100 Hz pumping options for EuPRAXIA Project

Status Talk

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Brief introduction to FBH

Requirements for 100 Hz pumps for EuPRAXIA

Technology status of high repetition rate, high intensity pump sources

Proposed path to pump availability

Conclusions

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Introduction to the Ferdinand-Braun-Institut (FBH)
... Innovations with microwaves & light

The FBH is situated in the south-east of Berlin, Germany

In Adlershof, Germany‘s leading science and technology park

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Ferdinand-Braun-Institut – Facts & Figures

- Institute within Forschungsverbund Berlin e.V., Member of Leibniz Association
- Shareholders: State of Berlin / Federal Republic of Germany
- Founded in: 1992

- **Staff: 290** (incl. 150 scientists & PhD students)
- **Budget / Turnover (2017): 33 M€** (incl. 16 M€ project revenues)
- Partner with / Joint Labs:
  - Technische Universität Berlin
  - Humboldt-Universität zu Berlin
  - Goethe-Universität Frankfurt a. M.
  - BTU Cottbus-Senftenberg
- **Associate member of EuPRAXIA**

Applied Research into High Power Diode Lasers for Pump Applications:

The FBH: leader in applied research into high power diode laser pumps

- Leader in (e.g.) diode laser bar power (kW bars) and efficiency (70% peak, > 60% at 1 kW)
  - Patent portfolio covering III-V design and technology

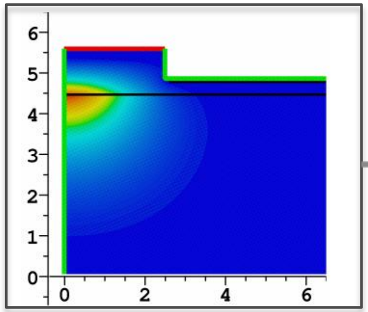
- Close cooperation with industry, from R&D prototyping to pilot-series fabrication to tech transfer
  - Including Trumpf, Jenoptik, OSRAM, DILAS/Coherent, Lastronics

- Close cooperation with sold state laser research facilities
  - MBI, IOQ (Uni. Jena), STFC, HILASE, Livermore

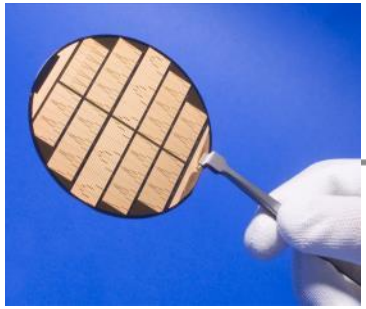
Applied Research into High Power Diode Lasers for Pump Applications:

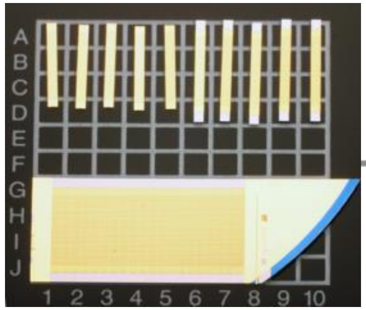
The FBH covers the complete value chain, from …

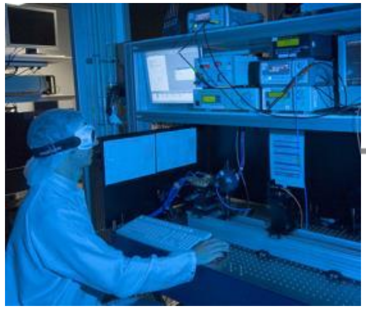
design...



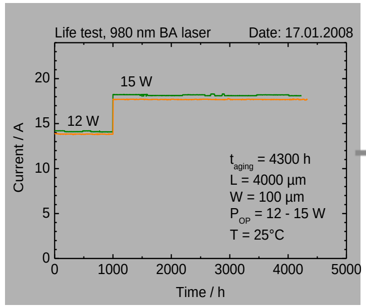
epitaxy & technology...



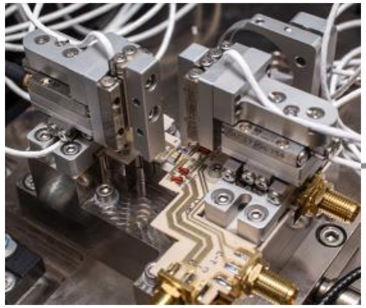




characterization...



