EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

EuPRAXIA Preparatory Phase

Development of diode laser pumps for high energy laser infrastructures

Paul Crump
Ferdinand Braun Institut gGmbH (FBH)
Berlin, Germany

Progress in developing advanced diode laser pumps for high energy laser systems will be presented, focusing on efforts to scale peak and average power (towards 1 kHz), make new wavelengths available, and implement wavelength stabilization. Updates from efforts within inertial fusion research programs will be shared.

Funded by the European Union

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from UK and Switzerland.

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Introduction to FBH Berlin (Reminder)

- A German (EU) excellence centre for high power diode lasers and their applications

Efforts within PACRI, in support of EuPRAXIA and future HELs

- Preparation for the EuPRAXIA Laser
  - Commissioning of an industrial design study
- Assessment of alternative pump concepts
  - Diode laser and module development for 1000 Hz pumping of Yb:YAG
  - Direct diode pumping of Thulium-doped materials
  - Paper study on path to direct diode pumping of TiSa

Efforts within National Fusion programs (BMFTR DIOHELIOS)

- Broad goals of diode development, with some headline results
  - First 1 kW monolithic grating stabilized bars at 885 nm (coop TRUMPF)
  - First 70% efficient grating stabilized diodes at 940 nm (coop Jenoptik)
  - First coupled multi-junction diodes at 885 nm (preparation for the future)
- Developing an IEC/IEEE qualification standard for diode laser pumps for large laser infrastructures

Conclusions

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Introduction to the FBH Berlin

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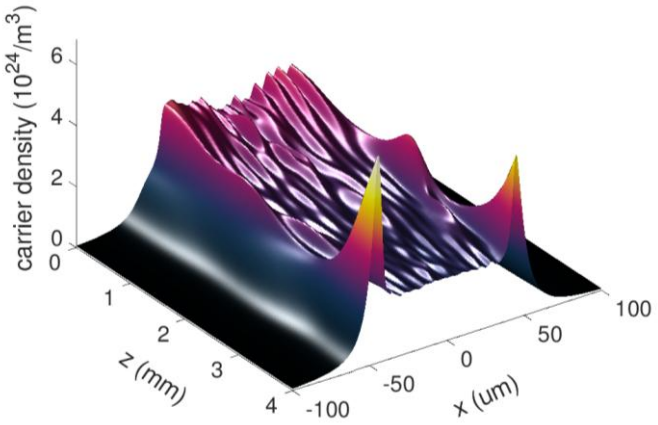
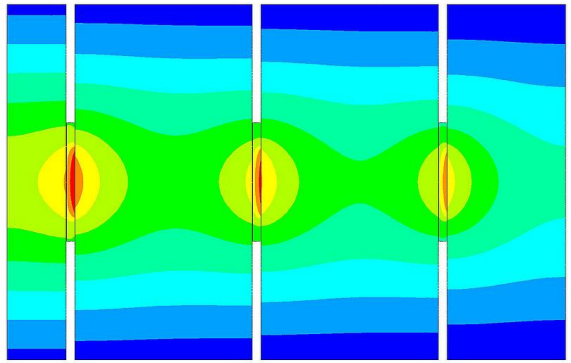
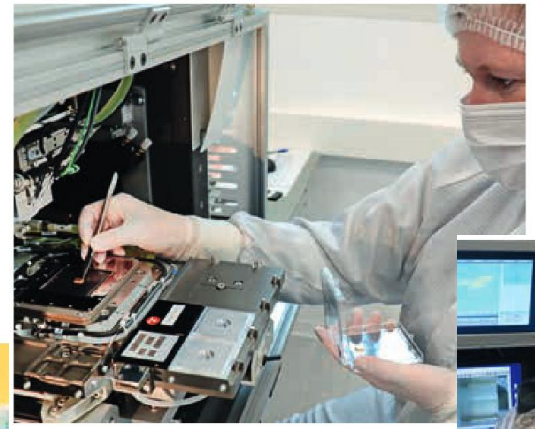
Innovative design based on Leading-edge simulation

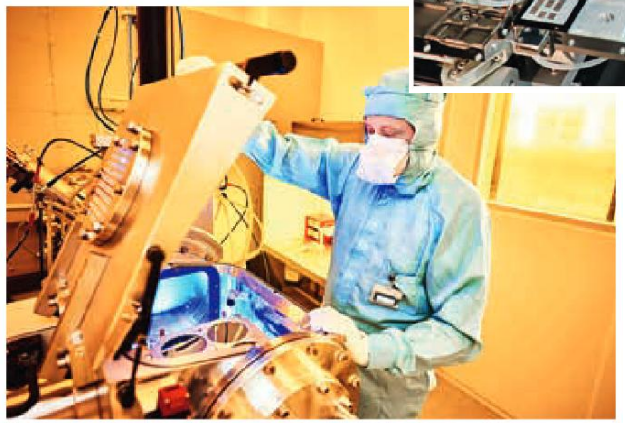


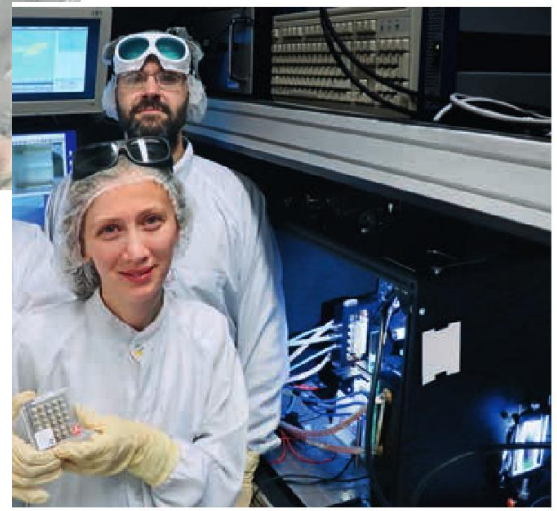


Realized with advanced process tools

(Full process chain , 2000 m^2 clean room)







Assembled and tested in sophisticated laser modules

Achieved in close cooperation between photonics and technology departments

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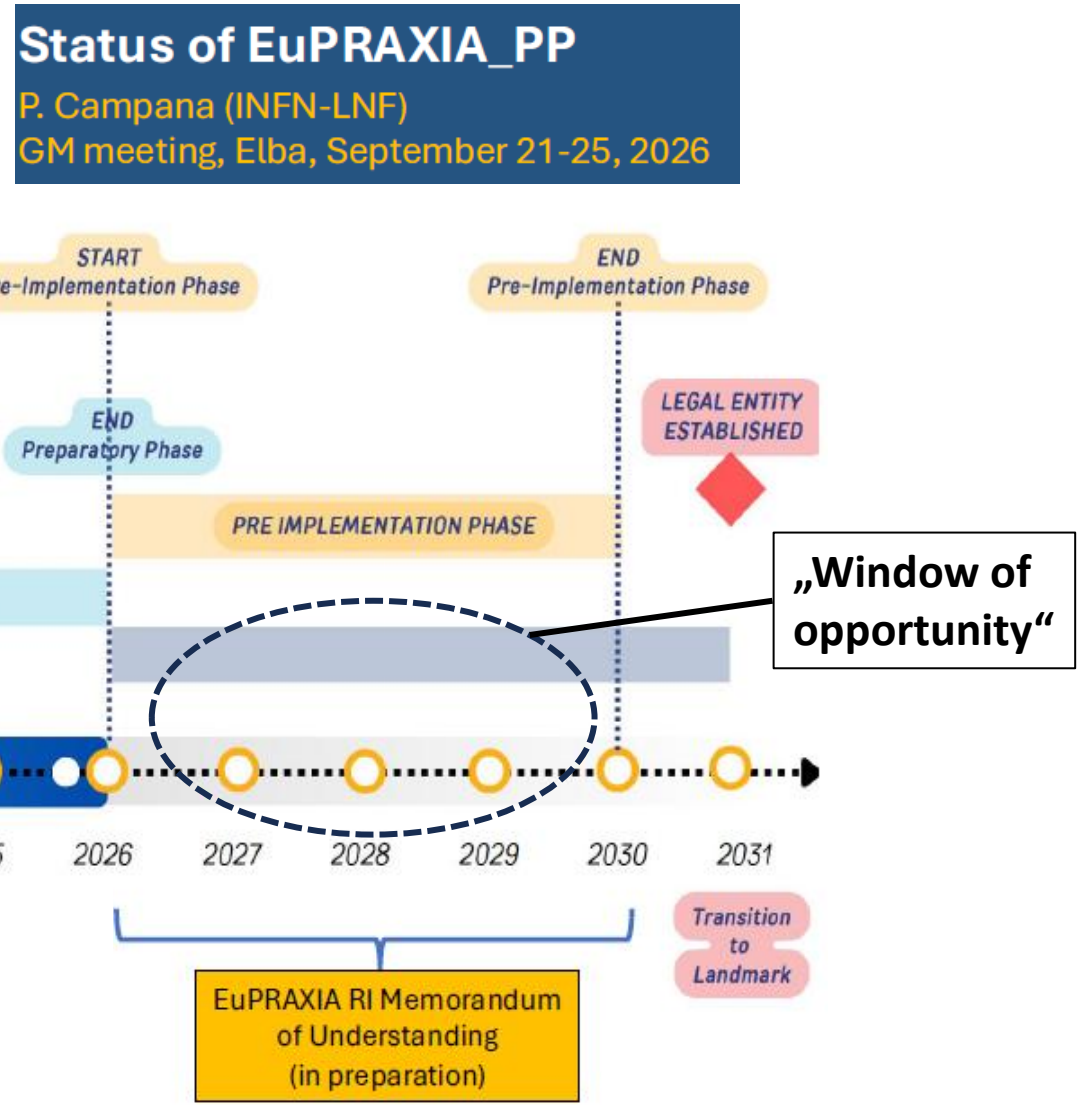
Preparation for the EuPRAXIA Laser

