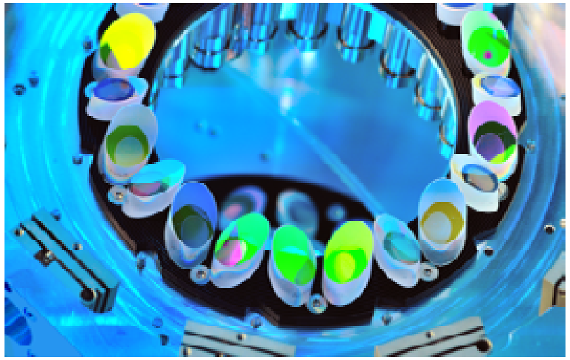
AVERAGE POWER SCALING OF ULTRAFAST LASERS

1. JuSPARC Workshop

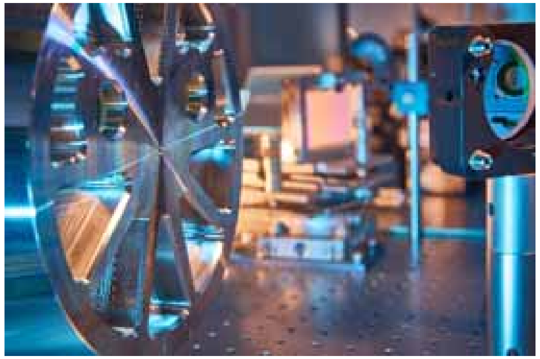
Vaals, 28.3.2019

Dieter Hoffmann

Innoslab Power Amplifiers



ThinDisc Booster



Spectral Broadening

Fraunhofer ILT

OUTLINE

- Introduction ILT – Lasers and Laser Optics
- INNOSLAB – the Concept for Power Scaling
  - Power Scaling at 1 µm
  - Energy Scaling at 1µm
  - Operation at longer Wavelengths
- Parameter Scaling of Ultrashort Pulse Lasers
  - Power Scaling – beyond 1 kW
  - Energy Scaling to mJ Range
  - Pulse Shortening – below 500 fs
- Summary
- Outlook

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Fraunhofer ILT

The Fraunhofer Institute for Laser Technology ILT

Facts and Figures

- € 34.4 M operating budget (without investments) in 2017
- 86% contract research revenue and 14% base funding
- € 5.5 M in investments in 2017

- 502 employees in 2017, of this 181 scientists and engineers, and 241 student assistants
- DQS certified according to DIN EN ISO 9001
- One patent per month on average
- One to two spin-offs per year on average (More than 30 ILT spin-offs in the last 25 years)

- Approx. 10-15 participations in trade fairs and more than 20 organized events (conferences, seminars) per year
- Approx. 15 Ph.D. graduates at RWTH Aachen University faculties per year
- Over 70 master, bachelor degrees per year

Tailored Lasers for Industrial Use

Laser Beam Sources

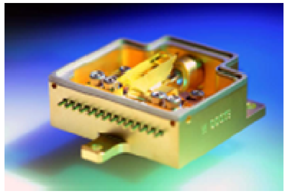
- Power / Energy
- Spatial Quality
- Temporal Quality
- Spectral Quality

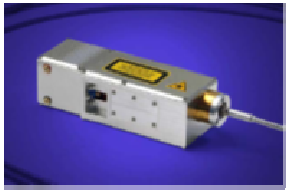
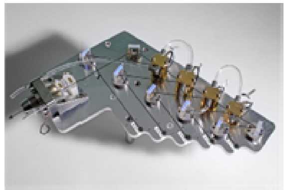
Applications

- Manufacturing Technology
- Measurement Technology
- Microelectronics (EUV)
- Life Sciences

Laserentwicklung am Fraunhofer-Institut für Lasertechnik





1990 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016

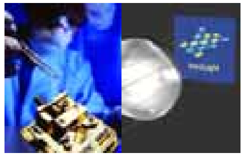





Fraunhofer ILT

Lasers and Laser Optics – ILT Working Groups

Optics Design / Diode Lasers



- Optics for Beam-
  - Forming
  - Propagation
  - Combination
- Free Form Optics
- Pump Sources
- DL Simulation

Solid State Lasers

- cw, ns and ps Oscillators and Amplifiers
- Single Frequency
- IR … MIR

Ultrafast Lasers

- fs, (as) Lasers
- Pulse Compression
- Chirped Pulse Amplification
- High Harmonics

Fiber Lasers

- Amplifiers and Oscillators
- Components
- Processing
- Testing
- Simulation

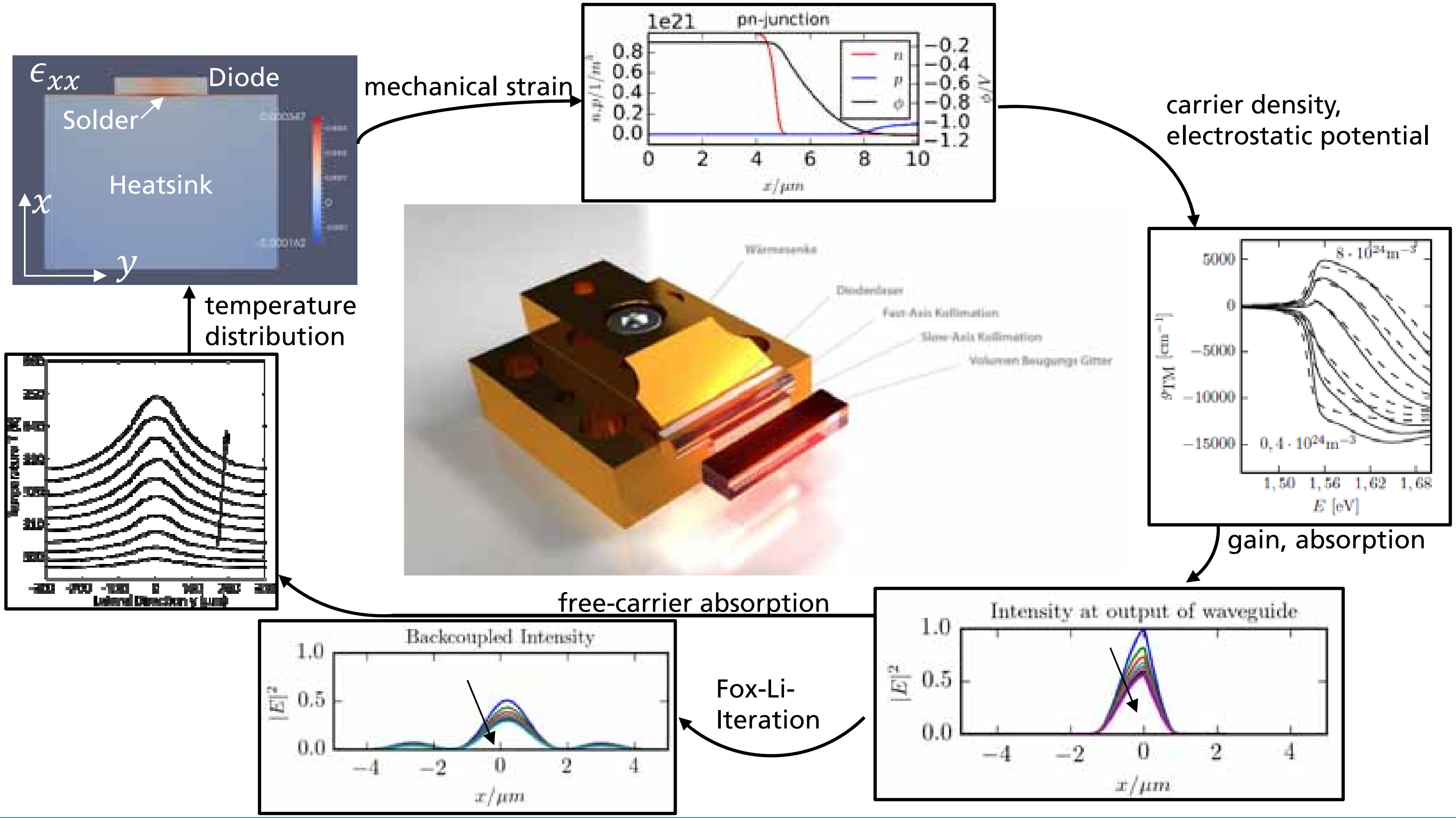
Nonlinear Optics / Tunable Lasers

- Tunable Lasers
- Parametric Oscillators
- Frequency Conversion
- Parametric Quantum Sources

Packaging

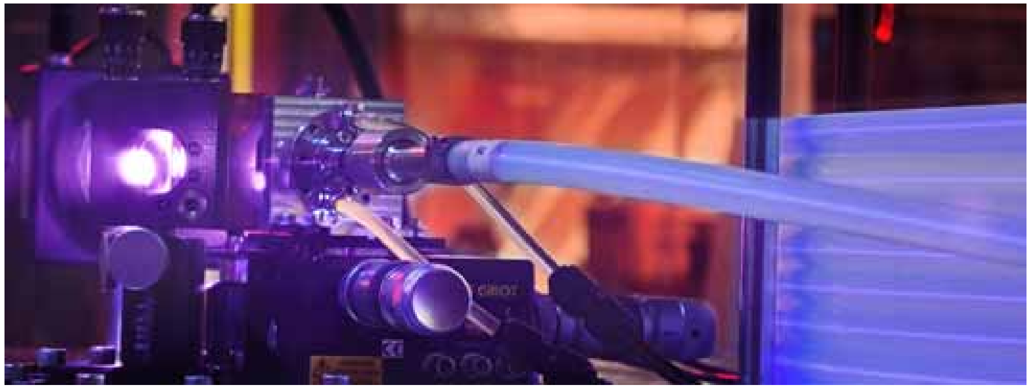
- Crystals
- Mirrors and Lenses
- Hybrid Integrated Optical Systems

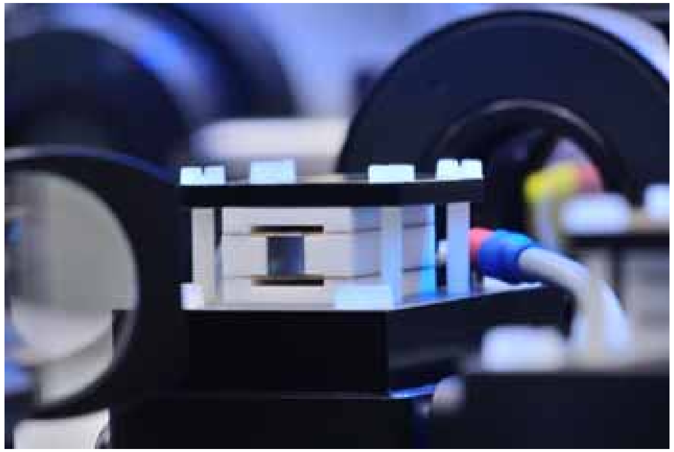
Semiconductor Laser Simulation Software (SEMSIS)

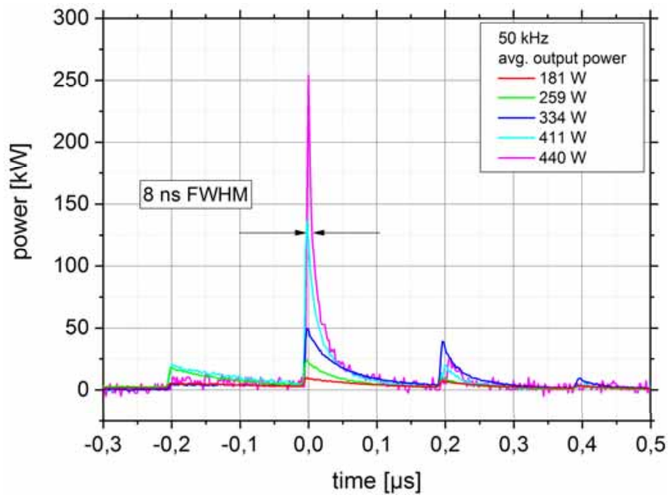


Q-switched high-power fiber laser

- High-power fiber resonator with external q-switches
  - Pulse duration of 8 ns (FWHM)
  - Peak power ~ 250 kW
  - Average power > 400 W
  - Pulse energy > 8 mJ
- Scaled to > 1 kW avg. power at Laserline







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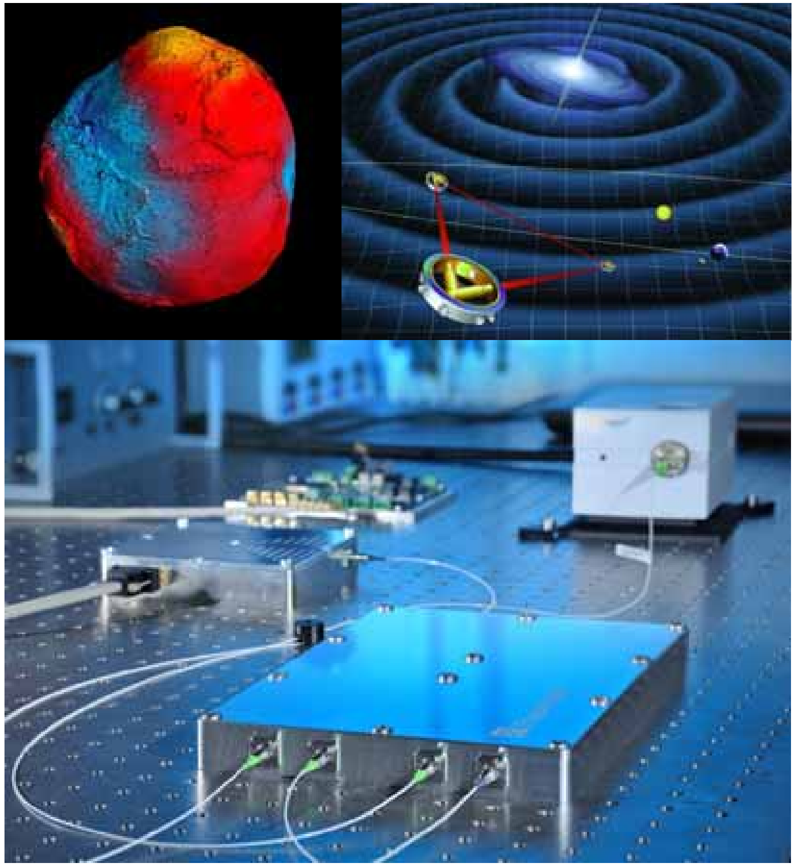
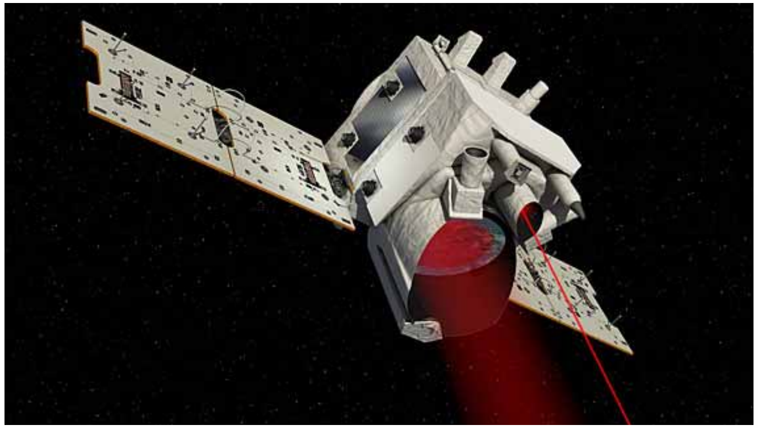
High-stability single-frequency fiber amplifier

