Diode Laser Pumps for Advanced Accelerators

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European Advanced Accelerator Concepts Workshop, 18th September 2023

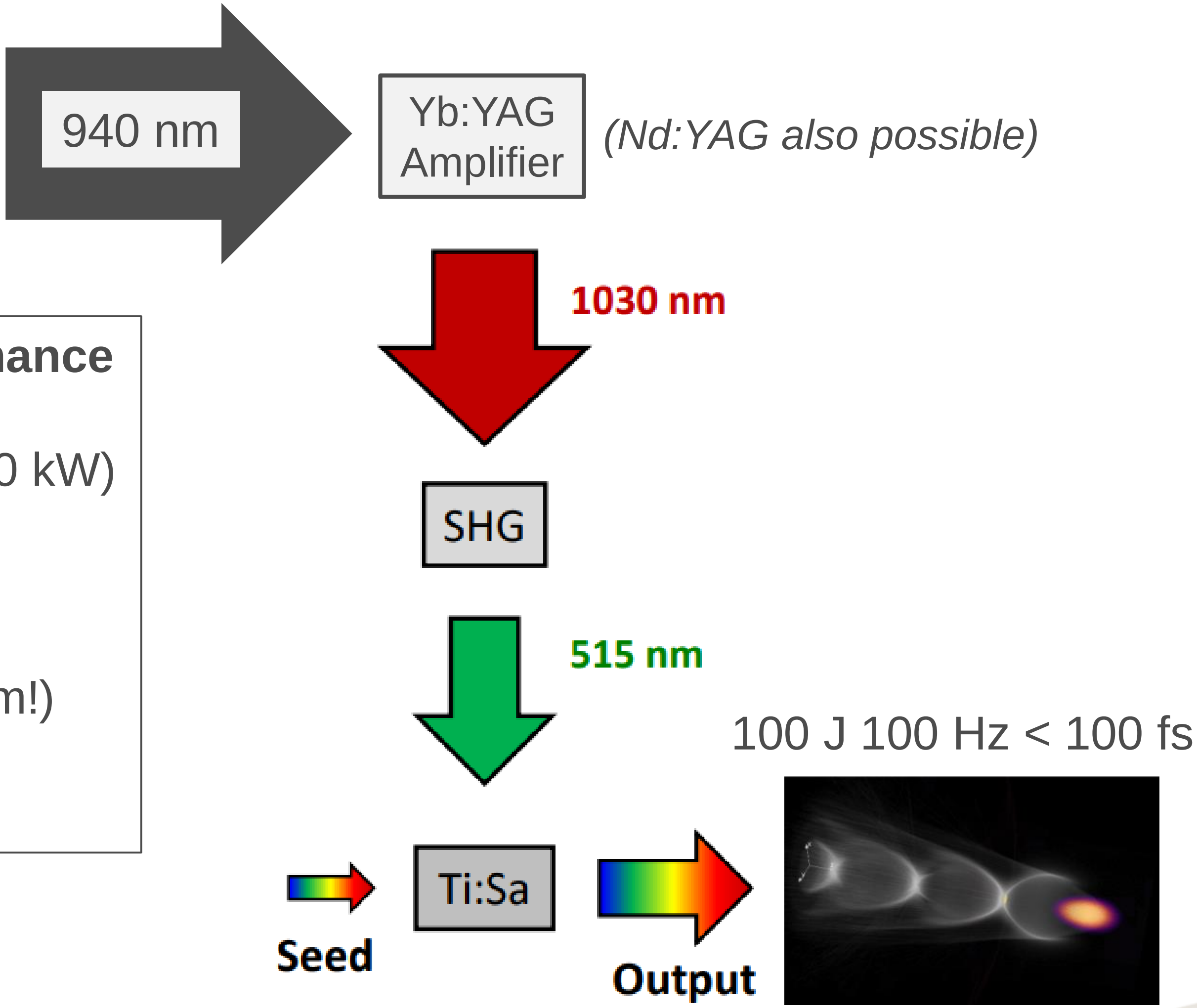
Leibniz
Ferdinand
Braun
Institut

Outline

- Summary of pump requirements for emerging high-energy-class pulsed laser systems
- Overview of commercial suppliers of diode lasers for large-scale systems
  - Leonardo
  - Trumpf
  - Coherent
  - Jenoptik
- FBH Berlin and its contribution to the laser accelerator community
  - International excellence center in high powers diode lasers and modules
  - Overview of current research
  - Ongoing developments in support of high energy laser community

Diode Lasers for Extreme Photonics: Example Requirements (100 Hz 100 J 100 fs)

Diode Laser Pumps



Key limit to achievable performance
Needed:
Very high power (many, many 100 kW)
Narrow beam
High repetition rate (100 Hz)
High reliability
Very low cost in €/W (large system!)

See: www.eupraxia-project.eu

Adapted from Paul Mason
"Recent Laser Developments @ CLF, High energy, High pulse rate Laser Driver Technology"
I.FAST Workshop 2022 Laser Drivers For Plasma Accelerators

Diode Lasers for Extreme Photonics: Example Requirements (100 Hz 100 J 100 fs)

Diode Laser Pumps

940 nm

Yb:YAG Amplifier

(Nd:YAG also possible)

1030 nm

SHG

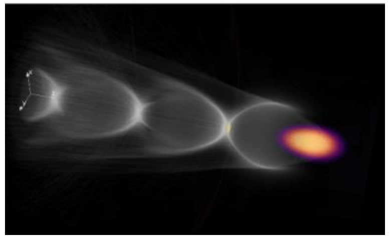
515 nm

Seed

Ti:Sa

Output

100 J 100 Hz < 100 fs



Open challenges:

Economic > 10 Hz diode laser pumps

Reliability of large systems

Security of supply

Supply bottlenecks

Performance and cost scaling

Flexible access to new approaches

E.g. Tm:YAG

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  - **Trumpf (Germany, USA)**
  - **Coherent (USA, Germany, Switzerland)**
  - **Jenoptik (Germany)**
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LEONARDO

6th European Advanced Accelerator Concepts Workshop

High Peak Power Laser Diode Arrays

Lukas Gruber

Isola d'Elba

September 17th-23rd 2023

Electronics

Helicopters

Aircraft

Cyber & Security

Space

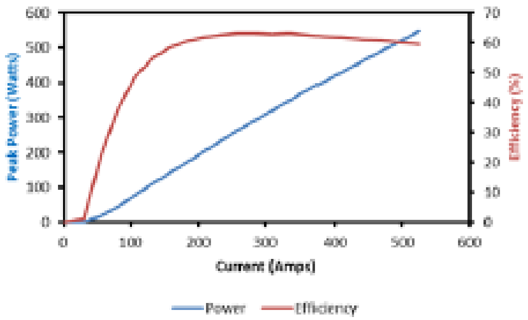
Unmanned Systems

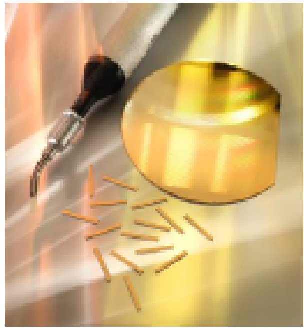
Aerostructures

HAPLS PERFORMANCE – INSTALLED AT ELI-BEAMLINES (L3)

