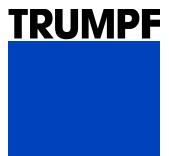




EUVLitho - 2023 Source Workshop, 24th October 2023

Lasers and Building Blocks for Secondary Sources

Dr. Torsten Mans, Productmanagement Secondary Sources
Trumpf Laser GmbH, Schramberg



Agenda

01 TRUMPF Group & Business Center Lasers

02 Secondary Sources Initiative @TRUMPF

03 Building Blocks of Solid-State Laser-Drivers

Unlocking Technological Worlds For Generations To Come

Family business drives innovations



Sales

5.4 bn.€

Employees

>17,800

R&D Quota

>10%

Subsidiaries

>70

Countries

>30

Technologies



MACHINE
TOOLS



LASER
TECHNOLOGY



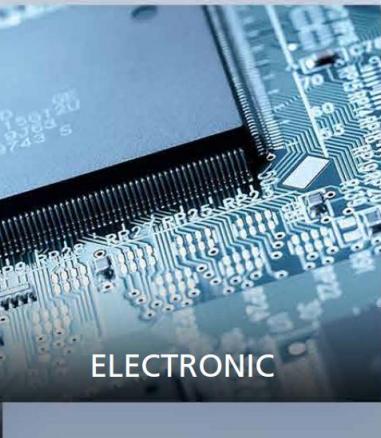
ADDITIVE
MANUFACTURING



EUV

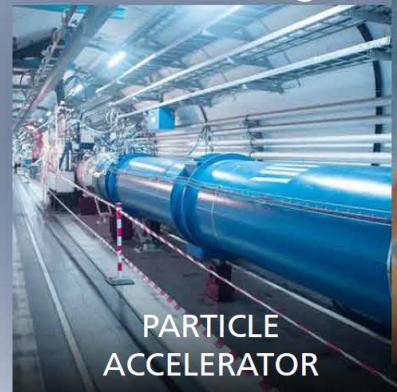


PHOTONIC
COMPONENTS



ELECTRONIC

Future technologies



PARTICLE
ACCELERATOR



QUANTUM
TECHNOLOGY



NEW SPACE

Business Divisions

Machine Tools

for flexible sheet metal manufacturing



Laser Technology

Laser for Production Technology



Business Fields

Extreme UV Light

TRUMPF Laser Amplifier

High-Power Laser Systems for EUV Lithography



ADDITIVE MANUFACTURING

for innovative components

Laser Metal Fusion (LMF) | Laser Metal Deposition (LMD)

PHOTONIC COMPONENTS

Laser Diodes for photonics and digital products

>1 Billion cell phones worldwide are already equipped with this laser diode technology



FINANCIAL SERVICES

Company-owned Full-Service bank for purchase loans



TRUMPF customers receive a lease or hire purchase offer.

Business Center Lasers

Product Centers & Technologies

Core Technologies

- Fiber Laser
- Ns pulsed, kW-cw
- Beam Delivery Optics
- Fiber-optic components
- Fiber Manufacturing

Core Technologies

- Semiconductor Fab (Epitaxy & Wafer Fab & Cleaving & Coating)
- Backend (Mounting & Testing | Lensing & Assembly)

Core Technologies

- Slab Laser
- ps pulsed, kW-amplifiers
- Customized laser systems
- SSL crystal mounting
- Opto-mechanics

TRUMPF
Laser
Southampton,
Great Britain

TRUMPF
Laser
Schramberg

TRUMPF
Photonics
Cranbury, USA

Business
Center
Lasers

TRUMPF
Laser Jena



TRUMPF
Laser
Herzogenrath

AMPHOS
Member of the TRUMPF Group

TRUMPF
Scientific
Lasers
Munich

Core Technologies

- Disk Laser, Fiber Laser
- TruDisk, TruMicro, TruFiber
- Processing Optics
- Beam Delivery | Control & Software
- Opto-Mechanics

Core Technologies

- High-end performance systems:
Ytterbium-based femtosecond laser
(multi-mJ- & kW-class) | Thulium-based
high power ultra-short pulsed source
with 2 μm wavelength | High-power XUV
beam lines
- Lasers for industrial applications
- Lasers for bio-med imaging

Core Technologies

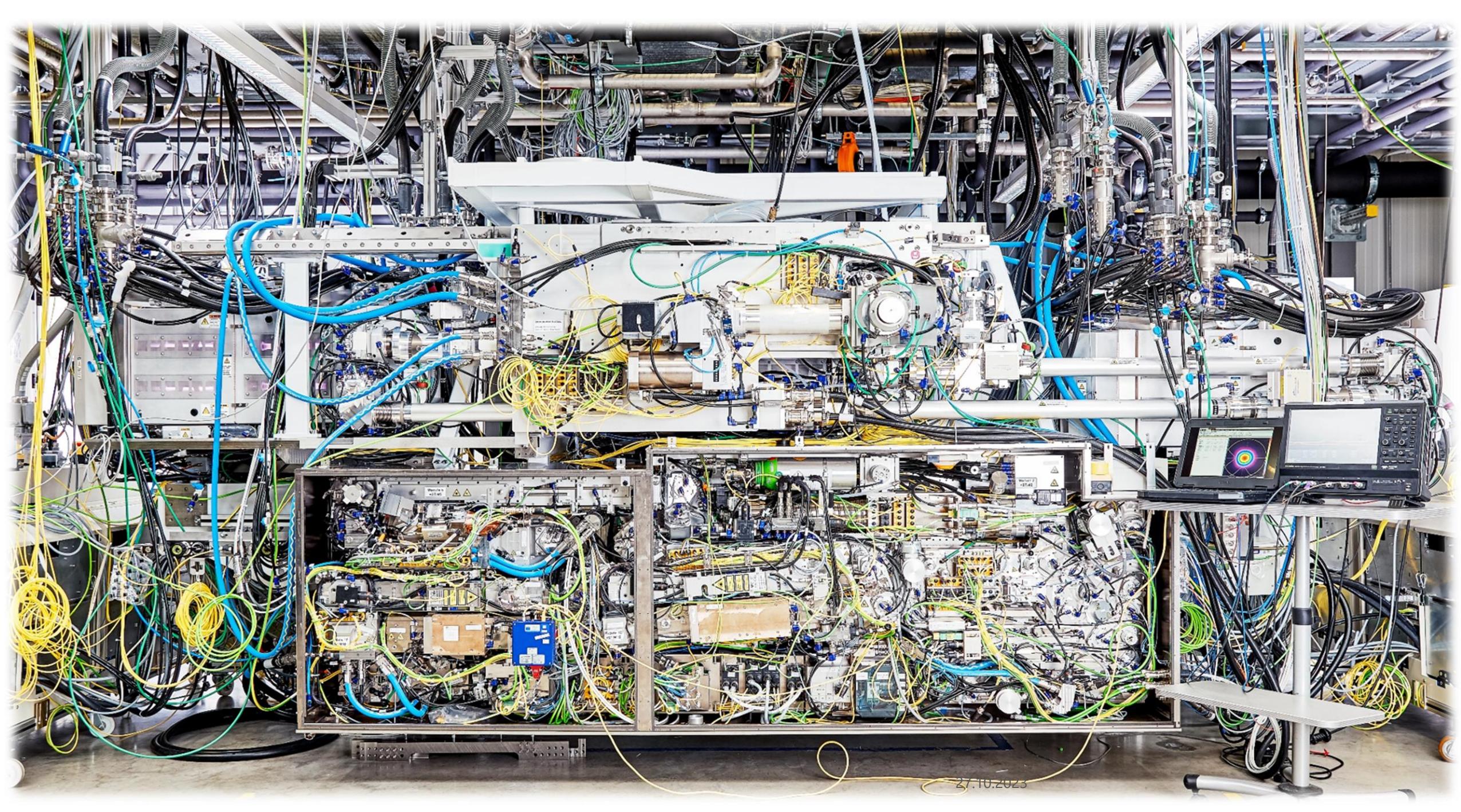
- High-Energy Lasers
- Customized solutions
- Few quantities

Agenda

01 TRUMPF Group & Business Center Lasers

02 Secondary Sources Initiative @TRUMPF

03 Building Blocks of Solid-State Laser-Drivers



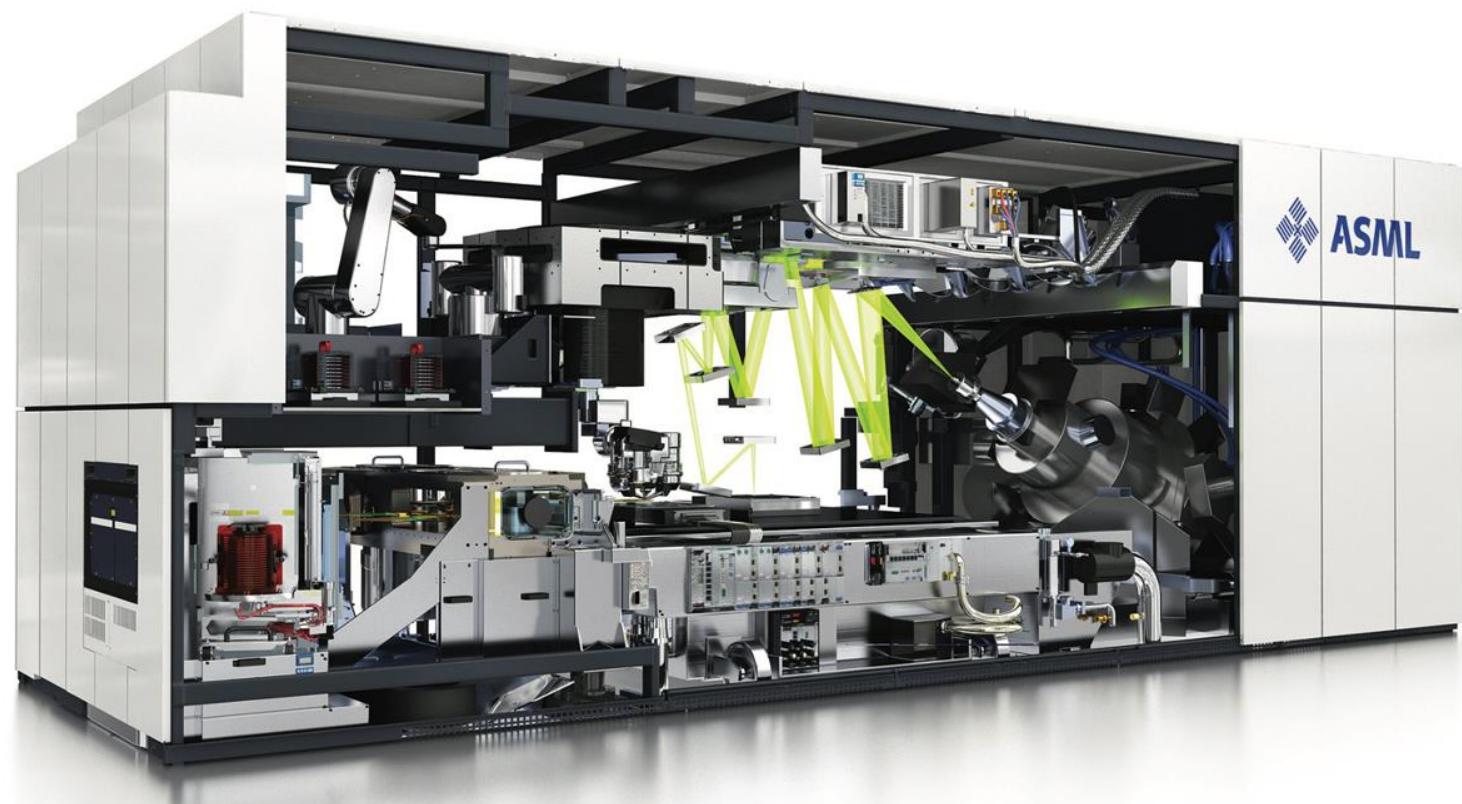
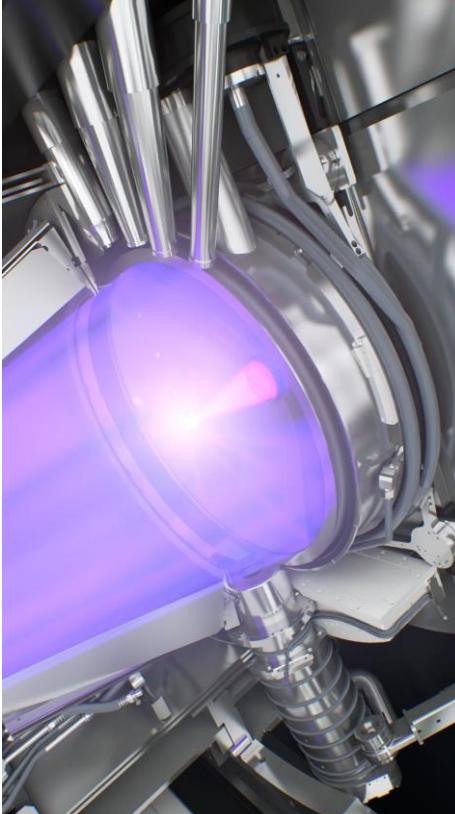
27.10.2023

What does “Secondary Source” mean?

First commercially successful Secondary Source: EUV

High-power driving laser + plasma/charged particles → secondary emission of photons/particles

ASML/TRUMPF EUV-Source is an industrial laser-plasma based secondary source!



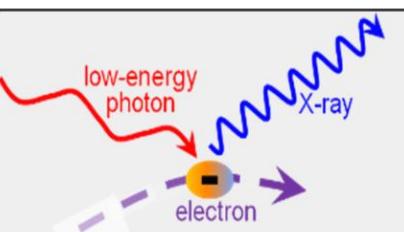
Secondary Source Processes and required Intensities (OoM)



**EUV
Generation**
 $\sim 10^{11} \text{ W/cm}^2$

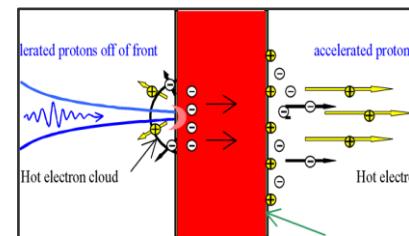
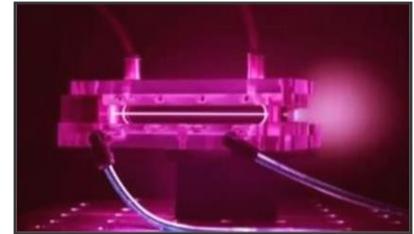


**X-Ray
Generation**
 $\sim 10^{18} \text{ W/cm}^2$

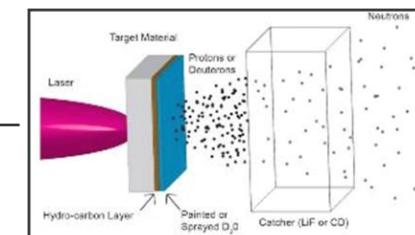


**Inverse Compton
Scattering**
 $\sim 10^{14} \text{ W/cm}^2$

**Electron
Acceleration**
 $\sim 10^{19} \text{ W/cm}^2$



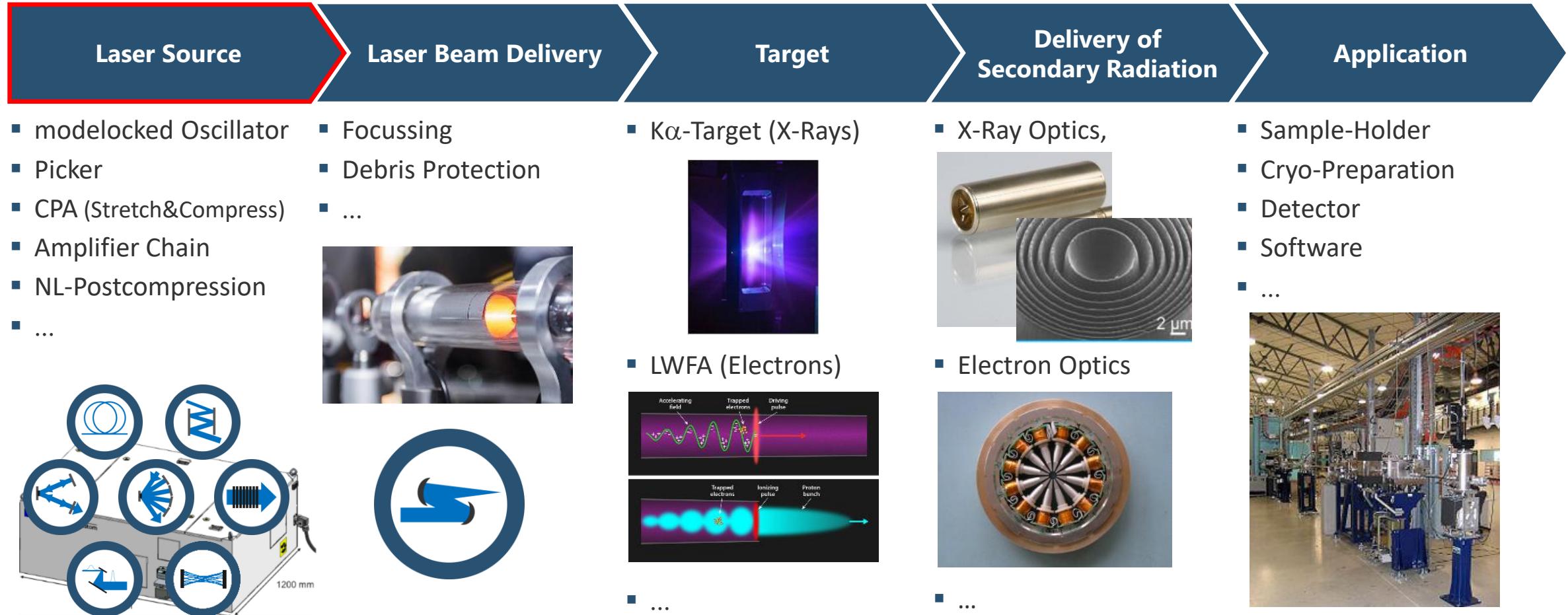
**Proton
Acceleration**
 $\sim 10^{20} \text{ W/cm}^2$