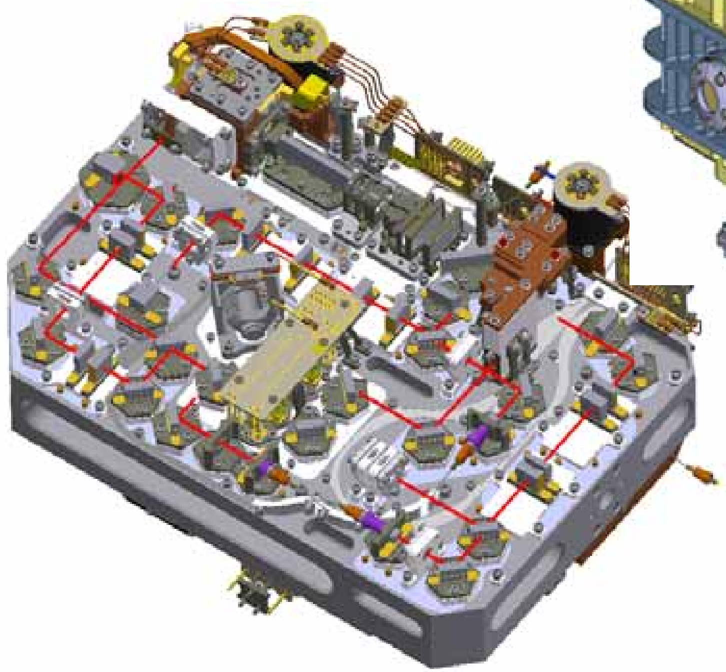
- Pre-studies of an ESA-mission to measure the gravitational field of the earth
- Interferometric setup with 2 satellites in tandem (distance ~ 200 km)
- Driving requirements:
  - Power stability
  - Bandwidth (< 10 kHz)
  - Frequency stability
  - Output power > 500 mW
  - PER > 20 dB
- Space compatibility of components (thermal, vacuum, shock, vibration)
- Successful environmental test campaign towards TRL 5

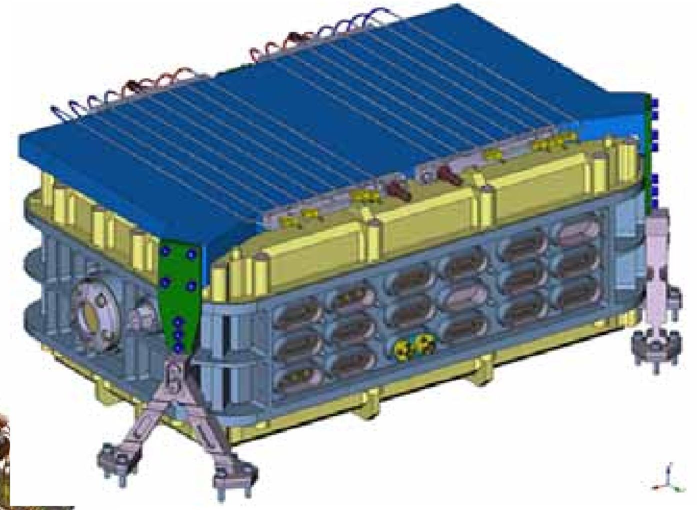


Fraunhofer ILT

MERLIN – LIDAR Beam Source for Satellite based Methane Detection







Packaging of Crystals and Optics

- Mounting technology for Space-Lasers
  - Highly stable optomechanical mounts: Tilt < 5..10 µrad (reliable), tested in harsh environment (25 grms, -40°… +60°C)
- Packaging of active optical components
  - KTP, BBO, LBO , TGG, Nd:YAG, Yb:YAG, $Nd:YVO_4$
- Complex optical setups with active alignment (Pick&Align) & passive reflow soldering
  - MERLIN-OPO-BB, FULAS-Demonstrator (tested: -30°C..+50°C)
- Quality assurance
  - Temperature & vibration testing
  - Database for full traceability of materials and processes

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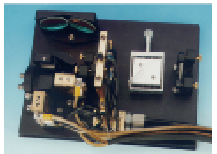
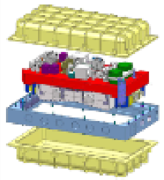
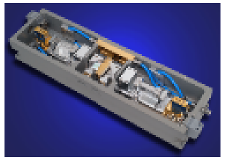
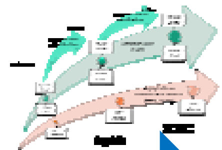
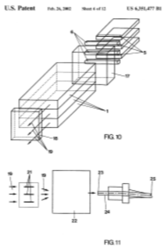
Innoslab Platform – History

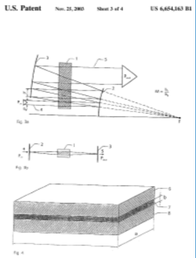




Patent partially pumped slab laser



Patent slab amplifier

edgewave


Foundation of EdgeWave 2001

AMPHOS

Foundation of AMPHOS 2010

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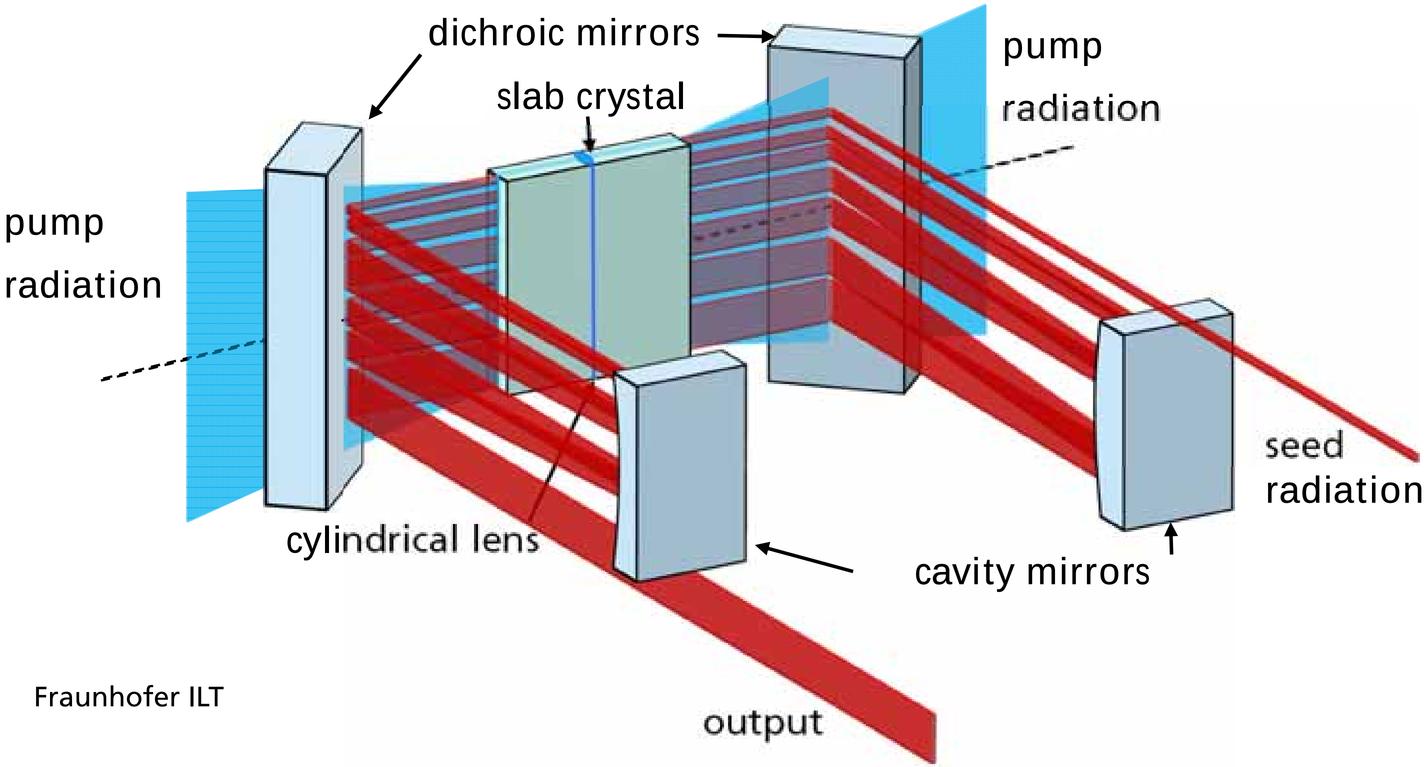
The INNOSLAB Laser Amplifier



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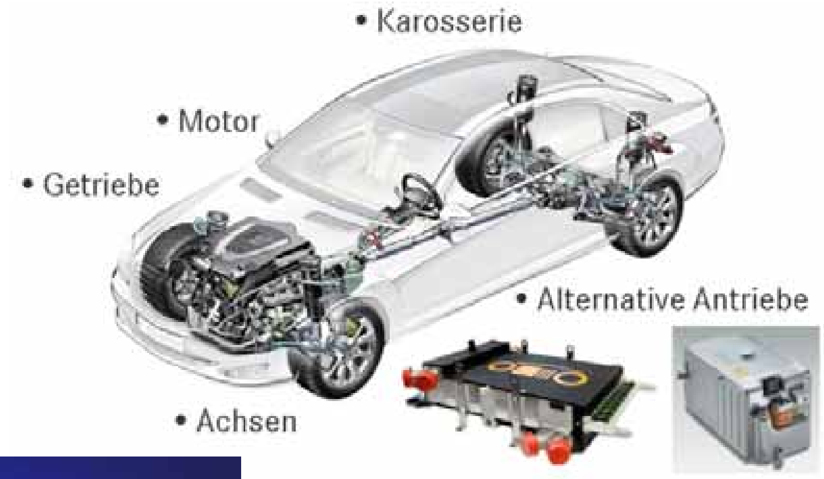
Low Cost High Gain Nd:Innoslab Amplifier



- Compact, energy- and cost efficient modular ps-Laser platform
  - Highly integrated, cost efficient Microchip-Laser, pulse length: 25 – 50 ps

  - compact, cost efficient $Nd:YVO_4$-INNOSLAB-amplifier
    - Single stage design
    - Power > 250 W
    - Amplification > 250

  - Efficient frequency converter to UV and MIR

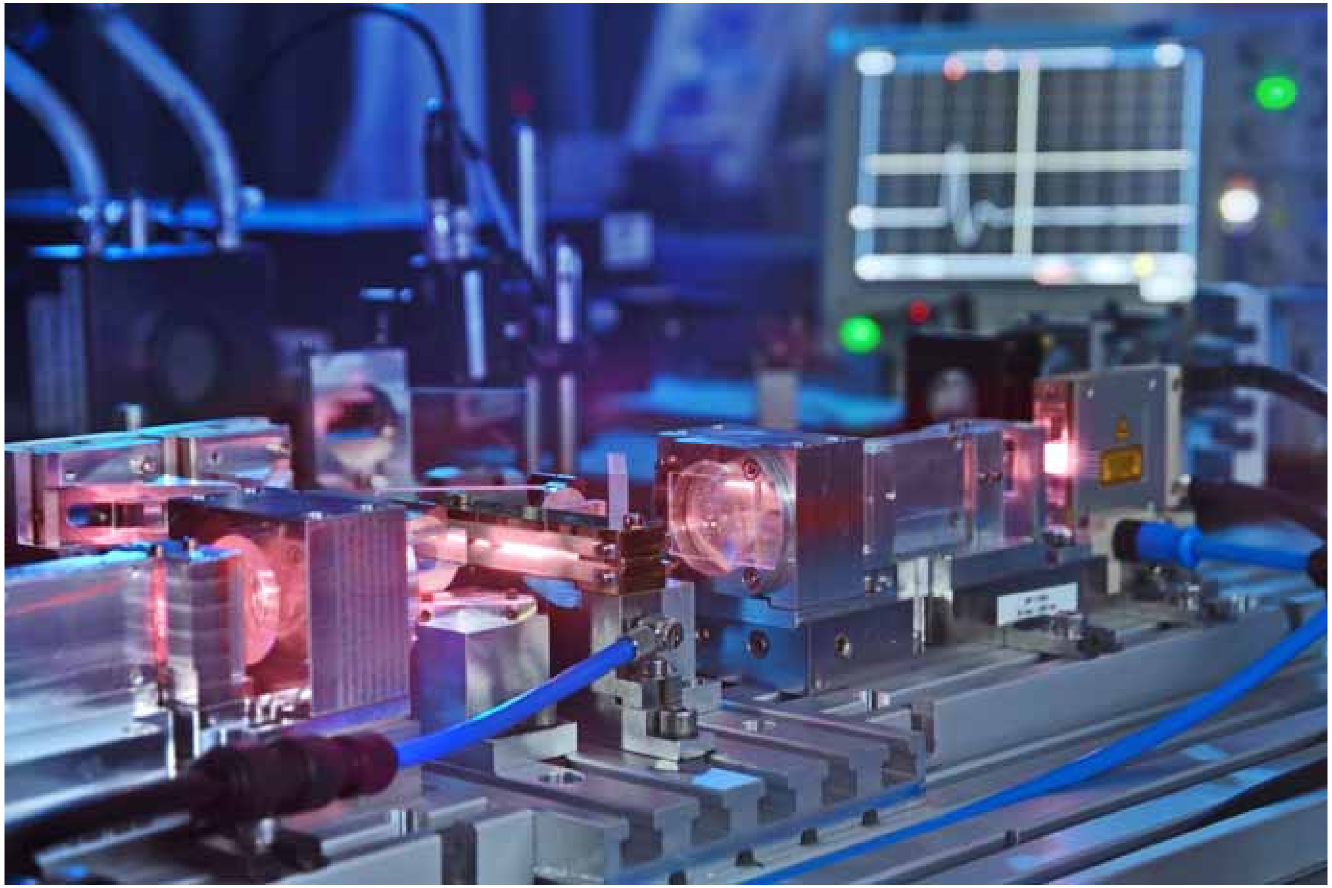
→ Clearly cost reduced provision of application relevant new laser source parameters

