Johannes Weitenberg, Jan Schulte, Sebastian Nyga, Martin Adams, Marie-Claude Dicaire, Bastian Gronloh, Joerg Luttmann, Jochen Wueppen, Marie Jeanne Livrozet, Jana Ammersbach, Jared-Ephraim Jorzig, Rolf Wester, Dominik Esser, Heinrich Faidel, Patrick Baer, Marco Hoefer, Bernd Jungbluth, Martin Traub, Peter Russbueldt, Dieter Hoffmann, Carlo Holly, and Constantin Haefner

Fraunhofer Institute for Laser Technology ILT, Aachen

Robust high-average-power lasers and scaling to high pulse energy

European Advanced Accelerator Concepts workshop (EAAC), La Biodola Bay, Isola d'Elba, 09/19/2023

Agenda

Robust high-average-power lasers and scaling to high pulse energy

Fraunhofer ILT

Innoslab Platform for Power Scaling

Airborne and spaceborne LIDAR lasers

Femtosecond Lasers / Cluster Advanced Photon Sources

Nonlinear Pulse Compression by Multi-Pass-Cell Spectral Broadening

Driver Laser for Inertial Confinement Fusion

Fraunhofer ILT, Aachen

Research Center DPP

Fraunhofer ILT

Industry Building DPP

Prof. Dr. Constantin Häfner

Tailored Photon Sources

- Power / Energy
- Spatial Intensity distribution
- Temporal Shaping
- Wavelength and spectrum control
- Quantum properties
- Secondary Sources

Applications

- Laser Production Technology
- Measurement Technology
- Microelectronics
- Life Sciences
- Quantum Networks, Computing, Sensing
- Laser Inertial Fusion Energy

The INNOSLAB Laser Platform – Example for a Fraunhofer Success Story

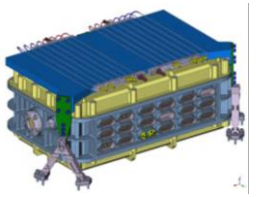
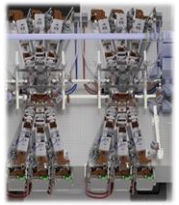
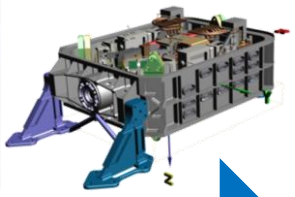
From Basic Patents over Scientific and Industrial Applications to LIDAR Transmitters for Space

First laboratory demonstration → Prototype for scientific partner (ANU) → Power Scaling 1 kW CW → First LIDAR Demonstrator → Power Scaling 400 W ps → Power Scaling 1 kW fs → Methane LIDAR MERLIN → Power Scaling 5 kW fs CAPS → Wind LIDAR AEOLUS II

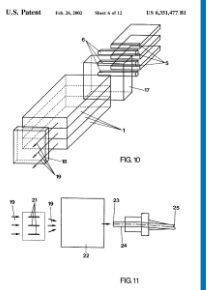




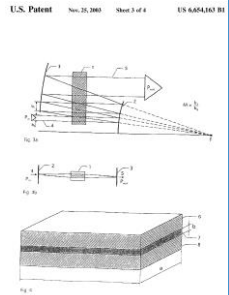


1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016 2018 2020 2022



Patent
partially pumped slab laser



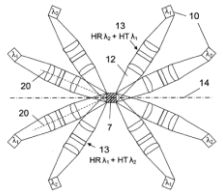
Patent
slab amplifier

edgewave

Spin Off
Foundation of EdgeWave
2001

AMPHOS

Spin Off
Foundation of AMPHOS
2010



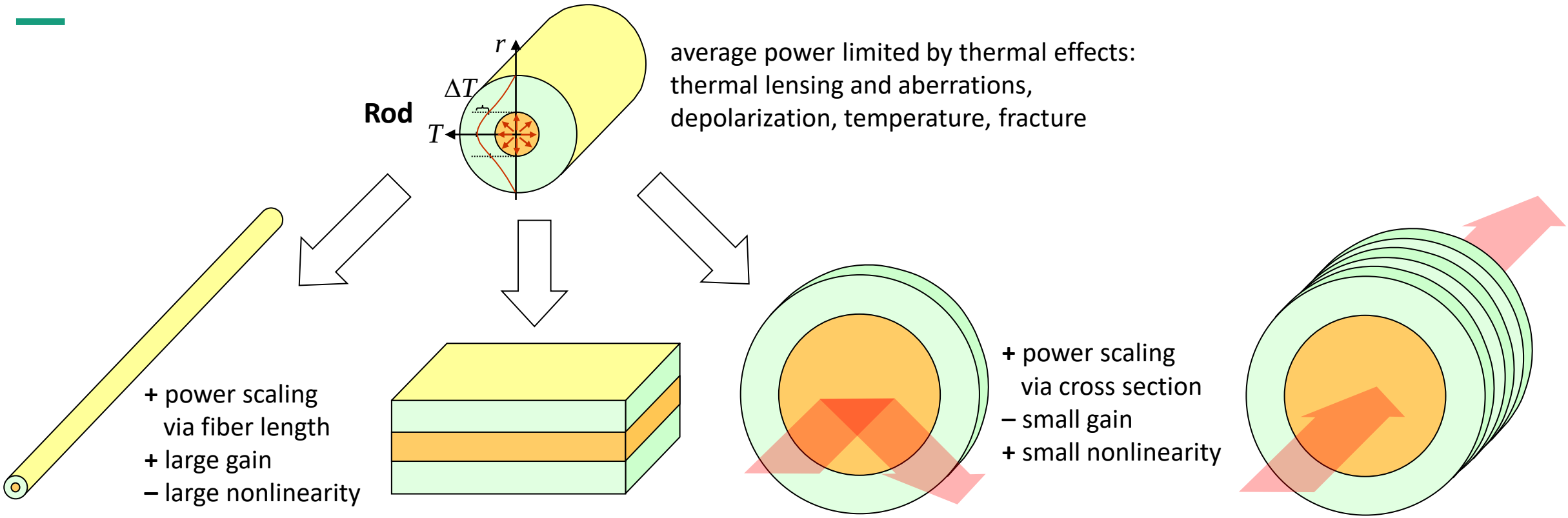
Patent
Angular Multiplexing
2013

Transfer and Cooperation

Amplitude · TRUMPF · DLR · esa · Airbus Defence and Space AIRBUS

Fraunhofer ILT

Power-scalable geometries of the active medium



Fiber

Waveguiding
(fundamental mode)

Innoslab

Aspect ratio
of the pumped volume

Thin-Disk („active mirror“)

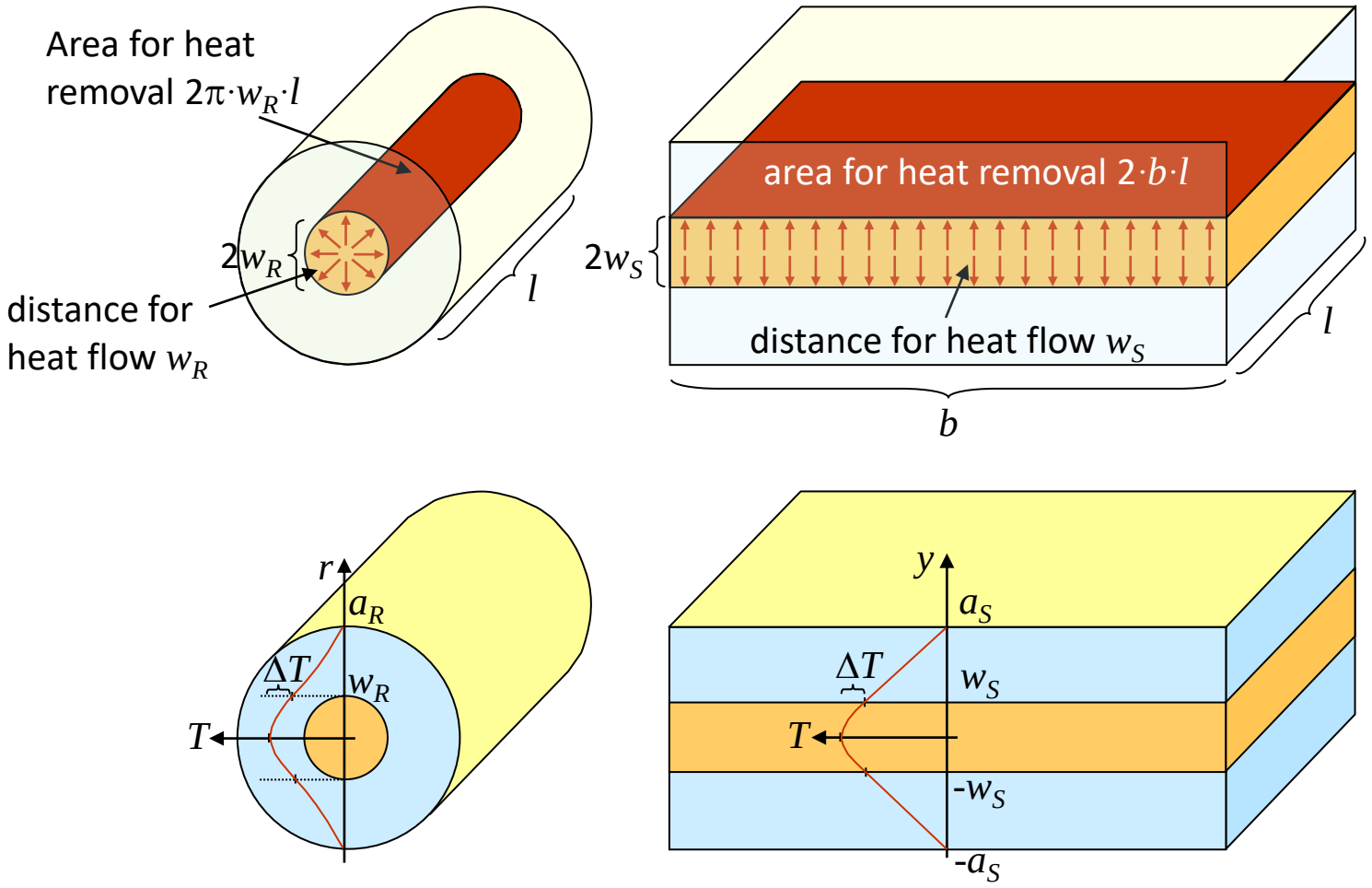
Heat flow in
propagation direction

Multi-Slab

Innoslab geometry – thermal Management

Rod
radial heat flow

Slab
1-dim. heat flow



The phase difference $\Delta\phi \sim \Delta T \cdot l$ determines the thermal aberrations and limits the power at diffraction-limited beam quality.

