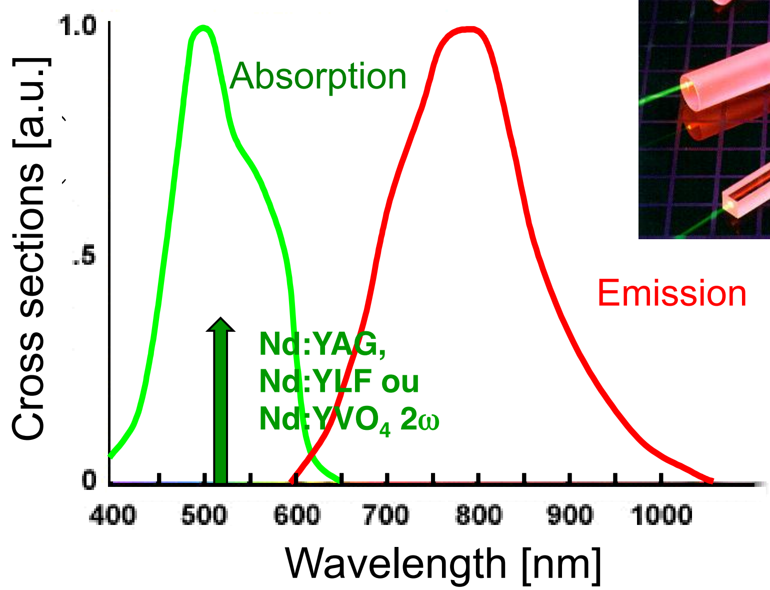
State of the art of high-power and high-repetition-rate femtosecond laser systems

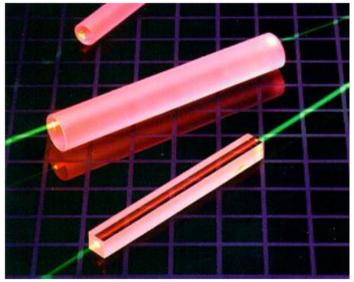
Frédéric Druon
Laboratoire Charles Fabry,
Institut d'Optique, CNRS, Univ Paris Sud, Palaiseau, France
frederic.druon@institutoptique.fr

Outlook

- Introduction : the Ti:Sa limitations and its alternatives
- Yb-doped technologies
  - Thin-disk, Slab, Fibers…
- Energy scaling
  - The coherent combining
  - Simple boosters
- Duration issues
  - Non-linear techniques
- Conclusion

Ti:sapphire as standard

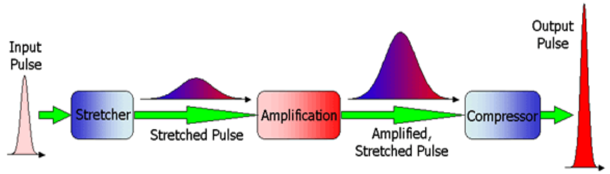


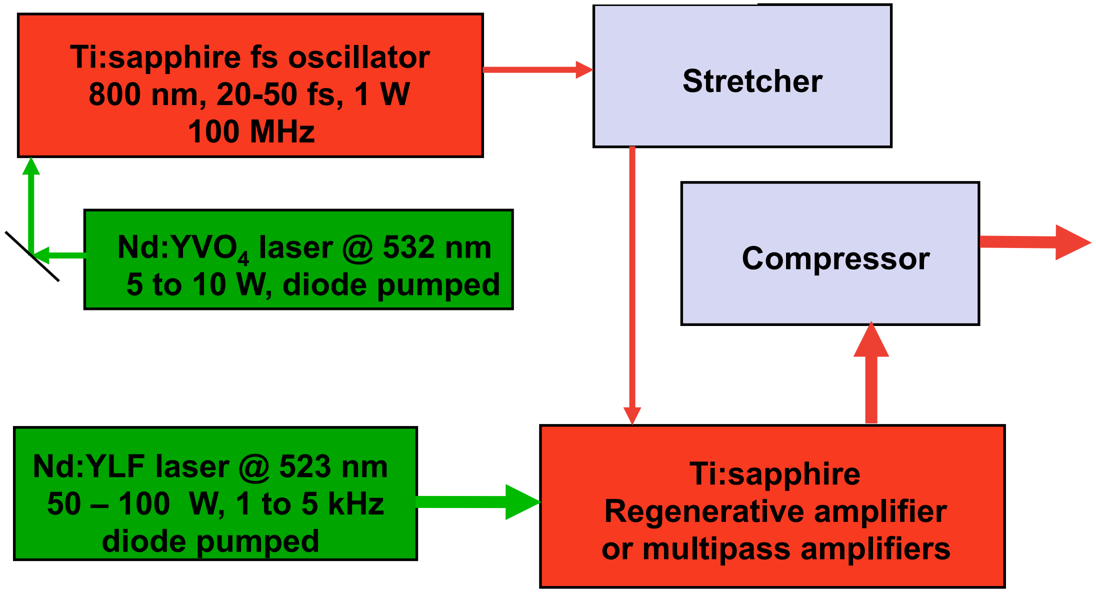


P. F. Moulton, "Spectroscopic and laser characteristics of Ti:Al_2O_3," J. Opt. Soc. Am. B 3, 125 (1986)

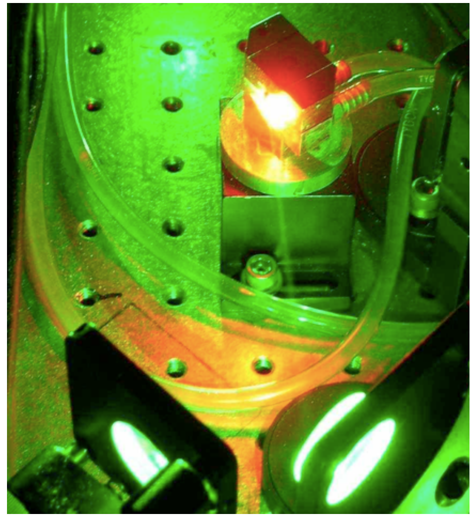
- Large gain bandwidth (**680 nm – 1080 nm**)
- Emission cross-section: 41 10^{-20} @ 780 nm
- Excited state lifetime: 3 µs
- Thermal conductivity: 35 $W.K^{-1}.m^{-1}$
- Pumped in the **green**

High power, high rep' rate Ti:Sa chains





High power fs Ti:Sa systems



Limitations in power:
- **Pump laser technology**
- **Efficiency (few %)**
- **Cryogenic systems**

Duration
20 - 30 fs, @ 800 nm
Energy
1 to 10s mJ
Rep' rate
1 to 10 kHz
Pmoy max :
20 W (20 mJ, 1 kHz)
50 W (5 mJ, 10 kHz)

Direct diode-pumping

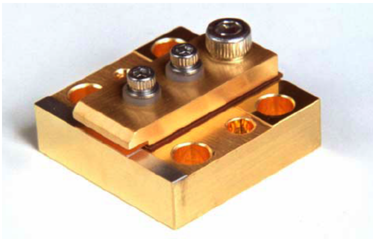
Problem: No high power diodes for Ti:Sa
Solution : Use another gain material

→ **AlGaAs diode @ 808 nm or 880 nm for Nd-doped materials**

→ **InGaAs diode @ 915 and 980 nm for Yb-doped materials**

LIMO, DILAS, JENOPTIK, BWT, IPG…
Wavelength for Nd: 808 nm, 880 nm,
Yb: 915 nm, 940 nm
976-980 nm

High brightness diodes
>100 W, 100 µm, ON: 0.12
High power diodes
500 W 400 µm, ON : 0.22
High energy diodes
>J, >kW on few ms



High power fs amplifiers

To reach 0.1 to 1 kW Diode pumping is not enough

Additional requirements on the MATERIAL and its GEOMETRY

	Heat removal	Efficiency	Beam quality	Δλ, Δt	Gain	Energy
MATERIAL	κ_{th}	η_q	dn/dT	$\sigma(\lambda)$	$\sigma(\lambda_0)$	Doping τ_{fluo}
GEOMETRY	Surf/Vol	Overlap	Guiding Cooling		L_{int}	Aeff Vol

Tradeoffs with material type, gain medium geometry, source architecture and compatibility between these three

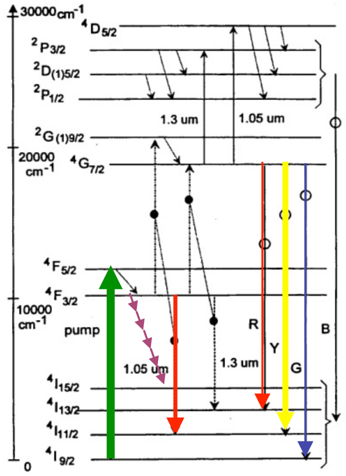
Yb^{3+} doping

• Main technology for fs high power: Yb-doped materials

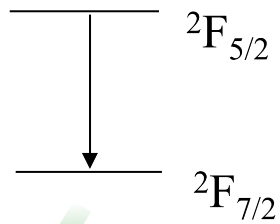
→ low quantum defect
→ diode pumping @ 980 nm
→ Simple spectroscopy
no quenching
no exited state abs.

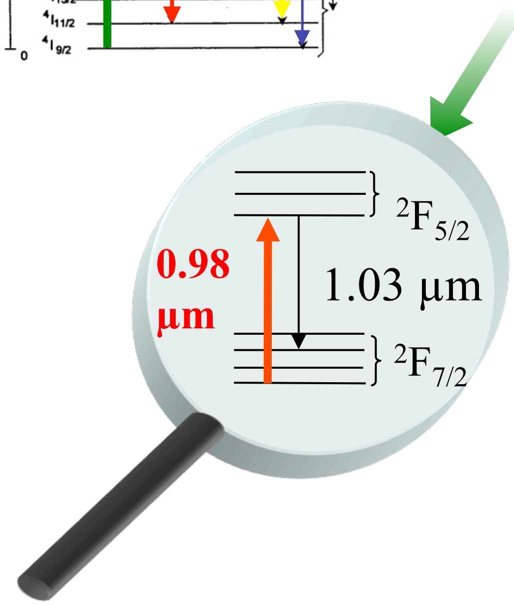
→ Limited gain bandwidth
(as least better than Nd)
→ quasi-3-level

Nd^{3+}

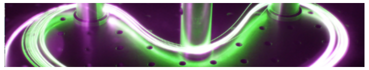


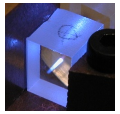
Yb^{3+}





Choice of the host for Yb^{3+}





Glass
(amorphous)

Crystals with complex structures
(complex cells)

Crystals with simple structure
(e.g. cubic)

- Emission bandwidth
- Thermal conductivity
- Cross section

Short pulses

opposition

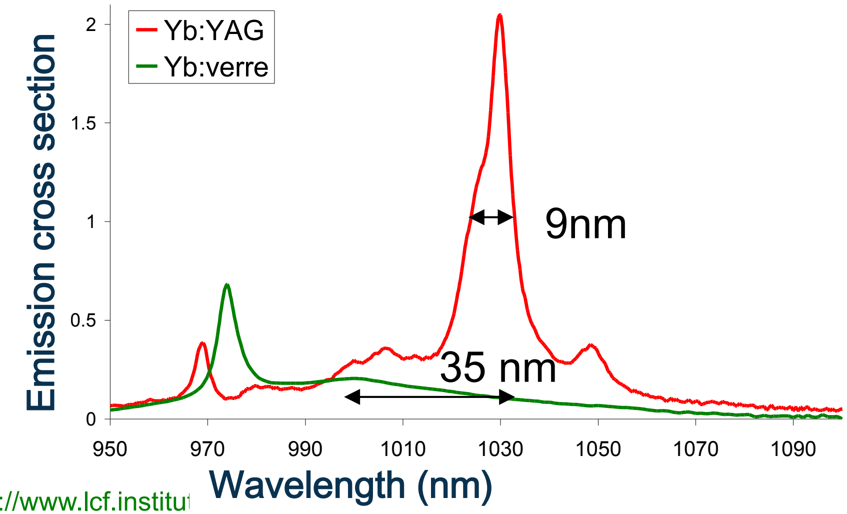
High power

Loss sensitivity

Glass

Thermal conductivity

0,8



YAG

Thermal conductivity

11

Yb-doped materials: a choice to be done

Large influence of host matrix on material properties
linked to the disorder of the matrix

	σ 10^{-24} m^2	$\Delta\lambda$ nm	τ_{fluo} ms	κ W/m/K
Yb:YAG	2.2	9	0.95	11
Yb:glass	0.05	35	1	0.8
Yb:KYW	3	20	0.7	3.3
Yb:CALGO	0.75	70	0.4	9.5
Yb:CaF_2	0.25	50	2.5	9.7

- Most used crystal: Yb:YAG ..
- …but limited gain bandwidth: Yb:KYW, Yb:CaF_2, Yb:CALGO …
- Fiber-guided technology requires Yb:glass

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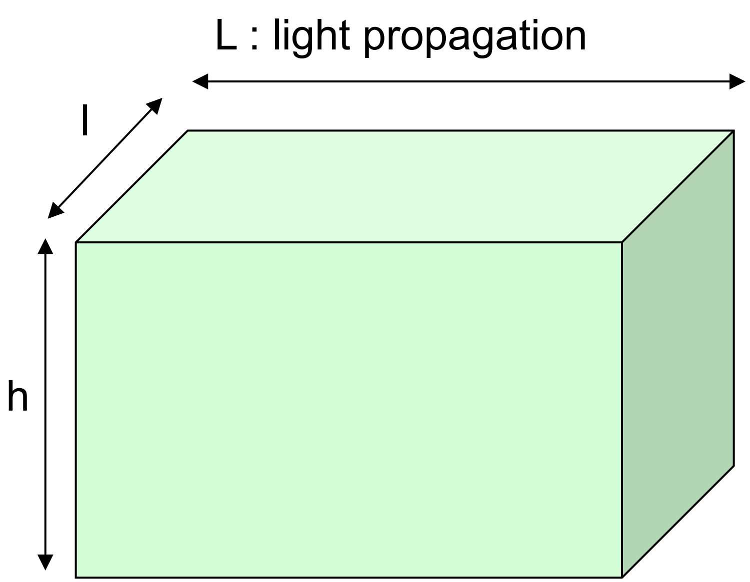
Geometries

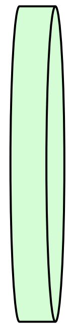
Increase the **surface / volume** ratio for efficient heat removal

$$S \propto hl + hL + Ll$$

$$V \propto Llh$$

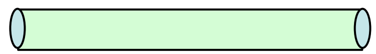


$L \rightarrow 0$ Thin disk
Yb:YAG



$h \rightarrow 0$ Slab
Yb:YAG

$h, l \rightarrow 0$ Fiber
Yb:glass



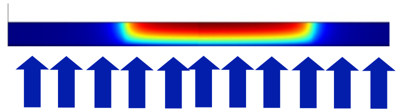
Crystal fiber
Yb:YAG

High power fs thin-disk systems

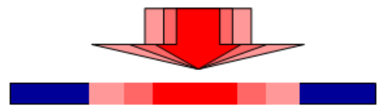
- Advantage : peak power
- Drawback : small gain