EFFILAS++

Fraunhofer ILT

400 W Single Stage Nd:YVO_4 INNOSLAB Amplifier

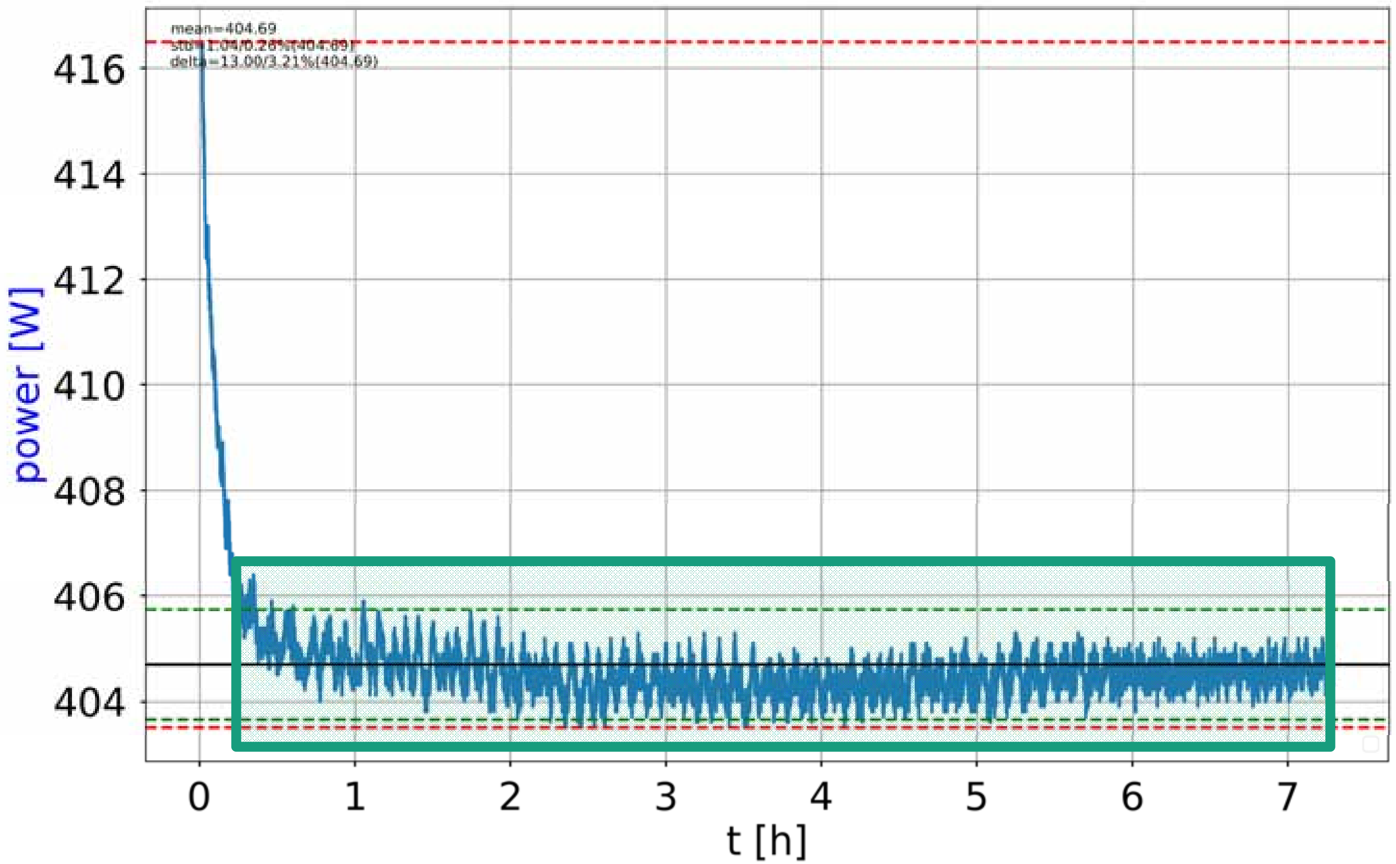
- Compact Low Cost System
- Results:
  - 411 W@800 kHz
  - 390 W@400 kHz (10 ps)
  - 220 W@200 kHz
  - > 40% o.-o. efficiency
  - $M^2_{90/10}$ < 1,5



EFFILAS++
Fraunhofer ILT

Nd:Innoslab - Power Stability: 1MHz, 6.7W Seed

- seeder + amplifier from cold start
- data: cold start + 2 min
- mean = 404.69W
  stdv = 1.04 (0.26%)
  delta = 13.00 (3.21%)
- Lab setup without any housing
- Measured with Coherent LM1000



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Solid State Lasers: Beam Sources for Aerospace

1µm Nd:YAG single-frequency MOPA Lasers + Frequency Conversion

airborne

CHARM–F
(CH_4 + CO_2 Lidar)

- 150mJ (CO_2) / 85mJ (CH_4), 100Hz, 30ns @1µm
- Successful flight campaign in 2015

A2D2G
(Doppler Wind Lidar)

- 60mJ, 100Hz, 30ns @355nm
- Final testing and qualification in progress

spaceborne

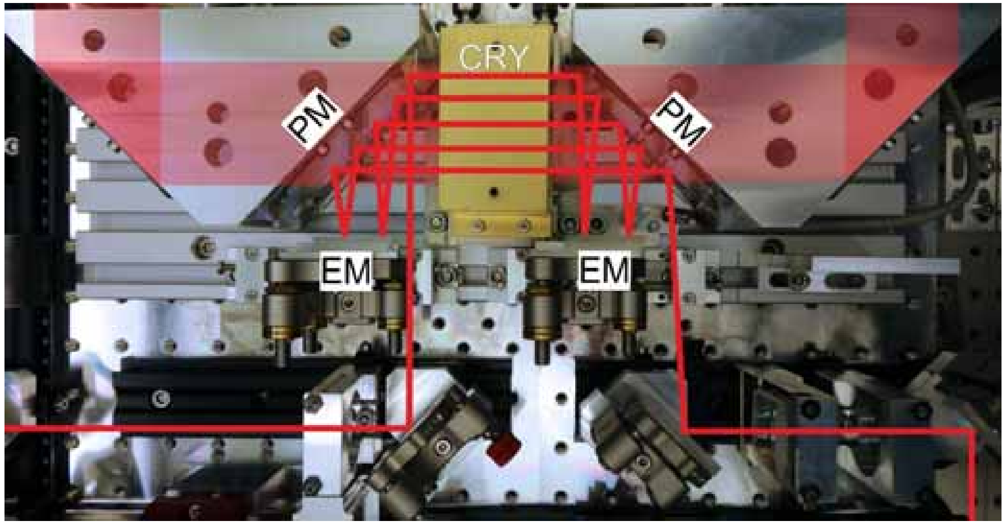
FULAS
(Future Laser System)

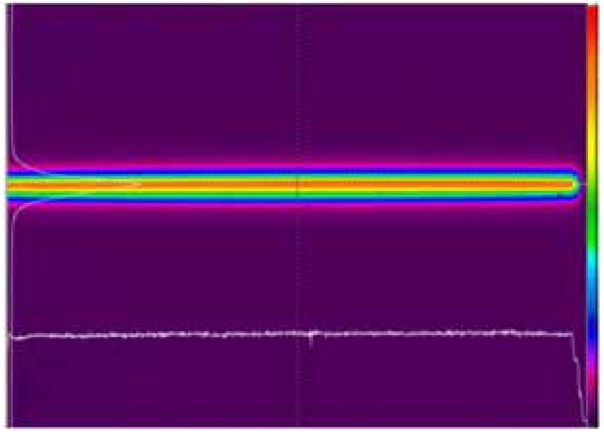
- 40 mJ, 100Hz, 30ns @355nm (IR: 100mJ)
- Successful Thermo-Vacuum Tests by Airbus

MERLIN
(CH_4 Space Lidar)

- 9mJ, 24Hz double pulse, 20ns@1645nm
- Launch in 2024

Setup – 500 mJ InnoSlab Amplifier





Parameter	Value
Folds	5
Resonator length	196 mm
Crystal size (WxHxL)	$40 \times 9 \times 45\ mm^3$
Nd doping level	0.3 %
Pump energy	1950 mJ
Pump spot size	$4 \times 40.2\ mm^2$

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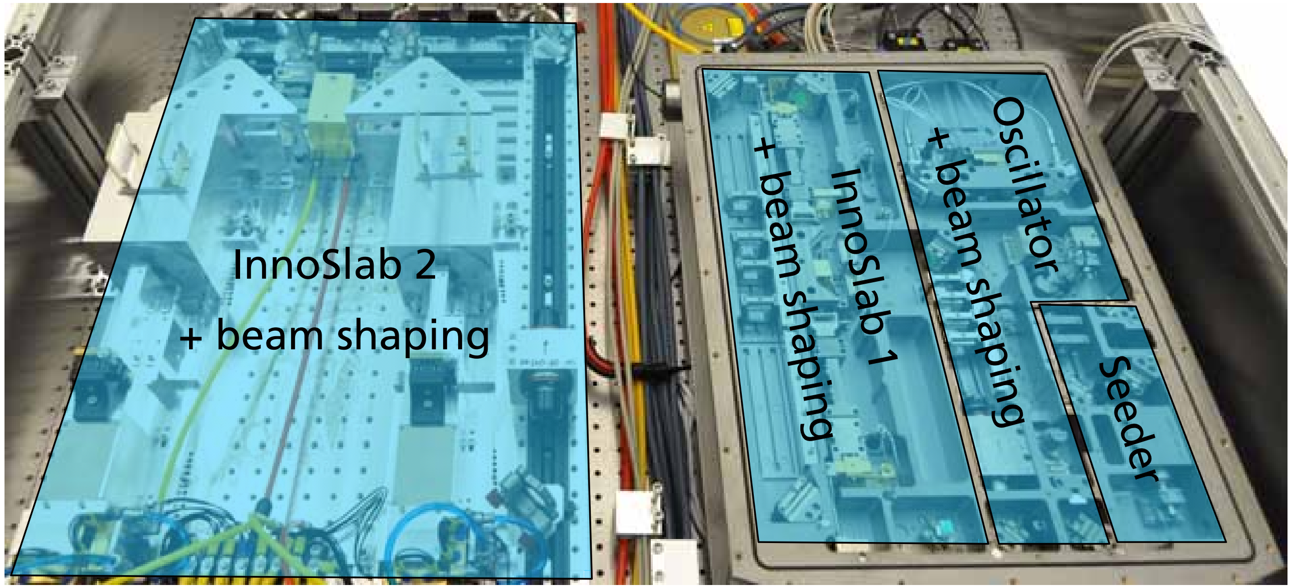
Energy scaling of a 100 Hz Nd:YAG Innoslab



CW-Seeder	Oscillator	InnoSlab amplifier	InnoSlab amplifier
▪ 1064 nm ▪ 10 mW	▪ 1064 nm ▪ 8 mJ	▪ 1064 nm ▪ 75 mJ (Max:110 mJ)	▪ 1064 nm ▪ >500 mJ

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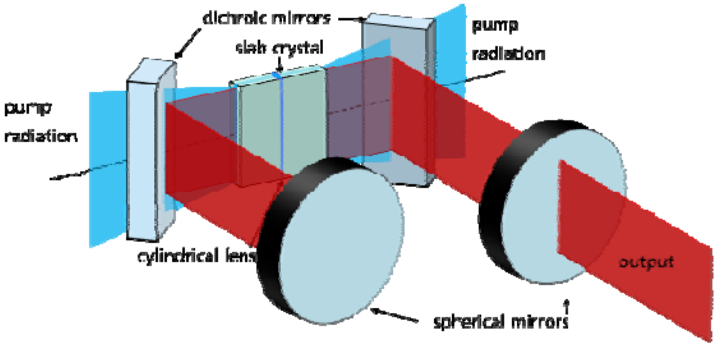
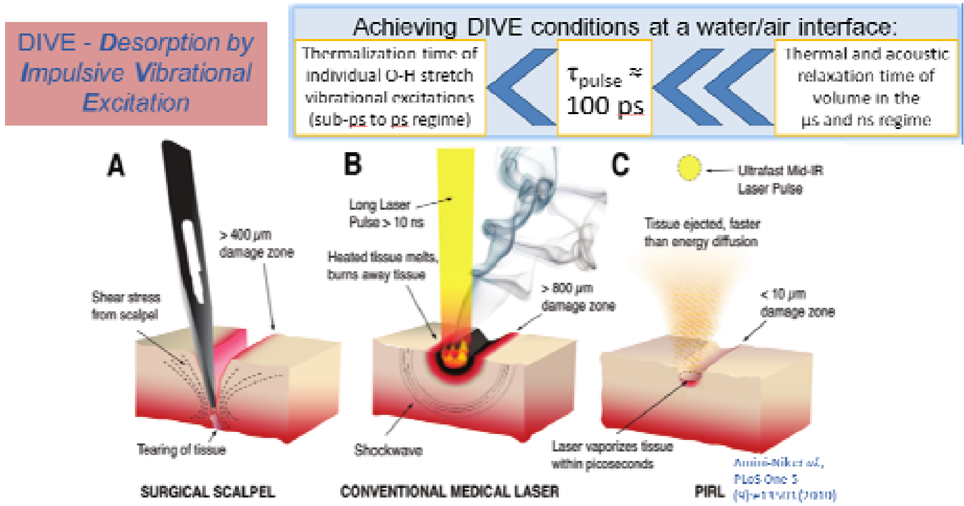
Thulium:YLF for 2 µm generation

