High-Harmonic Generation for Metrology Applications

EUV Source Workshop, Dublin, November 7th 2017

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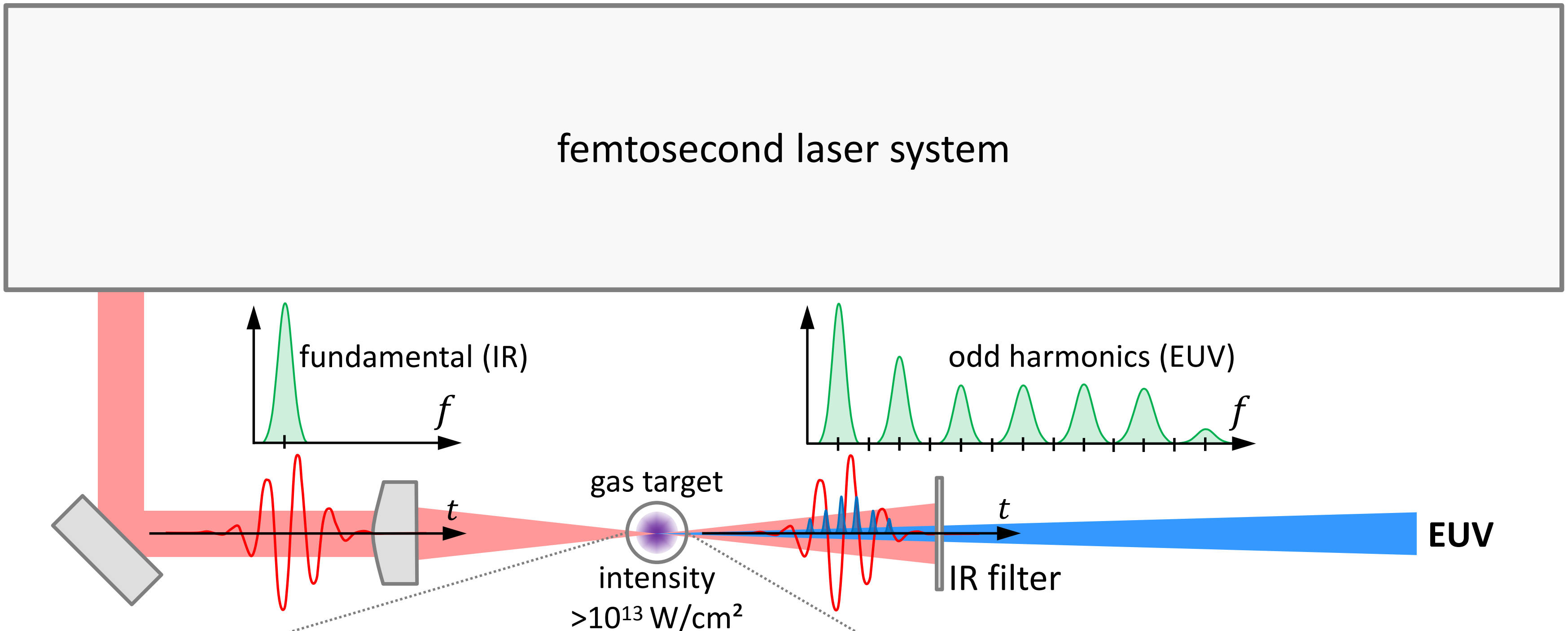
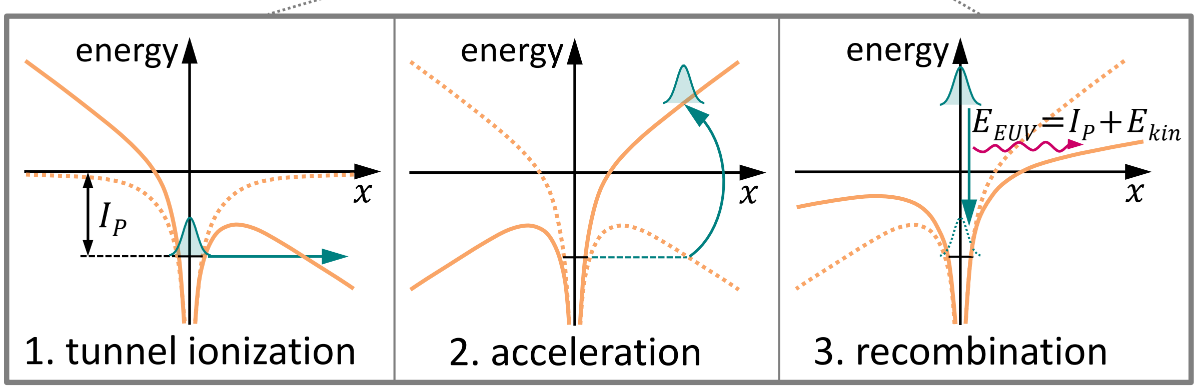
High-Harmonic Generation for Metrology Applications – Outline

- High-harmonic generation (HHG) as a coherent EUV source
- Applications of HHG-sources
  - EUV frequency comb spectroscopy
  - Photoelectron spectroscopy
- HHG at high repetition rate
  - Enhancement resonators
  - Geometrical output coupling
- Laser systems to drive HHG
  - High-power amplifier
  - Nonlinear pulse compression

High-Harmonic Generation as a Coherent EUV Source





High-harmonic generation

Coherent process: spatially and temporally/spectrally coherent EUV source [1],[2]

EUV pulse every half-cycle

Partial ionization of gas target

Phase matching crucial

[1] A. Cingöz et al., Nature 482, 68-71 (2012).
[2] Benko et al., Nature Photon. 8, 530-536 (2014).

