

InnoEUV: Results and Outlook

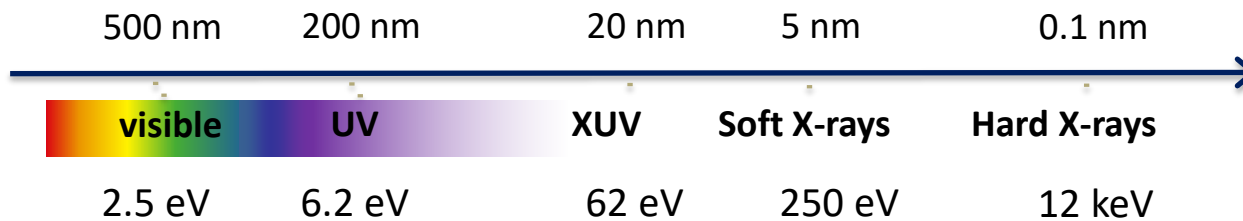
Jan Rothhardt^{1,2,3}

1. Helmholtz-Institute Jena, Fröbelstieg 3, 07743 Jena, Germany

2. Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany

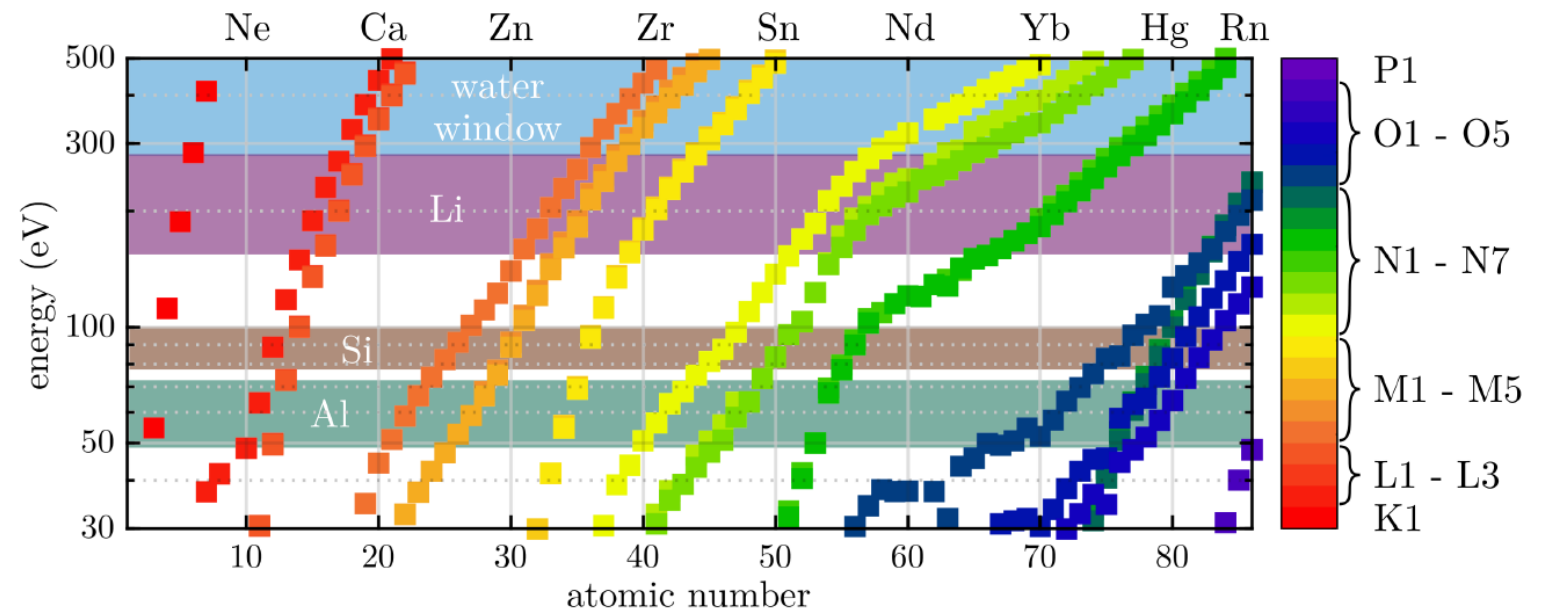
3. Fraunhofer Institute for Applied Optics and Precision Engineering IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany

Extreme Ultraviolet Radiation



Extreme ultraviolet (XUV)