- Tm:YLF rod laser at 1.9 µm
  - 25 W, 40 % o-o eff.
  - $M^2 \sim 1.5$
- Tm:YLF INNOSLAB Laser at 1.9 µm
  - $M_y^2 < 3$, $M_x^2 < 360$
  - 200 W cw, 270 W in 1.2 ms qcw
  - Pumping of Ho:YLF
- Cr:ZnSe for 3 µm ps pulses





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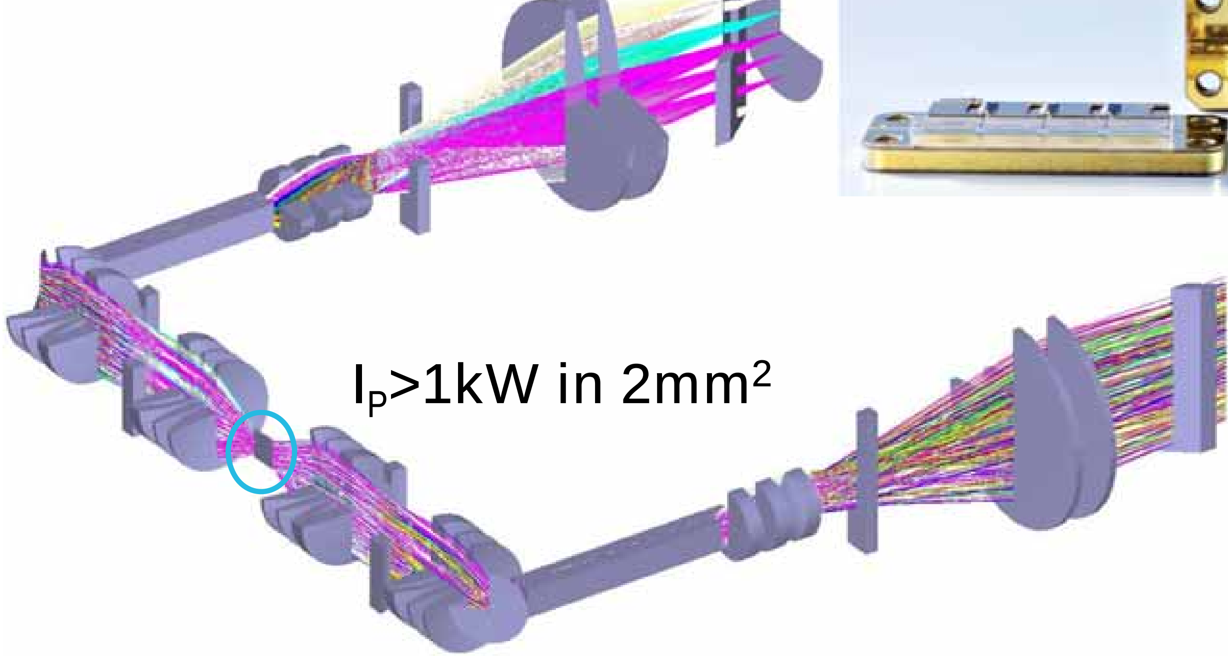
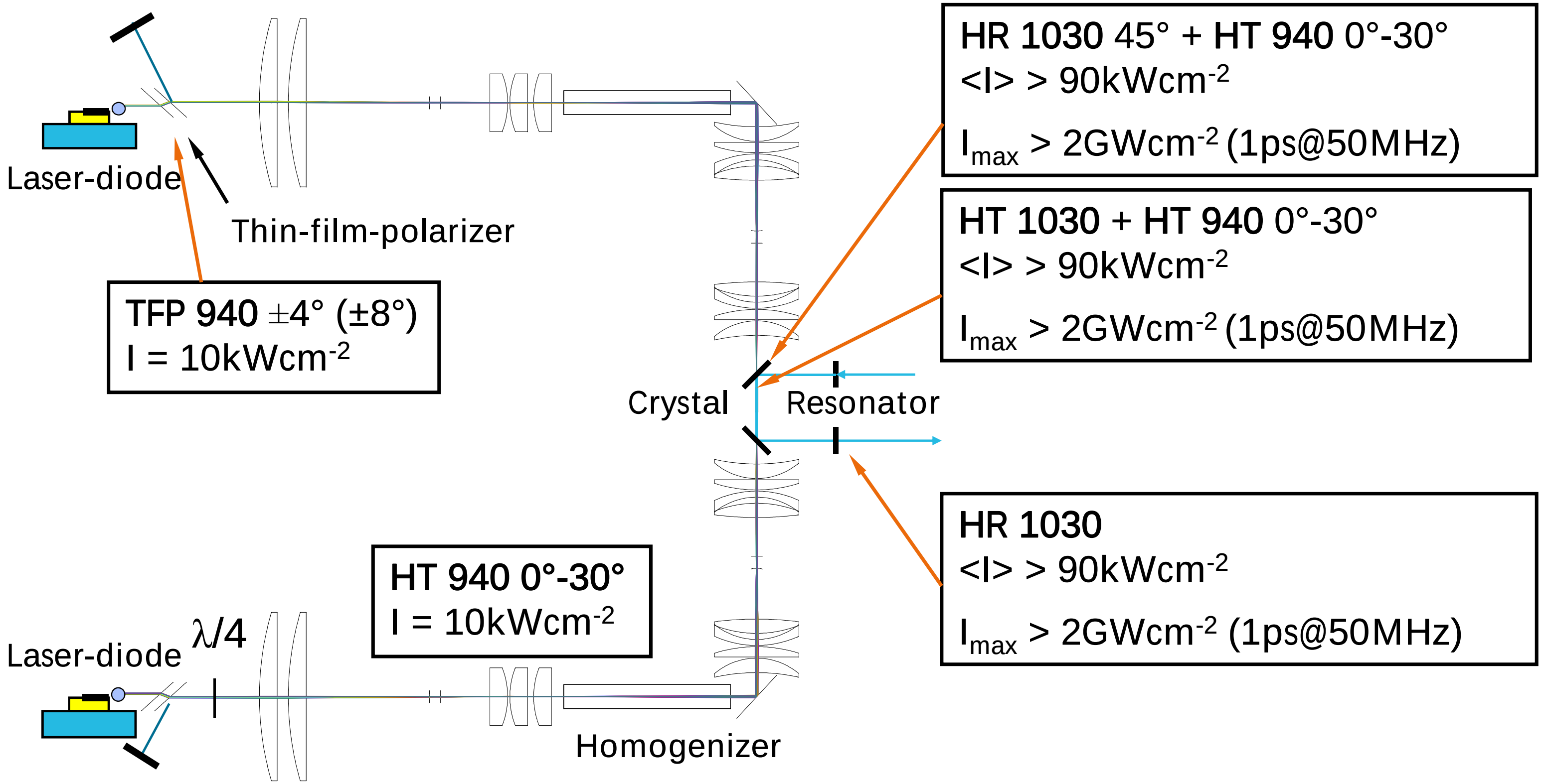
Challenge pump-intensity (ZEMAX)



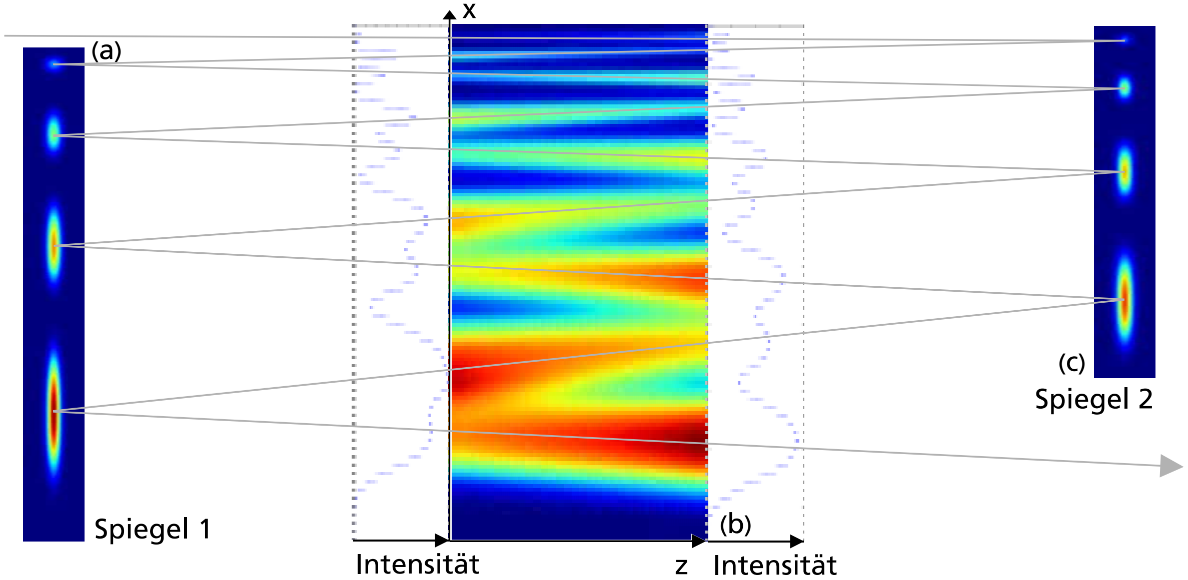
- 2x4 LD-bars
- collimated
- P = 2x480 W
- λ = 940 nm

Challenge damage-threshold



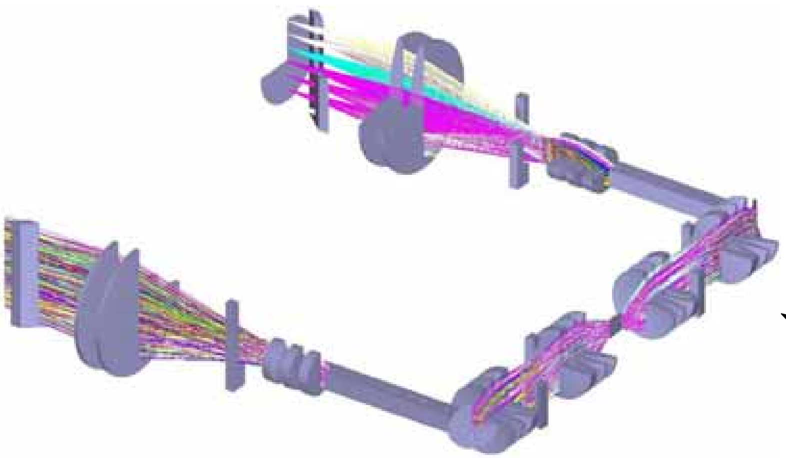
Numerical Simulation of the beam propagation (OPT)

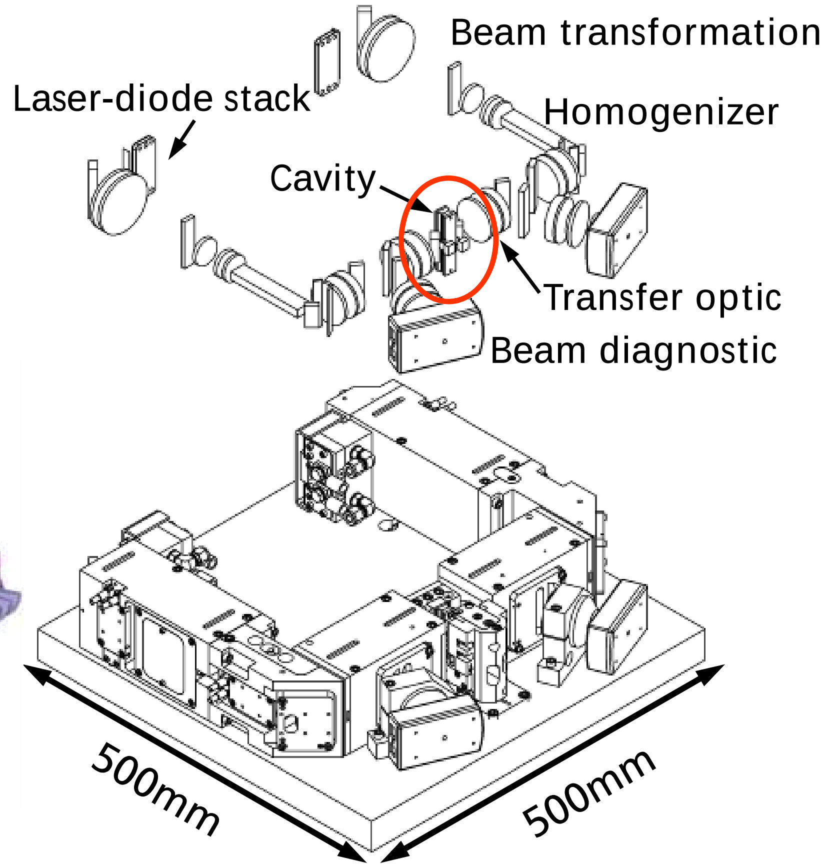
- 3D Spatial Resolution of Intensity in the crystal
- Laser intensity by Propagation of the Complex electrical Field



Experimental - Setup

- 2% Yb:YAG   10 x 10 x 1 mm³
- Confocal cavity M=1.4
- 9 paths
- Pumped double-sided, double pass





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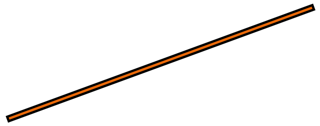
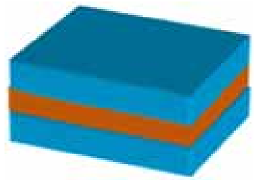
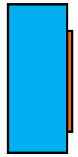
High Power Amplifier – combination of all designs!

