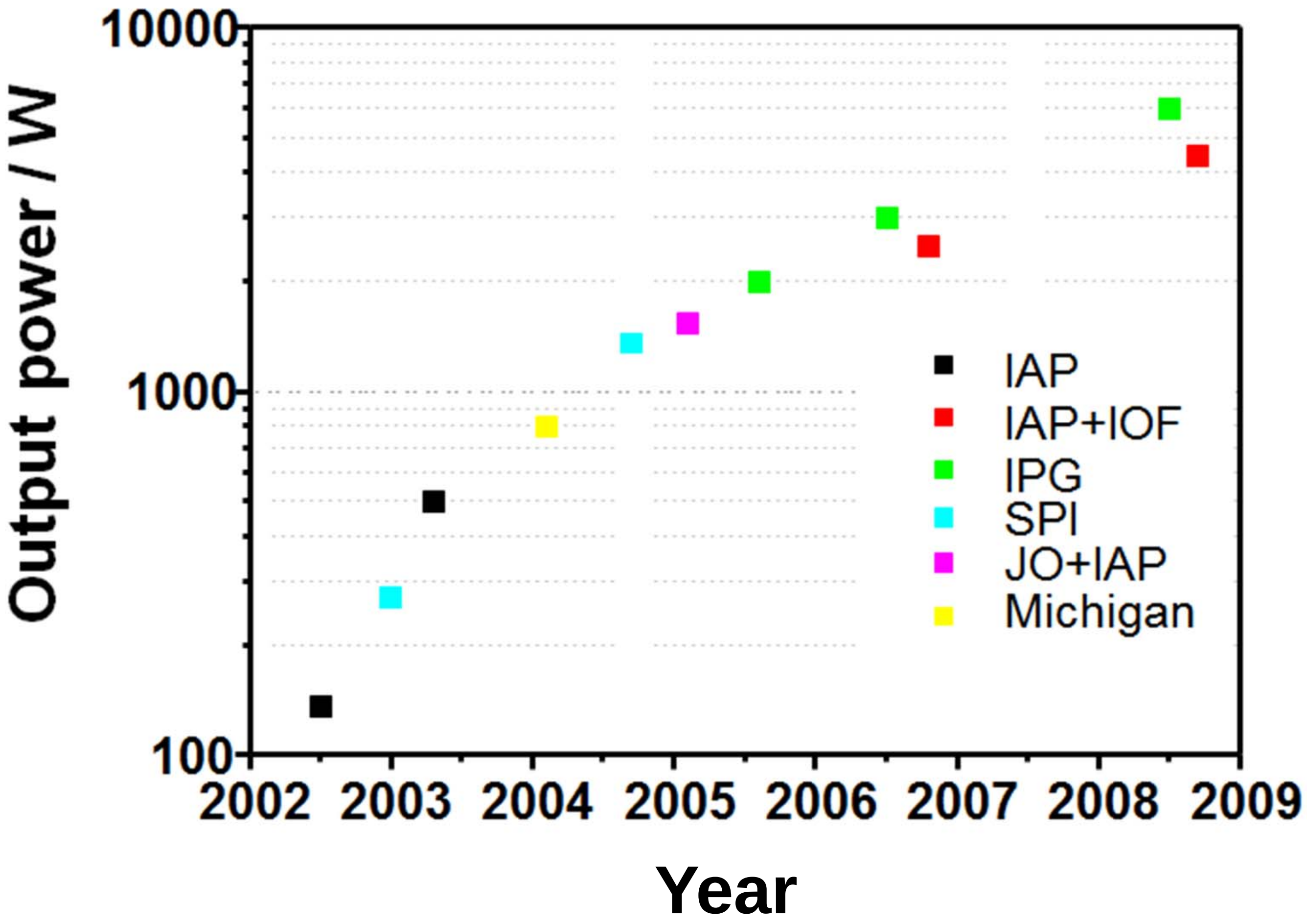
core ∅ = 30 .. 40 µm
core NA = 0.06 .. 0.08
absorption length < 10 m

increased mode-field diameter
reduced fiber length
➡
reduced nonlinearity

D. Taverner, D.J. Richardson, L. Dong, J.E. Caplen, K. Williams, and R.V. Penty, "158-µJ pulses from a single-transverse-mode, large-mode-area erbium-doped fiber amplifier," Opt. Lett. 22, 378 (1997)

Diode-pumped double clad fiber laser (cw output)

evolution of fibers laser operating close to diffraction limited output



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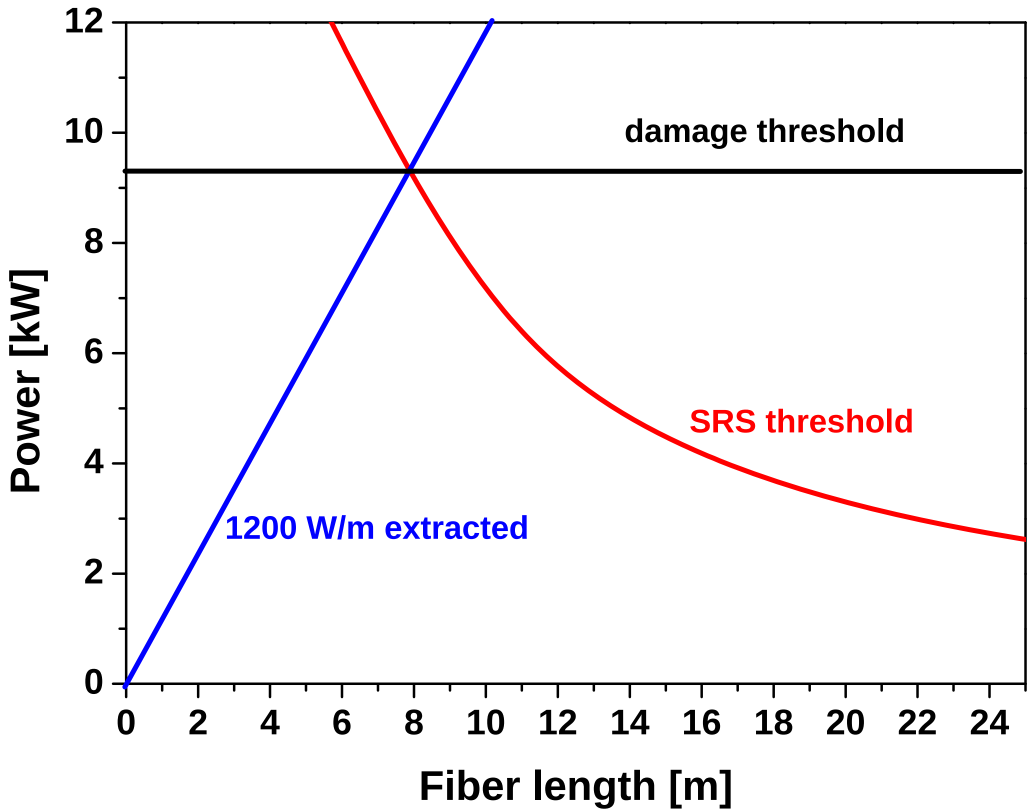
Power scaling limitations of diode-pumped fiber lasers

@ 40 µm core diameter



→ **cw 10 kW-class single-mode fiber laser**

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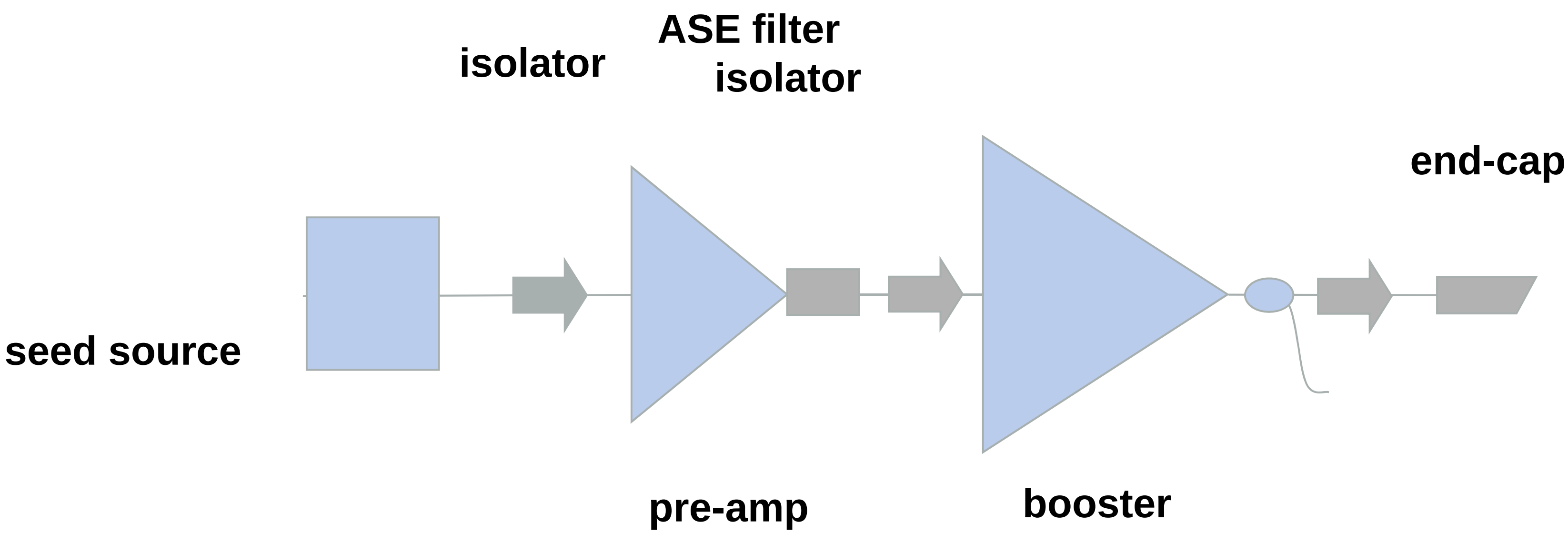
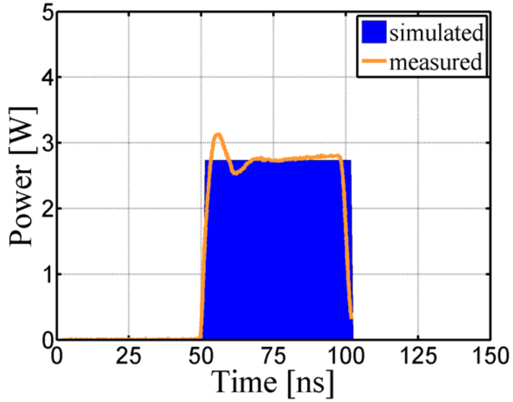
Pulsed fiber laser MOPA



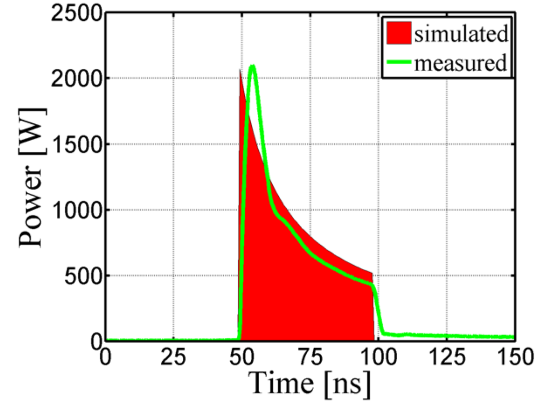
$$\phi_{s,0}(t) = \frac{\phi_{s,z}(t)}{1 - [1 - G_0(z)]\exp\left(-\sigma c \int_0^t dt' \phi_{s,z}(t')\right)}$$

