Pulse energy scaling of femtosecond ultrafast thin-disk laser oscillators towards the 100-µJ level

Cyrill R. E. Baer, Sergio V. Marchese, Oliver Heckl, Dr. Matthias Golling, Dr. Christian Kränkel, Dr. Thomas Südmeyer,

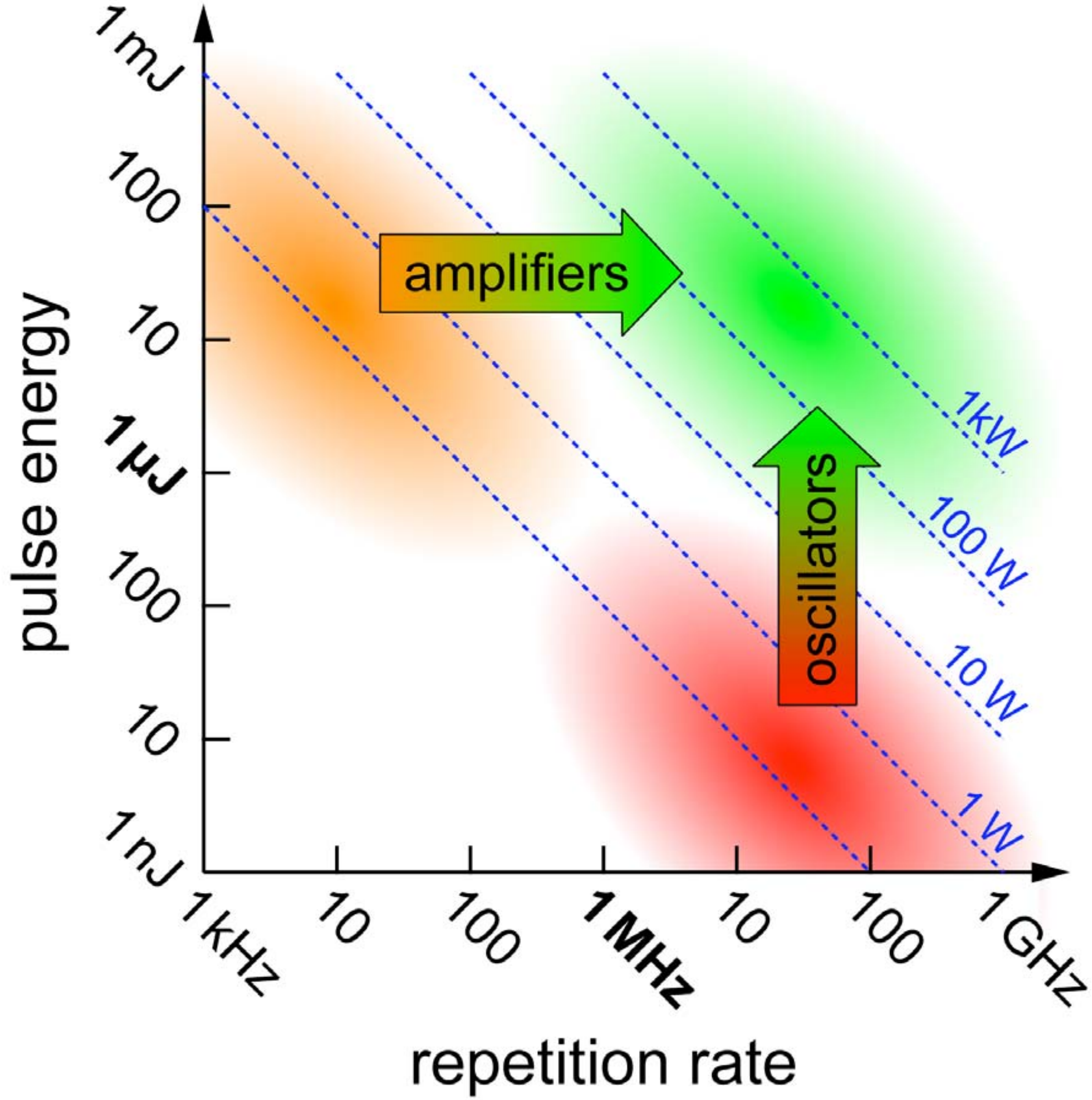
Prof. Ursula Keller

ETH Zurich, Switzerland

Industrial Photonics
13th SSOM Engelberg Lectures on Optics

Engelberg, Switzerland, 16-19 March 2009

High average power lasers



Motivation

Passiv modengekoppelte ps- und fs-Laser mit hoher mittlerer Leistung

MW Spitzenleistungen
µJ Pulsenergien } **MHz** Repetitionsraten

Vorteile:

- externe Verstärkung nicht notwendig
- kompakt, einfach und stabil

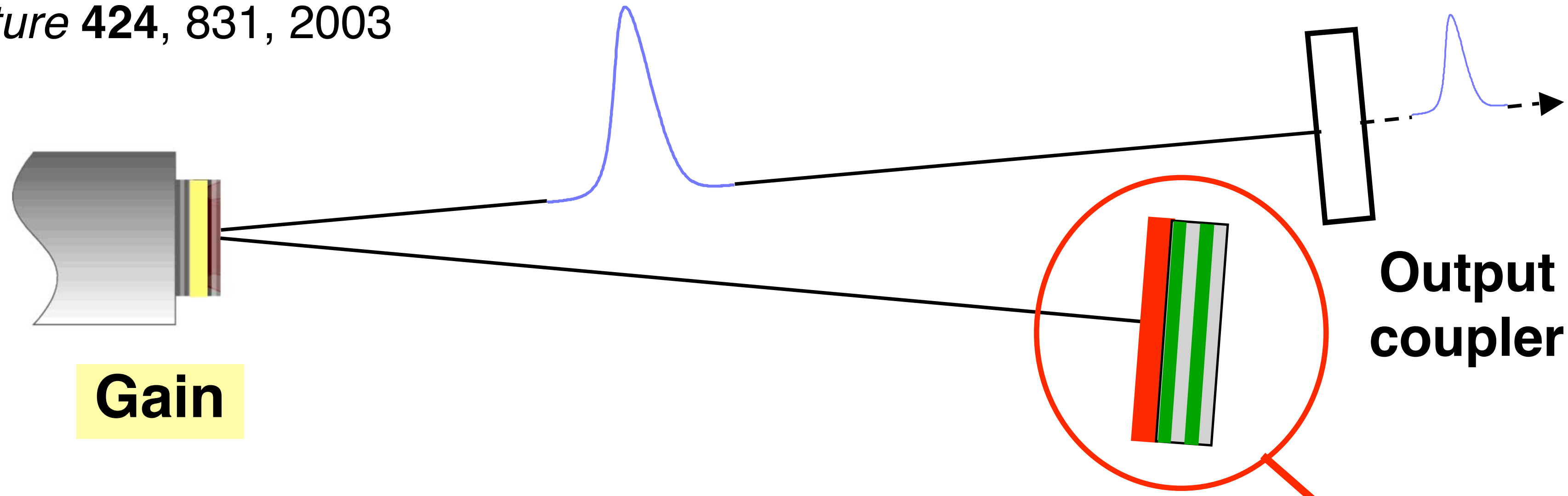
Anwendungen:

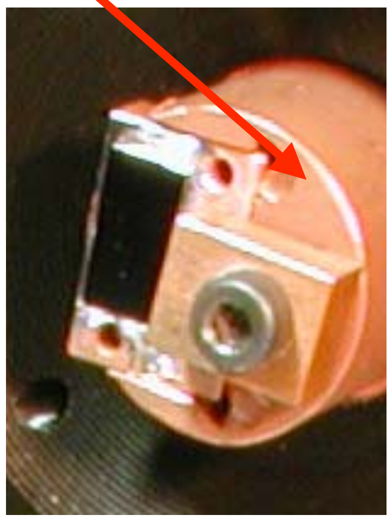
- Materialbearbeitung mit hohem Durchsatz
- Frequenzkonversion (RGB)[#1]
- High-Field-Physik (z.B. HHG) [#2]

[#1] F. Brunner, et al., *Opt. Lett.* **29**, 1921 (2004)
[#2] T. Südmeyer, et al., *Nature Photonics* **2**, 559, 2008

SESAM technology – a key technical know-how

U. Keller et al. *Opt. Lett.* **17**, 505, 1992
IEEE JSTQE **2**, 435, 1996
Progress in Optics **46**, 1-115, 2004
Nature **424**, 831, 2003





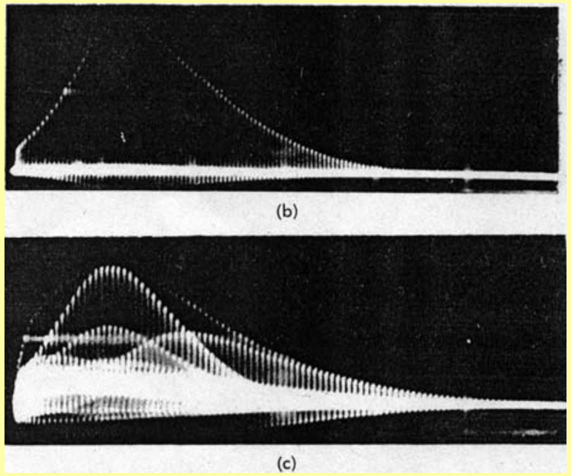
SESAM

SEmiconductor **S**aturable **A**bsorber **M**irror

self-starting, stable, and reliable modelocking of diode-pumped ultrafast solid-state lasers

Ultrashort pulse generation with modelocking

A. J. De Maria, D. A. Stetser, H. Heynau
Appl. Phys. Lett. **8**, 174, 1966



Nd:glass
first passively modelocked laser
Q-switched modelocked

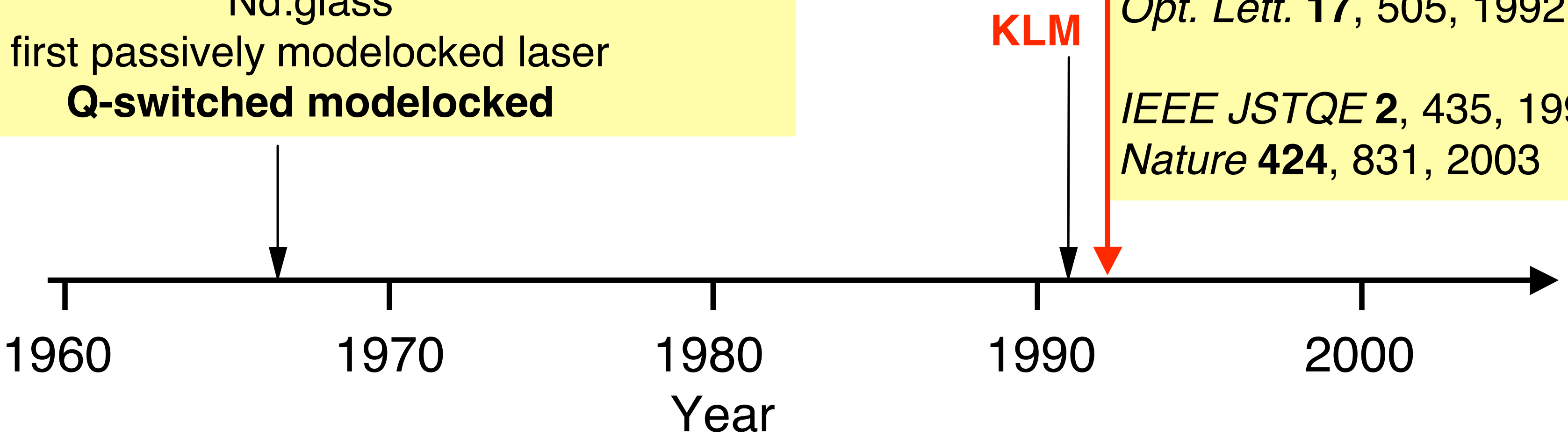
Q-switching instabilities continued to be a problem until 1992

SESAM

First passively modelocked (diode-pumped) solid-state laser without Q-switching

U. Keller et al.
Opt. Lett. **17**, 505, 1992

IEEE JSTQE **2**, 435, 1996
Nature **424**, 831, 2003

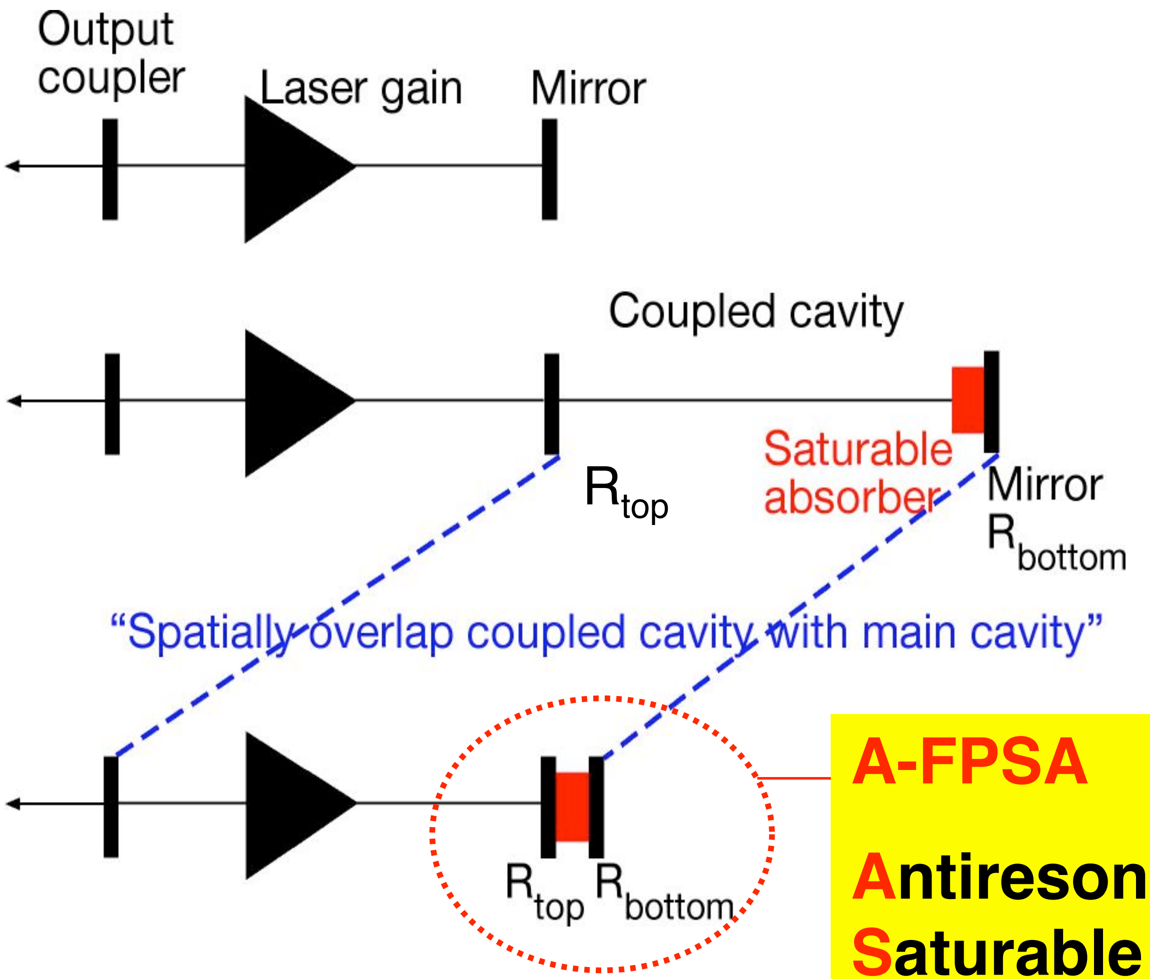


Flashlamp-pumped solid-state lasers

Diode-pumped solid-state lasers
(first demonstration 1963)

