INSTITUT d'OPTIQUE GRADUATE SCHOOL

High average power femtosecond laser systems

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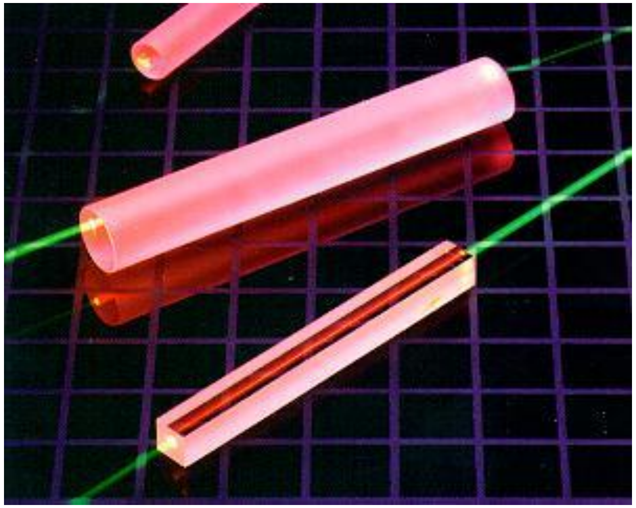
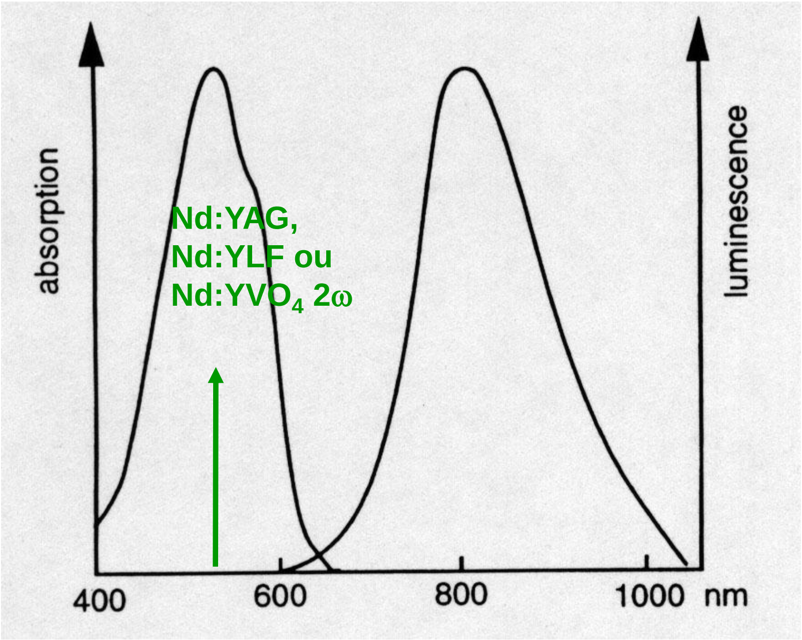


P. F. Moulton, "Spectroscopic and laser characteristics of Ti:Al_2O_3," J. Opt. Soc. Am. B 3, 125 (1986)



Large gain bandwdith (680 nm – 1080 nm)

Emission cross-section: 41 10^{-20} @ 780 nm

Excited state lifetime: 3 µs

Thermal conductivity: 35 $W.K^{-1}.m^{-1}$

High rep rate laser chain

Ti:Sapphire fs oscillator
800 nm, 20-50 fs, 1 W
100 MHz

Stretcher

Nd:YVO_4 laser @ 532 nm
5 to 10 W, diode pumped

Compressor

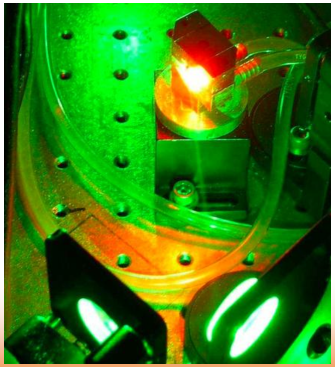
25 - 30 fs, @ 800 nm
1 to 10 mJ
1 to 10 kHz
Pmoy max :
20 W (20 mJ, 1 kHz)
50 W (5 mJ, 10 kHz)

Nd:YLF laser @ 523 nm
50 – 100 W, 1 to 5 kHz
diode pumped

Ti:Sapphire
Regenerative amplifier
or multipass amplifiers

Limitations :
- **Pump laser technology**
- **Efficiency (few %)**
- **Thermal effects in Ti:Sa (cm^3)**

→ cryogenic systems



Direct diode-pumping

Problem: Ti:Sa cannot be diode pumped

Solution : Use another gain material

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

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

LIMO
400 W @ 976 nm, 400 µm, ON: 0,22

IPG
100 W @ 915 nm, 105 µm, ON: 0,12

DILAS, JENOPTIK, OCLARO
250 W @ 808 nm, 200 µm, ON : 0,22

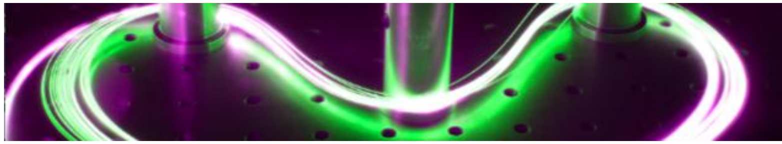
High power fs amplifiers

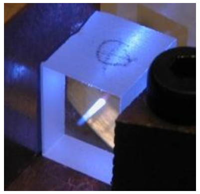
Requirements

	Heat removal	Efficiency	Beam quality	$\Delta\lambda$, 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 doping





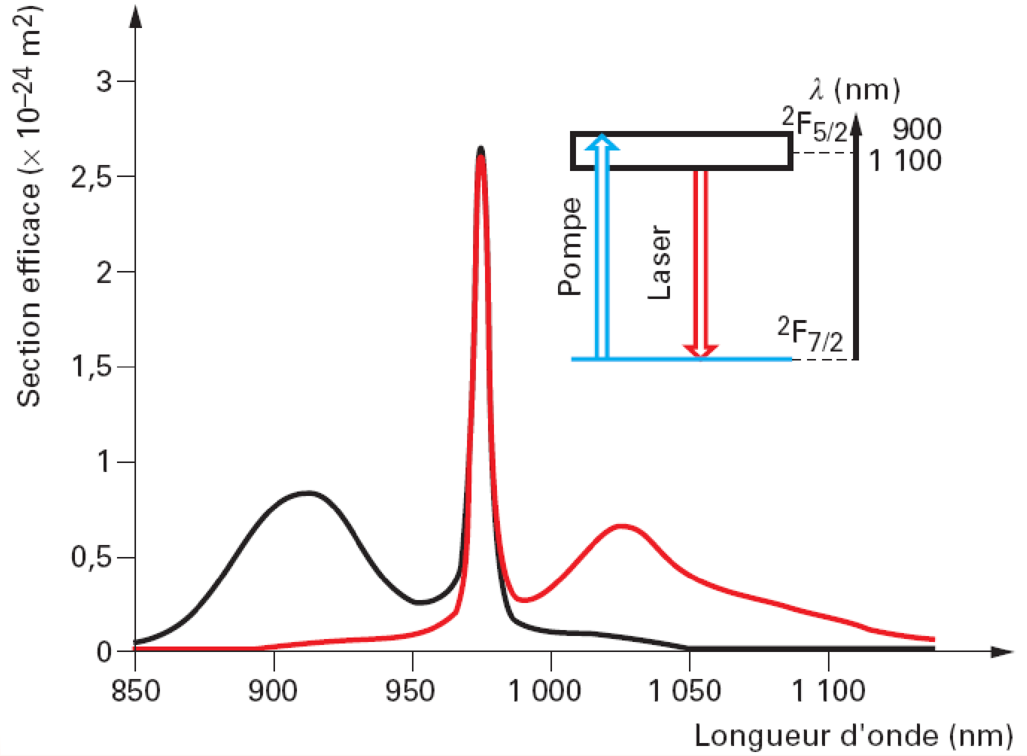
• Main technology for fs high power: Yb-doped materials