Pulsed fiber laser MOPA

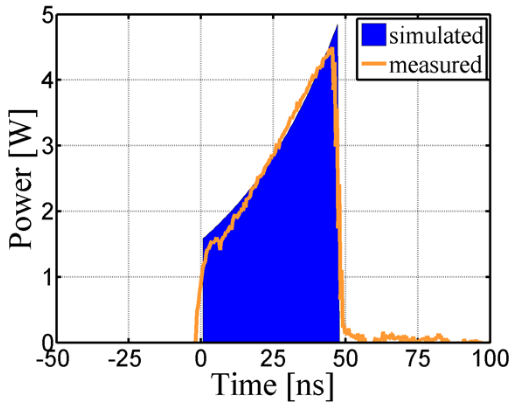
input



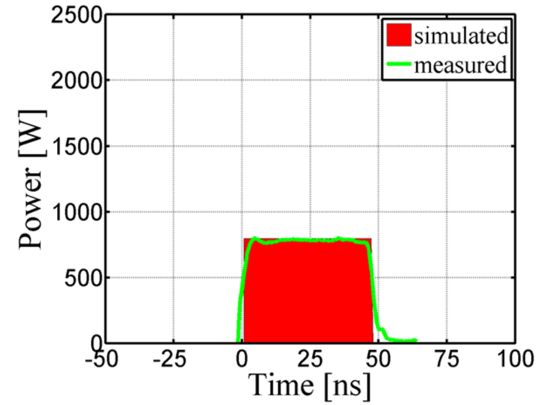
output



input



output



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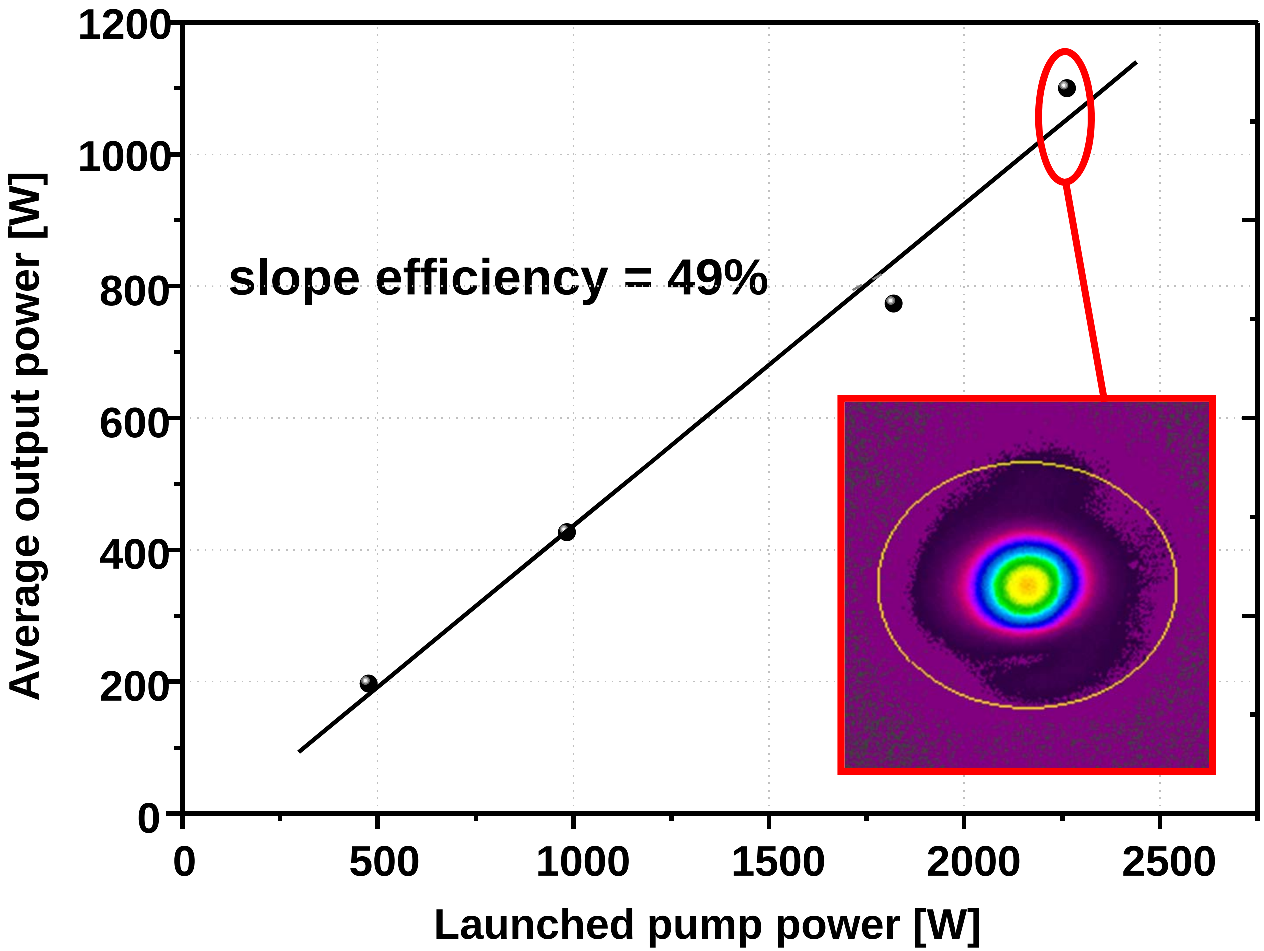
Short pulse high average power fiber laser system



P_{avg} = 1100 W

f_{rep} = 5 MHz

T_{pulse} = 5 ns

E_{pulse} = 220 µJ

P_{peak} = 44 kW

O. Schmidt, C. Wirth, I. Tsybin, T. Schreiber, R. Eberhardt, J.Limpert, A. Tünnermann," Opt. Lett. 34, 1567-1569 (2009)

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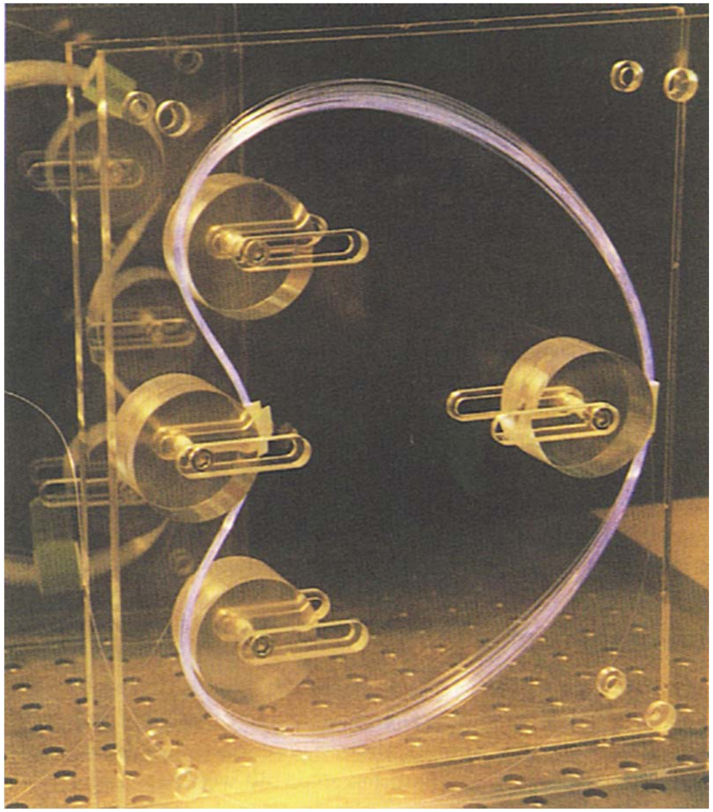
Properties of fiber lasers

- immunity against thermal problems

- high gain
  - low threshold
  - high efficiency

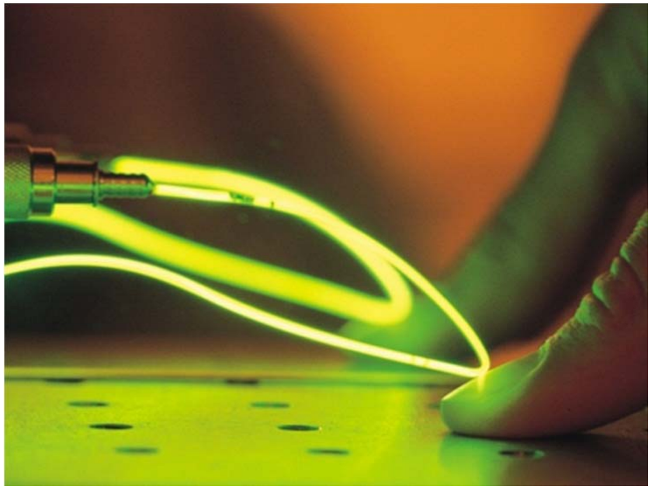
- low intrinsic loss
  - large interaction length
  - exploitation of weak transitions

- large bandwidth
  - tuneability
  - short pulse generation + amplification



Outline

- fiber lasers – basic principles
- advanced fiber designs
- high power ultrafast fiber amplifiers
- conclusion



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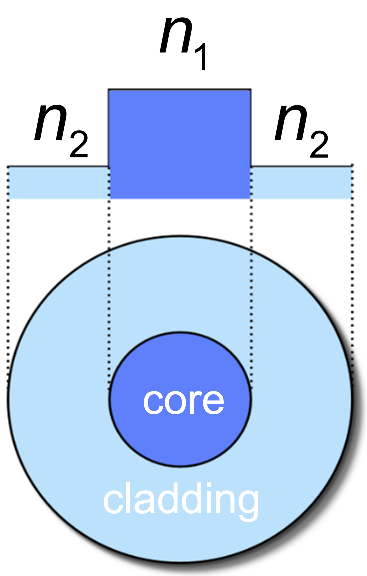
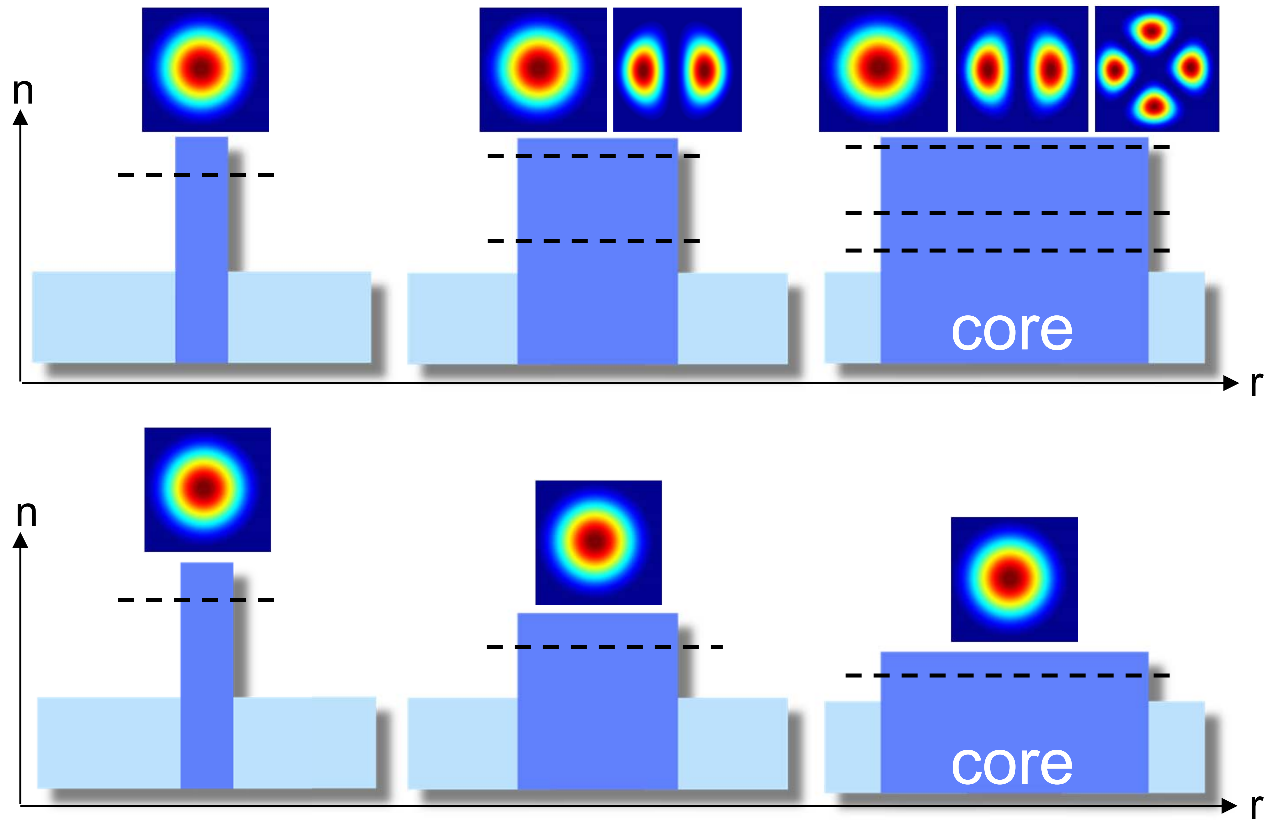
Mode area scaling to reduce the impact of nonlinearity





$$V_{SI} = \frac{2\pi}{\lambda} \cdot a \cdot \sqrt{n_{core}^2 - n_{cladding}^2}$$

