With funding from the:

Federal Ministry of Research, Technology and Space

afs

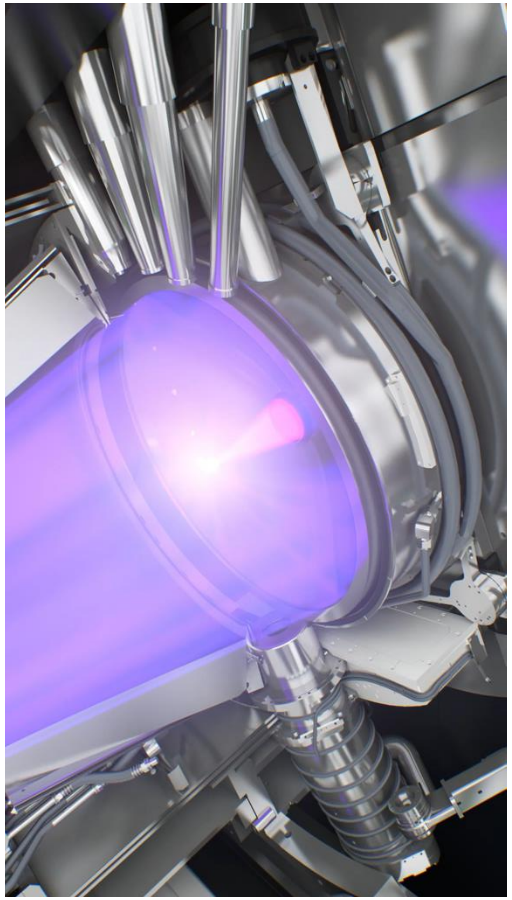
Member of the TRUMPF Group

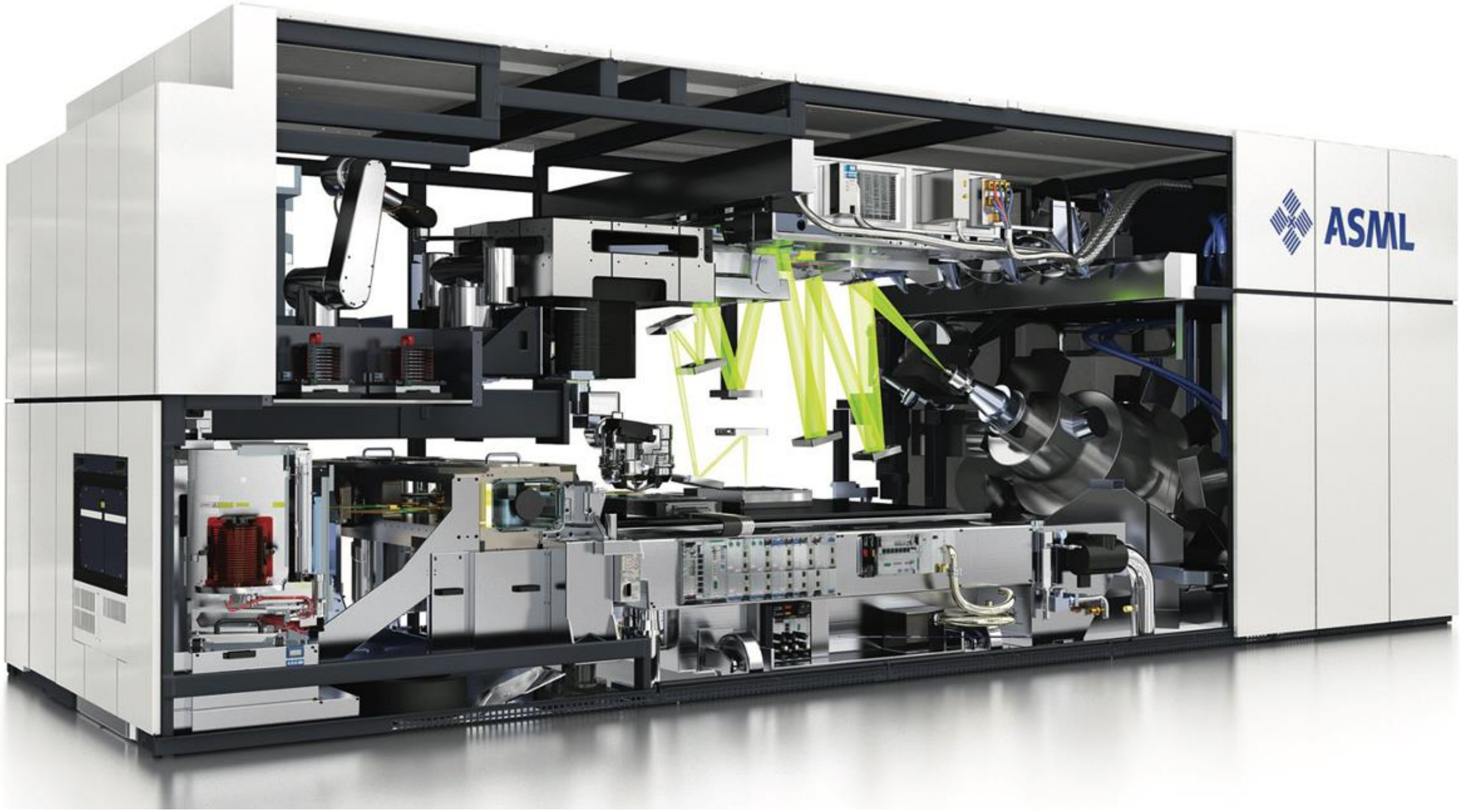
High-energy fiber lasers for secondary sources

Tino Eidam

Secondary sources

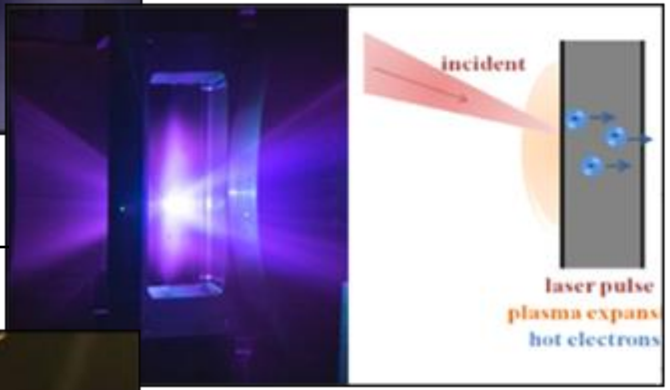
- High-power driving laser + plasma/charged particles → secondary emission of photons/particles
- ASML/TRUMPF EUV-Source is an industrial laser-plasma based secondary source already!



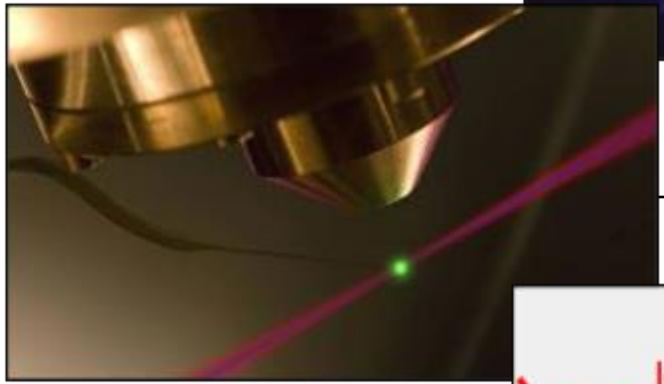


Secondary sources

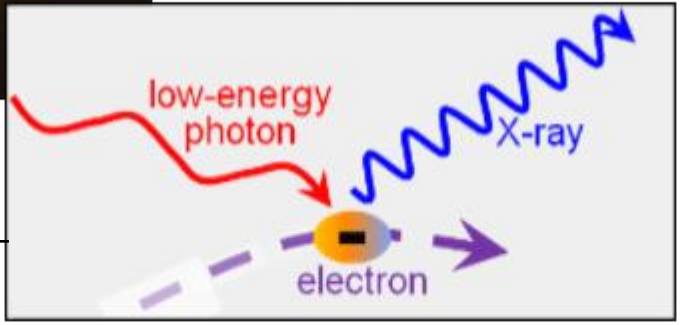
EUV Generation
~10^{11} W/cm^2



X-Ray Generation
~10^{17} W/cm^2

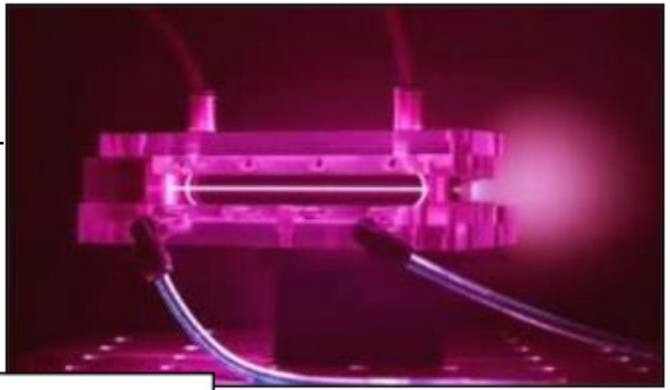


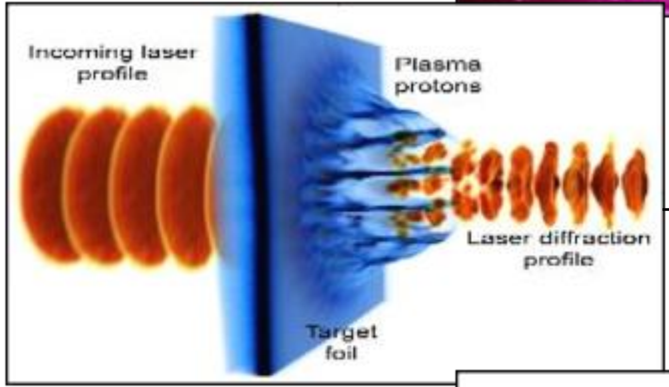
High-Harmonic Generation
~10^{14} W/cm^2



