Member of the TRUMPF Group

# High-Flux XUV Beamlines for Imaging and Spectroscopy

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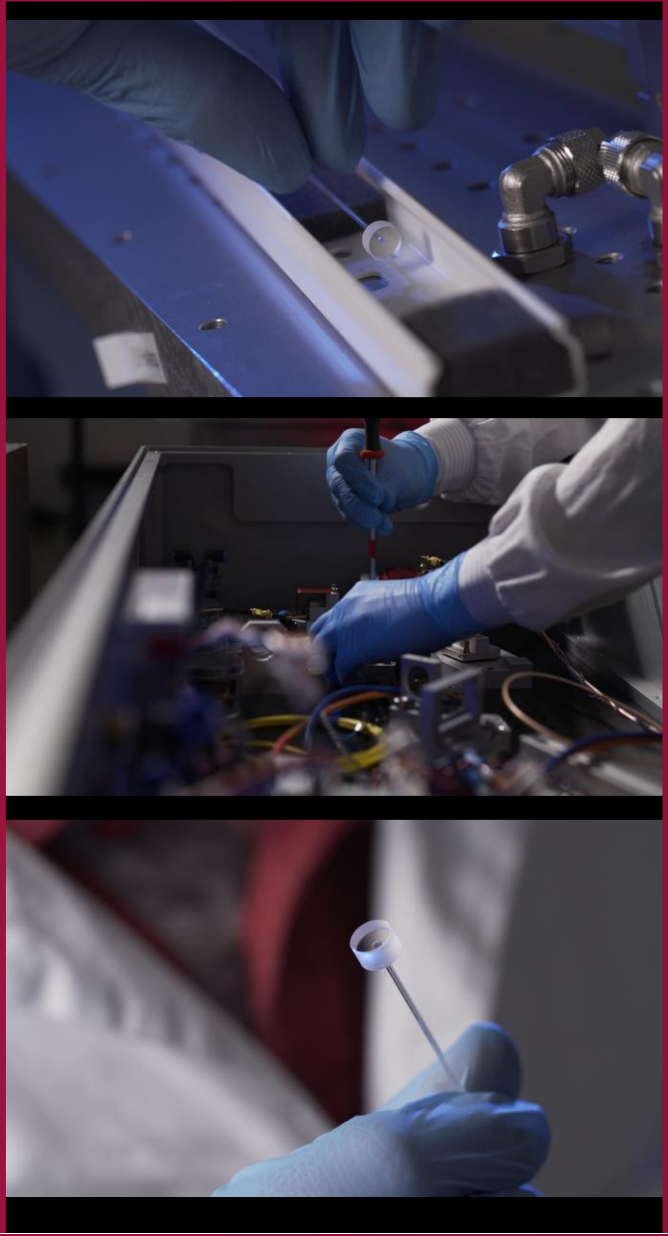
# What this talk is and what it is not

- **NO** detailed theoretical background on HHG
- **NO** complete overview on possible sources and HHG geometries
- **NO** details on applications

- General concepts
- Challenges and ways to overcome them
- Demands of typical applications and how to adress them
- Commercially available high-flux sources based on reliable fiber lasers



I. Motivation & Introduction HHG

II. Concept & Applications

III. Solutions driven by Yb-fiber lasers
- Setup
- Achievable spectrum
- Stability
- Beam handling and focusing

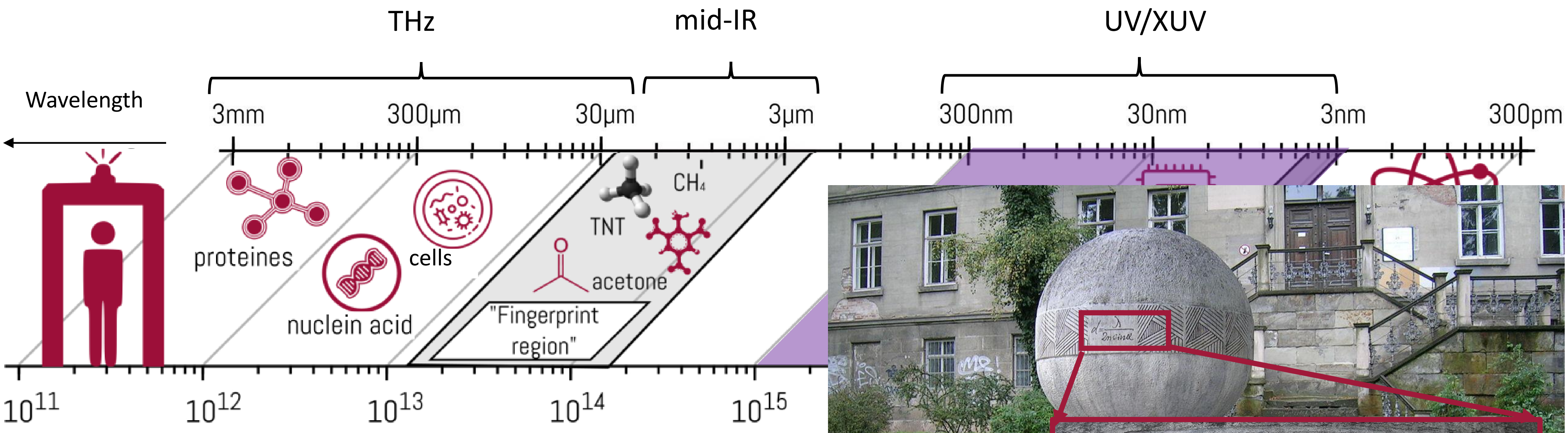
IV. Scaling of photon flux
- Conversion efficiency
- Average power of driving laser

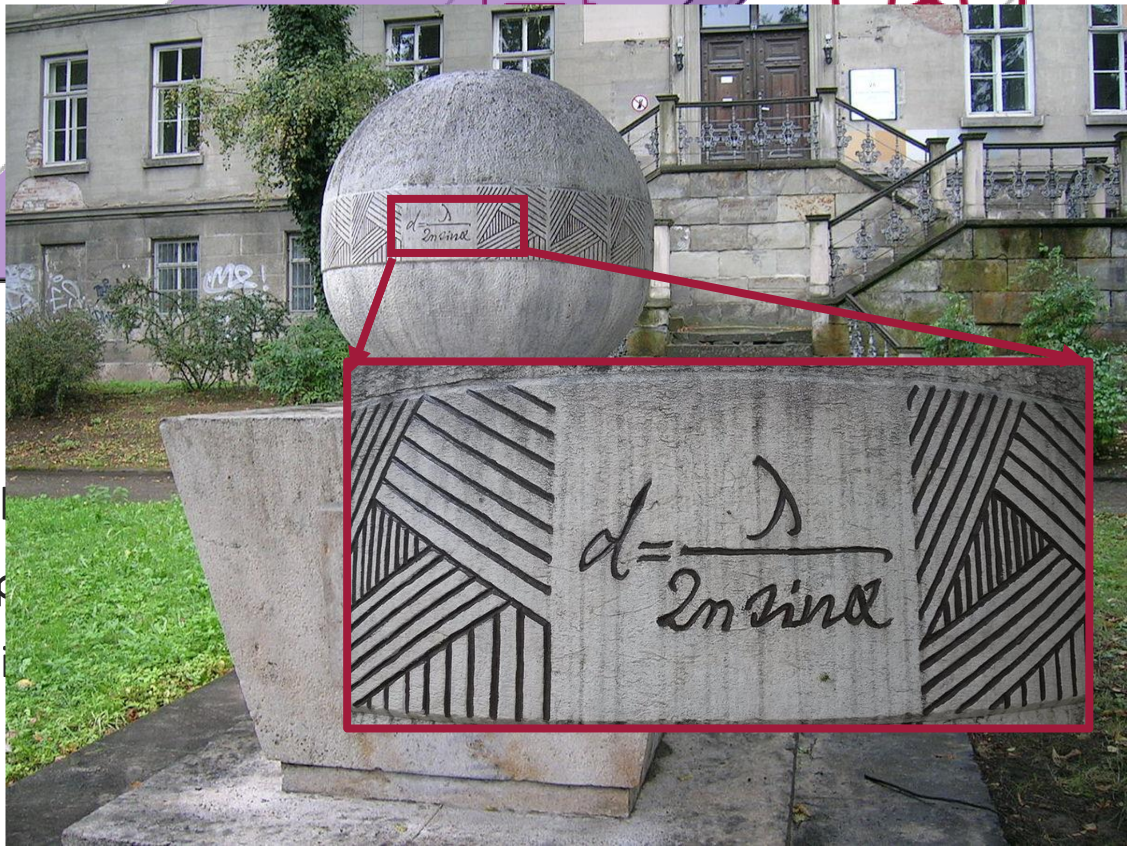
V. Scaling of Photon energy

VI. Atto science

VII. Summary & Outlook

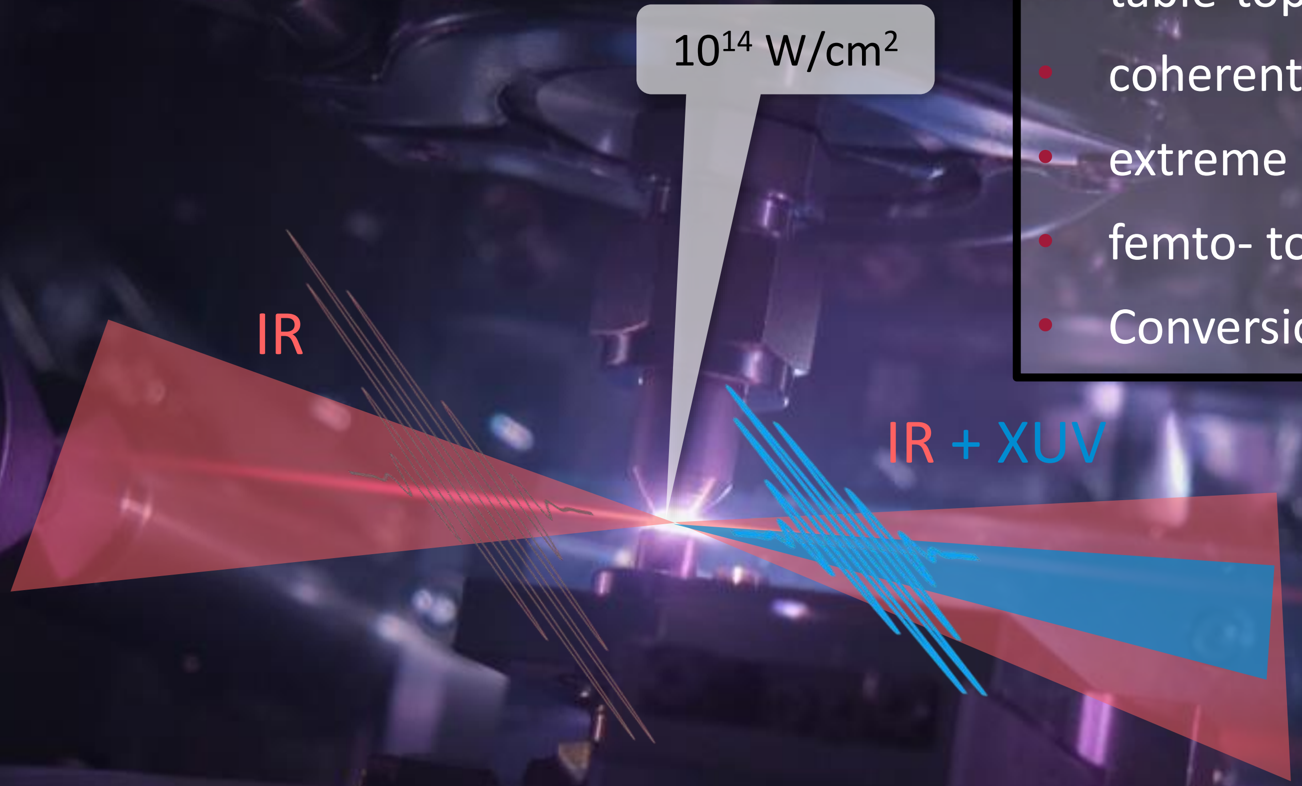
# Motivation




- Multitude of applications outside of accessible laser wavelength
- Special wavelength important for target specific responses in **sp**
- Shorter wavelength beneficial for **imaging** → Abbe diffraction li

## 2nd place for Sven Weerdenburg in Optica (OSA) 'Photo of the Year' contest 2022!




- table-top
- coherent (laser-like) – spatial and temporal
- extreme ultraviolet / soft x-ray radiation
- femto- to attosecond pulse duration
- Conversion efficiency $10^{-3}$...$10^{-12}$

Extreme UV (EUV) Generation enabled by AFS High Harmonics Generation System
Sven Weerdenburg (2021)

# Phase-matching in tight focusing geometry

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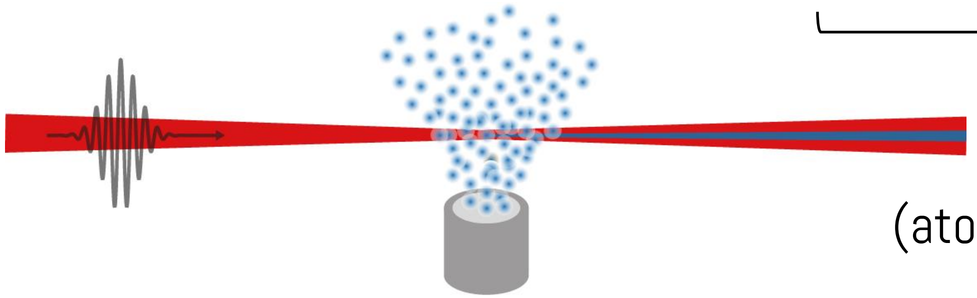
- Fiber lasers typically energy in the range ~100µJ …. 1mJ

$$\Delta k(t,\rho) = q \cdot k_0 - k_q = q \cdot \left(\frac{2\pi}{\lambda_0}\frac{\rho}{\rho_0}\Delta\delta\right)\cdot\left(1-\frac{\eta(t)}{\eta_{c,q}}\right) - \frac{q}{z_R}$$



+ dispersion (atoms, free electrons)

- focusing

- Density (pressure) dependent
- $\eta_c$ – critical ionization (gas specific)
- $\eta<\eta_c$: pressure tuned phase-matching
- Efficiency **independent** of focusing conditions

Flux scales with input average power and NOT energy

$P_{out} = P_{in} \cdot \eta$

[1]C. Heyl et al. Journal of Physics B 45, 074020 (2012)
[2]J. Rothhardt et al. New J. Phys. 16, 033022 (2014)
[3]C. Heyl et al. Optica 3, 75 (2016)

# High-harmonic generation

- Three-step model → Not discussed here

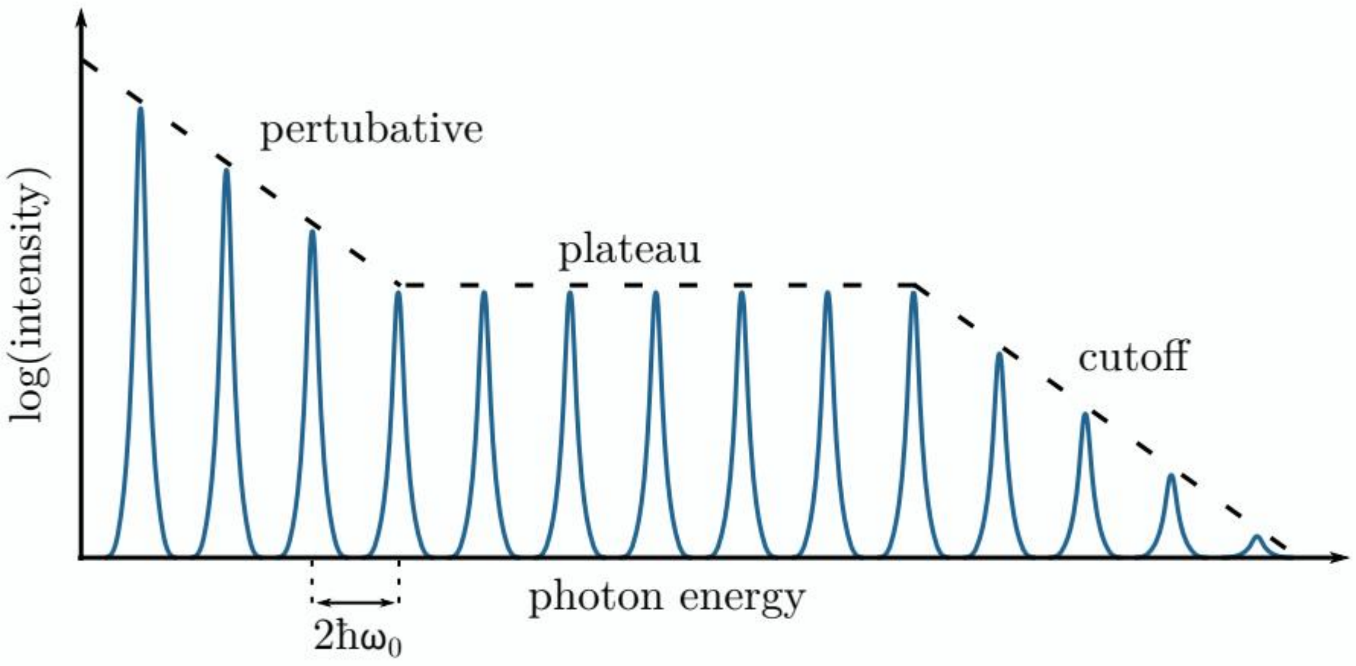
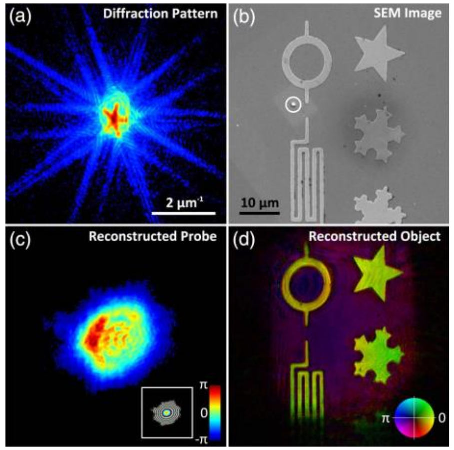



**Figure 2.3: Schematic high harmonic spectrum,** showing a comb of odd harmonics with the pertubative, plateau and cutoff region. The driving laser angular frequency is $\omega_0$.

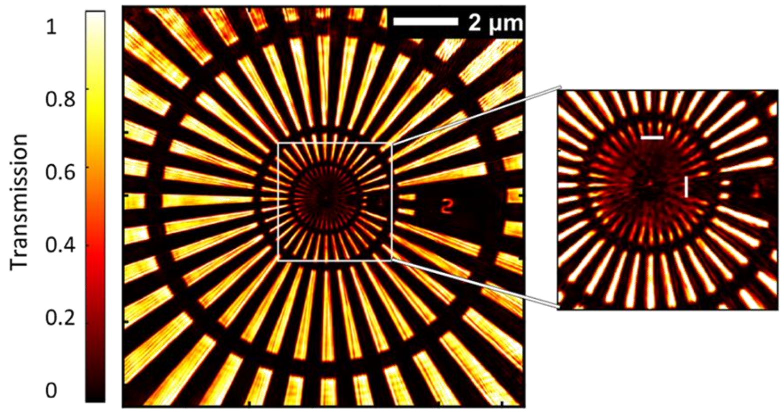
Robert Klas "Efficiency Scaling of High Harmonic Generation using Ultrashort Fiber Lasers," (2021).

# Typical applications for HHG radiation

## Coherent Diffractive Imaging



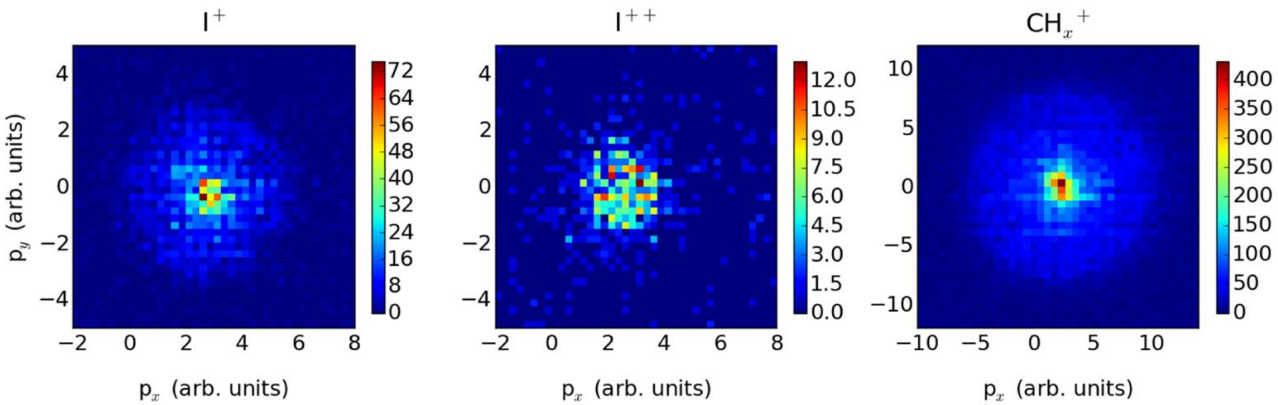

Seaberg et al. Optica **1**, 39 (2014)



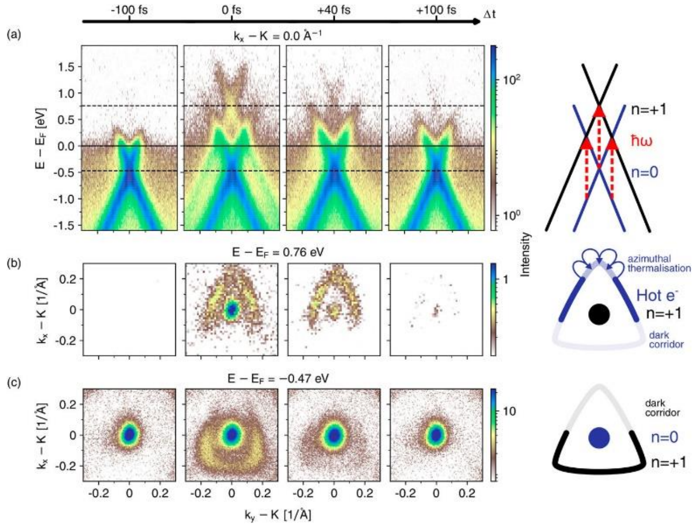

Tadesse et al. Scientific Reports **9**, 1735 (2019)

## COINCIDENCE

Rothhardt et al. Opt. Express **24**, 18133 (2016)




## (time-resolved) photoemission



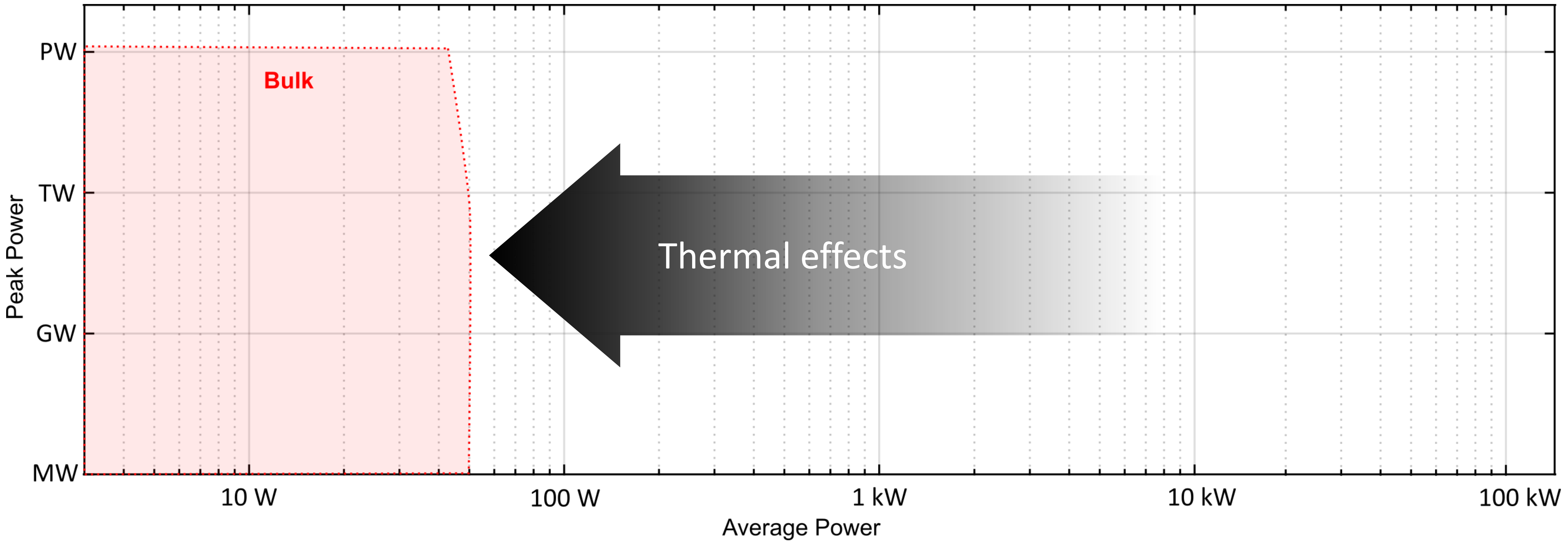

Keunecke et al. Rev. Sci. Instrum. **91**, 63905 (2020)

# HHG source requirements

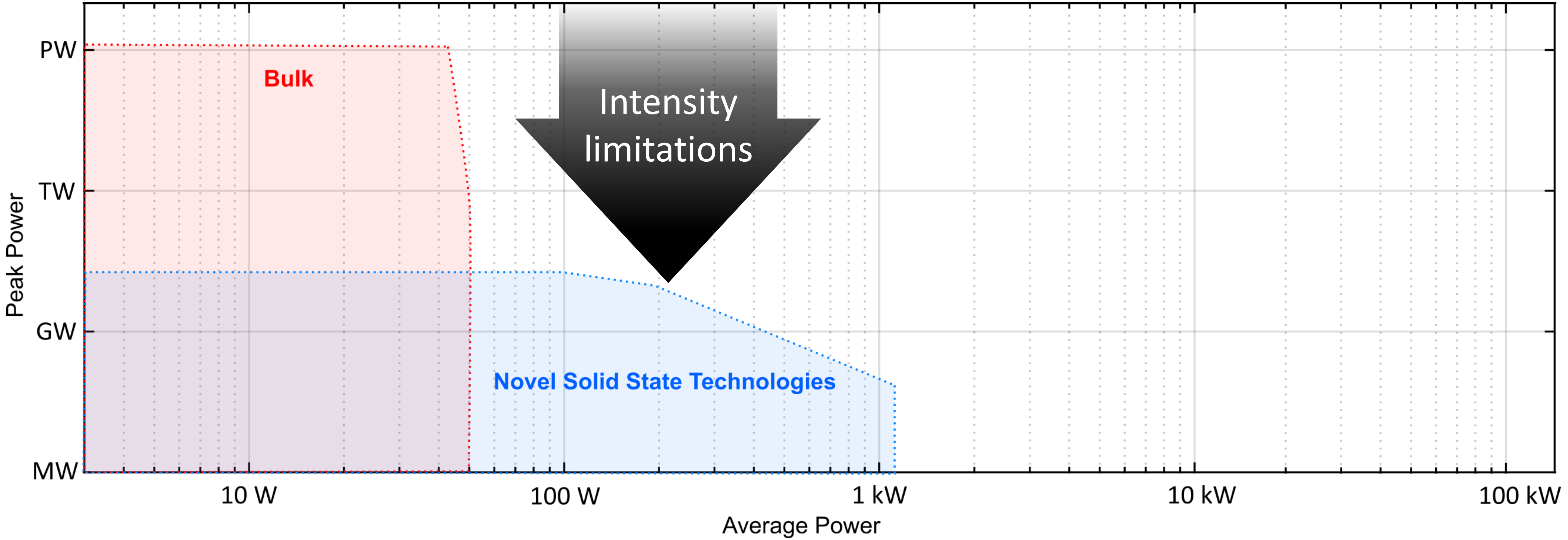
| | Photoelectrons | Coincidence | Imaging |
|---|---|---|---|
| Demands | Avoid space charging | 1 event per pulse | Short integration times |
| | | Statistics | Good Signal-to-noise ratio |
| **Solution** | **High repetition rate** | **High repetition rate** | **Higher photon flux** |

| Ideal Source |
|---|
| Low…medium energy |
| High rep-rate |
| High-flux |
| Reliable |
| **Fiber laser driven** |

# High-power laser systems

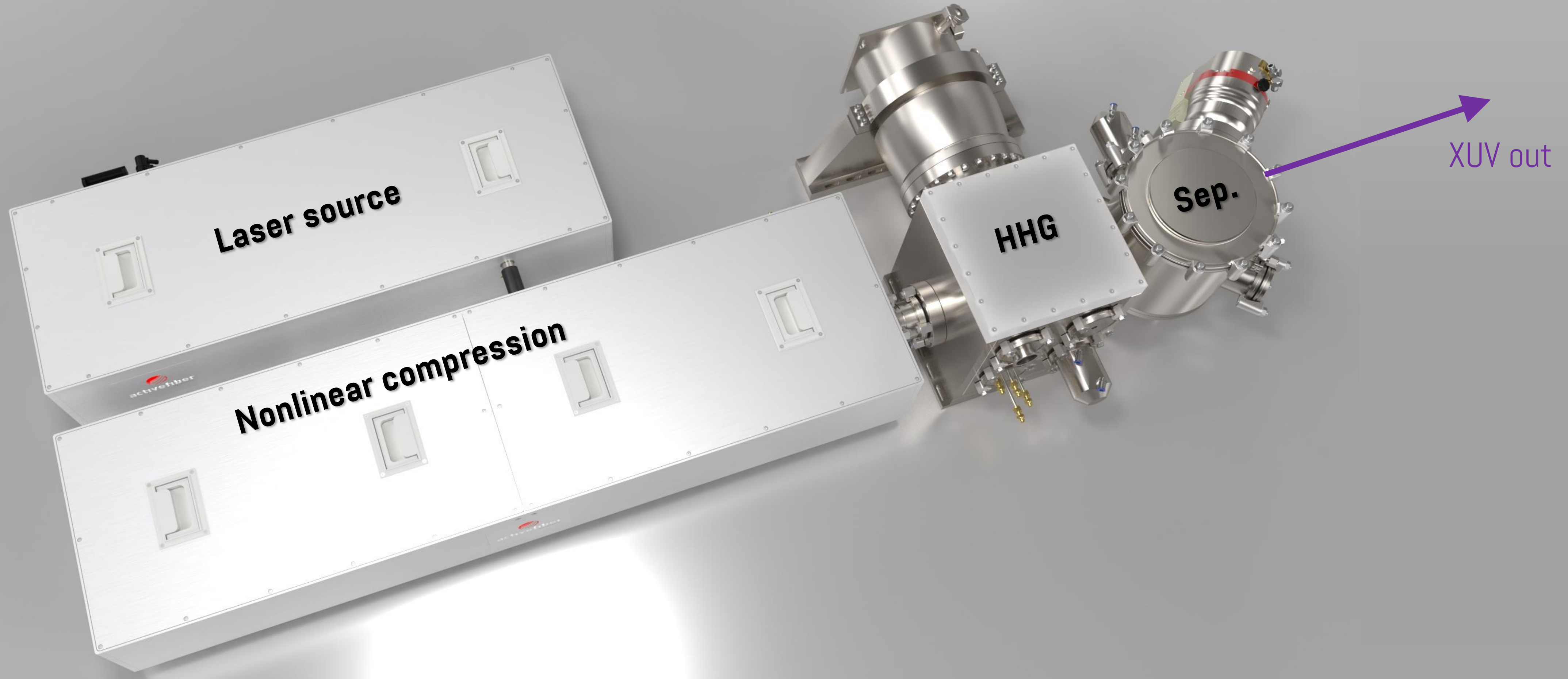



HHG Flux scaling: $P_{out} = P_{in} \cdot \boldsymbol{\eta}$

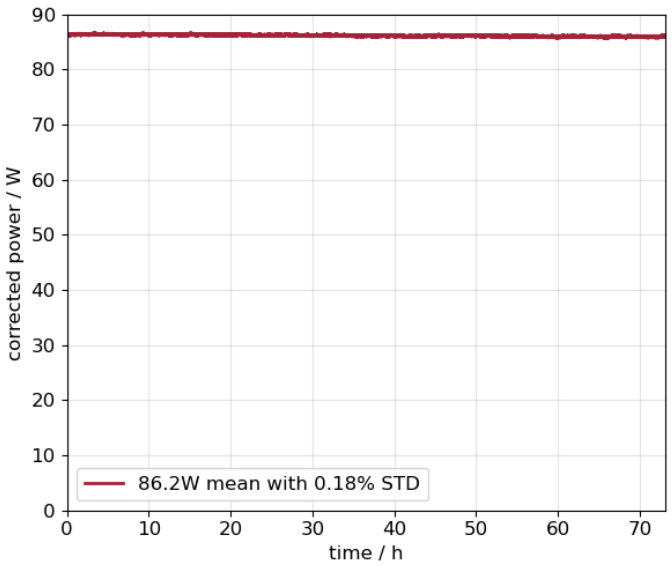


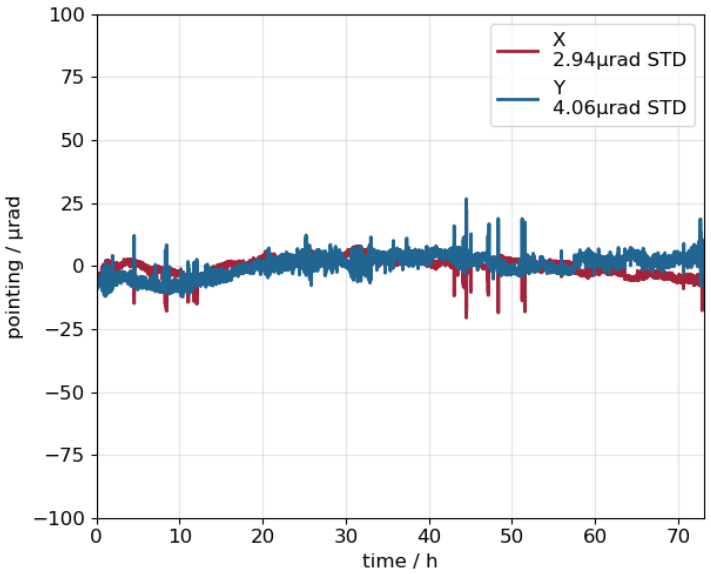

HHG Flux scaling: $P_{out} = P_{in} \cdot \eta$

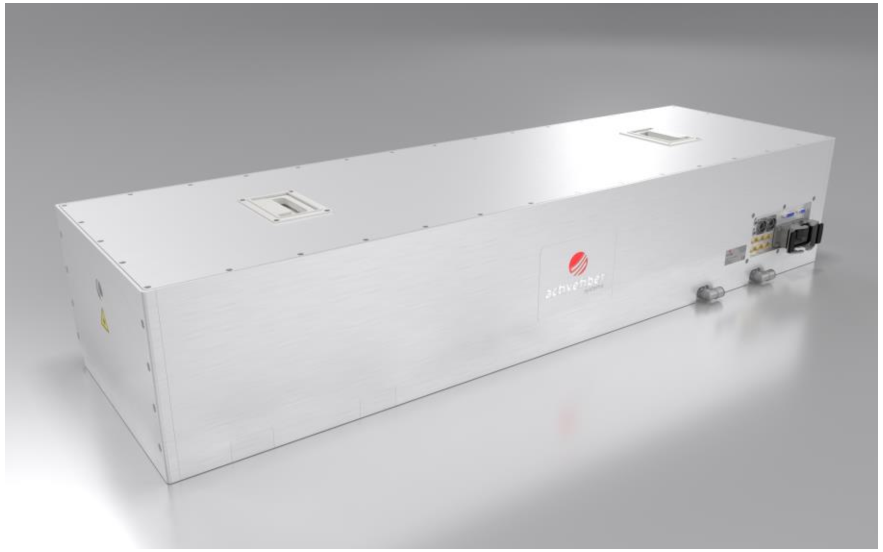
# XUV setup – Compact beamline (LINX driver at ARCNL)