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2}$$

$V_{SI} < 2.405$ **(single-mode condition)**

technological limitation: core NA ~0.06

SI SM core diameter < 15µm @ λ= 1 µm

The need for single-transverse-mode fibers

pulse quality

by mode delay due to different propagation constants of transversal modes

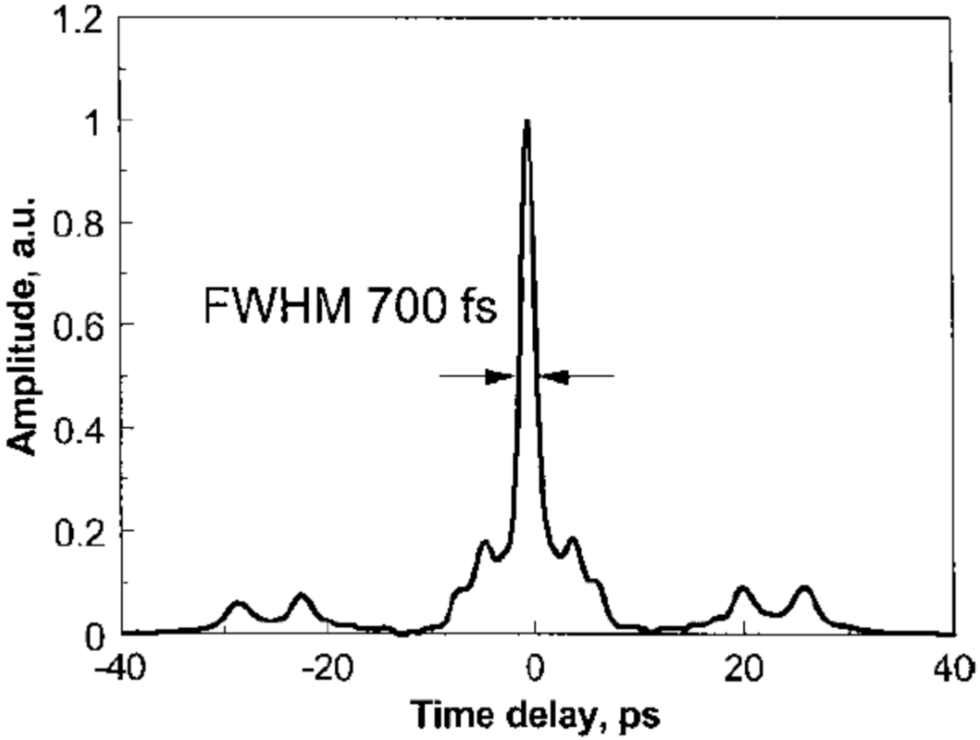
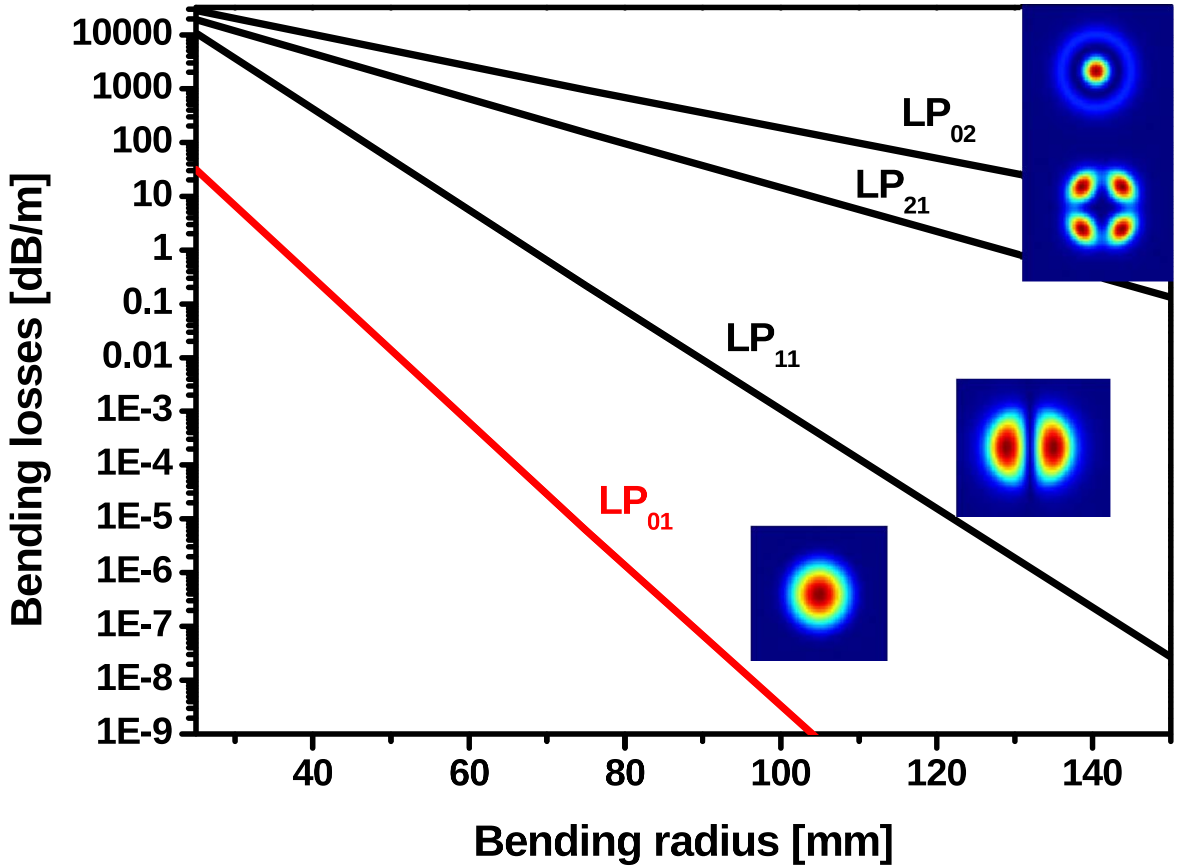


Figure 14 Measured autocorrelation trace of recompressed 100 μJ pulses.

G.C.Cho, A. Galvanauskas, M. Fermann, M. Stock, D. Harter, „100 μJ and 5.5 W Yb-fiber fs CPA system", CLEO 2000, p. 118

Forcing a multimode fiber to single mode operation

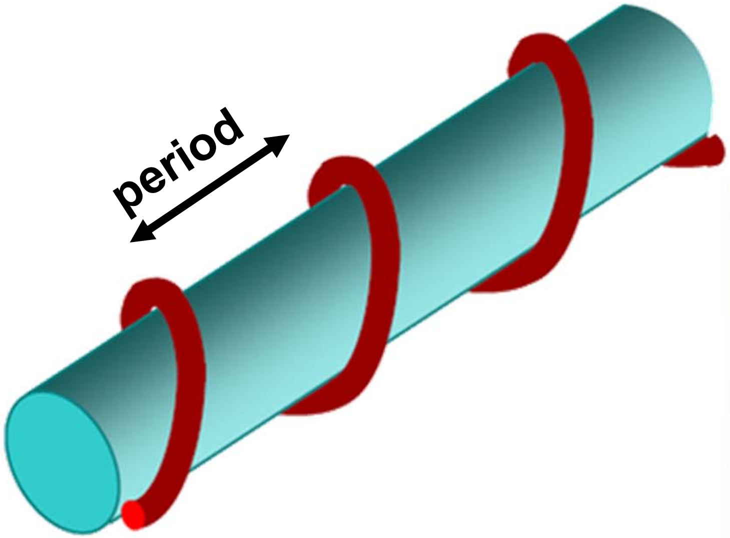
influence of bending to propagation losses of different fiber modes

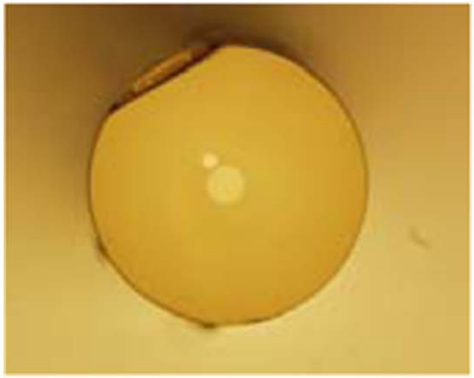


example: Ø = 30 µm, NA = 0.06

P. Koplow, L. Goldberg, R.P. Moeller, and D.A.V. Kliner, “Single-mode operation of a coiled multimode fiber amplifier,” Opt. Lett. 25, 442 (2000)

Advanced fiber designs - CCC



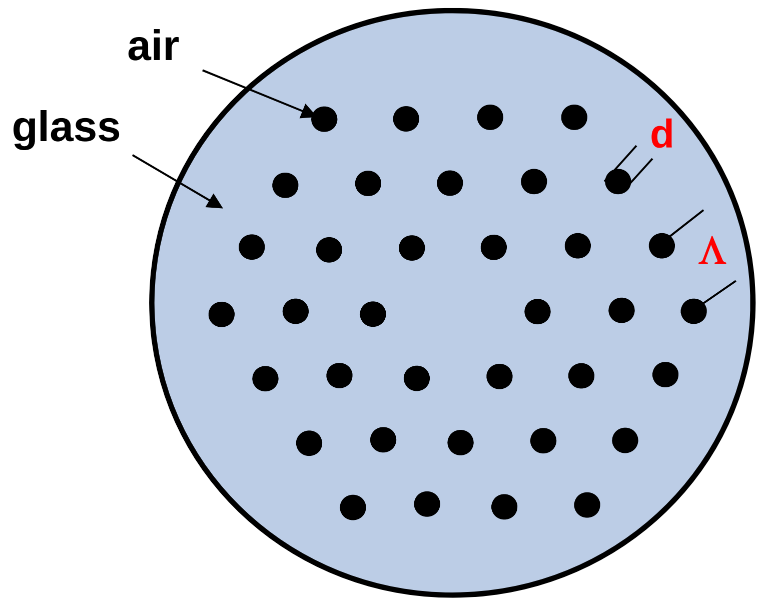


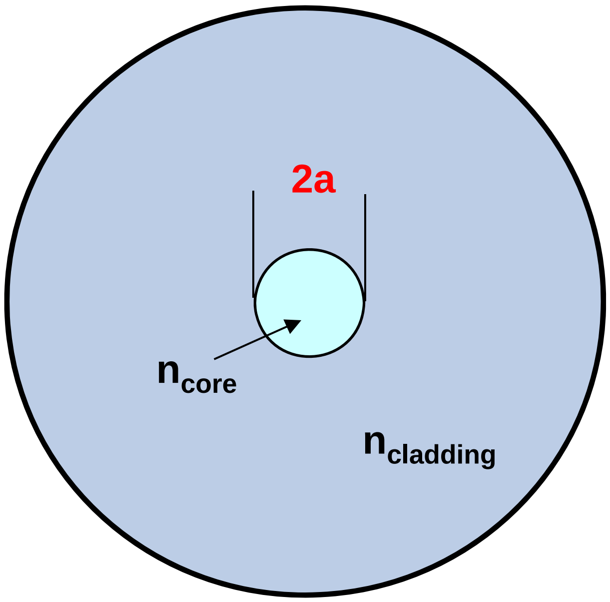
resonant coupling of HOM
long period grating over whole fiber length
high losses for HOM in curved side core

→ **Yb-doped SM cores up to 50 µm demonstrated**

C. Liu et.al., "Chirally Coupled Core Fibers at 1550-nm and 1064-nm for Effectively Single-Mode Core Size Scaling", in *CLEO/QELS and PhAST*, paper CTuBB3 (2007)
A. Galvanauskas, „Chirally-Coupled Core Fibers: Effectively-Single-Mode Path Towards Next-Generation High Power Lasers", OFC 2009, San Diego

Photonic crystal fibers (PCF) – microstructured fibers





microstructured fiber [index guiding]

step-index fiber

→ $\Delta n \sim 1 \cdot 10^{-4}$
NA ~ 0.02

→ $\Delta n \sim 1 \cdot 10^{-3}$
NA ~ 0.06

→ **significantly larger single-mode core possible**

N.A. Mortensen, J.R. Folkenberg, M.D. Nielsen, and K.P. Hansen, "Modal cut-off and the V-parameter in photonic crystal fibers", Opt. Lett. 28, 1879 (2003)