Funded by the European Union

- **Issue: 100 Hz diode lasers pumps**
  - Limited supply, high cost
- **Current options:**
  - High cost CW solutions
  - Low duty-cycle stacks driven to their limit
- **Goal: Develop optimized pump source for EuPRAXIA Laser**
  - Ensure available for implementation phase
  - Pending access to public funding
- **Approach followed:**
  - PACRI-funded design study with industry
  - Define requirements (co-op ELI)
  - Clarify status, gaps with industry
  - Estimate funding needed to address gaps
- **Results: target Month 24 (PACRI annual meet)**
  - Fulfil milestone M27
  - Diode pump requirements clarified with ELI
  - Project workshop, due Month 24, details to be agreed with ELI
- **Seek funding to address gaps**



Task 12.4: Design report on 100 Hz diode pumps

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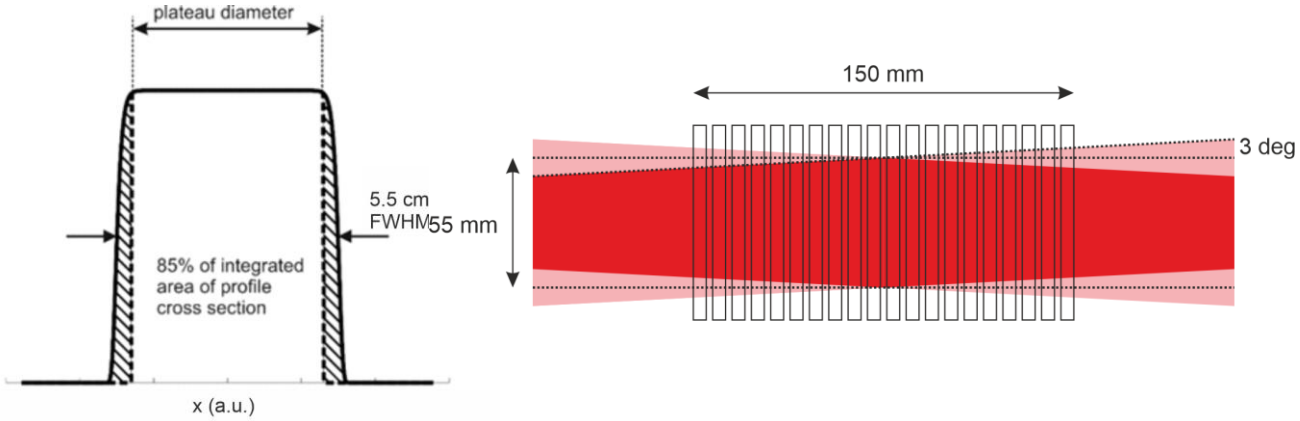
- **April 2026: parameters for the required pump sources agreed**
  - Data requested on: QCW Nd:YAG, Yb:YAG
  - Also CW for Tm:YLF
- **June 2026: Call for offers published online**
- **14 Sept 2026: extended deadline defined**
  - Delays due to holiday season
- **One complete application received**
- **In final compliance checking**
- **Official ordering process starts shortly**
  - max. 6 month delivery time requested in the call for offers
  - Goal: a preliminary report prior for the next PACRI meeting

#	Parameter (Nd:glass specific)	Desired value (description)
3.1	**Nominal Pulsed Peak Power at final image plane (kW)**	≥ 610
3.2	**Pulse Duration (ms)**	0.3 nominal
3.3	**FWHM width of profile (between parallel sides of square) (mm)**	55 ± 1
3.4	**Central Wavelength in each operational mode (wavelength above and below which 50% of the total energy is contained), λ_0 (nm)**	Between 873 and 875

Table 3 Nd:APG-1 pump diode module additional requirements



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The plan…

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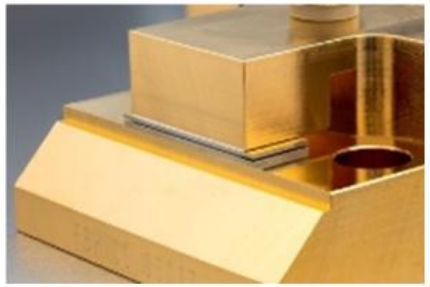
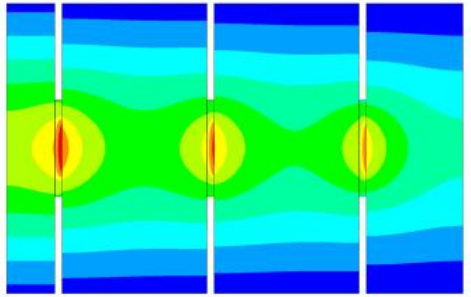
FBH research in diode pumps: scale duty cycle and power, trial new concepts

Efficient kilowatt bars + **High duty cycle stacks** + **Thermal re-engineering** + **Scaling of test capability**





Innovative multi-kilowatt, high duty-cycle stack technology

With high yield, low fabrication cost,
Tailored for use by high energy laser community

PACRI

See EU PACRI & IBB/ProFIT/ERDF HOTSTACK:
www.pacri.eu
https://www.fbh-berlin.de/en/research/photonics/diode-laser-uv-led-modules/high-power-efficiency/translate-to-english-hotstack 16

TRUMPF LayTec Finetech FBH

Task 11.4: Tech for kHz diode laser demonstrator

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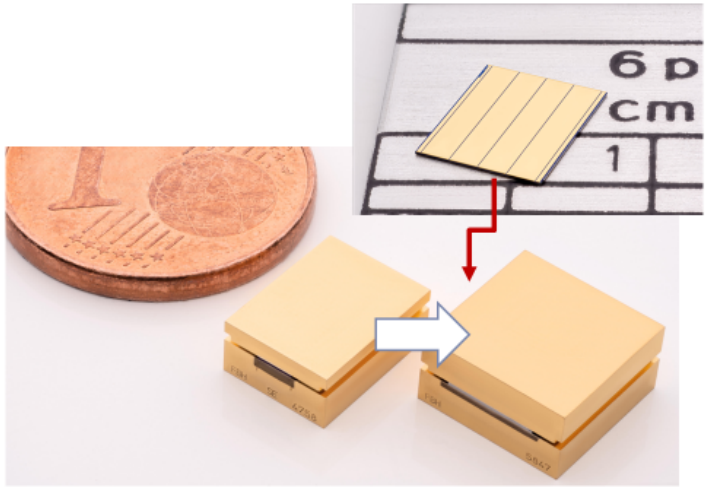
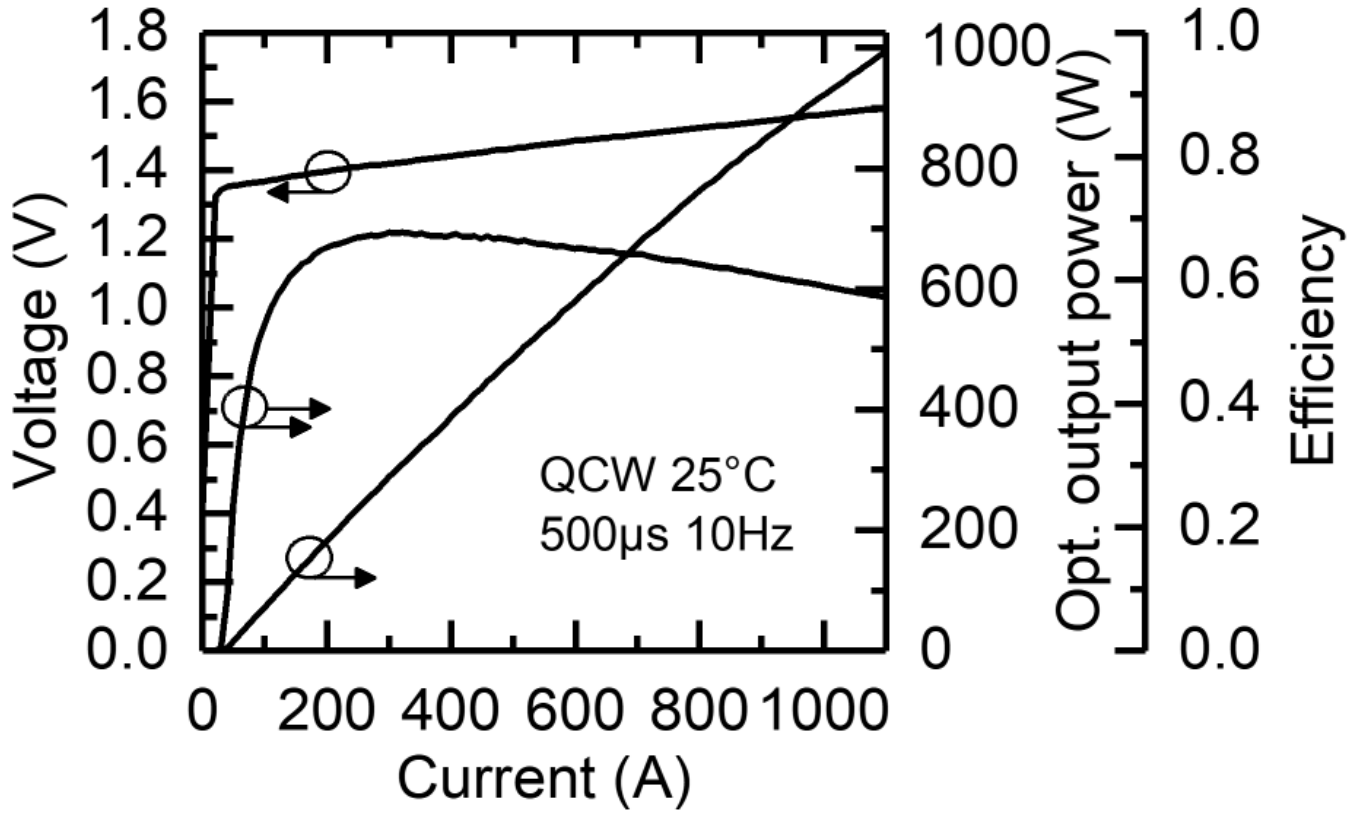
Power-optimized 940 nm Half-Bar, for integration in high duty cycle stacks