# Ytterbium-100 ultrafast fiber system

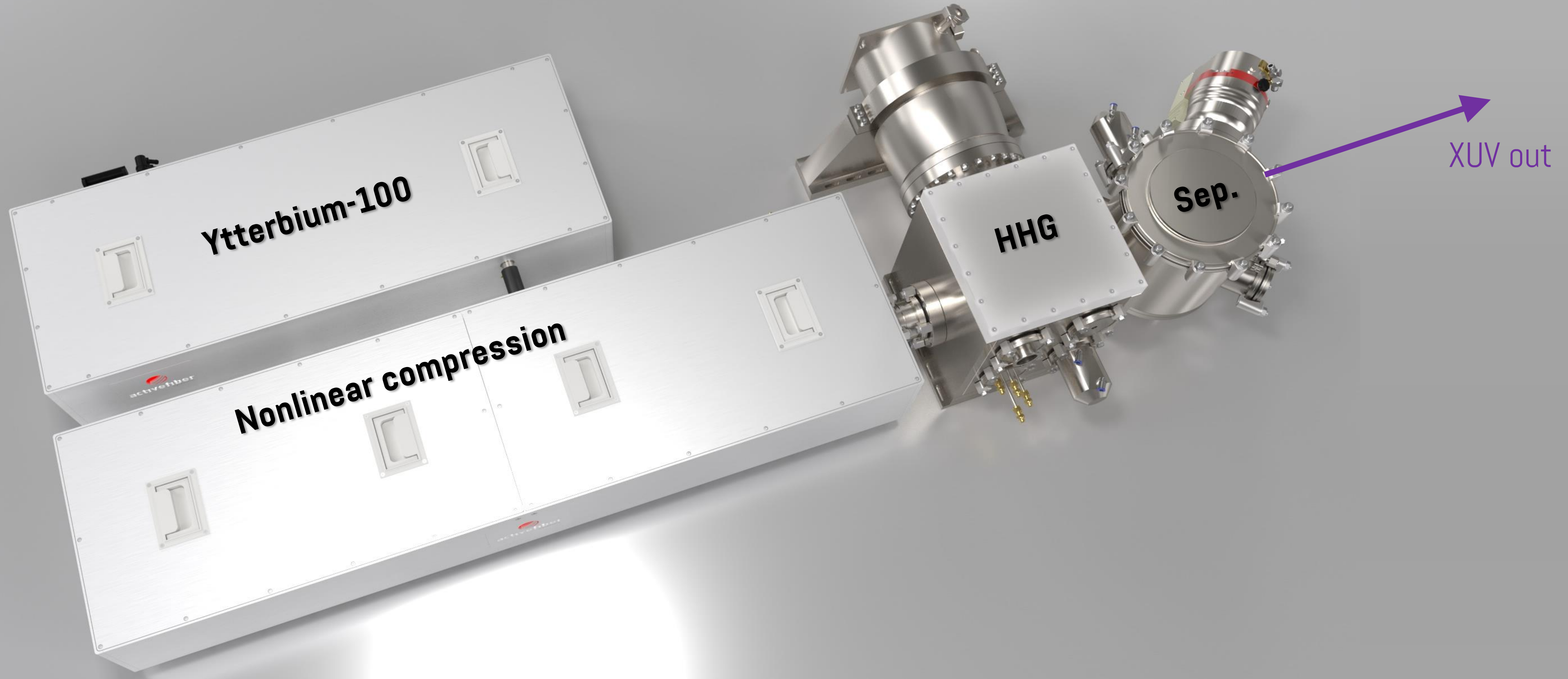


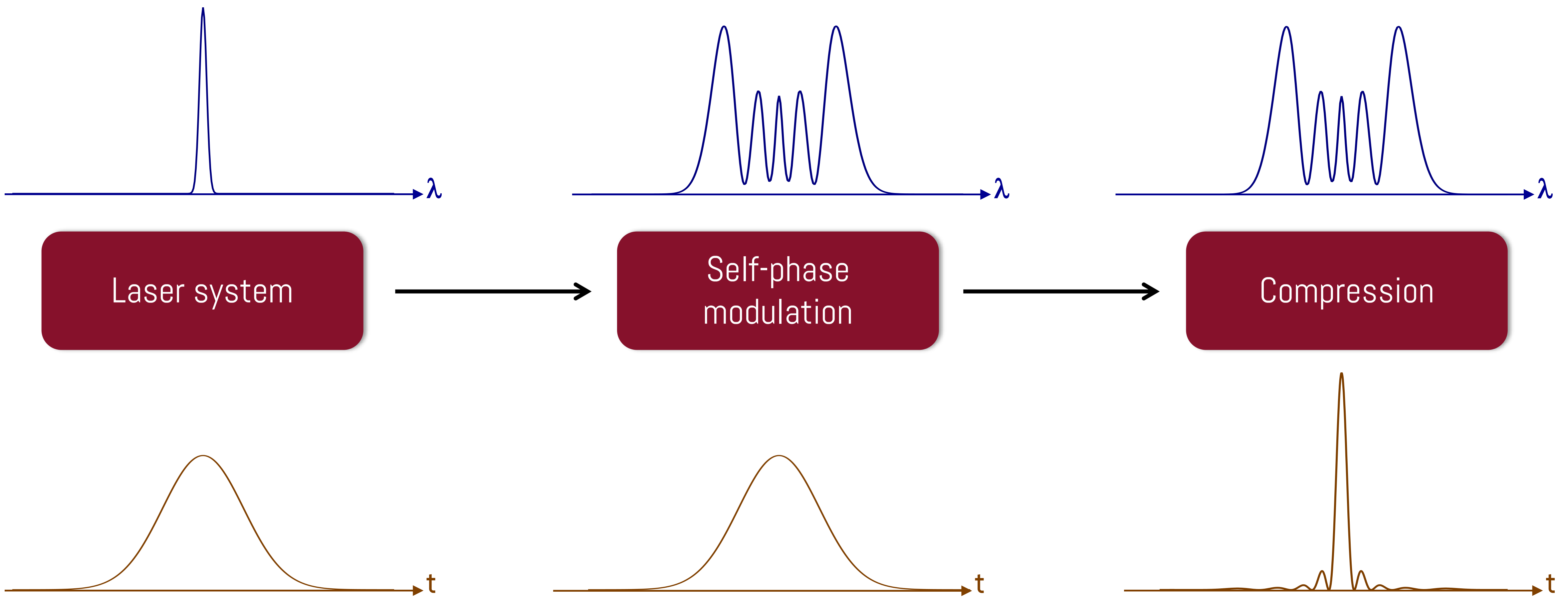



- Up to **100W** average power and **1mJ** pulse energy
- Pulse duration: **<250fs**
- Repetition rate: 50kHz … 50MHz (e.g. 1mJ & 100kHz or 200µJ & 500kHz)
- Software-based remote monitoring and service options
- Average-power/energy stability: <0.4% RMS
- Diffraction-limited beam quality: **$M^2 < 1.2$**

# XUV setup – Compact beamline (LINX driver at ARCNL)



# Nonlinear pulse compression

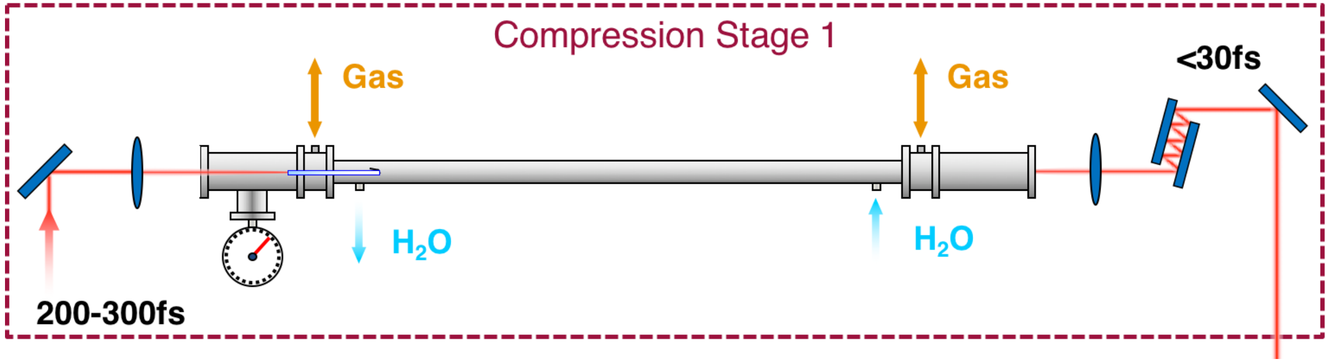



- Solid-core fiber[1]
- Hollow-core fiber[2]
- Multipass (Herriott) cell[3]

- Grating compressor
- Prism compressor
- Chirped mirrors

[1] C. Jocher et al., Opt. Lett. 37, 4407–9 (2012)
[2] M. Nisoli et al., Appl. Phys. Lett. 68, 2793 (1996)
[3] L. Lavenu et al., Opt. Lett. 43, 2252-2255 (2018)

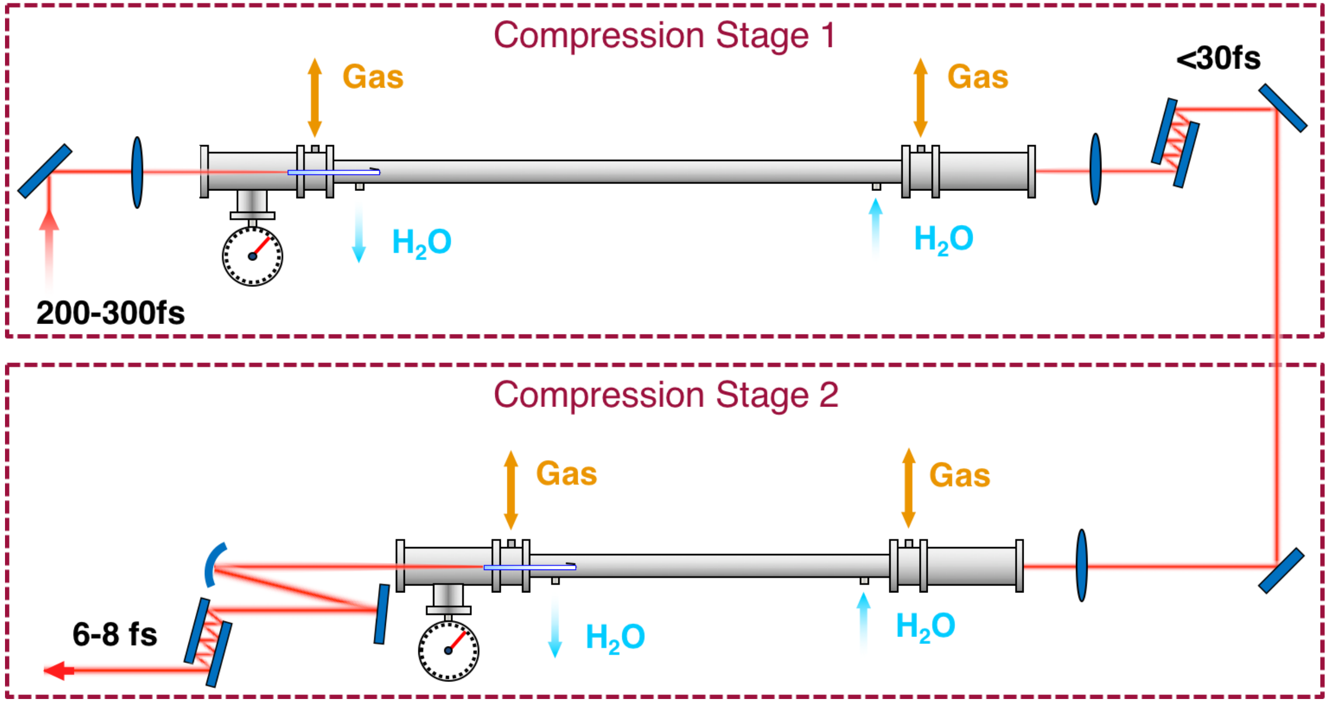
# Nonlinear compression – the old way




- Ytterbium doped fiber lasers: ~300fs pulses
- Nonlinear-compression in noble-gas filled hollow waveguides
- Sub-30fs with up to 400W average power[1] →kW-level (with MPC)[2]
- Flexible pulse parameters possible
- Average power scalable[3]

[1]S. Hädrich et al. Opt. Lett. **41**, 4332 (2016)
[2]Grebing et al. Opt. Lett. 45, 6250 (2020)
[3]S. Hädrich et al. Appl. Opt. **55**, 1636 (2016)

# Nonlinear compression – the old way



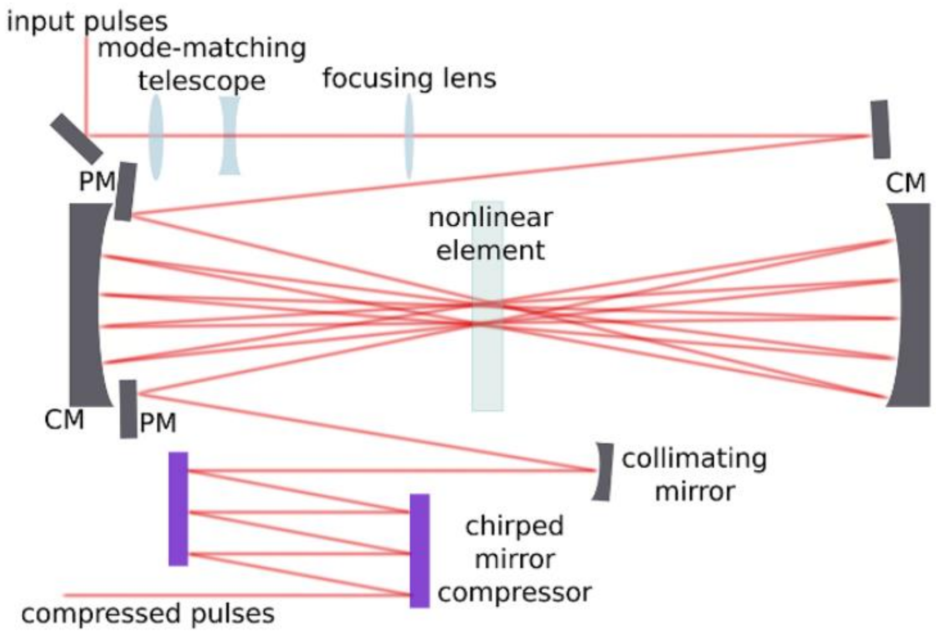

- Further pulse compression
- Sub-7fs (2 cycle) with up to 216W average power[1]
- Sub-10fs with >300W average power @100kHz[2]

[1] S. Hädrich et al. Opt. Lett. **41**, 4332 (2016)

[2] T.Nagy et al. Optica **6**, 1423 (2019)

# Transition to multipass-cell compression

- Recent advances in multipass cells [1,2]




F. J. Furch, et al. JPhys Photonics **4**, (2022).

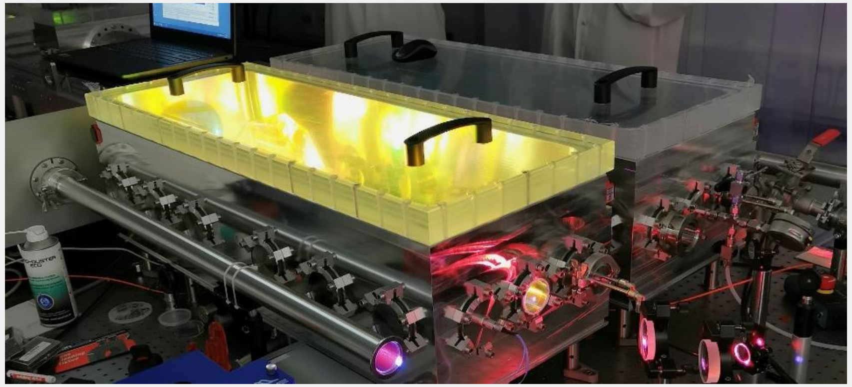
- Nonlinear element: often gas at high energies
- Higher transmission efficiency + power scalable + sufficient bandwidth

  →preferred solution for most use-cases

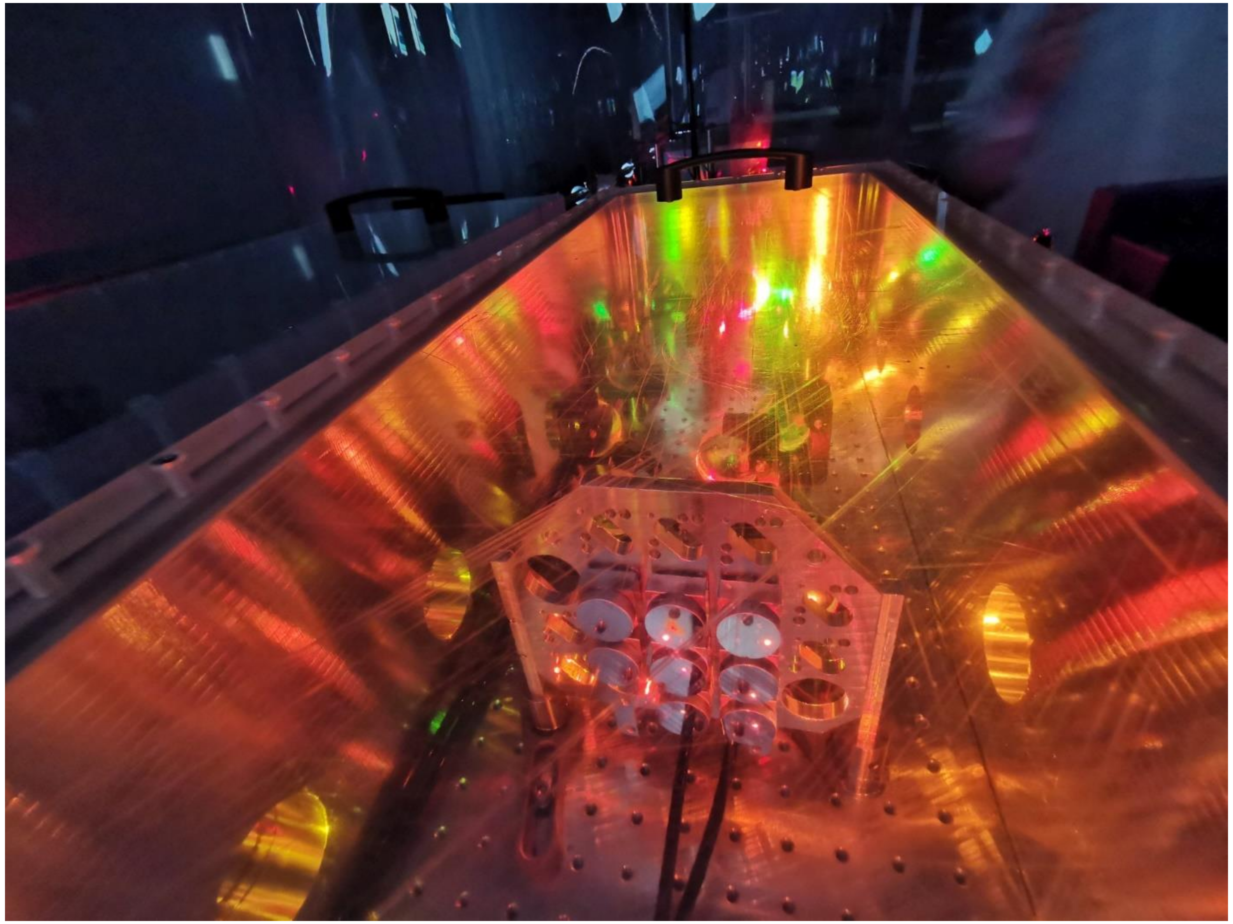

[1] P. Balla et al. Opt. Lett. 45, 2572 (2020)
[2] M. Müller et al. Opt. Lett. 46, 2678 (2021)

# Post compression scheme

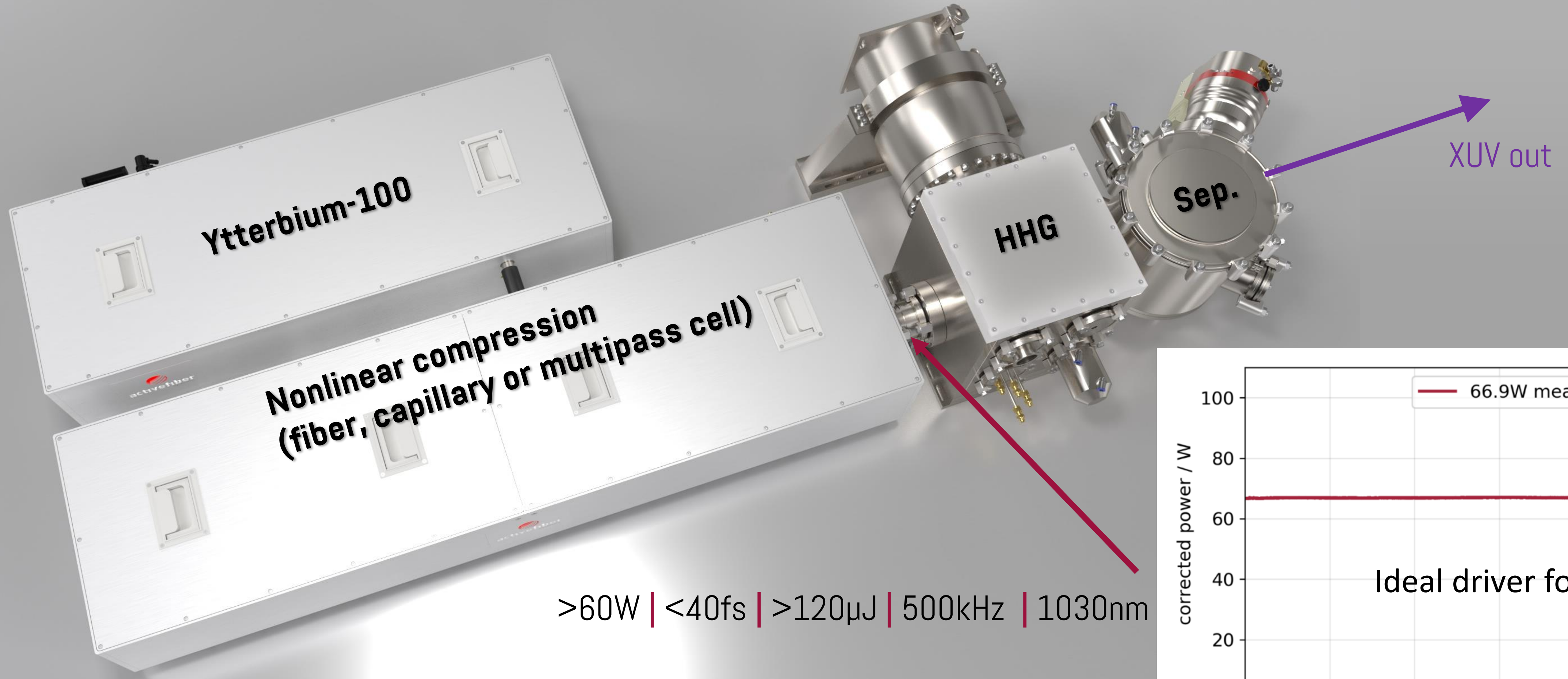
## MPC-based post compression



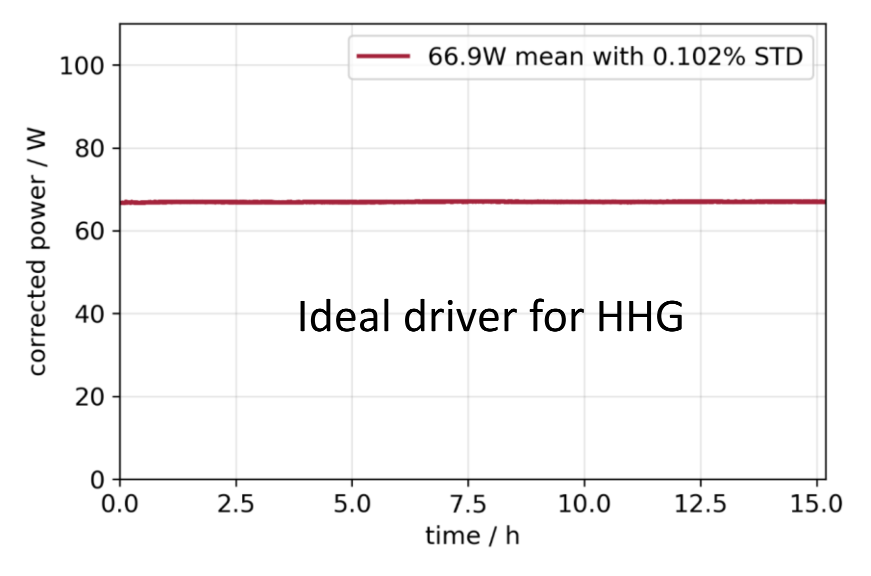
- **Input up to 2kW | 20mJ | 1030nm | 250fs**
- Down to <40fs (one stage) or <6fs (two stages)
- Flexible & customizable
- High efficiency (>90% one stage, >50% for two stages)



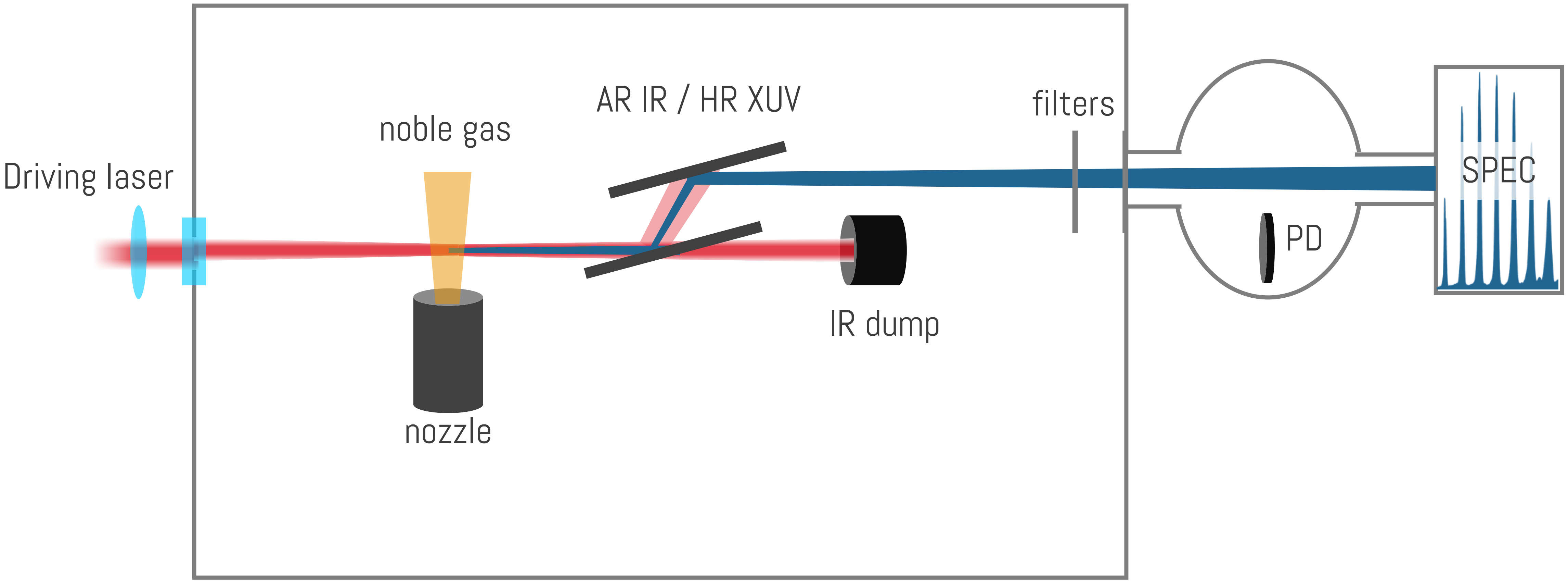
# XUV setup – Compact beamline (LINX driver at ARCNL)




>60W | <40fs | >120µJ | 500kHz | 1030nm



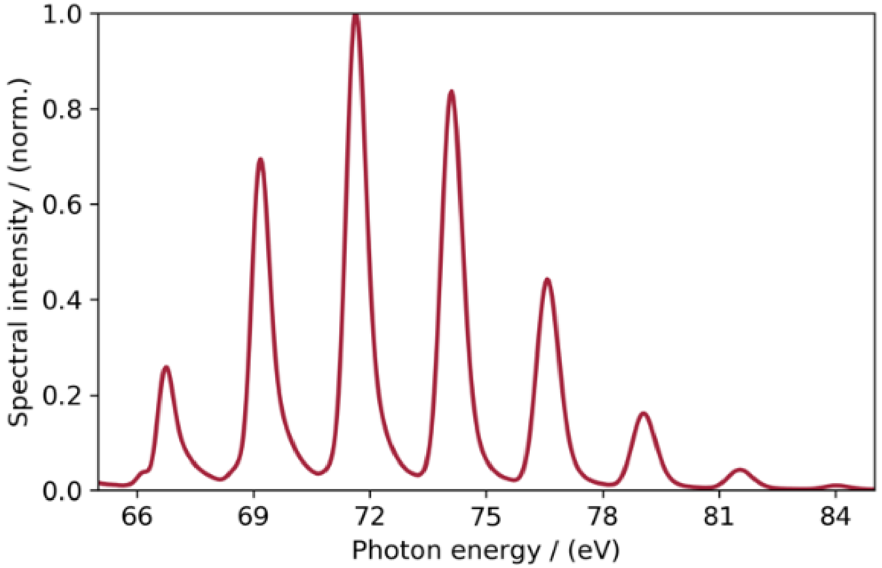
# XUV sources using high-harmonic generation (HHG)

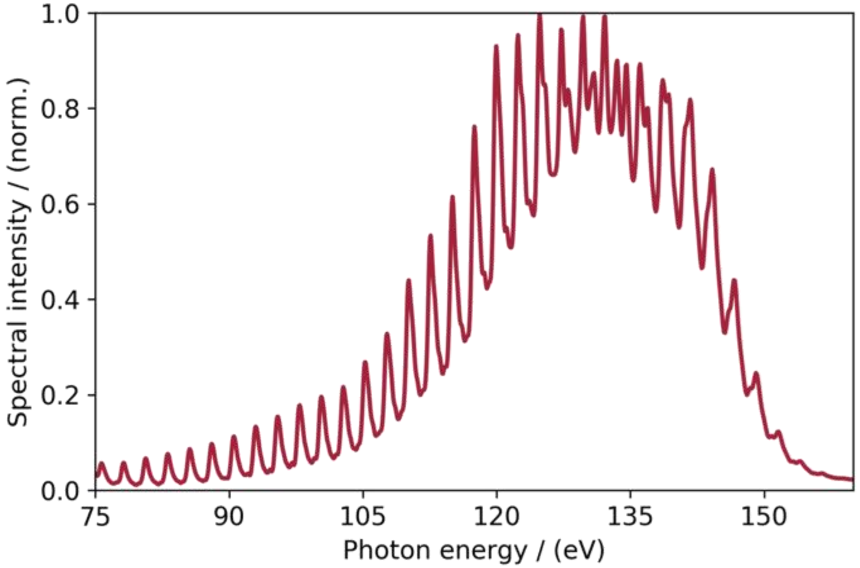


# XUV output results

| Harmonic | Photon energy /eV | Wavelength /nm | Flux /10^10 Photons/s/(1% bandwidth) |
|---|---|---|---|
| 59 | 71 | 17.5 | 30 |
| 77 | 93 | 13.3 | 0.2* |
| 93 | 112 | 11.1 | 0.8* |
| 109 | 131 | 9.5 | 1.9* |

Some exemplary photon fluxes of this source. The *-marked values state world-record fluxes.