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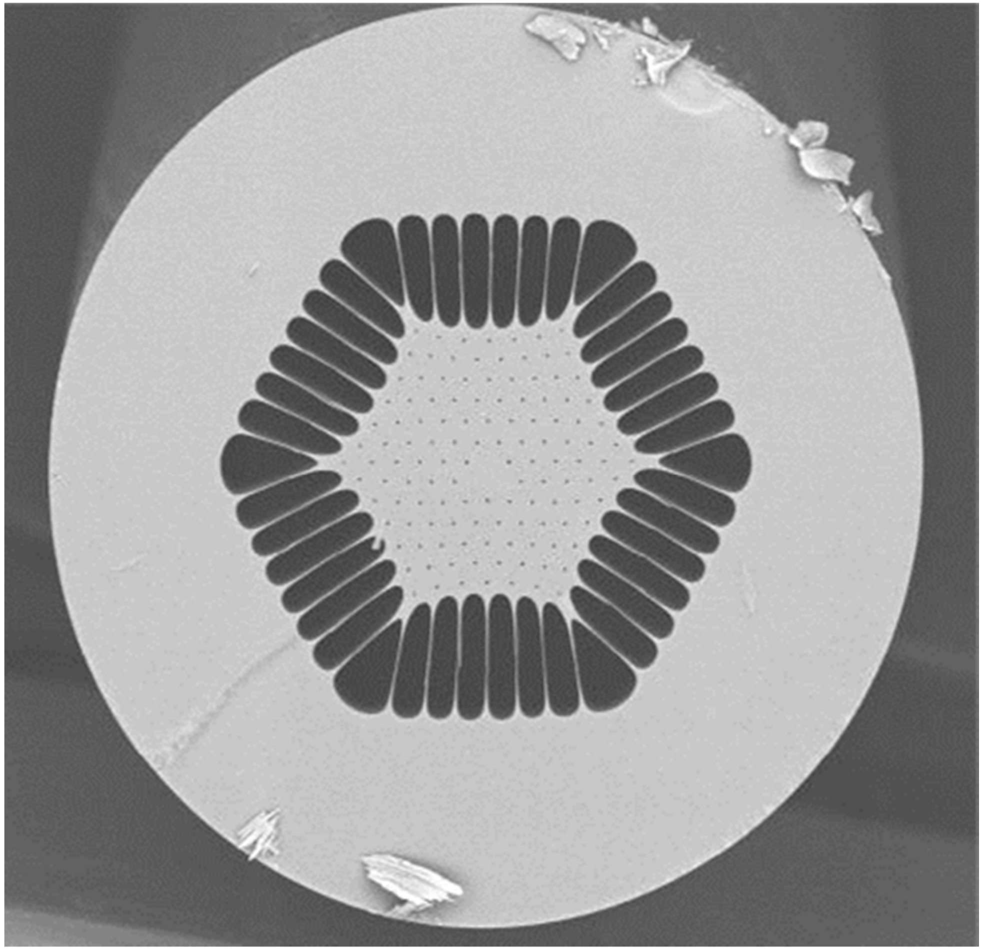
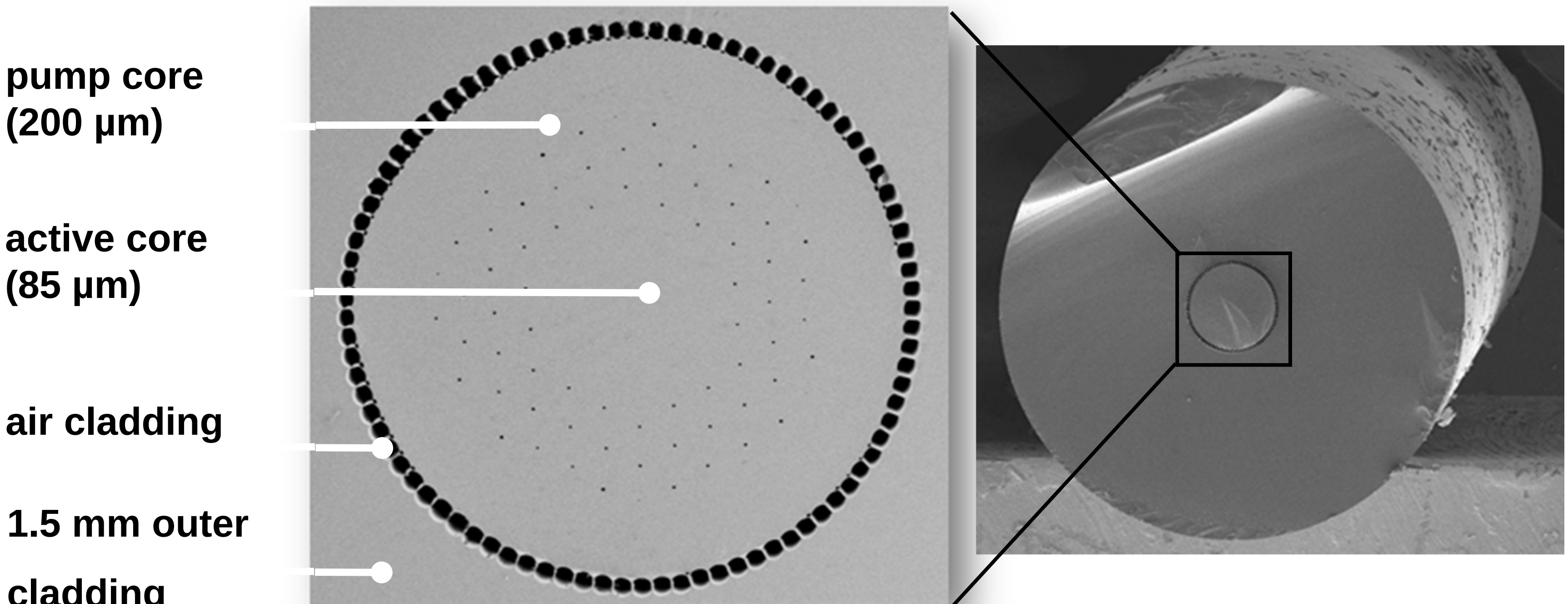
Air-clad large-mode-area photonic crystal fibers (PCF)



»Rod-type« photonic crystal fiber

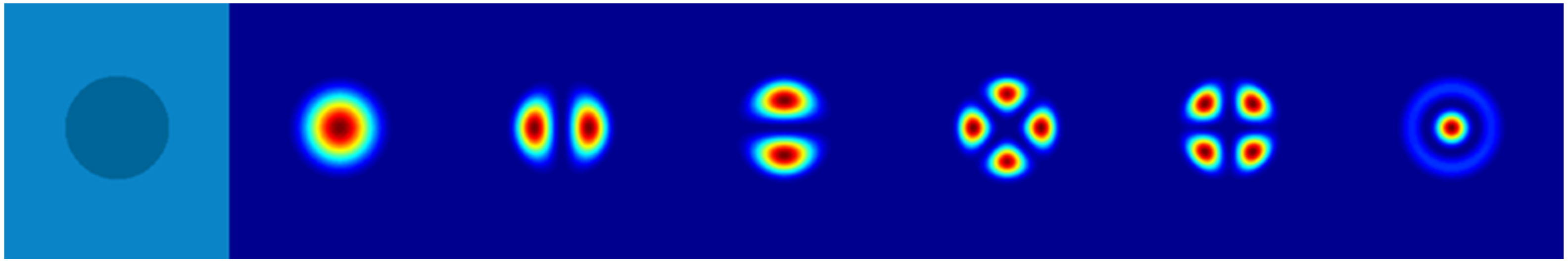


single-mode propagation with MFD ~ 70 µm (MFA ~4000 µm²)
high pump light absorption 30 dB/m @ 976 nm

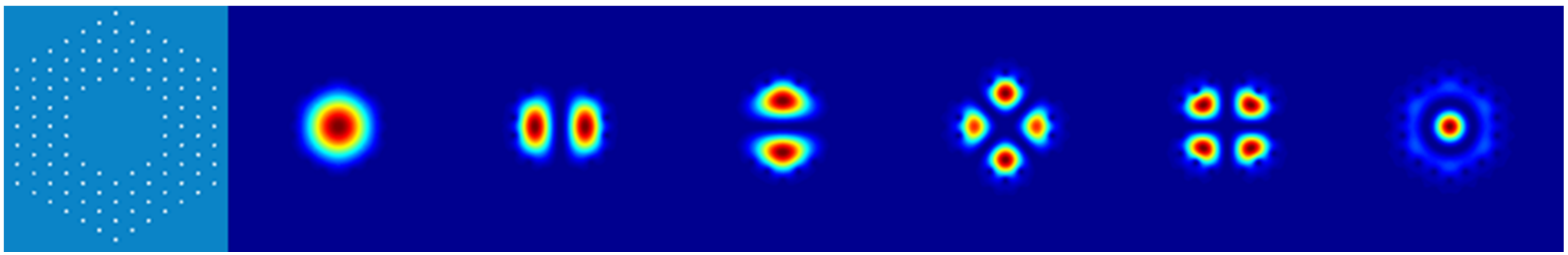
J. Limpert, O. Schmidt, J. Rothhardt, F. Röser, T. Schreiber, A. Tünnermann, S. Ermeneux, P. Yvernault, F. Salin, "Extended single-mode photonic crystal fiber lasers," Opt. Express 14(7), 2715–2720 (2006)

Advanced fiber designs – large pitch PCFs

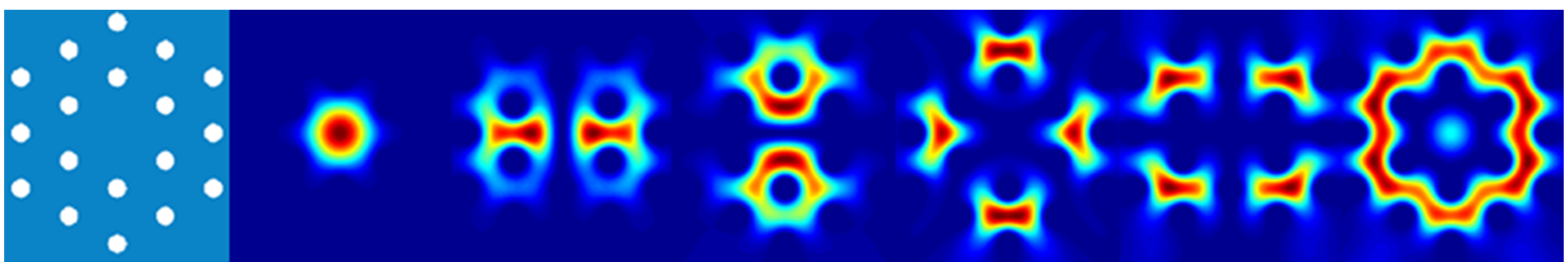
step-index fibers



index-guiding photonic crystal fibers

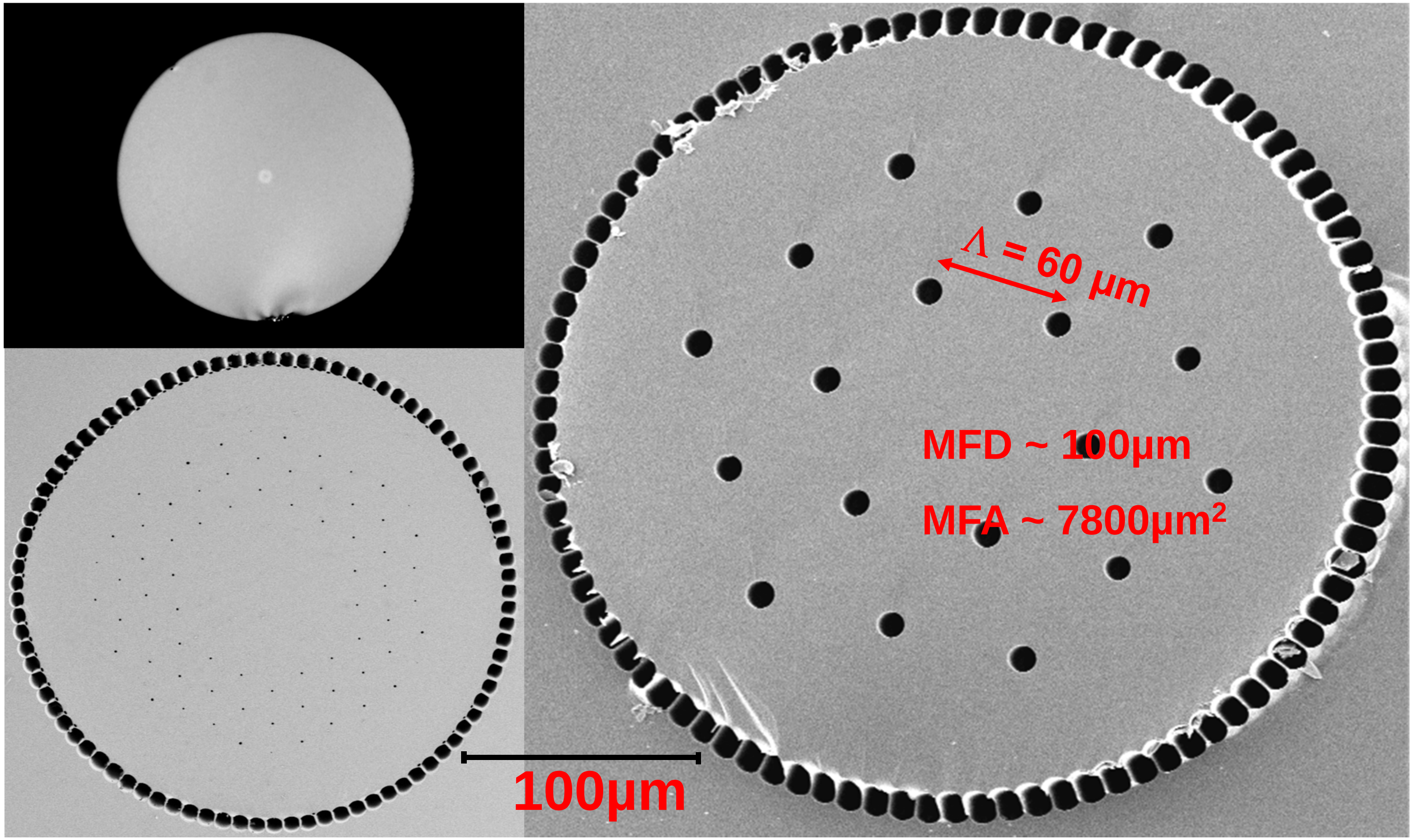


photonic crystal fibers with modal sieve / delocalization



P. St. J. Russell, „Photonic Crystal Fibers“, Science 299 (2003)
F. Stutzki et. al., „High average power large-pitch fiber amplifier […], “ Opt. Lett. 36, 689-691 (2011)