→ low quantum defect

→ diode pumping @ 980 nm

→ Simple spectroscopy

→ Limited gain bandwdith



Yb-doped materials

Large influence of host matrix on material properties

	σ 10^{-24} m^2	$\Delta\lambda$ nm	τ_{fluo} ms	κ W/m/K
Yb:YAG	2.2	5	0.95	11
Yb:glass	0.05	40	1	0.8
Yb:KYW	3	10	0.7	3.3
Yb:CALGO	0.75	60	0.4	6.5
Yb:CaF_2	0.25	30	2.5	9

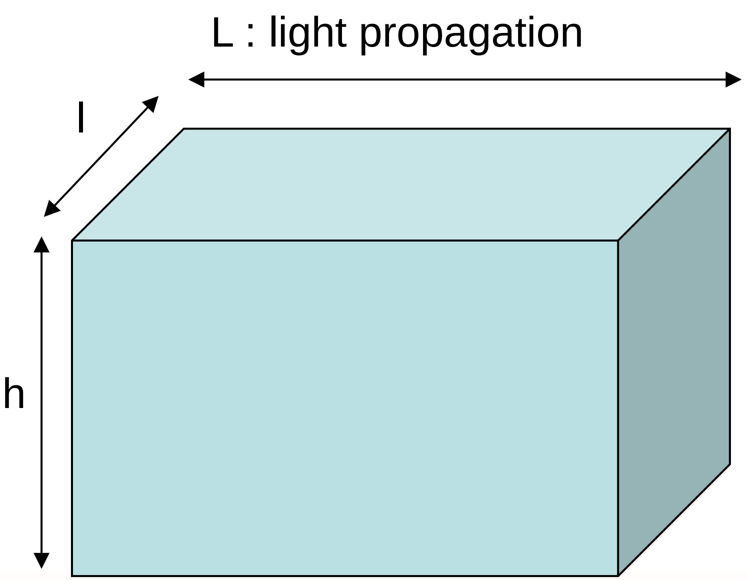
- Most used crystal: Yb:YAG
- But limited gain bandwidth: work on Yb:KYW, Yb:CaF_2, Yb:CALGO, Yb:LuO_3, etc…
- Fiber technology requires Yb:glass

Geometries

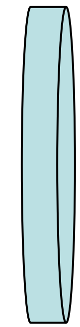
Increase the surface / volume ratio for efficient heat removal

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

$$V \propto Llh$$



$L \to 0$ Thin disk
Yb:YAG, Yb:Lu_2O_3

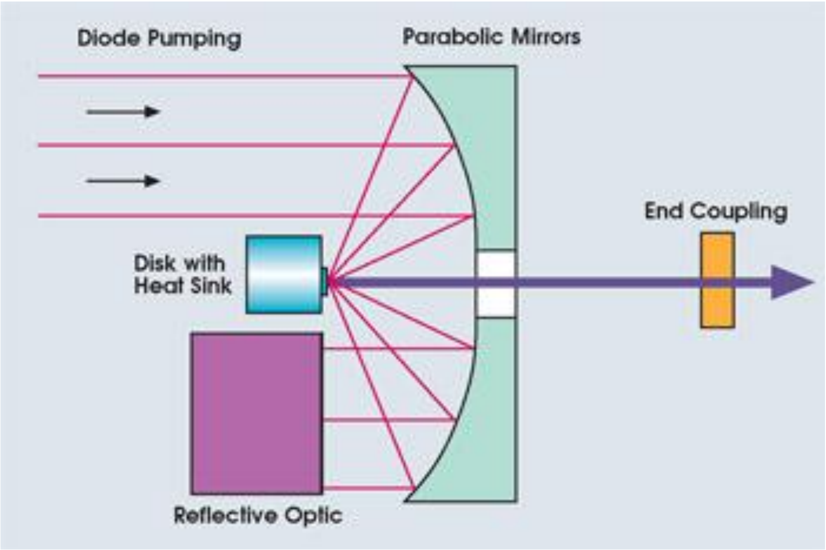


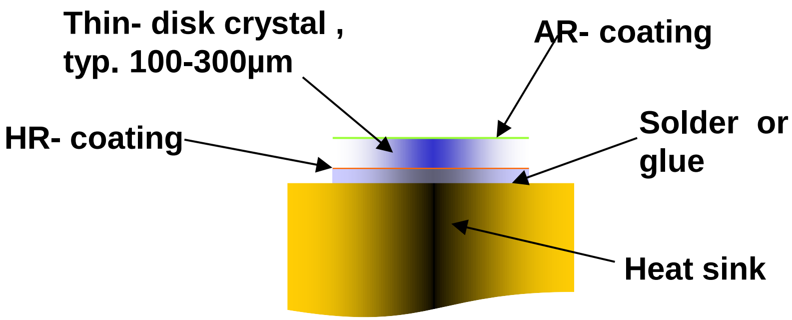
$h \to 0$ Slab
Yb:YAG

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

High power fs thin-disk systems

- Advantage : peak power
- Drawback : small gain, beam quality at high power
- State of the art





Advantages Thin Disk

• Optimized pump/ signal overlap, pump recycling

→ efficiency 40%

• Large transverse dimensions

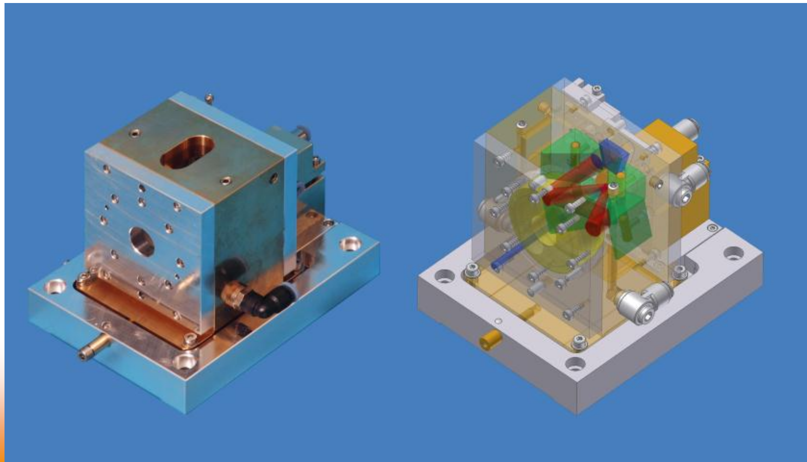
→ High energy (1 J) is possible

• Small longitudinal dimension: efficient cooling

→ Large average power

• Crystal medium

→ Choice of material



Drawbacks Thin Disk

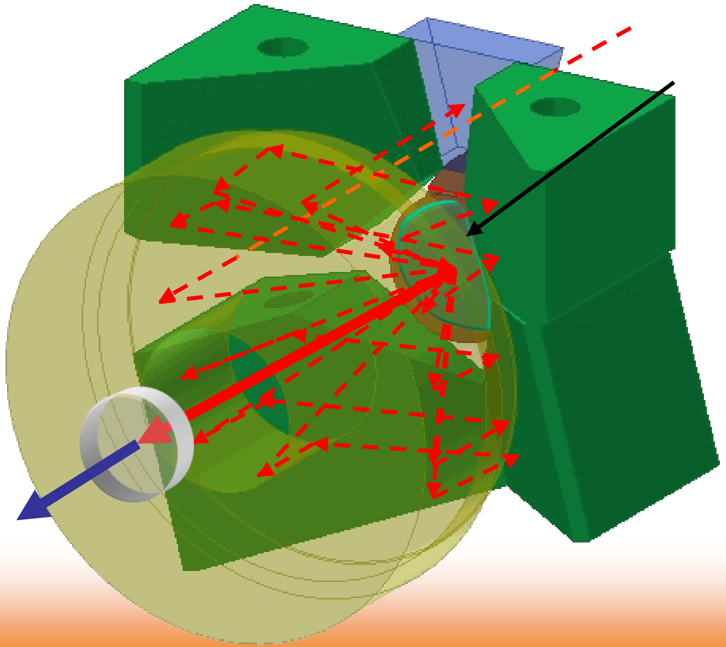
- Small longitudinal dimension

→ Small gain/absorption per pass

→ Complex systems for pump recycling and regen amplifiers

- Freespace propagation in gain medium

→ Thermal effects modify the beam



Thin disk fs amplifiers

Small gain leads to results in

- oscillator

- Regen amplifiers

• **Average power (oscillator)**

2.4 µJ, 2.8 MW peak, 141 W average, 740 fs, 60 MHz [1]

