Towards XUV frequency combs using high power Yb-based thin-disk oscillators

Oleg Pronin

Helmut Schmidt University (University of Federal Armed Forces)

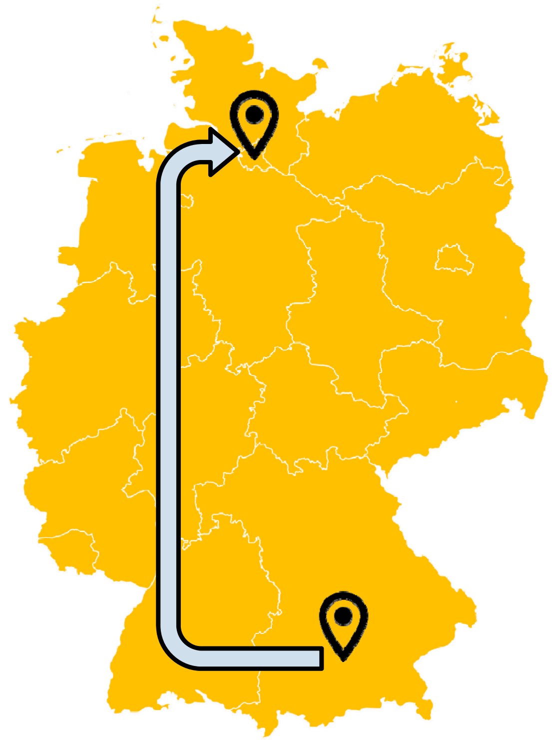
www. hsu-hh.de/lts

MEPhI 25.10.2019

LTS LASER TECHNOLOGY & SPECTROSCOPY

Preface. Munich→Hamburg

HELMUT SCHMIDT UNIVERSITÄT
Universität der Bundeswehr Hamburg



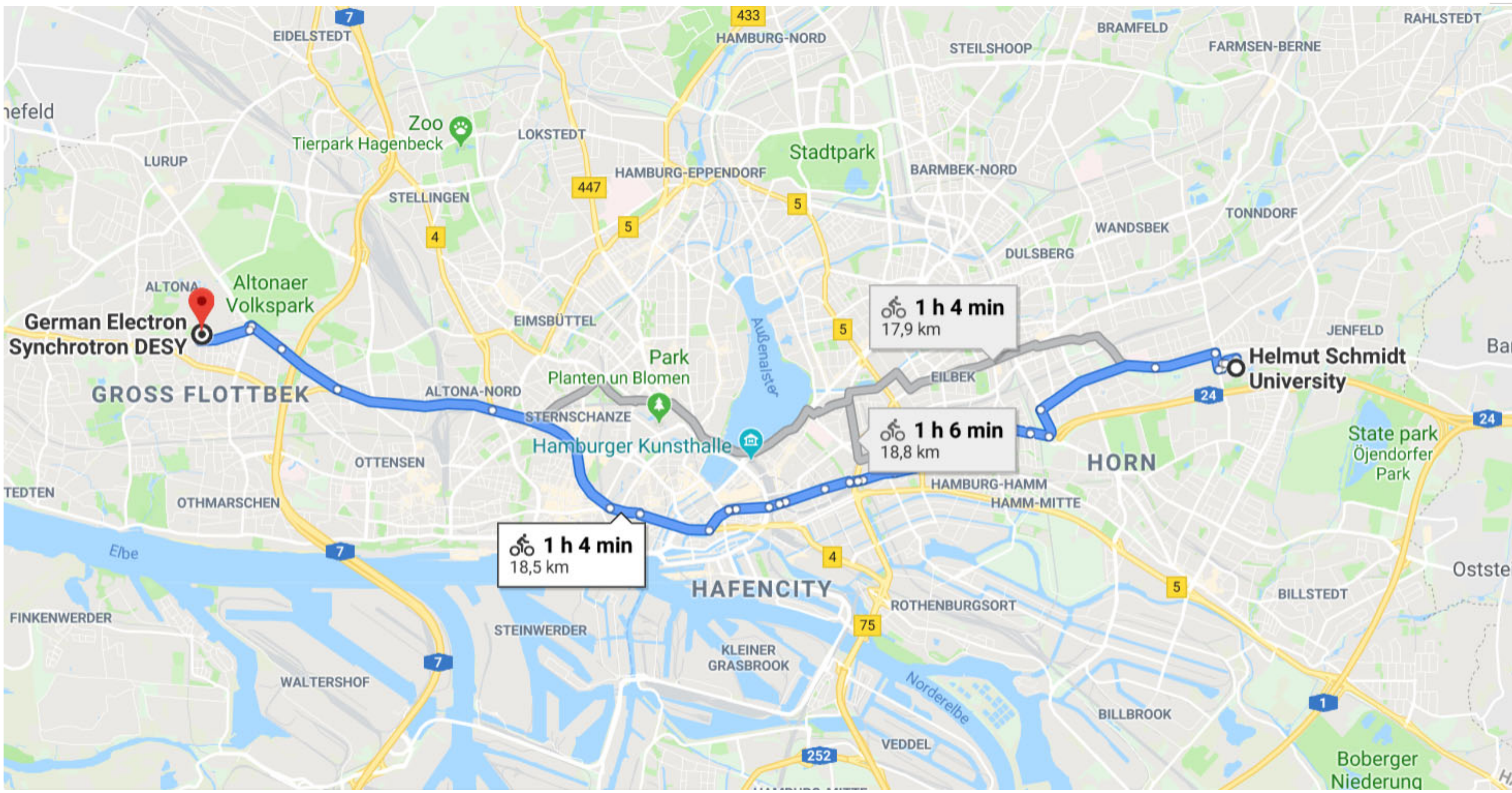
MPQ, Garching

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

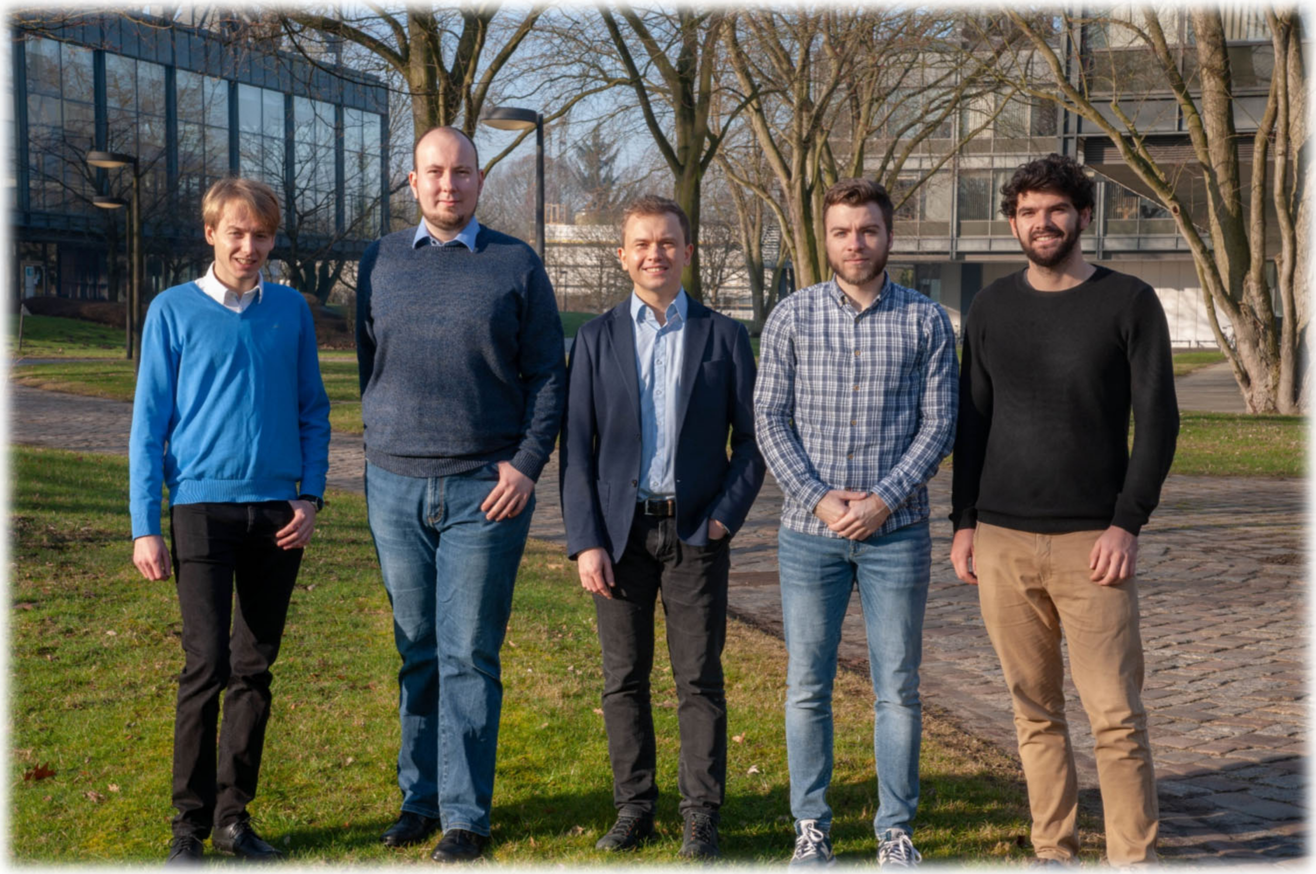
LTS
LASER TECHNOLOGY & SPECTROSCOPY

Preface: DESY <> HSU

HELMUT SCHMIDT UNIVERSITÄT
sität der Bundeswehr Hamburg



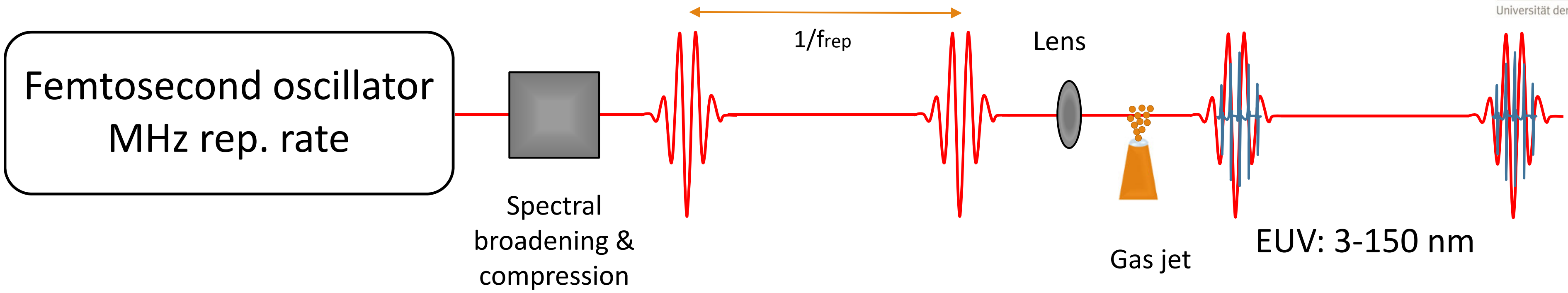
The team in Hamburg
www.hsu-hh.de/lts/



Outline

- Introduction (HHG, applications, different methods)
- Thin-disk Yb:YAG femtosecond oscillators (power, energy)
- CEO (CEP) stabilization of thin-disk femtosecond oscillators
- Spectral broadening and pulse compression

Extreme UV (EUV) Generation via HHG



High peak intensity $I=10^{14}\ W/cm^2$ → $\frac{energy}{area * pulse\ duration}$ →

- High pulse energy
- Short pulse duration
- High average power P
- CEP (CEO) stabilization

← High peak power >> 100 MW

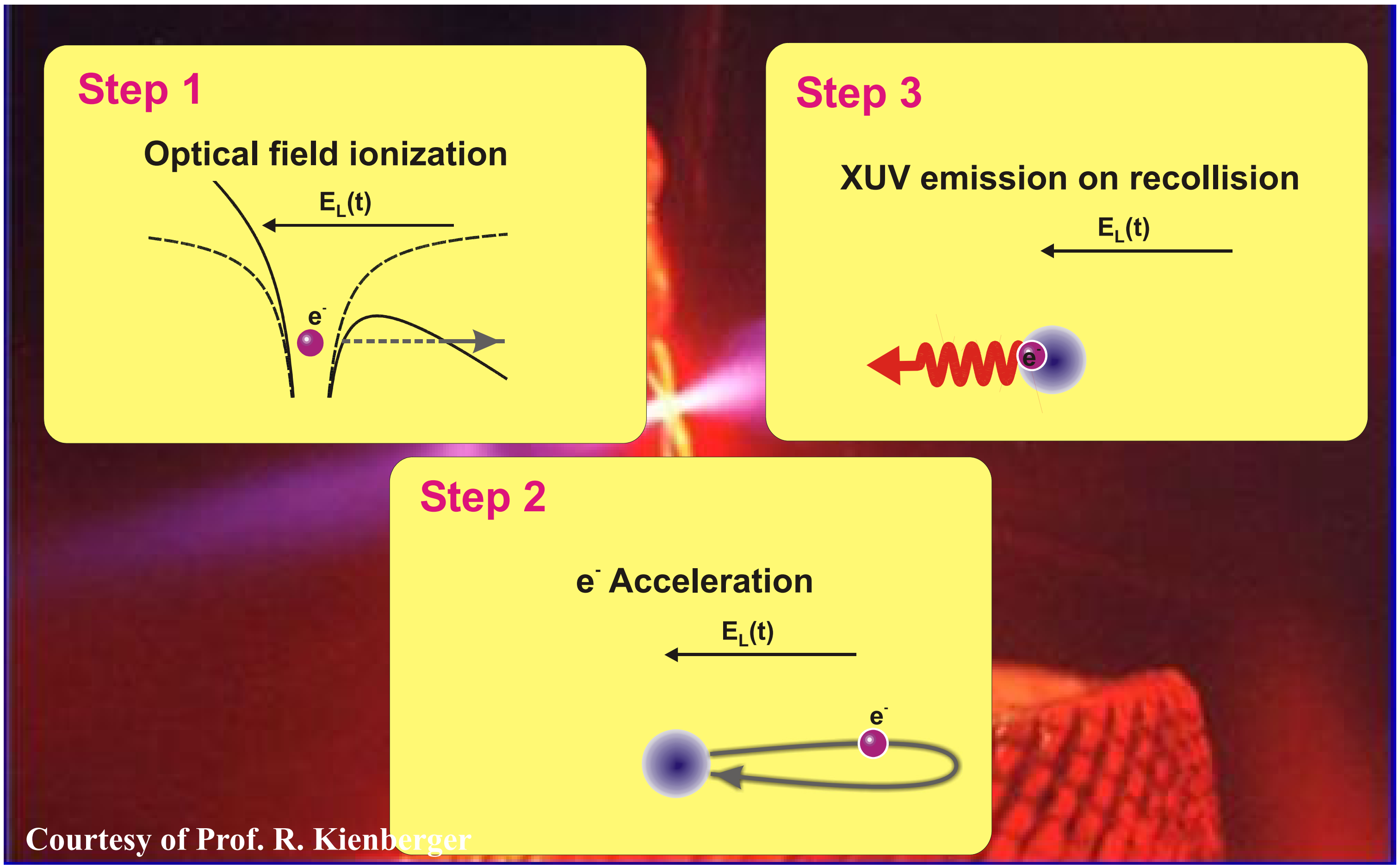
← Low EUV conversion efficiency **10^{-6}**

← For what kind of applications?

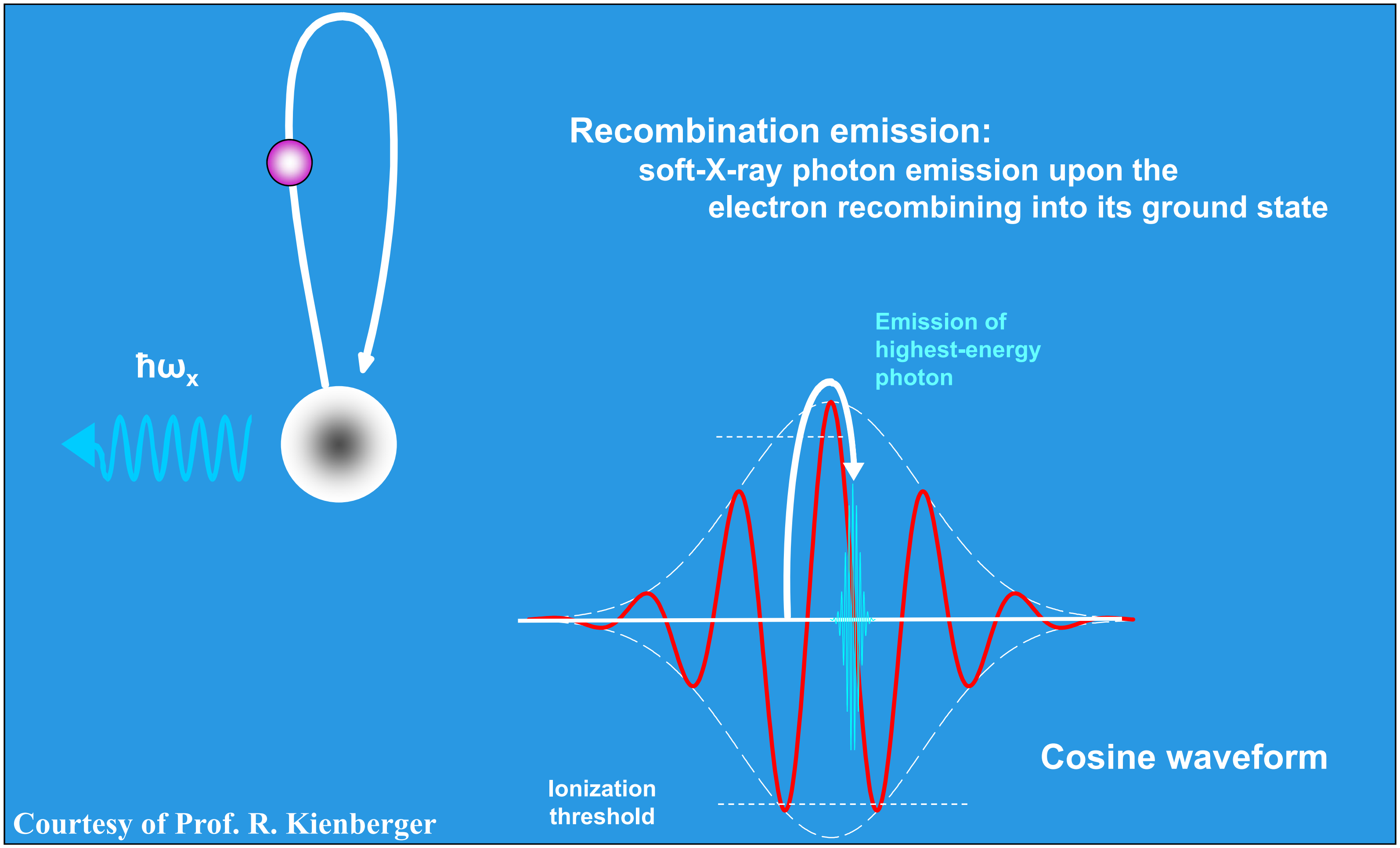
C. M. Heyl, et. al., Journal of Physics B: Atomic, Molecular and Optical Physics, vol. 50, p. 013001, 2017.