Inverse Compton Scattering
~10^{14} W/cm^2

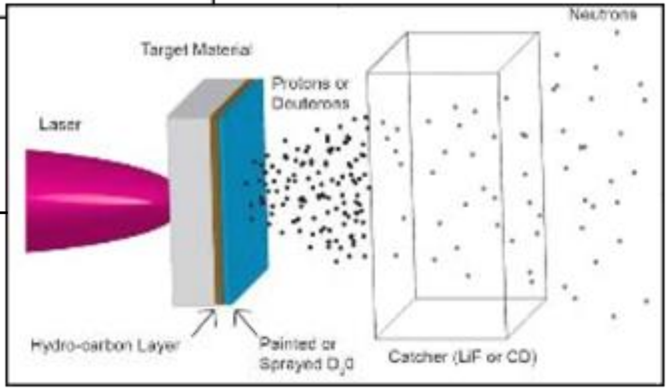
Electron Acceleration
~10^{18} W/cm^2



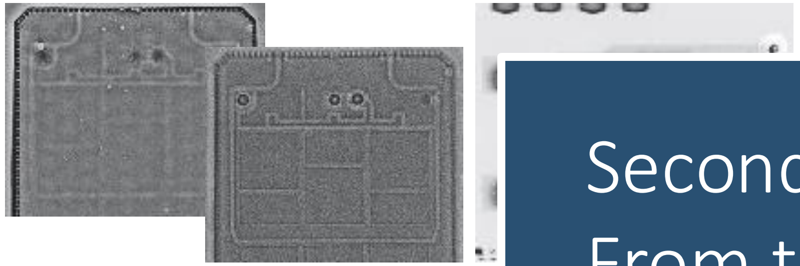


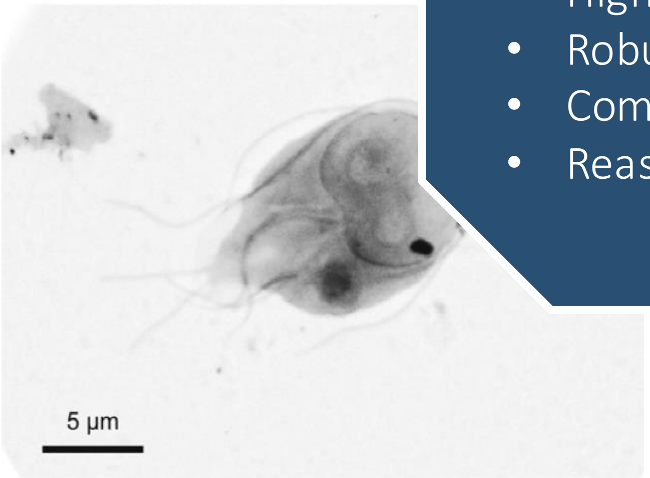
Proton Acceleration
~10^{18} W/cm^2

Neutron Generation
~10^{18} W/cm^2

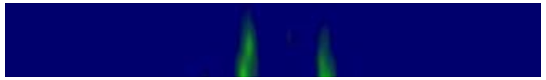


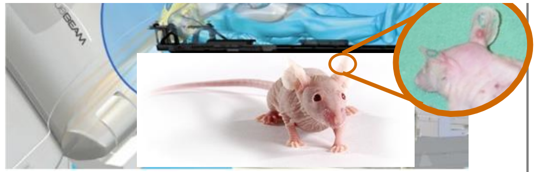
Imaging (photons)



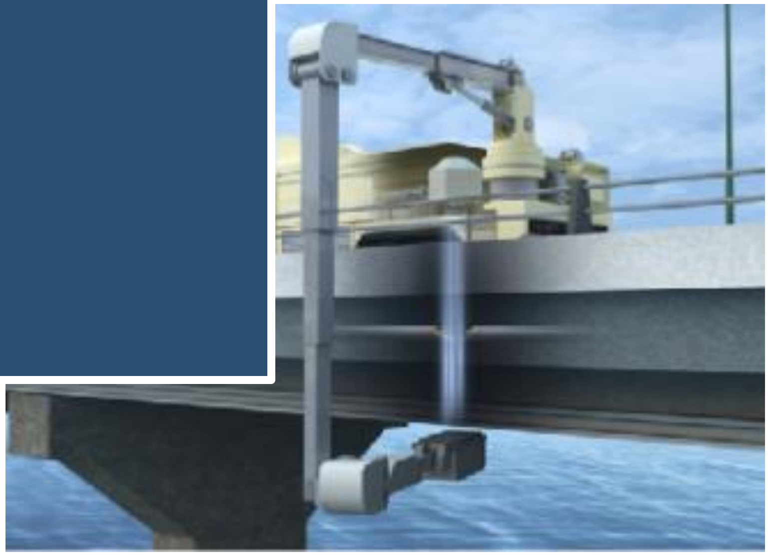


Attoscience





Imaging (neutrons)



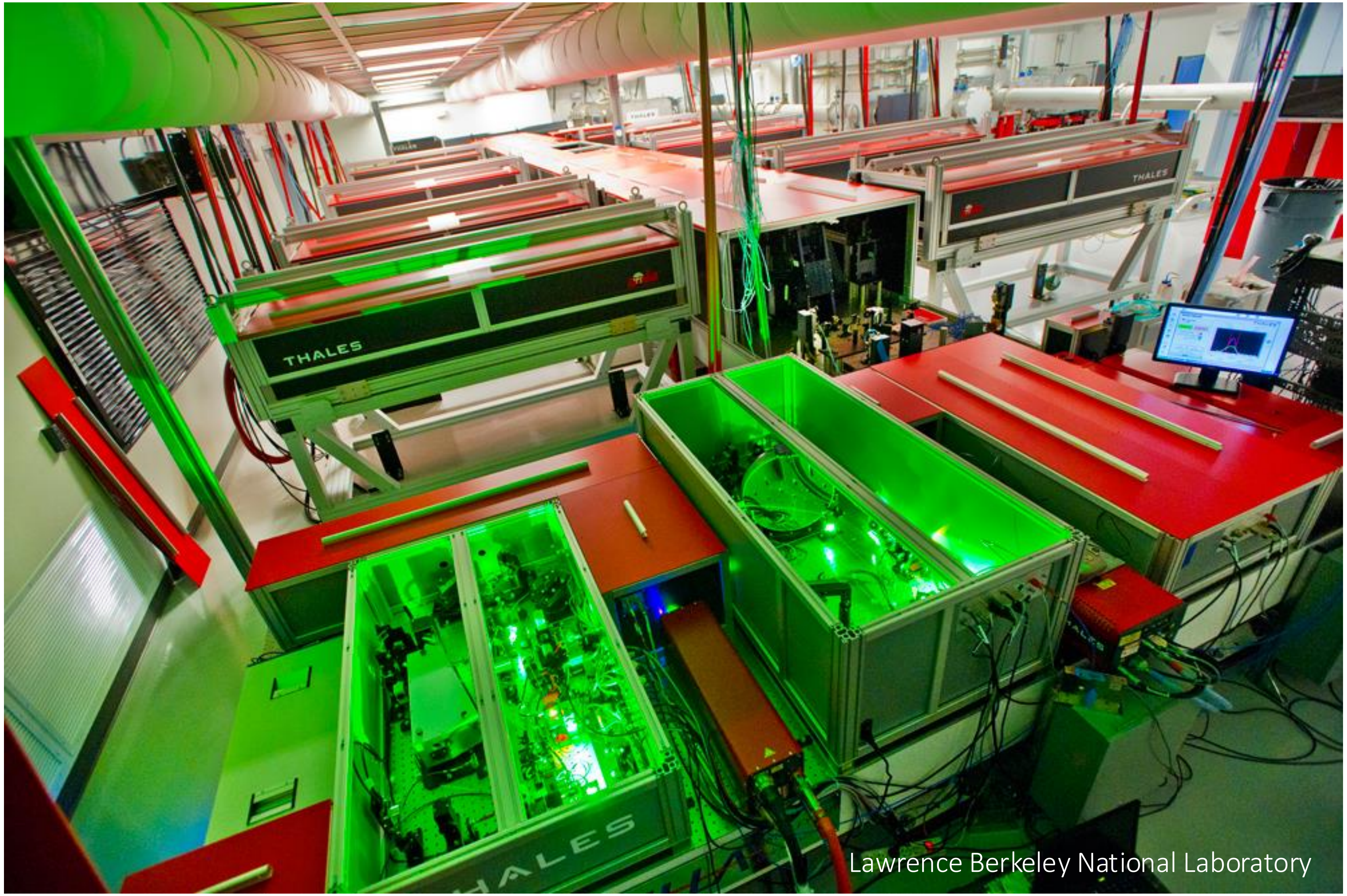
Secondary sources: From the lab to the real world!