Historical evolution for SESAMs

First intracavity saturable absorber - April 1, 1992

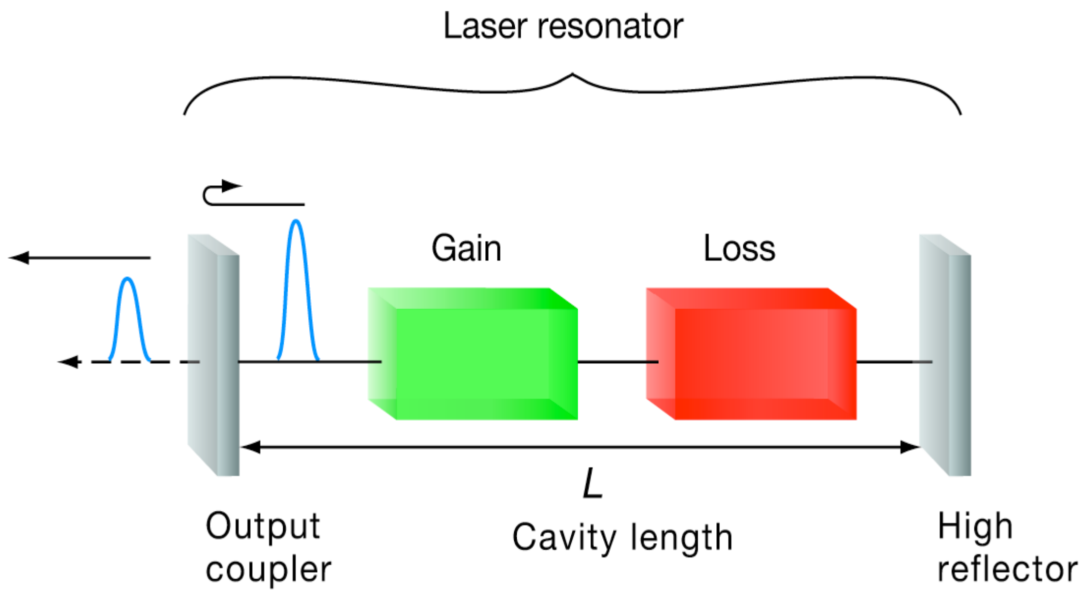


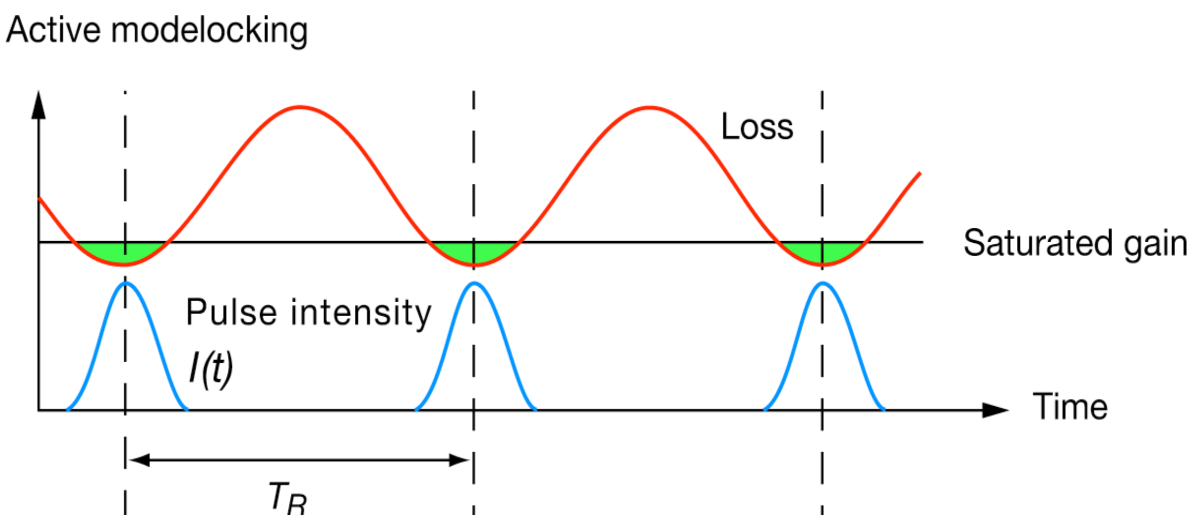
A-FPSA

Antiresonant Fabry-Perot Saturable Absorber

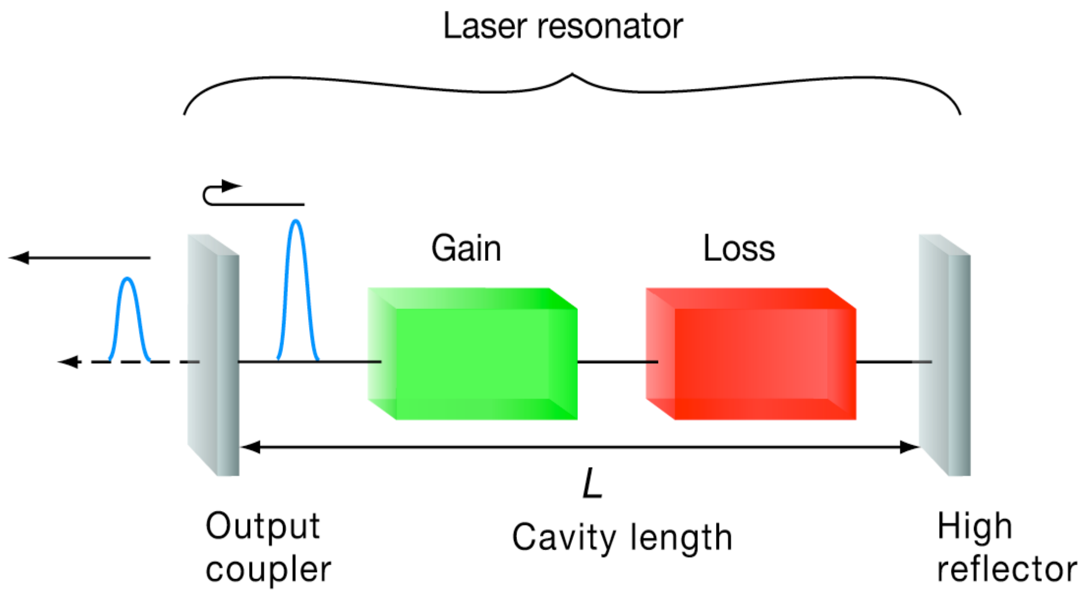
U. Keller et al., *Optics Lett.*, vol. 17, 505, 1992

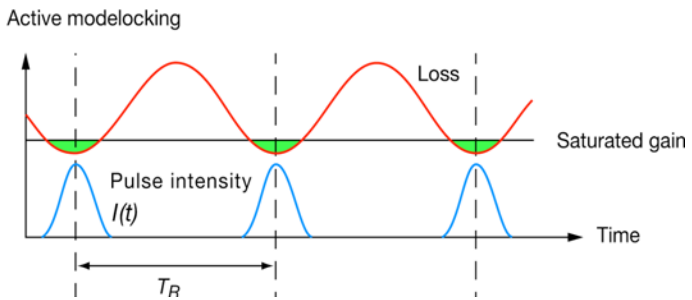
Active Modelocking

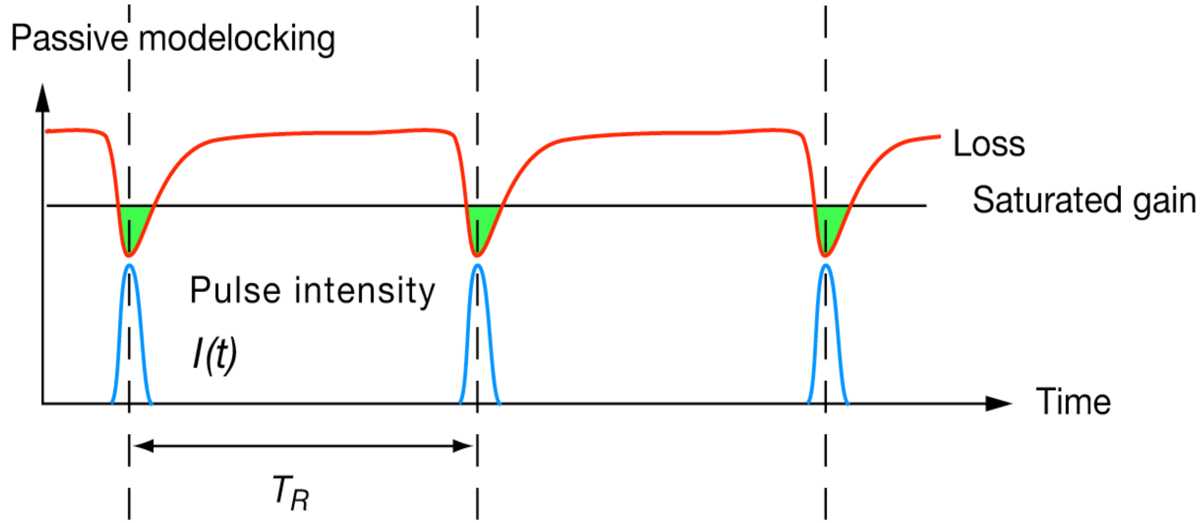




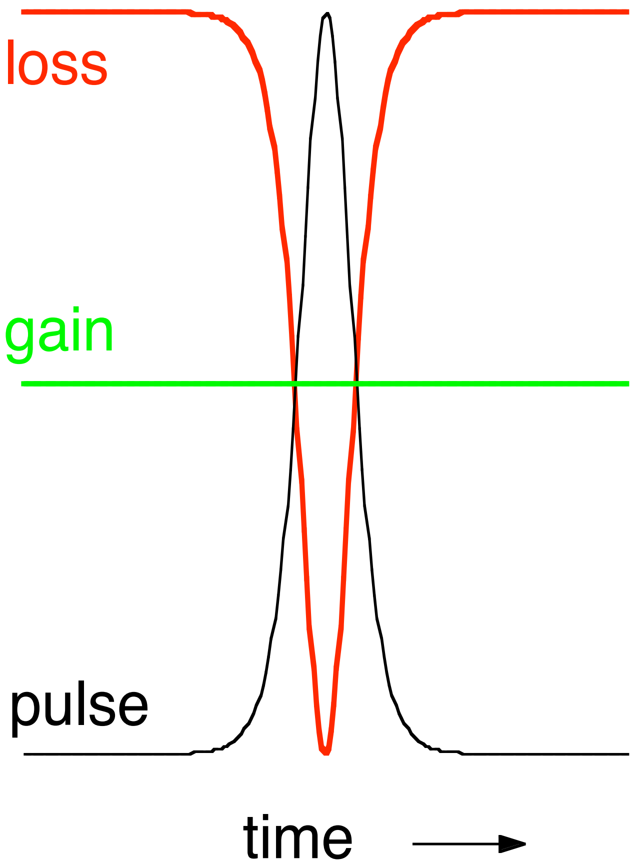
Passive Modelocking

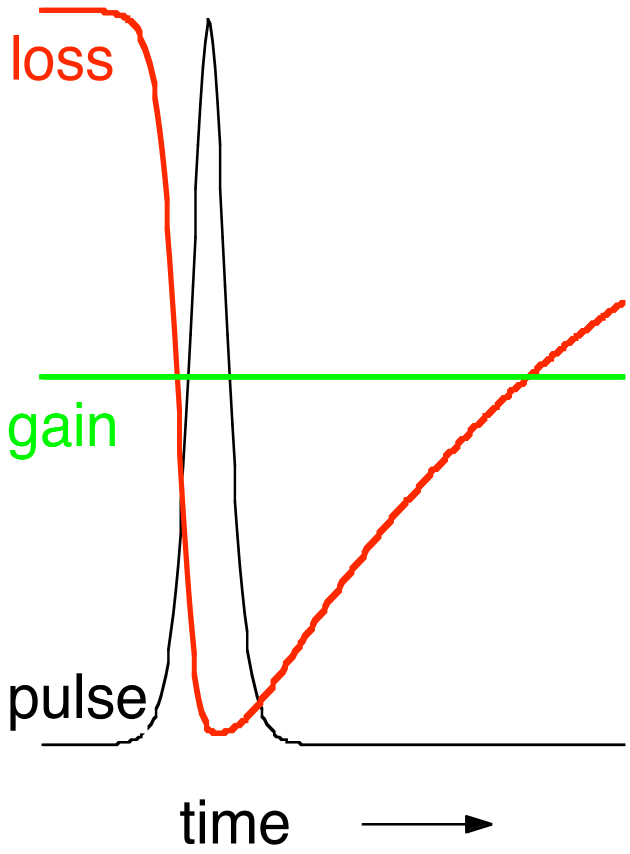






KLM vs. Soliton modelocking





Kerr lens modelocking (KLM)

Fast saturable absorber

D. E. Spence, P. N. Kean, W. Sibbett
Opt. Lett. **16**, 42, 1991

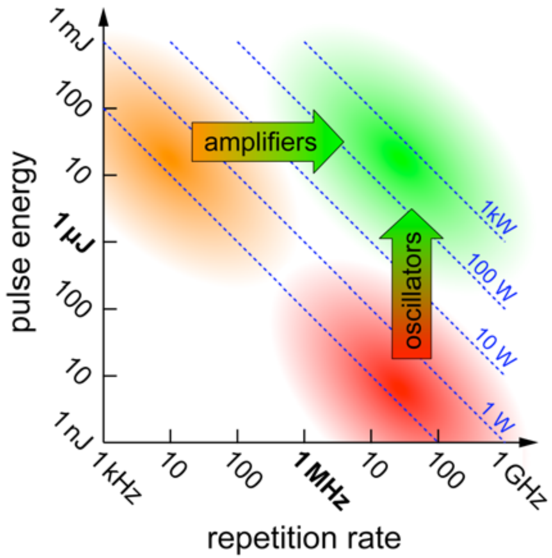
Soliton modelocking

“not so fast” saturable absorber

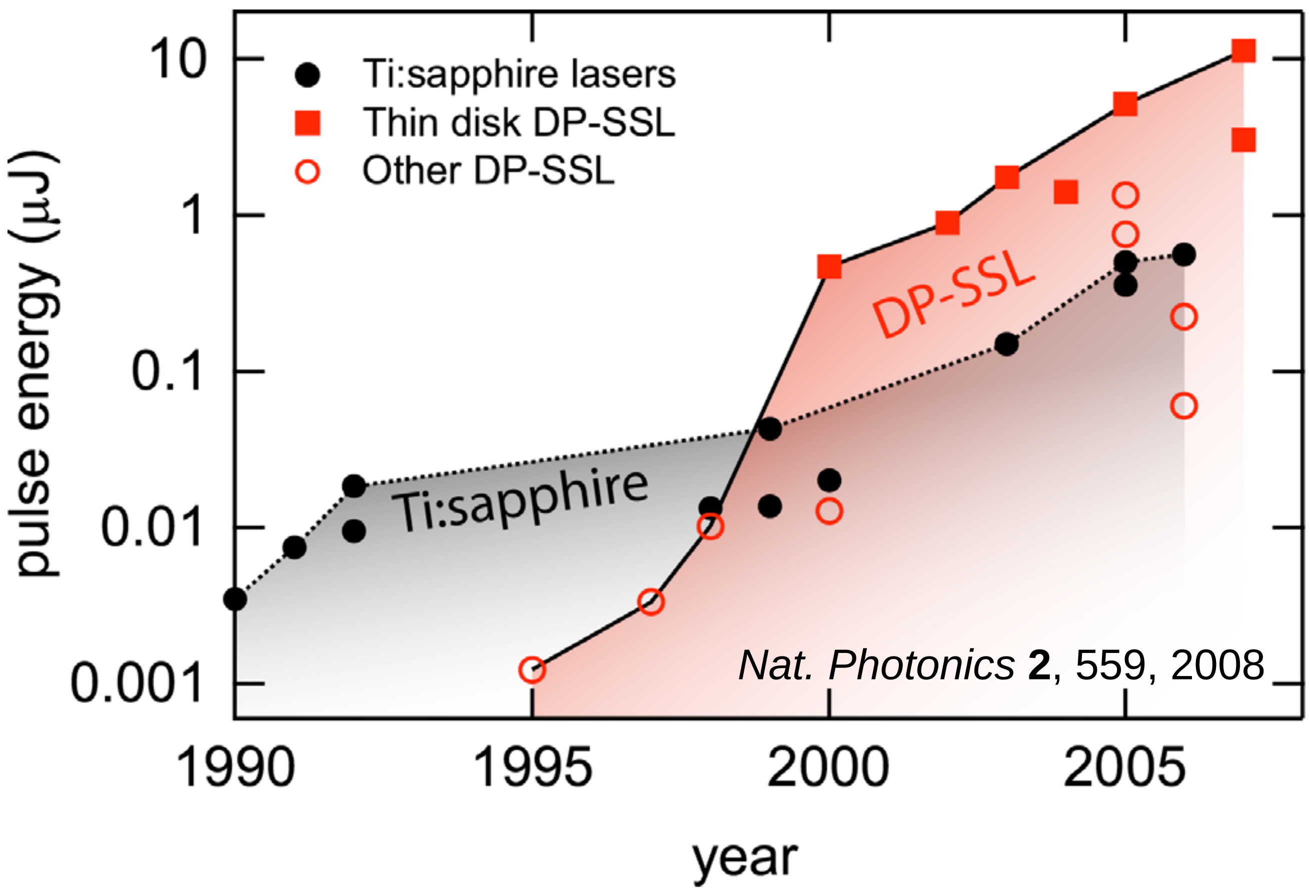
F. X. Kärtner, U. Keller,
Opt. Lett. **20**, 16, 1995