For the ro geoemtery, it is independent of the pump cross section. For the slab geoemtry, it scales with the aspect ratio:

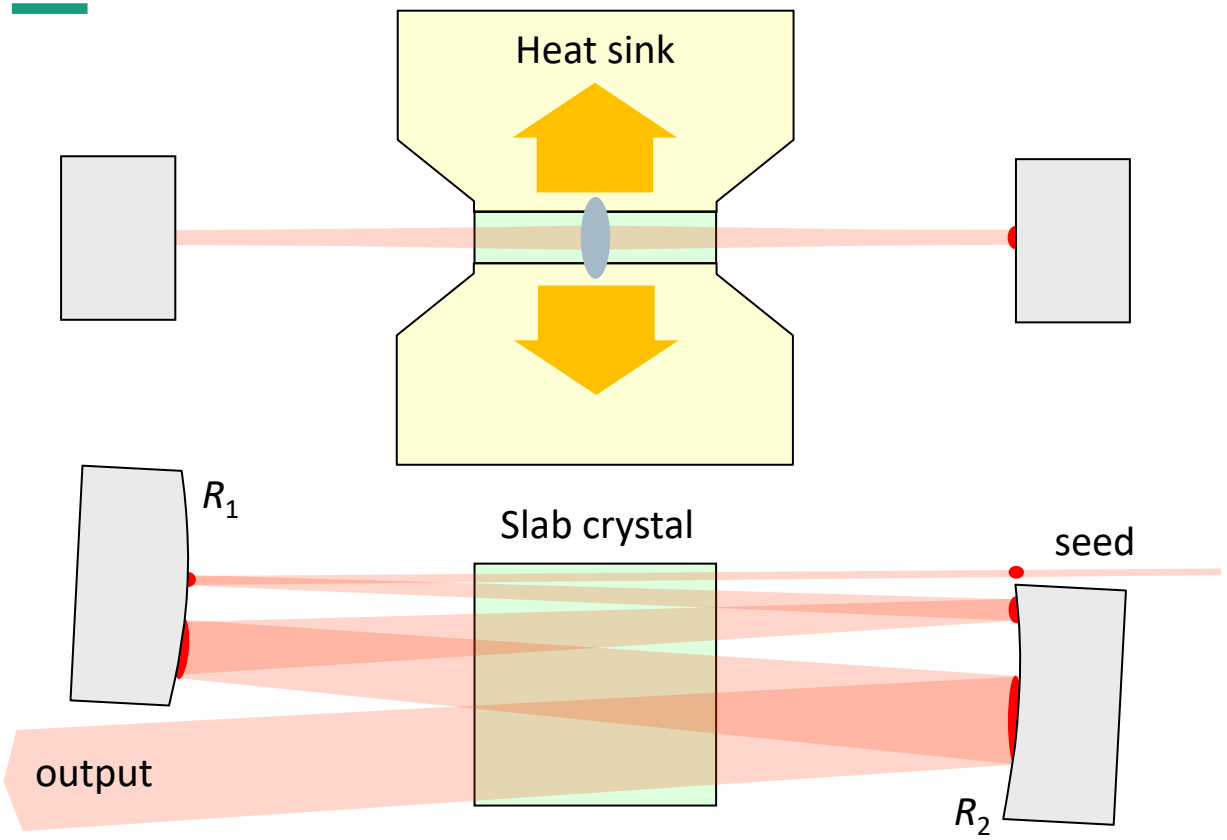
$$\Delta T_R l = \frac{P}{\kappa}\frac{1}{4\pi} \qquad \Delta T_S l = \frac{P}{\kappa}\frac{w_S}{4b}$$

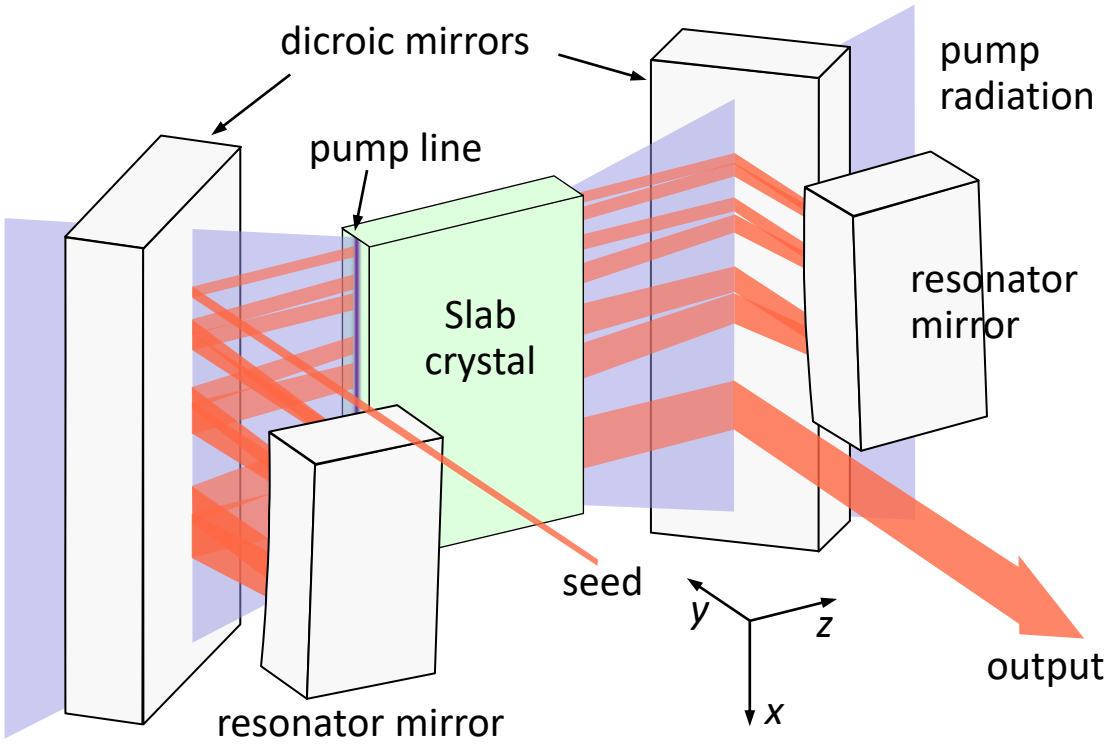
$$\frac{\Delta T_S}{\Delta T_R} = \frac{\pi}{2}\frac{2w_S}{b}$$

An aspect ratio of e.g. $b/2w_S = 50$ (10 mm / 0.2 mm) allows for a 30× larger power.

P. Russbueldt et al. „Innoslab amplifiers," IEEE Journal of Selected Topics in Quantum Electronics 21, 447-463 (2015). DOI 10.1109/JSTQE.2014.2333234

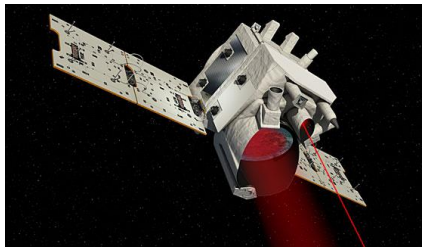
Innoslab amplifier – hybrid resonator

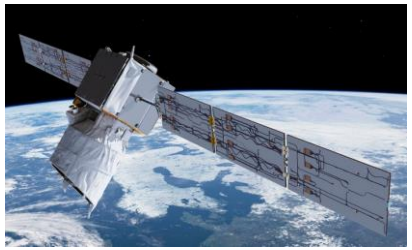


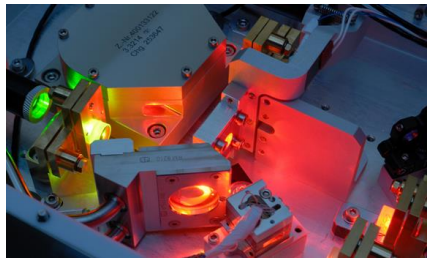


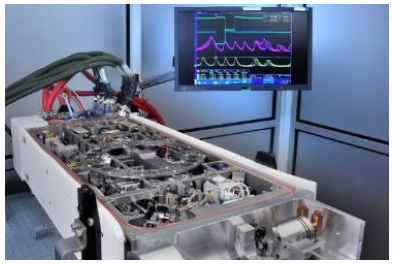
Fraunhofer ILT

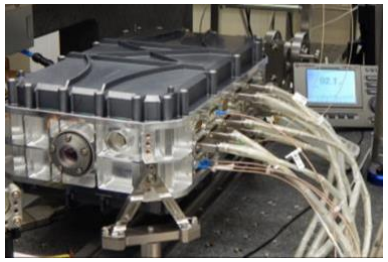
LIDAR – Laser Sources for Aerospace Operation

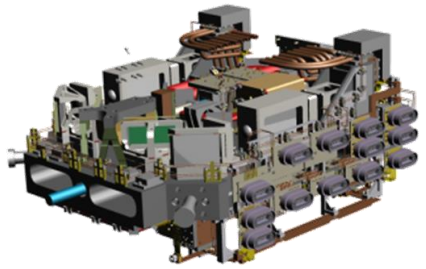












AirLIF

- OH concentration by LIF @315nm
- Successful flight campaign in 2011

CHARM

- CH4 @3µm
- System fully qualified
- Commercial operation

CHARM - F

- CH4@1.65µm
- CO2@2.05µm
- Successful HALO Flight campaigns in 2015 and 2018

FULAS

- ATLID Specs
- Successful demonstration including TV and long term tests

MERLIN

- CH4 @1.654µm
- Components and Sub Modules qualified
- EQM and FM AIT ongoing

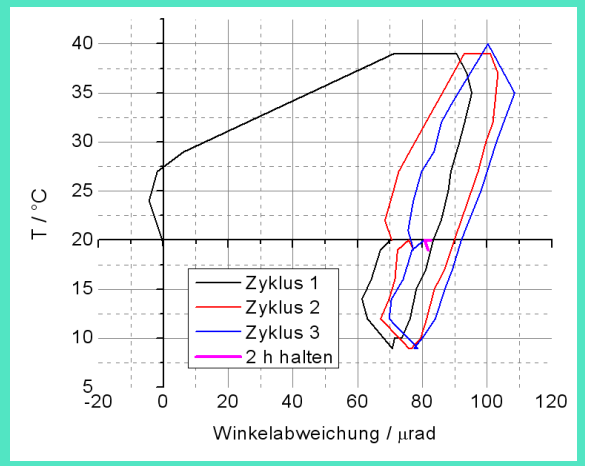
AEOLUS-2

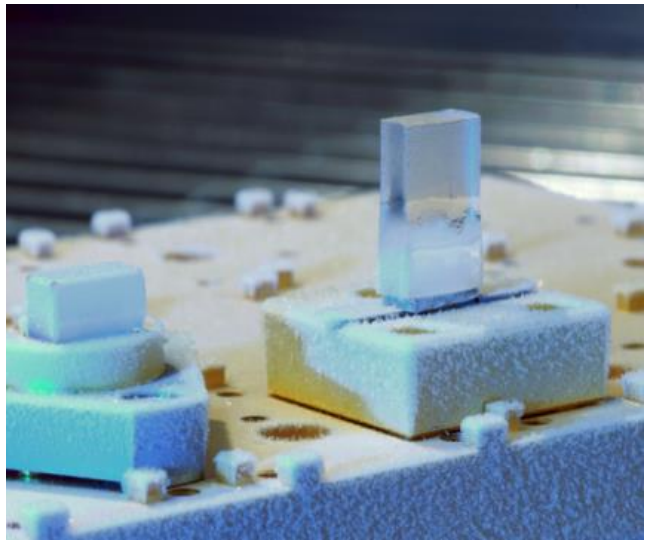
- Doppler Wind LIDAR
- UV @ 355 nm
- EM Components in Procurement