• **Peak power (CPA regen)**

200 mJ, ~100 GW peak, 20 W average, 1.3 ps, 100 Hz [2]

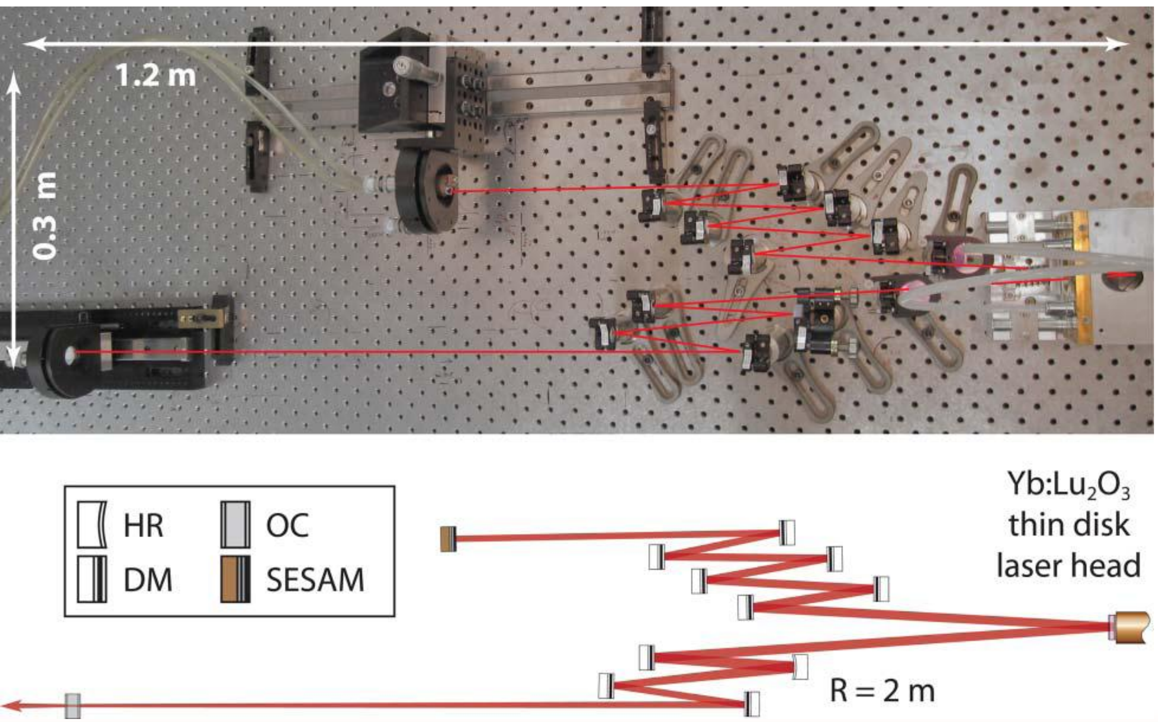
[1] Cyrill Roman Emmanuel Baer, Christian Kränkel, Clara Jody Saraceno, Oliver Hubert Heckl, Matthias Golling, Rigo Peters, Klaus Petermann, Thomas Südmeyer, Günter Huber, and Ursula Keller, "Femtosecond thin-disk laser with 141 W of average power," Opt. Lett. **35**, 2302-2304 (2010).

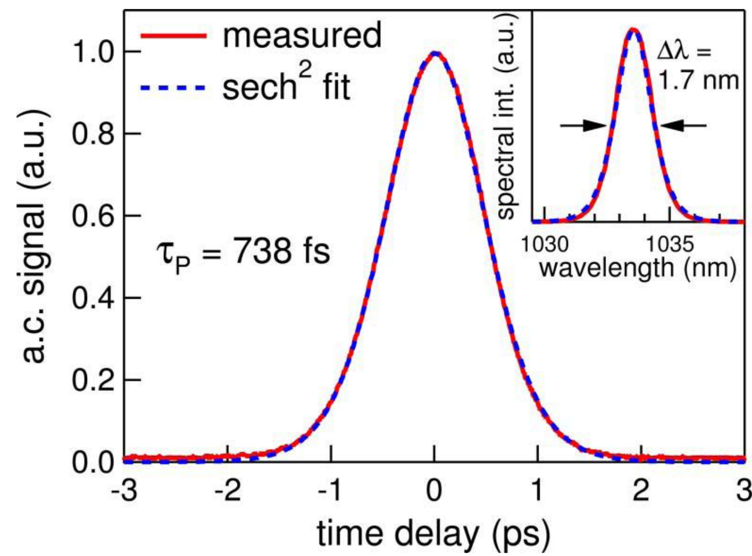
[2] J. Tümmler, R. Jung, H. Stiel, P. V. Nickles, and W. Sandner, "High-repetition-rate chirped-pulse-amplification thin-disk laser system with joule-level pulse energy," Opt. Lett. **34**, 1378-1380 (2009)

High power thin-disk oscillator

2.4 µJ, 2.8 MW peak, 141 W average, 740 fs, 60 MHz

- Soliton oscillator Yb:Lu_2O_3, pump 350 W, Crystal thickness 250 µm, beam quality M^2=1.2 (2.6 mm on crystal), efficiency 40%