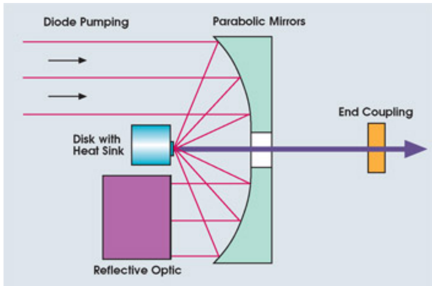
  pump recycling

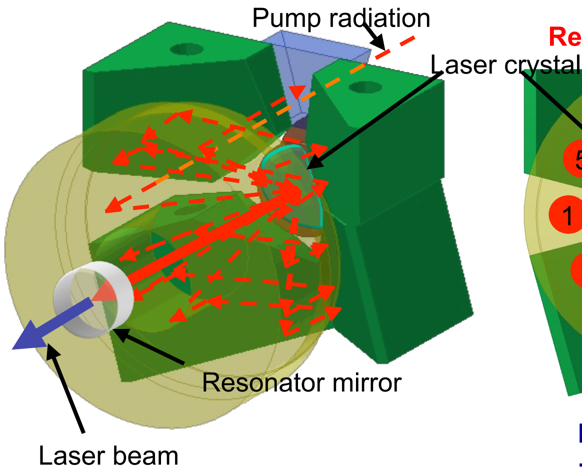
  beam quality at high power

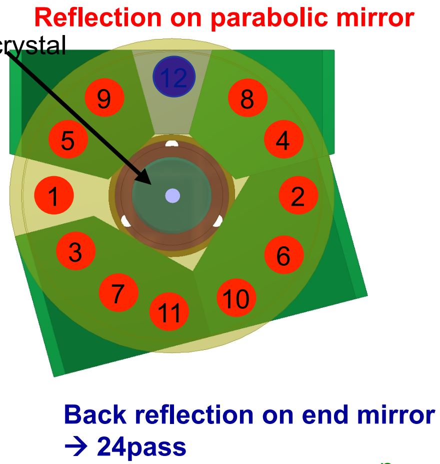


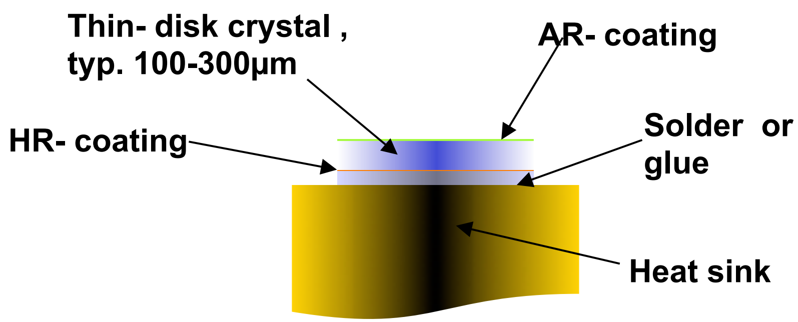
Efficient cooling
and energy scalable

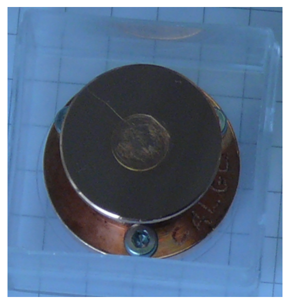






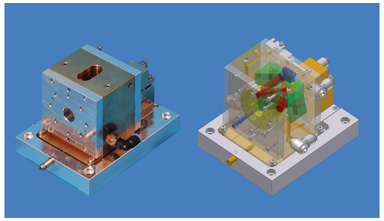






Advantages and drawbacks of Thin Disk

Advantages



Drawbacks

• Optimized pump/ signal overlap, pump recycling

→ efficiency 40%-70 %

• Large transverse dimensions (2D)

→ High energy (1 J) is possible

• Small longitudinal dimension: efficient cooling

→ Large average power (kW)

• Crystal medium

→ Choice of material

• Small longitudinal dimension

→ Small gain/absorption per pass => numerous passes

→ Complex systems for pump recycling

• Free space propagation in gain medium

→ Thermal effects modify the beam

• Only truly validated with Yb:YAG

→ ps-amplifiers

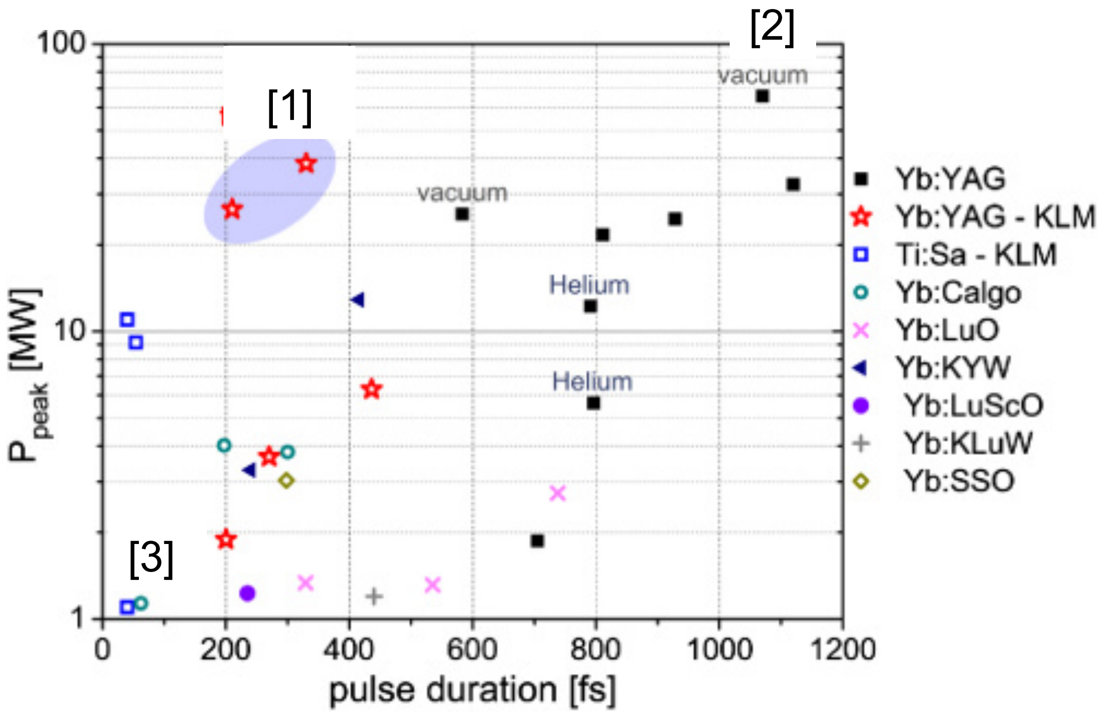
Thin disk fs oscillators

VERY-HIGH **average power oscillators**

270 W, 18 MHz 210 fs, 15 µJ, Yb:YAG [1]

80 µJ, 3 MHz, 242 W, 1.1 ps, Yb:YAG [2]

62 fs, 62 MHz, 5 W, 80 nJ, Yb:CALGO [3]



[1] Jonathan Bronset al., "Energy scaling of Kerr-lens mode-locked thin-disk oscillators," Opt. Lett. 39, 6442-6445 (2014)

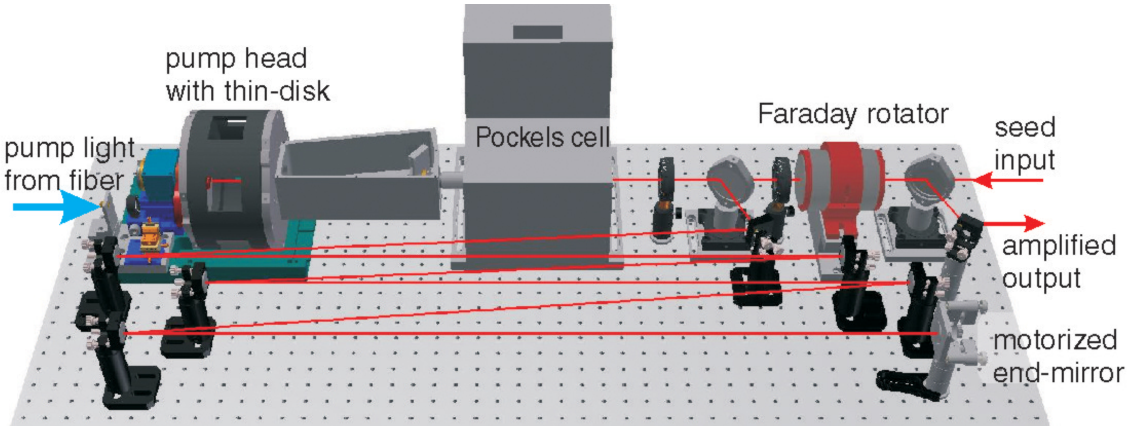
[2] Clara J. et al.and Ursula Keller, "Ultrafast thin-disk laser with 80 µJ pulse energy and 242 W of average power," Opt. Lett. 39, 9-12 (2014)

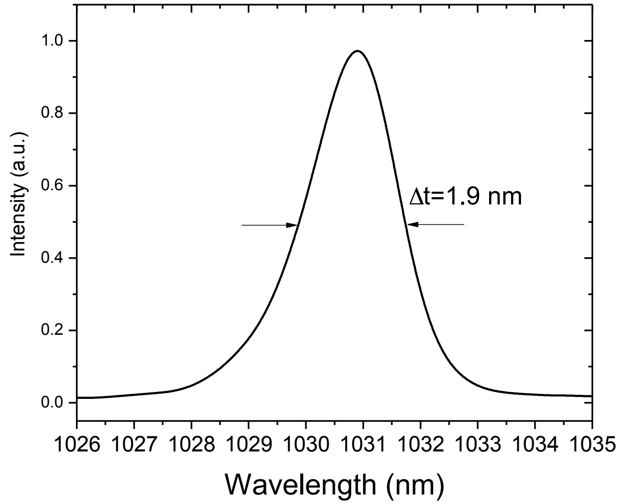
[3] Andreas Dieboldet al. Ursula Keller, "SESAM mode-locked Yb:CaGdAlO4 thin disk laser with 62 fs pulse generation," Opt. Lett. 38, 3842-3845 (2013)

High energy thin-disk amplifier

200 mJ, 200 W, ~100 GW peak, 1.3 ps, 1 kHz

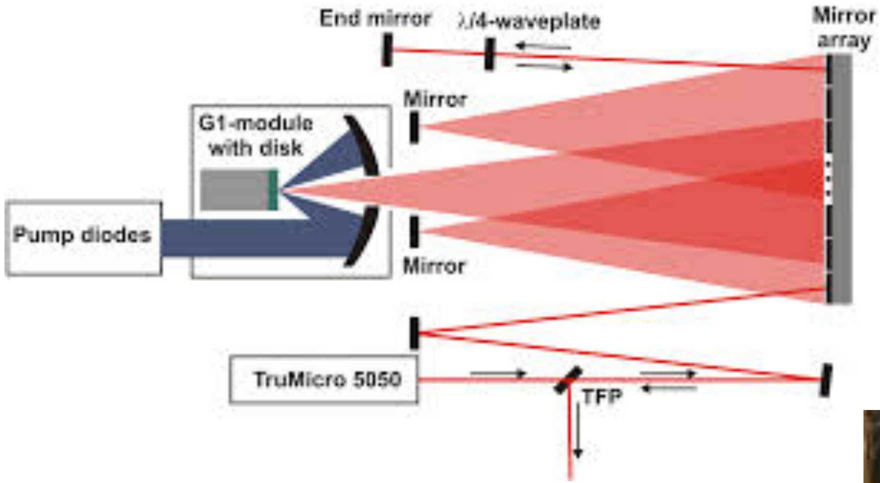
- Regenerative amplifier Yb:YAG, beam size (around 2.6 mm diameter on





TRUMPF

kW systems :Multipass amplifiers



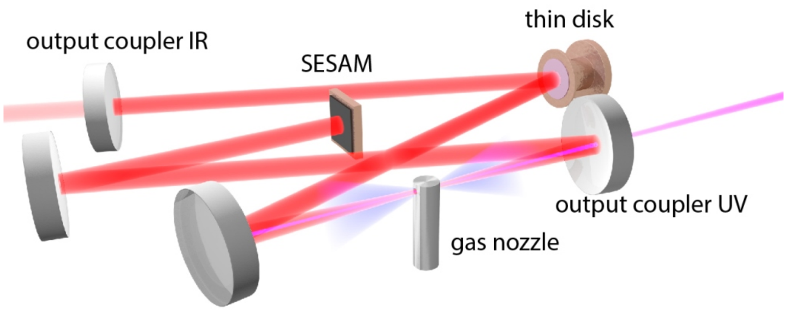
High number of passes

1420 W
300 kHz
sub-8 ps
4.7 mJ
Efficiency 70 %

Jan-Philipp Negel, et al. and Thomas Graf, "Ultrafast thin-disk multipass laser amplifier delivering 1.4 kW (4.7 mJ, 1030 nm) average power converted to 820 W at 515 nm and 234 W at 343 nm," Opt. Express 23, 21064-21077 (2015)

Future trends

Oscillators : Very high intra-cavity peak power oscillators

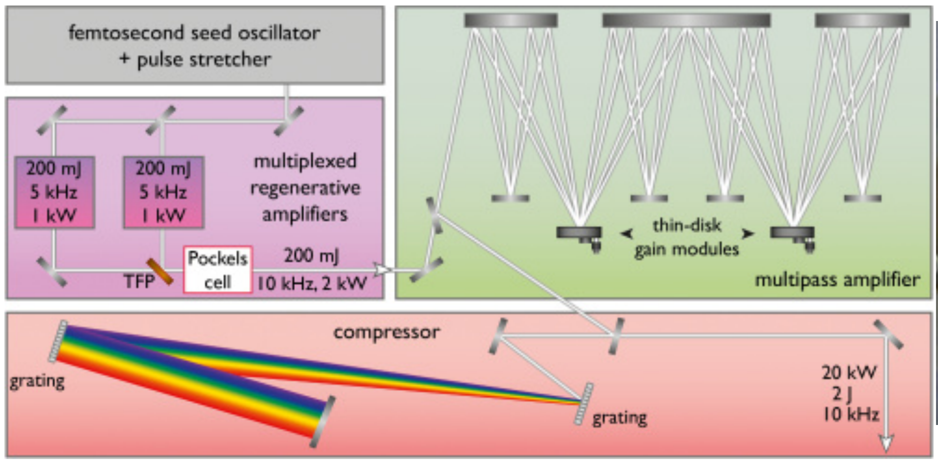


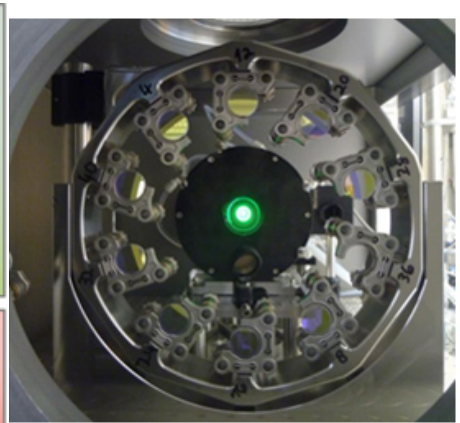
>100 MW (intra)
10 MHz

Clara J. Saraceno, et al. Ursula KellerTowards oscillator driven strong-field experiments using high-energy modelocked thin-disk lasers
A. Amani Eilanlou et al. « Femtosecond laser pulses in a Kerr lens mode-locked thin-disk ring oscillator with an intra-cavity peak power beyond 100 MW » Japanese Journal of Applied Physics Vol. 53, Issue 8 (2014)

Amplifiers : Route to the Joule, soon Joule level @ 1 kHz

And even more after
Project : 2J, 10 kHz

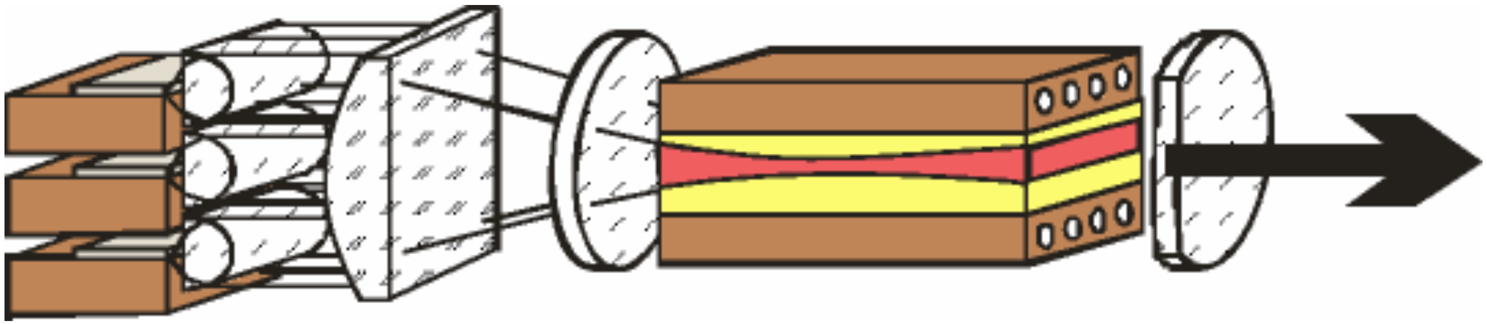


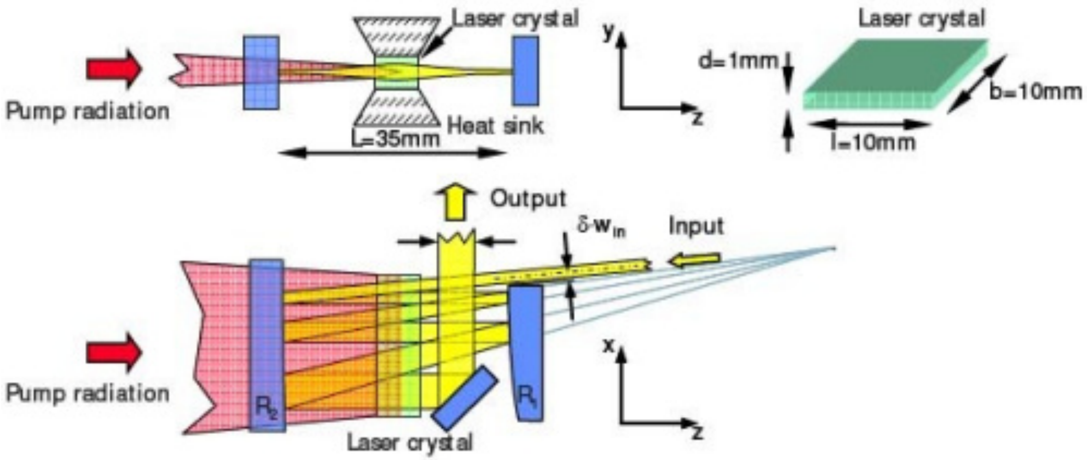


Hanieh Fattahi, et al. and Ferenc Krausz, "Third-generation femtosecond technology," Optica 1, 45-63 (2014)