H. Steffen, et. al, Journal of Physics B: Atomic, Molecular and Optical Physics, vol. 49, p. 172002, 2016.

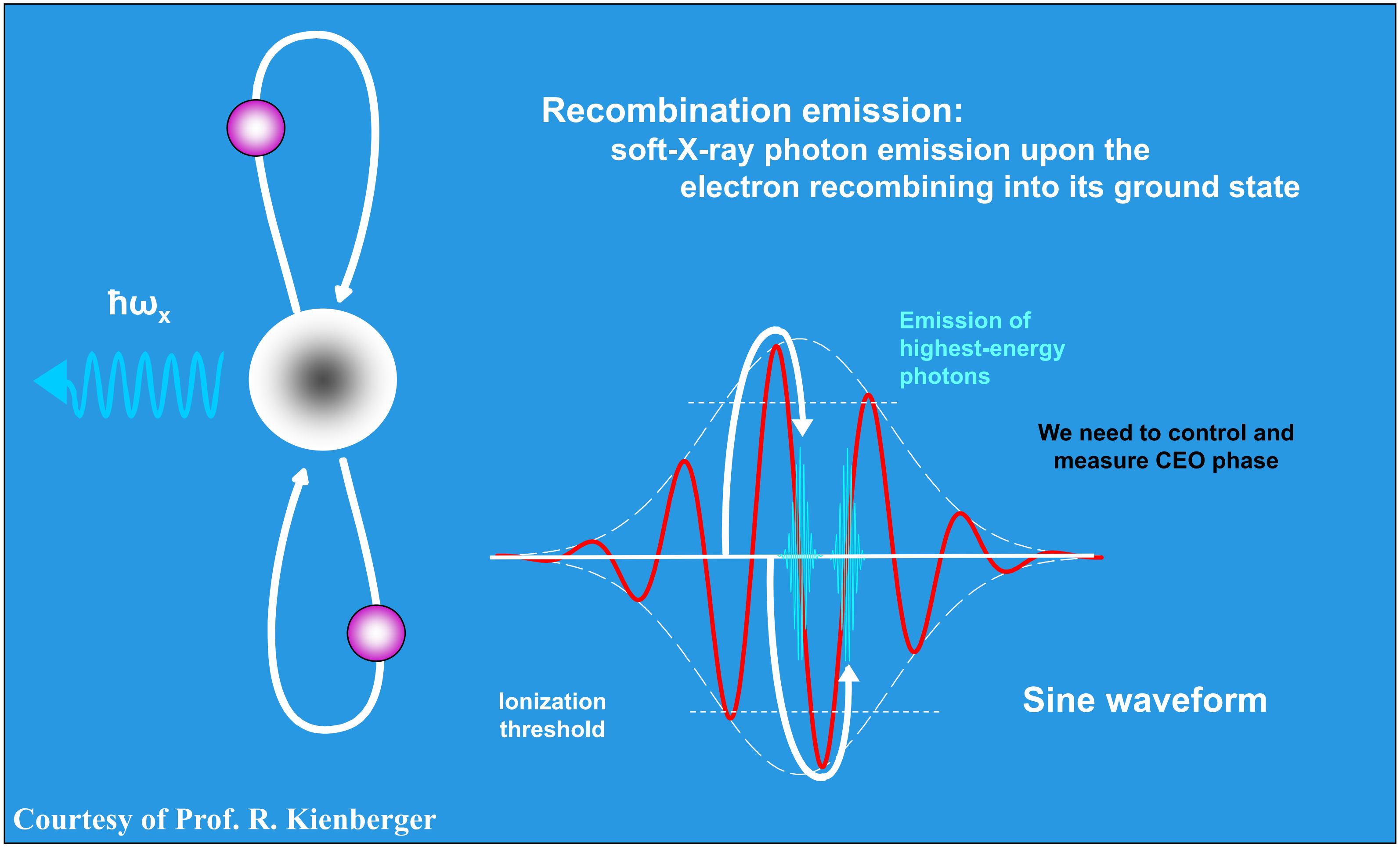
What is high harmonic generation?



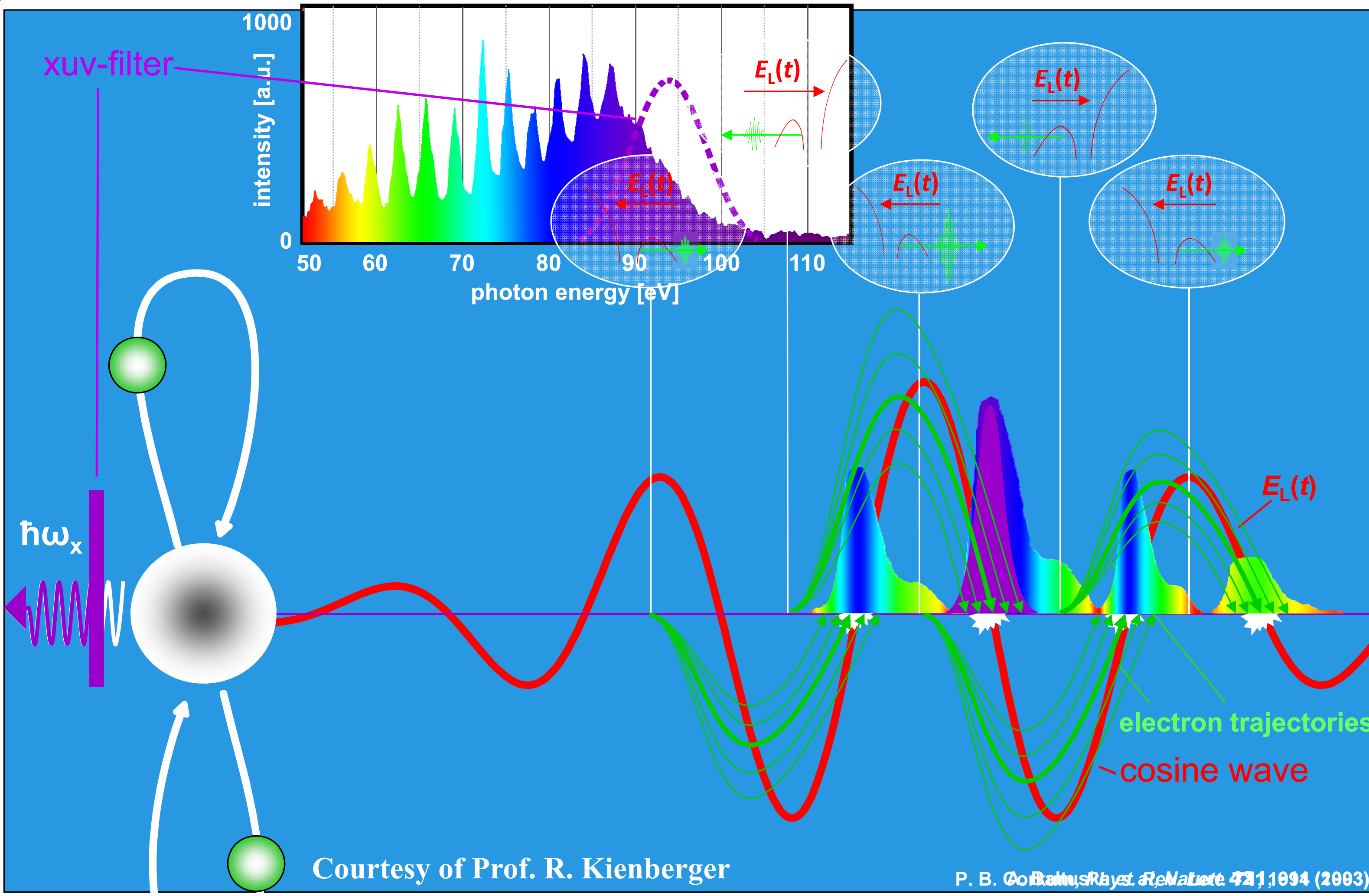
High harmonic generation. Cosine pulse



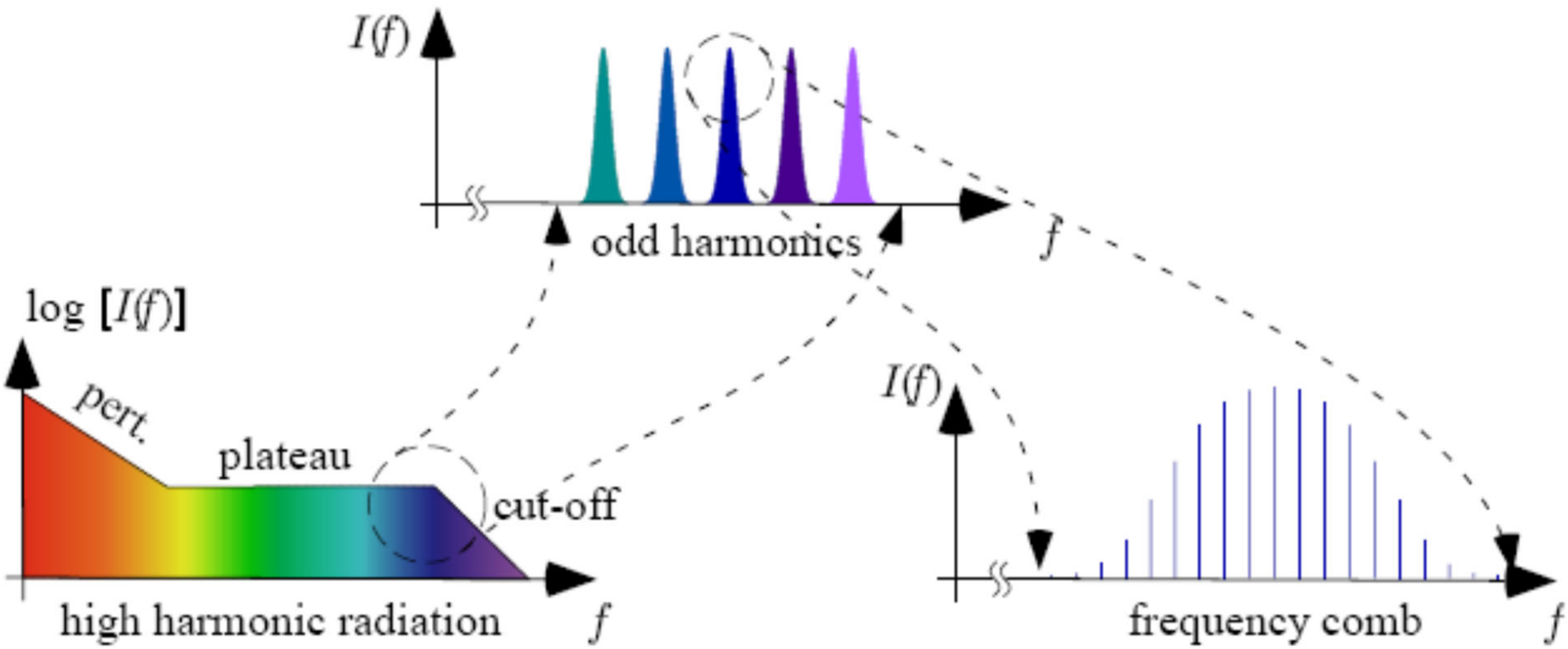
High harmonic generation. Sine pulse



Birth of attosecond pulse



XUV combs



*M. Hermann et. al., Phys. Rev. A **79** , 052505 (2009)*

XUV frequency combs

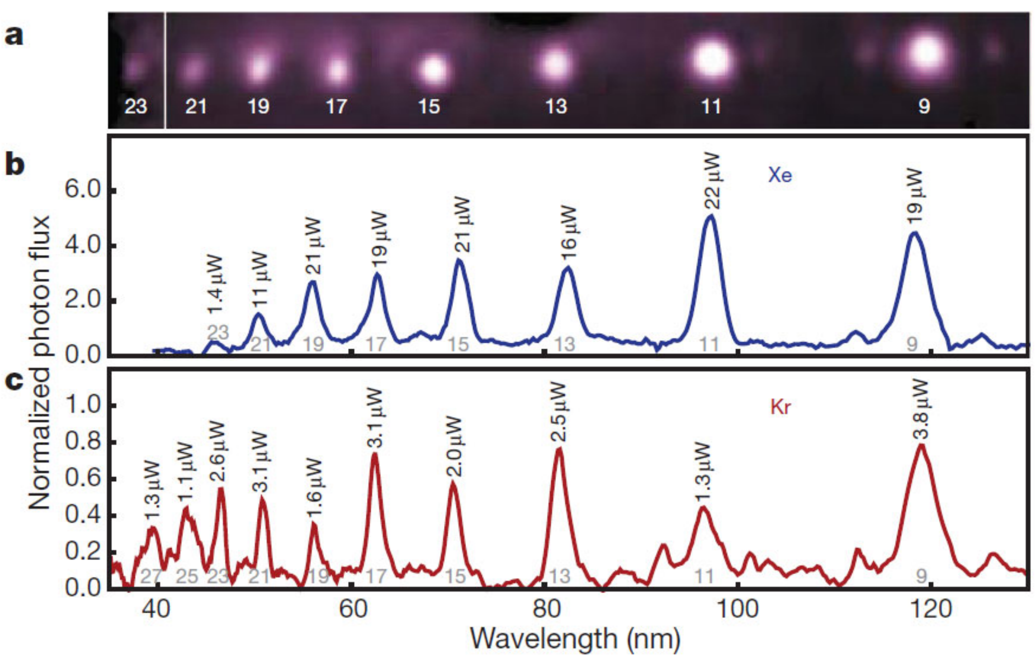
LETTER

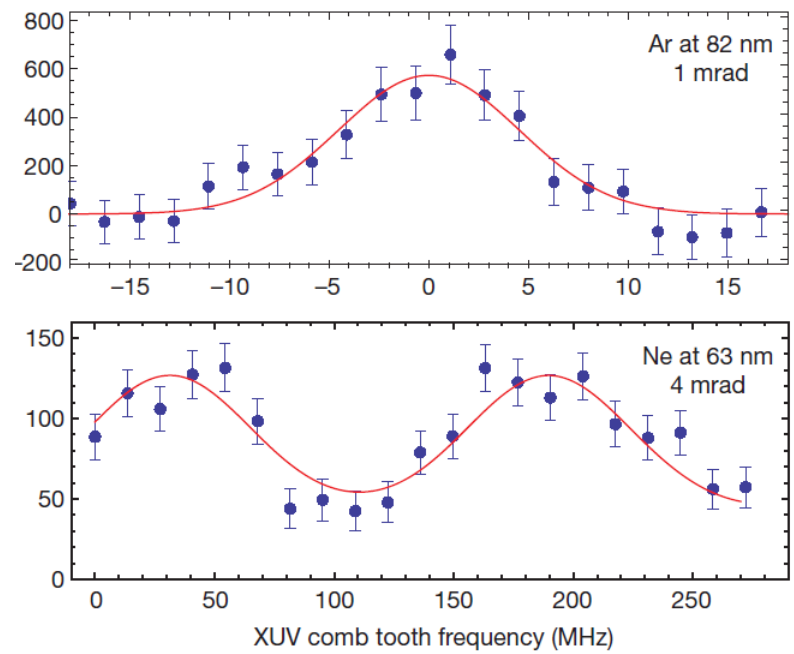
doi:10.1038/nature10711

Direct frequency comb spectroscopy in the extreme ultraviolet

Arman Cingöz[1]*, Dylan C. Yost[1]*, Thomas K. Allison[1], Axel Ruehl[2]†, Martin E. Fermann[2], Ingmar Hartl[2] & Jun Ye[1]

Only a single comb tooth with 10E-5 of the total power, 10 pW, contributes to the signal.





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XUV frequency combs

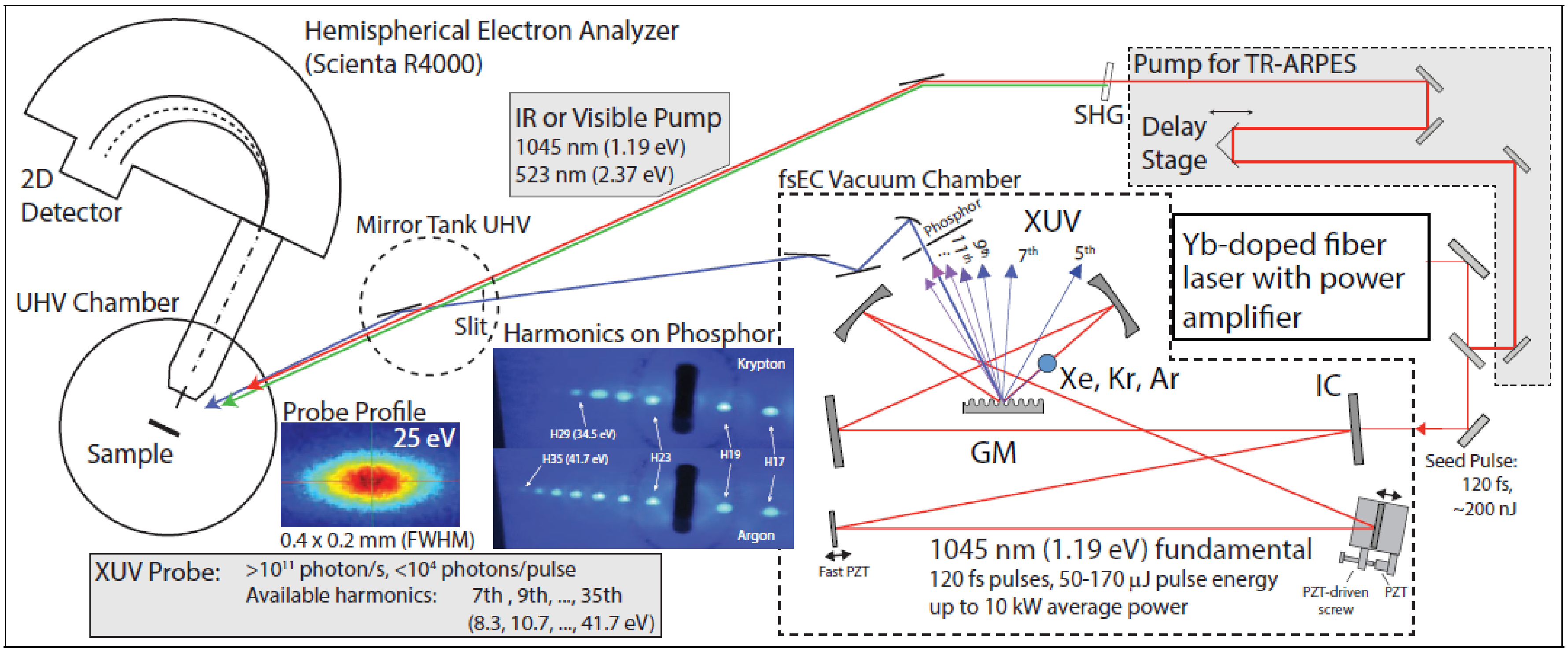
PHYSICAL REVIEW A **79**, 052505 (2009)

