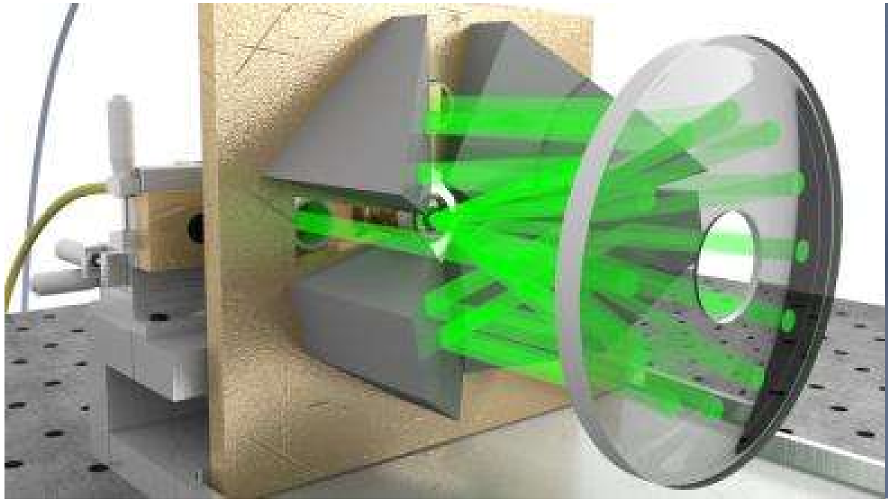
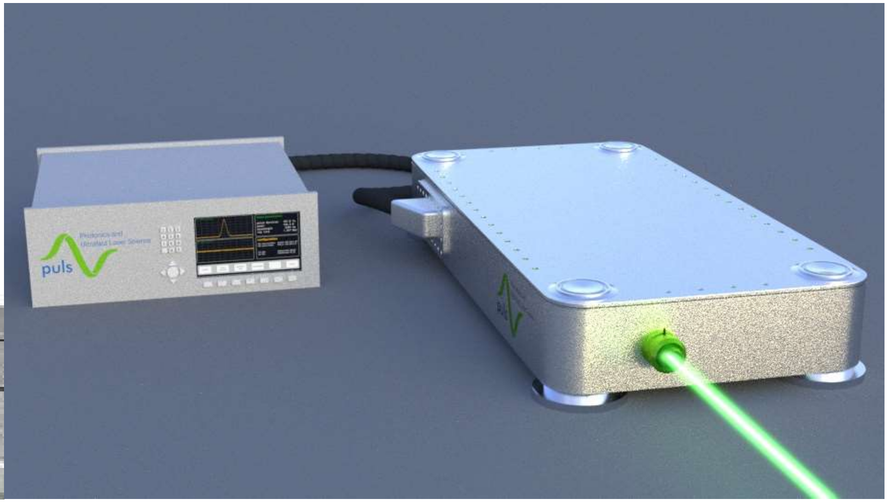




Trends, challenges and applications of high-average power lasers

Clara J. Saraceno

FEMTO-UP School- March 2021

About me

2002 - 2007
Studies in Lyon and Paris, France
'Classe Preparatoire' and 'Grande Ecole' specialized in optics

INSTITUT d'OPTIQUE GRADUATE SCHOOL
ParisTech

2008
Experience in Industry
Santa Clara, California, USA
Topic:
R&D in ultrafast oscillators

COHERENT

2009 - 2012
PhD degree
Physics
Topic:
High-power ultrafast thin-disk lasers

ETH zürich

2013 - 2016
Postdoc
Topic: High power ultrafast oscillators for compact XUV sources

unine
UNIVERSITÉ DE NEUCHÂTEL

ETH zürich

2016 - 2019
Associate Prof.
(Tenure Track)
Research:
High-power ultrafast lasers, THz sources, time-domain spectroscopy

2020
Full Prof.

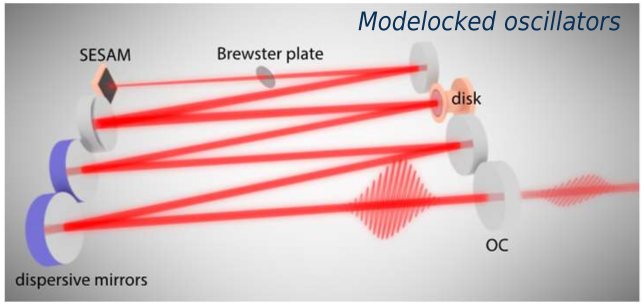
"Photonics and Ultrafast Laser Science" …

puls
Photonics and Ultrafast Laser Science

RUHR UNIVERSITÄT BOCHUM
RUB

Our research in a nutshell

High-average power ultrafast lasers



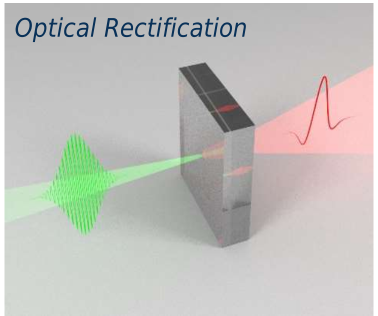
λ → near-infrared (1 – 3 µm)

f → near-infrared (300 – 100 THz)

Photonics and
Ultrafast Laser Science
puls

PULS group Feb. 2019

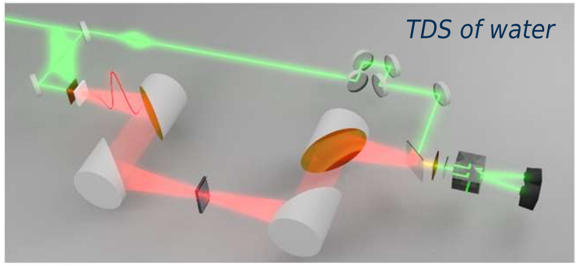
Ultrafast high average power THz sources

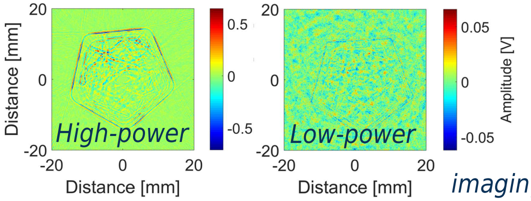


f → Terahertz (1 – 10 THz) & mid-IR (10 – 100 THz)

Lecture D. Turchinovich “Principles and applications of ultrafast terahertz spectroscopy” - Friday 12th 09:00

Terahertz applications

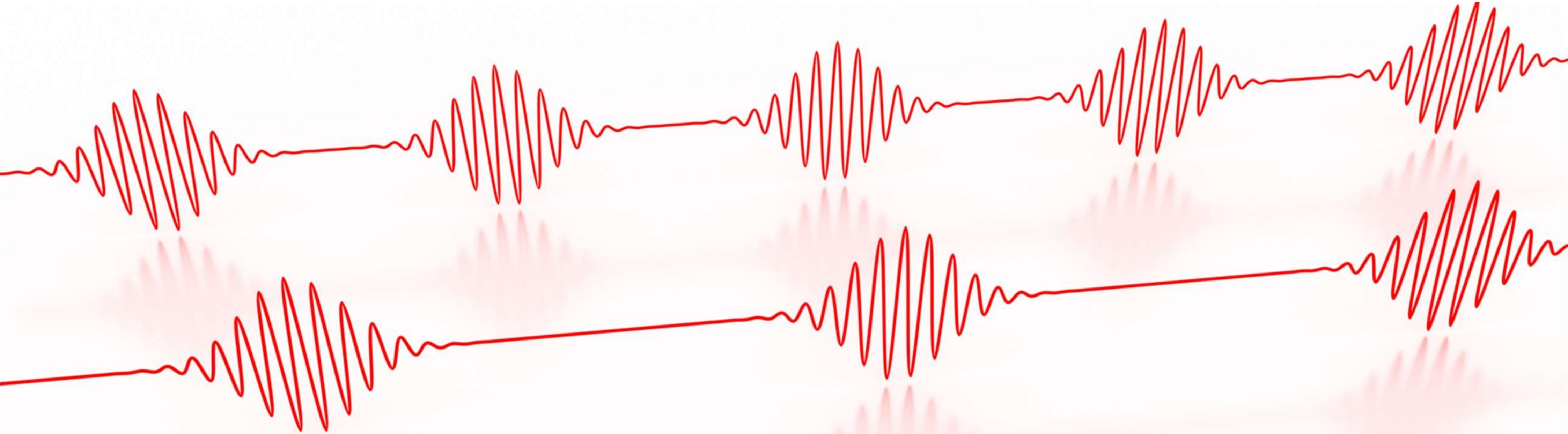




imaging

Etc...

ultrafast lasers

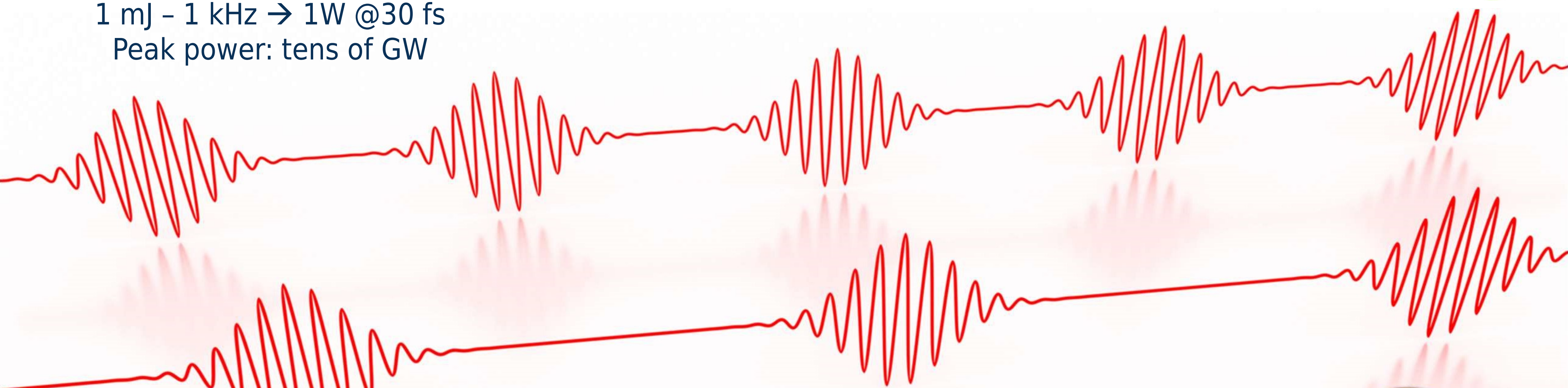


- Laser light pulses with **fs - ps durations**
- Broadband spectra with **hundreds of nm**
- Peak powers MW – GW, intensities **10^{12} – 10^{15} W/cm^2**

… and beyond

ultrafast lasers

Example: commercial Ti:Sa amplifier
1 mJ – 1 kHz → 1W @30 fs
Peak power: tens of GW



- Laser light pulses with **fs - ps durations – down to attoseconds**
- Broadband spectra with **hundreds of nm – up to several octaves**
- Peak powers MW – GW, intensities **10^{12} – 10^{15} W/cm^2 – above 10^{18} W/cm^2**

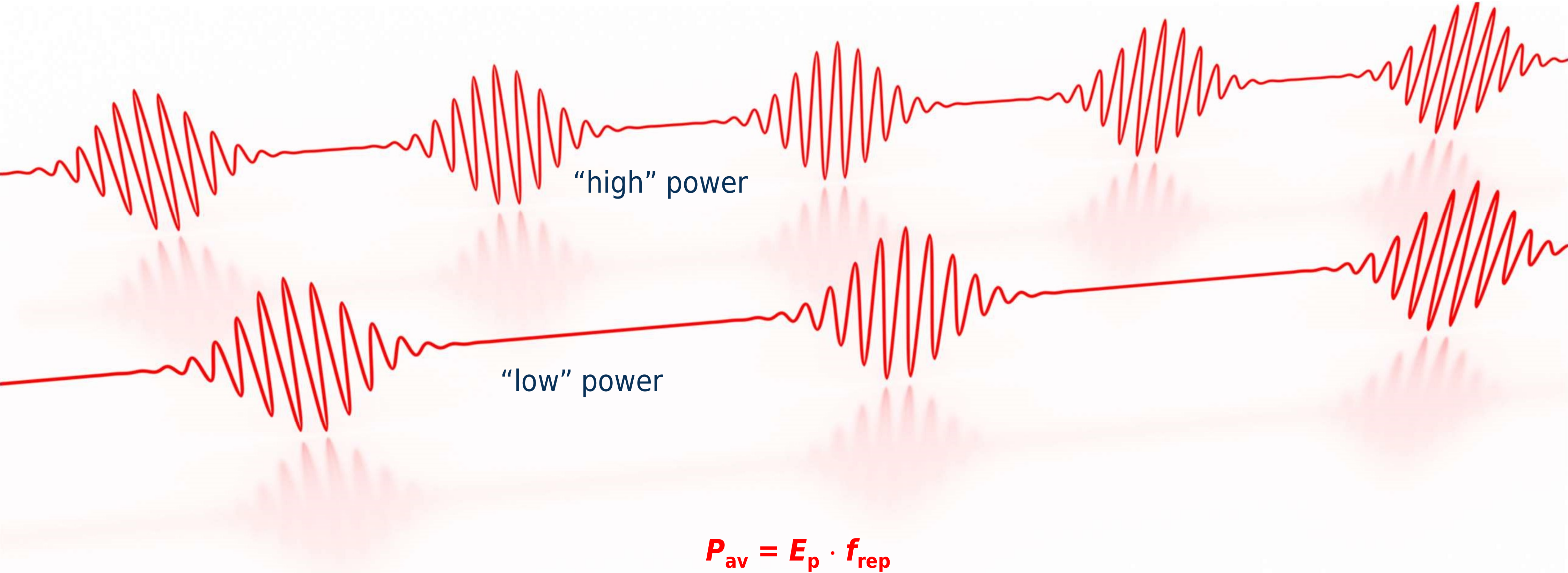
… and beyond

Physics 2018
"for their method of generating high-intensity, ultra-short optical pulses"

Important Parameters

Notation	Everyday parameters for ultrafast lasers	Subtleties
E_p	Pulse energy (J)	
τ_p	Pulse duration (fs)	• Definition often FWHM – can be misleading • RMS pulse duration better suited but rarely used
f_{rep}	Repetition rate (Hz)	
P_{av}	Average power (W)	$P_{av} = f_{rep} E_p$
P_{pk}	Peak power (W)	• Can be calculated from E_p and τ_p • Simple for well-known pulse shapes (Gaussian,…) P_{pk} = constant*E_p/τ_p • For complex pulse shapes
I_{pk}	Peak intensity (W/m^2)	Requires knowledge on transverse beam profile
λ_0, ν_0	Central Wavelength (nm), central frequency (Hz)	For complex spectra the central frequency might become different to the center of mass of the spectrum
$\Delta\lambda_p, \Delta\nu_p$	Spectral bandwidth (nm, Hz)	• Often defined by width of spectral intensity • Only relative bandwidths are the same in wavelength and frequency
TBP	Time-bandwidth product (no unit)	$\tau_p \Delta\nu_p$ • Defined with intensity FWHM • Reaches a minimum that gives us information about the shortest pulses reachable with a given spectral width • Can be flawed for complex, very short pulses

Focus here: higher average power



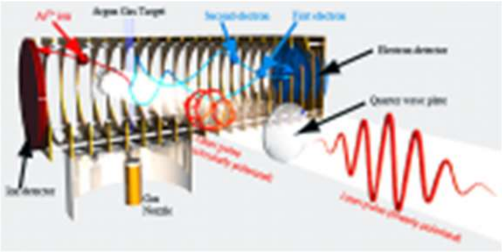
$$P_{av} = E_p \cdot f_{rep}$$

Higher average power at a given pulse energy = **more pulses / s**

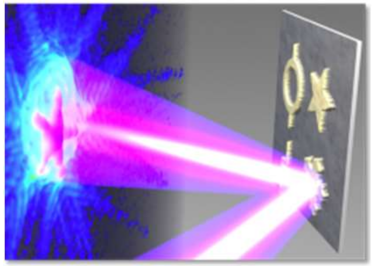
⇨ Higher signal to noise ratio, shorter measurement times, higher speed, …

two areas mostly ‘fueled’ progress in high average power

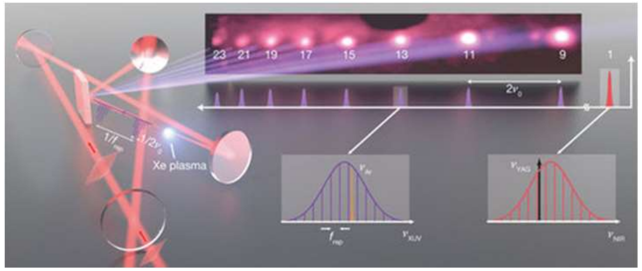
generation of high repetition rate XUV pulses via high harmonic generation



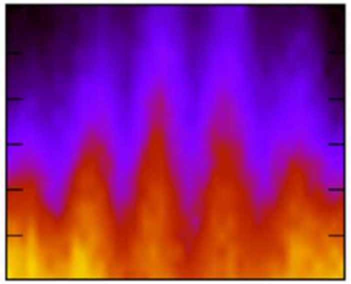
Reaction microscopes
M. Sabbar, et al
Rev. Sci. Instr. 85, 103113 (2014)



Coherent Diffractive Imaging
M. Zürch, et al,
Sci. Reports **4**, 7356 (2014)



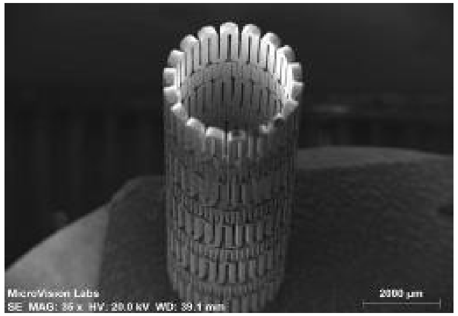
XUV Spectroscopy
A. Cingoz,
Nature 482 (2012)



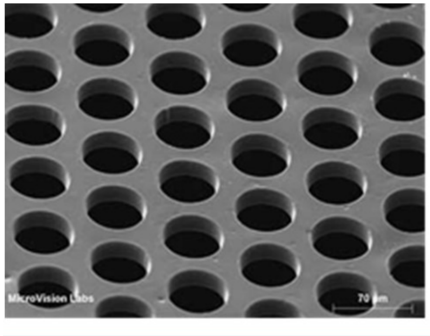
XUV photoemission
C. H. Zhang,
PRL 102 (2009)

higher speed material processing

Bioresorbable polymer

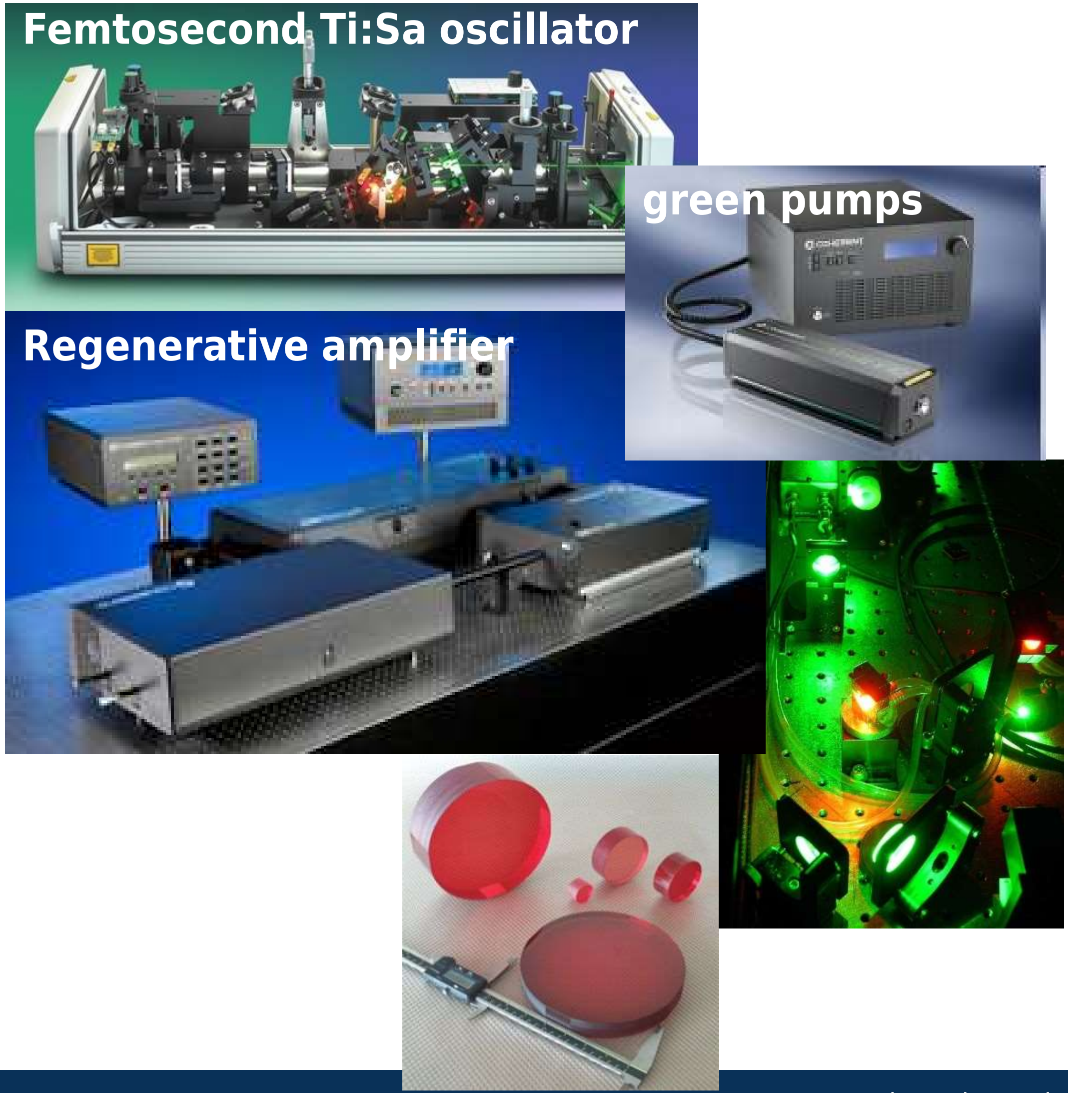


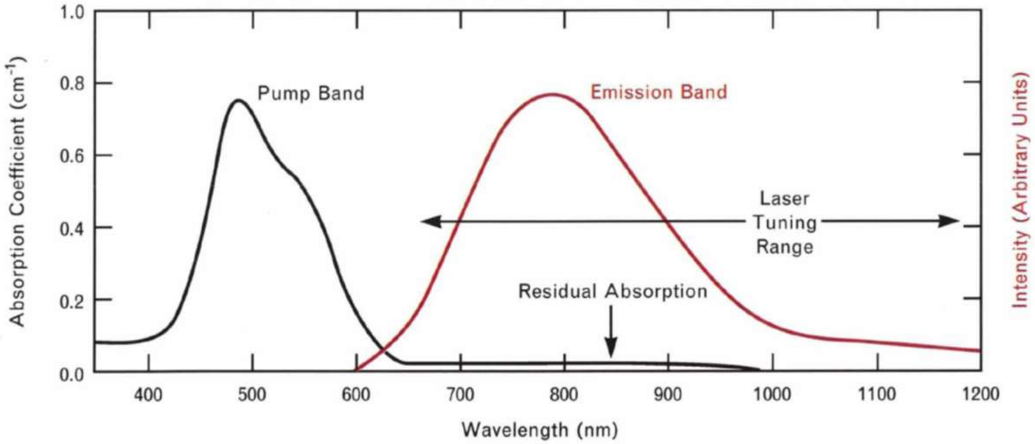
Polyimide Hole array drilling



Ceramics

the workhorse of ultrafast science





Typical amplifiers:

- **Pulse duration** ~30 fs
- **Pulse energy** ~mJ
- **Rep Rate** ~few kHz
- **Peak power** ~ GW

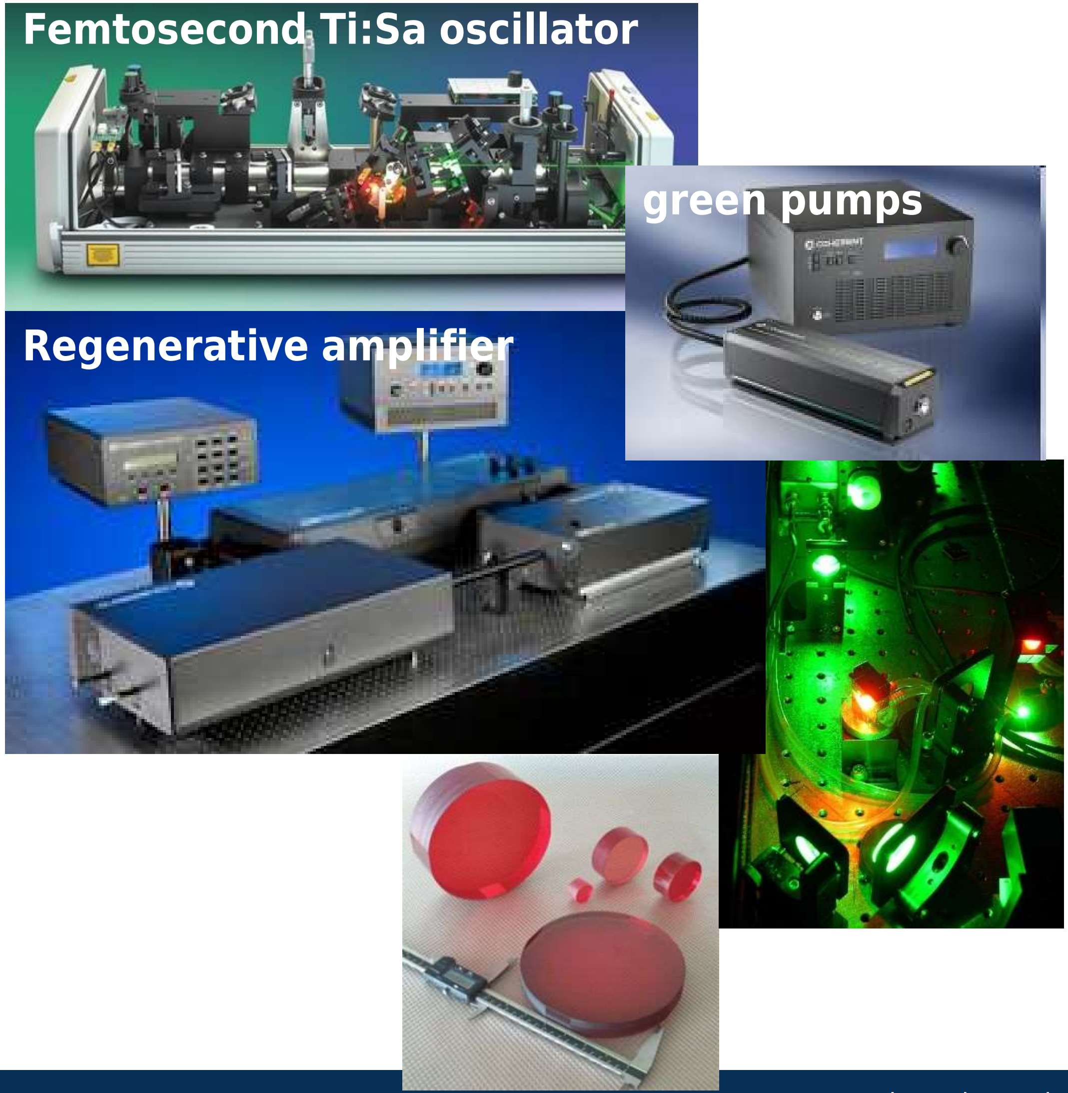
Typical oscillators:

- **Pulse duration** ~20 fs
- **Pulse energy** ~nJ
- **Rep Rate** ~ tens of MHz
- **Peak power** ~ 10s kW

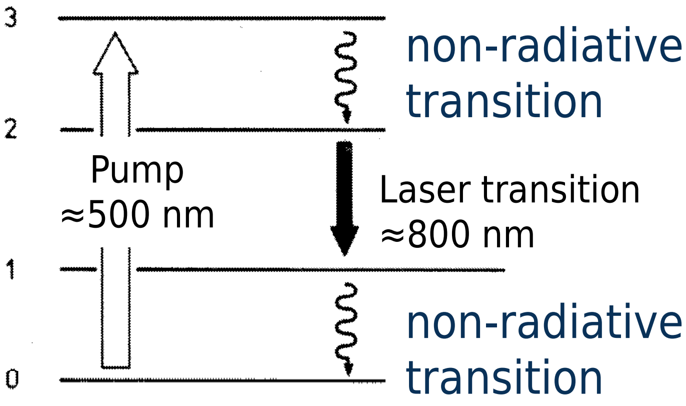
→ Average power limited to few watts

$$P_{av} = E_p \cdot f_{rep}$$

the workhorse of ultrafast science



Ti:sapphire laser:



non-radiative transition

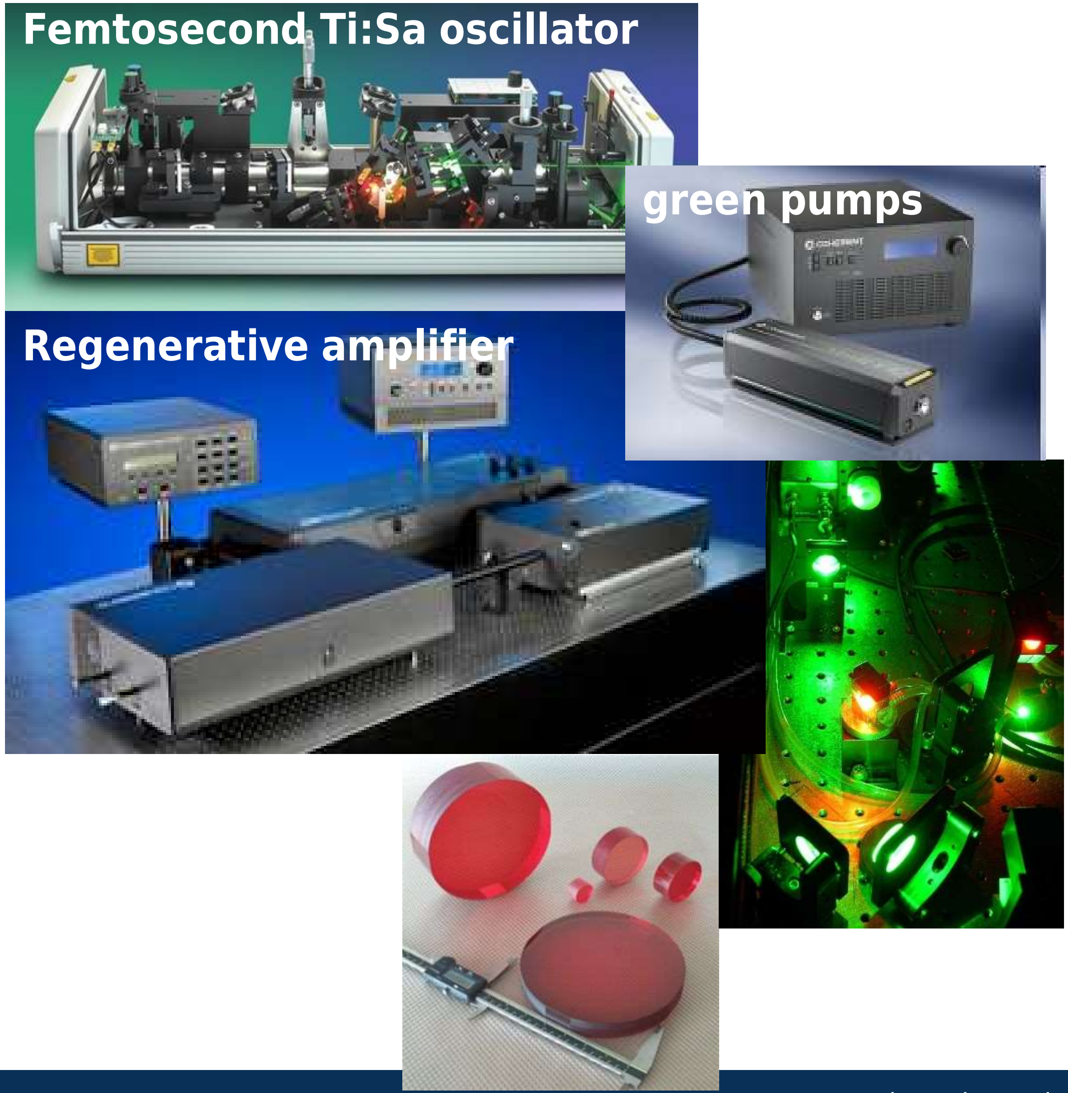
Pump ≈500 nm

Laser transition ≈800 nm

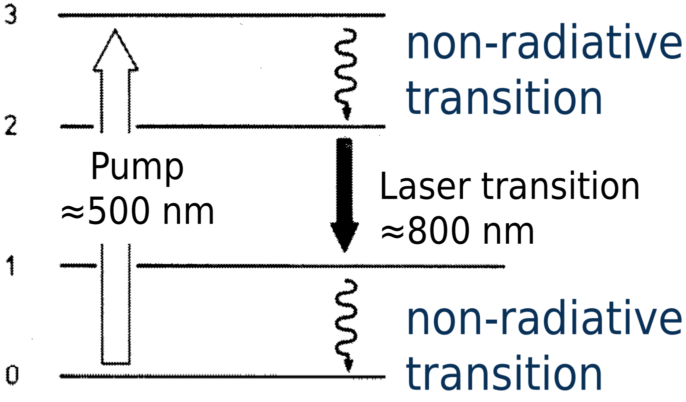
non-radiative transition

Non-radiative transitions: Large heat load

the workhorse of ultrafast science



Ti:sapphire laser:



Non-radiative transitions: Large heat load

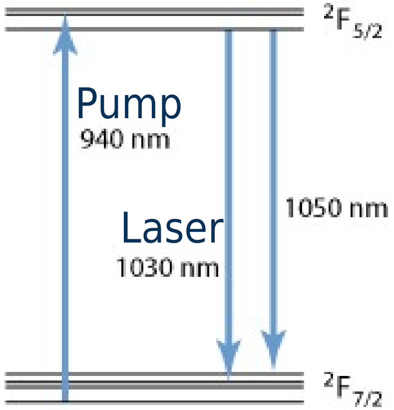
+ other problems:

- small upper-state lifetime (few µs) → high pump intensities needed to saturate
- degradation of crystal quality when increasing doping

Bulk geometry with large thermal load → thermal aberrations

material properties + advanced cooling geometries

Yb:YAG laser:



- **Small heat load < 10%**
- **Long lifetime (ms)**
- **High doping**

1090 OPTICS LETTERS / Vol. 16, No. 14 / July 15, 1991

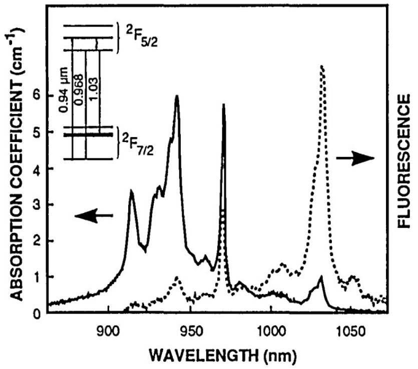
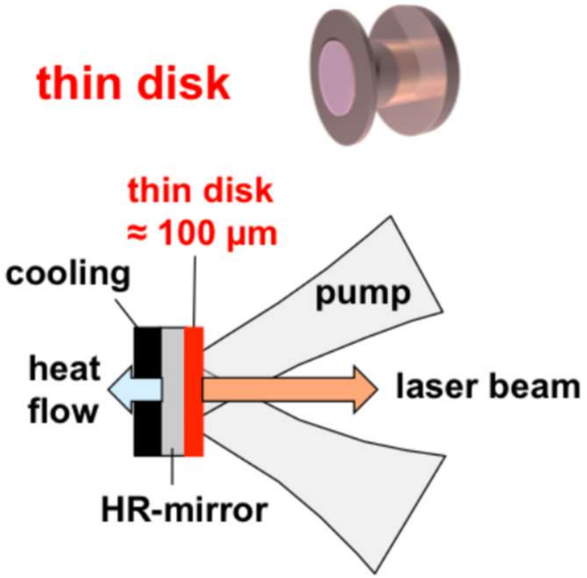
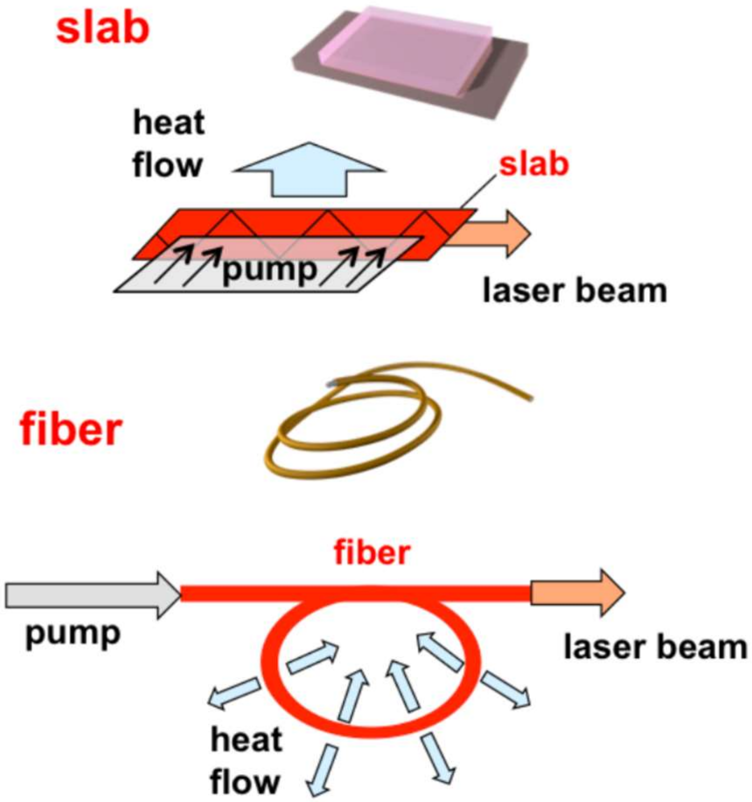


Fig. 1. Absorption and fluorescence spectra of 6.5 at.% Yb:YAG. The energy levels are from Ref. 13.

+

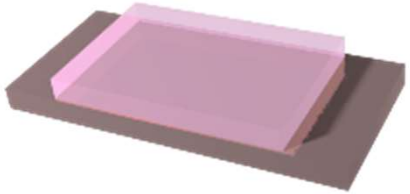


Advanced laser concepts for high average power



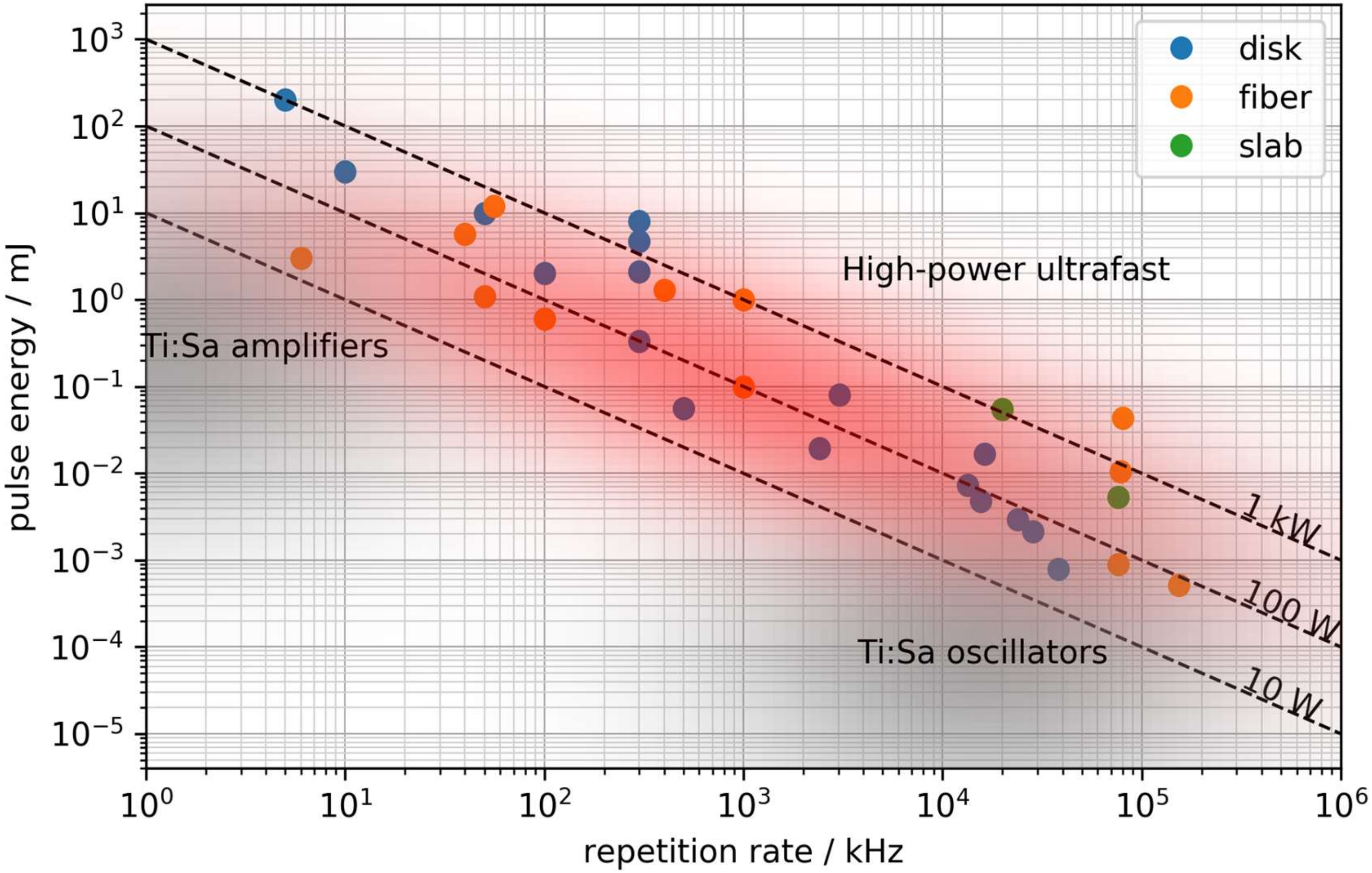
high-power lasers based on Yb-doped technology

✓ Fiber



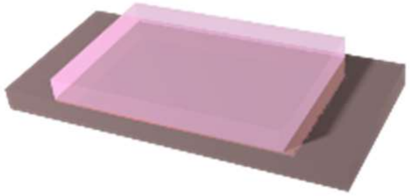
✓ Slab

✓ Thin disk



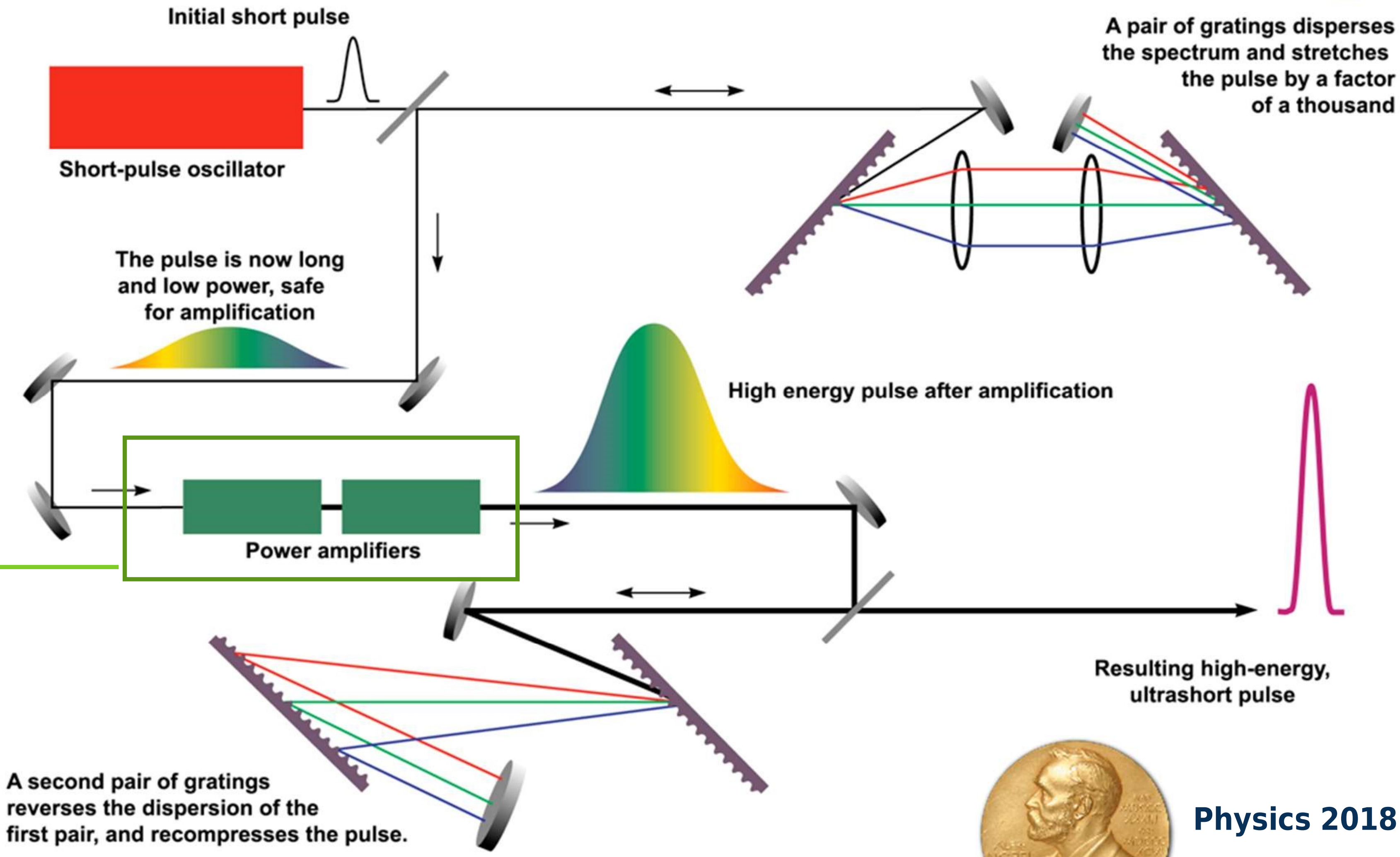
most commonly: chirped-pulse amplification

- ✓ Fiber



- ✓ Slab

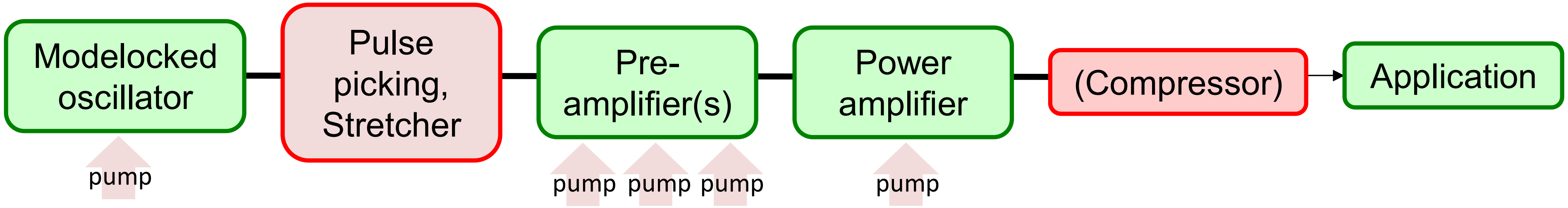
- ✓ Thin disk

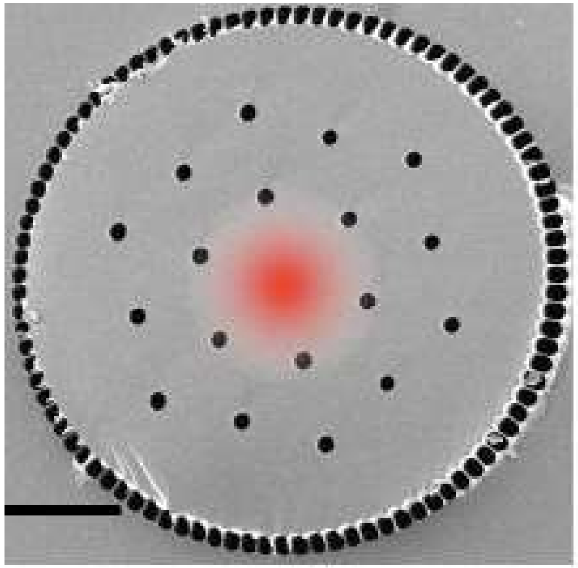


Physics 2018

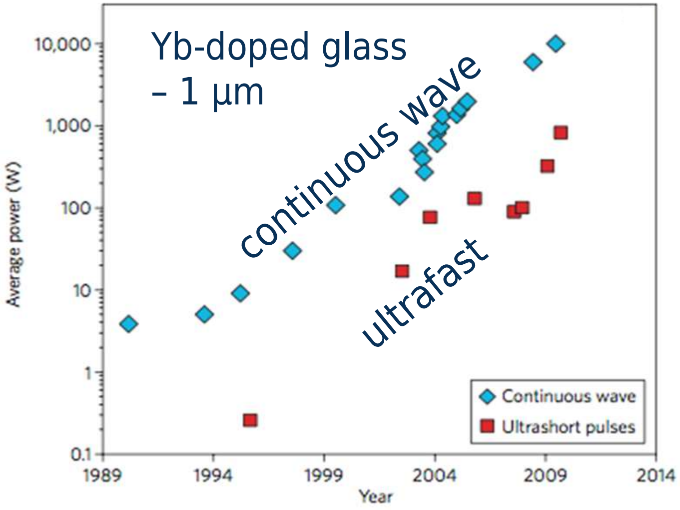
high power fiber CPA

Most commonly used: chirped pulse amplification (CPA)





large –mode-area photonic crystal fiber



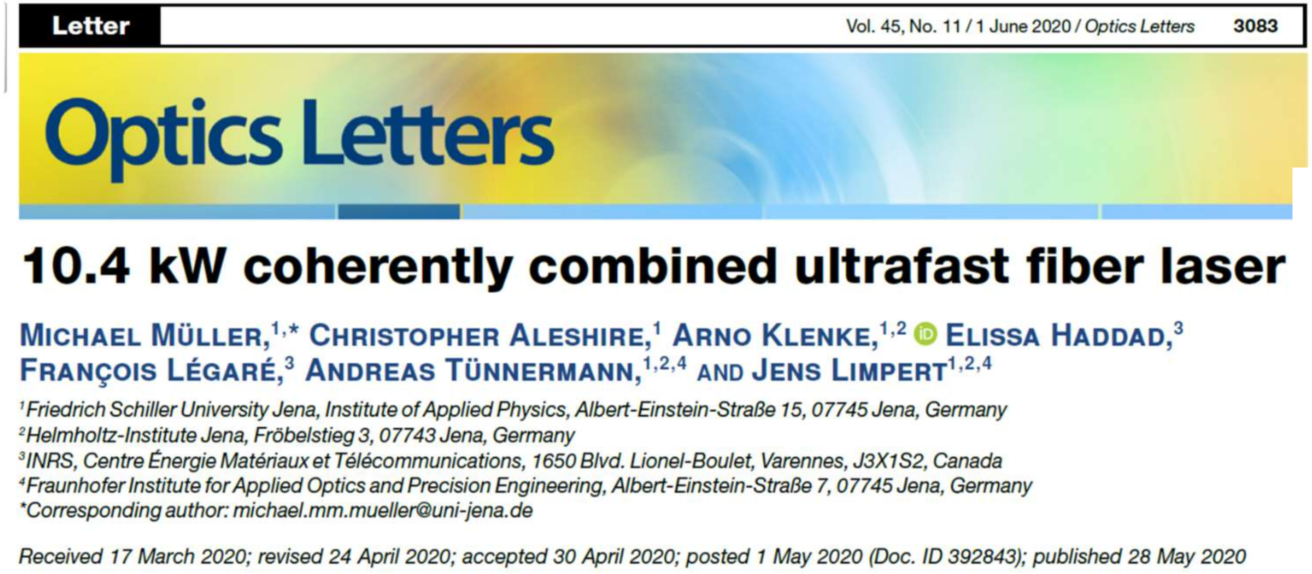
Single-stage ultrafast fiber amplifier @1µm
830 W, 640 fs,
78 MHz, 11 µJ