# State of the Art XUV sources

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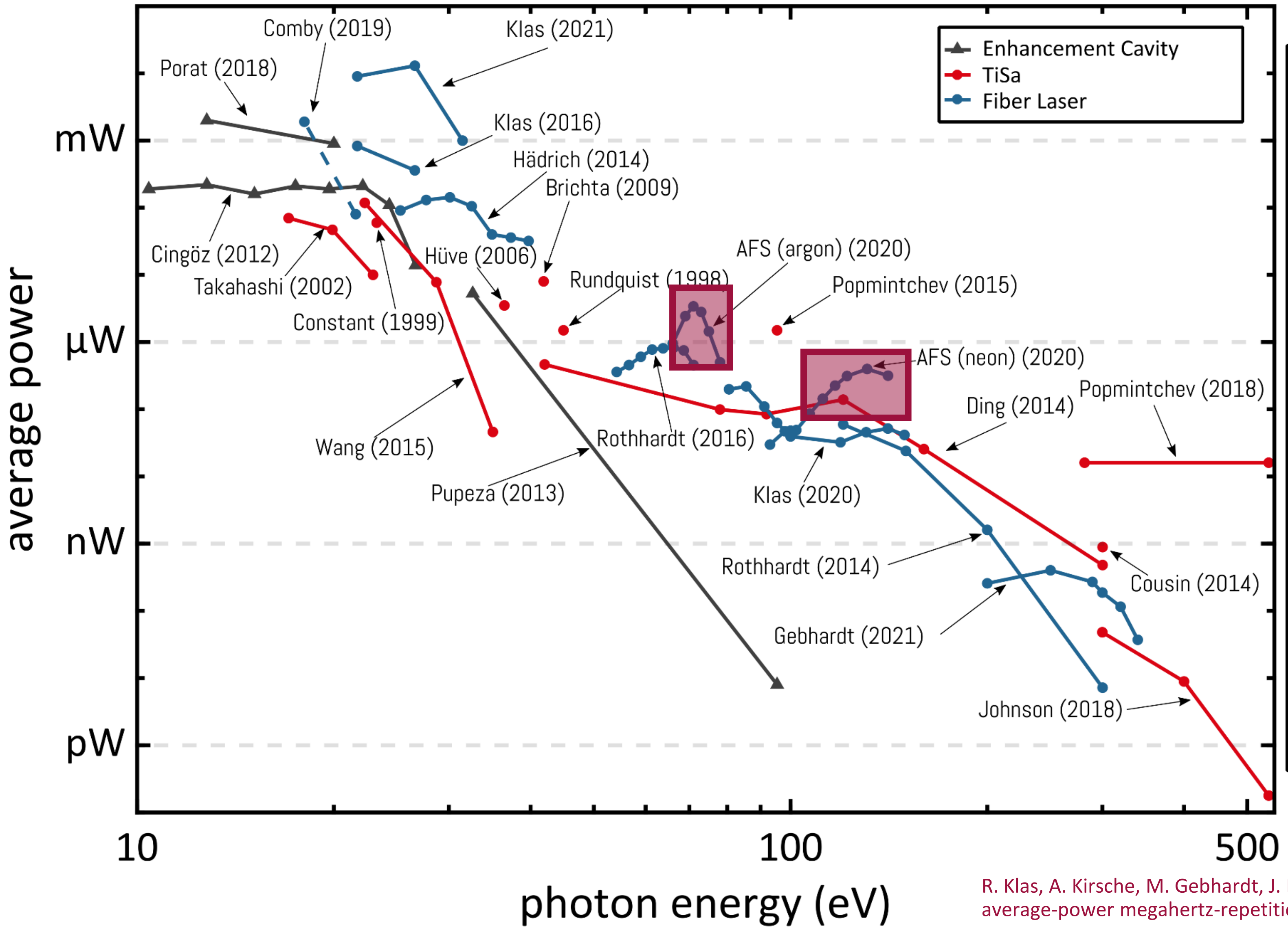
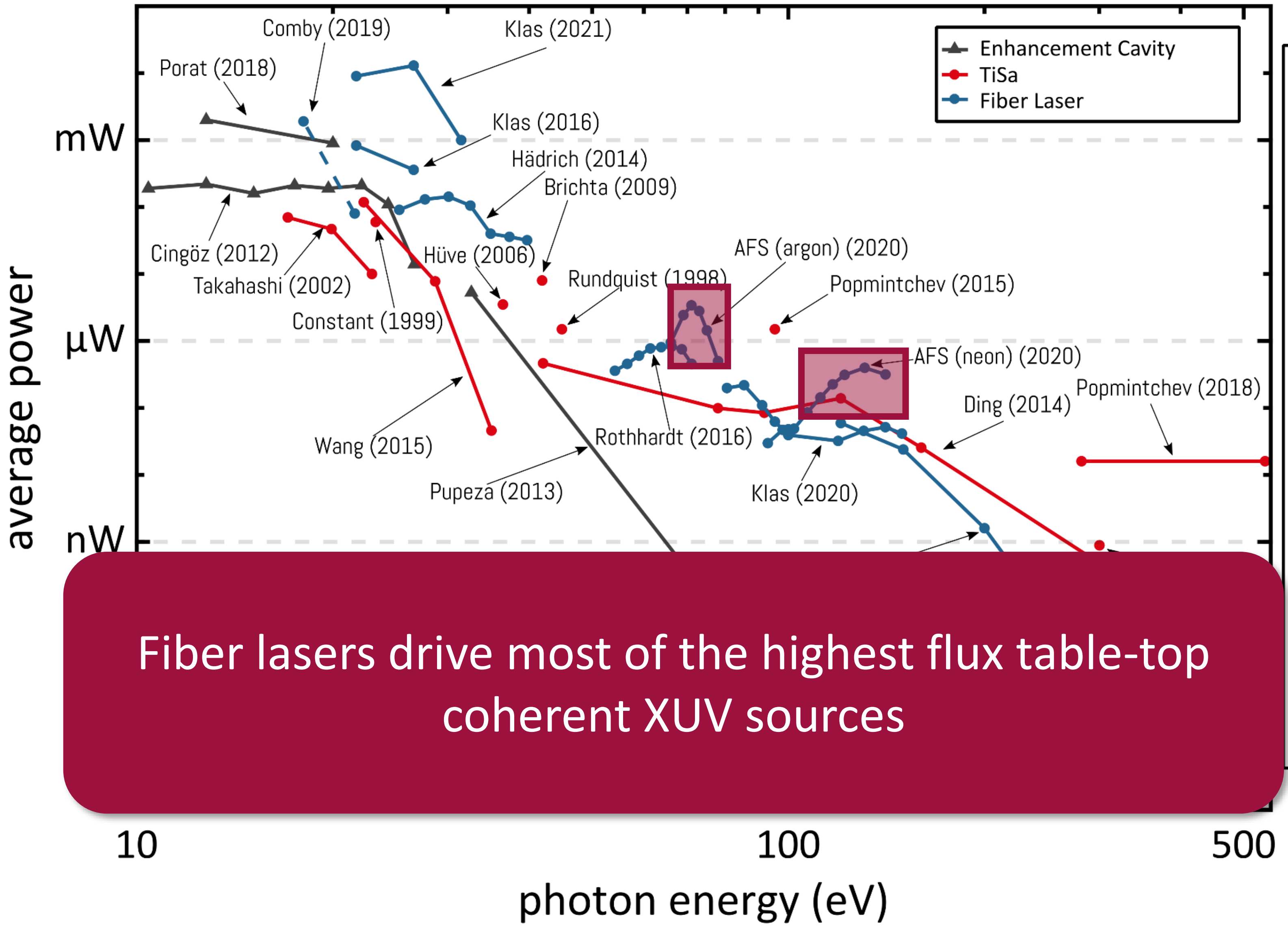




[1] Cingöz et al. Nat. 482, 68 (2012)
[2] Porat et al., Nat. Photon. 12, 387–391 (2018)
[3] Pupeza et al. Nat. Phot. 7, 608 (2013)
[4] Brichta et al. PRA 79, 033404 (2009)
[5] Constant et al. PRL 82, 1668 (1999)
[6] Cousin et al. Opt. Letters 39, 5383 (2014)
[7] Ding et al. Optics Express 22, 6194 (2014)
[8] Hüve et al.Opt. Comm. 266, 261 (2006)
[9] Johnson et al., Sci. Adv. 4, 3761 (2018)
[10] D. Popmintchev et al. PRL 120, 093002 (2018)
[11] Popmintchev et al. Science 350, 1225 (2015)
[12] Rundquist et al. Science 280, 1412 (1998)
[13] Takahashi et al. Opt. Letters 27, 1920 (2002)
[14] Wang et al. Nat. Comm. 6, 7459 (2015)
[15] Klas et al. Opt. Expr. 28, 5 (2020)
[16] This source
[17]
[18] Gebhardt et al., accepted at LSA (2021)
[19] Hädrich et al. Nat. Phot. 7, 608 (2014)
[20] Klas et al. Optica 3, 11 (2016)
[21] Klas et al. in preparation (2021)
[22] Rothhardt et al. Optics Letters 39, 17 (2014)
[23] Rothhardt et al. Opt. Express 24, 18133 (2016)
[24] Comby et al. Opt. Express 27 (2019)


R. Klas, A. Kirsche, M. Gebhardt, J. Buldt, H. Stark, S. Hädrich, J. Rothhardt, and J. Limpert, "Ultra-short-pulse high-average-power megahertz-repetition-rate coherent extreme-ultraviolet light source," PhotoniX **2**, (2021).

# State of the Art XUV sources




Fiber lasers drive most of the highest flux table-top coherent XUV sources


[1] Cingöz et al. Nat. 482, 68 (2012)
[2] Porat et al., Nat. Photon. 12, 387–391 (2018)
[3] Pupeza et al. Nat. Phot. 7, 608 (2013)
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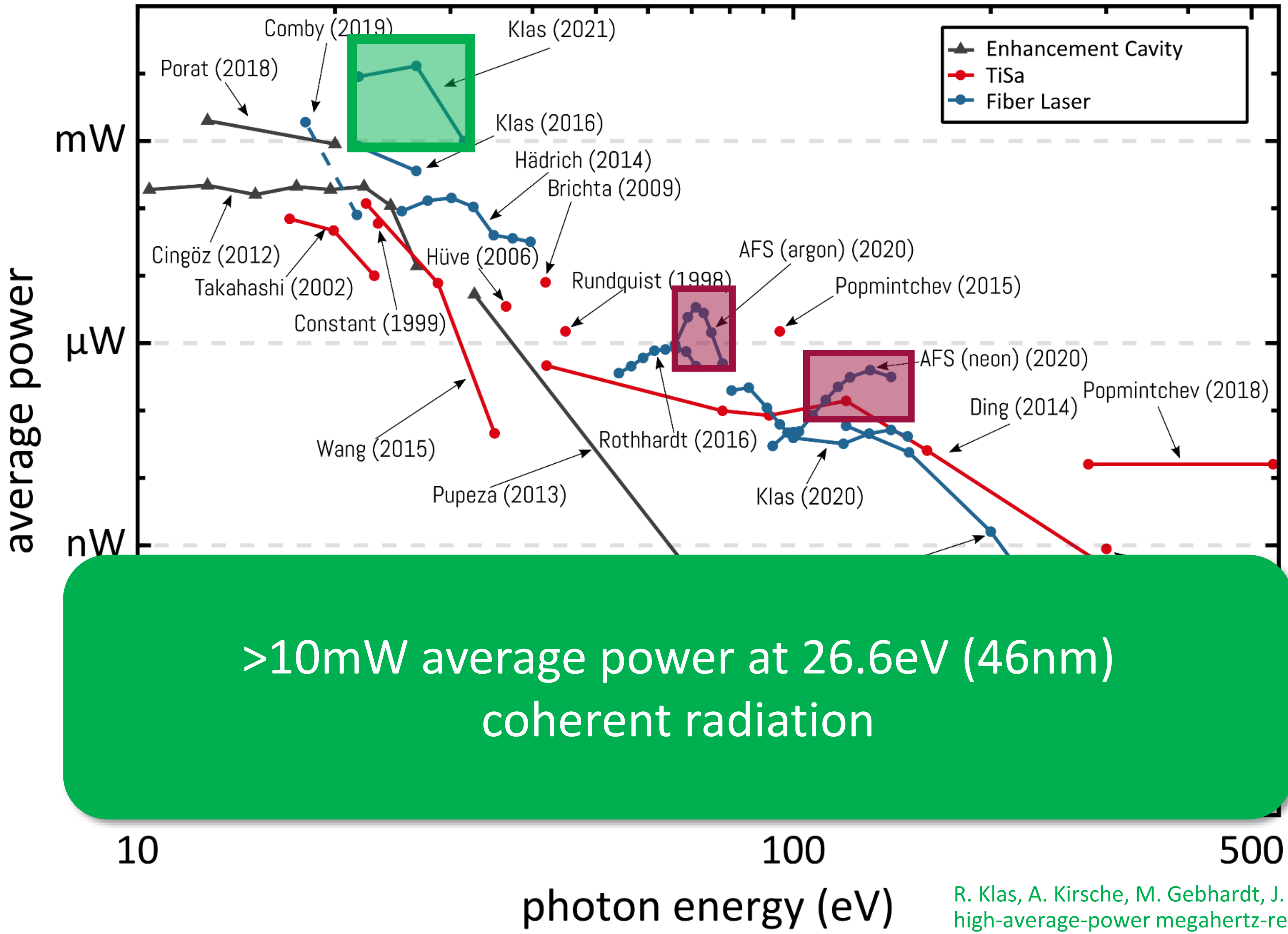
# State of the Art XUV sources




- [1] Cingöz et al. Nat. 482, 68 (2012)
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- [4] Brichta et al. PRA 79, 033404 (2009)
- [5] Constant et al. PRL 82, 1668 (1999)
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- [7] Ding et al. Optics Express 22, 6194 (2014)
- [8] Hüve et al.Opt. Comm. 266, 261 (2006)
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- [15] Klas et al. Opt. Expr. 28, 5 (2020)
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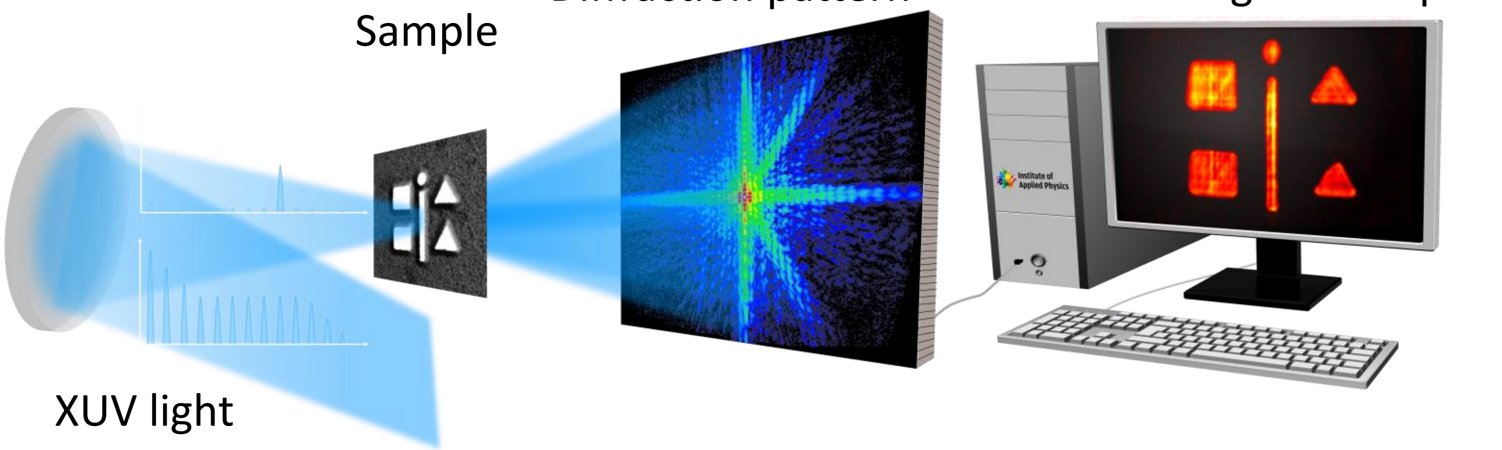
- [20] Klas et al. Optica 3, 11 (2016)
- [21] Klas et al. in preparation (2021)
- [22] Rothhardt et al. Optics Letters 39, 17 (2014)
- [23] Rothhardt et al. Opt. Express 24, 18133 (2016)
- [24] Comby et al. Opt. Express 27 (2019)

>10mW average power at 26.6eV (46nm) coherent radiation

R. Klas, A. Kirsche, M. Gebhardt, J. Buldt, H. Stark, S. Hädrich, J. Rothhardt, and J. Limpert, "Ultra-short-pulse high-average-power megahertz-repetition-rate coherent extreme-ultraviolet light source," PhotoniX **2**, (2021).




XUV Source requirements:

- Coherent
- Good Stability
- High Flux
- Rep-rate does not matter

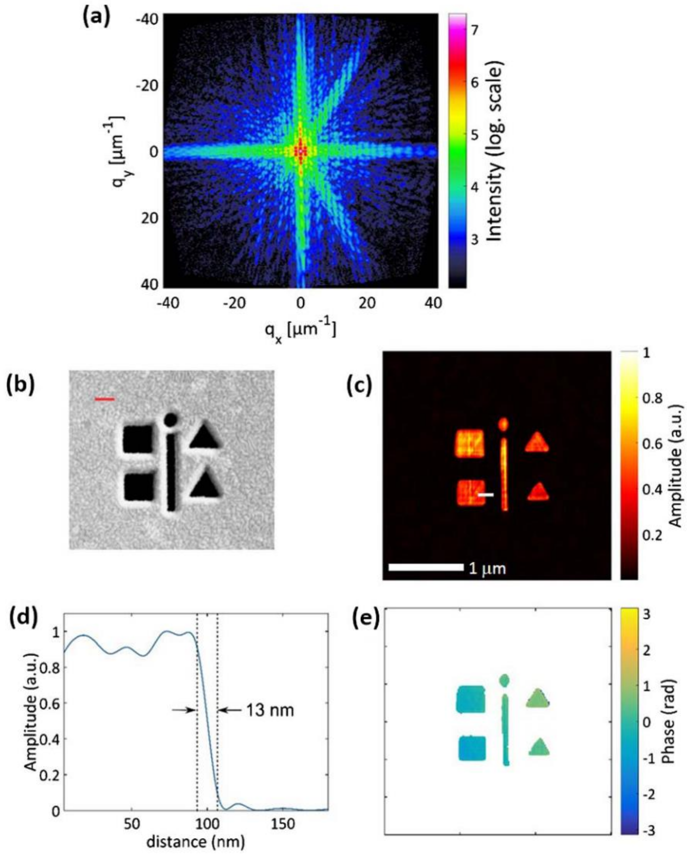



**Fig. 3.** (a) Curvature corrected high dynamic range diffraction pattern of the sample. (b) Scanning electron microscopy picture of the transmission sample; scale bar is 200 nm wide. Reconstructed exit surface wave (c) amplitude and (e) phase. (d) A cross section taken along the white line in (c) shows a 10%–90% resolution of 13 nm.

G. K. Tadesse, R. Klas, S. Demmler, S. Hädrich, I. Wahyutama, M. Steinert, C. Spielmann, M. Zürch, T. Pertsch, A. Tünnermann, J. Limpert, and J. Rothhardt, "High speed and high resolution table-top nanoscale imaging," Opt. Lett. **41**, 5170 (2016).

# Application example – pump-probe ARPES

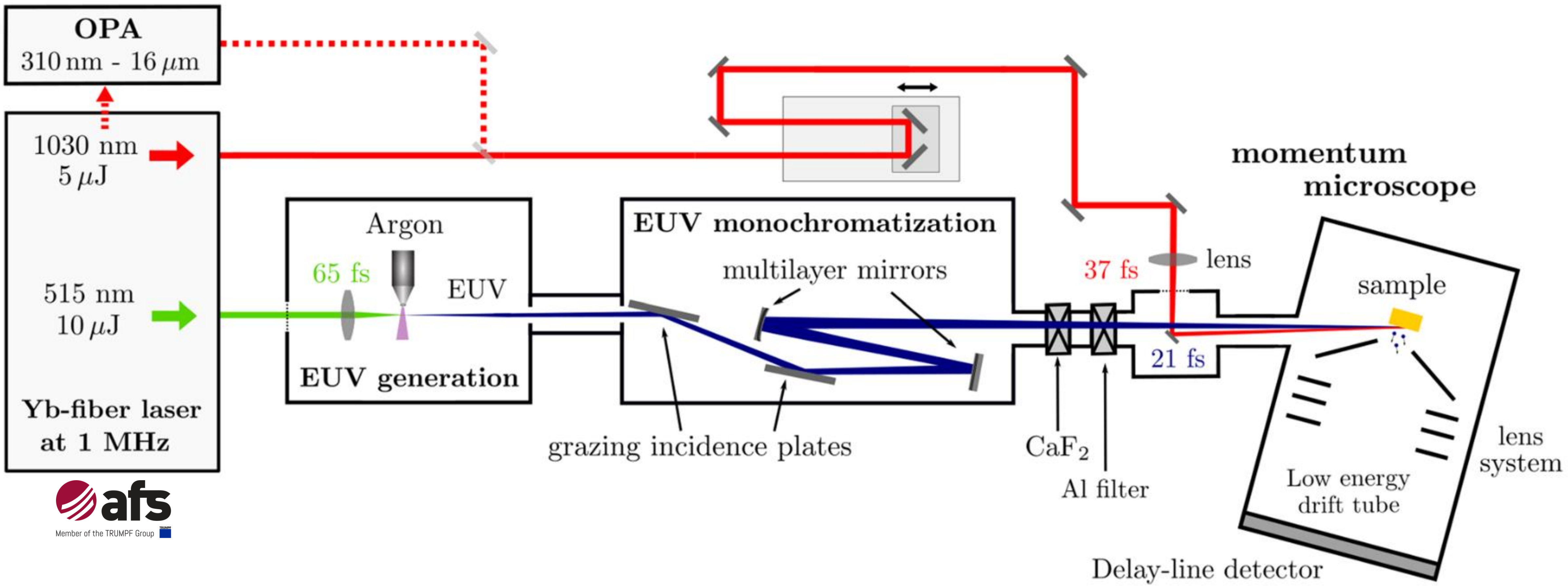
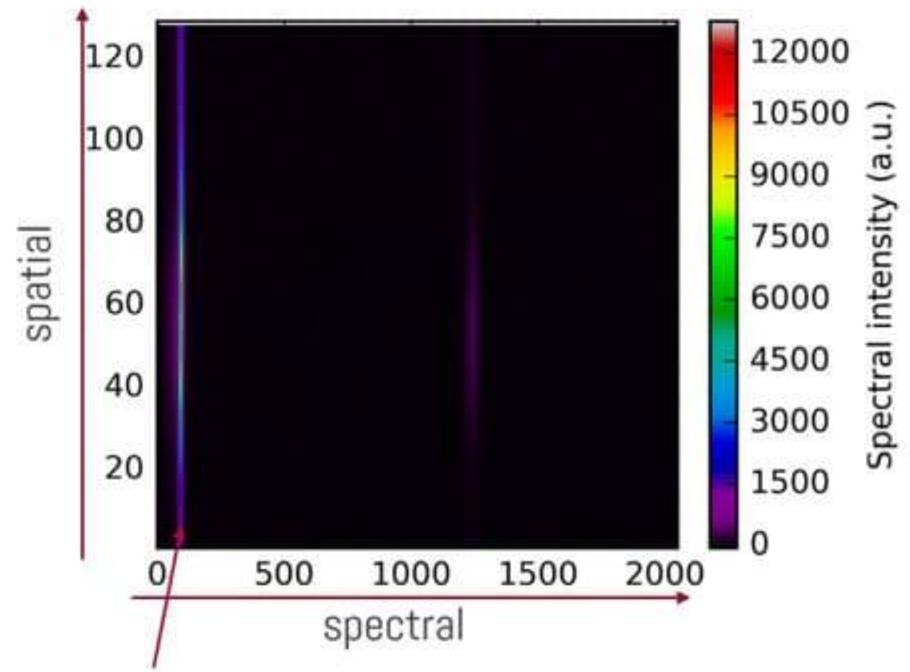
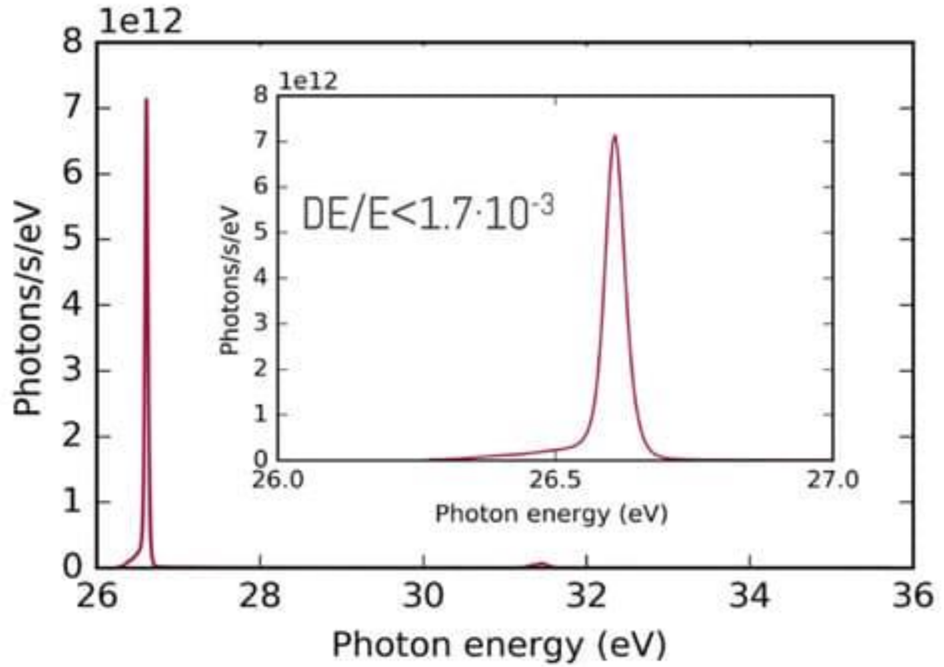



**FIG. 2.** Schematic layout of the experimental setup consisting of the 1 MHz EUV beamline, the pump line, and the momentum microscope. A detailed description is given in Secs. II and III A.

M. Keunecke, C. Möller, D. Schmitt, H. Nolte, G. S. M. Jansen, M. Reutzel, M. Gutberlet, G. Halasi, D. Steil, S. Steil, and S. Mathias, "Time-resolved momentum microscopy with a 1 MHz high-harmonic extreme ultraviolet beamline," Rev. Sci. Instrum. 91, (2020).

# ARPES source - 515nm driven

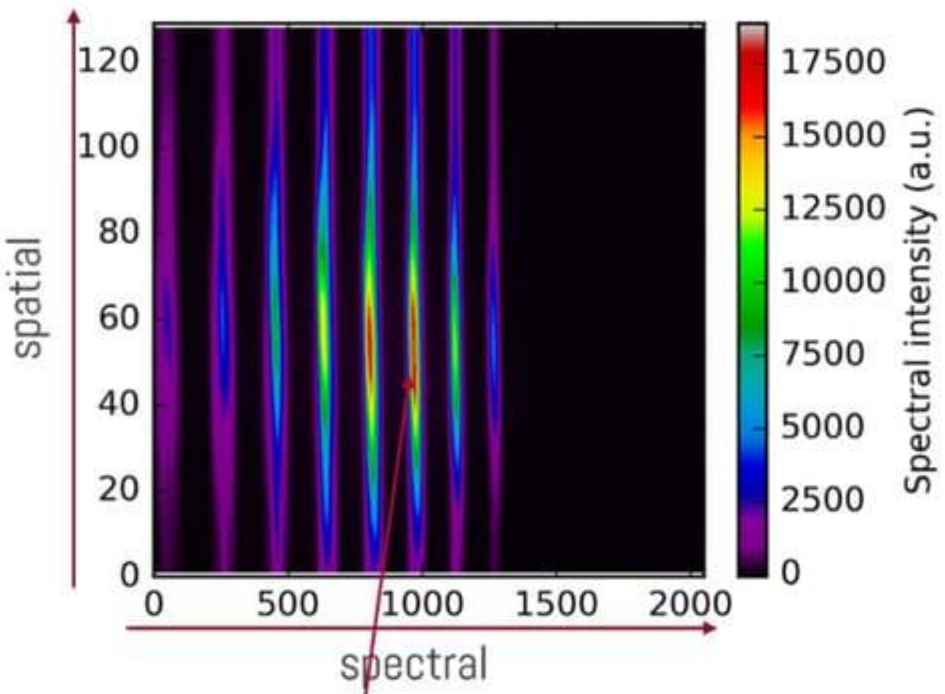


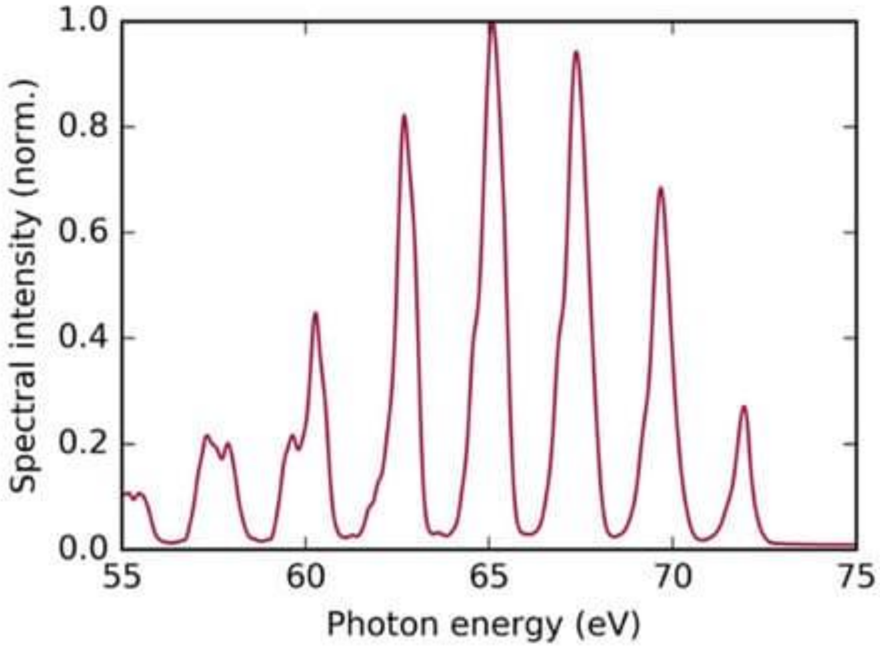




specific optimization to narrow bandwidth (26.6eV) via utilization of argon resonance

| Parameter | Value (measured) |
|---|---|
| Photon energy | 26.6eV |
| Photon Flux | $>8.6\cdot10^{11}$ photons/s |
| Divergence | ~5mrad |

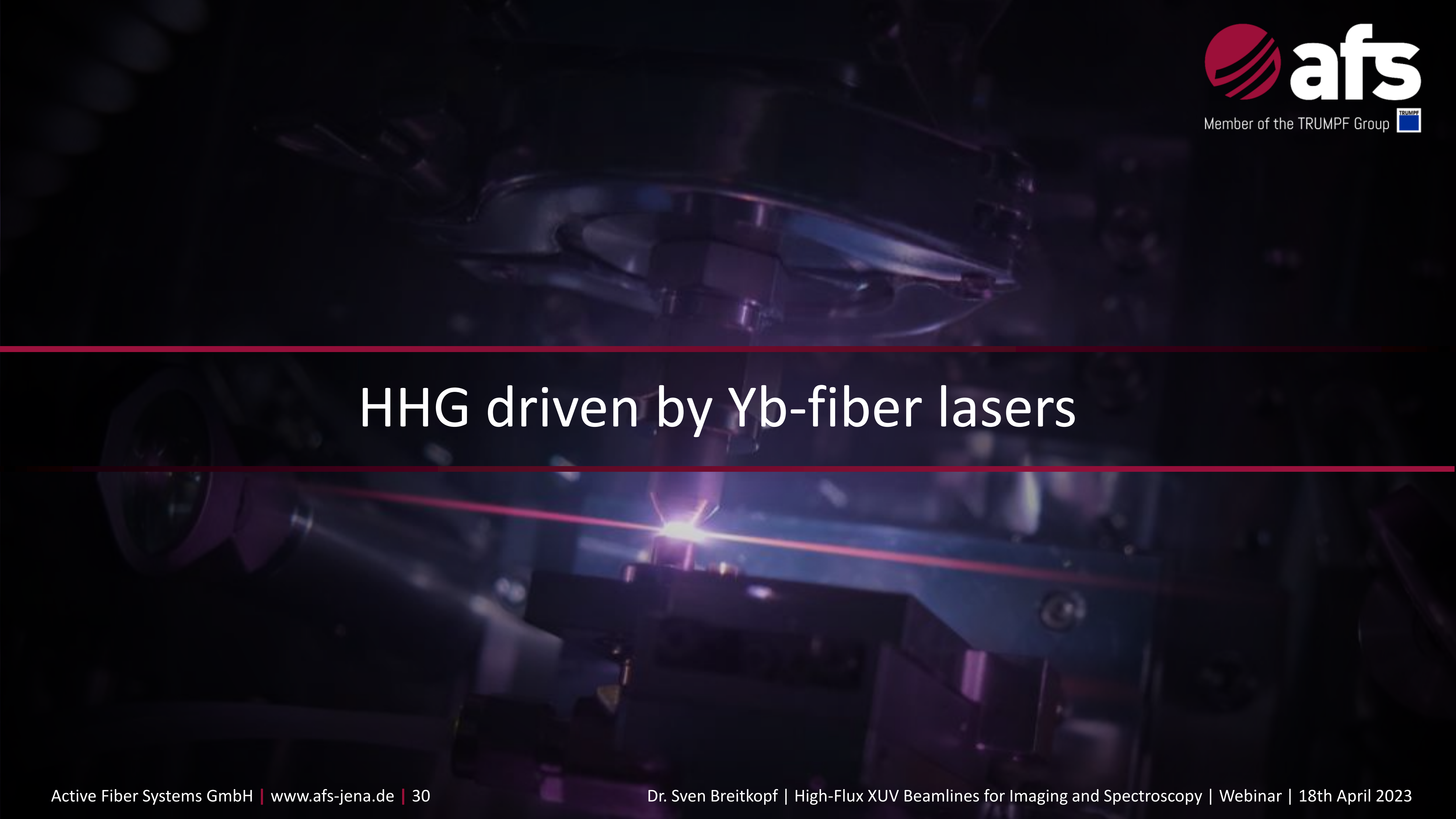
# ARPES source - 1030nm driven




Gaussian-like spatial profile,
optimization @68.6eV

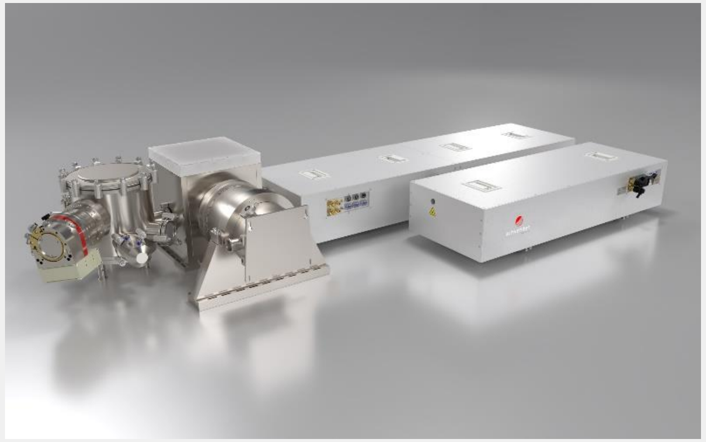
| Parameter | Value (measured) |
|---|---|
| Photon energy | 68.6eV |
| Photon Flux | $>4.5 \cdot 10^{10}$ photons/s |
| Divergence | ~7mrad |