Bar Performance

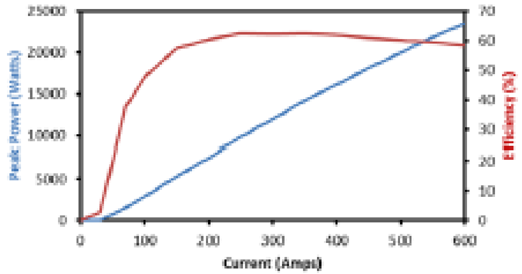
- **>500W**
- ~60% efficiency

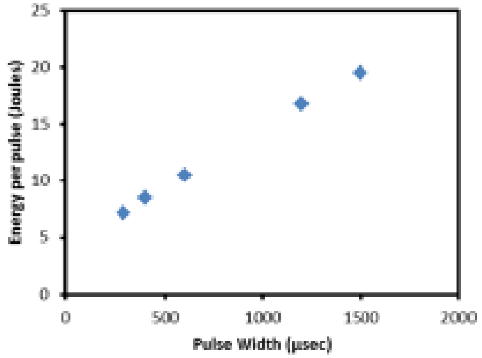




Array Performance

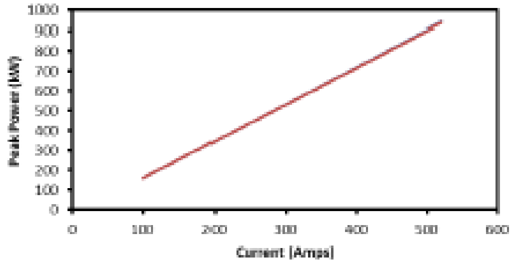
- **23kW** @ 600A
- Up to 20J 1.5ms

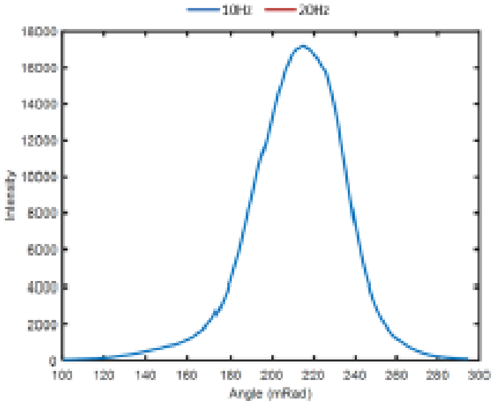




Module Performance

- **940kW @ 10 & 20Hz**
- 4.2nm FWHM
- 4.5° 1/e² divergence





System Performance

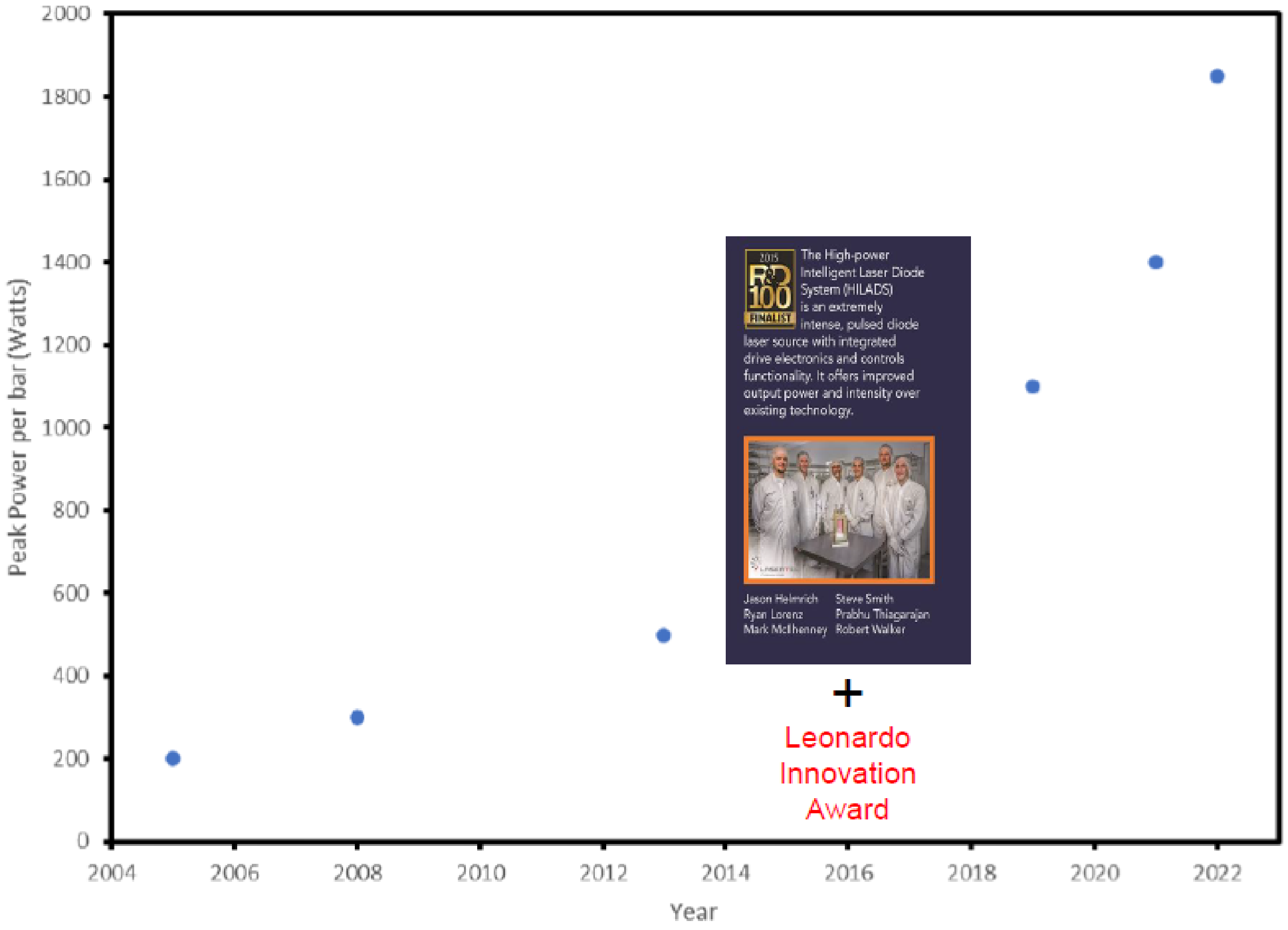
- **490TW**
- 3.3Hz
- 27.3fs

	Current parameters (Feb 2021)
Output pulse energy (main beam compressed)	13.3 J in single aperture
Pulse duration	27.3 fs FWHM
Repetition rate	3.3 Hz
Peak power	490 TW

https://www.eli-beams.eu/facility/lasers/laser-3-hapls-1-pw-30-j-10-hz/

LEONARDO – MAJOR MILESTONES

- 2005: 200W peak power laser diode bar
- 2005: Fully soldered pulsed laser diode array assembly
- 2009: Fully soldered continuous wave laser diode array assembly with scaling capability
- 2011: Multi-Wavelength fully soldered laser diode array for medical applications
- 2013: 500W peak power laser diode bar
- 2015: 25kW pulsed laser diode array assembly with scaling ability
- 2015: ~1MW laser diode array module with 10x power and 3x power density
- 2019: 20kW wavelength locked small pitch pulsed laser diode array
- 2019: >1000W peak power laser diode bar
- 2021: >50kW pulse laser diode array assembly with scaling ability
- 2021: ~1400W peak power laser diode bar
- 2022: 1850W peak power laser diode bar



SELECT PRODUCT PORTFOLIO

Conductively Cooled Components

- Many heat sinks from industry standards to very custom form factors
- Rugged design
- Hard solder
- Small pitch
- Collimation optics
- Custom micro-optics for other functions

Fluid Cooled Components

- Flagship “T6” heat sink (others available)
- Designed to be tiled in 2D to create large arrays
- >2.0kW cw capable
- Rugged & compact
- Modular & scalable

Integrated Modules

- Design to fit customer needs
- Conductively or fluid cooled base arrays

Systems

- Pulsers
- Laser modules
- Electronics
- Optics
- User interface
- Mechanical enclosure
- Sensors & controls

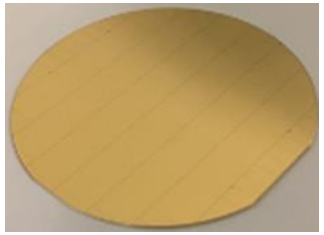
Commercial state of the art in CW and QCW diode laser sources

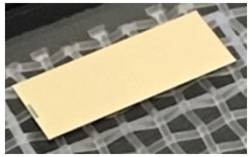
TRUMPF Photonic Inc

TRUMPF Photonics Inc

Core Chip Technology

- MOCVD wafer growth
- 4″ GaAs laser wafer fab
- QCW and CW chips and bars





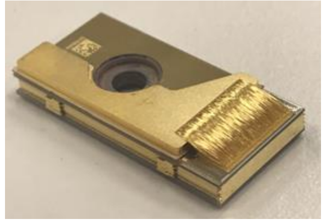
Diode Laser Facet Passivation

- State of the art- MBE based system
- Industry leading chip reliability

Assembly Technology →

Diode laser cooling technology

- Fully automated bar on cooler assembly
- Ultra-low corrosion diode laser bar micro-channel cooling (Internal source)



Optics

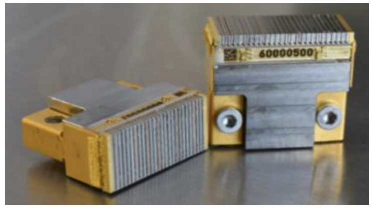
- In house manufacturing and assembly of micro-optics components

Automated High-Volume Manufacturing

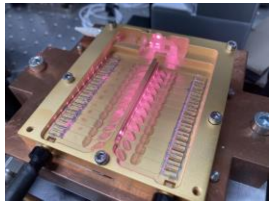
Diode module Production →

- Established in 2002
- Located in Cranbury, NJ (USA)
- 250 Employees
- 110k sqf facility with 35k sqf clean room
- Fully Integrated GaAs Diode Laser Fab
  - From Epitaxy to module

QCW stacks (20kW peak)



Fiber laser pump modules (500W+)



Fully integrated solid state laser pump sources

Thin disk laser pump modules up to 3kW CW power

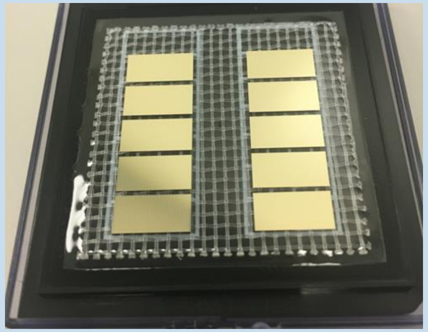
Complete Solution for Solid State Laser Pumping

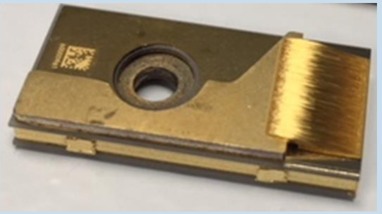
- Custom diode module development- vertically integrated production
  - 60MW CW power year output
  - 350k bars/year capacity (4 mm x10 mm) , expanding to 1M/year by 2026
- Industry leading pump laser diode reliability and performance

State of the art in commercially available diode pump modules

CW pumps for industrial solid state lasers

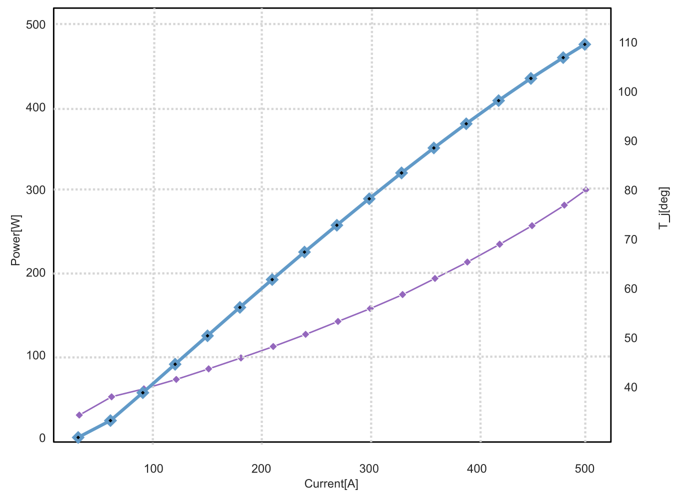
Laser diode bars 5mm x 10 mm from 940nm to 1060 nm