Feasibility of coherent xuv spectroscopy on the 1*S*-2*S* transition in singly ionized helium

M. Herrmann,[1] M. Haas,[2] U. D. Jentschura,[3] F. Kottmann,[4] D. Leibfried,[5] G. Saathoff,[1] C. Gohle,[1] A. Ozawa,[1] V. Batteiger,[1] S. Knünz,[1] N. Kolachevsky,[1,*] H. A. Schüssler,[6] T. W. Hänsch,[1,7] and Th. Udem[1]

1S-2S two-photon resonance at 61 nm in He+

Фотоэлектронная спектроскопия с угловым (ARPES) и временным разрешением at MHz rep. rate

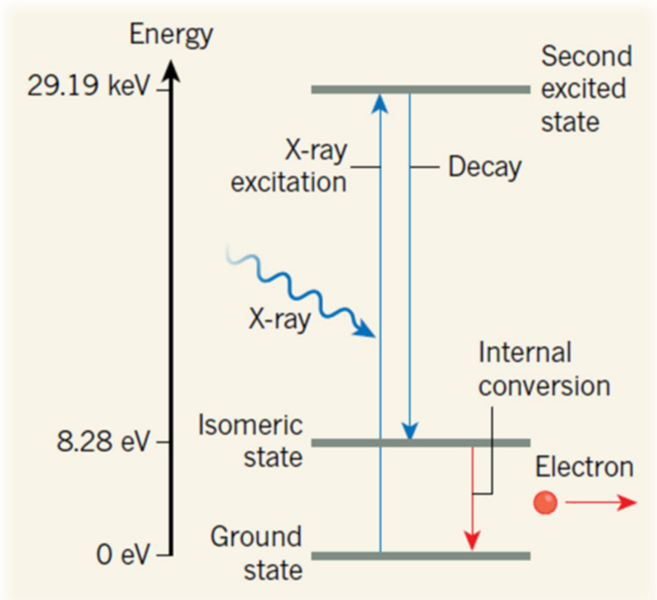


A.K. Mills, … D.J. Jones "Cavity-enhanced high harmonic generation for XUV time-resolved ARPES"
https://arxiv.org/abs/1902.05997

XUV frequency combs for nuclear clocks

nuClock

https://www.nuclock.eu/



149.7±3.1 nm

No direct photon detection yet

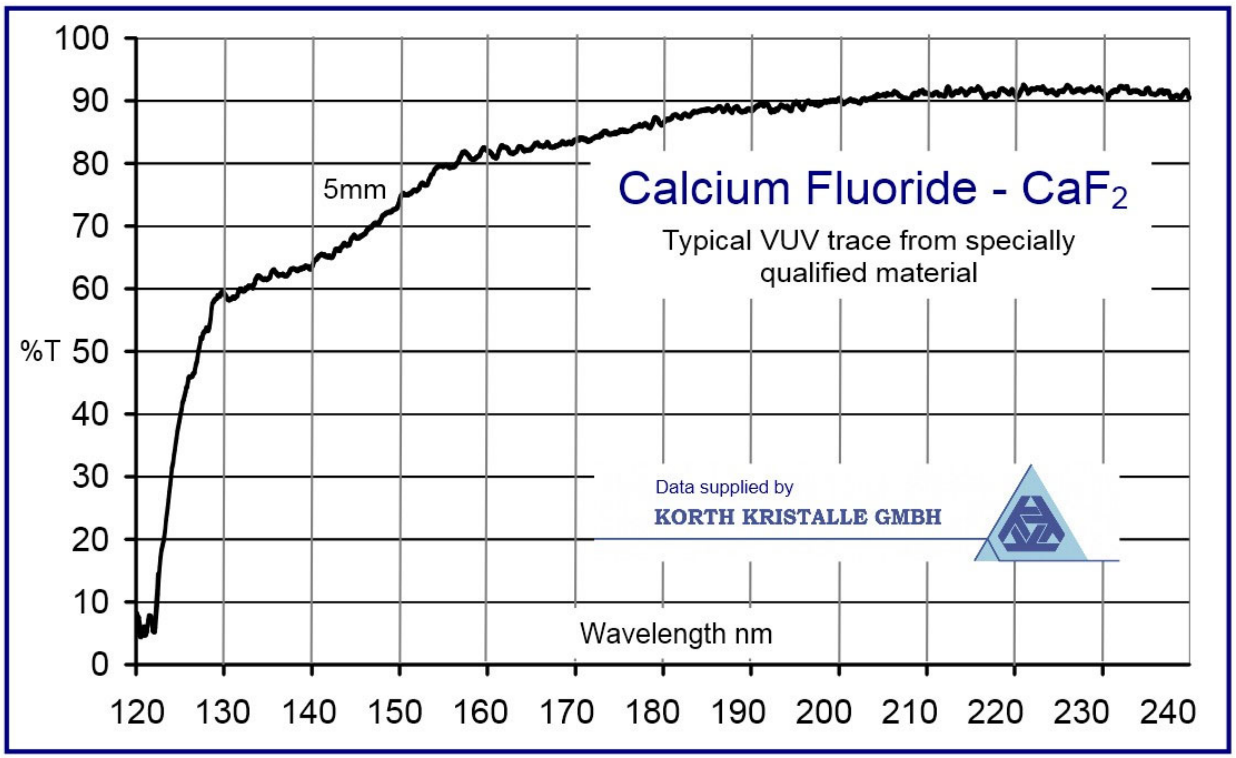
B. Seiferle, et. al., “Energy of the 229Th nuclear clock transition,” Nature 573, 243–246 (2019).

E. Peik & C. Tamm: Nuclear laser spectroscopy of the 3.5 eV transition in Th-229. Europhys. Lett. 61, 181 (2003)

150 nm is not so bad!

149.7±3.1 nm

B. Seiferle, et. al., “Energy of the 229Th nuclear clock transition,” Nature 573, 243 (2019).



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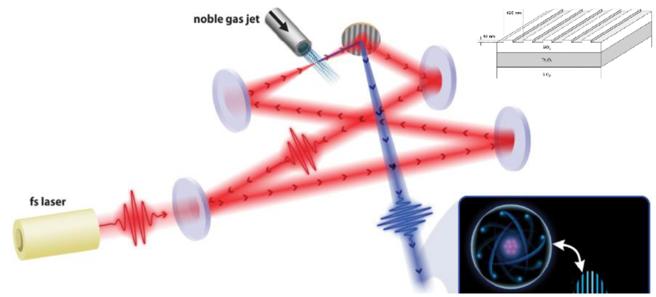
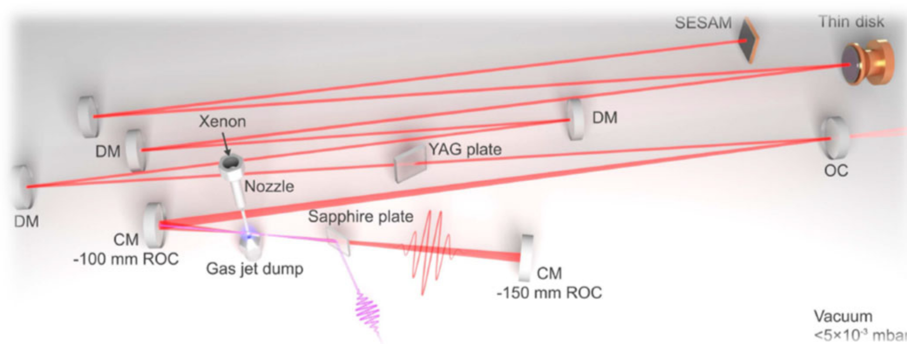
Different setups to achieve MHz rate XUV



❑ HHG inside enhacement cavities

https://jila.colorado.edu/yelabs/research/precision-measurement-ultrafast-science

A. K. Mills, et.al., "XUV frequency combs via femtosecond enhancement cavities," J. Phys. B: At. Mol. Opt. Phys. 45, 142001 (2012)



❑ HHG inside oscillator cavities

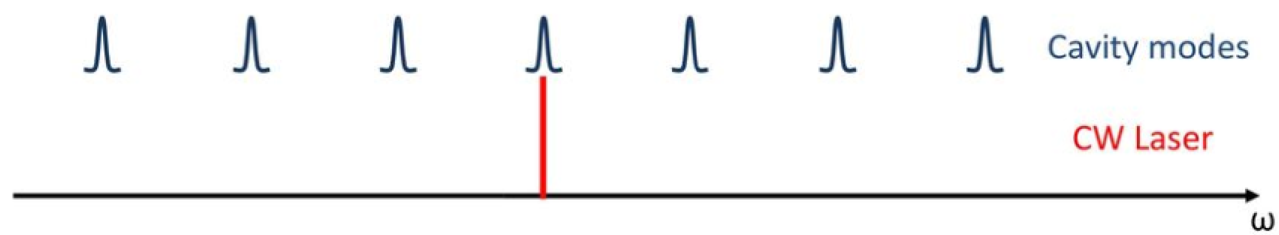
F. Labaye, et.al., Opt. Lett., OL 42, 5170 (2017)
E. Seres, et.al., Opt. Express, OE **20**, 6185 (2012).

❑ Directly laser-amplifier driven HHG

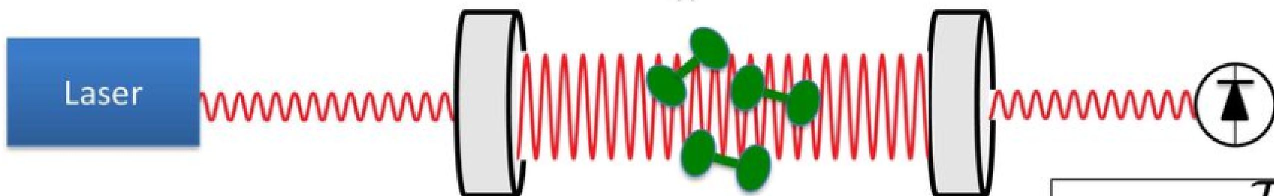
H. Steffen, et. al, Journal of Physics B: Atomic, Molecular and Optical Physics, vol. 49, p. 172002, 2016.

CW enhancement cavity

Frequency Domain



$$I \rightarrow \frac{\mathcal{F}}{\pi} I$$



$$\Delta I \rightarrow \frac{\mathcal{F}}{\pi} \Delta I$$

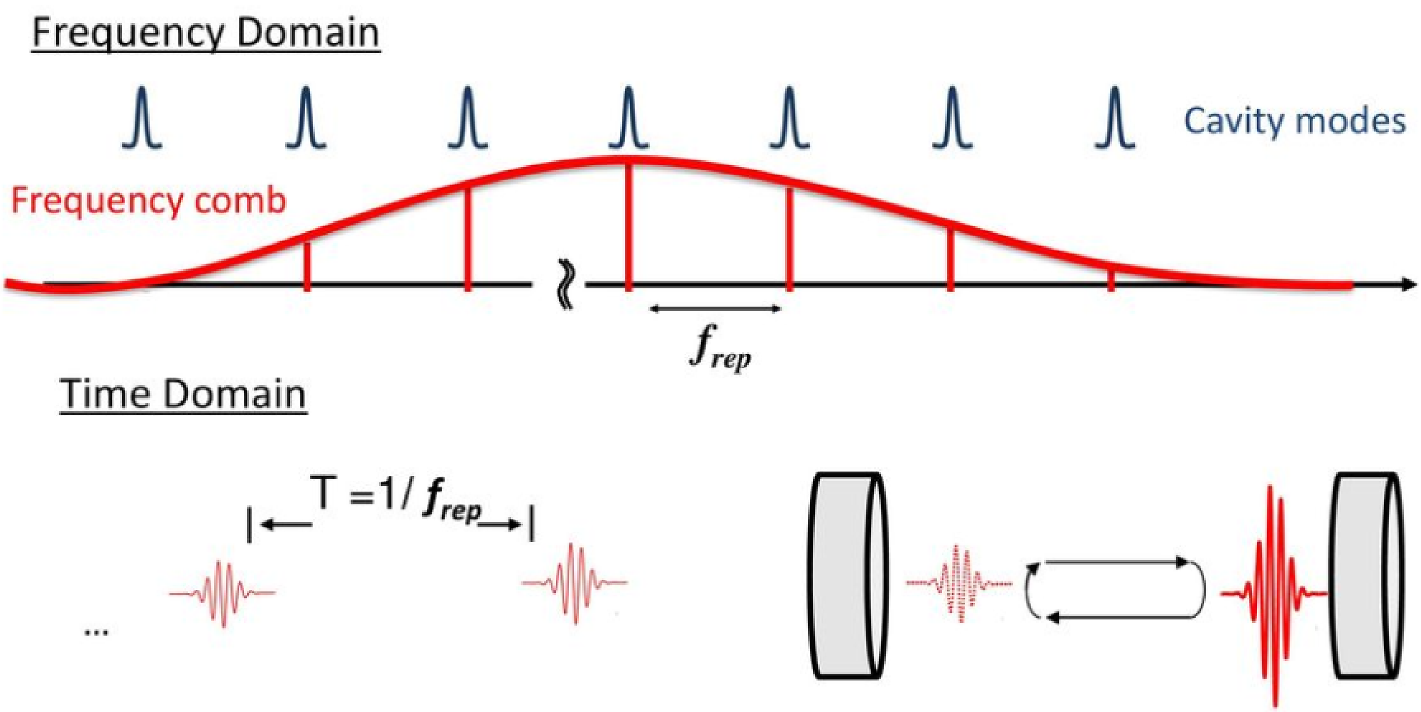
$$\mathcal{F} \approx \frac{2\pi}{loss} \approx 2\,\pi\, FSR\, \tau_p$$

Free spectra range

Photon lifetime

Credit Thomas Allison, https://slideplayer.com/slide/12978818/

Femtosecond enhancement cavity

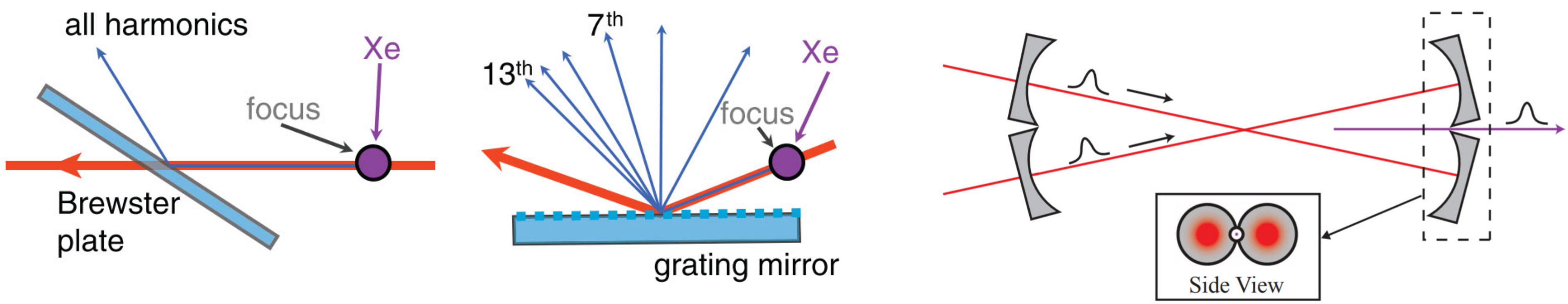


Finesses of > 1000 with cavity enhancements of several hundred are possible with bandwidth Δλ~ 30 nm

Credit Thomas Allison, https://slideplayer.com/slide/12978818/

Main problems with enhancement cavities

- XUV output coupling/separation

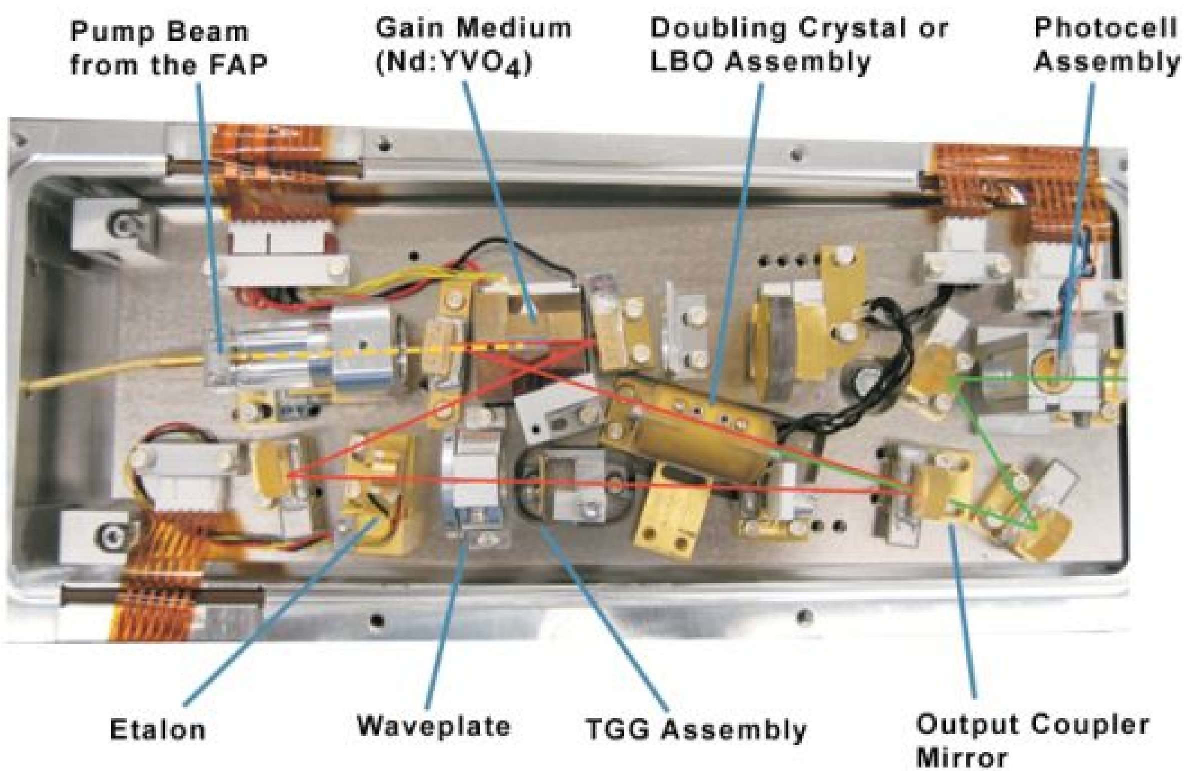


- Enhancement cavity is sensitive to low losses

A. K. Mills, et.al., "XUV frequency combs via femtosecond enhancement cavities," J. Phys. B: At. Mol. Opt. Phys. 45, 142001 (2012)

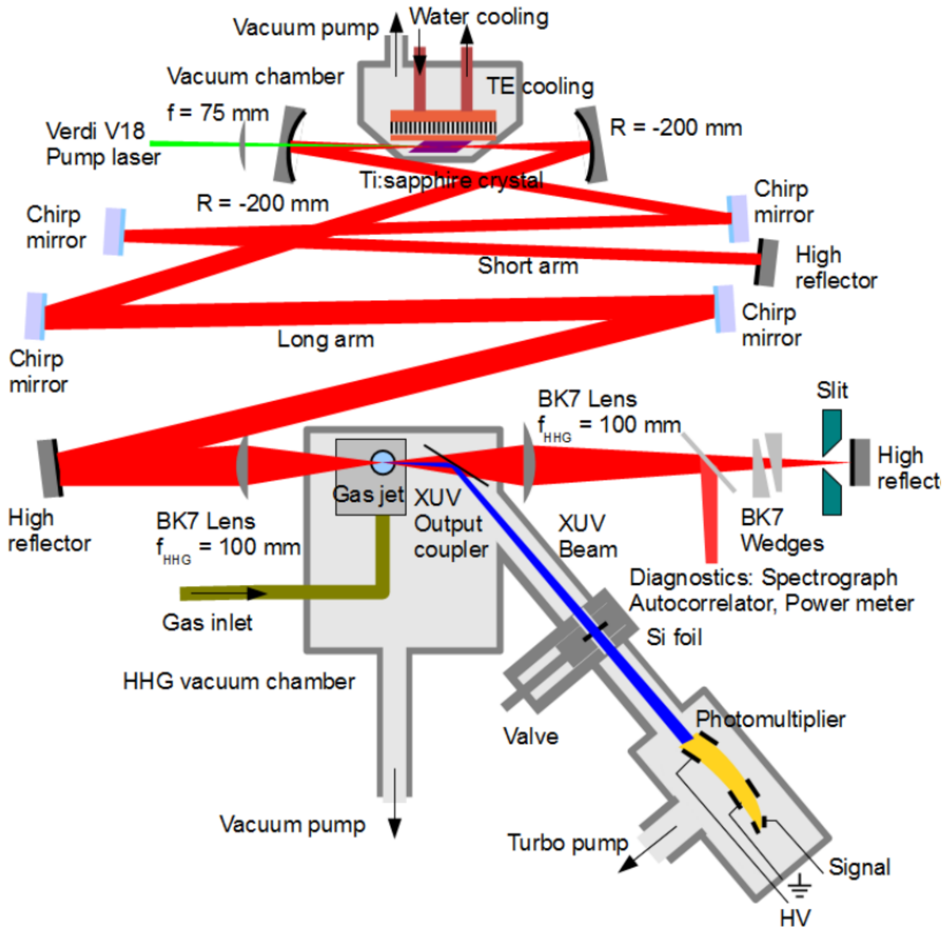
Why not doing it inside oscillator cavity?