# HHG driven by Yb-fiber lasers

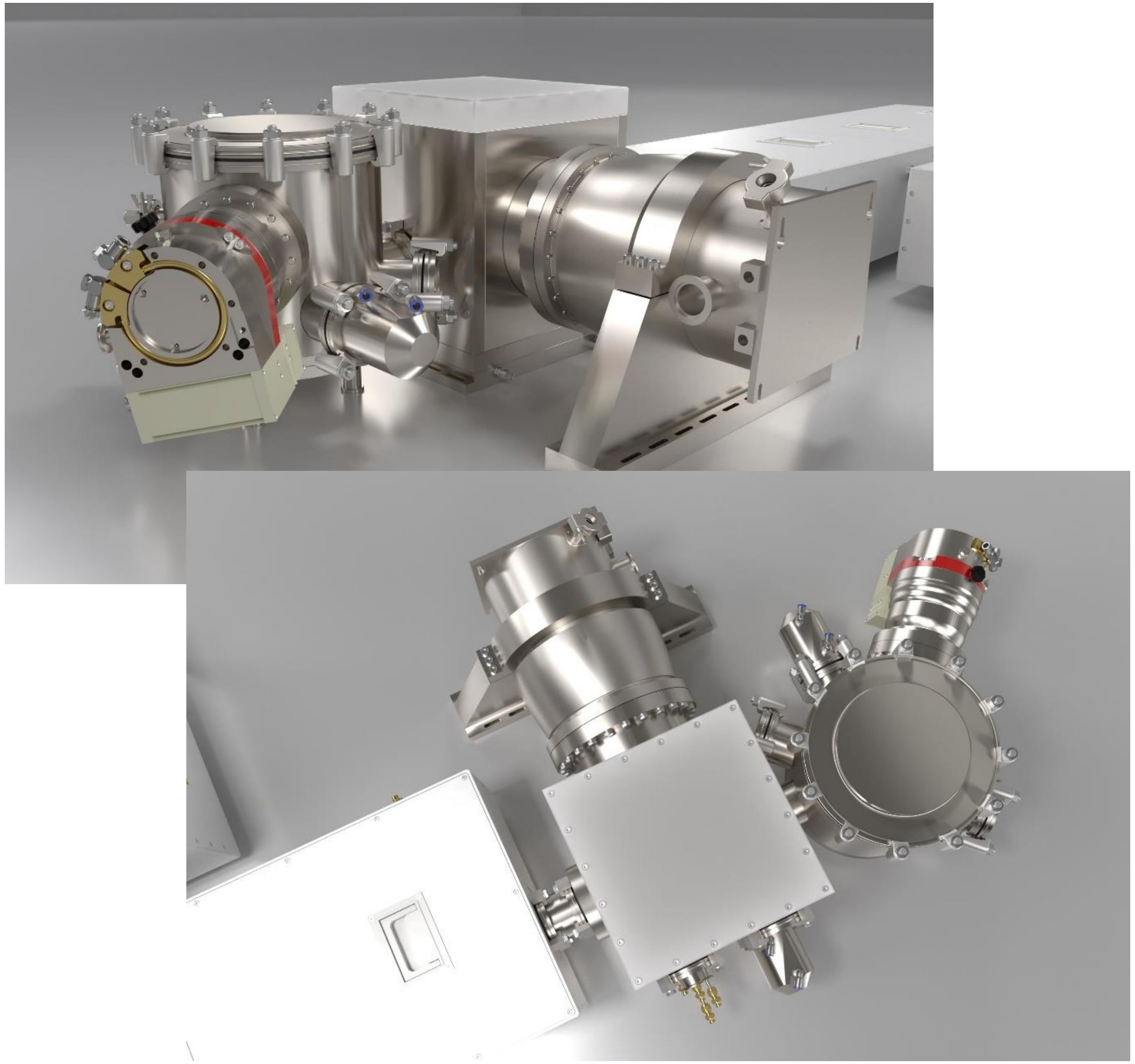
# Product platforms: XUV beamlines

## XUV sources

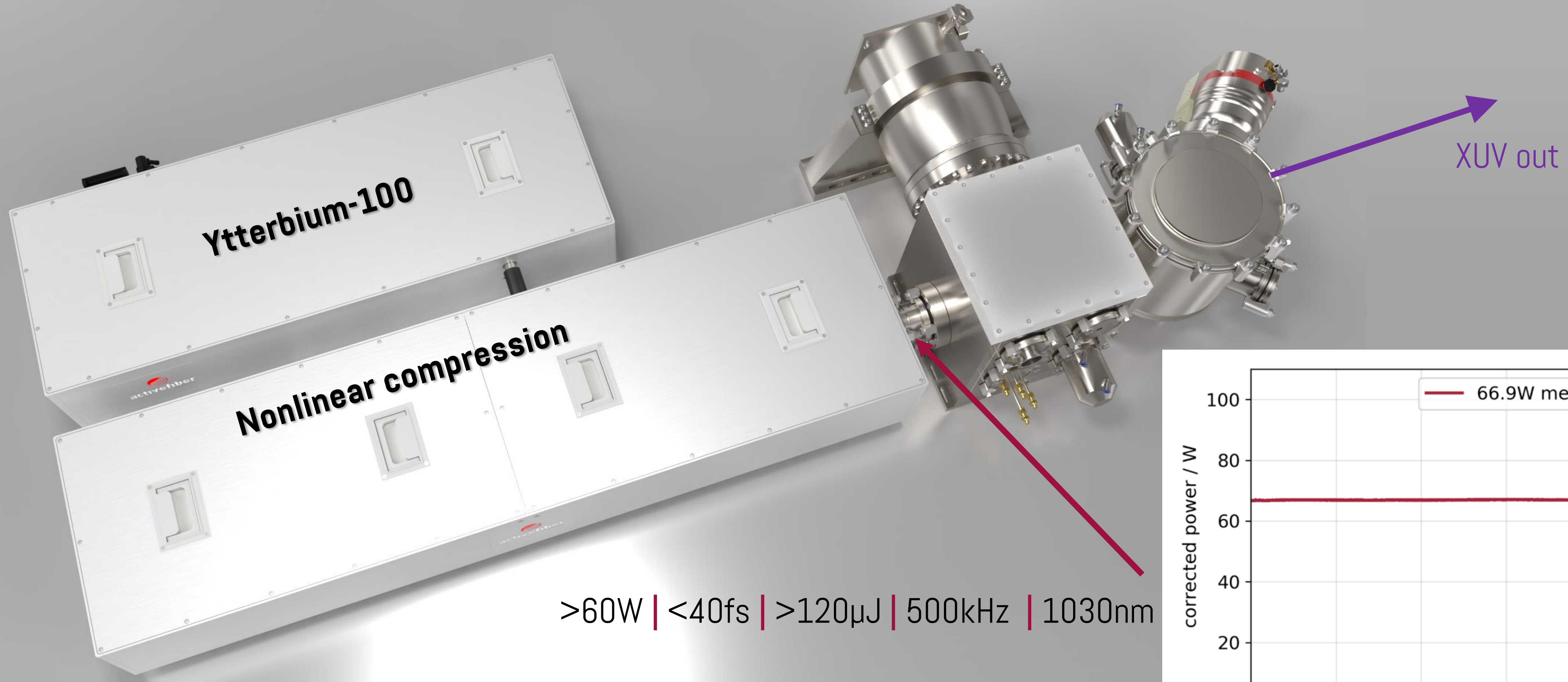


**High-flux and compact sources for coherent XUV radiation**

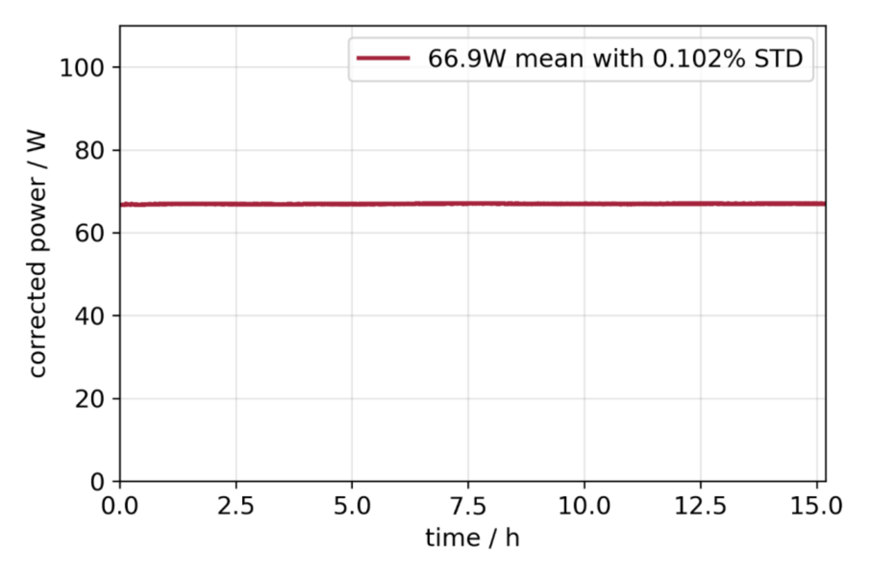
- Already realized between 20eV….150eV
- If driven by Tm-based or MidIR lasers → scalable towards water-window and keV



# XUV setup – Compact beamline (LINX driver at ARCNL)



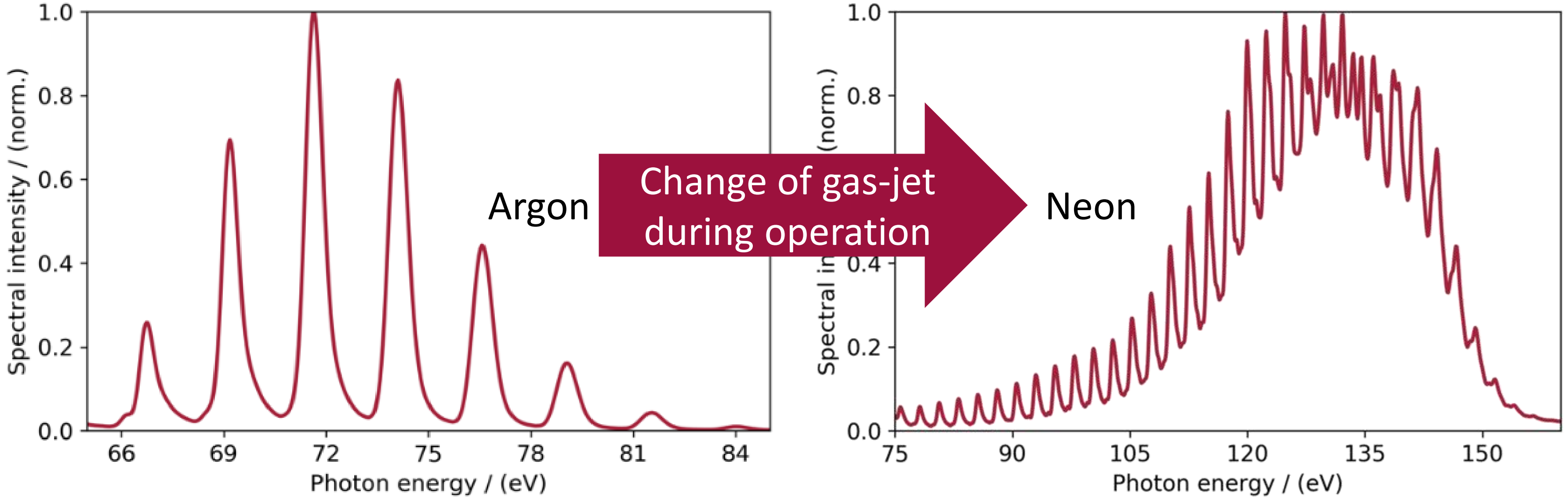

>60W | <40fs | >120µJ | 500kHz | 1030nm



# XUV output results

| Harmonic | Photon energy /eV | Wavelength /nm | Flux /10^10 Photons/s/(1% bandwidth) |
|---|---|---|---|
| 59 | 71 | 17.5 | 30* |
| 77 | 93 | 13.3 | 0.2 |
| 93 | 112 | 11.1 | 0.8* |
| 109 | 131 | 9.5 | 1.9* |

Some exemplary photon fluxes of this source. The *-marked values state world-record fluxes.



# Long-term stability

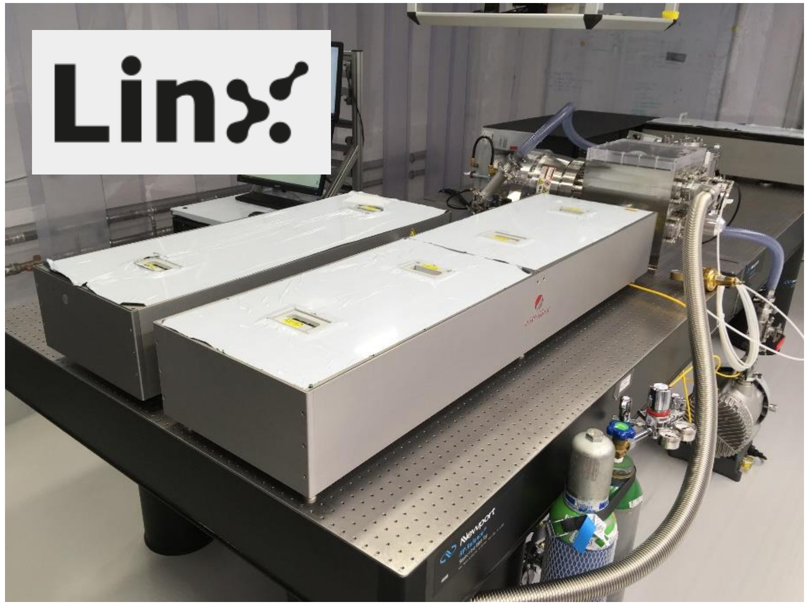
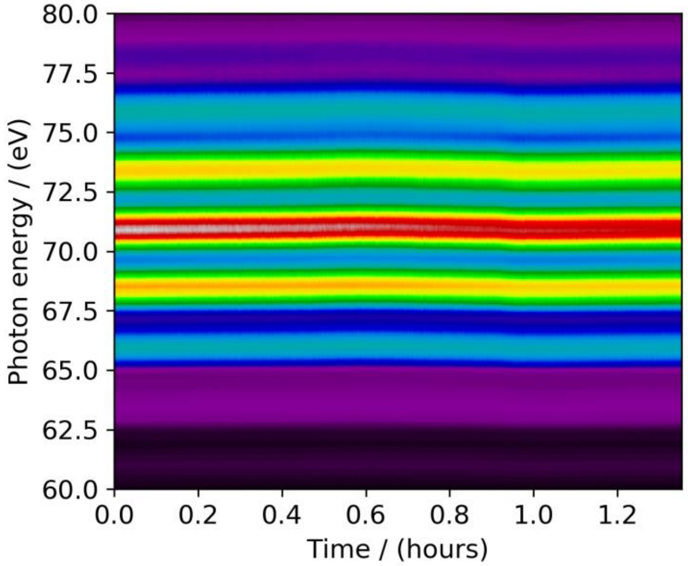
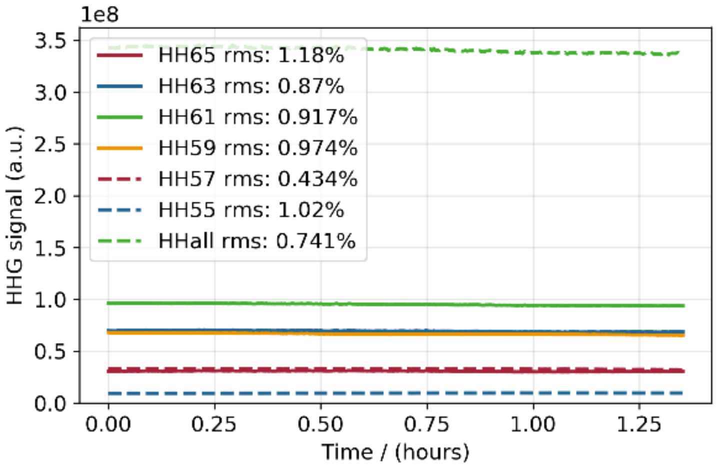


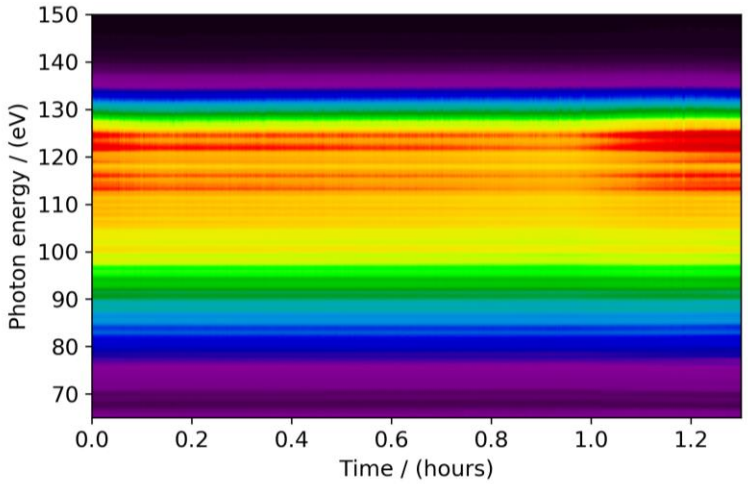

Photo of an XUV Beamline a few days before shipment to TU Delft within the LINX Project with ASML

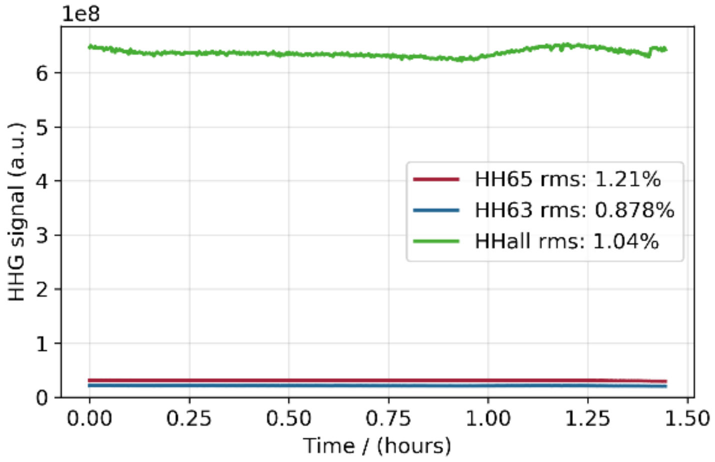
https://www.linx-nwo-ttw.nl




Long-term measurements of exemplary harmonics generated in Argon



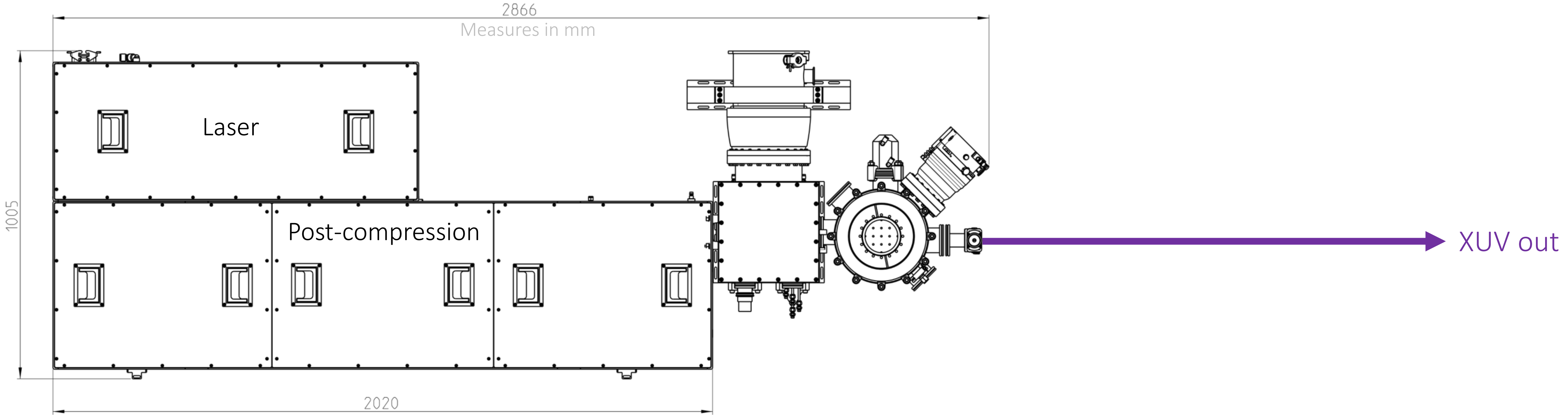




Long-term measurements of exemplary harmonics generated in Neon


**XUV out:**

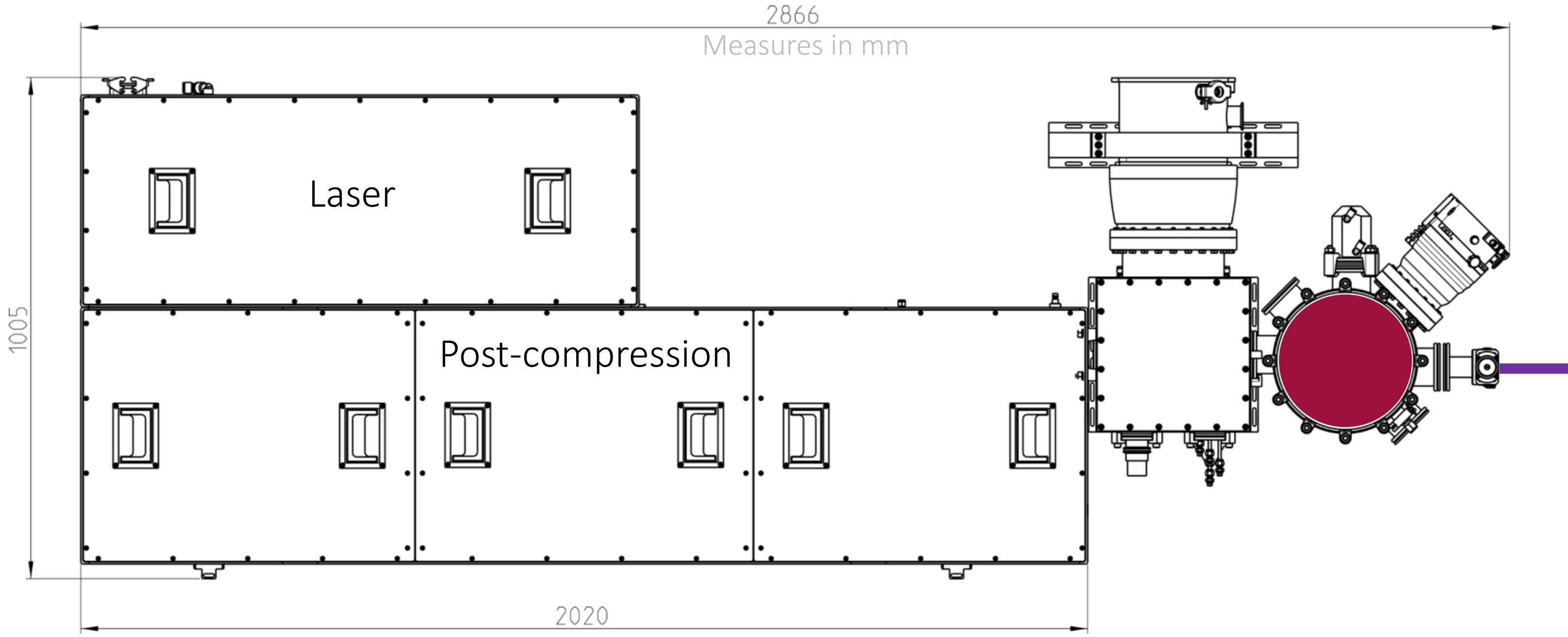
- 20eV…150eV
- up to $10^{15}$Photons/s
- Flexible bandwidths
- Flexible Pulse durations

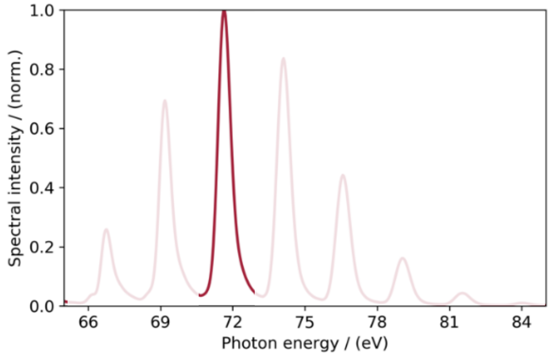
# XUV Modules




| Monochromization: | Dual-color driver: | Polarization tunability: | Focusing: | Differential pumping | Spectrometer |
|---|---|---|---|---|---|
| Pick the harmonic you want. Can be adjustable to pick multiple different lines | Generate harmonics with multiple driving laser wavelengths (e.g. 1030nm & 515nm) at the same time or switch between both drivers during an experiment on the same optical path | Using an annular beam and suitable separation techniques it is possible to generate XUV radition that can be switched from horizontal to vertical polaization during operation (circular on request) | Our radiation has an excellent beam quality and can be focussed as tightly as needed. Down to a few µm have been realized. | Target chambers often have strict requirements on the pressure. We can use the focusing section of the beamline to reduce the pressure down to <$10^{9}$mbar or less | Since it is always helpful to know the exact spectrum during your experiments, we offer integrated modules to measure the spectrum, even simultaneously to your experiment, if desired. |

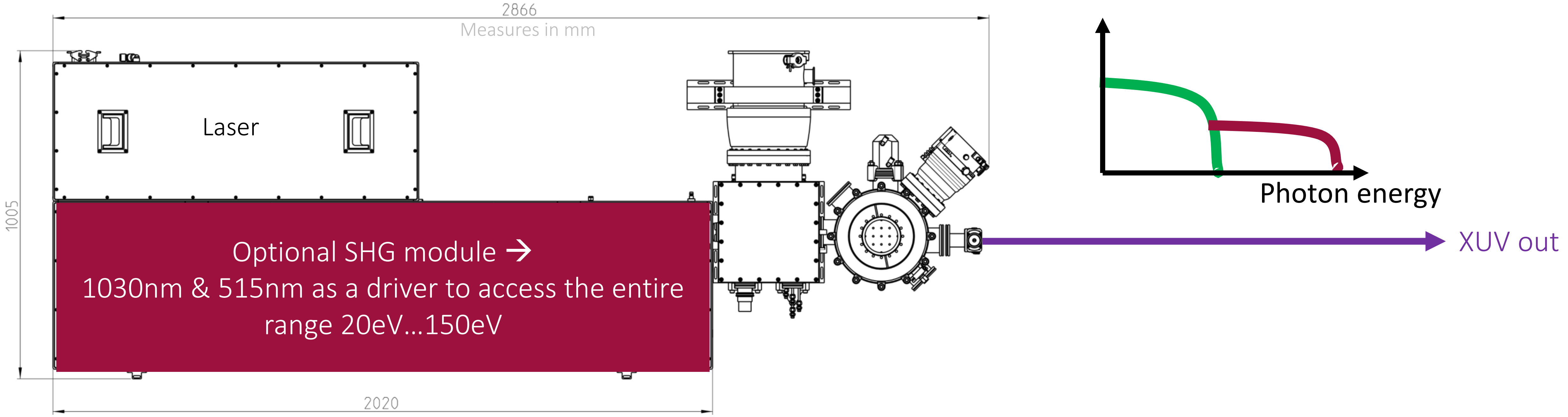
# XUV Modules




| **Monochromization:** Pick the harmonic you want. Can be adjustable to pick multiple different lines | **Dual-color driver:** Generate harmonics with multiple driving laser wavelengths (e.g. 1030nm & 515nm) at the same time or switch between both drivers during an experiment on the same optical path | **Polarization tunability:** Using an annular beam and suitable separation techniques it is possible to generate XUV radition that can be switched from horizontal to vertical polaization during operation (circular on request) | **Focusing:** Our radiation has an excellent beam quality and can be focussed as tightly as needed. Down to a few µm have been realized. | **Differential pumping** Target chambers often have strict requirements on the pressure. We can use the focusing section of the beamline to reduce the pressure down to <$10^9$mbar or less | **Spectrometer** Since it is always helpful to know the exact spectrum during your experiments, we offer integrated modules to measure the spectrum, even simultaneously to your experiment, if desired. |
|---|---|---|---|---|---|

# XUV Modules




**Monochromization:**
Pick the harmonic you want. Can be adjustable to pick multiple different lines

**Dual-color driver:**
Generate harmonics with multiple driving laser wavelengths (e.g. 1030nm & 515nm) at the same time or switch between both drivers during an experiment on the same optical path

**Polarization tunability:**
Using an annular beam and suitable separation techniques it is possible to generate XUV radition that can be switchen from horizontal to vertical polaization during operation (circular on request)

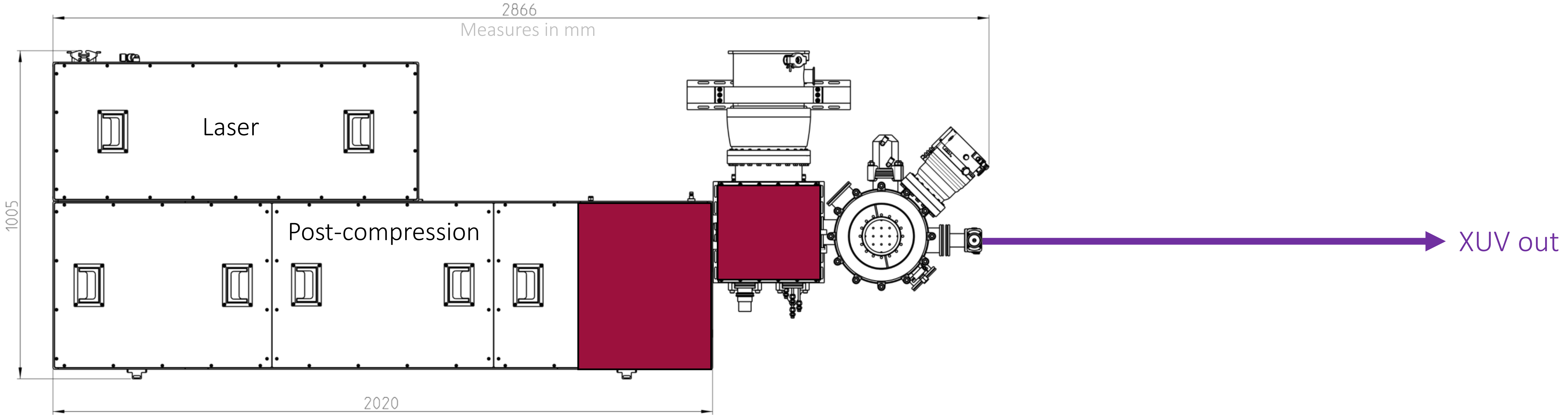
**Focusing:**
Our radiation has an excellent beam quality and can be focussed as tightly as needed. Down to a few µm have been realized.

**Differential pumping**
Target chambers often have strict requirements on the pressure. We can use the focusing section of the beamline to reduce the pressure down to <$10^9$mbar or less

**Spectrometer**
Since it is always helpful to know the exact spectrum during your experiments, we offer integrated modules to measure the spectrum, even simultaneously to your experiment, if desired.

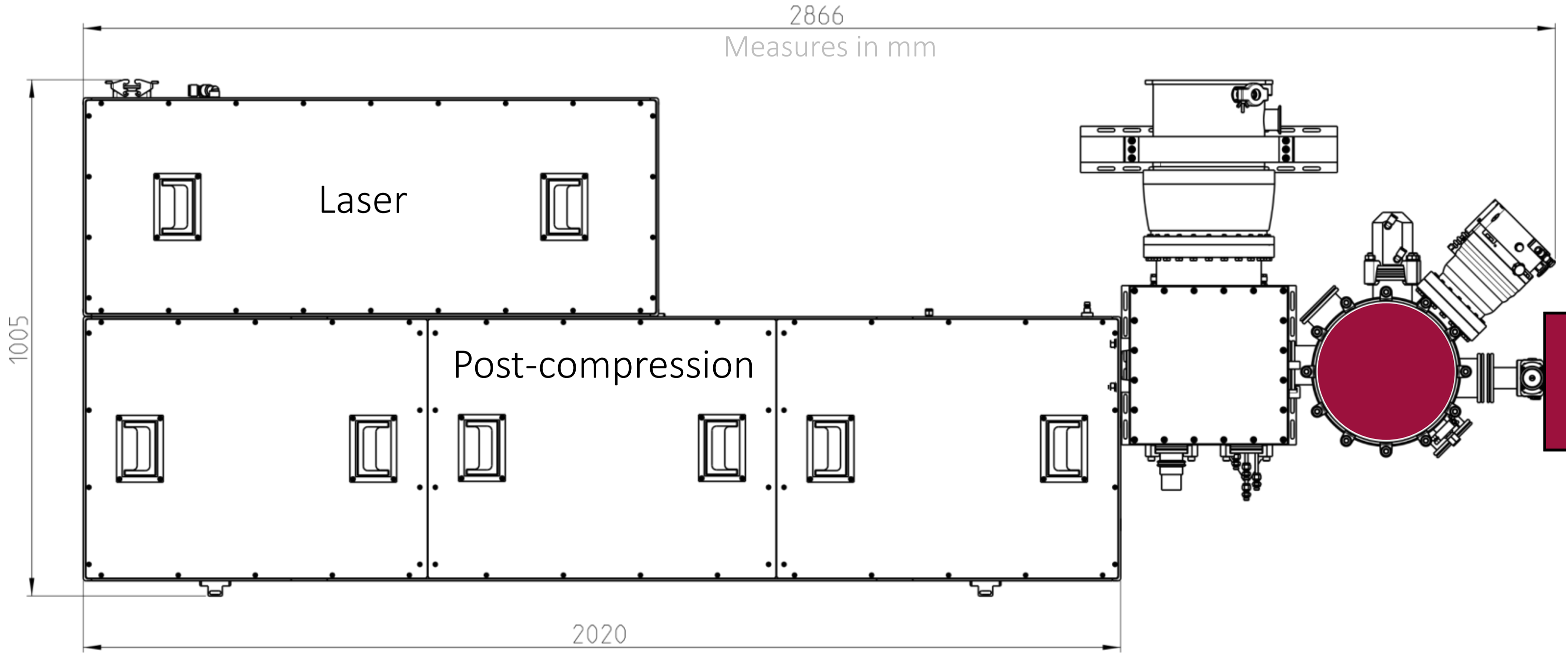
[1] M. Keunecke, et al "Time-resolved momentum microscopy with a 1 MHz high-harmonic extreme ultraviolet beamline," Rev. Sci. Instrum. **91**, (2020).