T. Eidam, … J. Limpert,
A. Tünnermann,
Opt. Lett. 35, 94-96 (2010)

→ Limit: high-order mode instabilities

Group of J. Limpert, Uni Jena

further scaling: coherent combination



Letter Vol. 45, No. 11 / 1 June 2020 / *Optics Letters* 3083

Optics Letters

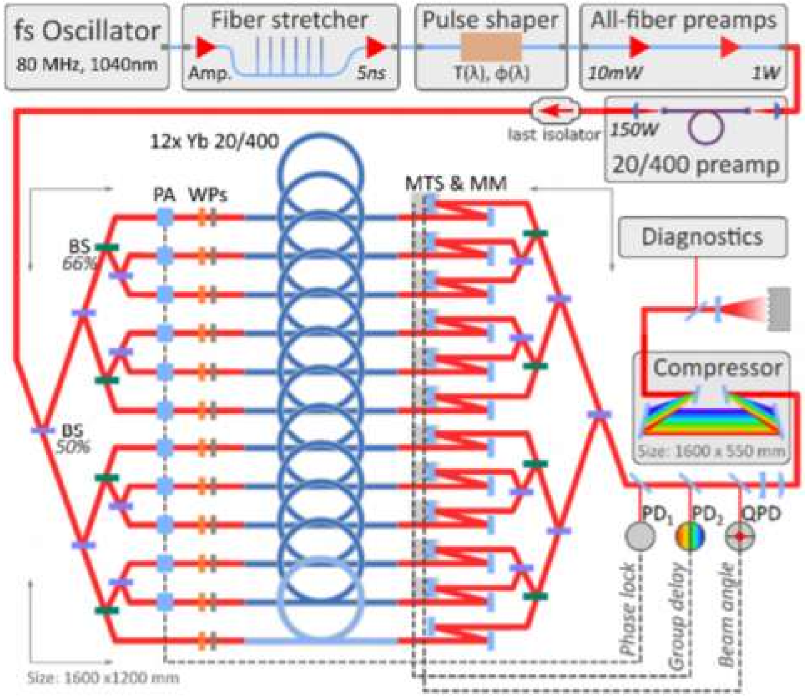
10.4 kW coherently combined ultrafast fiber laser

Michael Müller,[1,*] Christopher Aleshire,[1] Arno Klenke,[1,2] Elissa Haddad,[3] François Légaré,[3] Andreas Tünnermann,[1,2,4] and Jens Limpert[1,2,4]

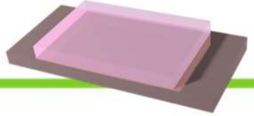
[1] Friedrich Schiller University Jena, Institute of Applied Physics, Albert-Einstein-Straße 15, 07745 Jena, Germany
[2] Helmholtz-Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
[3] INRS, Centre Énergie Matériaux et Télécommunications, 1650 Blvd. Lionel-Boulet, Varennes, J3X1S2, Canada
[4] Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Straße 7, 07745 Jena, Germany
**Corresponding author: michael.mm.mueller@uni-jena.de*

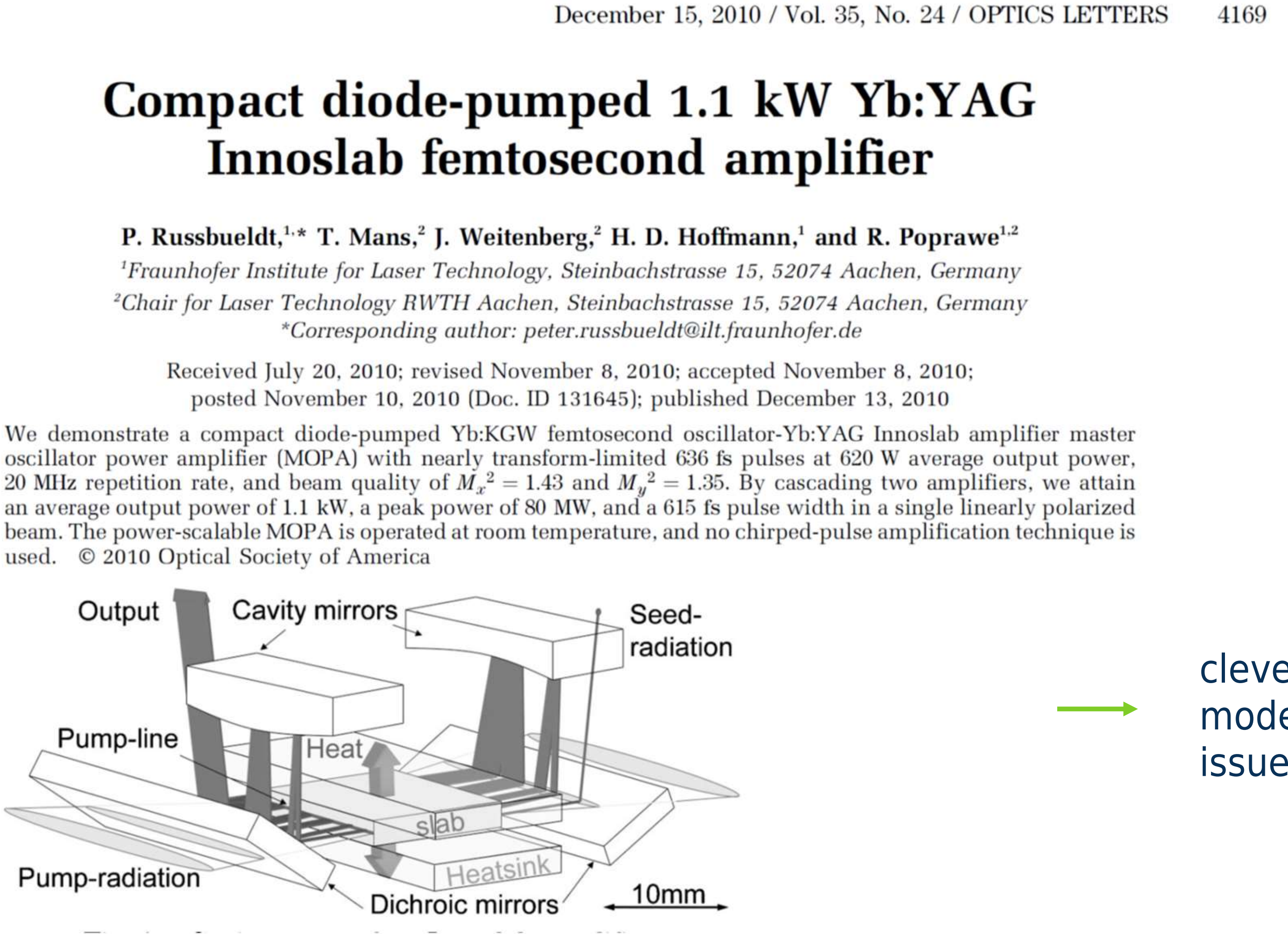
Received 17 March 2020; revised 24 April 2020; accepted 30 April 2020; posted 1 May 2020 (Doc. ID 392843); published 28 May 2020

Performance:
- 10.4 kW
- 254 fs pulses
- 80 MHz
- 130 µJ



slab amplifiers





December 15, 2010 / Vol. 35, No. 24 / OPTICS LETTERS 4169

Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier

P. Russbueldt,[1,*] **T. Mans,**[2] **J. Weitenberg,**[2] **H. D. Hoffmann,**[1] **and R. Poprawe**[1,2]
[1]*Fraunhofer Institute for Laser Technology, Steinbachstrasse 15, 52074 Aachen, Germany*
[2]*Chair for Laser Technology RWTH Aachen, Steinbachstrasse 15, 52074 Aachen, Germany*
**Corresponding author: peter.russbueldt@ilt.fraunhofer.de*

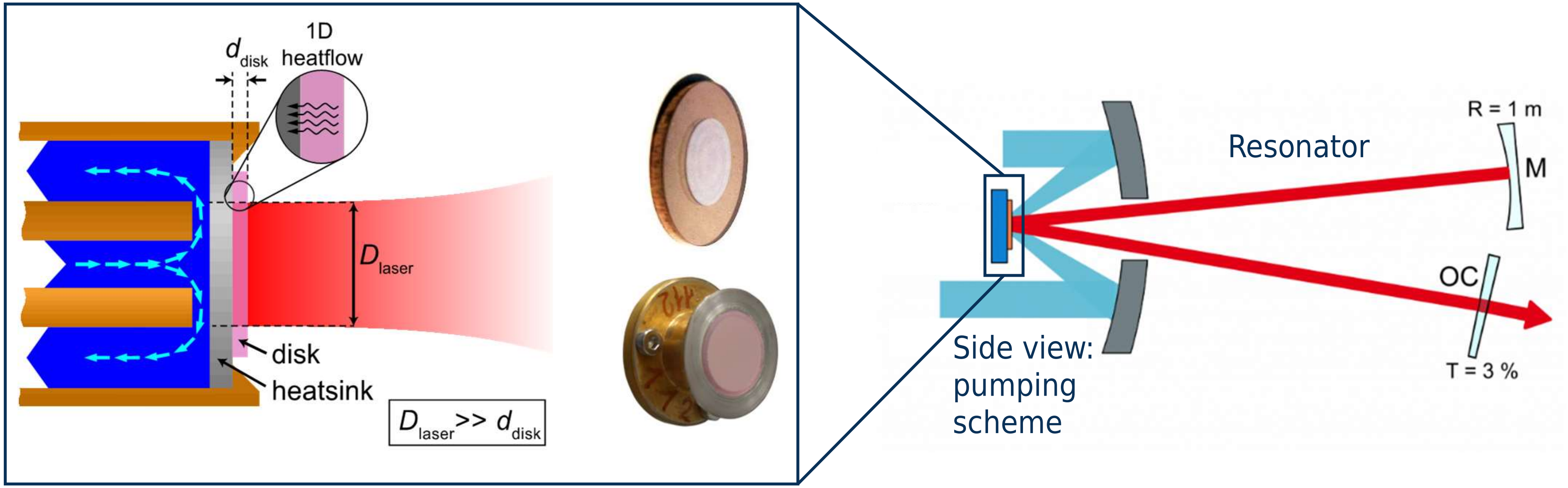
Received July 20, 2010; revised November 8, 2010; accepted November 8, 2010;
posted November 10, 2010 (Doc. ID 131645); published December 13, 2010

We demonstrate a compact diode-pumped Yb:KGW femtosecond oscillator-Yb:YAG Innoslab amplifier master oscillator power amplifier (MOPA) with nearly transform-limited 636 fs pulses at 620 W average output power, 20 MHz repetition rate, and beam quality of $M_x^2 = 1.43$ and $M_y^2 = 1.35$. By cascading two amplifiers, we attain an average output power of 1.1 kW, a peak power of 80 MW, and a 615 fs pulse width in a single linearly polarized beam. The power-scalable MOPA is operated at room temperature, and no chirped-pulse amplification technique is used. © 2010 Optical Society of America

- 1.1 kW,
- 615 fs
  20 MHz
- 55 µJ

→ clever geometry: CPA avoided for moderate pulse energies
issues: pointing, beam quality

thin-disk concept



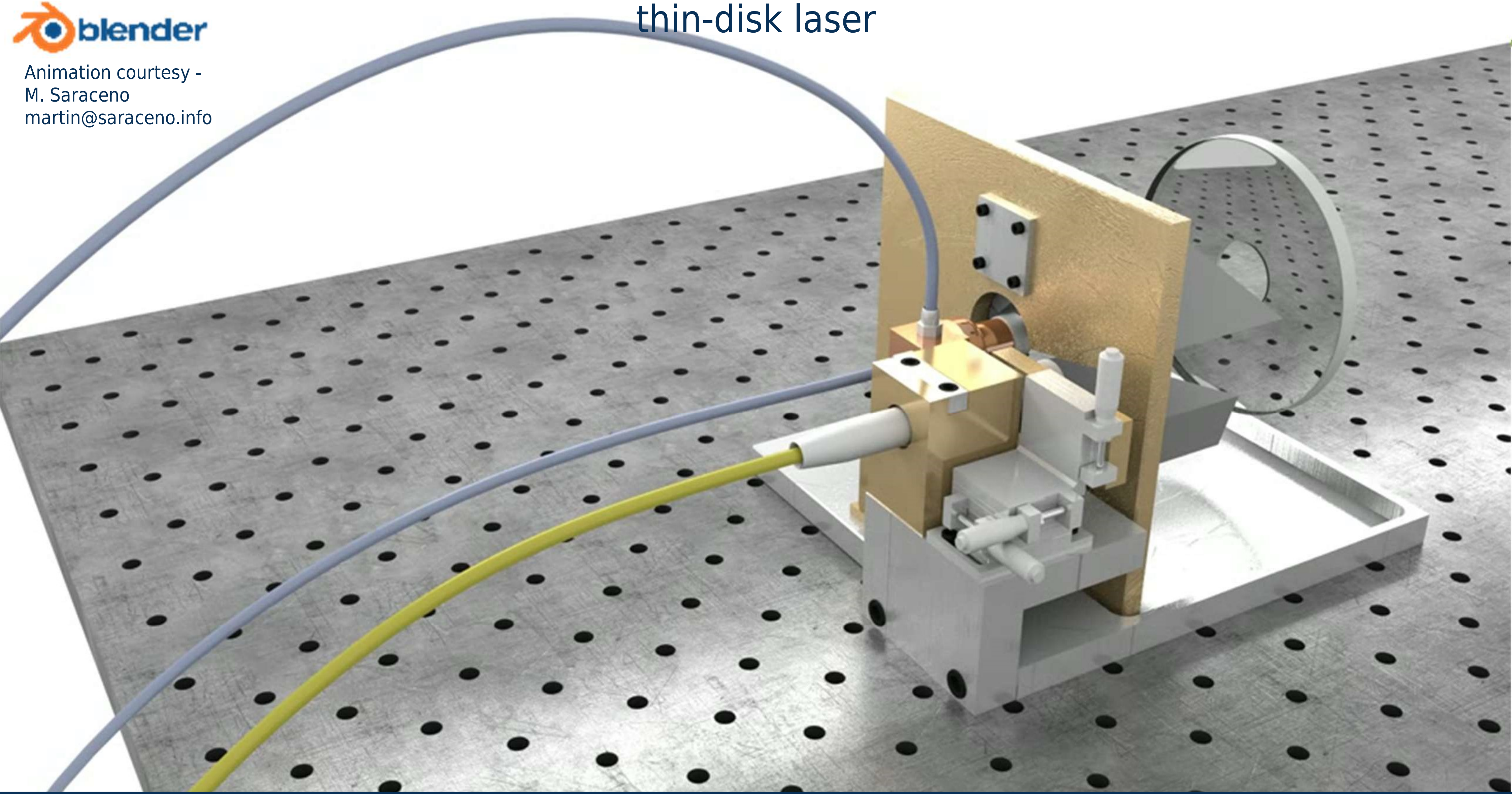
- → outstanding heat removal, extremely small thermal aberrations
- → Yb^{3+}-doped gain: diode pumped, accessible high-power diodes
- → good pump absorption: many passes through gain required
- → very small accumulated nonlinearities

→ ideal for ultrafast + high power

A. Giesen, et al., *Appl. Phys. B* **58**, 365 (1994)

thin-disk laser

Animation courtesy -
M. Saraceno
martin@saraceno.info



Single-disk high-power CW operation

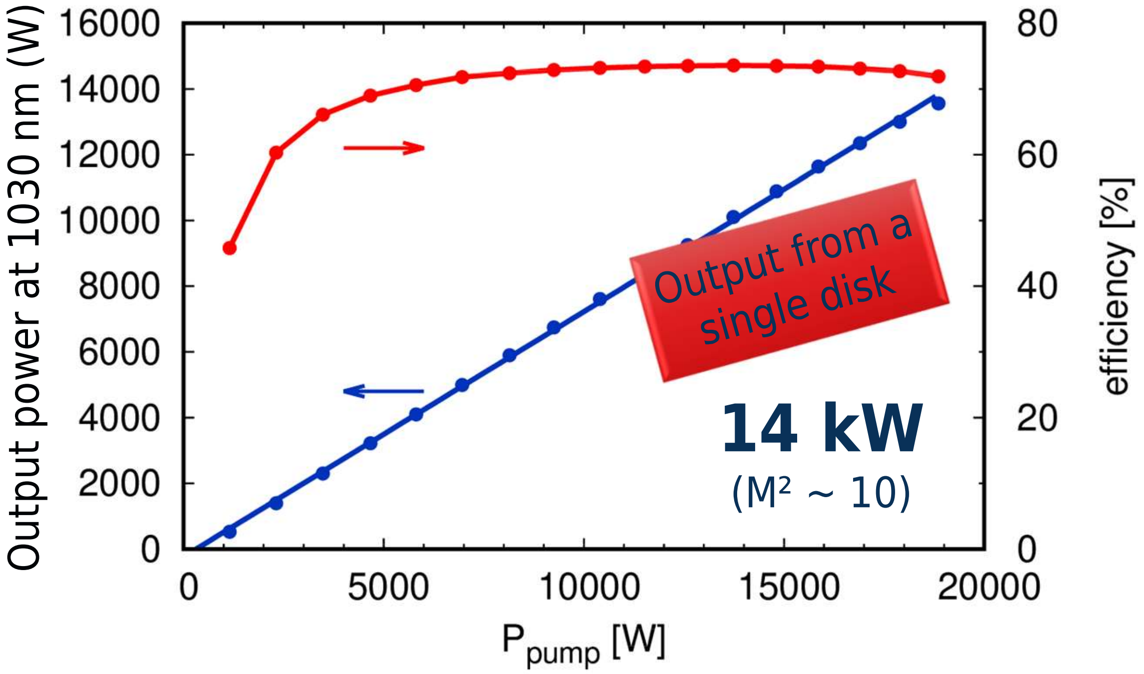
TRUMPF

Courtesy of Dirk Sutter

14 kW with $\eta_{opt.}$>70%

4 kW TEM_{00} (2013)

⇒ Further scaling w/ multiple heads, no barriers for power scaling beyond current levels

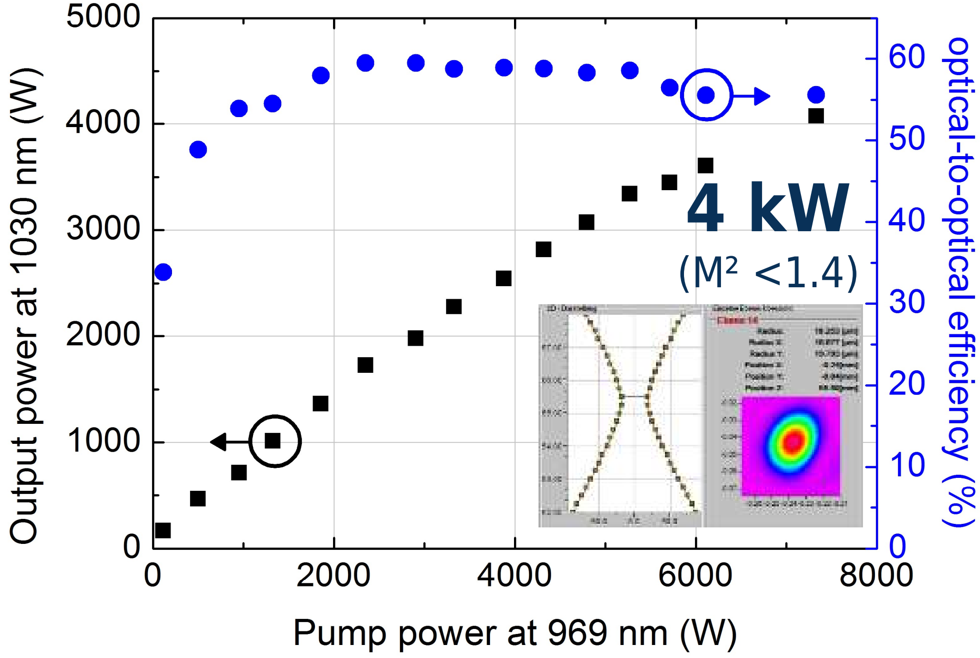


Output from a single disk

14 kW

(M² ~ 10)

B. Metzger et al. (TRUMPF, 2019)



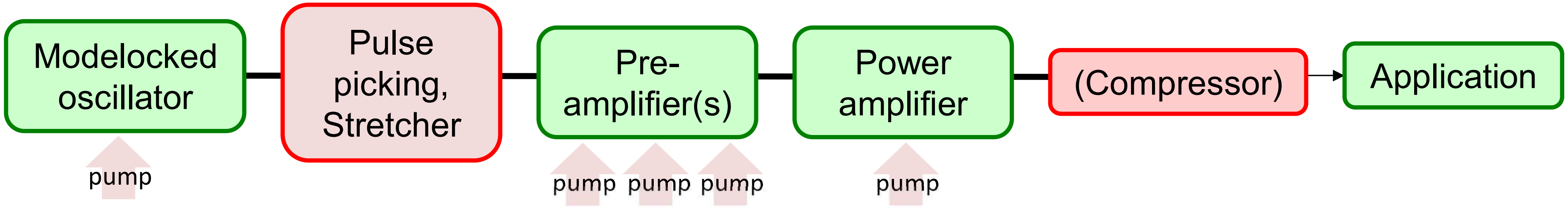
4 kW

(M² <1.4)

Gottwald et al., Security and Defense 2013

thin-disk ultrafast *amplifiers*

Most commonly used: chirped pulse amplification (CPA)



Modelocked oscillator

Pulse picking, Stretcher

Pre-amplifier(s)

Power amplifier

(Compressor)

Application

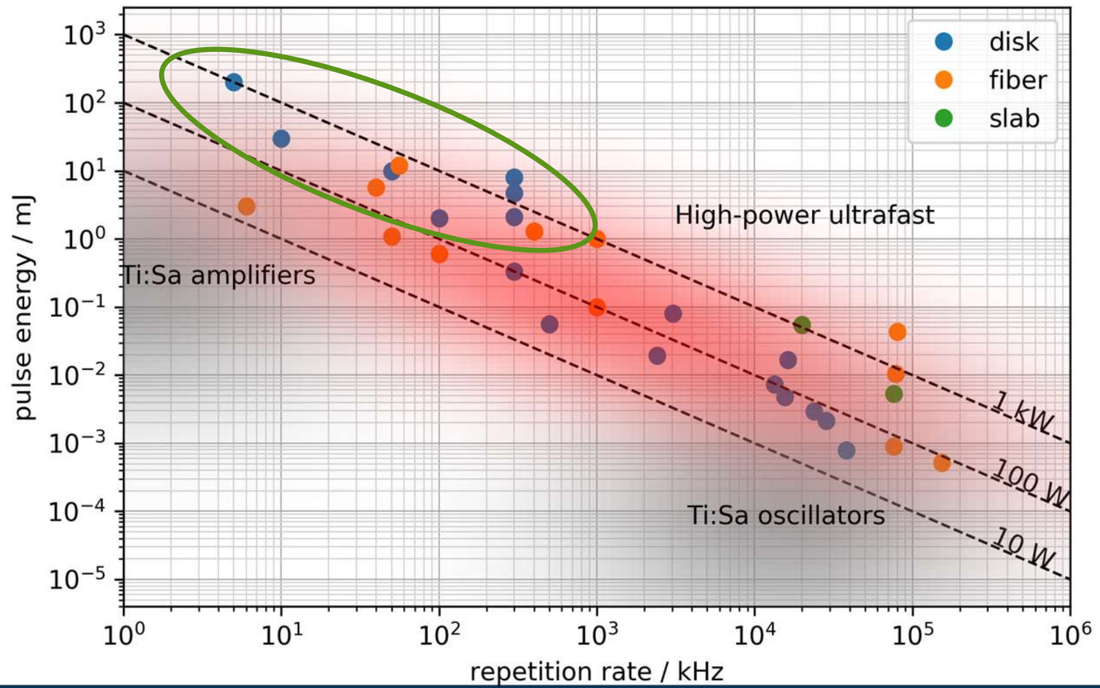
pump

pump pump pump

pump

unique combination of high energy and high average power:

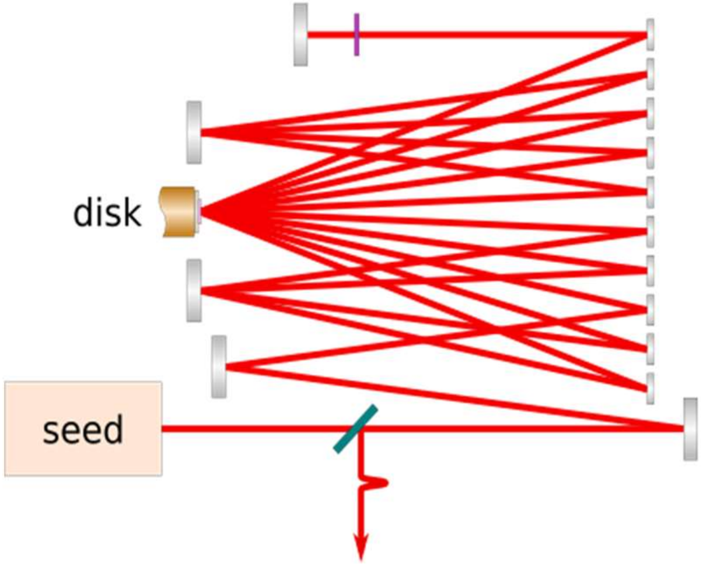
kilowatt powers
100s mJ
1-10s kHz



thin-disk *amplifier* geometries

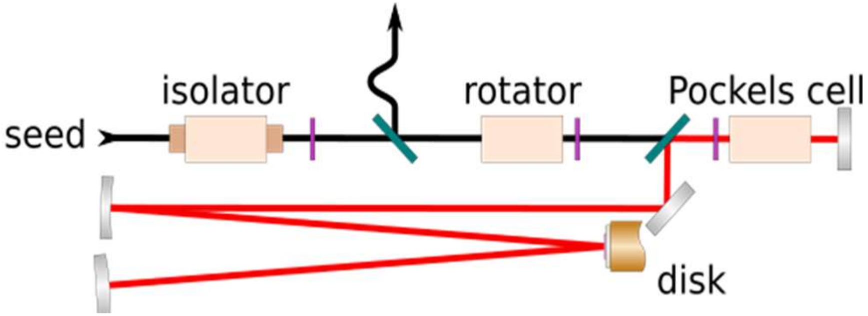
→ Thin-disk: low gain per pass (typical 10%)

