



**2443-6**

## **Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry**

***4 - 15 February 2013***

### **Femtosecond lasers/amplifiers**

U. Morgner  
*University of Hannover  
Germany*

## Femtosecond lasers and amplifiers

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<sup>2</sup> VENTEON Femtosecond Laser Technology GmbH

<sup>3</sup> Laser Zentrum Hannover (LZH)

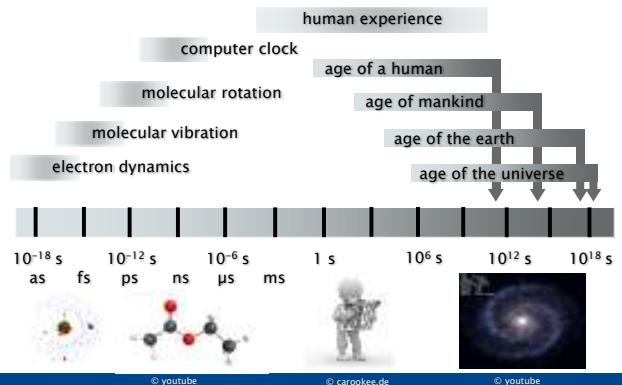
<sup>4</sup> Centre for Quantum Engineering and Space-Time Research (QUEST), Hannover, Germany



Trieste 2013

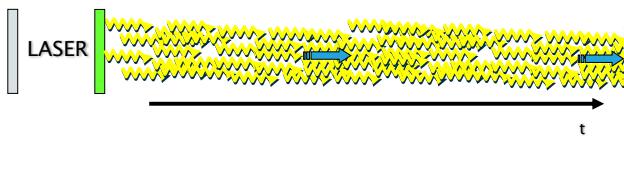
## Time constants

**IQ**



## Pulsed laser

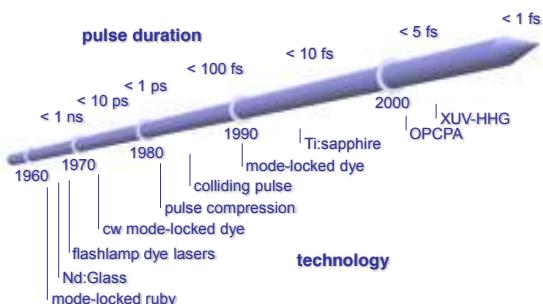
**IQ**



Trieste, Feb 2013

## History of short pulse lasers

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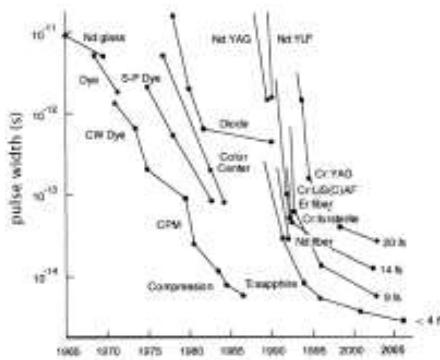


Trieste, Feb 2013

source: P. Dietrich

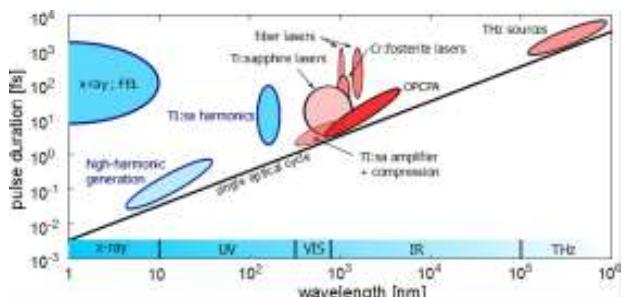
## Ultrafast oscillators

**IQ**



## Single-cycle pulse generation

**IQ**



## Outline

IQ

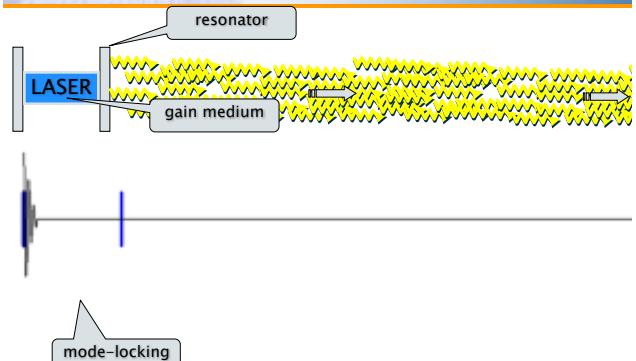
- ▶ The femtosecond laser oscillator
  - ▶ gain medium
  - ▶ dispersion compensation
  - ▶ mode-locking
- ▶ Power oscillators
- ▶ Laser amplifiers down to single-cycle generation
  - ▶ hollow capillary
  - ▶ filamentation

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## outline

IQ



## Section I

IQ

# the gain medium

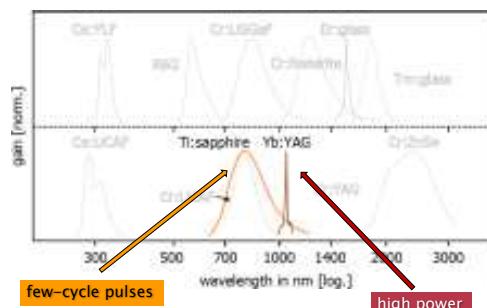
## 15 years ago: say bye to dye!