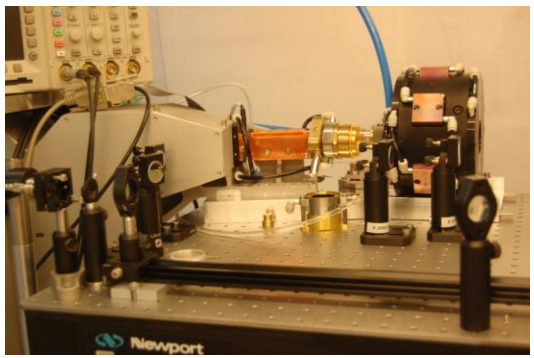


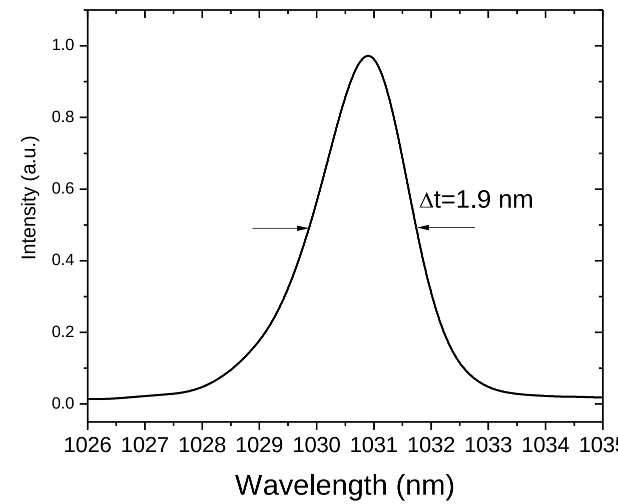
High energy thin-disk amplifier

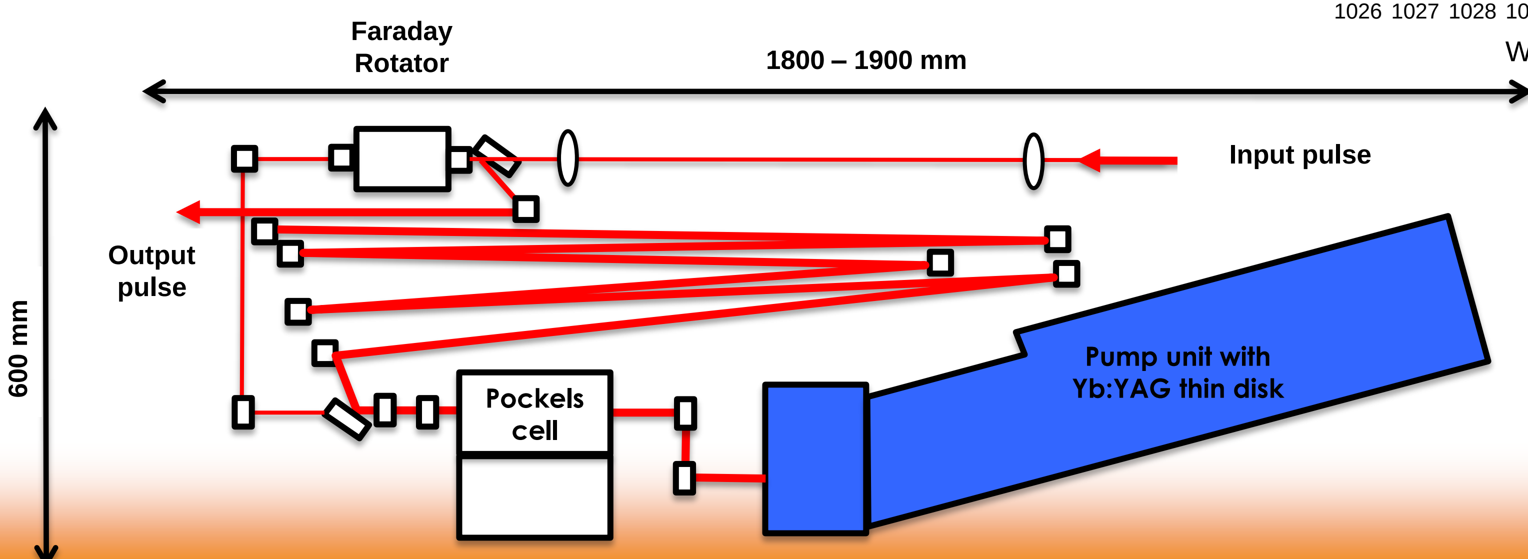
200 mJ, ~100 GW peak, 20 W average, 1.3 ps, 100 Hz

- Regen CPA 2 ns Yb:YAG, Pump 2 J, beam quality M^2=1.3 (2.6 mm on crystal)

, efficiency 10%







Conclusion on thin-disk

Current status

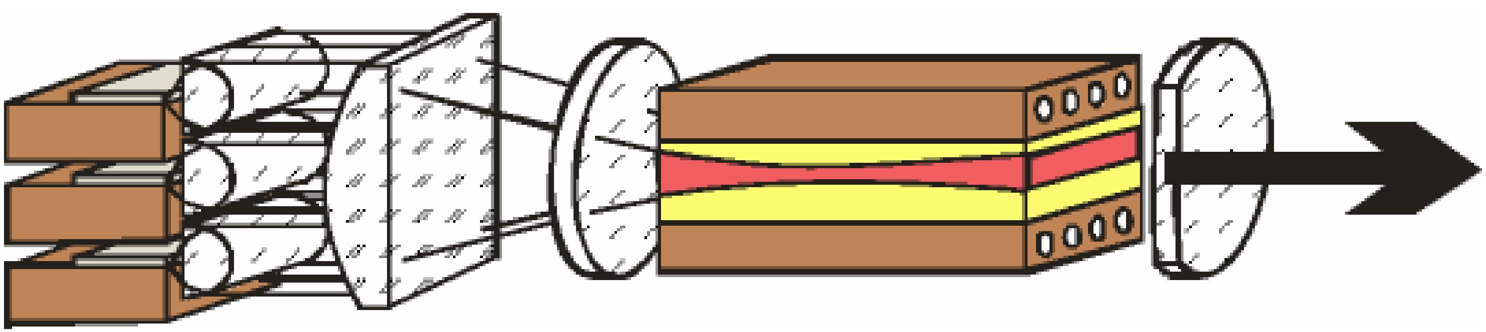
- Average Power ~ 100 W
- Energy per pulse ~ 200 mJ
- Pulsewidth ~ 600 fs (YAG)
- Shorter pulses: oscillator $LuScO_3$ 96 fs, 5.1W, 77 MHz

Perspectives

- Shorter durations at higher power (Yb:CaF_2, Yb:CALGO, etc)
- Higher average power regens (Pockels)

High power slab fs amplifiers

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



Advantages : geometry

- Large interaction length (several cm)

→ gain

- Pump / signal overlap

→ 50% efficiency

- Large surface/volume ratio

→ heat removal

- 1 large transverse dimension

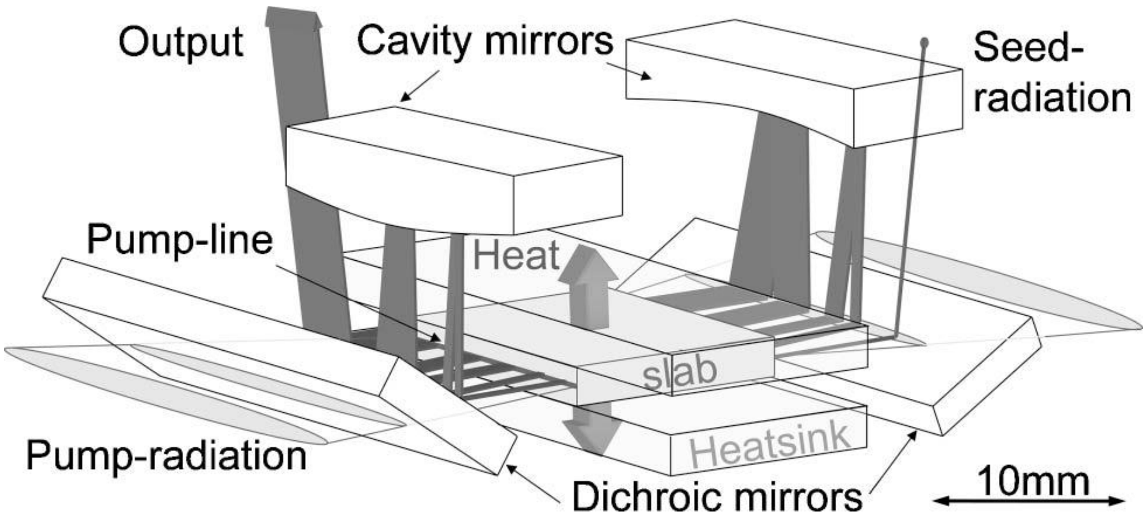
→ intermediate energy (10s of mJ) possible