Advanced fiber designs – large pitch PCFs



Tino Eidam, Jan Rothhardt, Fabian Stutzki, Florian Jansen, Steffen Hädrich, Henning Carstens, Cesar Jauregui, Jens Limpert, Andreas Tünnermann, "Fiber chirped-pulse amplification system emitting 3.8 GW peak power," Opt. Express 19, 255-260 (2011)

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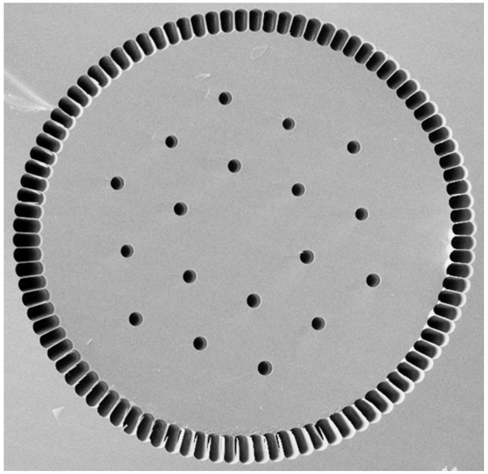
Large pitch PCFs – energy extraction @ ns-pulses

		976nm	
	doping-∅	stored	extractable*
LPF30	43 µm	5.3 mJ	4.2 mJ
LPF45	64 µm	11.8 mJ	9.3 mJ
LPF75	105 µm	31.7 mJ	25.1 mJ

$$E_{extr} = \left(1 - \frac{\ln G}{\ln G_0}\right) \cdot E_{avail}$$



*G = 8.5, doping concentration 3.2×10^{25} ions/m³

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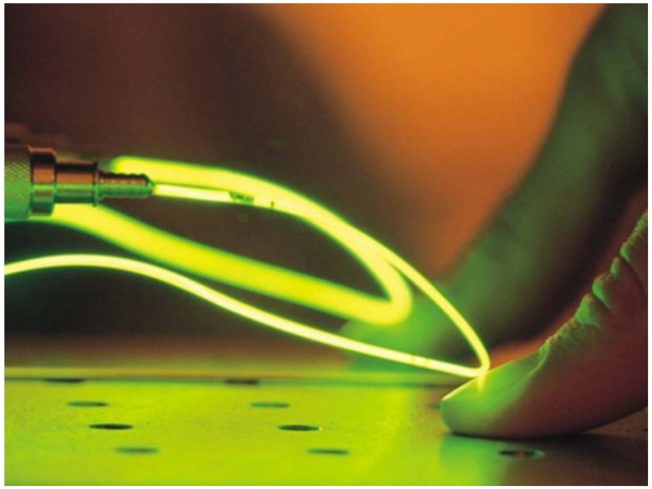
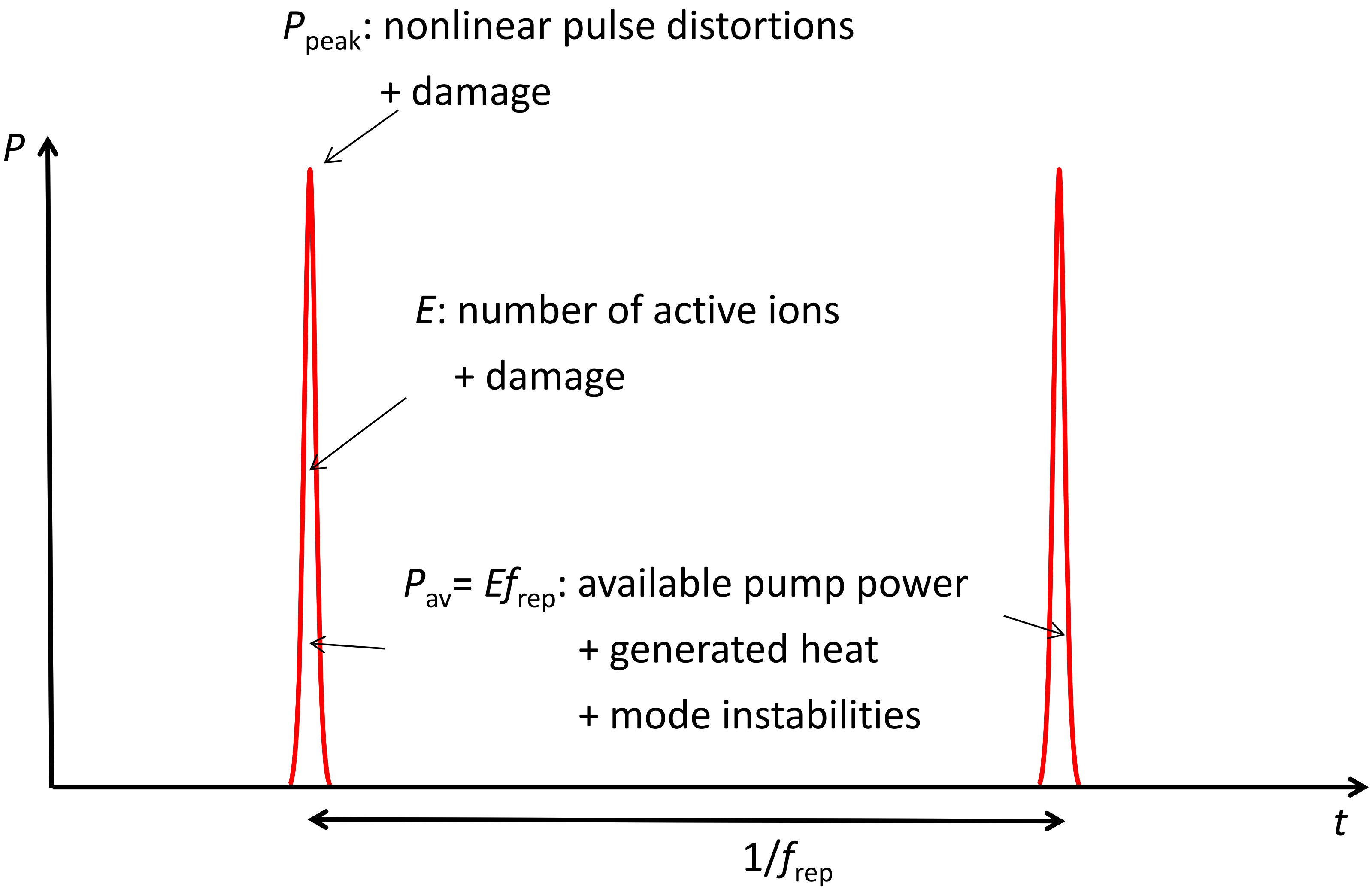
Outline

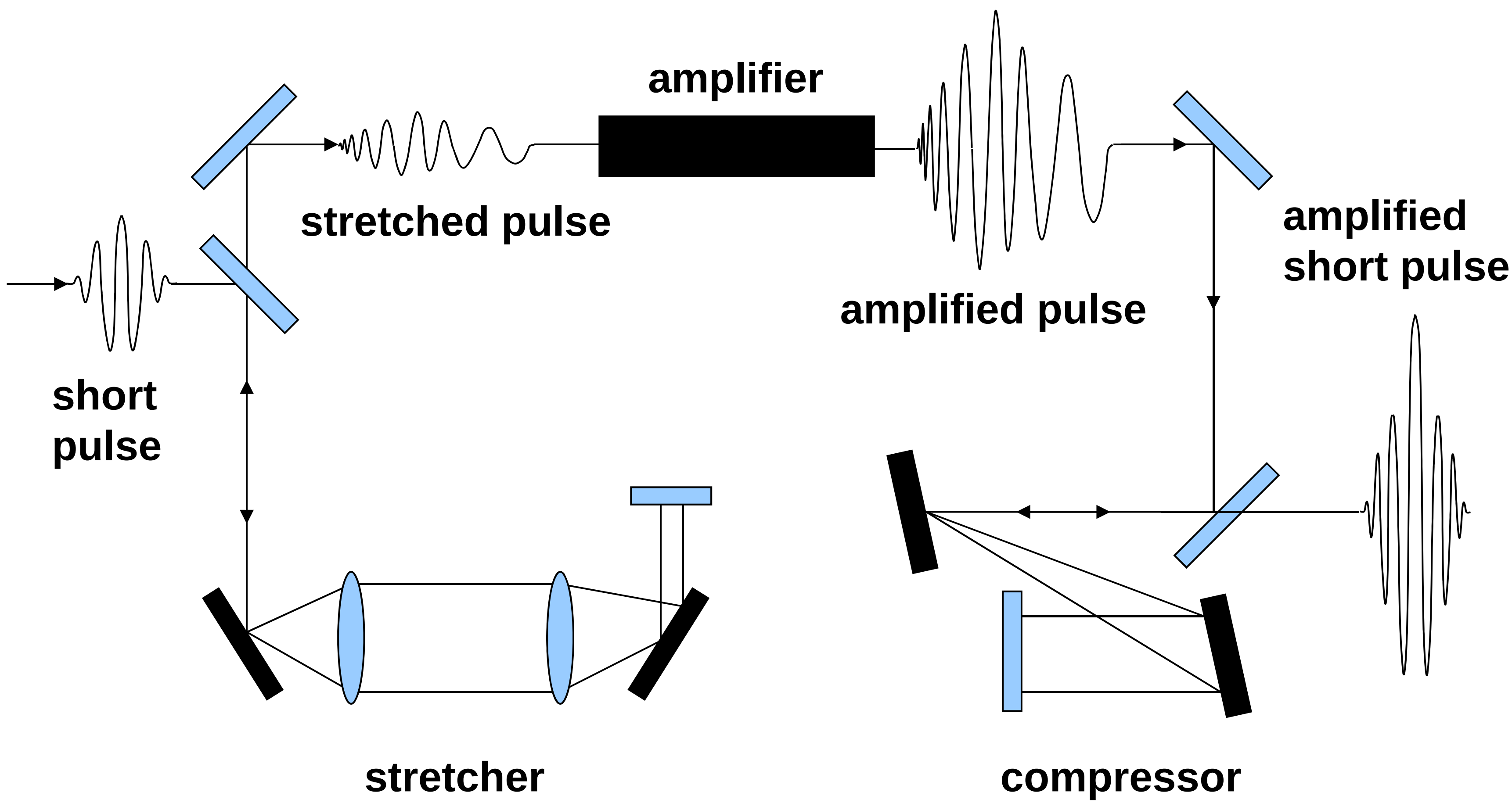
- fiber lasers – basic principles
- advanced fiber designs
- high power femtosecond fiber amplifiers
- conclusion