Stabilization: Dispersion spreads continuum out where it sees more loss

High average power lasers

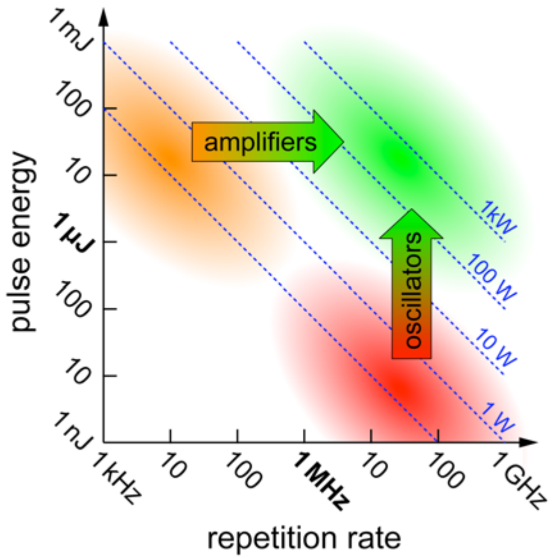


DP-SSL: diode-pumped solid-state lasers



First time >10 µJ pulse energy from a SESAM modelocked Yb:YAG thin disk laser:
>10'000 times improvement in diode-pumped lasers during the last 15 years
Opt. Express **16**, 6397, 2008 and *CLEO Europe* June 2007

High average power lasers



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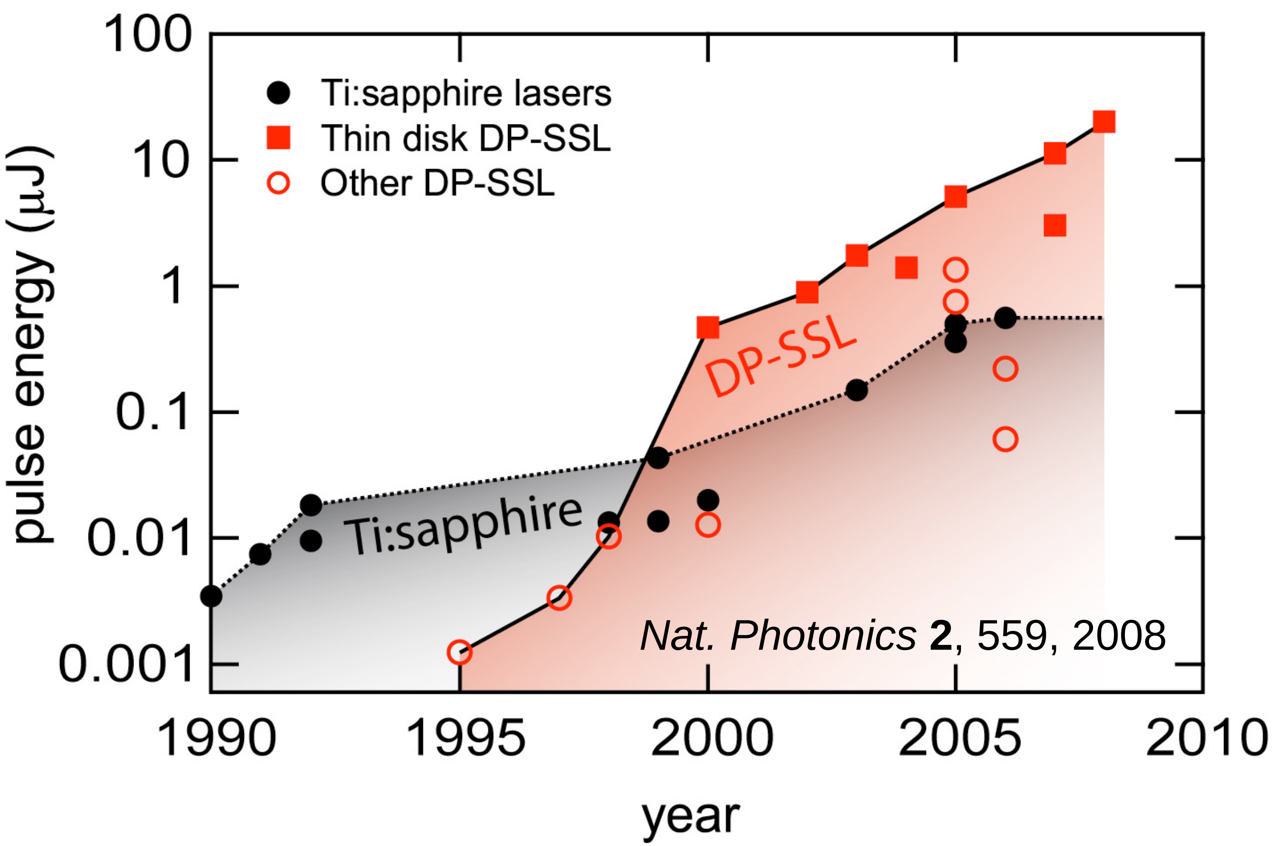
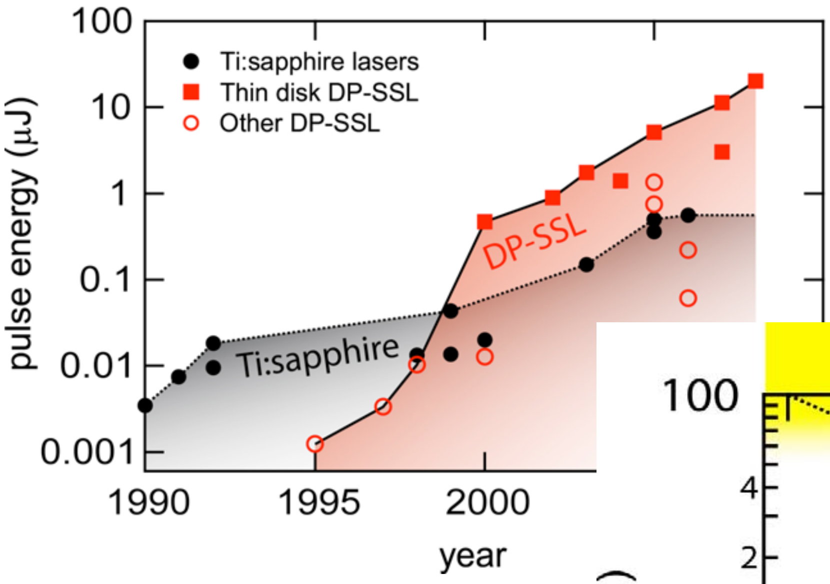
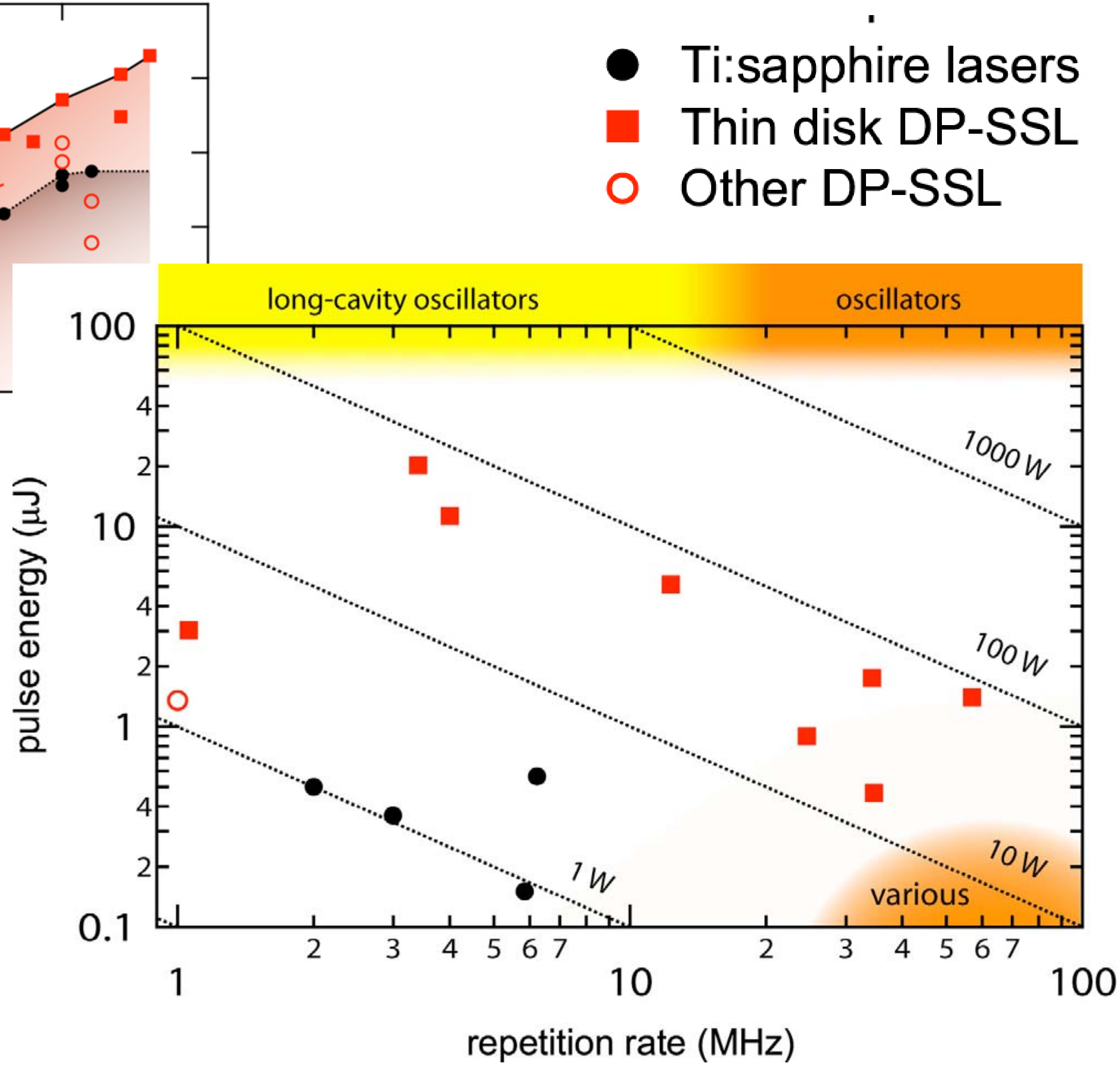


First time >10 µJ pulse energy from a SESAM modelocked Yb:YAG thin disk laser:
Opt. Express **16**, 6397, 2008 and *CLEO Europe* June 2007

26 µJ with a multipass gain cavity and larger output coupling of 70% (Trumpf/Konstanz)
Opt. Express **16**, 20530, 2008

High average power lasers - moving towards 100 µJ





100 µJ

5 MHz

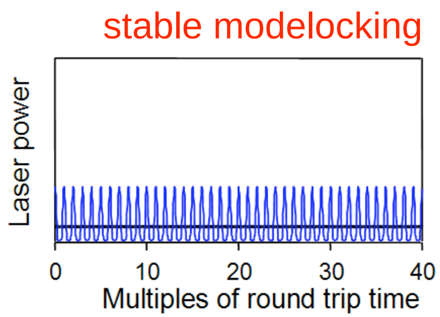
500 W average power

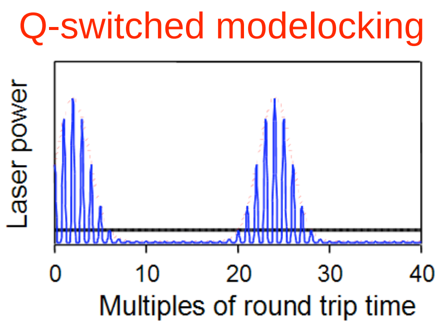
$$P_{av} = E_p f_{rep}$$

Challenges for high power femtosecond oscillators

- Femtosecond pulse formation at high power levels
  pulse forming element must sustain high intracavity power
  prevent instabilities (e.g. Q-switched modelocking)

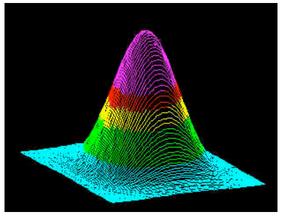
⇨ SESAM for pulse formation





- Laser technology operating at >100 W with Gaussian transverse beam profile (TEM_{00})
  prevent aberrations, provide cooling, …
  Resonator design for stability towards thermal lensing

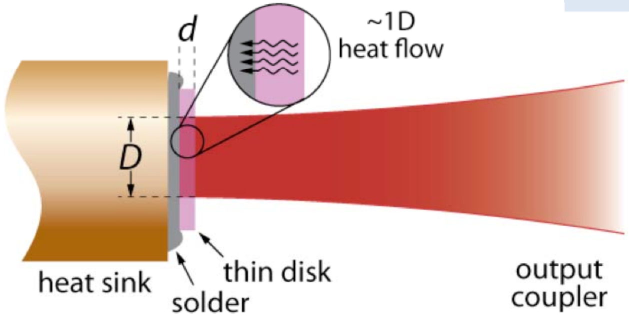
⇨ Thin disk laser head for high power levels



Passively Mode-Locked Thin Disk Laser

Thin disk laser head[#1]

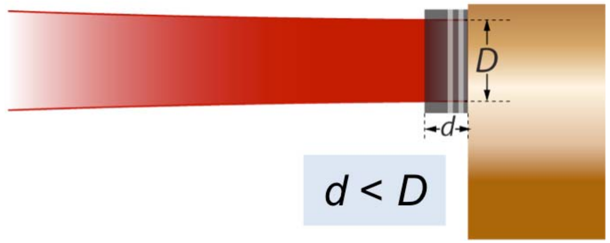
$d < D$



\+

SESAM[#2]

Semiconductor saturable absorber mirror



nearly 1-dimensional heat flow in **both** components → weak thermal lensing

power scaling

Increase $\boldsymbol{P}_{\mathbf{pump}}$, $\boldsymbol{A}_{\mathrm{L}}$ and $\boldsymbol{A}_{\mathrm{A}}$ by same amount to increase $\boldsymbol{P}_{\mathbf{out}}$

constant intensities →

- no change of thermal gradients
- **no change of QML-tendency**

gain medium requirements:

– high thermal conductivity
– good mechanical properties: thin disks (~100 µm)
– efficient absorption: large $\sigma_{\mathrm{abs,P}}$, high doping densities

} **high power operation**

– broad amplification bandwidth
– large emission cross sections to avoid QML

} **femtosecond pulses**

[#1] A. Giesen, et al., *Appl. Phys. B* **58**, 365 (1994)
[#2] U. Keller, et al., *Opt. Lett.* **17**, 505 (1992) *and* U. Keller, et al., *IEEE J. Sel. Top. Quant.* **2**, 435 (1996)

Progress in high power modelocked lasers

First cw modelocked thin-disk laser (Yb:YAG):
16 W, 730 fs, 0.5 MW
J. Aus der Au et al., *Opt. Lett.* **25**, 859 (2000)