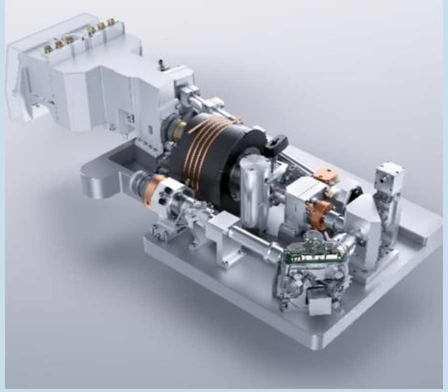


Isolated micro-channel cooling assembly

High reliability operation at 400W+



Integrated into 24 kW diode pump sources for TruDisk lasers

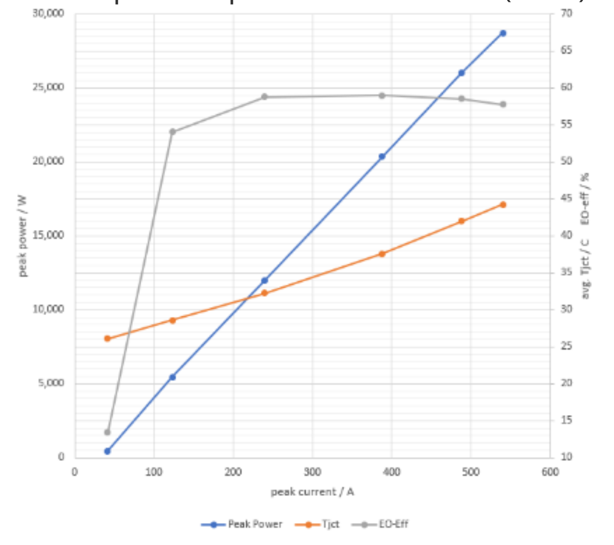


QCW pumps for high energy laser systems

High density compact 56 bar QCW stack

- <0.5 mm pitch with FAC
- Conduction or micro-channel cooled

Peak power operation at 25kW+ (0.3%)



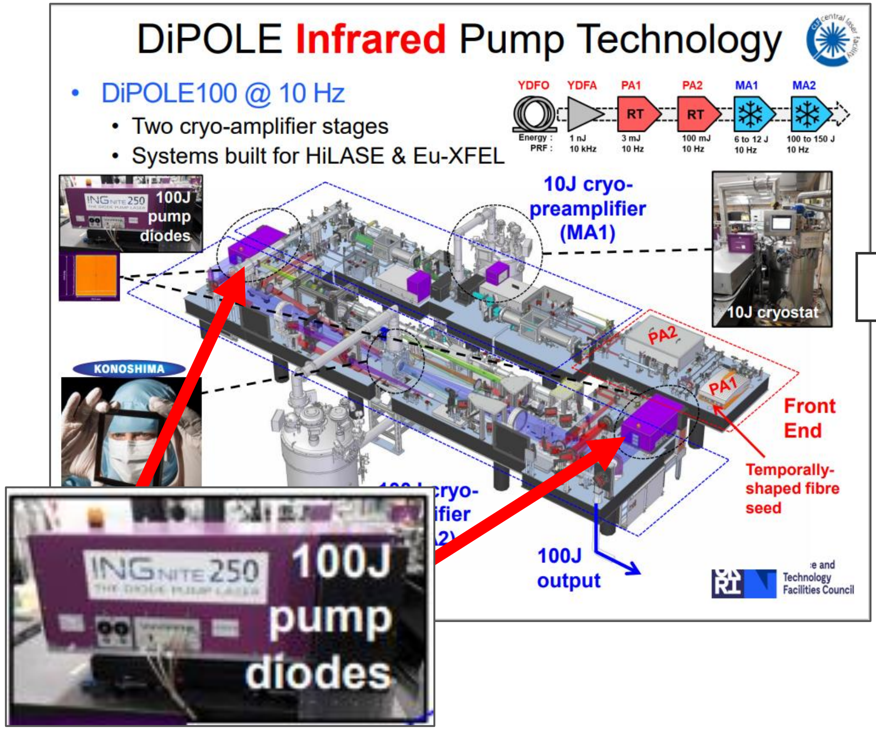
Key Challenges for power scaling to viable multi-100kW sources:

- High reliability >1Gshots- 3 solder interfaces
- Modularity- ease of stack replacement (field serviceably)
- High yield assembly- Automation, pitch control, lensing
- Machine learning for defect visualization and screening

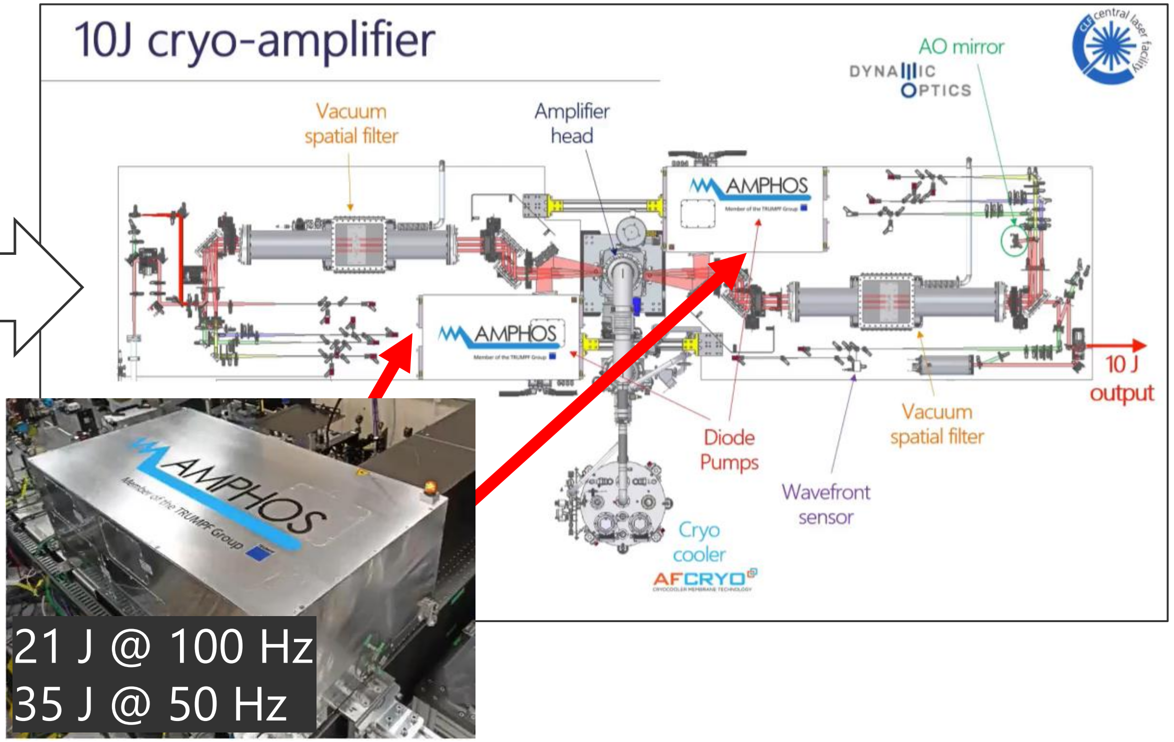
TRUMPF 100 1923–2023

Proven supplier of diode laser pumps for high-energy-class systems

100 J 10 Hz pumps for 100 J DiPOLE



21 J 100 Hz pumps for 100 Hz DiPOLE



From; Paul Mason 2022
"Recent Laser Developments @ CLF, High energy, High pulse rate Laser Driver Technology"
I.FAST Workshop 2022 Laser Drivers For Plasma Accelerators

From: Mariastefania De Vido 2023:
"Design and development of a 10 J, 100 Hz DiPOLE diode-pumped solid state laser"
Proc SPIE PC12399, PC123990C (2023); https://doi.org/10.1117/12.2654971