New FBH stack element

Key performance results

- **Peak power: 1 kW (margin for 500 W)**
- **Peak $\eta_{C,max}$ = 69 %**
- **P_{out} @ 600 A = 586 W**
- **η_C @ 600 A = 66 %**



PACRI Presentation tomorrow, EU Semicon. Las. Workshop Madrid:
Andrei Luferau: "1 kW 940 nm Half-Bars for Pulse-Pumping of HELs"

Task 11.4: Tech for kHz diode laser demonstrator

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Stack Module Design

GaAs based diode lasers

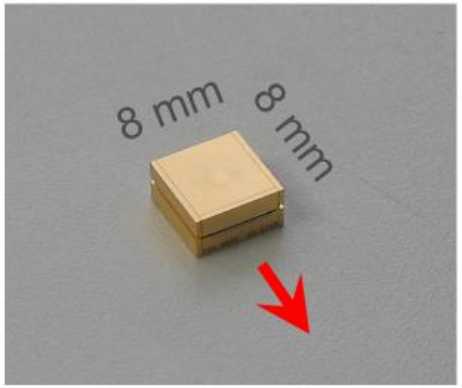
- highly vertically asymmetric epitaxial design
- emission wavelength around 940 nm

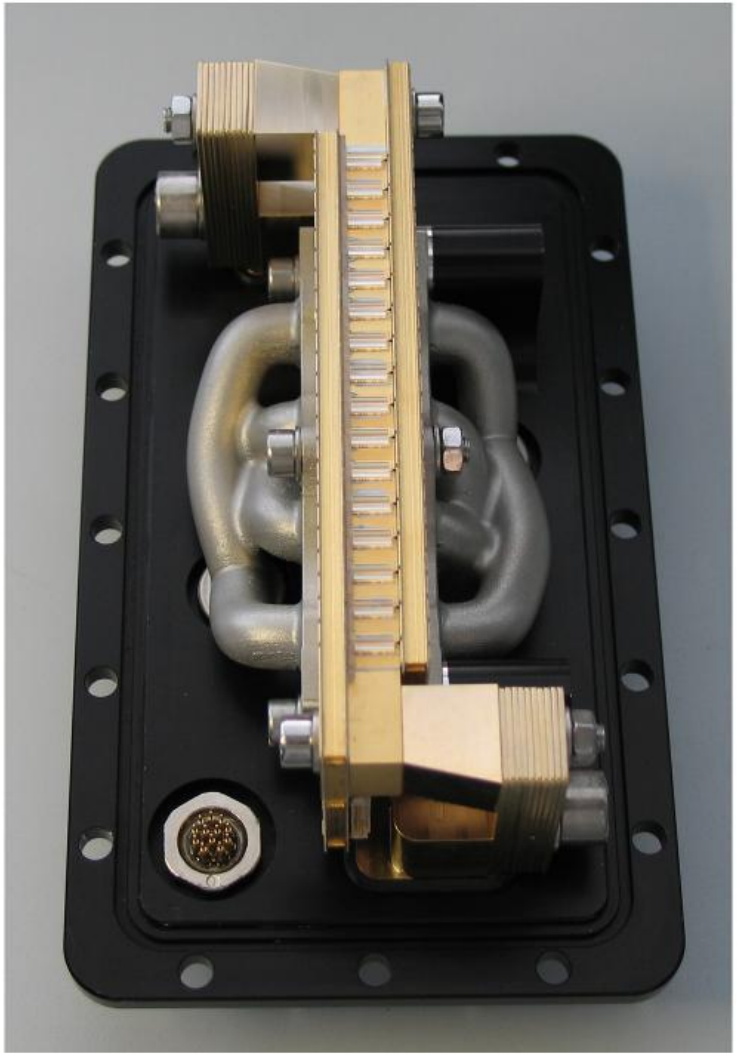
Stack elements

- 5 mm half-bars, four wide aperture diode lasers each
- cavity length of 6 mm
- Thermally expansion matched CuW heatsinks
- 8 mm length, 8 mm width, 4 mm thickness
- Nominal optical power approx. 500W

Stack module

- 16 stack elements
- two DCB large-channel water-cooler
- assembled into a stack module
- Individually fast axis collimating (FAC) lens
- Nominal optical pulse power approx. 8 kW





Task 11.4: Tech for kHz diode laser demonstrator

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Power & Emission Spectrum: 1 kHz 500 µs, from one stack → 2 kW average, 4 kW peak

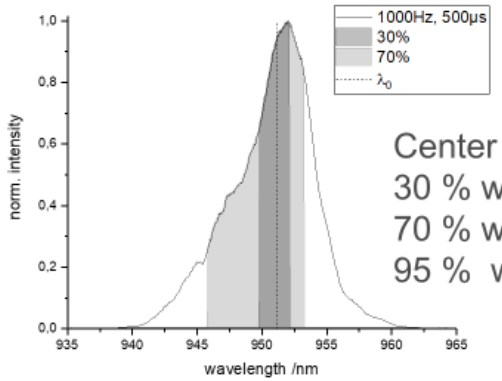
Results shown for

- 1000Hz
- 16 StEl, 500µs (50% DC)
- 28 StEl, 100µs (10% DC), old design
- 500 l / h @ 16°C

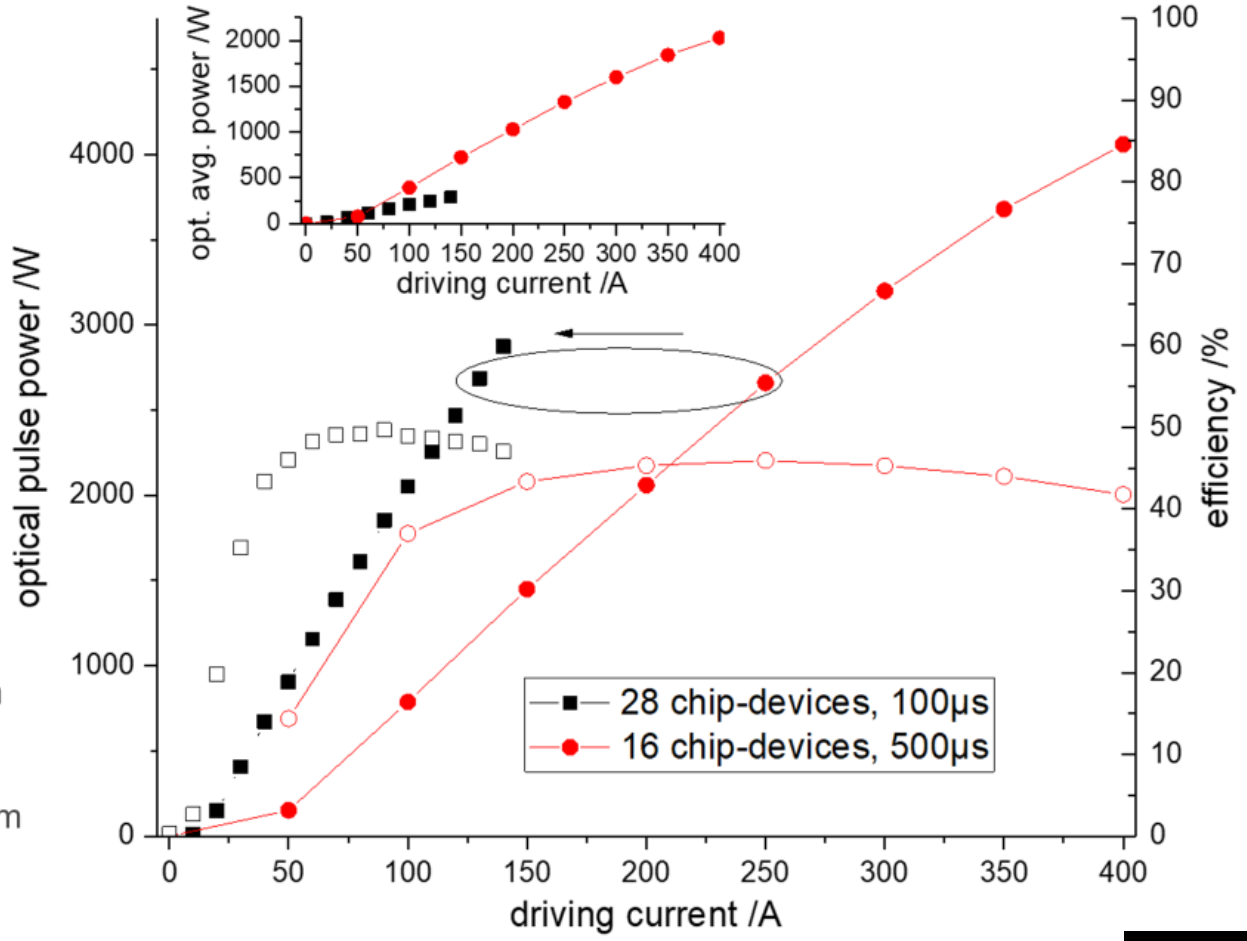
Optical power

- 4 kW, @ 400A (very first attempt)