High power slab fs amplifiers

- Advantages of slab: average power
- Drawback: complexity, difficult scalability
- State of the art





Advantages and drawbacks of slab

Advantages

- Large interaction length (several cm)

→ gain

- Pump / signal overlap

→ 50% efficiency

- Large surface/volume ratio

→ heat removal

- 1 large transverse dimension

→ intermediate energy (10s of mJ) possible

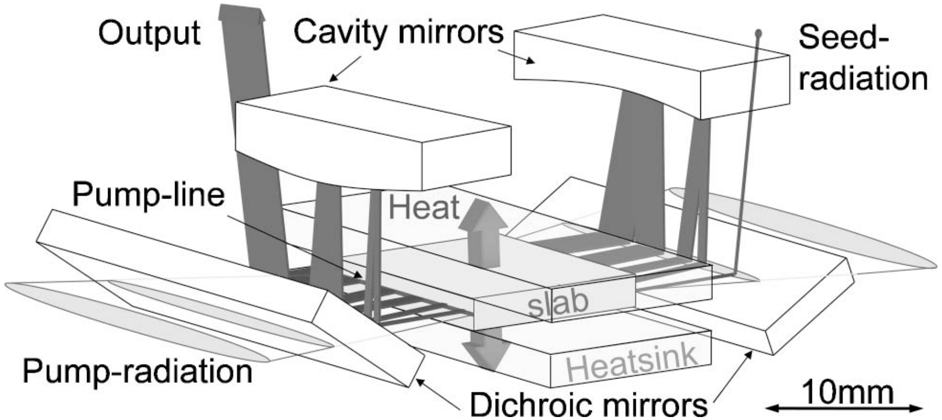
Drawbacks

- Large interaction length, no guiding

→ Complex management of pump and signal beams

→ Thermal effects modify the beam

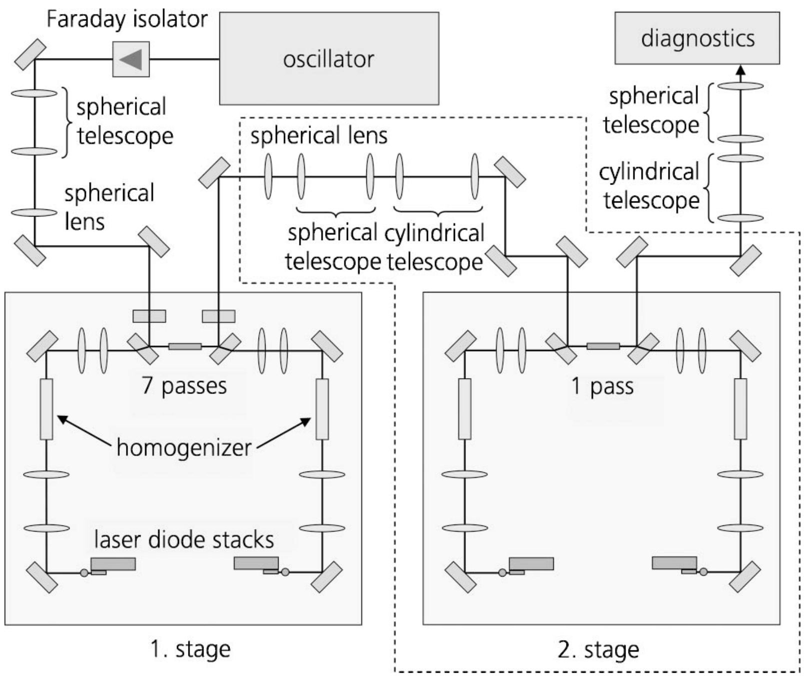
→ Linked to a precise operating point : difficult scalability

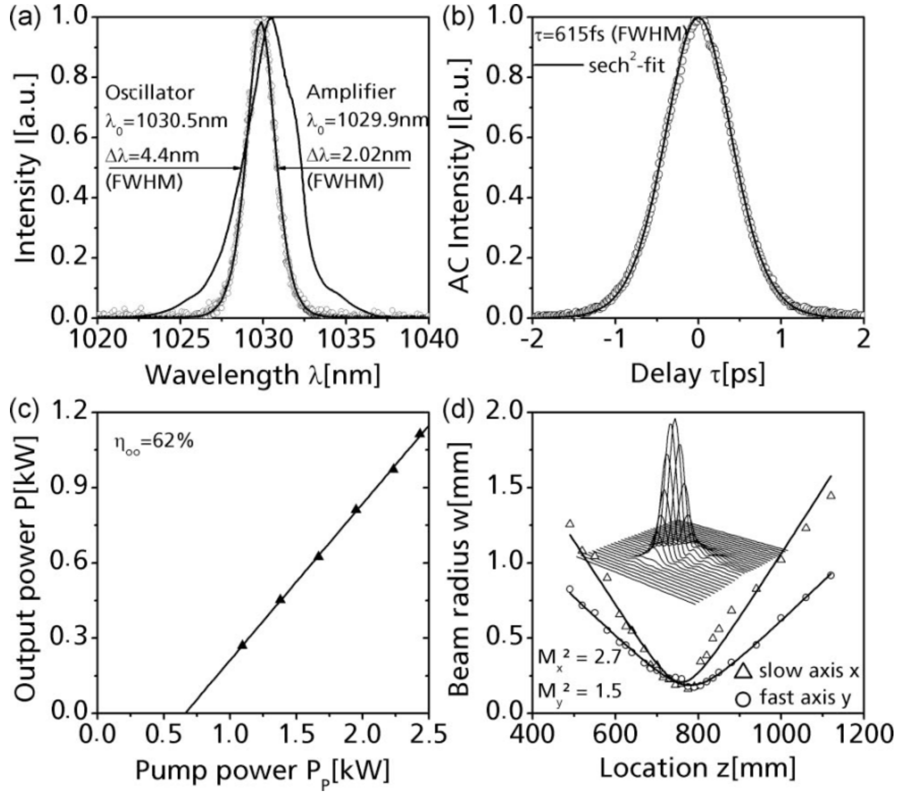


State of the art: high power

55 µJ, 80 MW peak, 1.1 kW average, 615 fs, 20 MHz

- Pump 2.4 kW, no CPA, 2 stages, crystal size 10×10×1 mm, beam quality M^2_x~2.7 (thermal effects)

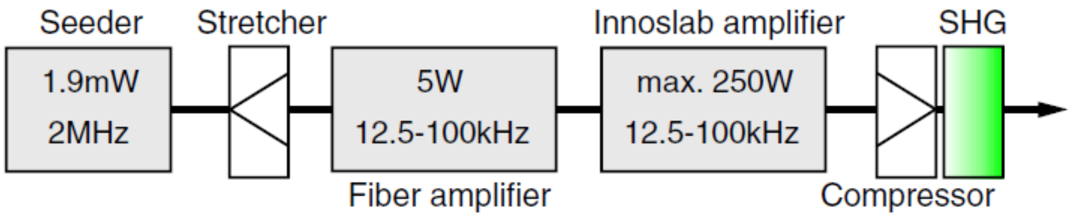


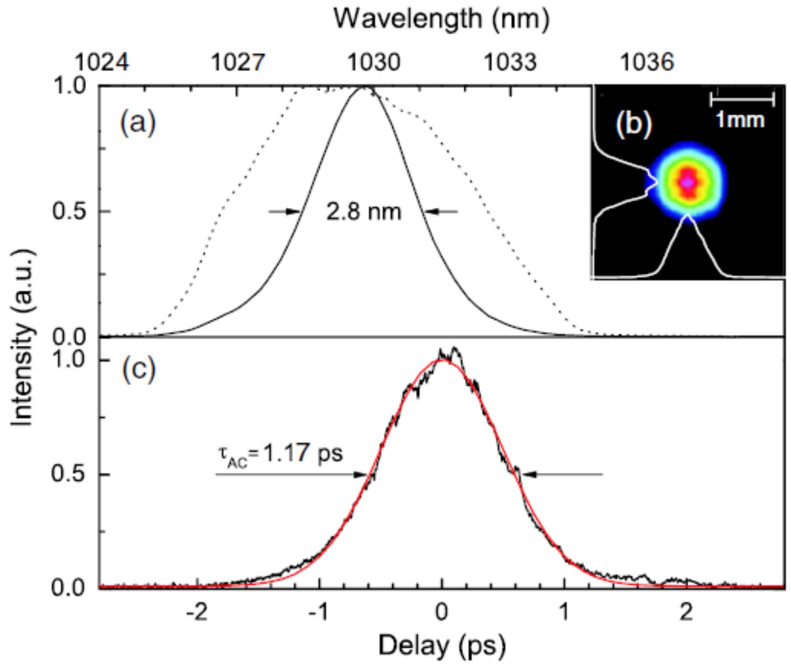


[1] P. Russbueldt, T. Mans, J. Weitenberg, H. D. Hoffmann, and R. Poprawe, "Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier," Opt. Lett. **35**, 4169-4171 (2010)

State of the art: high energy

20 mJ, 20 GW peak, 250 W, 1 ps, 12.5 kHz

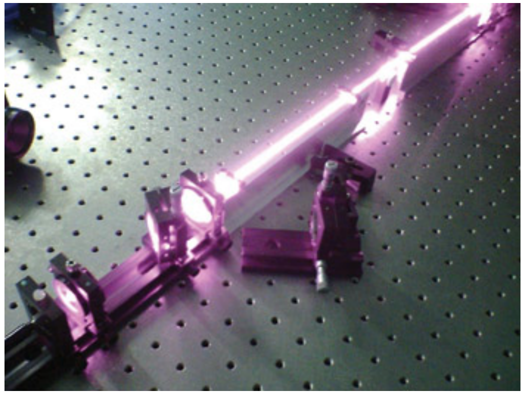


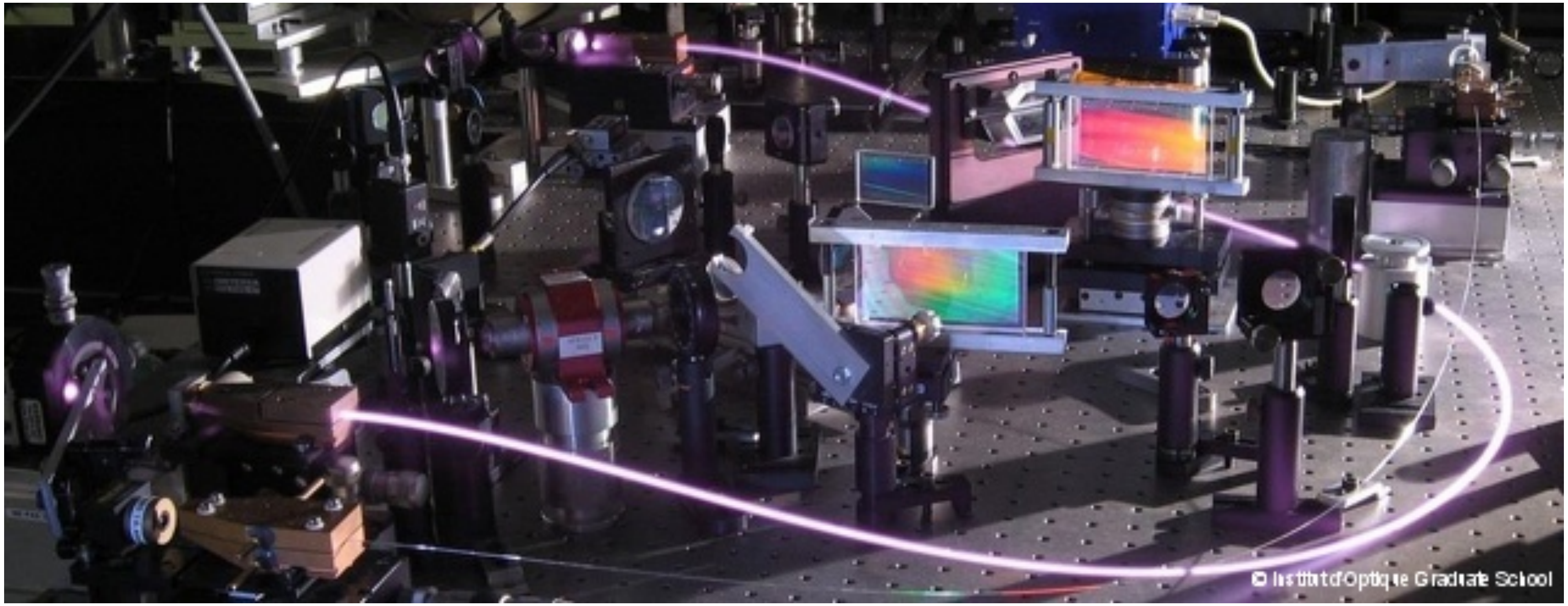


M. Schulz, R. Riedel, A. Willner, T. Mans, C. Schnitzler, P. Russbueldt, J. Dolkemeyer, E. Seise, T. Gottschall, S. Hädrich, S. Duesterer, H. Schlarb, J. Feldhaus, J. Limpert, B. Faatz, A. Tünnermann, J. Rossbach, M. Drescher, and F. Tavella, "Yb:YAG Innoslab amplifier: efficient high repetition rate subpicosecond pumping system for optical parametric chirped pulse amplification," Opt. Lett. 36, 2456-2458 (2011)

High power fs fiber amplifiers

- Advantages: average power, beam quality
- Drawbacks : peak power
- State of the art





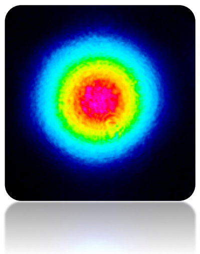
Advantages and drawbacks of fibers

Advantages

• Guided signal and pump:
large interaction length
→ large gain, high efficiency (70 %)

• Integrated systems
→ Compact and robust laser sources

• Small transverse dimensions
→ good heat removal



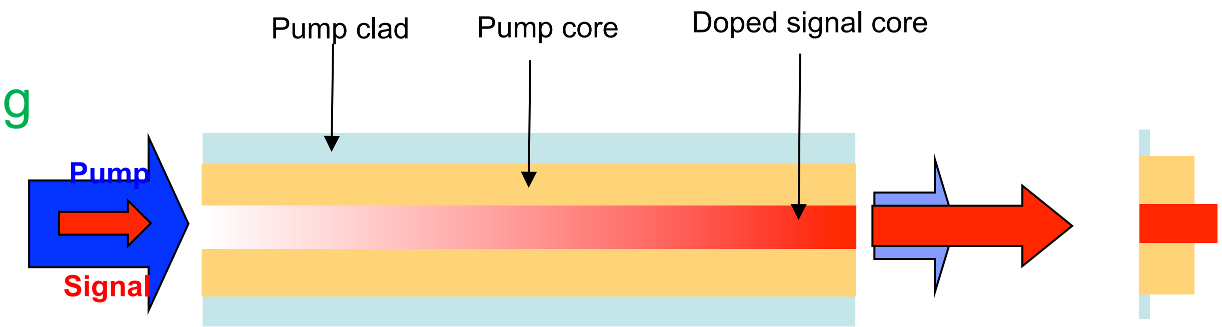
• Double clad geometry
→ single mode signal
→ High power
diode pumping