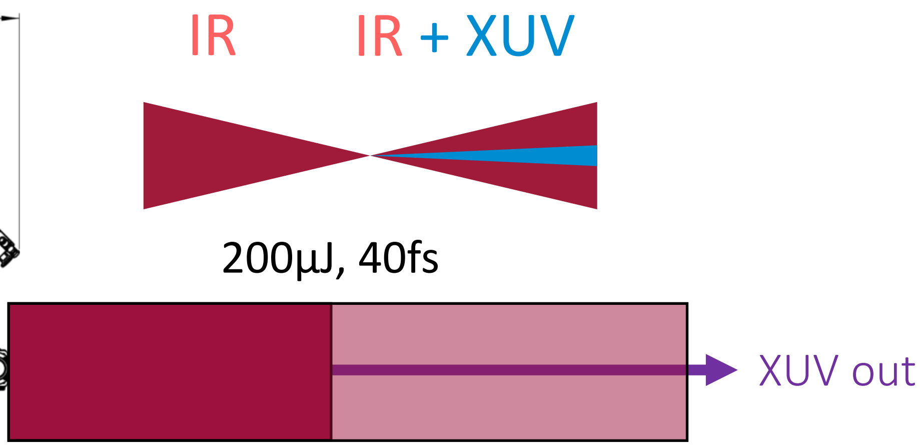
# XUV Modules




| Monochromization: Pick the harmonic you want. Can be adjustable to pick multiple different lines | Dual-color driver: Generate harmonics with multiple driving laser wavelengths (e.g. 1030nm & 515nm) at the same time or switch between both drivers during an experiment on the same optical path | Polarization tunability: Using an annular beam and suitable separation techniques it is possible to generate XUV radition that can be switched from horizontal to vertical polaization during operation (circular on request) | Focusing: Our radiation has an excellent beam quality and can be focussed as tightly as needed. Down to a few µm have been realized. | Differential pumping Target chambers often have strict requirements on the pressure. We can use the focusing section of the beamline to reduce the pressure down to <$10^9$mbar or less | Spectrometer Since it is always helpful to know the exact spectrum during your experiments, we offer integrated modules to measure the spectrum, even simultaneously to your experiment, if desired. |
|---|---|---|---|---|---|

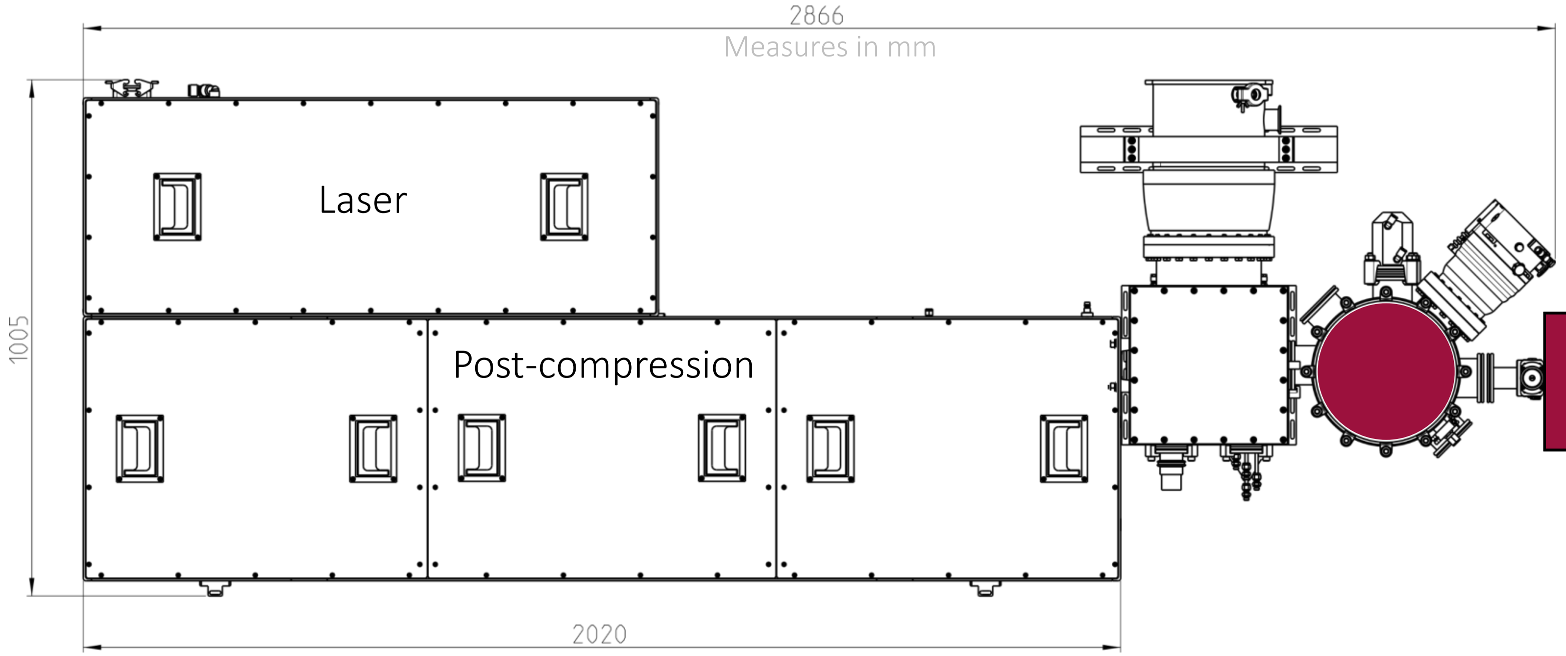
# XUV Modules

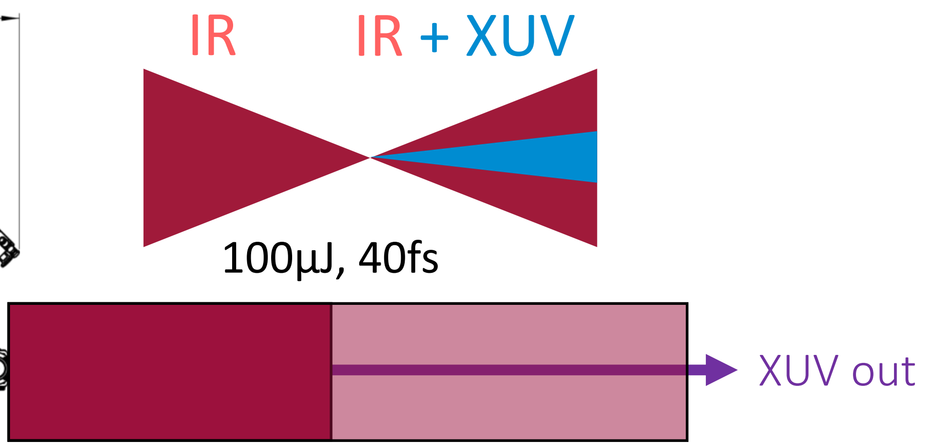



| | | | | | |
|---|---|---|---|---|---|
| **Monochromization:** Pick the harmonic you want. Can be adjustable to pick multiple different lines | **Dual-color driver:** Generate harmonics with multiple driving laser wavelengths (e.g. 1030nm & 515nm) at the same time or switch between both drivers during an experiment on the same optical path | **Polarization tunability:** Using an annular beam and suitable separation techniques it is possible to generate XUV radition that can be switched from horizontal to vertical polaization during operation (circular on request) | **Focusing:** Our radiation has an excellent beam quality and can be focussed as tightly as needed. Down to a few µm have been realized. | **Differential pumping** Target chambers often have strict requirements on the pressure. We can use the focusing section of the beamline to reduce the pressure down to <$10^9$mbar or less | **Spectrometer** Since it is always helpful to know the exact spectrum during your experiments, we offer integrated modules to measure the spectrum, even simultaneously to your experiment, if desired. |

# XUV Modules

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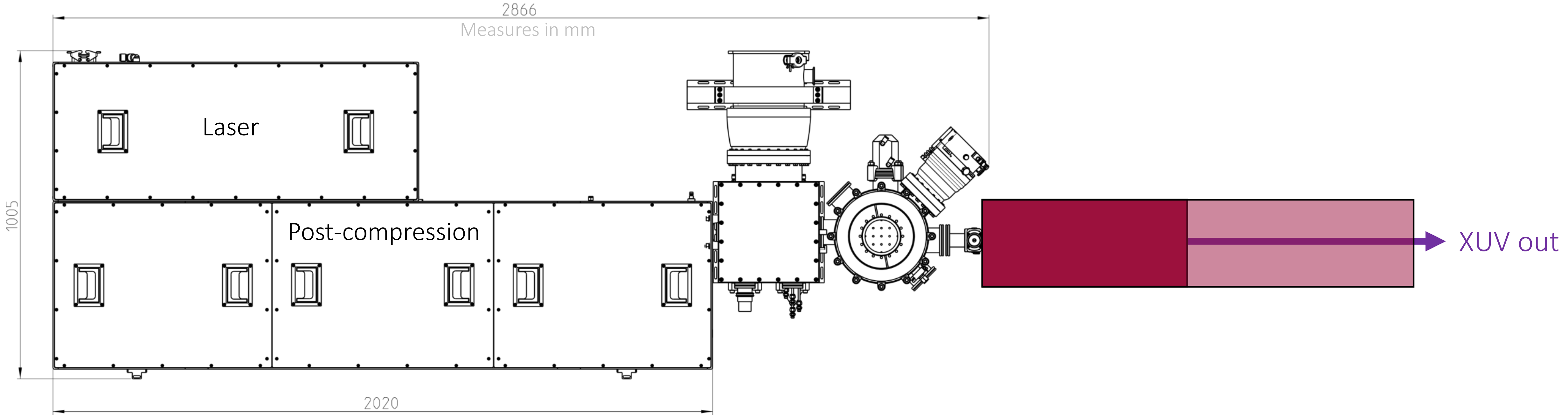
|---|---|---|---|---|---|

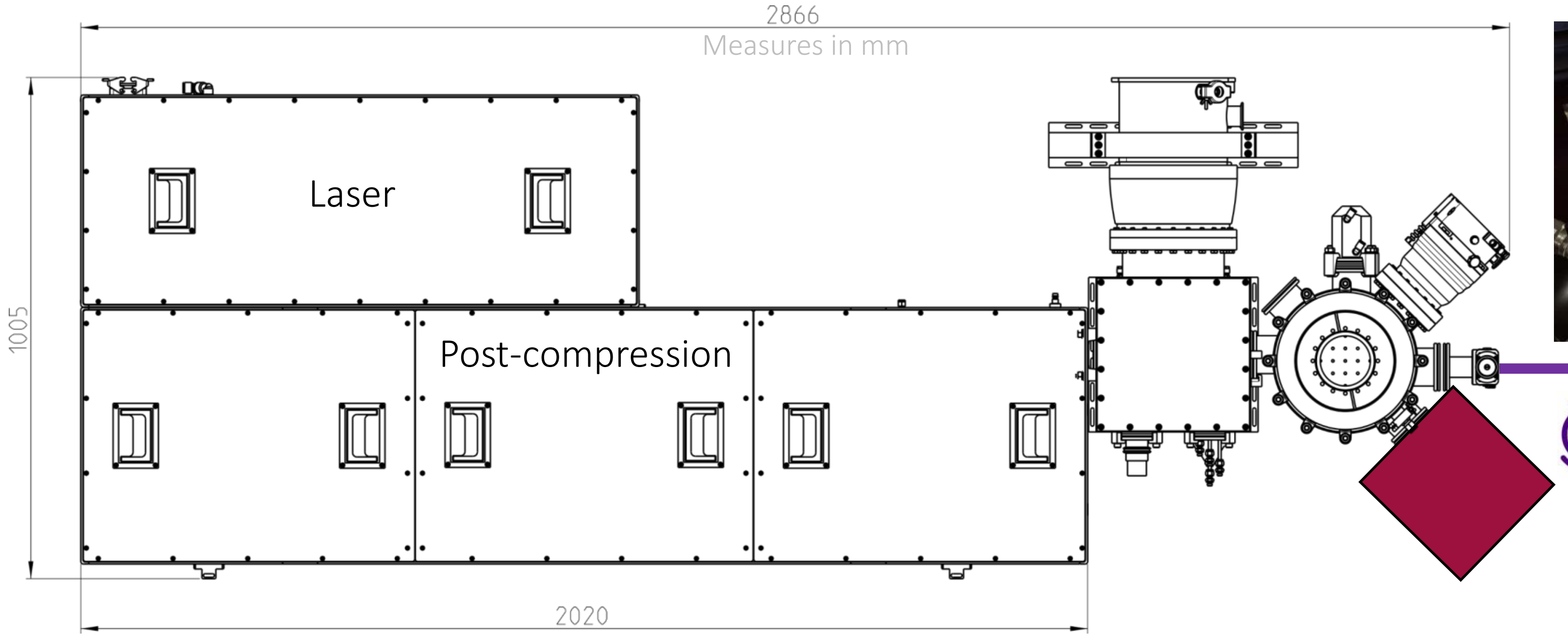
# XUV Modules

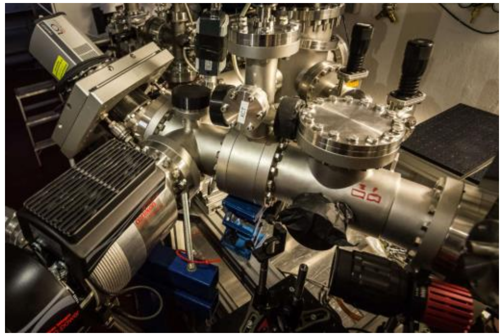



| Monochromization: | Dual-color driver: | Polarization tunability: | Focusing: | Differential pumping [1] | Spectrometer |
|---|---|---|---|---|---|
| Pick the harmonic you want. Can be adjustable to pick multiple different lines | Generate harmonics with multiple driving laser wavelengths (e.g. 1030nm & 515nm) at the same time or switch between drivers during an experiment on the same optical path | Using an annular beam and suitable separation techniques it is possible to generate XUV radition that can be switched from horizontal to vertical polaization during operation (circular on request) | Our radiation has an excellent beam quality and can be focussed as tightly as needed. Down to a few µm have been realized. | Target chambers often have strict requirements on the pressure. We can use the focusing section of the beamline to reduce the pressure down to <$10^9$mbar or less | Since it is always helpful to know the exact spectrum during your experiments, we offer integrated modules to measure the spectrum, even simultaneously to your experiment, if desired. |

[1] M. Tschernajew, P. Gierschke, H. Lin, V. Hilbert, J. Kurdal, A. Stancalie, J. Limpert, and J. Rothhardt, "Differential pumping unit for windowless coupling of laser beams to ultra high vacuum," Vacuum **178**, (2020).

# XUV Modules



INDIGO OPTICAL SYSTEMS

[https://indigo-optics.com/spectroscopy](https://indigo-optics.com/spectroscopy)

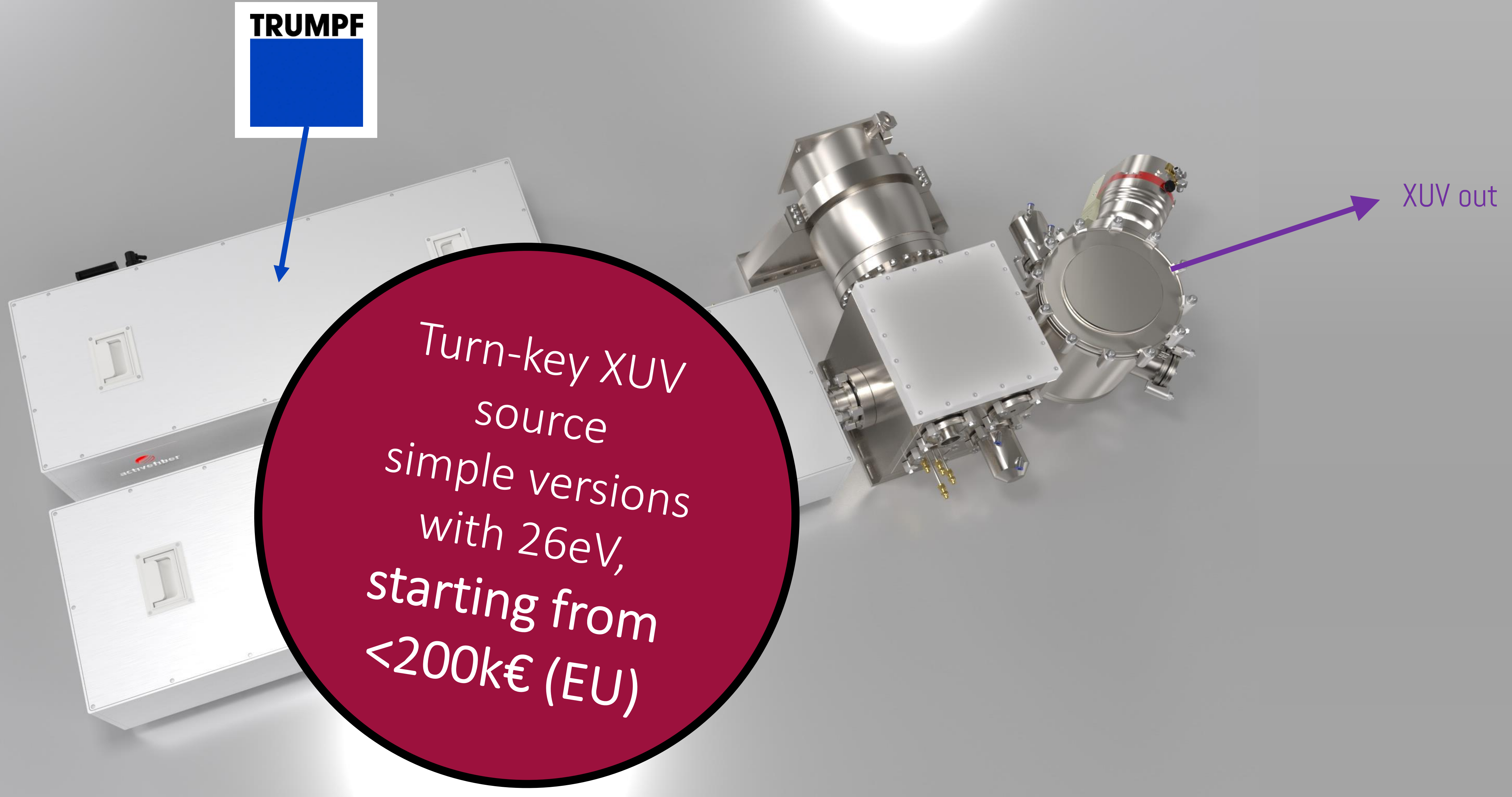
| | | | | | |
|---|---|---|---|---|---|
| **Monochromization:** Pick the harmonic you want. Can be adjustable to pick multiple different lines | **Dual-color driver:** Generate harmonics with multiple driving laser wavelengths (e.g. 1030nm & 515nm) at the same time or switch between both drivers during an experiment on the same optical path | **Polarization tunability:** Using an annular beam and suitable separation techniques it is possible to generate XUV radition that can be switched from horizontal to vertical polaization during operation (circular on request) | **Focusing:** Our radiation has an excellent beam quality and can be focussed as tightly as needed. Down to a few µm have been realized. | **Differential pumping** Target chambers often have strict requirements on the pressure. We can use the focusing section of the beamline to reduce the pressure down to $<10^{9}$mbar or less | **Spectrometer [2]** Since it is always helpful to know the exact spectrum during your experiments, we offer integrated modules to measure the spectrum, even simultaneously to your experiment, if desired. |

[2] M. Wünsche, et al, "A high resolution extreme ultraviolet spectrometer system optimized for harmonic spectroscopy and XUV beam analysis," Rev. Sci. Instrum. **90**, (2019).

# TRUMPF Synergies - XUV beamline


| Synergies with Trumpf Group |
| --- |
| Flexibility in terms of repetition rate and energy |
| Different foot-print options |
| Flexible XUV bandwidth and pulse duration options |

Member of the TRUMPF Group



Member of the TRUMPF Group

# HHG Flux scaling: $P_{out} = P_{in} \cdot \eta$

# Scaling of photon energy

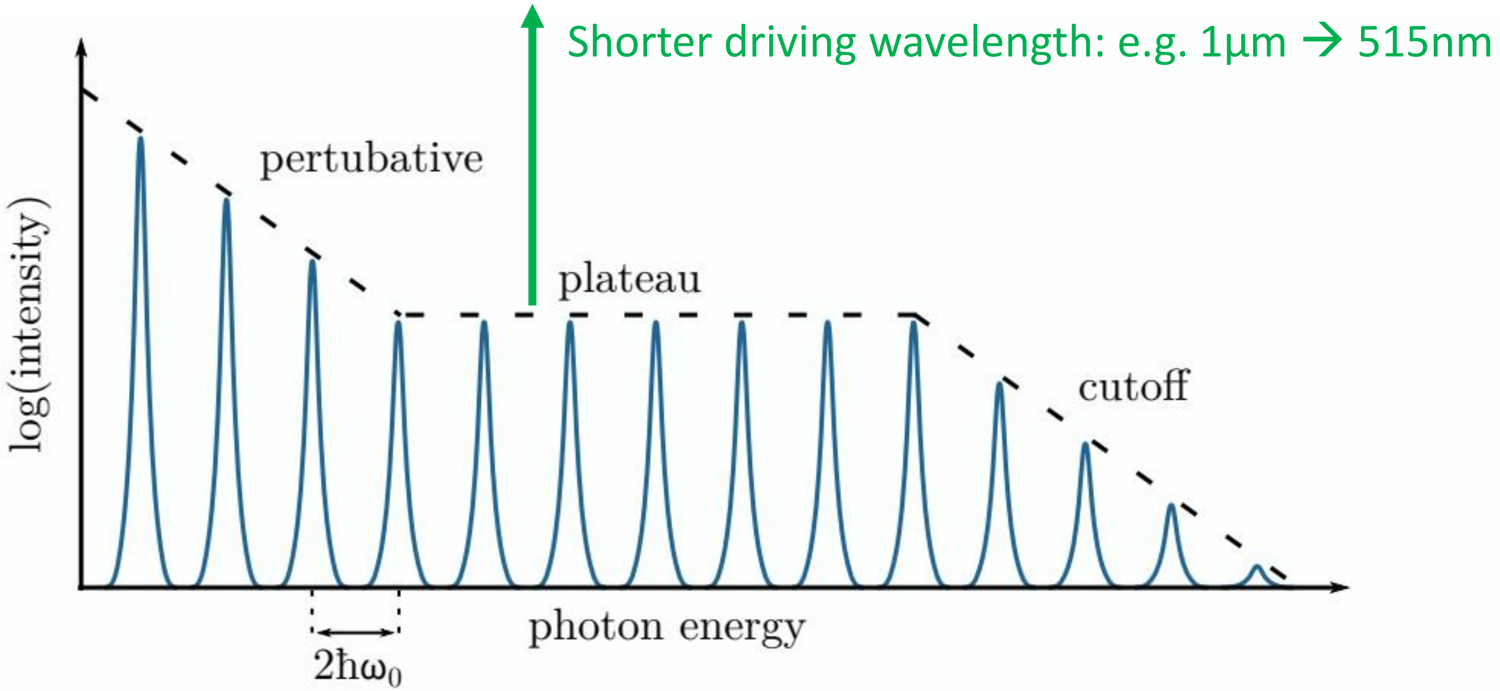



**Figure 2.3: Schematic high harmonic spectrum,** showing a comb of odd harmonics with the pertubative, plateau and cutoff region. The driving laser angular frequency is $\omega_0$.

- Robert Klas "Efficiency Scaling of High Harmonic Generation using Ultrashort Fiber Lasers," (2021).

# Flux scaling - efficiency

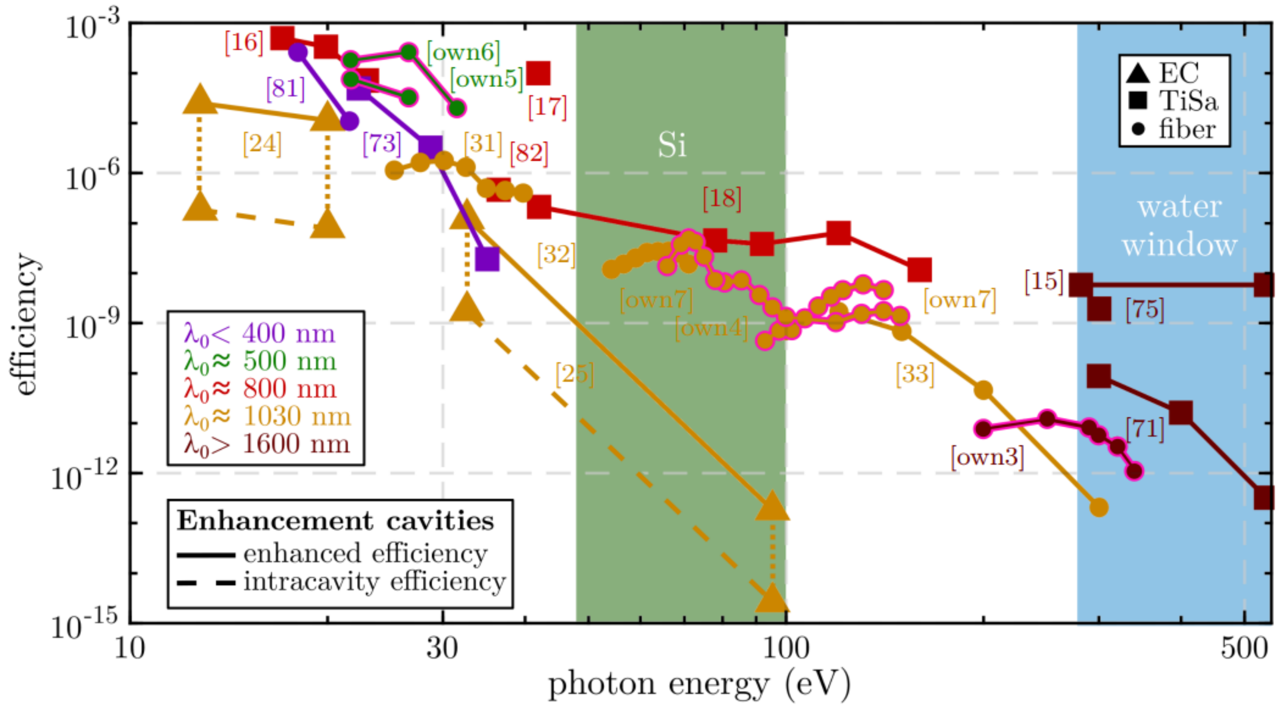



**Figure 3.5: High harmonic efficiency.** State-of-the-art HHG efficiency for single ionized gases and different XUV photon energies. The marker shape marks the laser architecture (triangle for enhancement cavities, square for Ti:sapphire lasers and circle for fiber lasers), while the color marks the driving wavelength and a pink boarder line marks sources developed in this thesis. Furthermore, the shaded areas mark the Si and the water window. To compare the efficiency of the enhancement cavities with the single pass efficiency of the other sources, the intracavity efficiency (dashed lines) and the enhanced efficiency is shown.

Robert Klas "Efficiency Scaling of High Harmonic Generation using Ultrashort Fiber Lasers," (2021).

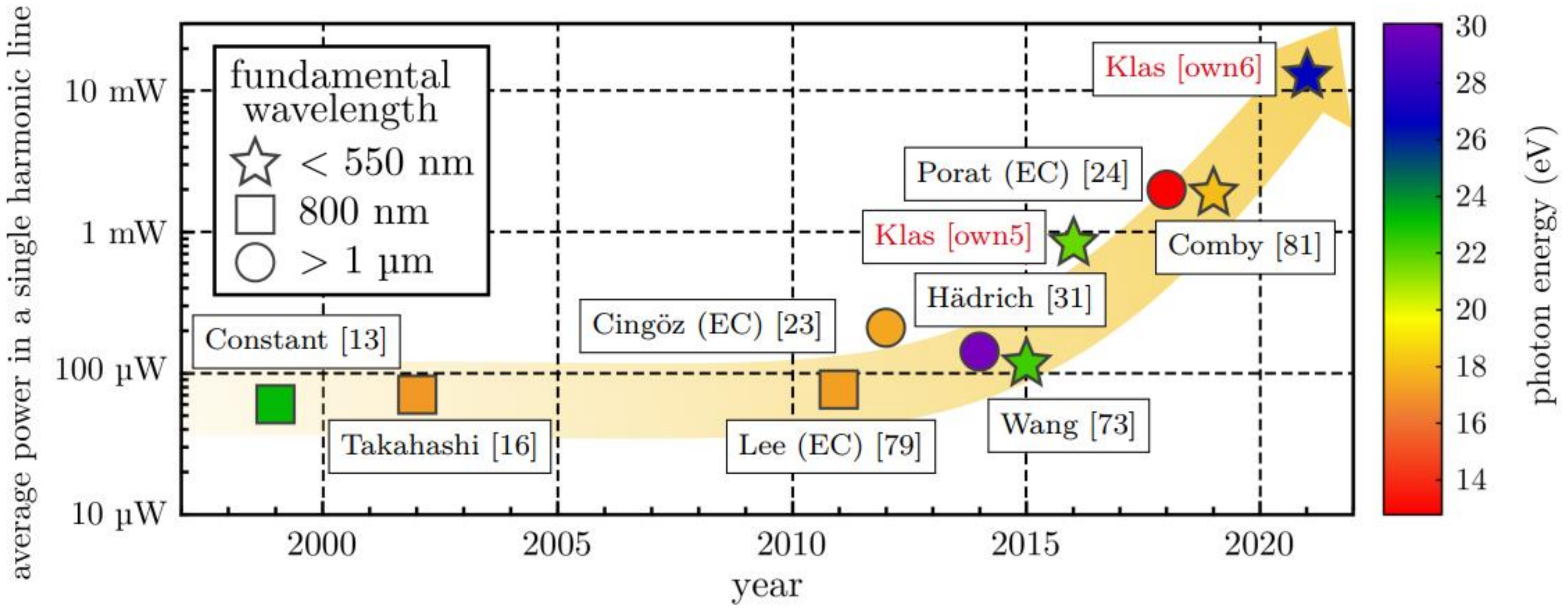
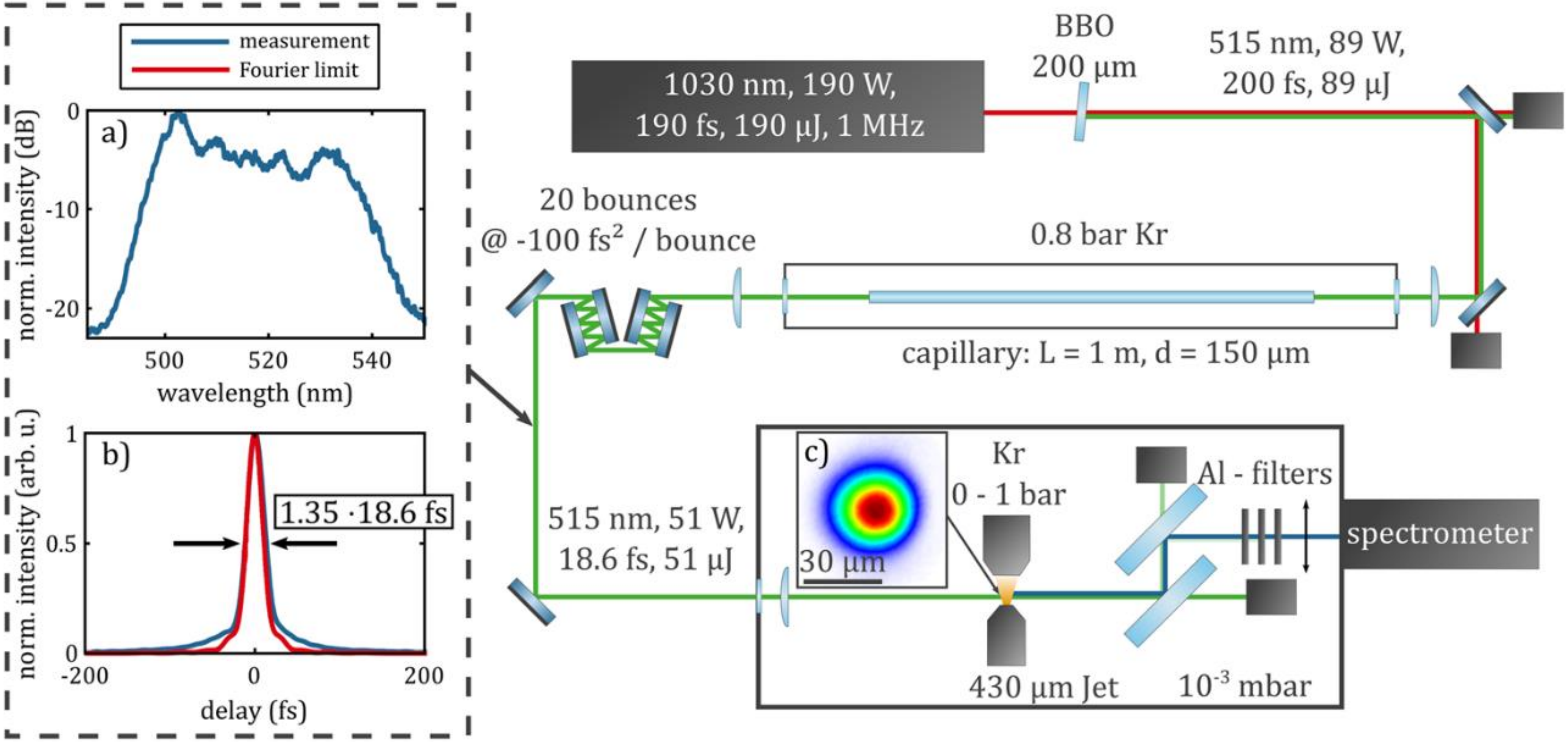



**Figure 6.1: State-of-the-art HHG sources.** Assorted HHG sources in the energy range of 12 eV to 30 eV, with a record high XUV average power above 10 µW. The marker shape indicates the driving wavelength and the marker color the XUV photon energy. Figure reproduced from [own6]. (EC: enhancement cavity)

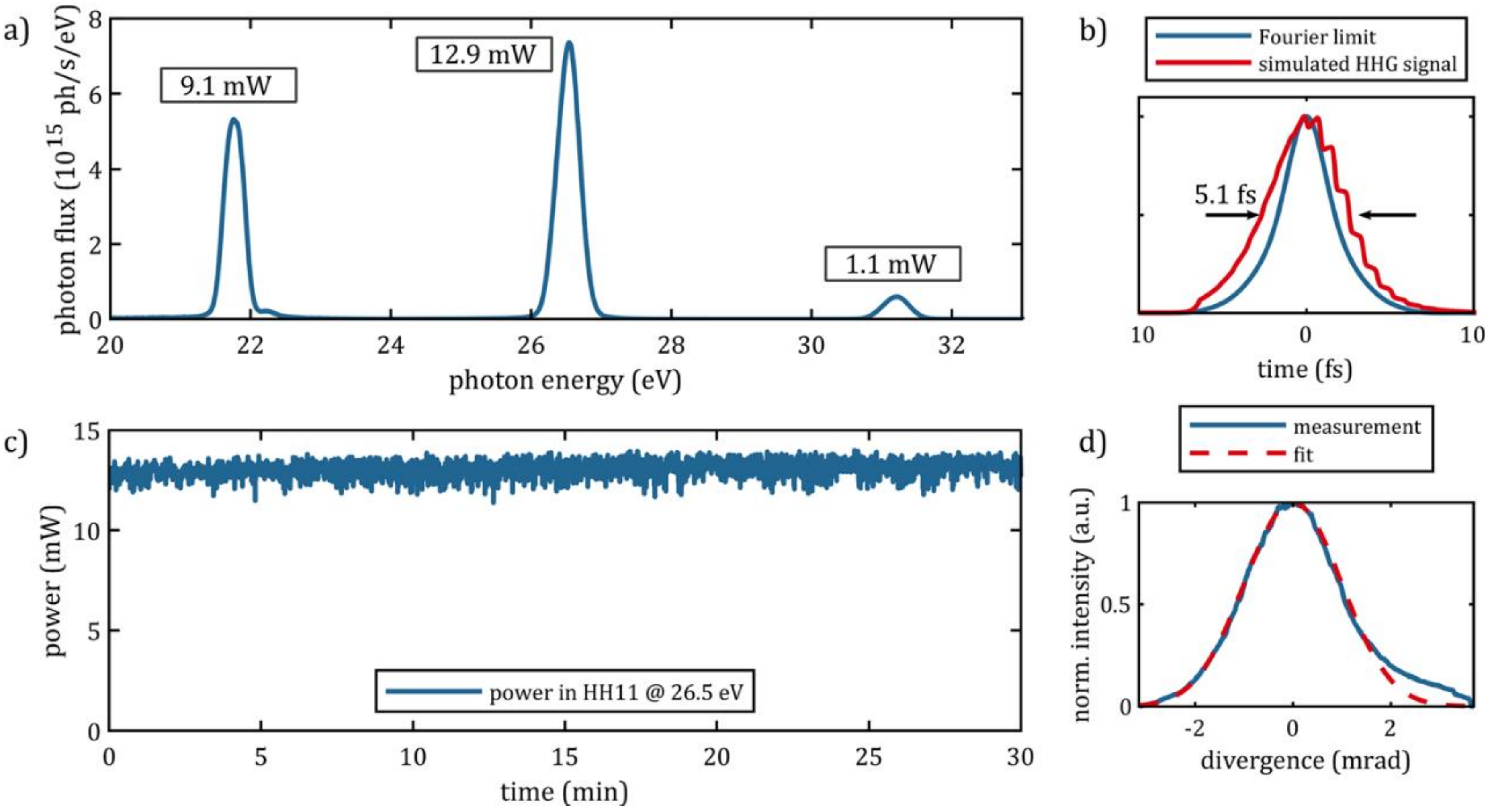
Robert Klas "Efficiency Scaling of High Harmonic Generation using Ultrashort Fiber Lasers," (2021).

# mW-class harmonics




R. Klas, A. Kirsche, M. Gebhardt, J. Buldt, H. Stark, S. Hädrich, J. Rothhardt, and J. Limpert, "Ultra-short-pulse high-average-power megahertz-repetition-rate coherent extreme-ultraviolet light source," PhotoniX **2**, (2021).

# mW-class harmonics




R. Klas, A. Kirsche, M. Gebhardt, J. Buldt, H. Stark, S. Hädrich, J. Rothhardt, and J. Limpert, "Ultra-short-pulse high-average-power megahertz-repetition-rate coherent extreme-ultraviolet light source," PhotoniX **2**, (2021).