Spectrum



Center @ 951.1 nm
30 % within 2.3 nm
70 % within 7.3 nm
95 % within 13.4 nm



Task 11.4: Tech for kHz diode laser demonstrator

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Beam forming

Stack module emission

- Highly discontinuous
- high aspect ratio laser emission

Requirements of SSL community

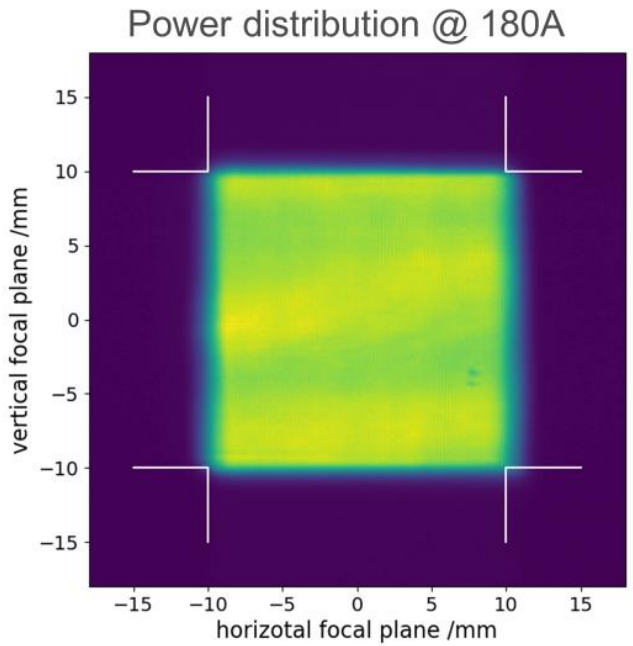
- working distance: > 800mm
- Intensity profile: square spot
- intensity distribution: near rectangular in the focal plane

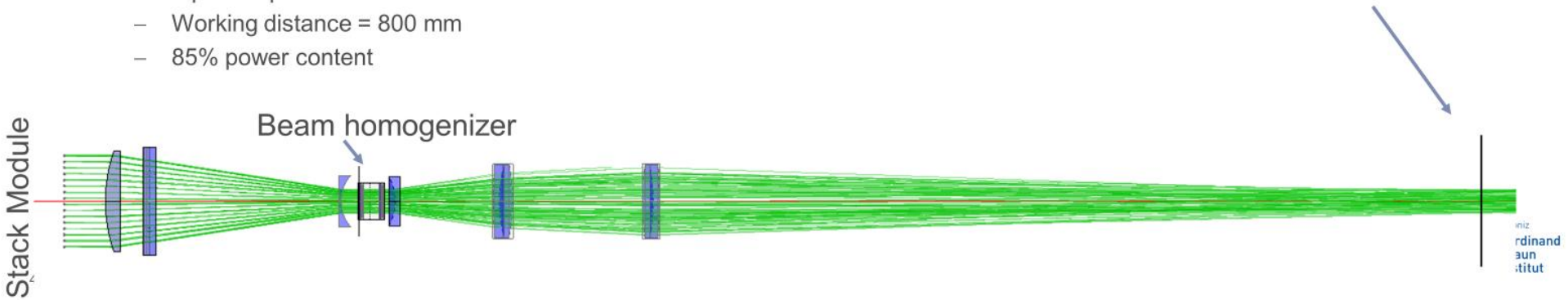
Beam homogenizer

- Two pairs of crossed cylindrical microlens arrays

Achievements

- square top hat 20 mm x 20 mm
- Working distance = 800 mm
- 85% power content





Task 11.4: Tech for kHz diode laser demonstrator

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Beam forming

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- Worki
- 85% power content

→ **PACRI Invited talk, HILAS Conference**

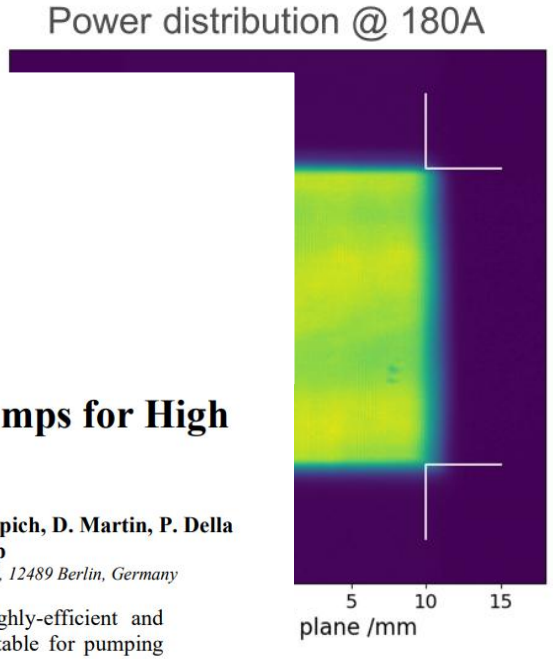
Optica Laser Workshop and Congress
Vilnius, Lithuania · 12 October 2026

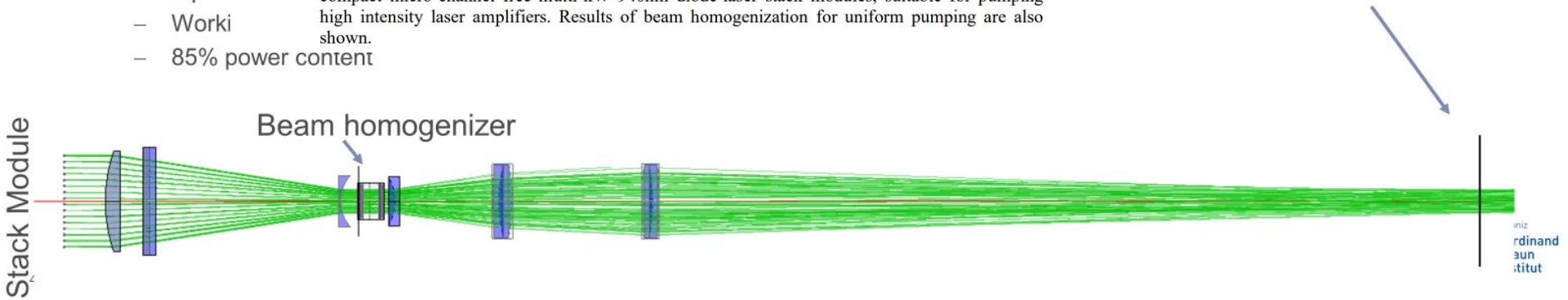
Progress in high repetition rate diode laser pumps for High Intensity Laser systems

M. Hübner*, M. Wilkens, S. Arslan, A. Luferau, L. Wittenbecher, J. Zender, B. Eppich, D. Martin, P. Della Casa, A. Ginolas, P. S. Basler, N. Lobo-Ploch and P. Crump

Ferdinand-Braun-Institut gGmbH, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Str. 4, 12489 Berlin, Germany
**marko.huebner@fbh-berlin.de*

Abstract: We present studies into kHz-level repetition-rate scaling of highly-efficient and compact micro-channel free multi-kW 940nm diode-laser stack modules, suitable for pumping high intensity laser amplifiers. Results of beam homogenization for uniform pumping are also shown.





Task 11.4: Tech for kHz diode laser demonstrator

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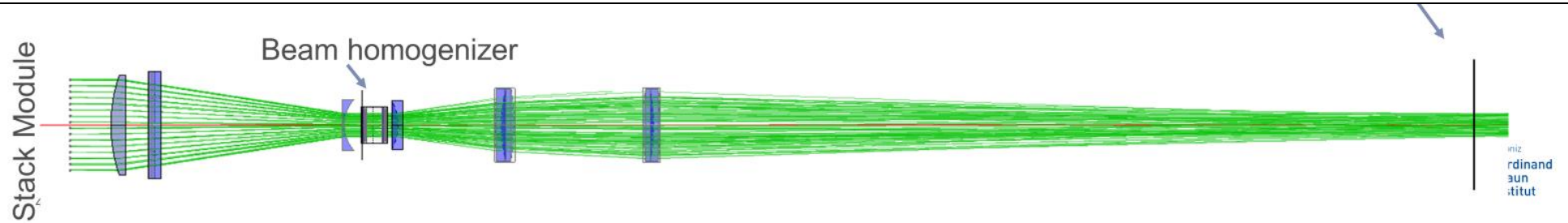
Beam forming

Stack module emission

ELI-ERIC / STFC visit to review lab demonstration planned
Target ca. end of Jan 2027

Ready to fulfil PACRI Milestone M25
“Design of kilohertz prototype diode pump module agreed” (FBH,STFC, ELI-ERIC)

Due Month 24, Int. Report



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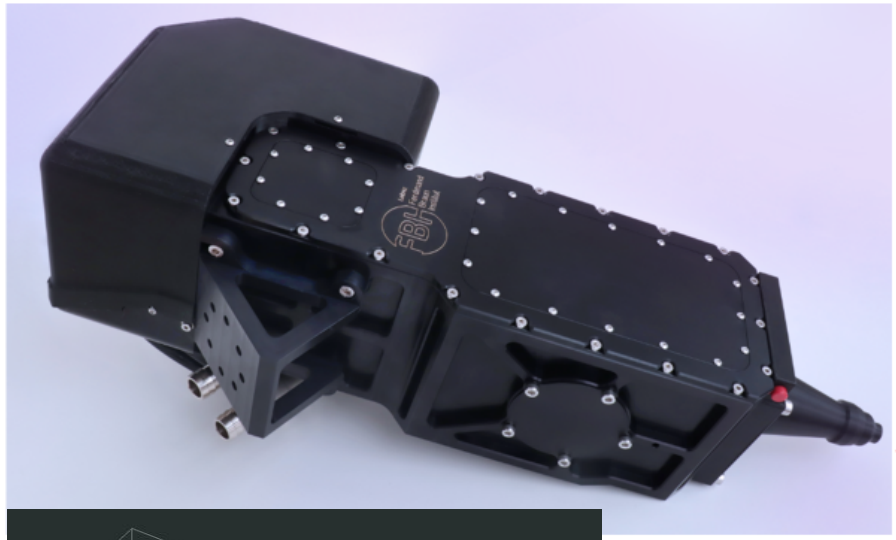
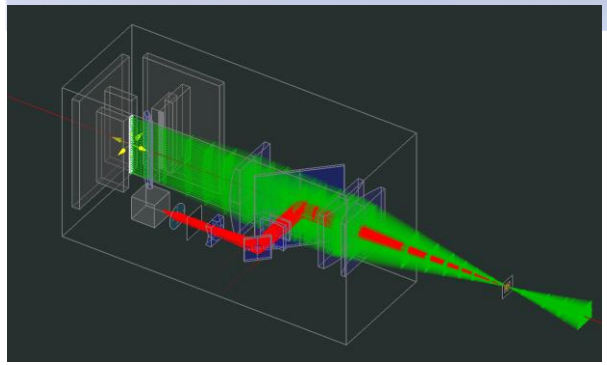
Task 11.3 – Pump diode for Tm-doped materials