Ultrafast fiber lasers – scaling limitations

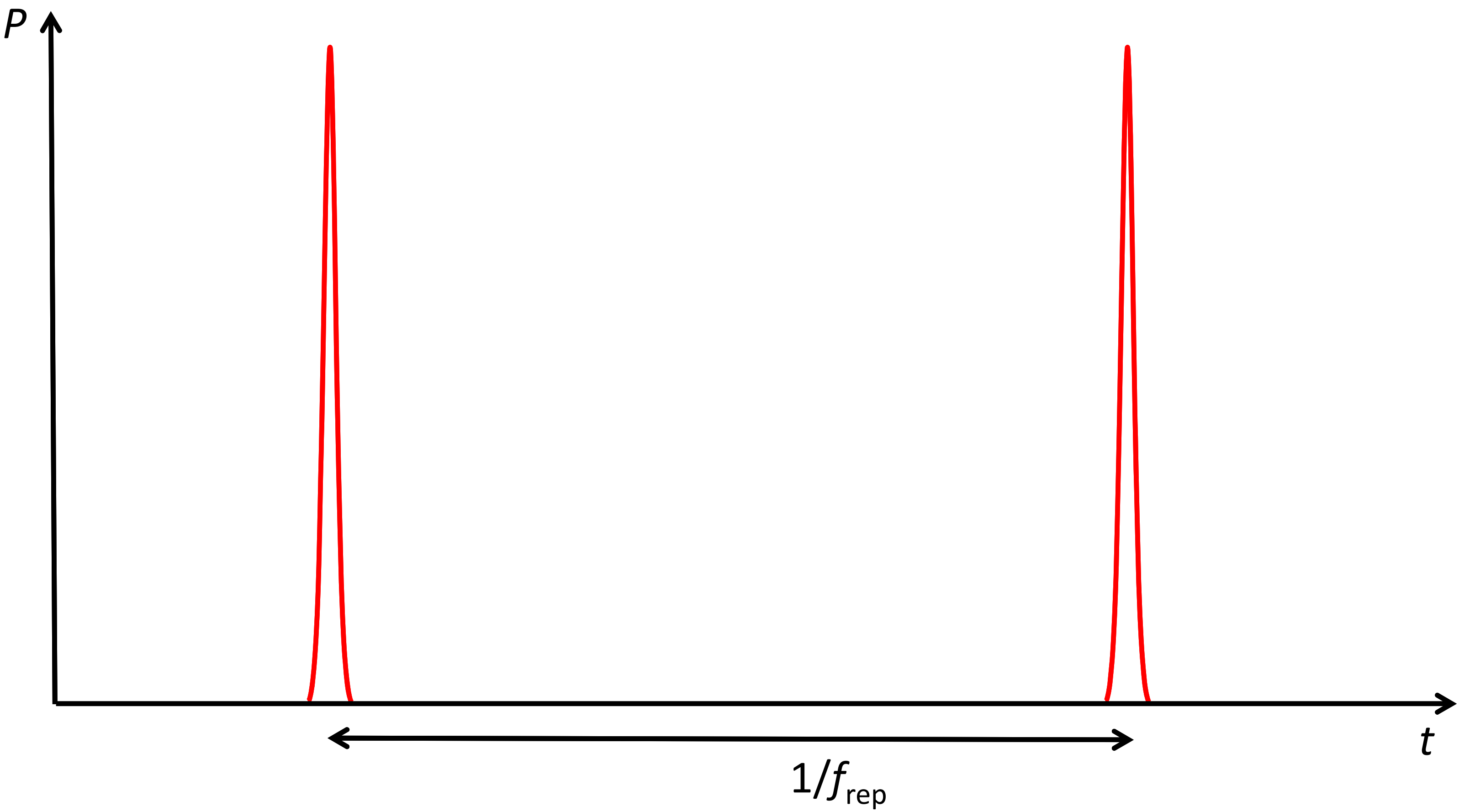


Chirped-pulse-amplification

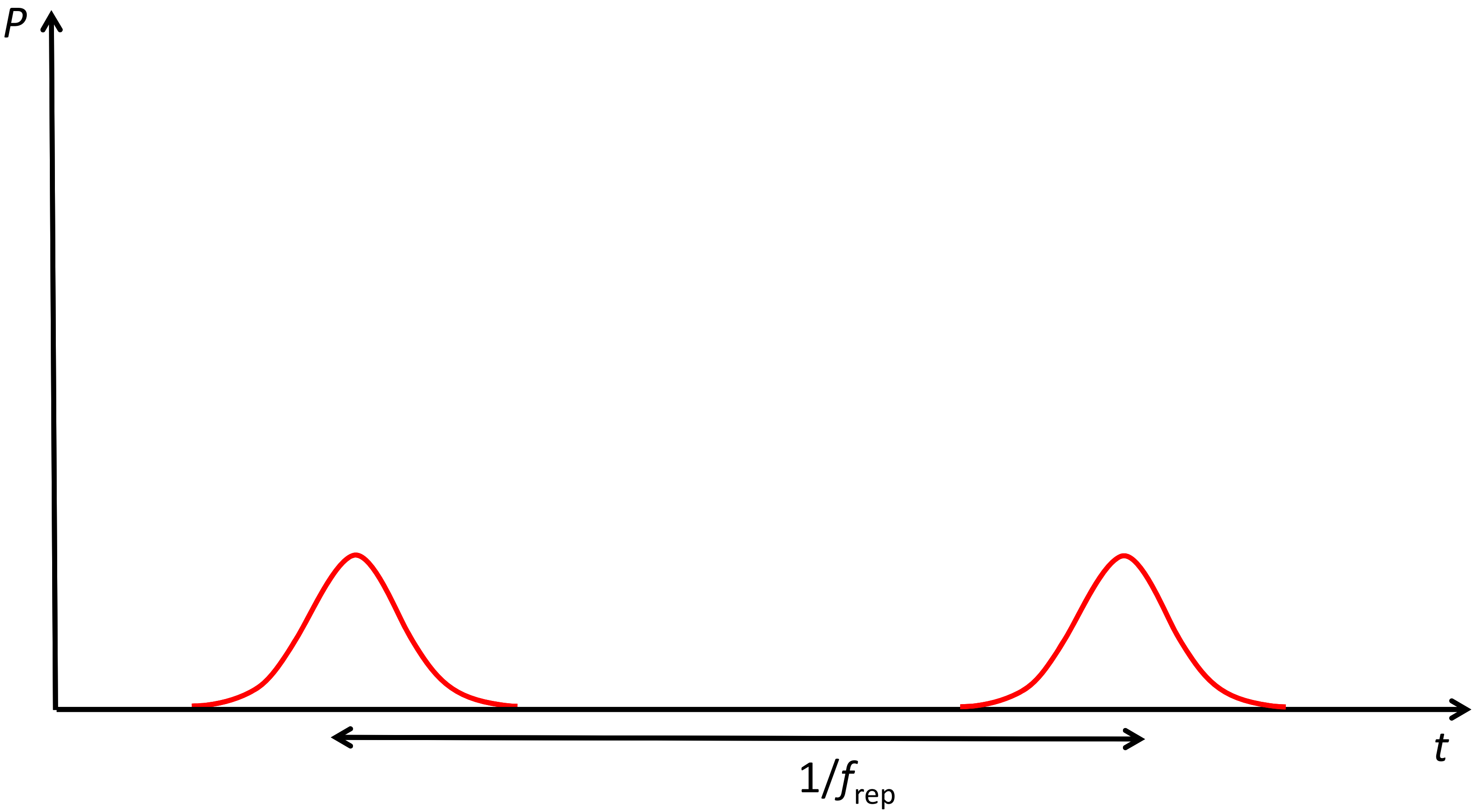


D. Strickland and G. Mourou, “Compression of amplified optical pulses,” Opt. Comm. 56, 3, 219 (1985)

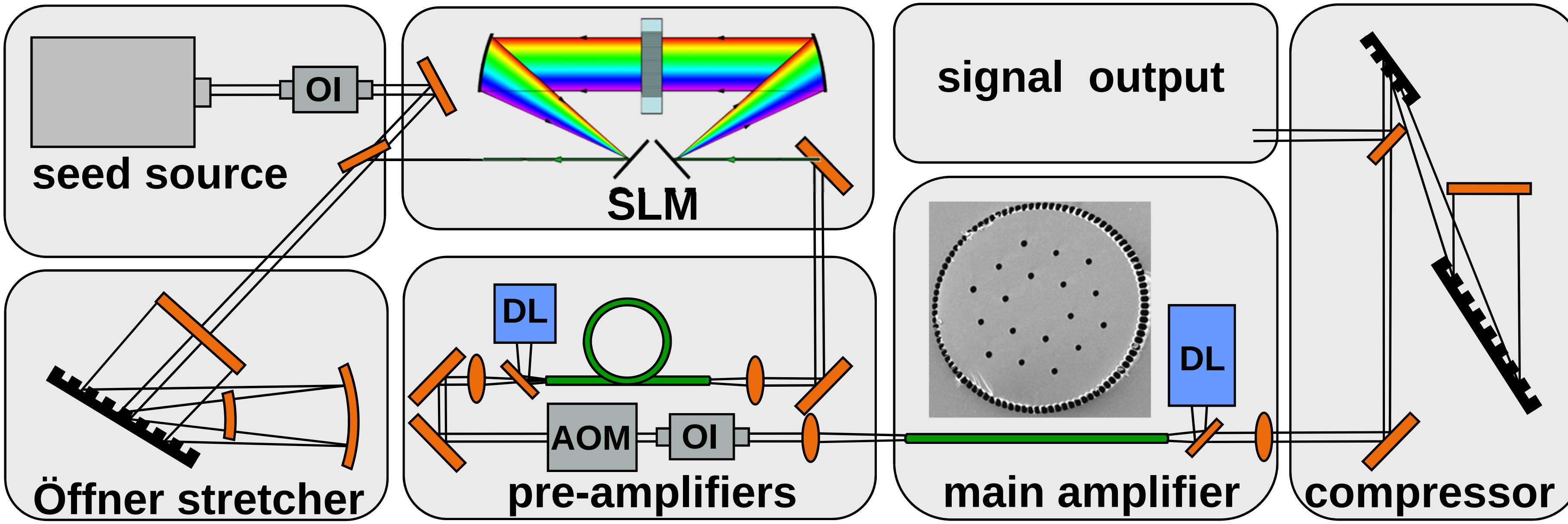
Chirped-pulse-amplification



Chirped-pulse-amplification



High energy fiber CPA system



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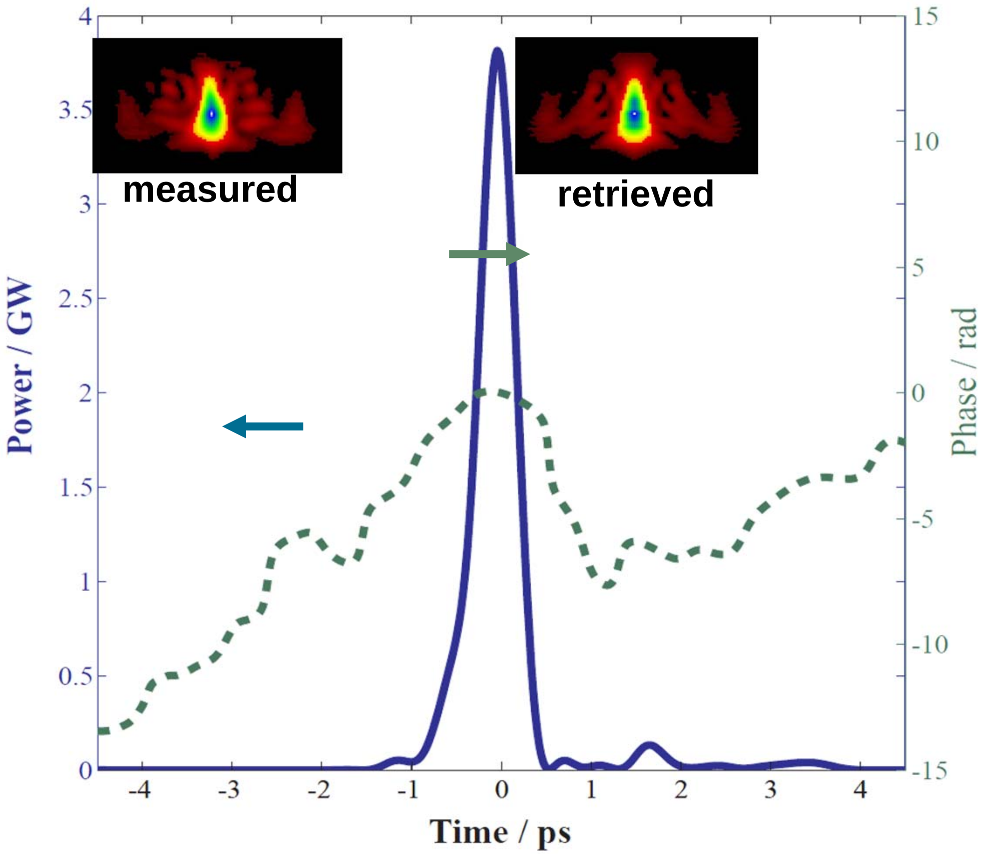
High energy fiber CPA system

output parameters



measured pulse shape using FROG

480fs pulse duration

2.2mJ → 3.8GW peak power

Tino Eidam, Jan Rothhardt, Fabian Stutzki, Florian Jansen, Steffen Hädrich, Henning Carstens, Cesar Jauregui, Jens Limpert, Andreas Tünnermann, "Fiber chirped-pulse amplification system emitting 3.8 GW peak power," Opt. Express 19, 255-260 (2011)