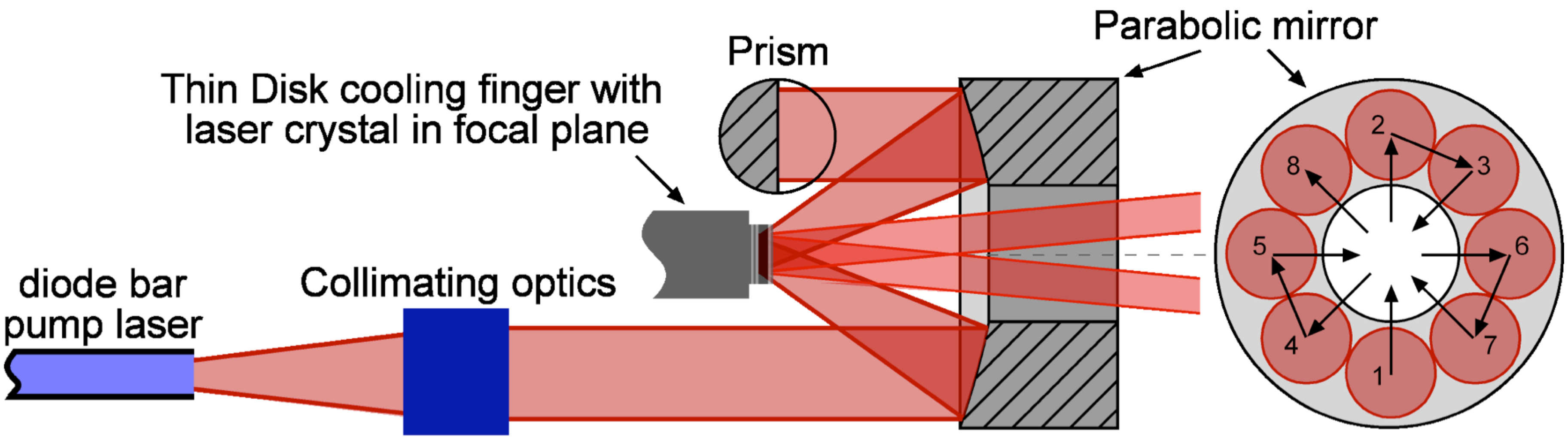
Power scaling

80 W, 705 fs, 1.75 MW
E. Innerhofer et al.,
Laser Phys. Lett. ***1**, 1 2004*

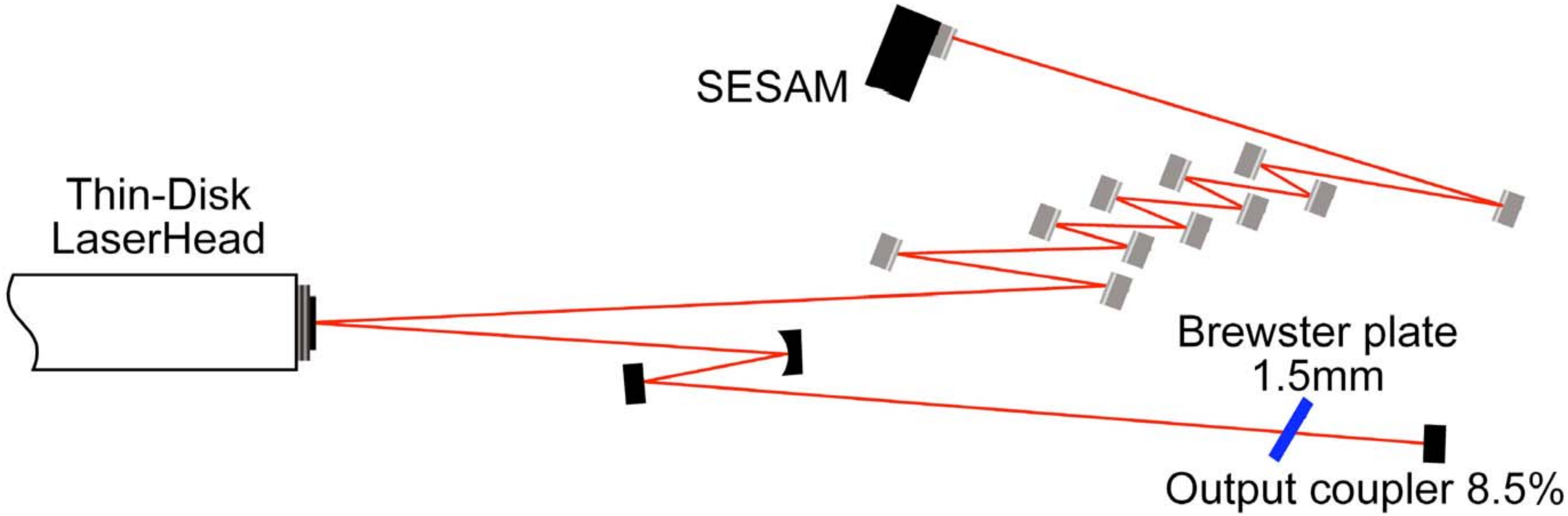
Yb:YAG Thin-Disk Laser Head

A. Giesen et al., *Appl. Phys. B* **58**, 365, 1994
constructed by TRUMPF Laser GmbH+Co. KG (Germany)

- Thickness of Yb:YAG disk: 100 µm (absorption length a few mm - need multiple passes of pump for efficient absorption)
- Diameter of pump spot: 2.8 mm
- Pump power: up to 370 W @ 940 nm
- 16 passes of pump radiation through disk



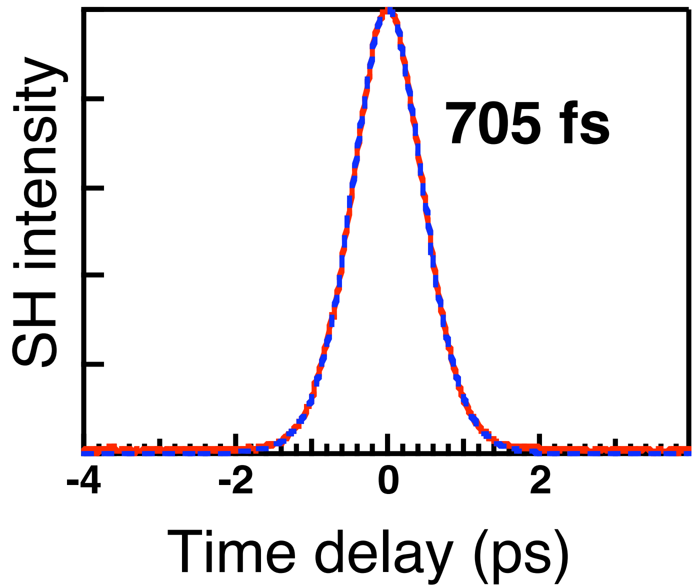
Thin disk laser: 57-MHz setup



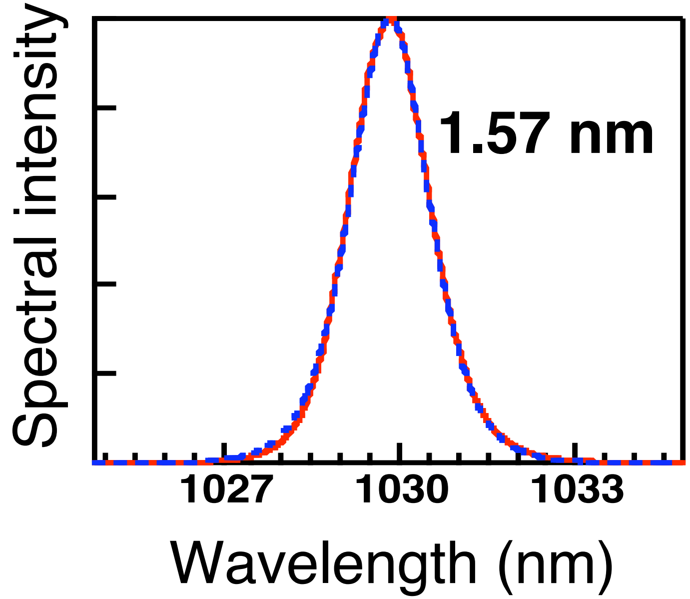
- Thin disk **as folding mirror**
- SESAM and output coupler **as end mirror**
- **Brewster plate for** linear polarization
- **Negative group delay dispersion from** GTI-type dispersive mirrors

80 W from Yb:YAG Laser

Autocorrelation



Optical spectrum

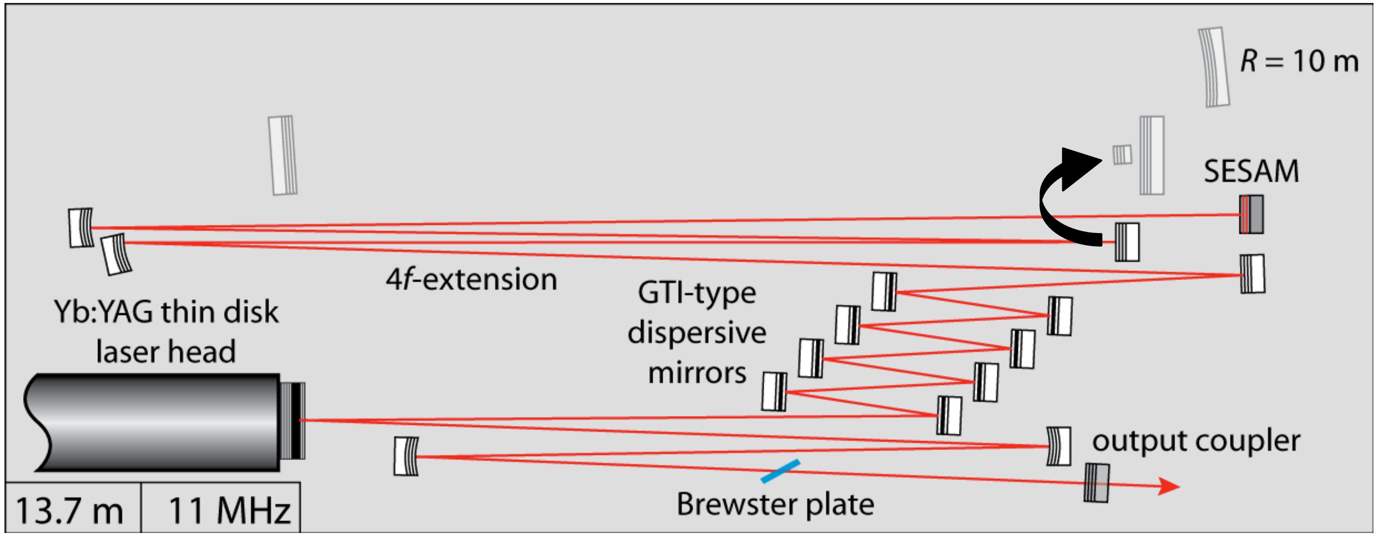


P_{avg}	= 80 W
τ_p	= 705 fs
f_{rep}	= 57 MHz

E_p	= 1.4 μJ
P_{peak}	= 1.75 MW
$\Delta\nu\tau_p$	= 0.32

First modelocked (ML) thin-disk, 16 W: *Optics Lett.* **25**, 859, 2000
60 W ML Thin Disk: E. Innerhofer et al., *Optics Lett.* **28**, 367, 2003
80 W ML Thin Disk: F. Brunner et al., *Optics Lett.* **29**, 1921, 2004

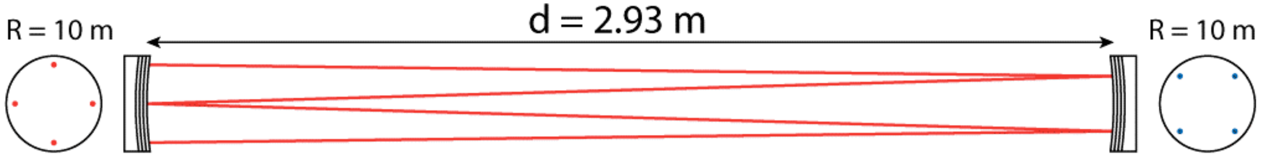
Moving to a few MHz pulse repetition rate



Multiple-pass cavity (MPC)

increase cavity length even further ⇨ insert multiple-pass cavity (MPC) ★

- curved-curved configuration, MPC-length: $D = n \cdot d$



★ *D. Herriott, et al., Appl. Opt.* ***3****, 523 (1964)*

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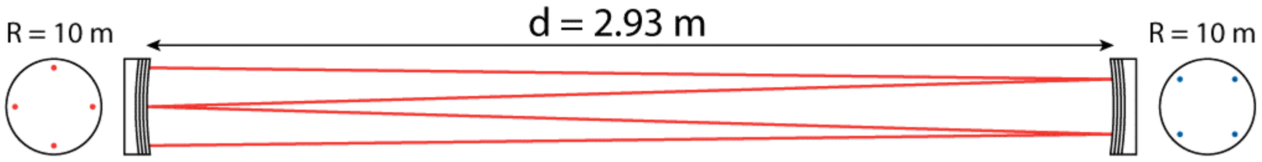
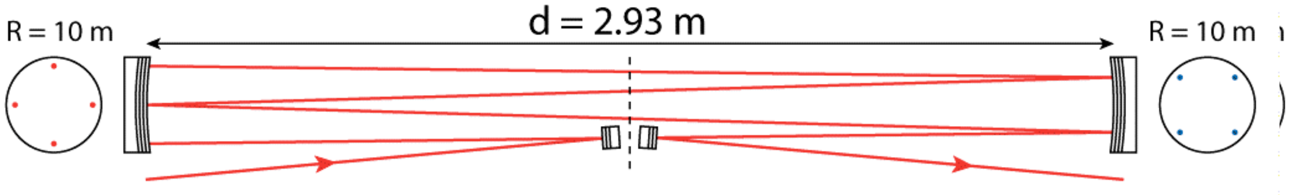


- two mirrors to couple in and out of the MPC



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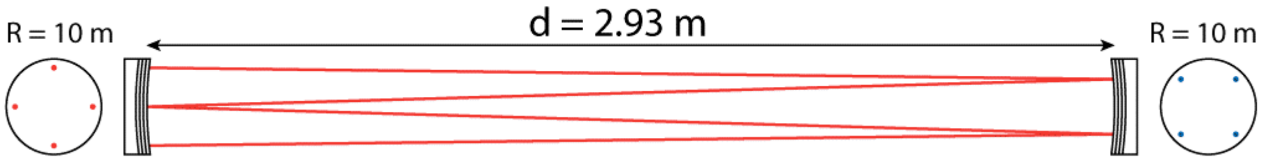

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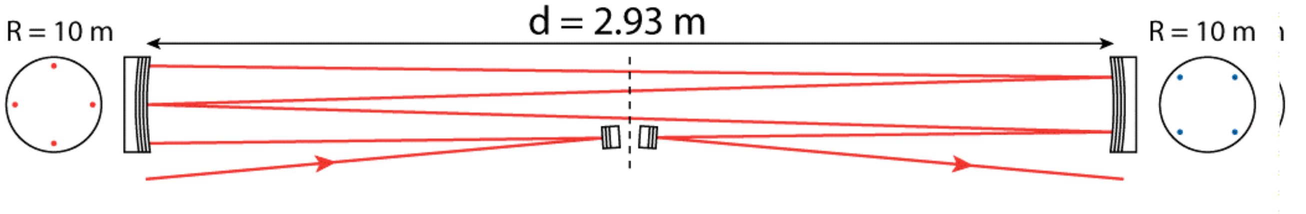
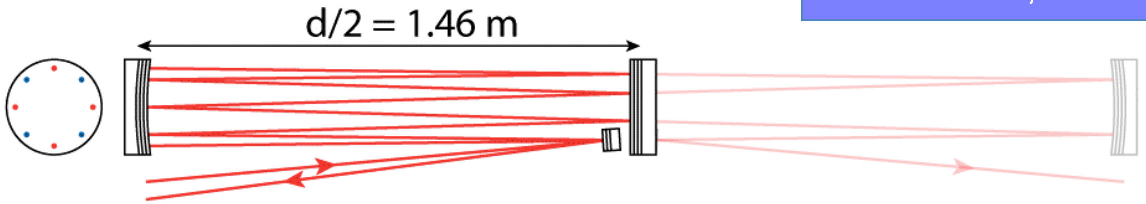


- folded geometry requires
  - only one curved mirror
  - **only one pickup mirror**

d = 2.93 m, *n* = 8, D = 23.4 m



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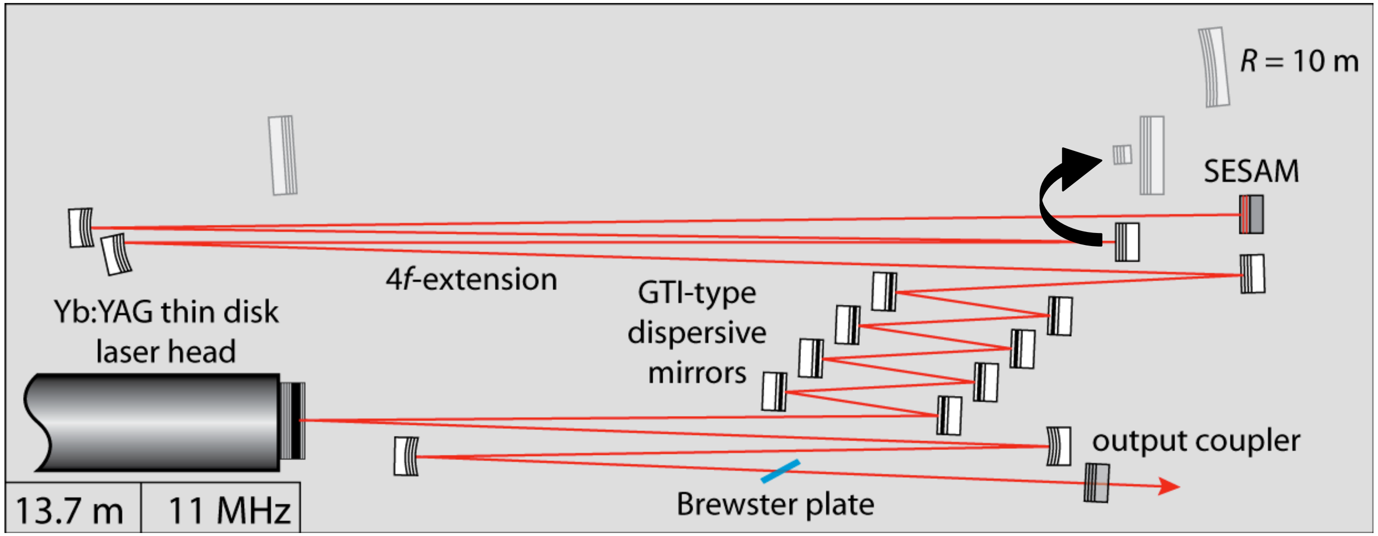
Moving to a few MHz pulse repetition rate