Task 11.3 – **Pump diode for Broadband amplification in Tm-doped gain media**

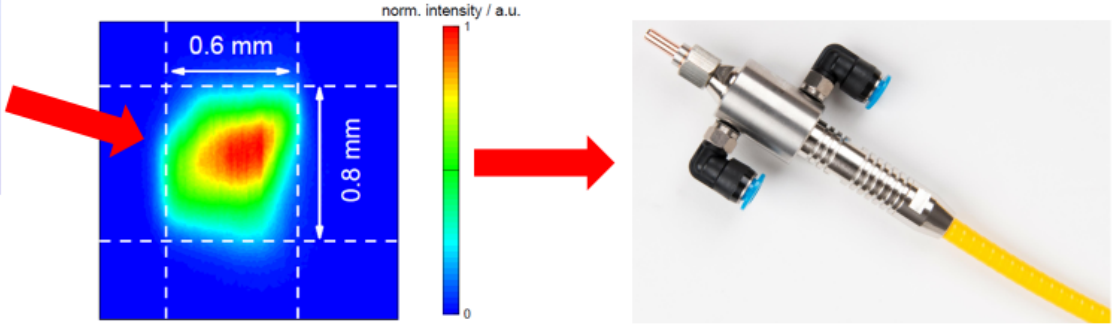
- Delivery of 1 kW ~ 796 nm diode laser module for pumping Tm:YAG, to CNR
- Operates from high rep-rate QCW (50-100 Hz, 50% duty cycle), to CW





Modifying existing 780 nm diode laser-module for direct material processing (1 kW, CW, within a < 1 mm spot)

- New diode lasers with wavelength shifted to 796 nm were fabricated, tested and mounted into diode laser stacks
- Output opening will be modified, so that an optical fibre with high-power fibre connector can be attached (under development)



- Optical fibre with high-power connector is ordered (1mm core, NA = 0.22, water cooled, AR coated, mode-stripper)
- Optical simulations predict fibre coupling efficiency >95%

2

Task 11.3 – Pump diode for Tm-doped materials

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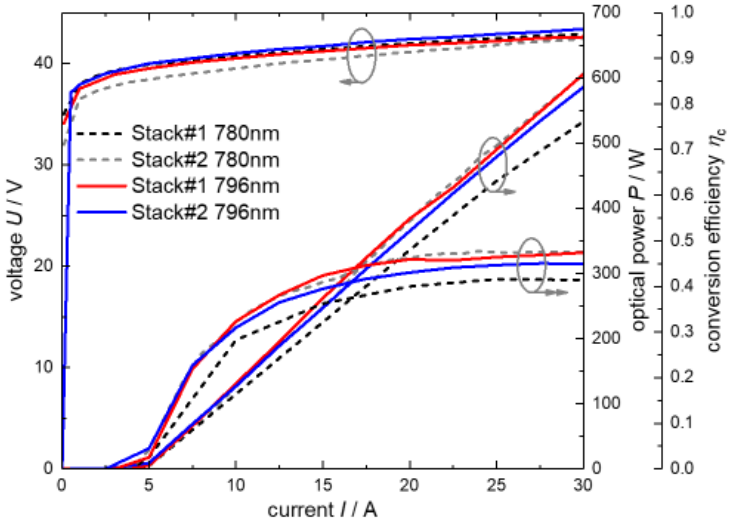
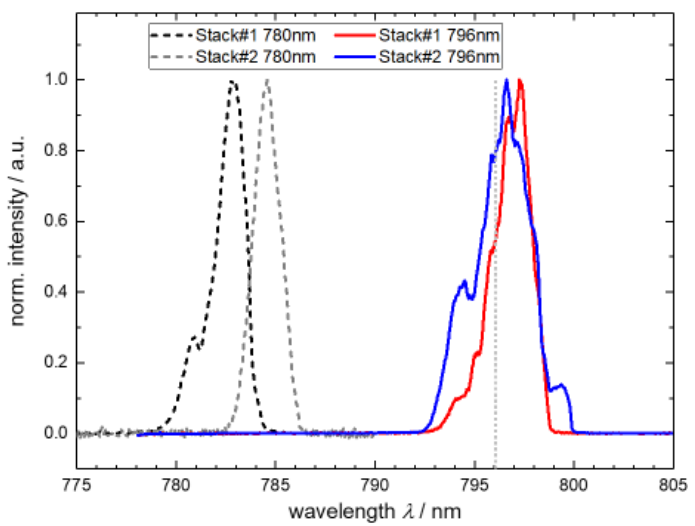
- 4× stacks with new diode lasers assembled (module only needs 2)
- 2× 796-nm stacks tested with results comparable to the best 780-nm stacks

P-V-I curves, CW, T_w~15°C



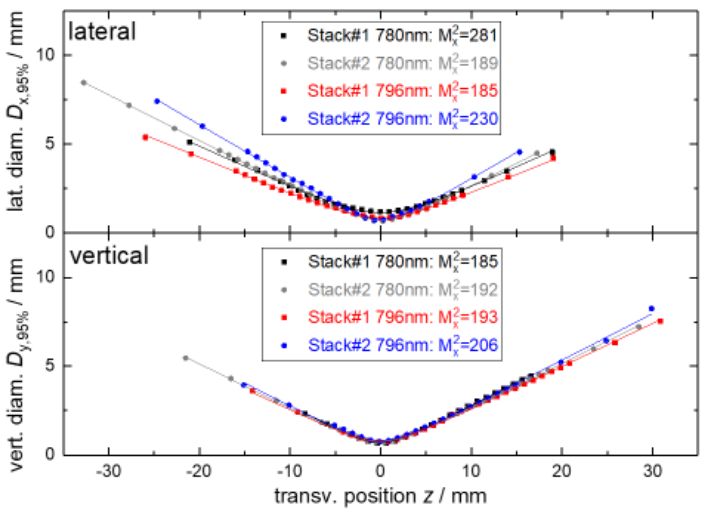
- P ~ 600 W optical power per stack @ 30A cw with >45% efficiency

Spectra @ 30A CW, T_w~15°C



- Wavelength transfer from 783nm to 796nm successful

beam quality @ ~600W optical power



- Similar beam quality with M²~200 in both axis

→ Stacks ready for module assembly

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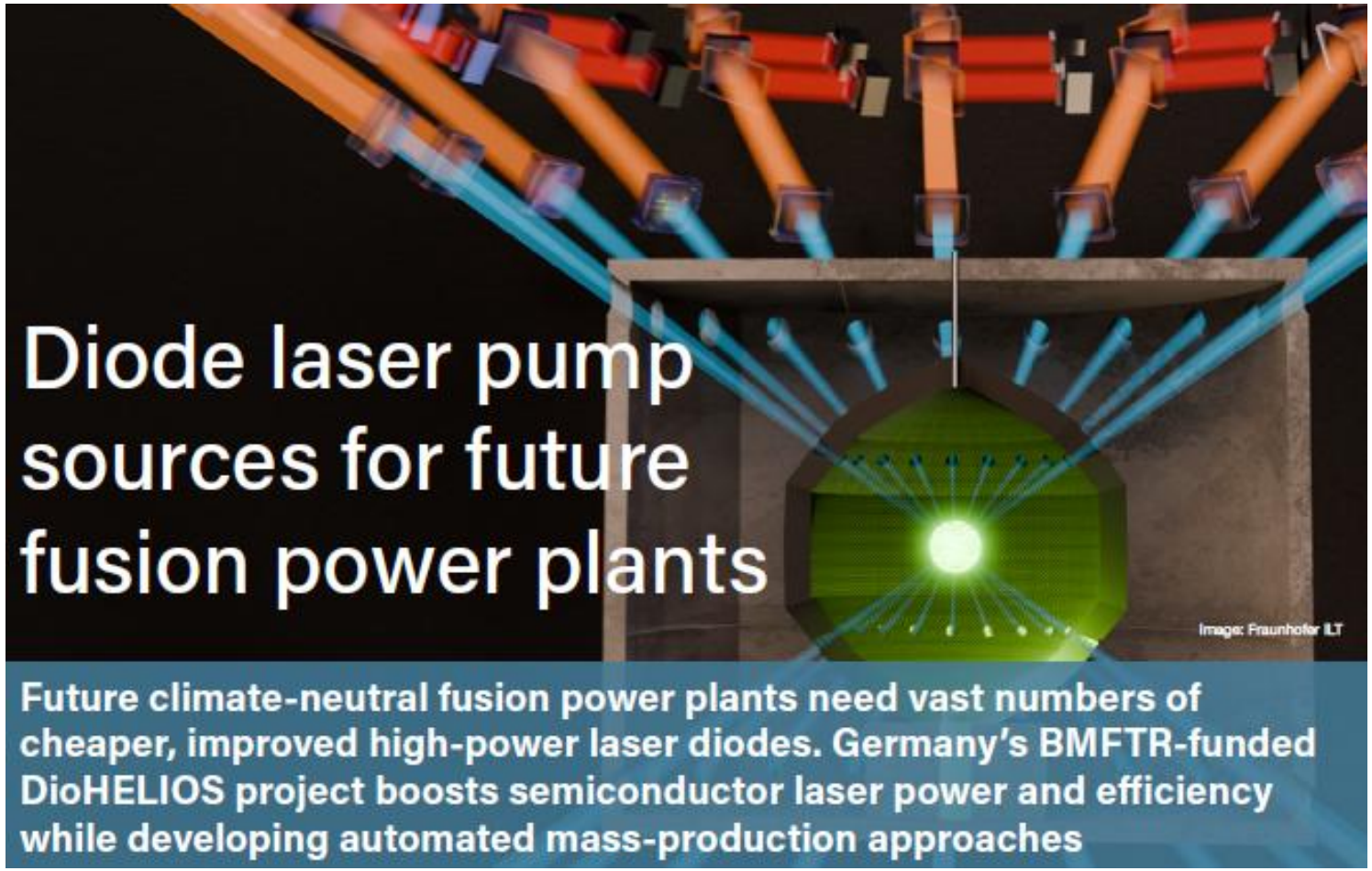
DIOHELIOS: Strong Investment in Diodes for HEL