TRUMPF 100 1923–2023

QCW PUMP ENGINES FOR LARGE-SCALE PETAWATT FACILITIES

LASER World of PHOTONICS 2023
Next Generation High-Power Diode Lasers

29th June 2023

Dr. Christian Lux
Coherent, Mainz, Germany

COHERENT

Result slides from Coherent

Sorry, only on request

Please write to: andrea.knigge@fbh-berlin.de

JENOPTIK

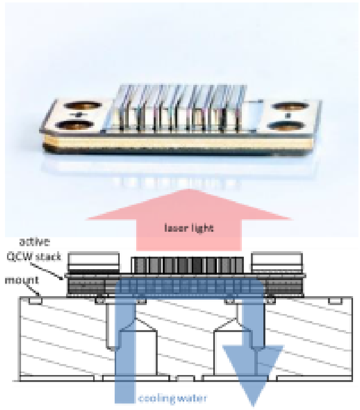
MORE LIGHT

High-Power Laser Diode Stacks for Pulsed Operation

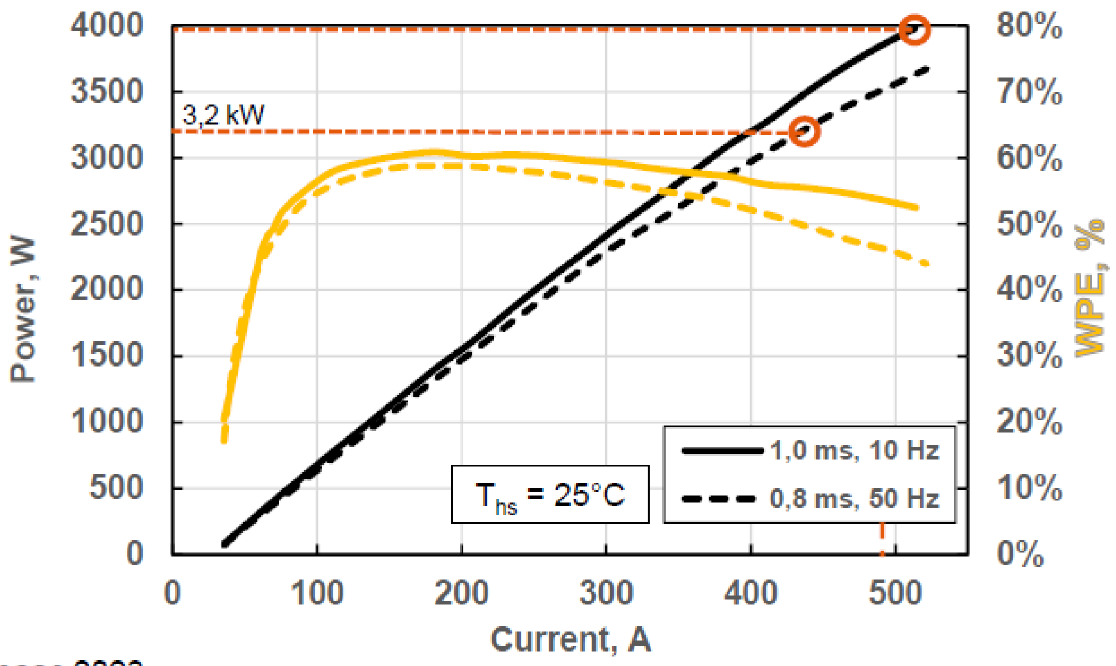
Jenoptik – European Advanced Accelerator Concepts Workshop 2023

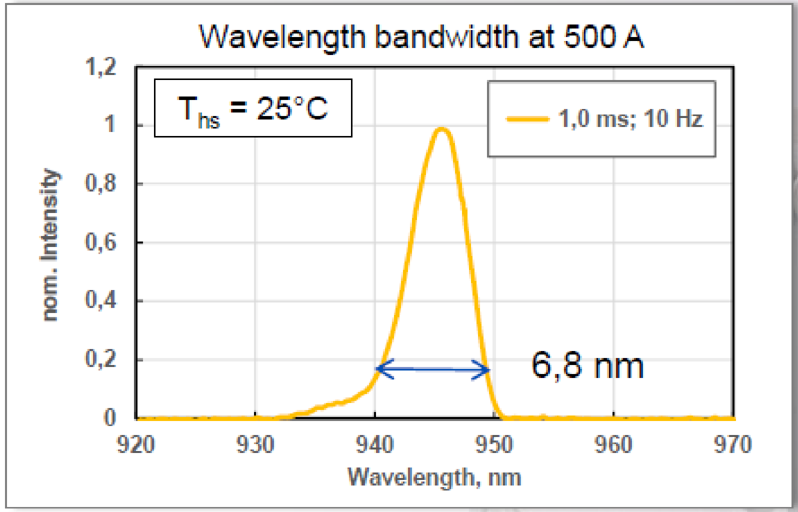
Author: Ralf Huelsewede

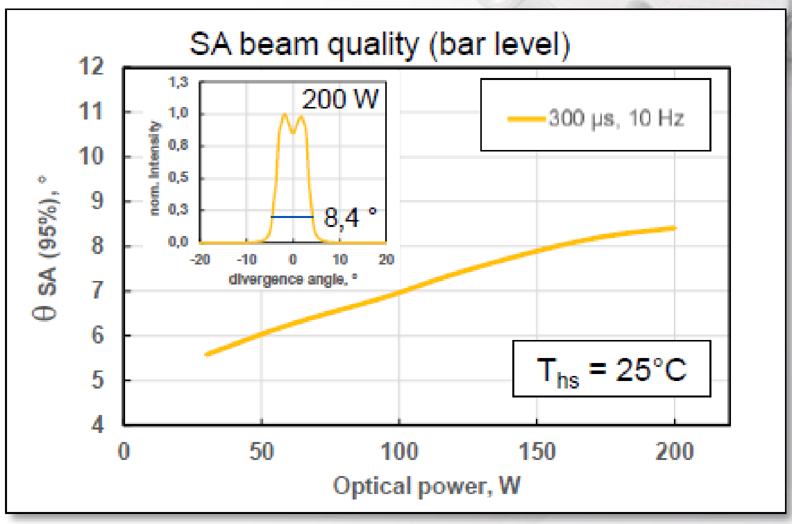
Jenoptik 940 nm QCW - stack



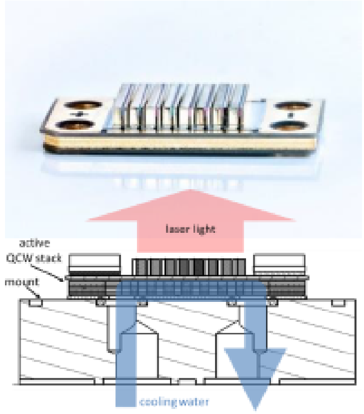
- 8 - bars stack, 75 % FF bars
- Actively cooled baseplate (tap water)
- Resonator length: 1,5 mm
- Measurement conditions:
  t = **1,0 ms**, f = **10 Hz** (1 % d.c.)
  t = **0,8 ms**, f = **50 Hz** (4 % d.c.)



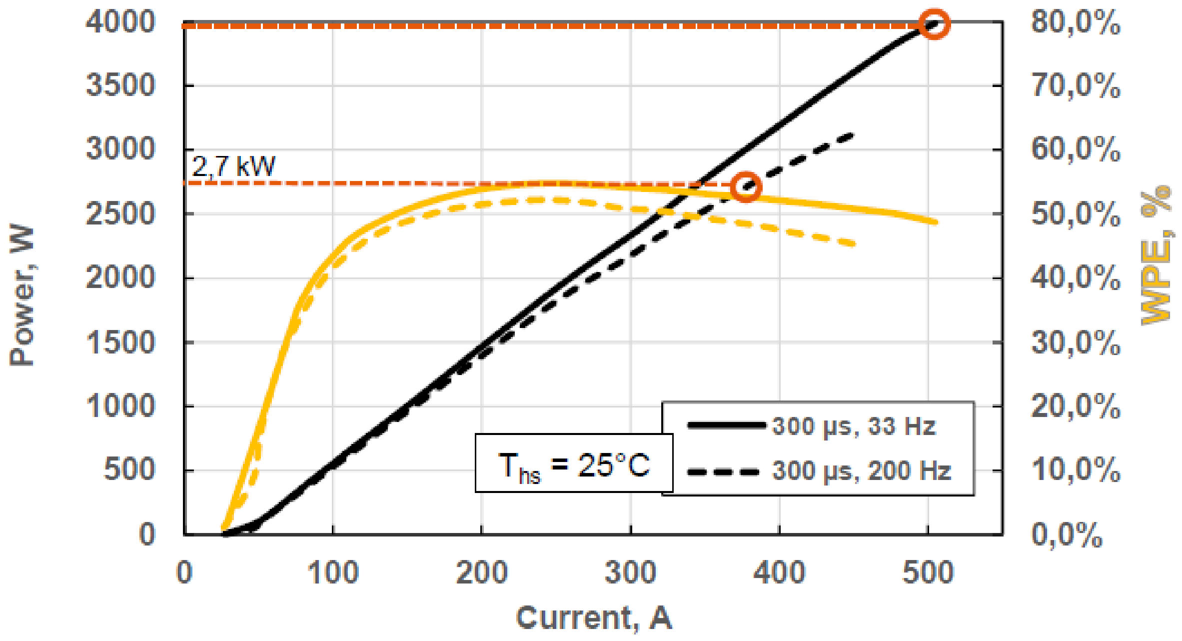


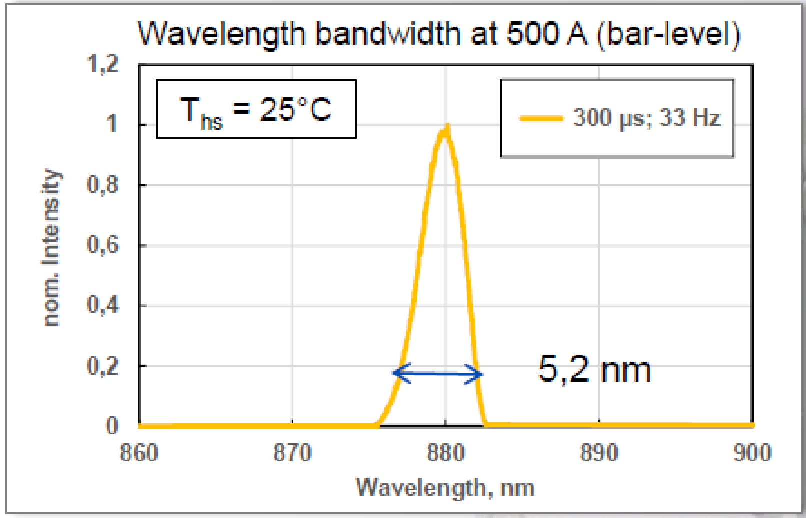


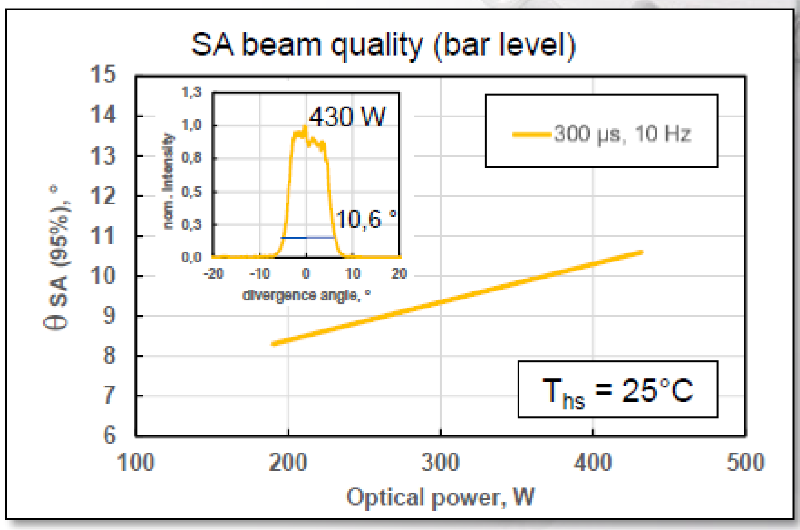
Jenoptik 880 nm QCW - stack



- 8 - bars stack, 75 % FF bars
- Actively cooled baseplate (tap water)
- Resonator length: 1,5 mm
- Measurement conditions:
  t = 300 µs, f = 33 Hz (1 % d.c.)
  t = 300 µs, f = 200 Hz (6 % d.c.)