**Neutron
Generation**
 $\sim 10^{20} \text{ W/cm}^2$

Building Blocks for Secondary Sources

Collaborate with Partners for Full Technological Depth



Agenda

01 TRUMPF Group & Business Center Lasers

02 Secondary Sources Initiative @TRUMPF

03 Building Blocks of Solid-State Laser-Drivers

03.1 Motivation for Parameter Range

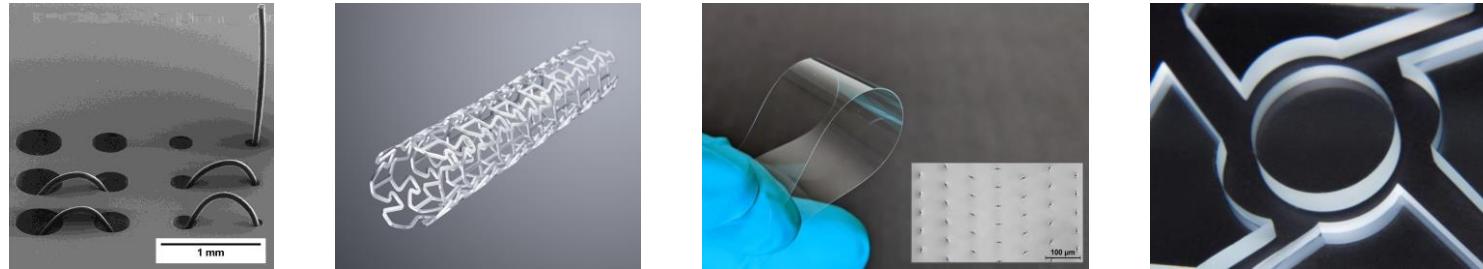
03.2 2µm Laser Sources

03.3 DPSSL - Technological Platforms

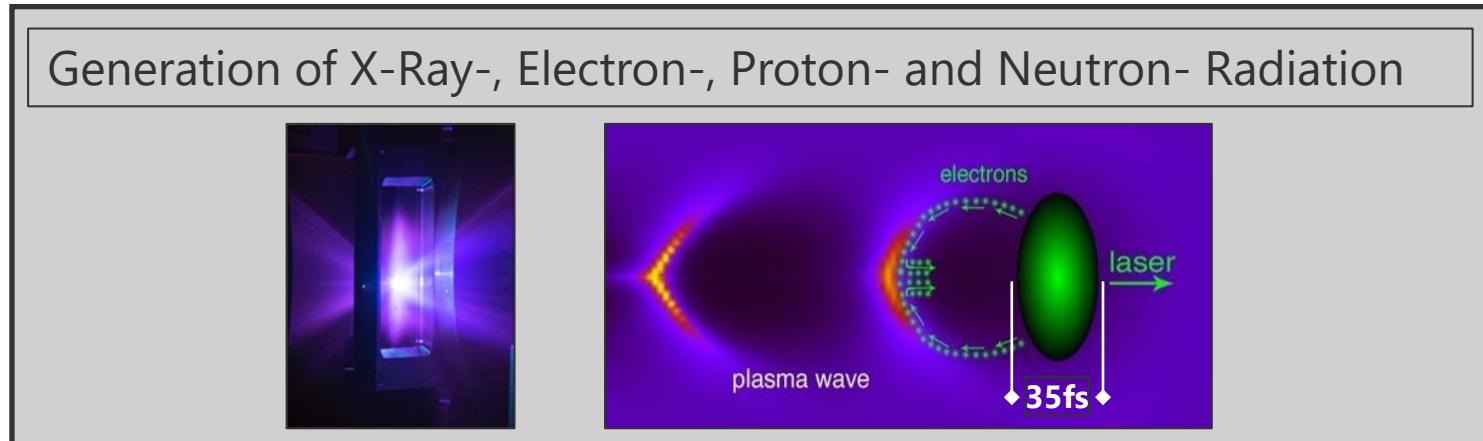
Motivation for Higher Peak Powers of Ultrafast Lasers

Reach Relativistic Intensities

Ultrafast Laser based Materials Processing: 10 μ J-1mJ & 300fs-10ps are Most Common and Ideal Parameter Regimes



New Applications based on Relativistic Intensities (10¹⁷ W/cm² – 10²⁰ W/cm²) and/or 10s of fs Pulse Durations



Brenner et.al. <https://doi.org/10.1088/0741-3335/58/1/014039>
Malka <https://doi.org/10.5170/CERN-2016-001.1>

27.10.2023

Motivation for ever Shorter Pulses of Ultrafast Lasers

Reach Relativistic Intensities

New Applications based on Relativistic Intensities ($10^{17} \text{ W/cm}^2 - 10^{20} \text{ W/cm}^2$) and/or 10s of fs Pulse Durations

Generation of X-Ray-, Electron-, Proton- and Neutron- Radiation



The diagram shows a cross-section of a target. A green elliptical region represents the target material. A blue arrow labeled "laser" points towards the target. Inside the target, a green circle represents a plasma wave, and several green arrows labeled "electrons" indicate their motion. A blue arrow labeled "proton" points away from the target. The text "Generation of X-Ray-, Electron-, Proton- and Neutron- Radiation" is at the top, and "Why now?" is prominently displayed in large white letters across the center.

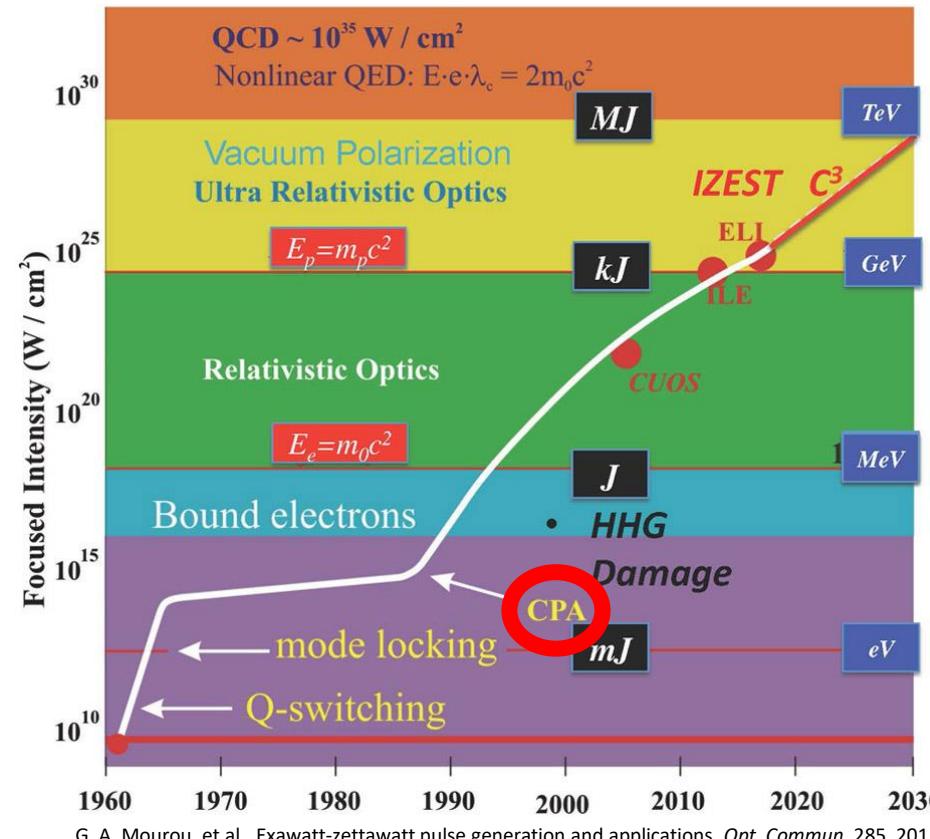
Example Calculation

$$I = 5 \cdot 10^{18} \text{ W/cm}^2 @ 2w_0 = 10 \mu\text{m} \Rightarrow P_{\text{Peak}} \sim 4 \text{ TW}$$
$$\Rightarrow P_{\text{Peak}} * \tau = 4 \text{ TW} * \underline{50 \text{ fs}} = \underline{200 \text{ mJ}}$$


Historical Development of Achieved Laser-Intensities

Towards Laser-Driven Secondary Sources

Solid-State Laser Technology has achieved technical maturity and price attractiveness to generate laser pulse energies which can provide **extreme electrical field strengths**.



G. A. Mourou, et.al., Exawatt-zettawatt pulse generation and applications, *Opt. Commun.* 285, 2011



State of the Art of High-Peak-Power Laser Systems

Titanium-Doped Sapphire

Pulse energy: 42J

Pulse length: 40fs

Peak power >1PW

Repetition rate: 1Hz

**Efficiency: 42W out for
130kW input: 0.03%**



Scientific Ultrashort Pulse Portfolio

Further Pulse Shortening to Economically Reach High Peak Powers



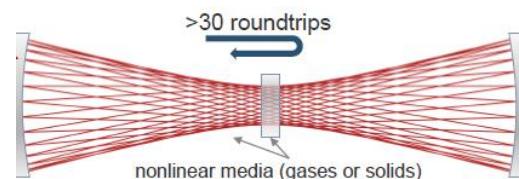
Fiber:
Ytterbium-1
1mJ, 100W, 2



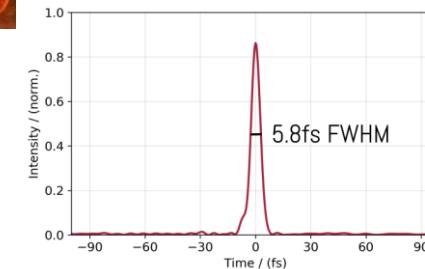
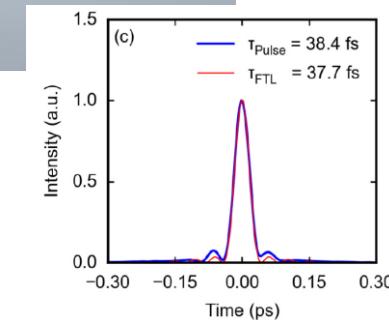
Member of the TRUMPF Group

10GW \Rightarrow 300GW

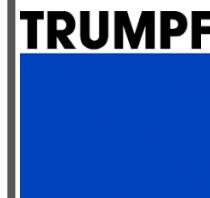
5GW \Rightarrow 100GW



>10-fold temporal compression:



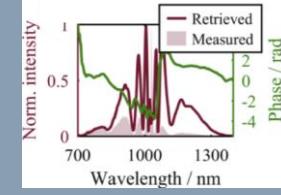
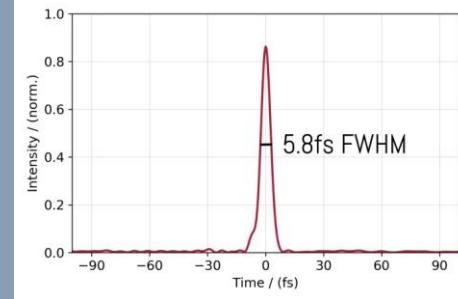
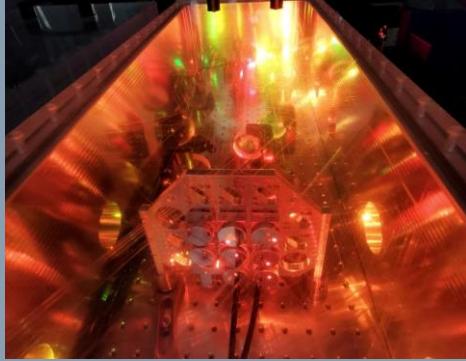
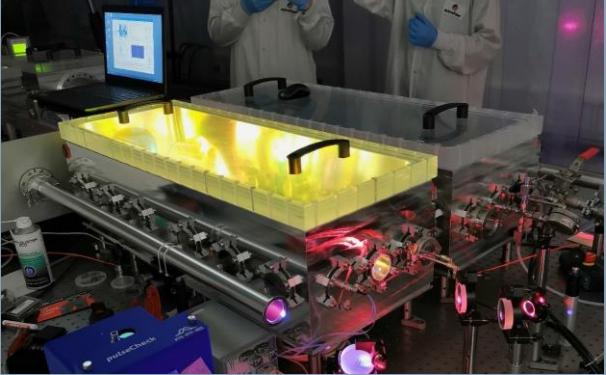
Thin disk:
Dura 1000-5
J, 1000W, 500fs



Serving the Scientific Community with Leading Edge Parameters

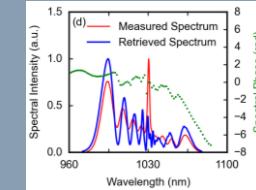
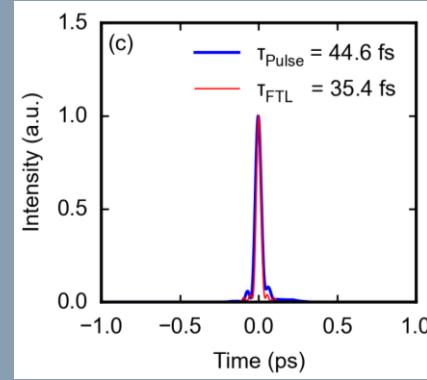
Record MPC-based Nonlinear Pulse Compression

Shortest Pulses



5.8fs | 1mJ | 100W

Highest Energies



200mJ | 45fs | 1000W

Agenda

01 TRUMPF Group & Business Center Lasers

02 Secondary Sources Initiative @TRUMPF

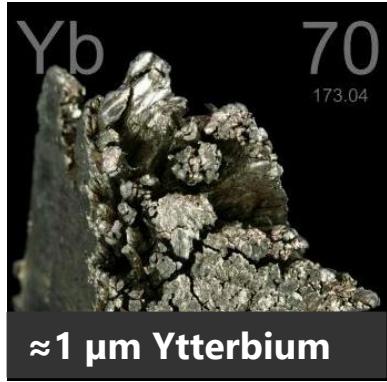
03 Building Blocks of Solid-State Laser-Drivers

03.1 Motivation for Parameter Range

03.2 2µm Laser Sources

03.3 DPSSL - Technological Platforms

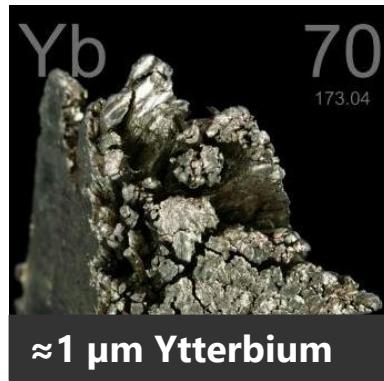
Ultrafast Solid State Lasers: Yb -> Tm



Properties of Ytterbium (Yb)-doped Active Media:

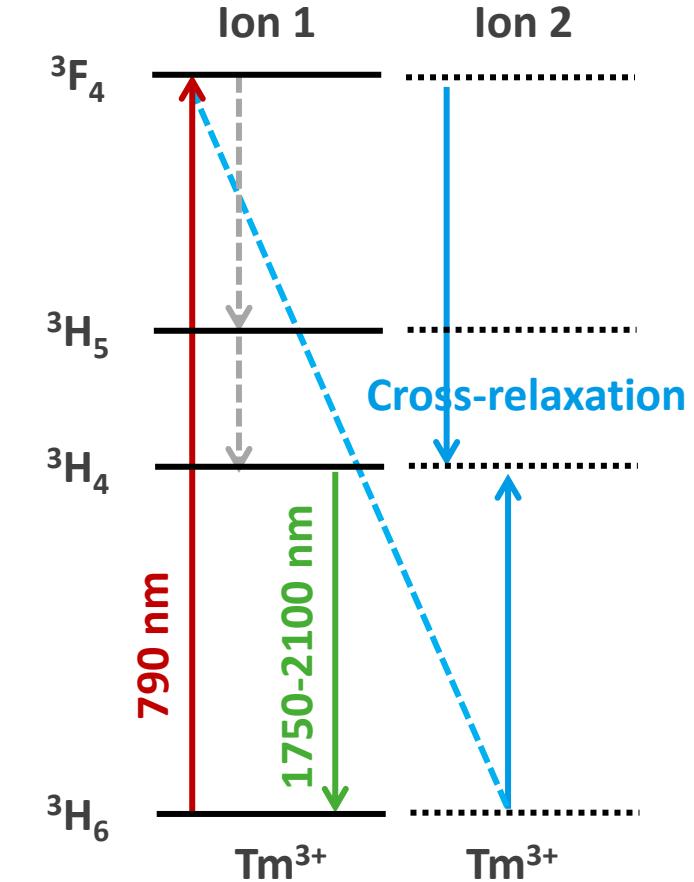
- Central Wavelength 1030nm
- Amplification Bandwidth support Multi-100fs Pulse Duration
- Quantum-Defect and Quantum-Efficiency >90%
- Pumping in 900-1000nm Spectral Range (typ. 940nm Laser Diodes)

Ultrafast Thulium Doped Fiber Lasers (TDFL)



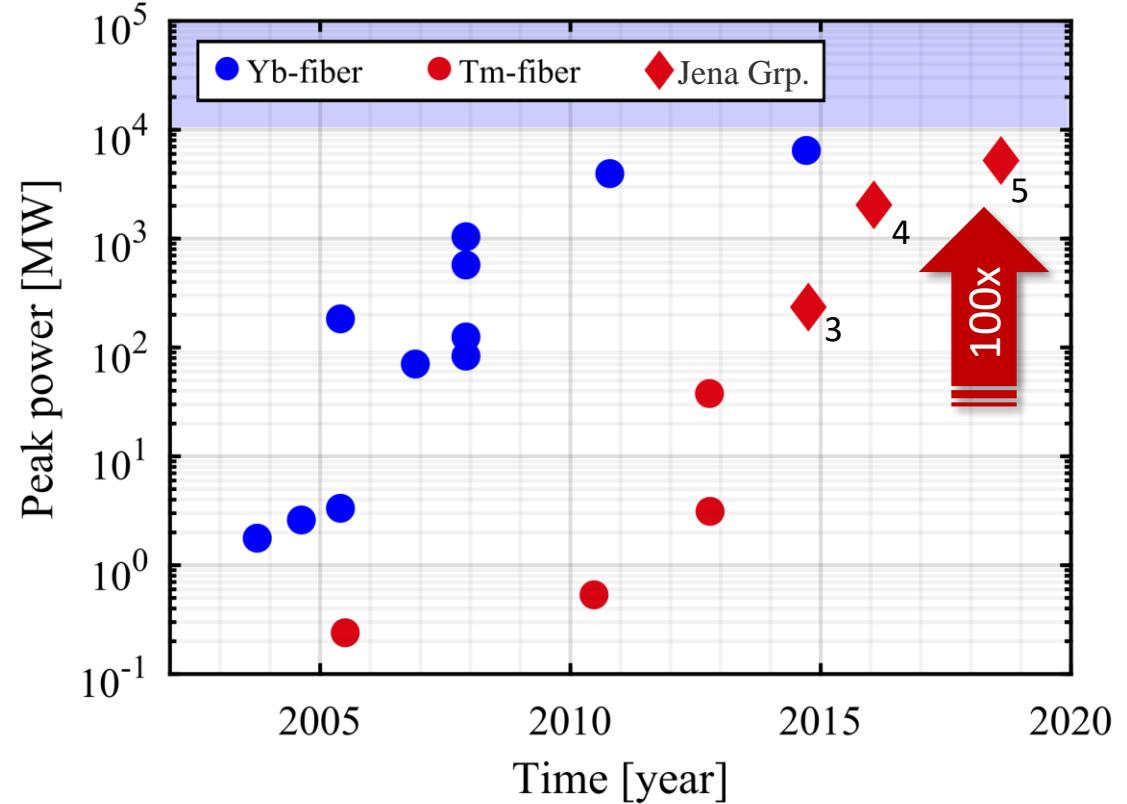
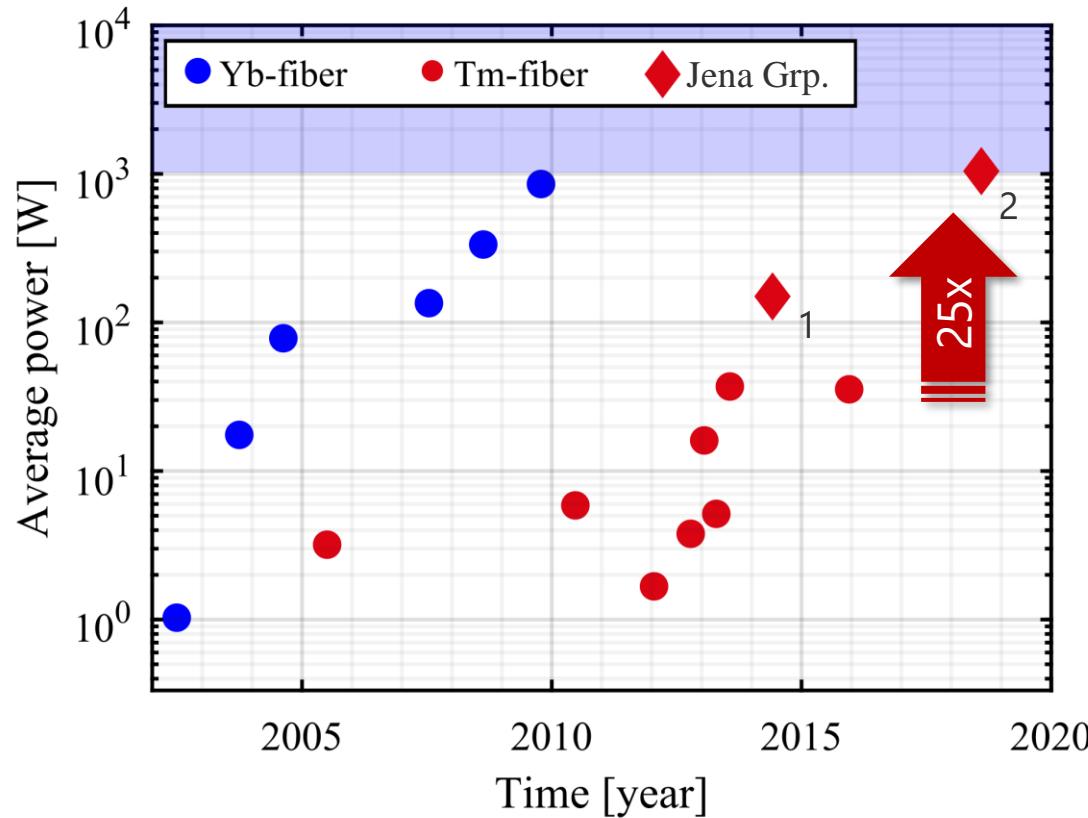
Properties of Thulium(Tm)-doped Fused Silica:

- 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% efficiency¹



[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).

From 1 μ m to 2 μ m - Development Status In Ultrafast Fiber Lasers



[1] F. Stutzki, C. Gaida et al., Opt. Lett. **39**, 4671–4 (2014).

[2] C. Gaida et al., Opt. Lett. **43**, 5853–5856 (2018)

[3] F. Stutzki, C. Gaida et al., Opt. Lett. **40**, 9–12 (2015).

[4] C. Gaida et al., Opt. Lett. **41**, 4130–4133 (2016).

[5] C. Gaida et al., in *Laser Congress 2017 (ASSL, LAC)*, p. ATH3A.5.

Ultrafast Thulium Fiber Laser for Research (1st generation)

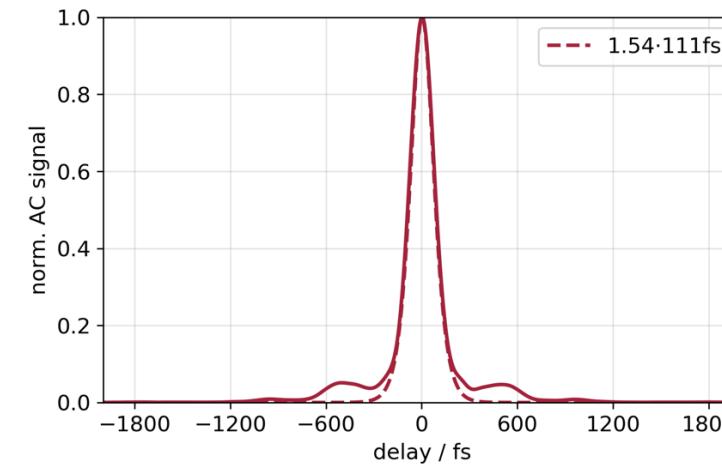
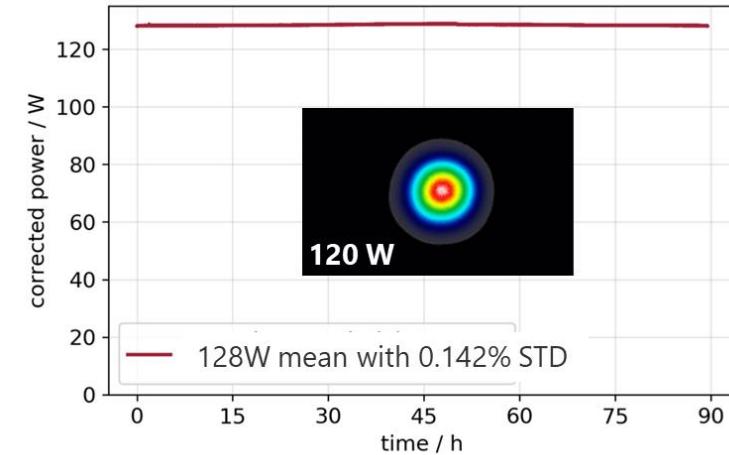
4-channel Tm-based System

1950nm center wavelength

>120W Average Power

>200μJ Pulse Energy

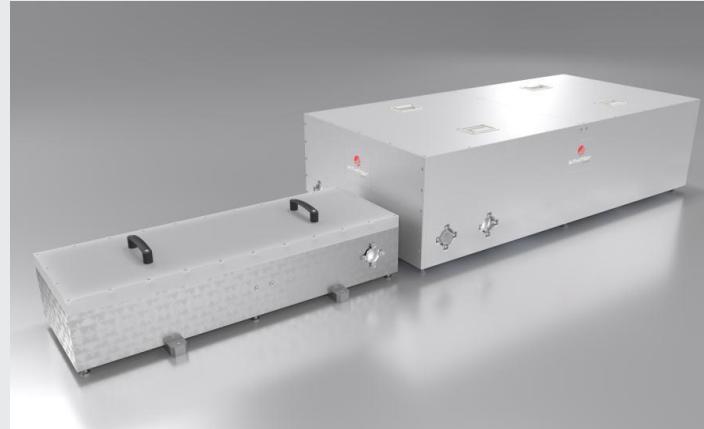
<150fs Pulse Duration



Product Platforms for Thulium-based Fiber Lasers

Coherent-combining-based & highly customizable

Thulium-300



1950nm | 2mJ | 200W | 150fs

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

Thulium-30



1980nm | 100 μ J | 40W | 400fs

- Compact & affordable
- Industrial-grade reliability

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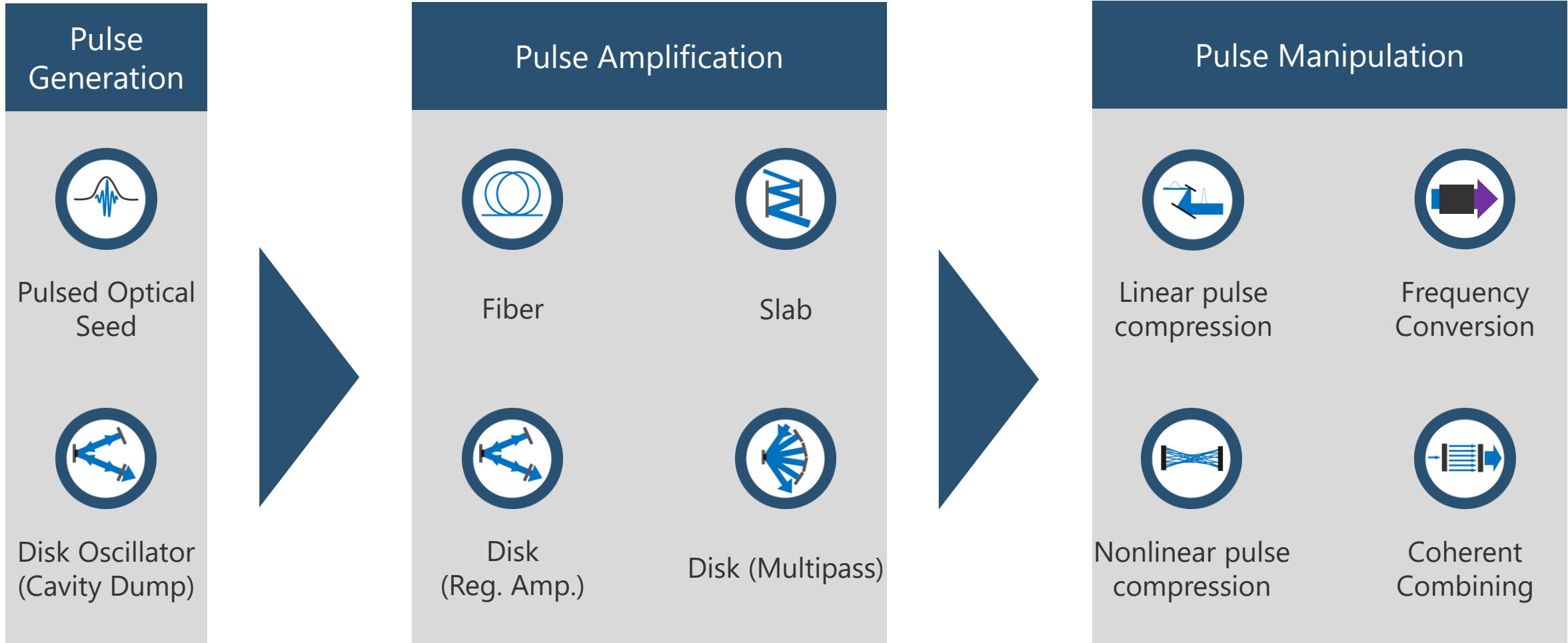
03.1 Motivation for Parameter Range