Multi-pass amplifier



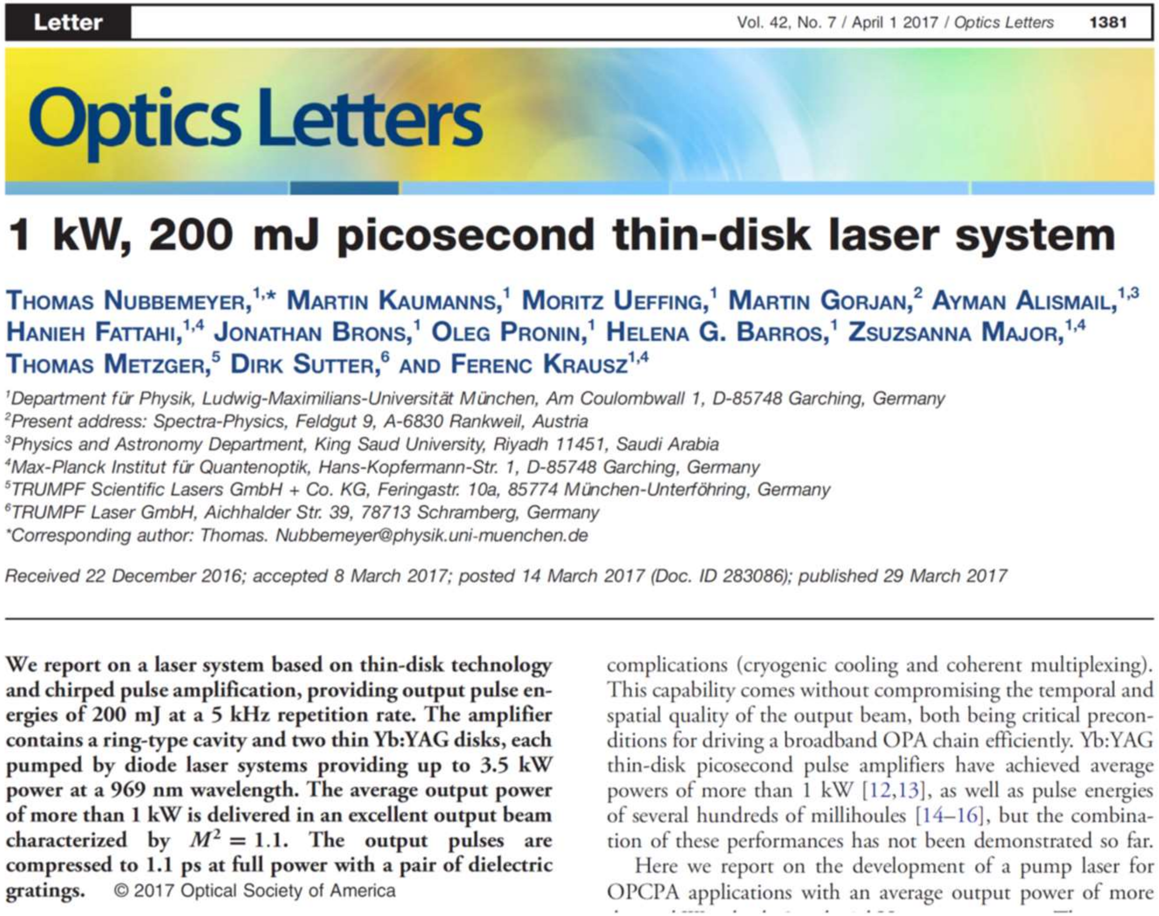
→ **moderate amplification,
high extraction (booster)**

Regenerative amplifier



→ **large amplification (main)**

state-of-the-art *thin-disk* regenerative amplifiers



Letter Vol. 42, No. 7 / April 1 2017 / *Optics Letters* **1381**

Optics Letters

1 kW, 200 mJ picosecond thin-disk laser system

THOMAS NUBBEMEYER,[1,*] MARTIN KAUMANNS,[1] MORITZ UEFFING,[1] MARTIN GORJAN,[2] AYMAN ALISMAIL,[1,3] HANIEH FATTAHI,[1,4] JONATHAN BRONS,[1] OLEG PRONIN,[1] HELENA G. BARROS,[1] ZSUZSANNA MAJOR,[1,4] THOMAS METZGER,[5] DIRK SUTTER,[6] AND FERENC KRAUSZ[1,4]

[1] *Department für Physik, Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany*
[2] *Present address: Spectra-Physics, Feldgut 9, A-6830 Rankweil, Austria*
[3] *Physics and Astronomy Department, King Saud University, Riyadh 11451, Saudi Arabia*
[4] *Max-Planck Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany*
[5] *TRUMPF Scientific Lasers GmbH + Co. KG, Feringastr. 10a, 85774 München-Unterföhring, Germany*
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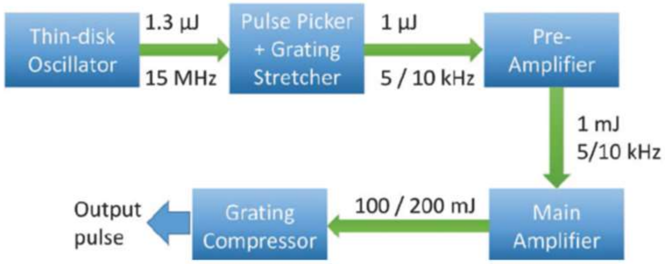
We report on a laser system based on thin-disk technology and chirped pulse amplification, providing output pulse energies of 200 mJ at a 5 kHz repetition rate. The amplifier contains a ring-type cavity and two thin Yb:YAG disks, each pumped by diode laser systems providing up to 3.5 kW power at a 969 nm wavelength. The average output power of more than 1 kW is delivered in an excellent output beam characterized by $M^2 = 1.1$. The output pulses are compressed to 1.1 ps at full power with a pair of dielectric gratings.

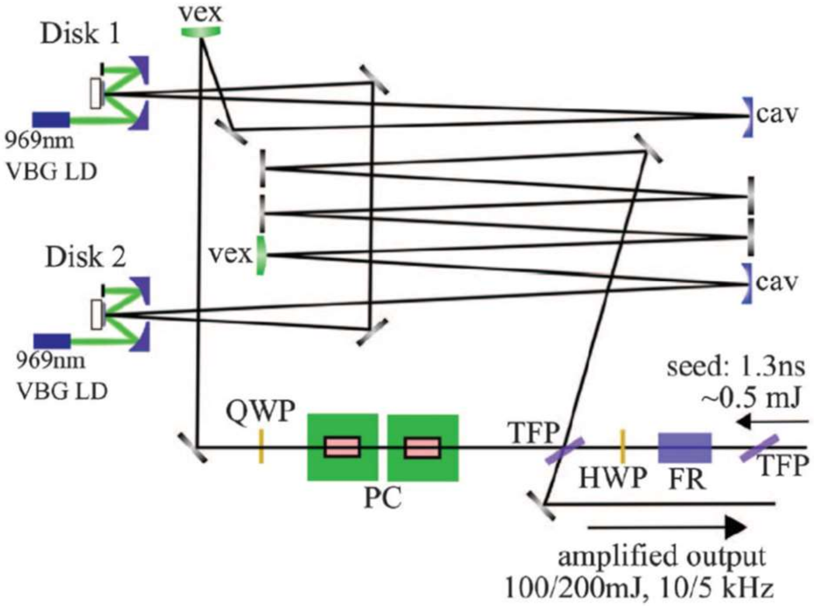
complications (cryogenic cooling and coherent multiplexing). This capability comes without compromising the temporal and spatial quality of the output beam, both being critical preconditions for driving a broadband OPA chain efficiently. Yb:YAG thin-disk picosecond pulse amplifiers have achieved average powers of more than 1 kW [12,13], as well as pulse energies of several hundreds of millihoules [14–16], but the combination of these performances has not been demonstrated so far.

Here we report on the development of a pump laser for OPCPA applications with an average output power of more

- 1 kW
- 200 mJ
- 5 kHz
- 1.1 ps



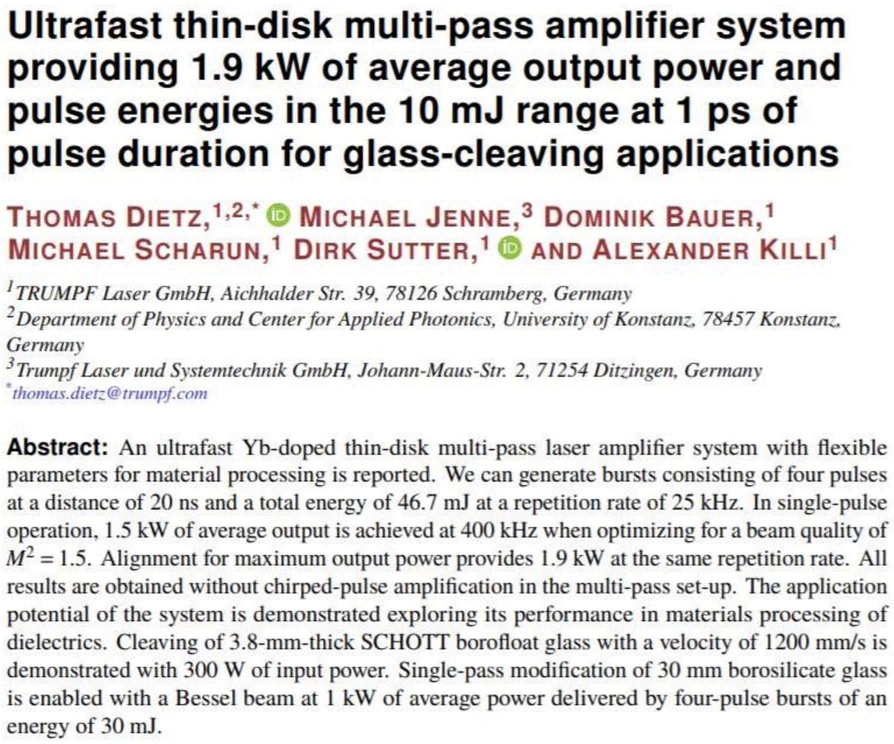
Thin-disk Oscillator → 1.3 µJ, 15 MHz → Pulse Picker + Grating Stretcher → 1 µJ, 5 / 10 kHz → Pre-Amplifier → 1 mJ, 5/10 kHz → Main Amplifier → 100 / 200 mJ → Grating Compressor → Output pulse



state-of-the-art thin-disk *multi-pass* amplifiers

- 1.9 kW
- 400 kHz
- 1.1 ps
- ! No CPA

(now up to 2.3 kW)



Ultrafast thin-disk multi-pass amplifier system providing 1.9 kW of average output power and pulse energies in the 10 mJ range at 1 ps of pulse duration for glass-cleaving applications

THOMAS DIETZ,[1,2,*] MICHAEL JENNE,[3] DOMINIK BAUER,[1] MICHAEL SCHARUN,[1] DIRK SUTTER,[1] AND ALEXANDER KILLI[1]

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Abstract: An ultrafast Yb-doped thin-disk multi-pass laser amplifier system with flexible parameters for material processing is reported. We can generate bursts consisting of four pulses at a distance of 20 ns and a total energy of 46.7 mJ at a repetition rate of 25 kHz. In single-pulse operation, 1.5 kW of average output is achieved at 400 kHz when optimizing for a beam quality of $M^2 = 1.5$. Alignment for maximum output power provides 1.9 kW at the same repetition rate. All results are obtained without chirped-pulse amplification in the multi-pass set-up. The application potential of the system is demonstrated exploring its performance in materials processing of dielectrics. Cleaving of 3.8-mm-thick SCHOTT borofloat glass with a velocity of 1200 mm/s is demonstrated with 300 W of input power. Single-pass modification of 30 mm borosilicate glass is enabled with a Bessel beam at 1 kW of average power delivered by four-pulse bursts of an energy of 30 mJ.

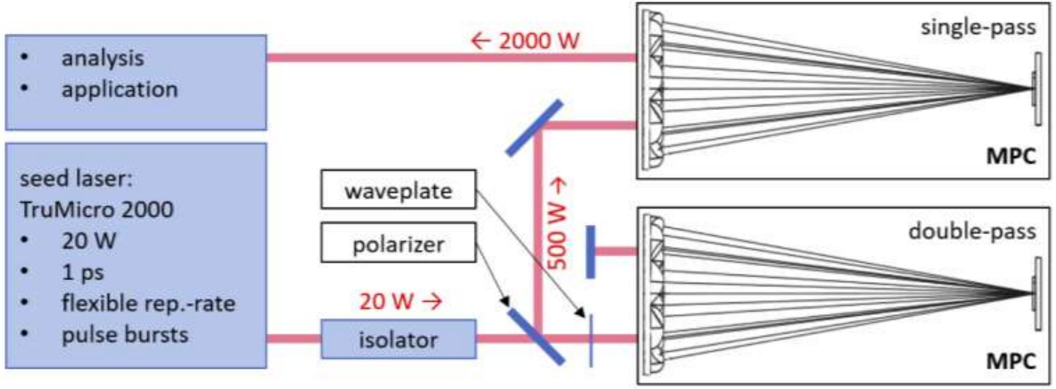
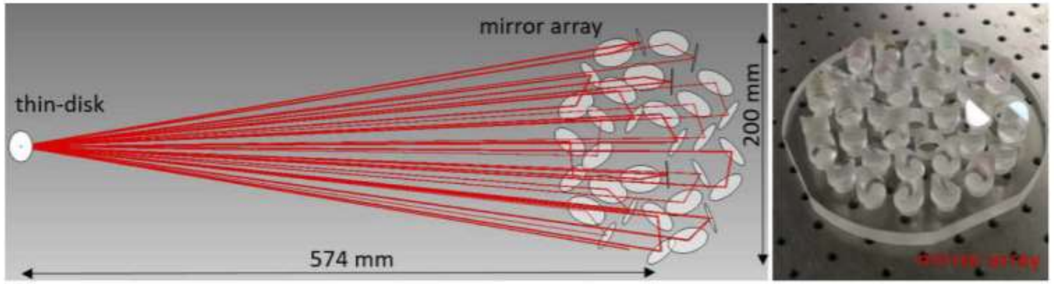


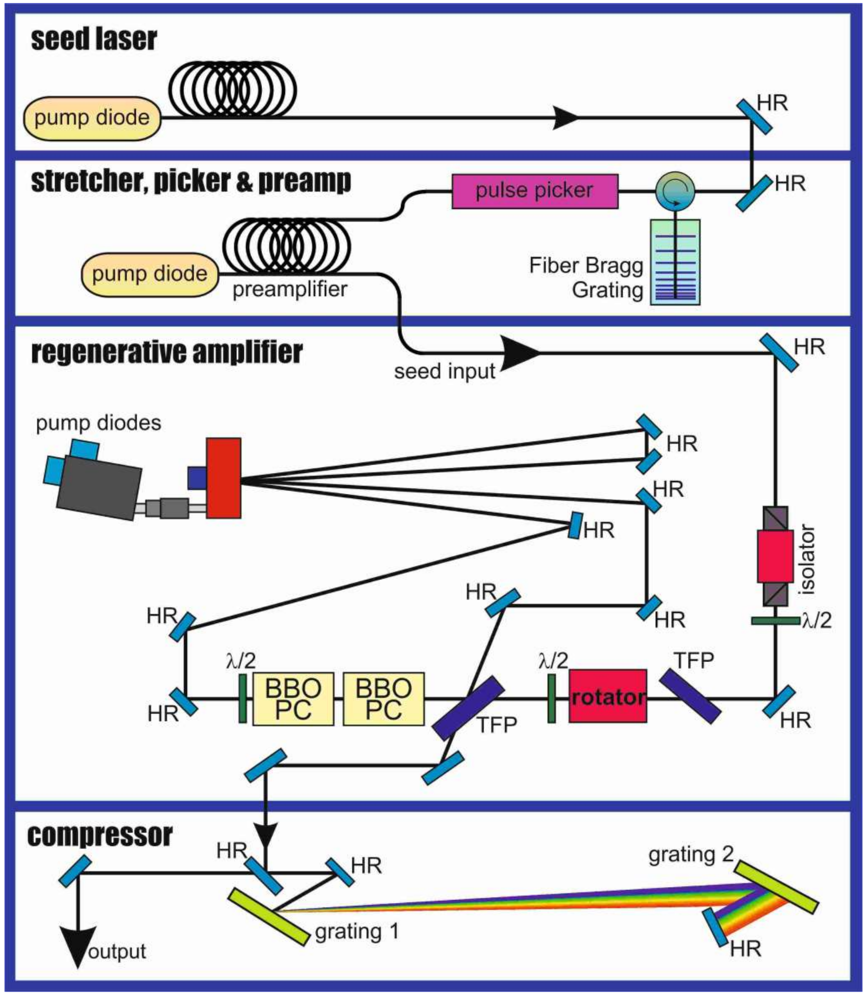
Fig. 1. Schematic set-up of the amplifier system. The seed laser is a commercial TruMicro 2000, followed by two amplifier stages. Red lines indicate the laser beam. MPC: Multi-pass cell.

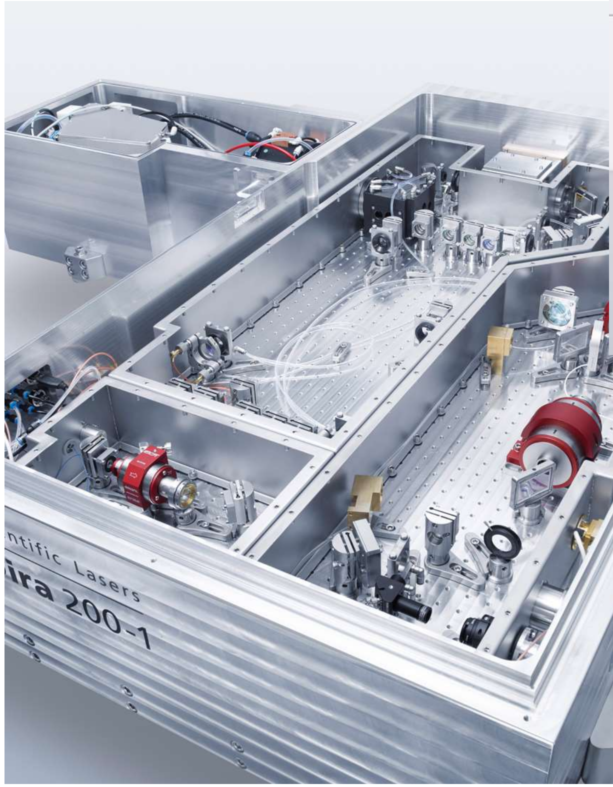


thin-disk regenerative amplifiers: state-of-the-art

TRUMPF

Courtesy of Thomas Metzger





“Flagship” Laser

Energy:	200 mJ
Power:	>1.0 kW
Duration:	500 fs
Peak Power:	0.4 TW

T. Nubbemeyer et al. OL 42, 7 (2017)

New developments: 2 kW – 20 kHz – ps, etc…

industrial application of kW-class thin-disk amplifiers

TRUMPF

Courtesy of Dirk Sutter

TECHNISCHE UNIVERSITÄT DRESDEN

TRUMPF

NIT New Infrared Technologies

next scan technology

lasea PRECISION LASER SOLUTIONS

BOSCH

B/S/H/

EPIC European Photonics Industry Consortium

LAMpAS Project

The first laser system for high throughput low cost production of surfaces with controlled topographic characteristics

High throughput (m²/min) laser structuring with multiscale periodic features for advanced surface functionalities

Anti-finger print properties

for ovens, cooktops, hoods, dish-washer fascia panels and fridge front.

Decorative finishes

novel decorative aesthetics surfaces for ovens, cooktops, hoods, dish-washers fascia panels and fridges front.

Anti-bacterial properties

For game tools, mill buckets.

Easy to clean

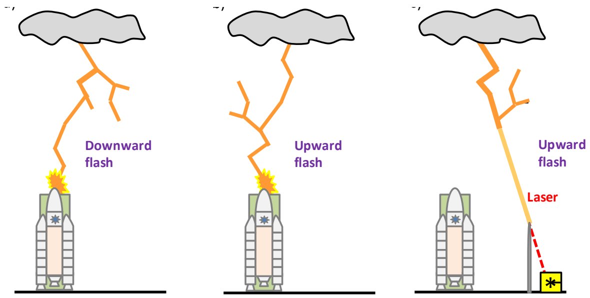
For ovens, cooktops, hoods, dish-washer fascia panels and fridge front.

scientific applications: Laser Lightning Rod “LLR” EU-Project

Courtesy of Thomas Metzger

Goal: Field campaign to actively trigger lightning at Säntis Mountain (CH)

Goal: 1 J – 1 kHz – 1 kW - 1 ps

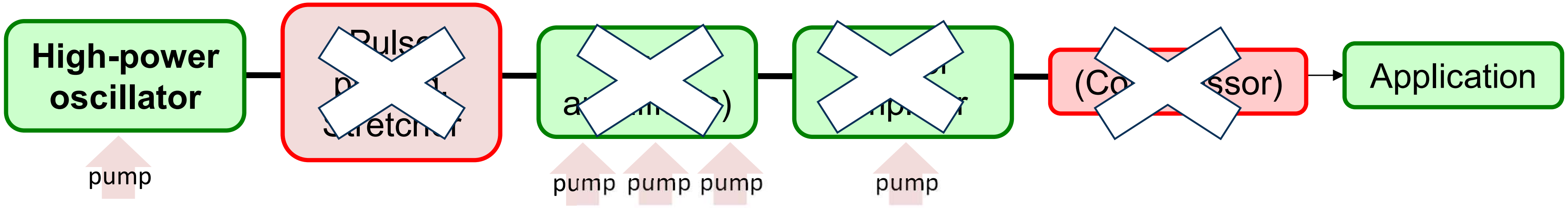


European Commission

http://llr-fet.eu/

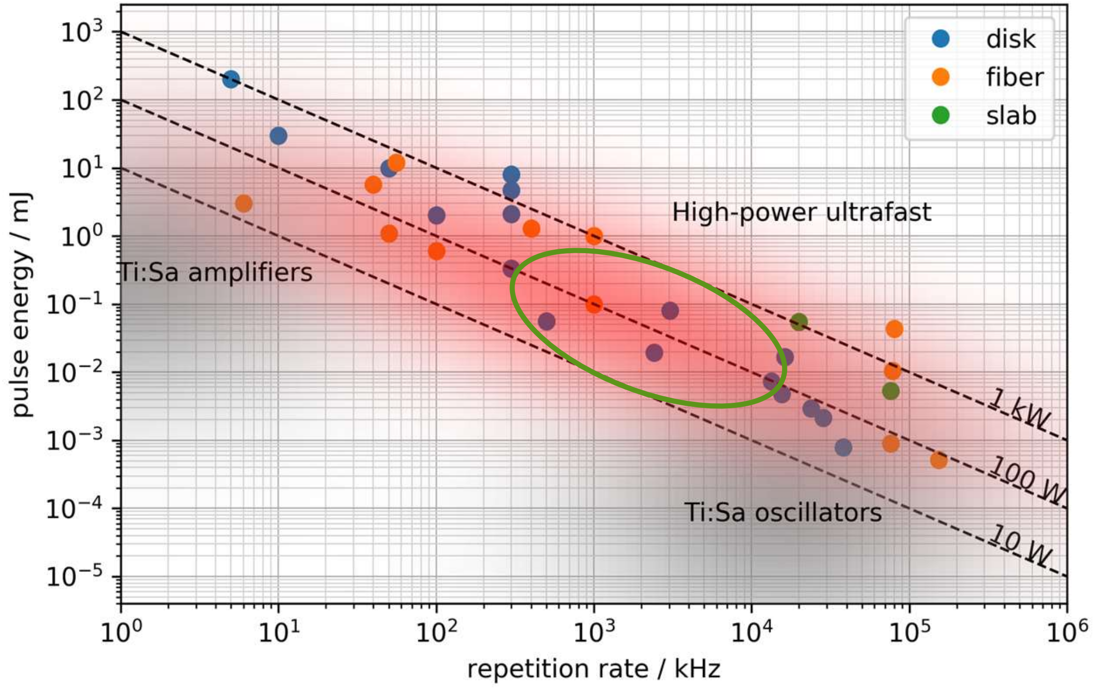
thin-disk ultrafast *oscillators*

High-power oscillators: one-box, MHz repetition rate

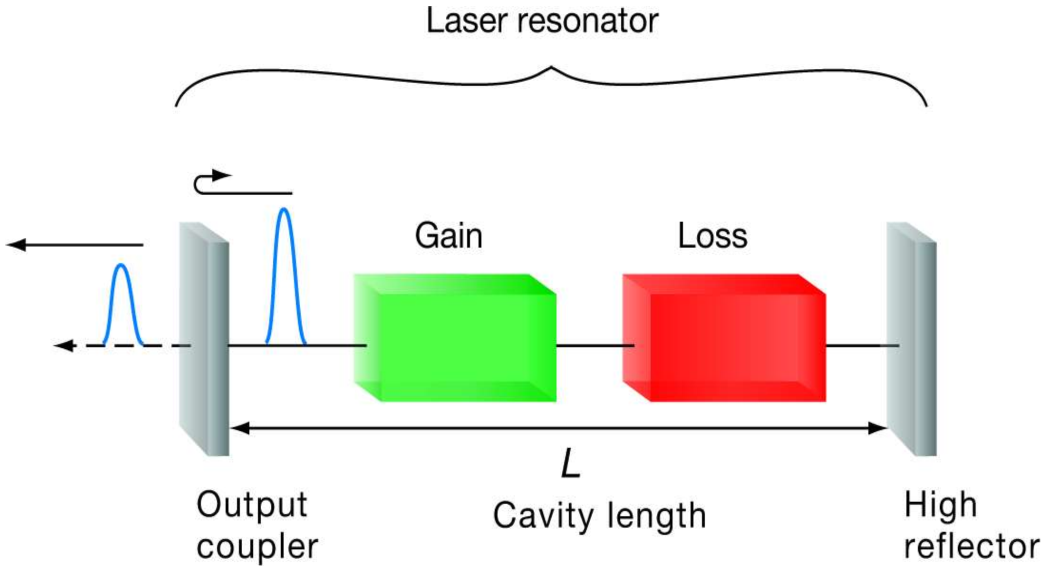


Amplifier-free, one-box modelocked oscillators:
hundreds of watts
3 - 100 MHz
10 - 100 µJ

.... the 'future' ?