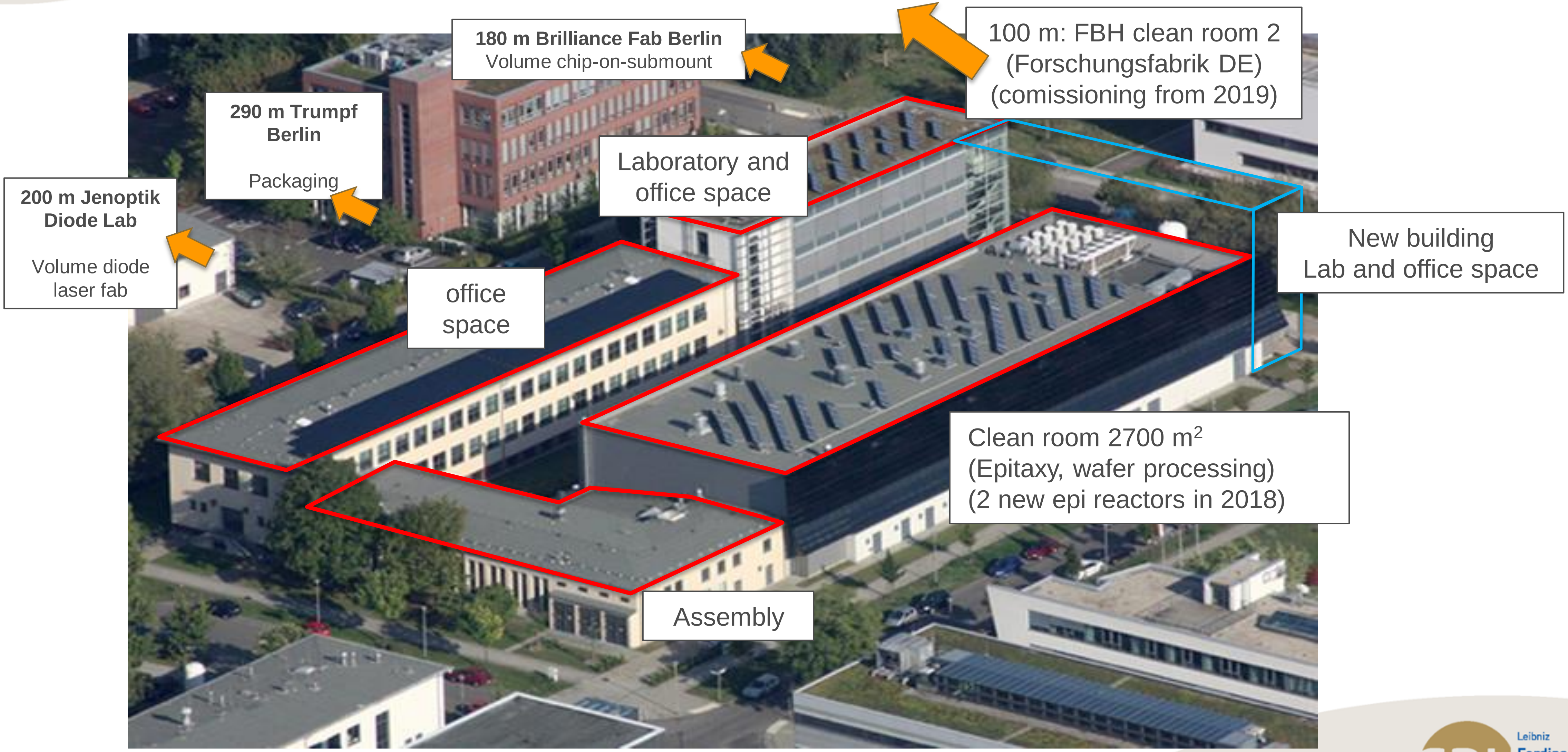
reliability…



modules…

…to demonstrator systems.