- High pulse energy / peak power
- High average power
- High wall-plug efficiency
- Robust
- Compact
- Reasonable cost

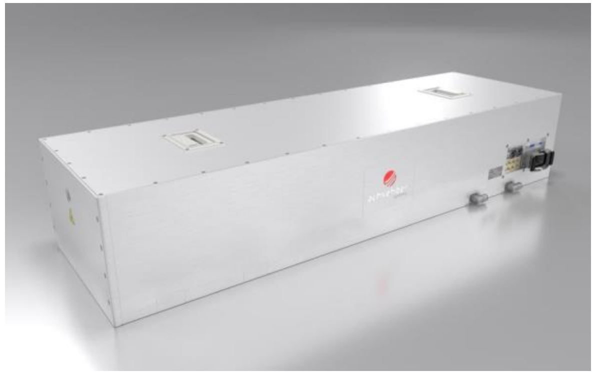
State-of-the-art high-peak-power systems

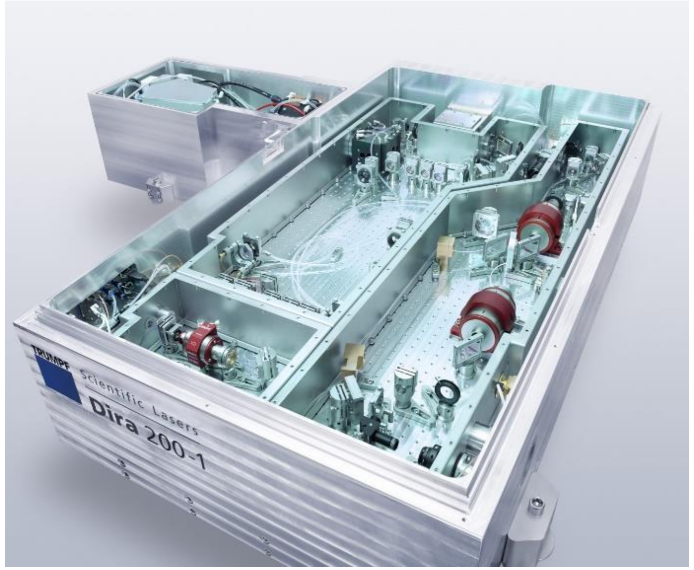
Titanium-doped sapphire

- Pulse energy: 42J
- Pulse length: 40fs
- Peak power >1PW
- Repetition rate: 1Hz
- Efficiency: 42W out for 130kW input: 0.03%



State-of-the-art solid-state laser systems





Fiber:
Ytterbium-100
1mJ, 100W, 250fs

Innoslab:
Amphos8000
5mJ, 200W, 1ps

Thin disk:
Dira 1000-5
200mJ, 1000W, 500fs

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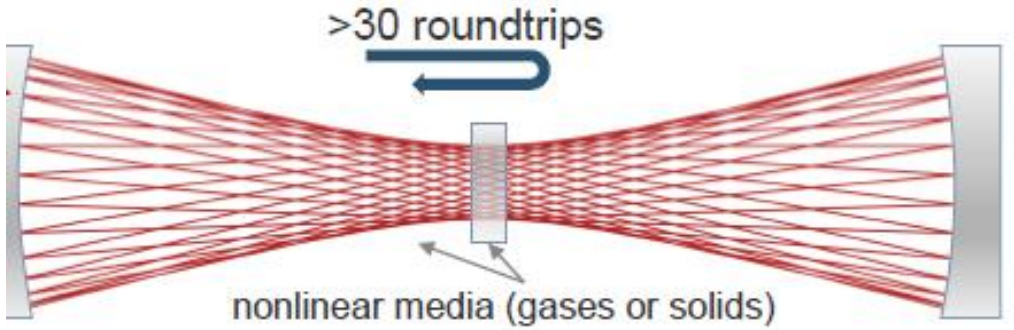
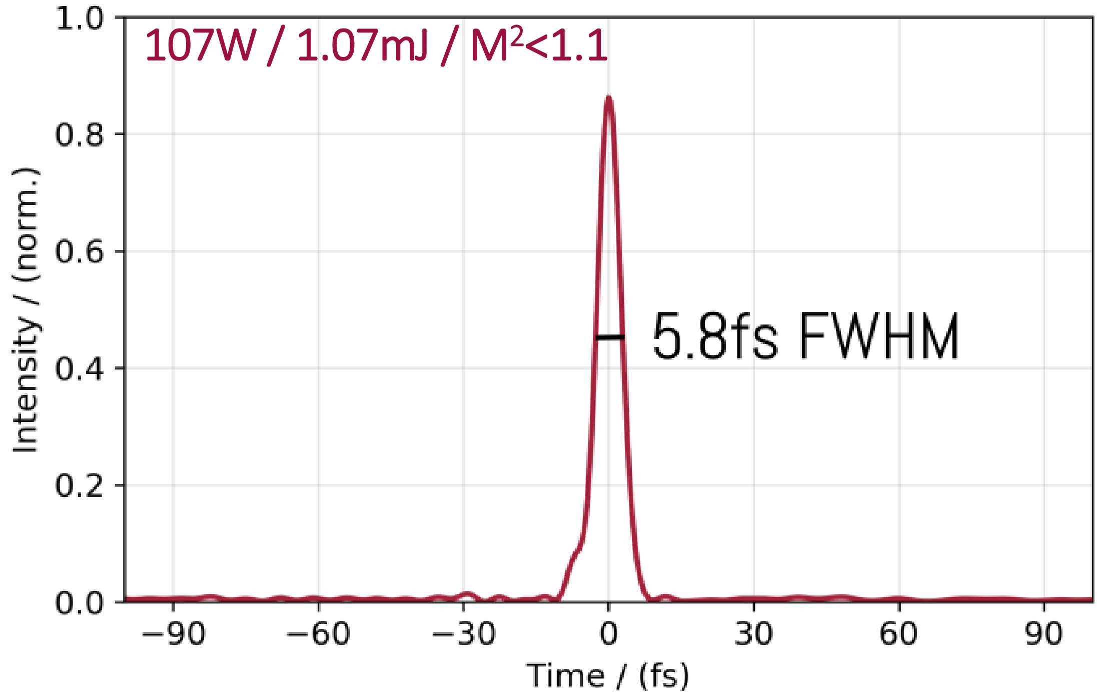
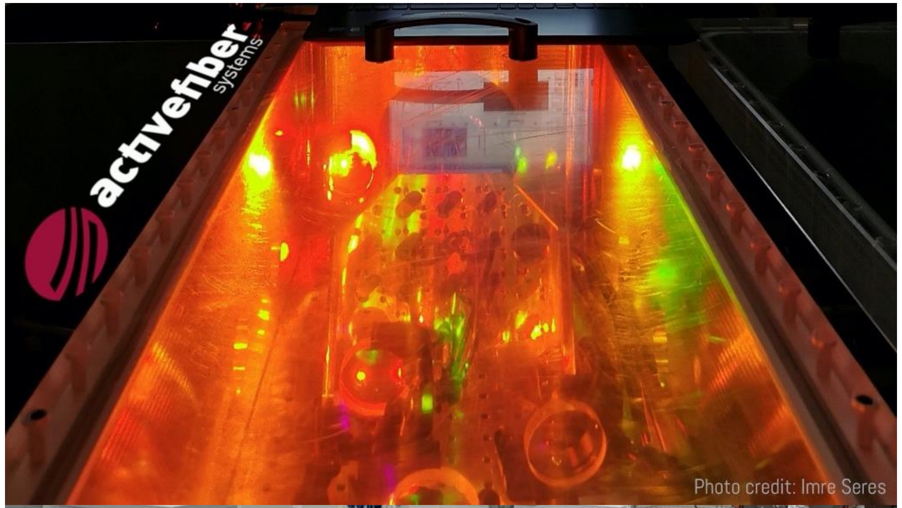
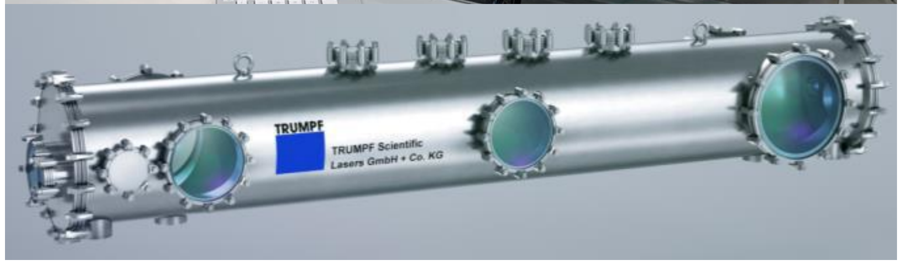
Shorter Pulses!

Herriott-cell nonlinear compression









NON-CONFIDENTIAL

New Driving-Laser Wavelength: 2µm

Ultrafast Tm-doped fiber laser @ 2µm wavelength

15 W	1980 nm	100 µJ	<1Hz - 25MHz	400 fs – 1.5ns

→ Can be post-compressed to <20fs

- Output prepared for connection to free space or fiber beamguiding system
- Safetey shutter included

RTC6 interface
Control via Software – API

Easy service access via side ports

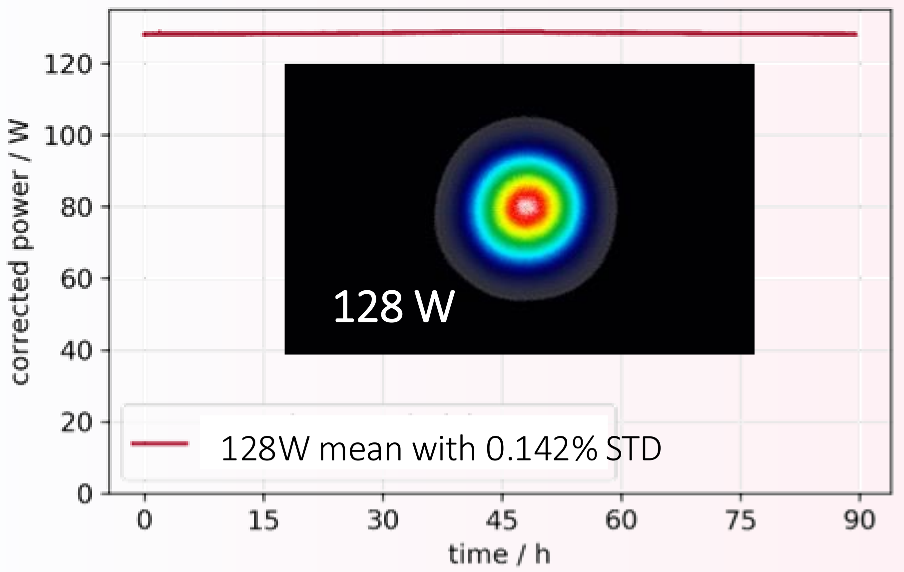
Footprint: 0.24 m^2 (2.6ft^2)