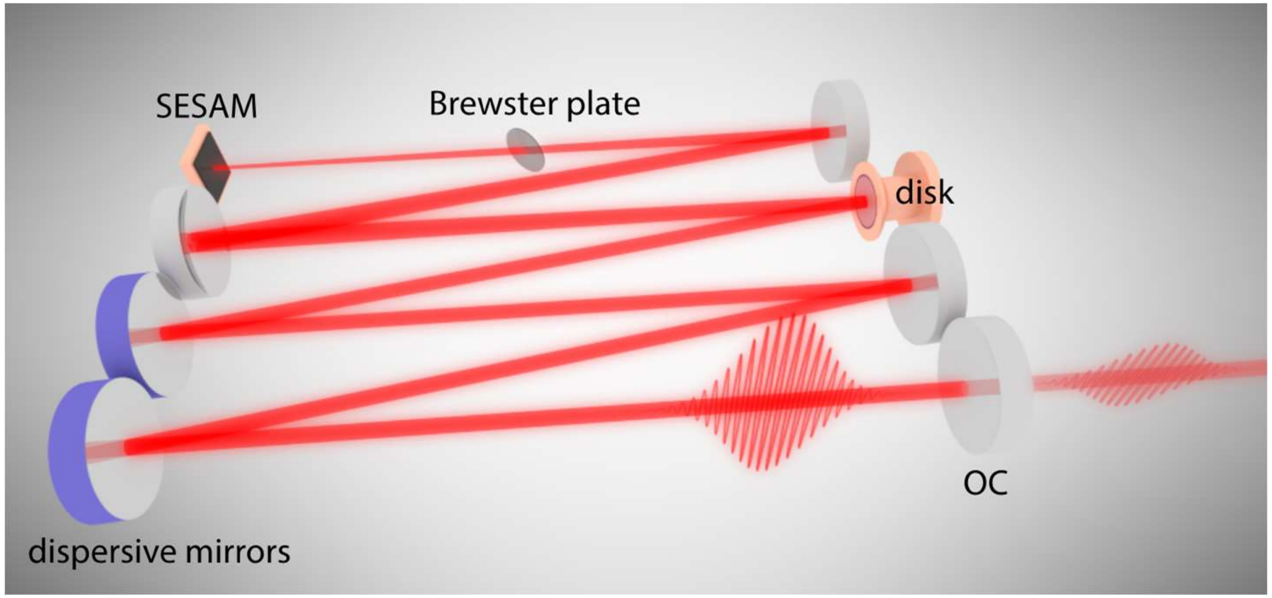


no different than a “textbook” modelocked laser



- Short pulse circulates in cavity (fs-ps)
- High repetition rate pulse train at the output (MHz)
- Pulse starting
    - Semiconductor saturable absorbers
    - Kerr lensing
- Pulse formation
    - Soliton modelocking
    - Kerr lens modelocking
- Steady-state pulse parameters: interplay of gain, (saturable) loss, dispersion, Kerr nonlinearity, etc.

the technology has come quite far

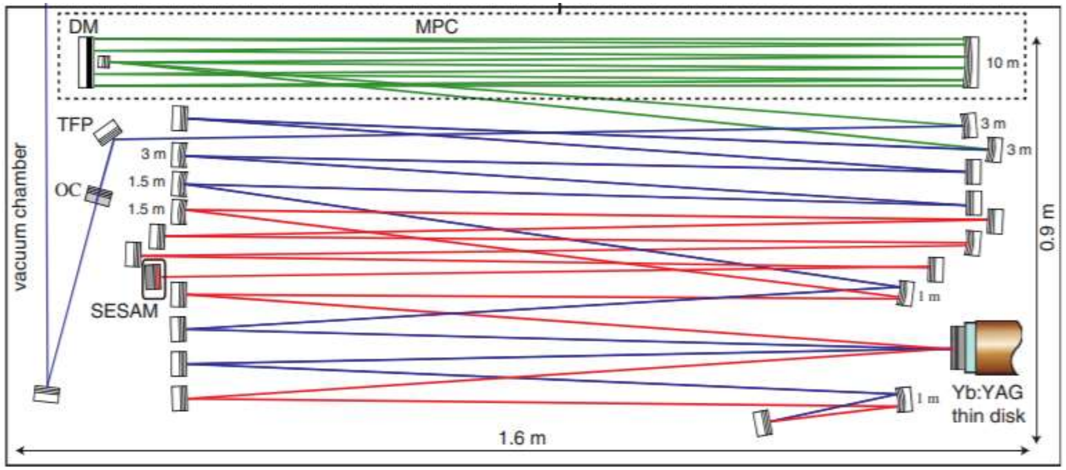


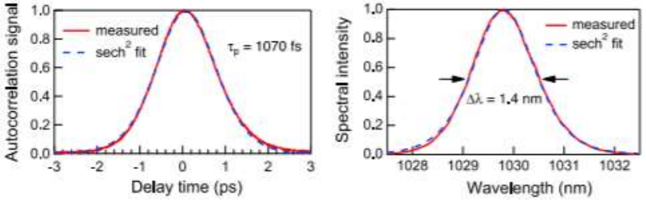
- ‘One-box’ oscillator
- Femtosecond soliton-type pulses
- megahertz repetition rate
- tens of microjoules pulse energy (up to **80 µJ** [#1])
- hundreds of watts of average power (up to **350 W** [#2])

→ **orders of magnitude higher levels than other modelocked laser technologies**

[#1] C J Saraceno et al, *Optics Letters* ***39*** (2014)
[#1] F. Saltarelli et al, *Optics Express* ***39*** (2019)

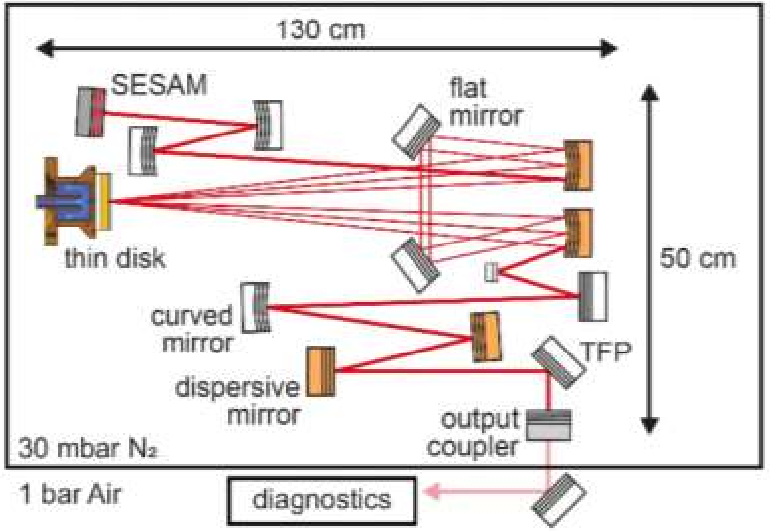
the technology has come quite far





- 242-W
- 1-ps,
- 80-µJ
- 3-MHz

- 'One-box' oscillator
- Femtosecond soliton-type pulses
- megahertz repetition rate
- tens of microjoules pulse energy (up to **80 µJ** [#1])
- hundreds of watts of average power (up to **350 W** [#2])



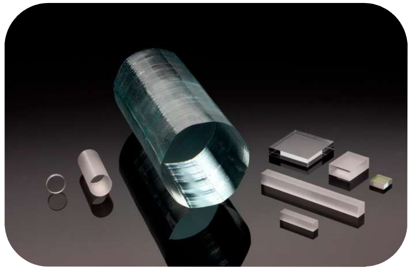
- 350-W
- 940-fs,
- 39-µJ
- 8.88-MHz

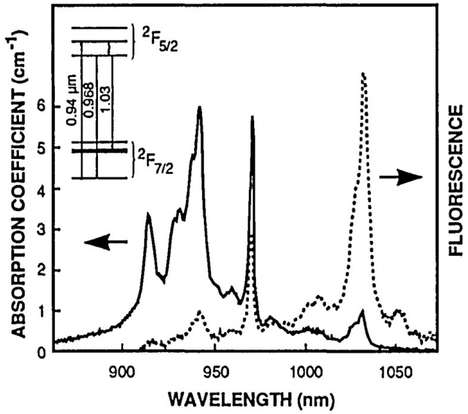
→ **Difficulties: intracavity nonlinearities, modelocking instabilities, thermal effects**

[#1] C J Saraceno et al, *Optics Letters* ***39*** (2014)

[#1] F. Saltarelli et al, *Optics Express* ***39*** (2019)

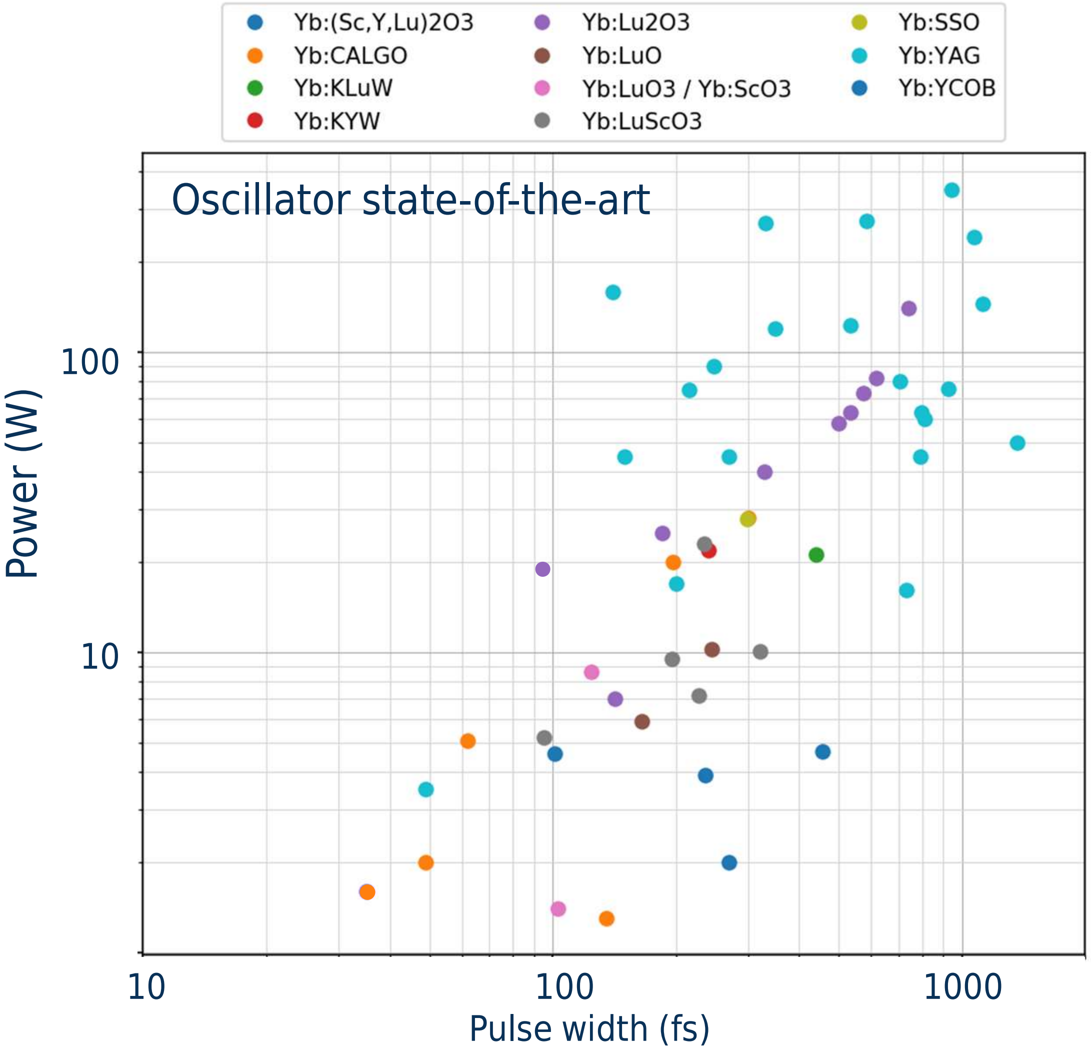
challenge: pulse duration





Yb:YAG: narrow emission bandwidth
$\Delta\lambda \sim 7$ nm

Strong compromise between pulse duration and average power/pulse energy

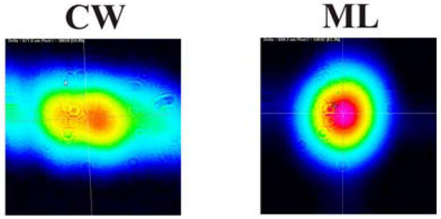


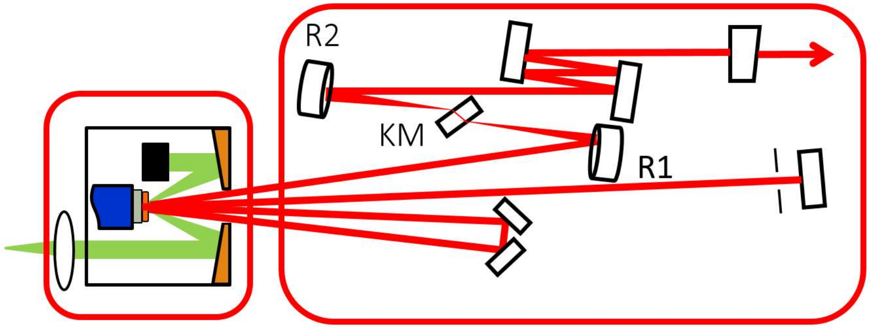
Kerr-lens modelocked thin-disk oscillators

First Kerr Lens modelocked TDL

O. Pronin, et. al., Opt. Lett., 36, 4746 (2011)

Now at:



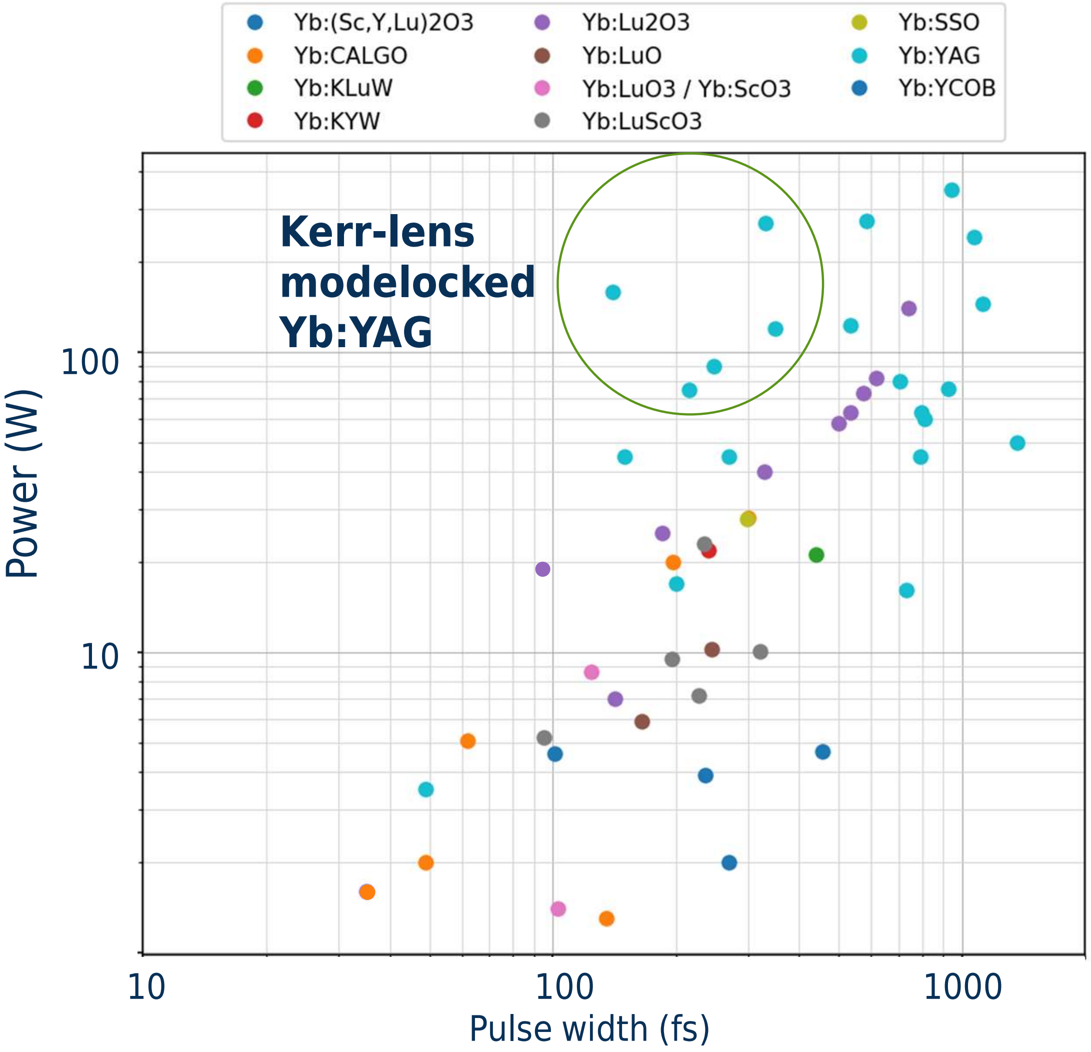


E_p = 14.4 µJ
P_{av} = 270 W
τ_p = 330 fs
f_{rep} = 18.8 MHz

J. Brons, et. al.
Opt. Lett., **39**, 6442 (2014)

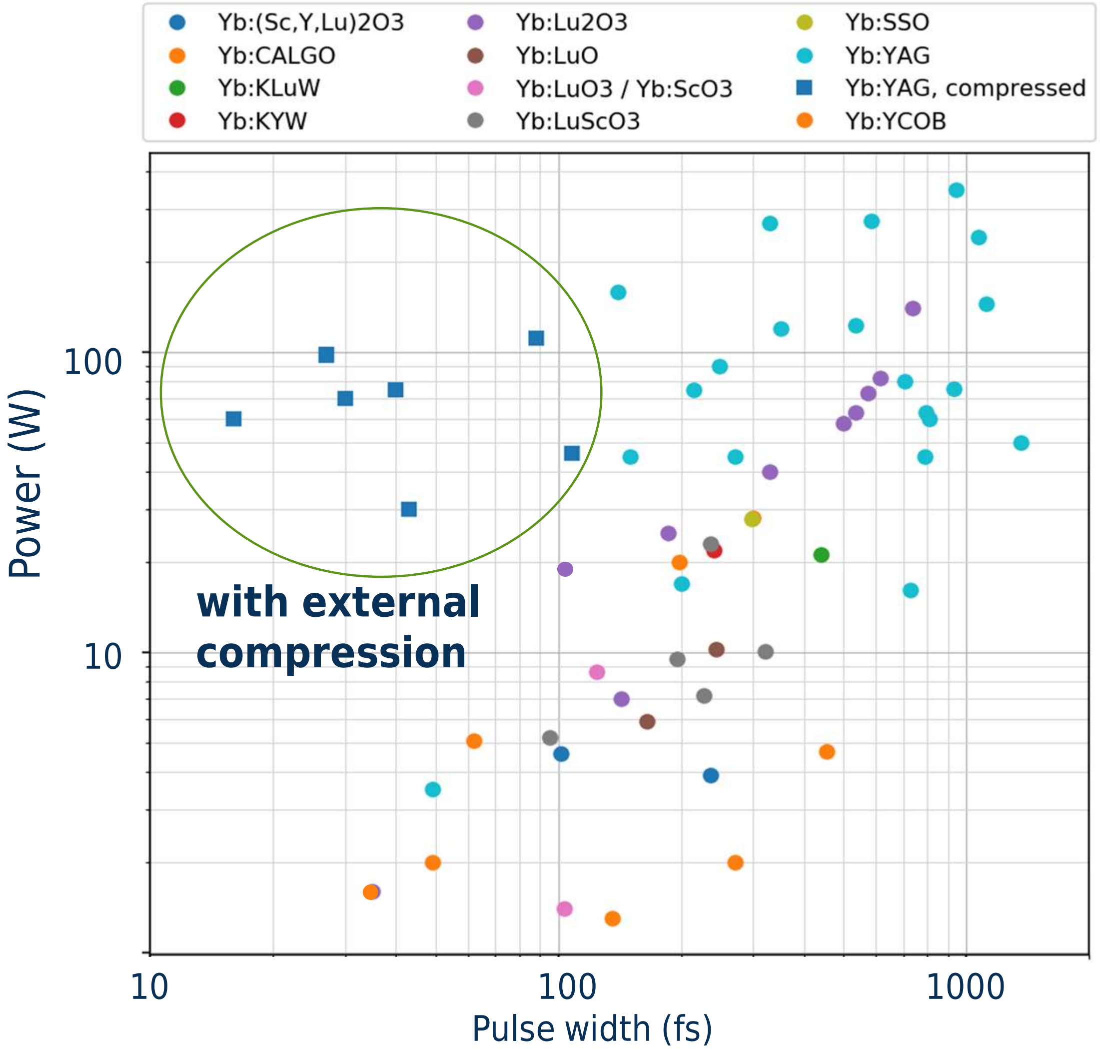
E_p = 10 µJ
P_{av} = 155 W
τ_p = 140 fs
f_{rep} = 15.6 MHz

J. Brons, et al.
Opt. Lett. **41**, (2016)



broadband laser materials are (still) needed!

- 100 W – sub-100 fs 'barrier' still undemonstrated from oscillators directly
- broadband materials suitable for the thin-disk geometry **still needed**!
- efficient pulse compression techniques for high average power allow to reach desired regime for applications



Reminder SPM

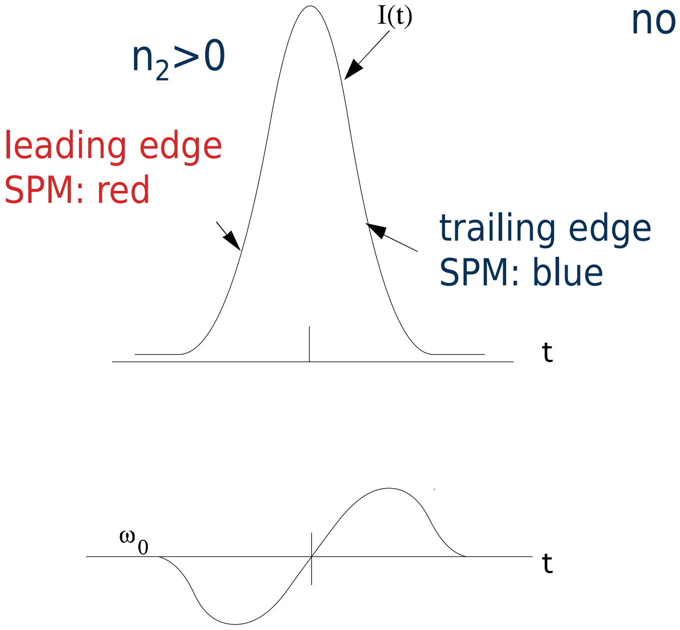
Self-phase modulation

$$n(I) = n + n_2 I$$

$I(t)$ → self-phase modulation
$I(x,y)$ → self-focusing

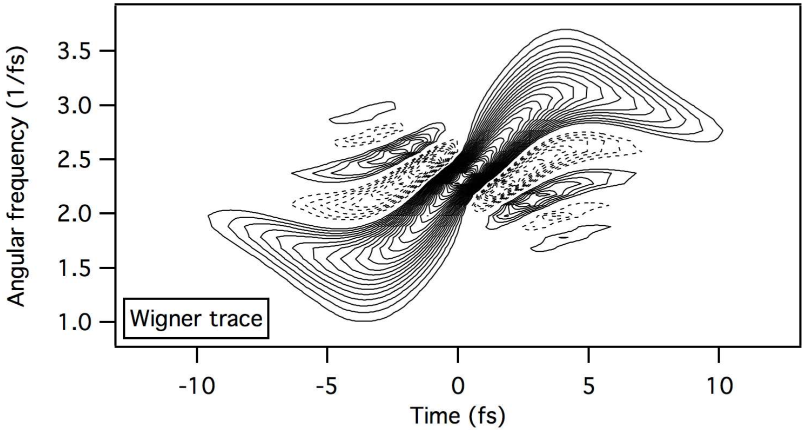
$$\phi(t) = -kn(I)L_K = -k\left[n + \boxed{n_2 I(t)\Big]L_K}\right.$$

nonlinear phase



→ spectral broadening of a **transform-limited input pulse**: “red before blue”

Wigner trace SPM, $n_2>0$



Reminder SPM

Self-phase modulation

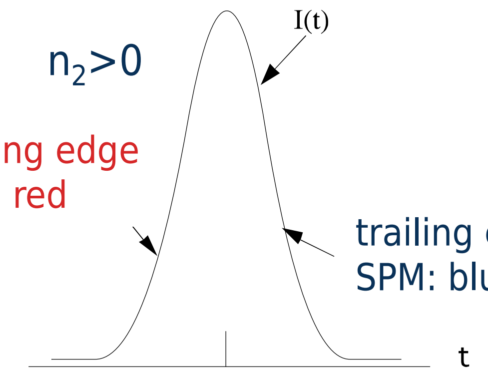
$$n(I)=n+n_2I$$

$I(t)$ → self-phase modulation
$I(x,y)$ → self-focusing

$$\phi(t)=-kn(I)L_K=-k\big[n+\boxed{n_2I(t)\big]L_K}$$

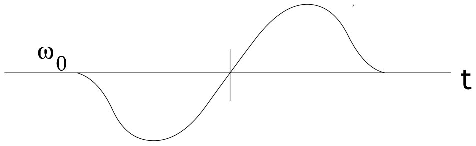
nonlinear phase

$n_2>0$



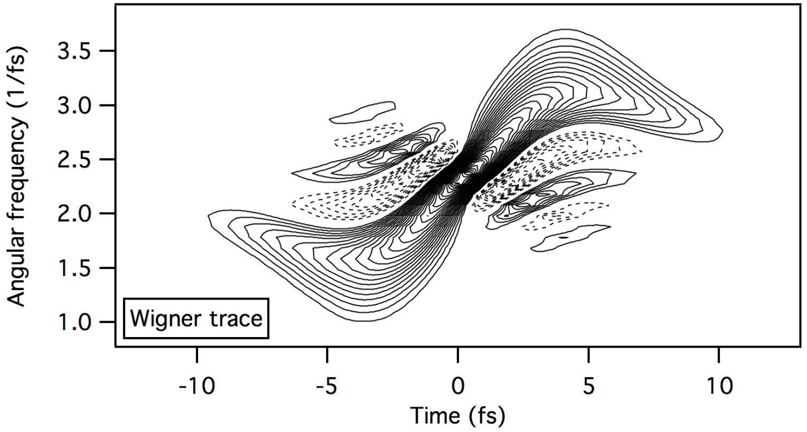
leading edge
SPM: red

trailing edge
SPM: blue



→ spectral broadening of a **transform-limited input pulse**: "red before blue"