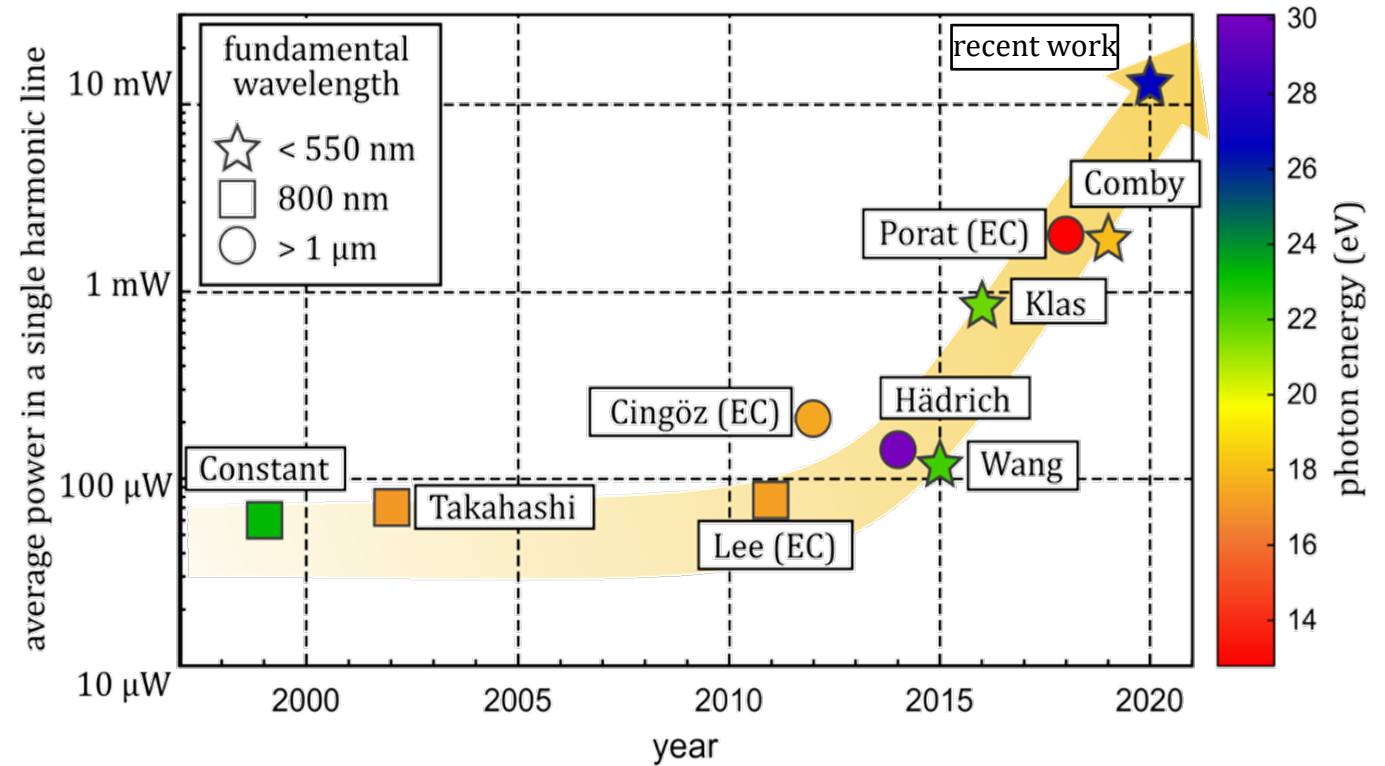
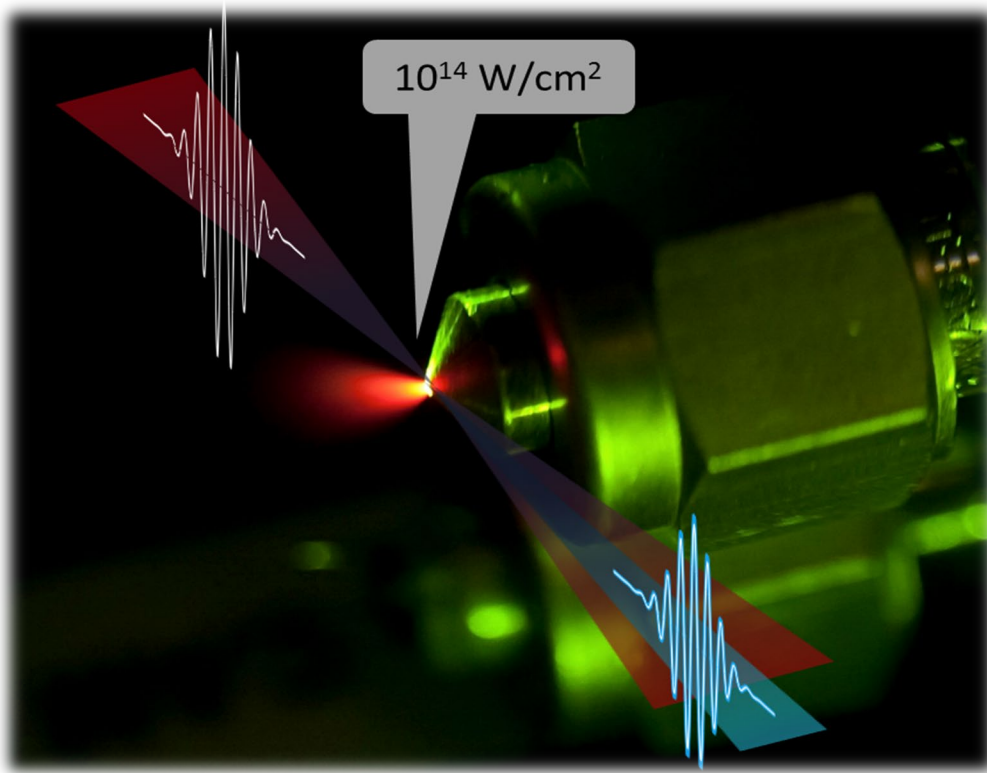
- 10 ... 100 nm wavelength
- 12 ... 120 eV photon energy



- High spatial resolution

- Characteristic atomic absorption edges
- Transparency windows (few- μm absorption length)

Compact EUV Sources based on High Harmonic Generation



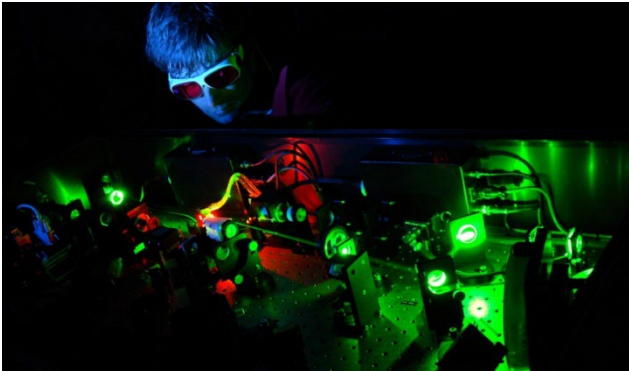
... deliver coherent laser-like EUV radiation !

... have seen an enormous development
& enable novel applications!

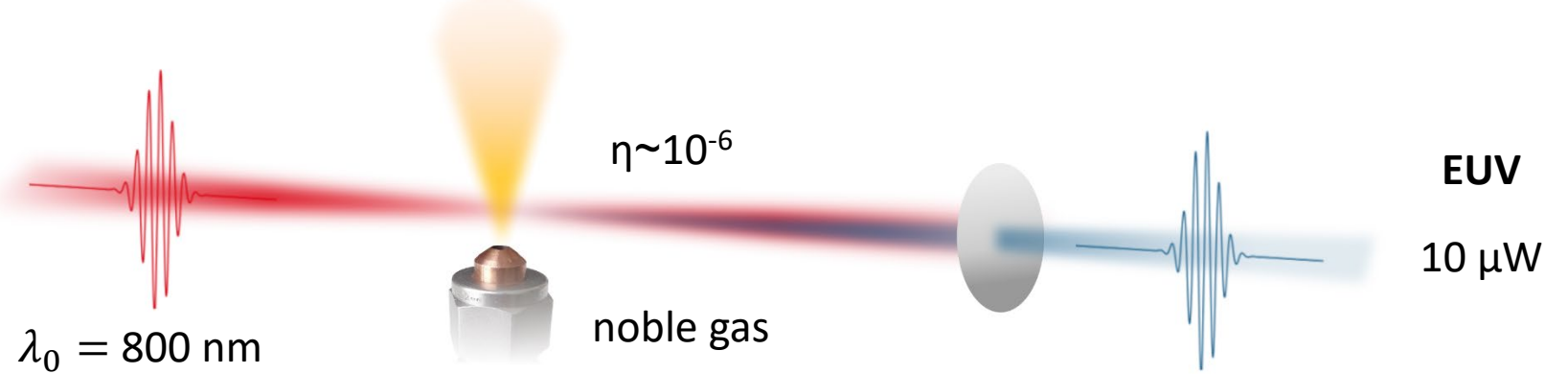
State of the Art: Laser-driven HHG-Sources

Femtosecond laser (Ti:Sa)

$P_{\text{avg}} \sim 10 \text{ W}$



High Harmonic Generation (HHG)