DIOHELIOS

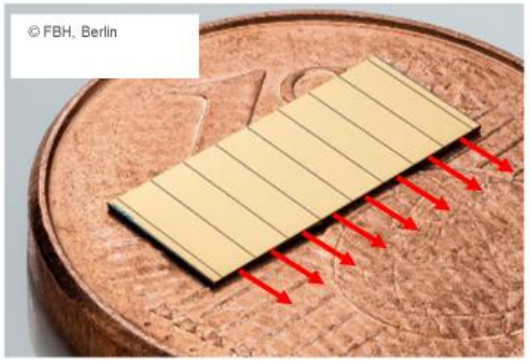
Dr Dirk Sutter
Coordinator for the DioHELIOS Project Consortium
TRUMPF Laser SE, Research & Development

D. Sutter (2026), "Diode laser pump sources for future fusion power plants", The Innovation Platform **26**, pp.166-169 (2026). https://www.innovationnewsnetwork.com/article/diode-laser-pump-sources-for-future-fusion-power-plants/70625/

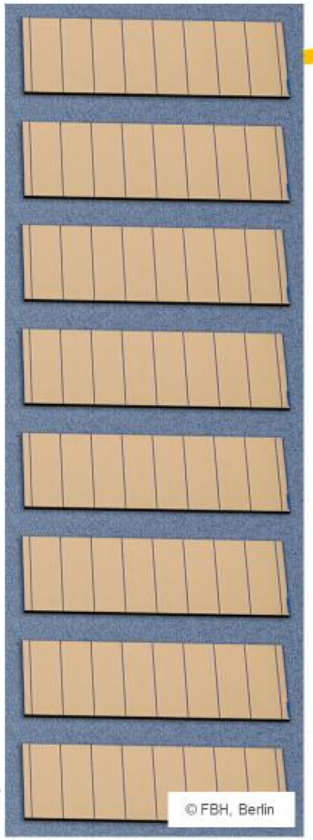
Supporting BMFTR Laserfusion Hub VEGA

Funded by the European Union

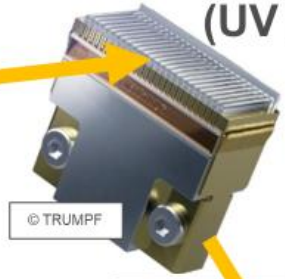
Diode Laser Arrays (bars)
Commercial: 500 W output power,
> 60% efficiency at 940 nm
1 cm aperture, 4 mm resonator

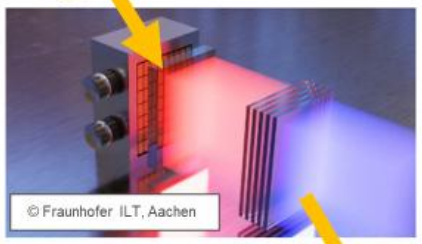


Fabricated in large numbers



Assembled into laser drivers (UV beam lines)





Integrated in fusion power plant

www.focused-energy.co/news-release/machbarkeitsstudie-zeigt-potenzial-fur-fusionskraftwerk-in-biblis-auf-dem-weg-zu-einem-europaischen-leuchtturmprojekt

See: „**German partners launch DioHELIOS project as part of the Fusion 2040 program**“
Press release 31.10.2024, Fraunhofer ILT, Aachen Germany

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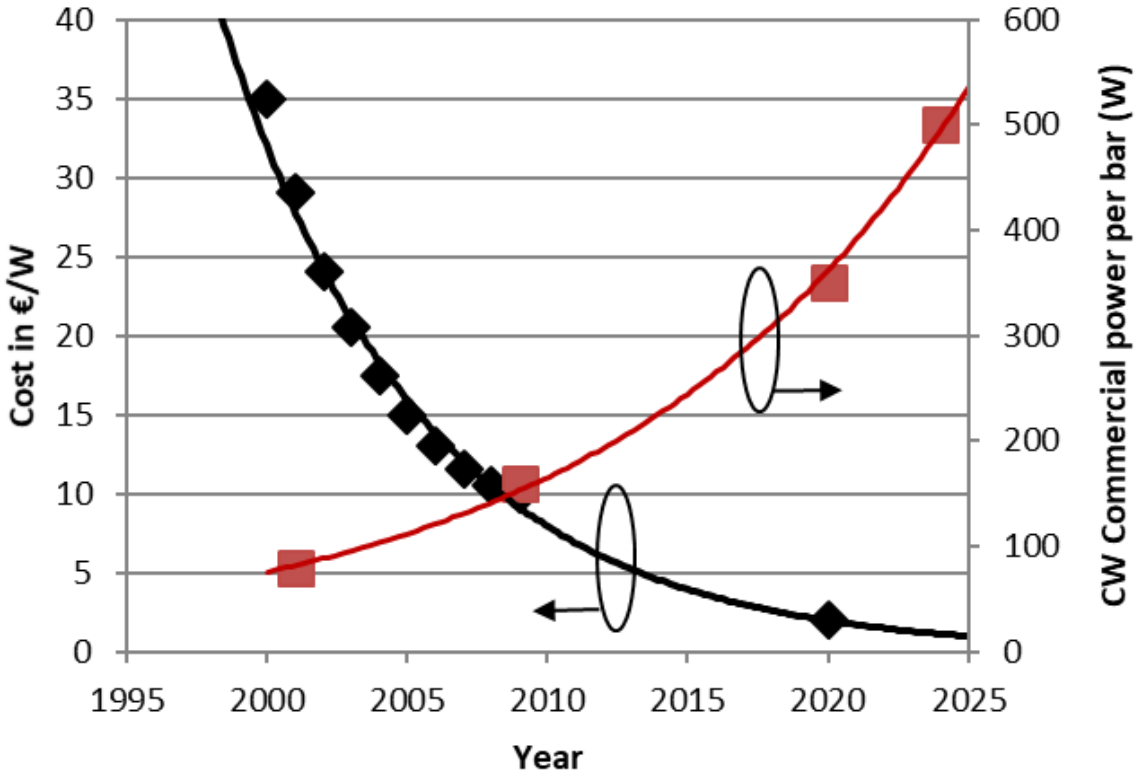
Higher power diodes enable lower overall cost

Funded by the European Union

Cost and power per bar, diode laser pumps for CW application



Sources:
H.G. Treusch *et al.* IEEE J Sel. Top. Quant. Electron. 6(4), p. 601 (2000)
G. Bonati Laser Techn. Journal 2, p. 37 (2010)
S.G. McDougall *et al*. Proc SPIE 11262, paper 5 (2020)
M.S. Zediker and E. Zucker, Proc. SPIE 11983, 1198302 (2022)

Goal: massive power scaling via new technology

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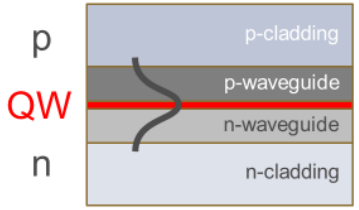
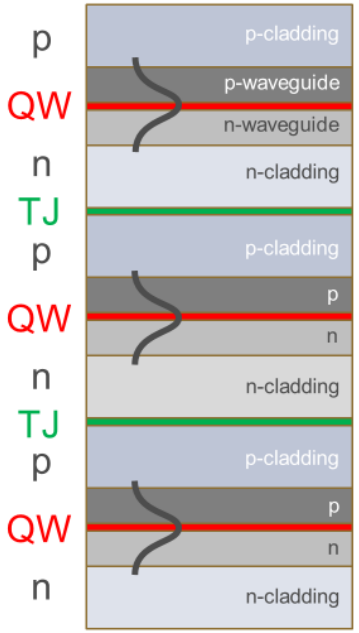
Funded by the European Union

View of future: Multi-kilowatt DBR-stabilized multi-junction bars for ultra-low cost

Single Junction

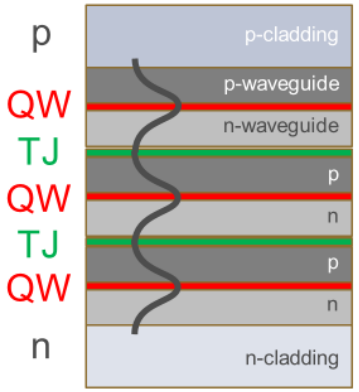


Multi-Junction



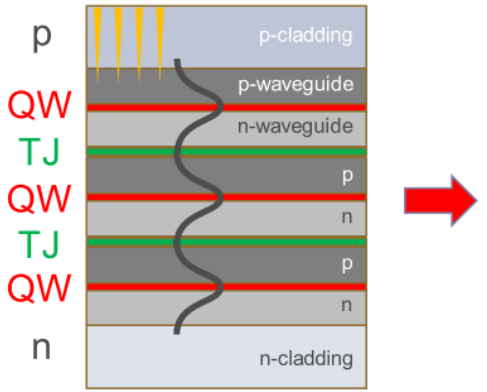
1..2 kW now, good efficiency *
Broad spectrum, far field