Drawbacks

• Beam is guided with diameter ~ 10s of µm
→ High intensity (W/m^2)
→ Low damage threshold (~ mJ)
→ endcaps

→ Nonlinear effects

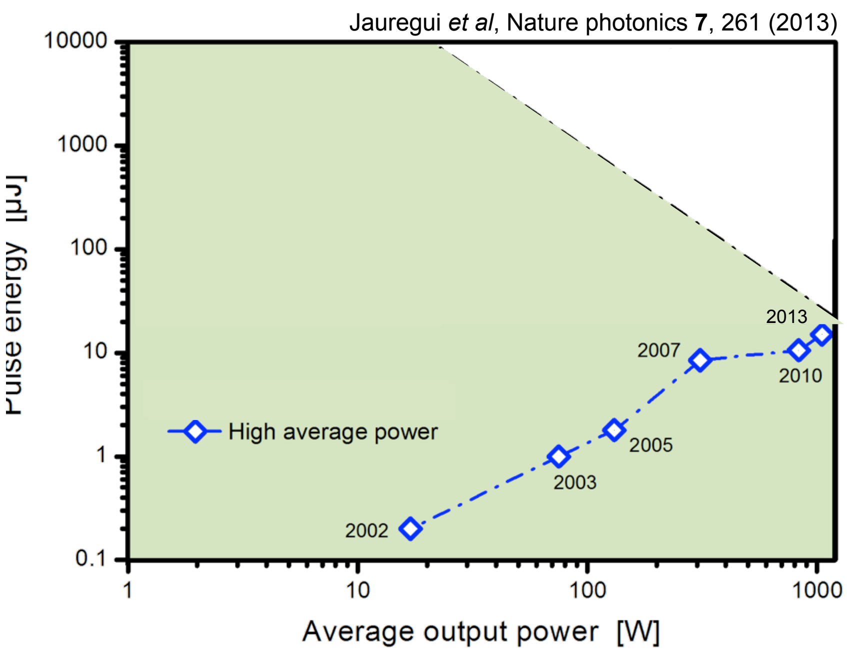
• Double clad geometry
→ glass : the only option



Energy or power

Tradeoff on the design of fibers

Average power : reducing local thermal loads : long LMA fibers



Long fiber: non-linearity issues

1 kW, 55 µJ, 69 MHz, , 800 fs [1]
30µm 8-m-long fiber

[1] Peng Wan, et al., "All fiber-based Yb-doped high energy, high power femtosecond fiber lasers," Opt. Express 21, 29854-29859 (2013)
[2] Tino Eidam, aet al. Limpert, and Andreas Tünnermann, "Fiber chirped-pulse amplification system emitting 3.8 GW peak power," Opt. Express **19**, 255 (2011)

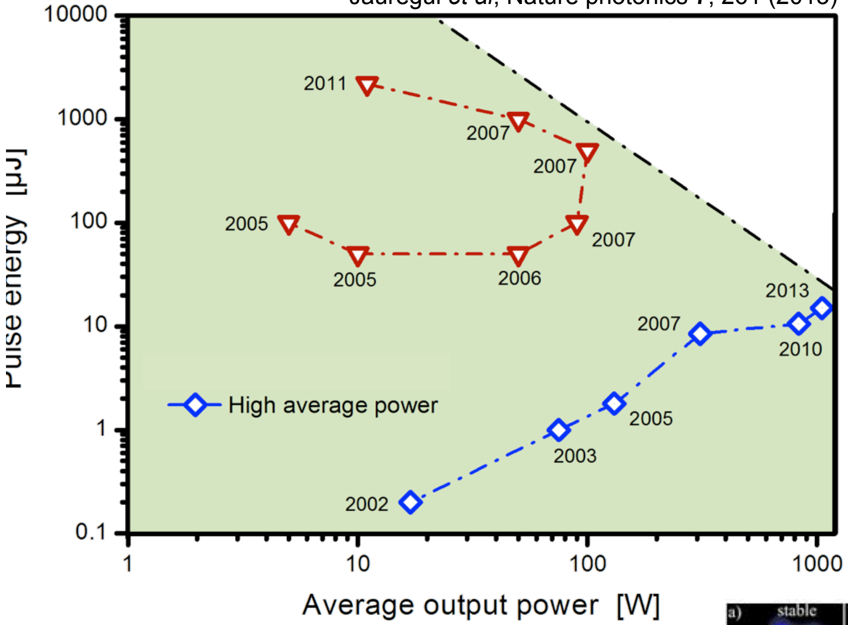
Energy versus power

Tradeoff on the design of fibers

Average power : reducing local thermal loads : long LMA fibers

Peak power, energy : reducing B-integral: short ultra LMA rodtype fibers)

Jauregui *et al*, Nature photonics **7**, 261 (2013)



Long fiber: non-linearity issues

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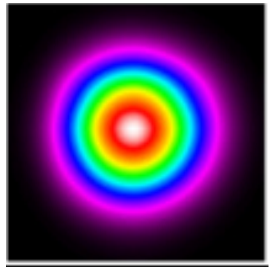
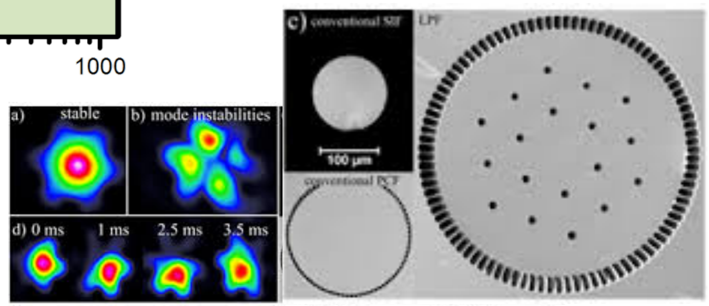


Large core : mode-instability issues



2.2 mJ, 3.8 GW peak,
11 W average,
500 fs, 5 kHz [2]
LMA 105 µm, length
1.3 m

[1] Peng Wan, et al., "All fiber-based Yb-doped high energy, high power femtosecond fiber lasers," Opt. Express 21, 29854-29859 (2013)

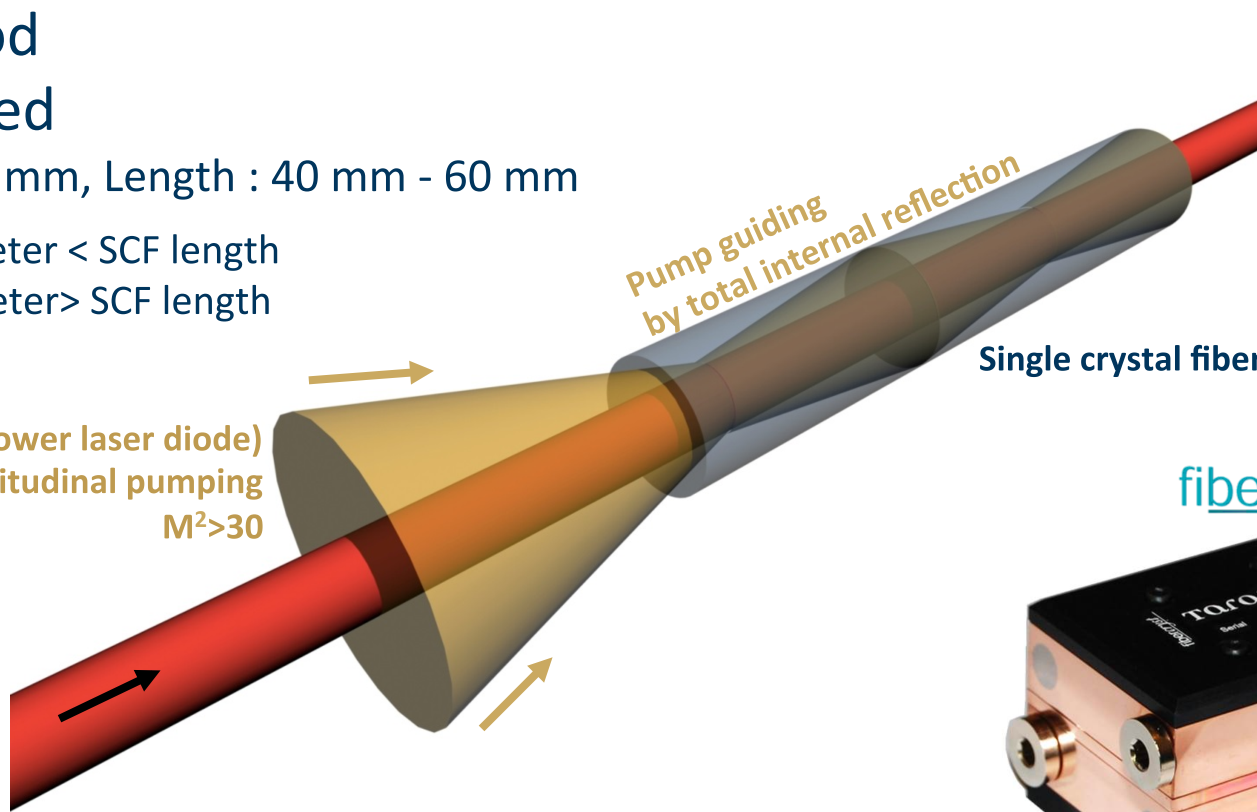
[2] Tino Eidam, aet al. Limpert, and Andreas Tünnermann, "Fiber chirped-pulse amplification system emitting 3.8 GW peak power," Opt. Express **19**, 255 (2011)

Fiber-like crystals

Long and thin rod
Signal NOT guided

diameter : 500µm - 1 mm, Length : 40 mm - 60 mm

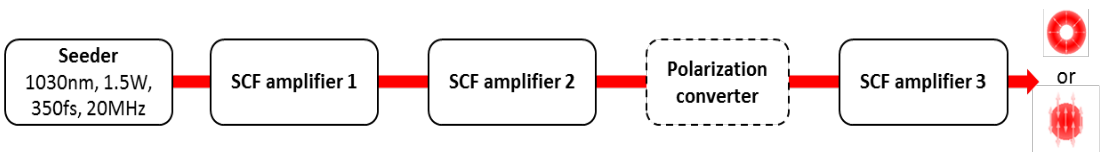
Pump confocal parameter < SCF length
Signal confocal parameter> SCF length



Pump beam (high power laser diode)
Longitudinal pumping
$M^2>30$

Laser beam
in free space propagation
$M^2=1$

fibercryst



85 W ; 700 fs ; 20 MHz → 4.3 µJ ; 6 MW

100 W ; 700 fs ; 20 MHz → 5 µJ ; 7 MW

Synthesis on thin-Disk, slab, fiber systems

Techno	Power	Rep'rate	Energy	Duration	max peak power
Thin disk	1.43 kW	300 kHz	4,7 mJ	8 ps	
	200 W	1 kHz	200 mJ	1,3 ps	100 GW
Slab	1,1 kW	20 MHz	55 µJ	615 fs	
	250 W	12 kHz	20 mJ	1,2 ps	20 GW
Fibre	1 kW	69 MHz	15 µJ	800 fs	
	11 W	5 kHz	2,2 mJ	500 fs	4 GW
Crystal fiber	100 W	20 MHz	5 µJ	700 fs	

Conclusions:

- Thin disk & Slab & fibres : kW technologies
- Energy issues especially for fibers
- Duration issues especially for Yb:YAG

Outlook

- Introduction : the Ti:Sa limitations and its alternatives
- Yb-doped technologies
  - Thin-disk, Slab, Fibers…
- Energy scaling
  - The coherent combining
  - Simple Yb:YAG boosters
- Duration issues
  - Non-linear techniques
- Conclusion

Higher energies with coherent combining

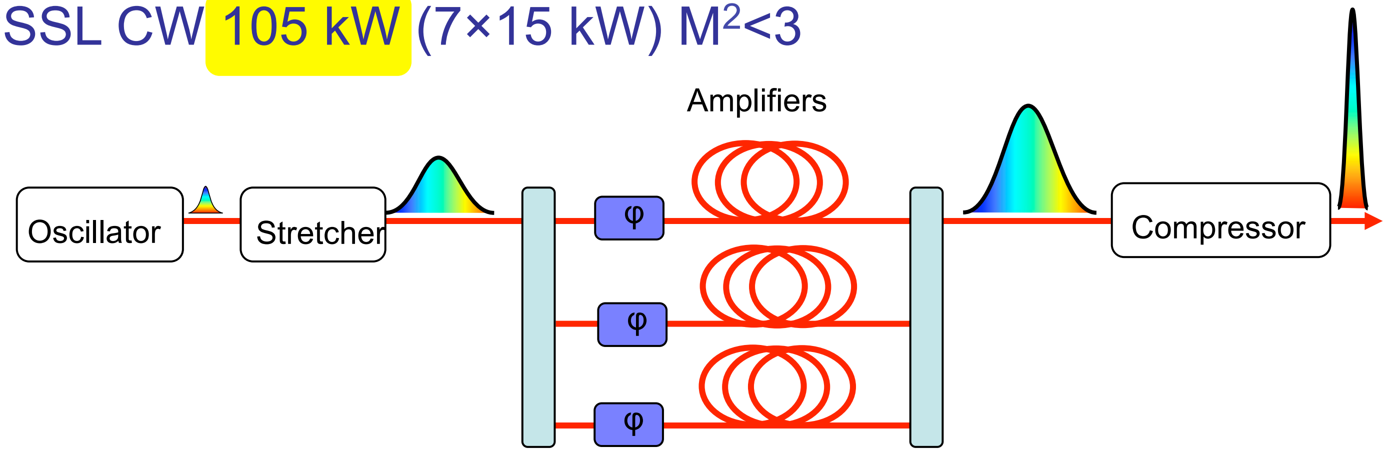
Option 1

N amplified beams are recombined

→ N×power, N×energy, same spatial and temporal properties

→ Laser DPSSL CW 105 kW (7×15 kW) $M^2<3$

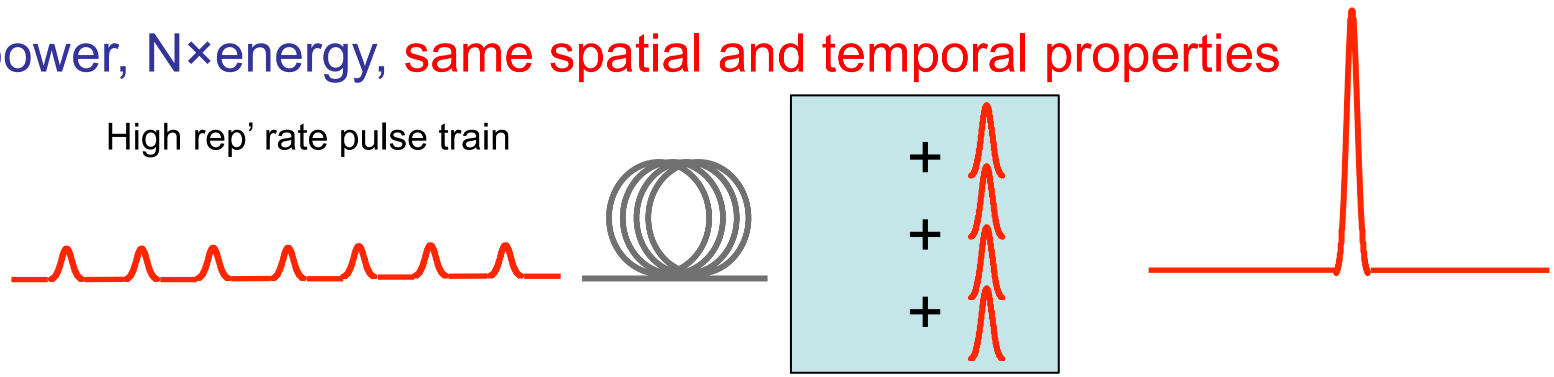
→ fs Lasers



Option 2

N beams are temporally recombined but amplified in 1 amplifier

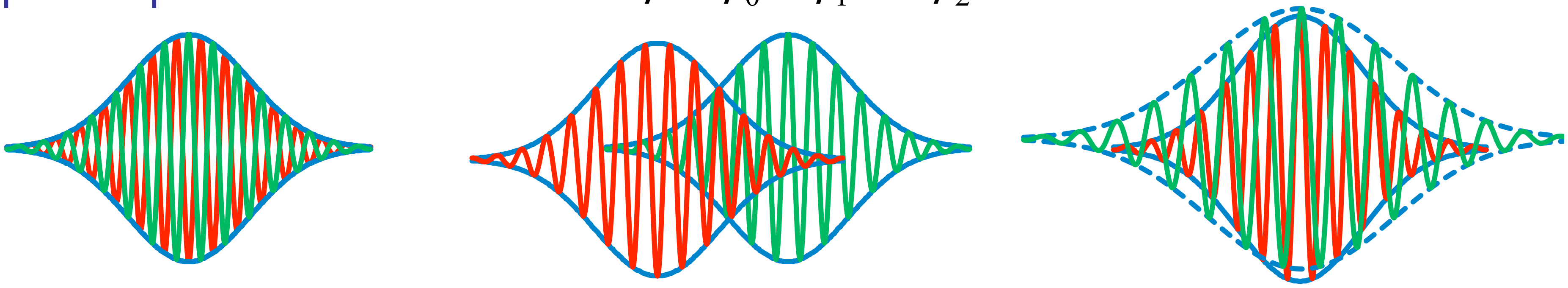
→ 1×power, N×energy, same spatial and temporal properties



fs Lasers → **Requires differential phase control of the beams**

Phase control in fs regime

Spectral phase must match: $\Delta\varphi = \varphi_0 + \varphi_1\omega + \varphi_2\omega^2$