State of the Art: Laser-driven HHG-Sources

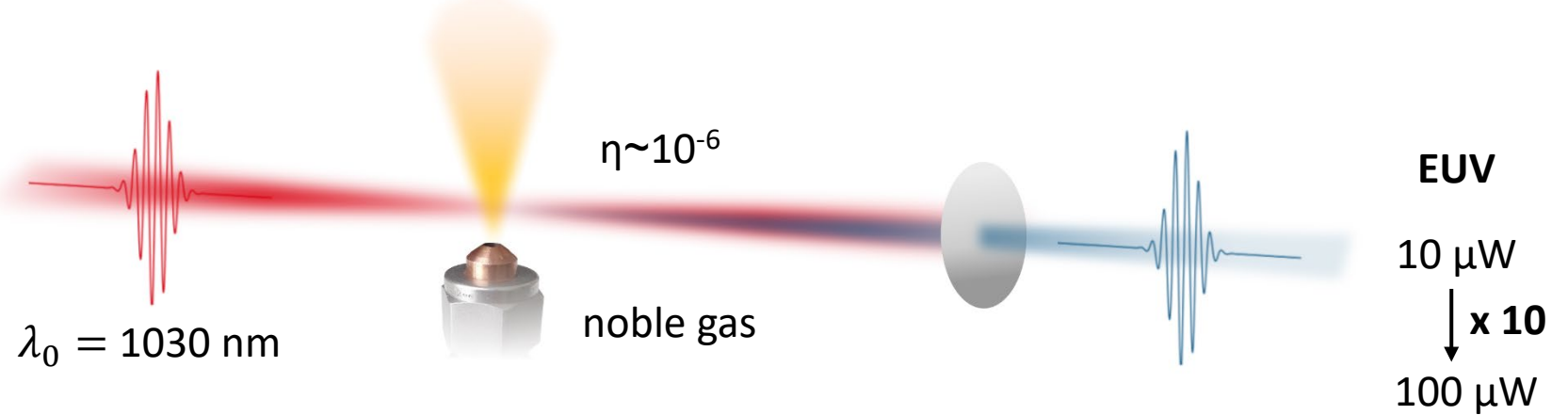
High Harmonic Generation (HHG)

Femtosecond laser

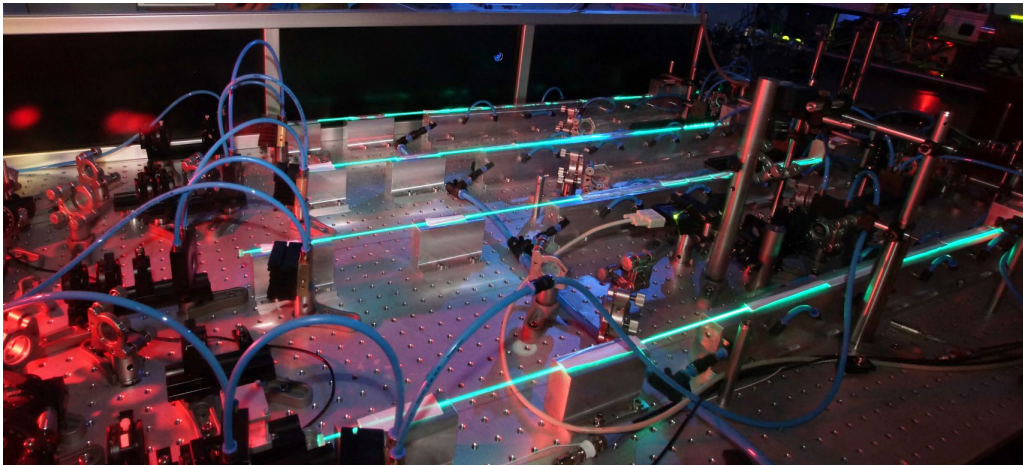
$$P_{\text{avg}} \sim 10 \text{ W}$$

↓ **x 10**

$$P_{\text{avg}} \sim 100 \text{ W}$$

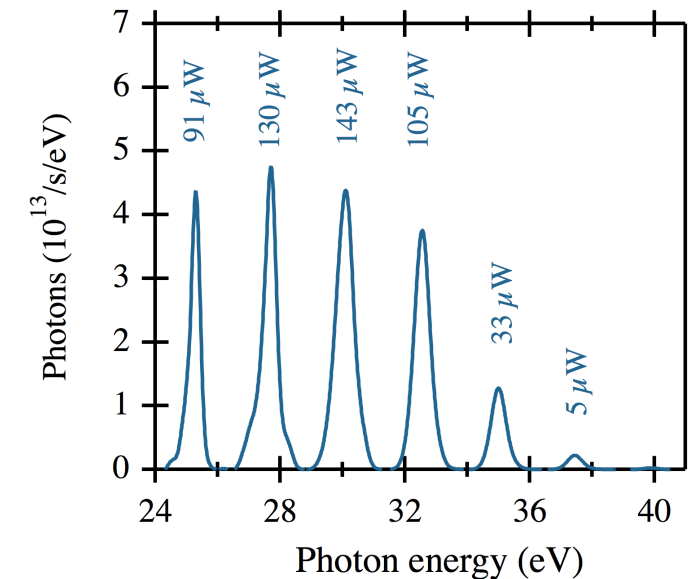


High average power fiber lasers

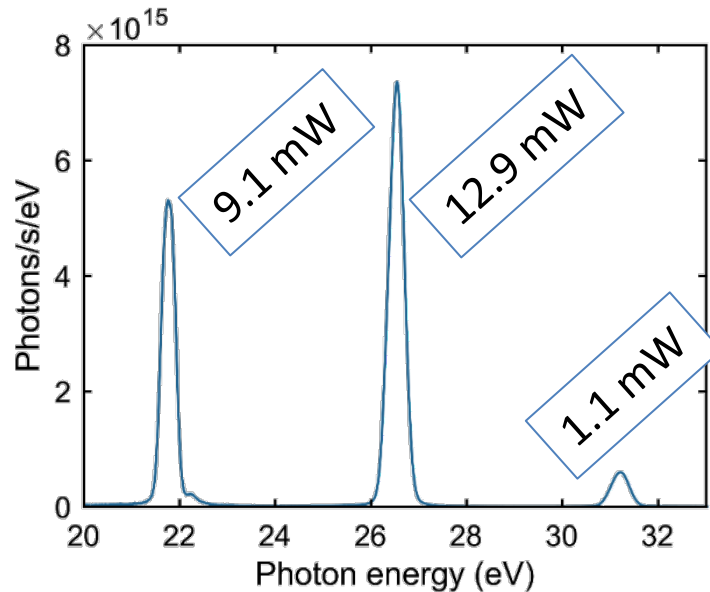
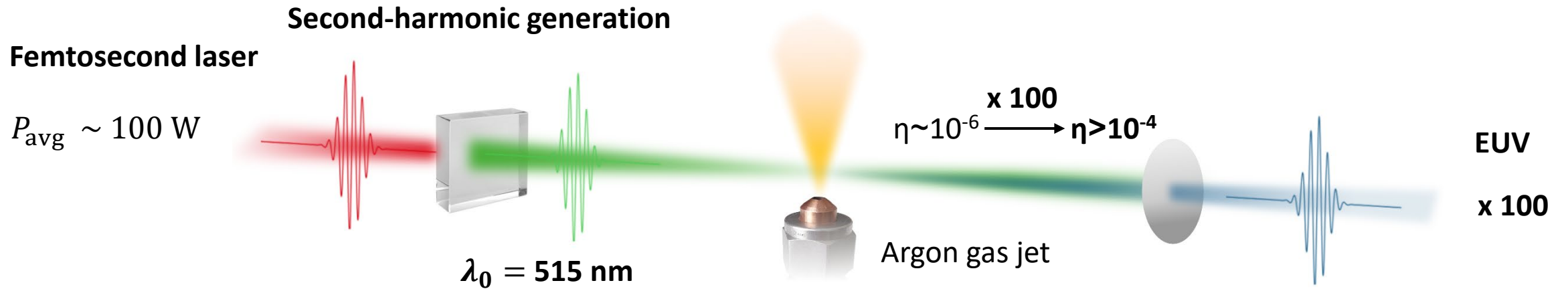