Drawbacks: geometry

Large interaction length, no guiding

→ Complex management of pump and signal beams

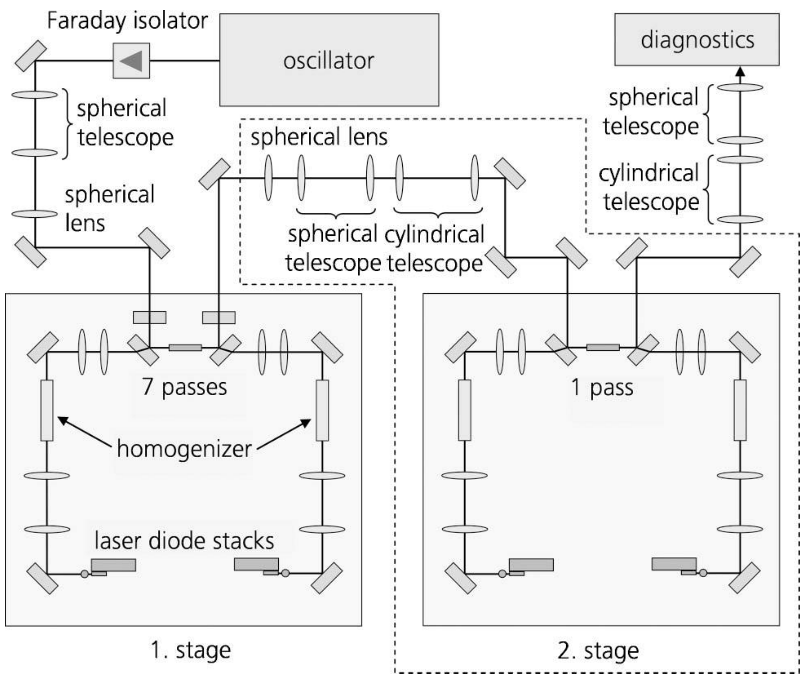
→ Thermal effects modify the beam

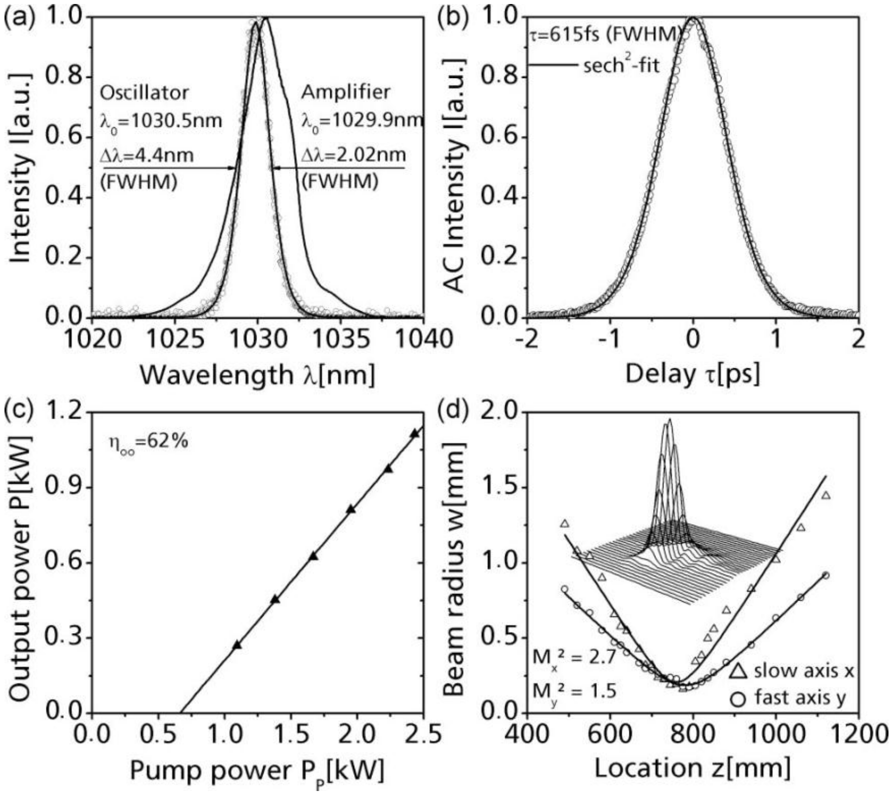


State of the art: high power

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)

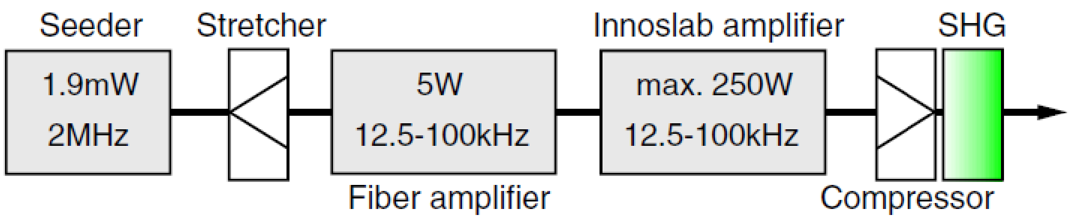


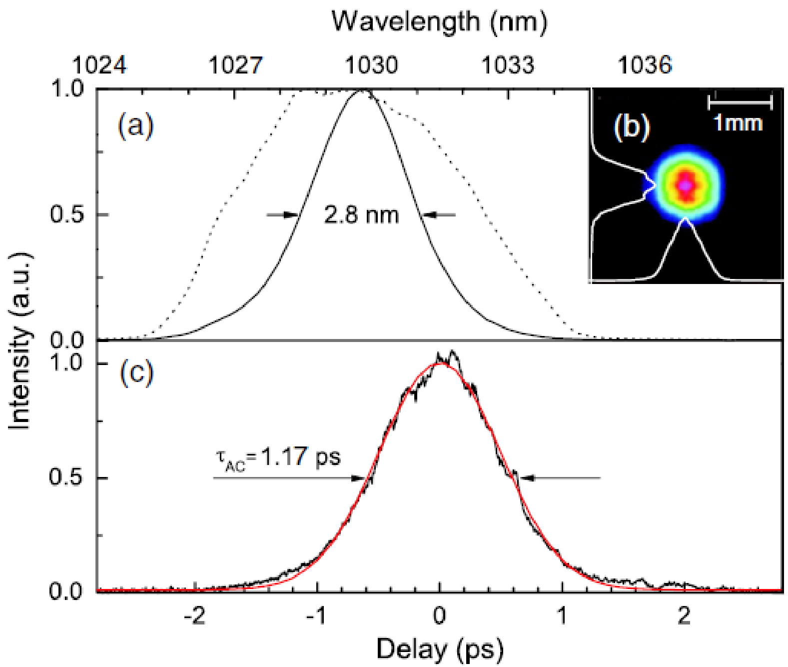


[1] P. Russbueldt, T. Mans, J. Weitenberg, H. D. Hoffmann, and R. Poprawe, "Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier," Opt. Lett. **35**, 4169-4171 (2010)

State of the art: high energy

20 mJ, 20 GW peak, 250 W average, sub ps, 12 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)

Conclusion on slab

Current status with Yb:YAG

- Average power ~ 1 kW / 250 W
- Pulse energy ~ 55 µJ / 20 mJ
- Pulsewidth ~ 615 fs / sub-ps

Perspectives

- Other crystals for shorter pulsewidths

High power fs fiber amplifiers

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

Advantages : geometry

- Guided signal and pump: large interaction length

 → large gain, efficiency

- Integrated systems

→ Compact and robust lser sources

- Small transverse dimensions

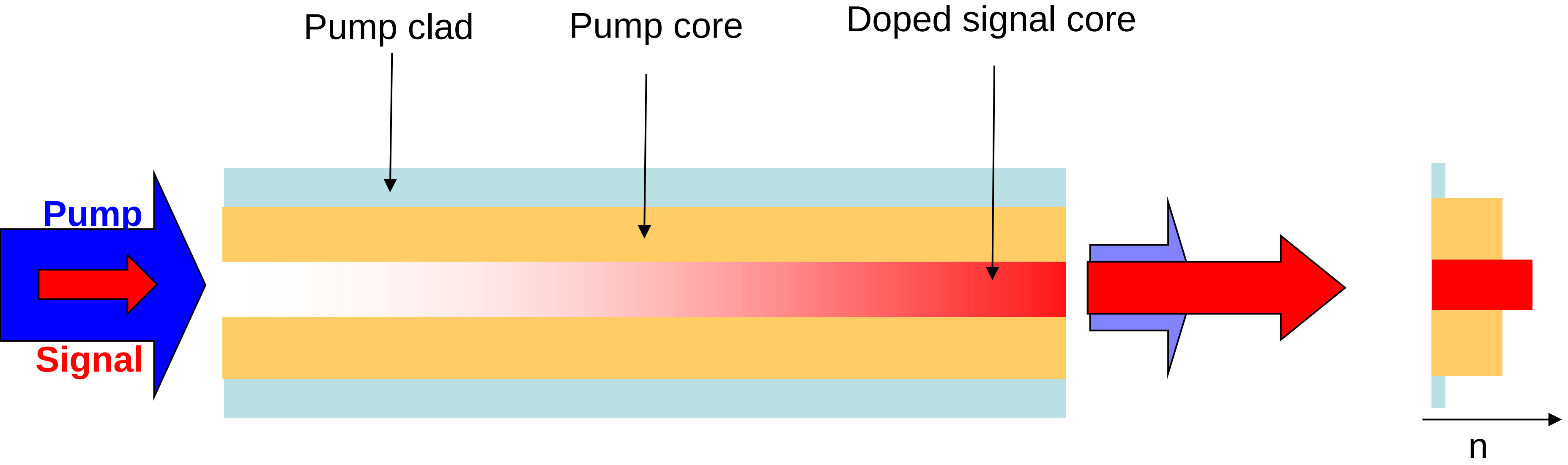
 → good heat removal

Advantages : geometry 2

- Double clad geometry

Single mode signal core → beam quality

Multimode pump core → High power diode pumping



« Brightness convertor »