IQ



## Solid state gain materials

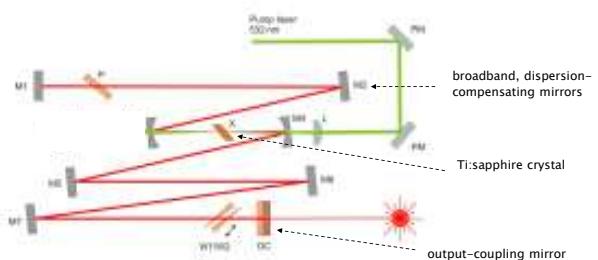
IQ



T. Metzger, Laser Journal 2005

## Octave-spanning Ti:sapphire Oscillator

IQ

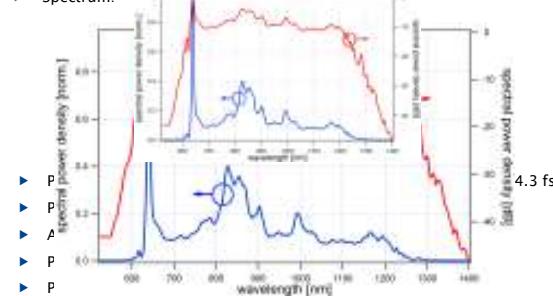


## Octave-spanning Ti:sapphire Oscillator

**IQ**

### Technical Data

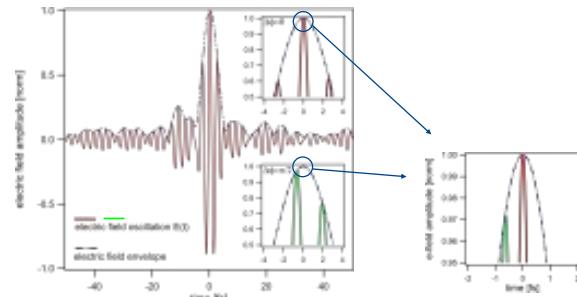
- Spectrum:



## Shortest pulses from an oscillator: 4.3 fs

**IQ**

### Electric Field Characteristics of Few-cycle Pulses



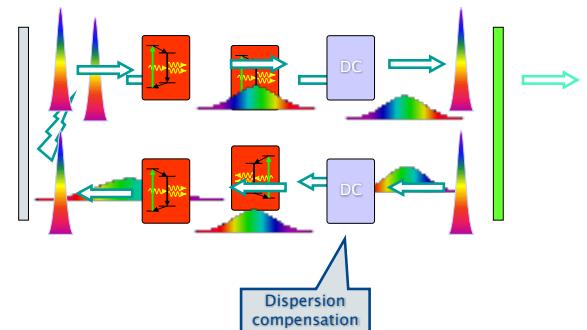
## Section V

**IQ**

# dispersion compensation

## Dispersion compensation

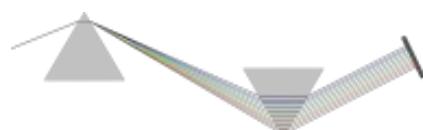
**IQ**



## Dispersion management – prism pair

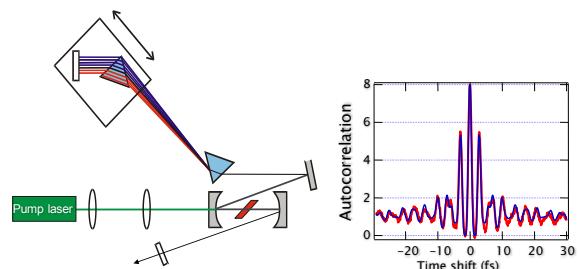
**IQ**

**Prism-sequence:**  
no independent control of different orders of dispersion

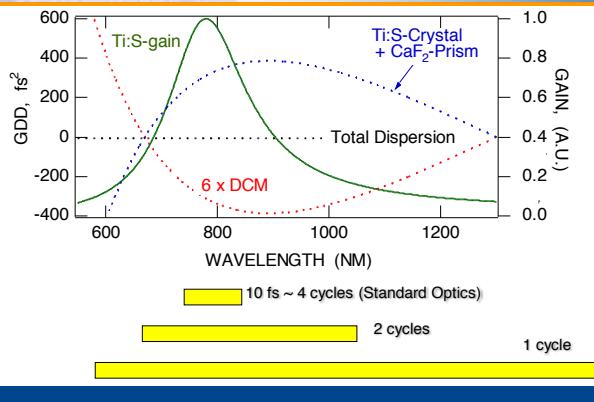


## Ti:sapphire laser oscillator with prisms

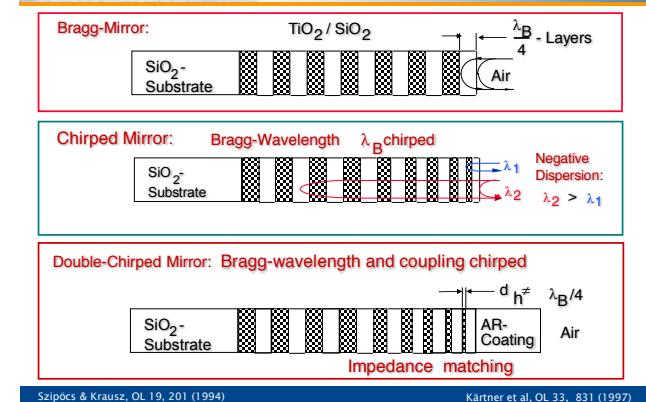
**IQ**



## Limitations to Few Cycle Pulse Generation IQ



## Dispersion compensation with double-chirped mirrors IQ



Szipoc̄s & Krausz, OL 19, 201 (1994)