FBH main building, facility, collaborators



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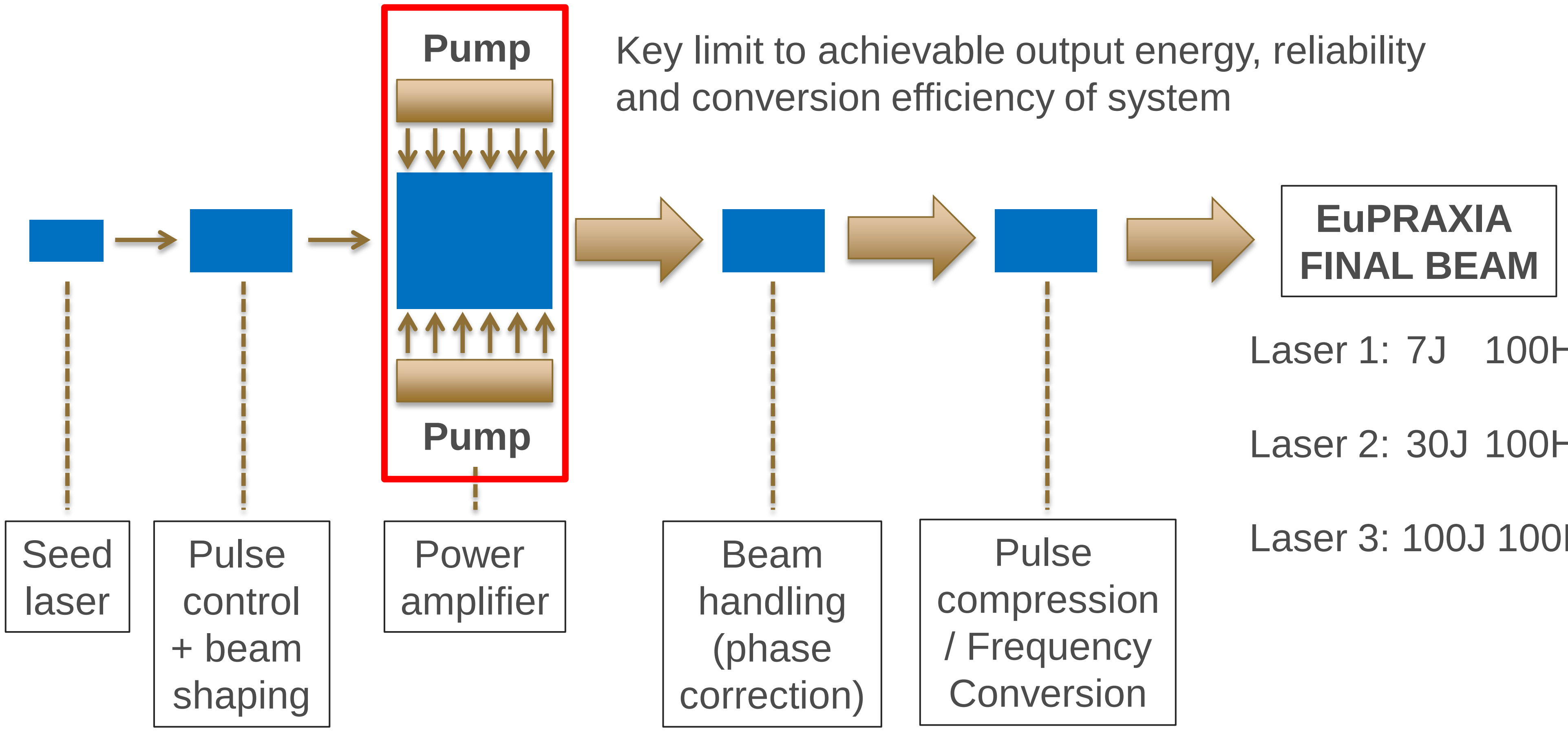
EuPRAXIA 100 Hz Schematic Configuration

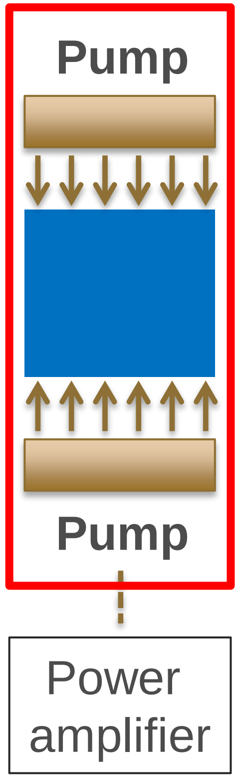


Laser 1: 7J 100Hz

Laser 2: 30J 100Hz

Laser 3: 100J 100Hz

EuPRAXIA 100 Hz Pump Requirements



Estimate of requirements shown (with thanks to STFC for input)