03.2 2µm Laser Sources

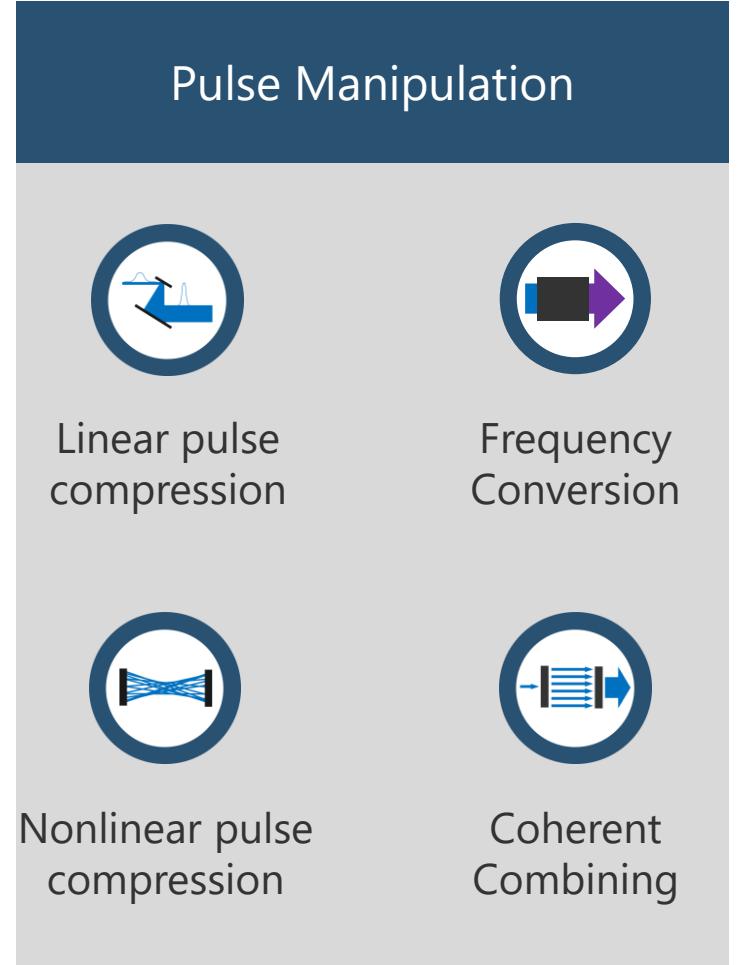
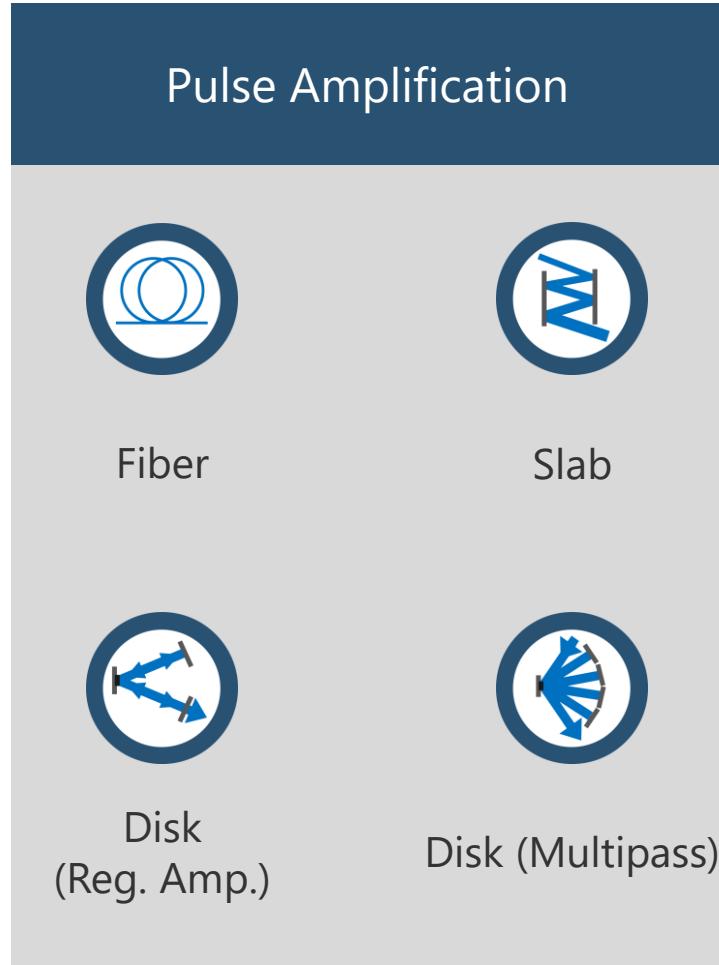
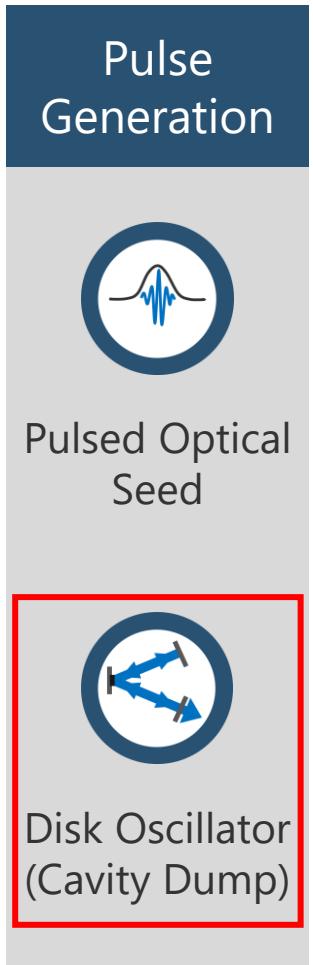
03.3 DPSSL - Technological Platforms

Solid State Lasers - Technological Building Blocks at TRUMPF

1µm Wavelength



Solid State Lasers - Technological Building Blocks at TRUMPF



Solid State Lasers - Technological Building Blocks at TRUMPF

Robust and Reliable Short Pulse at Multi-kW Level

Pulsed Optical Seed



TruMicro 7000



Fiber



InnoSlab



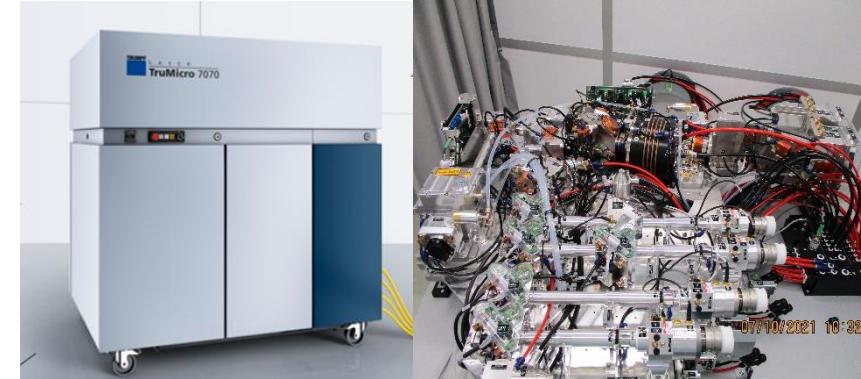
RegAmp-DISK



CavityDump-DISK

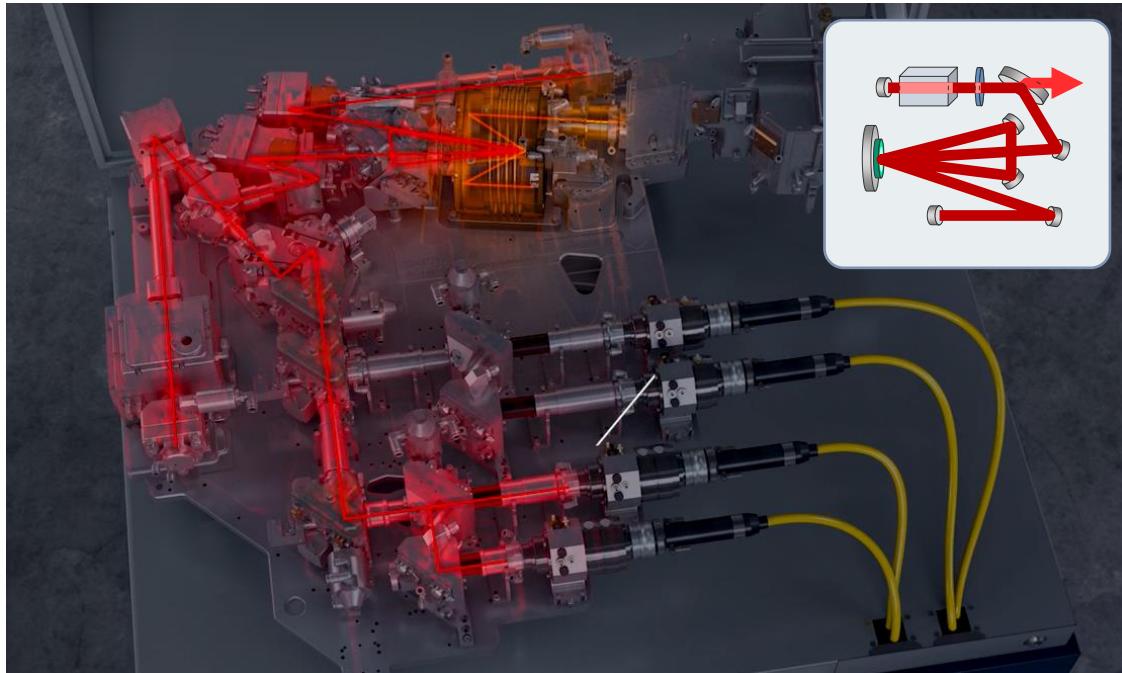


MultiPass-DISK



Industrial solution

- Fiber Coupled (Multimode)
- Wavelength 1030nm
- Pulse duration 30ns
- Average Power 2000W
- Pulse Energy 100mJ



Solid State Lasers - Technological Building Blocks at TRUMPF

kW Operation in the Green

Pulsed Optical Seed



TruMicro 7000



Industrial solution

Fiber



InnoSlab



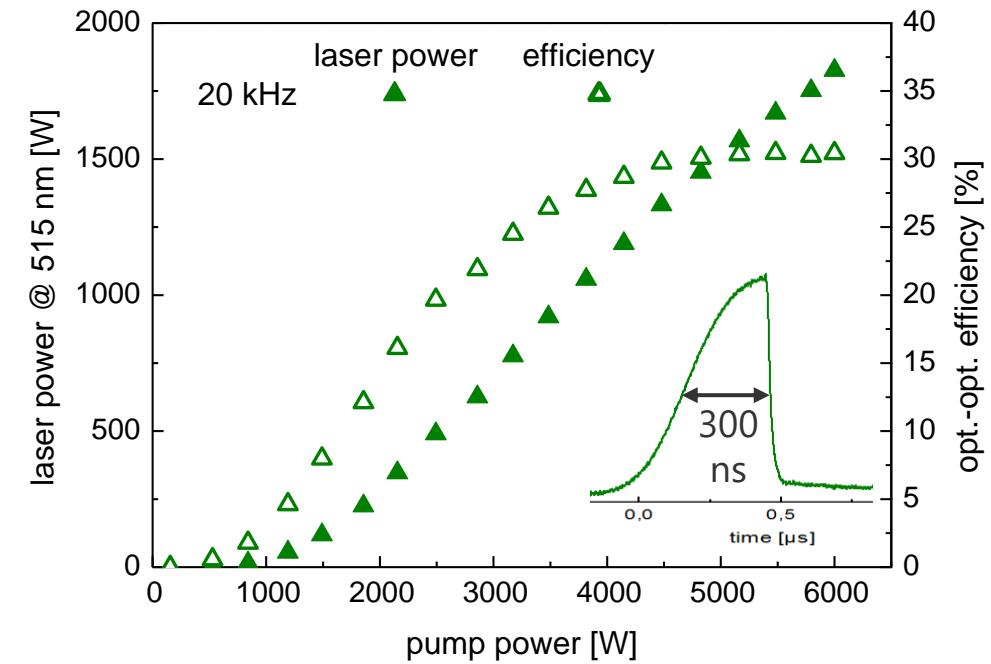
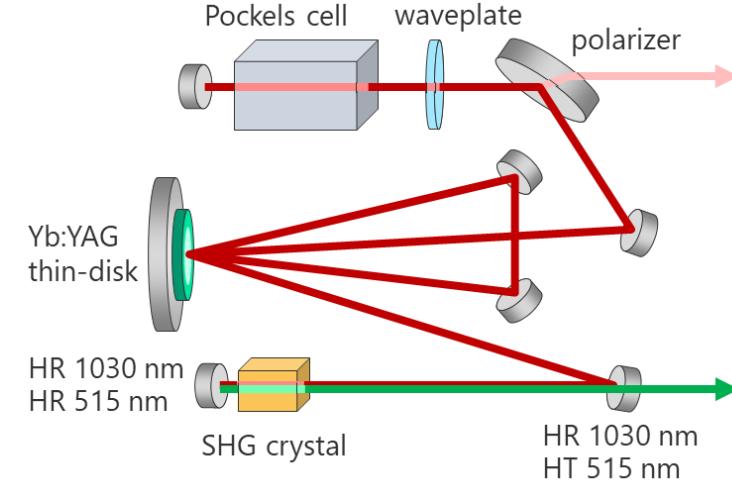
RegAmp-DISK



CavityDump-DISK

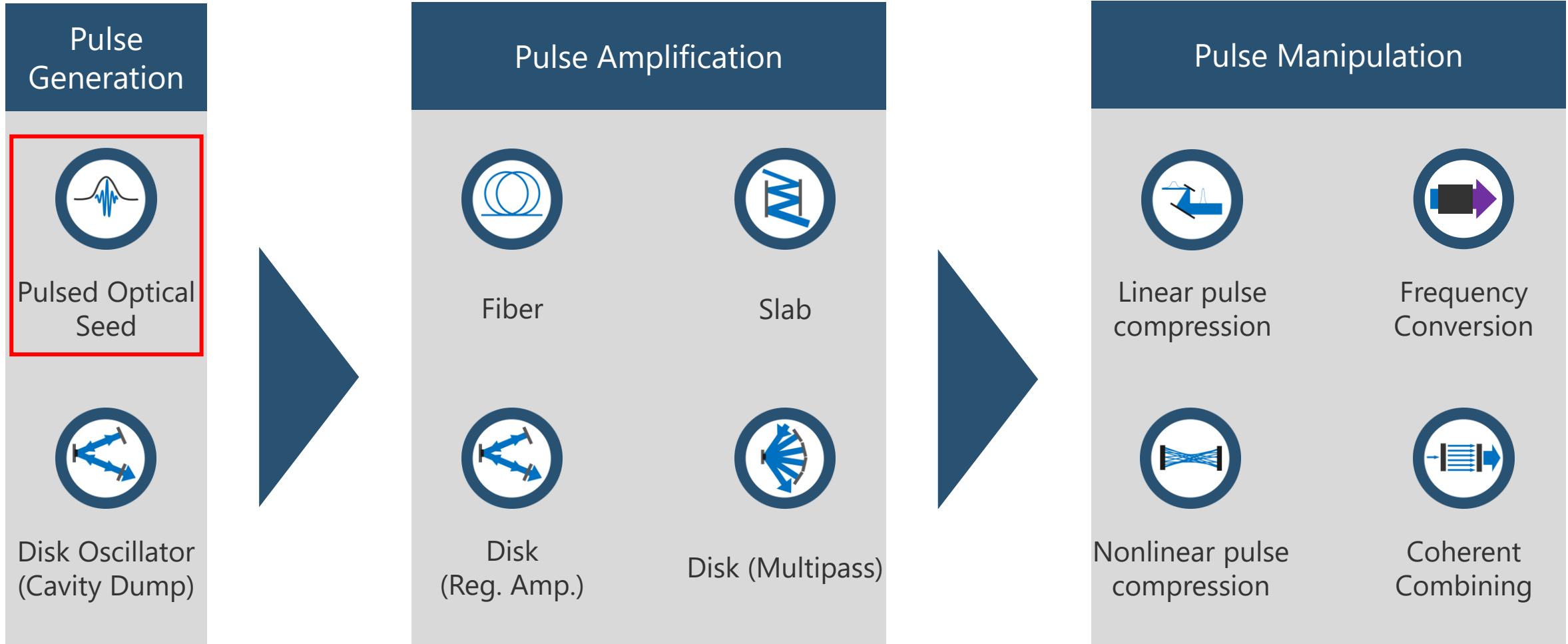


MultiPass-DISK



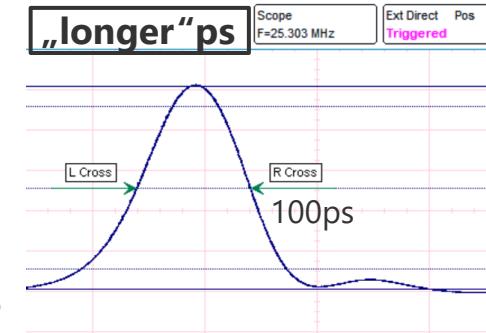
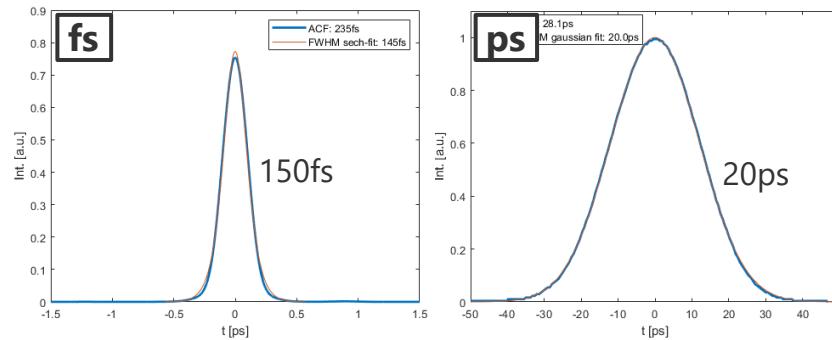
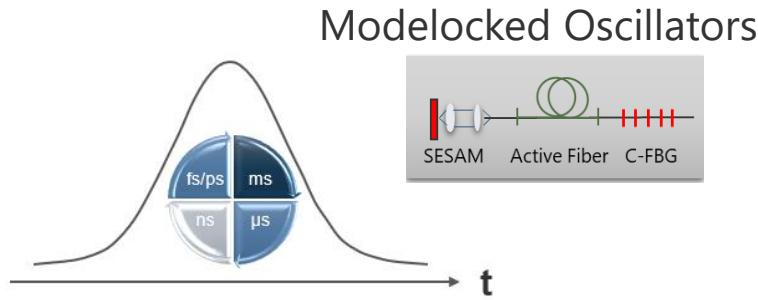
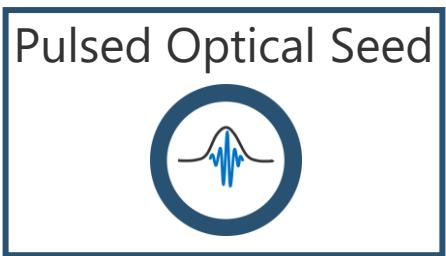
Solid State Lasers - Technological Building Blocks at TRUMPF