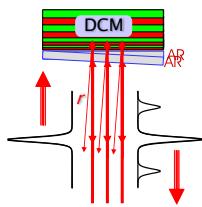
Kärtner et al., OL 33, 831 (1997)

## Improved ultra-broadband mirrors IQ



→ Backside coated DCMs

Matuschek, et al., APB 71, 509 (2000)



→ Wedged surface

Tempea, et al., JOSA B 18, 1747 (2001)

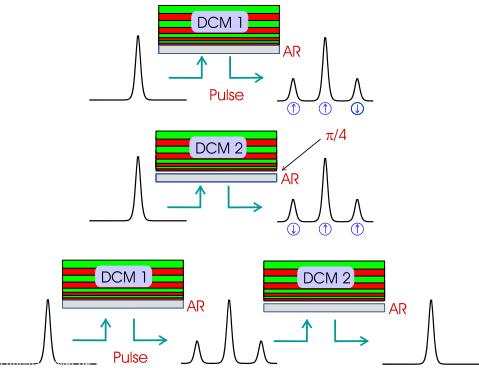
→ Brewster DCM

Steinmeyer, OE (2003)

→ DCM Pairs

Kärtner, et al., JOSA B 18, 882 (2001)

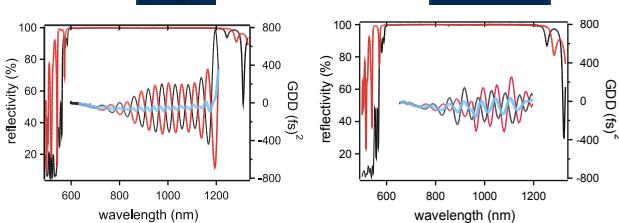
## Decreased spurious reflectivity with a mirror pair IQ



## Double-chirped mirror pairs IQ

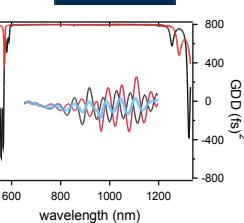


### Design



Kärtner et al., JOSA B 18 (2001)

### Measurement



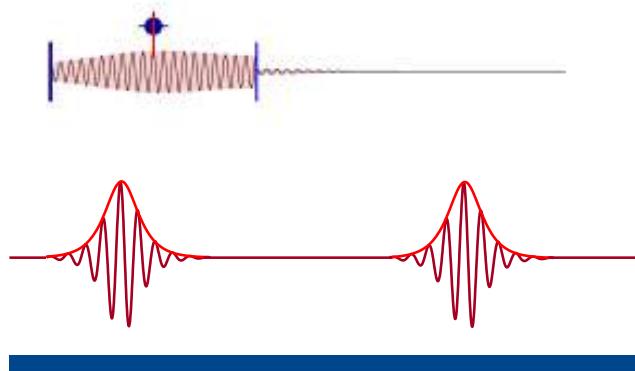
Pervak et al., APB 87 (2007)