- Assuming on TiSa system pumped using DPSSL cryo Yb:YAG (Yb:CaF_2, Tm:YAG are alternatives)

Laser 3: 100 J 100 Hz

- 1200 W peak pump power (Two pump units, 600 kW each)
- Pulse condition: 0.5…1 ms 100 Hz,
- Beam: 3.6…7 J/cm2 & 0.5…1 MW/(cm2-sr)

Laser 2: 30 J 100 Hz

- As for 100J, but ~ 360 W total peak pump power (linear scaling)

Laser 1: 7 J 100 Hz

- As for 100J, but ~ 84 W total peak pump power (linear scaling)

Reliability:

- 24/7 operation for 25…30 years, 100 Hz 0.5 ms (~ 100 e9 "shots")
- "Acceptable" reliability / diode laser replacement rate. To be defined!

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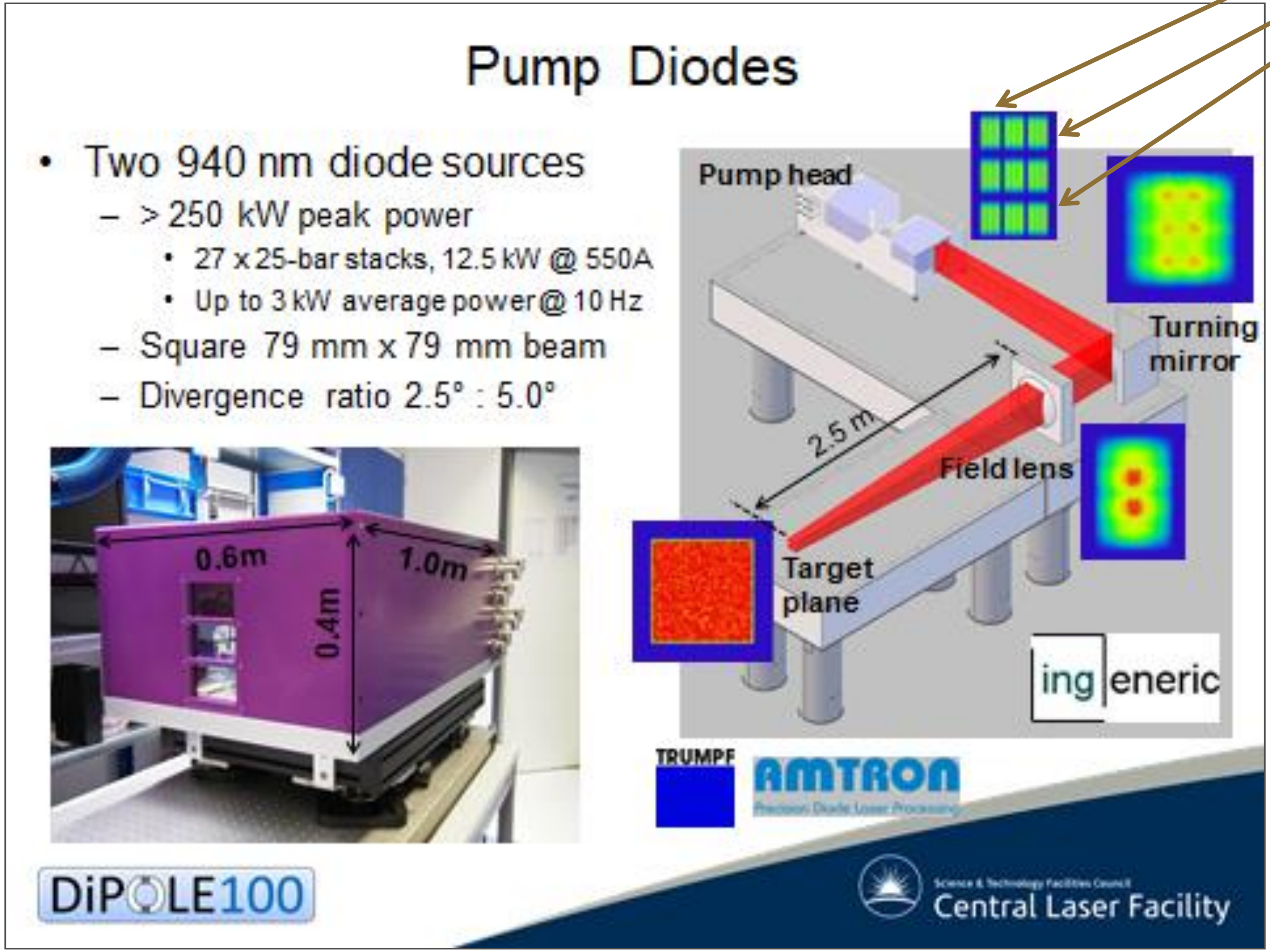
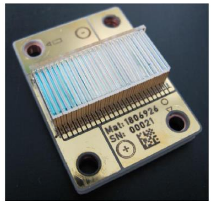
Pump units for DIPOLE100, > 250 kW, 10 Hz