Master Oscillator Power Amplifier (MOPA) Chain



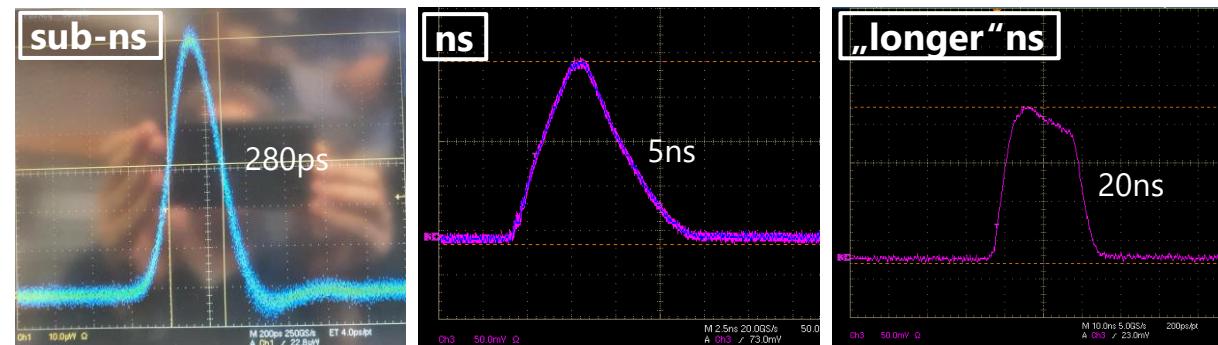
Solid State Lasers - Technological Building Blocks at TRUMPF

Determination of Time Structure



• • •

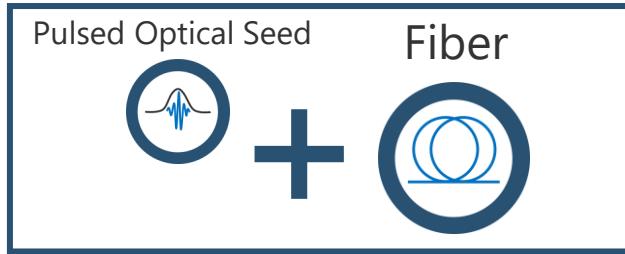
Gain-Switched Diodes



• • •

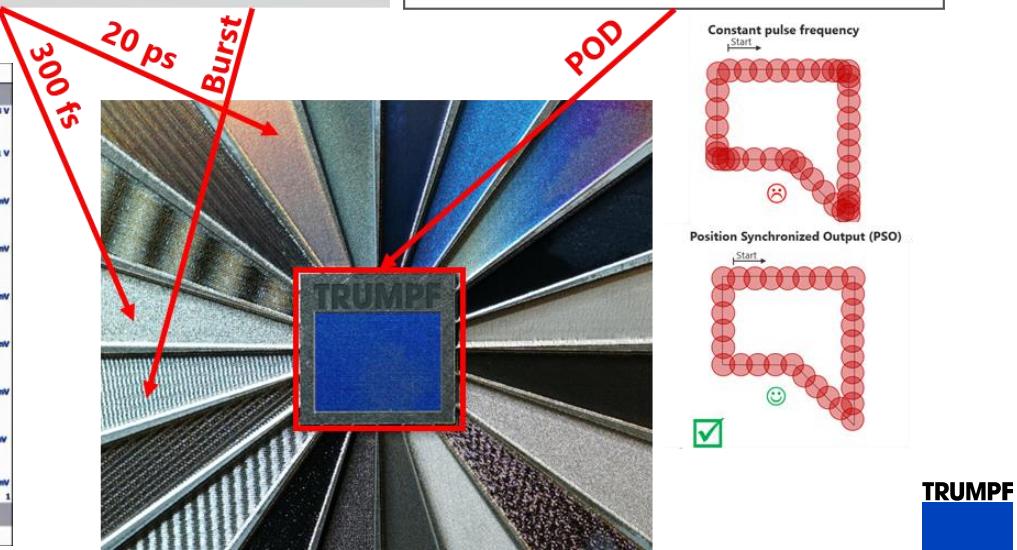
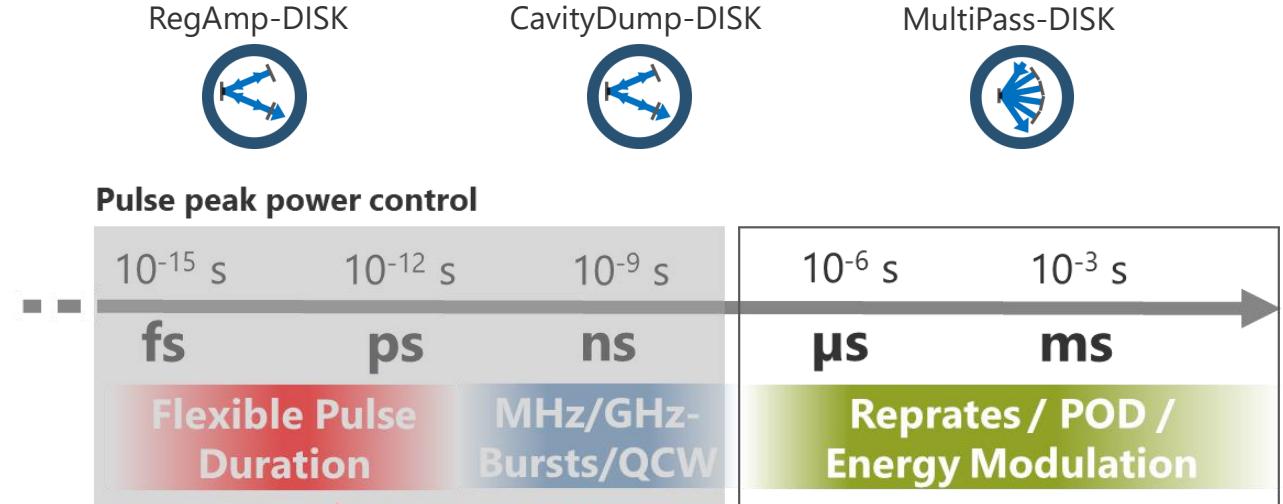
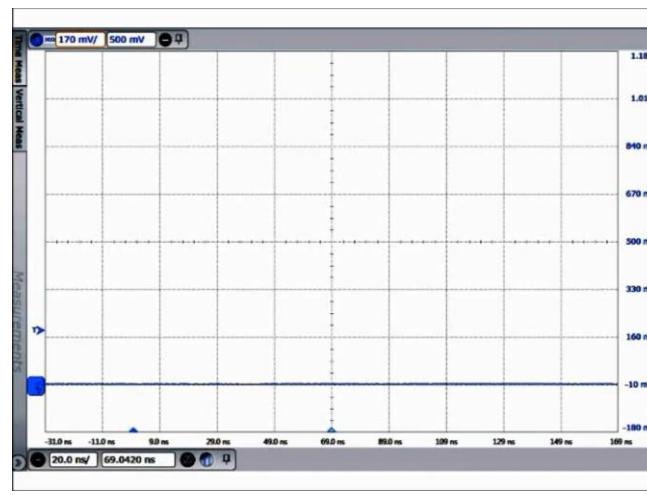
Solid State Lasers - Technological Building Blocks at TRUMPF

Fast Switching on Multiple Time Scales

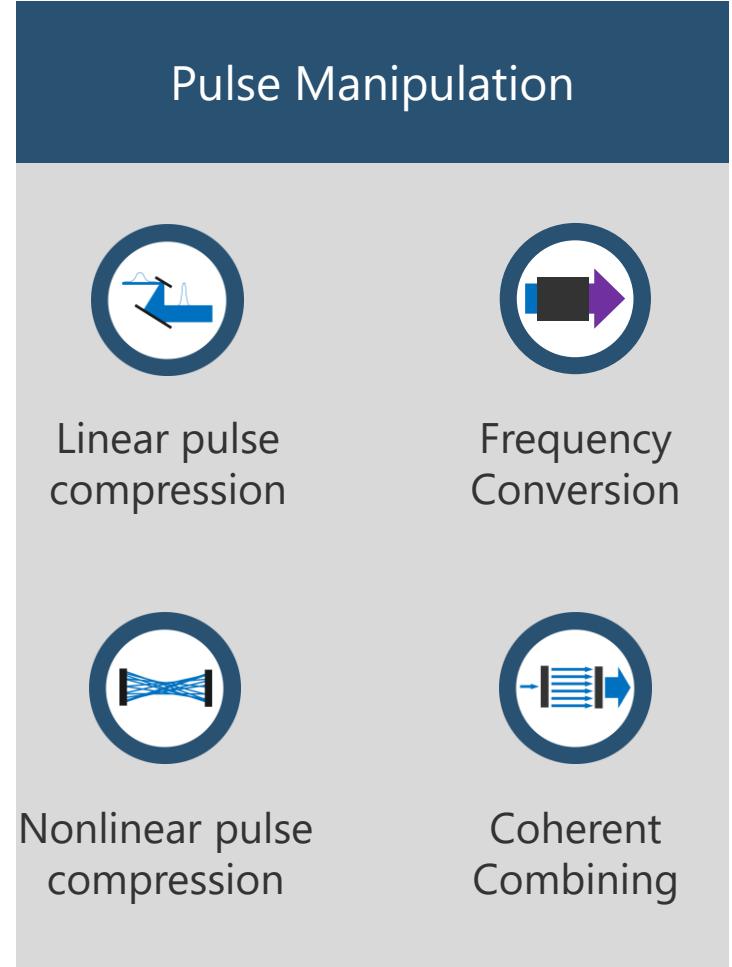
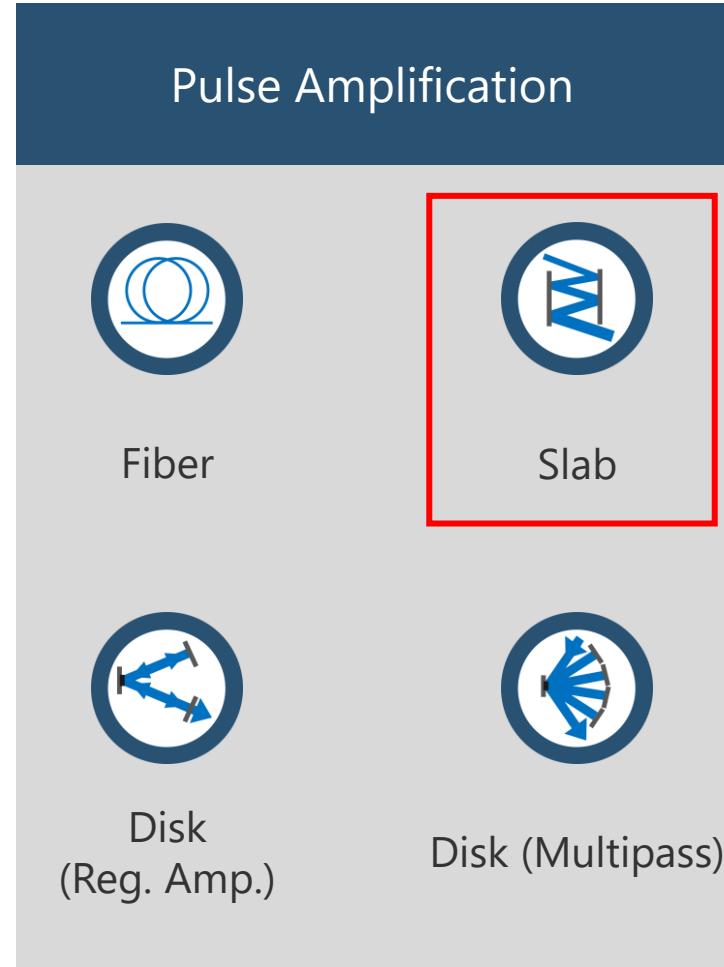
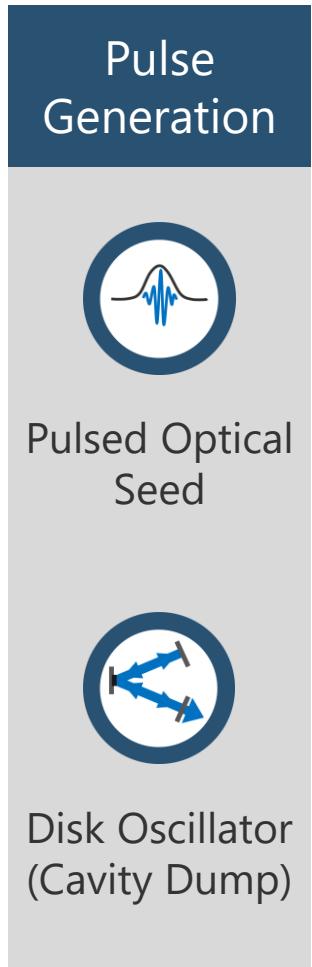


Industrial solution

- Wavelength 1030nm
- Bandwidth 8nm
- Pulse duration 300fs
- Average Power >20W
- Pulse Energy >20μJ

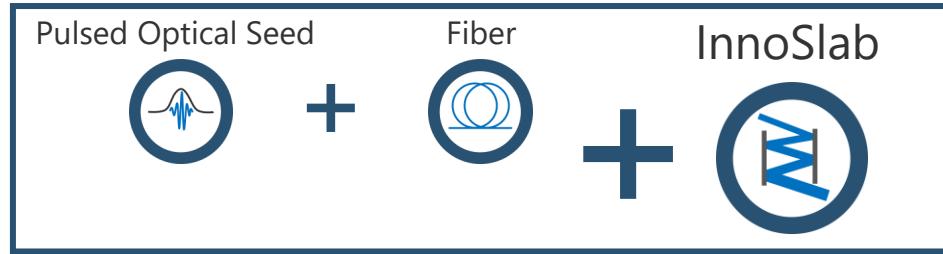


Solid State Lasers - Technological Building Blocks at TRUMPF



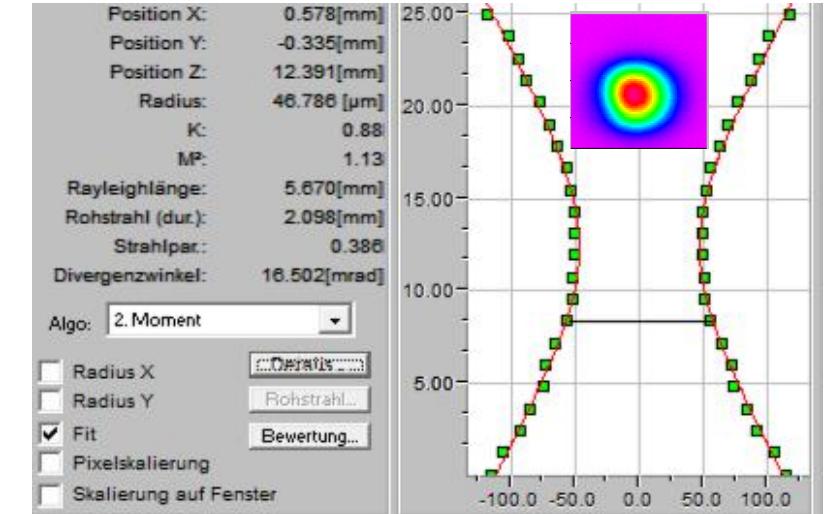
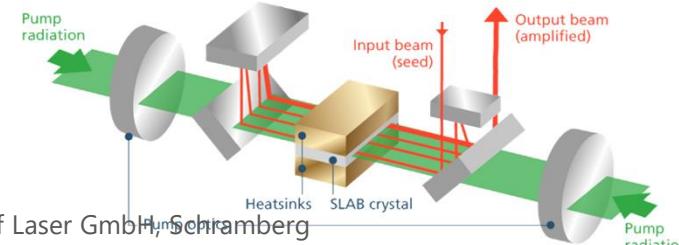
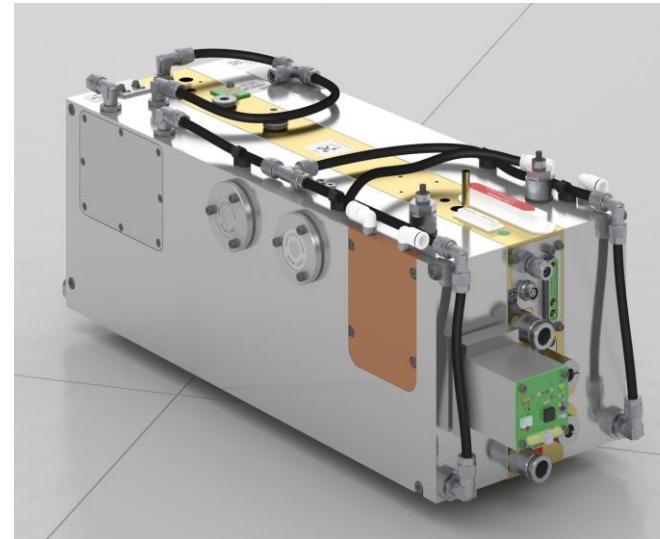
Solid State Lasers - Technological Building Blocks at TRUMPF