High-Harmonic Generation for Metrology Applications

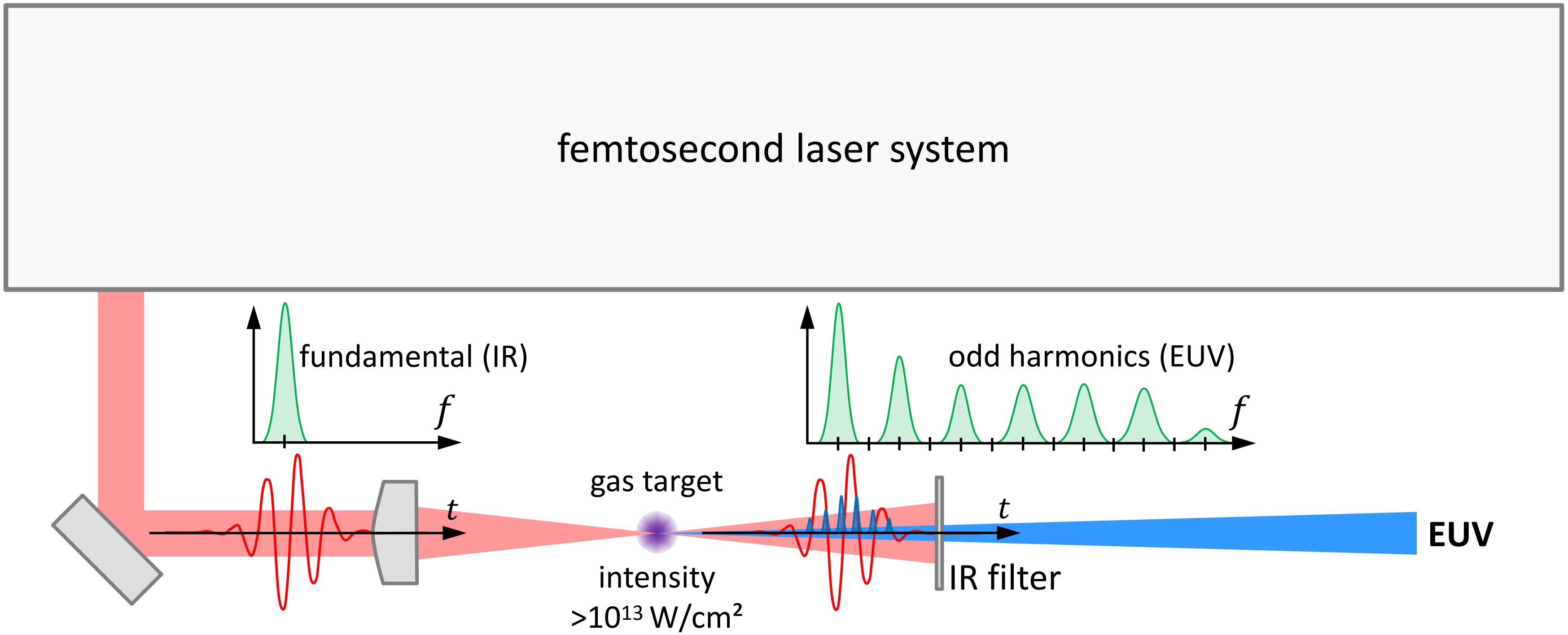


Table-top coherent EUV / soft X-ray source:

- EUV frequency comb spectroscopy
- (Time-resolved) photoelectron emission spectroscopy
- Attosecond physics
- Microscopy, surface inspection, coherent diffractive imaging
- EUV lithography, direct structuring

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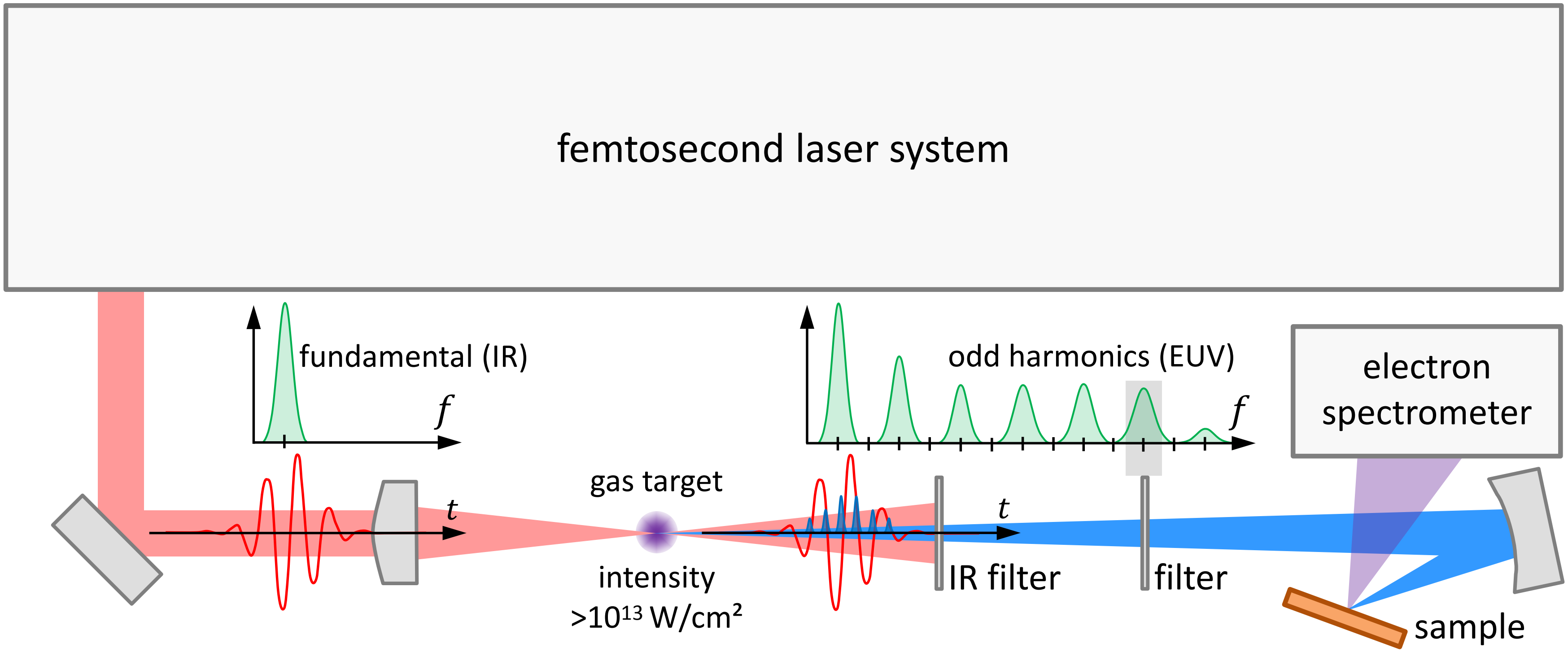

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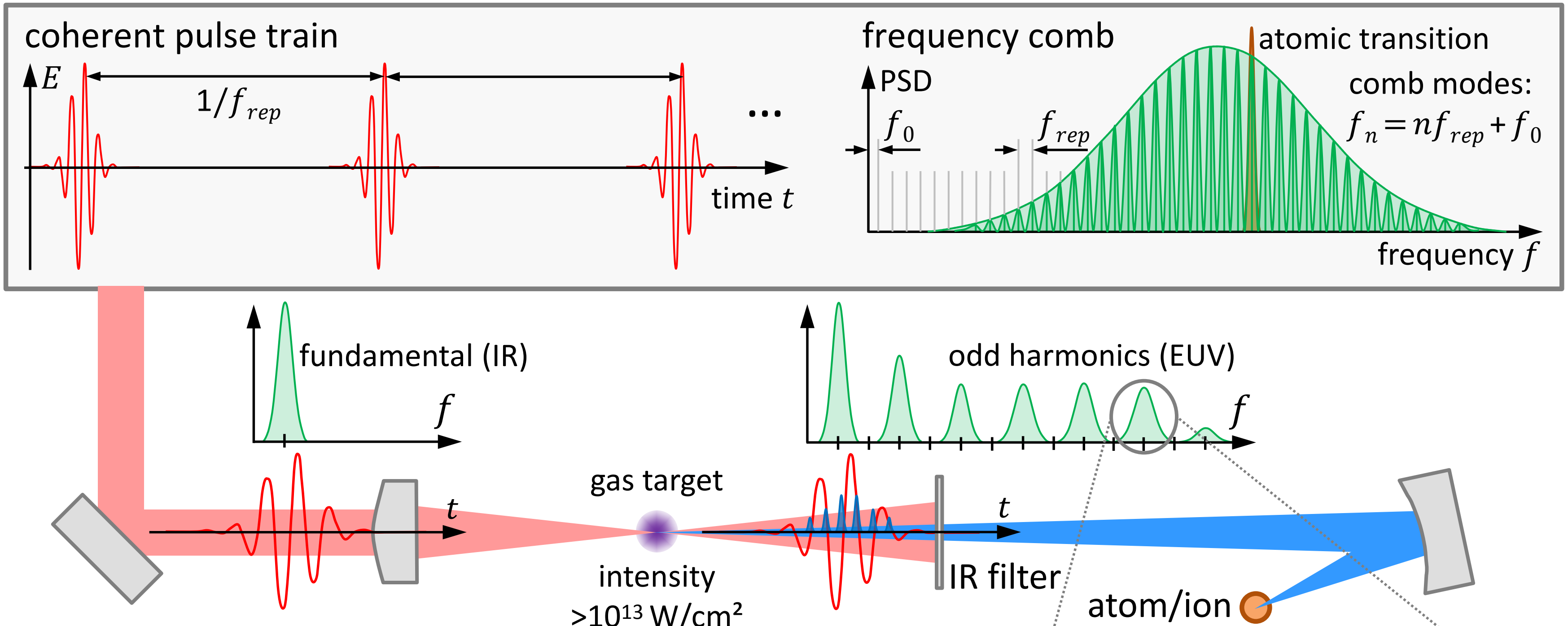
Photoelectron emission spectroscopy