Drawbacks

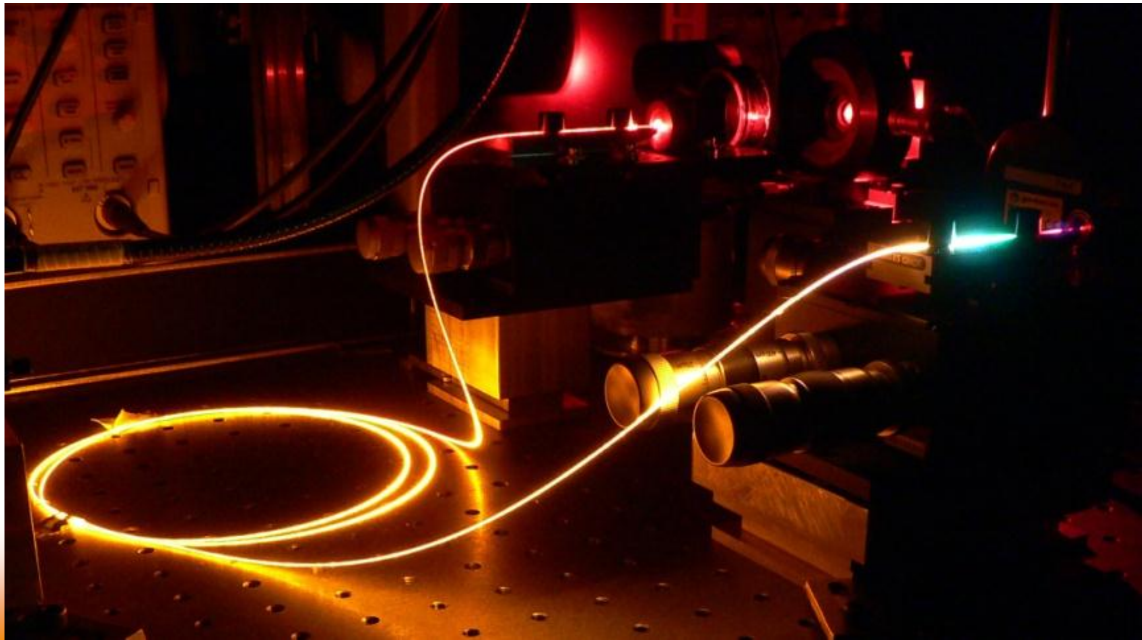
- Beam is guided with diameter ~ 10s of µm

→ High intensity (W/m^2)

→ Low damage threshold (~ mJ) → endcaps

→ Nonlinear effects

- Glass is the only option



State of the art

Tradeoff on the design of yb-doped fibers for peak power (short ultra LMA rodtype fibers) and average power (longer LMA fibers)

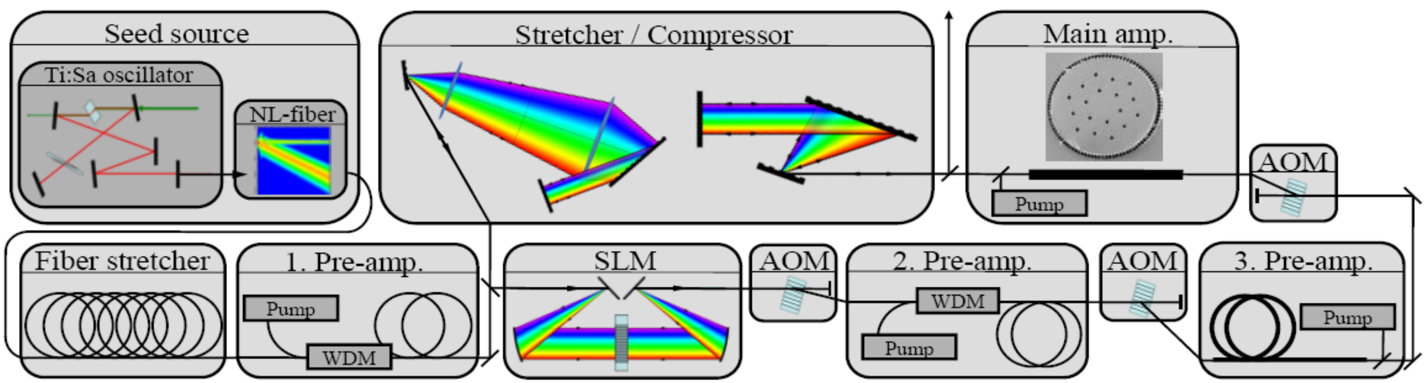
- **Peak power**: 2.2 mJ, 3.8 GW peak, 11 W average, 500 fs, 5 kHz [1]
- **Average power**: 10.6 µJ, 12 MW peak, 830 W average, 640 fs, 78 MHz [2]

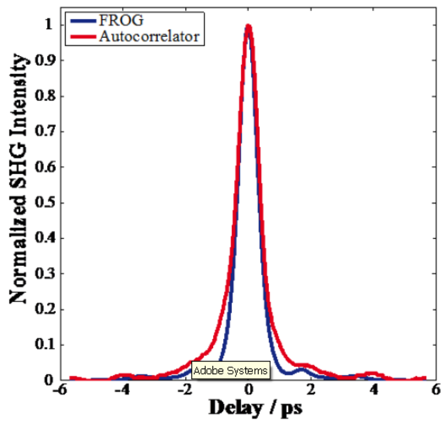
[1] Tino Eidam, Jan Rothhardt, Fabian Stutzki, Florian Jansen, Steffen Hädrich, Henning Carstens, Cesar Jauregui, Jens Limpert, and Andreas Tünnermann, "Fiber chirped-pulse amplification system emitting 3.8 GW peak power," Opt. Express **19**, 255-260 (2011)
[2] Tino Eidam, Stefan Hanf, Enrico Seise, Thomas V. Andersen, Thomas Gabler, Christian Wirth, Thomas Schreiber, Jens Limpert, and Andreas Tünnermann, "Femtosecond fiber CPA system emitting 830 W average output power," Opt. Lett. **35**, 94-96 (2010)

Peak power

2.2 mJ, 3.8 GW peak, 11 W average, 500 fs, 5 kHz

- Ultra LMA fiber, MFD 105 µm, length 1.3 m
- Active spectral phase control using SLM in zero-dispersion line

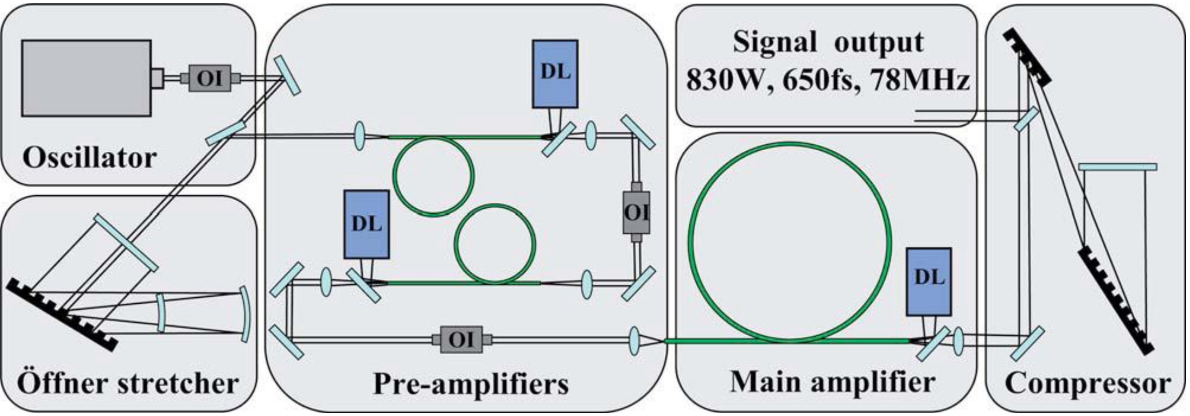


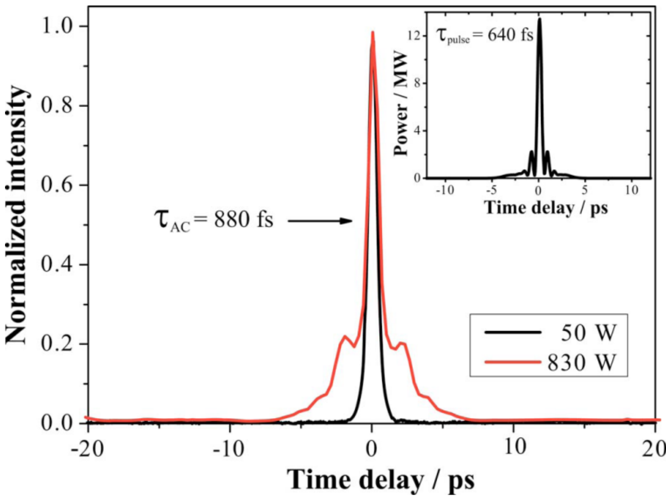


Average Power

10.6 µJ, 12 MW peak, 830 W moy, 640 fs, 78 MHz

• 8 m length fiber, MFD 27 µm, water-cooled, 500 µm air-clad, 1.45 kW pump, compression efficiency 95%, M^2<1.3