VERDI green laser from Coherent



https://www.rp-photonics.com/intracavity_frequency_doubling.html

HHG inside oscillator cavity

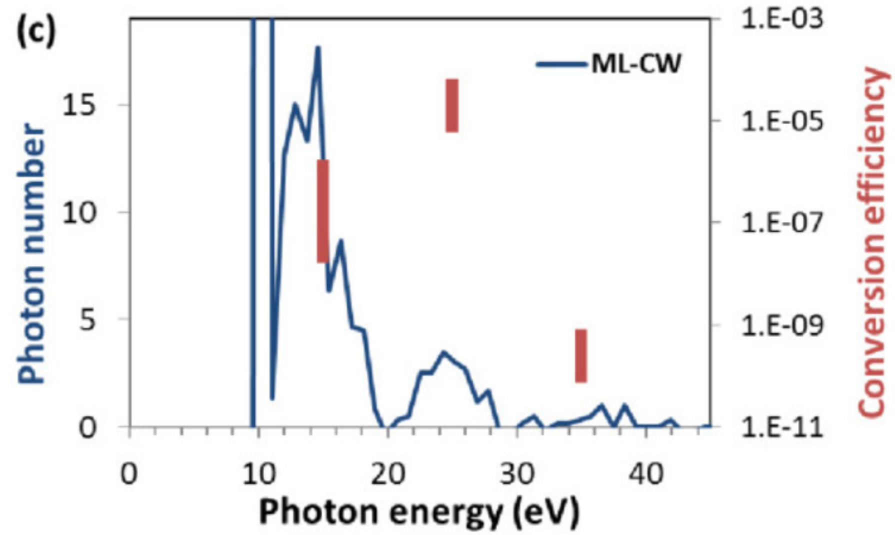


E. Seres, et.al., Opt. Express, OE **20**, 6185 (2012).

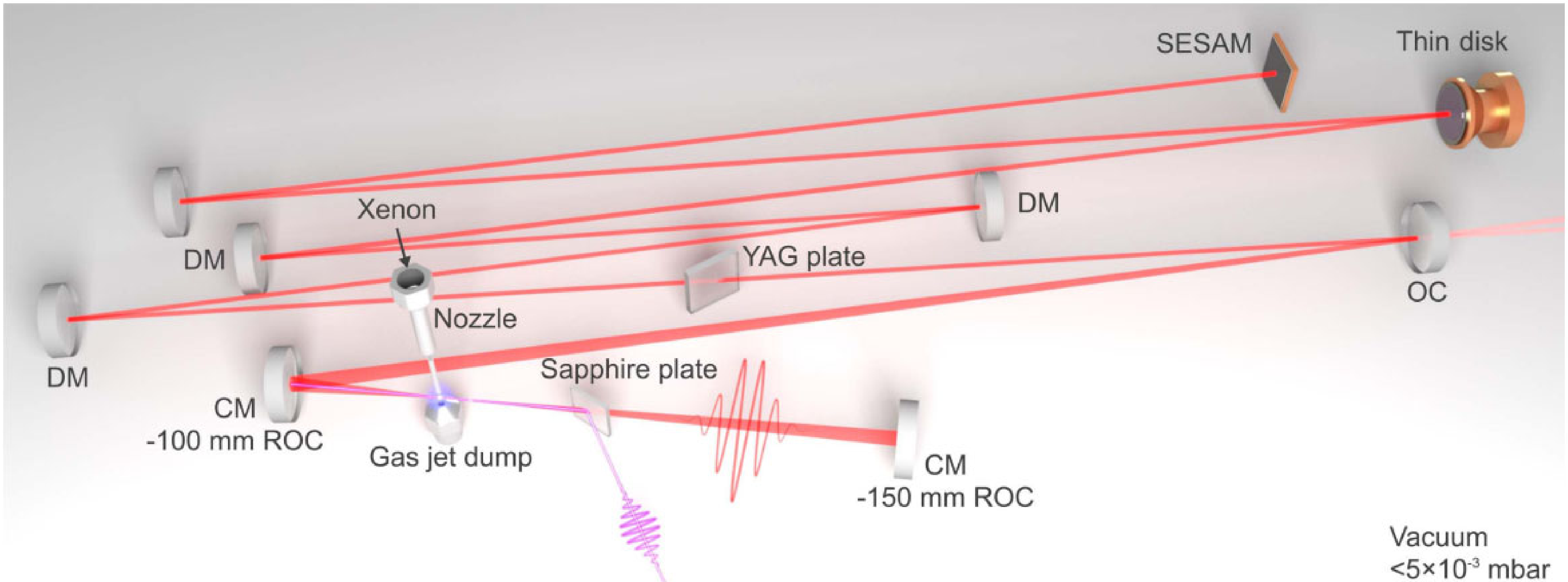
Intra-cavity average power: 11 W

Pulse duration: 17 fs

Repetition rate: 9.4 MHz



HHG inside oscillator cavity



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

Directly laser-amplifier driven HHG

❑ Directly laser-amplifier driven HHG

H. Steffen, et. al, Journal of Physics B: Atomic, Molecular and Optical Physics, vol. 49, p. 172002, 2016.

- Generally simple
- Simple XUV output coupling methods
- Relatively efficient XUV output coupling/separation
- Short path-length from XUV generation chamber to target
- Can be compact and transportable

- Low repetition rate <10 MHz
- Relatively low average power 1-2 kW

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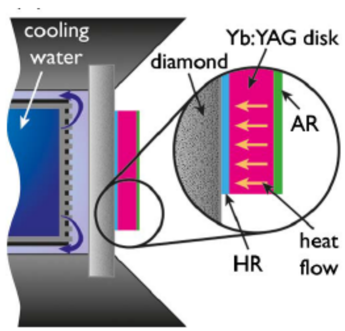
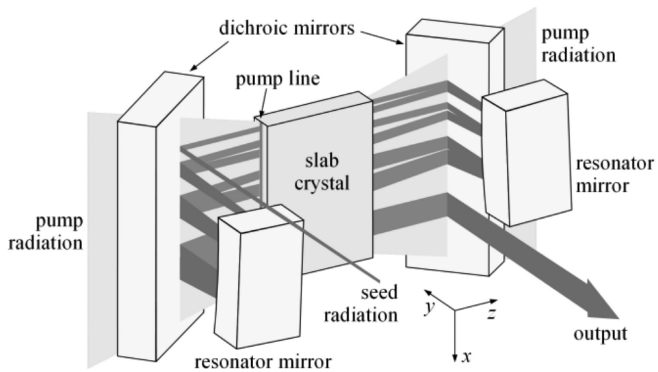
High power Yb-based technologies



Thin-disk technology

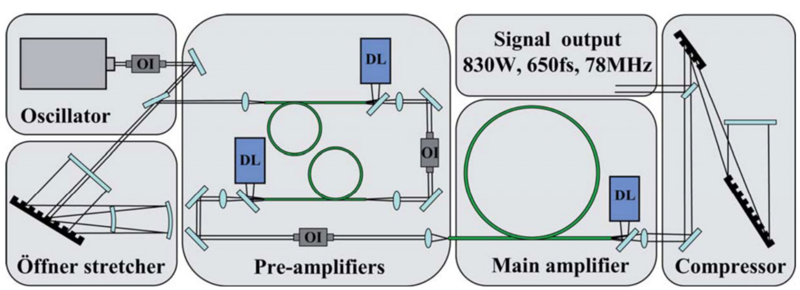
TRUMPF



Fraunhofer ILT

Slab amplifier

Russbueldt, P., et al., IEEE, 21, 447 (2015)

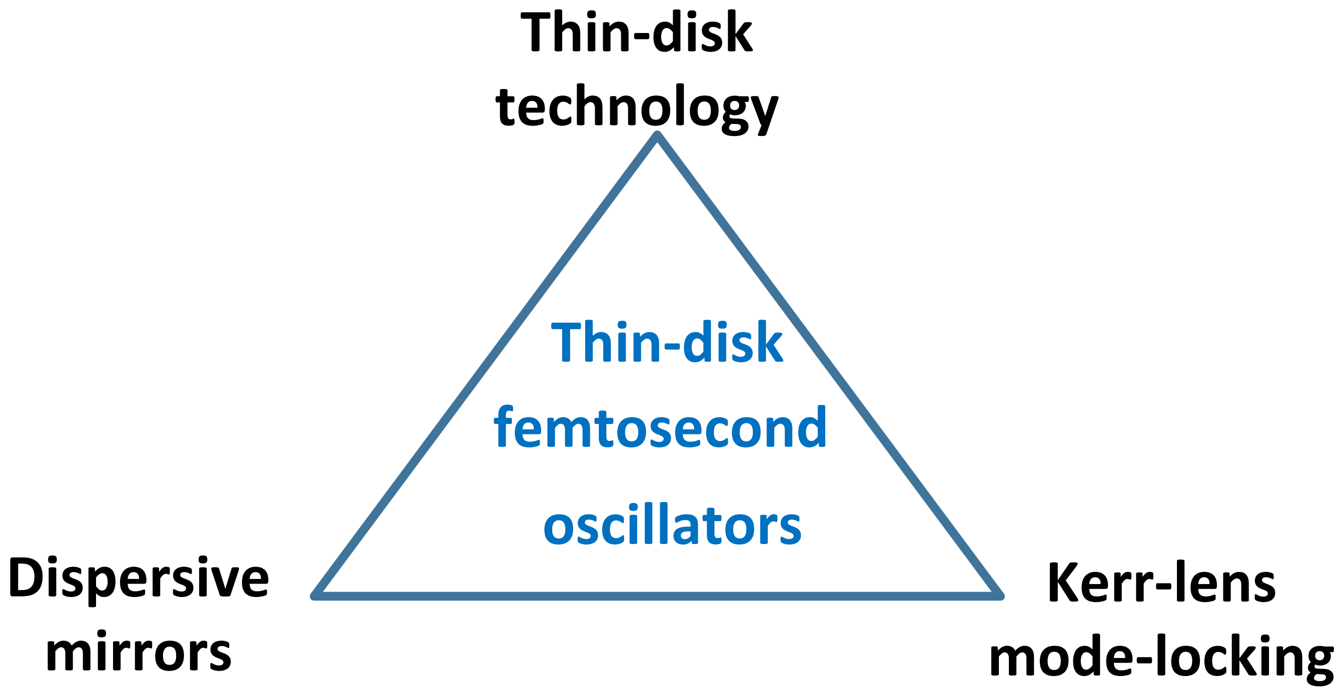


Fraunhofer IOF

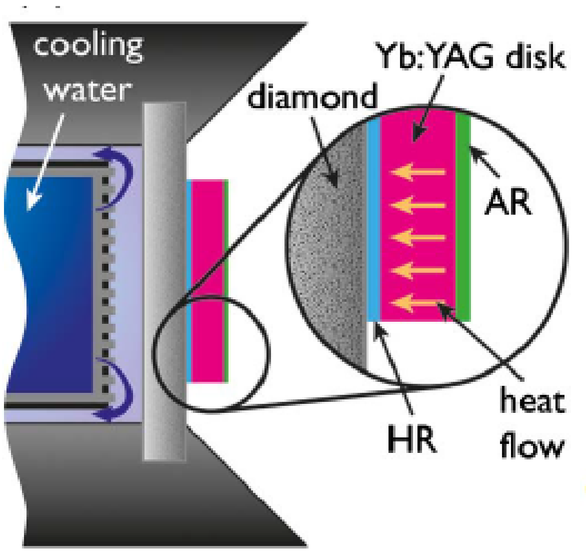
Fiber amplifier

T. Eidam, et. al., Opt. Lett. 35, 94 (2010)

Femtosecond thin-disk oscillators



Thin-disk technology



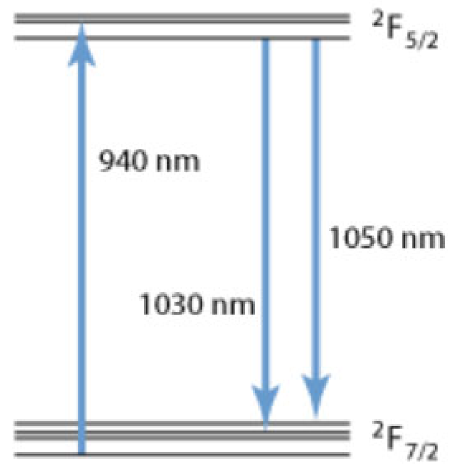


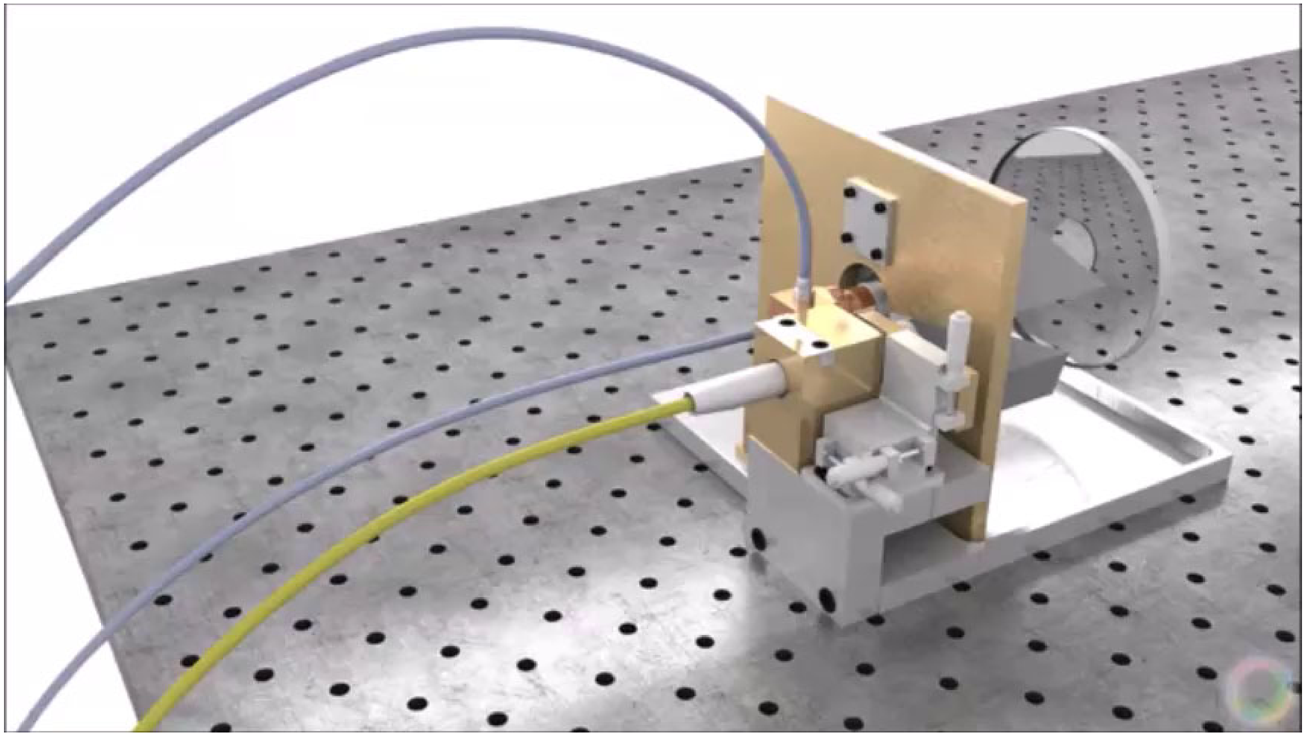
Figure 1: Energy levels of Yb^{3+} ions in Yb^{3+}:YAG, and the usual pump and laser transitions.