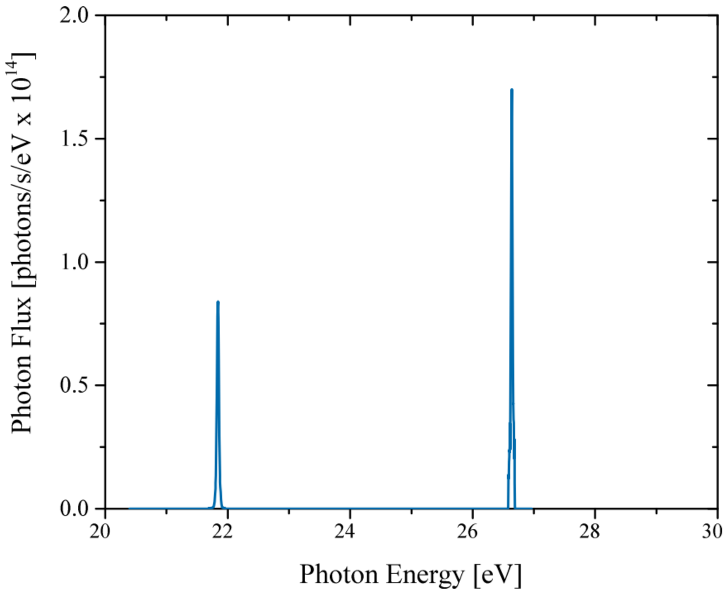
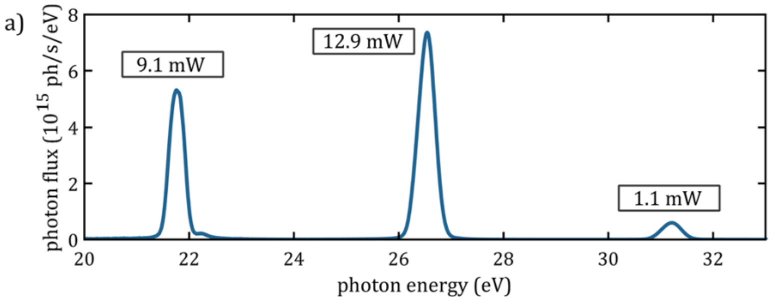



**FIG. 2**. Spectra of the 9th (21.5 eV, i.e., 57.6 nm) and the 11th (26.7 eV, i.e., 46.4 nm) harmonic.

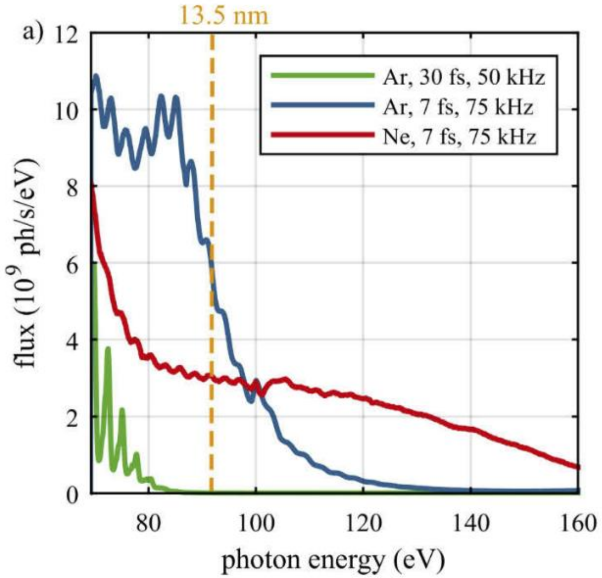
| |
|---|
| **400fs** |
| 515nm |

V. Hilbert, M. Tschernajew, R. Klas, J. Limpert, and J. Rothhardt, "A compact, turnkey, narrow-bandwidth, tunable, and high-photon-flux extreme ultraviolet source," AIP Adv. **10**, (2020).



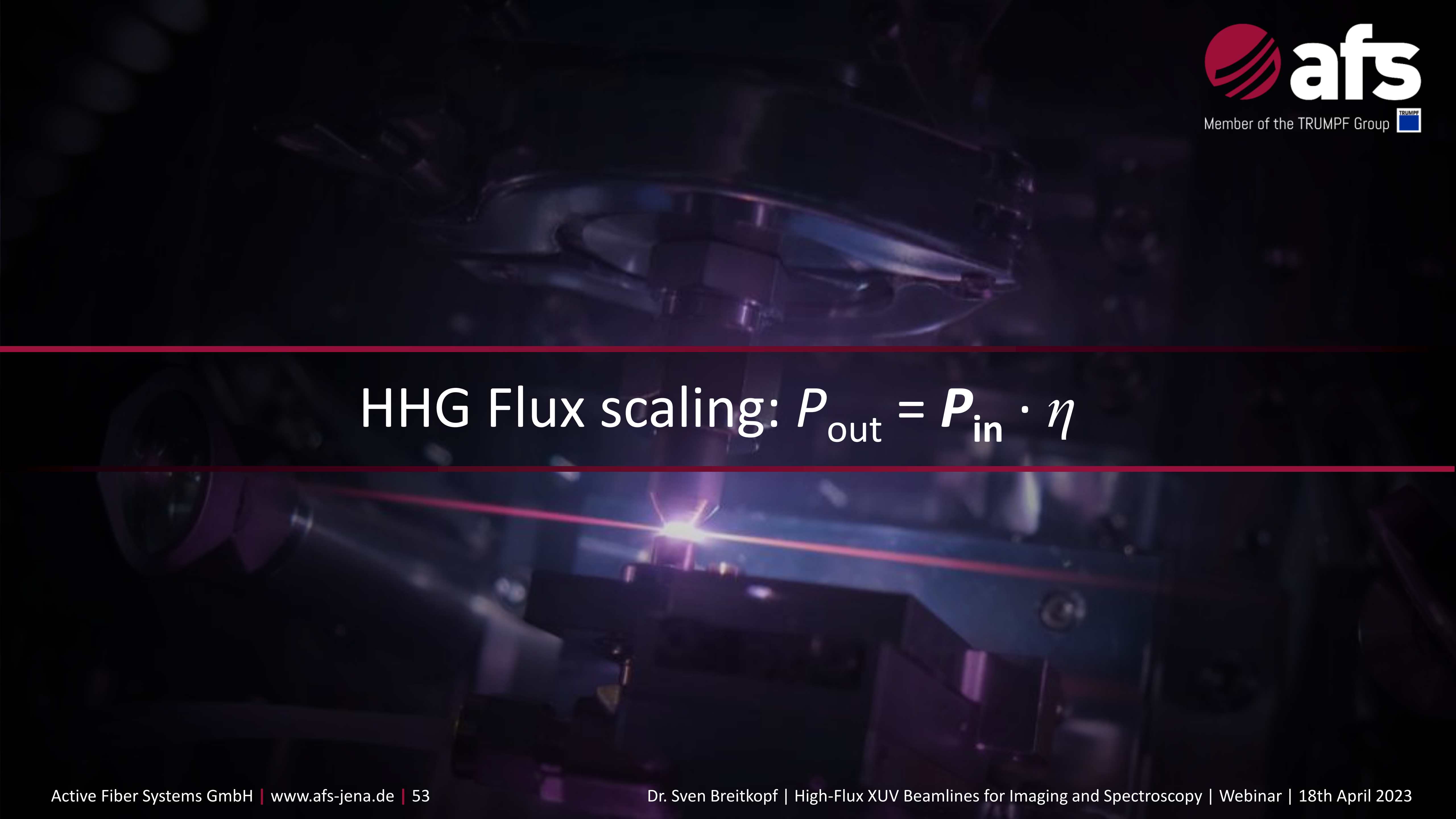

| |
|---|
| **18fs** |
| 515nm |

R. Klas, A. Kirsche, M. Gebhardt, J. Buldt, H. Stark, S. Hädrich, J. Rothhardt, and J. Limpert, "Ultra-short-pulse high-average-power megahertz-repetition-rate coherent extreme-ultraviolet light source," PhotoniX 2, (2021).




| |
|---|
| **7fs** |
| 1030nm |

R. Klas, W. Eschen, A. Kirsche, J. Rothhardt, and J. Limpert, "Generation of coherent broadband high photon flux continua in the XUV with a sub- two-cycle fiber laser," Opt. Express 28, 6188–6196 (2019).





# HHG Flux scaling: $P_{out} = \boldsymbol{P_{in}} \cdot \eta$

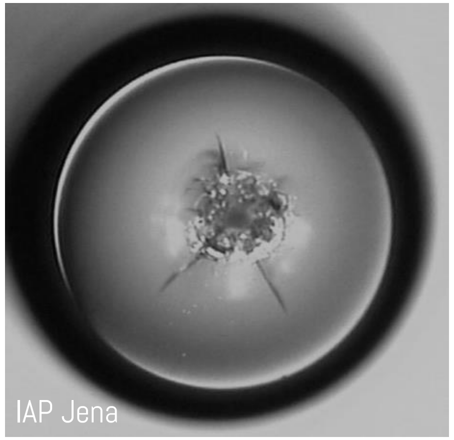
# Limitations of energy-scaling in femtosecond laser amplifiers

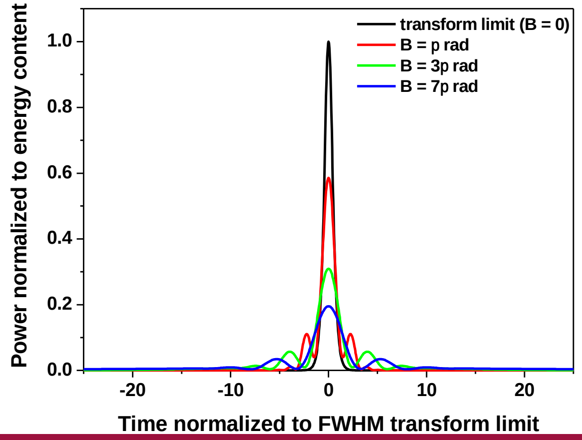
Fiber facet damage

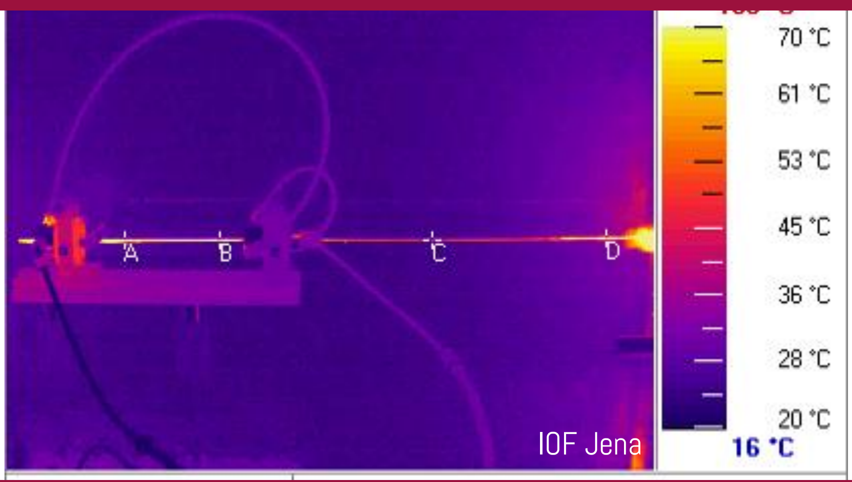
Nonlinear effects - e.g. SPM

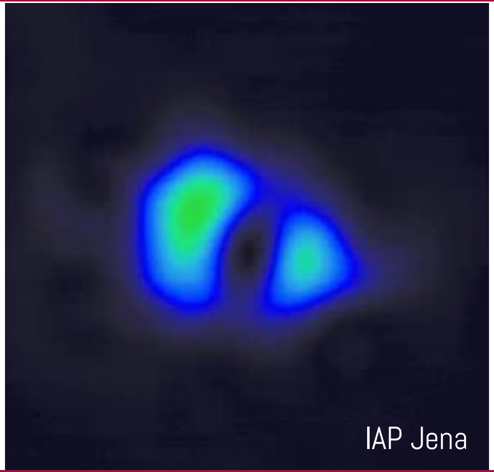
„Thermal“ issues

Real thermal issues - Mode instabilities[1]



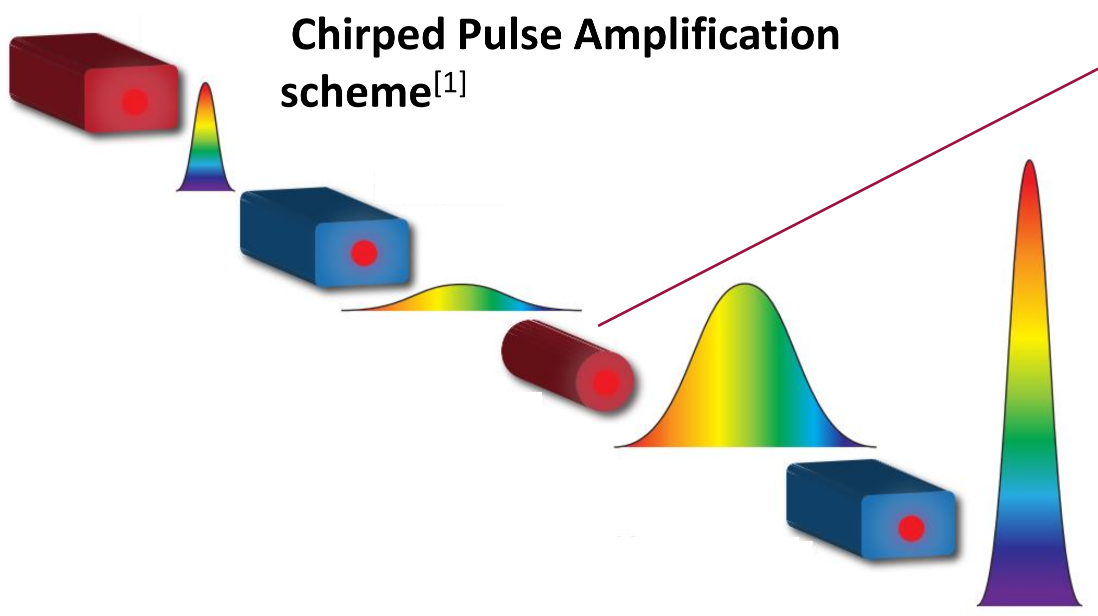



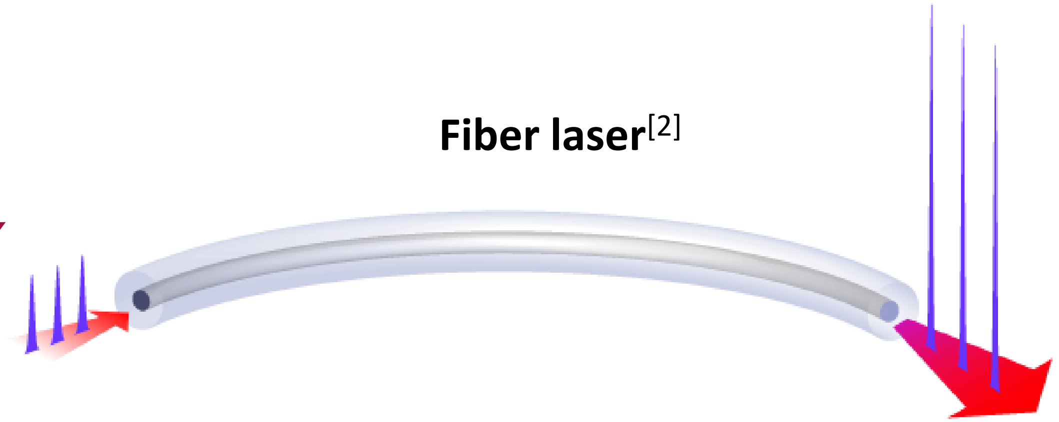



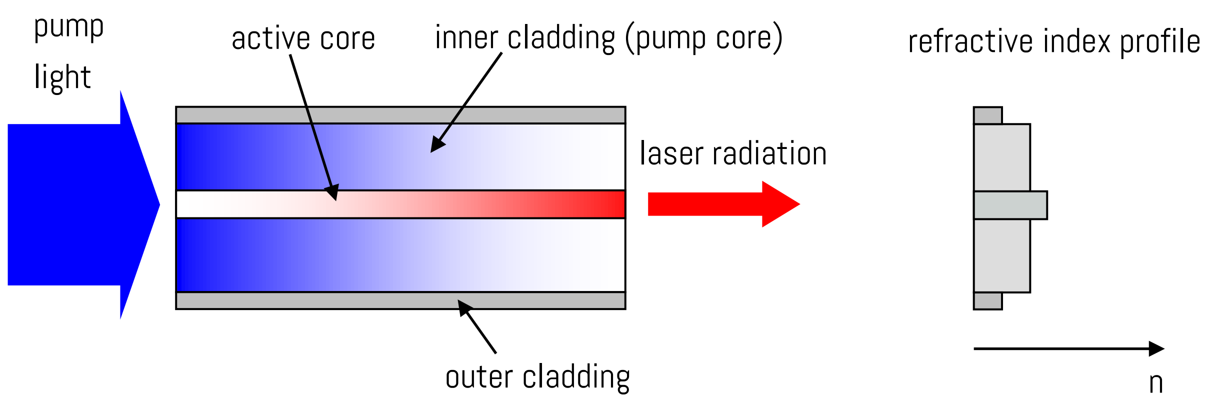

- Mode-area scaling: reduces nonlinear effects
- Parallelization: distribute the challenges to many emitters instead of only one

**Chirped Pulse Amplification scheme[1]**



**Fiber laser[2]**

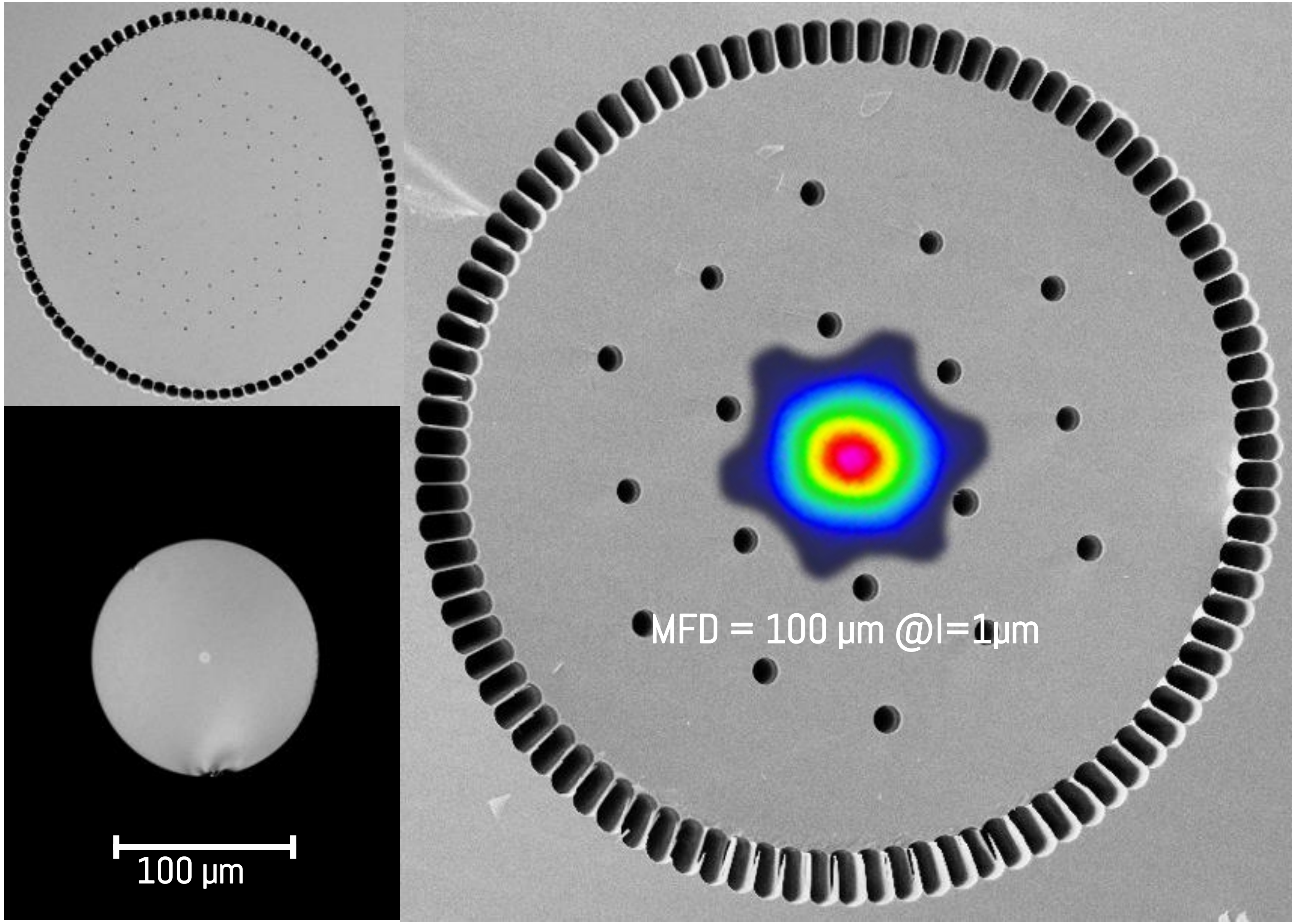





→ Compact | heat resistant | great beam quality

[1] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. 56, 219–221 (1985).
[2] C. J. Koester and E. Snitzer, "Amplification in a Fiber Laser," Appl. Opt. **3**, 1182 (1964).

# Key technology: Large-Pitch Fibers



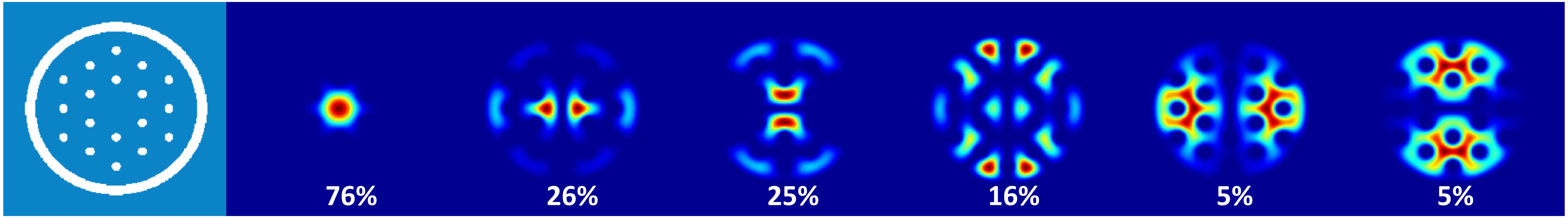

[1] T. Eidam et al., “Fiber chirped-pulse amplification system emitting 3.8 GW peak power,” Opt. Express 19, 255–60 (2011).

[2] H.-J. Otto et al., “2 kW average power from a pulsed Yb-doped rod-type fiber amplifier,” Opt. Lett. 39, 6446–9 (2014).

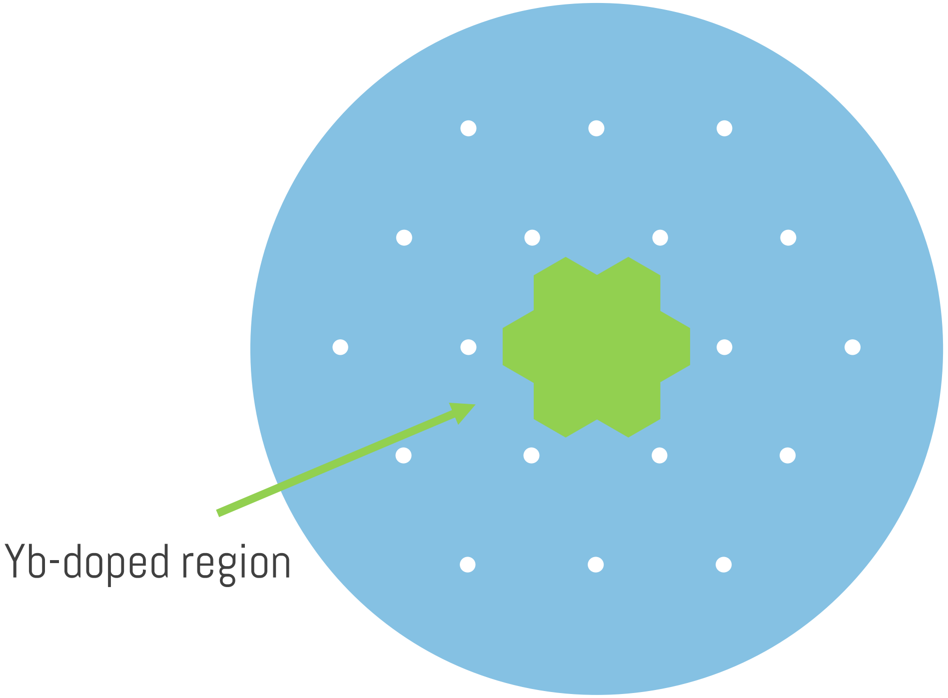
[3] F. Stutzki et al., “26 mJ, 130 W Q-switched fiber-laser system with near-diffraction-limited beam quality,” Opt. Lett. 37, 1073–1075 (2012).

# Large-Pitch Fibers (LPFs)

- Delocalization of higher-order modes [1,2]



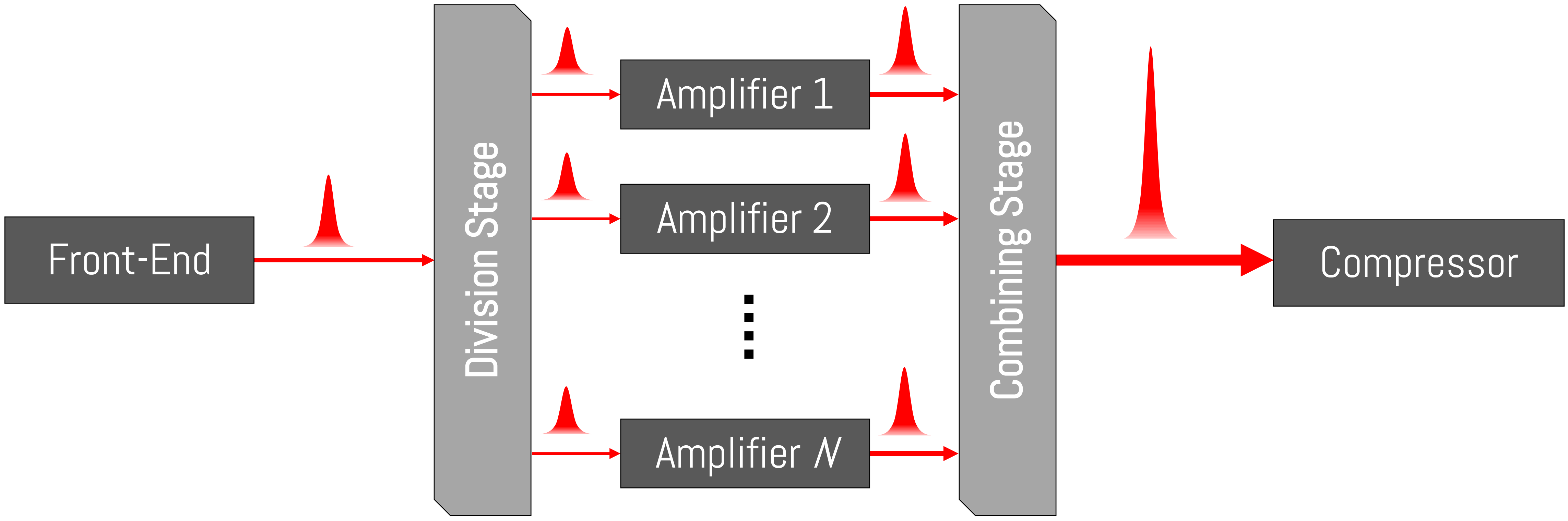

- Double-clad structure an integral part
- Favored excitation of fundamental mode by seed beam
- Favored amplification of fundamental mode by doping overlap
- → 30x higher amplification for fundamental mode (assuming 30dB small-signal gain)





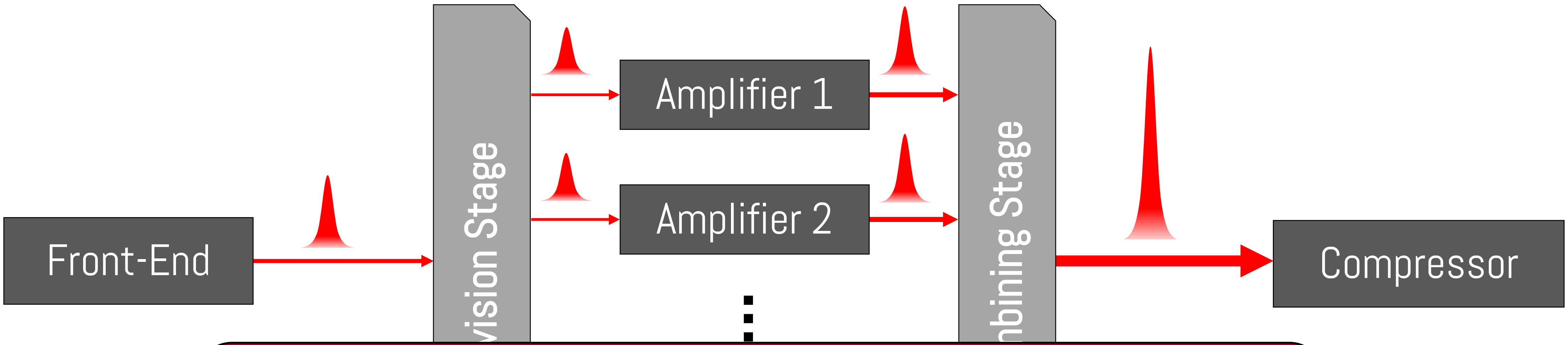
[1] F. Stutzki et al., Opt. Lett. 36, 689-691 (2011).
[2] J. Limpert et al., Light Sci. Appl. 1, 1–5 (2012).

# Key technology: Coherent Combining




- Use $N$ amplifiers and combine the spatially separated pulses
- Best case: Improvement of the pulse energy and average power by a factor of $N$
- Ideally suited to fiber lasers (parallelization)

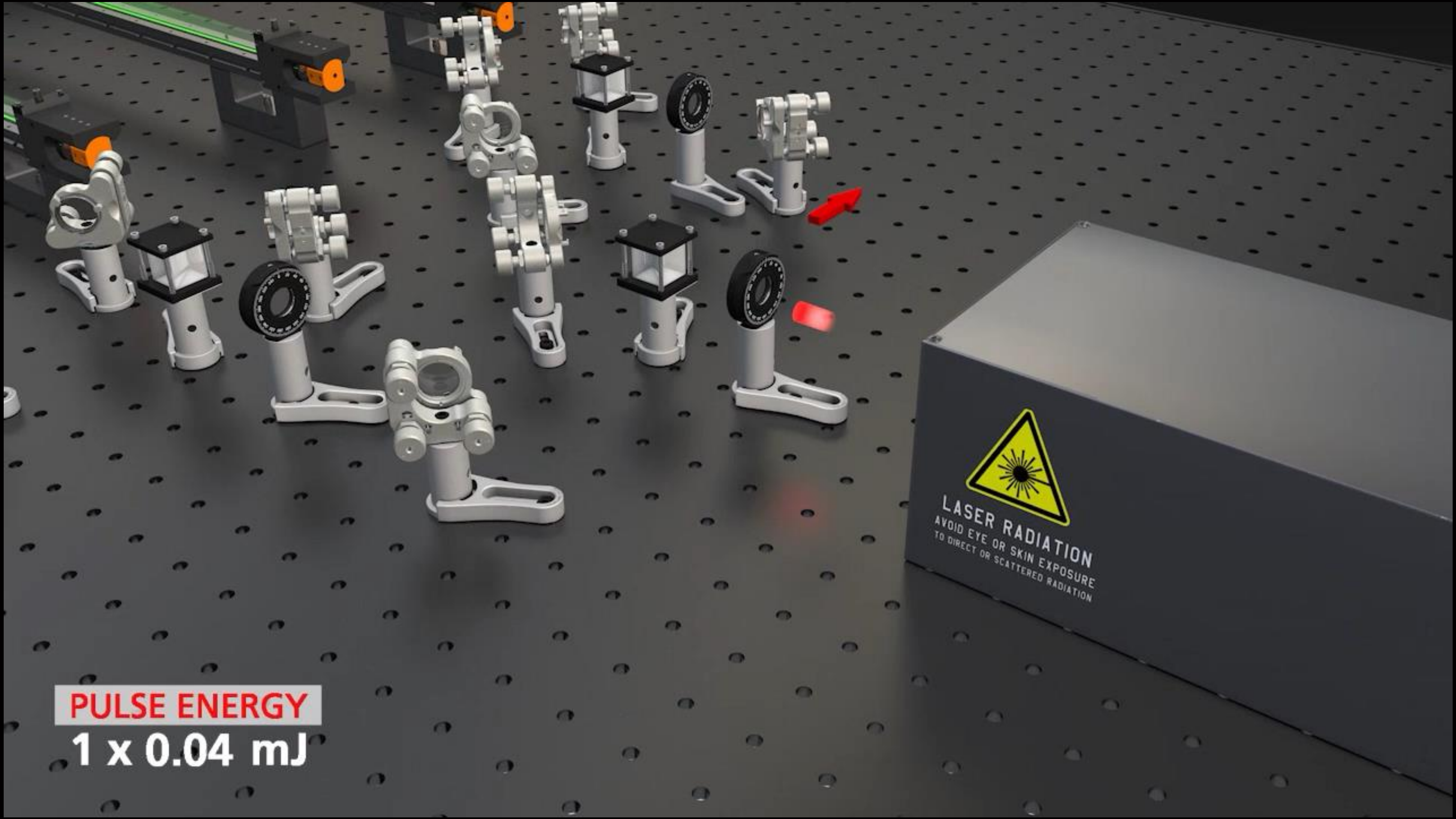
# Key technology: Coherent Combining



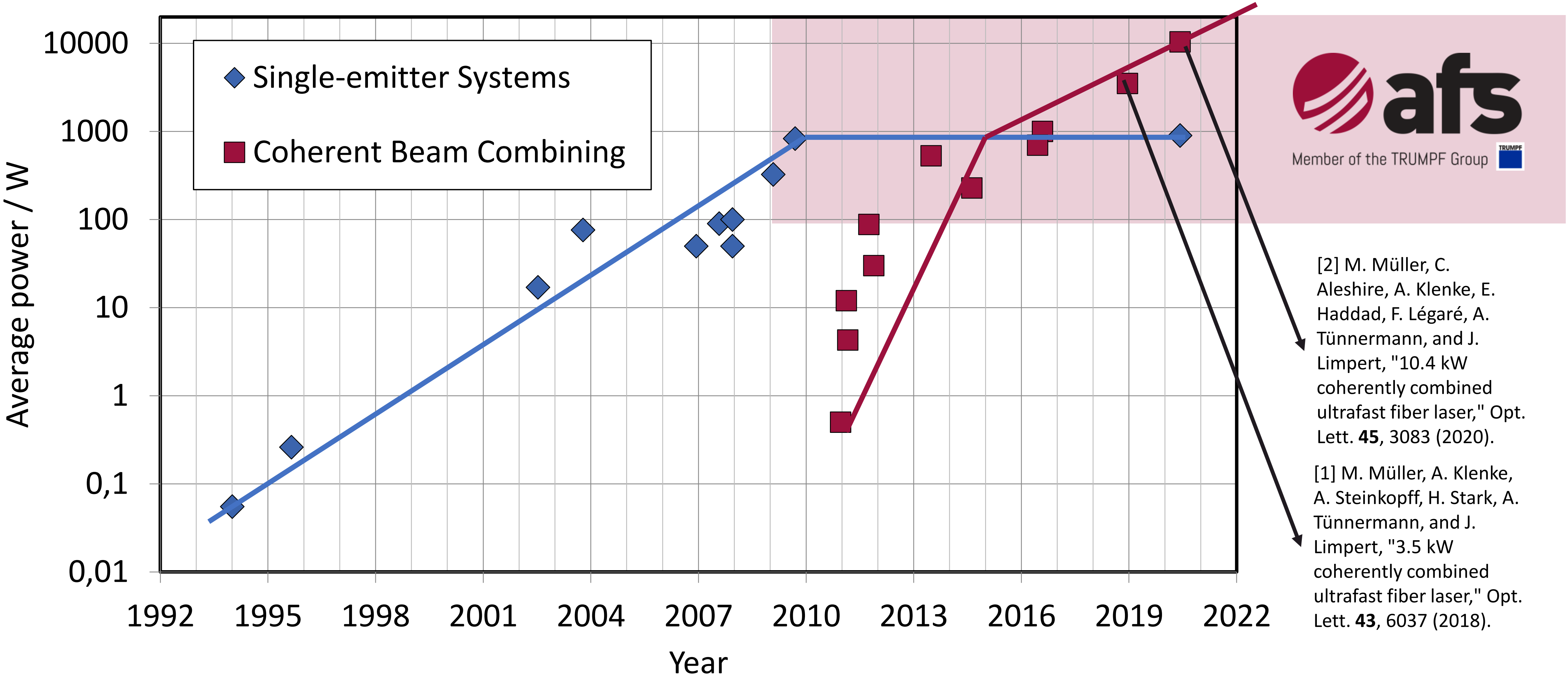

**Achievable laser parameters only limited by cost & size, but not by laser physics!**

- Use $N$ amplifiers and combine the spatially separated pulses
- Best case: Improvement of the pulse energy and average power by a factor of $N$
- Ideally suited to fiber lasers (parallelization)