... deliver up to 2 kW of average power

Phys. Rev. Lett. 112, 233002 (2014).
Nature Photon. 8, 779–783 (2014).
New J. Phys. 16, 033022 (2014).



Cascaded frequency conversion

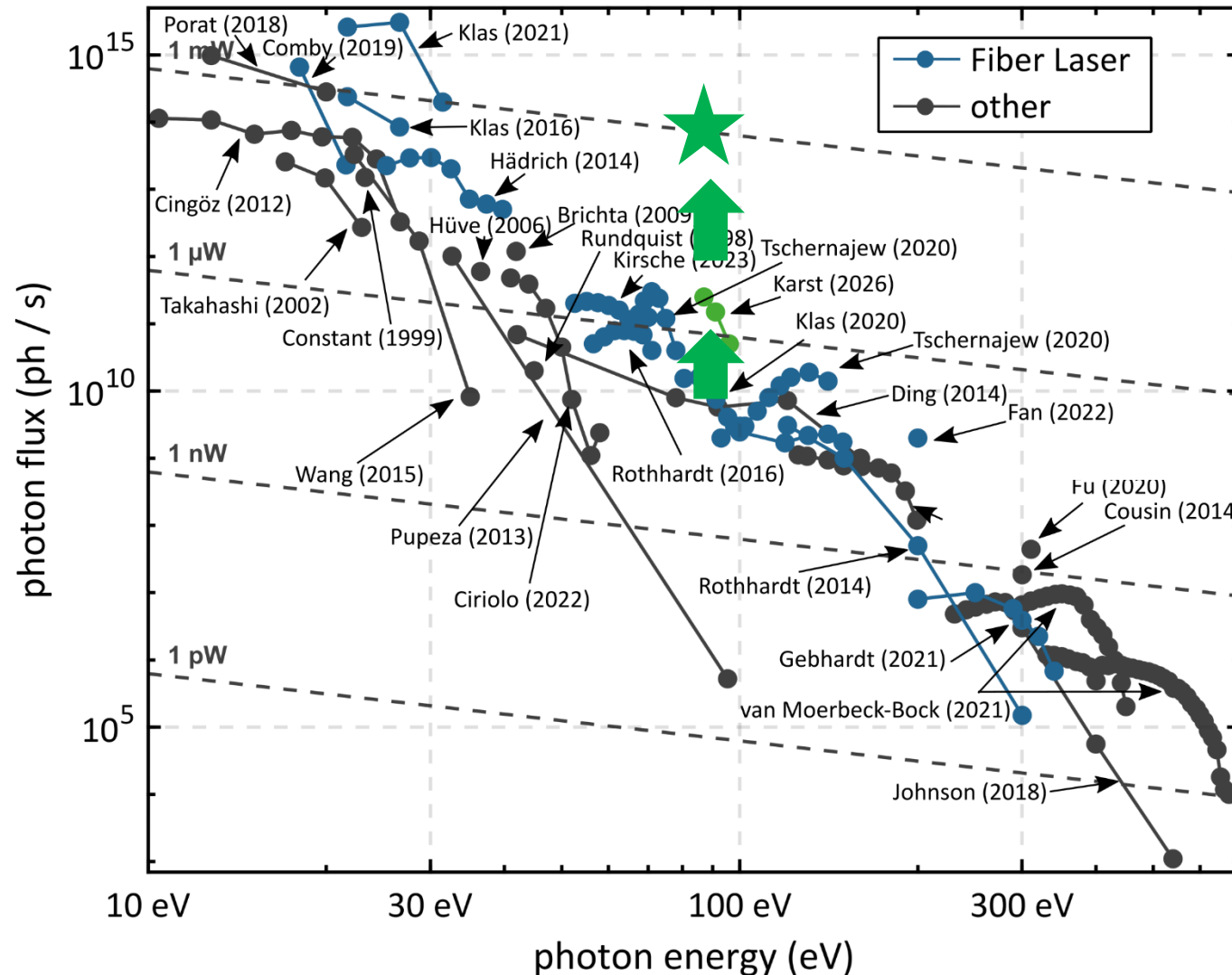


**> 10 mW average power
in a single harmonic line**

Klas et al., Photonix 2 (2021).

World record!

State of the Art in High Harmonic Sources



InnoEUV: Efficient HHG to 13.5 nm

- 10 x higher conversion efficiency
- Record 3 μ W power at 13.5 nm (2%BW)
- Scalable to mW - level

Co-Creation Project: InnoEUV



High Harmonic Generation

What are the optimum driving laser parameters for efficient generation of 13.5 nm (92 eV)?