Fraunhofer ILT

Proprietary Mounting Technology of ILT

Conventional mirror mounts



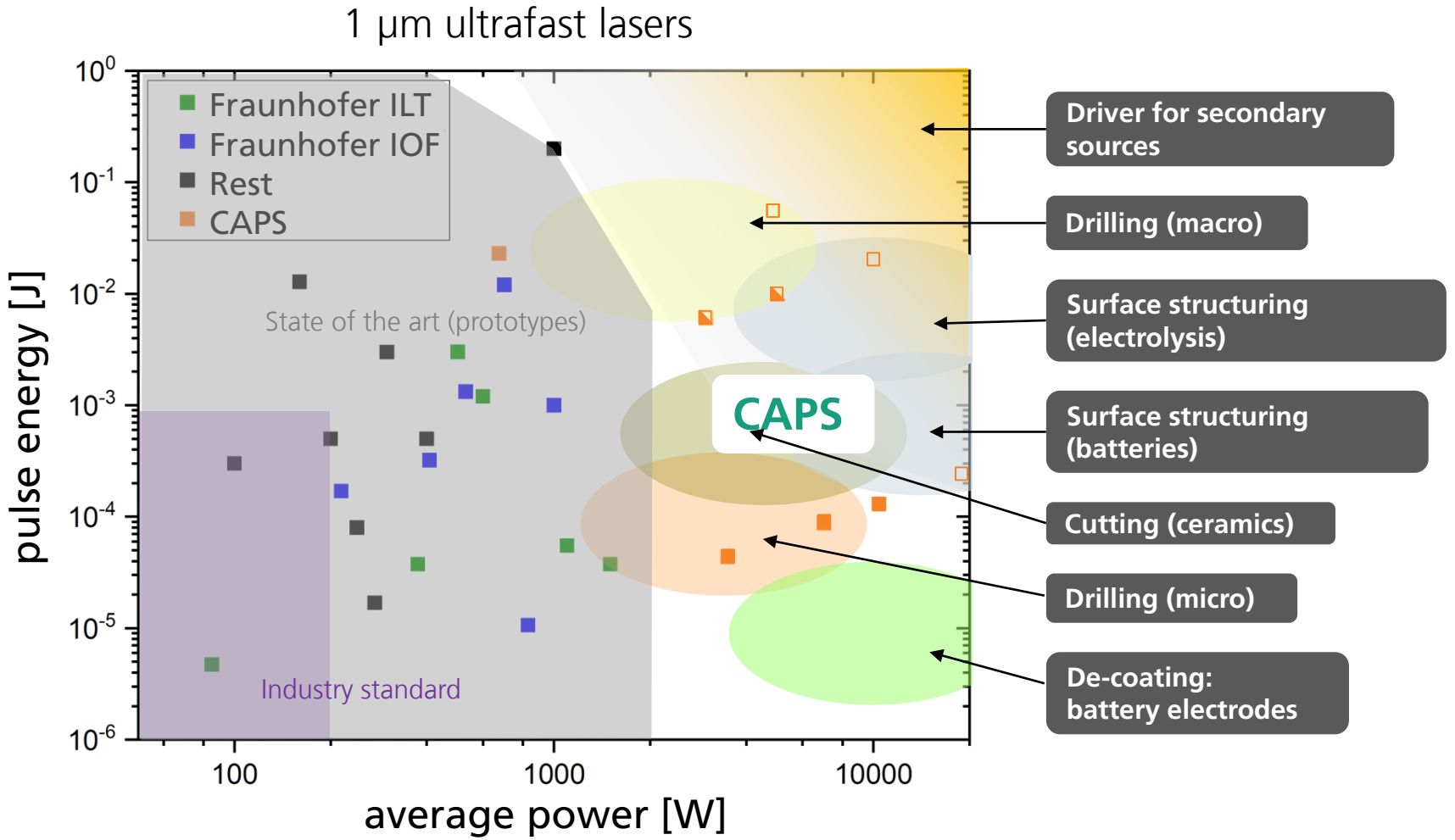


- No Alignment Screws
- Ultra High Thermomechanical Stability

→ **„Set and forget“**

Fraunhofer Cluster of Excellence Advanced Photon Sources (CAPS)

laser sources with unique parameters and enabling next-generation applications



Fraunhofer ILT

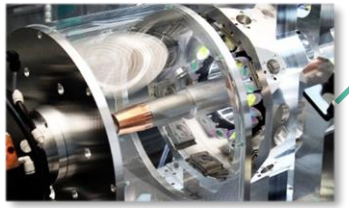
The Applications Labs of CAPS User-Facility are ready for testing your ideas

Application lab Aachen

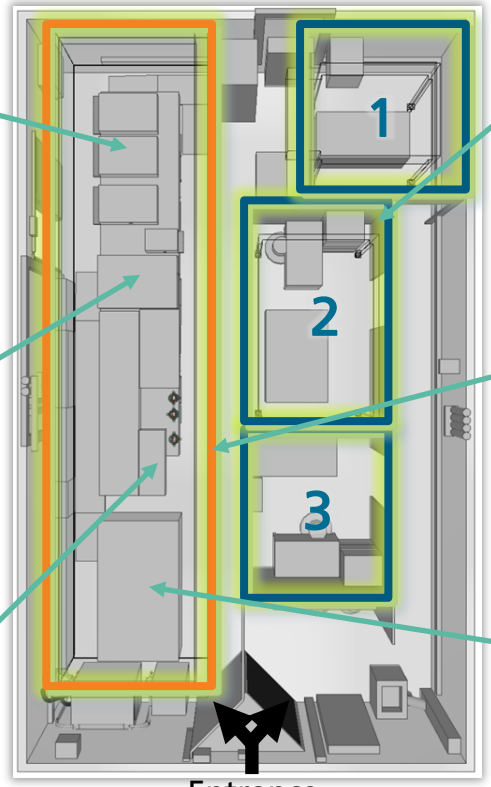
Focus: high-thoughput material processing