# Key technology: Coherent Combining



# Ultrafast Yb-fiber laser systems

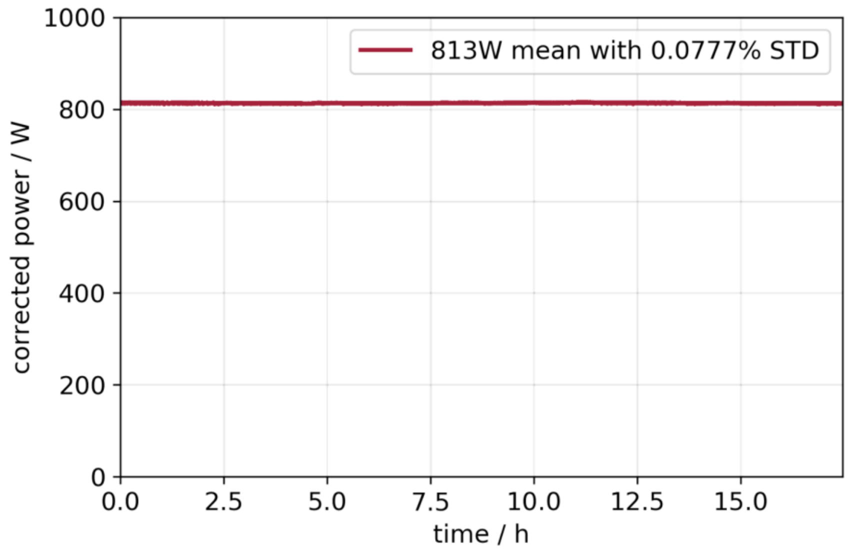


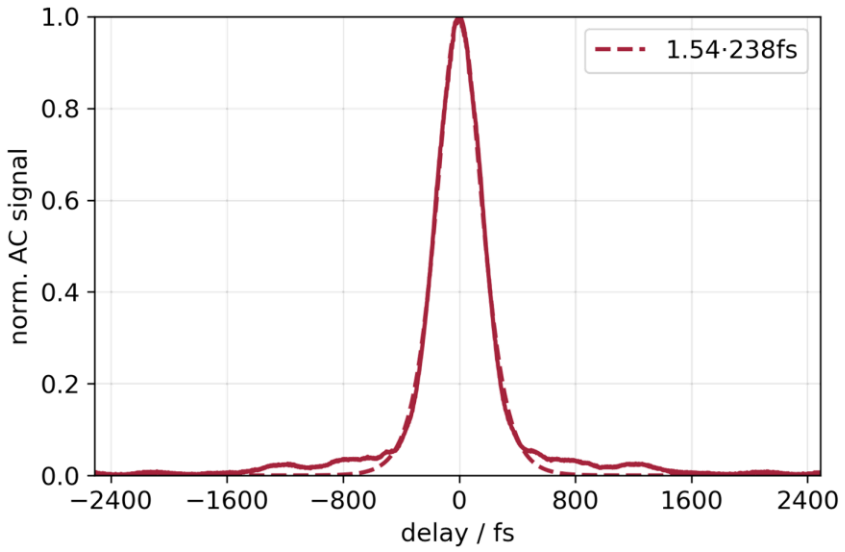

[2] M. Müller, C. Aleshire, A. Klenke, E. Haddad, F. Légaré, A. Tünnermann, and J. Limpert, "10.4 kW coherently combined ultrafast fiber laser," Opt. Lett. **45**, 3083 (2020).

[1] M. Müller, A. Klenke, A. Steinkopff, H. Stark, A. Tünnermann, and J. Limpert, "3.5 kW coherently combined ultrafast fiber laser," Opt. Lett. **43**, 6037 (2018).

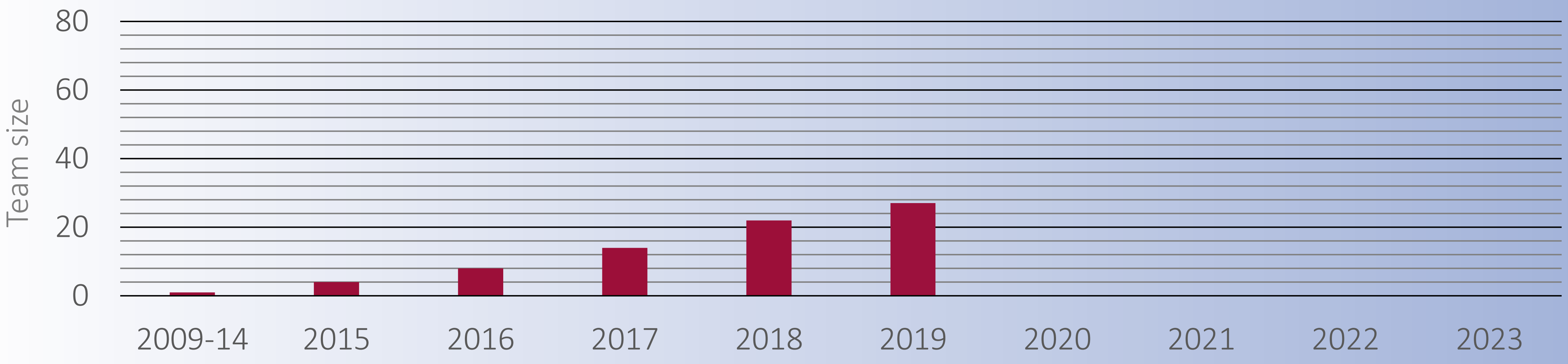
# Ytterbium-based ultrafast fiber laser systems

- Up to **2kW** average power and **20mJ** pulse energy
- Adjustable pulse length from **<250fs** … 10ps
- Repetition rate: 50kHz … 80MHz
- Average-power/energy stability: <0.5% RMS
- Diffraction-limited beam quality: **$M^2 < 1.2$**

# Company growth



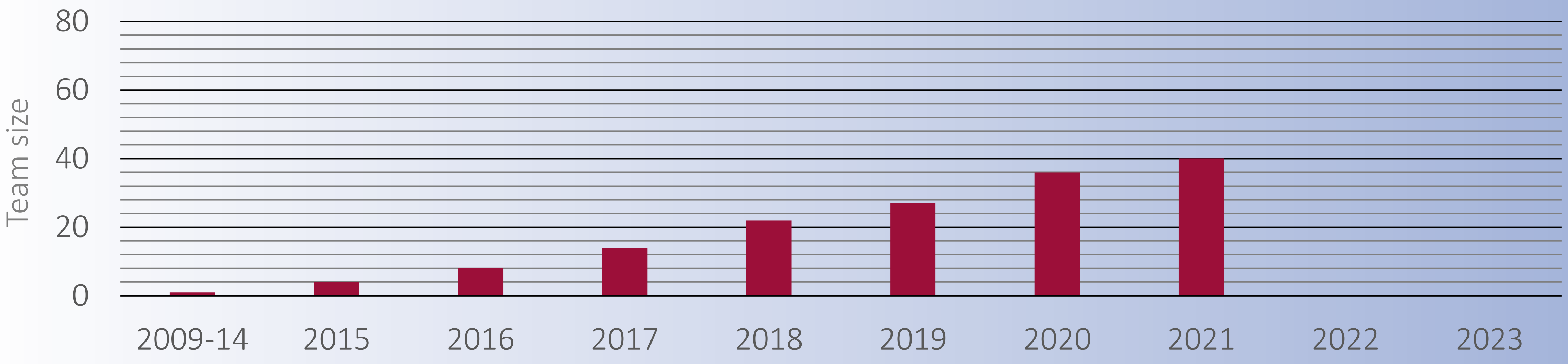

**Provider of laser sources**

Yb-doped, F-CPA,
Oscillators

**Provider of complex systems**

+ Coherent combining,
Tm-doped (2µm),
HHG (XUV), MIR, OPA

# Company growth



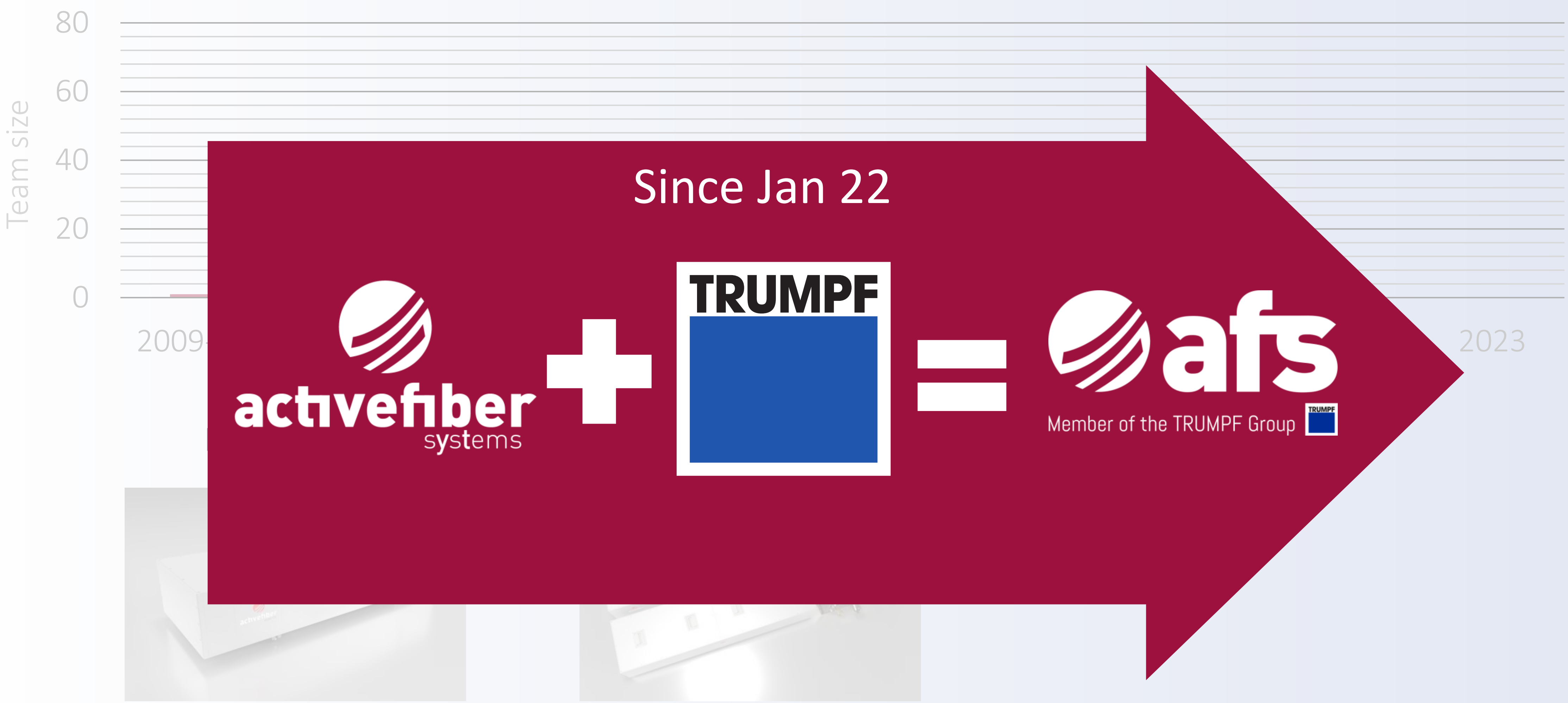

**Provider of laser sources**

Yb-doped, F-CPA, Oscillators

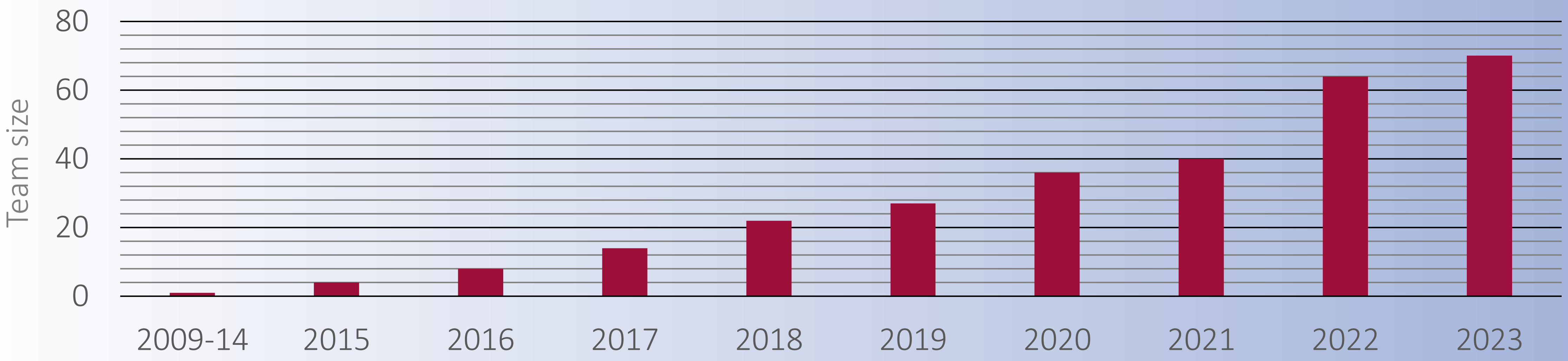
**Provider of complex systems**

+ Coherent combining, Tm-doped (2µm), HHG (XUV), MIR, OPA

# Company growth



# Company growth



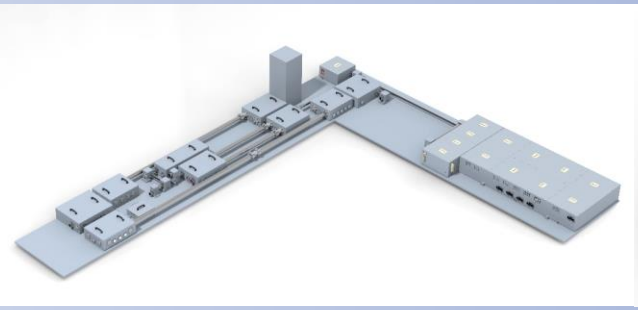

**Provider of laser sources**

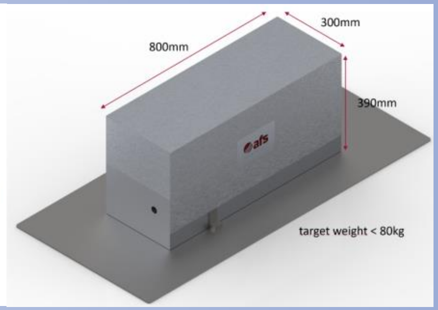
Yb-doped, F-CPA,
Oscillators

**Provider of complex systems**

+ Coherent combining,
Tm-doped (2µm),
HHG (XUV), MIR, OPA

**Provider of scientific beamlines & Industrial solutions**





# Exemplary installed systems


1.7mJ, 170W, 40fs

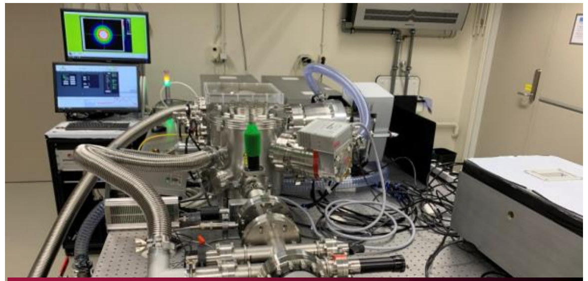

700µJ, 100W, 8fs

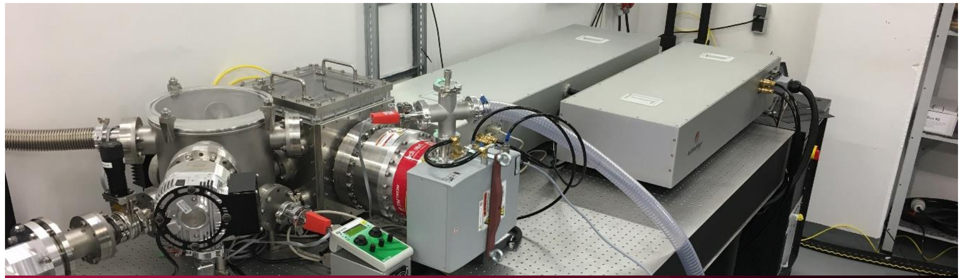

1kW, 10mJ, 300fs

1mJ, 100W, 6fs



600µJ, 60W, 8fs


30-150eV XUV source (CDI)


26.6eV & 70eV XUV sources for ARPES


700µJ, 100W, 8fs

# AFS Portfolio

Newly adressed market segment

- Developed for specific applications
- Optimized for realibility
- Still unique specs but more conservative

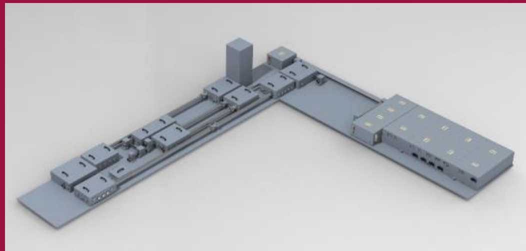
Not related to ultrafast lasers

Specific Industrial Lasers

Scientific beamlines & highly customized solutions

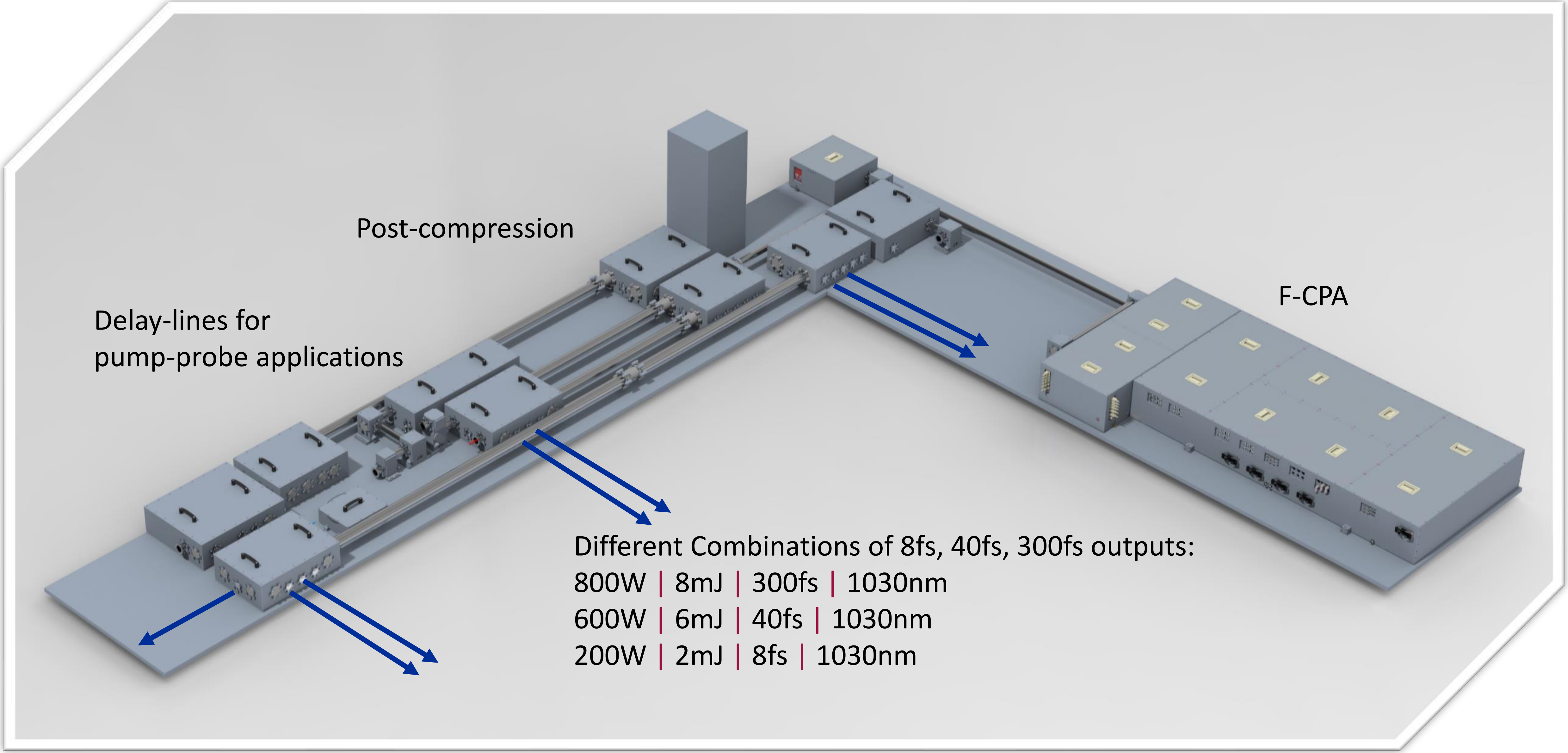
Bio-Medical Devices

Traditional playground of AFS



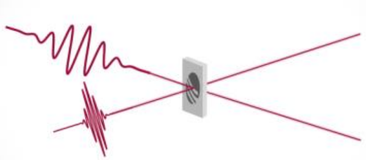
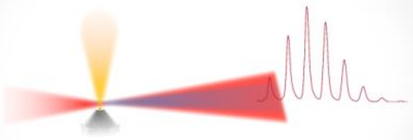
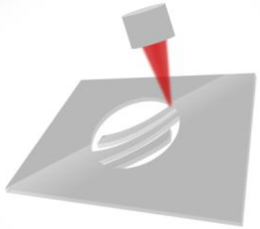
- Short time-to-market
- Flexible solutions
- Complex systems
- Usually unique in some way
- Combinations with partners in Trumpf Group

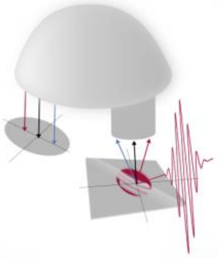
# The kW System-class | F-CPA



# Applications

Pump-probe | XUV-Generation | Materials processing | Imaging | Spectroscopy



- **High peak-power | high energy**

  ➡ enable applications

- **High repetition rates | high average powers**

  ➡ speed, signal | noise ratio

# Scaling of photon energy

# Scaling of photon energy

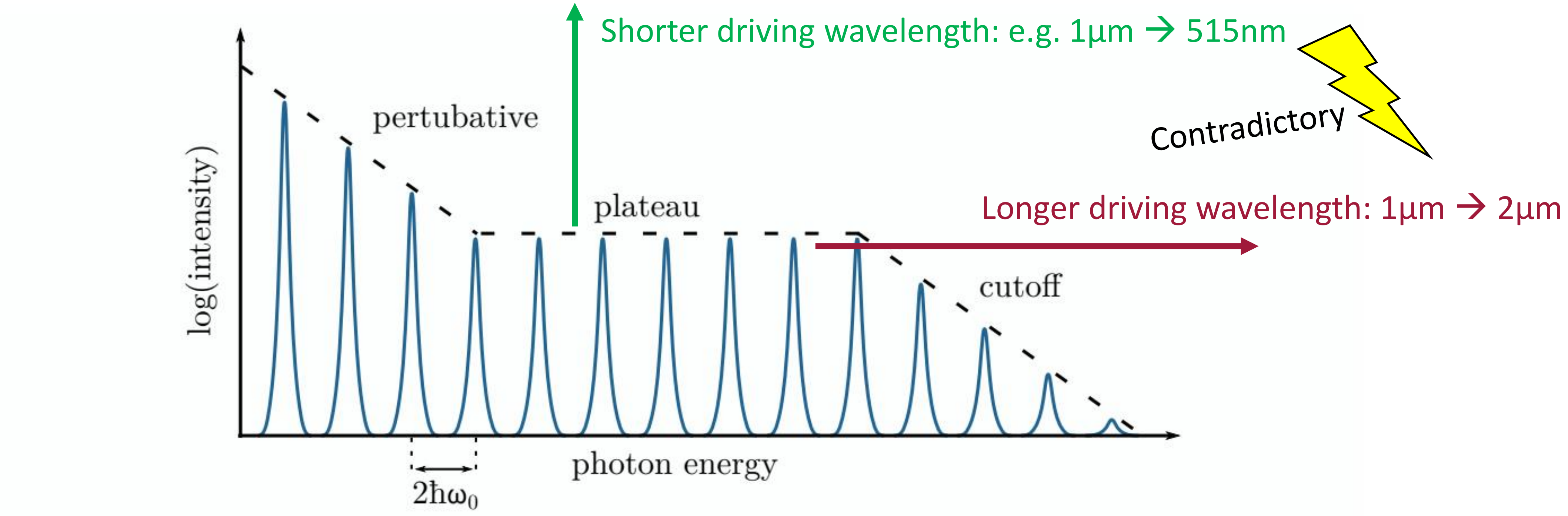
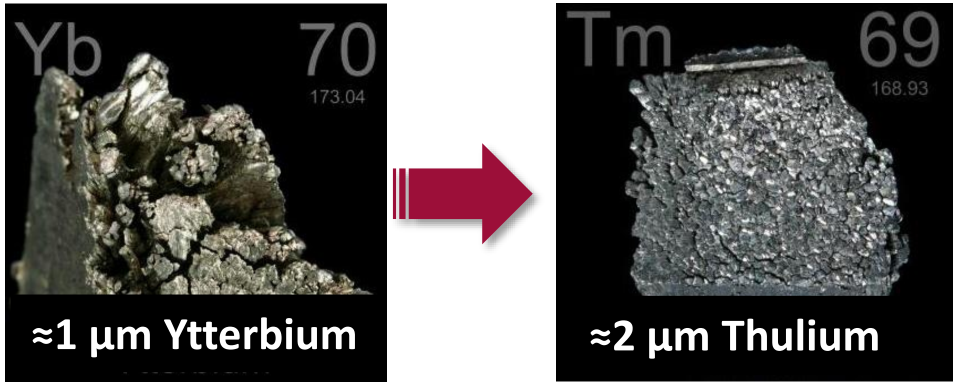



**Figure 2.3: Schematic high harmonic spectrum,** showing a comb of odd harmonics with the pertubative, plateau and cutoff region. The driving laser angular frequency is $\omega_0$.

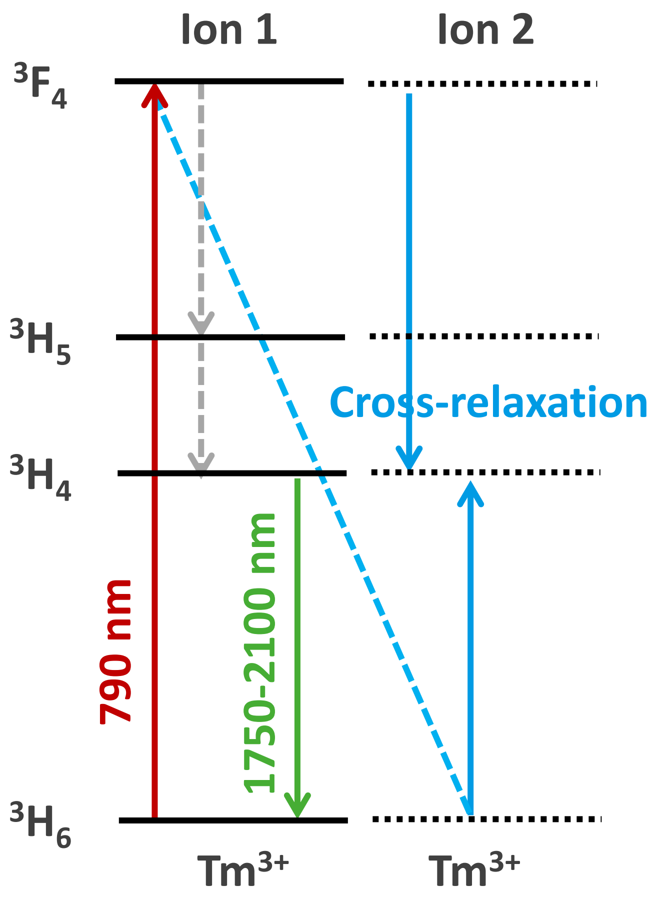
- Robert Klas "Efficiency Scaling of High Harmonic Generation using Ultrashort Fiber Lasers," (2021).

## Different signal-core doping




## Properties of Tm-doped fuses silica:

- Broad amplification bandwidth (<100 fs)
- Large quantum-defect (QD) when pumping at 790 nm
  - → Typically strong QD-heating
  - → Cross-relaxation allows for up to >70% efficiency[1]

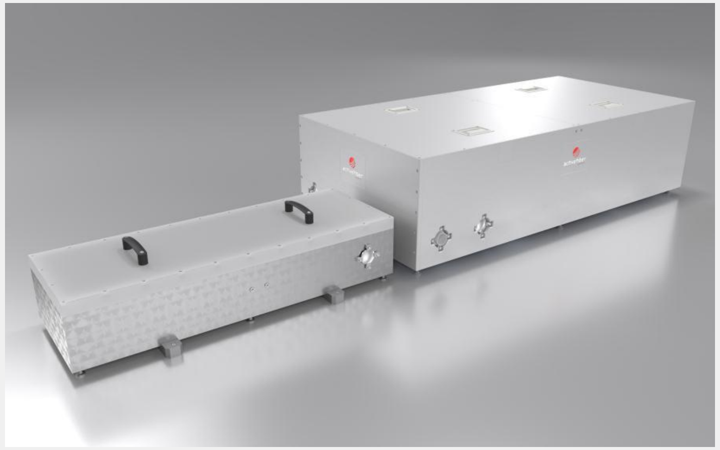



[1] S. D. Jackson and S. Mossman, "Efficiency dependence on the Tm3+ and Al3+ concentrations for Tm3+-doped silica double-clad fiber lasers.," Appl. Opt. 42, 2702–2707 (2003).