High Gain into Multi-mJ- & Multi-100W- Regime



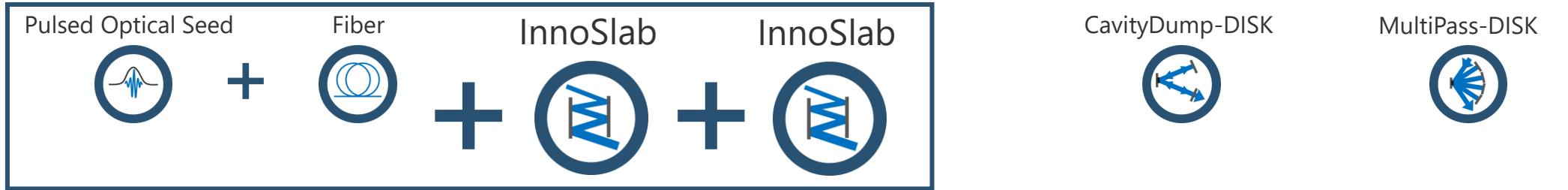
Industrial solution

- Wavelength 1030nm
- Bandwidth 2nm
- Pulse duration 850fs
- Average Power 200W
- Pulse Energy 2mJ



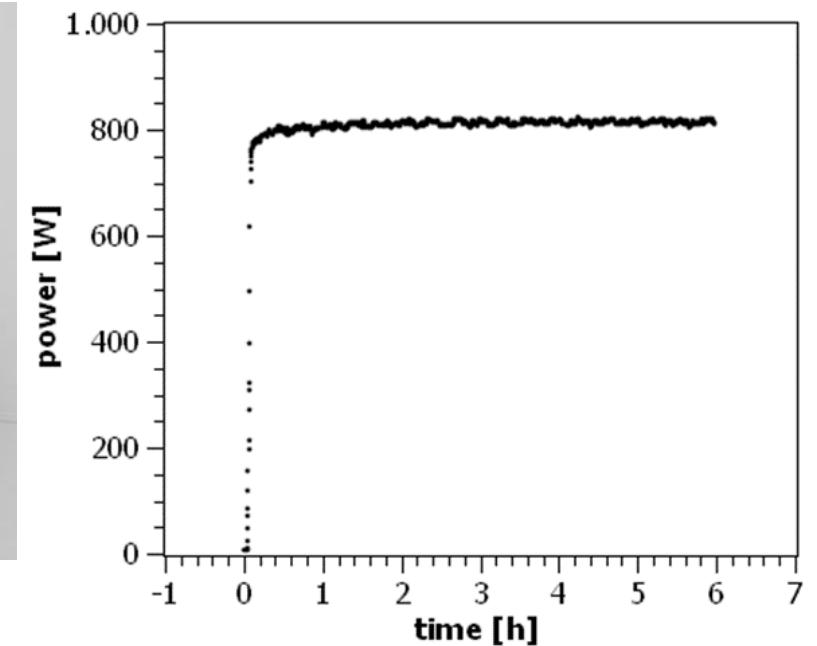
Solid State Lasers - Technological Building Blocks at TRUMPF

„Just“ Adding Average Power

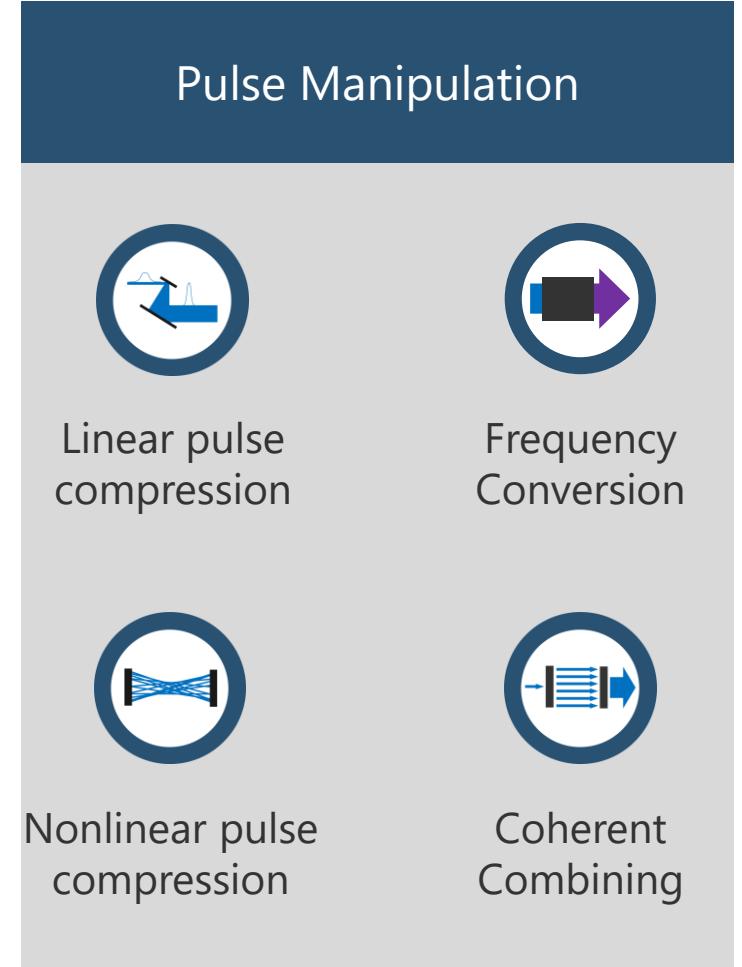
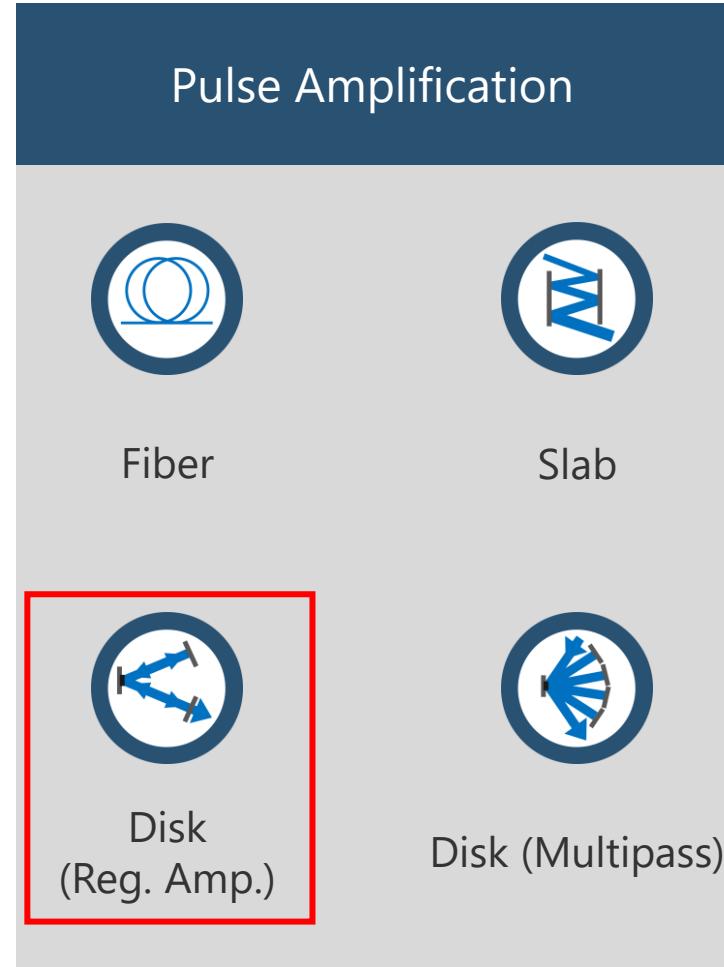
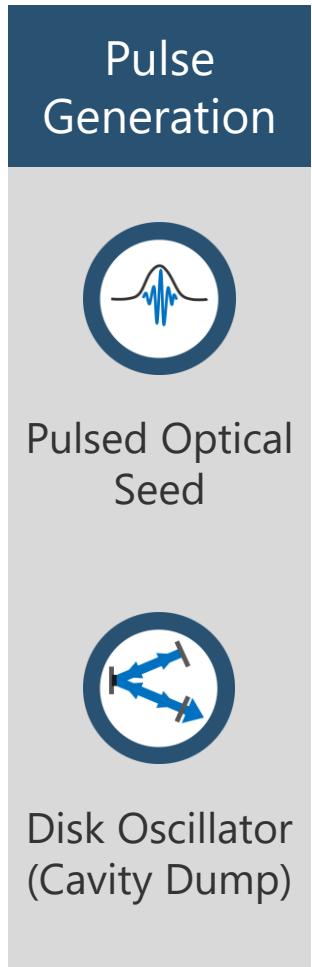


Industrial solution

• Wavelength	1030nm
• Bandwidth	2nm
• Pulse duration	850fs
• Average Power	200W
• Pulse Energy	2mJ

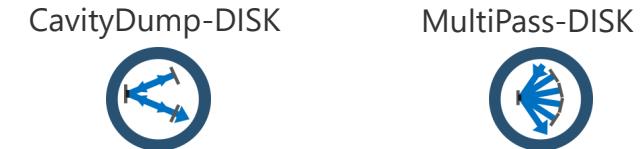
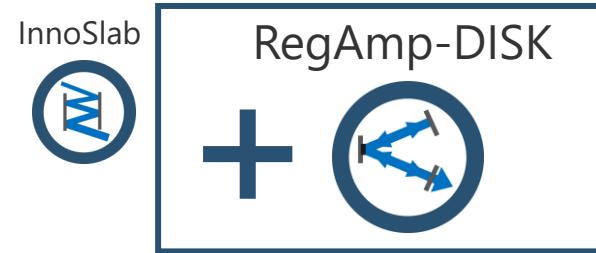
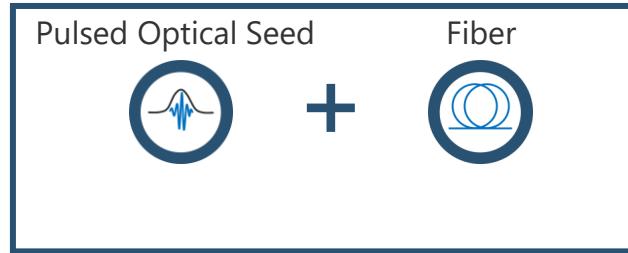


Solid State Lasers - Technological Building Blocks at TRUMPF



Solid State Lasers - Technological Building Blocks at TRUMPF

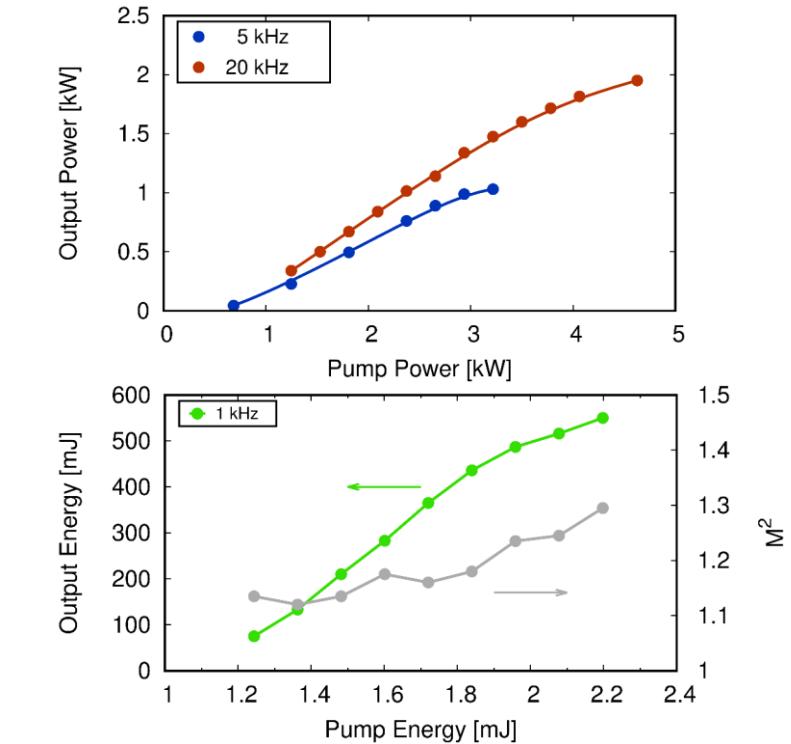
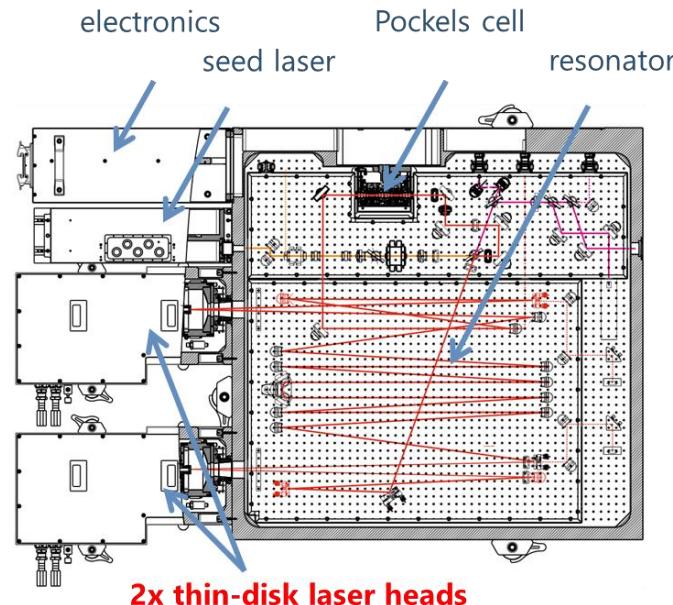
Pulse Energies into Multi-100mJ Regime