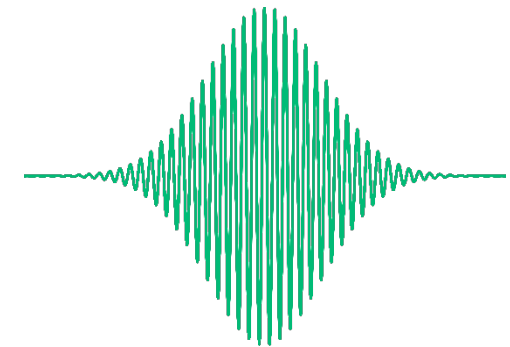
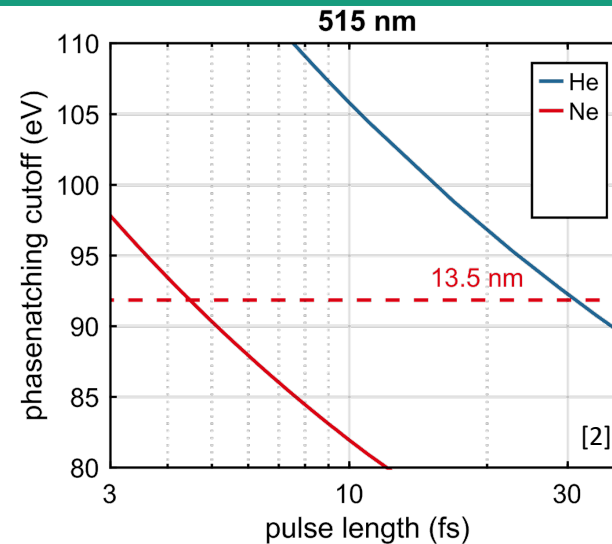
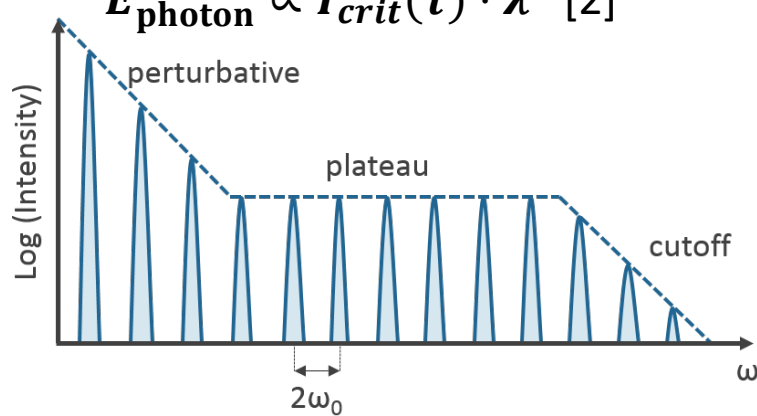
HHG Efficiency

$$\eta \propto \lambda^{-6} \cdot \tau^{-1} [1]$$

1. λ and τ as short as possible for highest efficiency
2. λ long enough to reach a cutoff energy of 92 eV

HHG cutoff (max. photon energy)

$$E_{\text{photon}}^{\text{max}} \propto I_{\text{crit}}(\tau) \cdot \lambda^2 [2]$$



**Perfect driving laser pulses:
515 nm, < 30 fs**

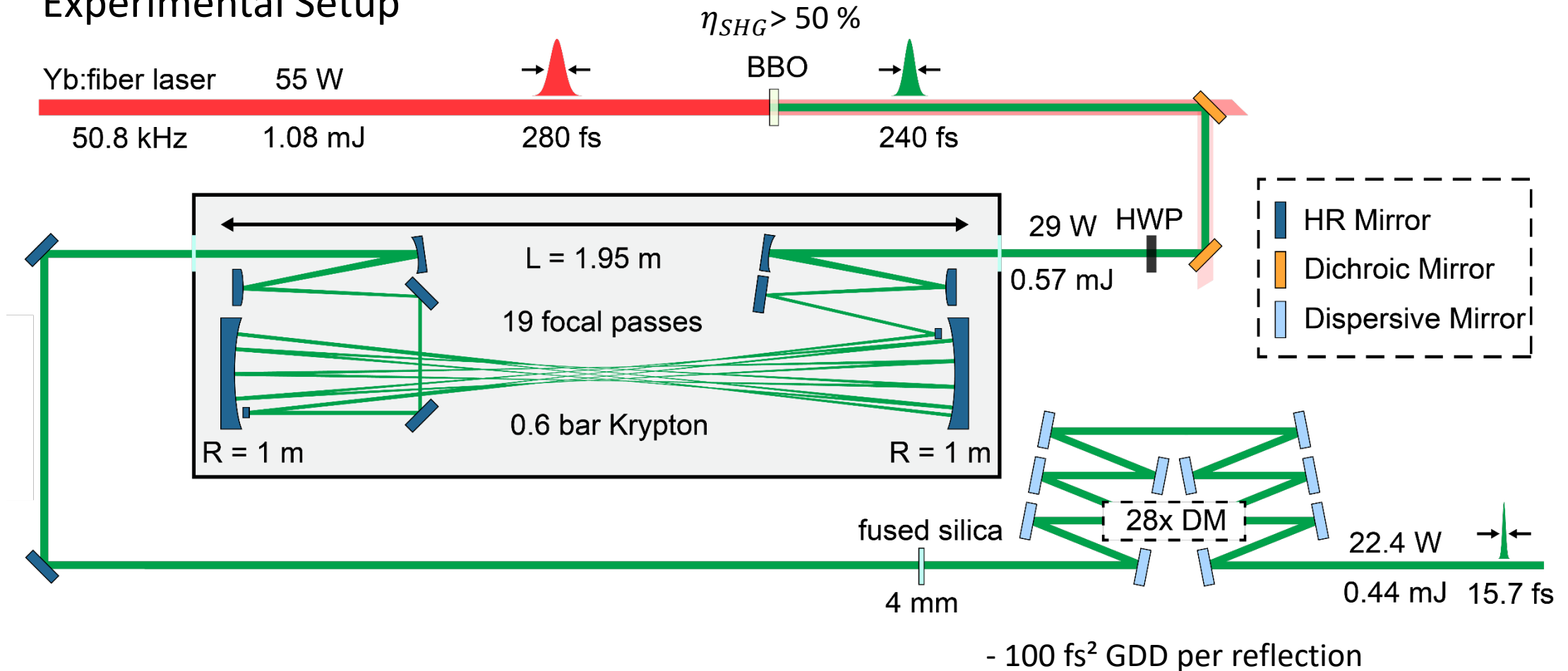
R. Klas et al., *Photonix* 7 (2026).

[1] A. D. Shiner et al., *Physical Review Letters* **103**, 073902 (2009).