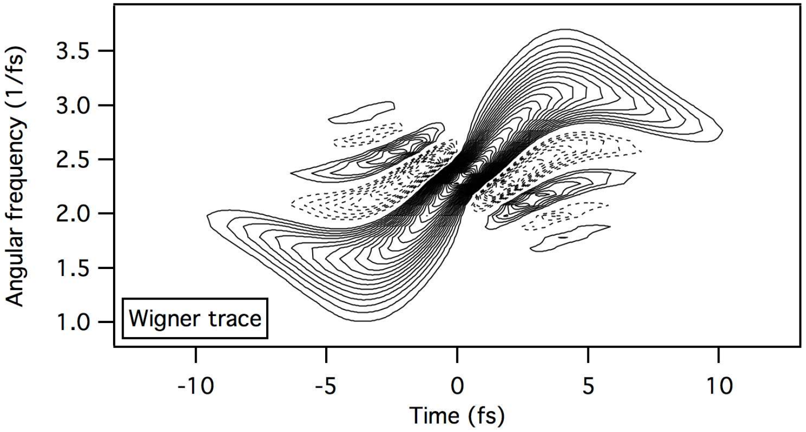
Wigner trace SPM, $n_2>0$



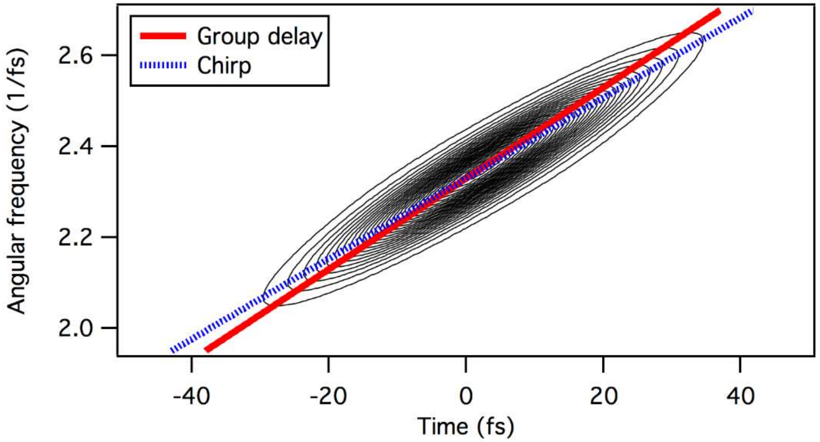
SPM broadening for pulse compression

Wigner function: time frequency representation

Only SPM, $n_2>0$



Only positive dispersion



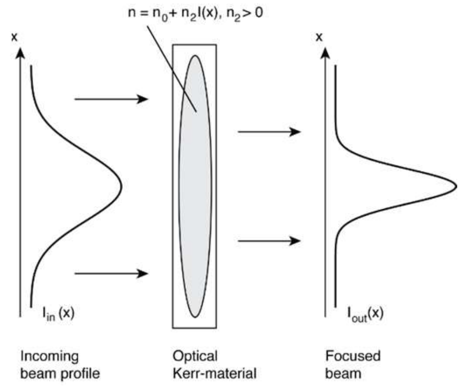
(positive) SPM can be (partly) compensated by negative dispersion

Subtleties:

- high-order terms in the spectral phase
- self-focusing occurs simultaneously as SPM

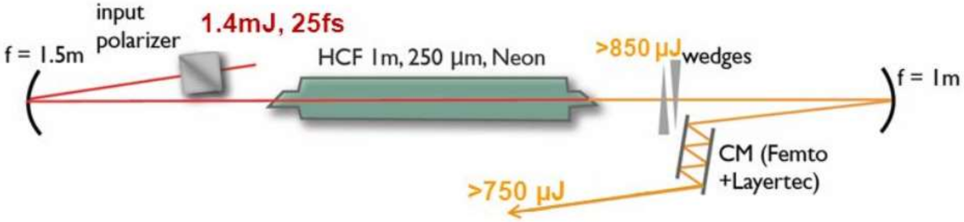
$$n(I) = n + n_2 I$$

$I(t)$ → self-phase modulation
$I(x,y)$ → self-focusing



pulse compression techniques

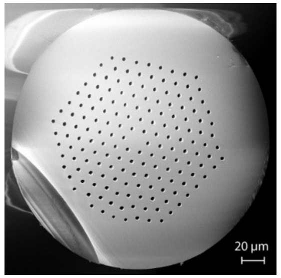
- Hollow capillaries



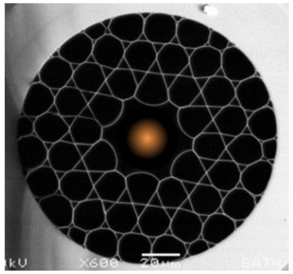
Nisoli et al, Appl. Phys. Lett. 68, 2793 (1996)

- Grazing incidence reflections
- Losses increase at moderate to small core sizes, typical 70% transmission
- Suited only for very high energies (mJ and above)

- Fibers
  - Solid-core fibers

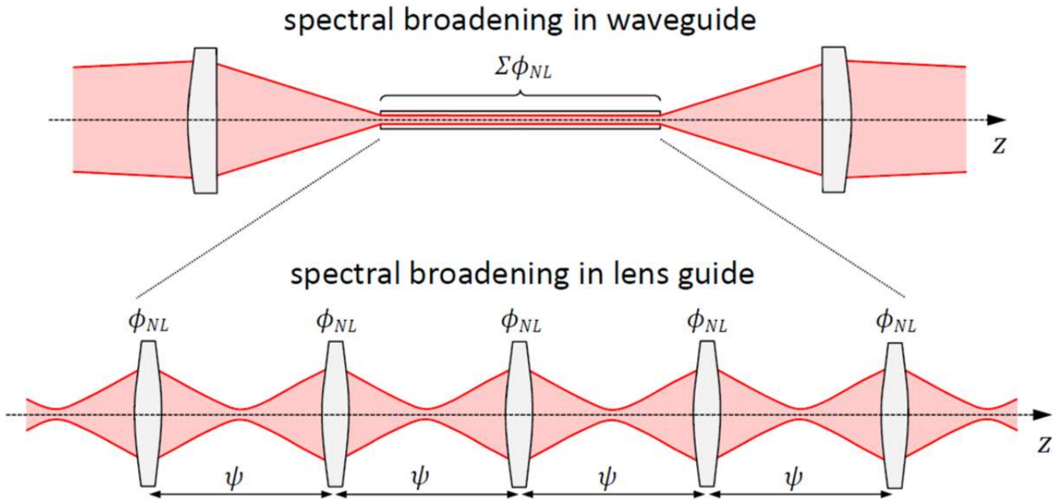


  - Hollow-core fibers

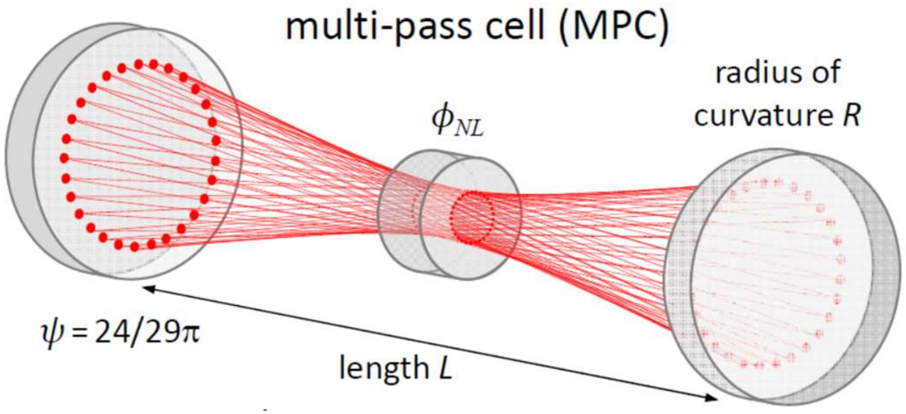


- Real guiding
- Solid-core: limited by self-focusing (4 MW for linear polarization and glass), damage threshold and bending loss at large mode areas
- Hollow-core: limited by difficulties in bending and damage

Compression in multi-pass cell



Idea: can one have the advantage of free-space propagation (for average power handling), and the large SPM provided by fibers - free of self-focusing?

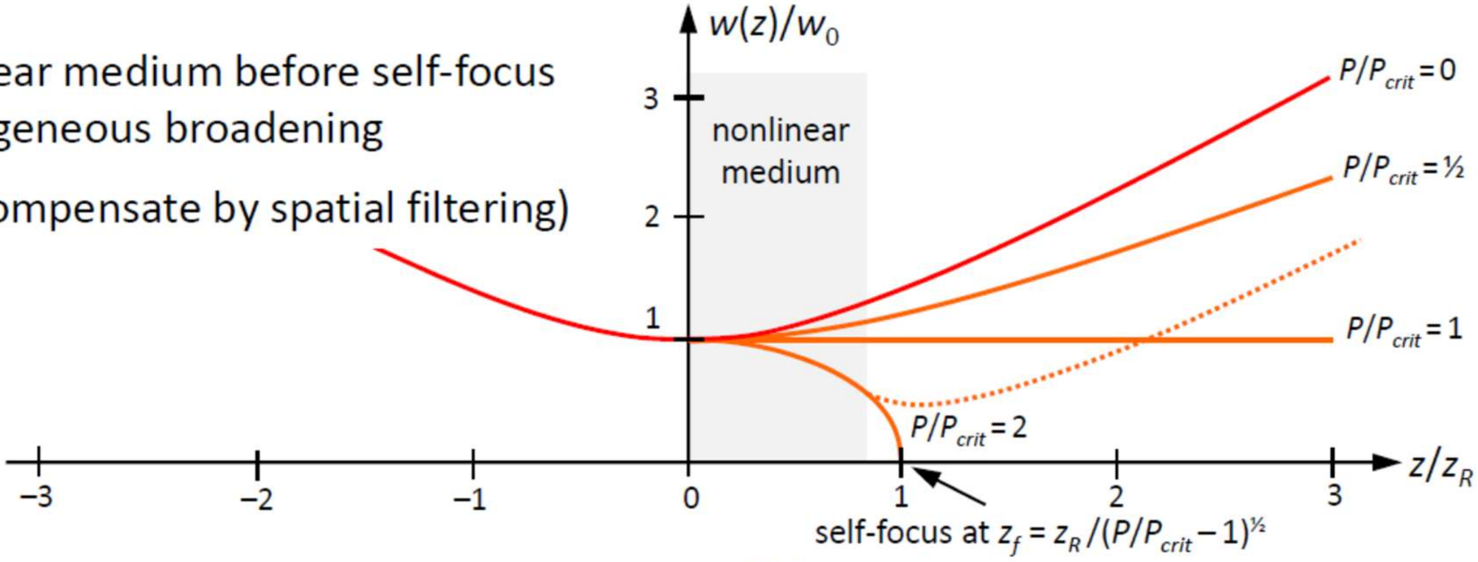


Figures courtesy J. Weitenberg
Fraunhofer ILT Aachen
First realization (ILT Aachen):
Schulte et al. "Nonlinear pulse compression in a multi-pass cell," Opt. Lett. 41, 4511-4514 (2016)

Key point: avoid self-focusing

End nonlinear medium before self-focus
→ inhomogeneous broadening

(partially compensate by spatial filtering)

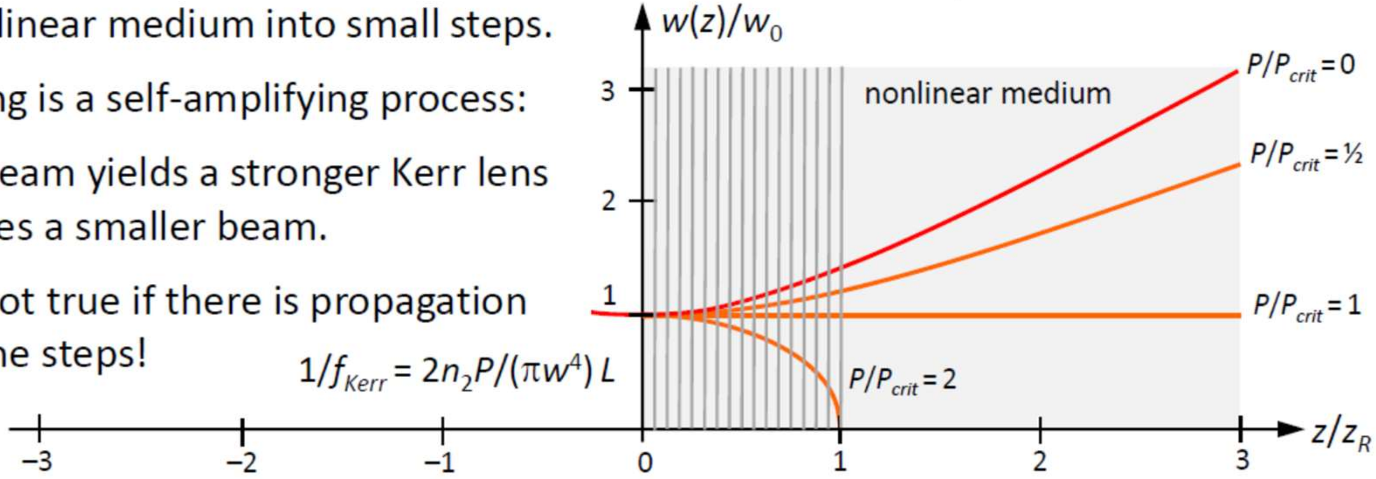


Divide nonlinear medium into small steps.

Self focusing is a self-amplifying process:

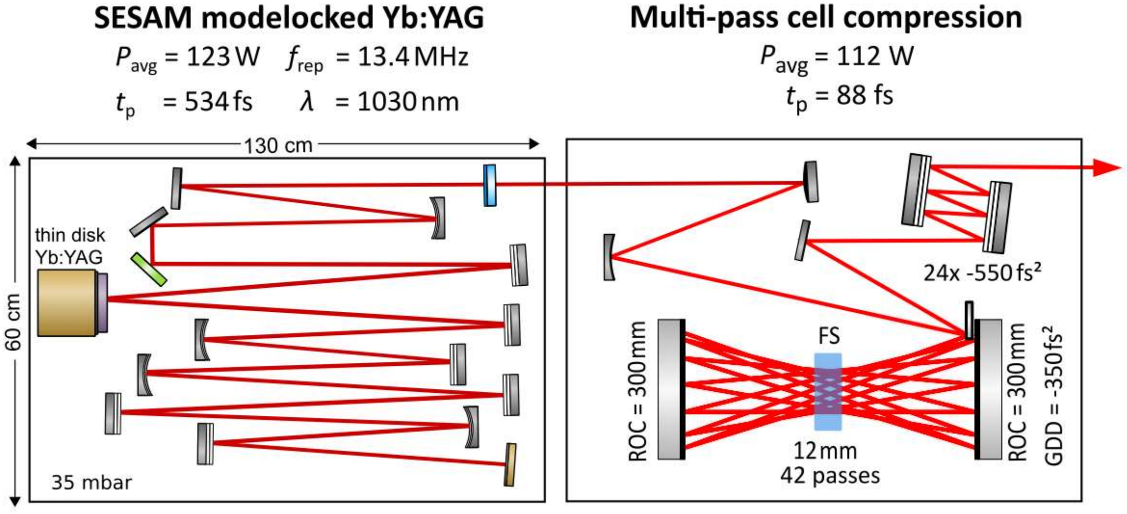
a smaller beam yields a stronger Kerr lens which makes a smaller beam.

→ This is not true if there is propagation between the steps!

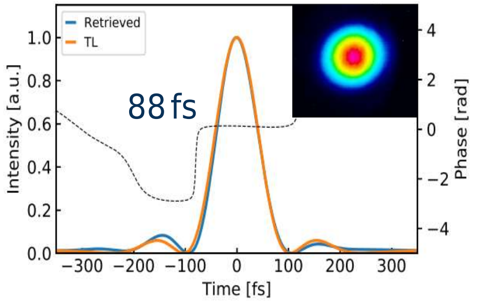


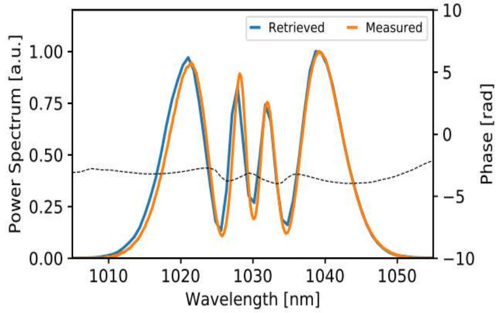
$1/f_{Kerr} = 2n_2P/(\pi w^4)\,L$

Example



P_{avg} = 112 W f_{rep} = 13.4 MHz **E_P = 8.4 µJ**
t_p = 88 fs P_{peak} = 80 MW λ = 1030 nm

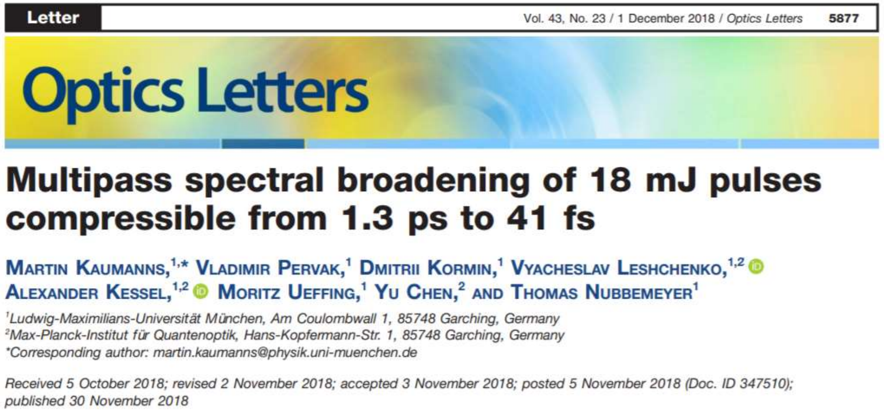




- Herriott type multi-pass cell[1] + fused silica + negative dispersive mirror pair
- Generated spectrum agrees well with 3D pulse propagation model
- $M^2 < 1.15$
- Excellent efficiency: 91%

Tsai et al. "Efficient nonlinear compression of a mode-locked thin-disk oscillator to 27 fs at 98 W average power," Opt. Lett. 44, 4115-4118 (2019)

Works for an extremely large variety of parameters



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Optics Letters

Multipass spectral broadening of 18 mJ pulses compressible from 1.3 ps to 41 fs

Martin Kaumanns,[1,*] Vladimir Pervak,[1] Dmitrii Kormin,[1] Vyacheslav Leshchenko,[1,2] Alexander Kessel,[1,2] Moritz Ueffing,[1] Yu Chen,[2] and Thomas Nubbemeyer[1]

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**Corresponding author: martin.kaumanns@physik.uni-muenchen.de*

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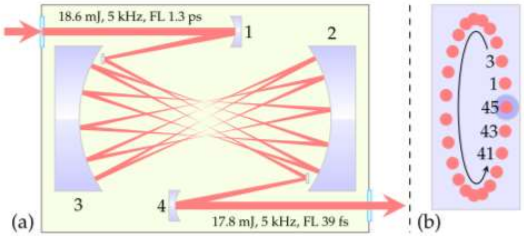
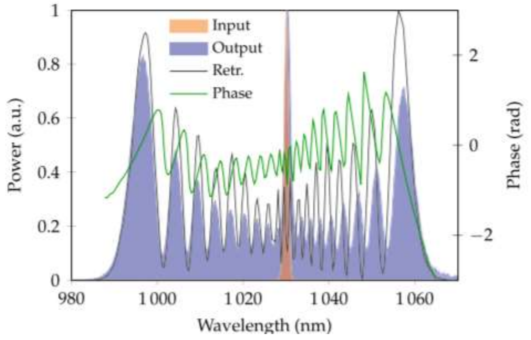
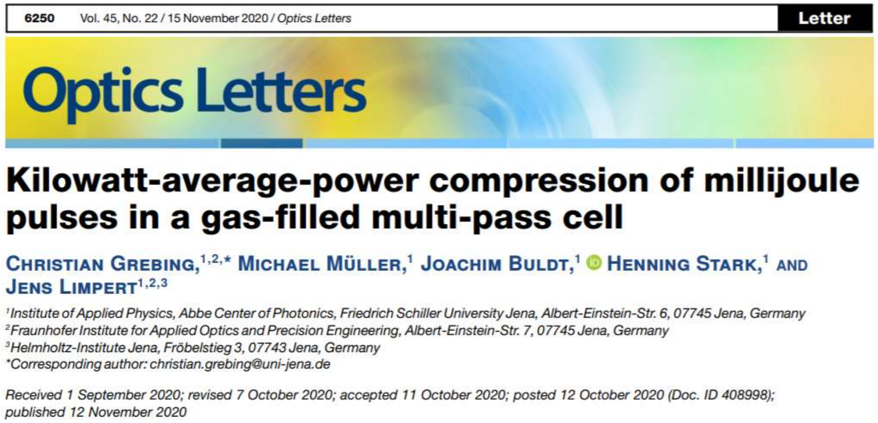




High energies – gas filled cell



6250 Vol. 45, No. 22 / 15 November 2020 / *Optics Letters* **Letter**

Optics Letters

Kilowatt-average-power compression of millijoule pulses in a gas-filled multi-pass cell

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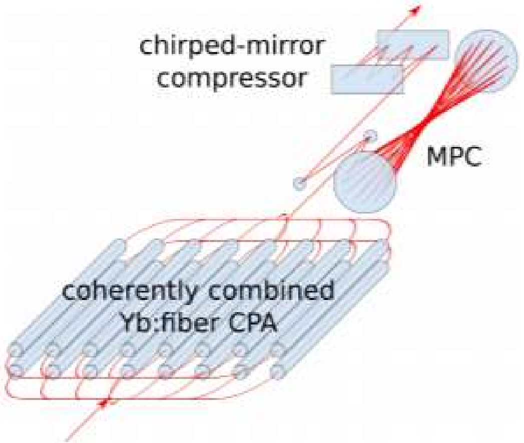
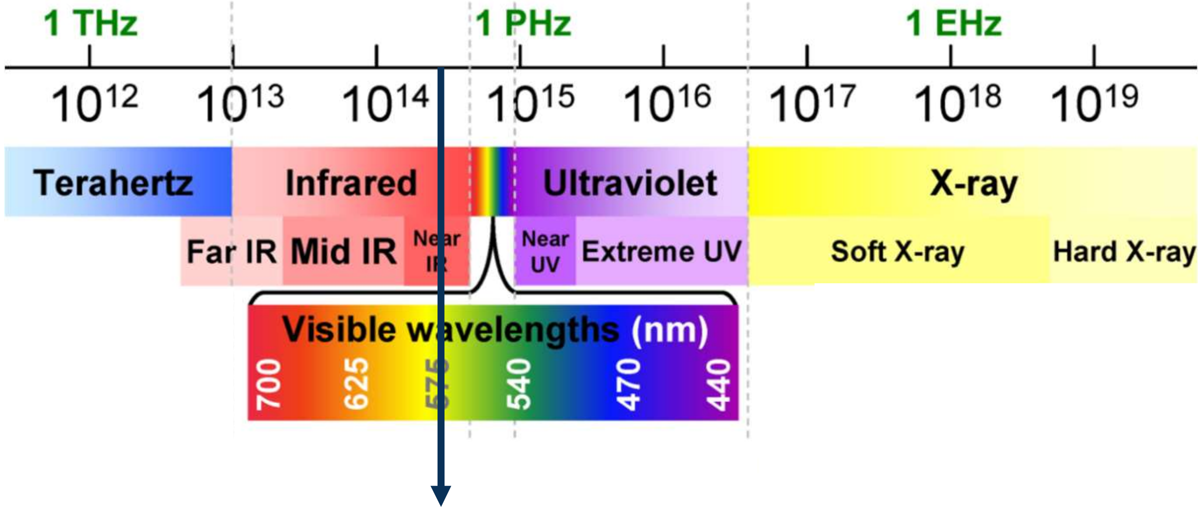
1 mJ, 31 fs pulses