## Section V IQ

# mode-locking

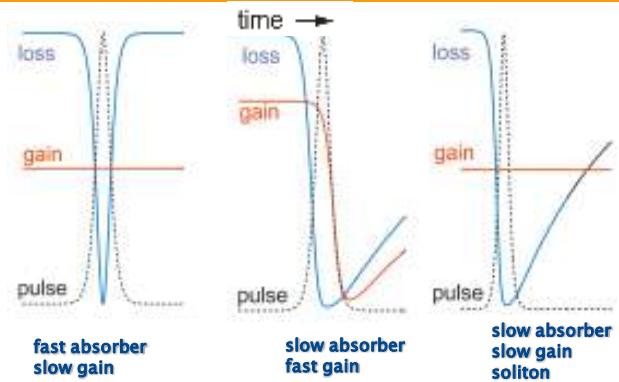
## Modulation intra-cavity

IQ



## Fast vs. slow saturable absorber

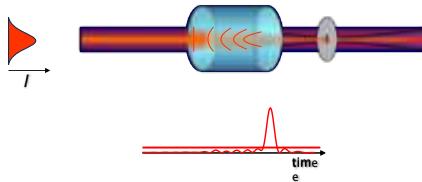
IQ



## Mode-locking via Kerr-lens = fast absorber

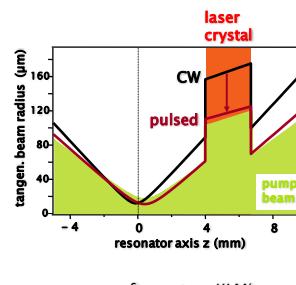
IQ

$$\text{Kerr effect: } n = n_0 + n_2 \cdot I$$



## Kerr-lens mode-locking = fast absorber

IQ



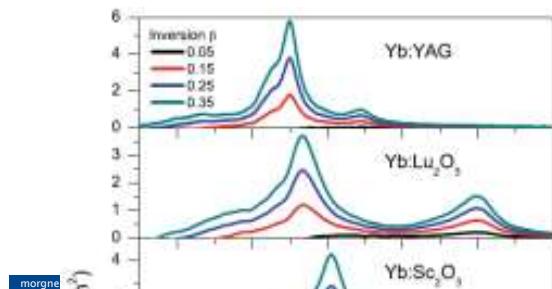
## Outline

IQ

- ▶ The few-cycle laser oscillator
  - ▶ gain medium
  - ▶ dispersion compensation
  - ▶ mode-locking
- ▶ Power oscillators
- ▶ Laser amplifiers for single-cycle generation
  - ▶ hollow capillary
  - ▶ filamentation

## Some Yb doped hosts

IQ

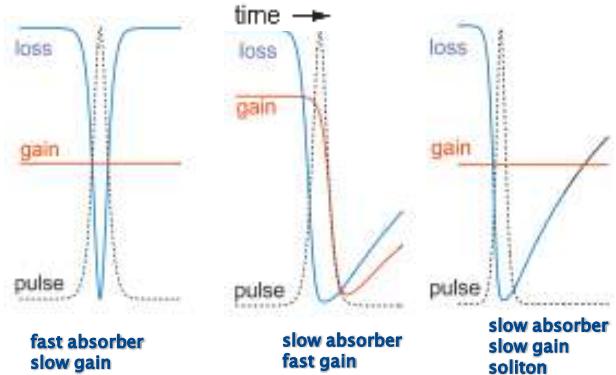


## High power / high brightness pump diodes IQ

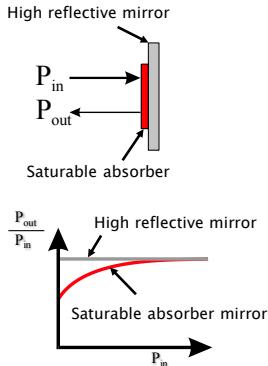


Wikipedia

## Fast vs. slow saturable absorber IQ

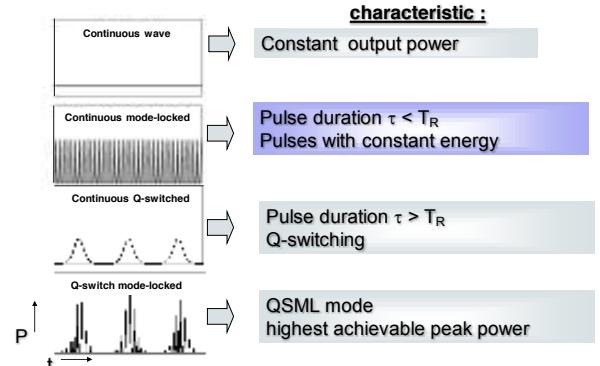


## SESAM = slow absorber IQ



Skript F.X. Kartner, MIT OCW

## Operating modes of a lasers IQ



## Solitary passive mode-locking IQ

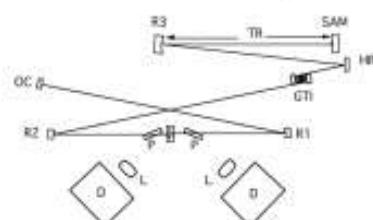
Saturable absorber mirror (SESAM / SBR)	chirped mirrors	Gain medium
$F_{\text{sat},A}, A_A, \Delta R$	$D$	$\sigma_L, A_L, d$
stability criterion:	soliton condition:	
$E_p^2 > E_{\text{sat},A} \cdot E_{\text{sat},L} \cdot \Delta R$		
$E_{\text{sat},L} = \frac{\hbar\omega}{2\sigma_L} \cdot A_L$	$3.53 \frac{D}{\tau} = k_0 n_2 d \frac{E_p}{A_L}$	
$E_{\text{sat},A} = F_{\text{sat},A} \cdot A_A$		

Hönninger et al., JOSA B16 (99)

## Ultrafast bulk oscillators IQ

### Mode-locked operation of a bulk Yb:KGW oscillator

- 10 W at 1039 nm with a 290 fs pulse width
- rep. rate of 45 MHz  $\rightarrow$  pulse energy > 200 nJ