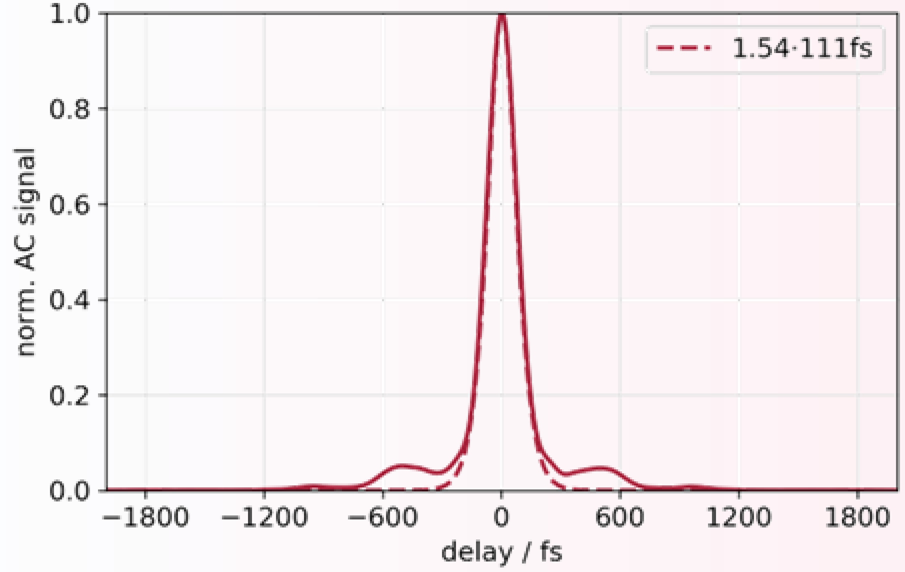
Removable foot holds for seamless integration

Visit us @ Booth A3.327

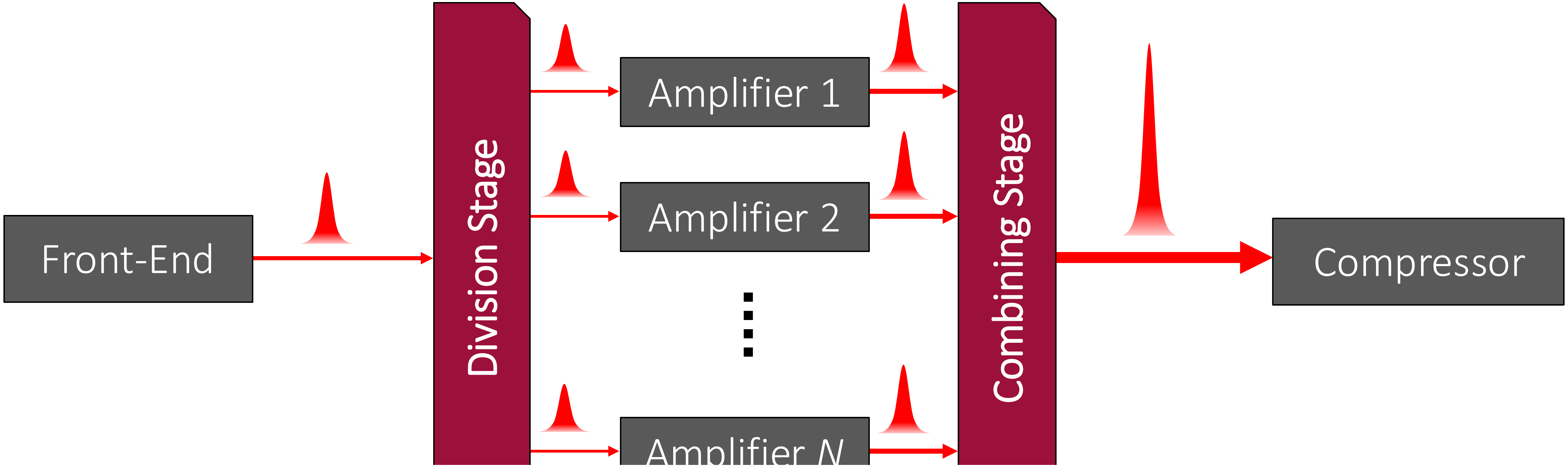
Ultrafast Tm-doped fiber laser @ 2µm wavelength

Tm-200
120W (200W)
200µJ (2mJ)
<150fs
1950nm





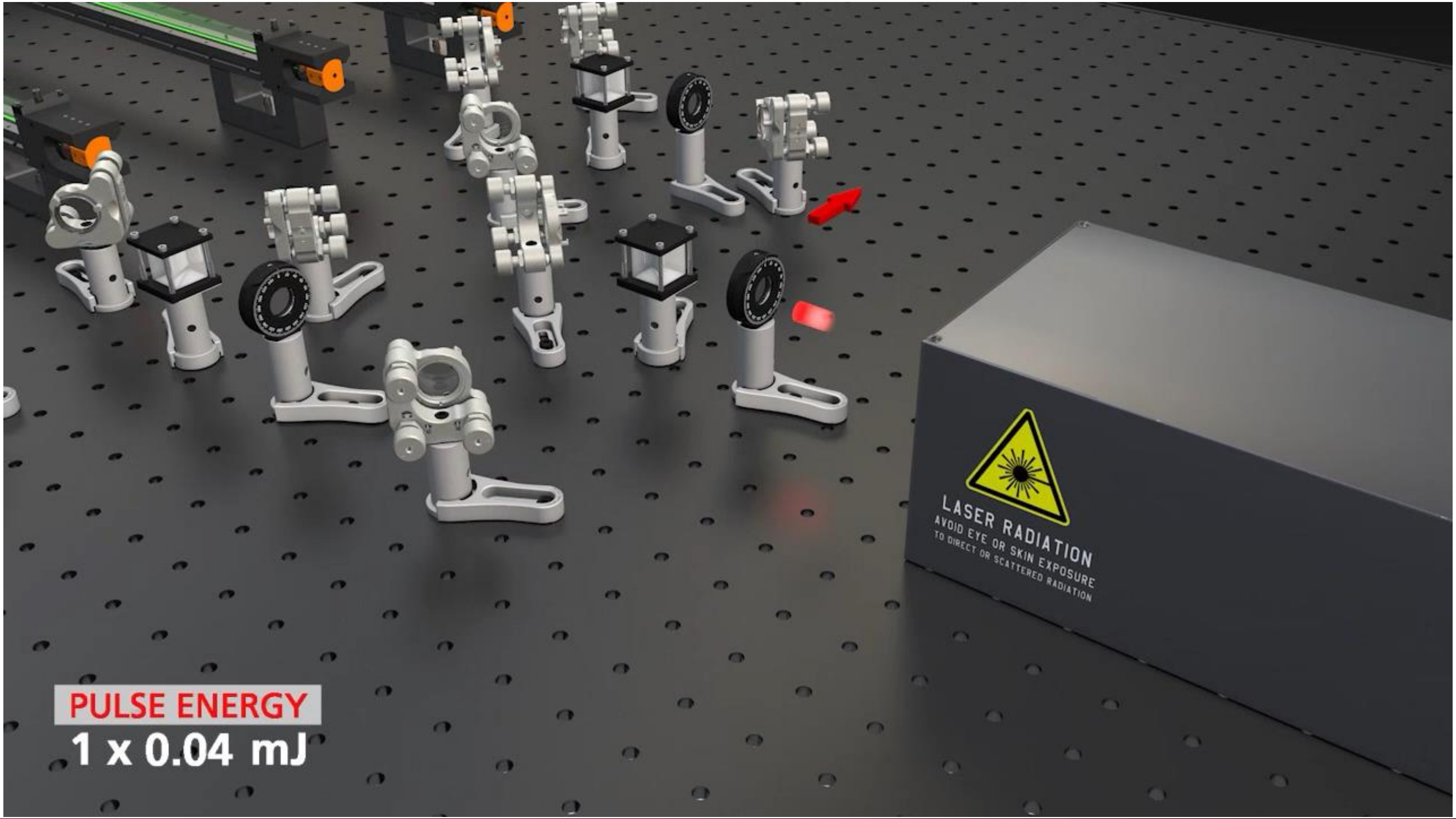
More Power!



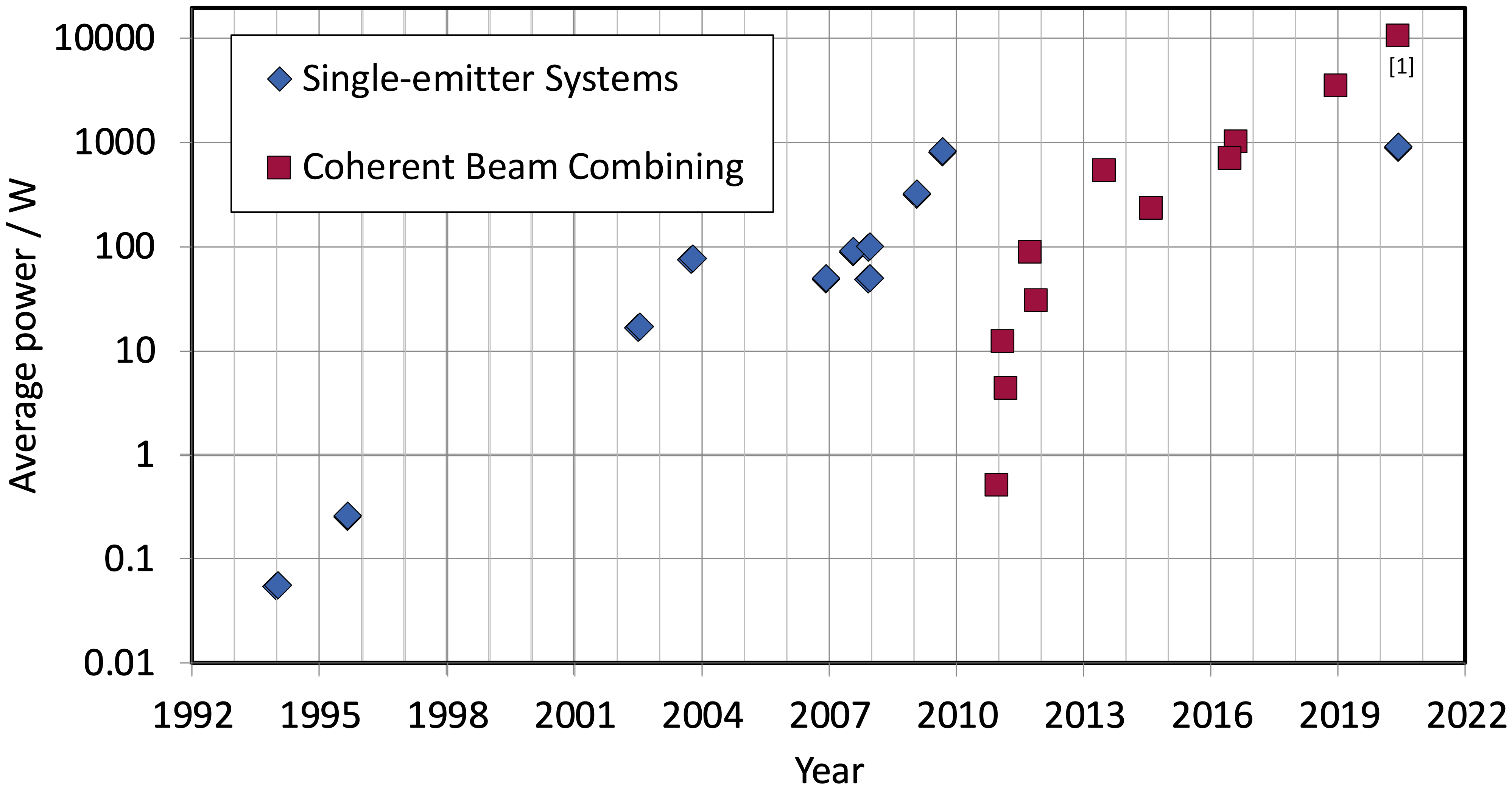
Achievable parameters limited by cost & size, not by physics!