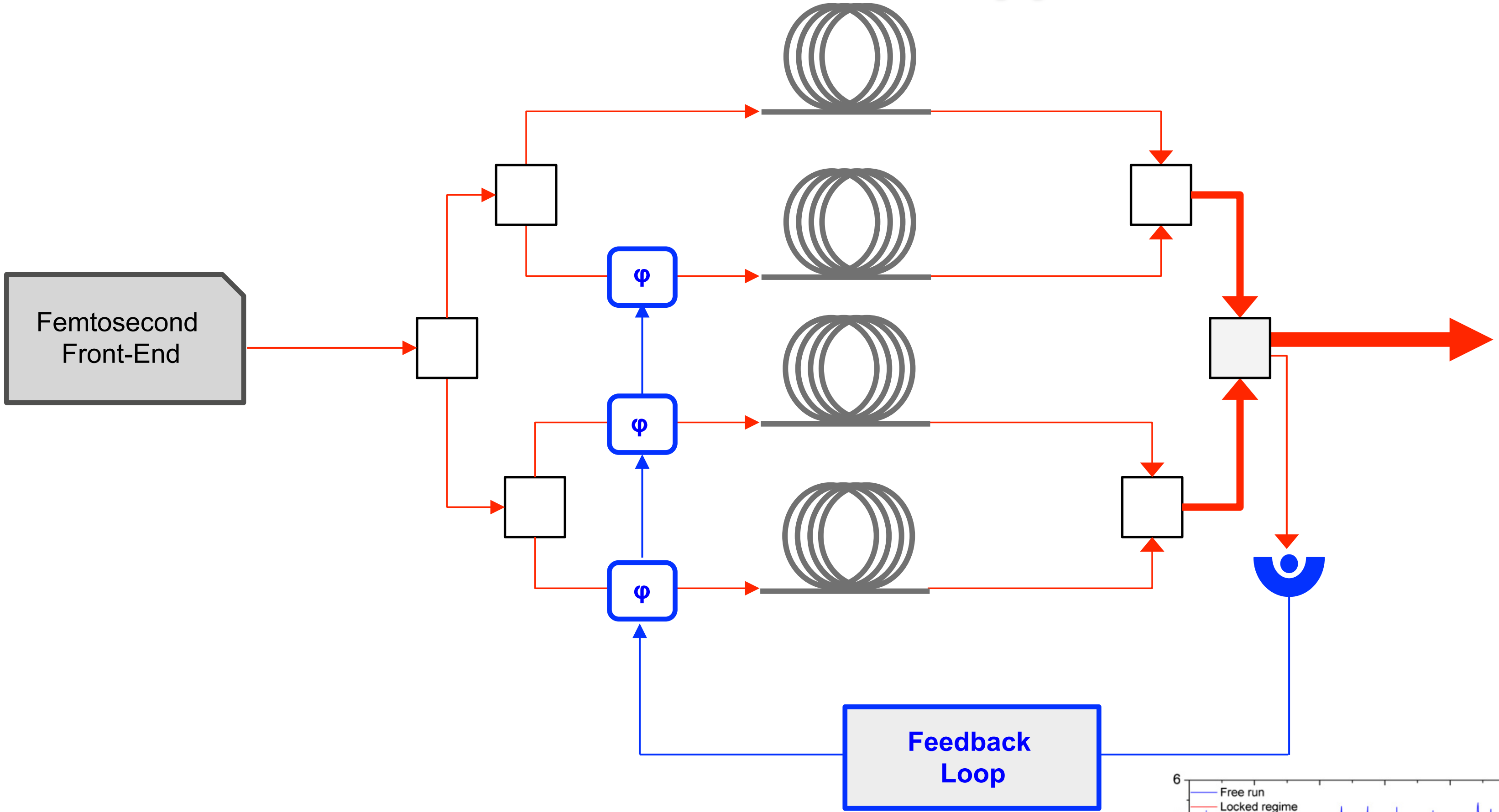
Zero-order phase φ_0 Group delay φ_1 GVD φ_2

Use of interferometric techniques

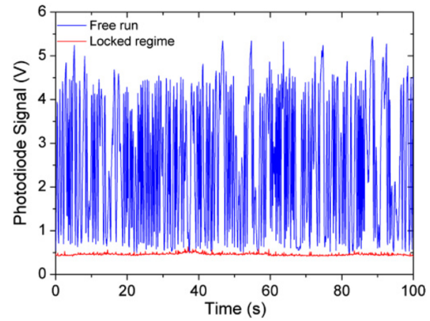
Active or passive

Active coherent combining

Mach-Zehnder type



Spatial active combining

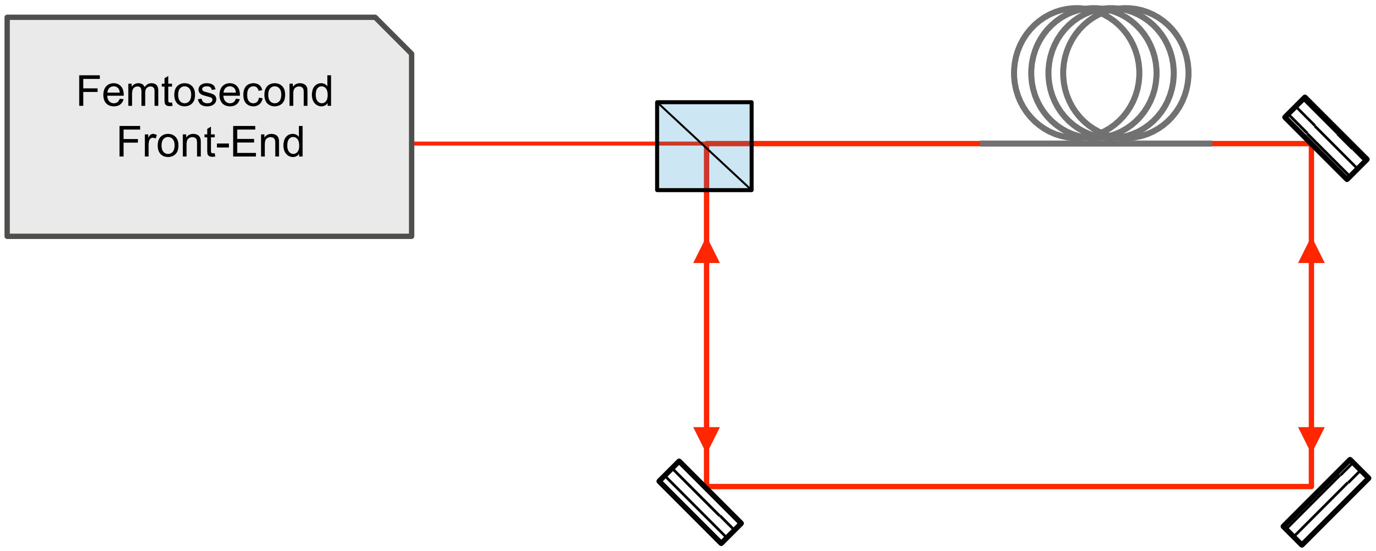


[4] Seise *et al*, Optics Letters **18**, 27827 (2010).

[5] Daniault *et al*, Optics Letters **36**, 621 (2011).

Passive coherent combining

Sagnac type



Spatial passive combining

[7] Daniault *et al*, Optics Letters **36**, 4023 (2011).

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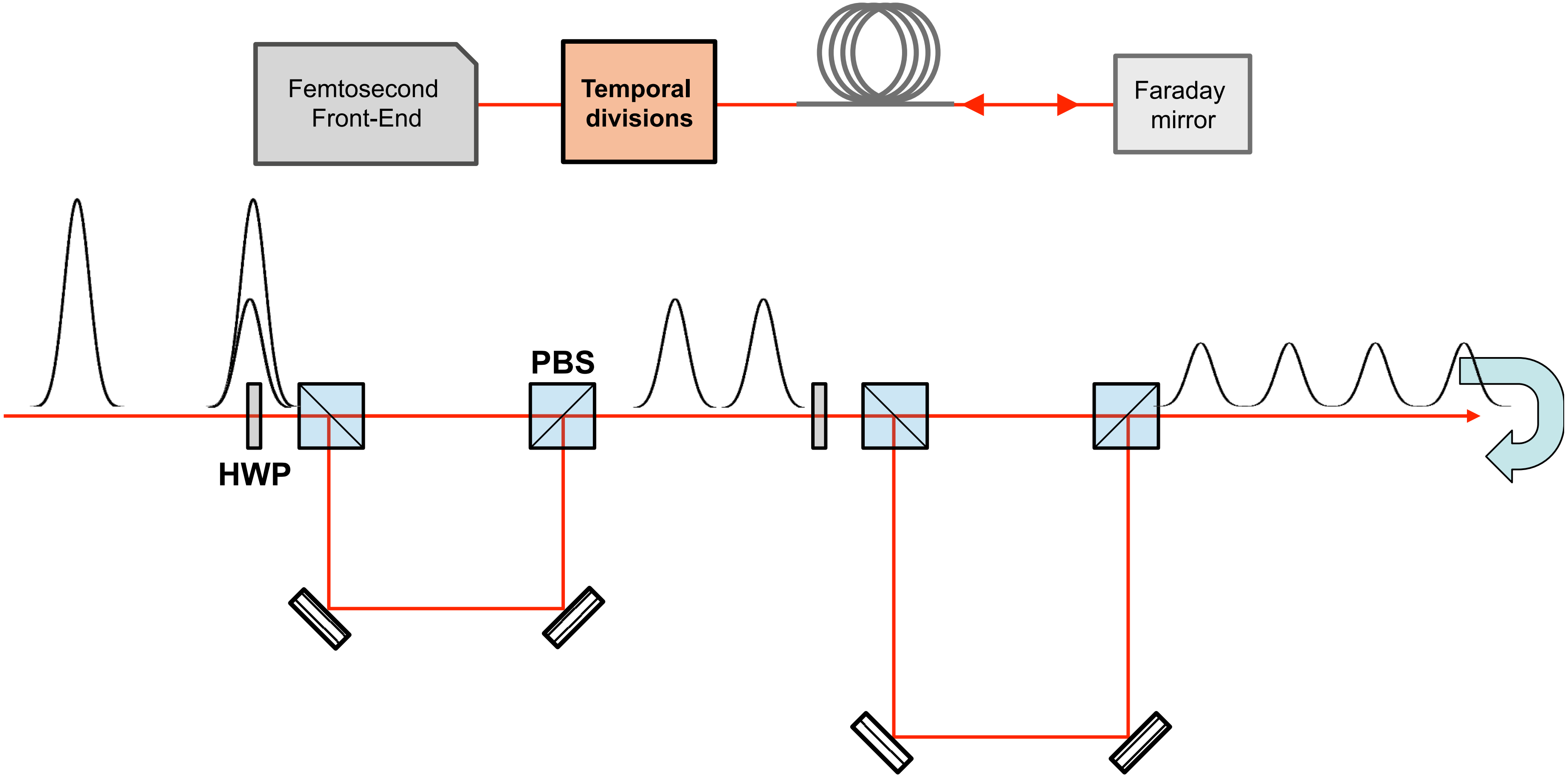
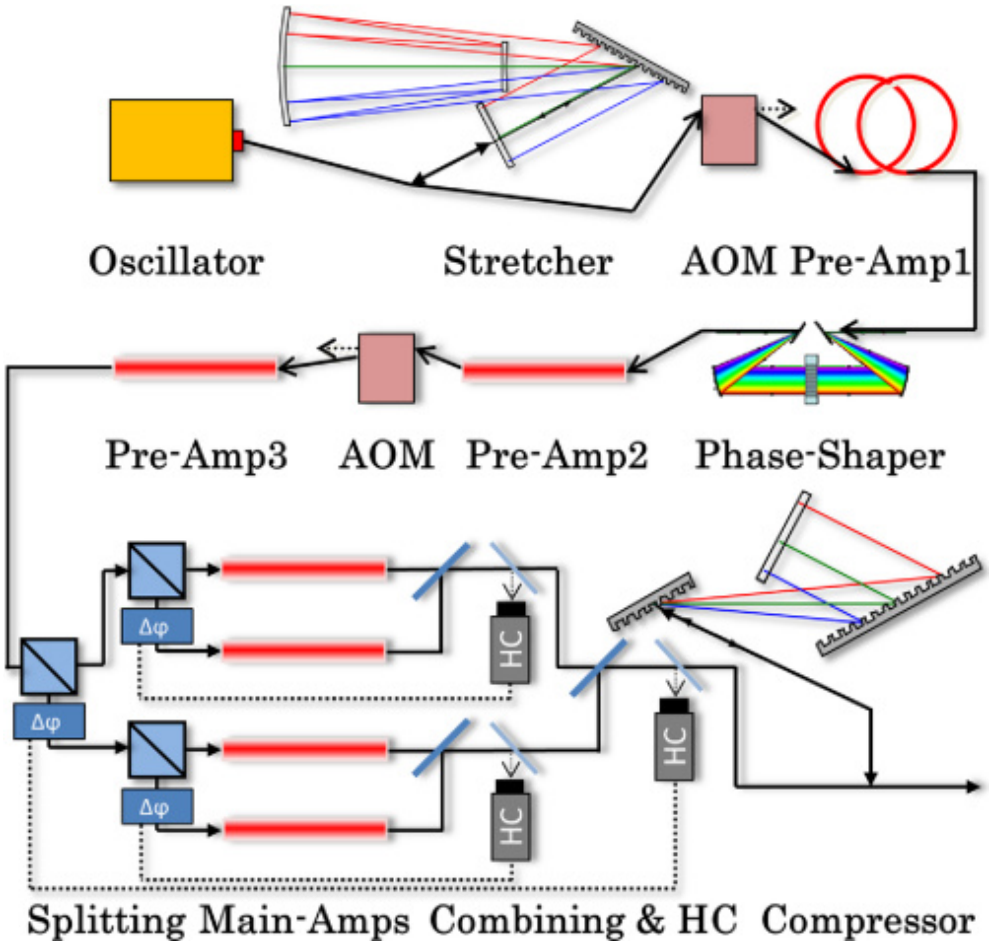
Divided pulse amplification : DPA



Temporal combining

[6] Zhou *et al*, Optics Letters. **32**, 871 (2007).
[8] Zaouter *et al*, Optics Letters **38**, 106 (2013).