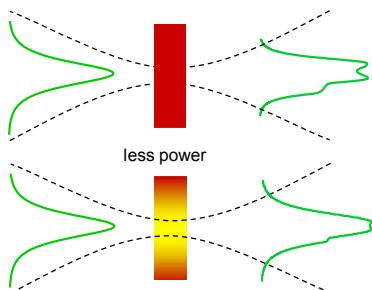


G. R. Holton, OL 31, 2719 (2006)

## Thermal lens

IQ

Problem: high pump power → high temperature gradient inside the crystal



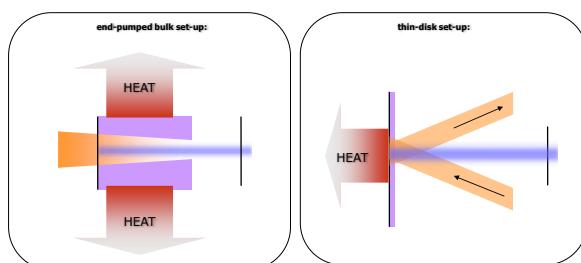
## Section III

IQ

# the thin-disk oscillator

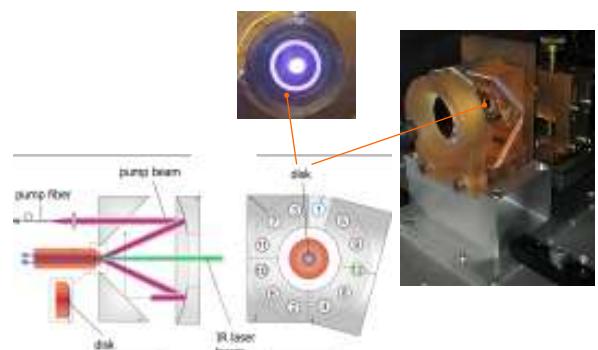
## Bulk vs. thin-disk

IQ



## Thin-disk

IQ



[www.ifsw.uni-stuttgart.de](http://www.ifsw.uni-stuttgart.de)

## History

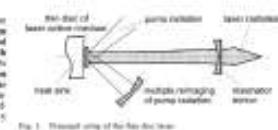
IQ

2000

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 6, NO. 4, JULY/AUGUST 2000

### A 1-kW CW Thin Disc Laser

Christian Sturm, Karsten Coene, Michael Lippert, Adolf Gaume, and Helmut Riegel

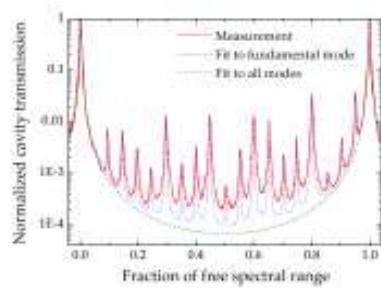


Abstract—The thin-disk laser is presented as an optimization design for the operation of a quasi-three-level laser active medium in the cw regime. The results of numerical calculations of the laser output power show that operation with an output power up to 1.379 with an optical efficiency of 49% and more is possible at room temperature utilizing 15 absorption passes. The maximum output power is limited by the maximum pump area using one or two lasers. The experiments on single lasers yield a maximum output power of 0.79 W at 51% optical efficiency for one crystal and of 0.79 W with 49% optical efficiency for four crystals at a temperature of the cooling water of 20 °C.

Index Terms—CM lasers, diode-pumped solid-state lasers, high-power lasers, lasers, thin-disk lasers.

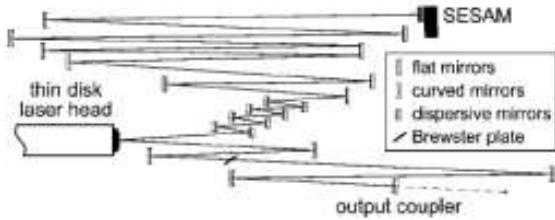
## Why $M^2=1$ so important ?

IQ



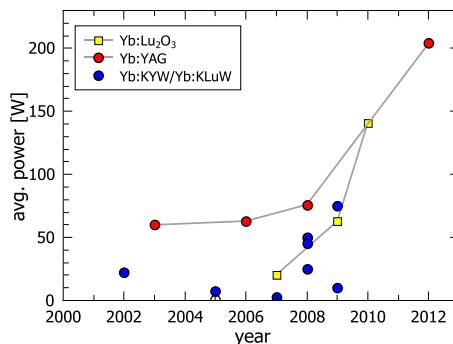
$$\nu_{pep} = \left( p + (m+n+1) \frac{\arccos(\sqrt{g_1 g_2})}{\pi} \right) \frac{c}{2L}$$

Mode-locked thin disk oscillator



Marchese et al., OL 31, (06)

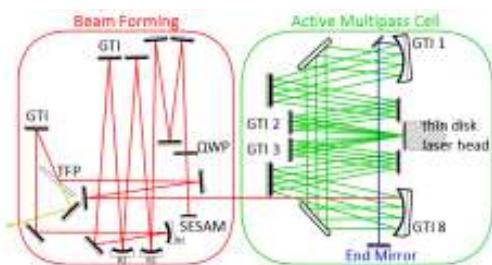
## Thin disk ultrafast oscillators



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## The active multipass cell

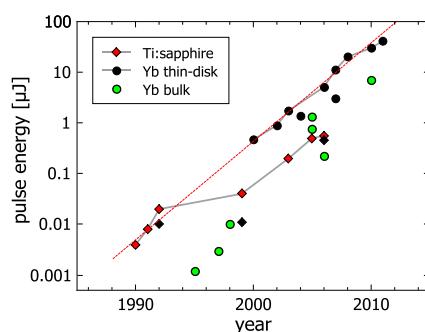


145 W output power,  
1 ps pulse duration

**41  $\mu$ J @ 3.5 MHz:** highest pulse energy from thin-disk oscillator

Bauer et al, OE 2012

## Oscillator hero results



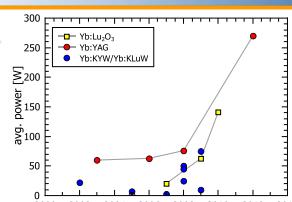
Südmeyer et al, Nat. Photon. 2, 2008

## Thin disk record values

10

## Yb:YAG vs. Yb doped sesquioxides

- better thermal conductivity
  - lower quantum defect
  - broader emission spectrum