- Use N
- Best case: Improvement of the pulse energy and average power by a factor of *N*
- Ideally suited to fiber lasers (parallelization)

Coherent beam combination



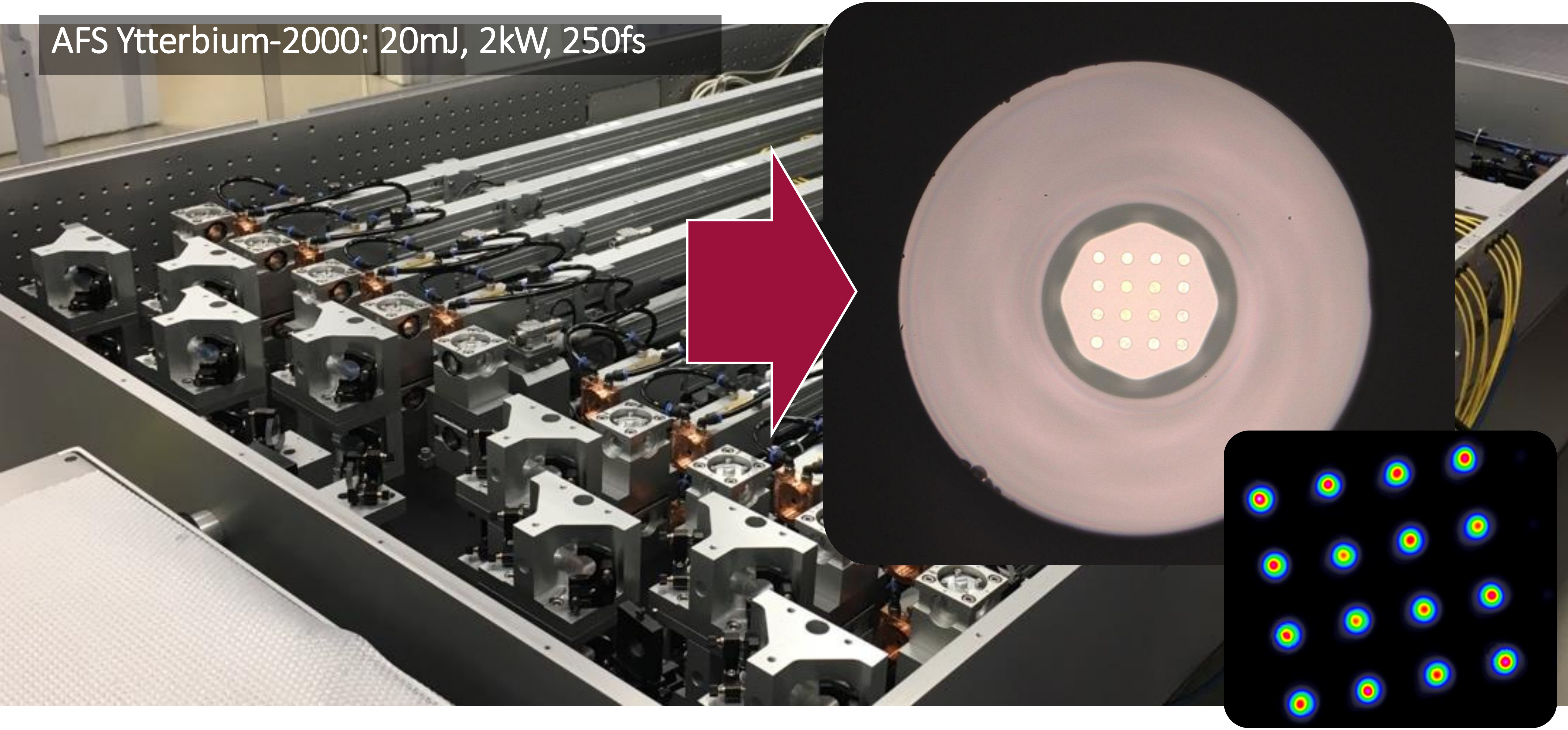
Coherent beam combination



[1] M. Müller et al., "10.4 kW coherently combined ultrafast fiber laser," Opt. Lett. 45, 3083 (2020).

Coherent beam combination

AFS Ytterbium-2000: 20mJ, 2kW, 250fs

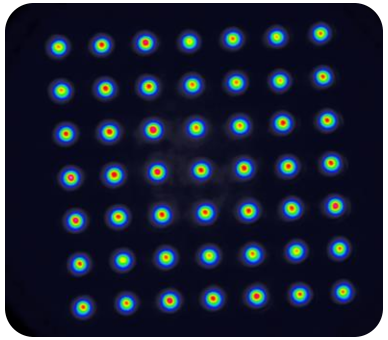


Coherent combination with multicore fibers

- **4x4 Yb MCF**, 21µm core diameter, 1m length
- 1kW total output power achieved
- Ultrafast: >500W, >600µJ, 300fs[1]

- **7x7 Yb MCF**, 32µm core diameter, 1.2m length
- 1kW total output power achieved
- Ultrafast: work in progress

- **10x10 Yb MCF** preform fabricated



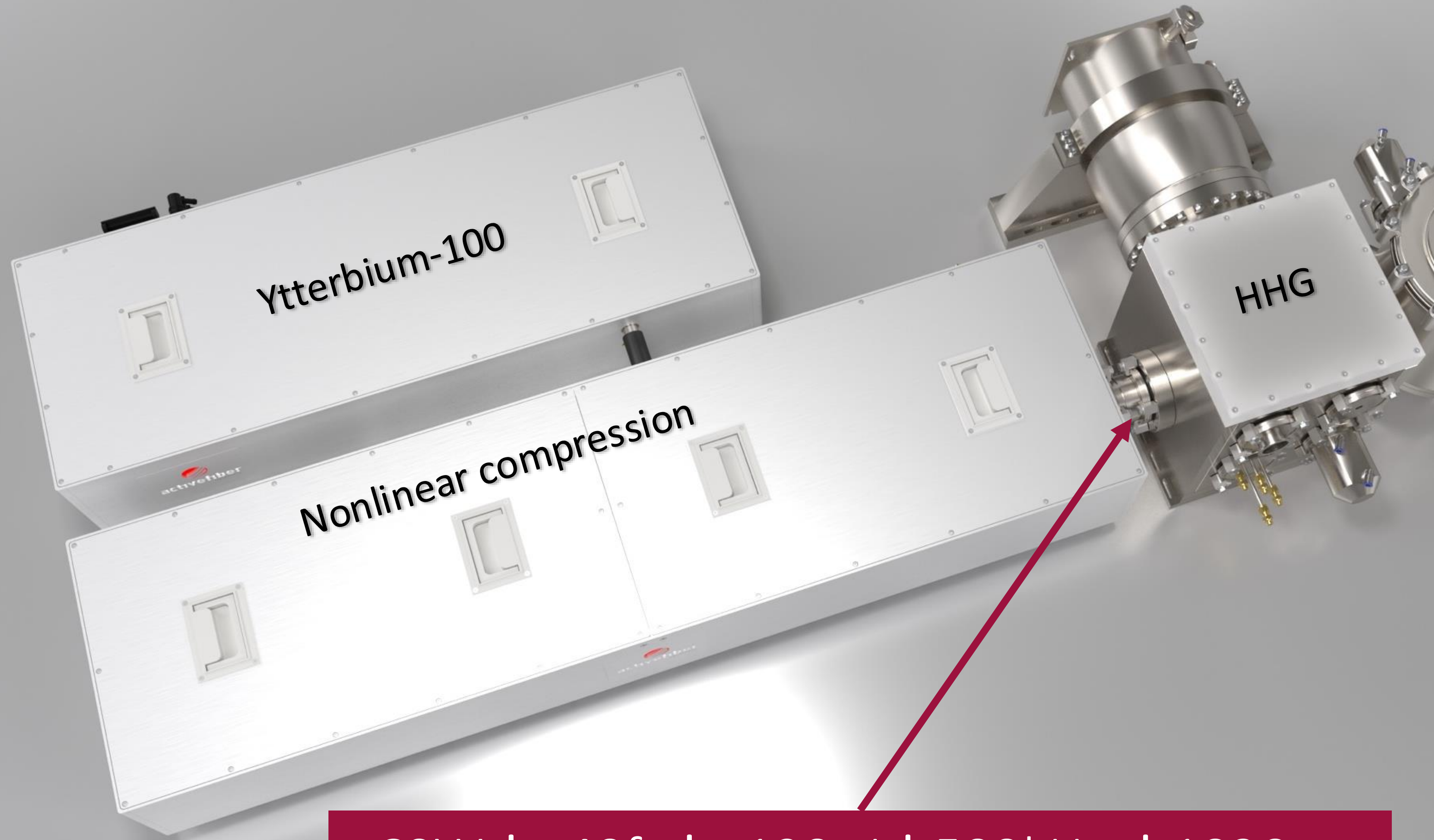
Outlook:

- **7x7 Yb MCF**, 80µm core diameter
- **200mJ, 2kW, 200fs** from a single MCF
- **3J, 30kW, 200fs** from 16x MCF

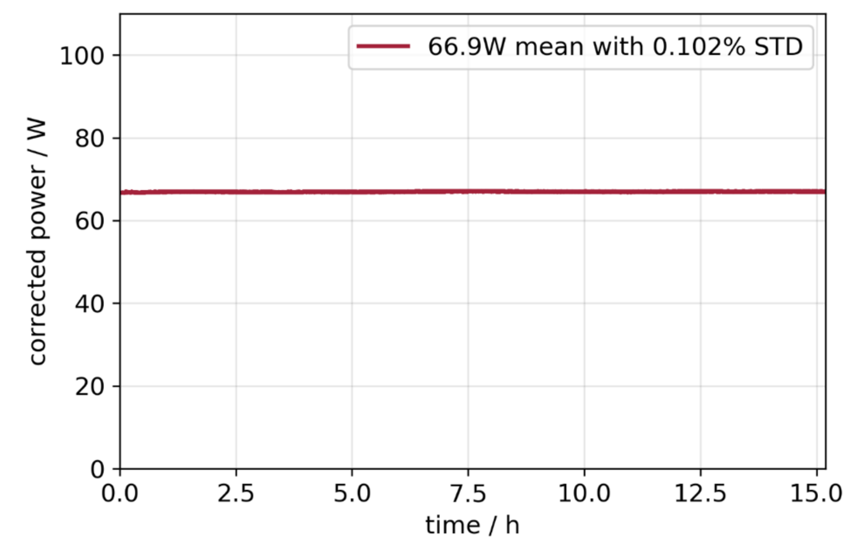
[1] A. Klenke, et al., "500 W rod-type 4×4 multicore ultrafast fiber laser," Opt. Lett. 47, 345-348 (2022)

HHG

XUV Setup – Compact Beamline



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



XUV output results

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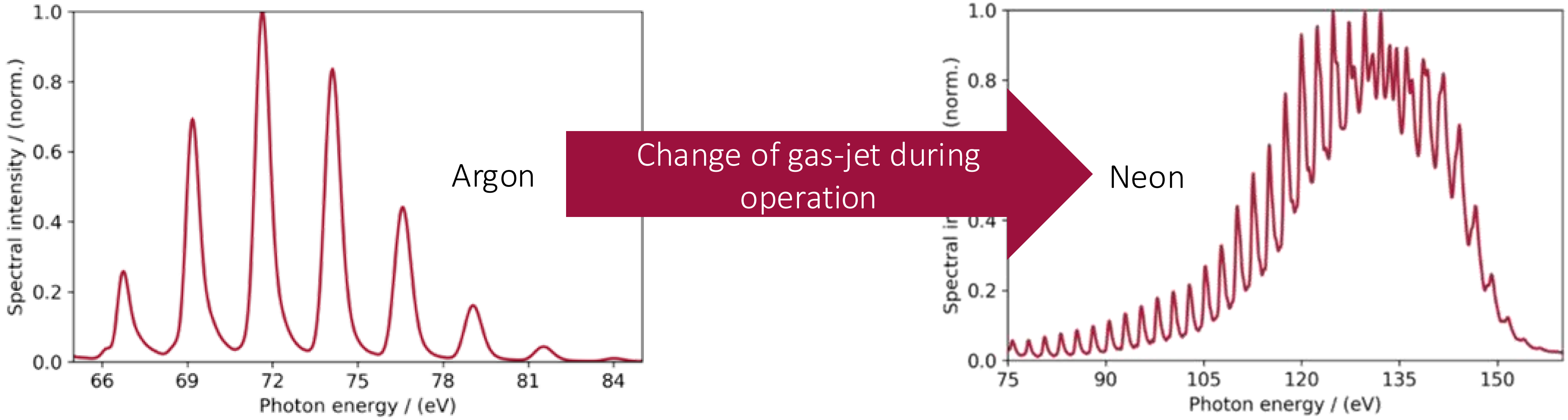
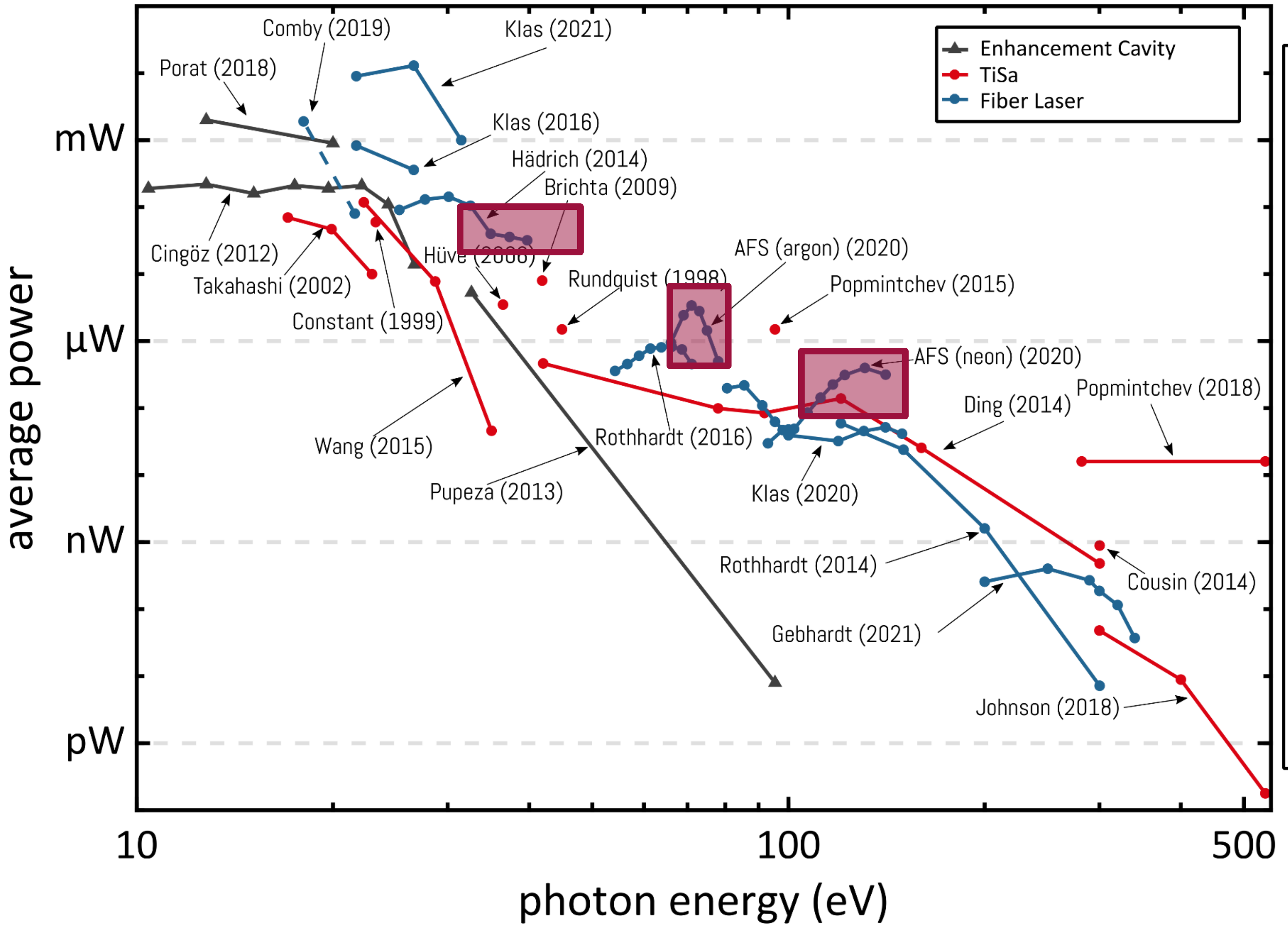
Harmonic	Photon energy /eV	Wavelength /nm	Flux /10^10 Photons/s/(1% bandwidth)
59	71	17.5	30*
77	93	13.3	0.2
93	112	11.1	0.8*
109	131	9.5	1.9*