State of the art: active



4 fibers
Mach-Zenhder

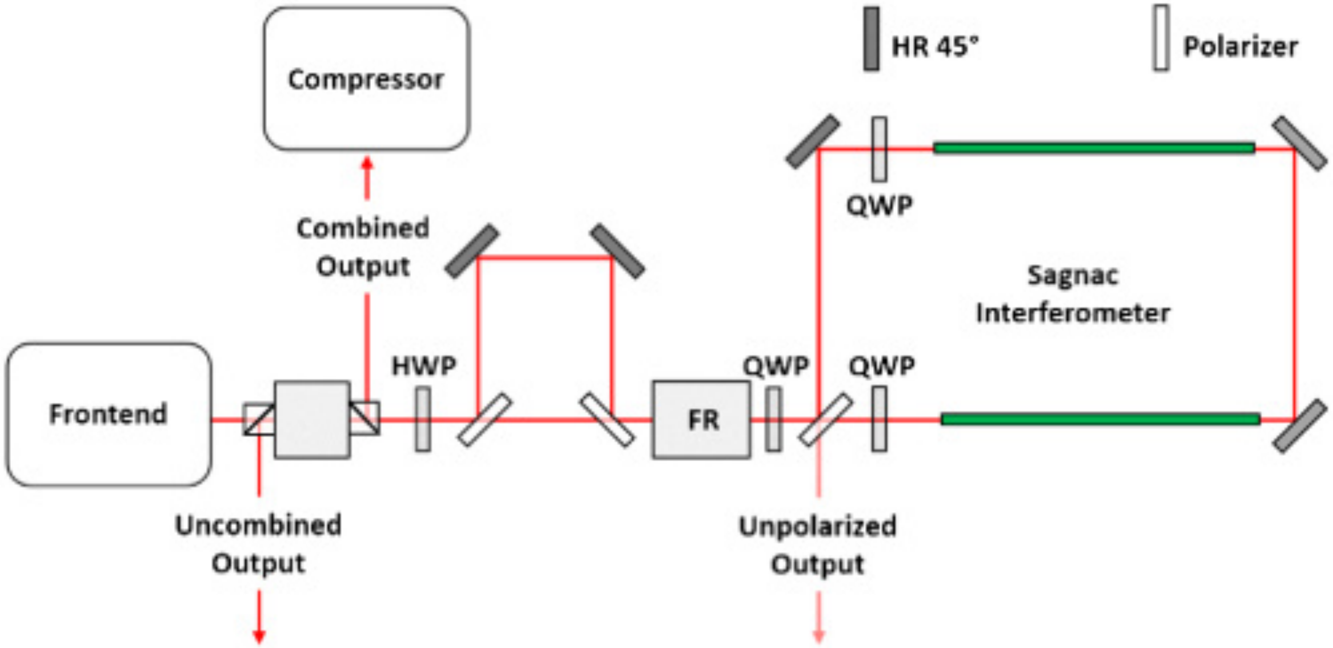
5.7 mJ, 230 W 40 kHz
200 fs 22 GW

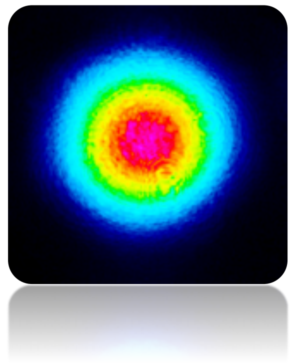
1.3 mJ , 530 W, 400 kHz
670 fs, 1.8 GW

Arno Klenke, et al. , "22 GW peak-power fiber chirped-pulse-amplification system Opt. Lett. 39, 6875-6878 (2014)
"530 W, 1.3 mJ, four-channel coherently combined femtosecond fiber chirped-pulse amplification system," Opt. Lett. 38, 2283-2285 (2013)

State of the art : passive

2 fibers : Sagnac + DPA

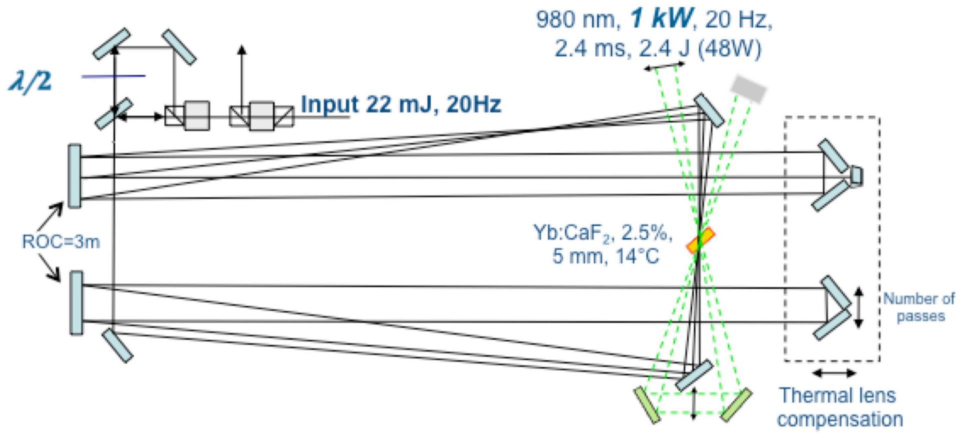


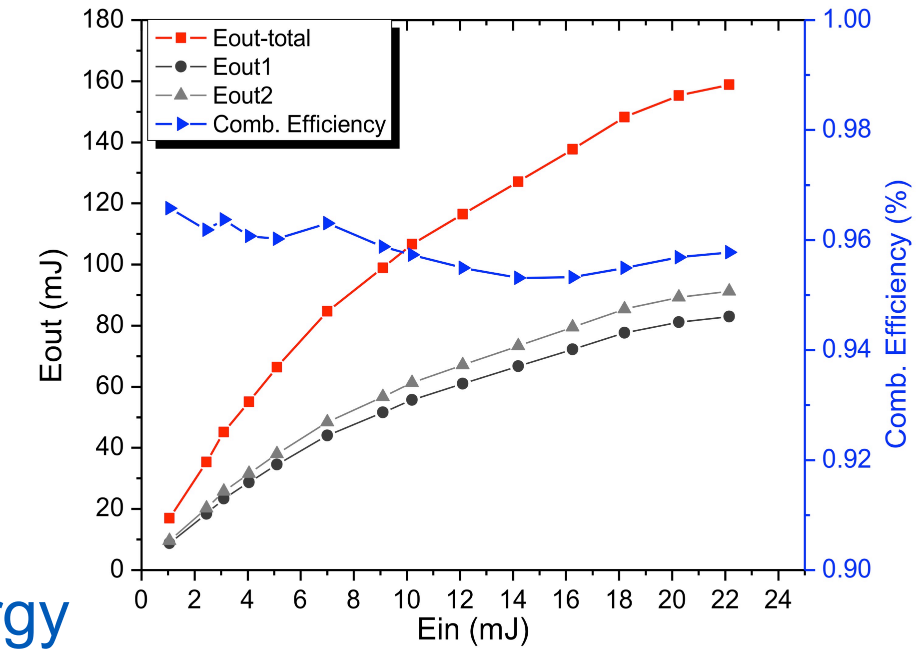


1.1-mJ, 55 W, 50 kHz
300-fs, 3.1 GW

Florent Guichard, et al., "High-energy chirped- and divided-pulse Sagnac femtosecond fiber amplifier," Opt. Lett. 40, 89-92 (2015)

Sagnac type:
130-m-long interferometer (12 passes)
Yb:CaF_2 160 mJ, 20 Hz





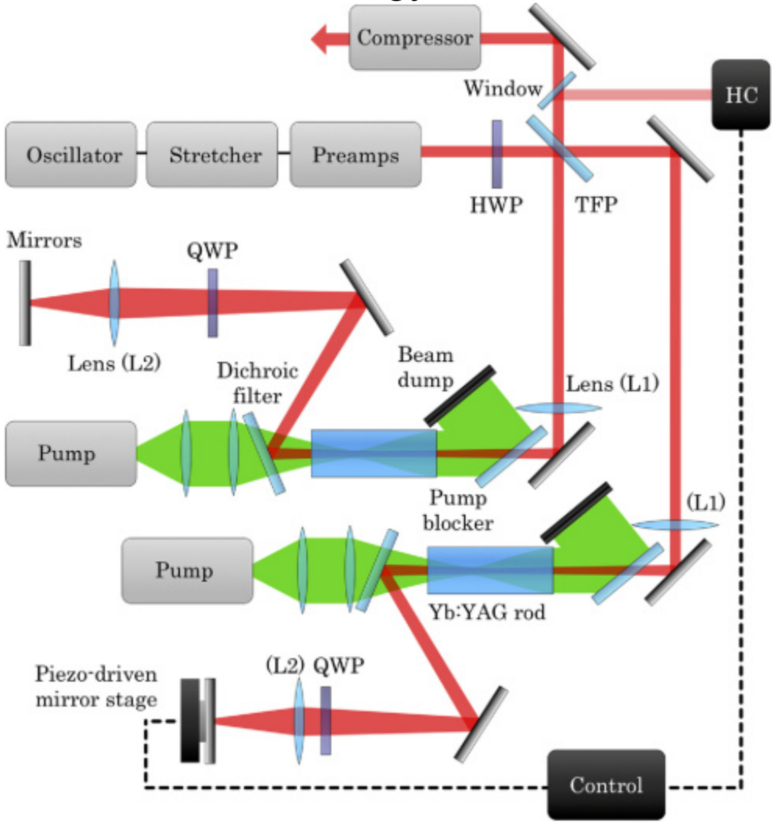
Conclusions:

It is possible even at high energy and complex systems

D.N. Papadopoulos, et al., "High Repetition Rate Yb:CaF2 Multipass Amplifiers Operating in the 100-mJ Range » Selected Topics in Quantum Electronics, IEEE Journal Issue: 1) (2015)

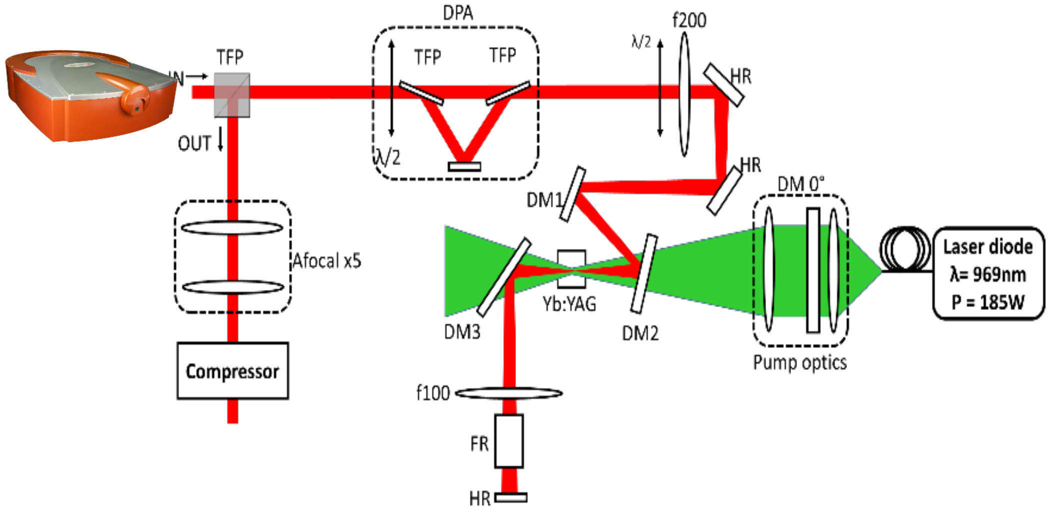
Hybrid fiber system – Yb:YAG booster

2 Single crystal fibers combined
6 kHz, 18 W
695 fs and an energy of 3 mJ, 3.7 GW



Marco Kienel, et al., "Coherent beam combination of Yb:YAG single-crystal rod amplifiers," Opt. Lett. 39, 3278-3281 (2014)

one 10mm long crystal + DPA
10 kHz, 23 W, 2.3 mJ
520 fs 4.4 GW
Or
40 W, 100 kHz, 400 µJ
360 fs, 1.1 GW



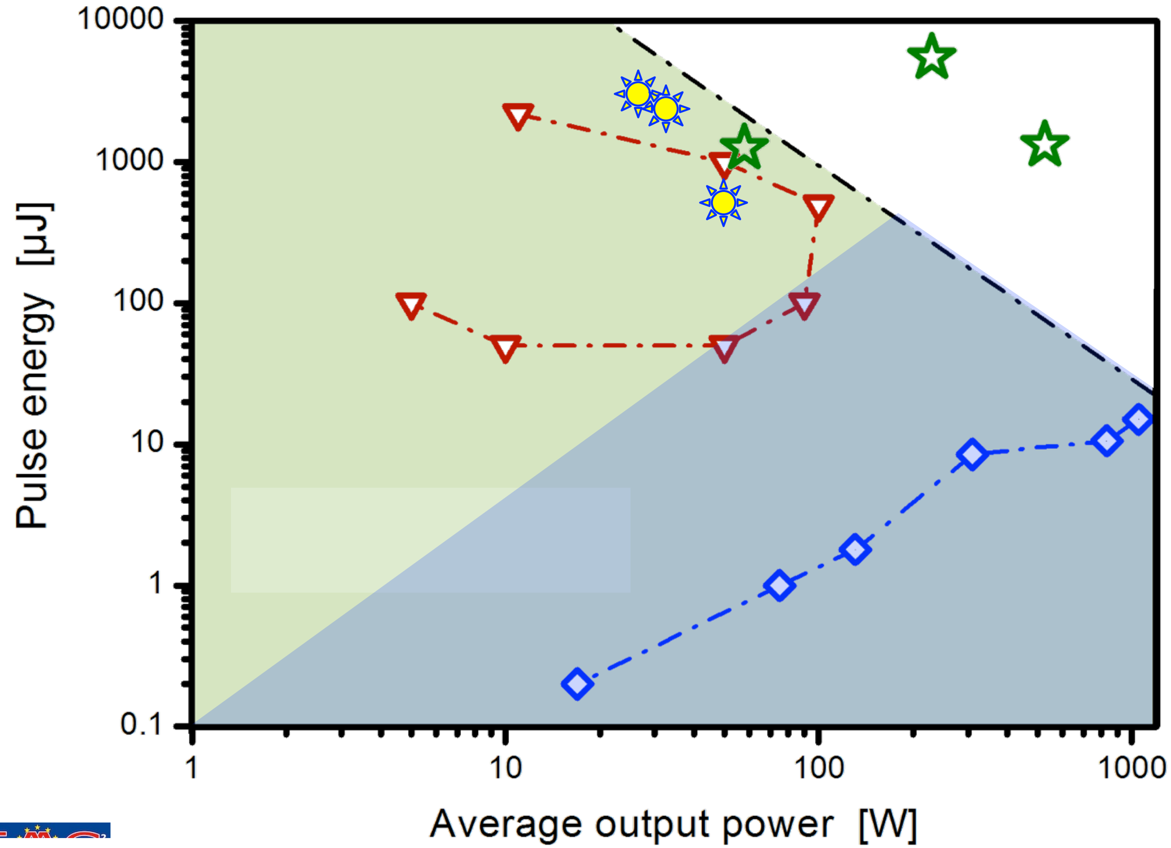
Julien Pouysegur et al. "Simple Yb:YAG femtosecond booster amplifier using divided-pulse amplification" submitted

Conclusion on these add-ons

Conclusion:

The solutions for high energy fiber based systems

- Coherent combining with fibers
- + booster Yb:YAG straightforward amplifiers



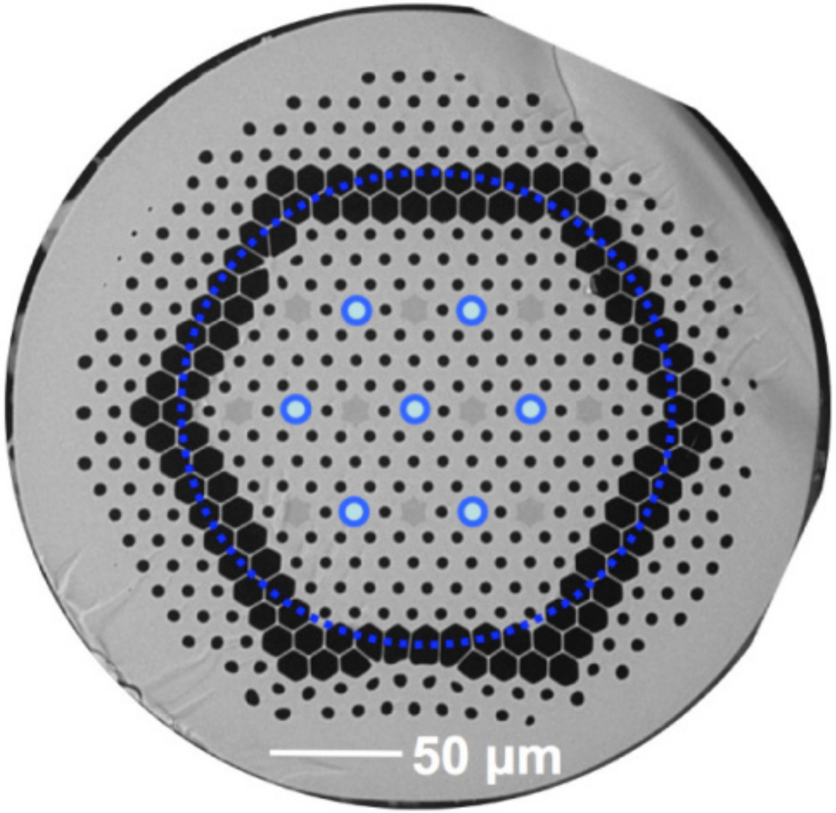
Gain in energy

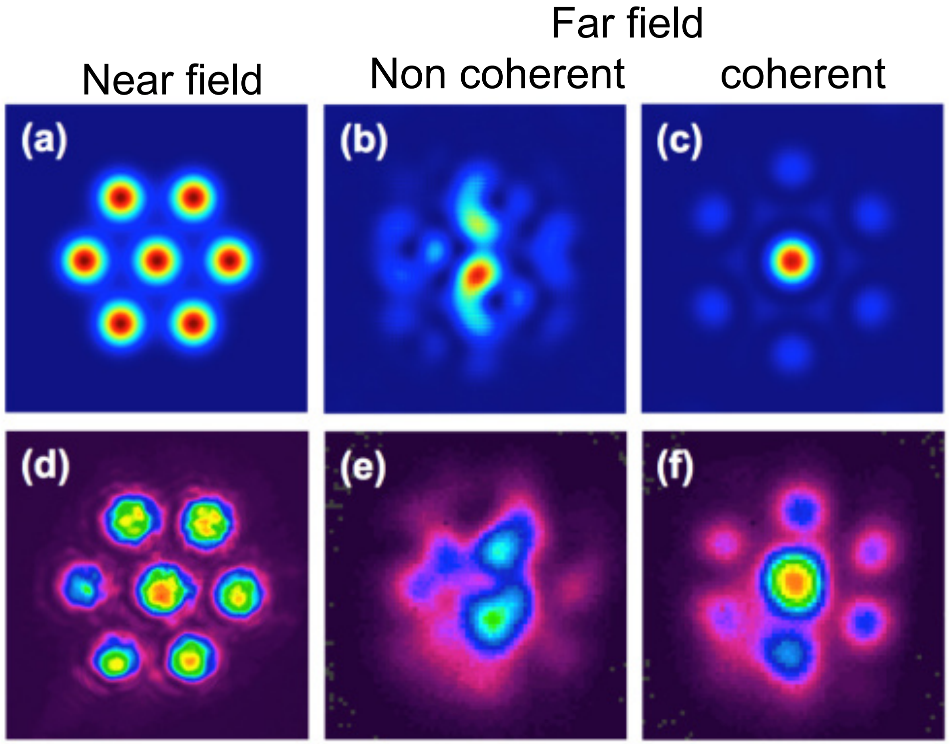
Few mJ, few GW

Prospects in coherent combining

Coherent beam combining in Multicore fibers

An unique fiber for less perturbations

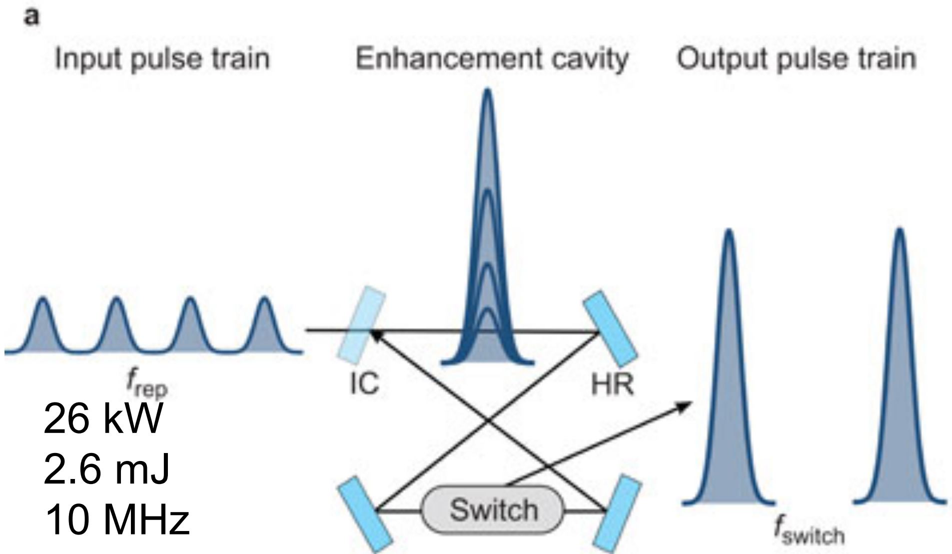




Lourdes Patricia Ramirez, et al., "Coherent beam combining with an ultrafast multicore Yb-doped fiber amplifier," Opt. Express 23, 5406-5416 (2015)

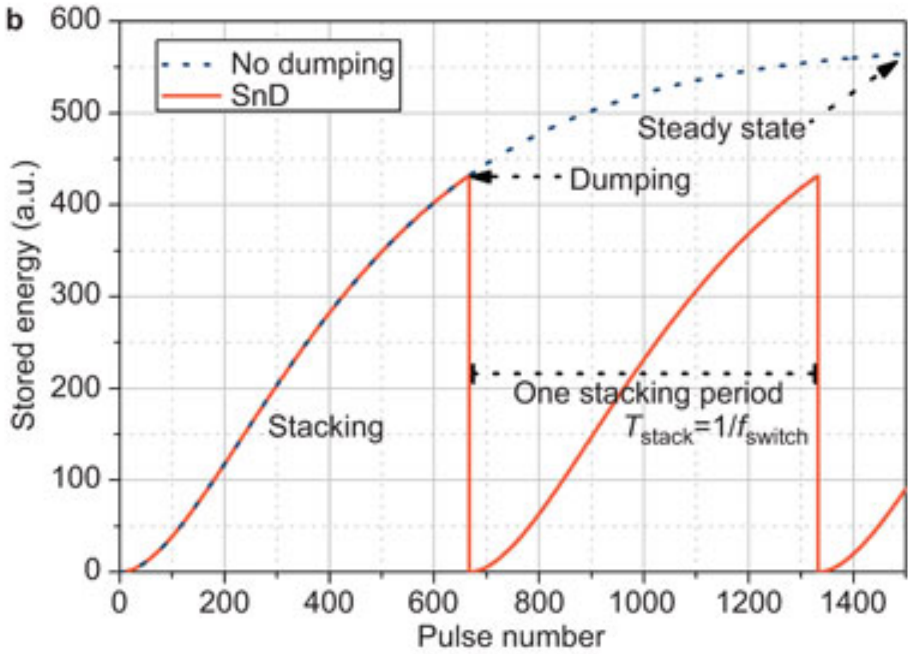
« Stack and dump » technique

Project : 1J, 15 kHz, with fibers

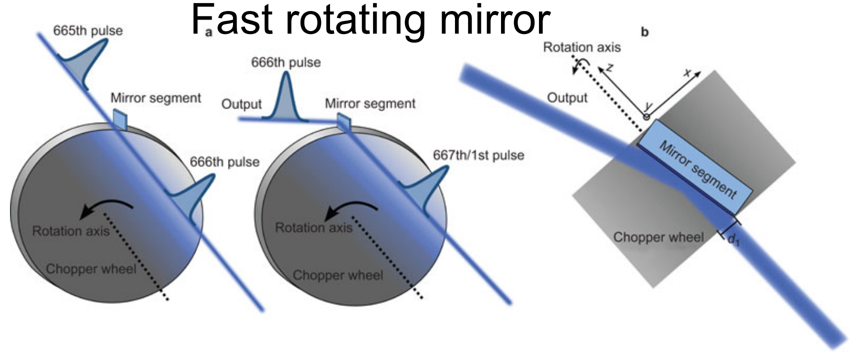


26 kW
2.6 mJ
10 MHz
Fiber system
With 16 coh-co
amplifiers

19 kW
1.3 J
15 kHz



Fast rotating mirror

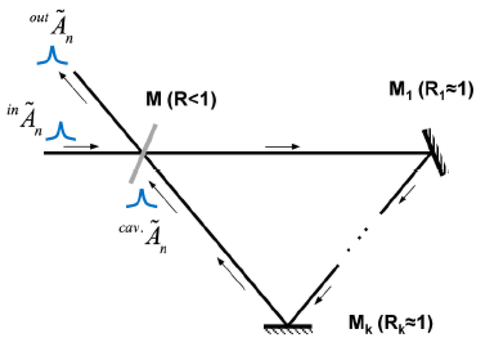


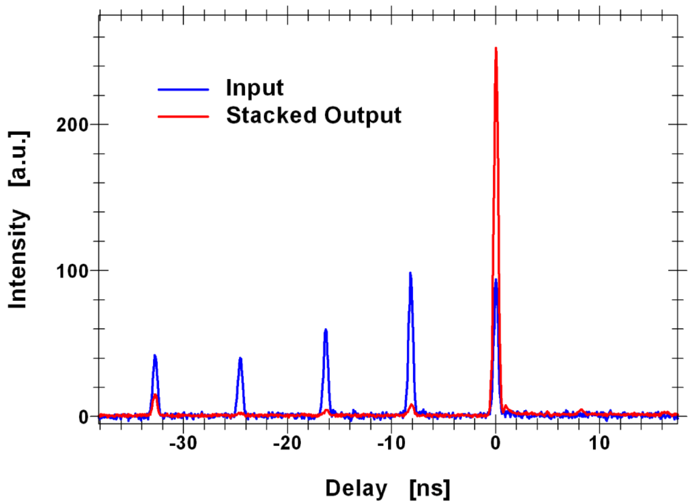
In and Fabry-Perrot cavity 666 repetition rate divider

Science & Applications (2014) **3**, Published online 10 October 2014

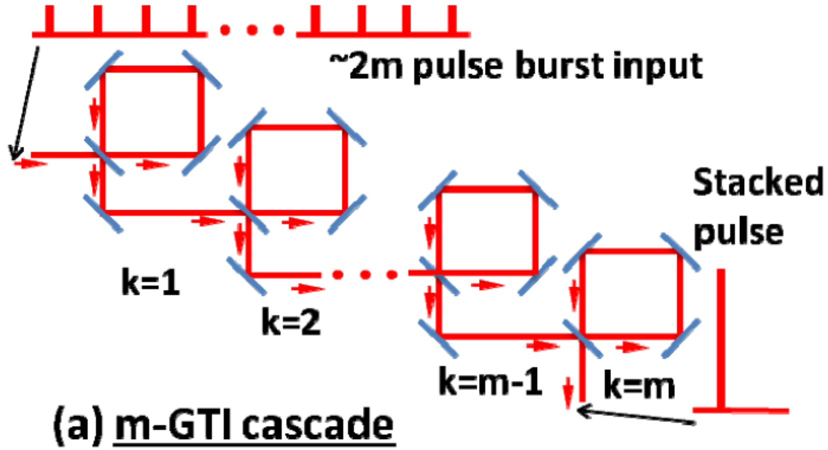
Cascaded Gires_Tournois

Demonstrated with on GTI





Extendable to 2m pulses



Tong Zhou; et al.; Almantas Galvanauskas "Coherent pulse stacking amplification using lowfinesse Gires-Tournois interferometers" Optics Express. 2015;23(6):7442-7462.

Outlook

- Introduction : the Ti:Sa limitations and its alternatives
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- Duration issues
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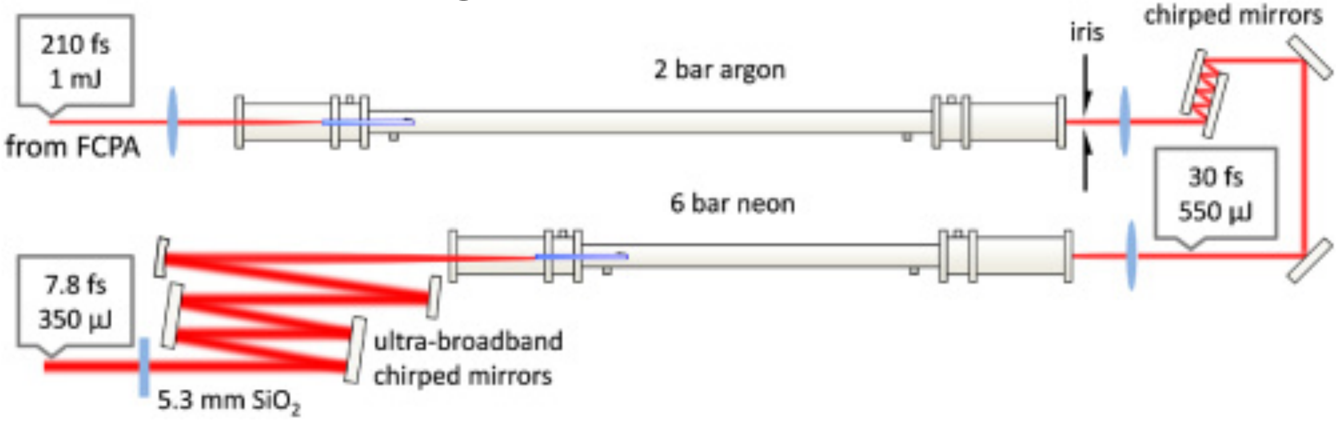
Direct compression

SPM in gas-filled hollow core fibers

High power fibre system

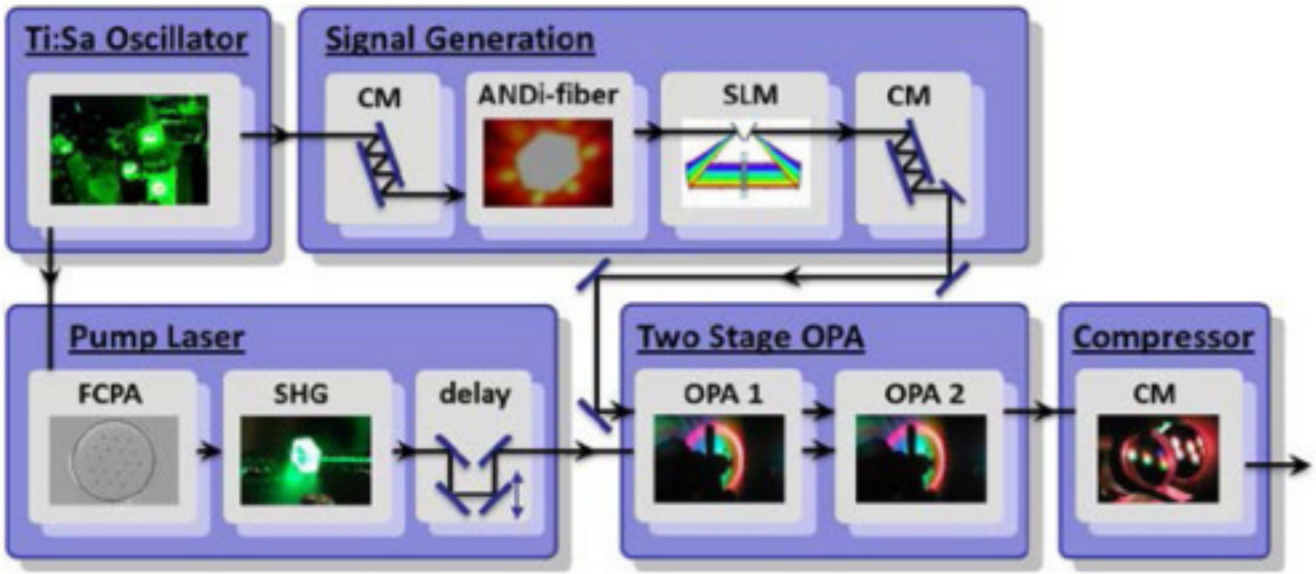


53 W 150 kHz
7.8 fs, 353 µJ 25 GW

Jan Rothhardt, et al., "53 W average power few-cycle fiber laser system generating soft x rays up to the water window," Opt. Lett. 39, 5224-5227 (2014)