Many „square“ diode laser beams combined

Generated by stacks of pulsed diode laser bars



Need for EuPRAXIA „Laser 3“
~ 2x higher peak power
~ 10x faster repetition rate

Thanks to Paul Mason STFC for the slide

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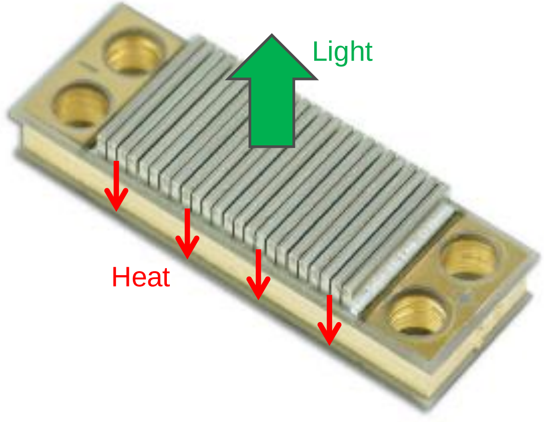
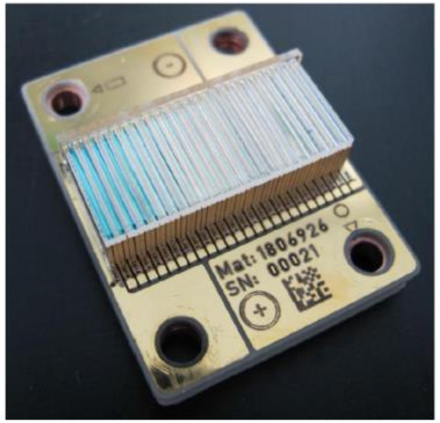
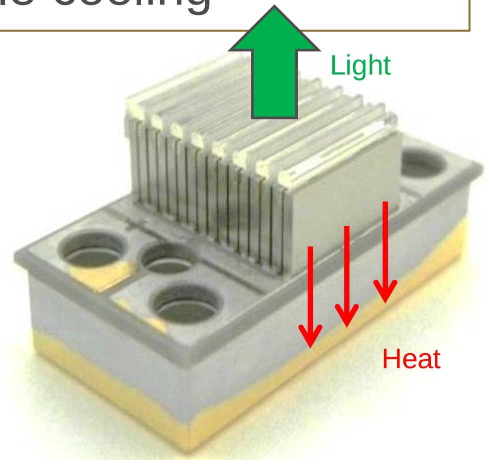
Challenge 1 for EuPRAXIA: economic pump diode packaging can‘t do 100 Hz

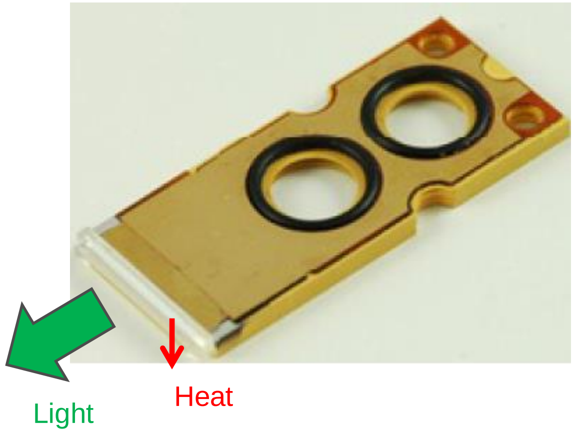
Challenge: “off the shelf” commercial diode laser pumps show performance gap