Coupled Multi-junction
One mode! → collimate
Less layers → potentially higher efficiency



In commercial use
In VCSELs **

Grating-stabilized Multi-junction
„Everything at once“
DBR



Focus of FBH studies, seeking:
at high heat (fusion) levels:
Near term: > 1.5 kW
Long term: > 5 kW

* G. Liu et al. Proc. SPIE 13345, 133450V (2025)
** A. Ghods, IEEE JSTQE 31(2) 1700907 (2025)

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Steps along the way:
World's first 1 kW bar at λ=885 nm with grating

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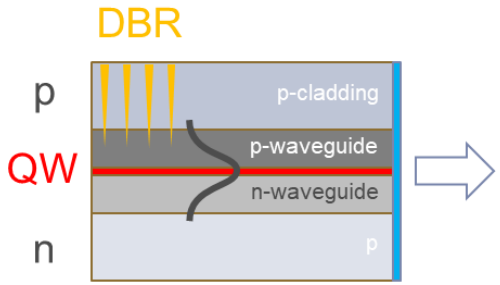
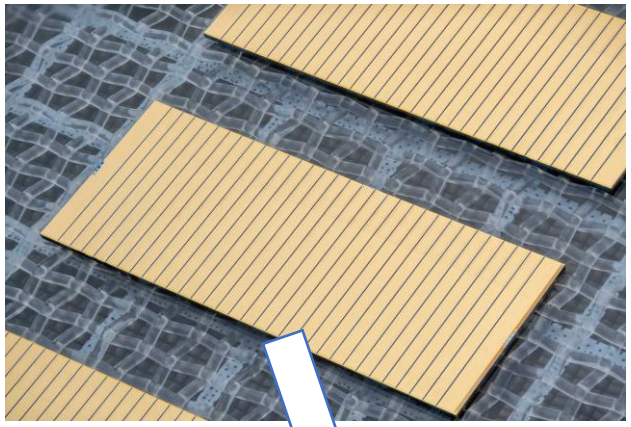
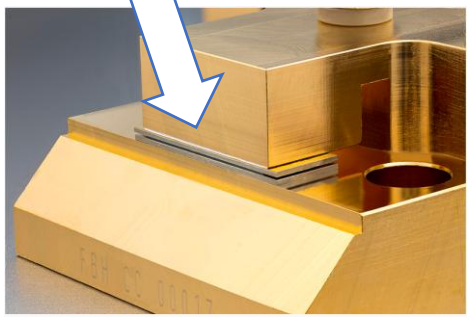
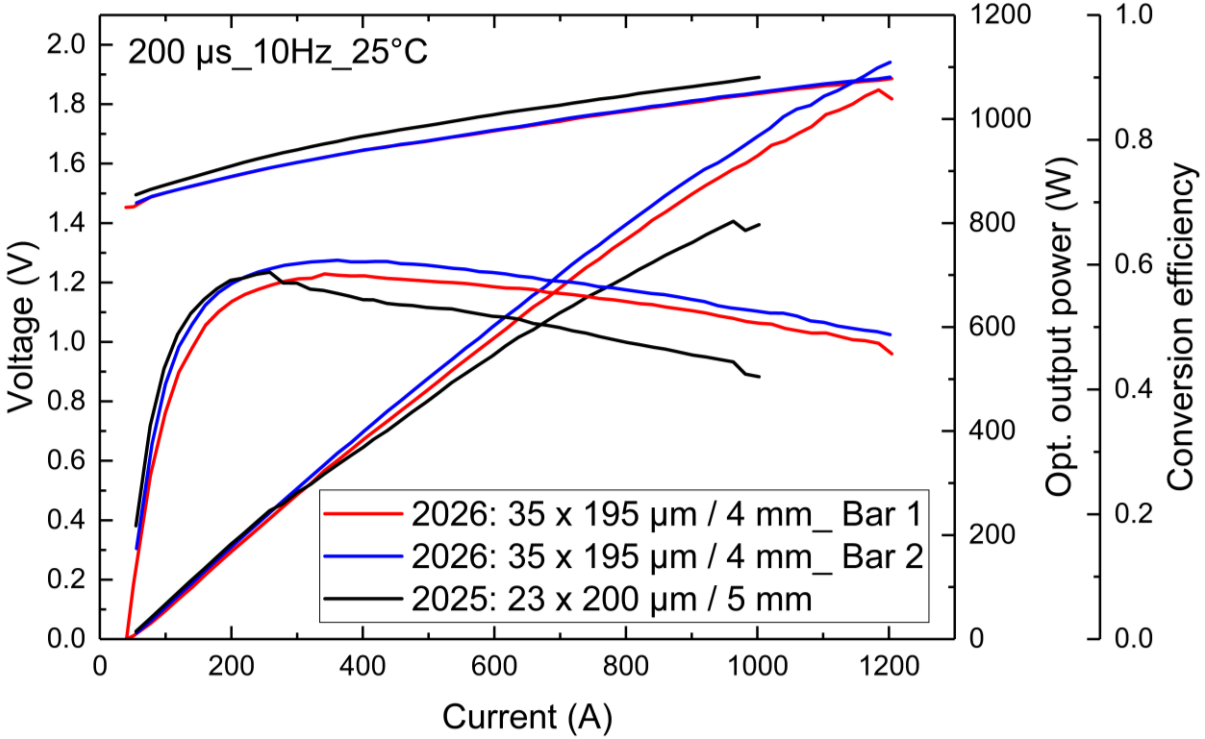
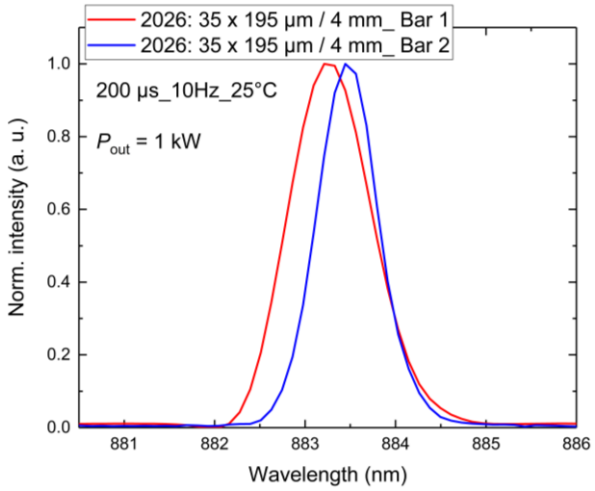






Conversion efficiency η_E **(1000W) → 50%; P_{max} → 1000 W**





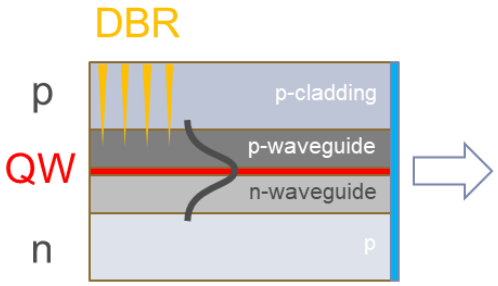
$\Delta\lambda_{95\%}$ ~ 1.8 nm

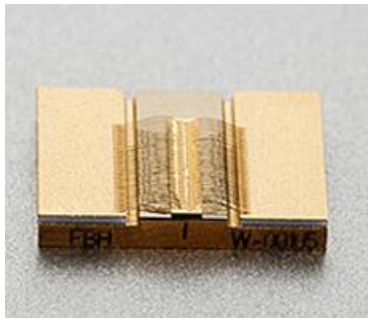
TRUMPF Coop TRUMPF

P. Crump *et al.* (Invited) „High-power diode lasers for fusion energy applications: perspectives from research and industry" Compound Semiconductor Week (CSW 2026), Kumamoto, Japan, May 24-28, art. MoD3-01 (2026).