H. Fattahi et al., Optica 1, 45, 2014;

A. Giesen et al., Appl. Phys. B 58, 65, 1994 ;

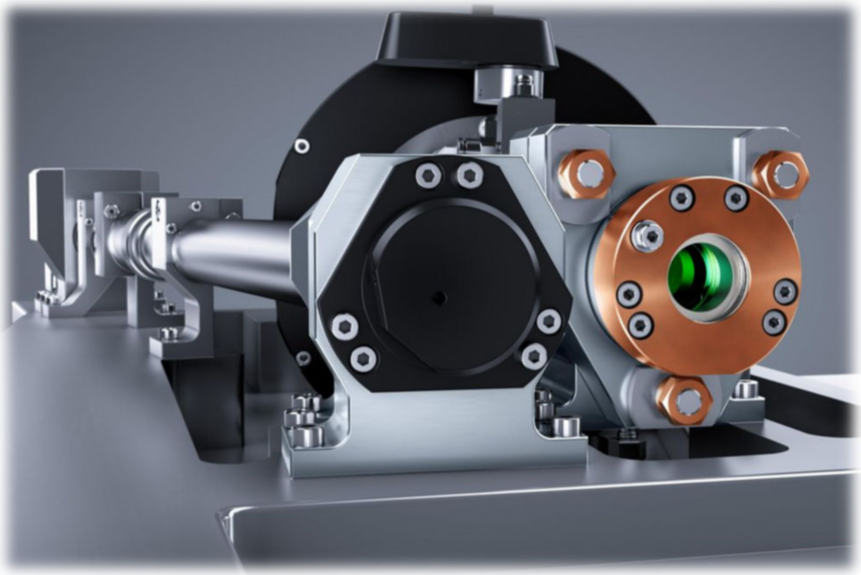
B. J. Mende et al., Proc. of SPIE 7193, 71931V-1

Multi-pass pumping



https://www.rp-photonics.com/thin_disk_lasers.html

Commercial products, up to 16 kW.



LASERPARAMETER	
LASERLEISTUNG AM WERKSTÜCK	16000 W
TYP. LEISTUNGSKONSTANZ BEI NENNLEISTUNG	± 1 % bei aktiver Leistungsregelung
KONTINUIERLICH EINSTELLBARER LEISTUNGSBEREICH	320 W - 16000 W
STRAHLQUALITÄT AN DER EINKOPPLUNG IN DAS LLK	8 mm▪mrad
NUMERISCHE APERTUR AN DER AUSKOPPLUNG NACH LLK	0,1
WELLENLÄNGE	1030 nm
MIN. DURCHMESSER LASERLICHTKABEL	200 µm

https://www.trumpf.com/de_INT/produkte/laser/scheibenlaser/

Thin-disk technology

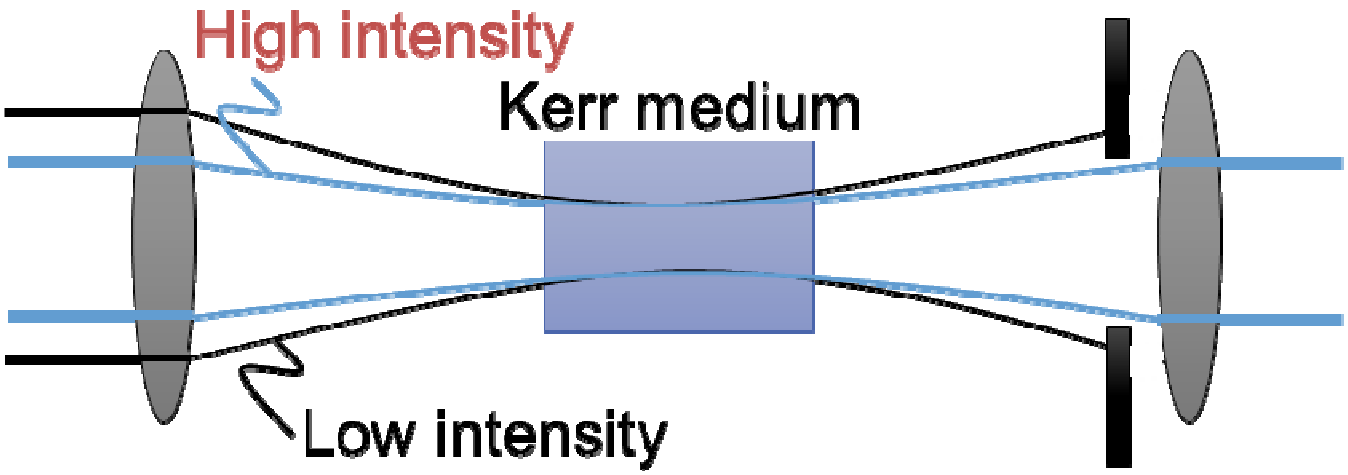
SCALABLE CONCEPT !

Efficient laser medium cooling	→	High average power
Thin disk (0.1 mm), lower total nonlinearity	→	High peak powers

H. Fattahi et al., Optica 1, 45, 2014;
A. Giesen et al., Appl. Phys. B 58, 65, 1994 ;
B. J. Mende et al., Proc. of SPIE 7193, 71931V-1

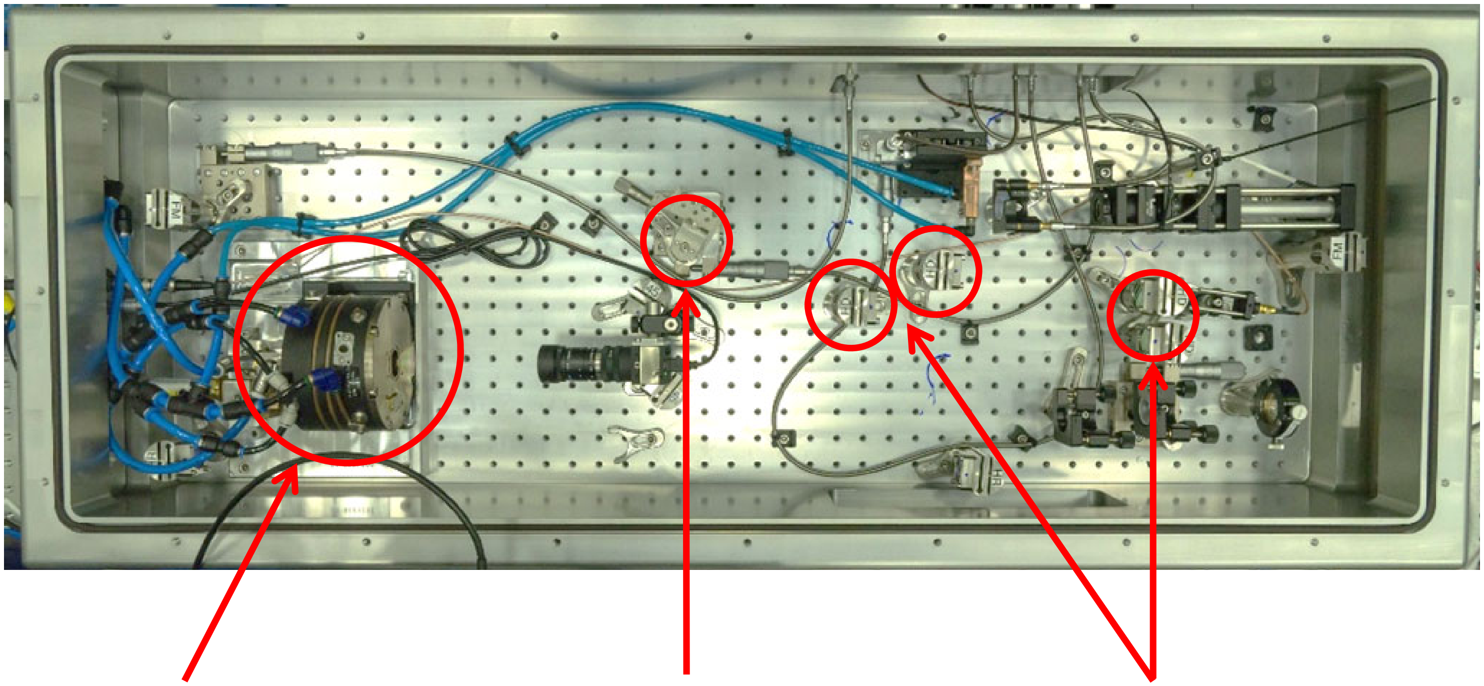
Kerr lens mode-locking

(Magic mode-locking)



D. E. Spence et al., Opt. Lett. 16, 42 (1991)
F. Krausz et al., IEEE J. Quantum Electron . QE-28 , 2097 (1992)
B. Henrich and R. Beigang, Opt. Comm. 135, 300 (1997)

Typical oscillator, 100 W oscillator



M. Seidel, J. Brons, G. Arisholm, K. Fritsch, V. Pervak, and O. Pronin, Scientific reports 7, 1410 (2017).

Parameter range (high rep. rate. &low pulse energy)

P_{avg}, W	E_p, μJ	f_{rep}, MHz	τ_p, fs	P, MW	P_{avg}, W (compressed)	τ_p, fs (compressed)	Application	Status
40	3	13	300	9			Seed oscillator	In use [3]
90	0.9	100	250	3.5	>50	20	MIR generation	In use [4]
42	1.1	38	250	4.2	6 (10)	7.7 (10)	MIR generation	In use [5, 6]
270	14	19	330	37.8			Development itself	Not in use [7]
155	10	15.5	140	63	130	30	XUV generation, Raman spectroscopy	In use [8]
10 (3.5)	0.7 (0.4)	100–200	70 (47)	0.6			Development itself	In use [9]
100	4.1	24	190	19.3	65	30	Commercial system	In use [10]

All oscillators use Yb:YAG as a gain medium. Most of the oscillators are successfully operating in the laboratories with the parameter sets originally published.

Table 1. Summary table of the KLM thin-disk oscillators developed at MPQ, LMU and UFI GmbH from 2012 till 2017.

O. Pronin and J. Brons, “Kerr-Lens Mode-Locked High-Power Thin-Disk Oscillators,” in High Power Laser Systems, (InTech, 2018).

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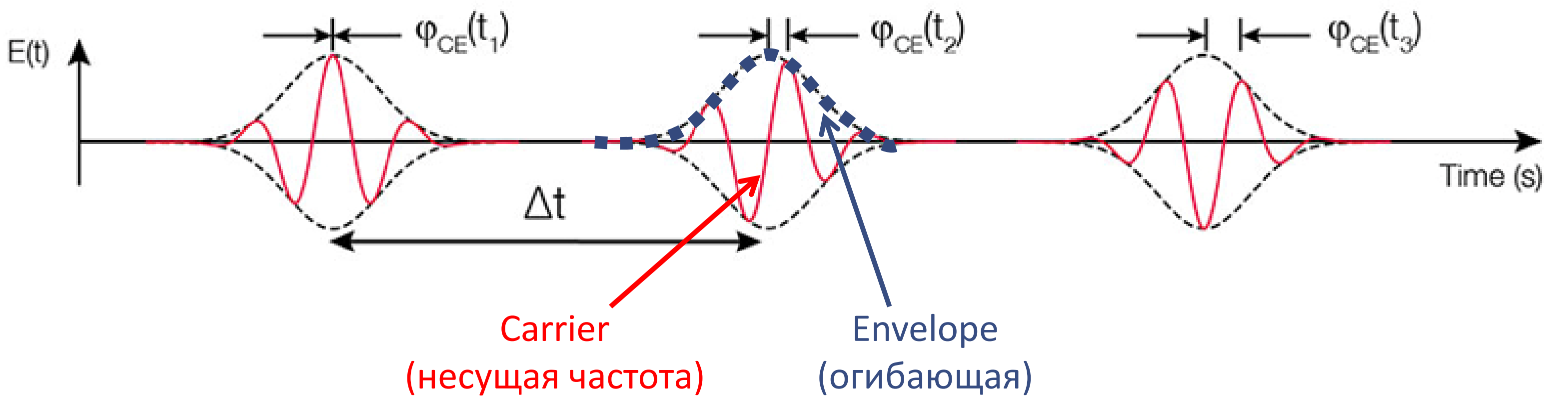
Frequency comb. Time domain

Laser output. Pulse train

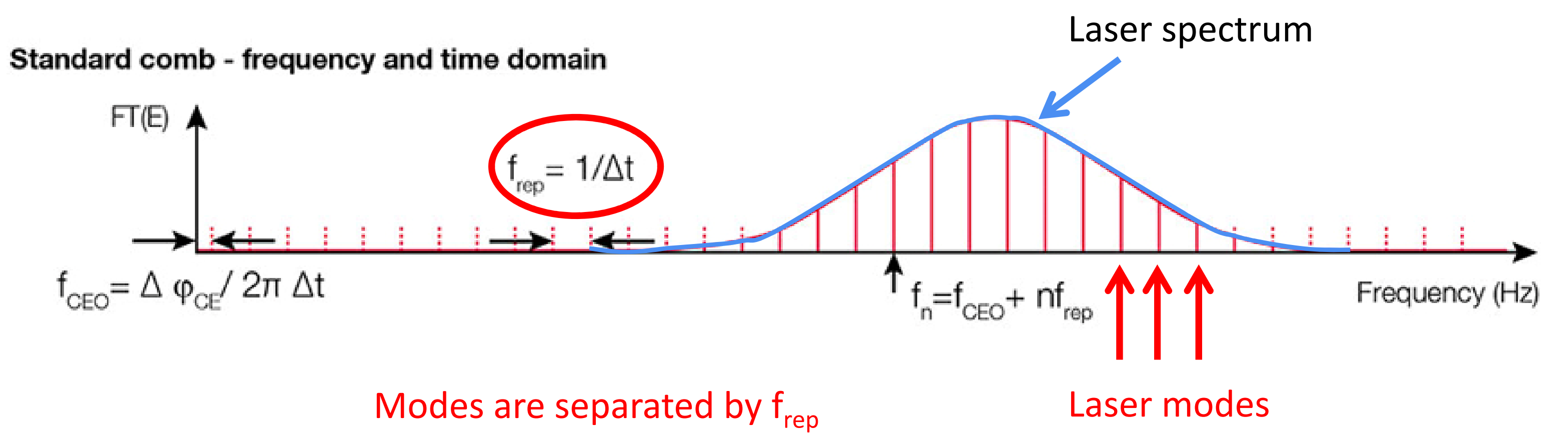


Carrier envelope phase is constant

http://www.toptica.com/technology/technical-tutorials/frequency-combs/

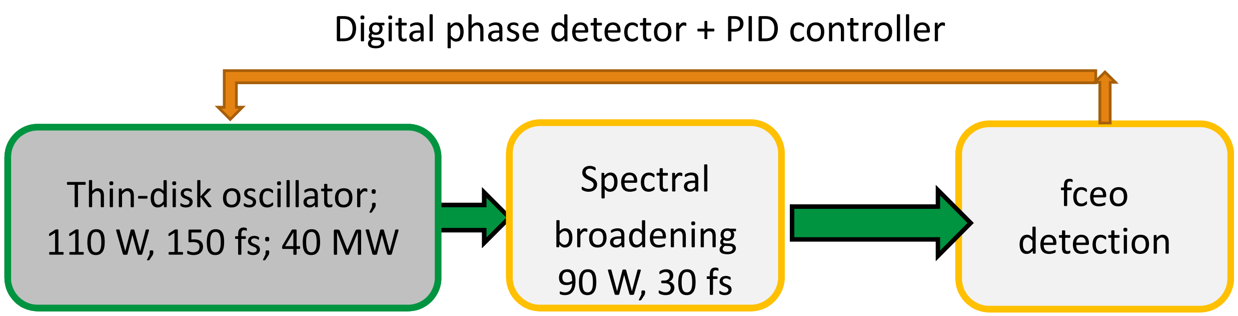
Frequency comb

Allows a direct link from radio frequency standards to optical frequencies
f_{ceo} and f_{rep} are usually in 10-100 MHz range



http://www.toptica.com/technology/technical-tutorials/frequency-combs/

CEO frequency stabilization



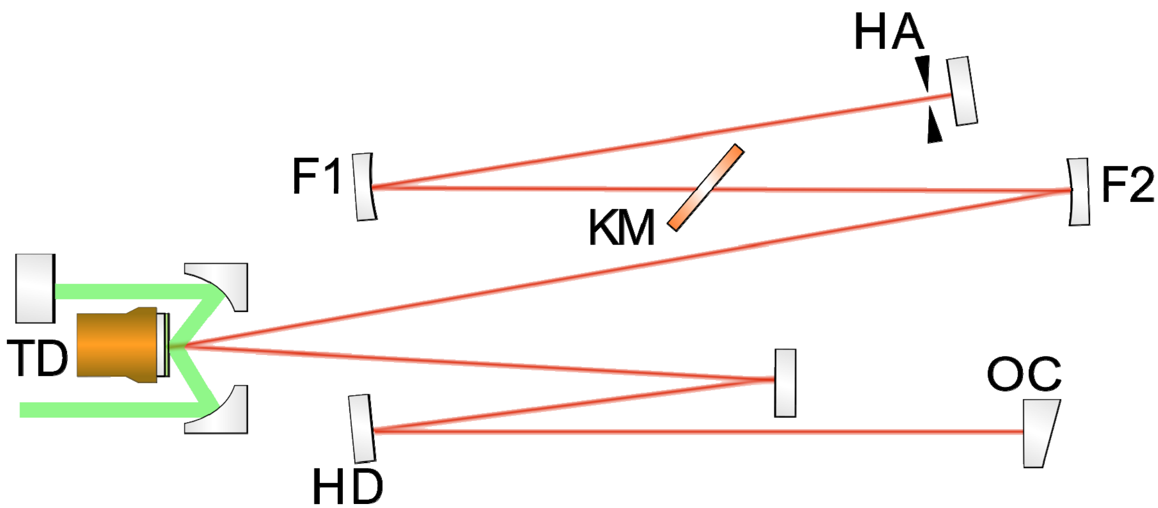
CEO frequency stabilization techniques

AOM in pump beam (Ti:Sa) → Not suitable for high power thin-disk oscillators

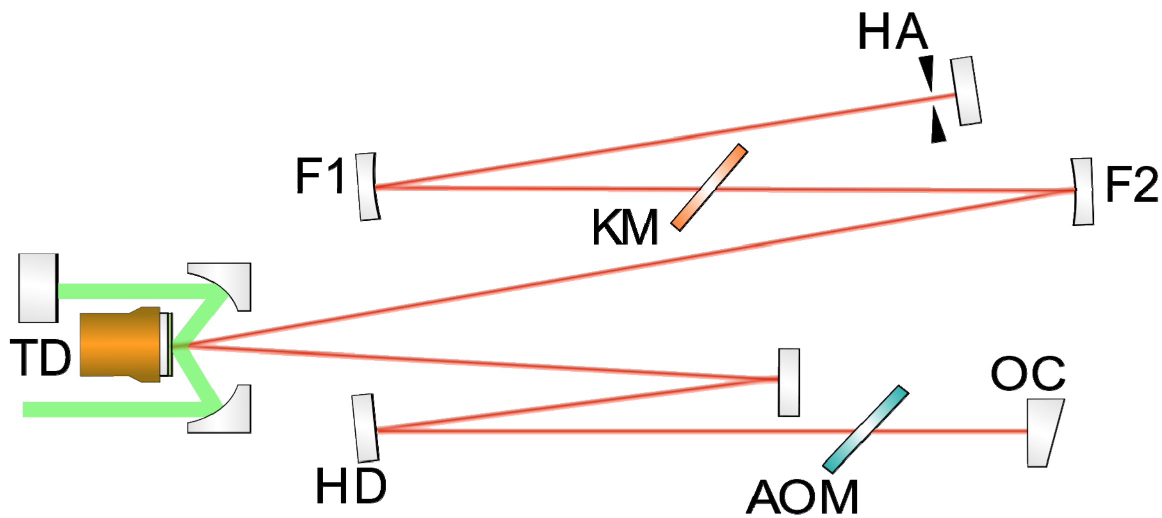
Direct pump current control → Low control bandwidth (Low-pass filtering)

[1] M. Seidel et al., "Carrier-envelope-phase stabilization via dual wavelength pumping," Opt. Lett. **41**, 1853 (2016)
[2] S. Koke et al., "Direct frequency comb synthesis with arbitrary offset and shot-noise-limited phase noise," Nature Photonics **4**, 462-465 (2010).