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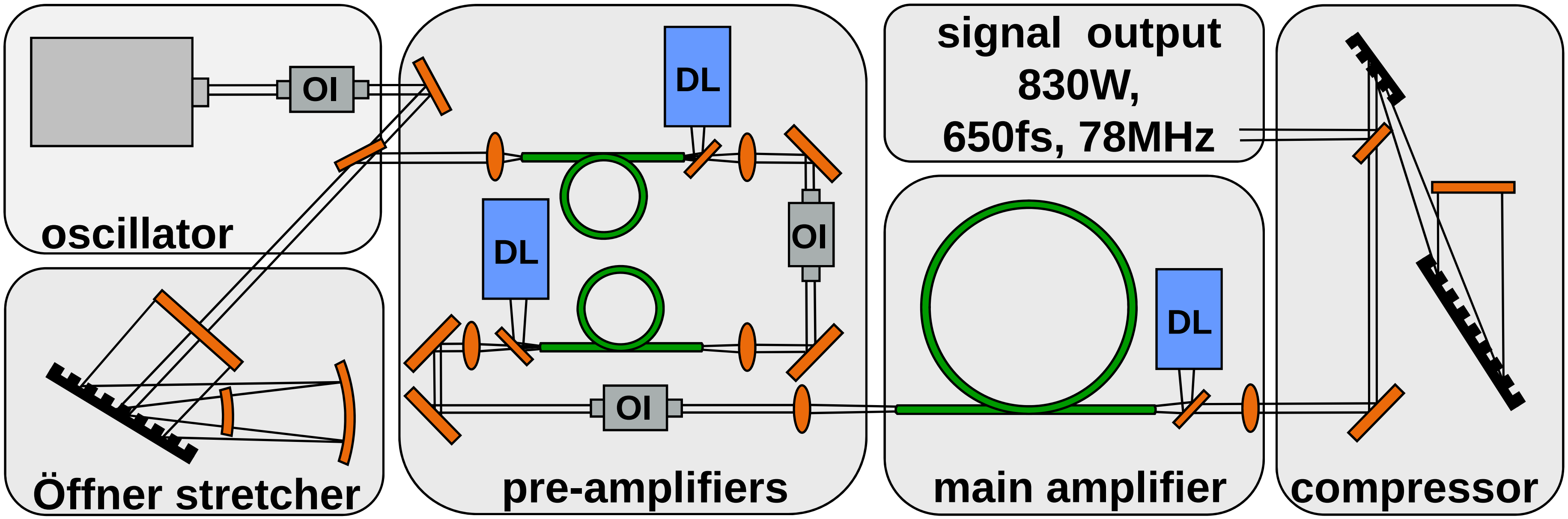
High average power fiber CPA system



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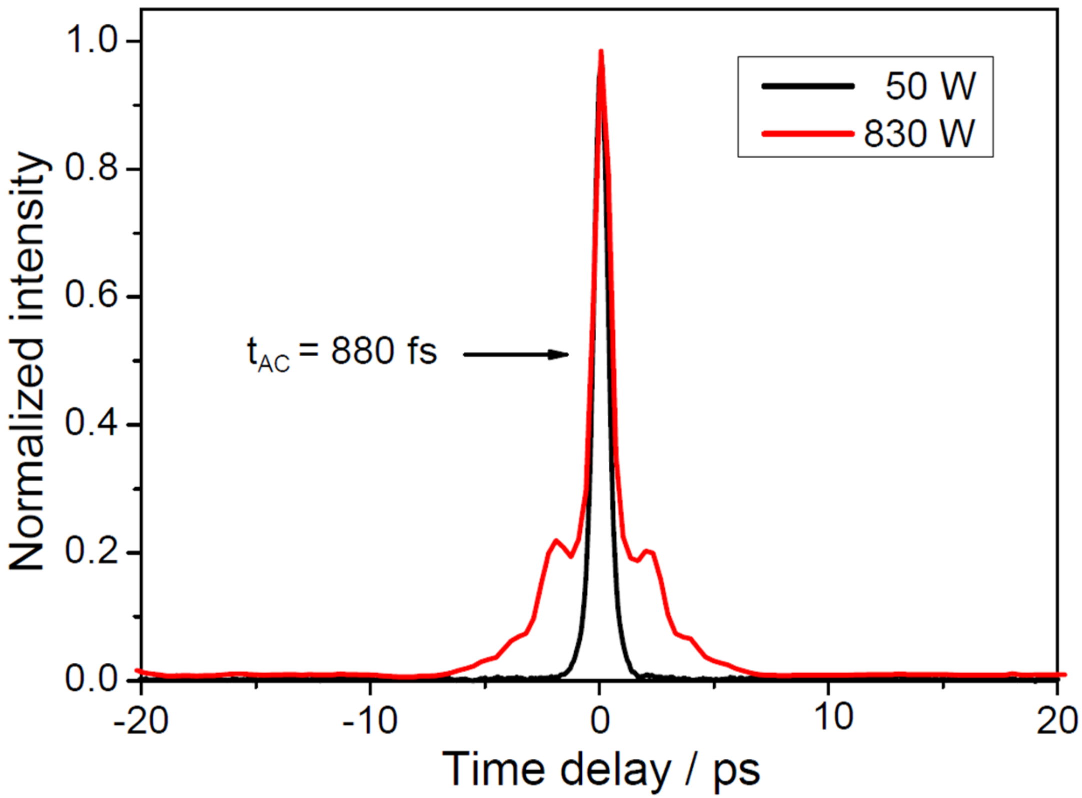
High average power fiber CPA system

output parameters

830 W output power

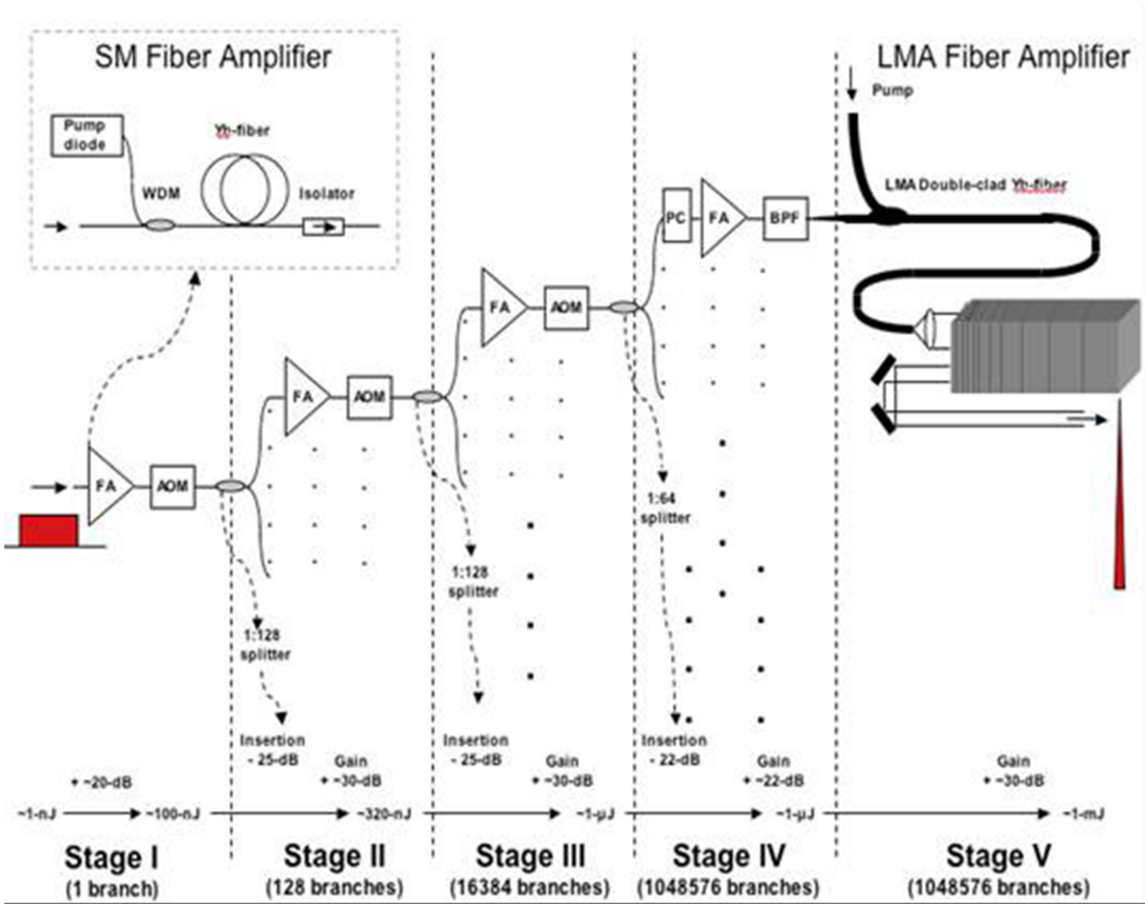
880 fs autocorrelation width

pulse broadening due to acquired nonlinear phase (B = 11 rad)



Tino Eidam, Stefan Hanf, Enrico Seise, Thomas V. Andersen, Thomas Gabler, Christian Wirth, Thomas Schreiber, Jens Limpert, Andreas Tünnermann, "Femtosecond fiber CPA system emitting 830 W average output power," Opt. Lett. 35, 94-96 (2010)