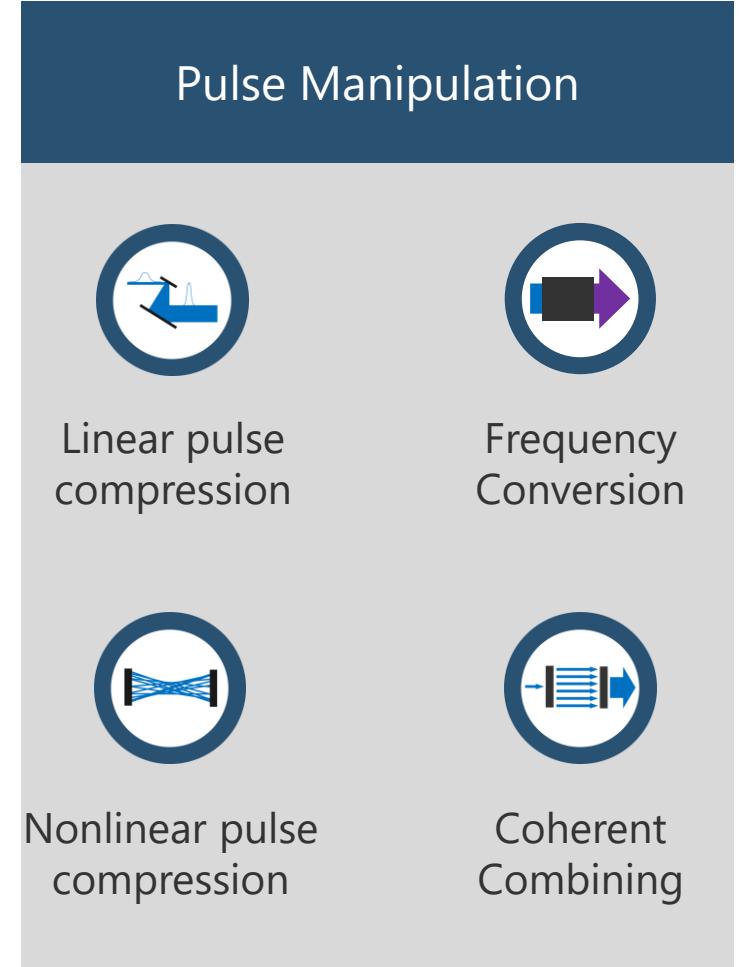
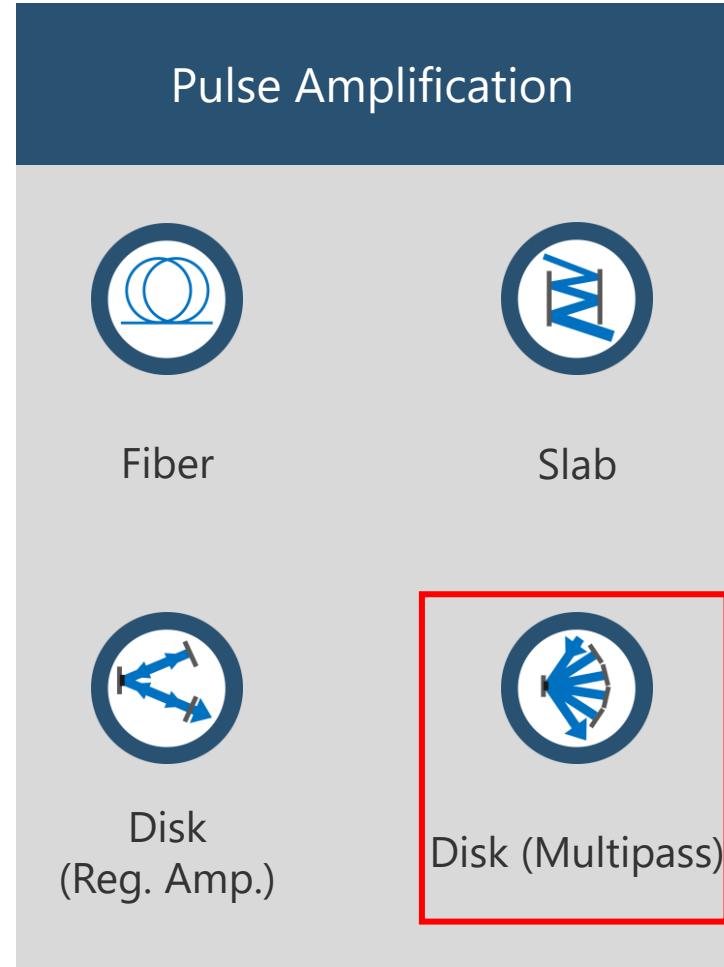
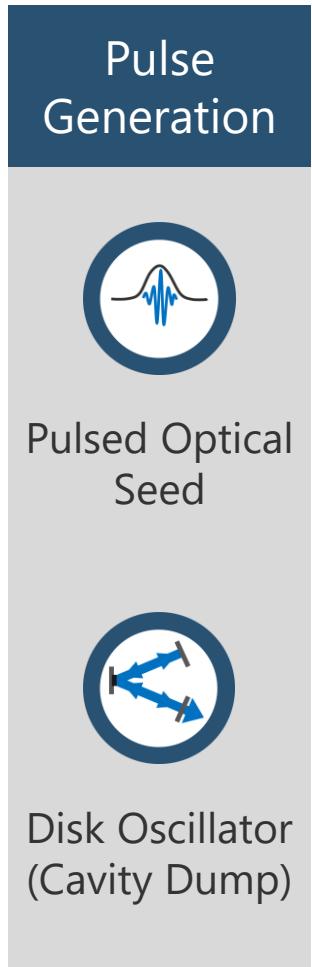
Solution for Science

- Wavelength
- Pulse duration
- Average Power
- Pulse Energy

1030nm
<500fs
1000W
200mJ



Solid State Lasers - Technological Building Blocks at TRUMPF



Solid State Lasers - Technological Building Blocks at TRUMPF

>10kW Regime and GW Peak Power Operation

Pulsed Optical Seed



Fiber



InnoSlab



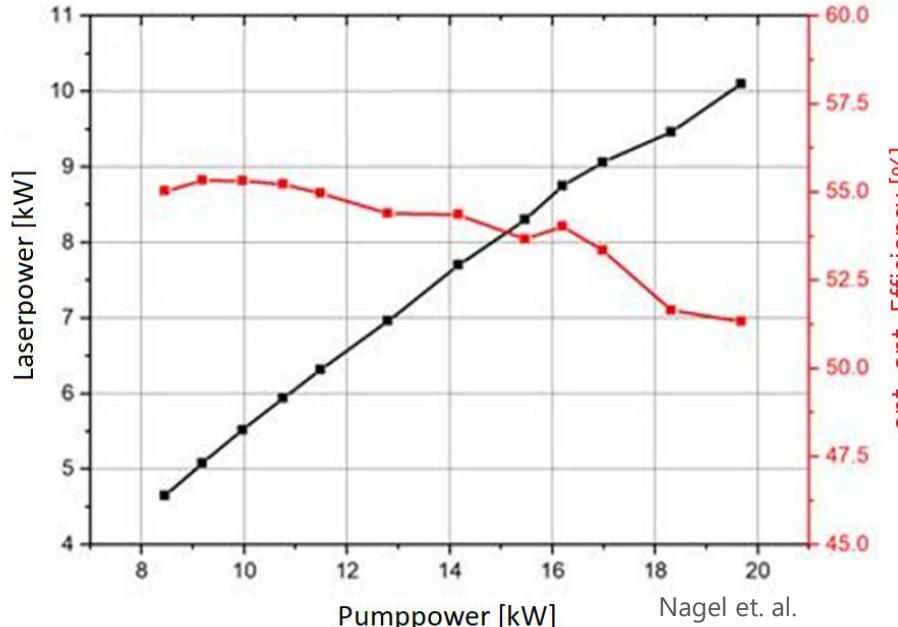
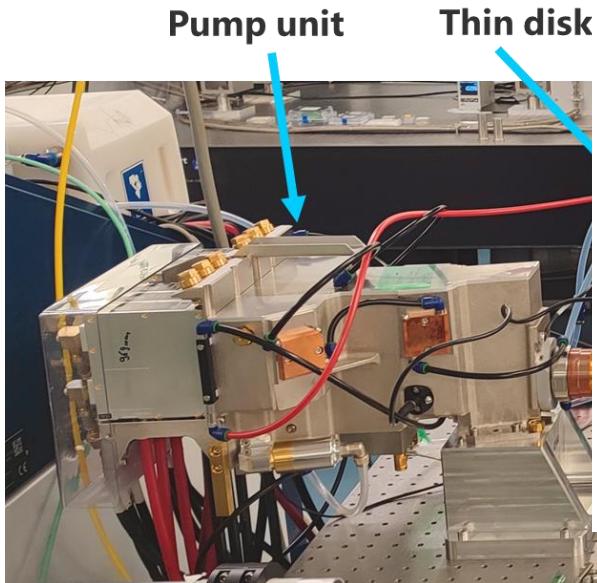
RegAmp-DISK



CavityDump-DISK



MultiPass-DISK

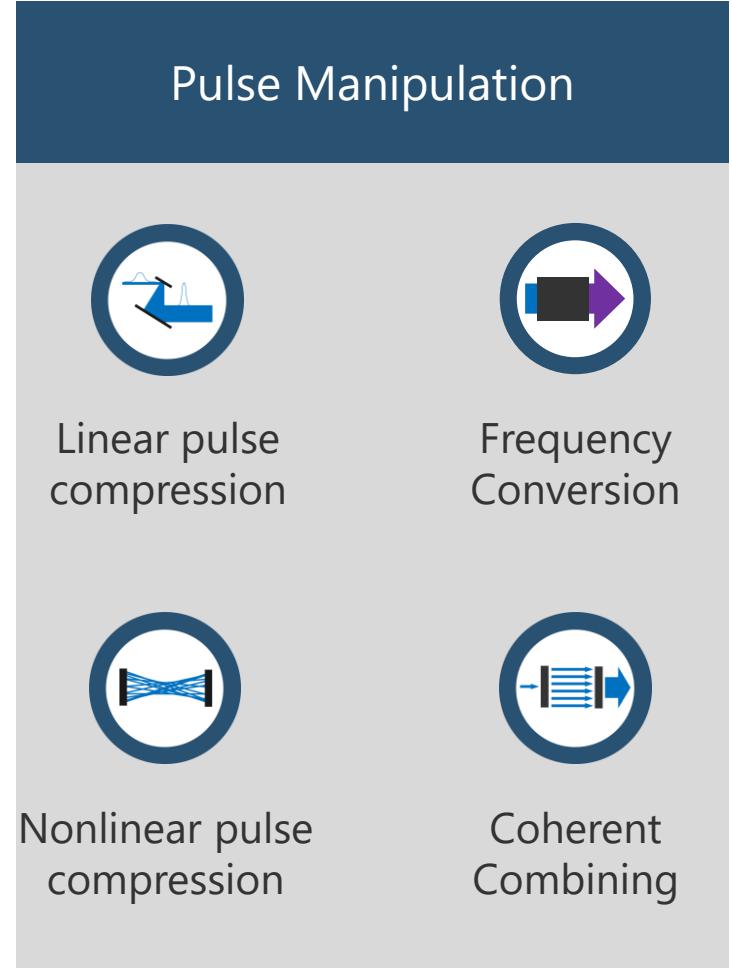
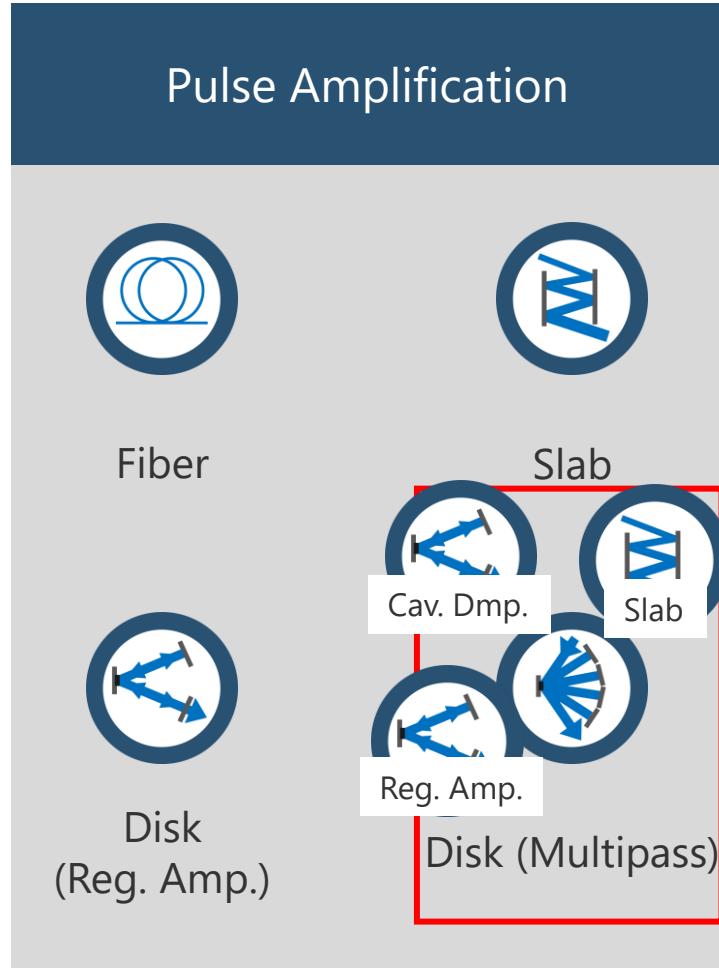
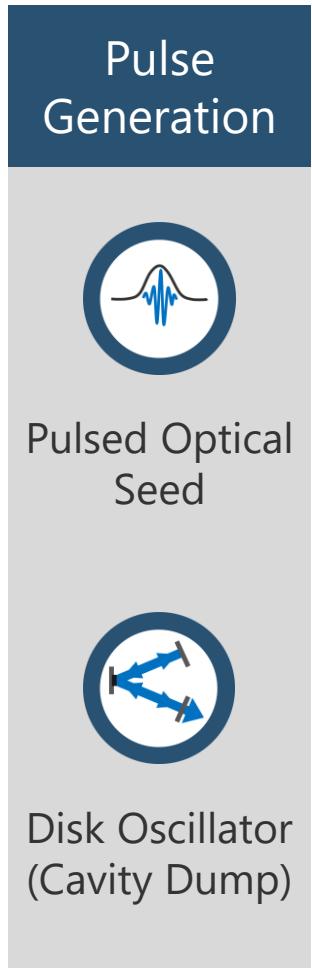


Pump head

Input beam



Solid State Lasers - Technological Building Blocks at TRUMPF



Solid State Lasers - Technological Building Blocks at TRUMPF

Highest Power and Stability in Short Pulse Regime

Pulsed Optical Seed



Fiber



InnoSlab



RegAmp-DISK



CavityDump-DISK

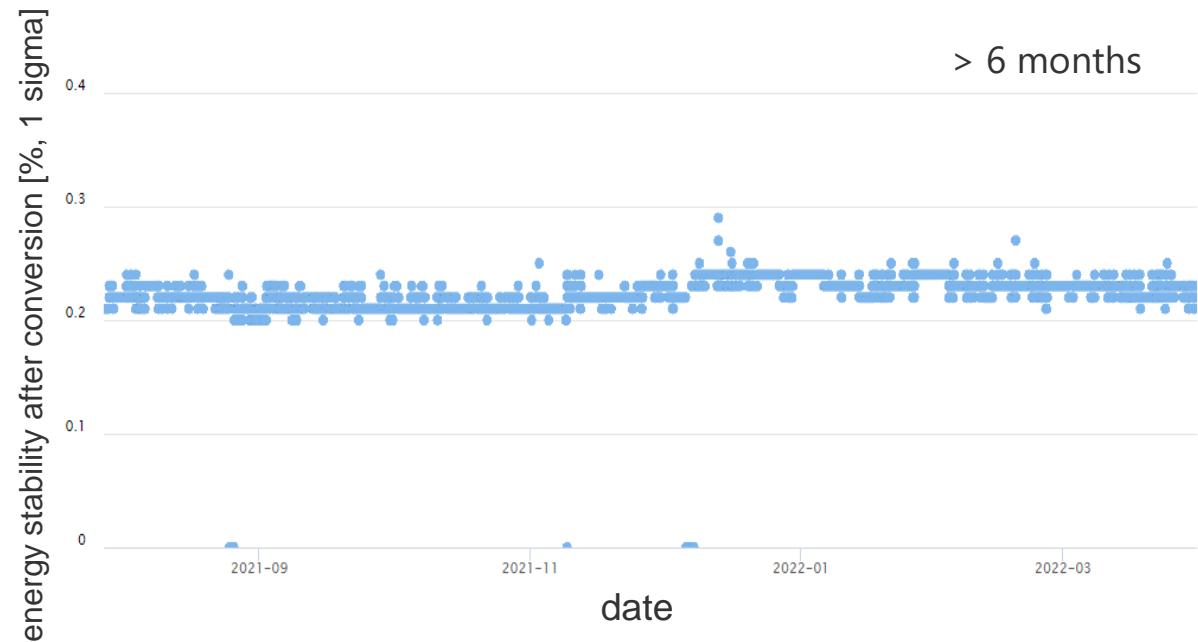


MultiPass-DISK



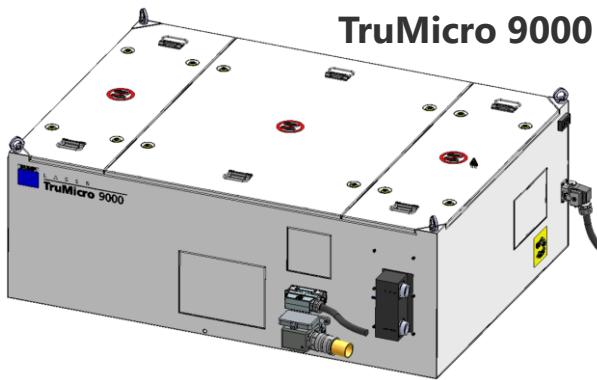
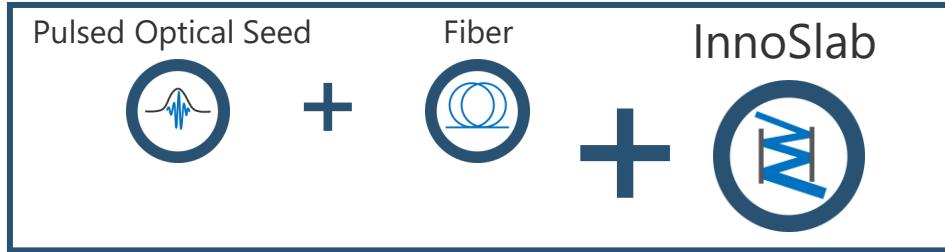
Industrial solution

- Wavelength 343nm
- Pulse duration 20ns
- Average Power 720W
- Pulse Energy 72mJ