Intra-cavity loss modulation



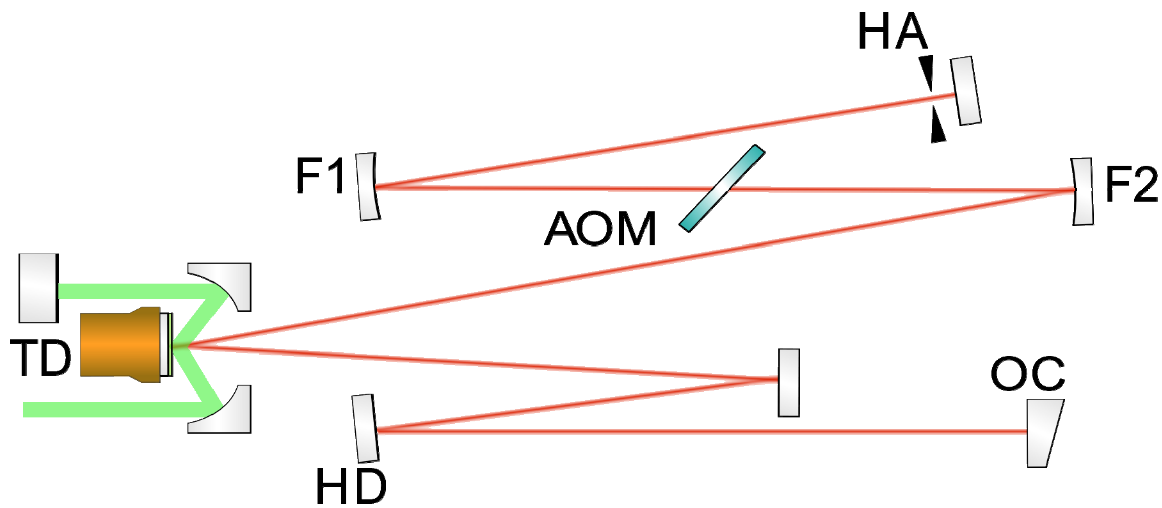
Intra-cavity loss modulation



$f_{Kerr} \propto w_{AOM}^4$ ⟷ $\Delta\nu_{mod} \propto 1/w_{AOM}$

O. Pronin et al., "High-power multi-megahertz source of waveform-stabilized few-cycle light," Nat. Commun. **6**, 6988 (2015)

AOM as a Kerr medium



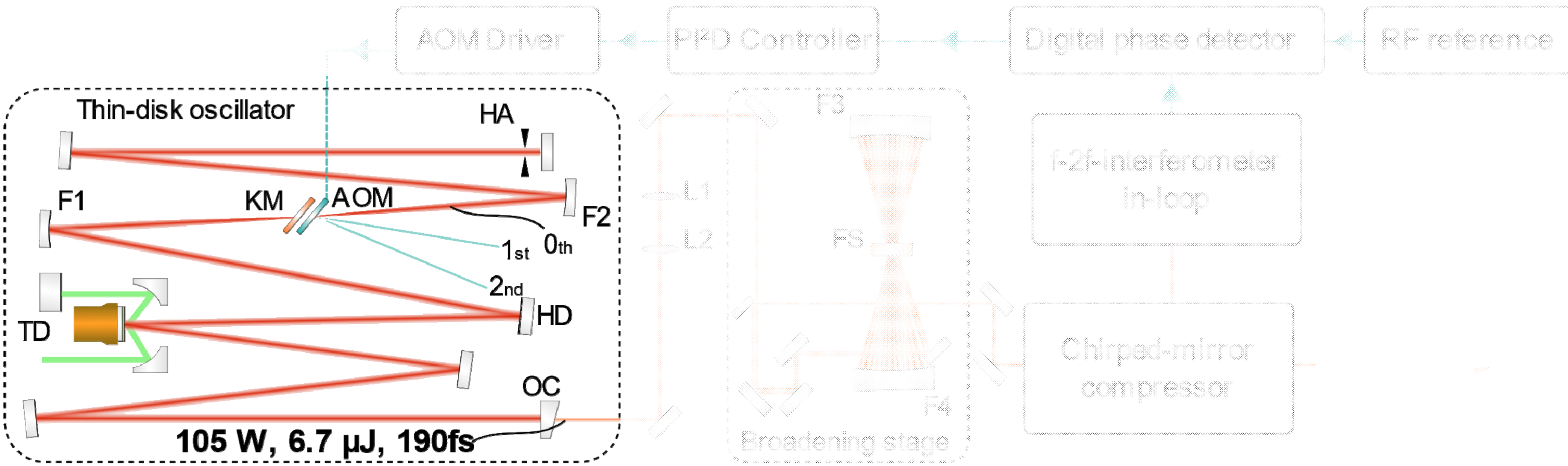
$f_{Kerr} \propto w_{AOM}^4$

+

$\Delta\nu_{mod} \propto 1/w_{AOM}$

S. Gröbmeyer, J. Brons, M. Seidel, and O. Pronin, Laser & Photonics Reviews 13, 1800256 (2019).

Oscillator layout



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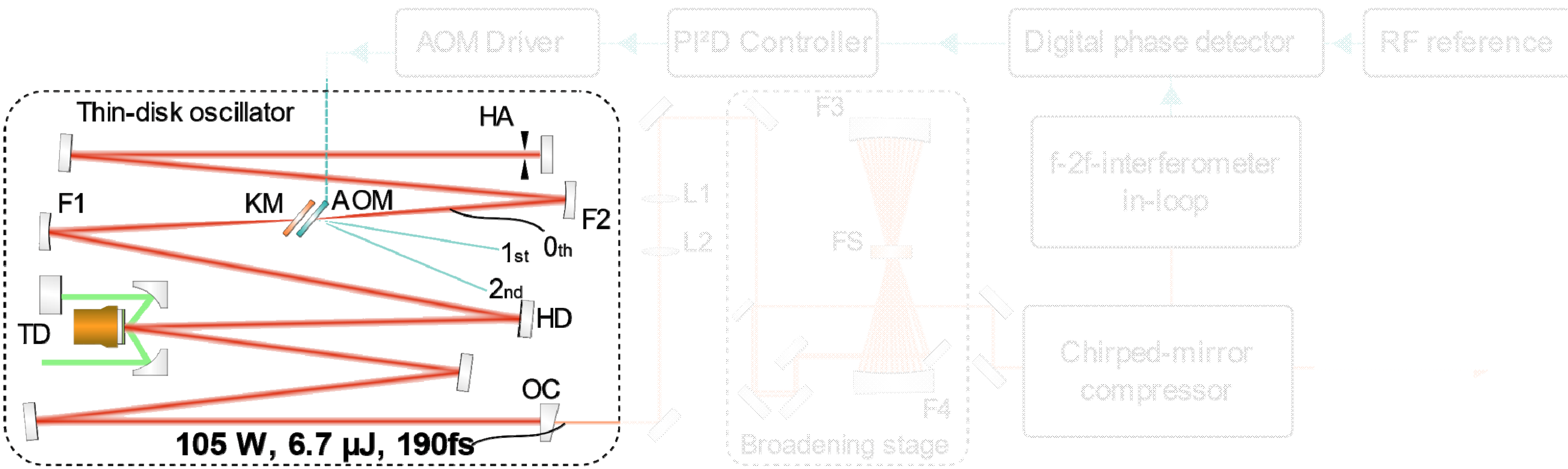
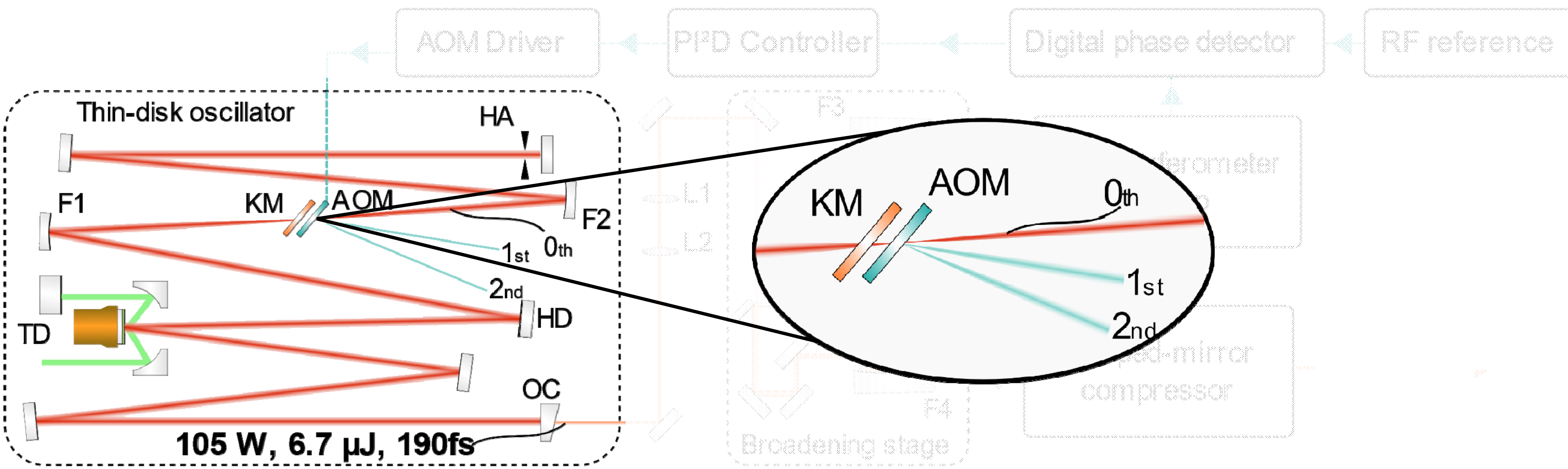


S. Gröbmeyer, J. Brons, M. Seidel, and O. Pronin, Laser & Photonics Reviews 13, 1800256 (2019).



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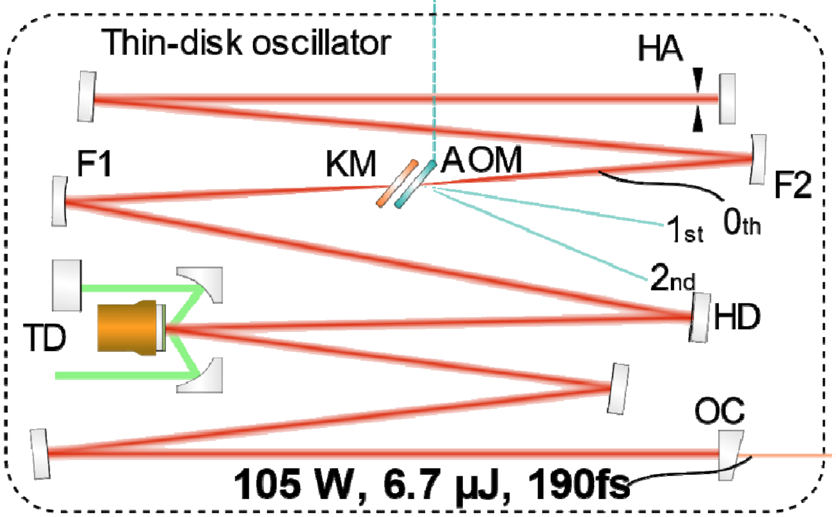
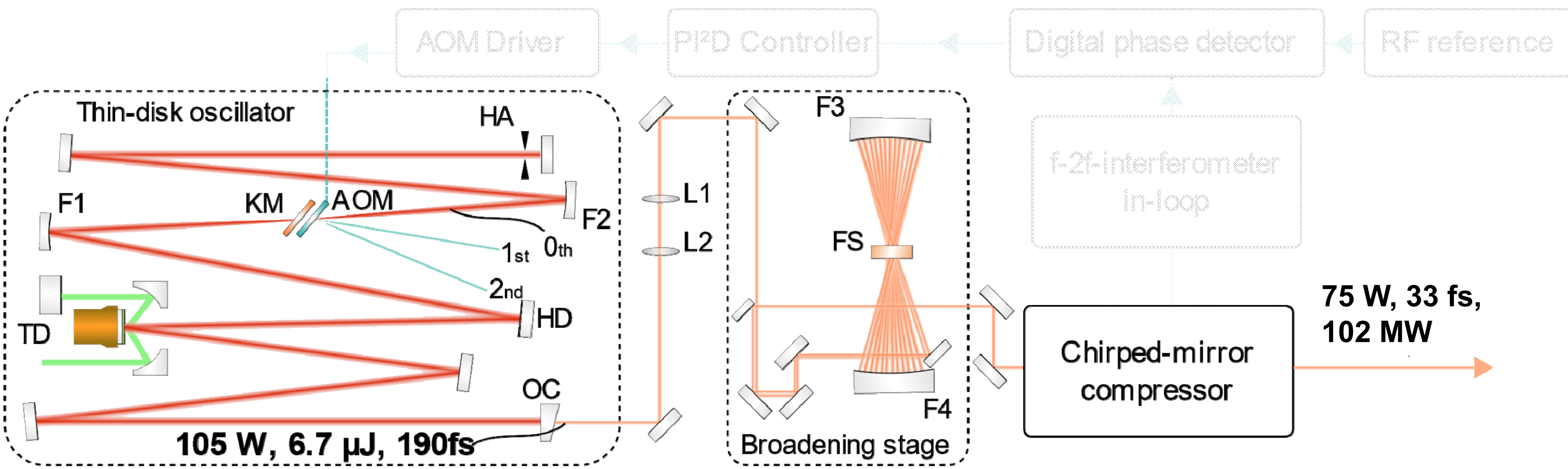


Oscillator parameters	
P_{avg}	105 W
P_{peak}	42 MW
τ_{FWHM}	190 fs
E_{pulse}	6.7 µJ
f_{rep}	15.6 MHz
λ_c	1030 nm

S. Gröbmeyer, J. Brons, M. Seidel, and O. Pronin, Laser & Photonics Reviews 13, 1800256 (2019).



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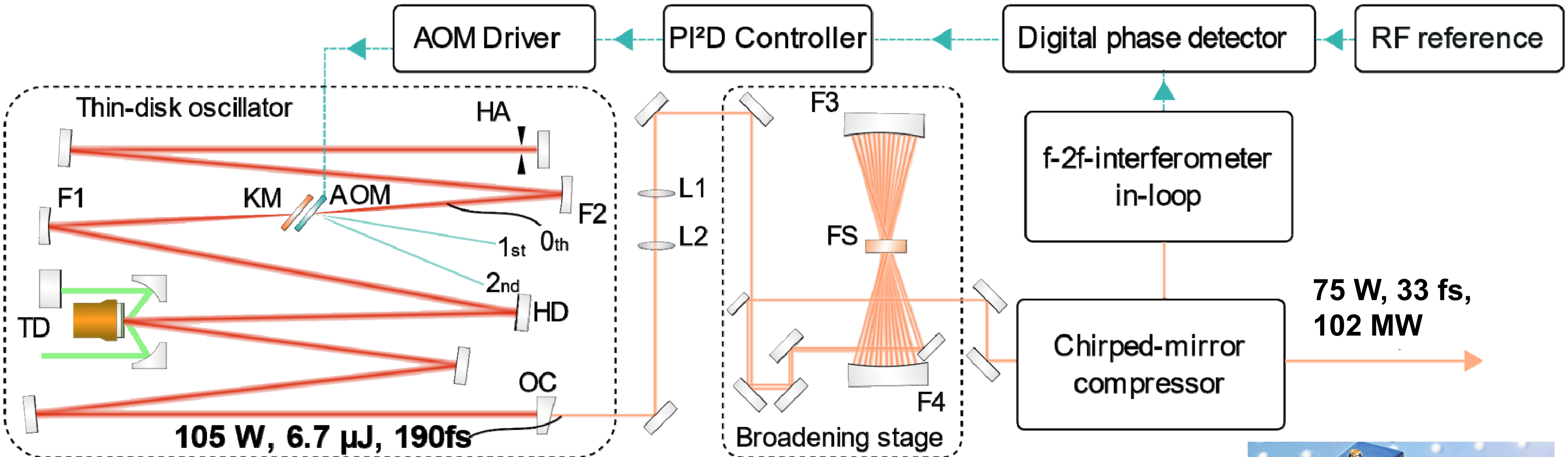
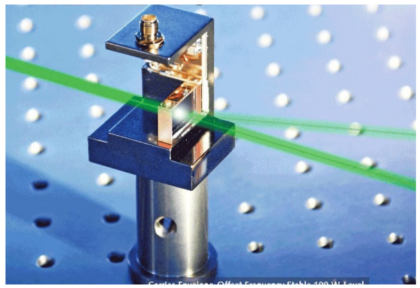