# Product platforms: Thulium

- Coherent-combining-based & highly customizable. Capable of world-record power/energy for ultrafast sources

## Thulium-300



1950nm | 2mJ | 200W | 150fs

- Unprecedented commercial specs at 2µm central wavelength
- Suitable for scientific environments

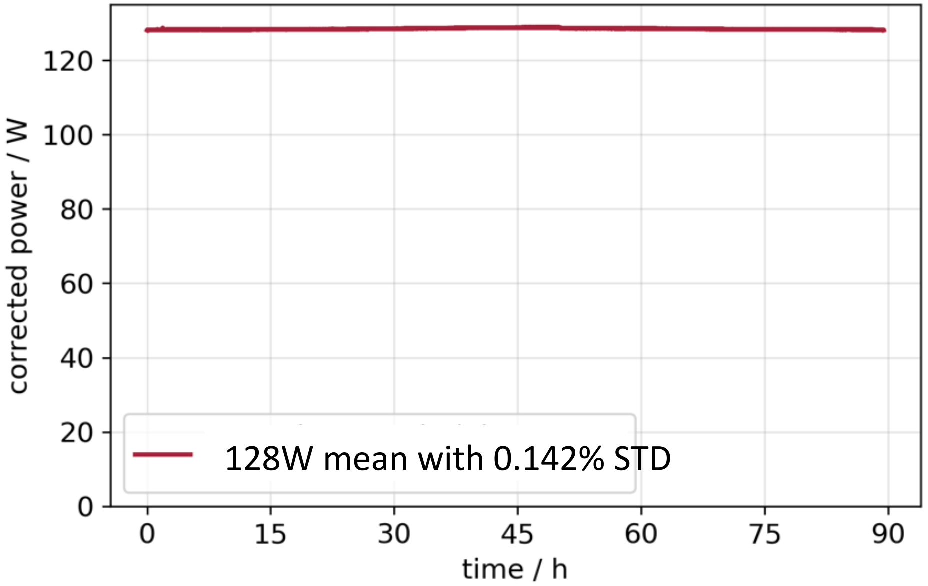
## Thulium-30

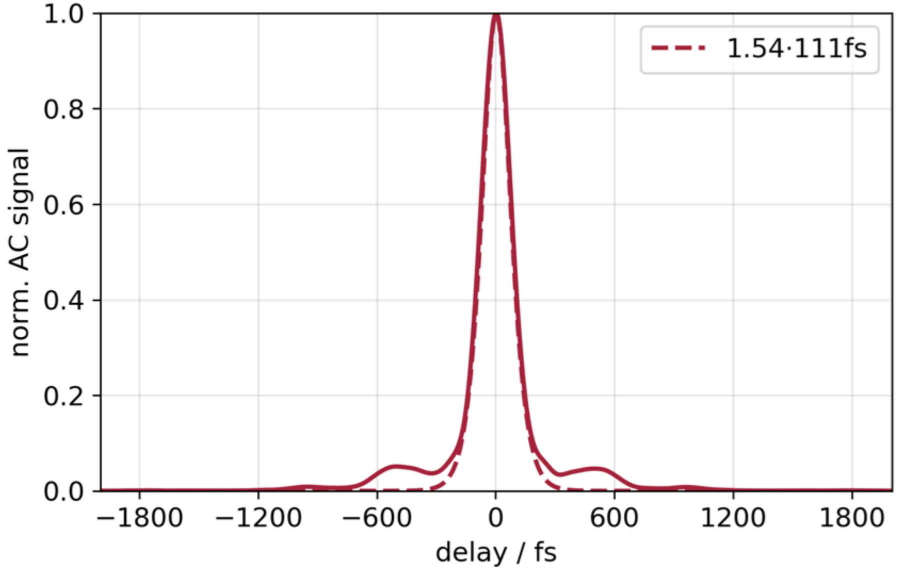
1980nm | 100µJ | 40W | 400fs

- Compact & affordable
- Industrial-grade reliability

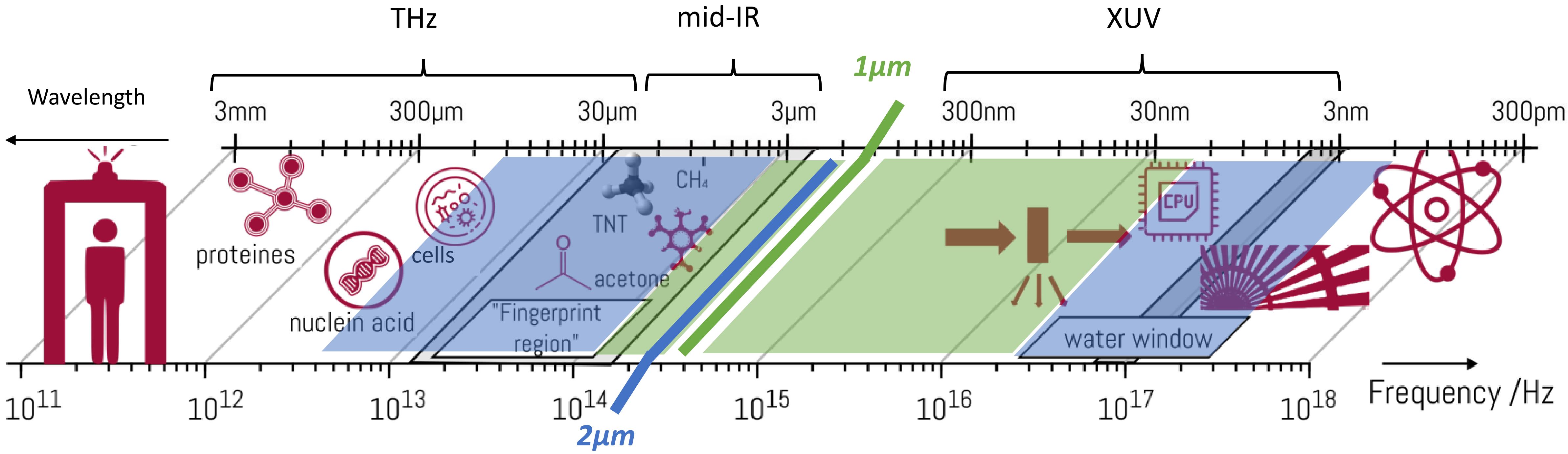
# Coherent beam combining system at 2µm

- 4-channel Tm-based system with vacuum compressor
- >120W average power long-term stable
  (upgrade to >200W scheduled)
- >200µJ pulse energy (2mJ being set up at the moment)
- <120fs pulse duration



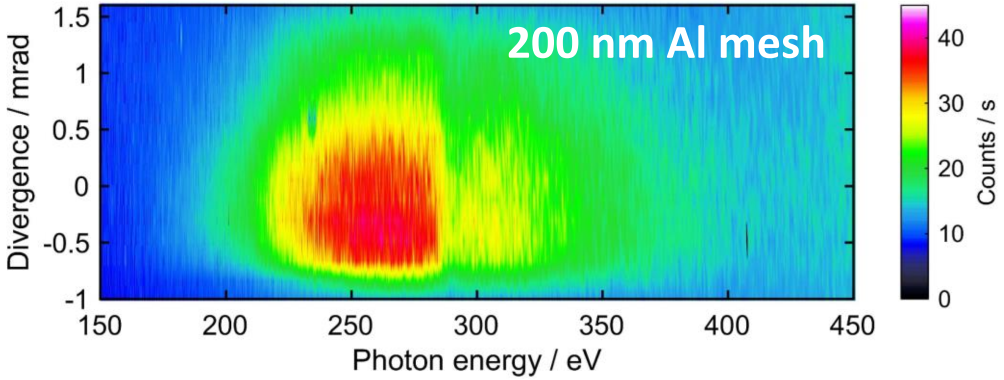
# Advantages of 2-µm driving laser

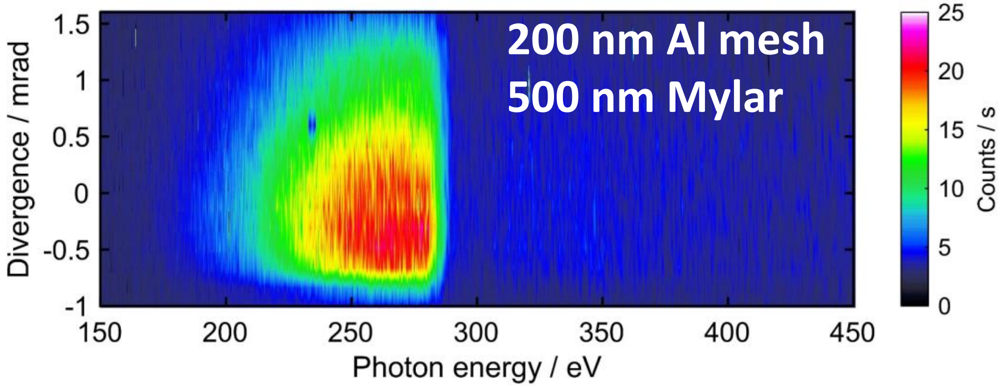


Institute of Applied Physics Friedrich-Schiller-Universität Jena | afs Member of the TRUMPF Group

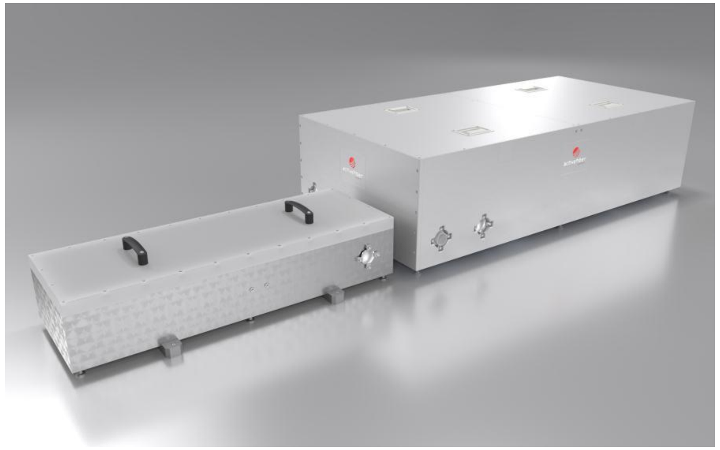
Fingerprint mid-IR, DFG

Water-window XUV, HHG[1]



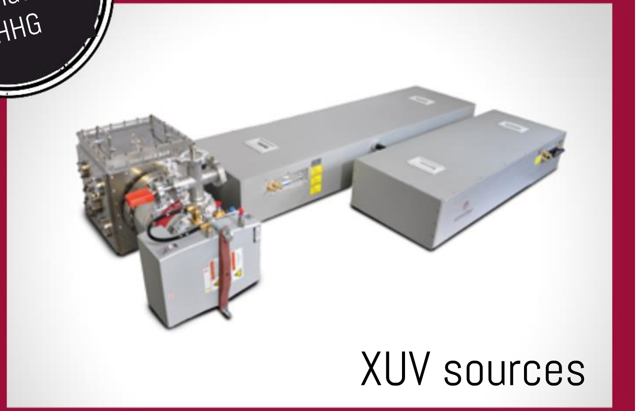




[1] M. Gebhardt et al., Light Sci Appl 10, 36 (2021).



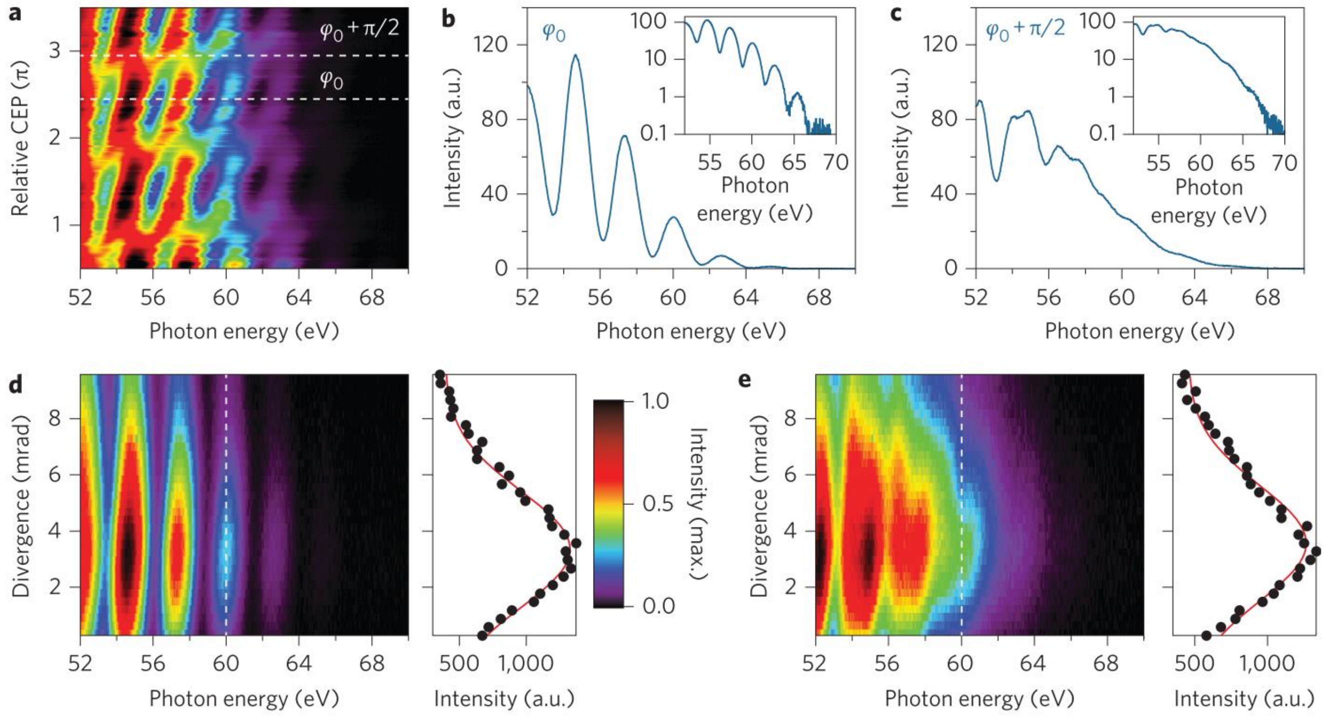
Thulium platforms

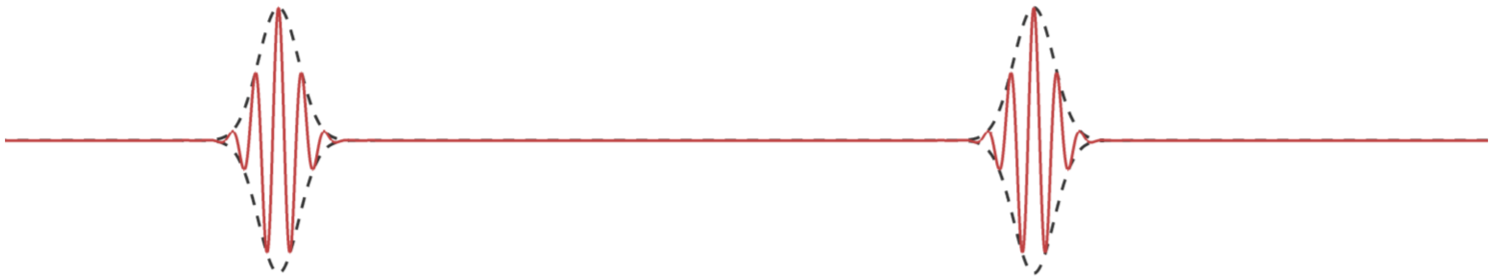
Water-window HHG



XUV sources

# Atto science



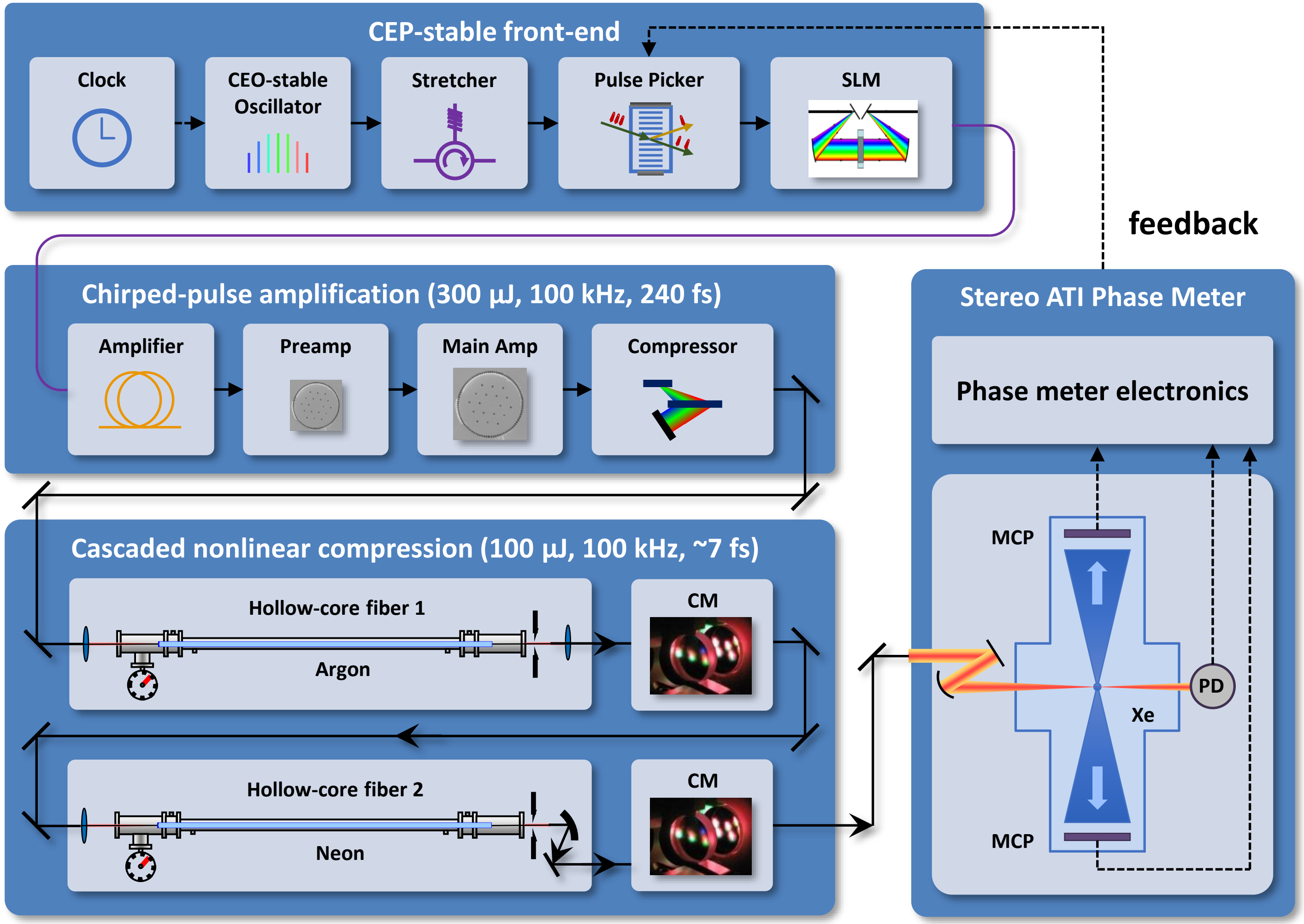



- Generates train of atto second pulses
- Isolated pulse →
- Requires stable carrier-envelope phase relationship → CEP stability

M. Krebs, S. Hädrich, S. Demmler, J. Rothhardt, A. Zaïr, L. Chipperfield, J. Limpert, and A. Tünnermann, "Towards isolated attosecond pulses at megahertz repetition rates," Nat. Photonics 7, 555–559 (2013).

# CEP stability fo Atto science

- CEP stable system delivering few-cycle, 100 µJ pulses at 100 kHz




Front-end:

- Highly CEO-stable oscillator
- All-PM-fiber spliced front-end
- Phase-preserving pulse picker

CPA:

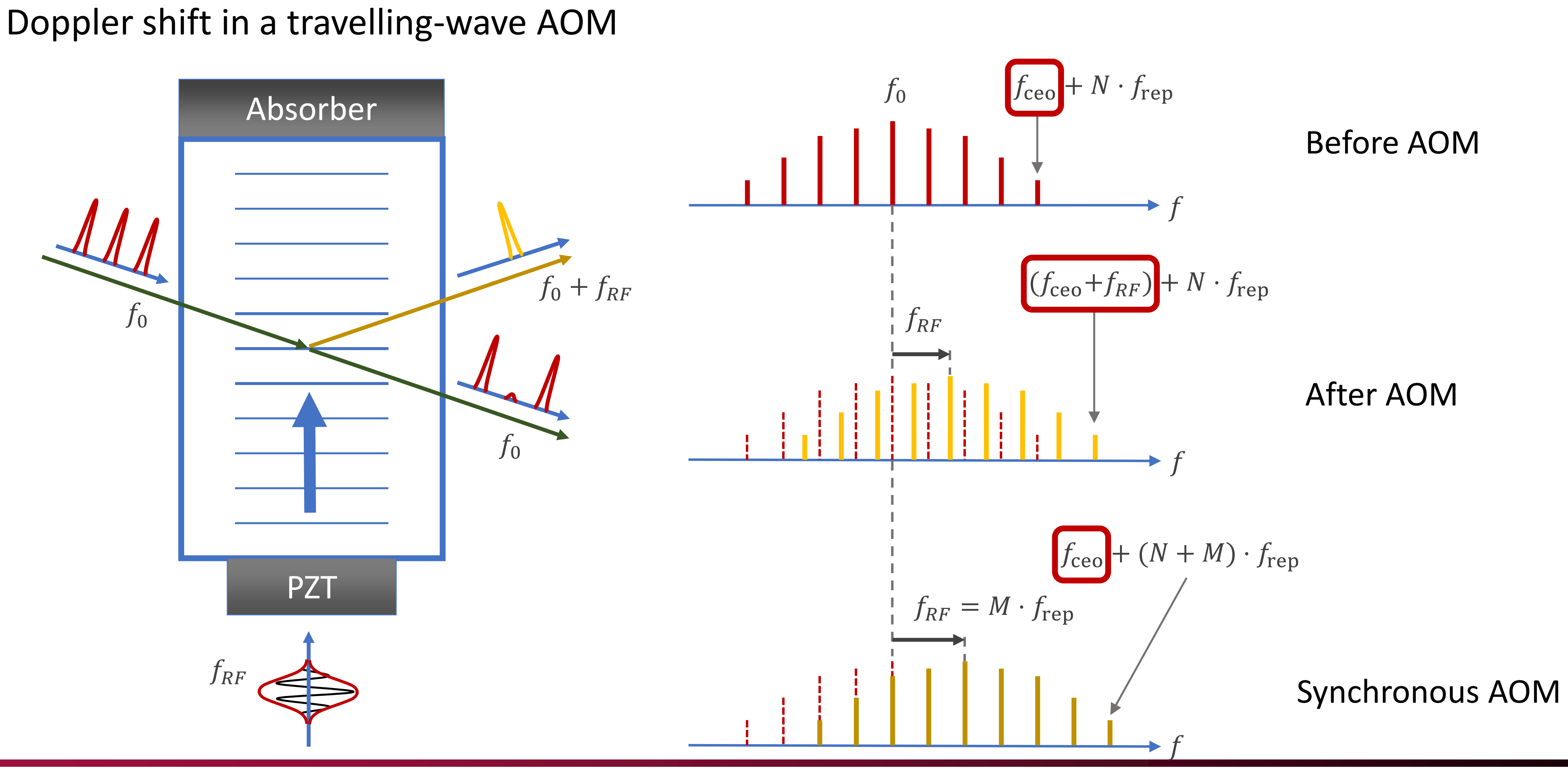
- Large mode area Yb-doped large pitch fibers
- 300 µJ, 100 kHz, 240 fs

Nonlinear compression:

- Two-stage HCF and chirped mirrors
- 100 µJ, 100 kHz, ~7.6 fs

# CEP stability fo Atto science

- Phase-preserving reduction of pulse repetition rate with an AOM

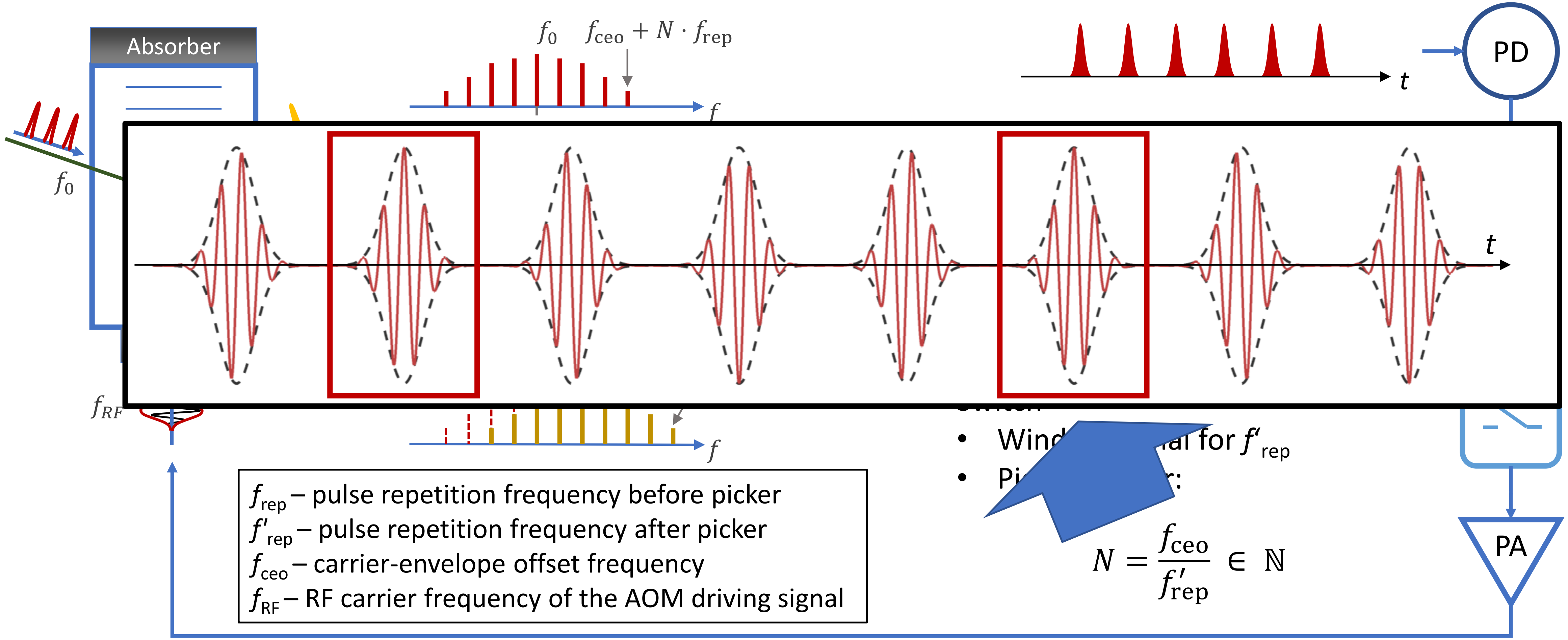


- Phase-preserving reduction of pulse repetition rate with an AOM

[15] O. de Vries *et al.*, "Acousto-optic pulse picking scheme with carrier-frequency-to-pulse-repetition-rate synchronization", Opt. Express 23, 19586 (2015).

Doppler shift in a travelling-wave AOM

**Synchronous Picking**[15] setup

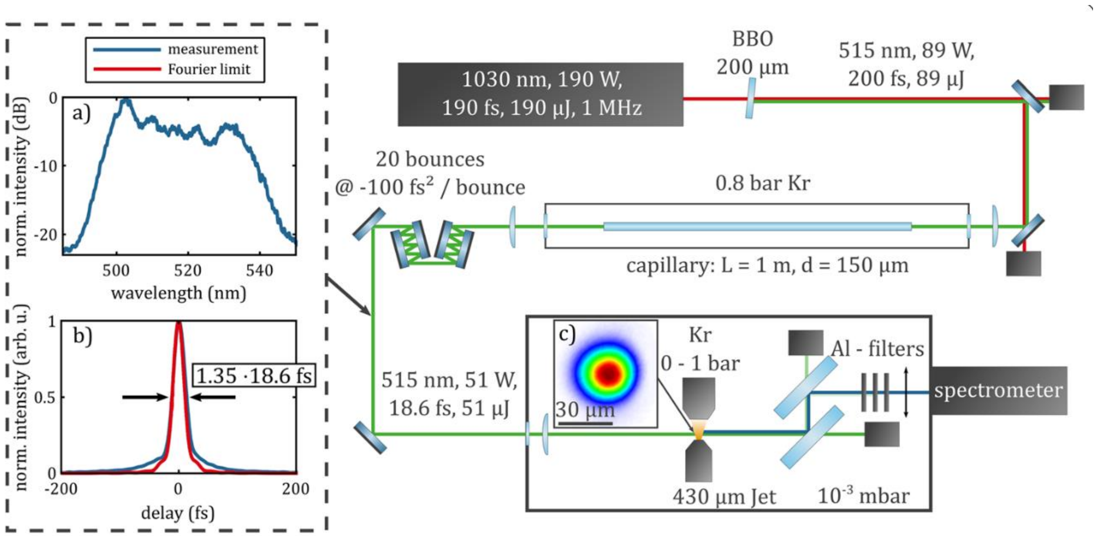



- Wind... al for $f'_{rep}$
- Pi... r:

$$N = \frac{f_{ceo}}{f'_{rep}} \in \mathbb{N}$$

$f_{rep}$ – pulse repetition frequency before picker
$f'_{rep}$ – pulse repetition frequency after picker
$f_{ceo}$ – carrier-envelope offset frequency
$f_{RF}$ – RF carrier frequency of the AOM driving signal

# Conclusion & Outlook



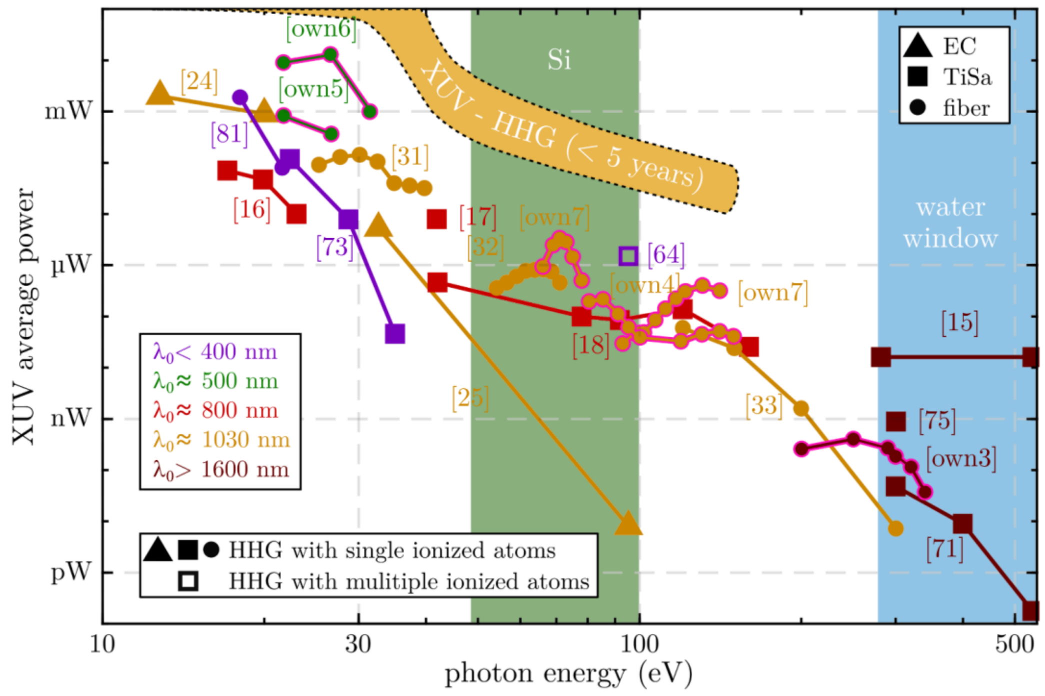




**Figure 7.1: State-of-the-art high harmonic sources.** Assorted HHG sources, with an at the time record high XUV average power at its respective photon energy, while the sources developed in this thesis are marked with a pink boarder line. The marker shape corresponds to the used laser architecture (triangles for enhancement cavities, square for Ti:sapphire based systems and circles for fiber laser based systems), while the color marks the driving wavelength. Furthermore, filled markers are used for „classical" HHG based on single ionized atoms, while empty markers are used for HHG of multiple ionized atoms or ions. The yellow shaded area shows the expected progress for HHG sources in the XUV over the next five years. The spectral region of different transparency windows is depicted as the shaded areas.

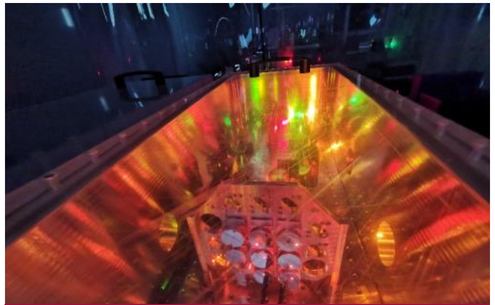
Robert Klas "Efficiency Scaling of High Harmonic Generation using Ultrashort Fiber Lasers," (2021).

# AFS Portfolio


250fs | 20mJ | 2kW | 1030nm


Industrial lasers

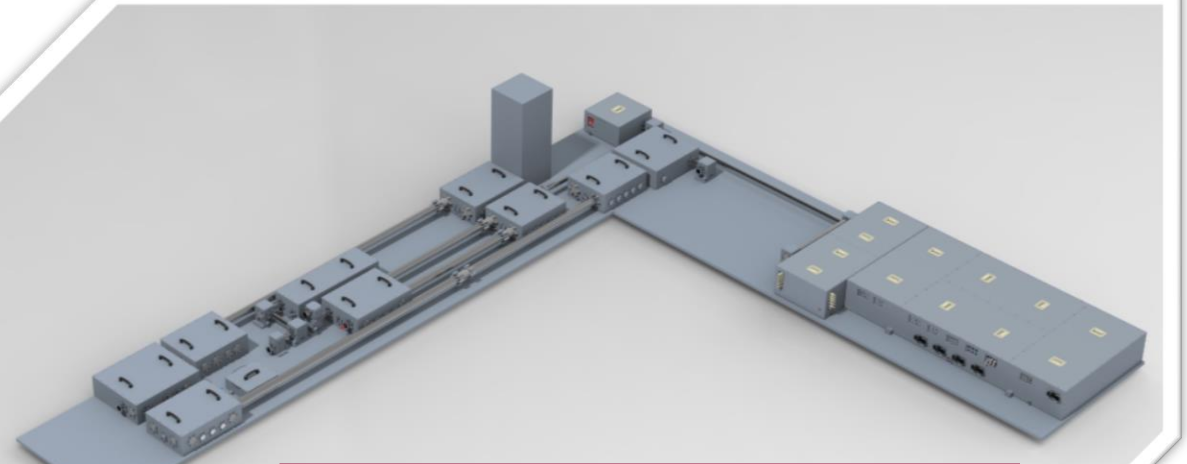

150fs | 2mJ | 200W | 1950nm


MPC to <6fs (CEP-stable)


Freq. Conversion (XUV, OPA, ...)


AMPHOS

TRUMPF Scientific Lasers


Customized beamlines

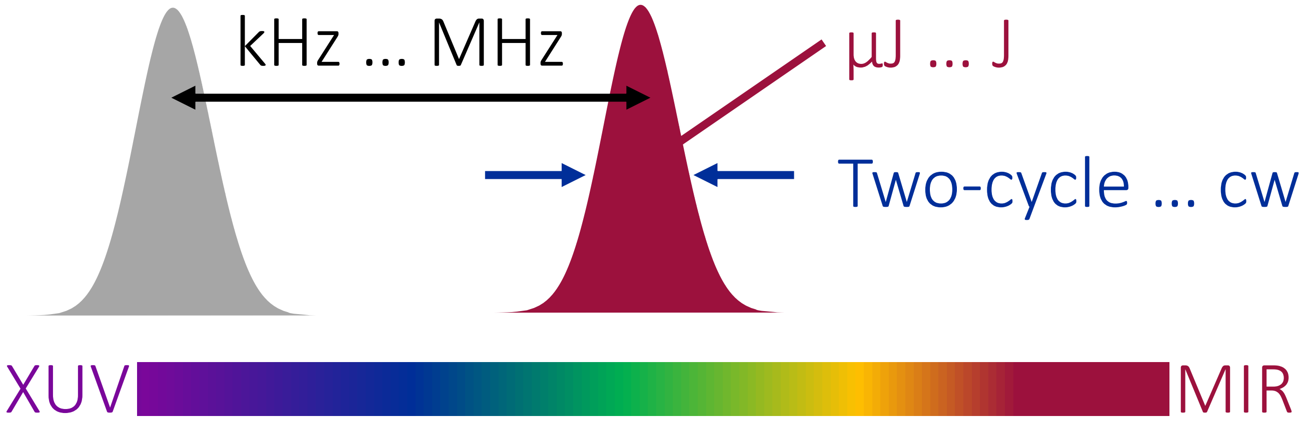
# The TRUMPF Group network

afs
Member of the TRUMPF Group

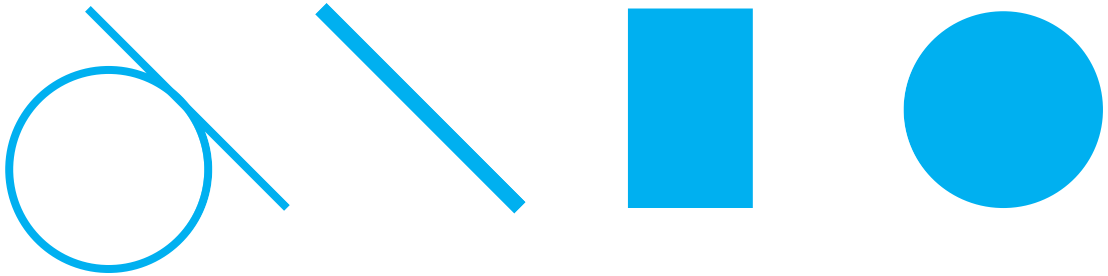
AMPHOS
Member of the TRUMPF Group

TRUMPF
TRUMPF Scientific Lasers

TRUMPF




Do you have a preferred amplifier geometry?



The TRUMPF Group covers your needs!

# Commercial XUV beamlines

afs
Member of the TRUMPF Group

Turn-key XUV source
simple versions with 26eV,
**starting from <200k€ (EU)**

| Possible specs | | |
|---|---|---|
| Wide range of Photon energy (20eV...150eV) → 300eV using 2µm | | |
| Flexible bandwidth & pulse duration | | |
| Modular addons for XUV beam handling (Monochrom., Focusing, ...) | | |
| Record-high photon flux over a wide range of photon energies (Photons/s/eV) | | |
| 10nm (124 eV) | 18nm (68 eV) | 46nm (26.6 eV) |
| up to $10^{11}$ | up to $10^{12}$ | up to $10^{15}$ |

| Outlook |
|---|
| Further extension into water-window (300eV realized) |
| Gas-recycling to be implemented |
| Further price optimizations |

Member of the TRUMPF Group

# Lasers beyond the state of the art

Active Fiber Systems GmbH