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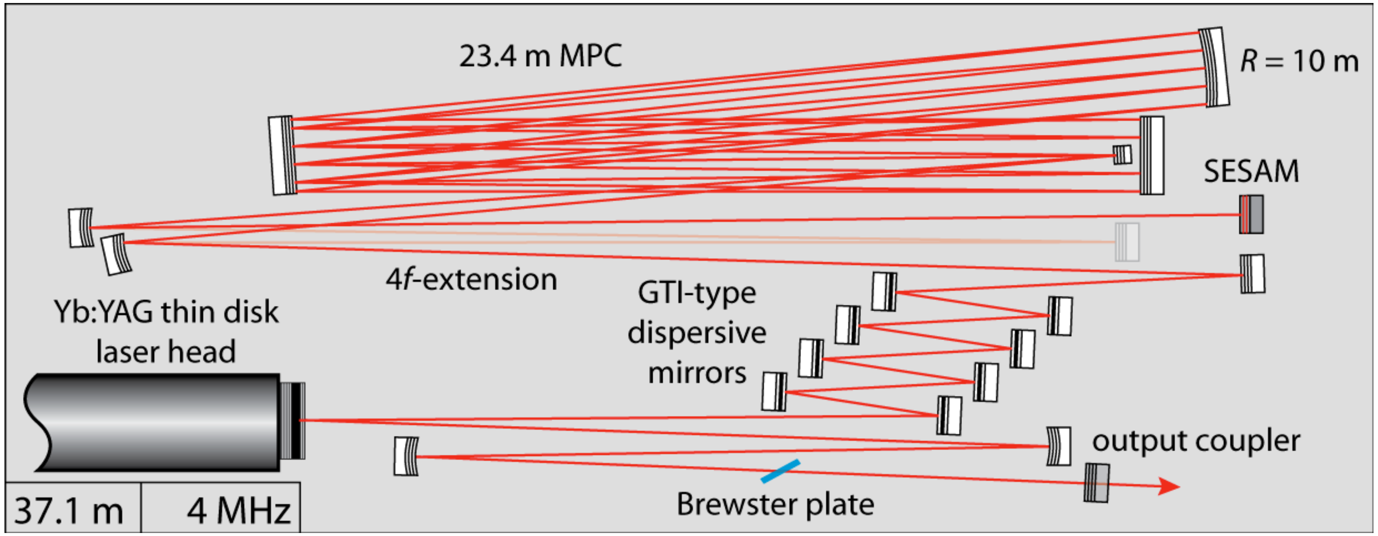
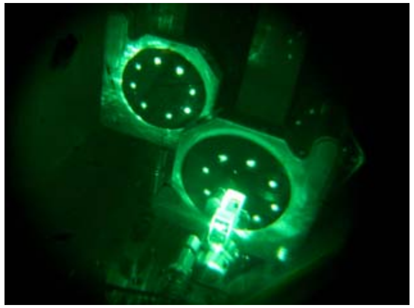
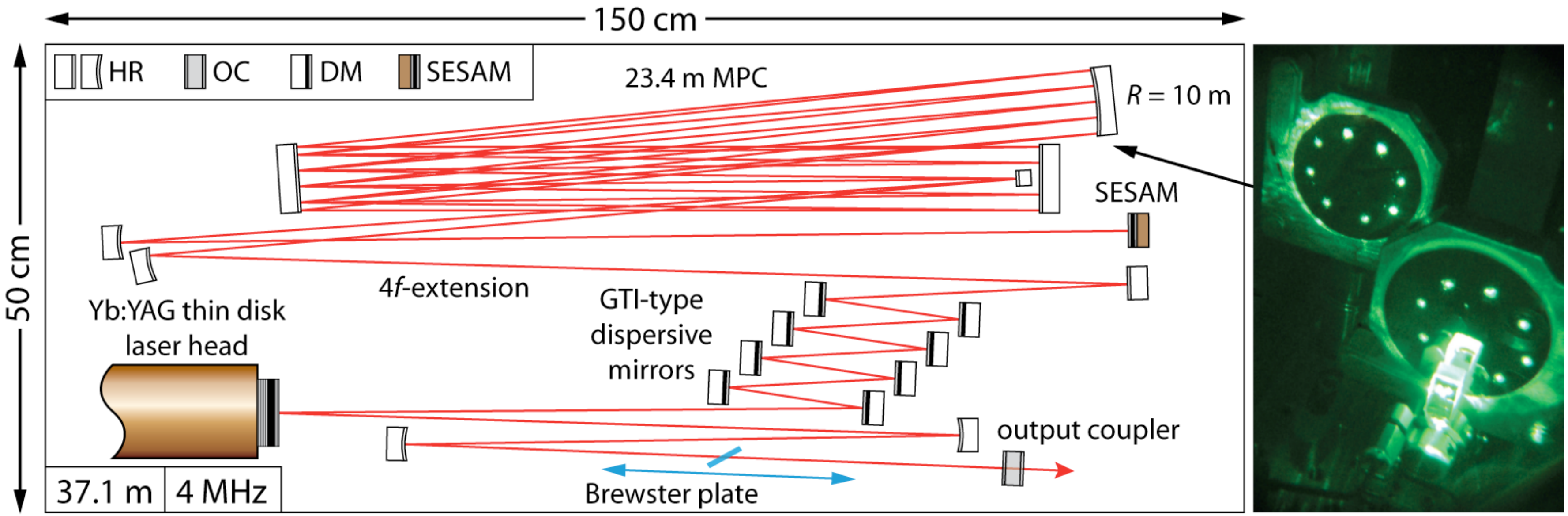




11 µJ SESAM modelocked Yb:YAG thin disk laser



Yb:YAG laser head

- ≈ 9% Yb-doped YAG
- d_{disk} ≈ 200 µm, w_{pump} ≈ 1.4 mm
- P_{pump} up to 230 W @ 940 nm

(TGSW, Stuttgart, Germany)

SESAM

- F_{sat} ≈ 115 µJ/cm^2
- ΔR ≈ 0.5 %

13 dispersive mirrors

- ≈ -550/1000 fs^2 GDD per bounce
- ≈ -20000 fs^2 GDD per roundtrip

Brewster plate (SPM + linear pol.)

- 1 mm thick fused silica

Output coupler

- 10% at 1030 nm

Challenge: Nonlinearity in air

in air atmosphere

no stable mode locking achieved → instabilities & multiple pulses

Challenge: Nonlinearity in air

in air atmosphere

no stable mode locking achieved → instabilities & multiple pulses

helium flooding

in helium atmosphere

P_{avg} = 45 W

f_{rep} = 4 MHz

→ E_p = 11.3 µJ

pulse energy limited by:

- **strong saturation of the SESAM**
- **air-tightness of the helium box**

Challenge: Nonlinearity in air

in air atmosphere
no stable mode locking achieved → instabilities & multiple pulses

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P_{avg}	=	45 W
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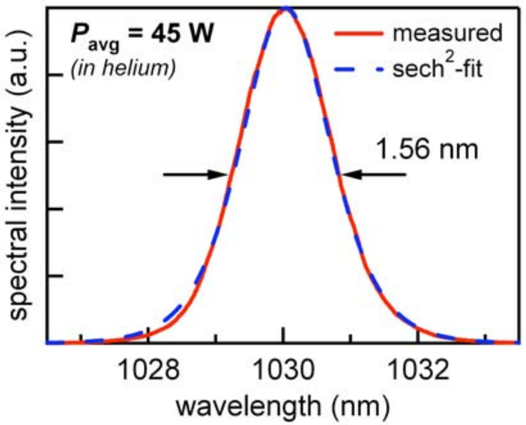
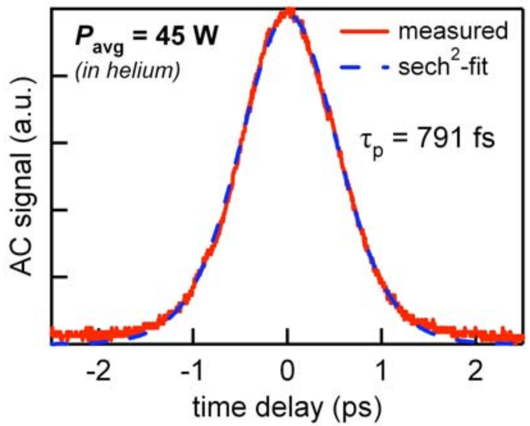




Opt. Express **16**, 6397, 2008

λ	=	1030 nm
$\Delta\lambda$	=	1.56 nm

M^2	=	1.1
P_{peak}	=	12.5 MW

τ_p	=	**791 fs**
$\tau_p \cdot \Delta\nu$	=	0.35 (ideal 0.315)

Multi-pass gain Yb:YAG thin disk laser

726 OPTICS LETTERS / Vol. 33, No. 7 / April 1, 2008

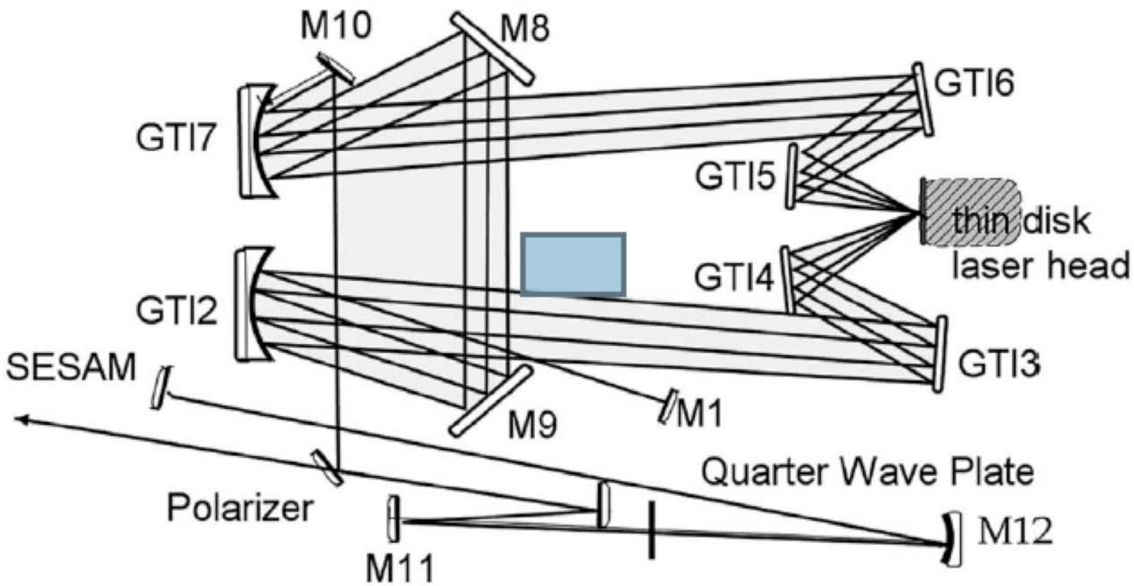
Passively mode-locked Yb:YAG thin-disk laser with pulse energies exceeding 13 μJ by use of an active multipass geometry

Joerg Neuhaus,[1,2,*] Jochen Kleinbauer,[1] Alexander Killi,[1] Sascha Weiler,[1] Dirk Sutter,[1] and Thomas Dekorsy[2]

[1]*TRUMPF-Laser GmbH + Company KG, Aichhalder Strasse 39, 78713 Schramberg, Germany*
[2]*Department of Physics, University of Konstanz, 78465 Konstanz, Germany, and Center for Applied Photonics, University of Konstanz, 78465 Konstanz, Germany*

20 passes through gain
13.4 μJ (stability limit)
cw background 8%
3.8 MHz
1.36 ps
55 W average out

T_{out} = 50%



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J. Aus der Au et al., *Opt. Lett.* **25**, 859 (2000)

Power scaling

80 W, 705 fs, 1.75 MW
E. Innerhofer et al.,
Laser Phys. Lett. ***1**, 1 2004*

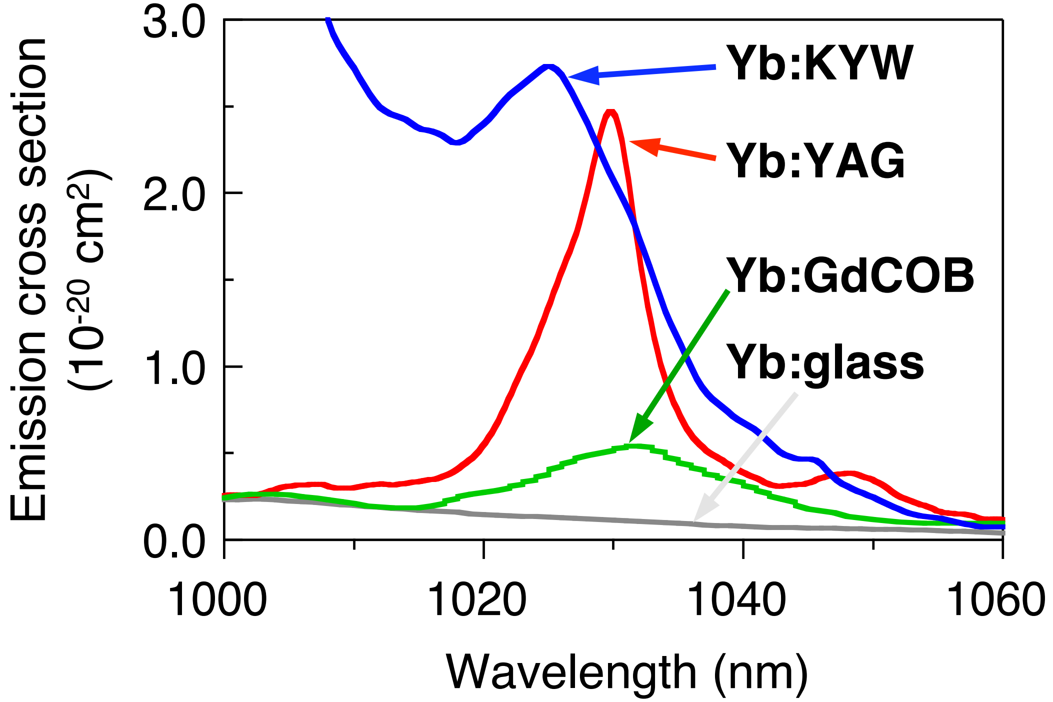
Pulse duration reduced with different laser materials:

Yb:KYW
22 W, 240 fs, 3.3 MW
F. Brunner et al.,
Opt. Lett. **27**, 1162 (2002)

Yb:Lu_2O_3
20.5 W, 370 fs, 0.75 MW
S. V. Marchese et al.,
Opt. Exp. **15**, 16966 (2007)

Yb-doped tungstate laser: Yb:KYW {Yb:KY$(WO_4)_2$ }

N. V. Kuleshov et al., *Opt. Lett.* **22,** 1317 (1997)

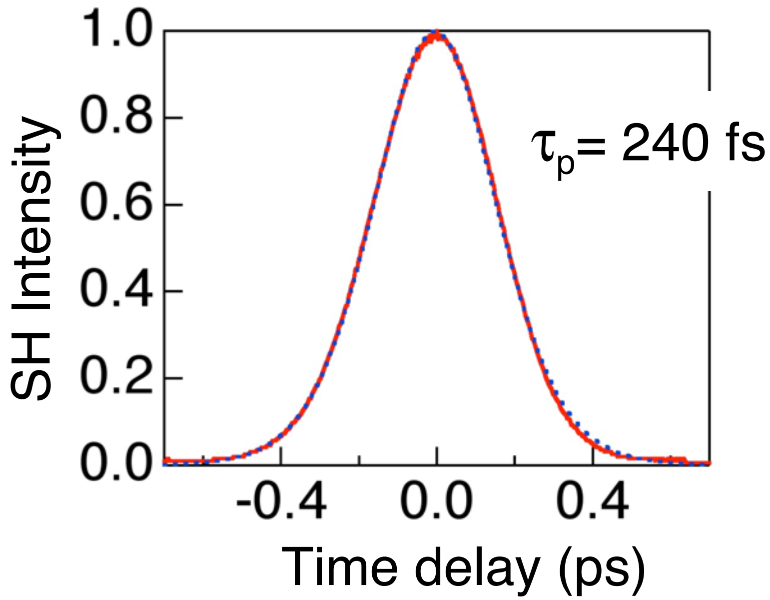


- broad emission spectrum ➡ potential for ≈100-fs pulse
- large emission cross section ➡ lower tendency for QML
- small quantum defect (4%) ➡ reduced heating effects
- good thermal conductivity, κ = 3.3 W/Km ➡ efficient cooling