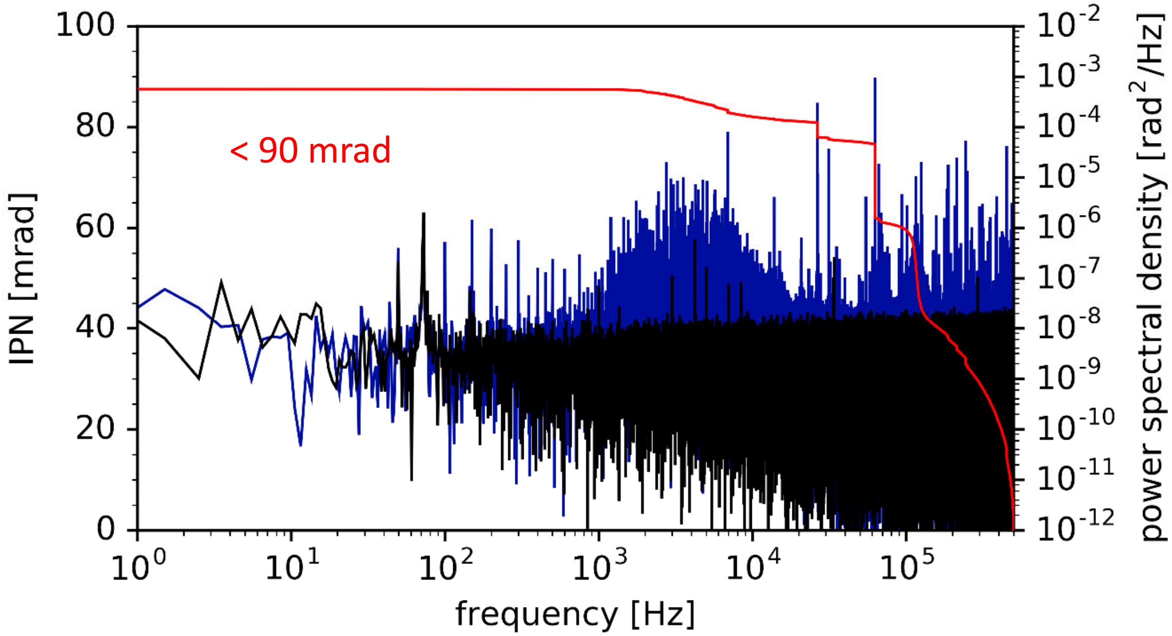


Highest average power CEP stable laser

S. Gröbmeyer, J. Brons, M. Seidel, and O. Pronin, Laser & Photonics Reviews 13, 1800256 (2019).

Noise characteristics

In-loop phase noise

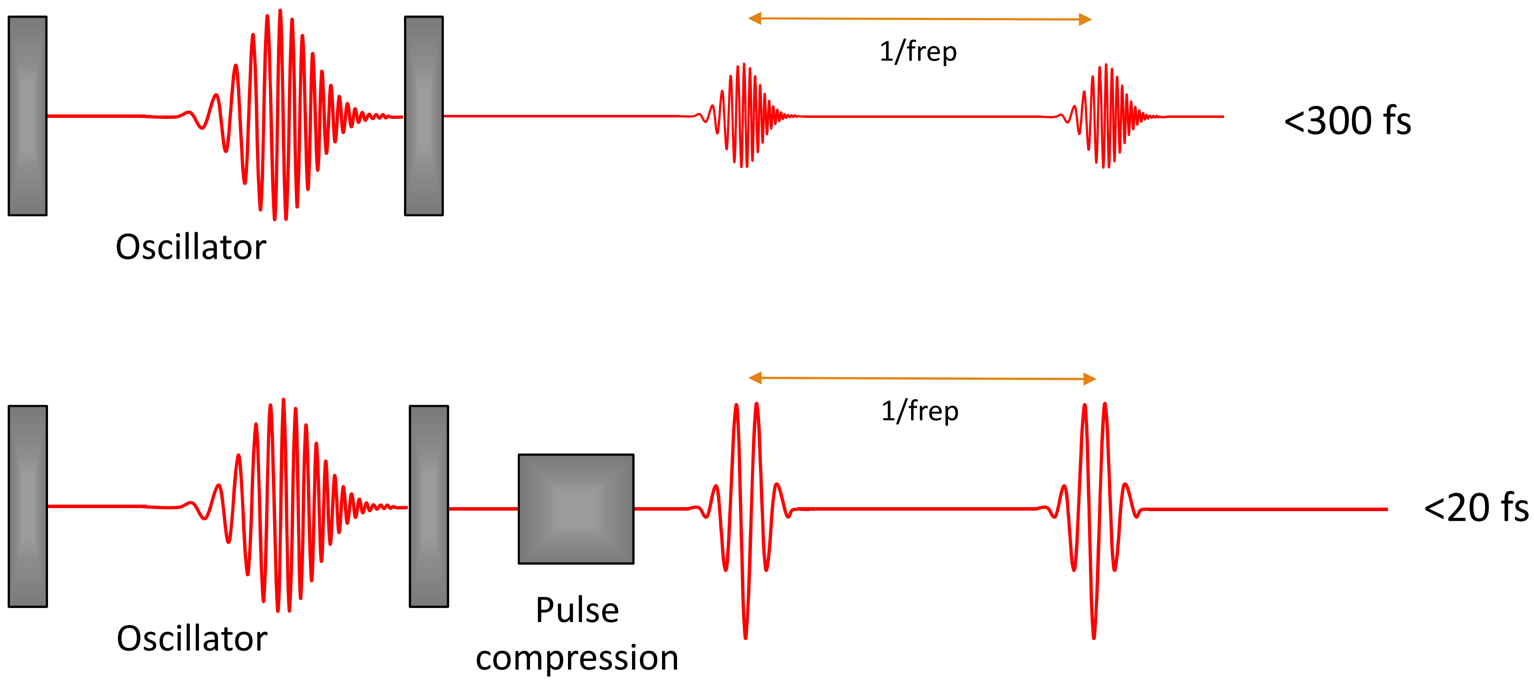


Sebastian Gröbmeyer

Outline

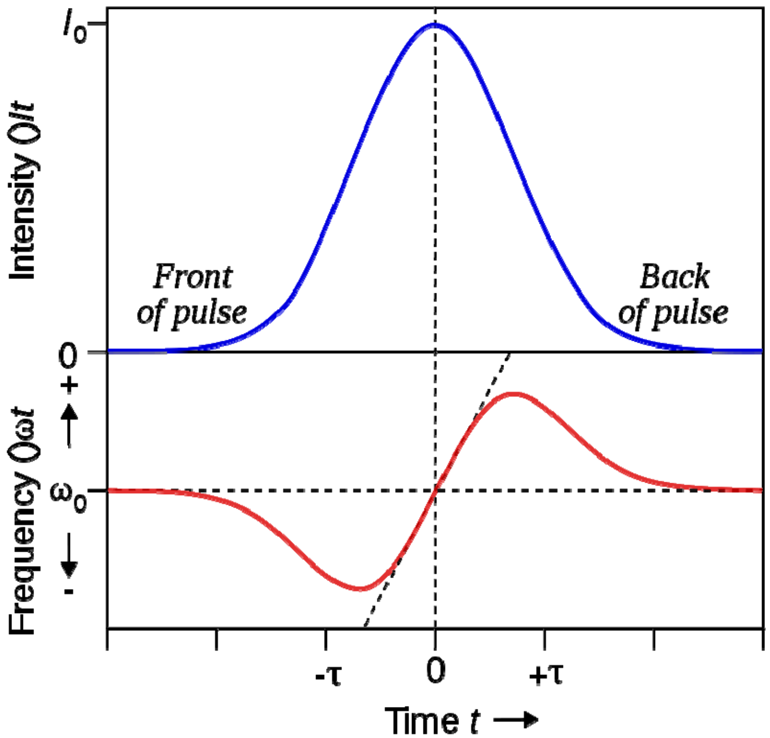
- Introduction (HHG, applications, different methods)
- Thin-disk Yb:YAG femtosecond oscillators (power, energy)
- CEO (CEP) stabilization of thin-disk femtosecond oscillators
- Spectral broadening and pulse compression

Pulse shortening



Short pulses are good for EUV and IR generation

Spectral broadening
Self phase modulation



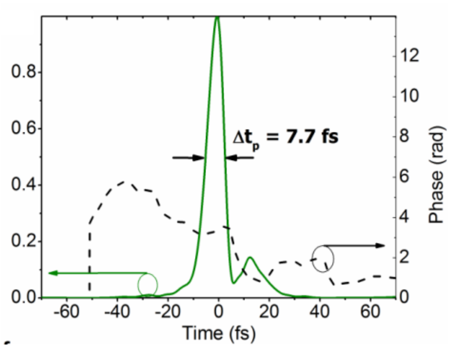
$$\phi(t) = \omega_0 t - kz = \omega_0 t - \frac{2\pi}{\lambda_0} \cdot n(I)L$$

$$\omega(t) = \frac{d\phi(t)}{dt} = \omega_0 - \frac{2\pi L}{\lambda_0}\frac{dn(I)}{dt}$$

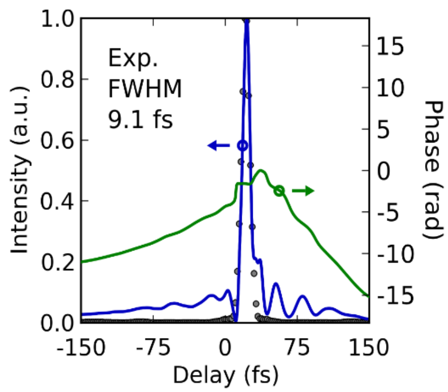
$$n(I) = n_0 + n_2 \cdot I$$

Different methods

Solid-core fibers	Hollow core fibers (gas inside)	In bulk crystals (multi-pass)



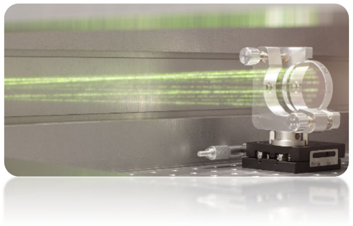
O. Pronin, et al., Nature Commun 6, 6988 (2015)



K.F. Mak et al. Opt. Lett. 40, 1238 (2015)

New method

Developed by **ILT Aachen (Germany)**



Spectral broadening in multi-pass cell

S. N. Vlasov, E. V. Koposova, and V. E. Yashin, Quantum Electron. 42, 989–995 (2012).

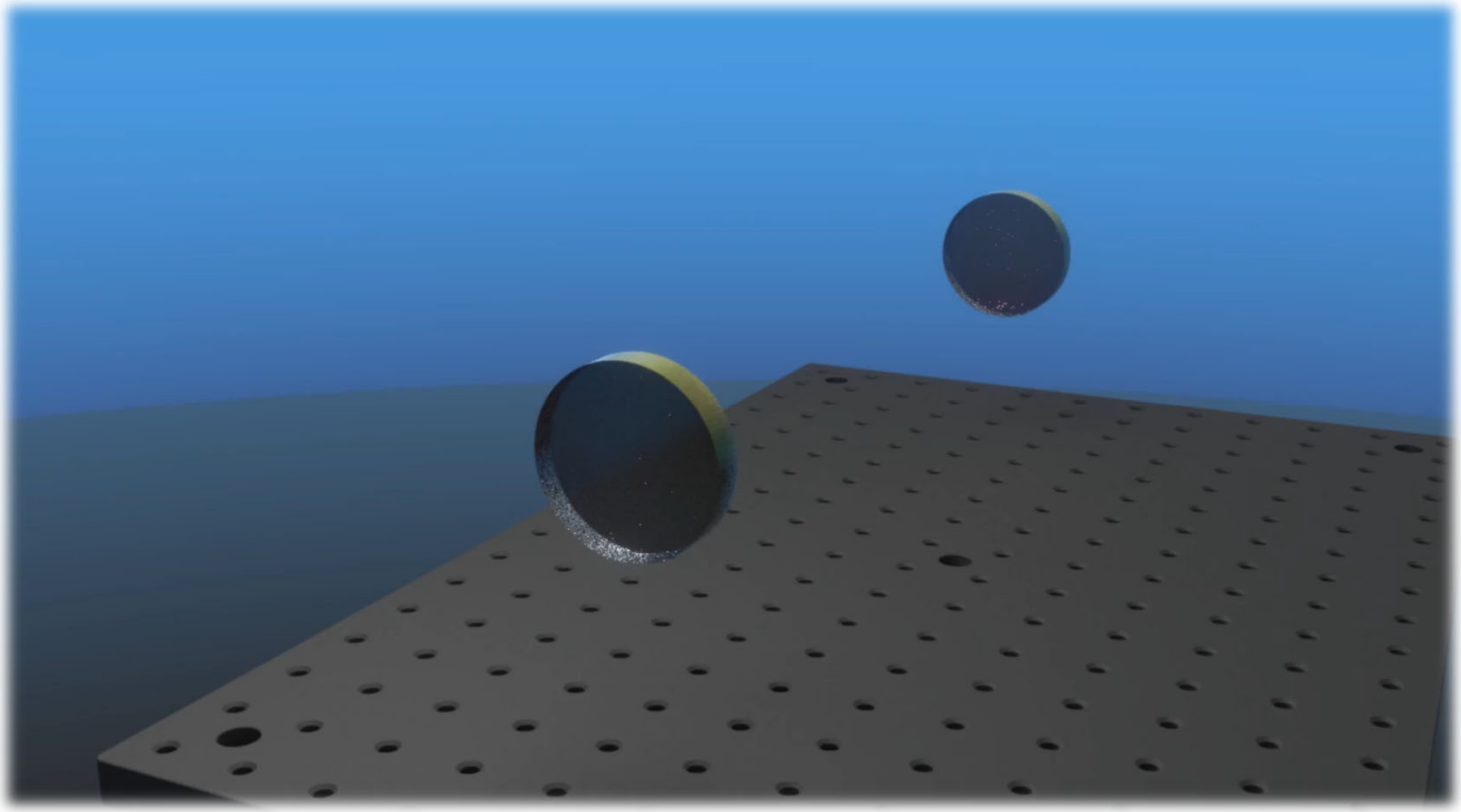
Schulte, et al., Optics Letters., 41, 4511 (2016)

K. Fritsch, et al., Optics Letters., accepted (2018)

M. Ueffing, et al., Optics Letters, vol. 43, 2070 (2018)

L. Lavenu et al., "Nonlinear pulse compression based on a gas-filled multipass cell," Opt. Lett. 43, 2252 (2018).

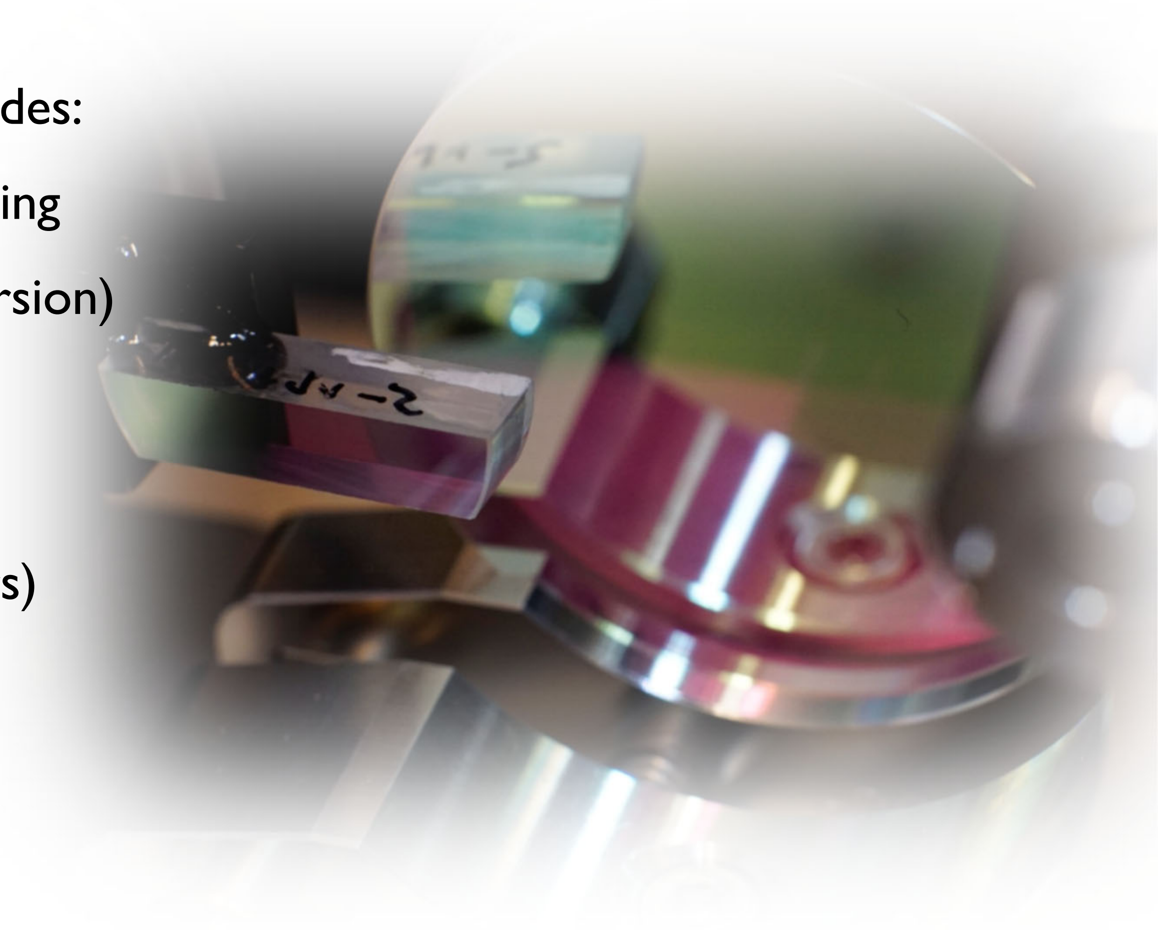
Courtesy Kilian Fritsch



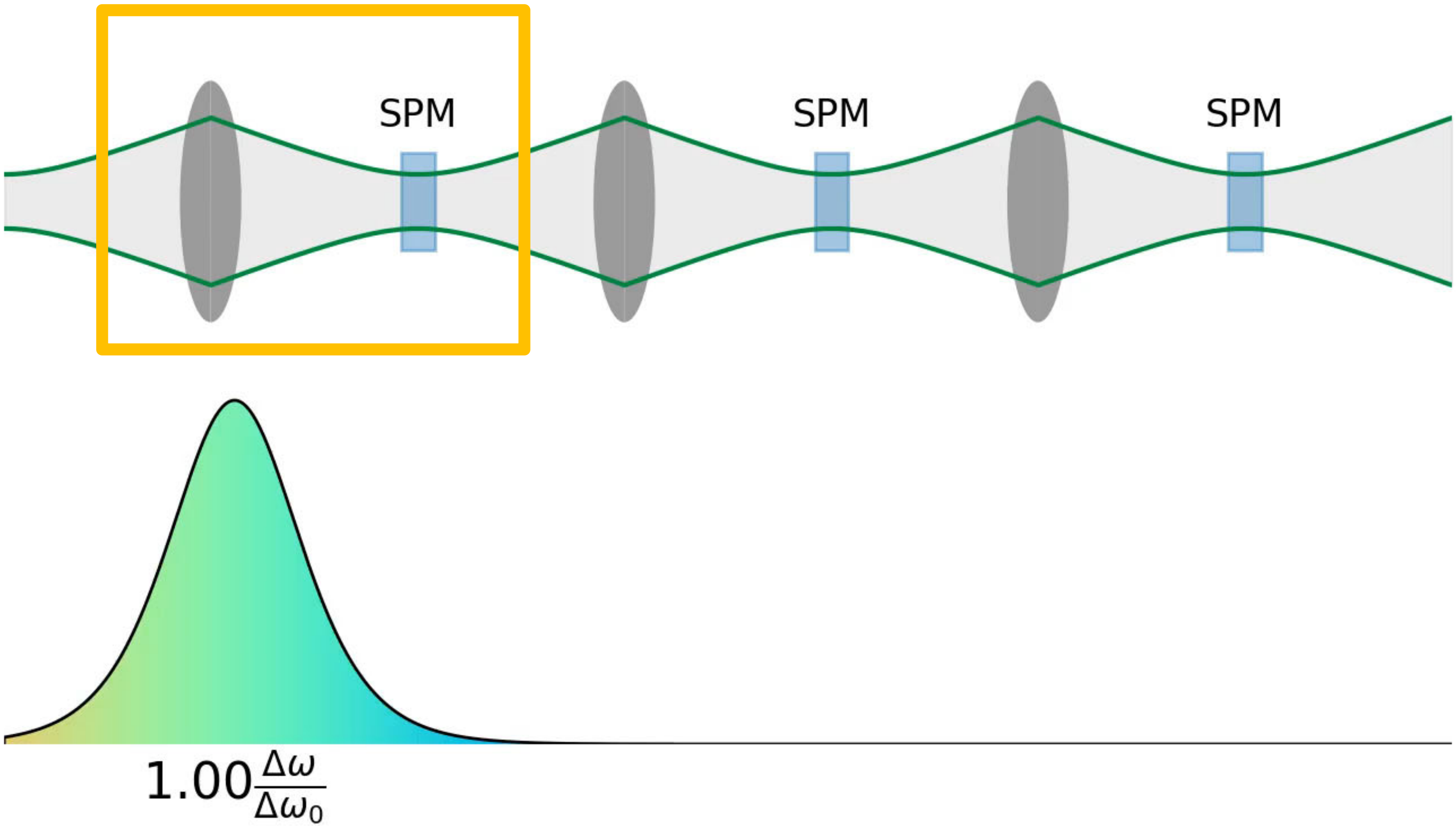
Spectral broadening at high peak powers

- Herriott-type multi-pass geometry provides:
  - easy access to dispersion engineering
    (gas, bulk material or mirror dispersion)
  - peak and average power scalability
  - robustness and simplicity