Yb-YAG

Vibration

Td.Lu<sub>2</sub>O<sub>3</sub>  
141 W  
738 fs  
60 MHz

→ highest output power  
from a thin-disk oscillator

→ shortest pulse duration  
from a thin-disk oscillator

Südmeyer et al, ASSP 2011

Baer et al, OL 35, 2010

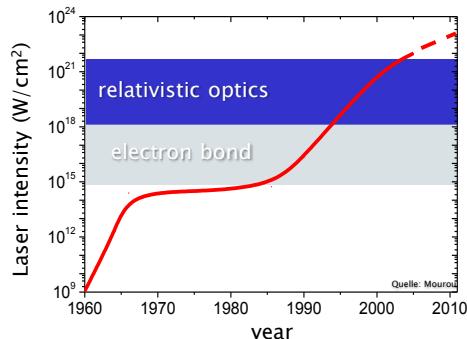
Baer et al, OE 17, 2009

**Intensity = power per unit area**

10

## Laser pulse intensities

IQ



## Outline

IQ

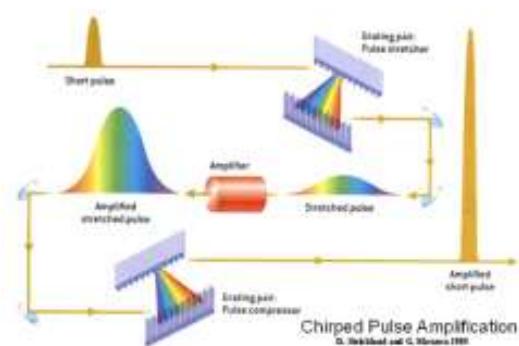
- ▶ The few-cycle laser oscillator
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  - ▶ hollow capillary
  - ▶ filamentation

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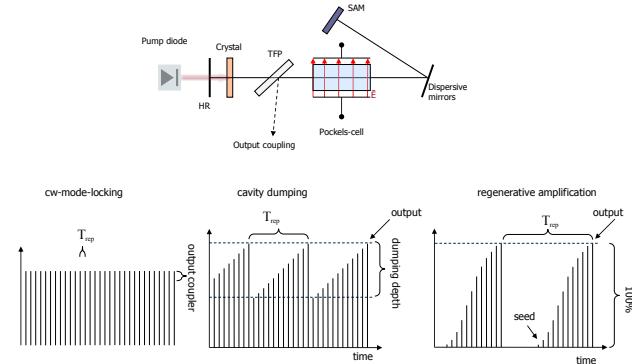
## Chirped Pulse Amplification

IQ



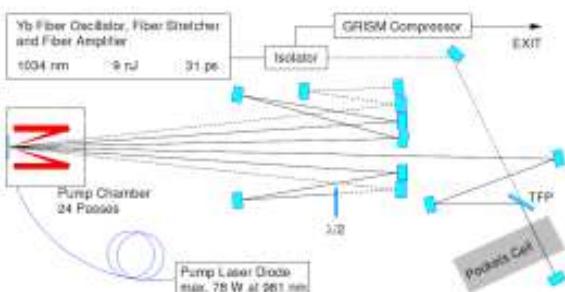
## Dynamic output coupling

IQ



## Regenerative Yb:KYW amplifier

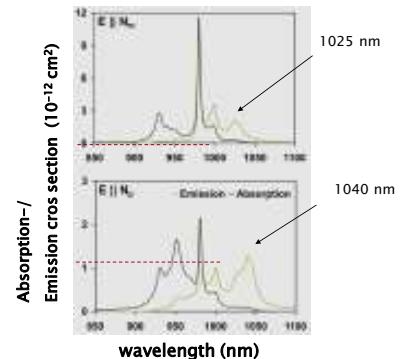
IQ



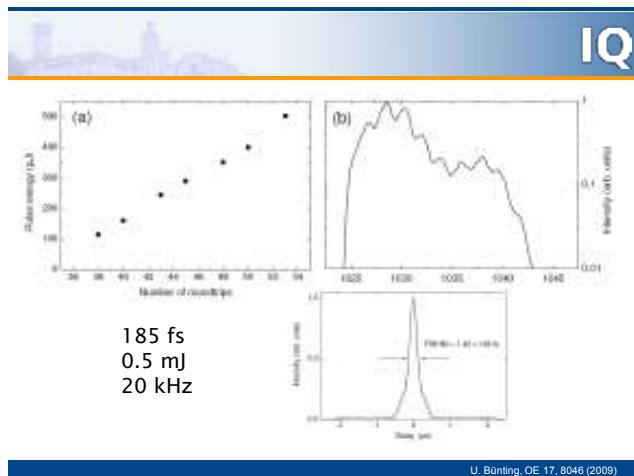
U. Bünting, OE 17, 8046 (2009)