1 kW Frontend

5 kW Innoslab-Verstärker



10 kW Thin-Disk amplifier



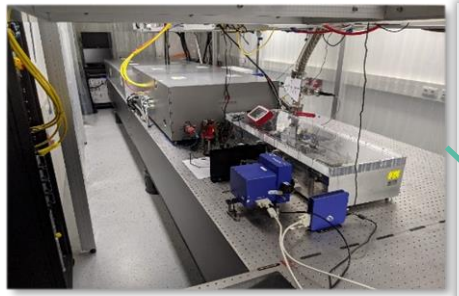
Application chambers 1-3

Beam routing

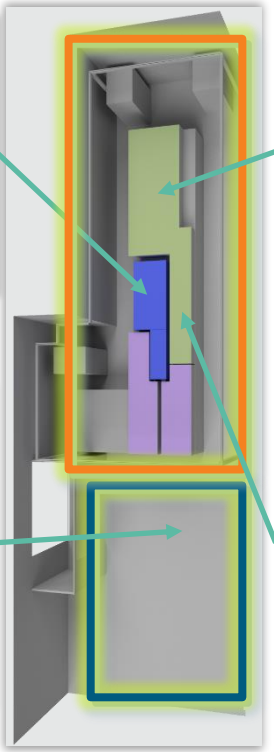
500 W, 30 fs laser system

Application lab Jena

Focus: high-harmonic generation

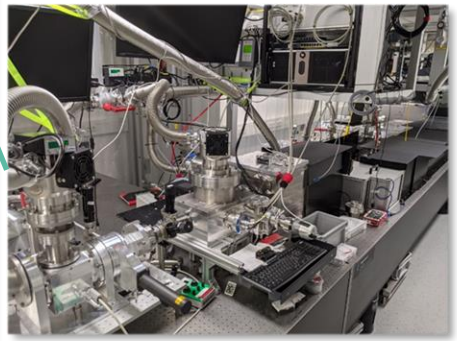


2µm ultrafast fiber Laser



1µm ultrafast fiber laser

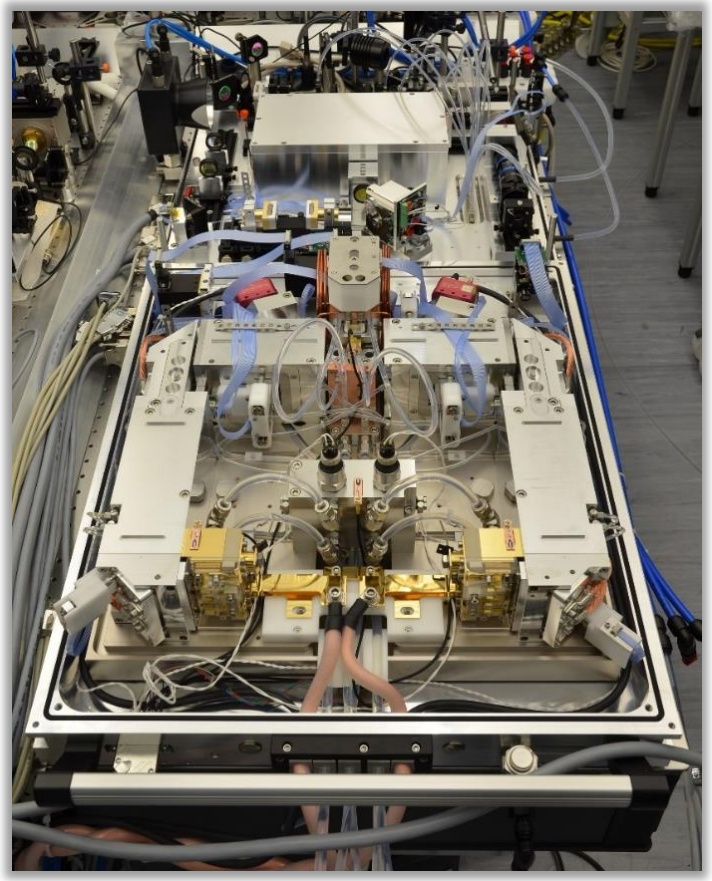
Application area



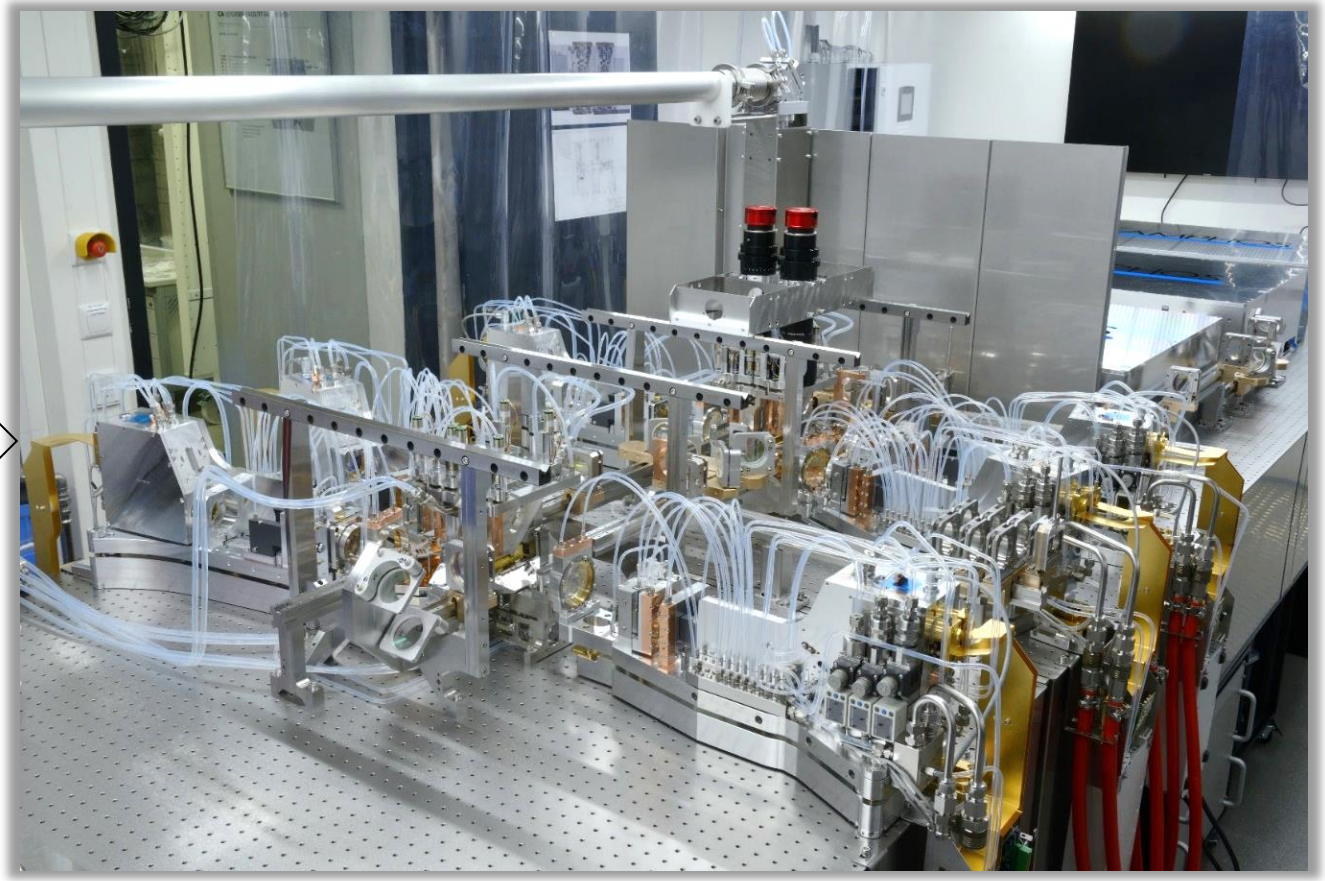
1µm pulse compression

Fraunhofer ILT

Next-Generation Femtosecond Yb-Innoslab amplifiers



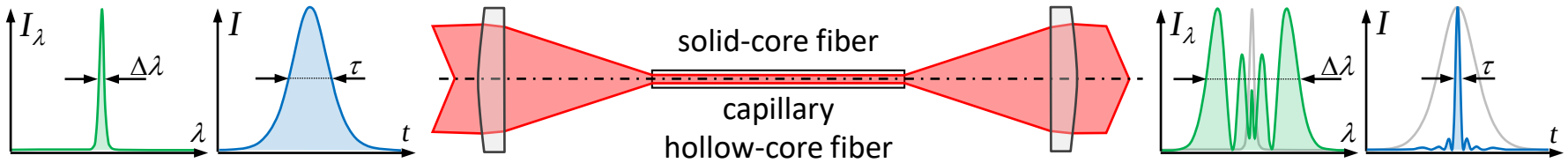
Fraunhofer CAPS

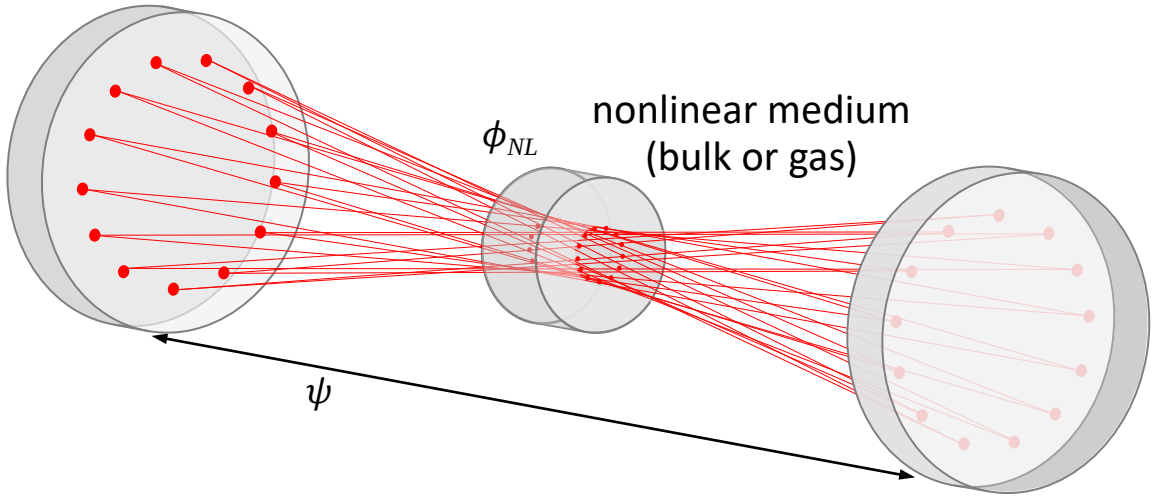


2017: 500 W extracted power per gain module

2022: >2000 W extracted power per gain module

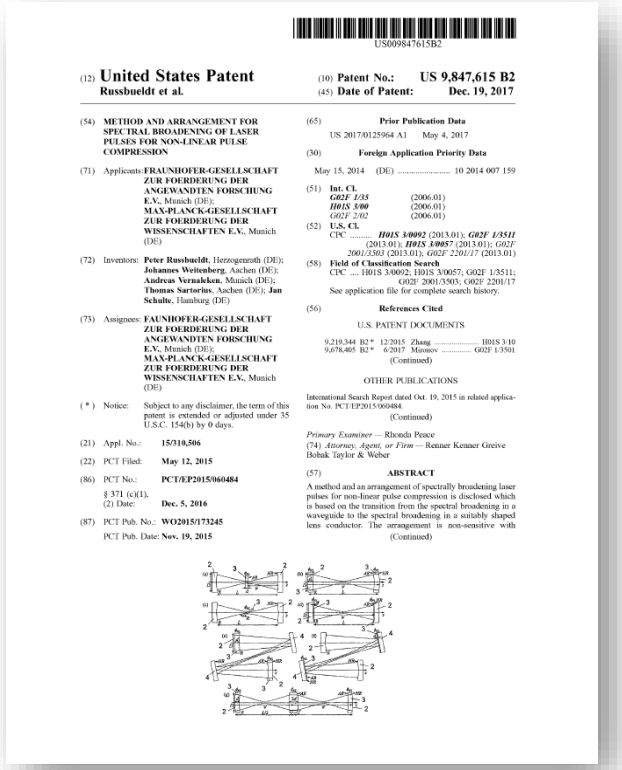
Nonlinear pulse compression at highest average powers





Multi-pass-cell spectral broadening (MPCBS):

- **Applicable for 1-100 µJ (solid) or >100 µJ (gas-filled)**
- **Highly efficient (>90%)**
- **Insensitive to variations of pulse energy, beam position/profile**



US009847615B2

(12) **United States Patent**
Russbueldt et al.

(10) **Patent No.: US 9,847,615 B2**
(45) **Date of Patent: Dec. 19, 2017**

(54) **METHOD AND ARRANGEMENT FOR SPECTRAL BROADENING OF LASER PULSES FOR NON-LINEAR PULSE COMPRESSION**

(71) Applicants: **FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.**, Munich (DE); **MAX-PLANCK-GESELLSCHAFT ZUR FOERDERUNG DER WISSENSCHAFTEN E.V.**, Munich (DE)

(72) Inventors: **Peter Russbueldt**, Herzogenrath (DE); **Johannes Weitenberg**, Aachen (DE); **Andreas Vernaleken**, Munich (DE); **Thomas Sartorius**, Aachen (DE); **Jan Schulte**, Hamburg (DE)

(73) Assignees: **FAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.**, Munich (DE); **MAX-PLANCK-GESELLSCHAFT ZUR FOERDERUNG DER WISSENSCHAFTEN E.V.**, Munich (DE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **15/310,506**

(22) PCT Filed: **May 12, 2015**

(86) PCT No.: **PCT/EP2015/060484**
§ 371 (c)(1),
(2) Date: **Dec. 5, 2016**

(87) PCT Pub. No.: **WO2015/173245**
PCT Pub. Date: **Nov. 19, 2015**

(65) **Prior Publication Data**
US 2017/0125964 A1 May 4, 2017

(30) **Foreign Application Priority Data**
May 15, 2014 (DE) 10 2014 007 159

(51) **Int. Cl.**
G02F 1/35 (2006.01)
H01S 3/00 (2006.01)
G02F 2/02 (2006.01)

(52) **U.S. Cl.**
CPC ***H01S 3/0092*** (2013.01); ***G02F 1/3511*** (2013.01); ***H01S 3/0057*** (2013.01); *G02F 2001/3503* (2013.01); *G02F 2201/17* (2013.01)

(58) **Field of Classification Search**
CPC ... H01S 3/0092; H01S 3/0057; G02F 1/3511; G02F 2001/3503; G02F 2201/17
See application file for complete search history.

(56) **References Cited**
U.S. PATENT DOCUMENTS
9,219,344 B2 * 12/2015 Zhang H01S 3/10
9,678,405 B2 * 6/2017 Mosnoy G02F 1/3501
(Continued)
OTHER PUBLICATIONS
International Search Report dated Oct. 19, 2015 in related application No. PCT/EP2015/060484.
(Continued)

Primary Examiner — Rhonda Peace
(74) *Attorney, Agent, or Firm* — Renner Kenner Greive Bobak Taylor & Weber