<1 electron per EUV pulse to avoid space-charge effects

large repetition rate improves signal

EUV Frequency Comb Spectroscopy



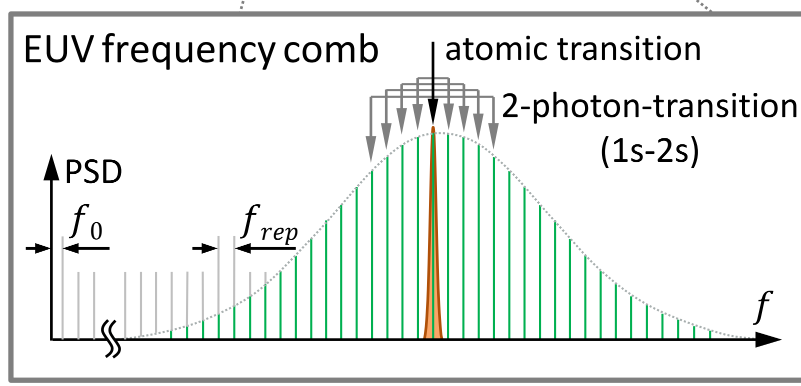
EUV frequency comb spectroscopy has been performed on argon (82 nm), neon (63 nm) [1] and xenon (147 nm) [2].

We aim for spectroscopy of the 1s-2s transition in He^+:

Experimental test of bound-state QED.

Comb at 60.8 nm can be generated as H17 of 1033 nm.

All comb modes can contribute to 2-photon-transition, required power >100 µW for reasonable excitation rate [3].



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[1] A. Cingöz et al., Nature 482, 68-71 (2012).
[2] A. Ozawa et al., Phys. Rev. A 87, 022507 (2013).
[3] M. Herrmann et al., Phys. Rev. A 79, 052505 (2009).

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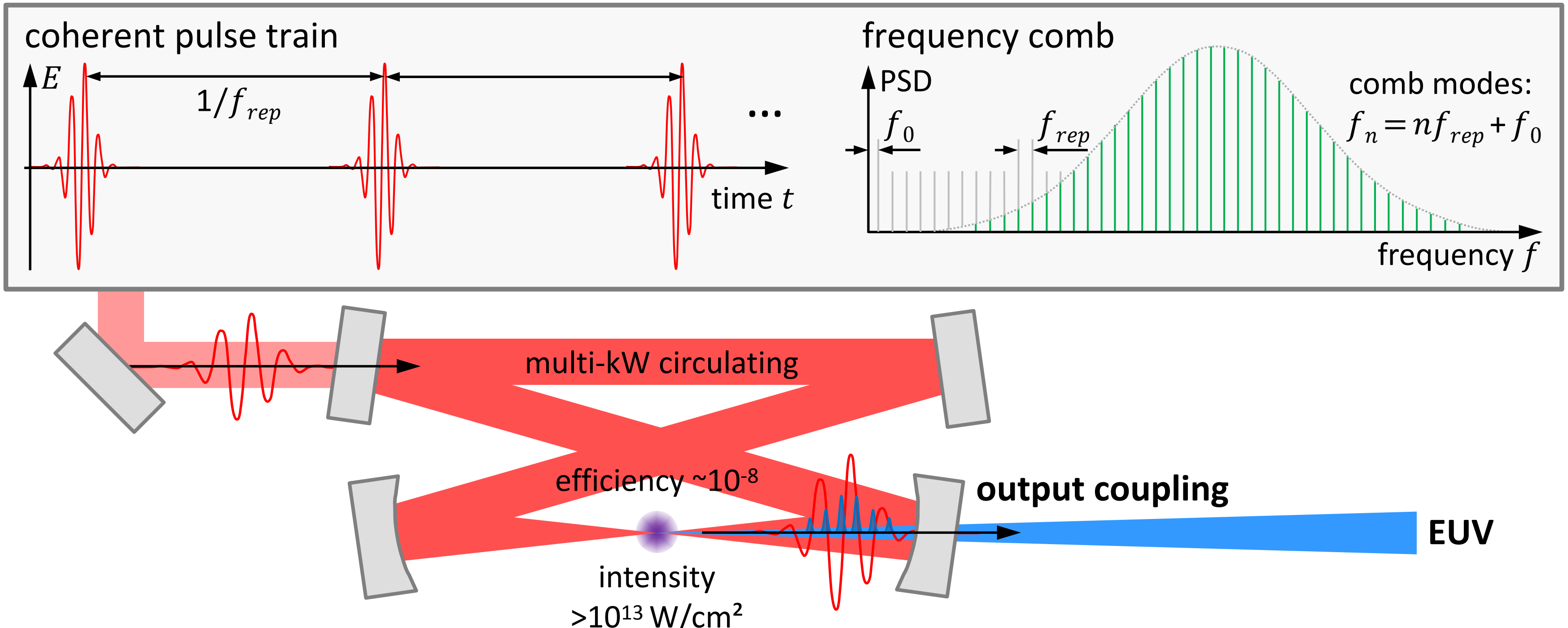
High-Harmonic Generation at High Repetition Rate



Enhancement resonator

Reach necessary intensity also at high repetition rates

Efficiency boost (~100) by recycling of non-converted driving radiation

Feasible for repetition rates >10 MHz (length <30 m)

Resonator has to be locked to the incident frequency comb

Intensity clamping due to ionization [1]

Challenge: Output-coupling of harmonics from the resonator

[1] I. Pupeza et al., Nat. Photon. 7, 608 (2013).