## Combined gain spectra

IQ

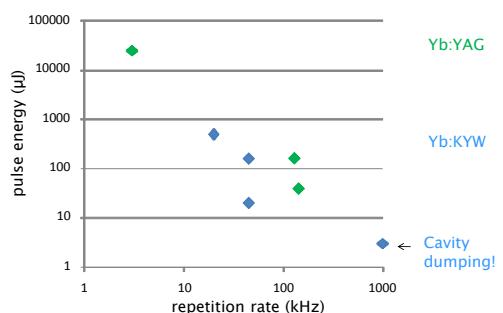


Pujol et al., PRB 65, (2002)



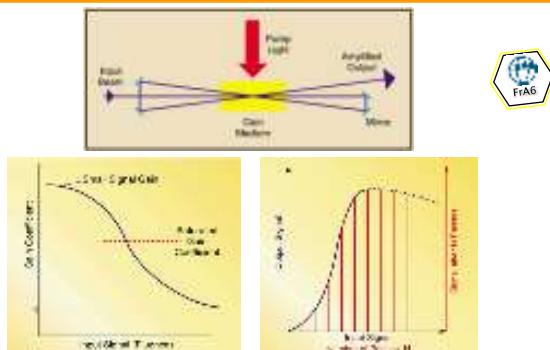
## Thin disk regenerative amplifiers

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## Multipass amplifier

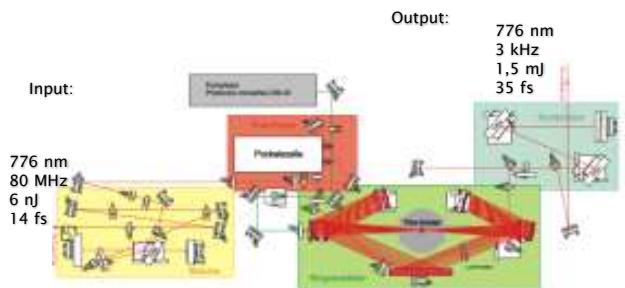
**IQ**



A. Krüger, spie's oe magazine (2002)

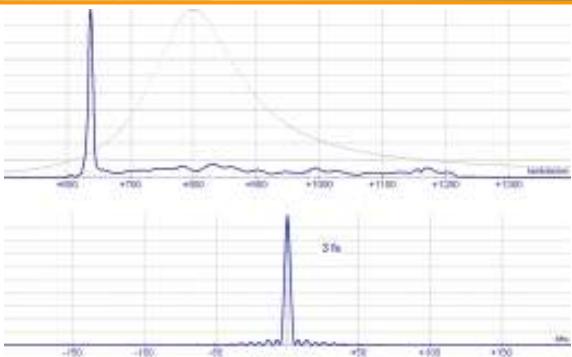
## Typical commercial CPA laser system

**IQ**



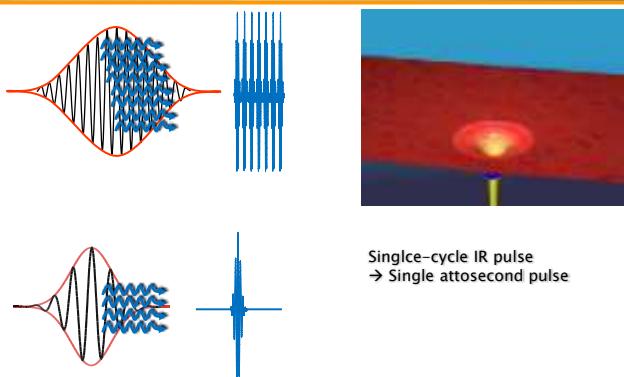
## Gain narrowing

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## → Attoscience

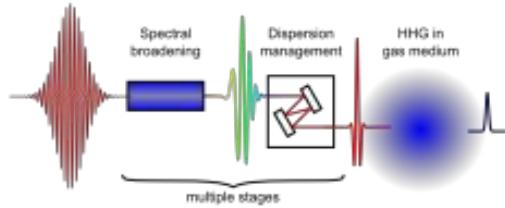
**IQ**



## Few-cycle pulse generation

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- Spectral broadening (hollow core fiber<sup>1</sup>, filamentation<sup>2</sup>)
- Recompression



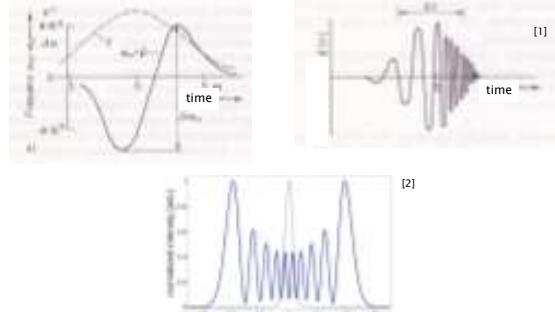
[1] M. Nisoli, et al., Opt. Lett. 22, 522 (1997)

[2] C. P. Hauri et al., Appl. Phys. B 79, 673 (2004)