	Fiber 	Innoslab 	Thin-disk  multi-pass
Average power (fundamental mode)	< 100 W	100-5000 W	>1 kW
Mode area	< 0.004 mm²	0.1mm² ⇒ 2 mm²	>10 mm²
Amplification factor	> 60 dB	30 dB	<10 dB
Nonlinearity @100W $B/(P_{peak}/P)$	$1 \cdot 10^{-3}$	$2 \cdot 10^{-5}$	10^{-10}
Pulse energy (CPA)	1 mJ	100 mJ	1 J
Repetition rate	>10 kHz	>10 kHz	>10 kHz

Setup - seeder

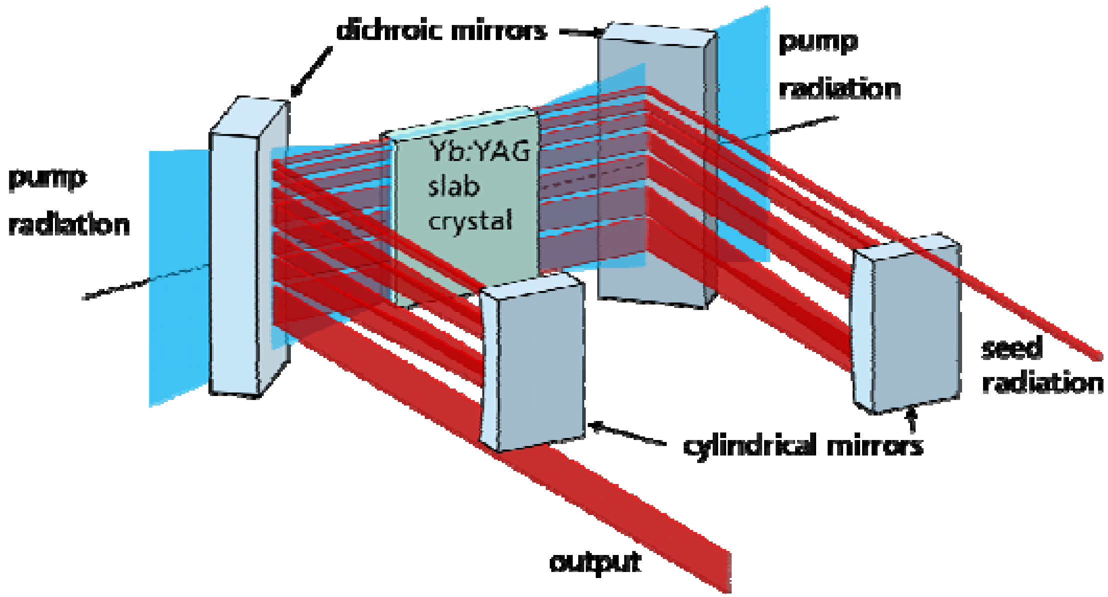
Seeder → Innoslab Amplifier → Innoslab Amplifier → Thin-Disk Amplifier

- Amplitude Satsuma HP
- Industrial fiber MOPA system
- Average power 7 W (up to 10 W)
- Pulse repetition rate 40 MHz

Setup - Innoslab

Seeder → **Innoslab Amplifier** → Innoslab Amplifier → Thin-Disk Amplifier

- 7-pass
- Power 375 W
- Gain ~ 53
- $M^2 = 1.43 \times 1.06$



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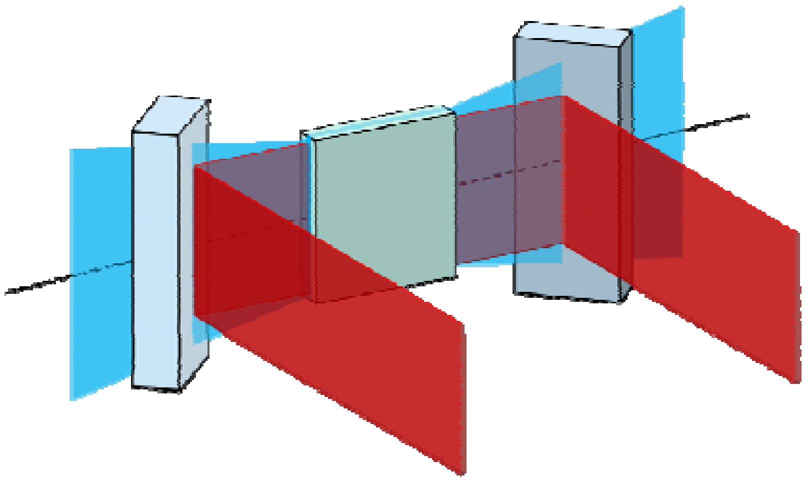
Setup - Innoslab

Seeder → Innoslab Amplifier → **Innoslab Amplifier** → Thin-Disk Amplifier

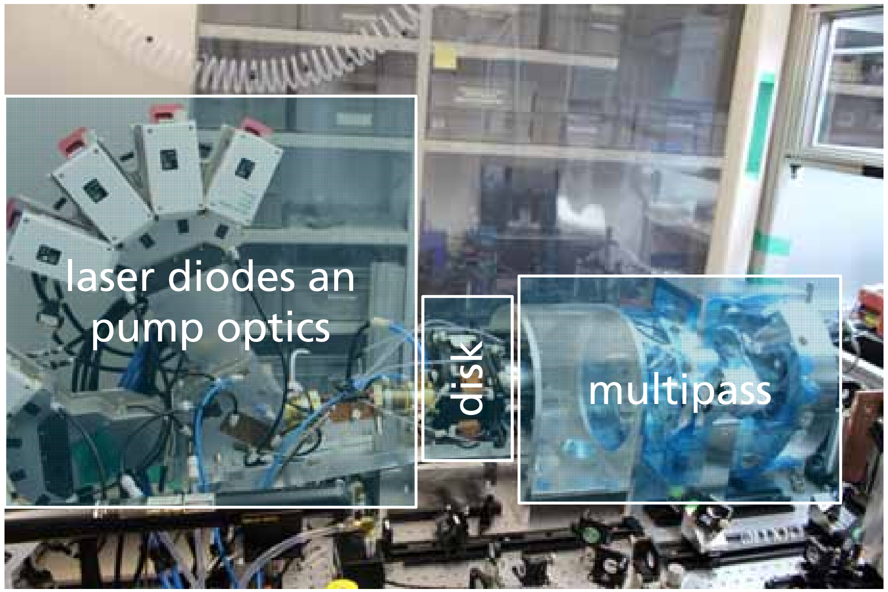
- 1-pass
- Power 720 W
- Gain ~2
- Pulse energy 16 µJ



Setup – Thin-Disk

Seeder → Innoslab Amplifier → Innoslab Amplifier → **Thin-Disk Amplifier**

- Yb:YAG disk
- Up to 9 kW pump power at 940 nm
- Pump spot diameter 10 mm
- 12 pump passes



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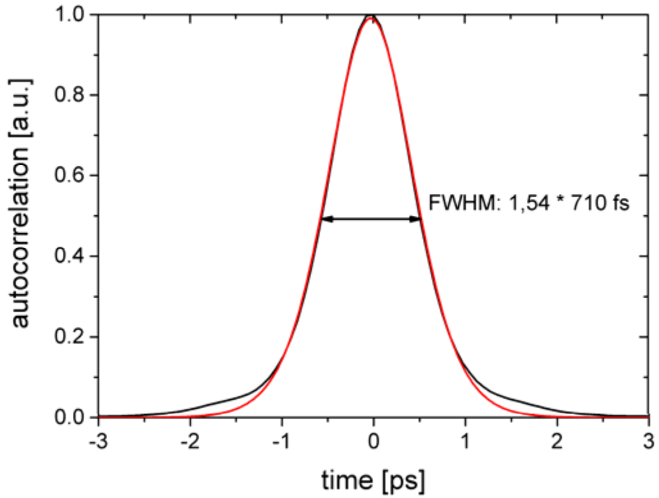
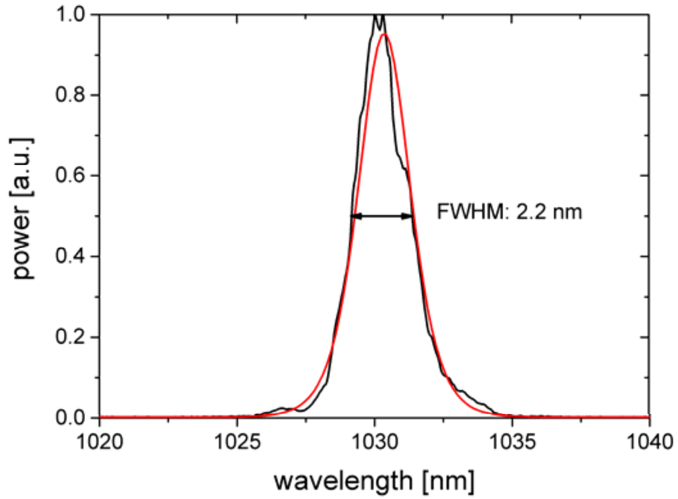
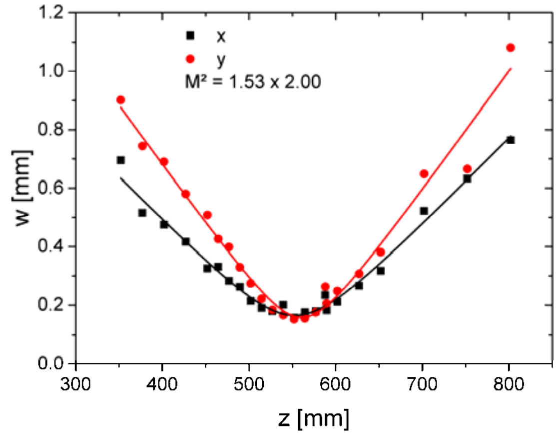
Experimental results







Average power	1.5 kW
Pulse energy	37 µJ
M^2 =	1.53 x 2.00
Pulse duration	710 fs
TBP	0.44

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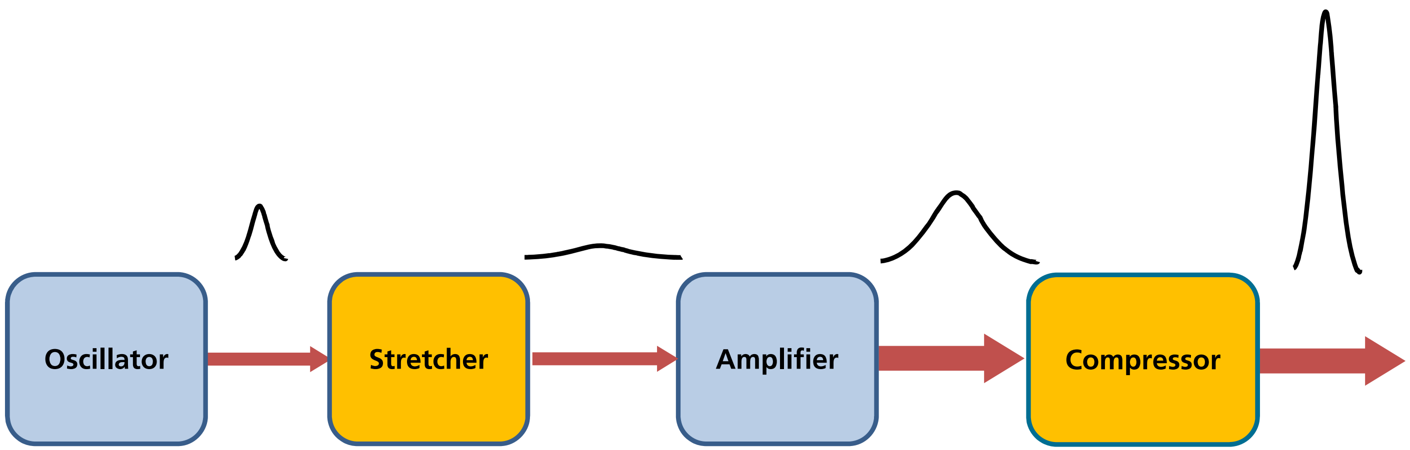
- Outlook

Yb:Innoslab – Energy scaling by CPA

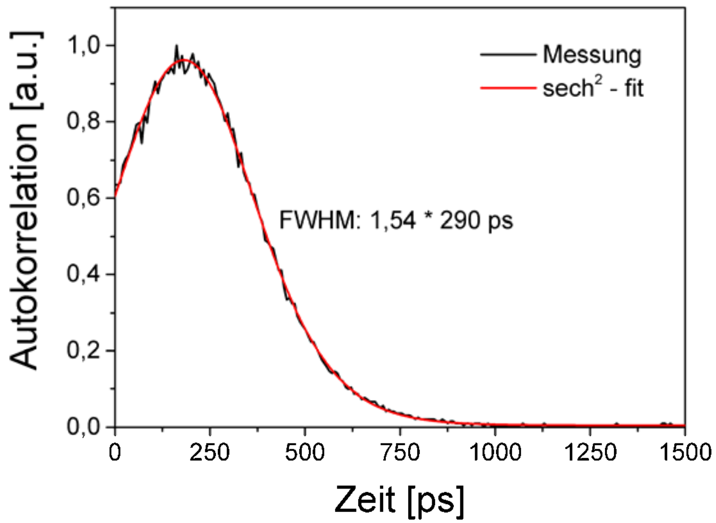
- No CPA: Limitation to < 100 µJ by nonlinear effects or damage of the slab crystal
- CPA enables multi-mJ pulse energy

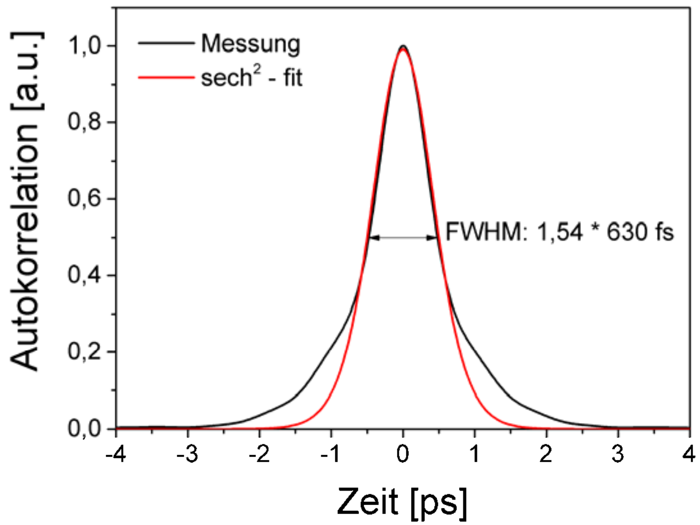


CPA Results

- After grating compressor:
  - P_{avg} 495 W
  - E ≈ 1,0 mJ
  - frep 500 kHz
  - tp 630 fs

Total transmission: 91,6 %





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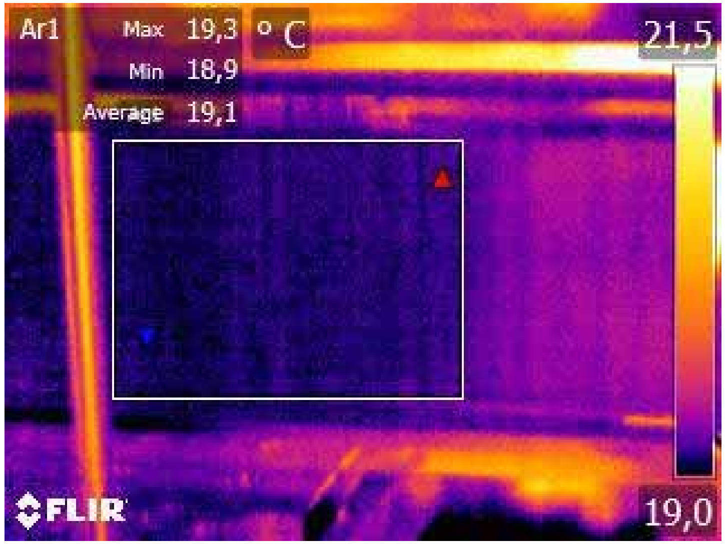
CPA Results