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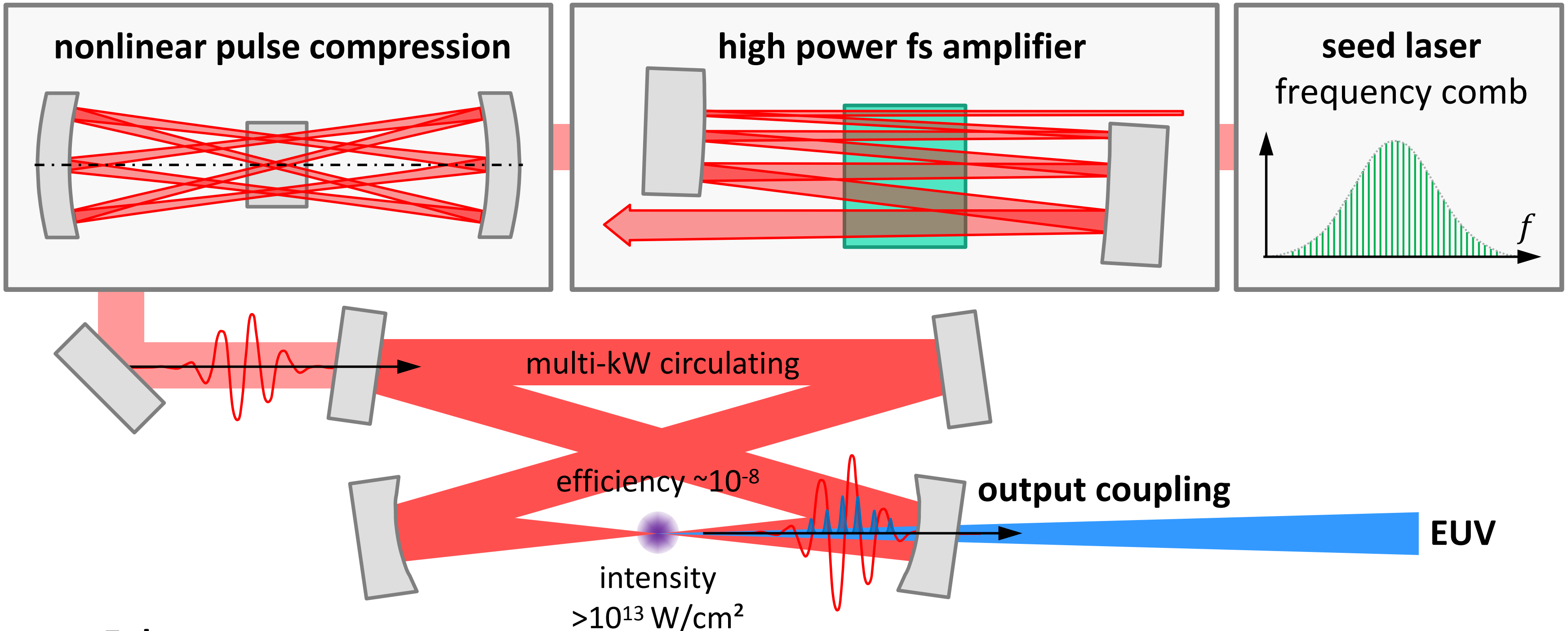

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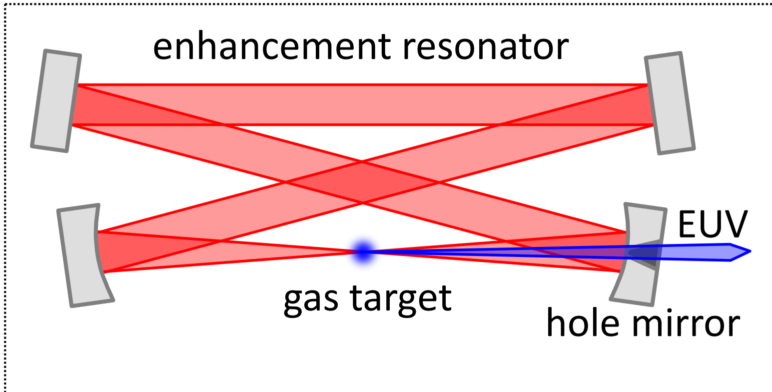
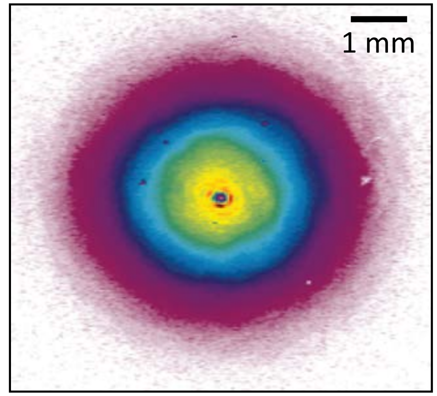
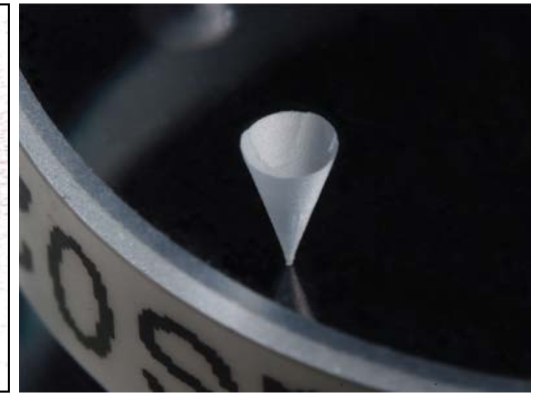
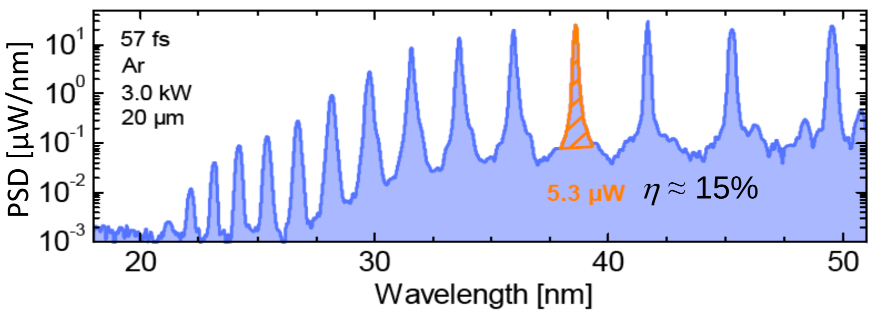
Geometrical Output Coupling with Hole Mirror

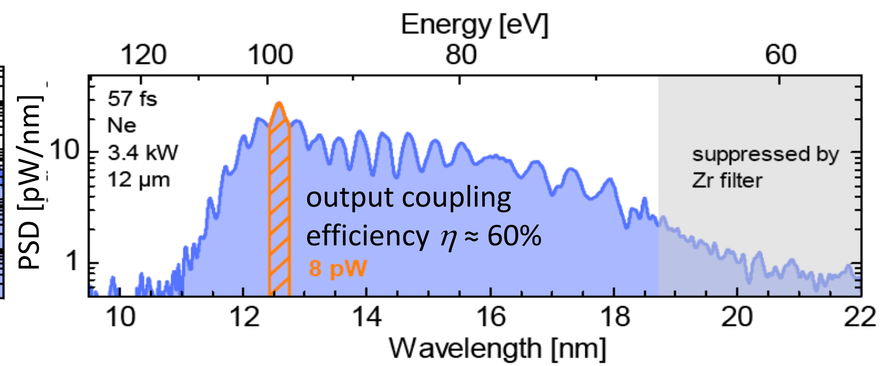






- Circulating fundamental mode and small hole (~100 µm) in mirror behind focus.
- Harmonics have smaller divergence angle than fundamental radiation.
- Output coupling is more efficient for higher order harmonics.
- Harmonics with photon energy >100 eV at 78 MHz generated and coupled out [1].