QCW package short resonator 500 W / bar to 1% DC (1ms 10 Hz) € / simple cooling	QCW package, long resonator 500 W / bar to 2% DC (2 ms 10 Hz) €€ simple cooling	CW package 500 W / bar to > 10% DC €€€ / complex cooling









e.g. DILAS/Coherent
Fassbender SPIE 1008509 (2017)

Trumpf
Vethake HECDPSSL (2014)

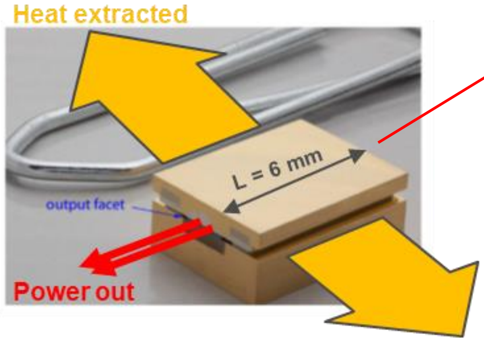
Current solution for
DIPOLE-100 J system
(0.5 ms 10 Hz)

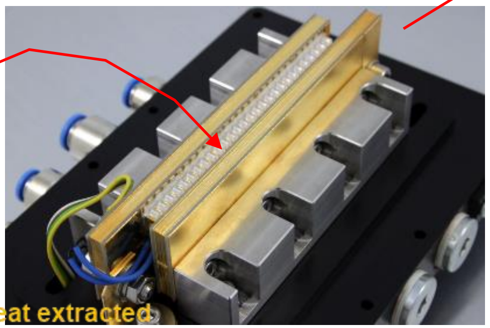
FBH/DILAS/Lastronics
Crump SPIE 1008612 (2017)

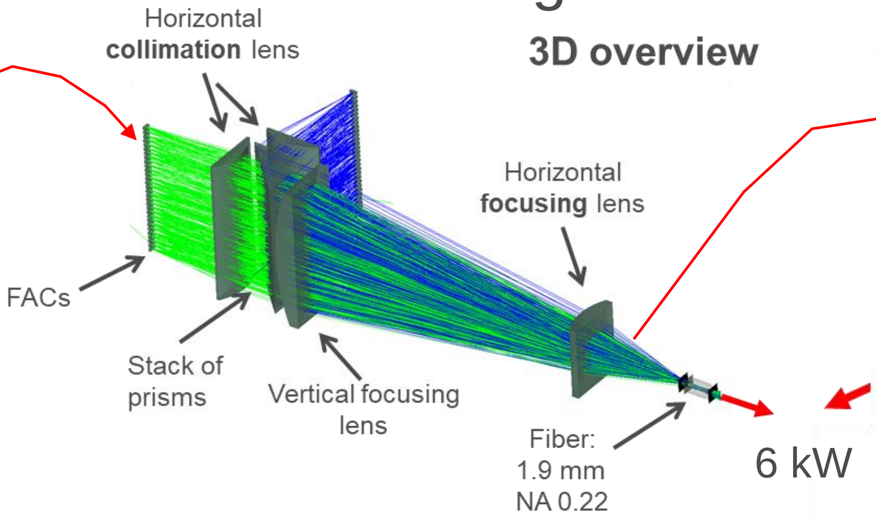
e.g. DILAS/Coherent
Fassbender SPIE 1008509 (2017)

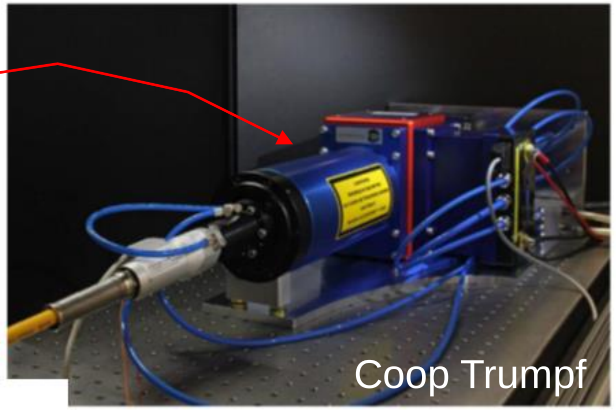
Possible solution: FBH brilliant high duty cycle pump: small-series prototype