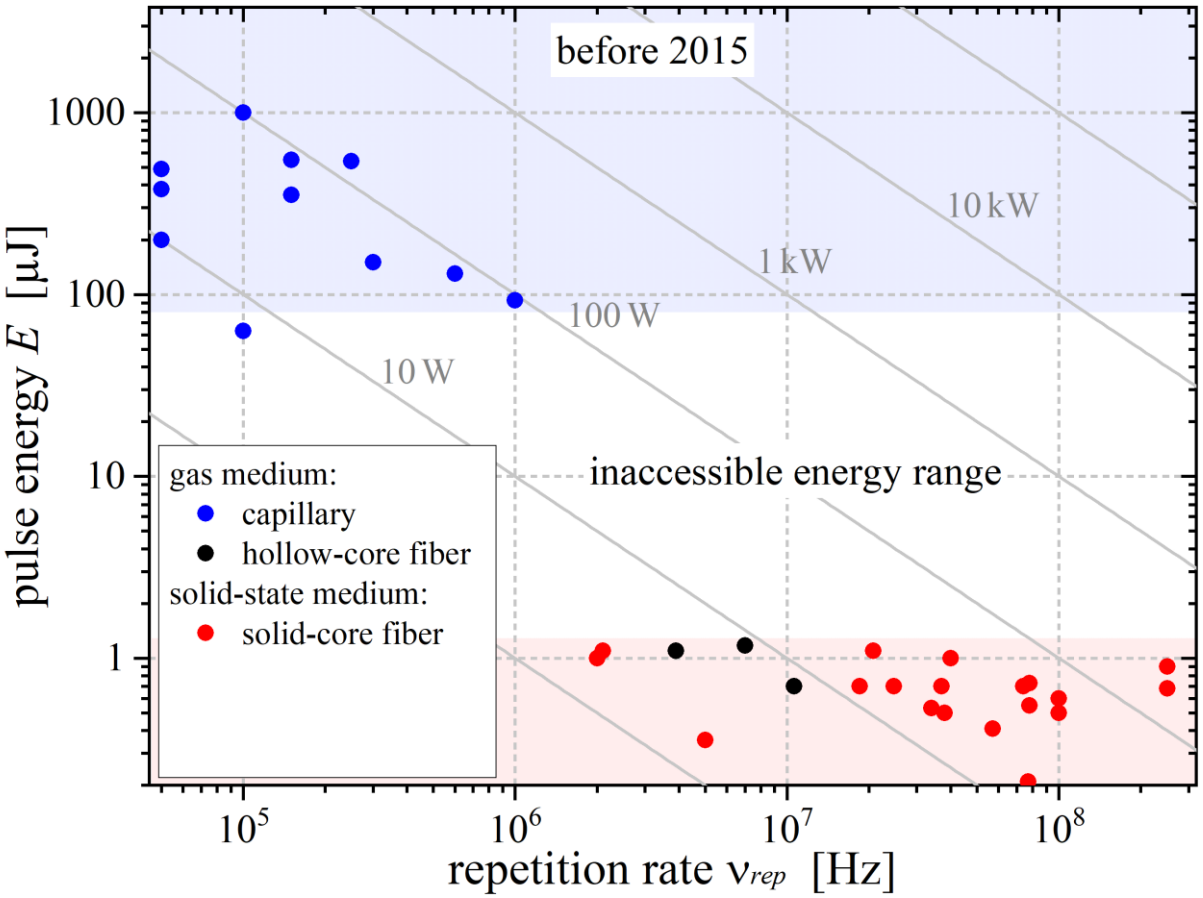
(57) **ABSTRACT**
A method and an arrangement of spectrally broadening laser pulses for non-linear pulse compression is disclosed which is based on the transition from the spectral broadening in a waveguide to the spectral broadening in a suitably shaped lens conductor. The arrangement is non-sensitive with
(Continued)

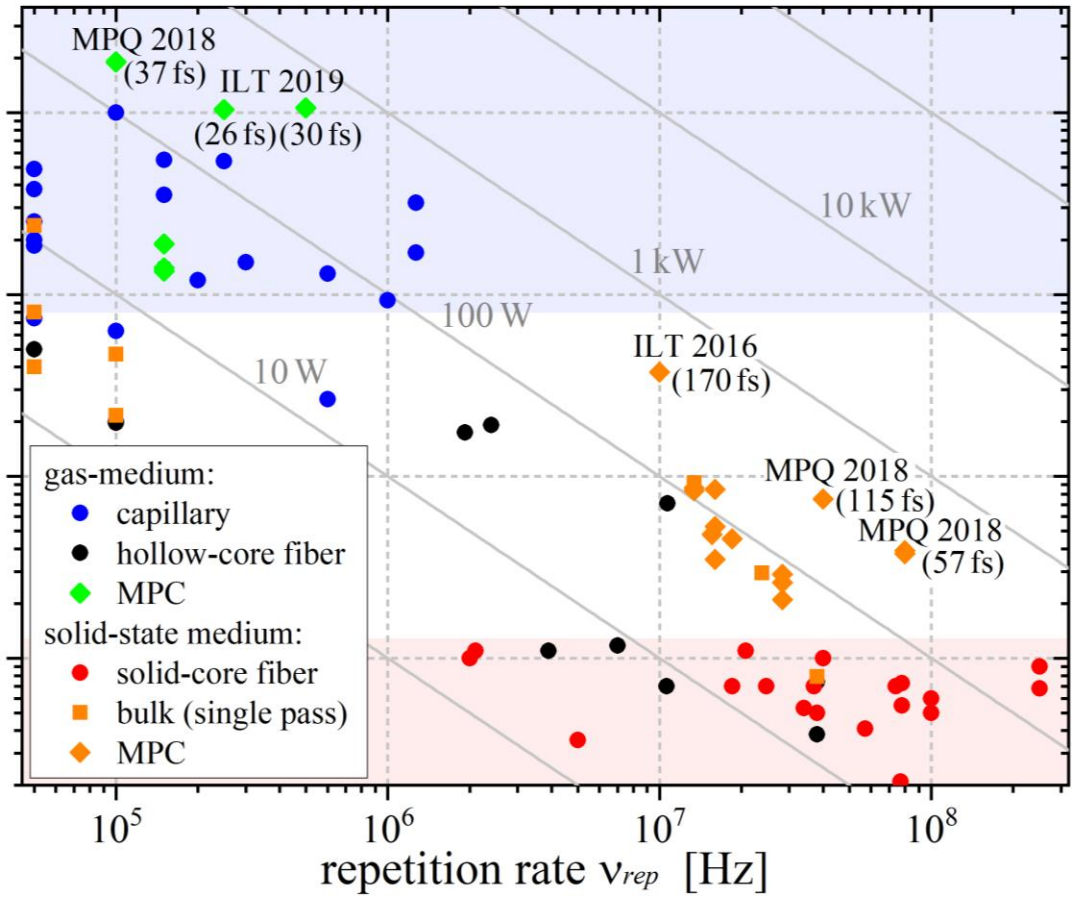
Patents: DE102014007159B4; US 9,847,615 B2

J. Schulte et at., Opt. Lett. 41, 4511-4514 (2016).

Fraunhofer ILT

Nonlinear pulse compression – overview

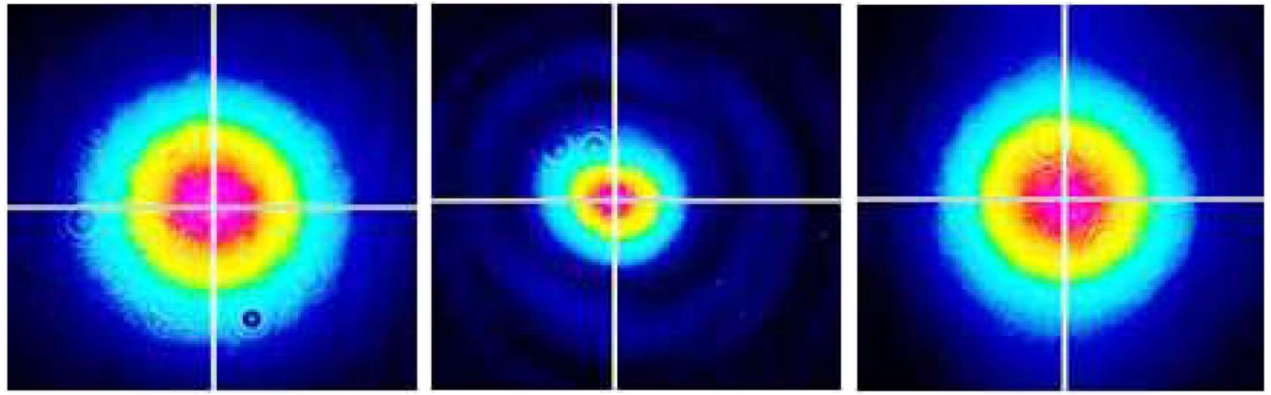




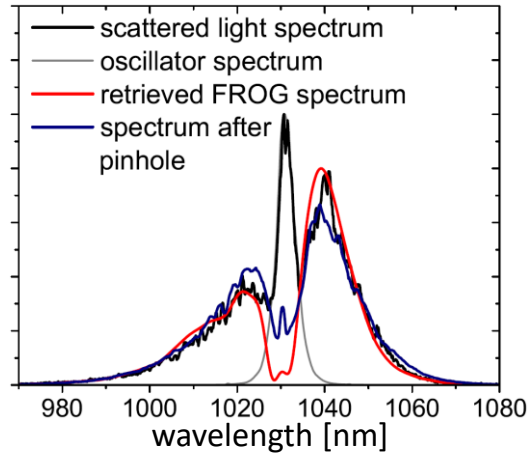
Fraunhofer ILT

Homogeneity of nonlinear spectral broadening

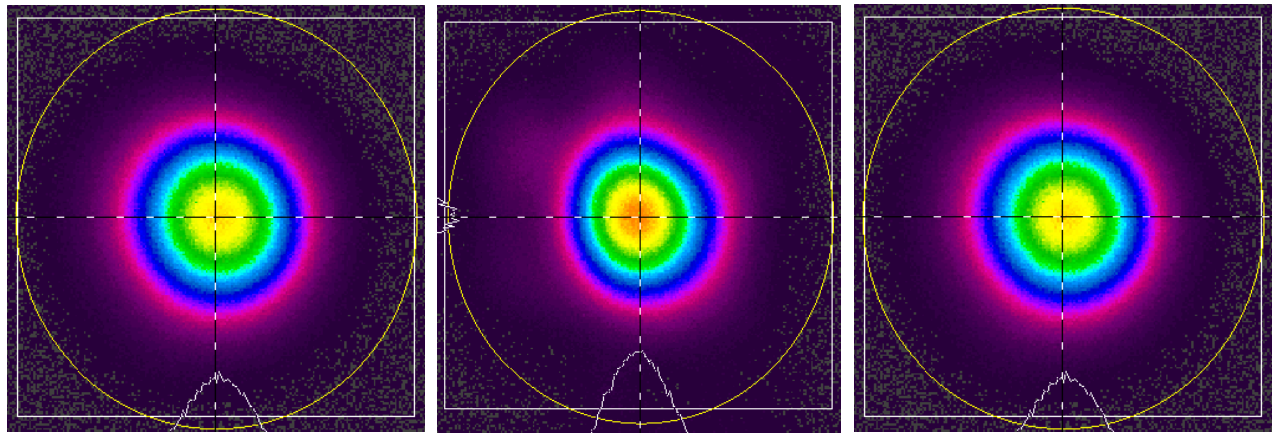
Single-pass bulk compression (before filtering to $M^2 < 1.1$ with pinhole and 53% transmission) [1].



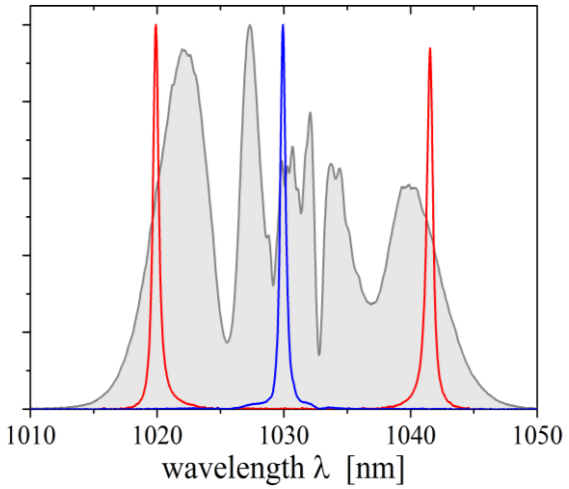
1010 nm 1030 nm 1050 nm



MPCSB – bulk compression with many passes (57) through nonlinear medium ($M^2 = 1.15$) [2].



1020 nm & 1042 nm 1030 nm 1020 nm & 1042 nm



spatial overlap $U > 98.5\%$ for all wavelengths.