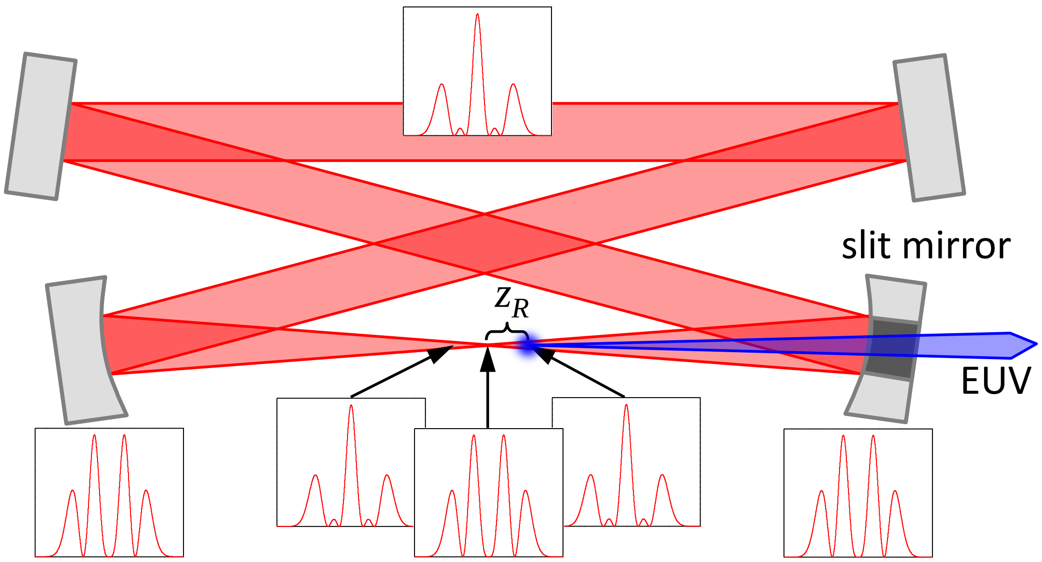




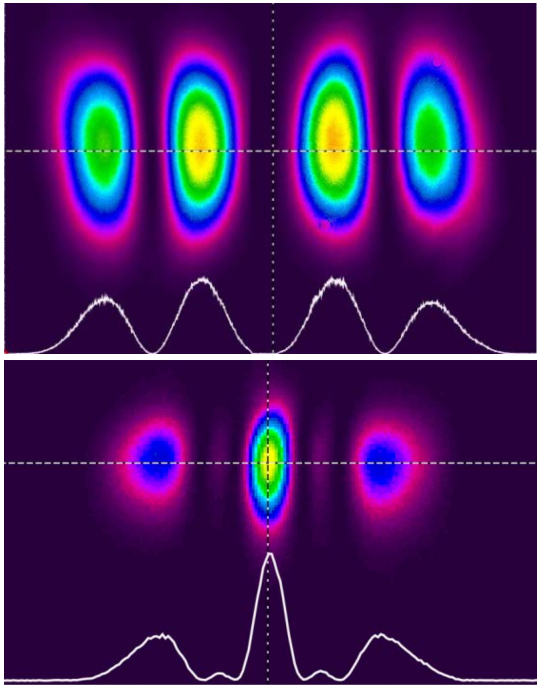
[1] I. Pupeza et al., Nat. Photon. 7, 608 (2013).

Geometrical Output Coupling by Quasi-Imaging

- Degenerate resonator with an obstacle in the beam path
- Transverse modes are combined to avoid the obstacle
- On-axis intensity maximum at different position in the resonator
- »Simple slit mode« from Gauss-Hermite modes GH_{00} and GH_{40} (at middle of stability range)
- Small loss for circulating field at a broad opening (<0.1%)
- Large output-coupling efficiency also for low order harmonics (estimated >60% @H17)

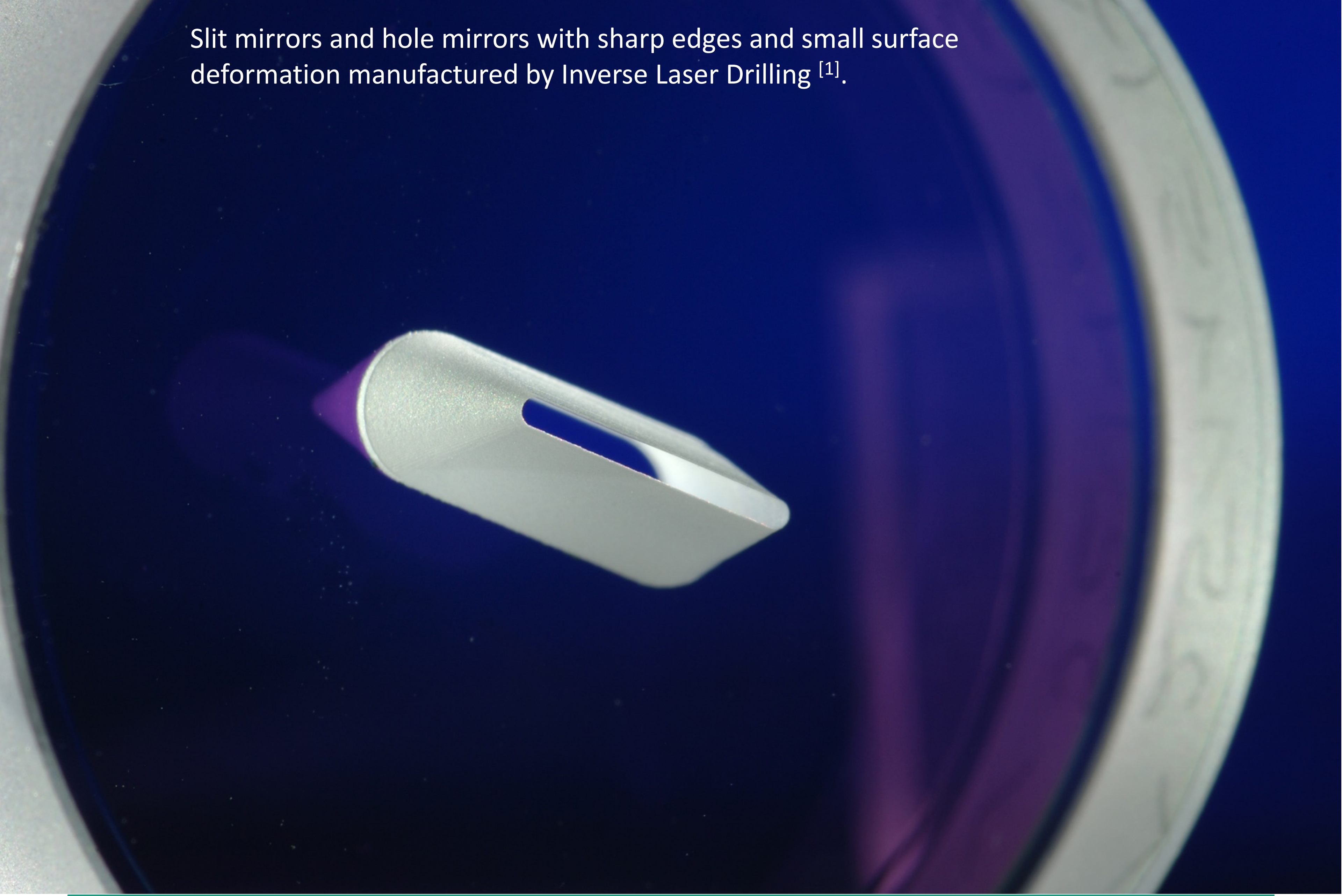


Intensity profiles in transverse direction of quasi-imaging at selected positions within the resonator (Rayleigh length z_R).