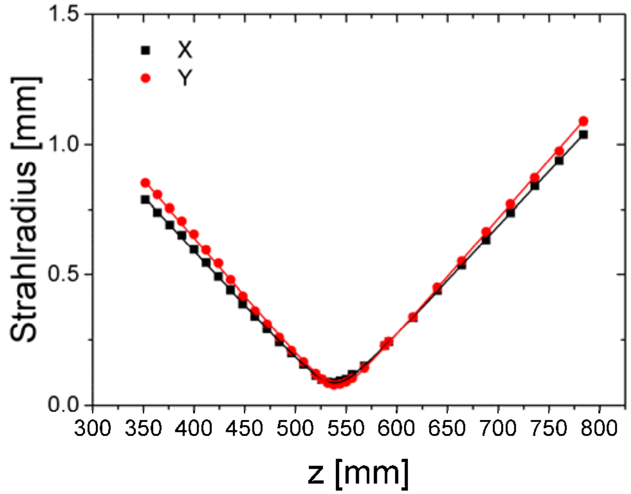
No relevant temperature increase of gratings



Beam quality

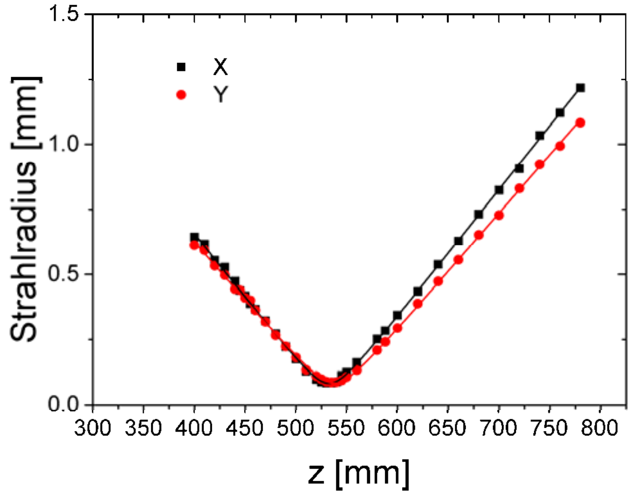
before compression

M² = 1,12 x 1,05



after compression

M² = 1,24 x 1,15



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OUTLINE

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Nonlinear Pulse Compression

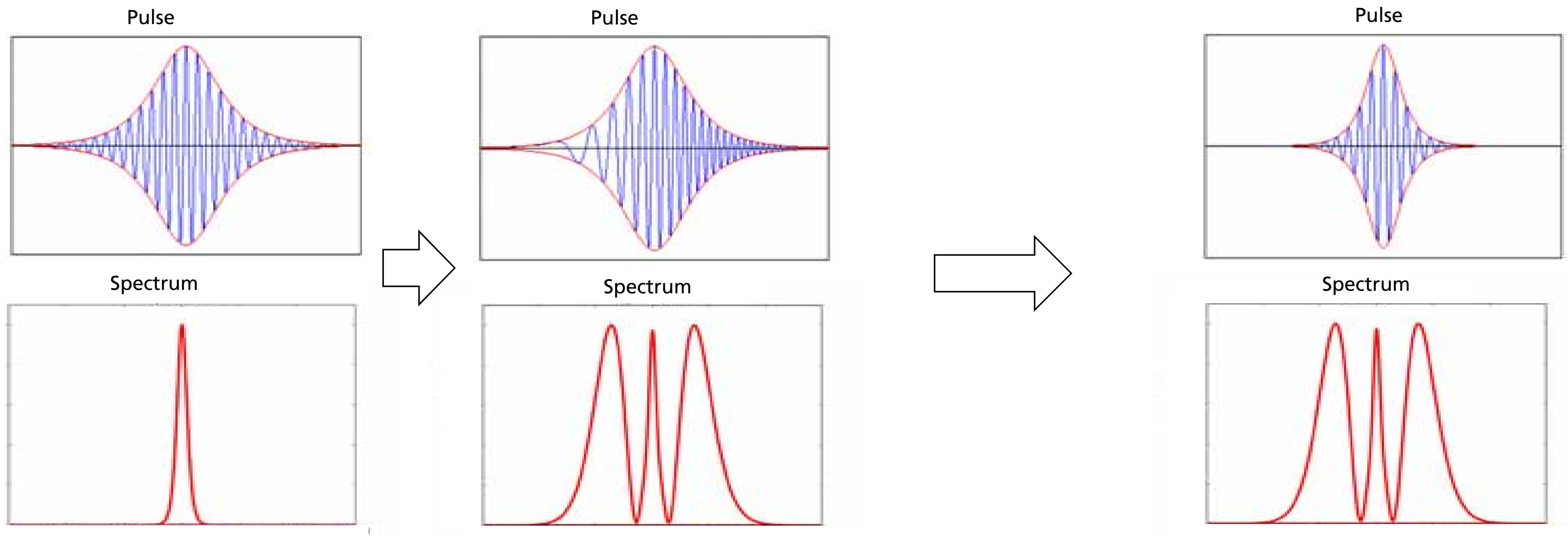
Spectral Broadening:

Kerr-effect: $n = n_0 + n_2 \cdot I(t)$

⇨ nonlinear phase: $\phi_{\mathrm{NL}}(t) = k \cdot l \cdot n_2 \cdot I(t)$

⇨ frequency shift: $\delta\omega(t) = -\dfrac{\partial \phi_{\mathrm{NL}}}{\partial t}$

Dispersion Compensation:



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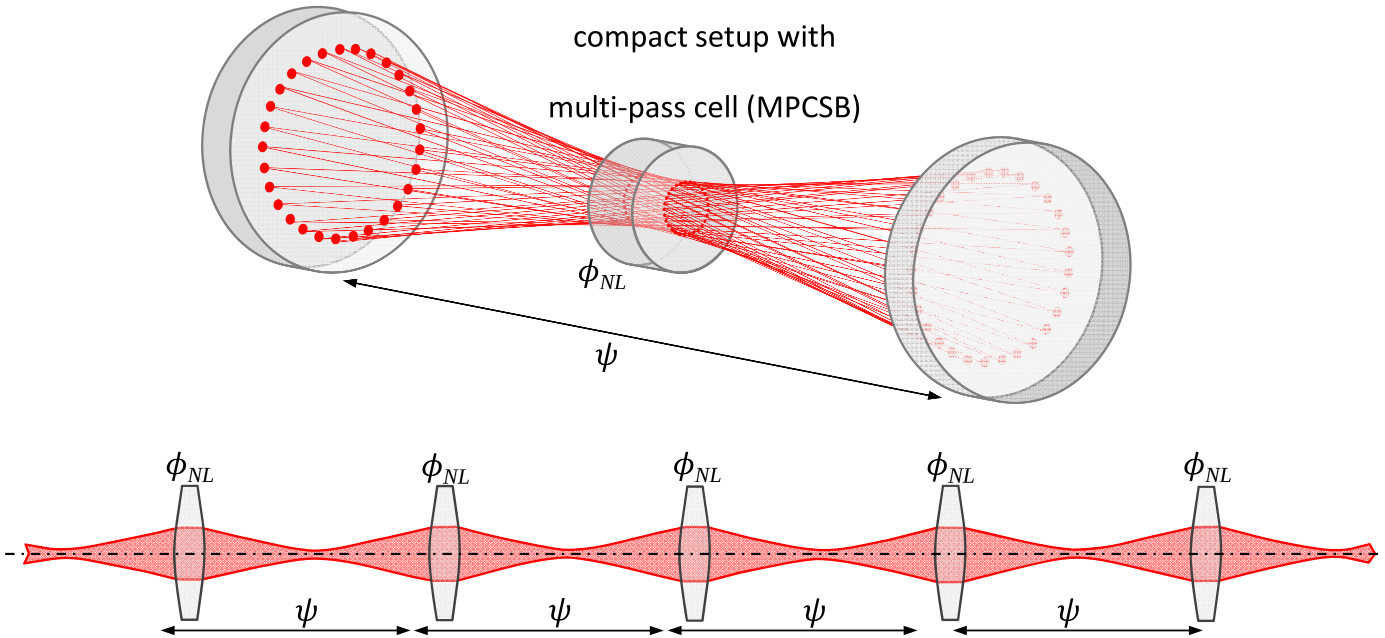
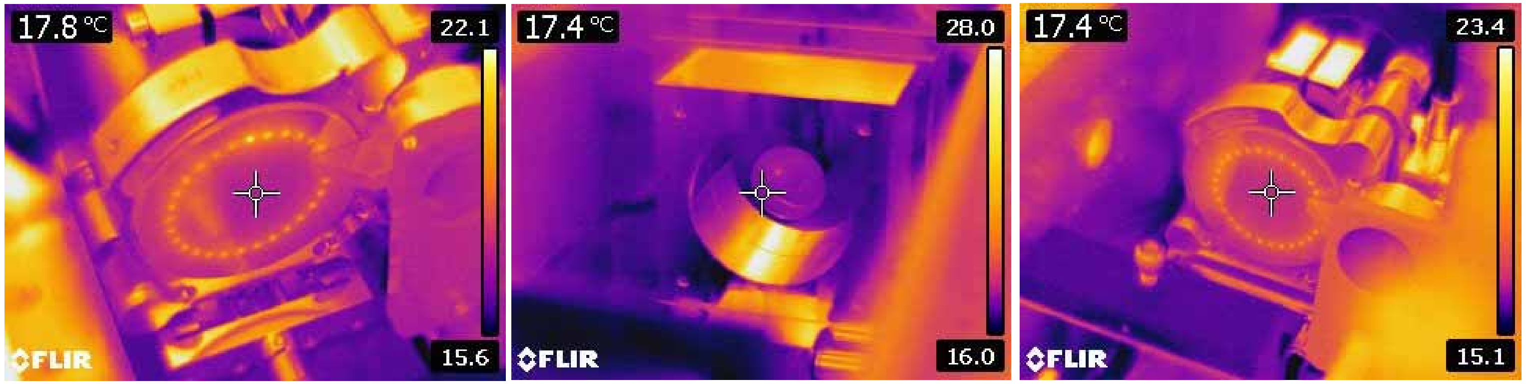
Nonlinear Pulse Compression

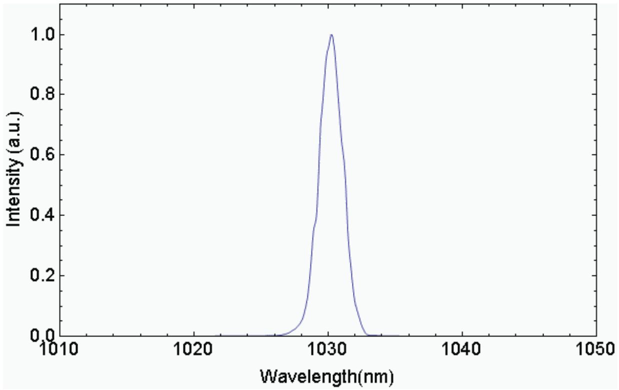


- Transition from a waveguide to a suitably designed lens duct overcomes self-focusing limit.
- Pulse compression at 1-100 µJ energy desirable (e.g. HHG at MHz repetition rate).
- Insensitive to variations of power, beam position and profile, and highly efficient (>90%) → suitable for high average power.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

MPCSB Nonlinear Pulse Compression



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



Spectral broadening vs. roundtrips in MPC (from 2 nm to 25 nm).

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

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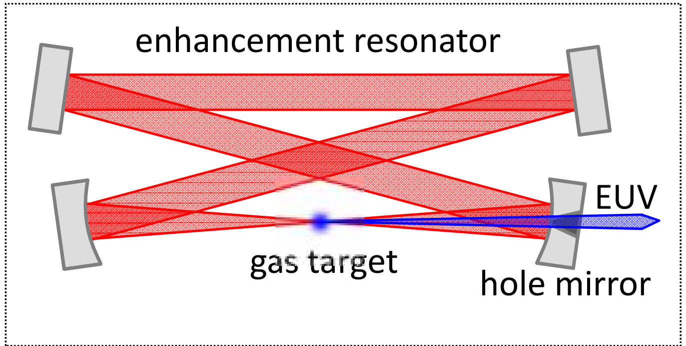
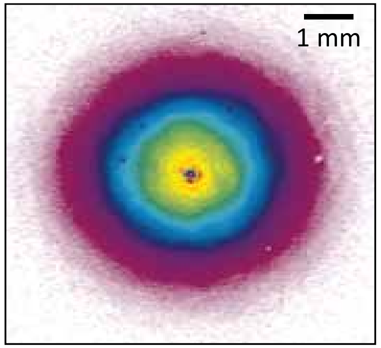
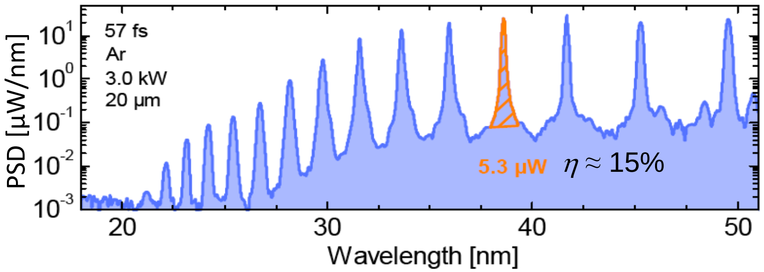
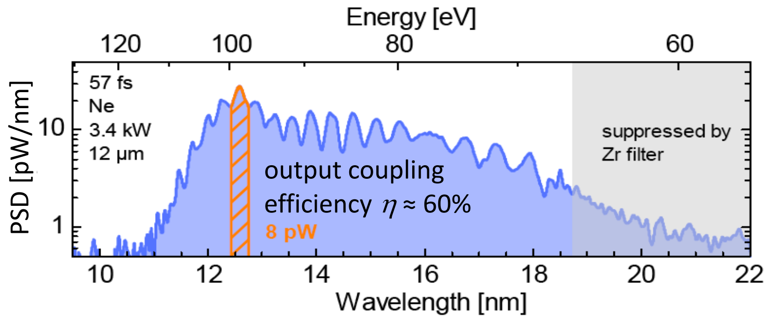
Geometrical Output Coupling with Hole Mirror





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





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

[2] T. Saule, et al., Nat. Comm. 10, 485 (2019).