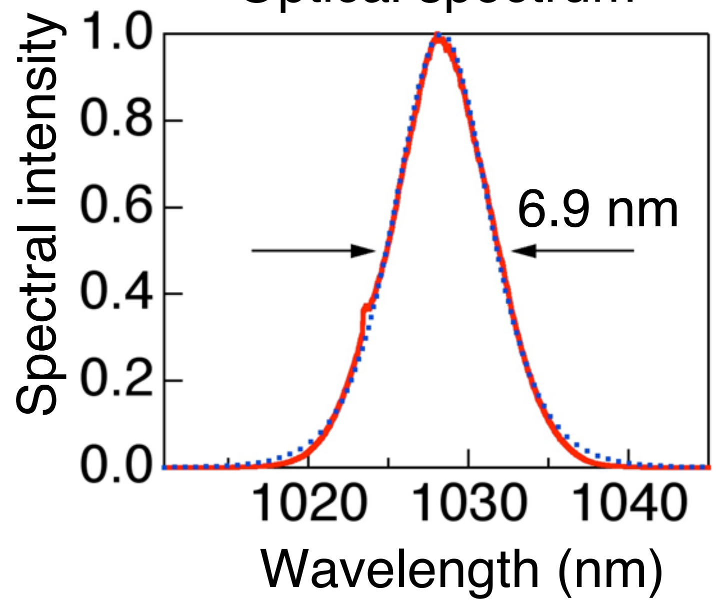
High power SESAM modelocked Yb:KYW laser

F. Brunner et al., *Opt. Lett.* **27**, 1162 (2002)

Autocorrelation



Optical spectrum



P_{avg} = 22 W

τ_p = 240 fs

f_{rep} = 25 MHz

M^2 = 1.1

E_p = 0.9 μJ

P_{peak} = 3.3 MW

linear polarisation

P_{pump} = 100 W

Properties of $Yb:Lu_2O_3$ (Prof. Huber, Univ. Hamburg)

previous thin disk results

Yb:YAG	P_{avg}	f_{rep}	τ_P	E_P	P_{peak}
highest P_{avg} [#1]	80 W	57 MHz	705 fs	1.4 µJ	1.75 MW
highest E_P & P_{peak} [#2]	45 W	4 MHz	791 fs	11.3 µJ	12.5 MW
Yb:KYW					
shortest pulses[#3]	22 W	25 MHz	240 fs	0.9 µJ	3.3 MW

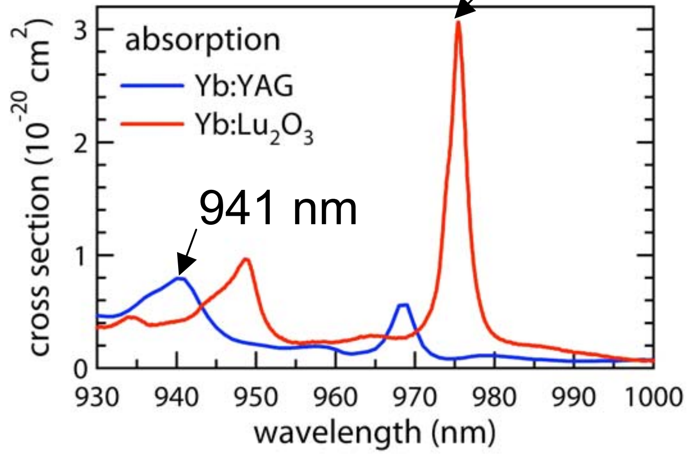
limited gain bandwidth

astigmatism: **limited scalability**

$Yb:Lu_2O_3$

- **high thermal conductivity[#4]**
  κ = 11 W/(m·K) for 3 at.% $Yb:Lu_2O_3$
- **large σ_{abs} at 976 nm → thinner disks**

  → **efficient heat removal** for high power thin disk laser operation



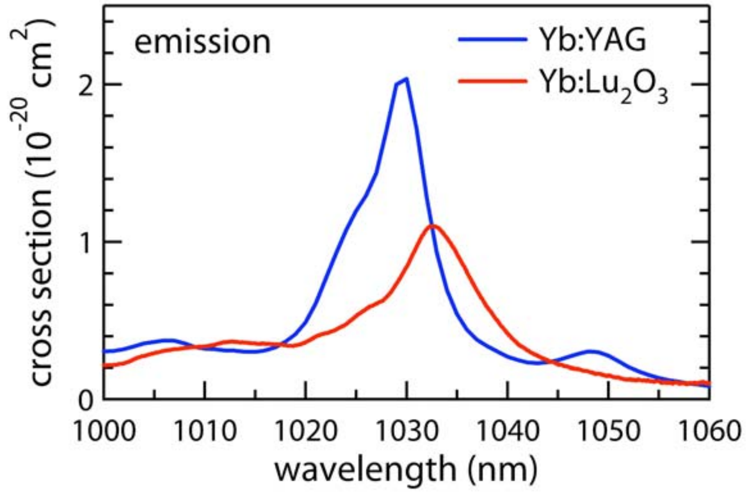
- **narrow absorption bandwidth (≈ 2.2 nm)** → increased demands on pump diodes

[#1] F. Brunner, et al., *Opt. Lett.* **29**, 1921 (2004) *and* E. Innerhofer, et al., *J. Opt. Soc. Am. B* **23**, 265 (2006)
[#2] S. V. Marchese, et al., *CLEO-Europe*, talk CF3-2-MON, 2007
[#3] F. Brunner, et al., *Opt. Lett.* **27**, 1162 (2002)
[#4] V. Peters, et al., *J. Cryst. Growth* **237**, 879 (2002)

Properties of $Yb:Lu_2O_3$ (Prof. Huber, Univ. Hamburg)

- **broad amplification bandwidth**

	Yb:YAG	$Yb:Lu_2O_3$
λ_L (nm)	1030	1034
$\Delta\lambda_L$ (nm)	6.3	12
$\sigma_{em,L}$ (10^{-20} cm^2)	2.1	1.1



→ **generation of femtosecond pulses**
(demonstrated[#1]: 220 fs with P_{avg} = 266 mW, $\eta_{opt\text{-}opt}$ = 15.5%, n_{slope} = 23%)

- **high melting point (>2400 °C)**
challenging crystal growth → performance limited by insufficient crystal quality

recently

high quality $Yb:Lu_2O_3$ crystals grown by HEM[#2]
→ highly efficient multi-mode cw thin disk laser operation[#3]

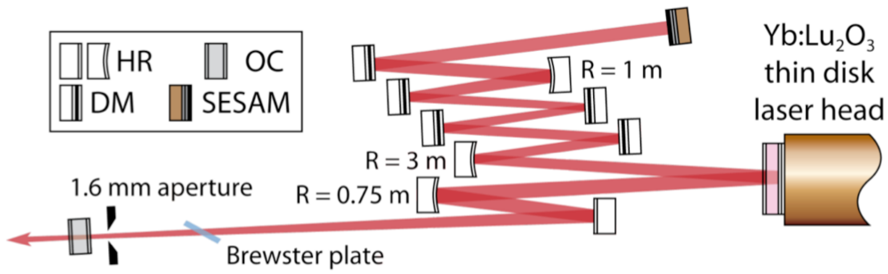
P_{max} **= 32.6 W** $\eta_{opt\text{-}opt}$ **= 72%** η_{slope} **= 80%**

[#1] U. Griebner, et al., *Opt. Express* **12**, 3125 (2004)
[#2] R. Peters, et al., *J. Cryst. Growth* (2007), doi:10.1016/j.jcrysgro.2007.10.078
[#3] R. Peters, et al., *Opt. Express* **15**, 7075 (2007)

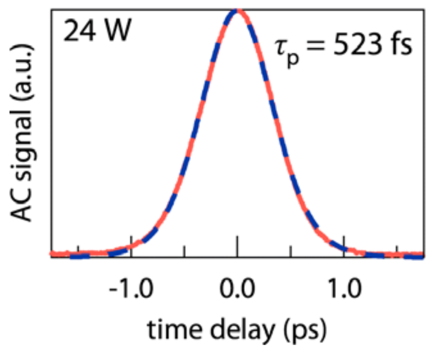
SESAM modelocked thin $Yb:Lu_2O_3$ thin disk laser

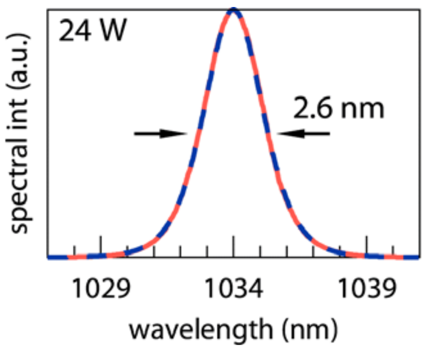
SESAM No.1

- standard low-finesse design with 1 InGaAs-QW absorber
- F_{sat} = 22 µJ/cm^2 ΔR = 0.9%

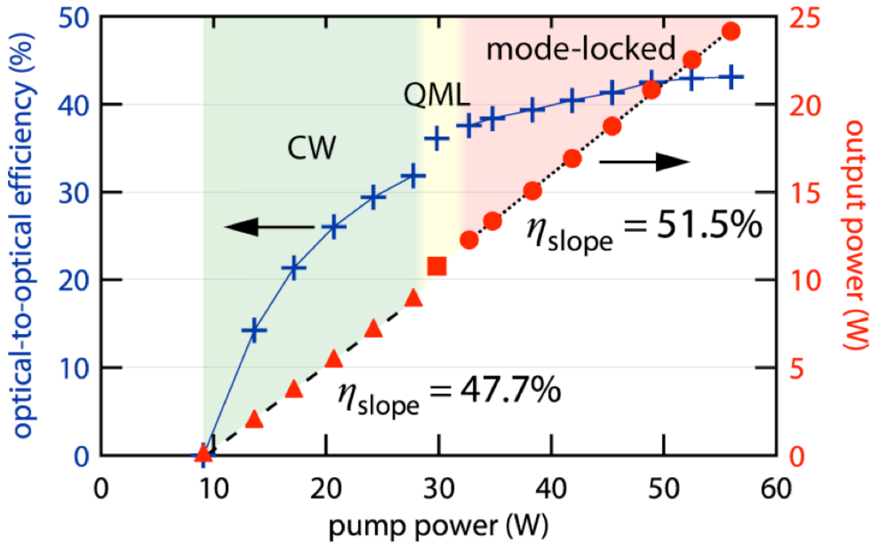


Result (with SESAM No.1)





P_{avg}	= 24 W	P_{pump}	= 56 W
$\eta_{opt\text{-}opt}$	= 43%	$\eta_{sl,ML}$	= 51.5%
M^2	< 1.1	$\tau_p \cdot \Delta\nu$	= 0.38
f_{rep}	= 65 MHz	(ideal: 0.315)	



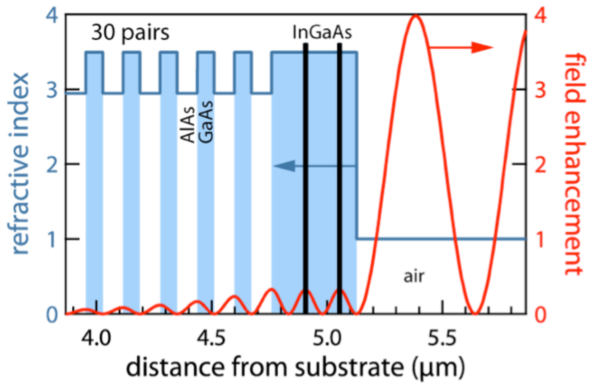
→ no signs of thermal limitations

→ **output limited only by P_{pump}**

SESAM modelocked thin $Yb:Lu_2O_3$ thin disk laser

SESAM No.2

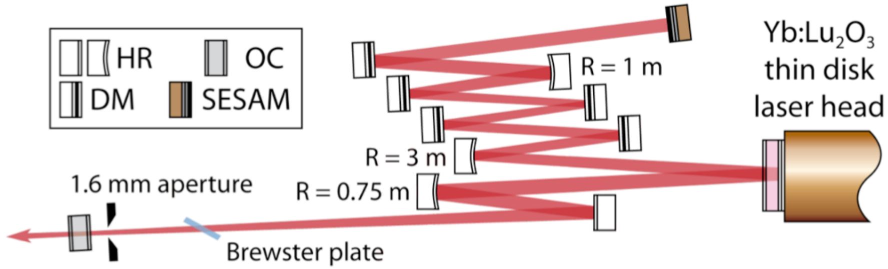
- standard low-finesse design with **2 InGaAs-QW absorbers**
- F_{sat} = 19 µJ/cm² ΔR = 2%



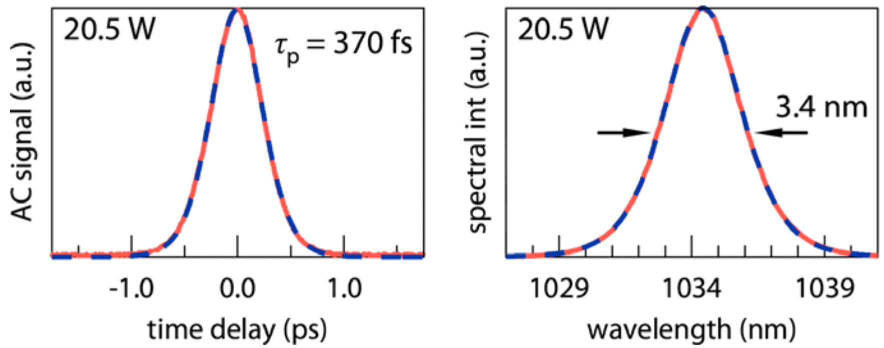
→ larger ΔR compensates for gain advantage of cw-background[#1]

→ stable operation with **larger pulse bandwidth**

→ **shorter pulse durations**



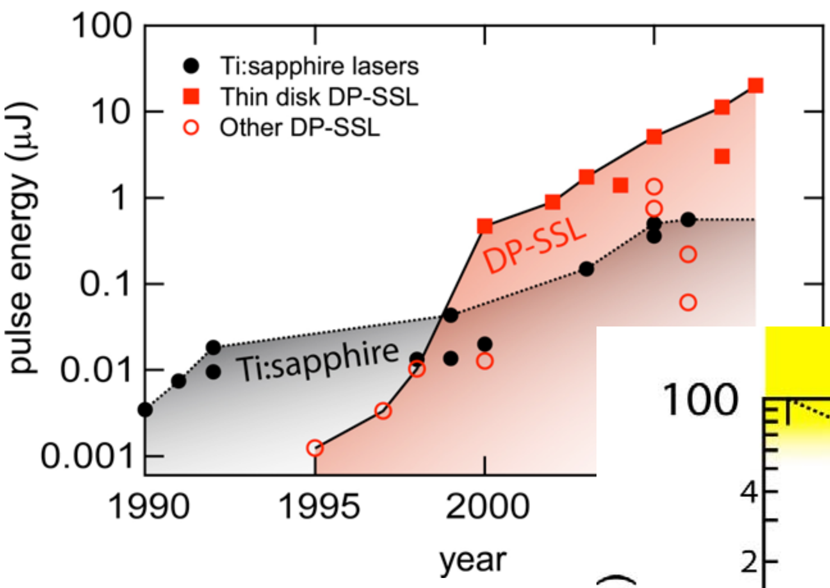
Result (with SESAM No. 2)