[1] J. Weitenberg et al., Opt. Express 19, 9551-9561 (2011).
[2] I. Pupeza et al., PRL 112, 103902 (2014).
[3] J. Weitenberg et al., J. Opt. 17, 025609 (2015).

Slit mirrors and hole mirrors with sharp edges and small surface deformation manufactured by Inverse Laser Drilling [1].



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[1] D. Esser et al., Opt. Express 21, 26797 (2013).

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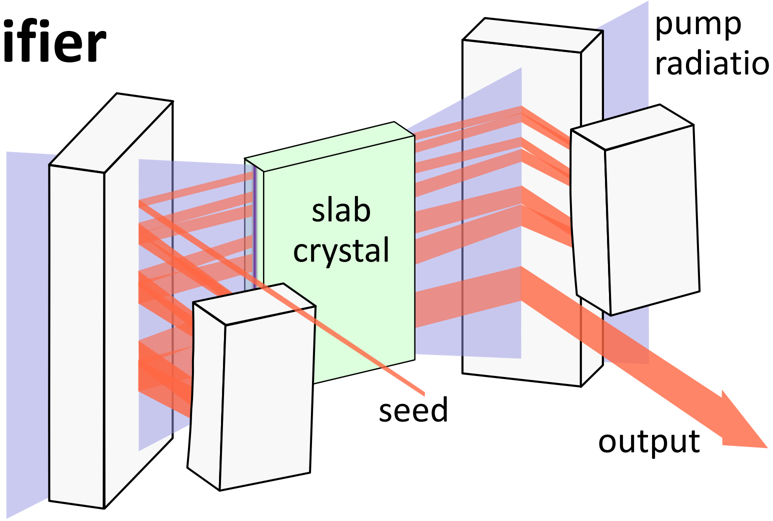
High-Power Yb:YAG Innoslab Amplifier

Amplifier for He^+ spectroscopy setup (MPQ):

- P = 400 W / 370 W before / after isolator
- P = 330 W after spatial filter, $M^2 < 1.2$
- λ = 1030 nm, $\Delta\lambda$ = 2 nm, τ = 0.85 ps



Key features of Innoslab amplifier [1],[2]

Thermal Management

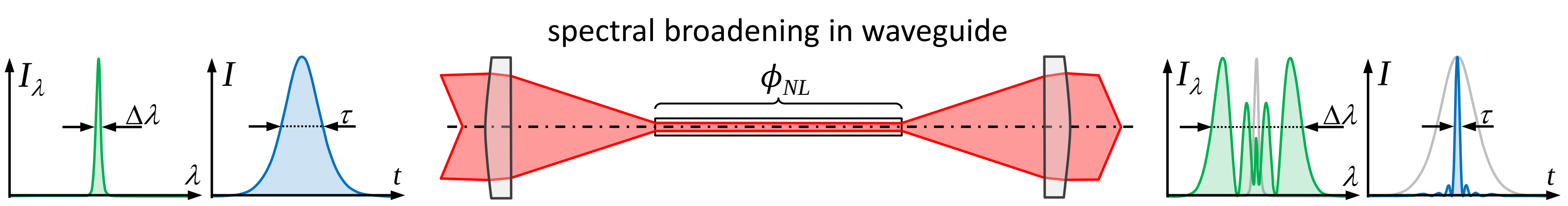
- High average power
- Good beam quality
- Small depolarization

Folded beam path with beam expansion

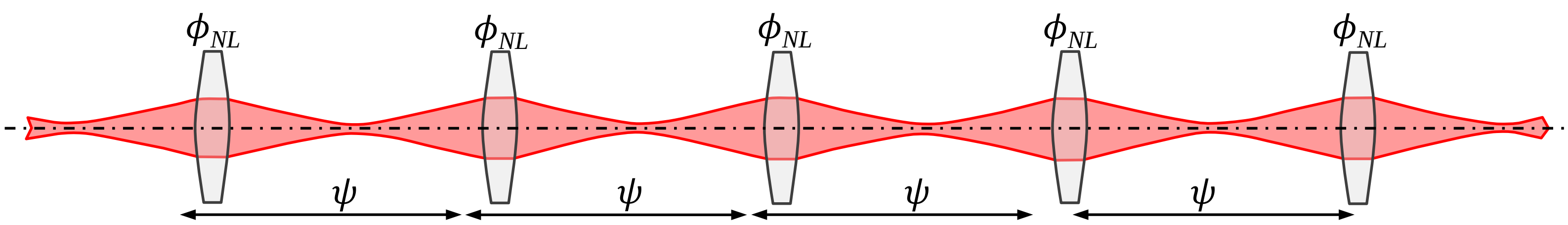
- Constant saturation, high efficiency
- Uniform margin of intensity and fluence to damage thresholds
- Small B-integral, high pulse energy
- High gain (100-1000)

[1] P. Russbueldt et al., JSTQE 3100117 (2015).
[2] P. Russbueldt et al. Opt. Express 17, 12230-12245 (2009).

Nonlinear Pulse Compression



- Spectral broadening by Self-Phase Modulation (SPM) due to the Kerr effect, pulse shortening by subsequent chirp removal.
- Kerr effect goes along with self-focusing, which is compensated by the waveguide.
- Peak power limited to $P < P_{crit}$ (4 MW for fused silica) by self-focusing.



- Transition from a waveguide to a suitably designed lens duct overcomes self-focusing limit.
- Pulse compression at 1-100 µJ energy desirable (e.g. HHG at MHz repetition rate).
- Insensitive to variations of power, beam position and profile, and highly efficient (>90%) → suitable for high average power.
- Compact implementation with multi-pass cell (MPC).