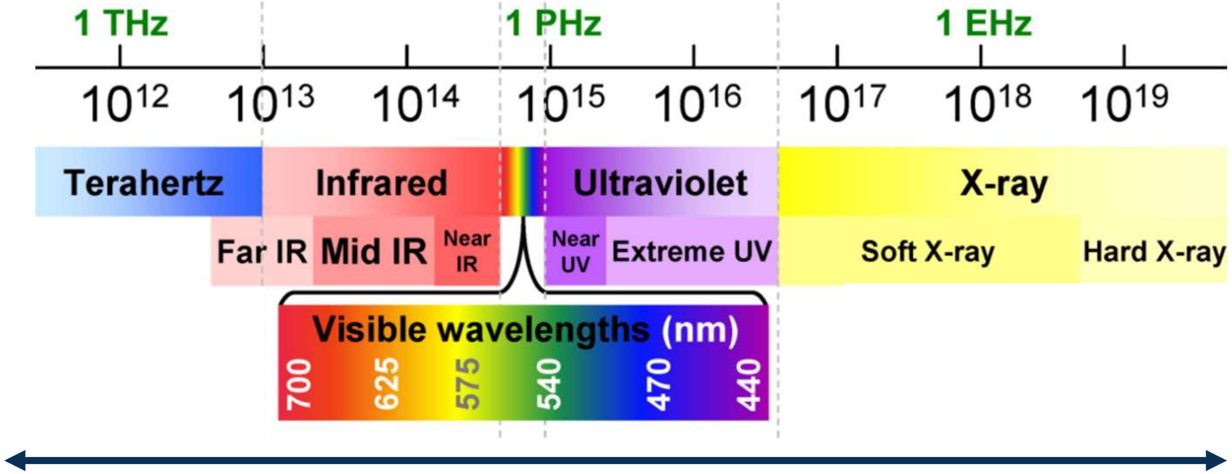


challenge: spectral coverage



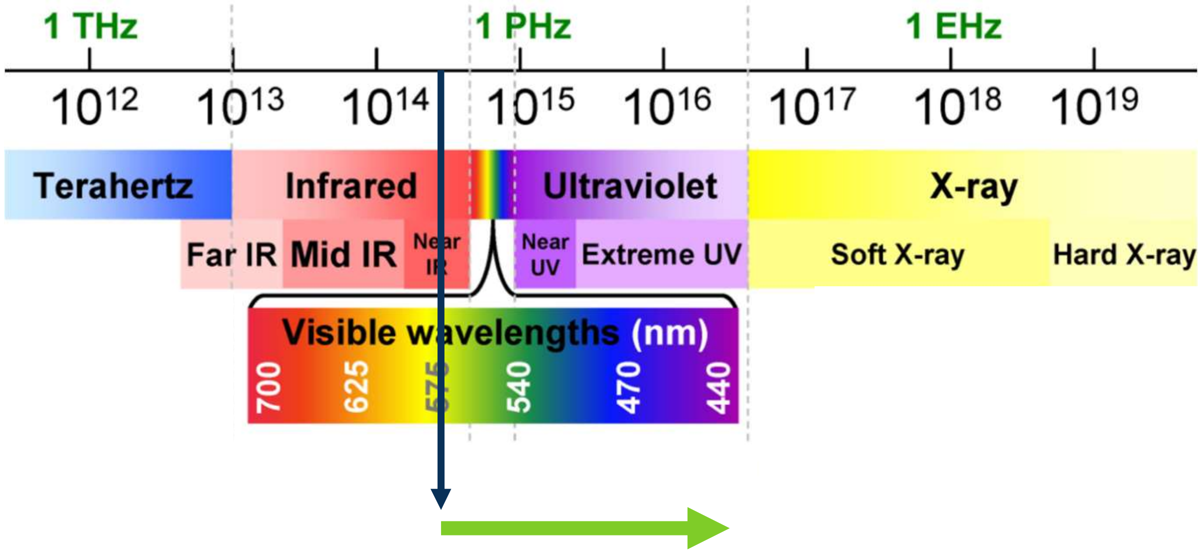
‘novel’ high-power laser technology: limited spectral coverage
Yb:YAG - 1030 nm

spectral coverage

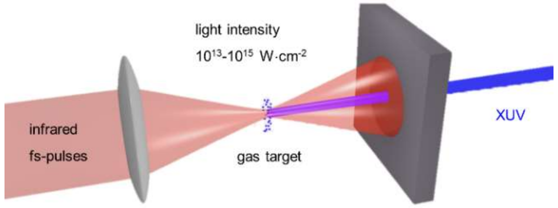


Trend: high-power from THz to XUV

spectral coverage



XUV radiation via HHG



MHz repetition rate HHG

ETH zürich

Ultrafast Laser Physics

Driving compressed laser

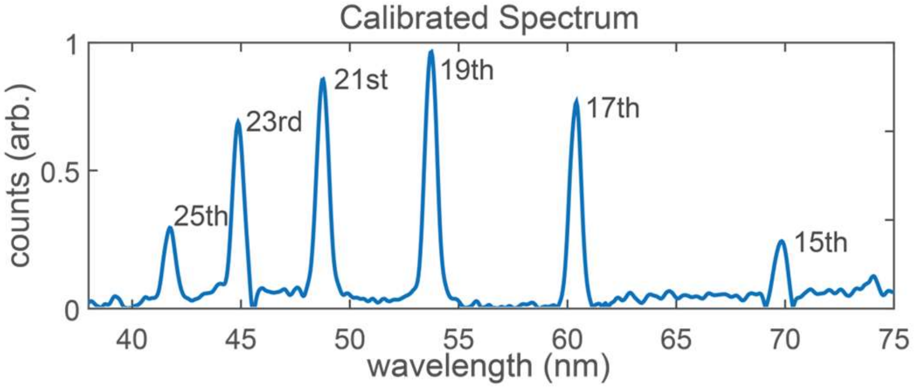
P_{av} = 46 W

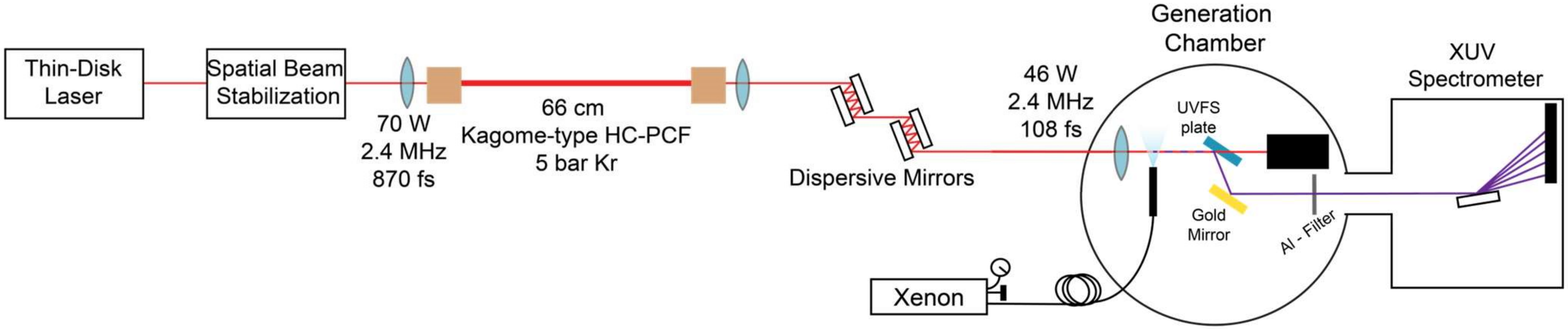
τ_p = 108 fs

P_{peak} = 105 MW

f_{rep} = 2.4 MHz

E_p = 19 µJ



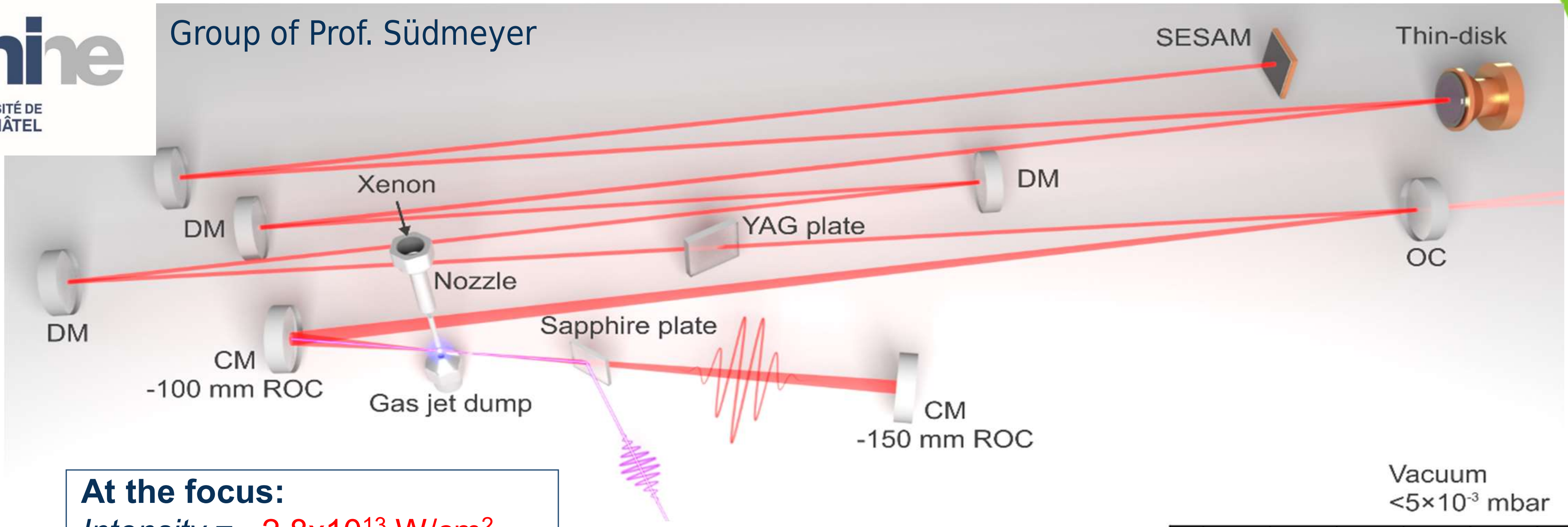


- Oscillator-Driven High Harmonic Generation at MHz Repetition Rate
- Compact and simple set-up for HHG with up to 5×10^7 ph/s on the 19th harmonic
- Further improvement: shorter pulse duration, higher driving powers

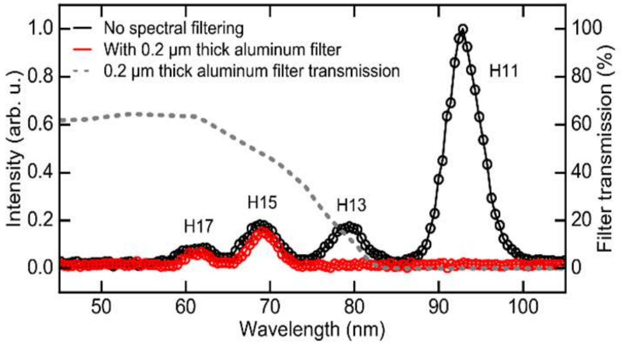
F. Emaury, et al. Optica 2, 11 (2015)

Intracavity high-harmonic generation

Group of Prof. Südmeyer



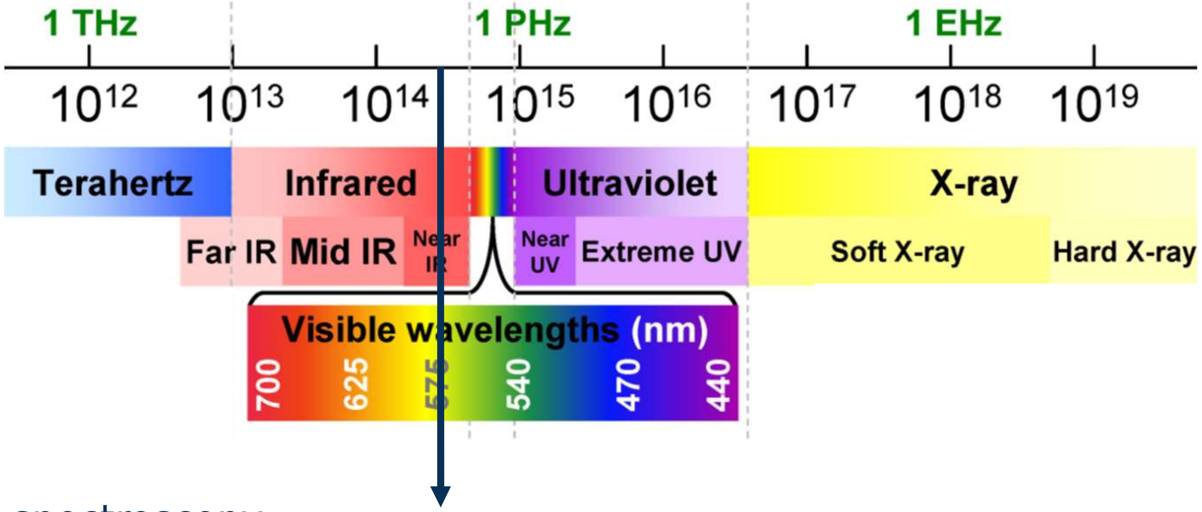
At the focus:
Intensity = $2.8\text{x}10^{13}$ W/cm^2



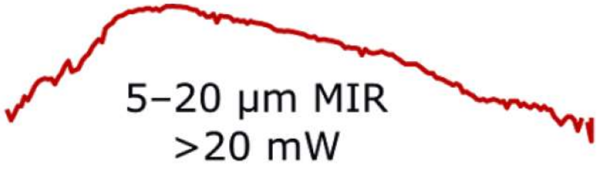
- Intracavity HHG driven at 320 W average power - 250 fs – 17 MHz
- Remarkable: 50 W of pump power
- 2.6×10^8 photons/s for the 11th harmonic (94 nm, 13.2 eV)

F. Labaye, et al., Opt. Lett.42, 5170-5173 (2017)

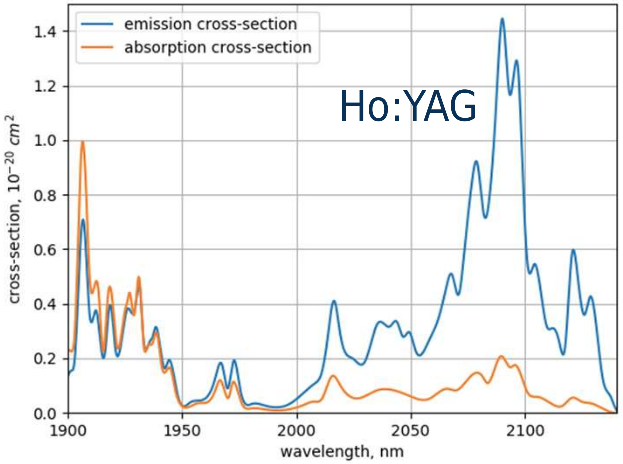
spectral coverage



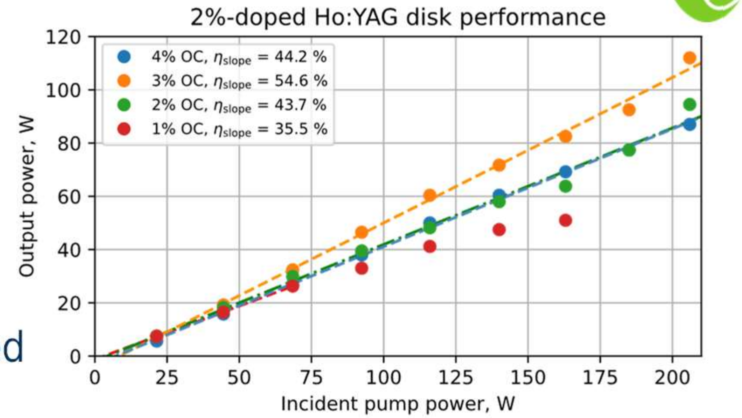
Mid-IR sources for spectroscopy



“exotic” gain materials emitting directly at longer wavelengths

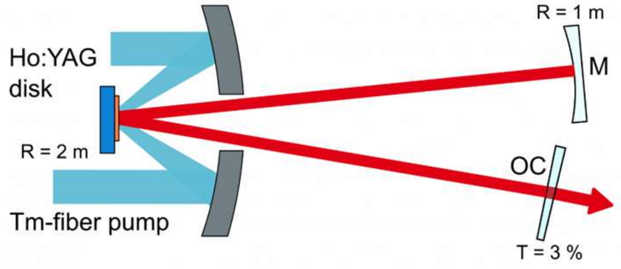


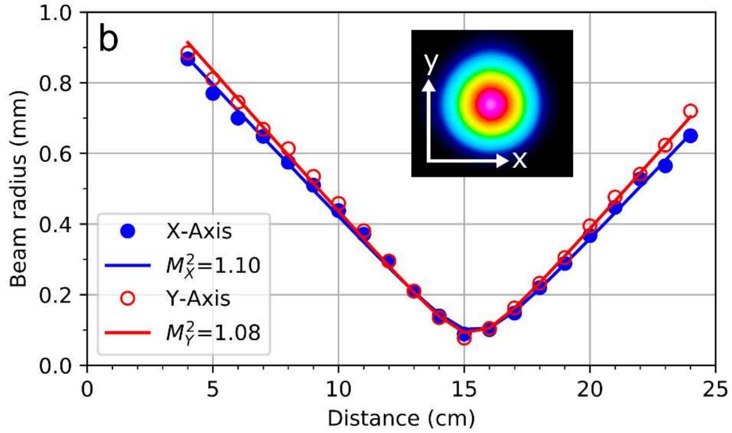
- Dopants: Tm, Ho, Cr….
- Much less explored and understood materials
- Characterization tools and components not as well developed



Example: Ho:YAG thin-disk laser emitting at 2.1 µm

- 112 W fundamental-mode CW thin-disk laser at 2 µm
- 40 W modelocked oscillator: highest power oscillator at 2 µm

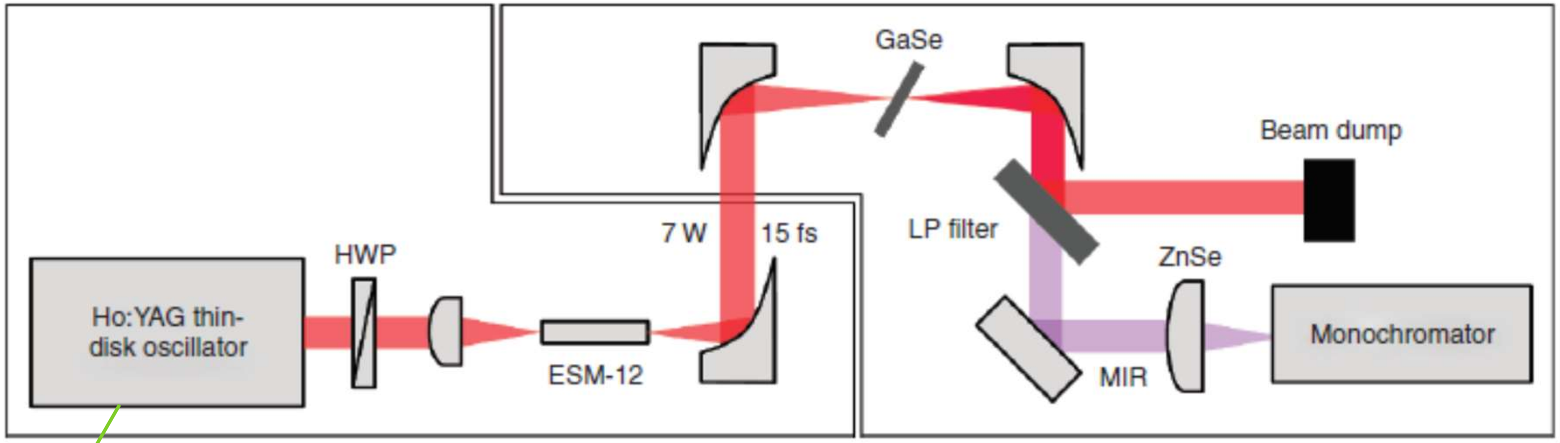


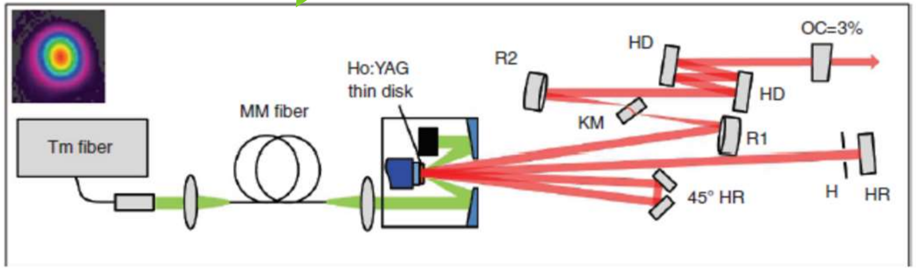


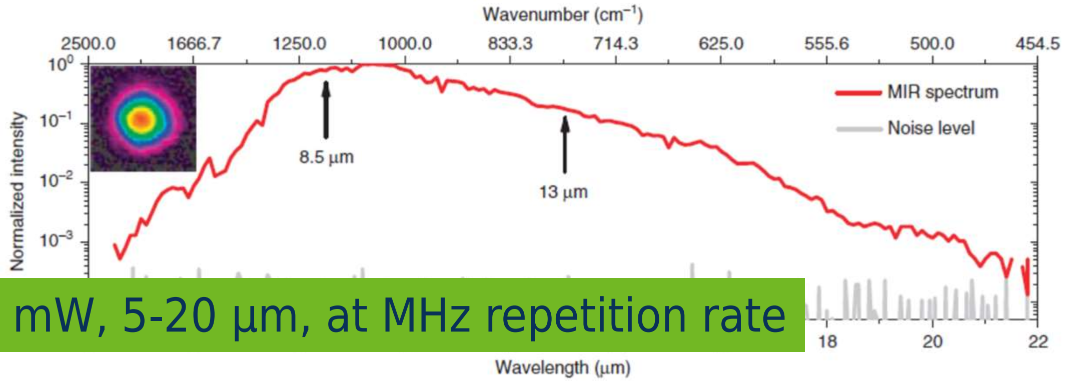
Tomilov et al. “Moving towards high-power thin-disk lasers in the 2-µm wavelength range“, J. Phys. Photonics 3 022002 (2021)

Nonlinear conversion (DFG, OPA)

J. Zhang, et al., Light: Science & Applications, 7 (2018)







Ho:YAG **@2.1 µm**

P_{av} = 25 W
τ_p = 270 fs
f_{rep} = 77 MHz

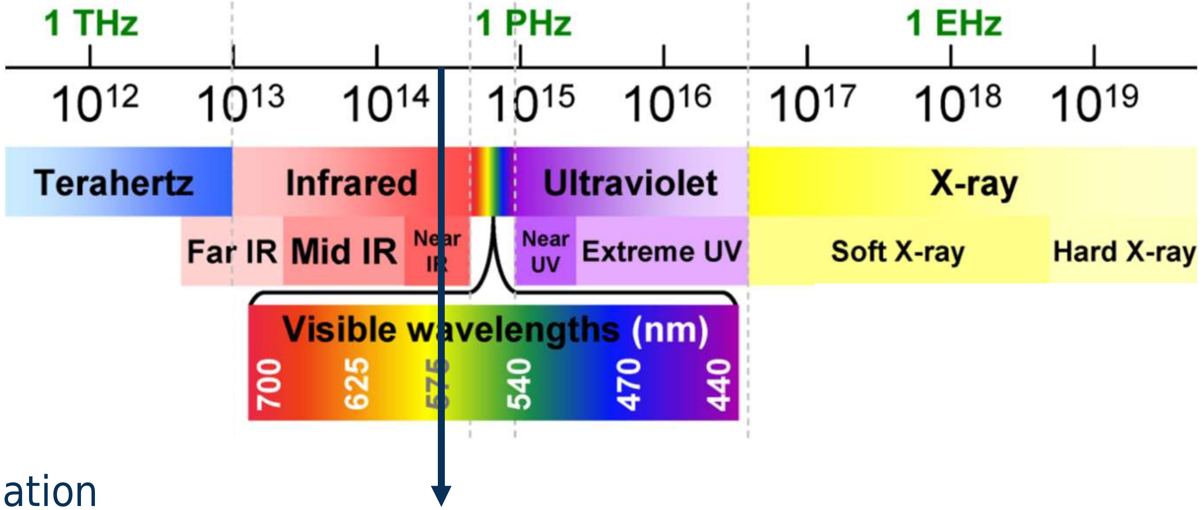
J. Zhang, et. al., IEEE JSTQE, 24, 1–11 (2018)

>20 mW, 5-20 µm, at MHz repetition rate

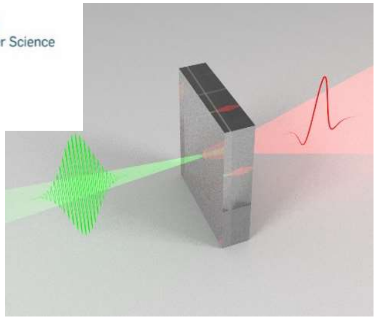
Group of Oleg Pronin

Now at:

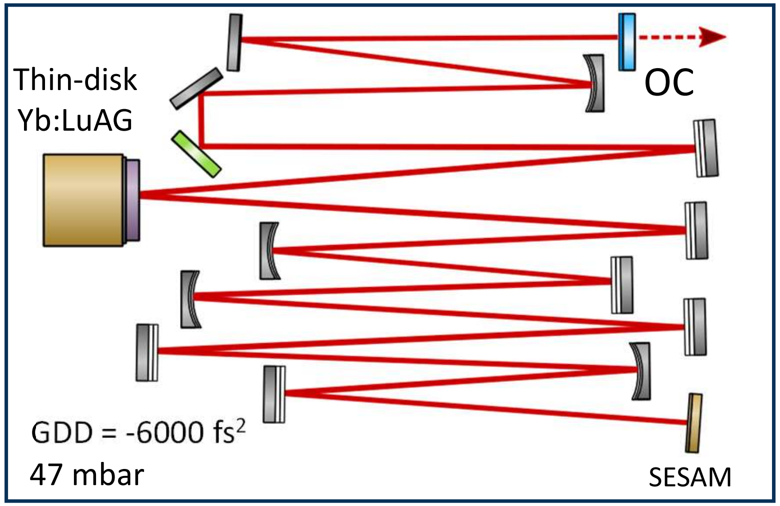
Spectral coverage

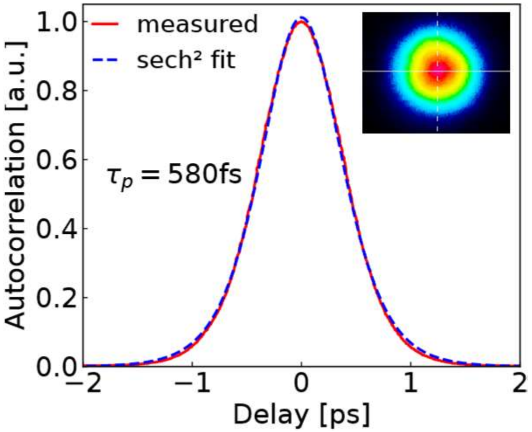


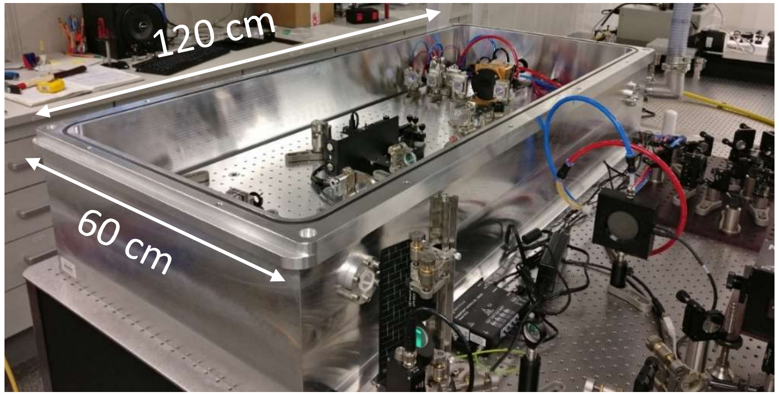
High power THz radiation



Laser system in our lab







P_{avg} = 125 W

f_{rep} = 13.4 MHz

E_p = 9.3 µJ

τ_p = 580 fs (/ 88 fs)