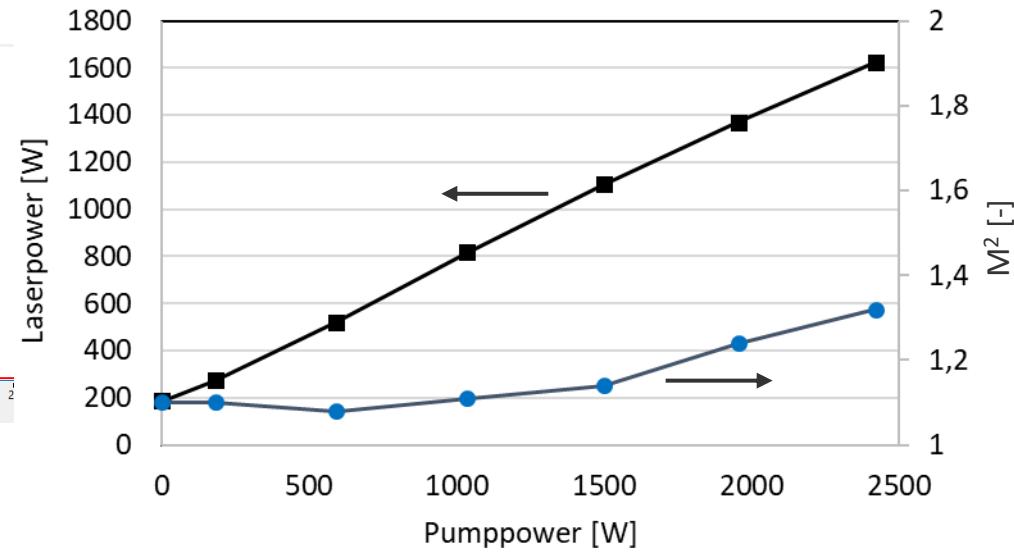
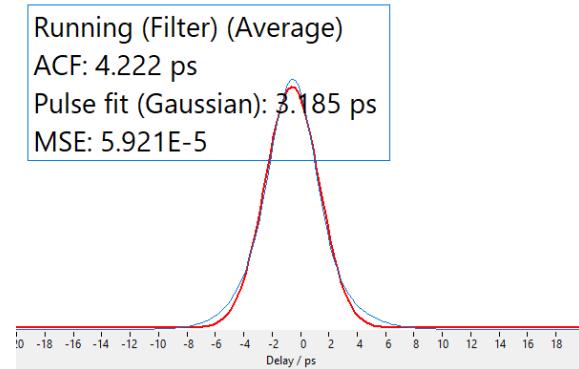
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The First kW-Class Femtosecond Laser for Industrial Applications



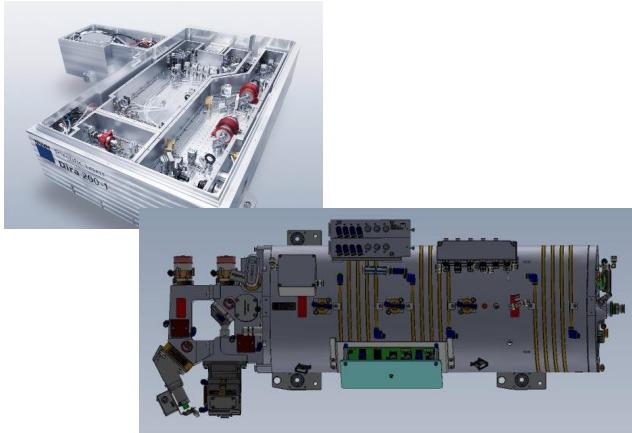
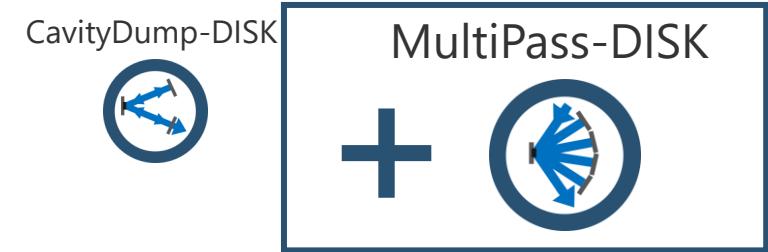
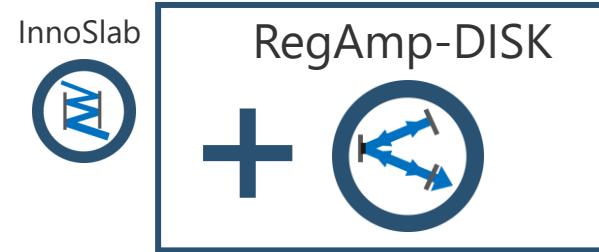
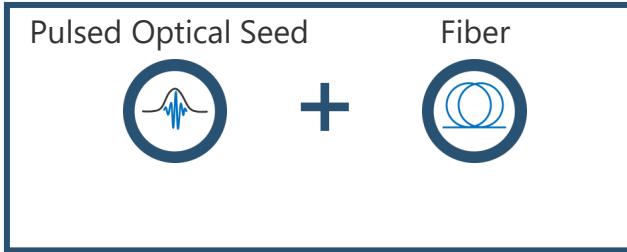
Ongoing Development

- Wavelength 1030nm
- Pulse duration <1ps
- Average Power 1000W
- Pulse Energy 10mJ



Solid State Lasers - Technological Building Blocks at TRUMPF

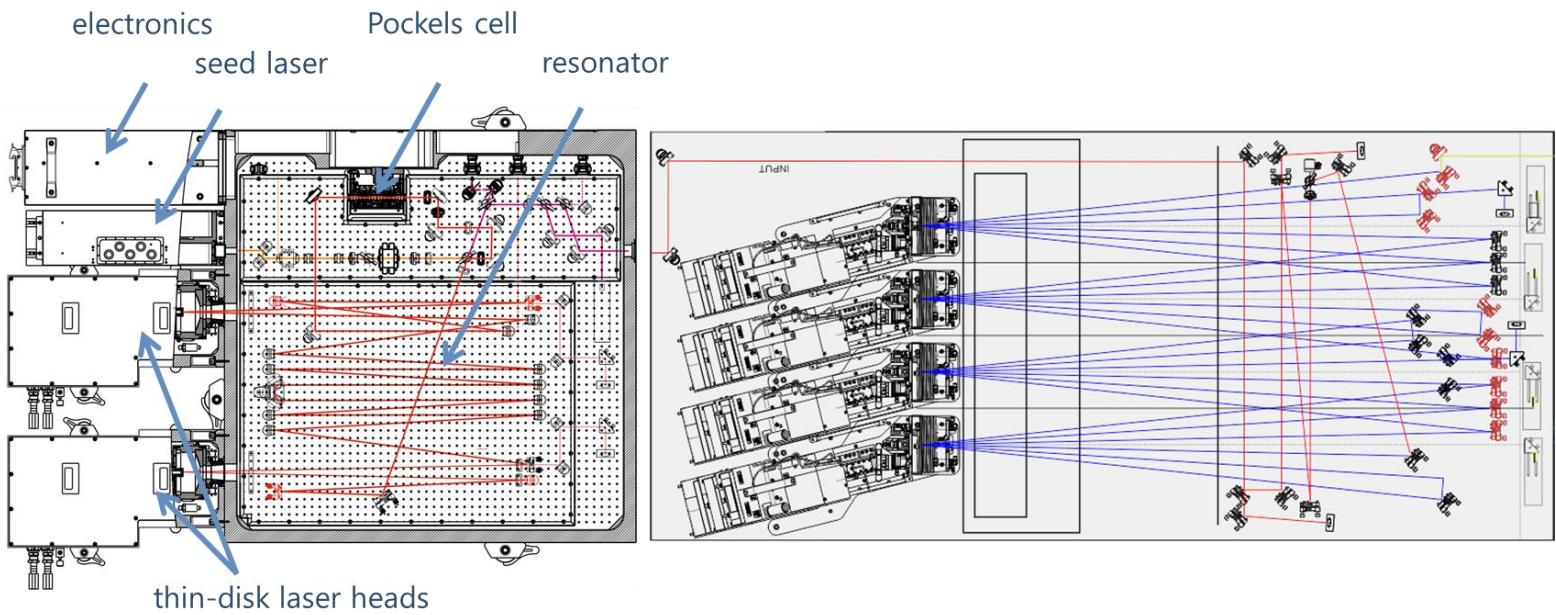
Joule- & kW-Class Ultrafast Laser



Solution for Science

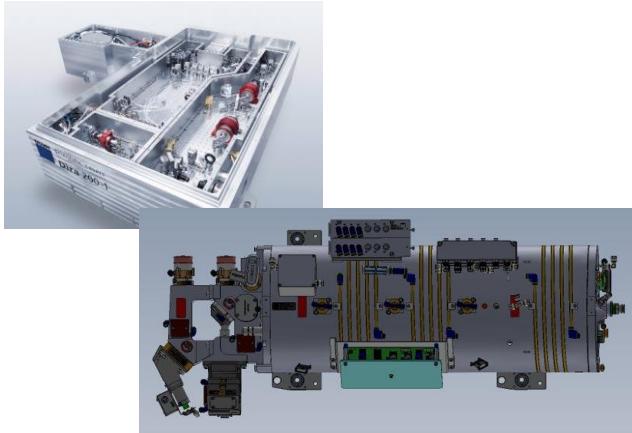
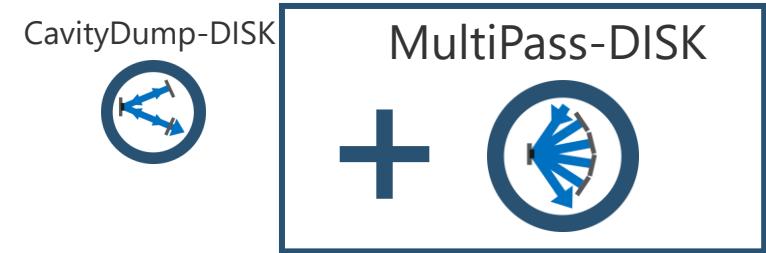
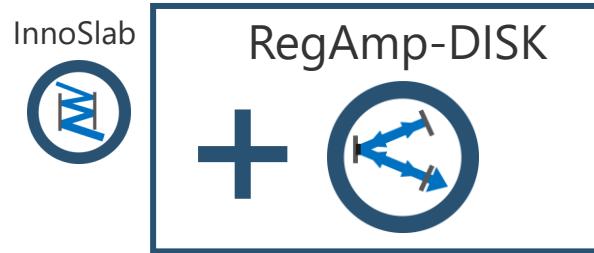
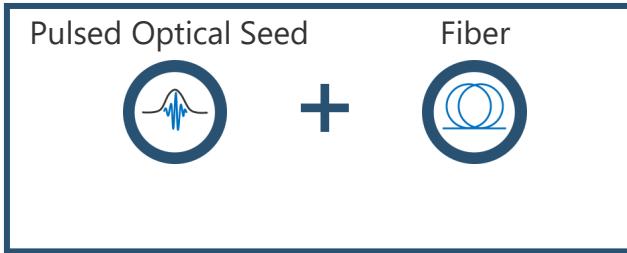
- Wavelength
- Pulse duration
- Average Power
- Pulse Energy

1030nm
<1ps
720W
720mJ



Solid State Lasers - Technological Building Blocks at TRUMPF

„Laser Lightning Rod“ Project



Solution for Science

- Wavelength 1030nm
- Pulse duration <1ps
- Average Power 720W
- Pulse Energy 720mJ

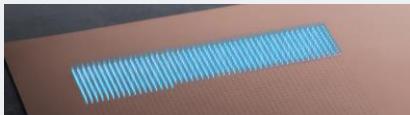


Wolf et. al.
DOI: 10.1038/s41566-022-01139-z



Unique Portfolio of Technology Building Blocks enable:

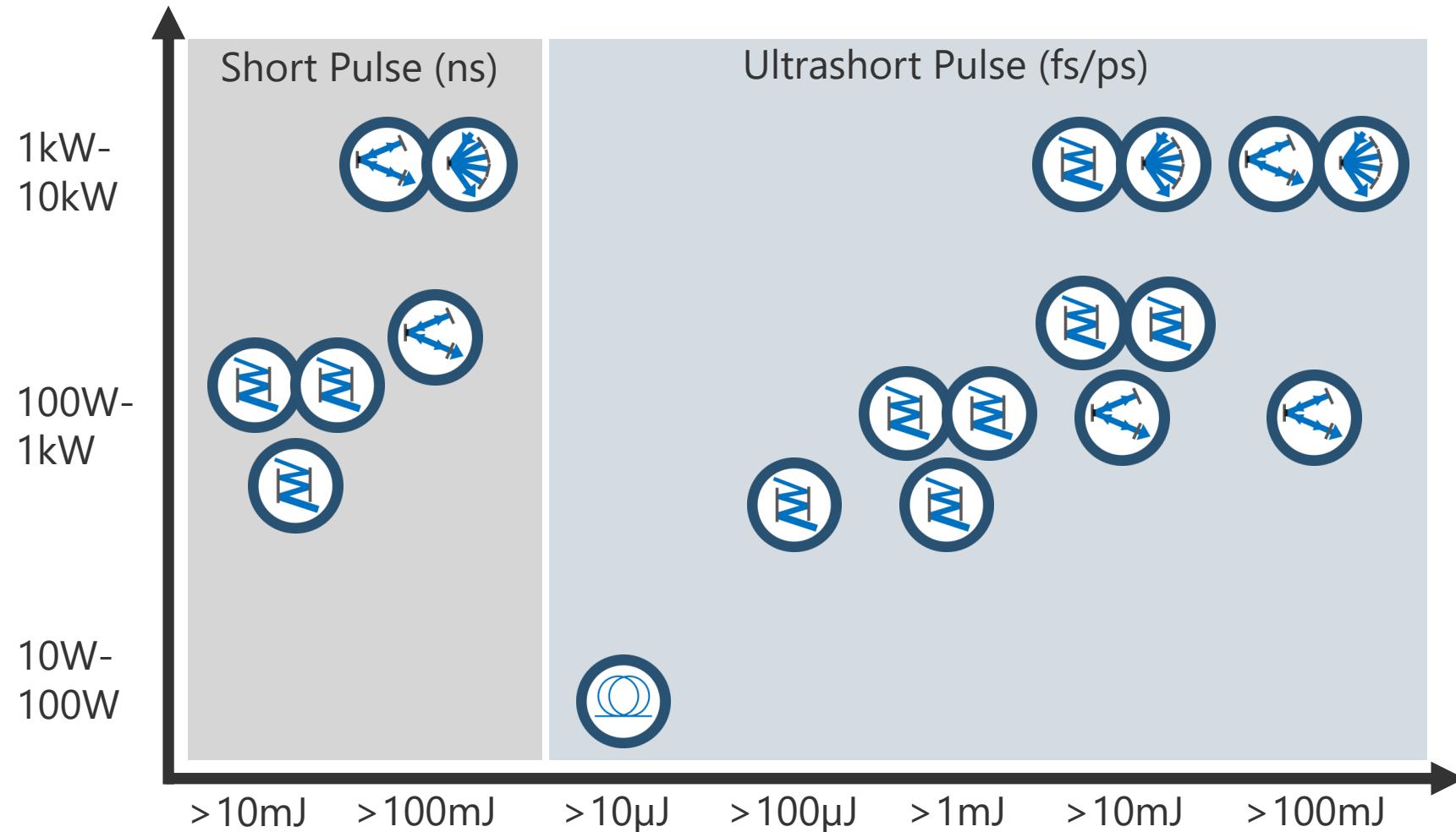
Orders of Magnitude of Pulse Energies, Pulse Powers and Intensities

	~ 1 mJ	~ 10 mJ	~ 100 mJ	~ 100 mJ	~ 1 J
	 Fiber	 InnoSlab	 RegAmp	 CavityDumped	 Multipass
 Industrial range	TruMicro 2000 20 W, 100 µJ TruPulse nano 200 W, 5 mJ	TruMicro 6000 300 W 2 mJ 800 fs	TruMicro 5000 150 W 500 µJ 800 fs	TruMicro 7000 2000 W (IR) 100 mJ 30 ns	TruMicro 8000 720 W (UV) 72 mJ 20 ns
 Scientific Range	AFS-Yb-60 100 W 100 µJ 250 fs	Amphos A5000 1000 W 20 mJ 800 fs	Dira 200 1000 W 200 mJ 500 fs	n.a.	Dira 1000 700 W 700 mJ 900 fs



Model Kit for Reaching Broadest Parameter Space in Todays SSL

Overview 1μm-Wavelength Regime





Vielen Dank!

Contact

Dr. Torsten Mans
Productmanagement Secondary Sources
+49 7422 515-8930
torsten.mans@trumpf.com