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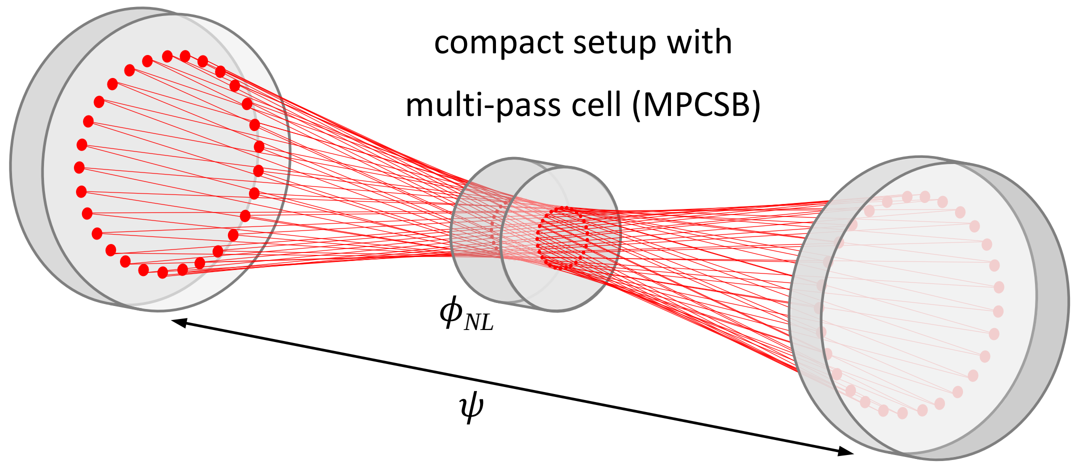

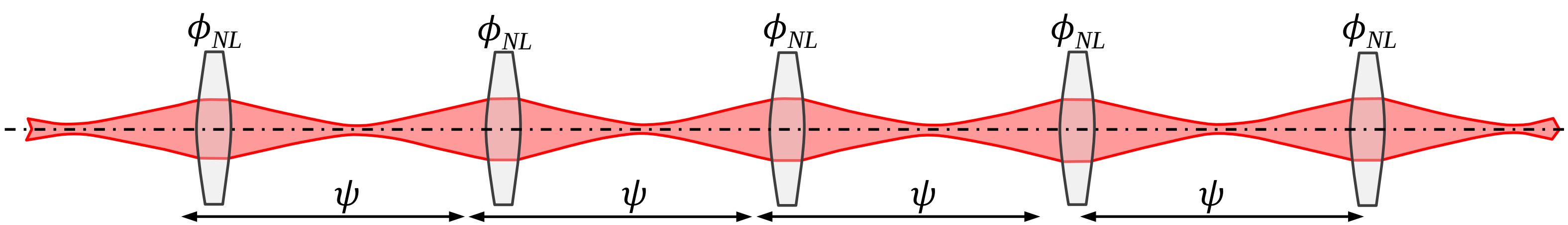

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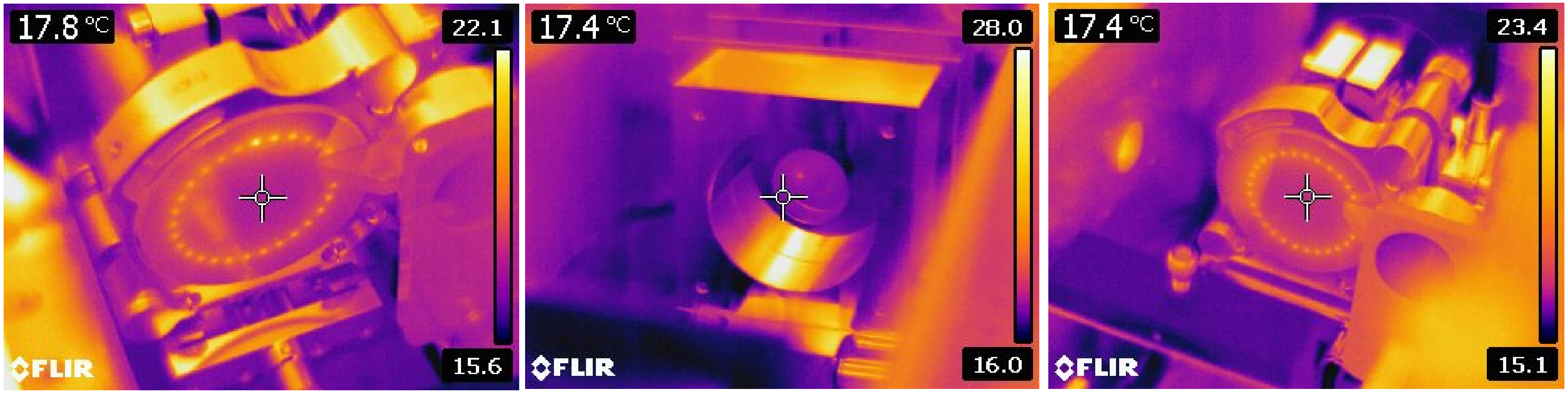
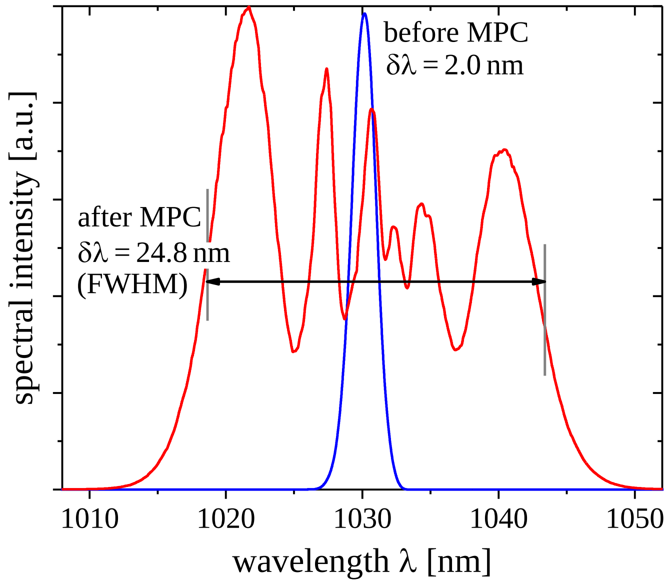
MPCSB Nonlinear Pulse Compression