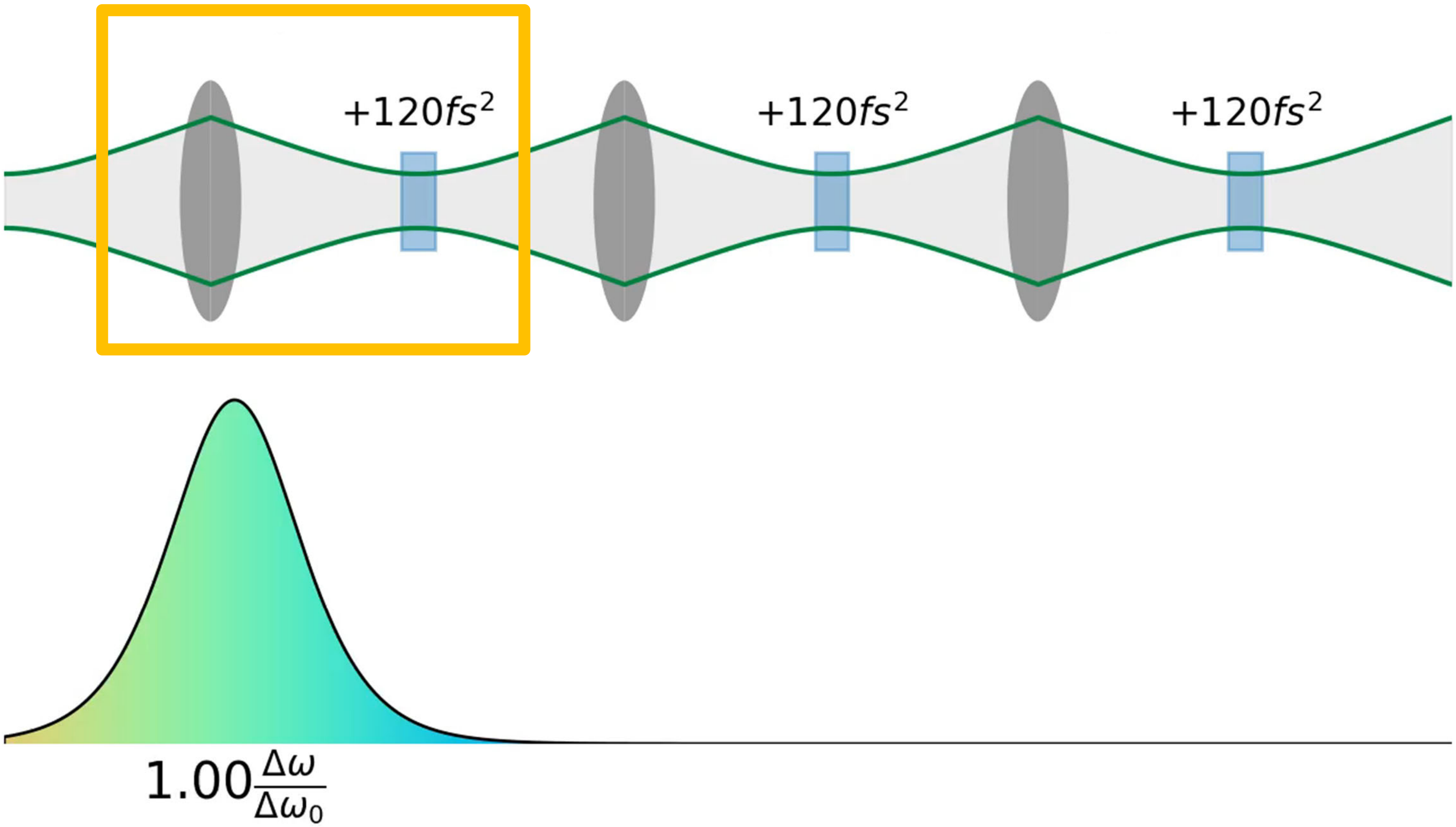
  (compared to photonic crystal fibers)



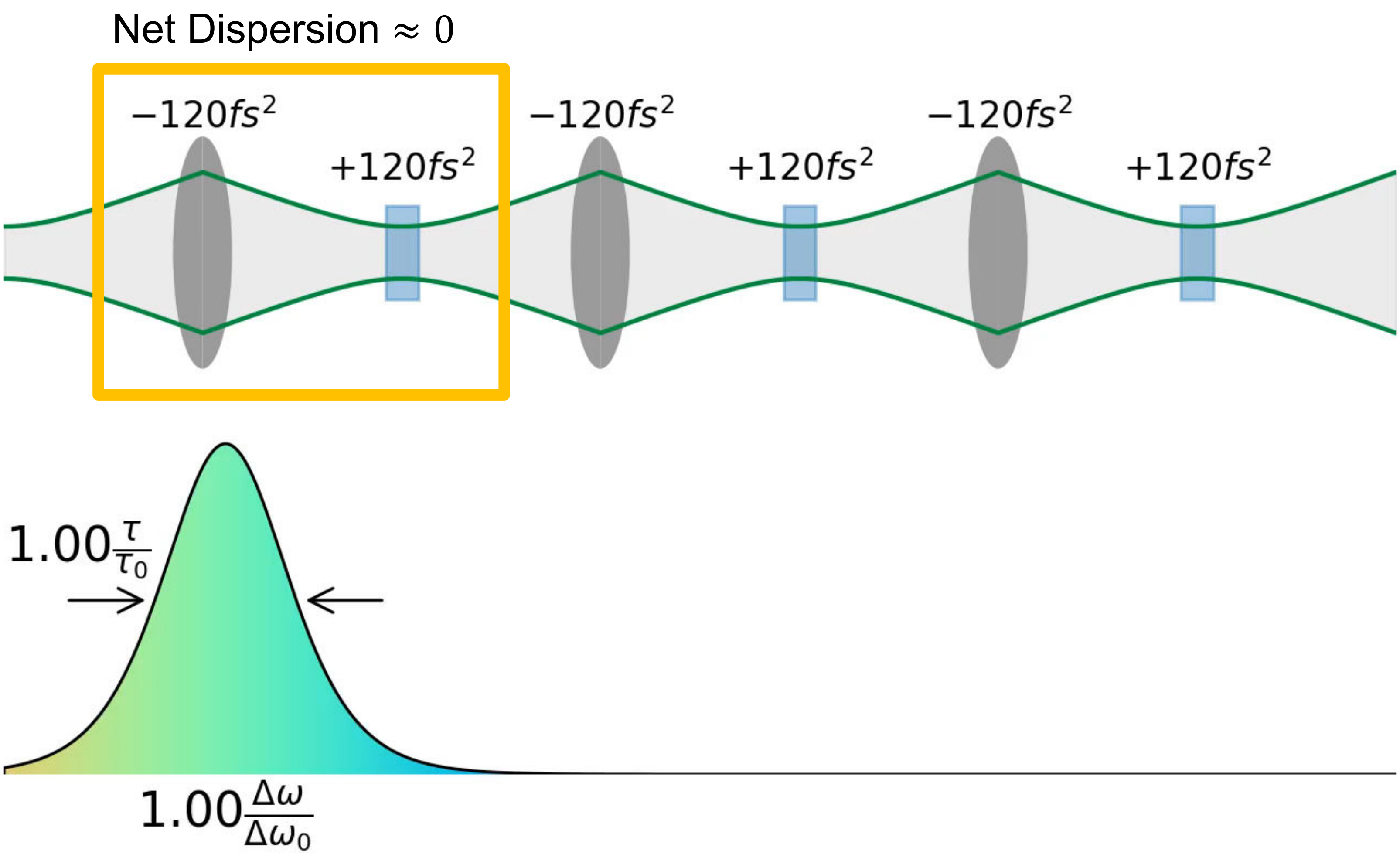
Basic Broadening Principle



Linear Dispersion

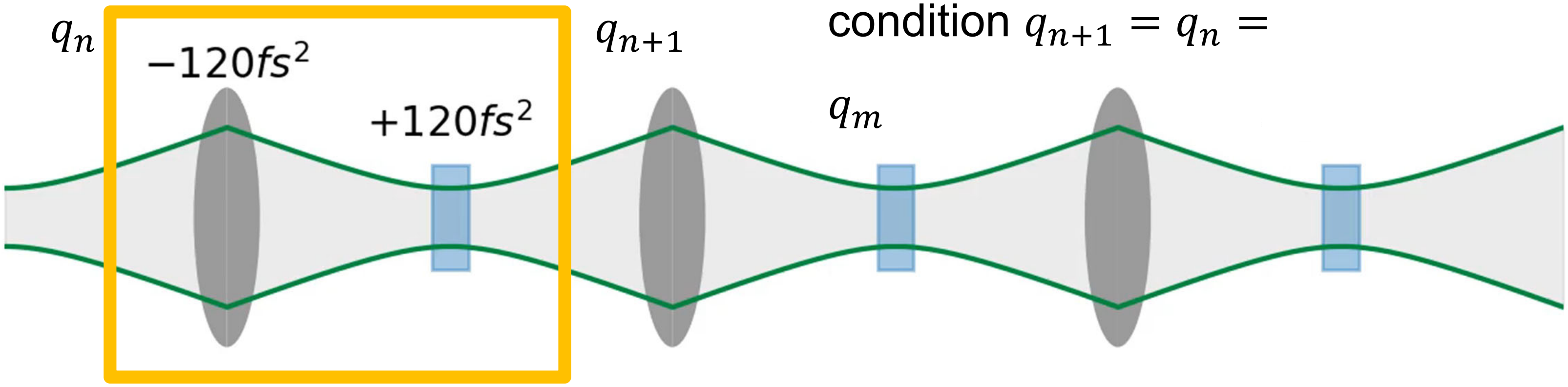


Net Zero Dispersion Regime

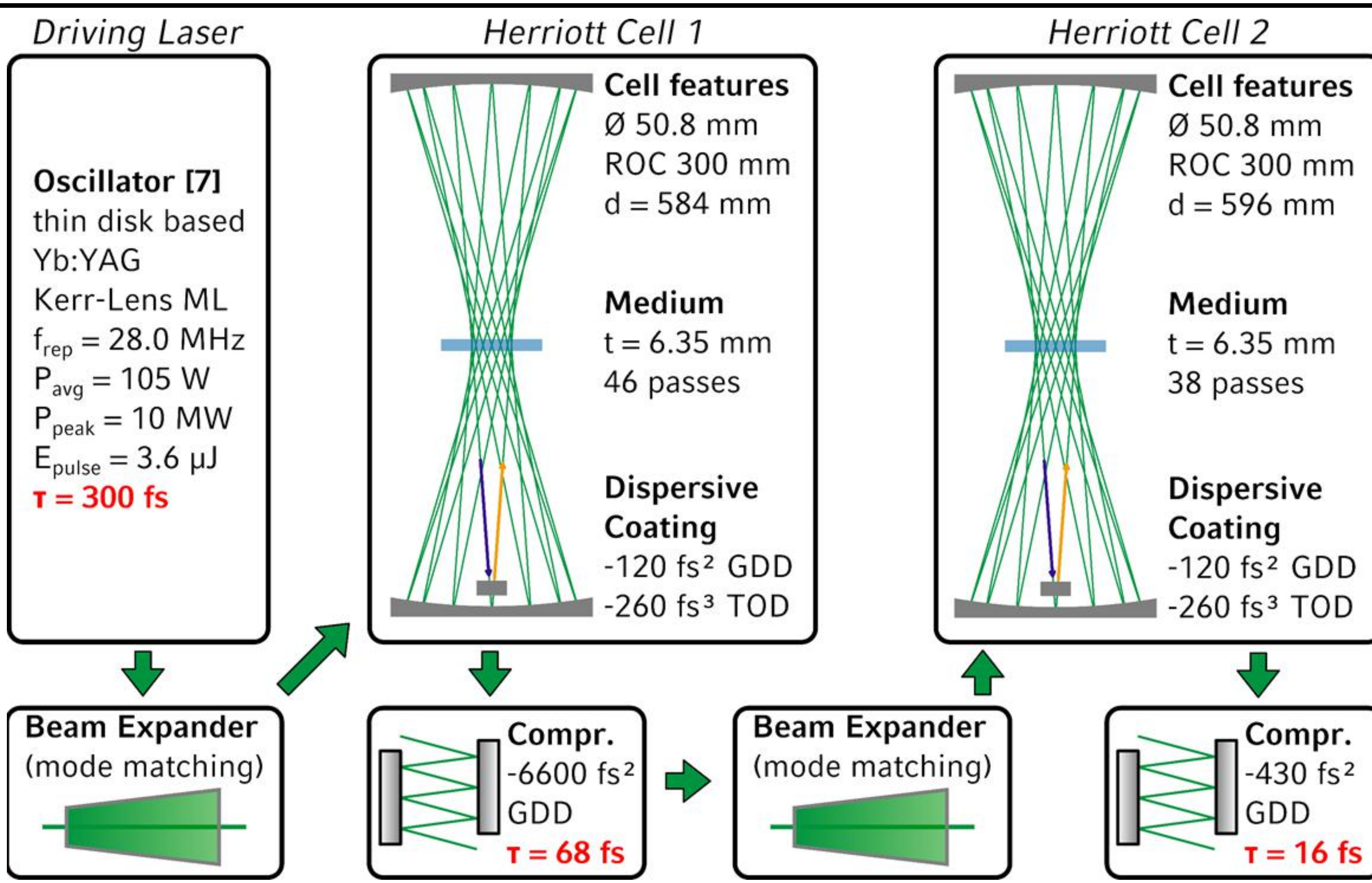


mode-matching

condition $q_{n+1} = q_n = q_m$



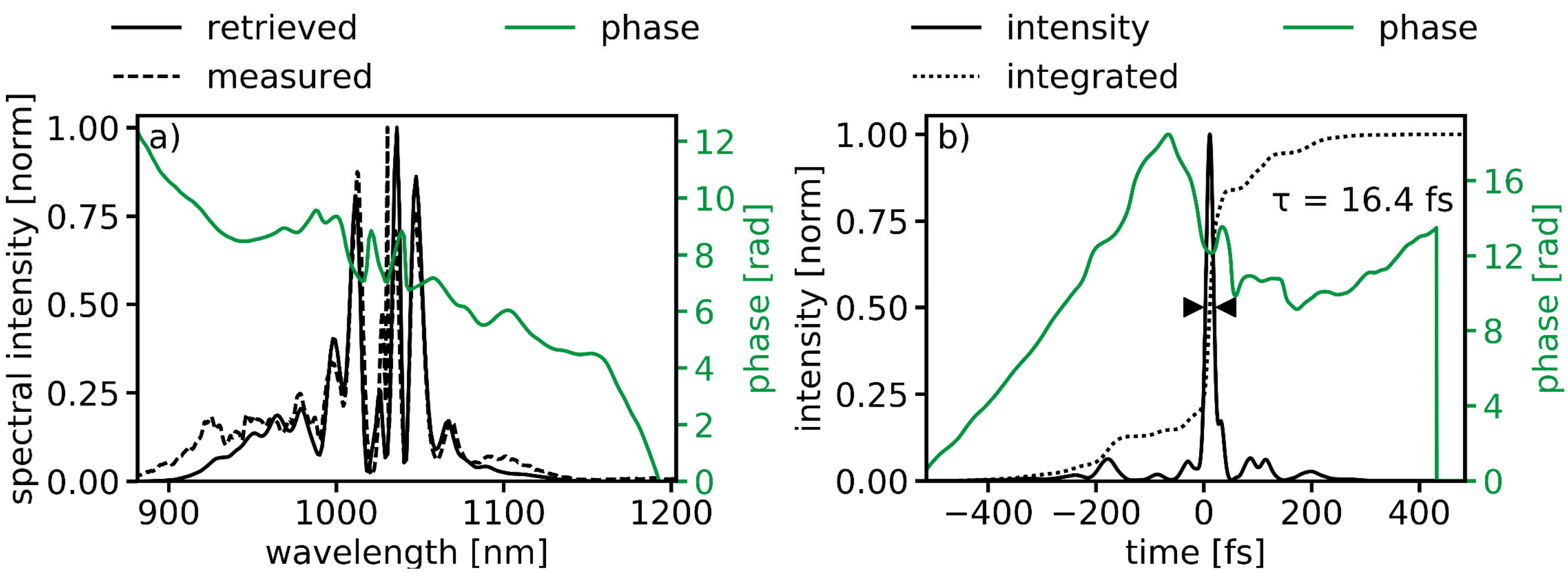
Result: 70 W, 2.6 μJ, 16 fs, 28 MHz



K. Fritsch, et al., Optics Lett.,43, 4643 (2018)

Result: 70 W, 2.6 µJ, 16 fs, 28 MHz

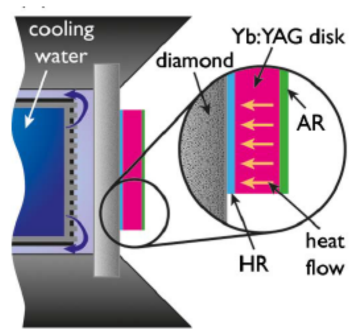
Kilian Fritsch



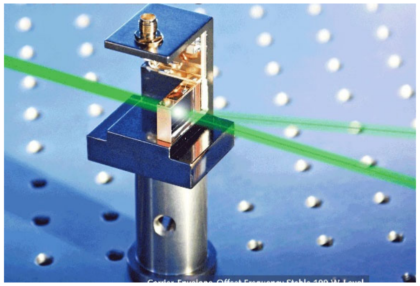
- Two-stages efficiency 70 %
- Peak and average power scalable
- Pulse compression down to 15 fs

Summary

- ❑ Compact, simple and powerful thin-disk oscillators almost ready to go for EUV frequency combs



- ❑ CEO stable thin-disk oscillators



- ❑ Spectral broadening and pulse compression in multi-pass cells