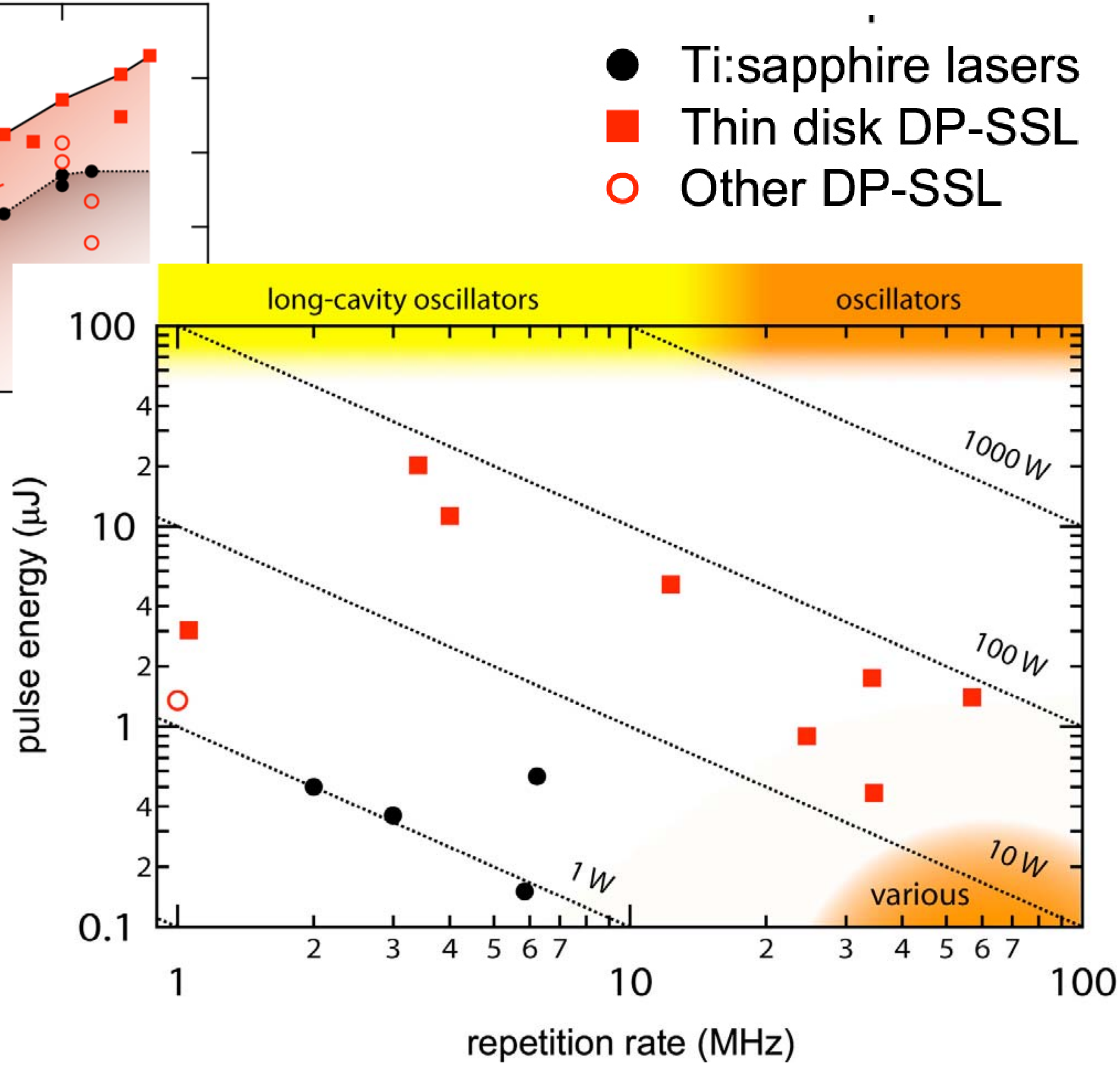


$\boldsymbol{P_{avg}}$	**= 20.5 W**	$\boldsymbol{P_{pump}}$	**= 56 W**
$\boldsymbol{\eta_{opt-opt}}$	**= 36.6%**	$\boldsymbol{\tau_P}$	**= 370 fs**
M^2	< 1.1	$\tau_P \cdot \Delta\nu$	= 0.35
f_{rep}	= 65 MHz	(ideal: 0.315)	

[#1] *Appl. Phys. B* **72**, 267 (2001)

High average power lasers - moving towards 100 µJ





100 µJ

5 MHz

500 W average power

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

RGB laser source

Optics Lett. 29, 1921, 2004

•Multi-Watt RGB laser source

- entire pump power from one laser oscillator
- no amplifier
- no synchronized cavities
- only one temperature-stabilized nonlinear crystal - not needed any more

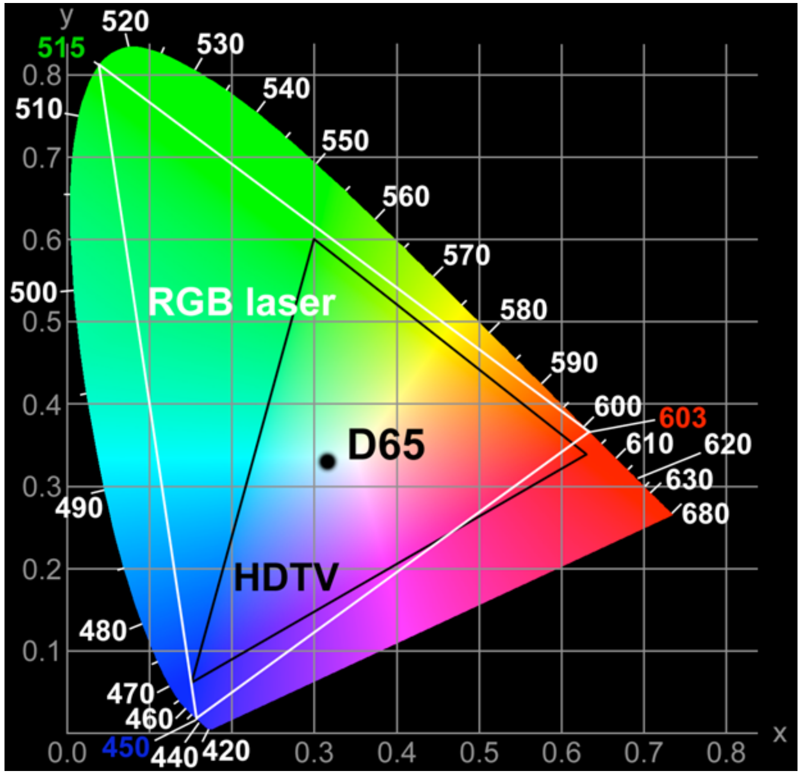
P_{avg}	@1030 nm	=	79 W
P_{avg}	@ 603 nm	=	8 W
P_{avg}	@ 515 nm	=	23 W
P_{avg}	@ 450 nm	=	10 W

- conversion efficiencies:

  IR → visible: 52 %

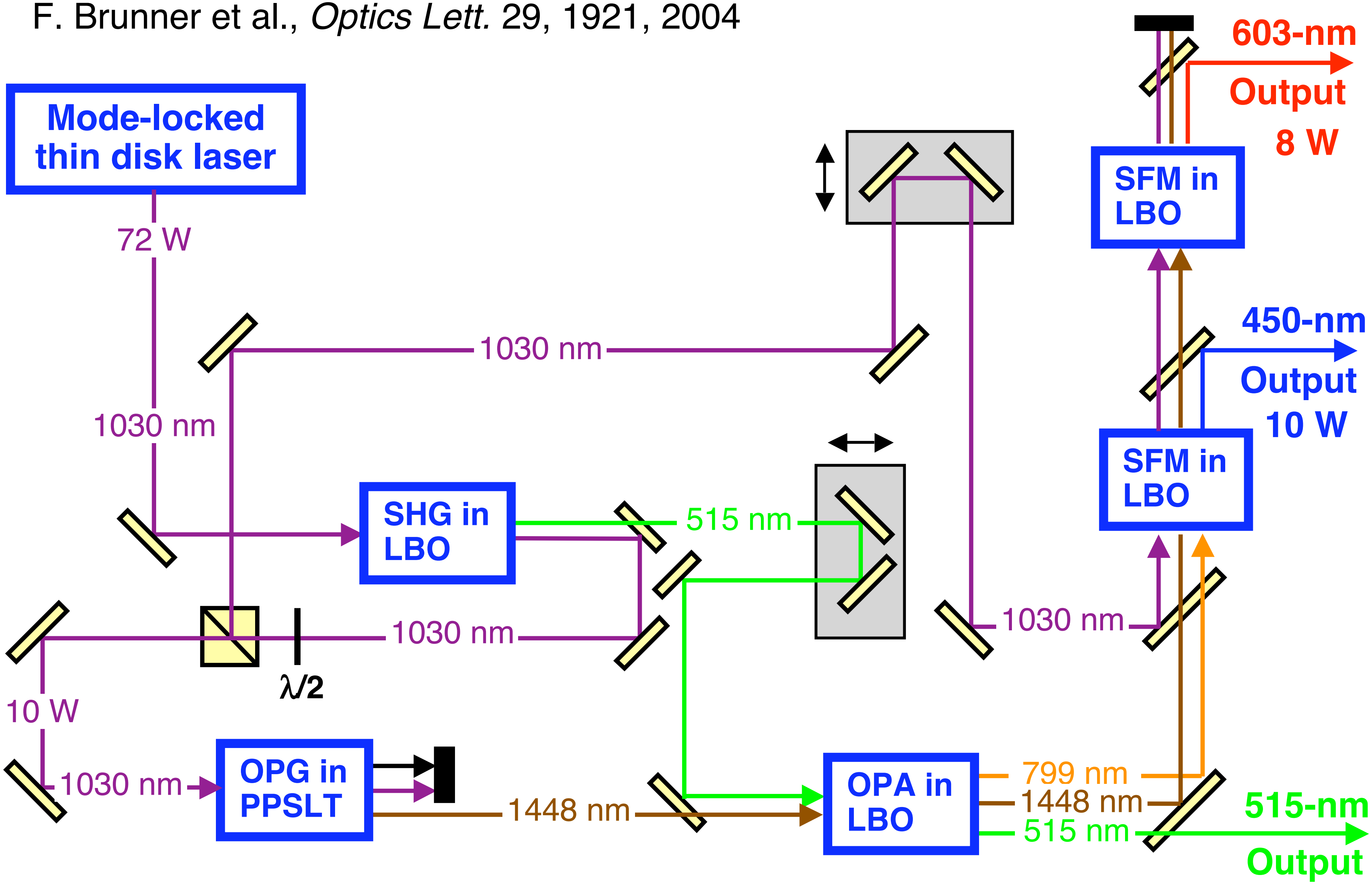
  IR → D65 white: 31 % (25.1 W)

  (R: 8 W, G: 10.7 W, B: 6.4 W)



CIE 1931 chromaticity chart

F. Brunner et al., *Optics Lett.* 29, 1921, 2004



PPSLT: periodically poled stoichiometric $LiTaO_3$

Progress in high power modelocked lasers

First cw modelocked thin-disk laser (Yb:YAG):
16 W, 730 fs, 0.5 MW
J. Aus der Au et al., *Opt. Lett.* **25**, 859 (2000)

Power scaling

80 W, 705 fs, 1.75 MW
E. Innerhofer et al.,
Laser Phys. Lett. ***1**, 1 2004*

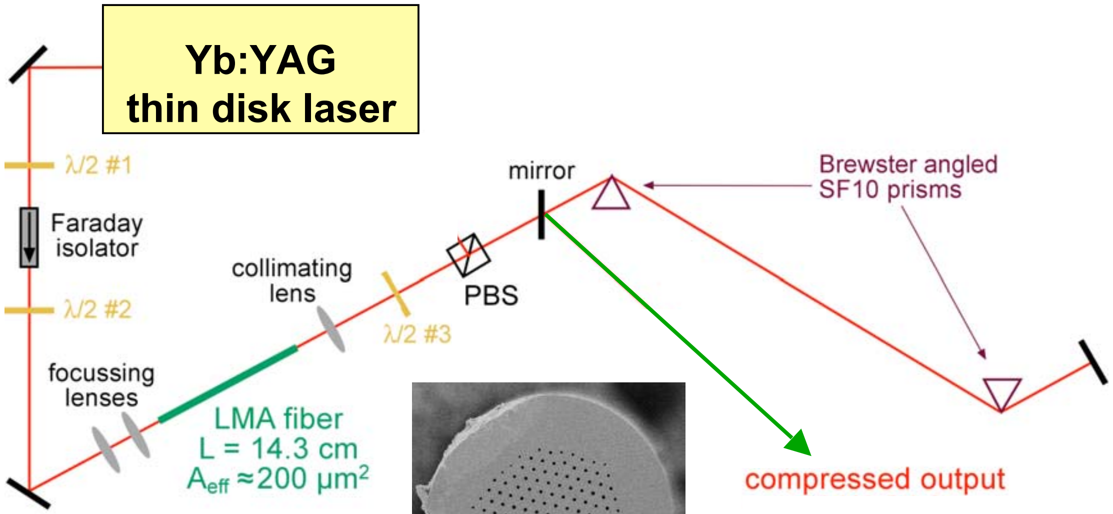
Pulse duration reduced with different laser materials:

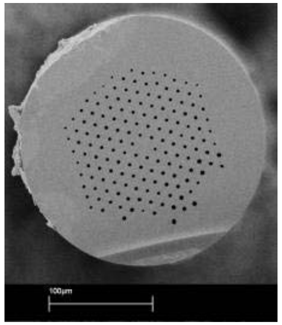
Yb:KYW 240 fs
Opt. Lett. **27**, 1162 (2002)
Yb:Lu_2O_3 370 fs
Opt. Exp. **15**, 16966 (2007)

even shorter pulse duration?

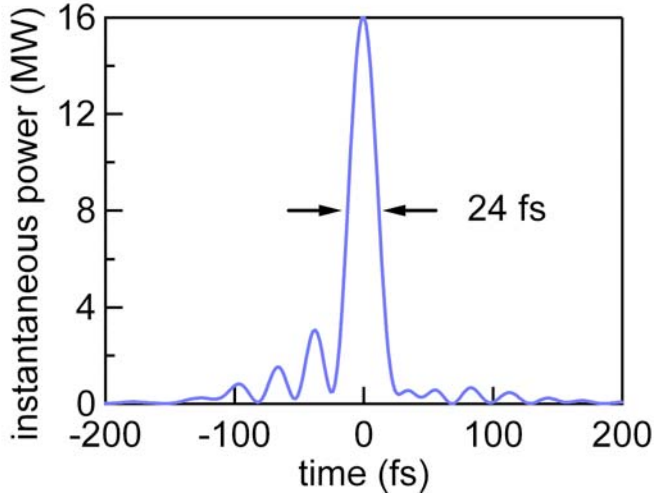
No laser material

Fiber compression system





ORC Southampton



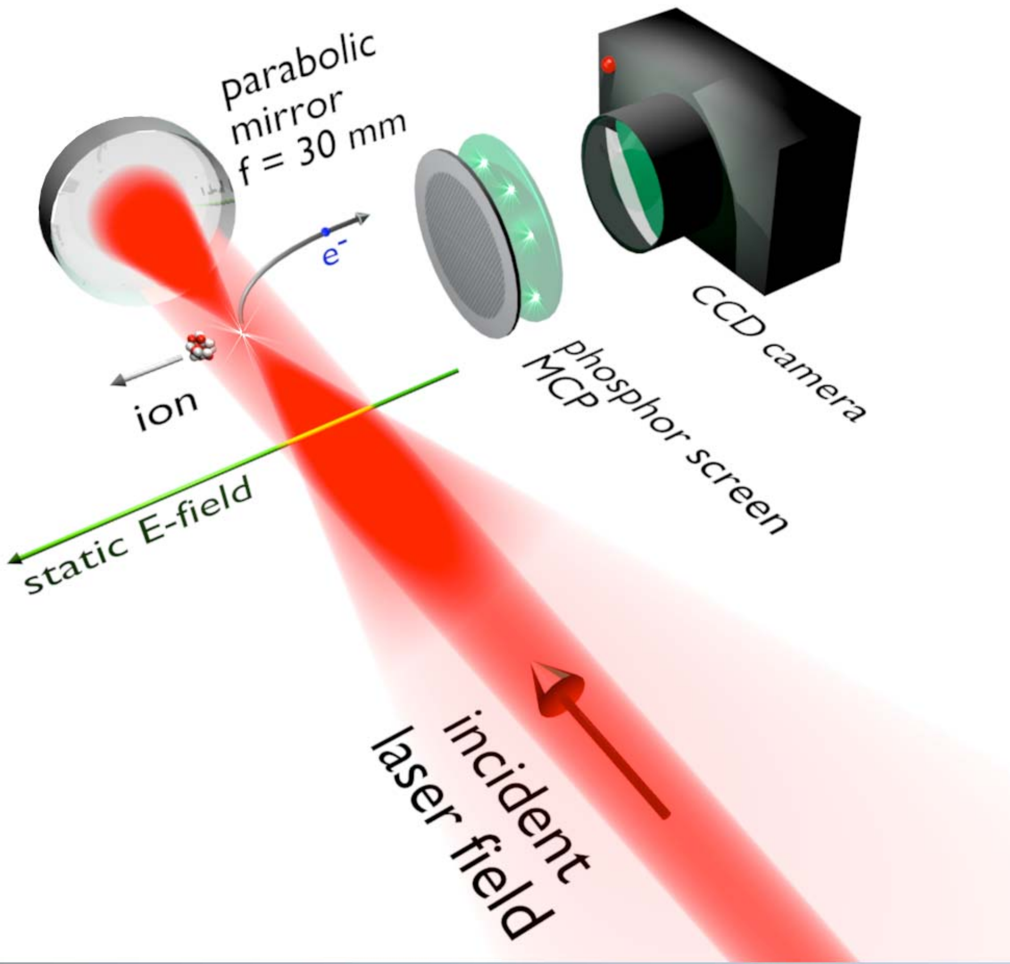
Incident on fiber		**After compression**
P_{peak} = 1.2 MW	➡	P_{peak} = 16 MW
τ_p = 760 fs		τ_p = 24 fs
E_{p_inc} = 1 µJ		E_{p_inc} = 0.6 µJ