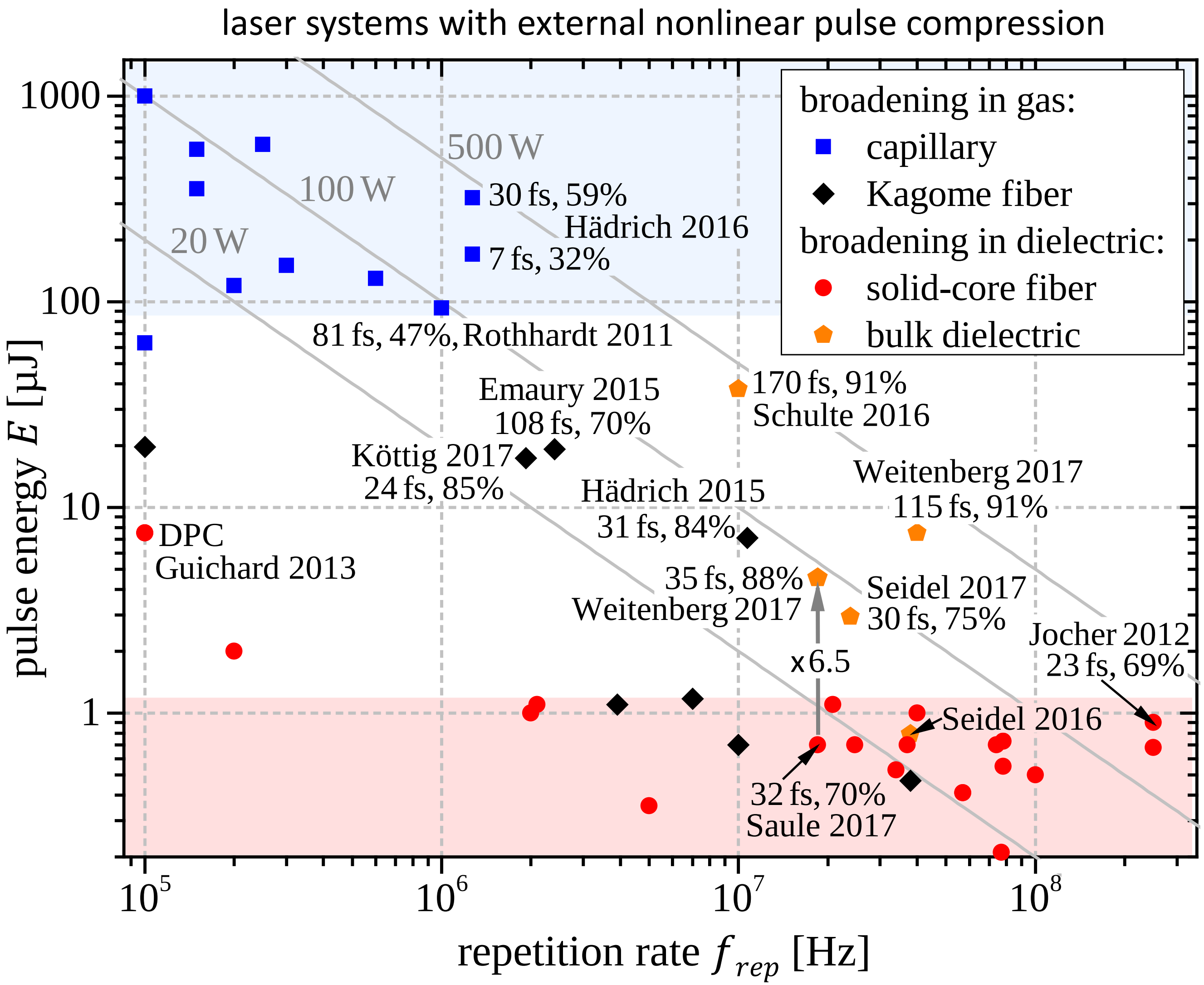


- First demonstration of MPCSB scheme (2016) [1]:
  Compression from $\tau = 880$ fs to 170 fs at 10 MHz, 37.5 µJ
- Setup for EUV frequency comb spectroscopy [2]:
  Compression from $\tau = 860$ fs to 115 fs at 40 MHz, 7.5 µJ
- Setup for photoelectron spectroscopy [3]:
  Compression from $\tau = 230$ fs to 35 fs at 18.5 MHz, 4.5 µJ
- High transmission for all setups ($T = 91\%$, 91%, 88%).
  Beam quality preserved ($M^2 < 1.2$).



[1] J. Schulte et at., Opt. Lett. 41, 4511-4514 (2016).
[2] J. Weitenberg et al., Opt. Express 25, 20502-20510 (2017).
[3] J. Weitenberg et al., JQE 53, 8600204 (2017).

Comparison of Nonlinear Pulse Compression Schemes



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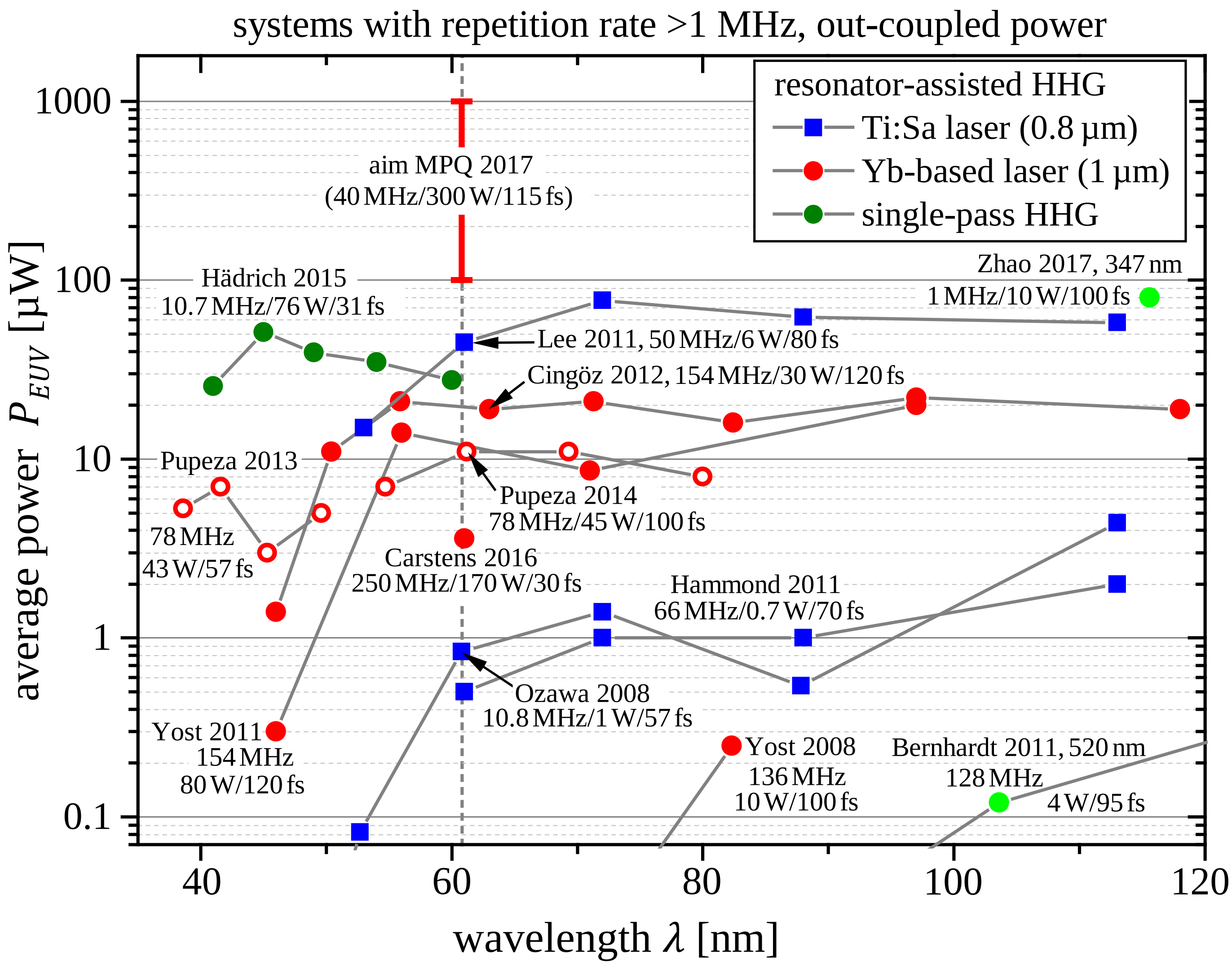
EUV Power from HHG at High Repetition Rate



Summary & Outlook

- Many HHG-EUV applications afford / benefit from high repetition rate:
  EUV frequency comb spectroscopy, photoelectron emission spectroscopy.
- HHG at >10 MHz repetition rate affords
  enhancement resonator and/or high-power amplifier.
- Geometrical output coupling is an efficient and power-scalable scheme.
- Short pulses by nonlinear pulse compression increase HHG efficiency,
  MPCSB compression scheme allows compression for 1-100 µJ pulse energy at high power, is robust and efficient.
- Combining high-power amplifiers with nonlinear pulse compression will allow (resonator-assisted) HHG with mW EUV power at MHz repetition rate.