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



State of the Art coherent XUV sources

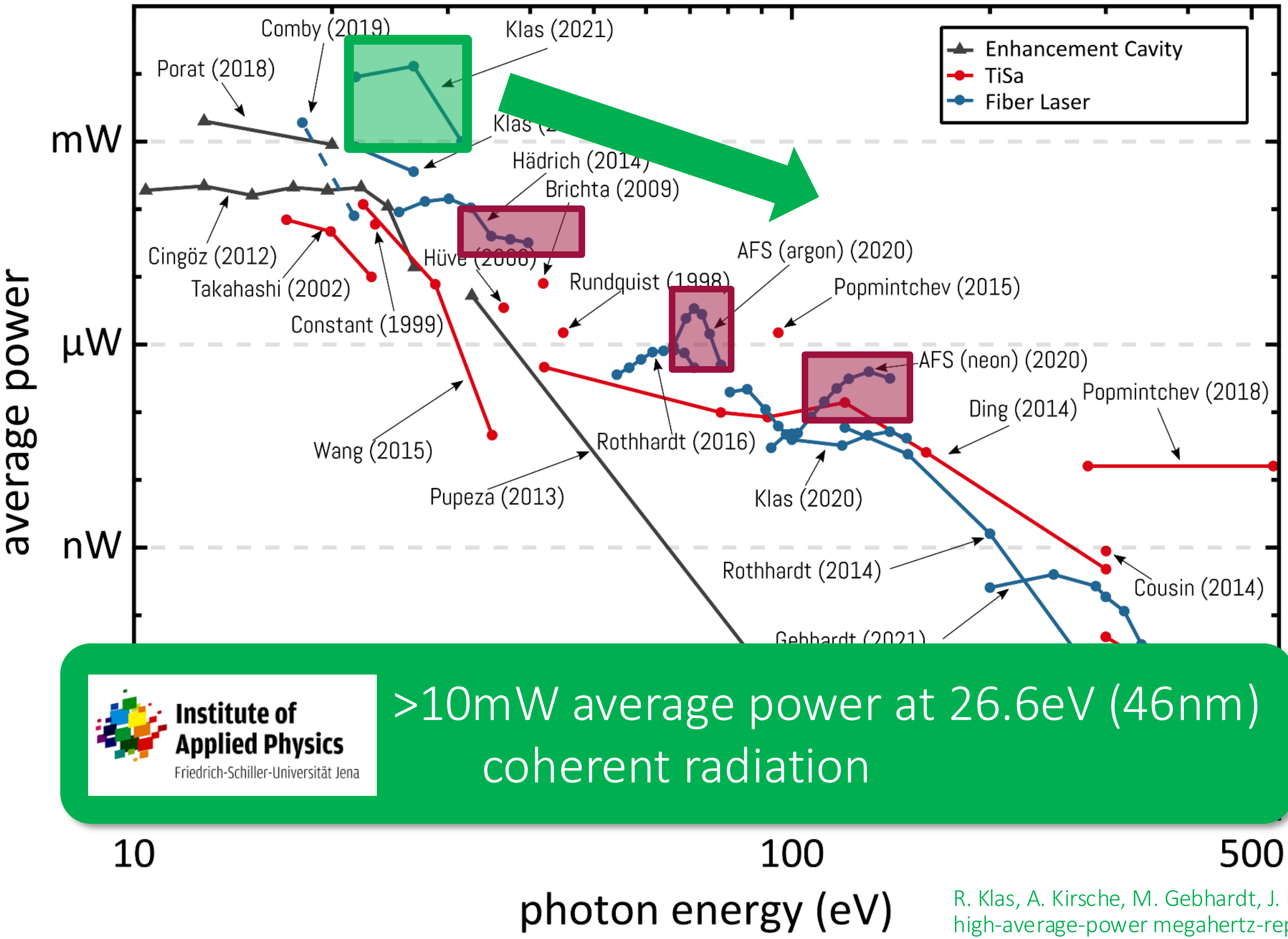


- [1] Cingöz et al. Nat. 482, 68 (2012)
- [2] Porat et al., Nat. Photon. 12, 387–391 (2018)
- [3] Pupeza et al. Nat. Phot. 7, 608 (2013)
- [4] Brichta et al. PRA 79, 033404 (2009)
- [5] Constant et al. PRL 82, 1668 (1999)
- [6] Cousin et al. Opt. Letters 39, 5383 (2014)
- [7] Ding et al. Optics Express 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]
- [17]

AFS sources

- [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)

State-of-the-Art coherent XUV sources



- [1] Cingöz et al. Nat. 482, 68 (2012)
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- [13] Takahashi et al. Opt. Letters 27, 1920 (2002)
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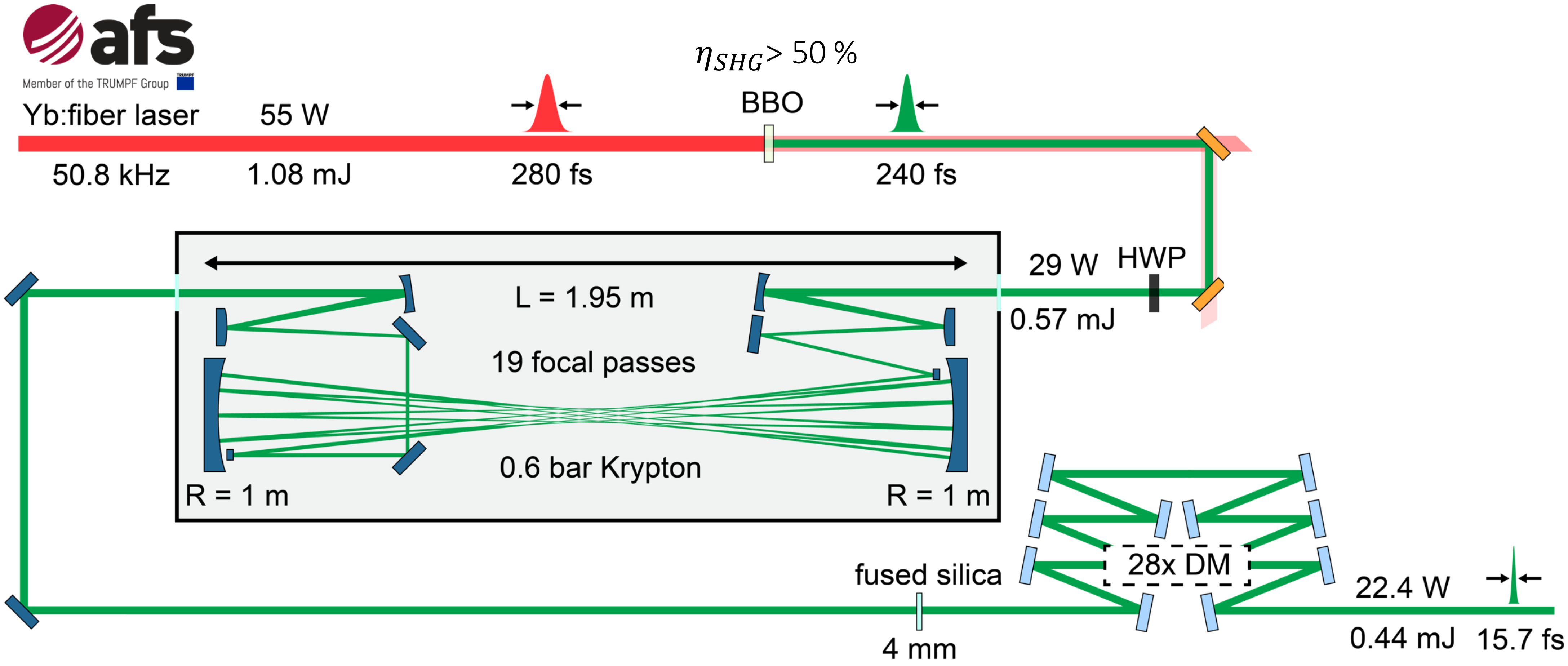
- [23] Rothhardt et al. Opt. Express 24, 18133 (2016)
- [24] Comby et al. Opt. Express 27 (2019)

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

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

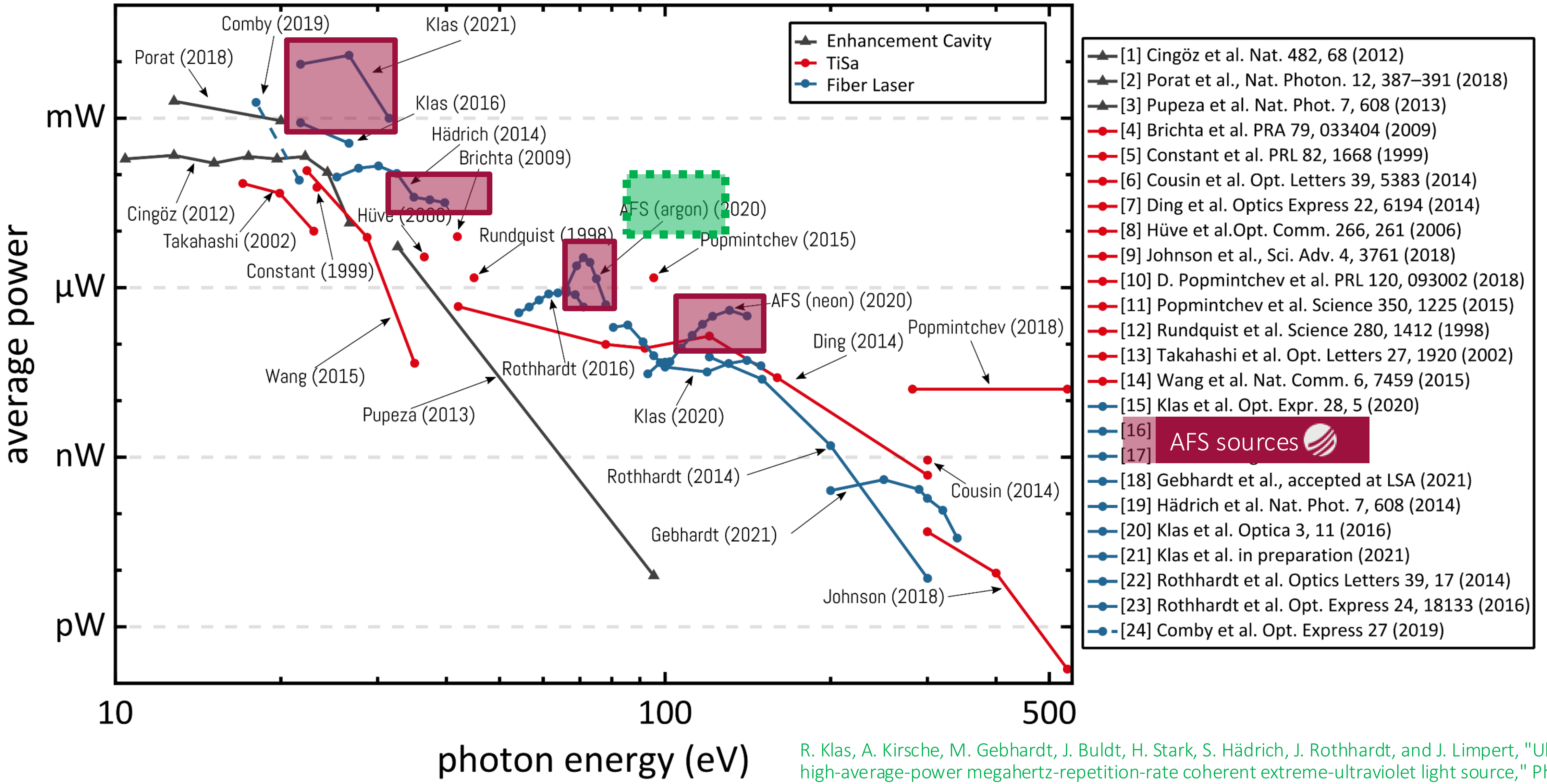
R. Klas, A. Kirsche, M. Gebhardt, J. Buldt, H. Stark, S. Hädrich, J. Rothhardt, and J. Limpert, "Ultra-short-pulse high-average-power megahertz-repetition-rate coherent extreme-ultraviolet light source," PhotoniX **2**, (2021).