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- Overview of commercial suppliers of diode lasers for large-scale systems
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- **FBH Berlin and its contribution to the laser accelerator community**
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Leibniz Ferdinand Braun Institut

Ferdinand-Braun-Institut – Facts & Figures

III-V semiconductor technologies for
electronics | photonics | quantum technologies

- Founded in 1992
- Part of Research Fab Microelectronics Germany (FMD)
- 9 Joint Labs with 5 German universities
- Staff: 370 (headcount)
  incl. 200 scientists & PhD candidates from 30 nationalities
- Revenue (2022): 43.5 M€
  (incl. 24.6 M€ third-party funding)
- International competence center covering the full value chain
  → from basic research to ‘products’ (TRL 1-9)

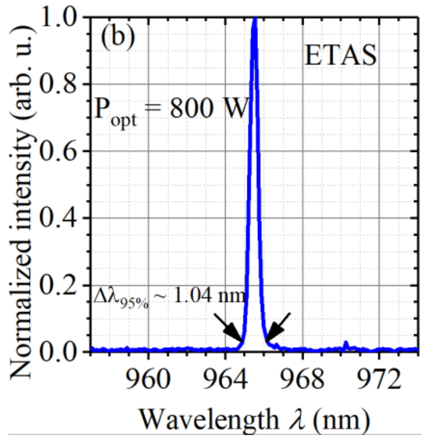
FBH gGmbH is a 100% subsidiary of State of Berlin and a member of the Leibniz Association

FBH: National excellence in high power diode lasers, as key enabling technology

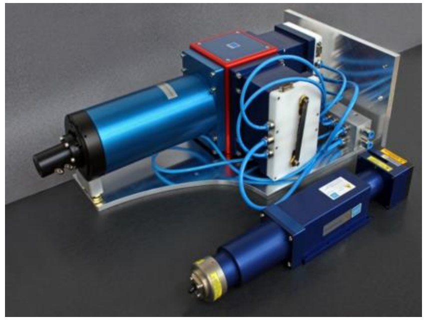
Keys for high-performance diode lasers

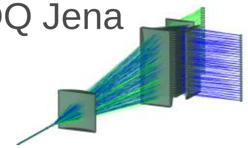
- Highly efficient and reliable laser diodes and laser diode bars
- In-chip grating for narrow spectrum to pump narrow lines
- Narrow, symmetric beam for direct low-loss coupling into fiber
- Effective cooling for operation at high duty cycles
- Alternative wavelengths

Progress in Yb:YAG
940 nm: 1 kW bars
970 nm: 2x efficiency, 4x power
Coop Trumpf



965 nm DBR laser bar
First $\Delta\lambda_{95\%}$ ≈1.04 nm @ 800 W
Coop Trumpf

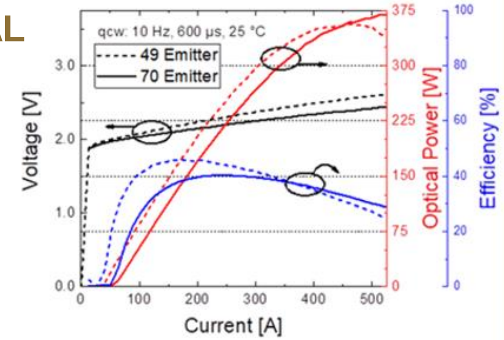




940 nm 6 kW modules
First 200 Hz 1 ms units
Over 10 years operation
Coop Jenoptik, Trumpf
MBI & IOQ Jena

Progress in Tm:YAG
780 nm pumps
First 1.5 kW 10 ms 50Hz
Coop Jenoptik Lastronics
IOQ Jena
→ new: 900W / stack CW

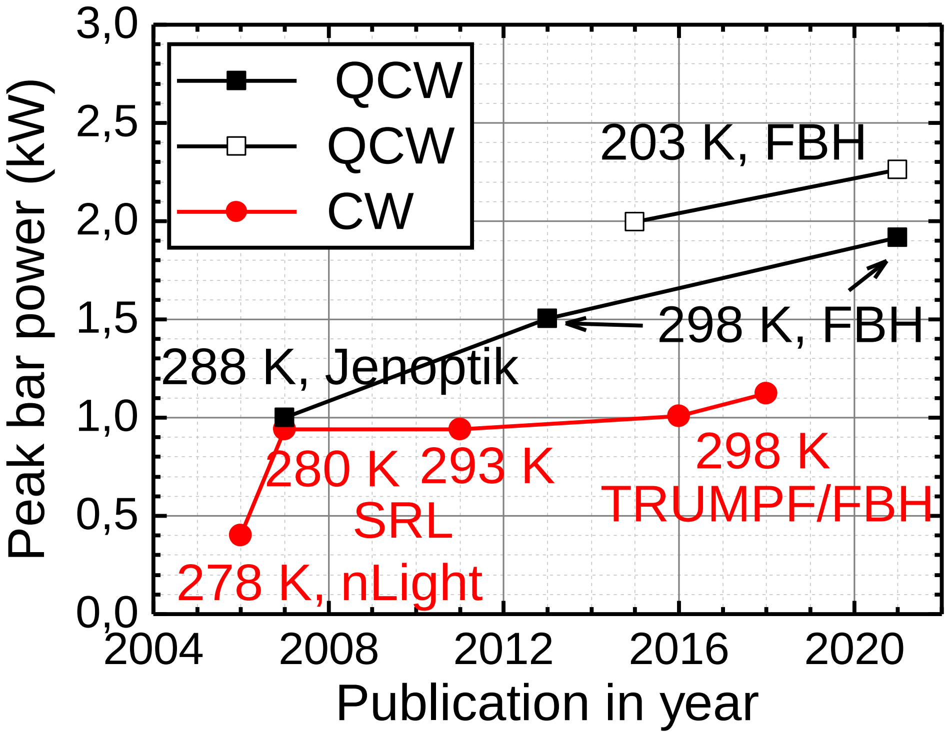
Progress in DPAL Alexandrite
First >300W bars at 665nm
Coop Coherent | DILAS

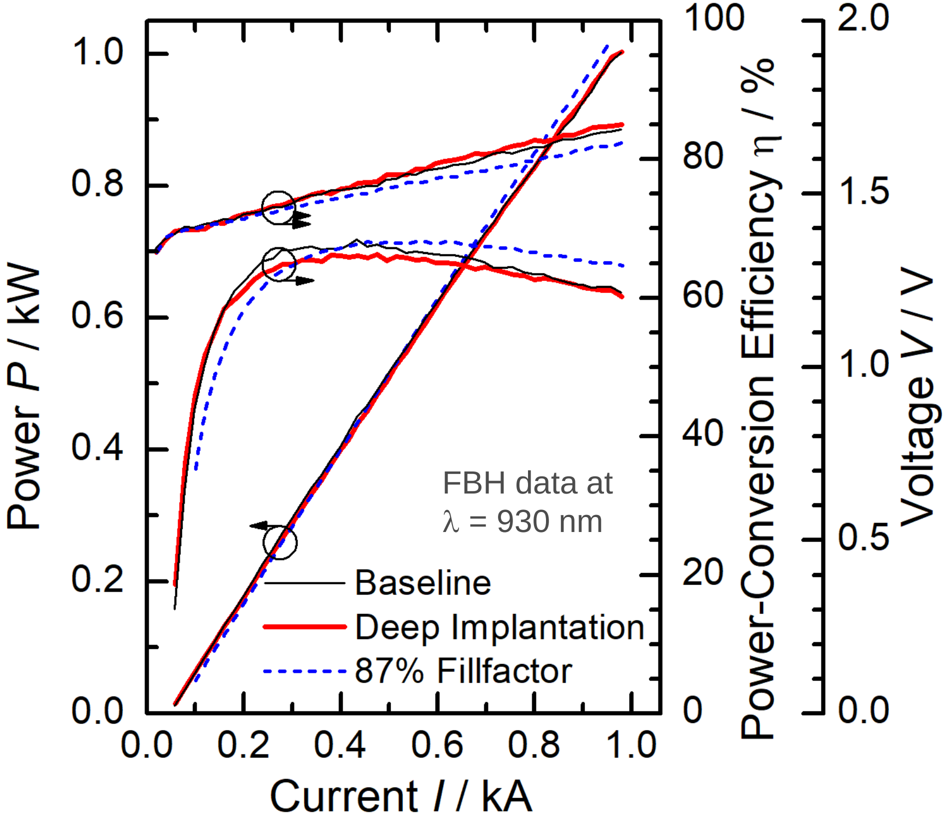


Performance scaling at 940nm for Yb:YAG:
strong progress in peak power and efficiency per bar (co-op Trumpf)

Power per bar:
strong increase in 10 years to 2 kW

Efficiency at 1 kW:
> 1.8x in 10 years to 66 % (70 % @ 200 K)





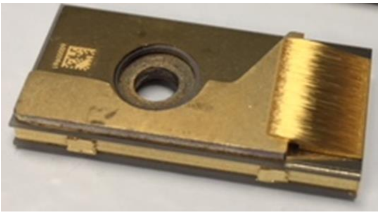
C. Frevert *et al.* Proc SPIE 9733, 97330L-1 (2016).
S. Strohmaier *et al.* Proc. SPIE 10085, 100850F-1 (2017)

66% @ 1 kW: M. Karow Proc. SPIE 11262, (2020).
35% @ 1 kW: D. Schröder *et al.* Proc. SPIE 64560N, 64560N-1 (2007).