[1] M. Seidel et al., Opt. Express 24, 9412-9428 (2016).
[2] J. Weitenberg et al., Opt. Express 25, 20502-20510 (2017).

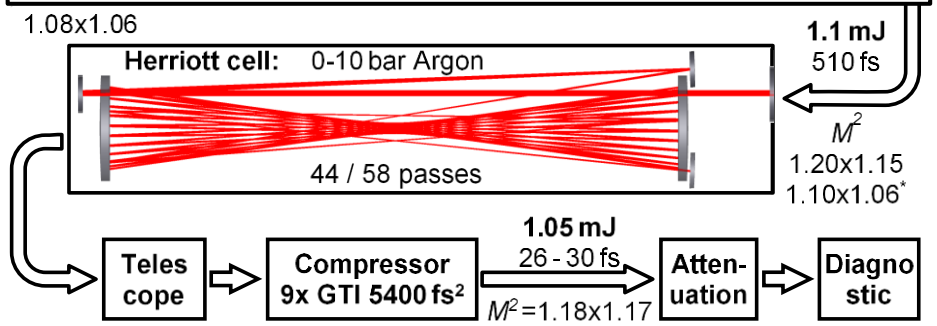
MAX PLANCK INSTITUTE OF QUANTUM OPTICS

Fraunhofer ILT

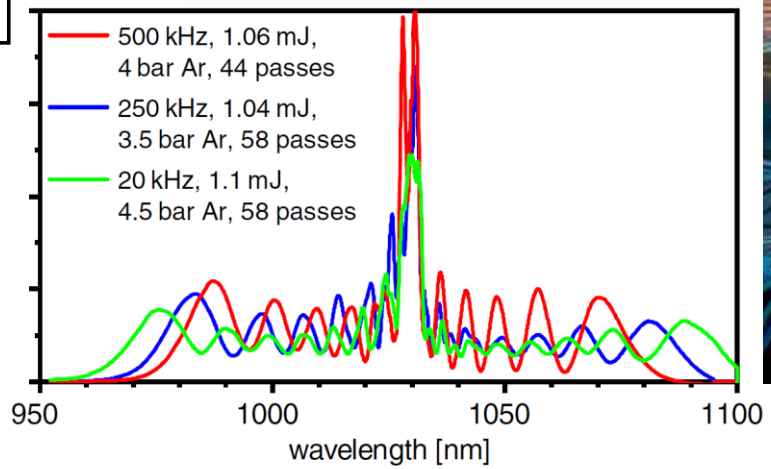
Nonlinear pulse compression in CAPS

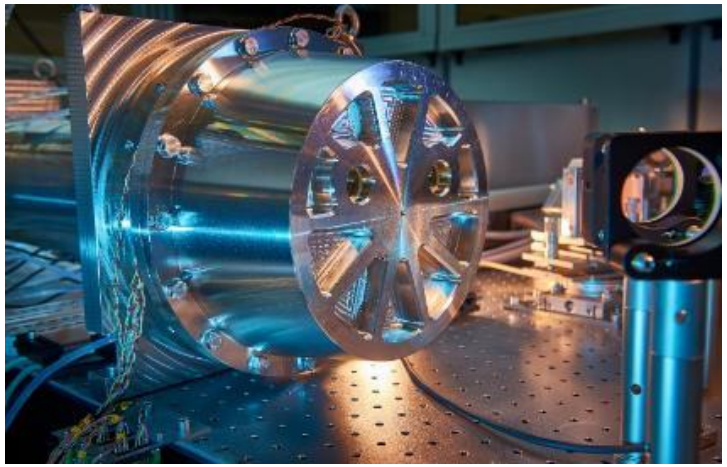
Laser system:

- Center wavelength: 1.03 µm
- Input power: 550 W
- Pulse energy: 1.1 mJ
- Pulse duration: 510 fs



- Output power: 530 W
- Pulse energy: 1.06 mJ
- Pulse duration: 28 fs
- Beam quality M²: 1.18 × 1.17
- Efficiency: 96%

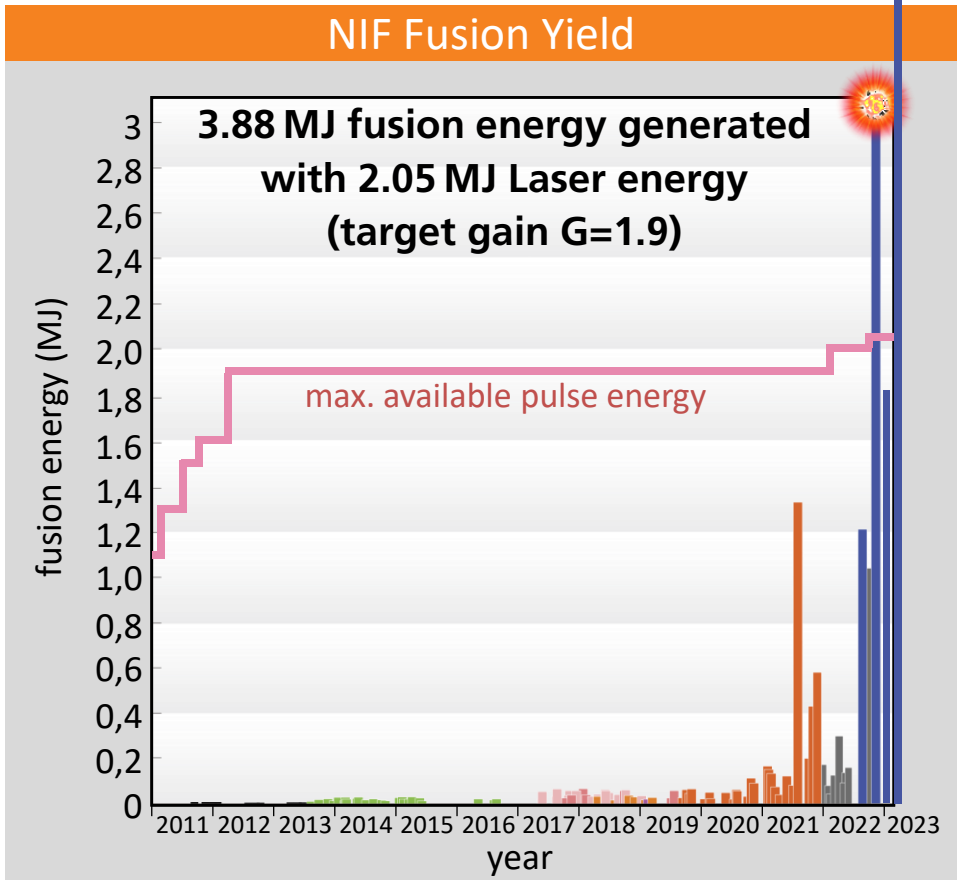




P. Russbueldt et al., Opt. Lett. 44 (21), 5222 (2019)

Fraunhofer ILT

Breakthrough for nuclear fusion: Ignition at National Ignition Facility (NIF) 12/05/2022 and 07/30/2023



H. Abu-Shawareb et al., PRL 129, 075001 (2022).
A. L. Kritcher et al., PRE 106, 025201 (2022).
A. B. Zylstra et al., PRE 106, 025202 (2022).

Lawrence Livermore National Laboratory

SPIEGEL Wissenschaft

Was der Durchbruch bei der Kernfusion für die Energiegewinnung der Zukunft bedeutet

Zum ersten Mal haben Fachleute bei der Kernfusion mehr Energie gewonnen als reingesteckt wurde. Die Methode könnte die Stromproduktion revolutionieren – doch noch sind viele Fragen offen.

Von Anika Freier
14.12.2022, 18.30 Uhr

Frankfurter Allgemeine

DEBATTE UM KERNFUSION

Irrlichter, keine Leuchtfeuer

Eine Entbürokratisierung soll der Kernfusion laut FDP-Fraktionsvize Christian Dürr Aufwind verleihen. Doch Naturgesetze lassen sich nicht entschlacken.

Hinnerk Feldwisch-Drentrup
18.04.2023 , 13:32 Uhr

ATOMKRAFT IN DEUTSCHLAND

Kernfusion als Königsweg

Die Regierung bereitet einen Plan zur Entwicklung neuer Atomkraftwerke vor. Die Industrie verspricht Unterstützung.

Marcus Theurer
03.06.2023 , 09:02 Uhr

PHYSICS TODAY

SHARE

National Ignition Facility earns its name for a second time

11 August 2023

Promotion of the achievement is muted as the laboratory saves the details of fusion energy ga

David Kramer

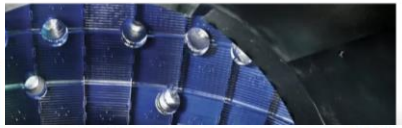
DOI: https://doi.org/10.1063/PT.6.2.20230811a

Energie

Diamanten made in Freiburg

27. April 2023, 17:30 Uhr | Lesezeit: 5 min

Süddeutsche Zeitung



Durchbruch bei Kernfusion

FOCUS online

Politik Finanzen Perspektiven Klima Wissen Gesun

The New York Times

Nachrichten › Wissen › Technik › US-Wissenschaftler verkünden D

Schier unerschöpfliche saubere Energiequelle

US-Wissenschaftler feiern Kernfusion

Scientists Achieve Nuclear Fusion Breakthrough With Blast of 192 Lasers

The advancement by Lawrence Livermore National Laboratory researchers will be built on to further develop fusion energy research.

Give this article 944

Kernfusion

ZEIT

Fusionsreaktor

Durchbruch in der Kernfusion! Das be
Doch die Sache ist komplizierter. Viel,
Welche sechs Probleme auf dem Weg
lösen sind.

Von **Dirk Asendorpf** und **Ulrich Schna**

Aktualisiert am 22. Dezember 2022, 5:55 Uhr

Investments of >1 Mrd € for the next 5 years in fusion research announced by the German federal gouvernment

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05/22/2023: BMBF Expert Commission (head Prof. Häfner, Fraunhofer ILT) presents Memorandum on Laser Fusion to German Research Minister Stark-Watzinger.

09/07/2023: Minister Stark Watzinger announces an increase of funding of nuclear fusion (ICF & MCF) by 370 Mio. € to >1 Mrd. € for the next 5 years.

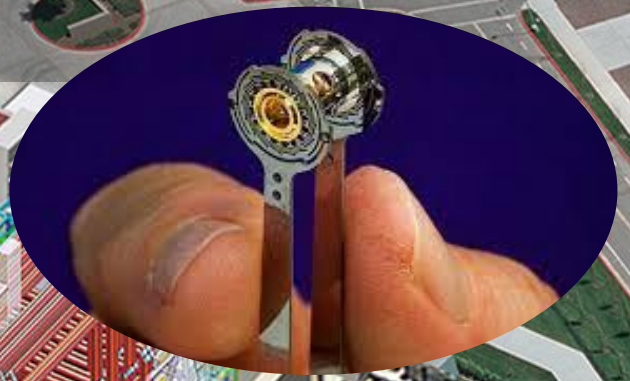
New: Programmatic funding of laser fusion in Germany.