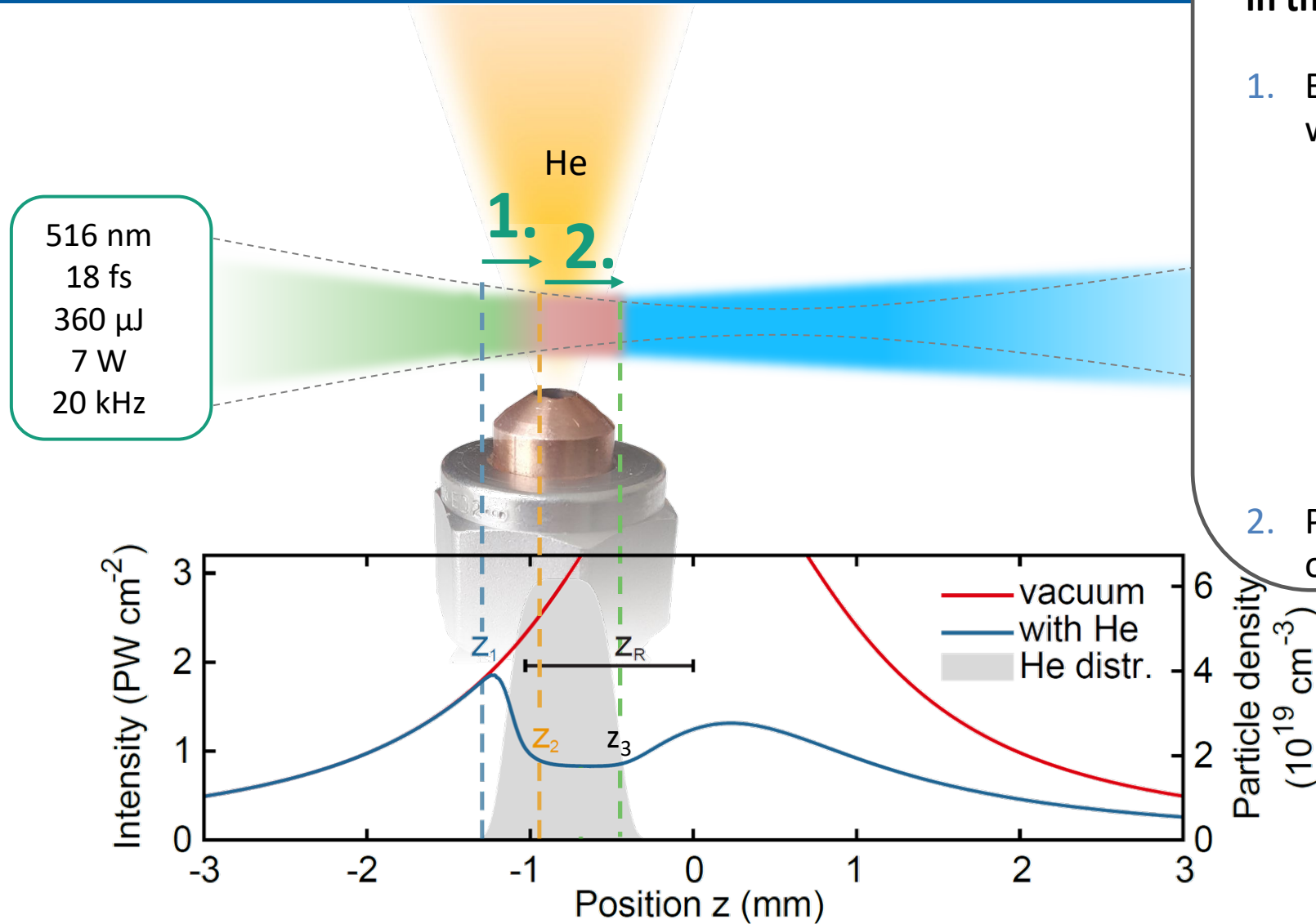
[2] P. B. Corkum, *Physical Review Letters* **71**, 1994–1997 (1993).

Generation of ultrashort, energetic and visible driving pulses

Experimental Setup

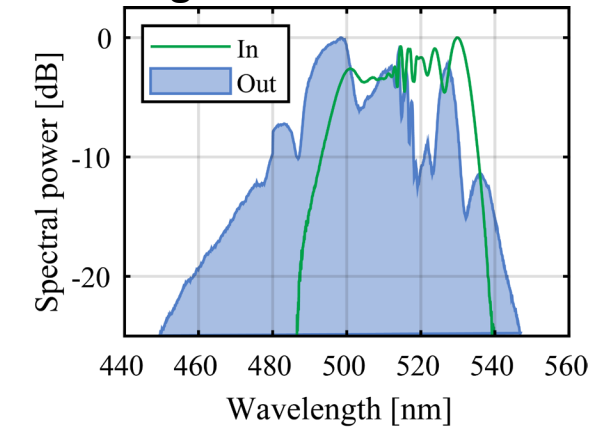


High average power EUV source



2-Step Propagation of the driving laser in the high-density gas-target:

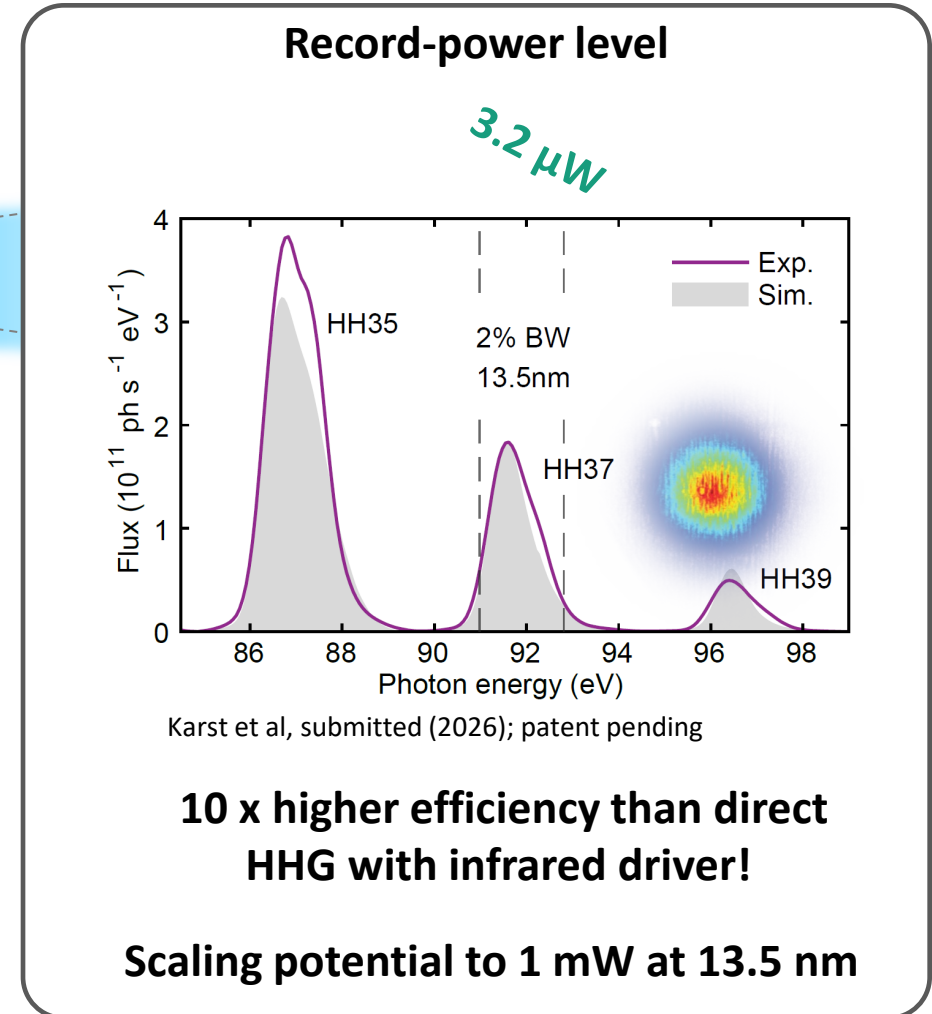
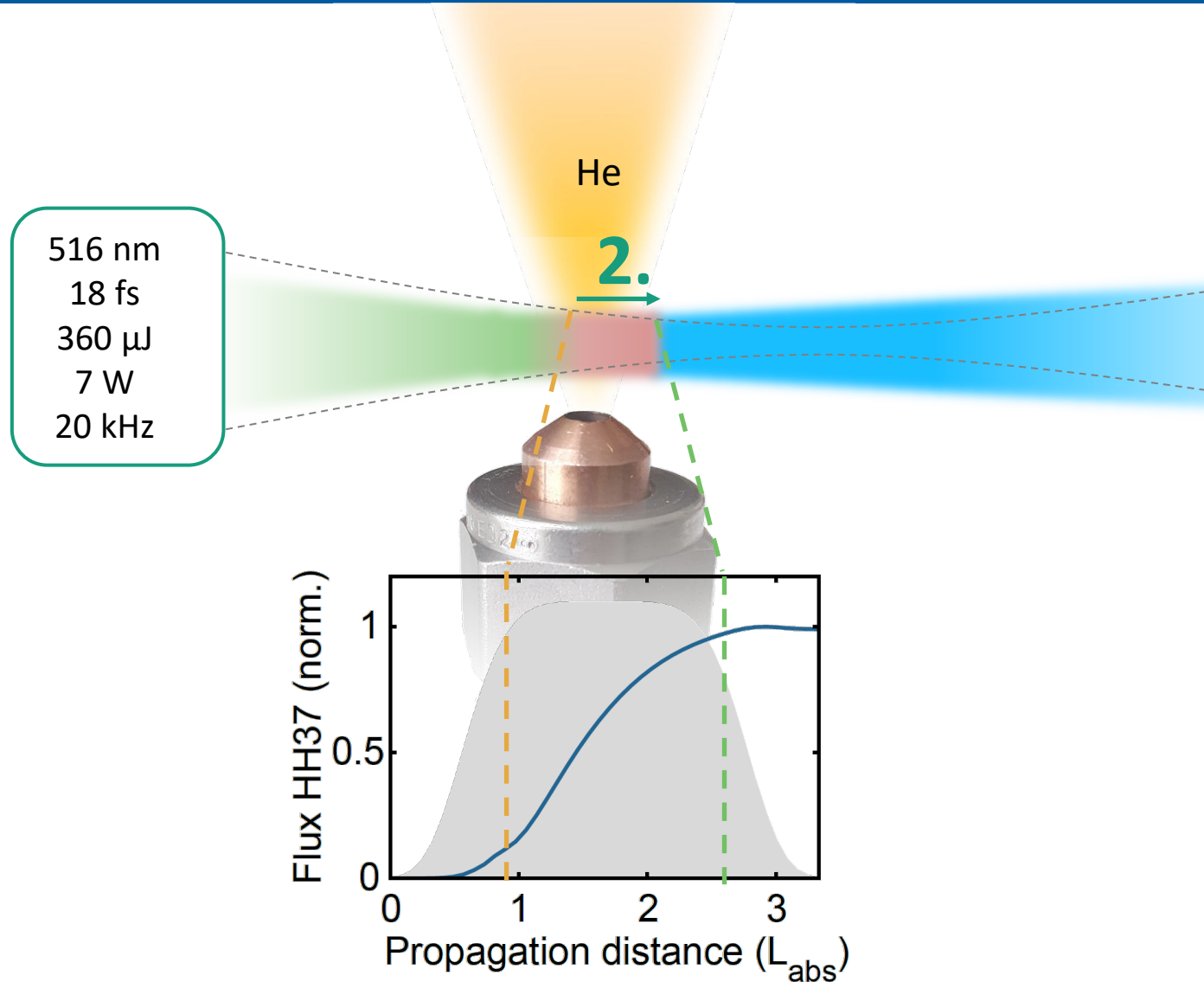
1. Blue shifting of the central wavelength



2. Propagation with constant intensity over a prolonged distance

Patent pending
Karst et al, submitted (2026).

High average power EUV source



- Strategic partnership with industry partner established
- Framework agreement drafted
- German patent application 10 2025 110 210.4 + PCT
- Publication under review in Nature Communications
- Potential industrial applications identified

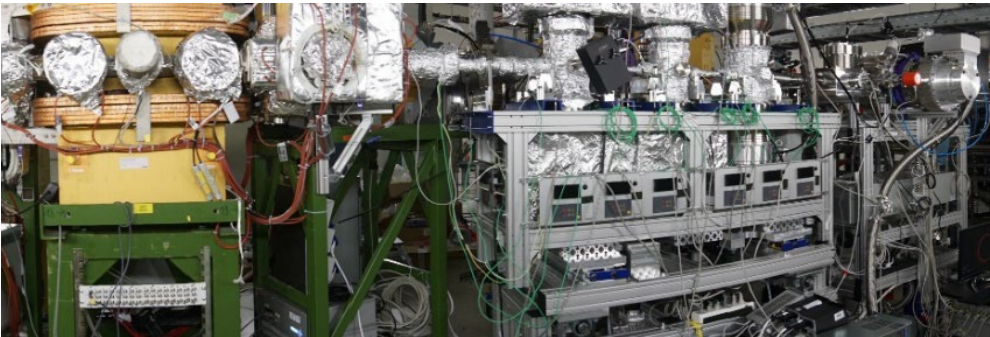


Follow-up proposal for Helmholtz Validation Project

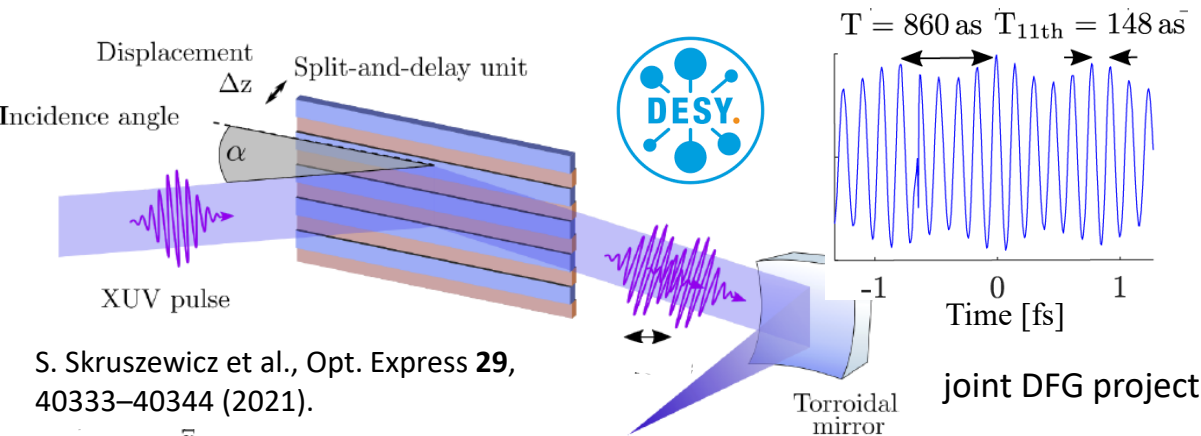
Scientific Applications

Research field matter

EUV enables spectroscopy and interferometry on extreme temporal scales!