Diode laser bars in commercial packages
Packaging challenge: high duty cycle pumps

LEONARDO

TRUMPF



TRUMPF

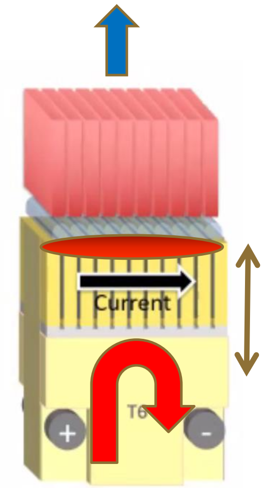
Low cost QCW bar package
Major drop in performance for >= 2% duty cycle (~ 20 Hz)

High cost CW package
Microchannels: high performance **& €**
Reliability hazard in large systems

Optical output

Heat generation

Heat extraction
(water channels)



LEONARDO

Long distance limits
resonator length
➔ efficiency and
power limit!

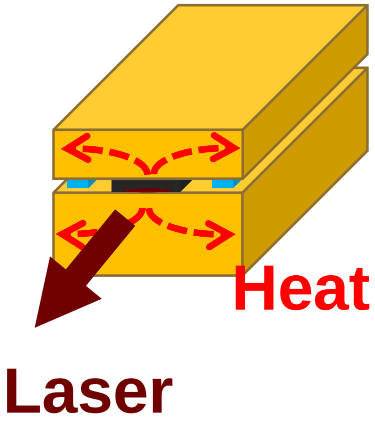
➔ Commercial sources with needed performance at high duty cycle not available

See review in: M. Hübner et al. MDPI instruments, 3(3), p. 34 (2019).

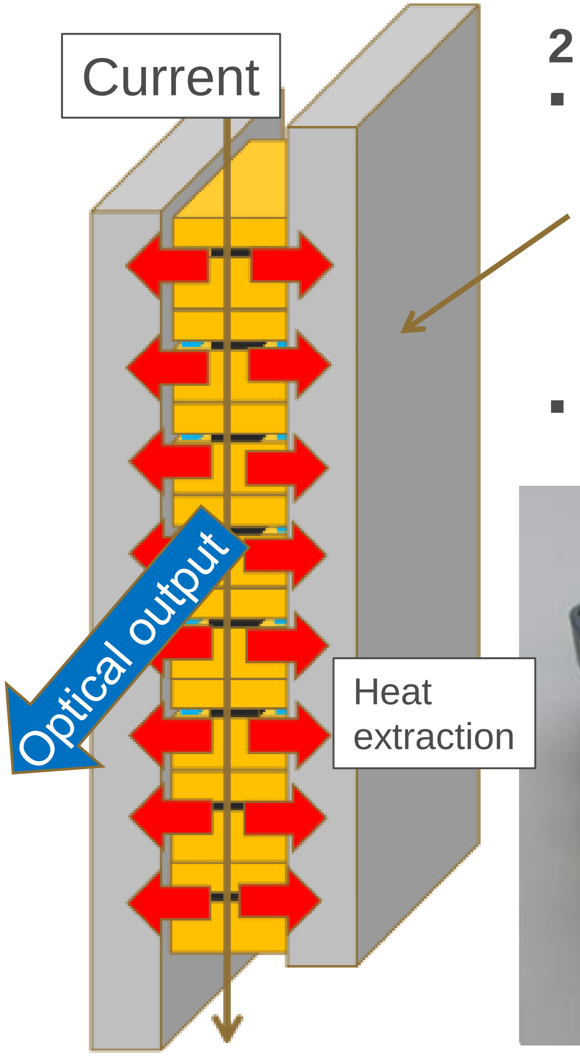
Adressing the cooling challenge at FBH: 2 x edge side-cooling

Stack element (StE) with large area single emitters

- "sandwich" design:
  - 2 CuW (10:90) heat sinks
  - Al_2O_3 spacers soldered
  - ➔ edge-cooled chip
  - ➔ Low electrical & thermal resistance
  - ➔ Expansion matched assembly
- 10 years in use at FBH for 940 nm pumps
- 10…20% duty cycles and cw

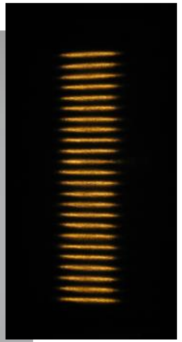


Stack of 24…28 StE



2 x edge cooling:

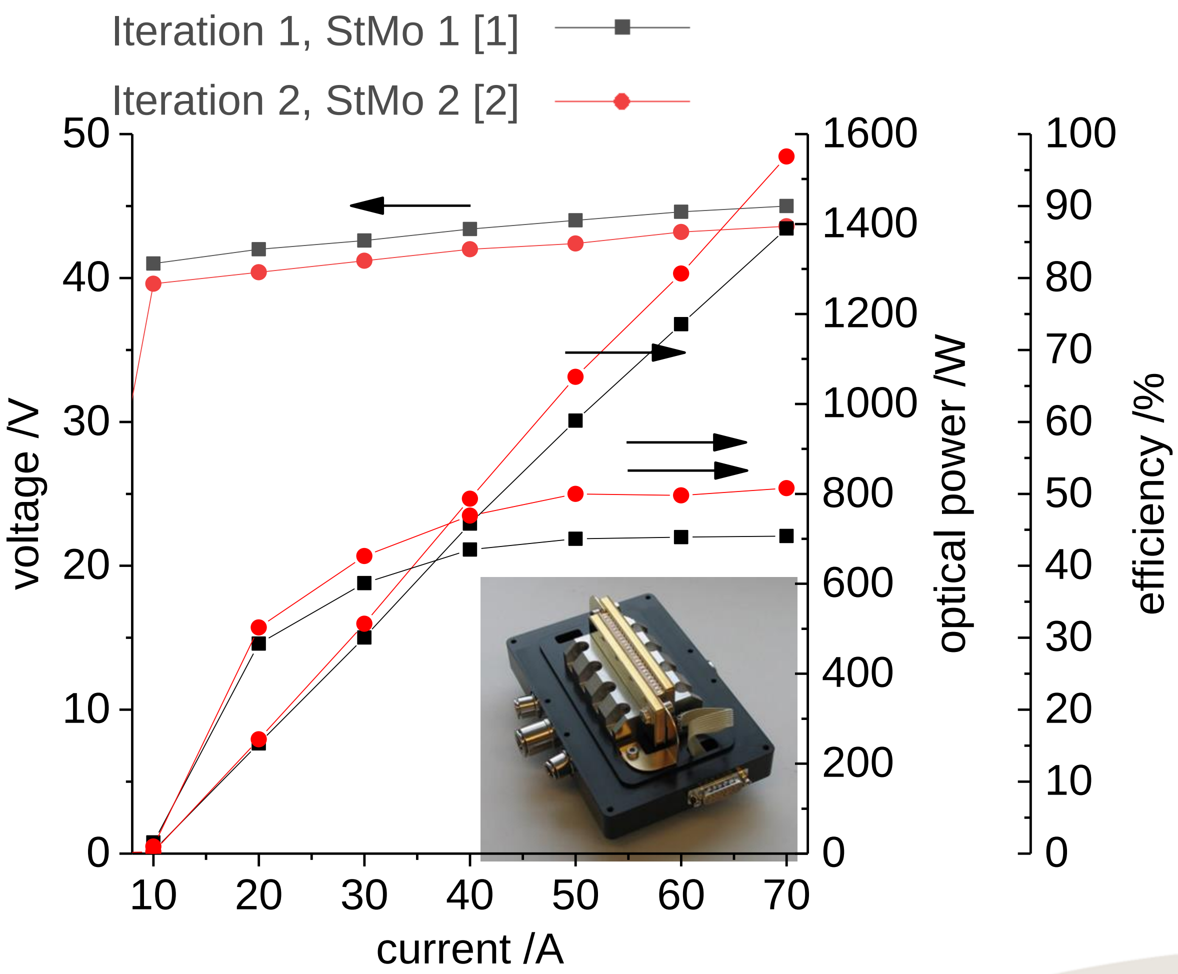
- StE soldered as stack and sandwiched by AlN-Cu DCB cooler (macro-channel water-cooled)
  - ➔ Large contact area,
  - ➔ low thermal resistance
  - ➔ efficient heat removal
- Each with FAC, common SAC



Performance of stack modules at 780 nm: power and efficiency

Operation:

- Pulse width: 10 ms
- Pulse repetition rate: 10 Hz
- Duty Cycle: 10 %



Baseline performance [1]: StMo 1

P_{max} = 1.4 kW at 70 A, eff.: 44 %

Iteration 2 performance [2]: StMo 2

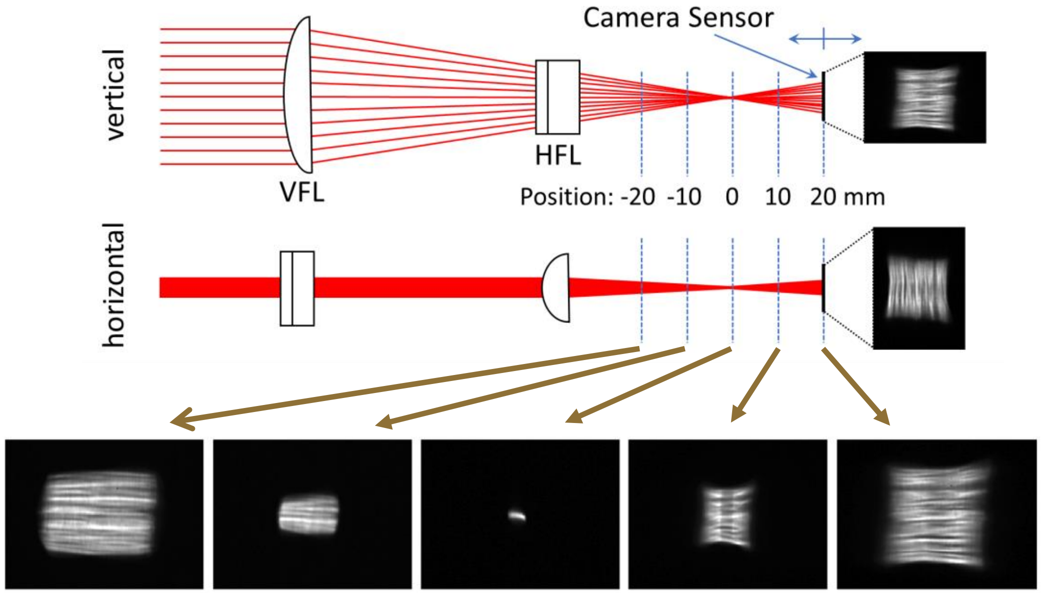
- Implementation of improved epi design
  - Highly asymmetrical design
  - low optical losses
- 1.1x increase in power and efficiency

P_{max} → 1.6 kW at 70 A, eff.: → 50 %

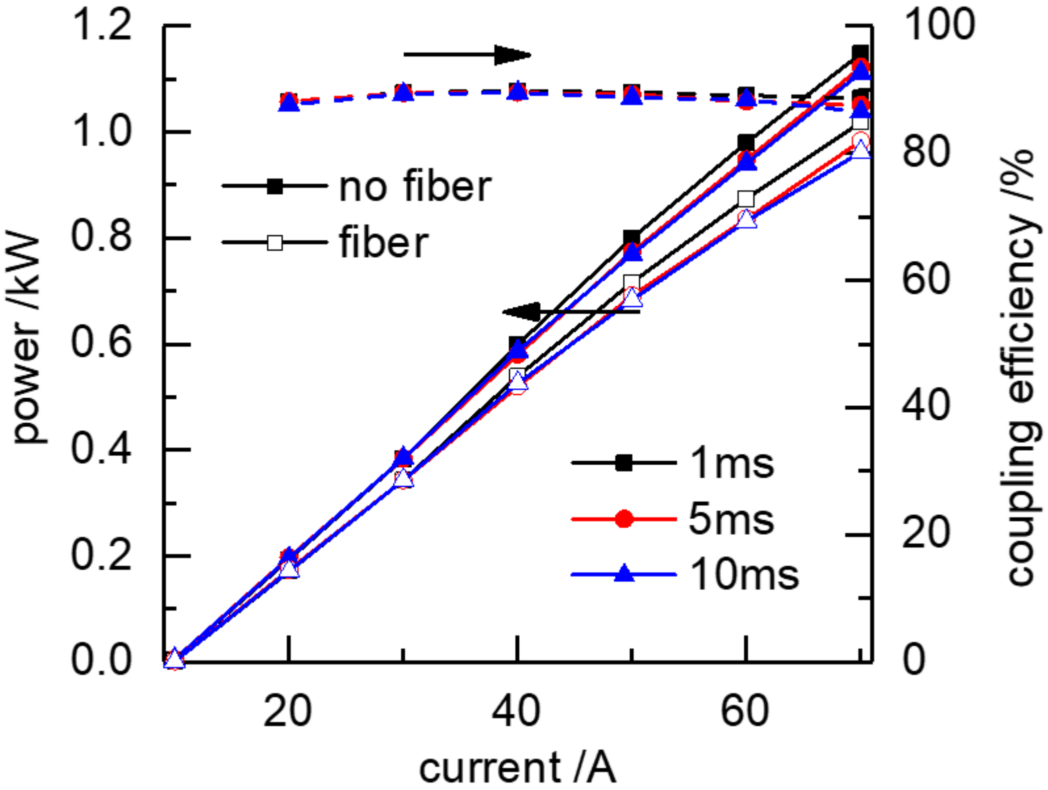
[1] Crump et al., Proc. SPIE, 11262, p. 1126204, 2020
[2] Arslan et al., IEEE Phot. Conf. (IPC), Vancouver, BC, Canada, 2021

Performance of stack modules at 780 nm: symmetric, narrow beam

Beam analysed following ISO11146 [1]



Horizontal: M^2: 287, vertical: M^2: 222



➔ **Narrow, symmetric beam makes direct low-loss coupling into 1 mm fiber possible**

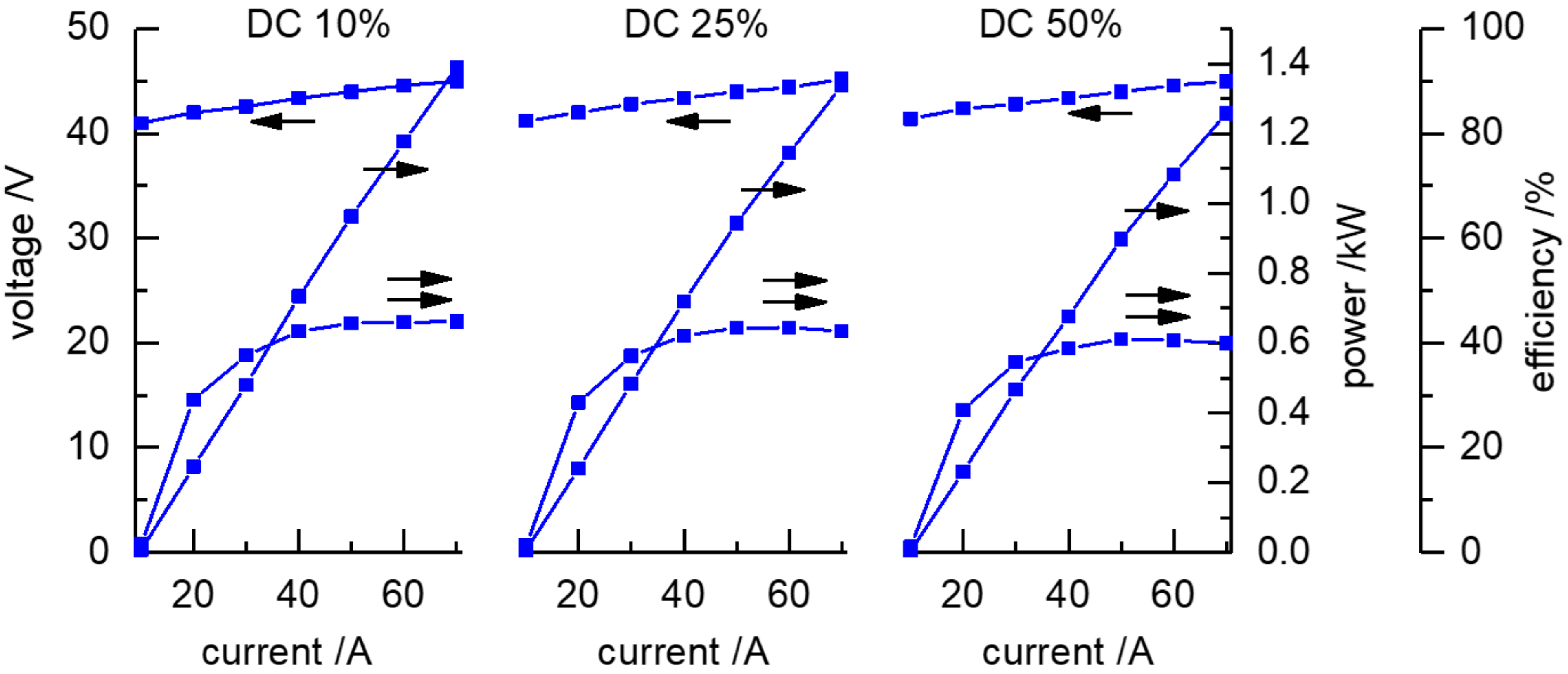
Coupling efficiency ~ 85…90 %; Brightness from fiber: 0.83 MW / cm^2 / sr