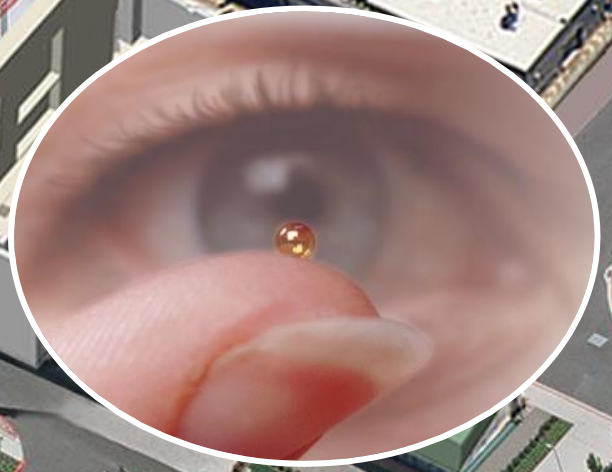
www.bmbf.de/SharedDocs/Downloads/de/2023/230522-memorandum-laser-inertial-fusion-energy.html
www.bmbf.de/bmbf/shareddocs/kurzmeldungen/de/2023/09/230905_fusion-PK.html

Fraunhofer ILT

The National Ignition Facility (NIF) at Lawrence Livermore National Lab (LLNL) is the world's largest and most energetic laser enabling the study of extreme conditions for high energy density science.

192 laser beams are concentrated into a mm^3 target.

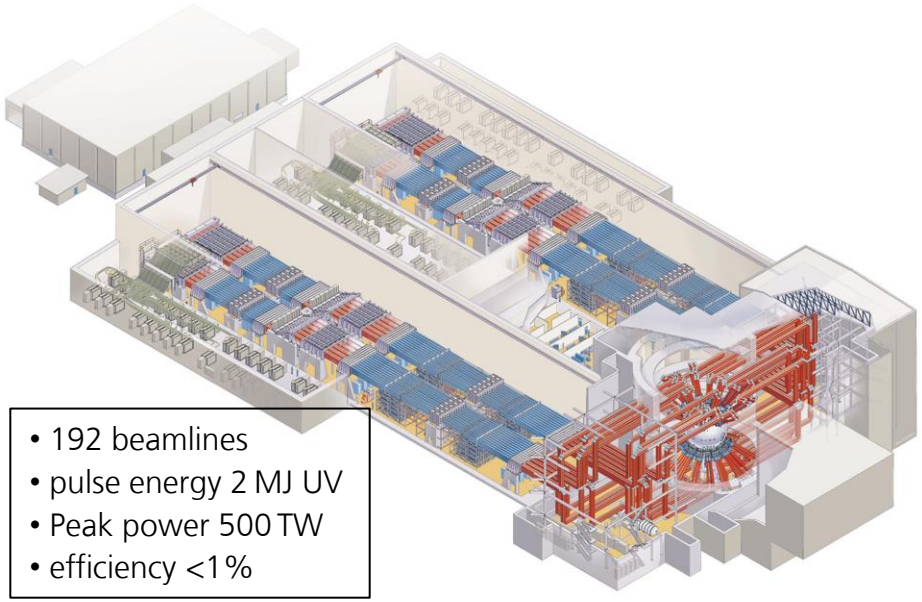




- 192 Beamlines
- energy 2 MJ
- power 500 TW
- Frequency-tripled Nd:glass
- wavelength 351 nm
- pulse duration 25 ns

The leap from NIF to an IFE power plant requires higher repetition rate and technology advances in many subsystems

NIF: single shot

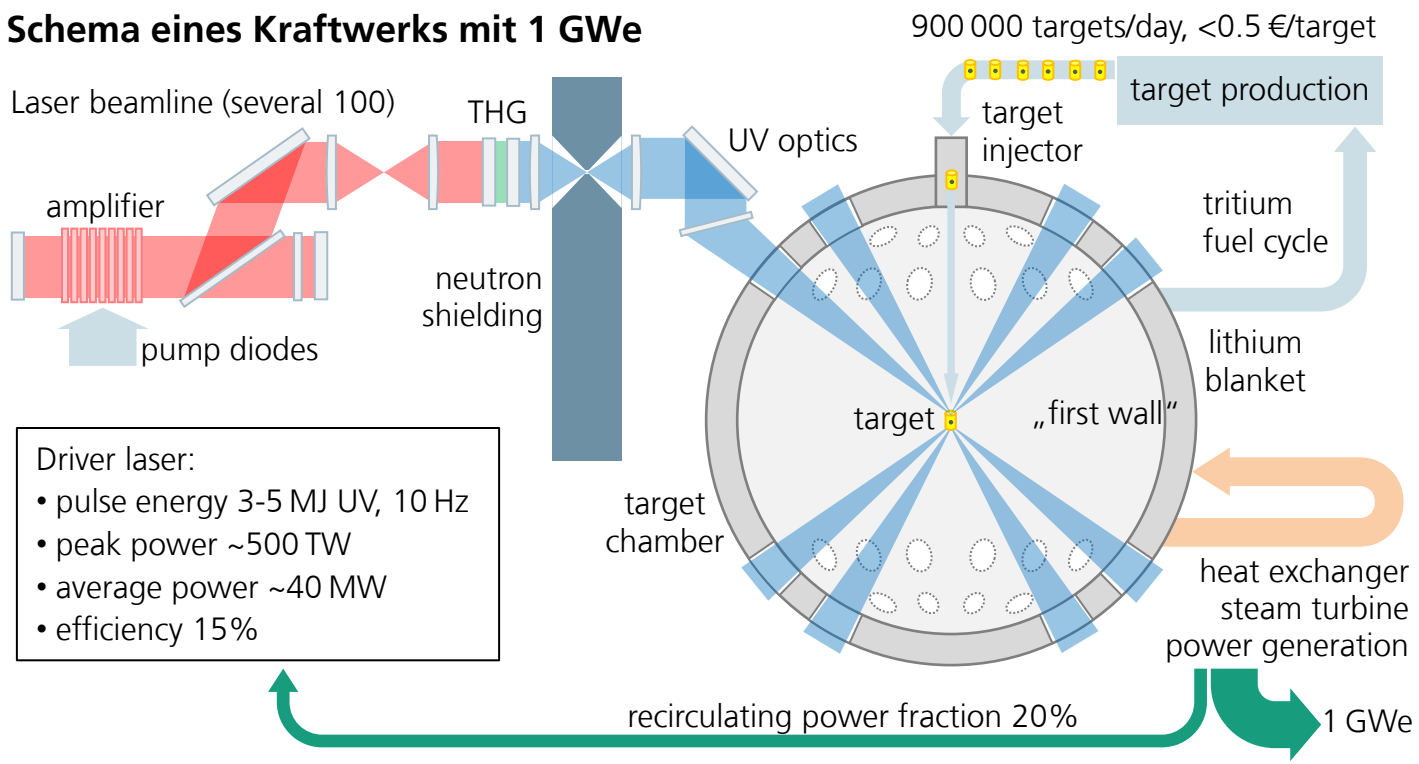


- 192 beamlines
- pulse energy 2 MJ UV
- Peak power 500 TW
- efficiency <1%

E. Moses, 19th IEEE/IPSS, SOFE (Cat. No.02CH37231), 487-492 (2002).

Fusion power plant: repetition rate 10 Hz

Schema eines Kraftwerks mit 1 GWe



Driver laser:
- pulse energy 3-5 MJ UV, 10 Hz
- peak power ~500 TW
- average power ~40 MW
- efficiency 15%

compare: A. Bayramian et al. Fusion Science and Technology 60, 28-48 (2011).

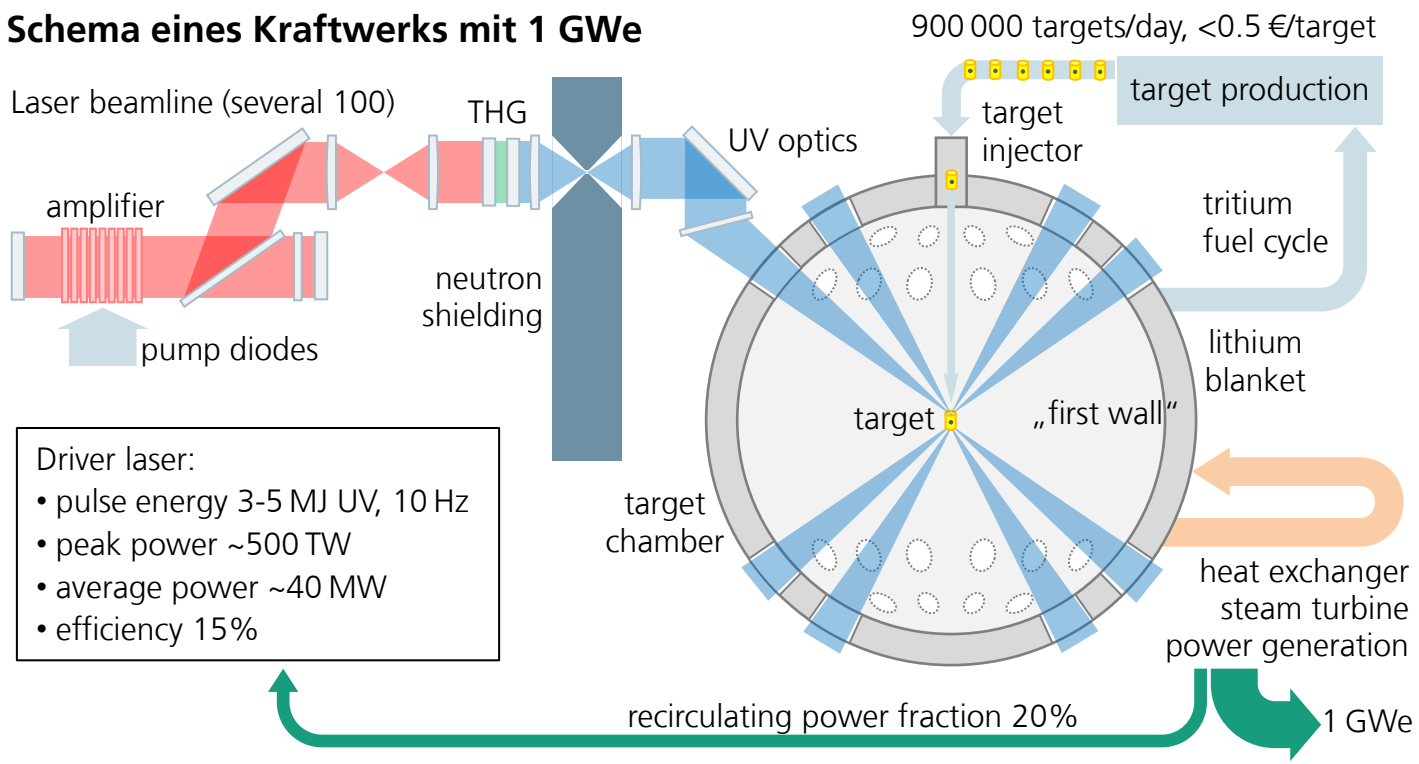
Fraunhofer ILT

The leap from NIF to an IFE power plant requires higher repetition rate and technology advances in many subsystems

An IFE power plant requires:

- A more robust, high-margin ignition scheme
- A high-efficiency, high repetition rate driver
- High repetition-rate target production, injection and tracking
- An energy conversion system
- Robust first walls and blankets
- Tritium processing and recovery
- Remote maintenance systems
- Viable economics