Conclusion on fiber systems

Current performances with Yb

- Average power ~ 1 kW (10 kW CW, 1 kW fs)
- Pulse energy ~ 1 mJ, peak power ~ 1 GW
- Pulsewidth ~ 300 fs at high energy

Lookout

- All-fiber integration for Yb systems
- Extend this performances to Tm, and Er systems

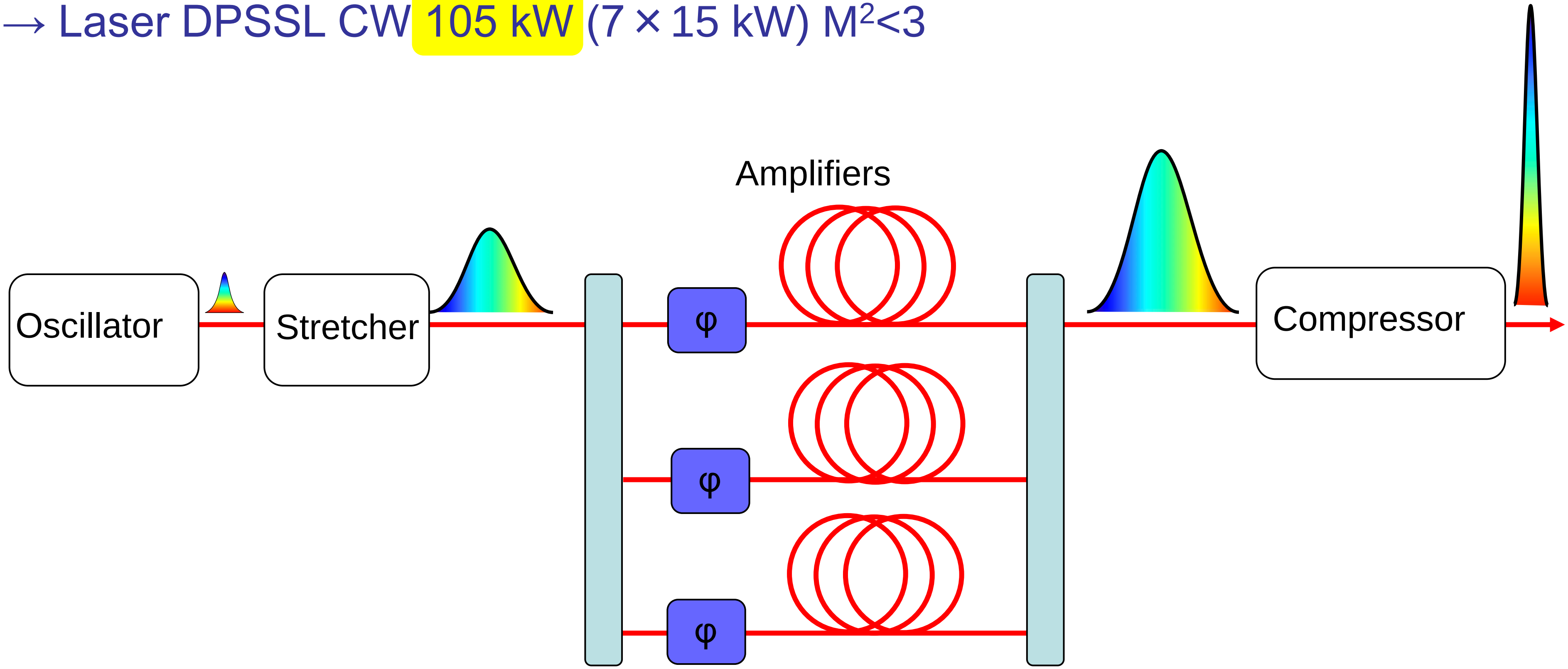
Further : coherent combining

N amplified beams are recombined

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

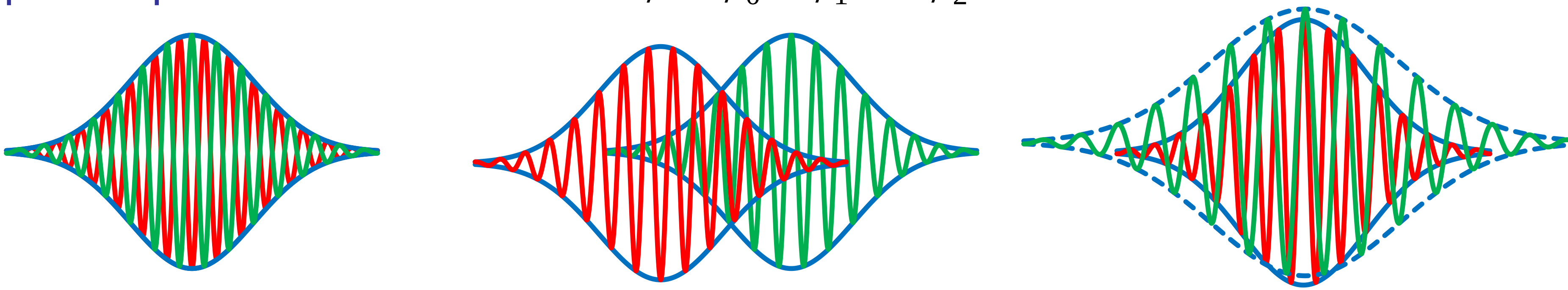
→ Requires differential phase control of the beams

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



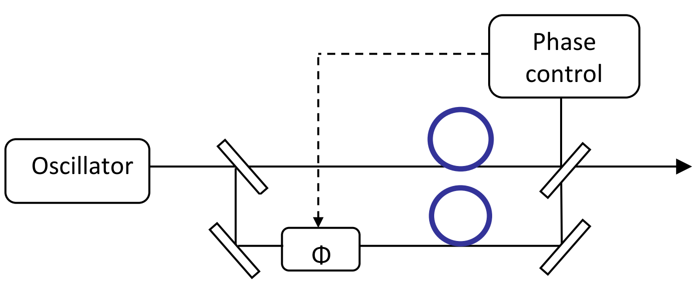
Phase control in fs regime

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

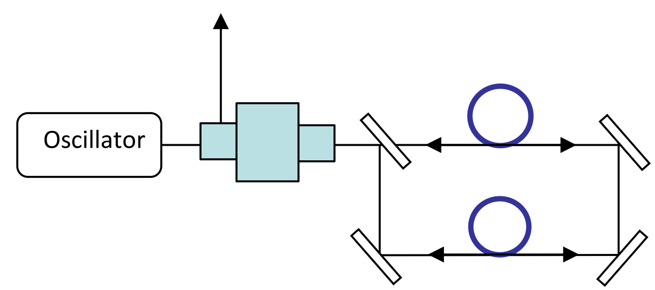


Zero-order phase φ_0 | Group delay φ_1 | GVD φ_2

Active system [1]



Passive system [2]



[1] Arno Klenke, Enrico Seise, Stefan Demmler, Jan Rothhardt, Sven Breitkopf, Jens Limpert, and Andreas Tünnermann, "Coherently-combined two channel femtosecond fiber CPA system producing 3 mJ pulse energy," Opt. Express **19**, 24280-24285 (2011)

[2] Y. Zaouter, L. Daniault, M. Hanna, D. N. Papadopoulos, F. Morin, C. Hönninger, F. Druon, E. Mottay, and P. Georges, "Passive coherent combination of two ultrafast rod type fiber chirped pulse amplifiers," Opt. Lett. 37, 1460-1462 (2012)

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Conclusion

State of the art for fs high average power single system

- Average power ~ 1 kW
- Power / energy tradeoff (200 mJ 250 W, 50 µJ 1kW) (geometry)
- Pulsewidth / energy tradeoff (1 ps 1 J, 50 fs 1µJ) (gain narrowing)