[1] Hübner et al., Optics Express, Vol. 29, No. 7, p. 9749, 2021

Effective cooling allows operation at duty cycles up to 50%

StMo 1

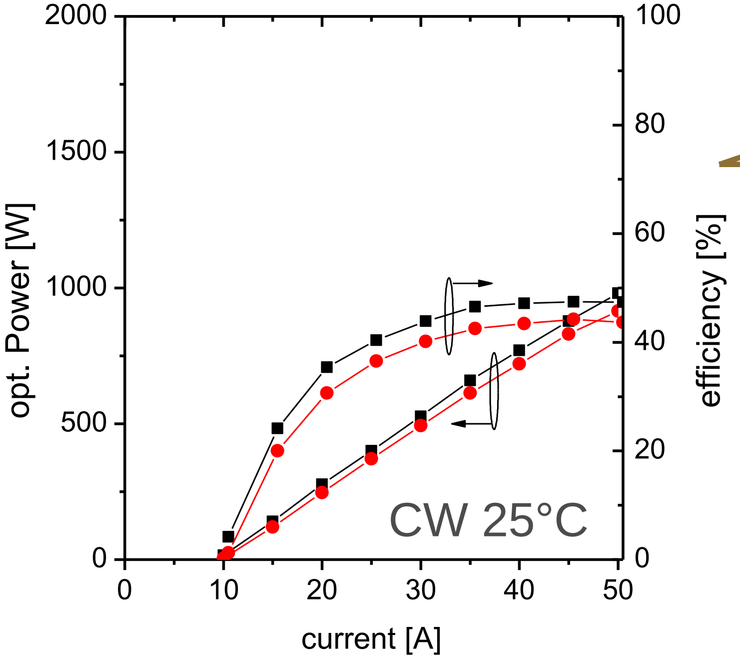
Pulse: 10 ms



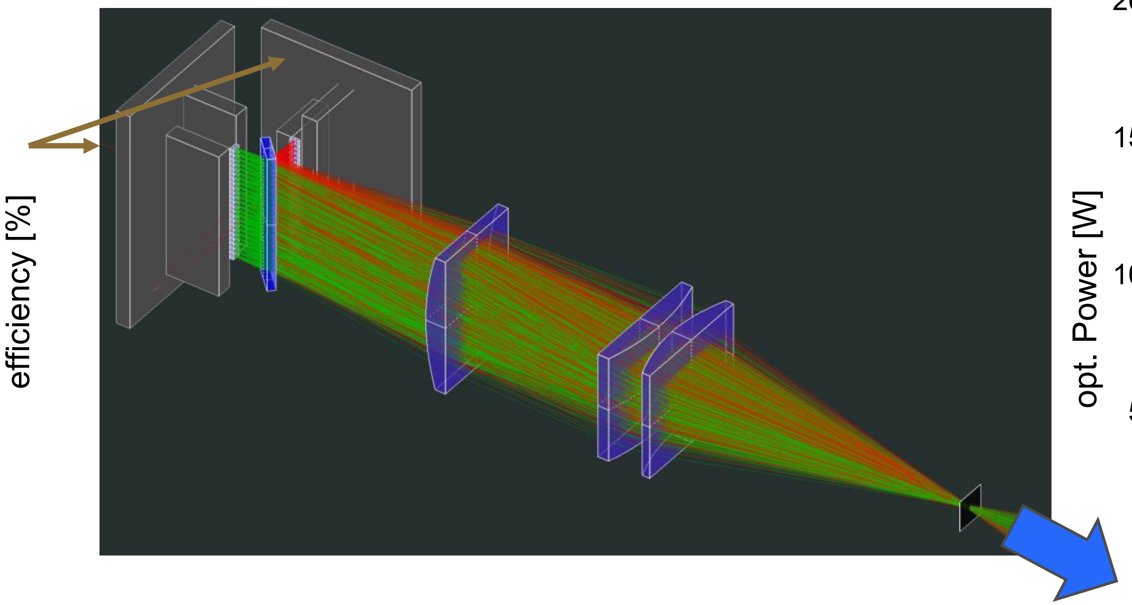
	DC = 10 %	DC = 25 %	DC = 50 %
pulse repetition frequencies	10 Hz	25 Hz	50 Hz
optical power (at 70 A)	1389 W	1337 W	1258 W
conversion efficiency (at 70 A)	44 %	42 %	40 %

New: development of CW-kilowatt module at 780 nm

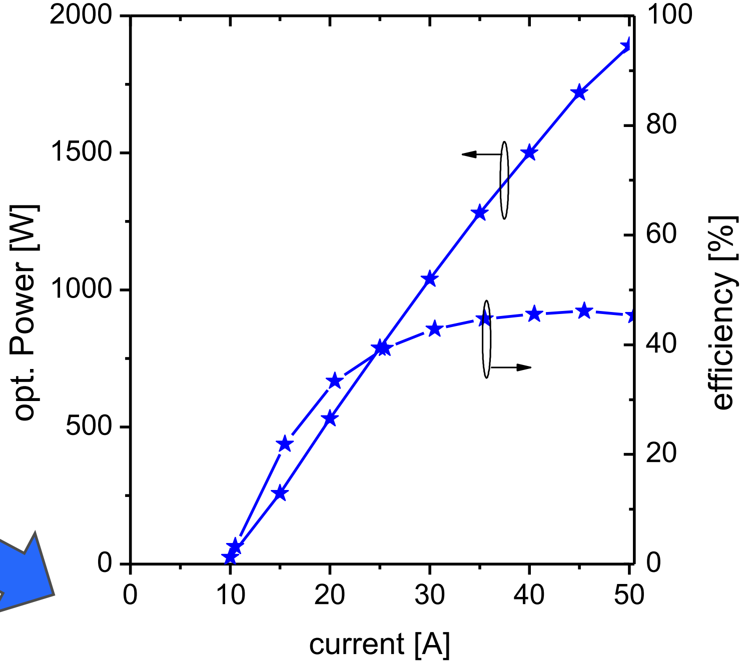
Two 780 nm 900 W stacks



Beams combined



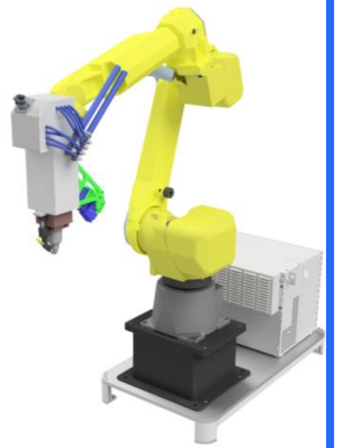
1900 W CW in a 1 mm spot

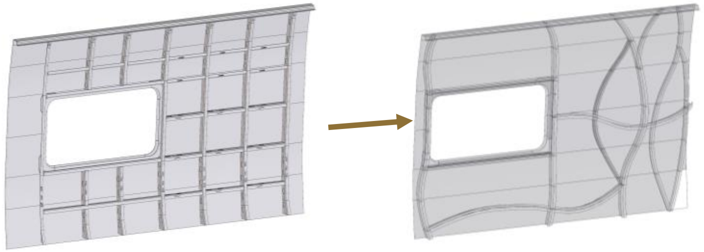


FBH: current research for further scaling

Progress in Tm:YAG

- **TRL increase of FBH CW stacks**: Delivery of 780 nm kW modules
- Photon Laser Manufacturing GmbH, Develop application lab: demonstration of laser cutting and laser-based additive manufacturing for for lightweight construction
- Coop PLM / SKDK ERDF project SAMBA



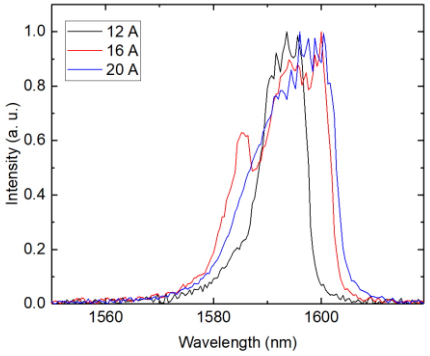


Progress in Yb:YAG: mounting & cooling

- **Develop advanced stack concepts** ➔ 100W @ 200 Hz → 1000 W @ kHz
- Coop Trumpf, ERDF „HOTSTACK“

Trial Tm-pumping at 1.6 µm

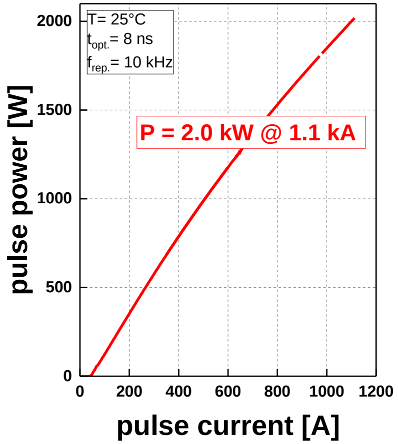
Research prototypes
Coop CNR-IO/ HHI

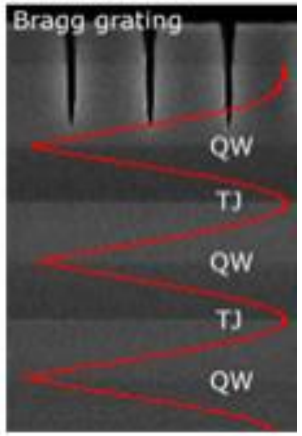


Progress in bar power

- Scale into multi-kW by tunnel-junction technology for cw operation
- Coop AMS-OSRAM, Amplitude, Eurostars „Super8“ (subm.)

From FBH:
Tunnel-junction laser bars for LiDAR:
8 ns pulses: P = 2.2 kW
905 nm, $\Delta\lambda$ = 0.3 nm





Conclusions and next steps

- Diode laser pumps: essential part of high duty-cycle (> 10 Hz) laser accelerators
  - Only source that can deliver needed 100’s kW in a narrow beam at high repetition rate (100 Hz) with high reliability
- Multi-100 kW industrial diode pumps available, based on economic cooling at < 4% duty cycle
  - Overview presented of capabilities at Leonardo (ELI), Trumpf (DIPOLE), Coherent (DPAL), Jenoptik (DC to 6%)
  - Scaling to duty cycle > 6% increases €/W (economic coolers with low W <u>or</u> CW coolers with high €)
- FBH Berlin supporting laser accelerator community via applied research into advanced diode pumps
  - Scaling duty cycle: from 10…20…50…100% using innovative diode laser packaging
  - Scaling performance: Scaling power to 1000 W / bar with efficiency > 60%, as pumps for Yb:YAG and Nd:YAG
  - Efficient pumping: “In-chip” wavelength stabilization: 800 W bars at 970 nm for pumping narrow lines in Yb:YAG
  - Pumping new materials: high power 665 nm bars for alexandrite; high duty cycle kW modules at 780 nm for Tm:YAG

Next steps: advance accelerator field in close cooperation with research and industry

- EU-funded efforts to make higher duty cycle modules and higher power diodes available
- Enable new applications (e.g. direct-diode CW kW 780 nm modules for AM)

Thank you for your attention!

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– The companies for the material provided

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