State-of-the-Art coherent XUV sources



- 100 fs² GDD per reflection

State-of-the-Art coherent XUV sources



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X-Ray

Laser-Sources

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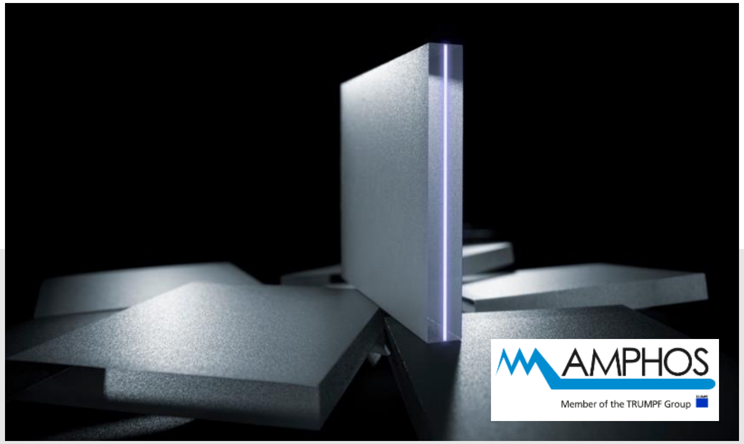

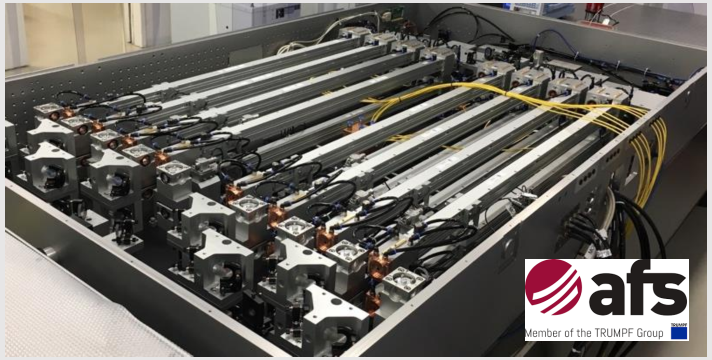

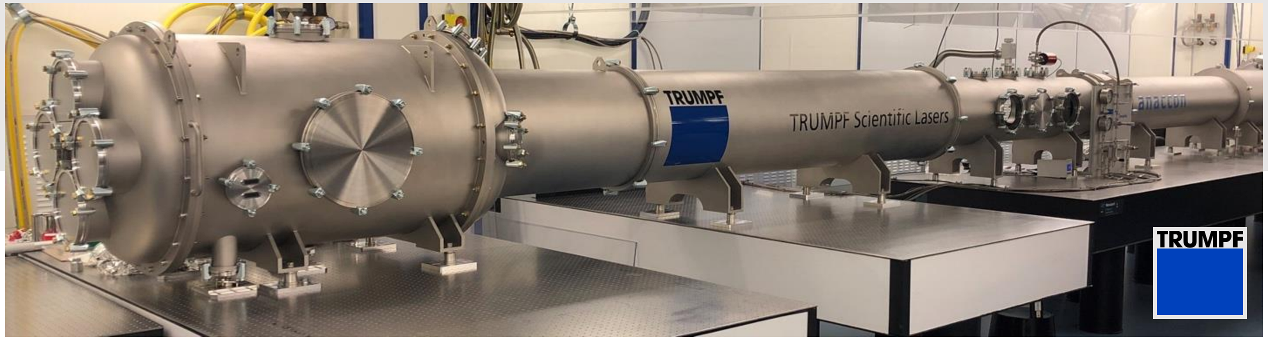

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Target (X-Ray - Source)

With funding from the:

Federal Ministry of Research, Technology and Space

Fraunhofer

Fraunhofer

excillum

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X-Ray - Application

With funding from the:

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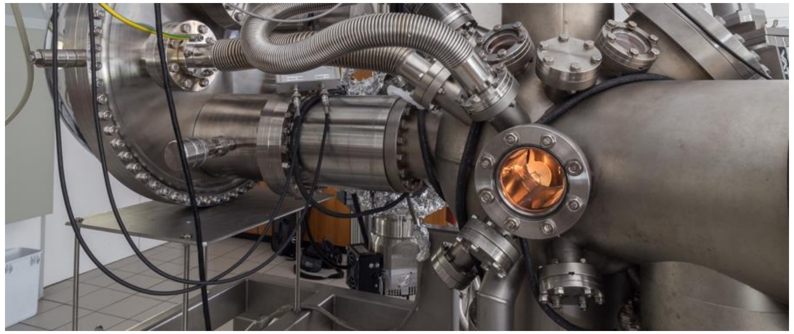
of Research, Technology
and Space

BRUKER
X-Ray Diffraction



b-tu Brandenburgische
Technische Universität
Cottbus - Senftenberg

VISCOM
vision technology

Associated Partners

BASF
We create chemistry

ZEISS

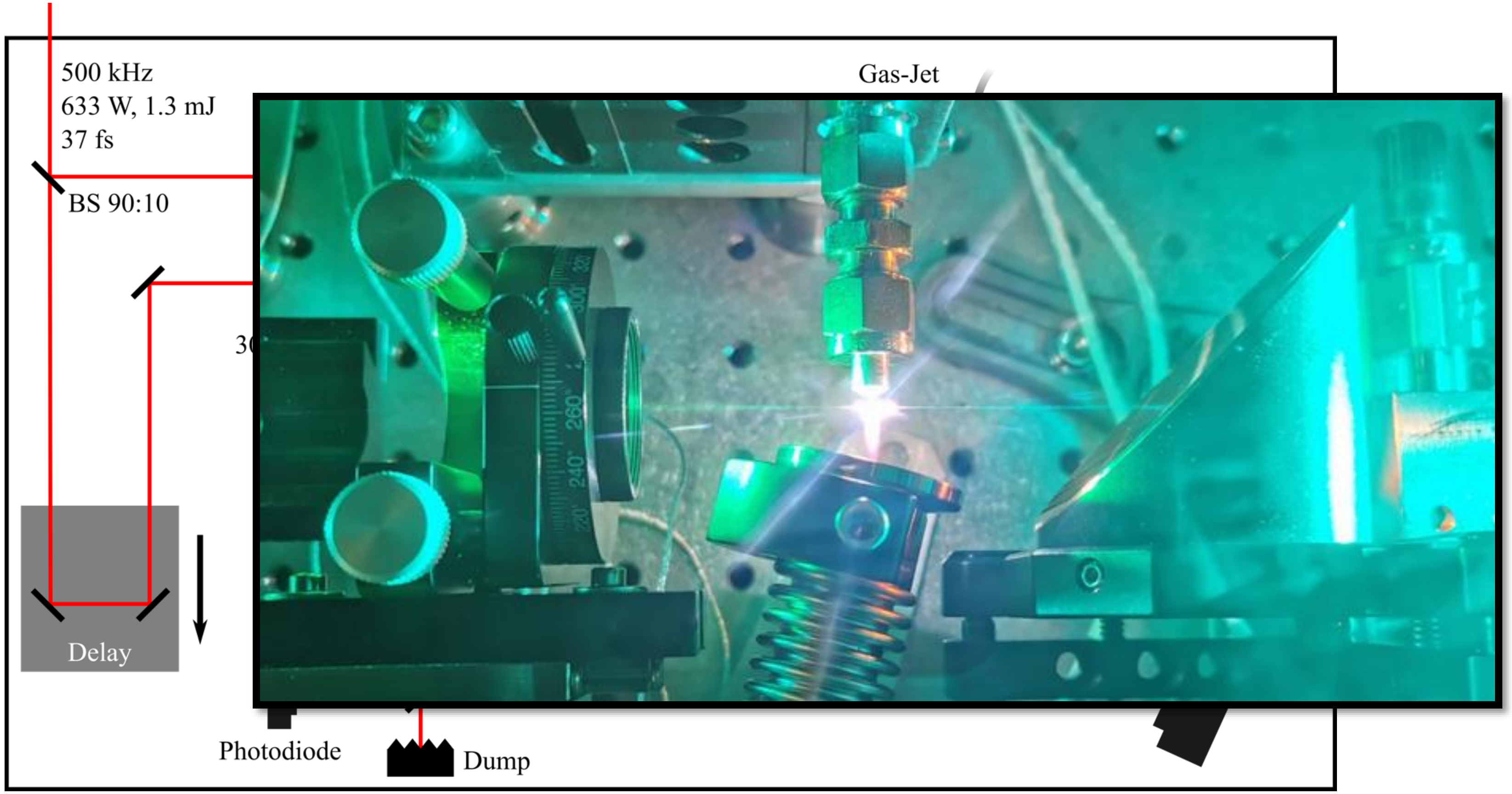
CELLFORCE

NON-CONFIDENTIAL

THz

Experimental Setup – THz Generation

- Two-color gas-plasma approach[1,2]
- Input: 500 kHz, 1.3 mJ, 37 fs
- Argon gas-jet in focus
- Spatial separation of THz/pump light



Output

- Average power of 640 mW
- Efficiency of 0.1% (state of the art at 1 µm)

[1] J. Buldt et al., "Gas-plasma-based generation of broadband terahertz radiation with 640 mW average power," Opt. Lett. 46, 5256-5259 (2021)
[2] J. Buldt et al., "High-power two-color plasma-based THz generation driven by a Tm-doped fiber laser," Opt. Lett. 48, 3403-3406 (2023)

Current AFS-Project: Beamline including Momentum Microscope

- Pump-probe setup using different output ports
- 3mJ/300W/1µm/100fs for THz-generation
- 400µJ/40W/1µm/7.5fs CEP-stable for as-HHG
- Narrowband & broadband HHG driven by 515nm/1030nm
- OPA: 250nm – 2.5µm, <100fs
- MIR: 8 – 15µm
- All outputs temporally synchronized

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Thank you.

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