J. Rothhardt et al. X-Ray Spect. **49**, 165–168 (2020).

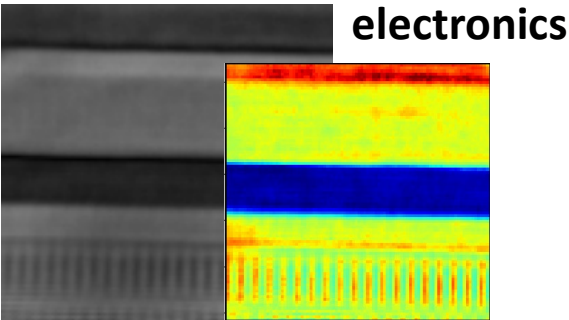


Links to other research fields

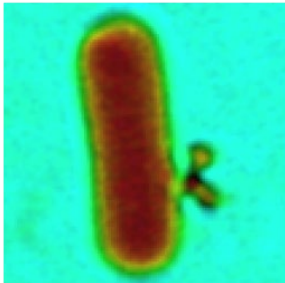
EUV microscopy provides novel insights into structure and dynamics at the nanoworld!

Security

W. Eschen et al.,
Light: Science & Applications 11,
(2022).



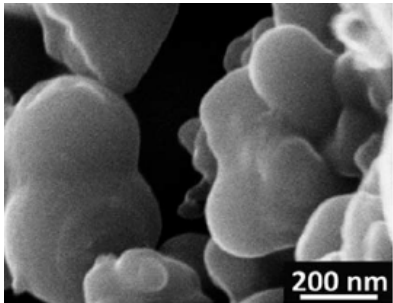
Health



biological imaging

C. Liu et al. PhotoniX 4, (2023).
C. Liu et al., PhotoniX 7, (2026).

Sustainability

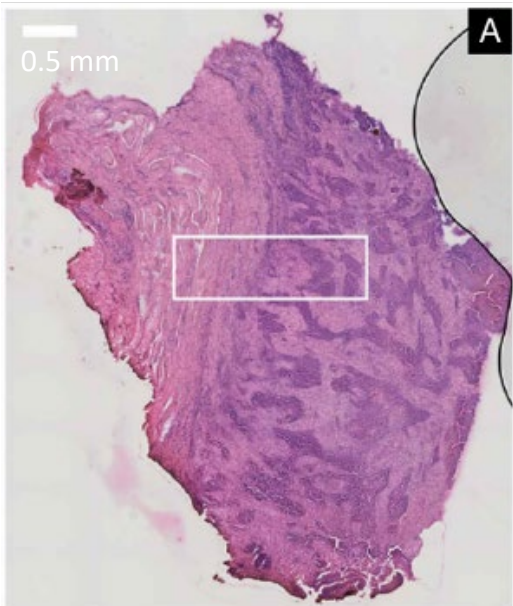


energy materials

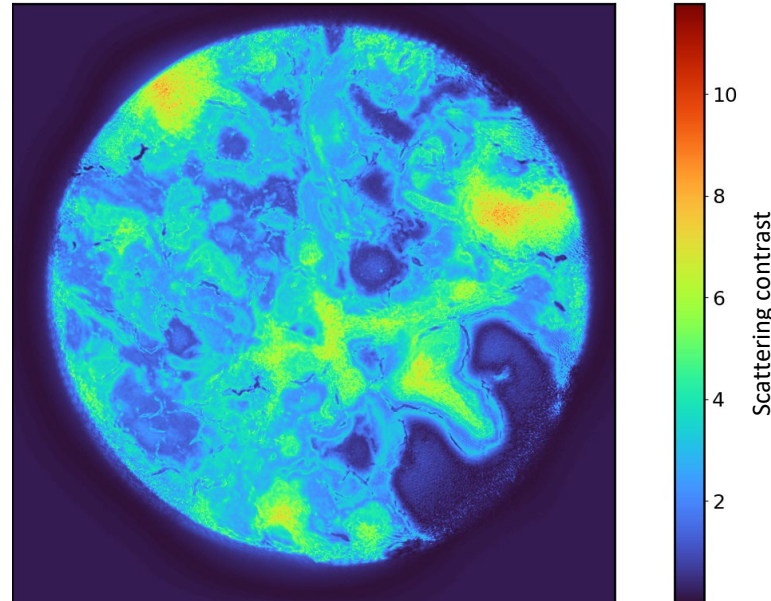
A. Baasner et al., J. Mater. Chem. A 6, 14787–14796 (2018).

High-resolution and chemically sensitive medical diagnostics

EUV microscopy as a new label-free high resolution diagnostic tool



A) Overview of an H&E-stained tissue section;
Calvarese et al., Sci. Adv. 10, eado9721 (2024)



First EUV microscopy image of biological tissue

Proposal „MediEUV“ submitted to BMBF- call „*Photonic and Quantum-Based Technologies for Medical Diagnostics*“

Conclusion & Outlook

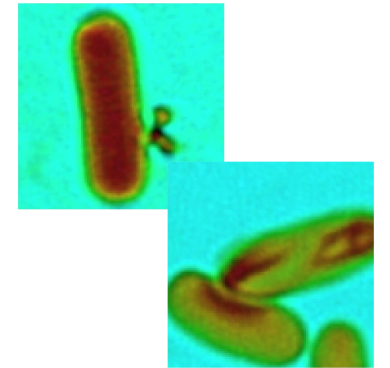
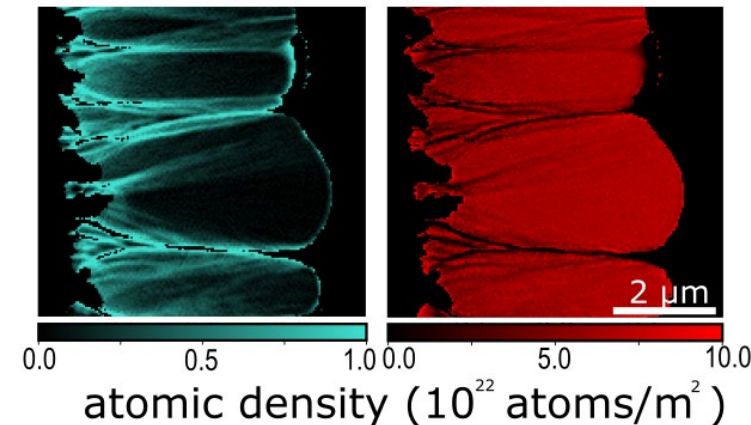
New performance level of HHG sources at 13.5 nm

- Record 3 μW power in 2%BW
- Scalable to mW - level

Strategic partnerships with industrial partners established - new projects towards applications!

Applications in fundamental science:

- ultrafast spectroscopy of atoms, molecules and HCl
- EUV microscopy for material science applications and medical diagnostics



Thank you for your attention!