## Nonlinear pulse propagation I

IQ

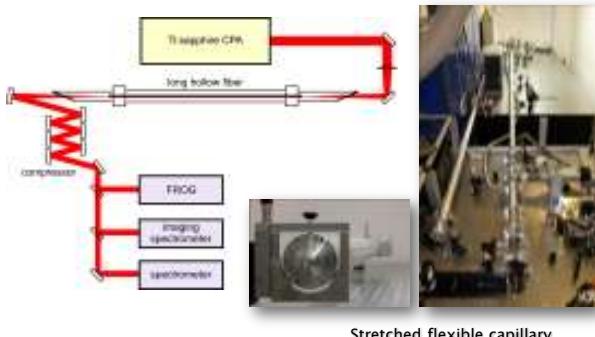
- Self-phase modulation



Bergmann Schaefer, „Optik“, Walter de Gruyter, (1993)

## Hollow fiber technique

IQ



Nisoli et al., APL 68, 2793 (1996), OL 22, 522 (1997)

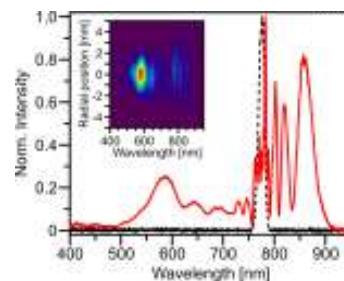
T. Nagy et al., Appl. Opt. 47, 3264 (2008)

## Results

IQ

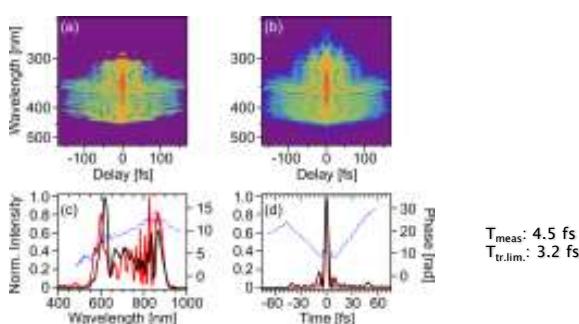
Stretched flexible hollow fiber  
ID: 320  $\mu\text{m}$   
length: 3 m

Gas: 500 mbar Ar  
Ein: 1.1 mJ, Tin: 71 fs  
Eout: 0.53 mJ



## FROG

IQ

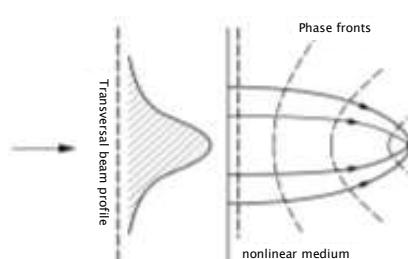


T. Nagy et al., Opt. Lett. 36, 4422 (2011)

## Nonlinear pulse propagation II

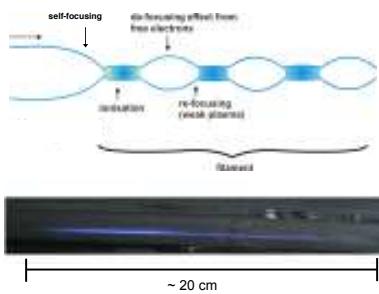
IQ

- Self-focusing



## Filamentation – Self-guiding model

IQ



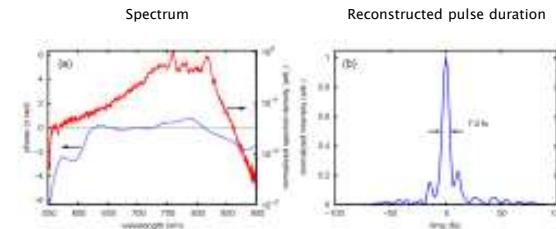
### Balancing effects:

- ▶ Kerr self-focusing
- ▶ Nonlinear absorption
- ▶ free electron plasma de-focusing

$$P_{kr} = \frac{\lambda^2}{2\pi n_0 n_2}$$

## Few-cycle pulses from filamentation

IQ



D. S. Steingrube et al., OE 17, 16177 (2009)

## Summary

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- ▶ For few-cycle pulses from the oscillator:
  - ▶ Take the Ti:sapphire oscillator
- ▶ For high energies (up to 40μJ) from the oscillators:
  - ▶ Take the Yb:YAG thin-disk oscillator
- ▶ For high average powers from the oscillator:
  - ▶ Take the Yb:YAG thin-disk oscillator
- ▶ For high energies:
  - ▶ Take multipass or regenerative post-amplification
- ▶ For high energy few-cycle pulses:
  - ▶ Take amplifier plus hollow fiber or filament

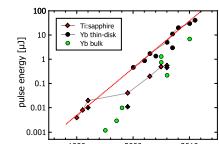
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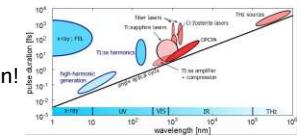
## Conclusion

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- ▶ Adapted Moore's law:  
*Every five years the pulse energy directly from the laser oscillator is increased by an order of magnitude*



- ▶ There's plenty of uncharted territory → the quest goes on!



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## Book chapter

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Feel free to download a recent book chapter  
„Ultrafast laser oscillators and amplifiers – a quick overview“  
with >100 topical references:

<http://uwe.morgner.info/bookchapter.pdf>

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