T. Südmeyer et al, Optics Lett. ***28****, 1951 (2003), E. Innerhofer, TuA3, ASSP 2004*

Photoelectron imaging spectroscopy

→ measure energy and momentum distribution of photoelectrons

→ identify ionization processes and dynamics



Measurement principle

- small focus ($w \approx 2$ μm) acts as **point-like source of photoelectrons**
- *E*-field accelerates e^- towards MCP
- phosphorescence recorded with high-speed CCD camera

High quality images

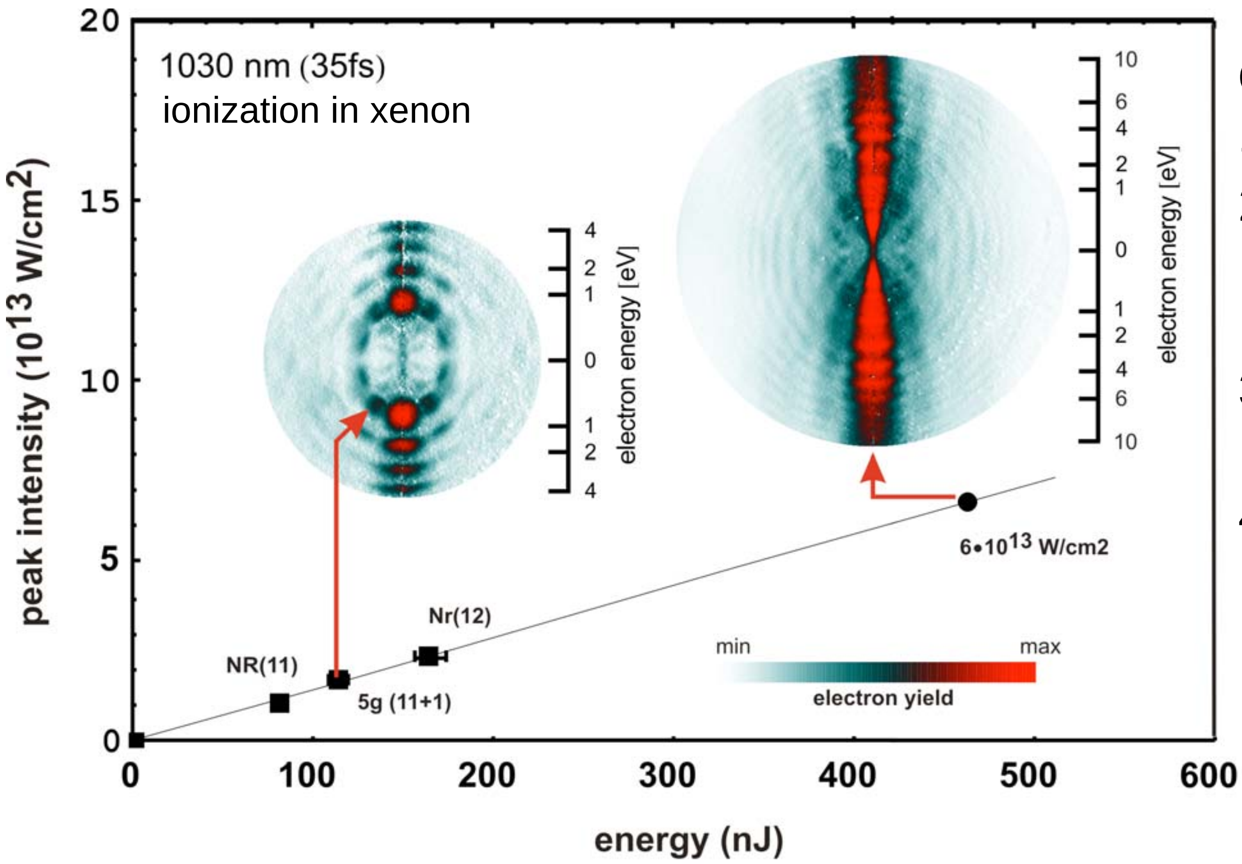
- point-like source
  → use small laser focus
- no interaction between e^-
  → limits density of generated e^-

⇨ **limited signal per pulse**

Megahertz repetition rate

- higher signal-to-noise ratio
- shortens measurement time

High field physics with 0.6 µJ, 35 fs, 7.5 MW peak



Calibration I_{peak} (E_p) #

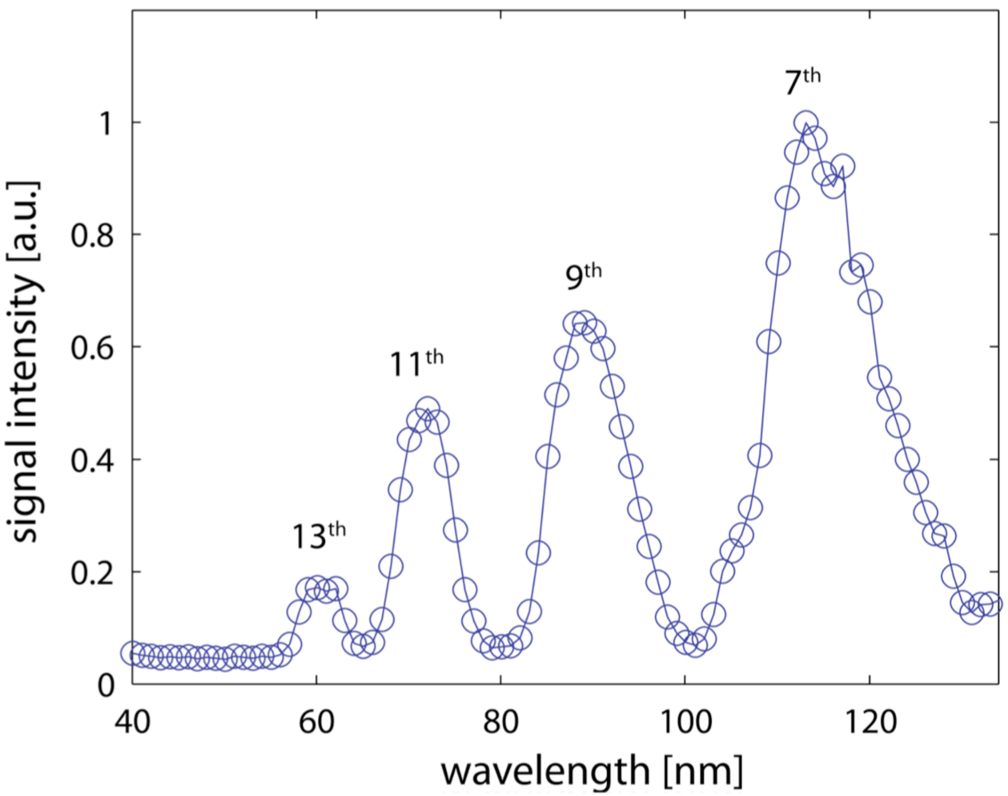
1. Zero-energy level
2. Appearance resonance enhanced (11+1) ioniz. via 5g-Rydberg state
3. Channel-closing non-resonant 11-phot. ioniz.
4. Channel-closing non-resonant 12-phot. ioniz.

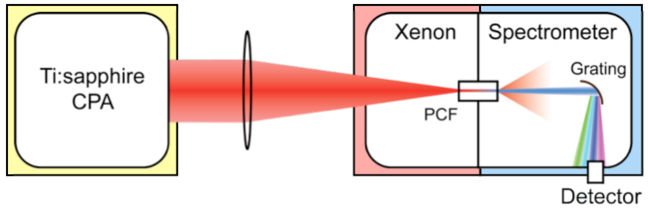
⇨up to $6 \cdot 10^{13}$ W/cm²

- Series of photoelectron momentum images as function of laser intensity
- Pulse duration: 79 fs (4 cm fiber) and 35 fs (16 cm) , target gas: xenon, argon
- Data currently being evaluated and compared with theoretical models

R. Wiehle, and B. Witzel, *Phys. Rev. Lett.* **89**, 223002 (2002), V. Schyja, et al., Phys. Rev. A 57, 3692 (1998)
T. Südmeyer et al, *Nature Photonics* **2**, 599-604, 2008

Measured Harmonic Spectrum





Laser parameters

f_{rep} = 1 kHz

E_p = 10.5 µJ (incident)

λ_c = 795 nm

HC-PCF

d_{eff} = 15 µm

L ≈ 15 mm

η ≈ 35 %

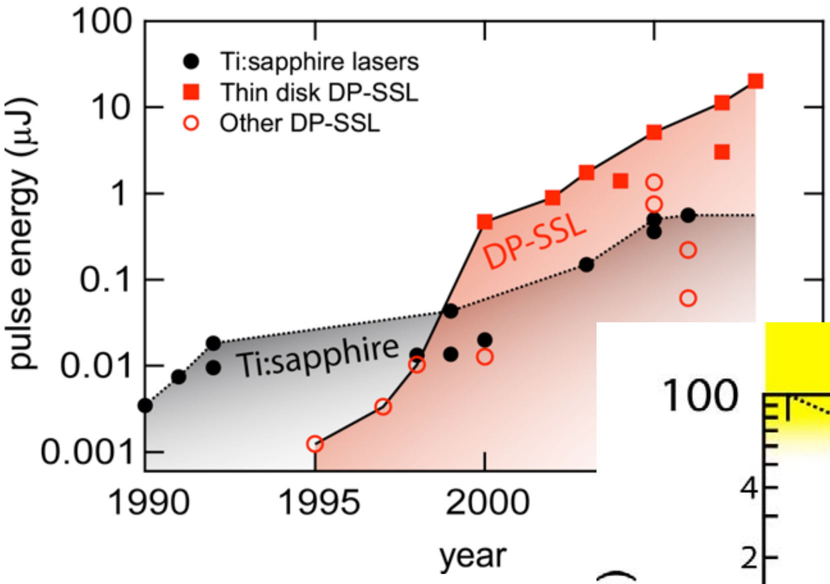
Xenon

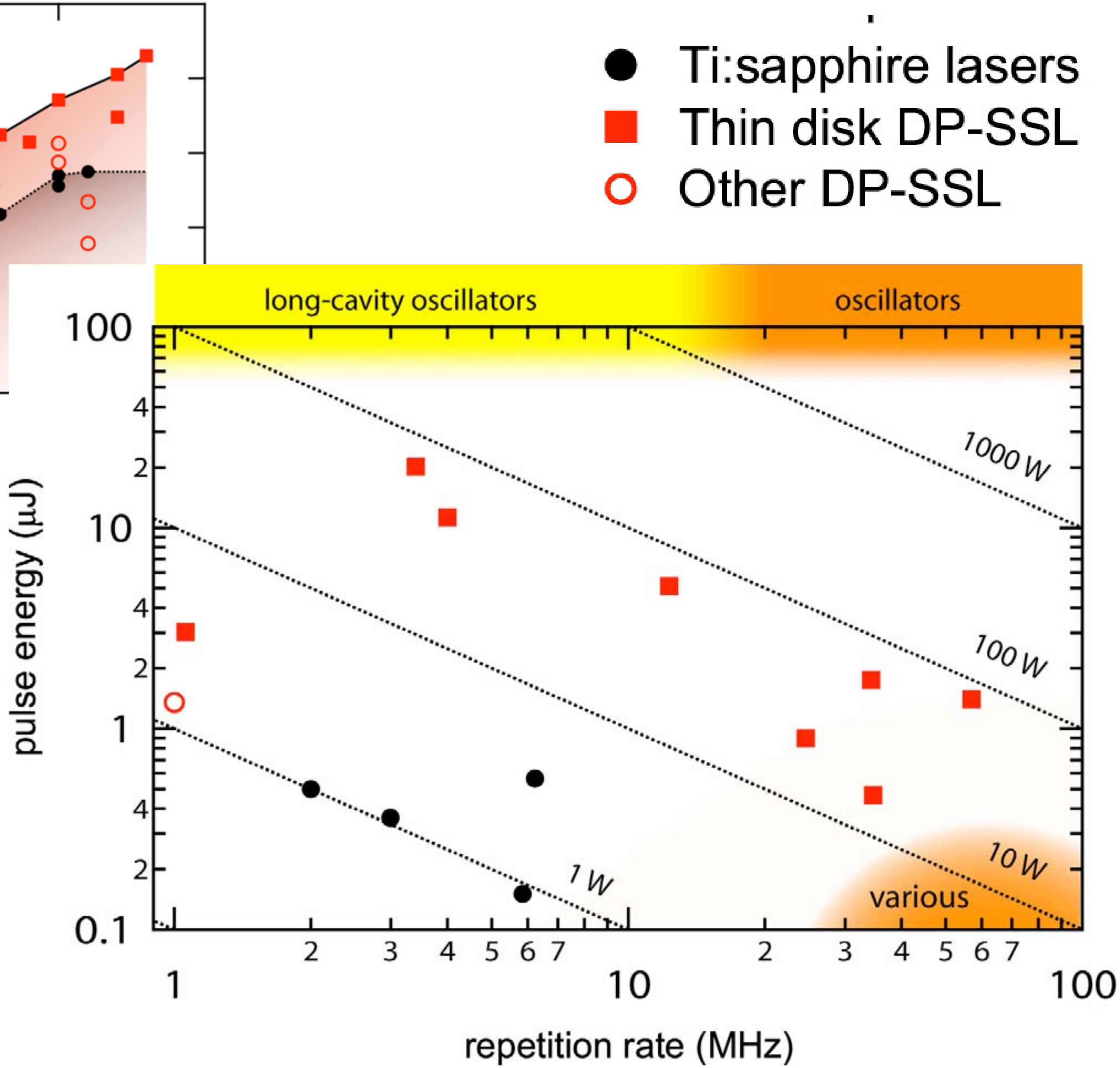
P = 27.5 mbar

Clear signal of 7th to 13th harmonic of 800 nm

C. R. E. Baer, O. H. Heckl, et al, Postdeadline Paper, ASSP 2009

High average power lasers - moving towards 100 µJ





100 µJ

5 MHz

500 W average power

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

Keller group

Ultrafast solid-state lasers: High average power (ML thin-disk laser)
Sergio Marchese, Cyrill Bär, Anna Enquist, Oliver Heckl, Dr. Thomas Südmeyer

Ultrafast solid-state lasers: High pulse repetition rate
Max Stumpf, Andreas Oehler, Selina Pekarek, Dr. Thomas Südmeyer

Ultrafast surface-emitting semiconductor lasers (ultrafast VECSELs and MIXSELs)
Deran Maas, Aude-Reine Bellancourt, Benjamin Rudin, Andreas Rutz, Martin Hoffmann, Dr. Yohan Barbarin, Dr. Thomas Südmeyer

MBE and MOVPE growth in ETH clean room facility (FIRST-lab)
Dr. Matthias Golling
ETH FIRST Lab staff: Dr. Silke Schön (MBE), Dr. Emilio Gini (MOVPE)

High field laser physics, attosecond pulse generation and science
Dr. Lukas Gallmann, Dr. Amelle Zair (left), Dr. Claudio Cirelli, Dr. Thomas Remetter
Christian Erny, Petrissa Eckle, Mirko Holler, Florian Schlapper, Matthias Weger, Adrian Pfeiffer, Clemens Heese