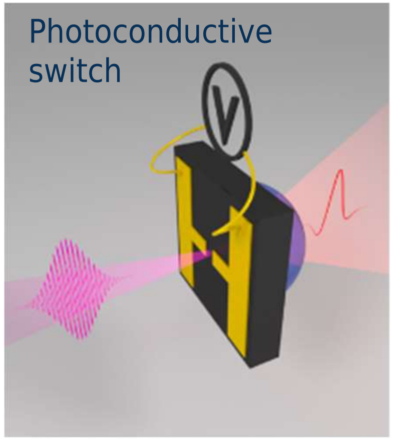
λ = 1030 nm

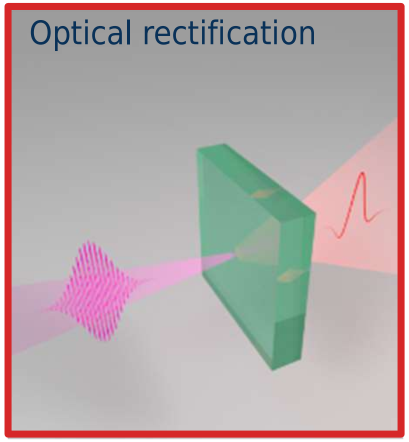
THz generation Method

carrier acceleration in semiconductor

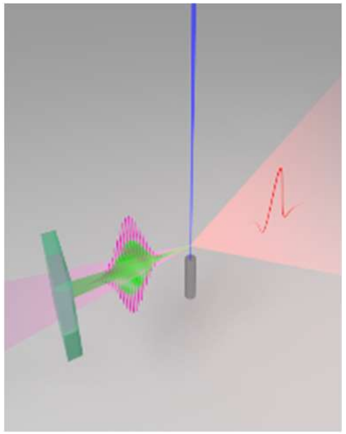
$\chi^{(2)}$ in non-centrosymmetric crystals

Photo-currents


Photoconductive switch


Optical rectification


Difference frequency mixing



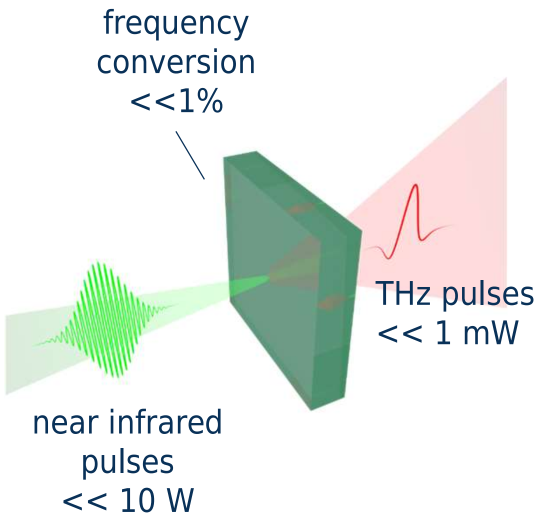
Pulse energy required/suited

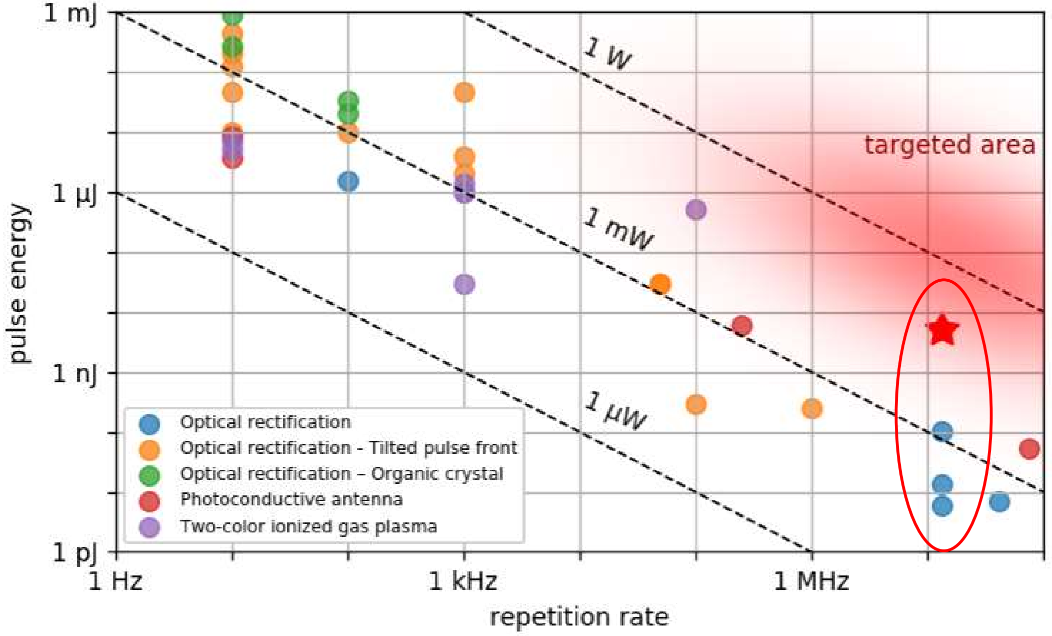
nJ-µJ

tens to hundreds of µJ:
ideal for MHz TDLs

mJ and above

High average power THz Sources




Lab THz-TDS sources

- state-of-the-art THz power in the lab: <mW level
- repetition rate or pulse strength: compromise necessary
- origin of limitations: low driving power and efficiency
- most experiments requiring average power: accelerator facilities

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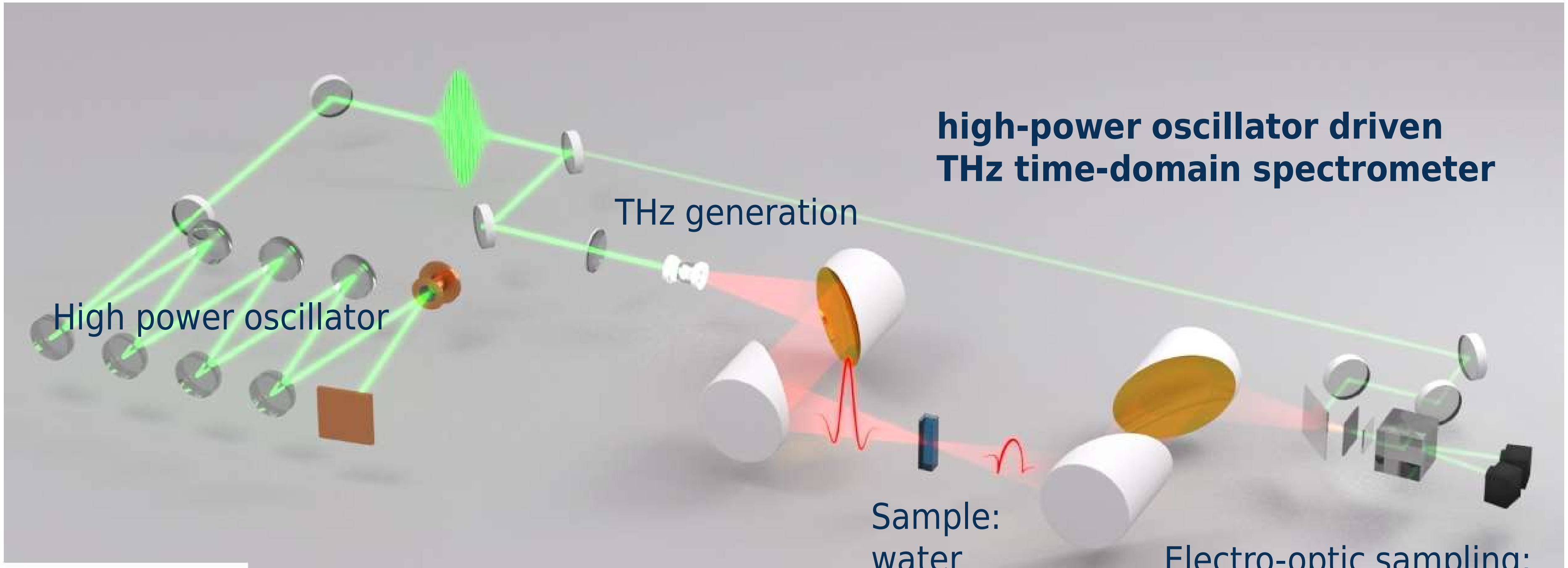
THz spectroscopy of water



high-power oscillator driven THz time-domain spectrometer

High power oscillator

THz generation

Sample: water

Electro-optic sampling: full-field reconstruction

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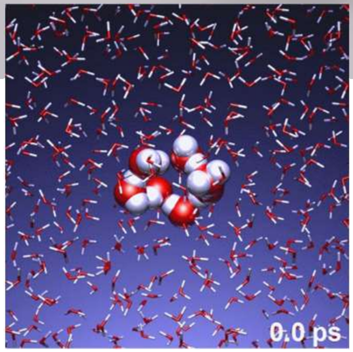
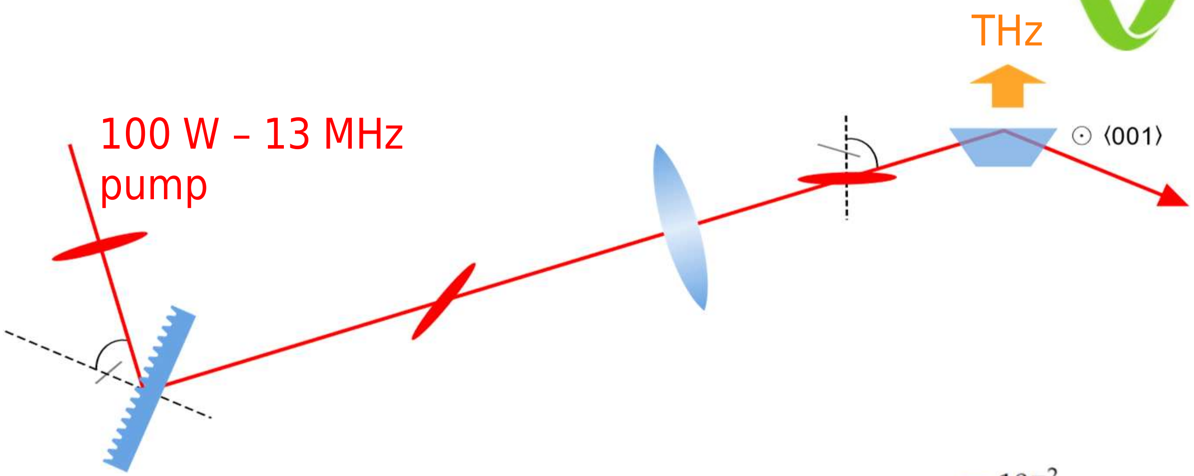


Problem: water is highly absorptive!

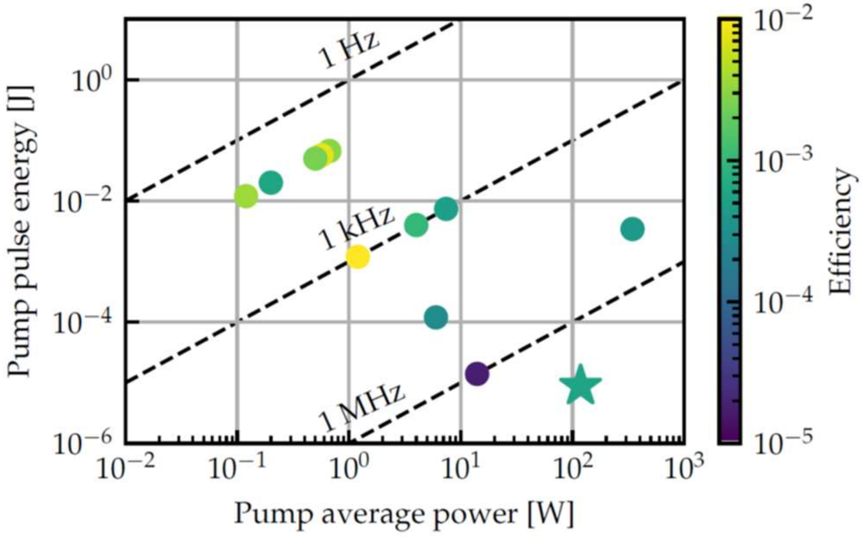
Very difficult experiments!

Promising for High Powers: Lithium Niobate

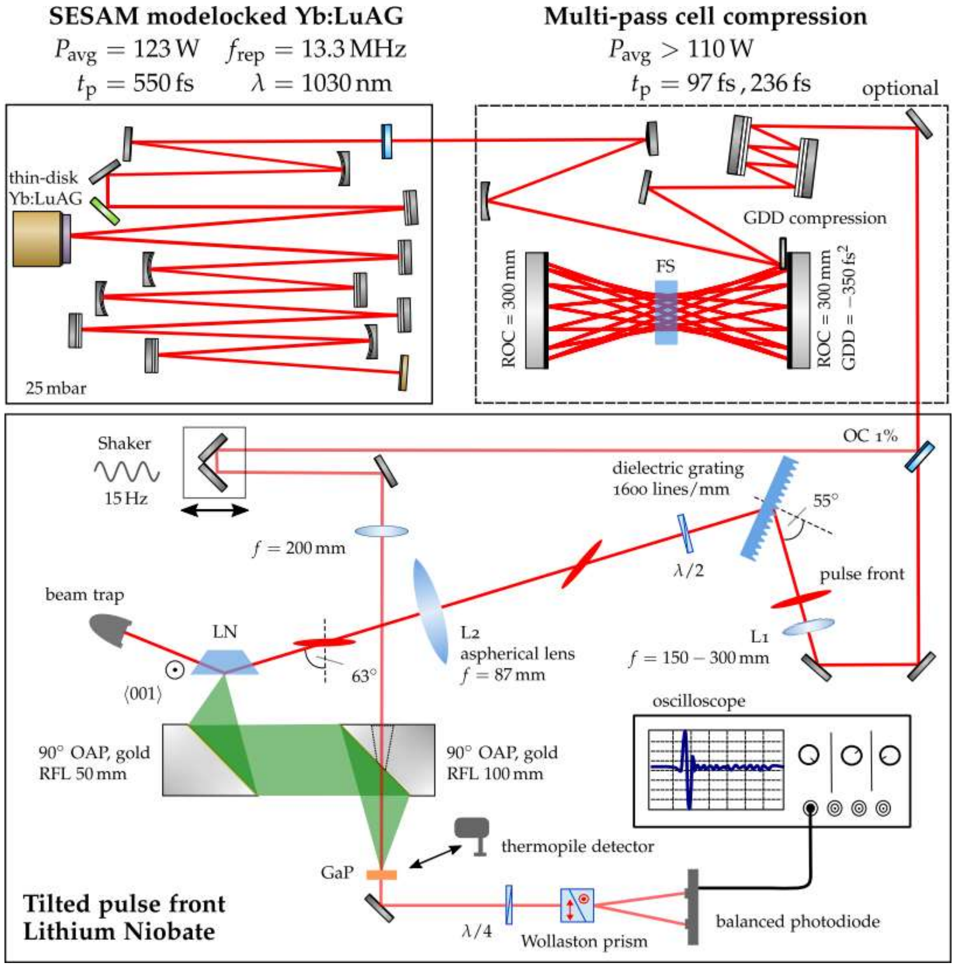
- Lithium Niobate (LN): high nonlinearity and little multi-photon absorption
- <u>But:</u> phase matching requires tilting the pulse front $v_{NIR}^{gr} \cos \gamma = v_{THz}$
  $(n_{gr,\ NIR} \simeq 2.2)$ $(n_{THz} \simeq 5)$
- Rather complex generation process
- **Conversion efficiencies on the 1% level demonstrated (but only at lower repetition rate)**



100 W – 13 MHz pump



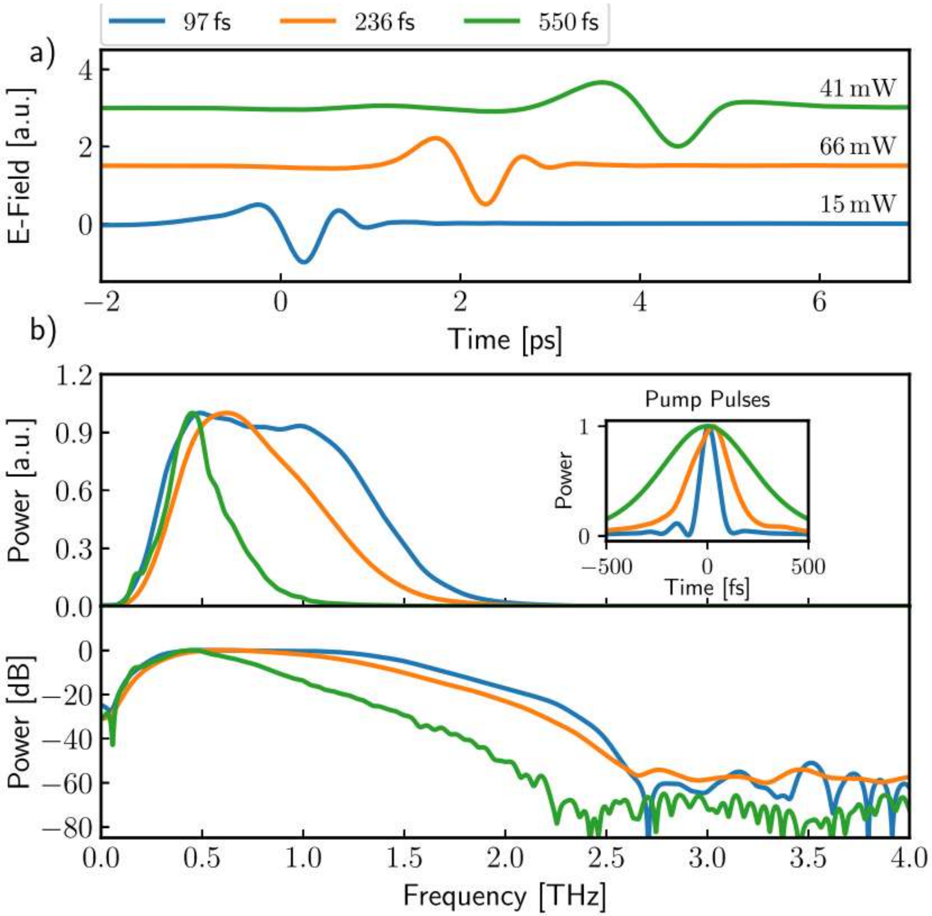
Setup



- Optional MPC compressor allows for variable pulse duration (97fs, 236fs, 550fs)
- 0.6% MgO-doped sLN crystal on water cooled mount
- Quasi instantaneous electro-optic sampling with 15Hz refresh rate
- Power measurements with pyroelectric detector

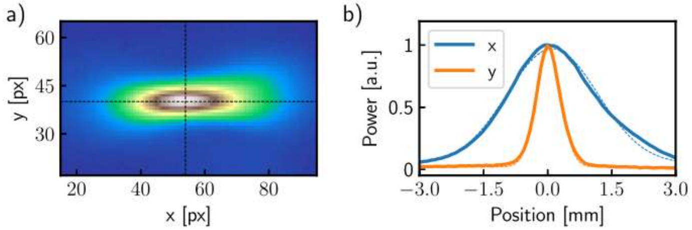
F. Meyer et al., "Single-cycle, MHz repetition rate THz source with 66 mW of average power," Opt. Lett. **45**, 2494-2497 (2020)

Results: Lithium Niobate



- Similar EOS traces for all pulse durations
- Slight increase in bandwidth for shorter pulses
- Signal-to-noise ratio up to 70 dB

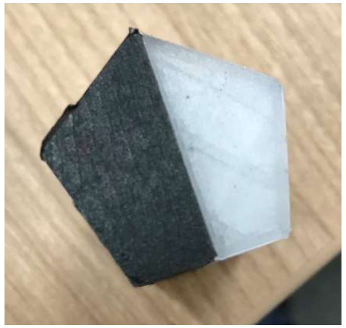
(20 averages, 15 traces/s)

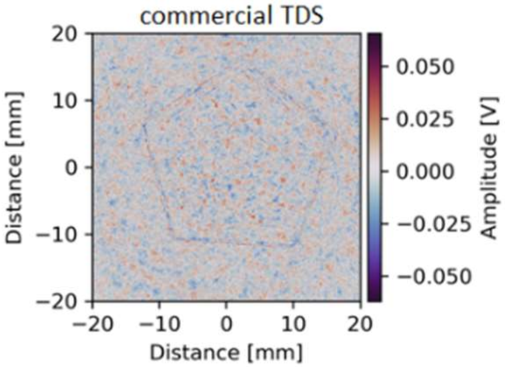


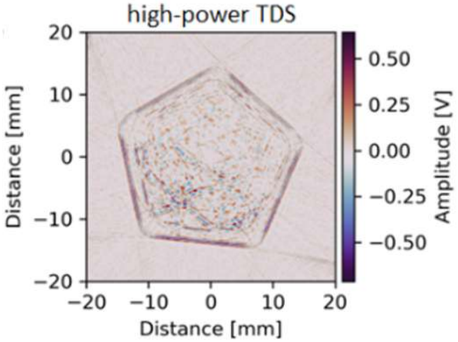
THz	**P_{THz}**	66 mW
	E_{peak}	~16.7 kV/cm
	P_{peak}	~18 kW
	η	$6 \cdot 10^{-4}$
	f_{rep}	13.3 MHz

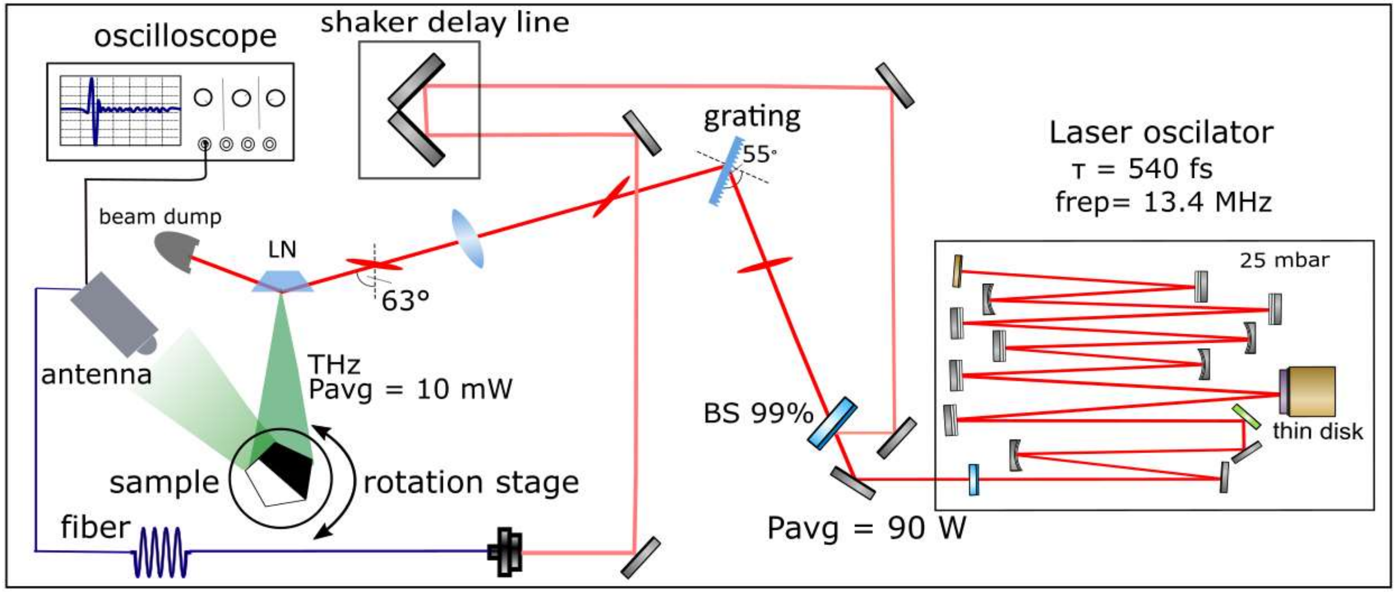
F. Meyer et al., "Single-cycle, MHz repetition rate THz source with 66 mW of average power," Opt. Lett. **45**, 2494-2497 (2020)

THz imaging









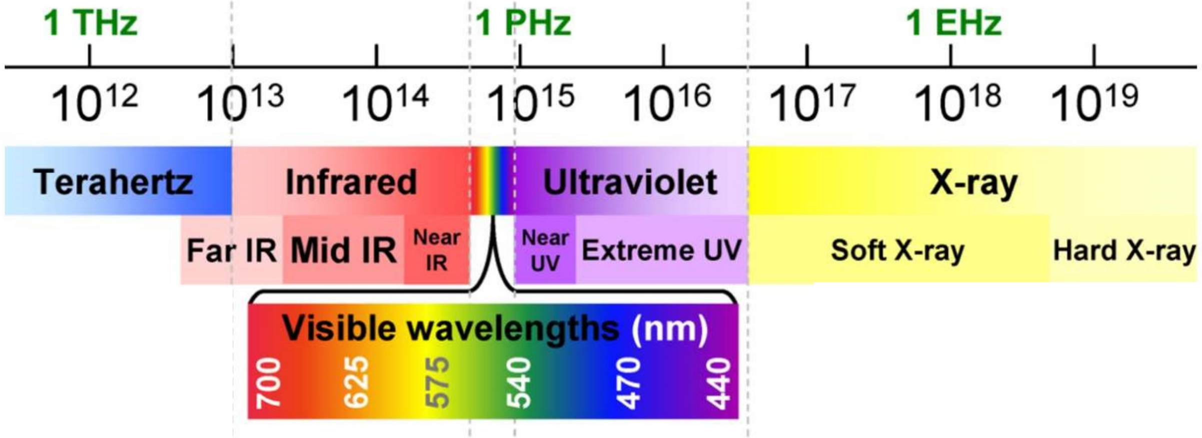
Images:

- Large contrast enhancement
- Difference in material is recognizable

S. Mansourzadeh *et al.*, "High-Power Lensless THz Imaging of Hidden Objects," in *IEEE Access*, vol. 9, pp. 6268-6276 (2021)

Conclusion

- Ultrafast lasers have seen spectacular progress lately
- No real end in sight
- Time for applications to catch up



high-power, high-repetition rate from X-ray to THz

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