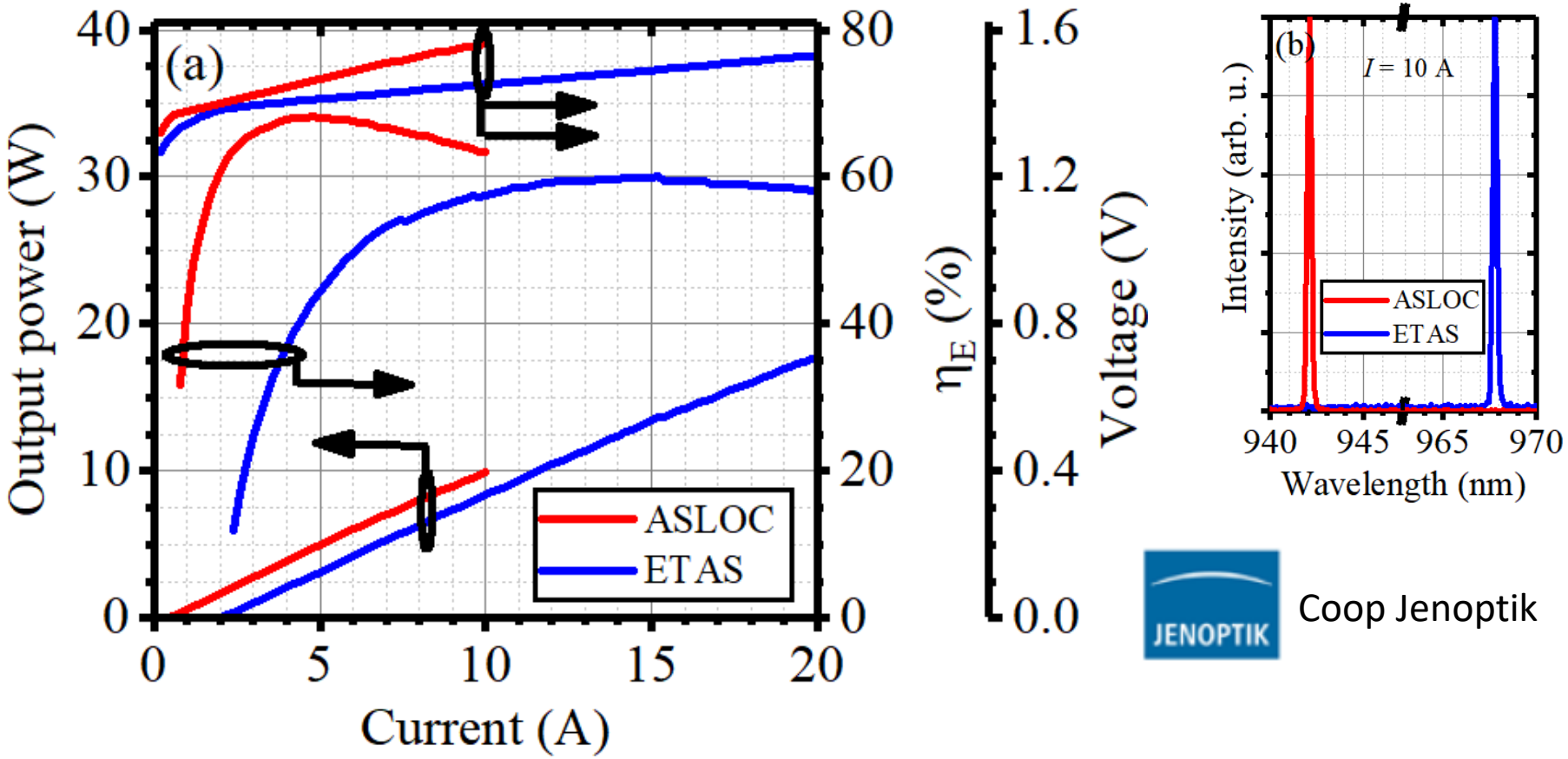
Steps along the way:
World's first 70% efficient HPDL with grating

Leibniz Ferdinand Braun Institut
Funded by the European Union





Improved design and technology, to scale efficiency

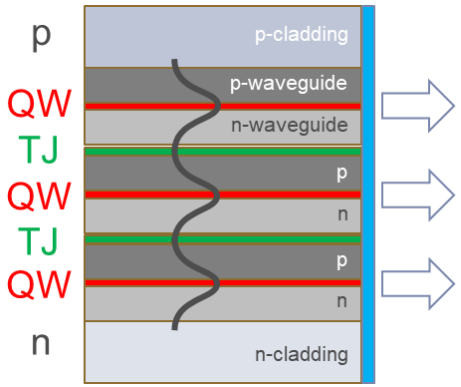


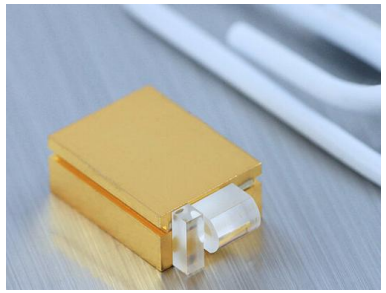
Coop Jenoptik

A. Luferau *et al.* (Invited) „Efficient Monolithically Grating-Stabilized Diode Laser Pumps for Inertial Laser Fusion Energy" IEEE Photonics Conference (IPC 2026), Denver, CO, USA, 8-12 November, art. WB1.4 (2026).

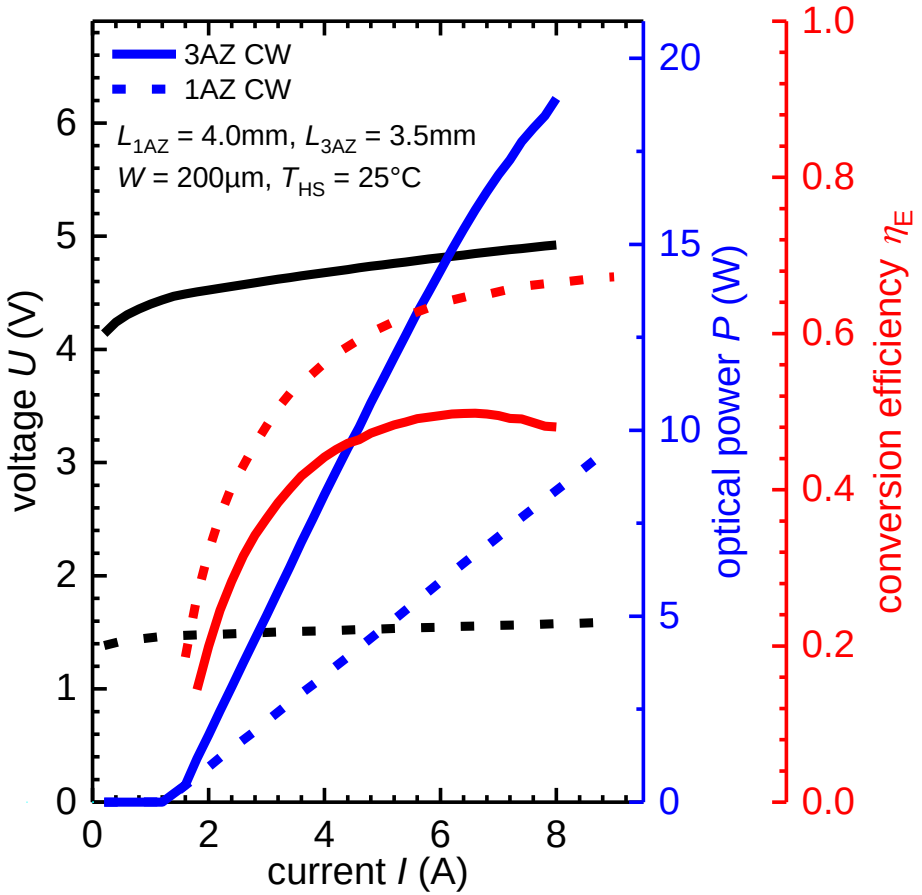
World's first triple-junction HPDL at λ=885 nm

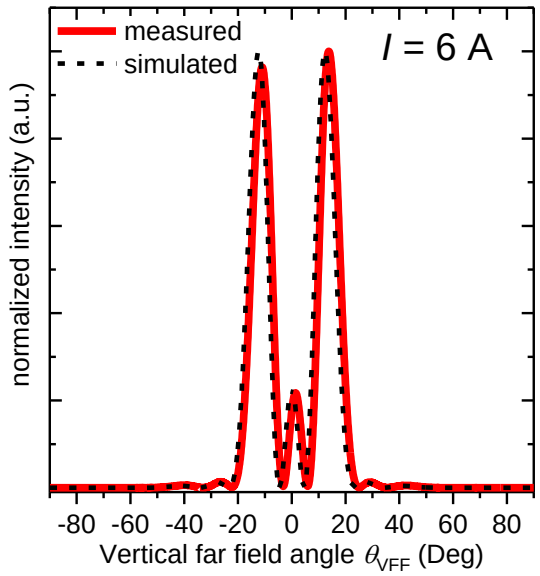
Funded by the European Union





Threefold power increase, but with efficiency penalty (work in progress)





E. Bahat Treidel *et al.* „88x nm Coupled Multijunction Diode Lasers for Power-Scaling in Inertial Fusion Energy (IFE) Application" 30th Int. Semi. Laser Conf. (ISLC 2026), Tampere, Finland, 14-17 June, art. WePD4 (2026).

Contents

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Introduction to FBH Berlin (Reminder)

- A German (EU) excellence centre for high power diode lasers and their applications

Efforts within PACRI, in support of EuPRAXIA and future HELs

- Preparation for the EuPRAXIA Laser
  - Commissioning of an industrial design study
- Assessment of alternative pump concepts
  - Diode laser and module development for 1000 Hz pumping of Yb:YAG
  - Direct diode pumping of Thulium-doped materials
  - Paper study on path to direct diode pumping of TiSa

Efforts within National Fusion programs (BMFTR DIOHELIOS)

- Broad goals of diode development, with some headline results
  - First 1 kW monolithic grating stabilized bars at 885 nm (coop TRUMPF)
  - First 70% efficient grating stabilized diodes at 940 nm (coop Jenoptik)
  - First coupled multi-junction diodes at 885 nm (preparation for the future)
- **Developing an IEC/IEEE qualification standard for diode laser pumps for large laser infrastructures**

Conclusions

Conclusions

The FBH is an excellence centre for high power diode lasers and a strong supporter of high energy lasers

Progress demonstrated within PACRI, in support of EuPRAXIA and future HELs

- In industrial design study on diode laser pumps for the EuPRAXIA Laser is on its way
- Goal: make highest performance units available for the implementation phase
- New concepts for future HELs: Pulsed pumping into kHz, high intensity, advanced pump for Tm, direct pump of TiSa

Stong investment in diode technology via National Fusion programs → rapid performance progress

- First 1 kW monolithic grating stabilized bars at 885 nm (coop TRUMPF)
- First 70% efficient grating stabilized diodes at 940 nm (coop Jenoptik)
- First coupled multi-junction diodes at 885 nm (preparation for the future)

Developing an IEC/IEEE qualification standard for diode laser pumps for large laser infrastructures

- Scaling towards very large systems under high heat load: there are no current suitable protocols or procedures

Good progress, much to do

Acknowledgements

EuPRAXIA Preparatory Phase

Funded by the European Union

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VDI Technologiezentrum

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Thanks for your attention!

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