OPCPA pump

fiber system pumping

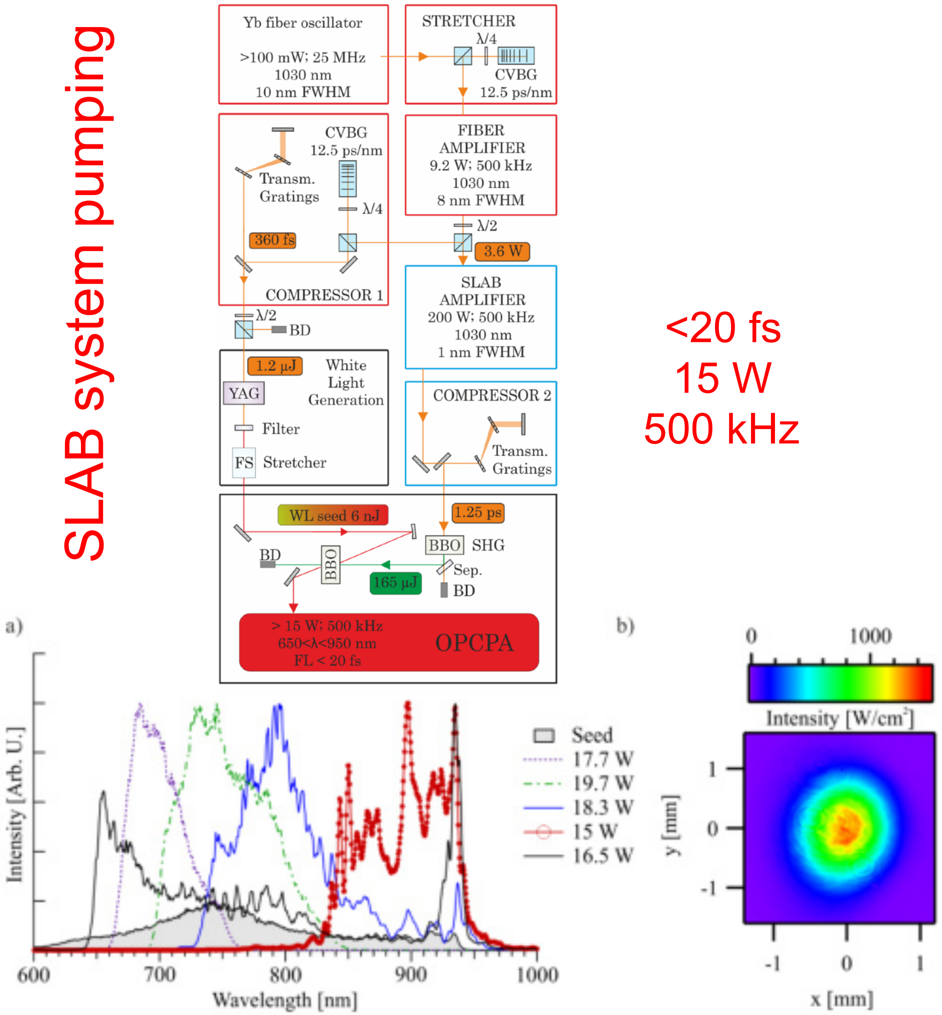


22 W, 1 MHz
5 fs 22 µJ, 2 GW

Jan Rothhardt, et al;"Octave-spanning OPCPA system delivering CEP-stable few-cycle pulses and 22 W of average power at 1 MHz repetition rate," Opt. Express 20, 10870-10878 (2012)

Slab or Thin-disk OPCPA pumping

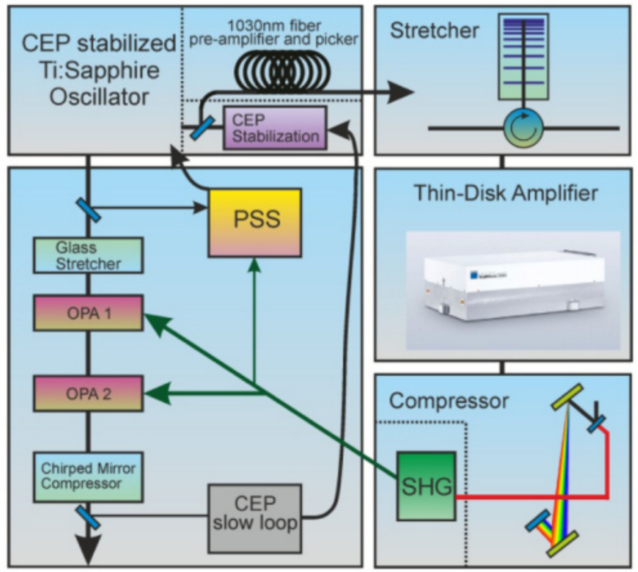
SLAB system pumping



<20 fs
15 W
500 kHz

Thin-disk system pumping

6 fs
15 W
300 kHz



Michele Puppin, et al."500 kHz OPCPA delivering tunable sub-20 fs pulses with 15 W average power based on an all-ytterbium laser," Opt. Express 23, 1491-1497 (2015)

Stephan Prinz, "CEP-stable, sub-6 fs, 300-kHz OPCPA system with more than 15 W of average power," Opt. Express 23, 1388-1394 (2015)

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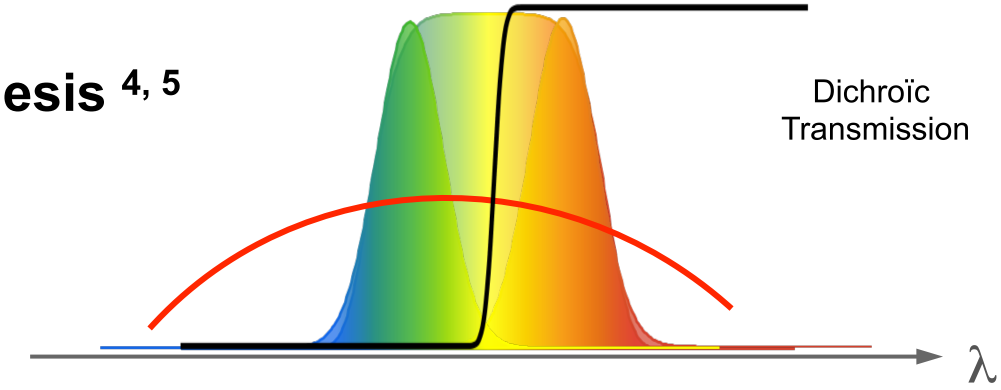
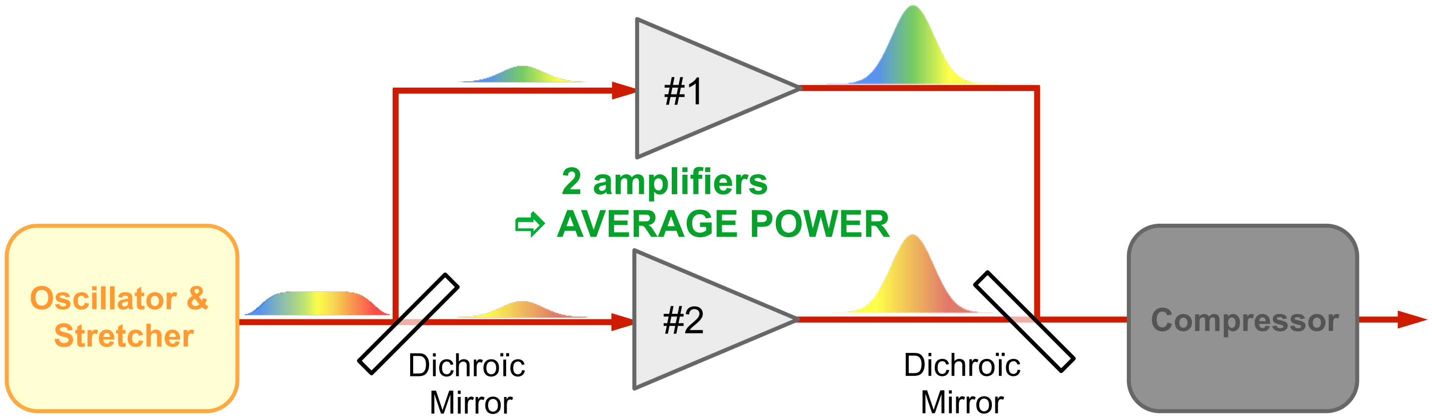
Pulse synthesis amplifier

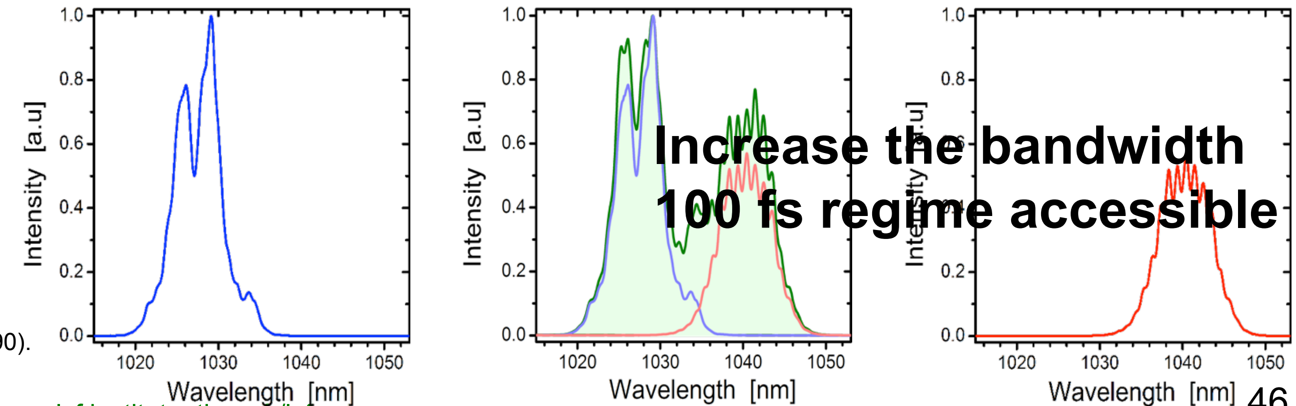
Pulse synthesis [4, 5]

Spectrum &
Gain





Recombined spectra



Increase the bandwidth
100 fs regime accessible

[4] T. W. Hänsch, Optics Communications **80**, 71 (1990).
[5] R. K. Shelton *et al*, Science **293**, 1286 (2001).

Outlook

- Introduction : the Ti:Sa limitations and its alternatives
- Yb-doped technologies
  - Thin-disk, Slab, Fibers…
- Energy scaling
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  - Simple Yb:YAG boosters
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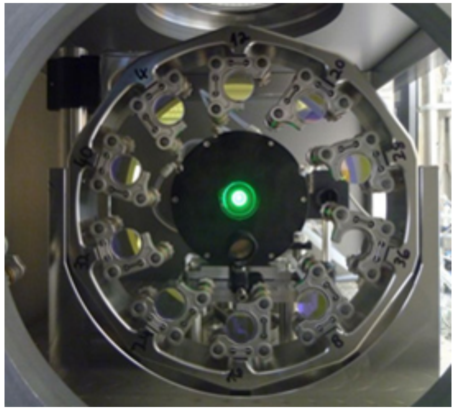
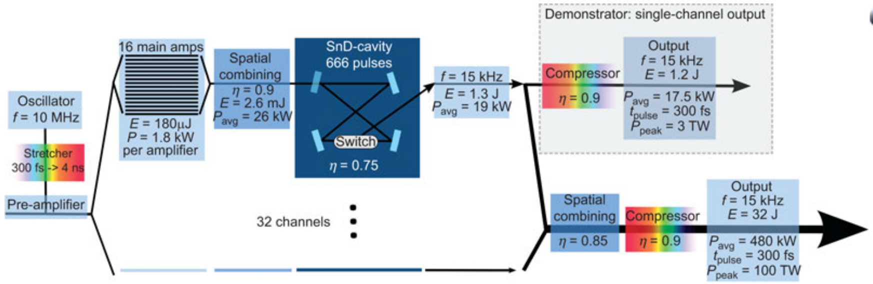
Conclusion

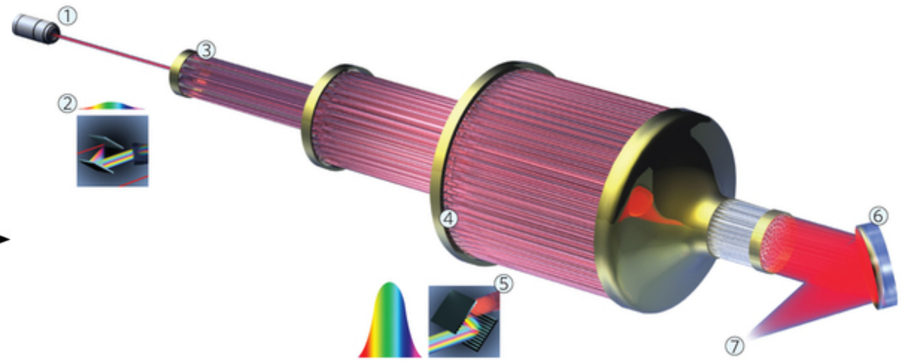
- Yb:doped technology
  - kW, high repetition rate
- Advanced architectures
  - Thin disk, Slab, Fibers
  - Different peak powers : 100, 20 and 5 GW
    different optimal rep' rates : 10 kHz to MHz
- Energy issues
  - Coherent combining is an efficient answer
- Duration issues
  - SPM or OPCPA: 100 kHz 53 W 8 fs or ≈20 W 6 fs

Prospects

Fibers or thin disks
> 1 J
≈20 kW
>10 kHz







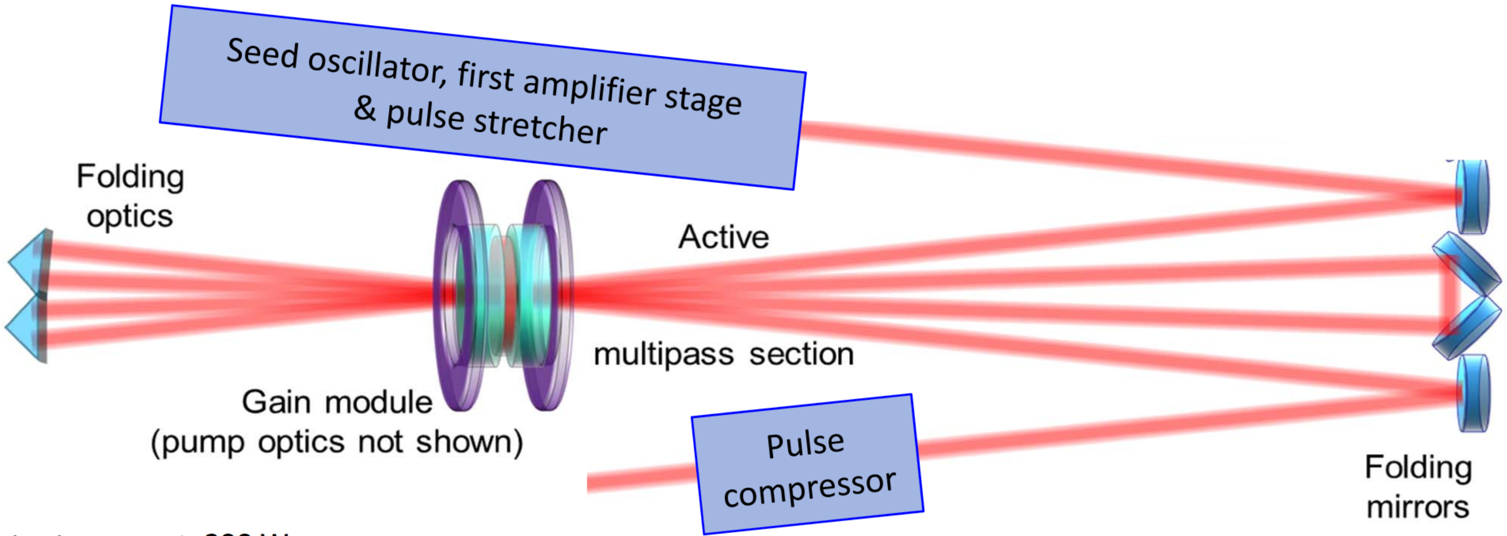
Grazie mille !

Special thanks for my coworkers who helped with this conference:
Marc Hanna, Florent Guichard, Julien Pouysegur and Fabien Lesparre

Question

- What about a high power Ti:Sa system?

Current project : 200 W sub-100-fs Ti:Sa pumped with 600 W



Output power: ≥ 200 W av.
Pulse duration: < 100 fs
Pulse energy: ≥ 10 mJ

The multipass amplifier will be pumped using two frequency-doubled nano-second pulsed lasers with an average output power of 300 W each at 532 nm

http://www.tisa-td.eu/project/index.html