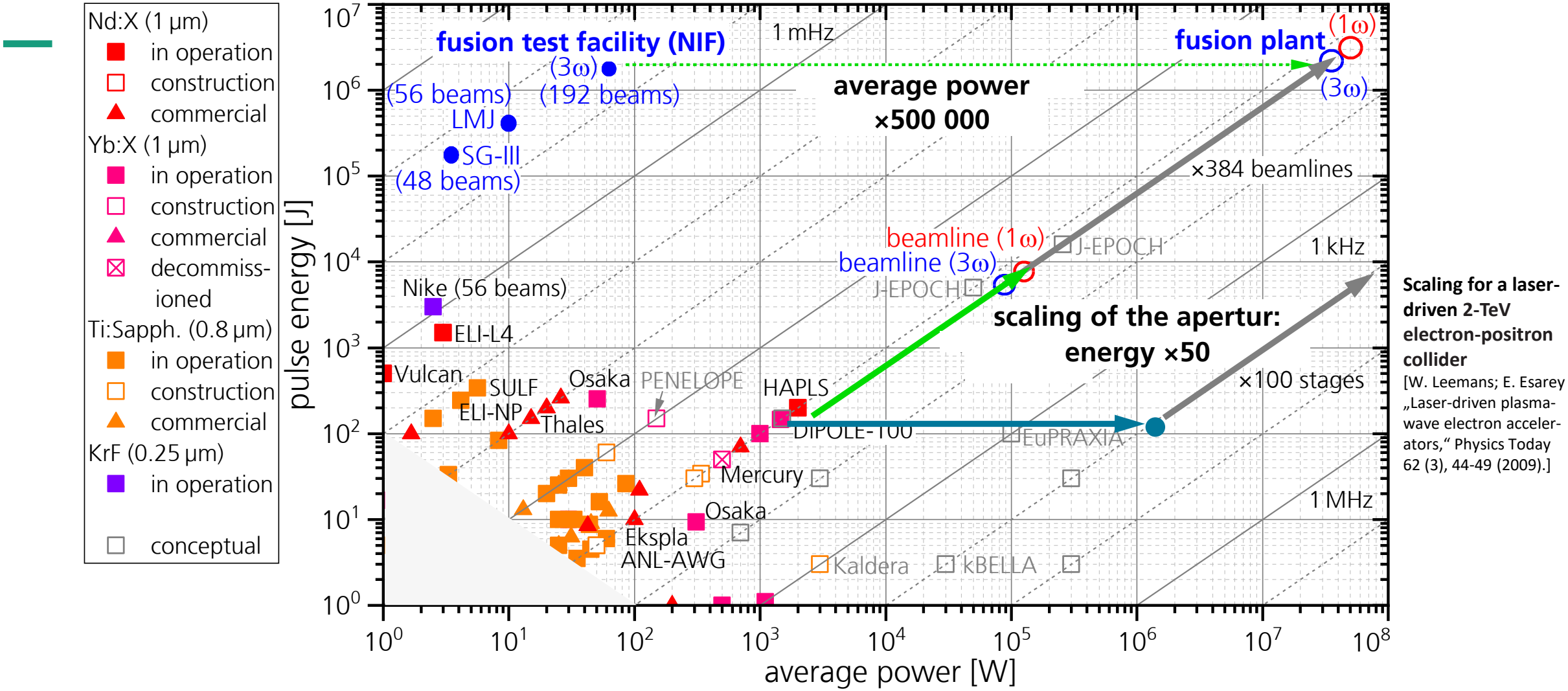
Fusion power plant: repetition rate 10 Hz



compare: A. Bayramian et al. Fusion Science and Technology 60, 28-48 (2011).

Fraunhofer ILT

An ICE fusion power plant requires new laser technology



Scaling for a laser-driven 2-TeV electron-positron collider
[W. Leemans; E. Esarey „Laser-driven plasma-wave electron accelerators," Physics Today 62 (3), 44-49 (2009).]

Fraunhofer ILT

Lasers with 10 Hz repetition rate and high pulse energy are demonstrated

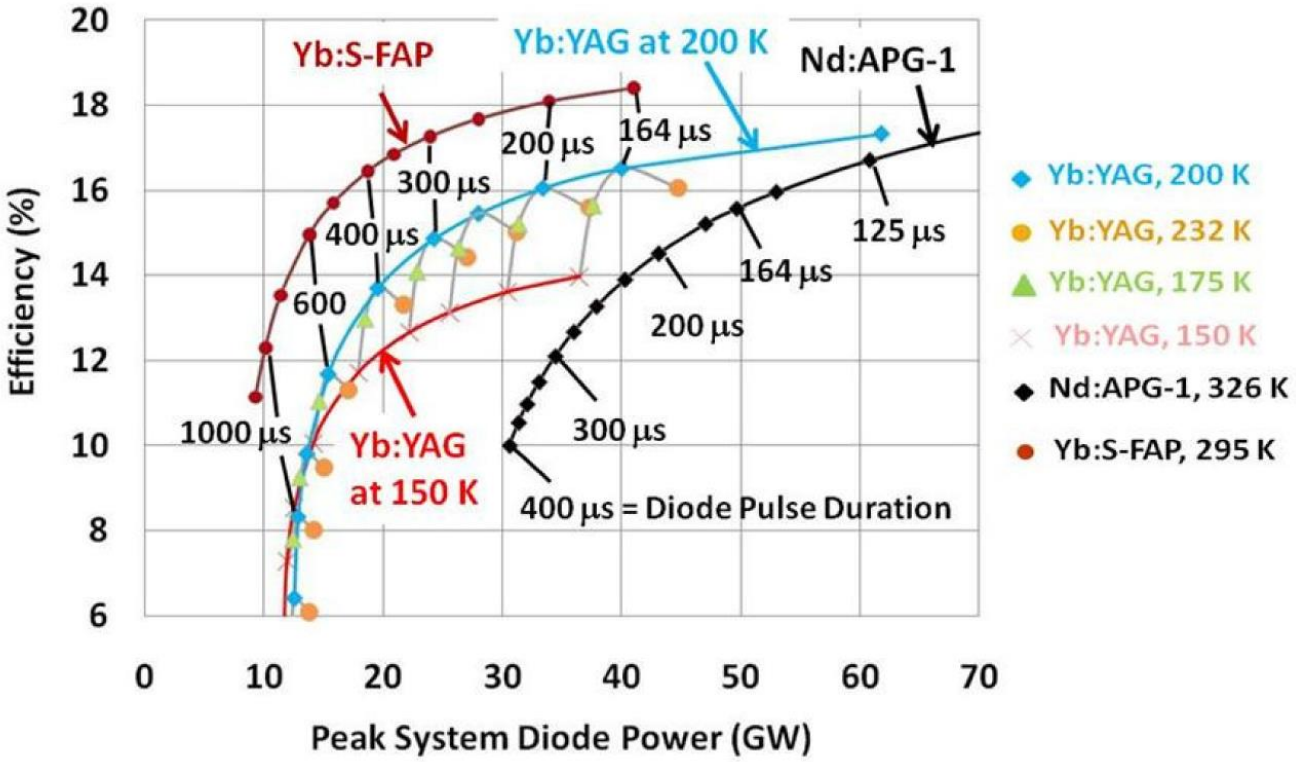
RAL: DiPOLE, Diode Pumped Optical Laser for Experiments (2017)

150 J, 10 Hz, Yb:YAG (cryo)

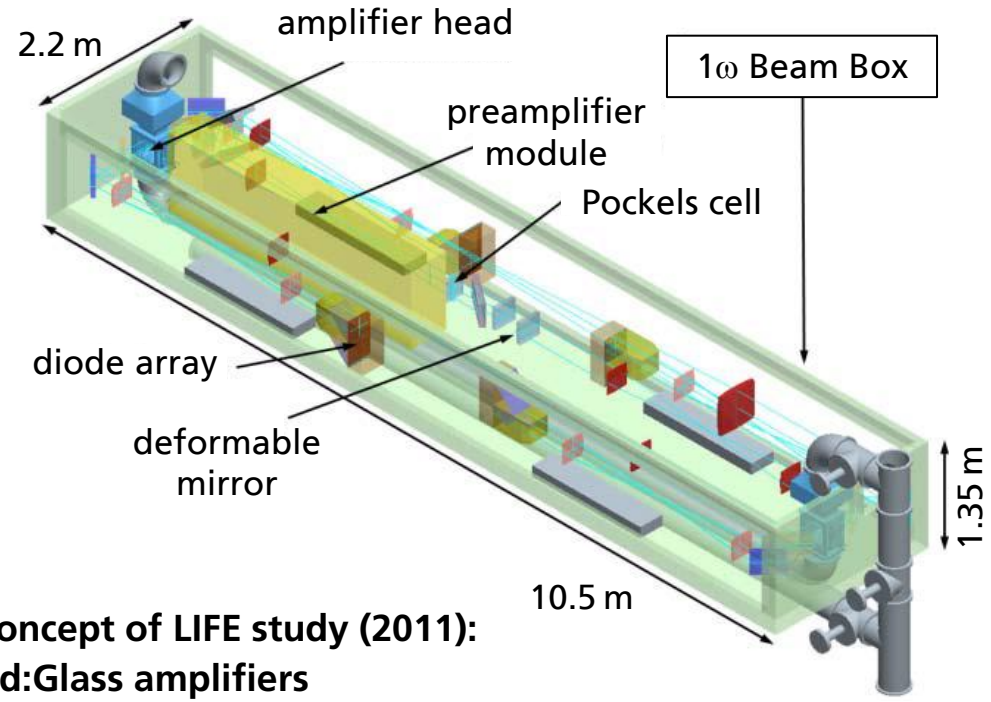
LLNL: HAPLS, High Repetition Rate Advanced Petawatt Laser System (2017)

200 J, 10 Hz (3.3 Hz), Nd:Glass

Laser Inertial Fusion Energy (LIFE) study 2011



A. C. Erlandson, et al, "Comparison of Nd:phosphate glass, Yb:YAG and Yb:S-FAP laser beamlines for laser inertial fusion energy (LIFE) [Invited]," Opt. Mater. Express 1, 1341-1352 (2011)



Concept of LIFE study (2011):
Nd:Glass amplifiers
exchangeable "beam boxes"
384 beam lines with each 8.1 kJ IR (5.7 kJ UV)

A. Bayramian et al. "Compact, Efficient Laser Systems Required for Laser Inertial Fusion Energy," Fusion Science and Technology 60, 28-48 (2011).

Fraunhofer ILT

Summary & Conclusion

- The Innoslab is a robust and power-scalable laser platform.
  Fraunhofer ILT employs it for spaceborne LIDAR lasers and high-power ultrafast lasers (CAPS).
- Nonlinear pulse compression: MPCSB is efficient, robust and power scalable.
- Inertial Fusion Energy is a game-changing technology and promises a clean and abundant energy source.
- The time is now!
  - Ignition has been demonstrated at NIF.
  - There is an unprecedented fusion energy momentum in the public and private spheres.
- Fusion energy is a multi-decadal endeavor and requires development and innovation.
  It requires international cooperation.
- A major challenge is the development of a driver laser with high pulse energy (>kJ), high repetition rate (10 Hz) and high efficiency (>10%).

Fraunhofer ILT

BMBF Fusion Memorandum

Career Opportunities

Contact

Dr. Johannes Weitenberg
Taskforce Laser-Trägheitsfusion
Tel. +49 241 80 40427
Johannes.weitenberg@ilt.fraunhofer.de