Perspectives

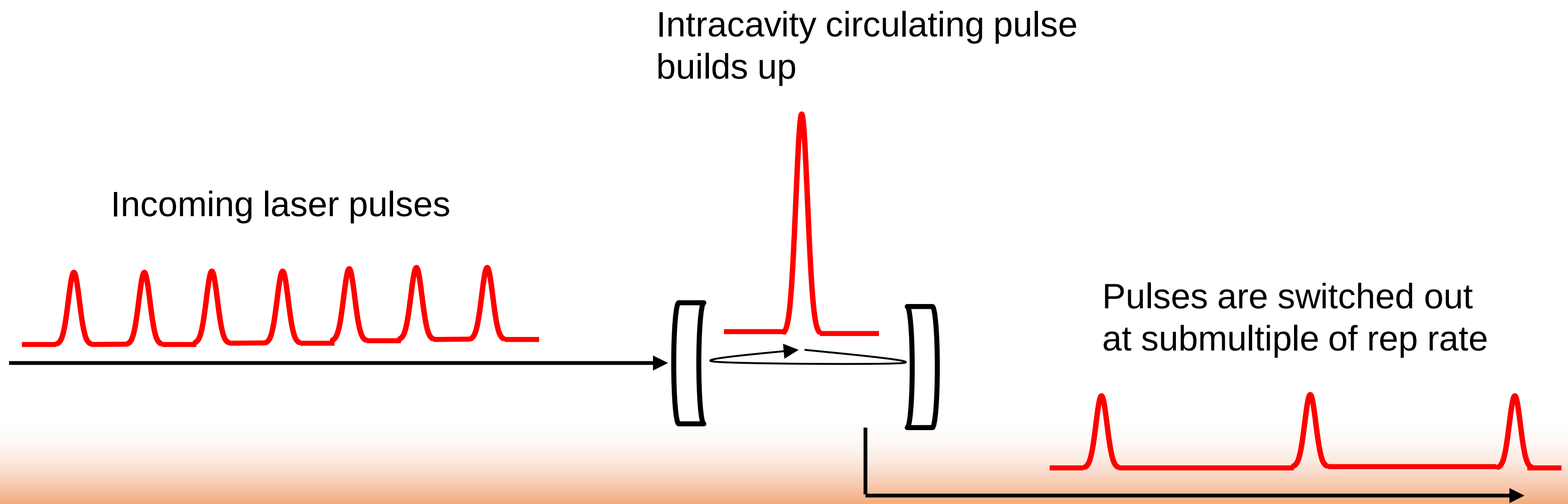
- Pump OPCPA towards few cycle regime
- Coherent combining ideas : beam combining, pulse synthesis, cavity enhancement

ICAN Project: laser-based acceleration

Coherent combining, fiber amplifiers

- Preliminary specs for demonstrator : 1 J / 10 kHz / 10 kW / 200 fs
- One option is to combine several 10 kHz fiber laser sources
- Another option is to use a higher rep rate and cavity enhancement with dumping

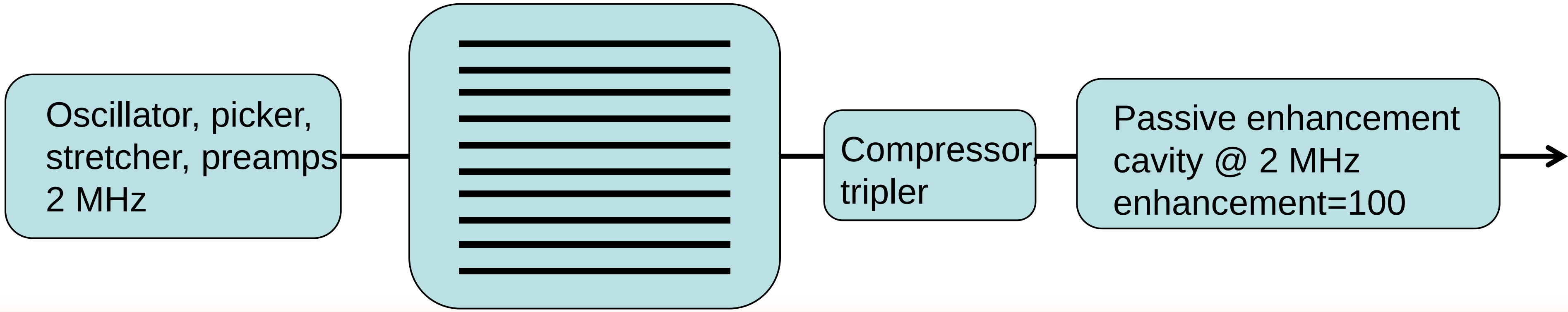
Passive cavity-dumped enhancement



Possible laser system

- Hypothesis : 2 MHz 100 × cavity, tripling yield 50%
- Required laser system 100 mJ 2 MHz 200 kW 5 ps (extremely challenging)
- Recirculating power is 10 MW, energy is 5J → is the cavity feasible ???

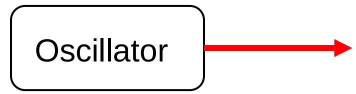
500 amplifiers combined
200 µJ / pulse / amplifier
400 W / amplifier



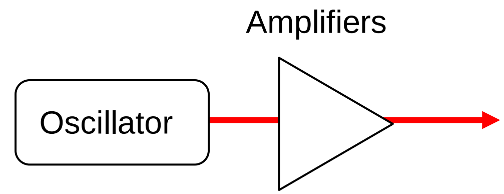
Thank you

Architectures

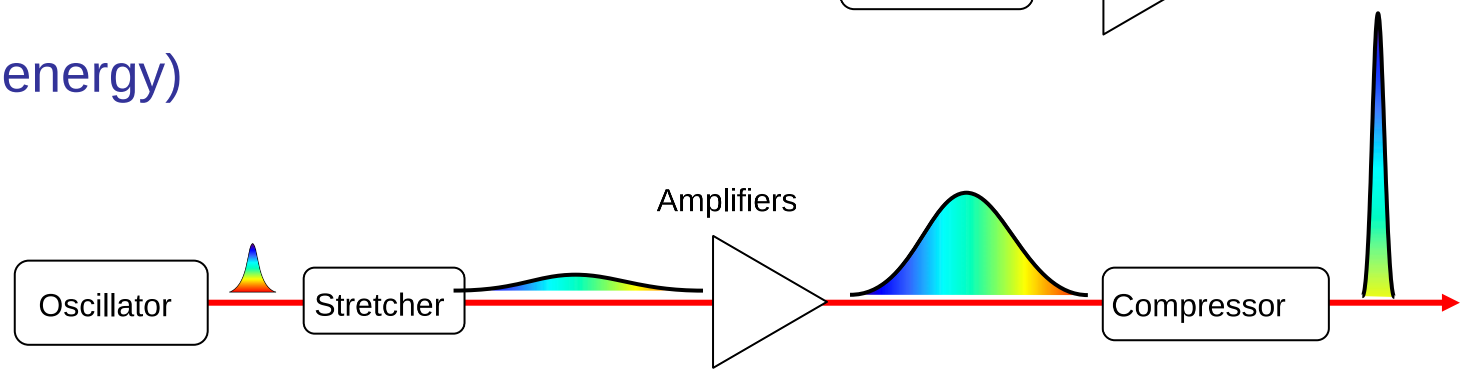
- High power oscillator



- MOPA (separate generation and amplification)



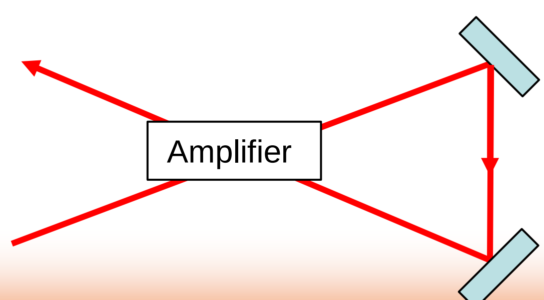
- CPA (higher energy)



- Amplifier architecture

single pass (small gain)

multipass (intermediate gain)



regenerative (high gain)