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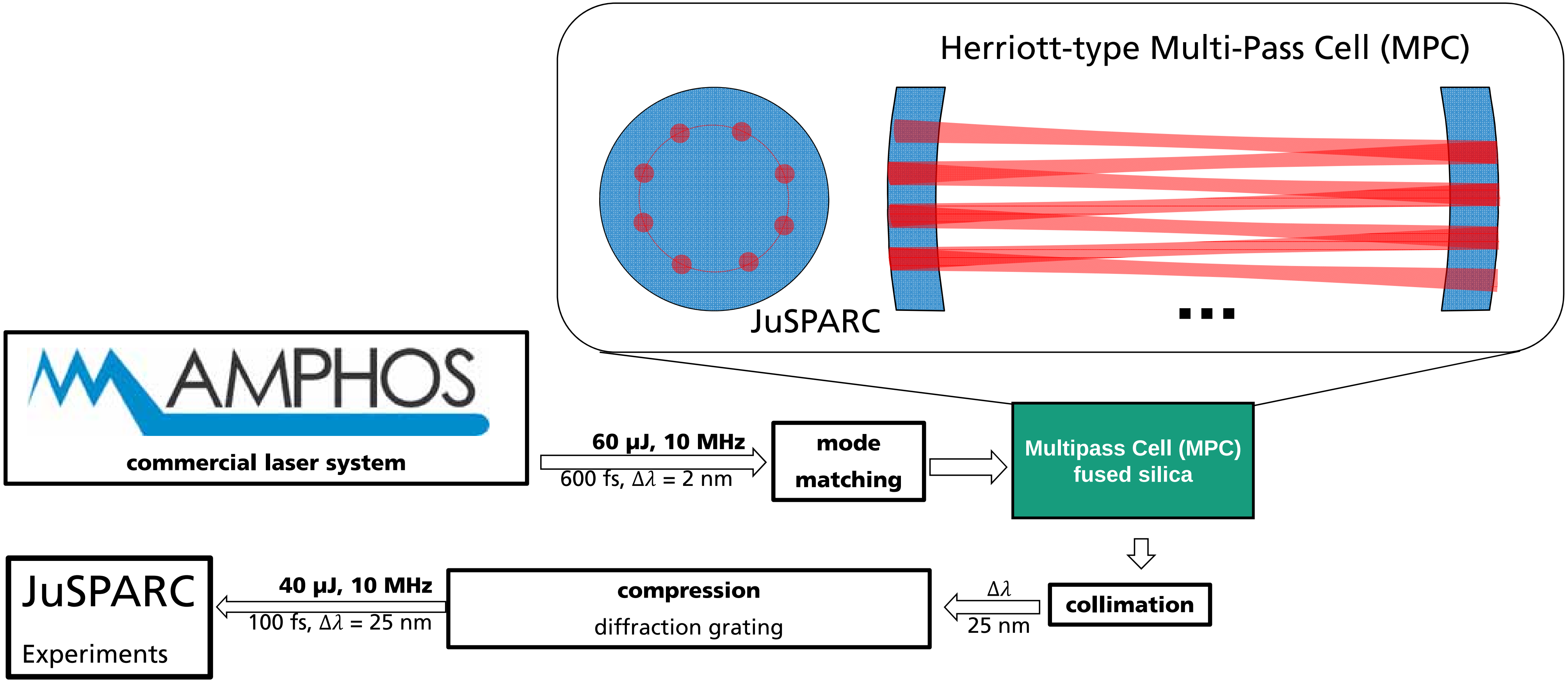
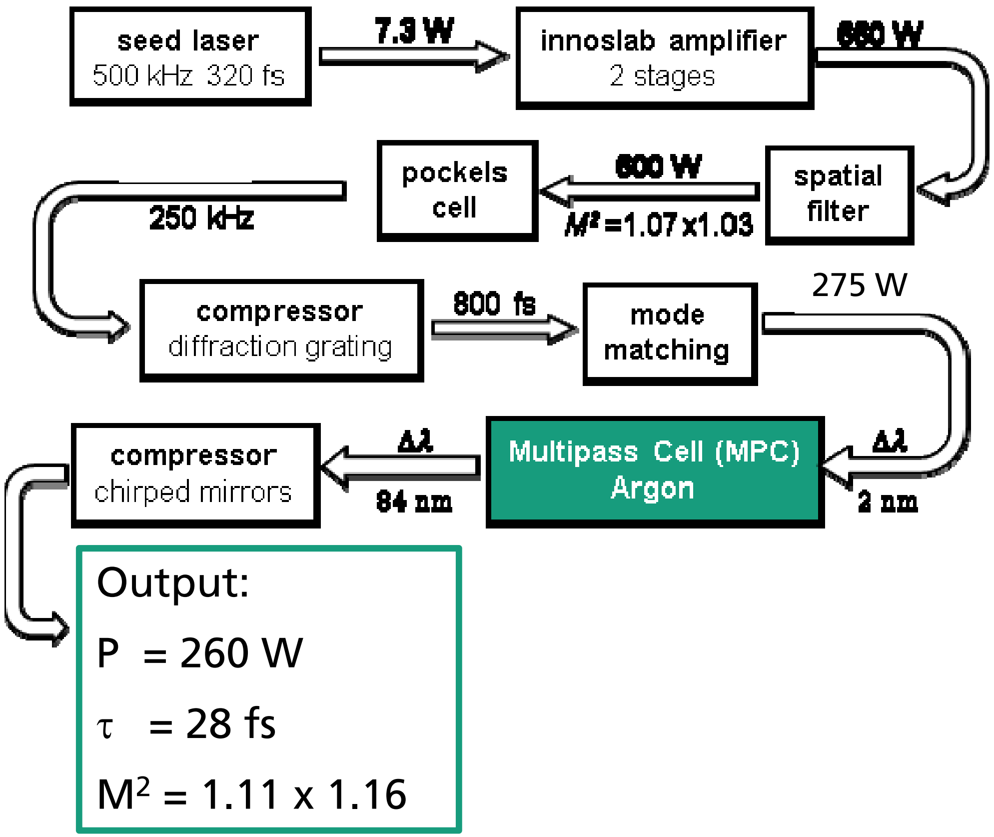
Pulse Compression Setup at JuSPARC, Jülich

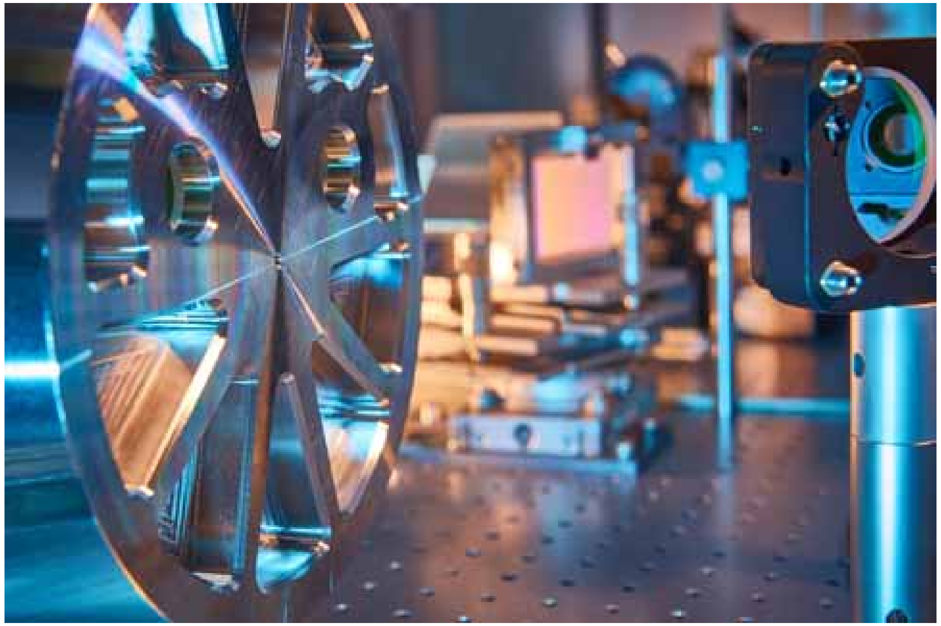


ILT Multipass Cell for JuSPARC

- Shipped in December 2018
- Parameters
  - 400 W
  - 100 fs
  - 10 MHz

Spectral Broadening in Gas-Filled MPC





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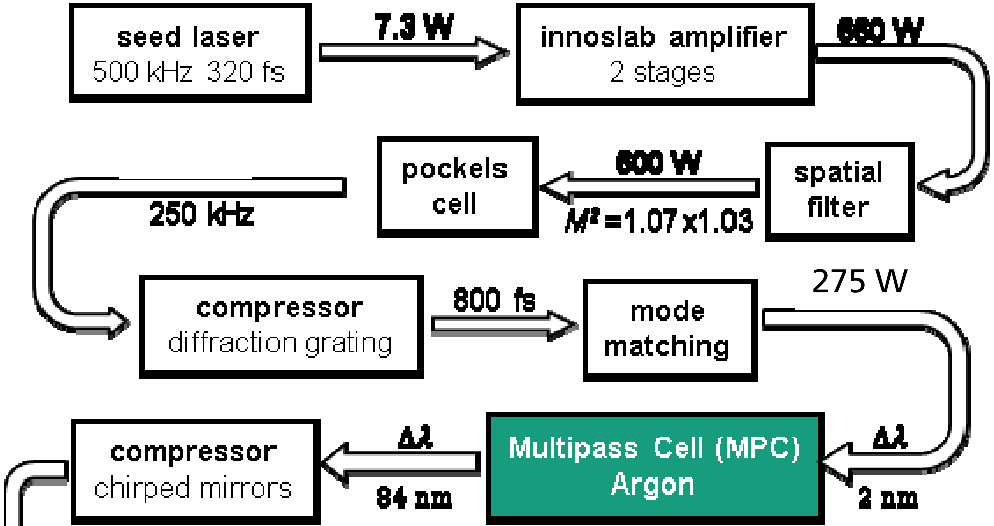
Spectral Broadening in Gas-Filled MPC

- Heriott cell length 1 m
- atmosphere: Argon 4 bar
- laser input 275 W / 1 mJ / 620 fs / M^2 <1.1

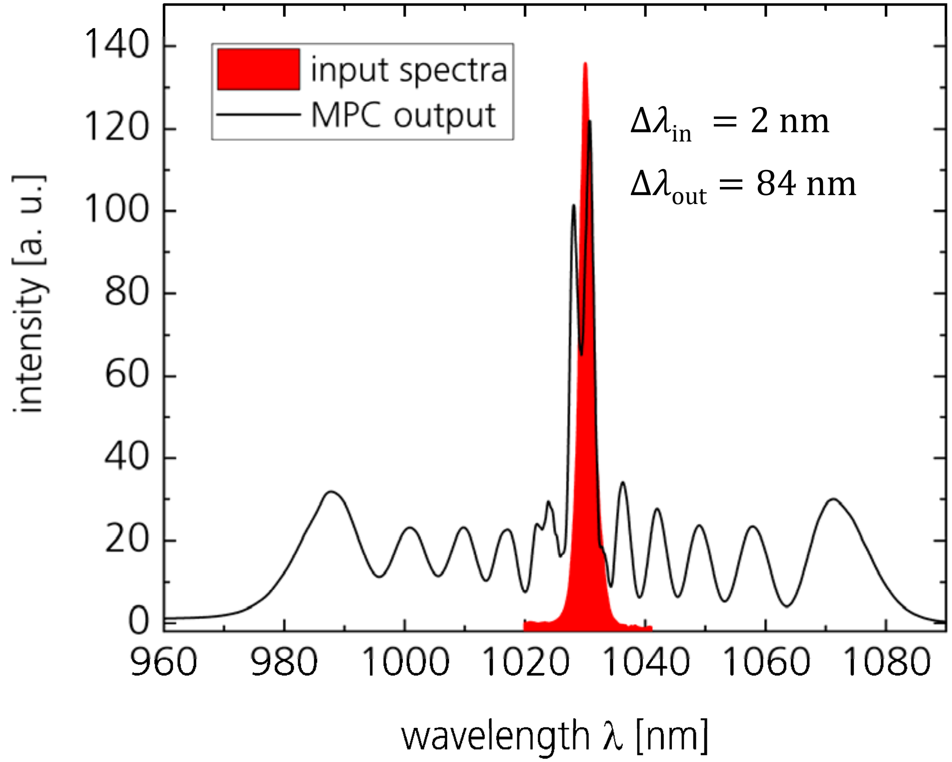


Output:

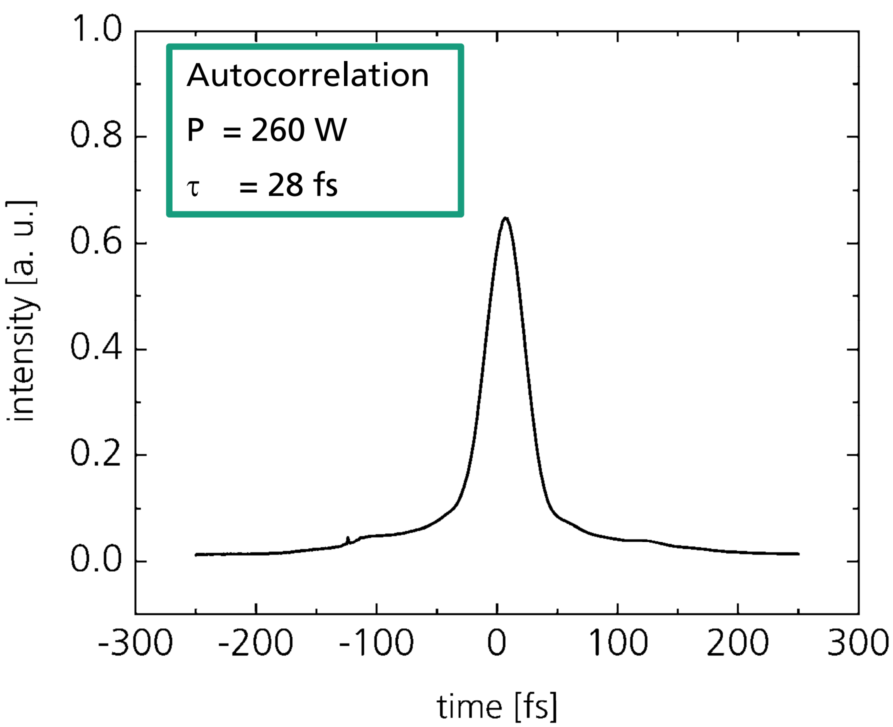
P = 260 W

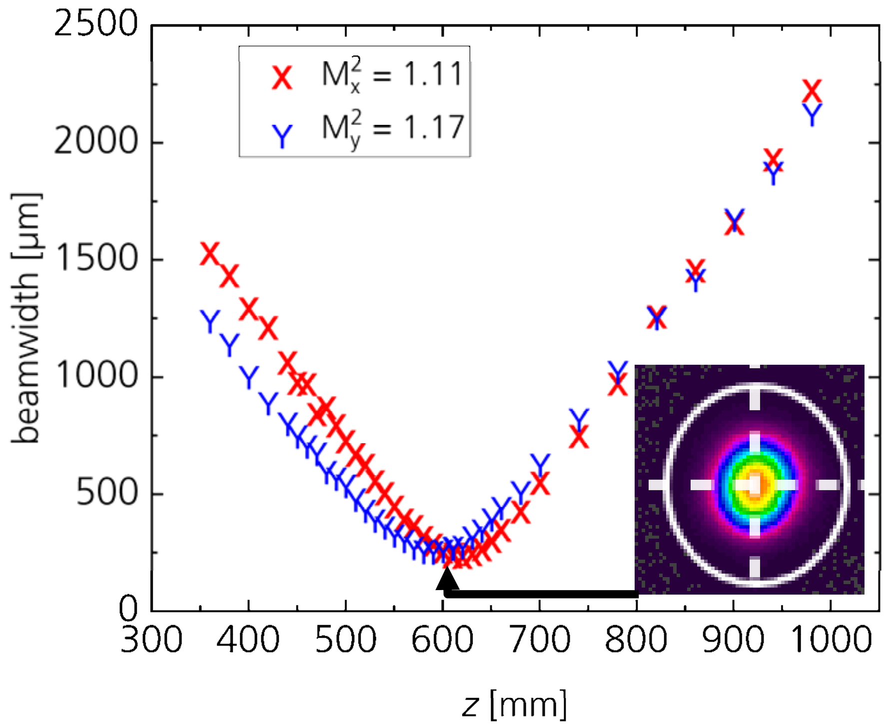
τ = 28 fs

M^2 = 1.11 x 1.16



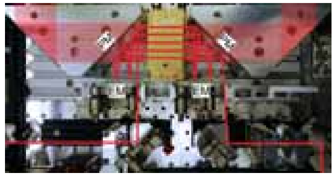
Pulse Compression after Nonlinear Spectral Broadening





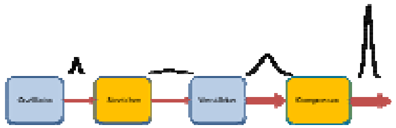
SUMMARY

- > 500 mJ @ ns with 2 stage amplifier demonstrated → further energy scalability and / or pulse shortening possible

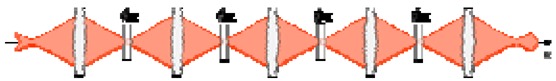


- 1.5 kW @ 600 fs power scaling by INNOSLAB and ThinDisk → scalable

- mJ pulse energy @ 630 fs and 500 W by efficient CPA → scalable



- Efficient pulse shortening demonstrated 260 W @ 28 fs → scalable



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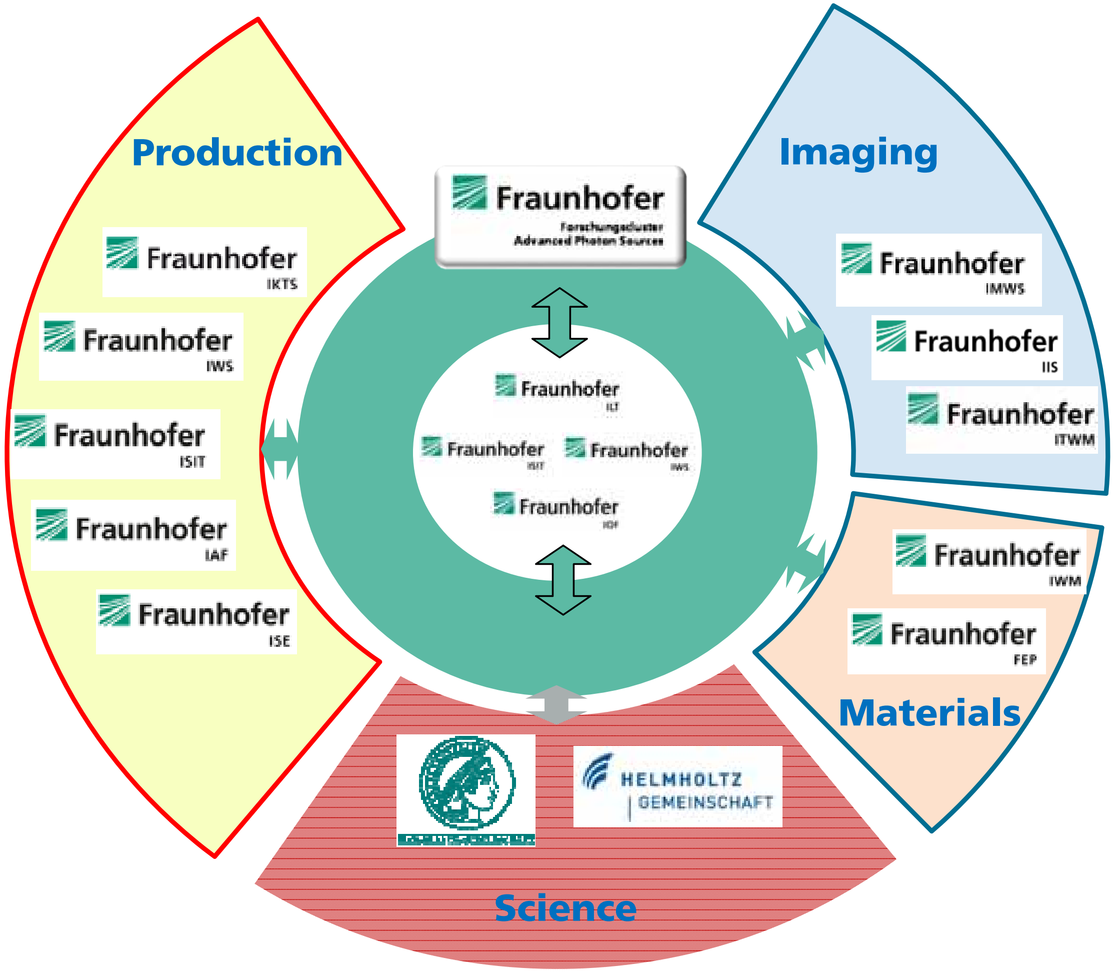
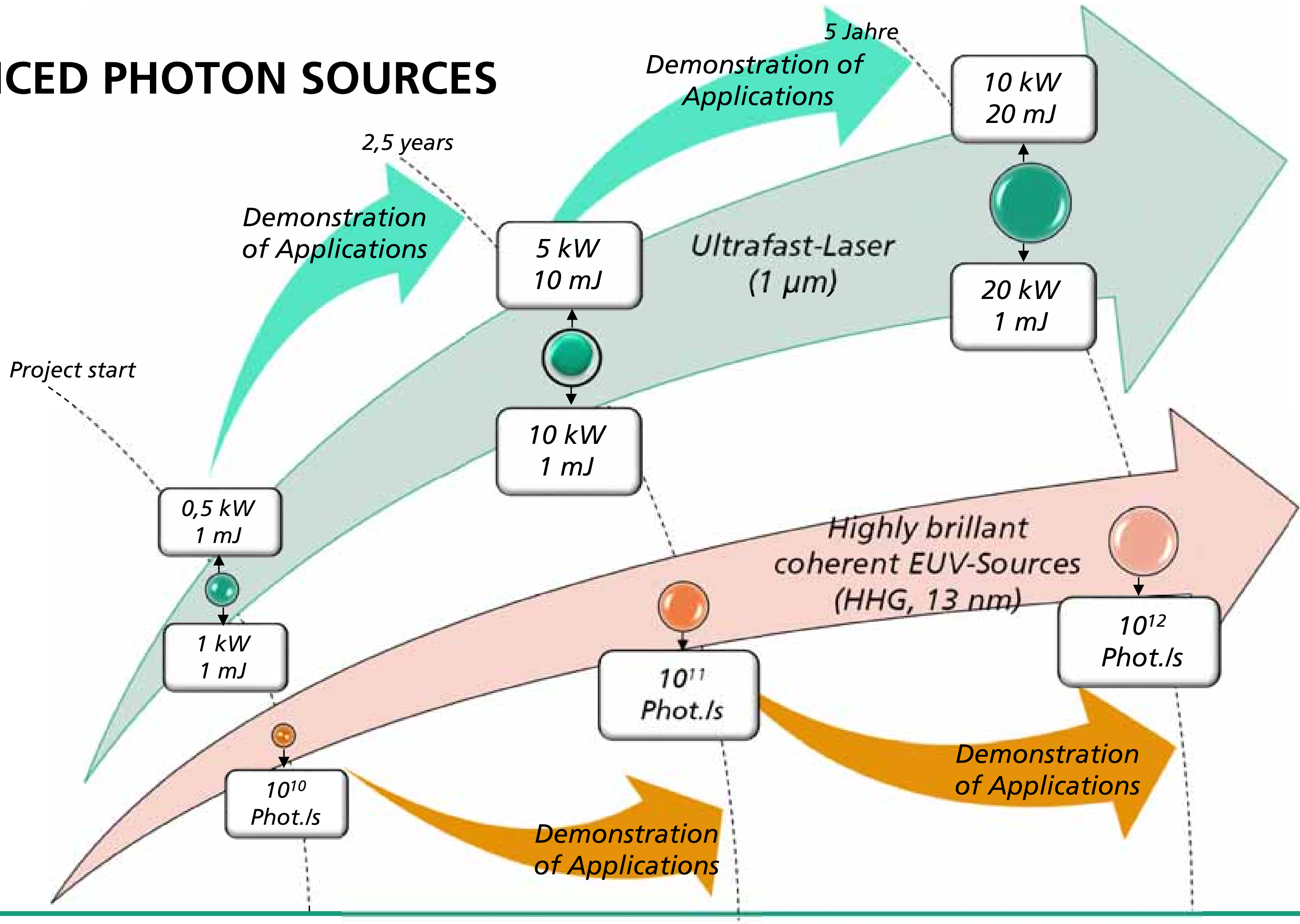
ADVANCED PHOTON SOURCES – Fraunhofer Cluster of Excellence

Vision - Scaling of Ultrafast Lasers to the Average Power Range of Industrial CW Sources

ADVANCED PHOTON SOURCES



ADVANCED PHOTON SOURCES



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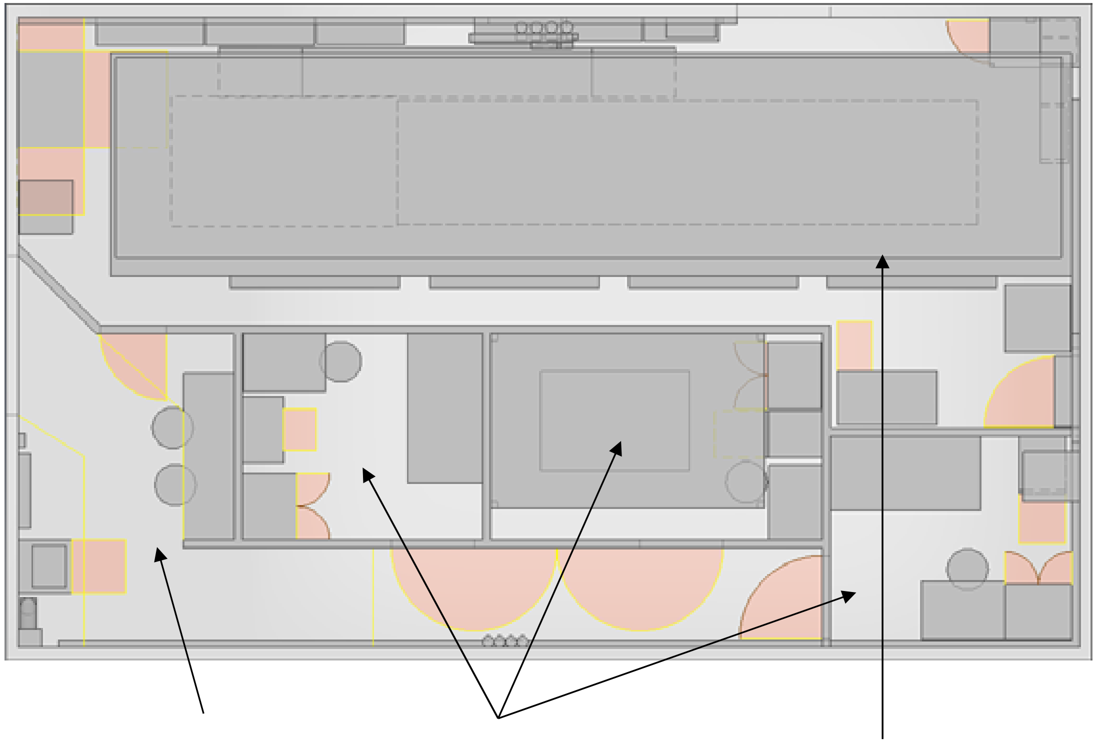
Advanced Photon Sources User Facility – Application Lab ILT



- Lab will be available in September 2019
  - 1 kW 600 fs in 2019
  - 500 W < 100 fs in 2019
  - 2.5 kW < 100 fs in 2020
  - 5 kW end of 2020

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- Peter Rußbüldt, Jan Schulte, Thomas Sartorius, Johannes Weitenberg, Marco Hoefer, Philip Kucirek, Benjamin Erben, et. al.

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Thank You for listening