Network of femtosecond fiber lasers

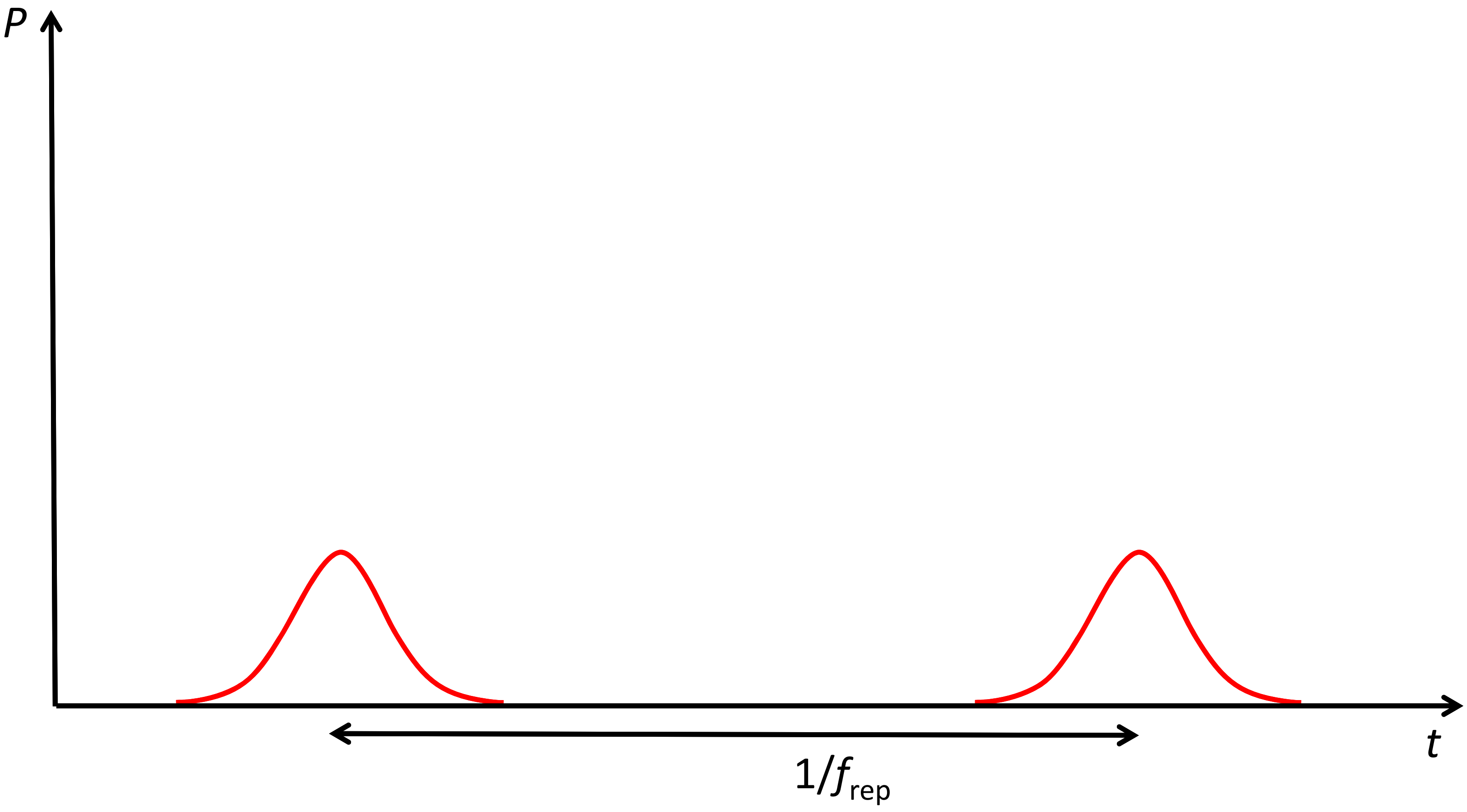


40 J
10 kHz
400 kW
100 fs

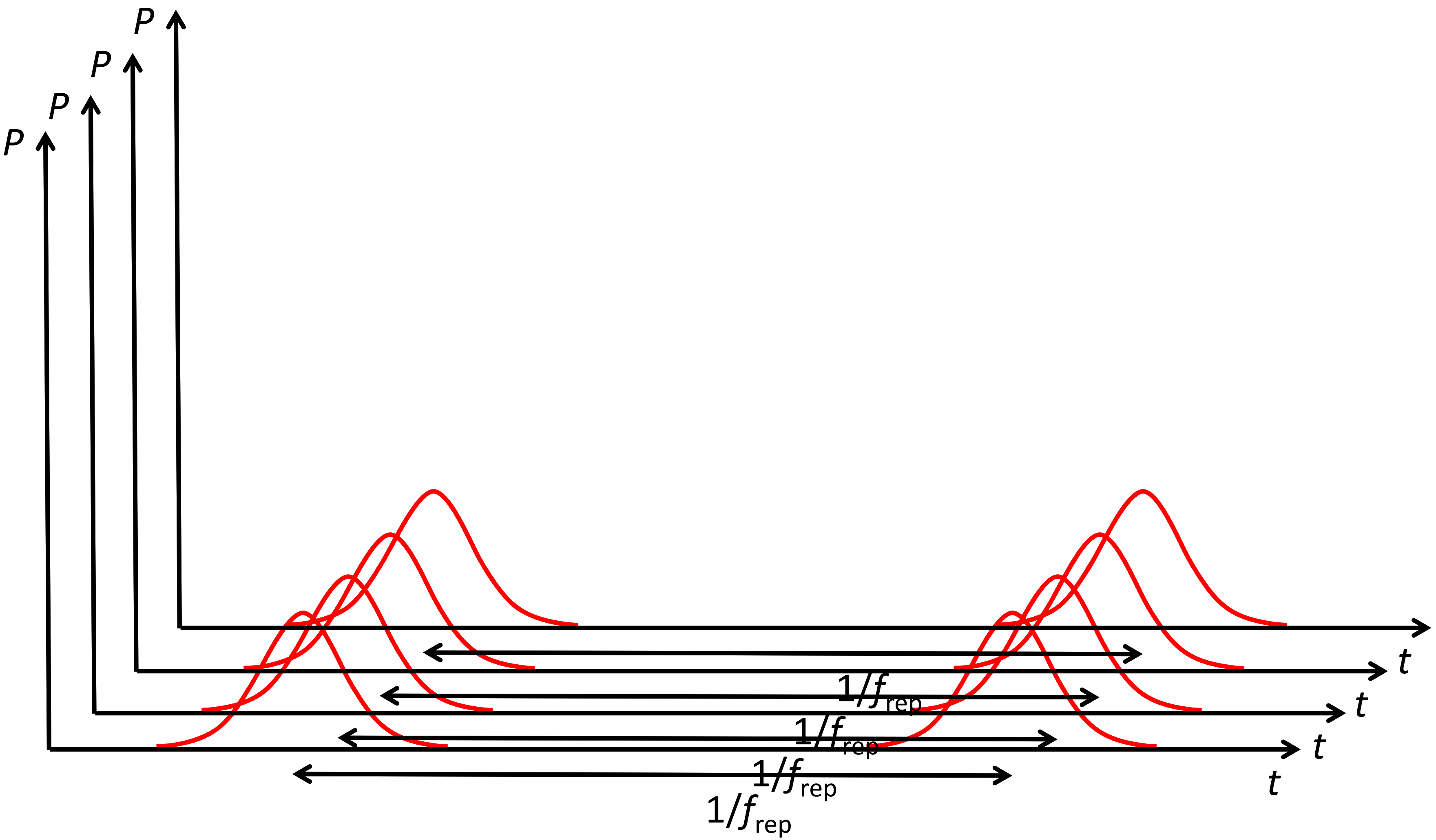
G. Mourou et al.

C. Labaune, D. Hulin, A. Galvanauskas, G.A. Mourou, “On the feasibility of a fiber-based inertial fusion laser driver,” Optics Communications, 281, 4075-4080(2008)

Chirped-pulse-amplification

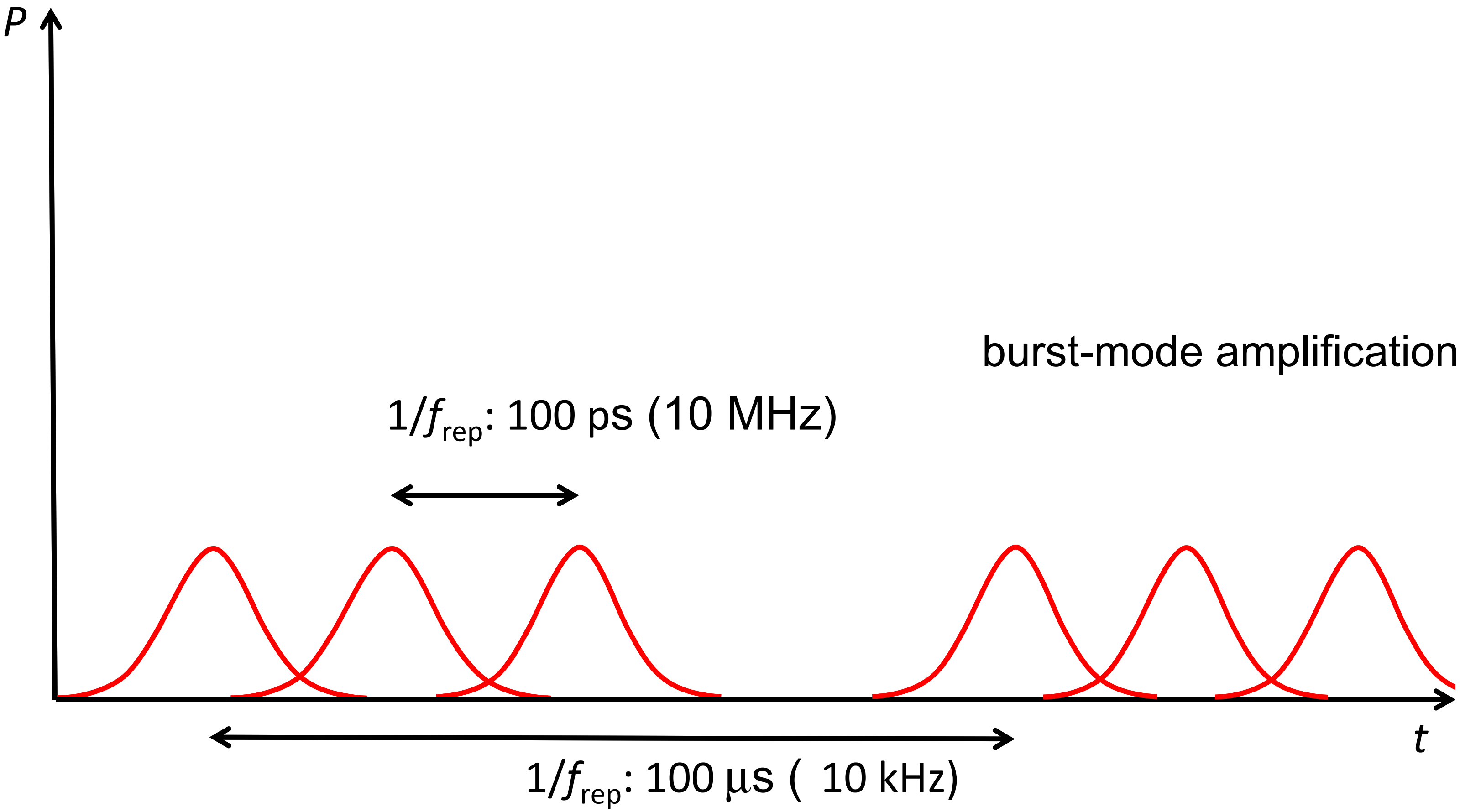


Chirped-pulse-amplification & coherent combining



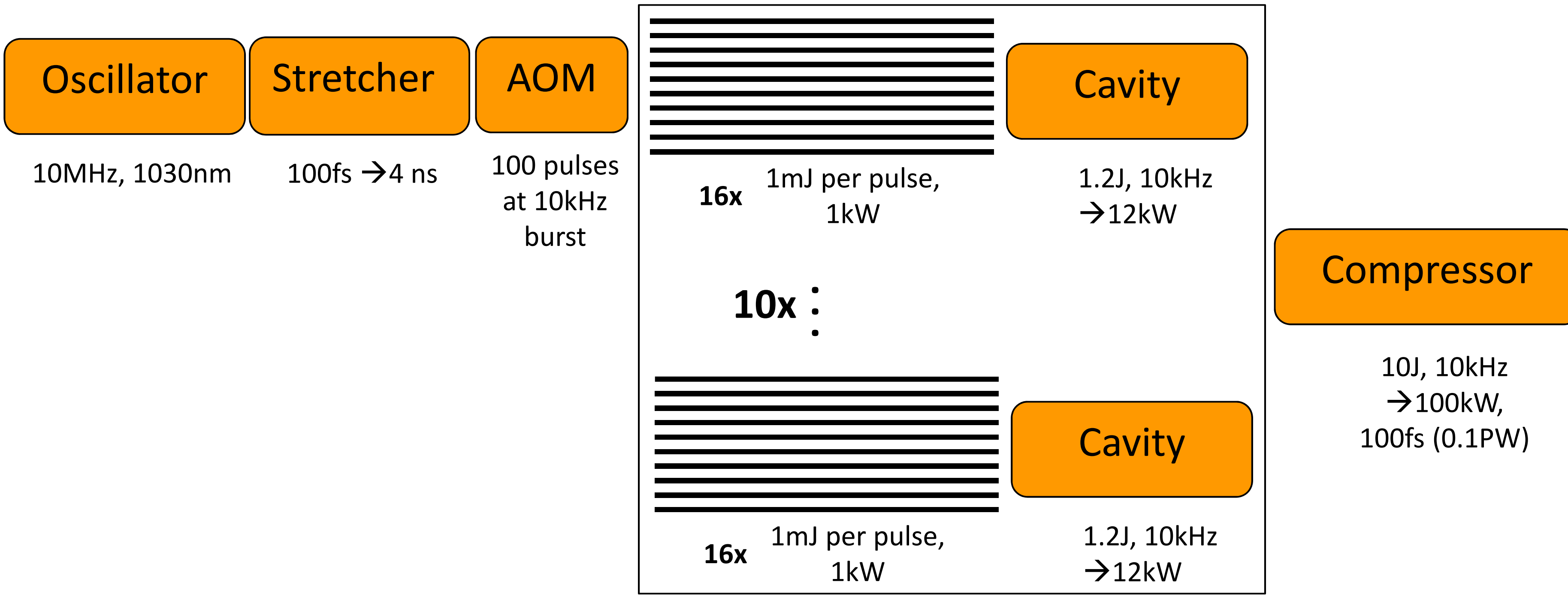
Burst pulse amplification

increase of pulse energy via reduction of repetition rate @ constant ave. power



Design proposal: table-top PW-class laser

chirped pulse amplification & burst pulse amplification & coherent combining



Outline

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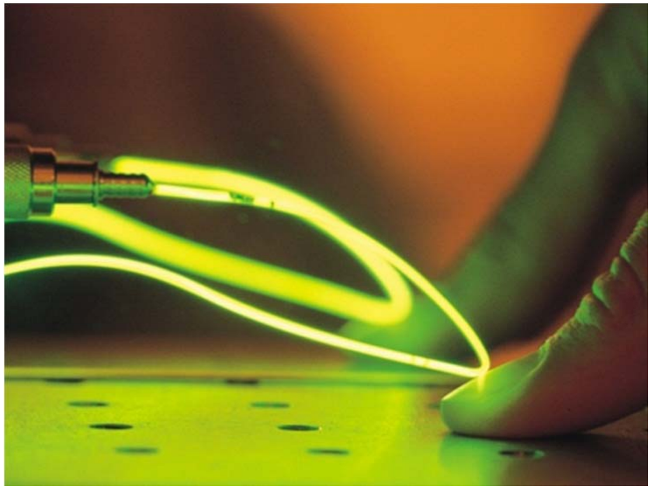
- conclusion



Conclusion

- advanced thin disc and fiber laser technology:

  tailored and energy efficient laser tools for fundamental science and accelerator physics

collider

x-ray source

laser stripping

hadron therapy

ICAN - International Coherent Amplifier Network
ICFA - The International Committee for Future Accelerators
ICUIL - The International Committee on Ultra-High Intensity Lasers
IZEST - International Zeta-Exa-Watt Science and Technology