Novel chip, carrier → Novel passive Side cooler → Custom beam forming → Brilliant, high duty cycle fibered module









130W from 1.2mm
Peak: ~ 245 W
60% efficiency
2x brighter than bars

1…20% DC
1…100ms
Passive cooling

6 kW 60% efficiency
M^2 ~ 300 x 300

1.4 MW/cm^2-sr
50% efficiency
M^2 ~ 700

6 units delivered to Max Born Institut, Berlin;
1 more completed, used for 100 Hz Pump trials in IOQ Jena
1 in build

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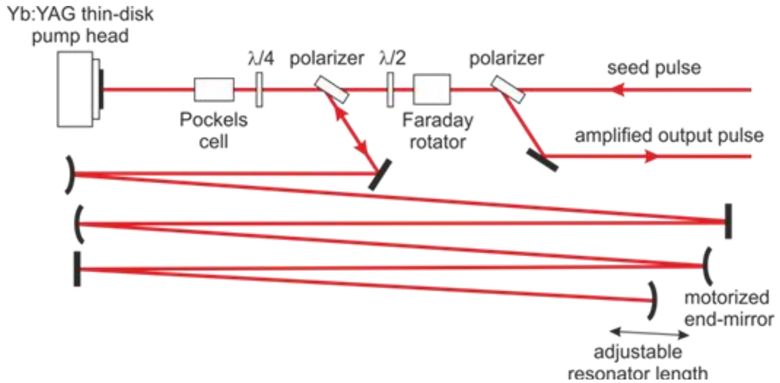
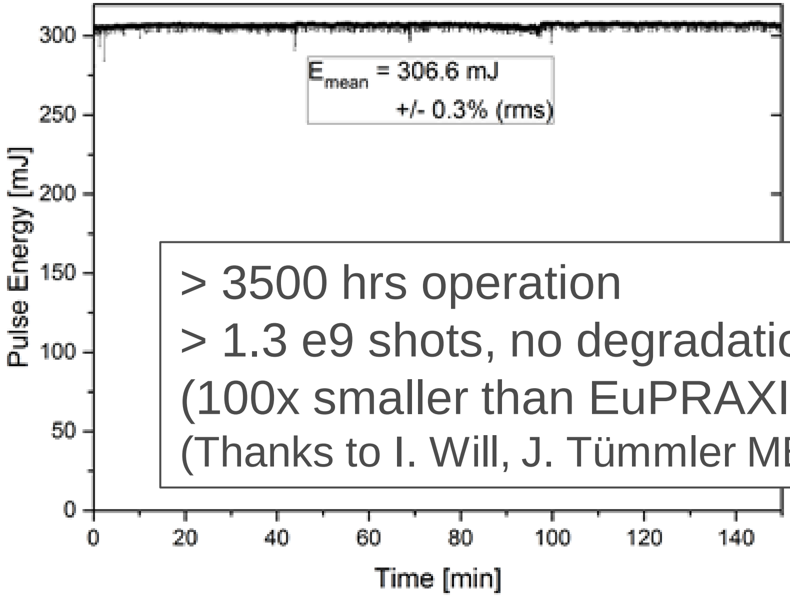
FBH brilliant high duty cycle pump in regular use at Max Born Institut, Berlin

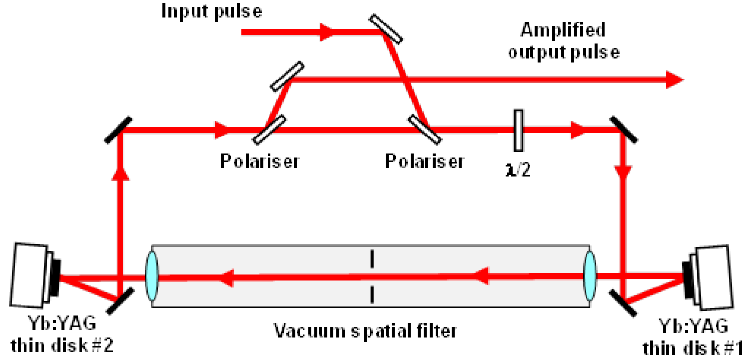
Application 1:
300mJ 100 Hz regenerative amplifier

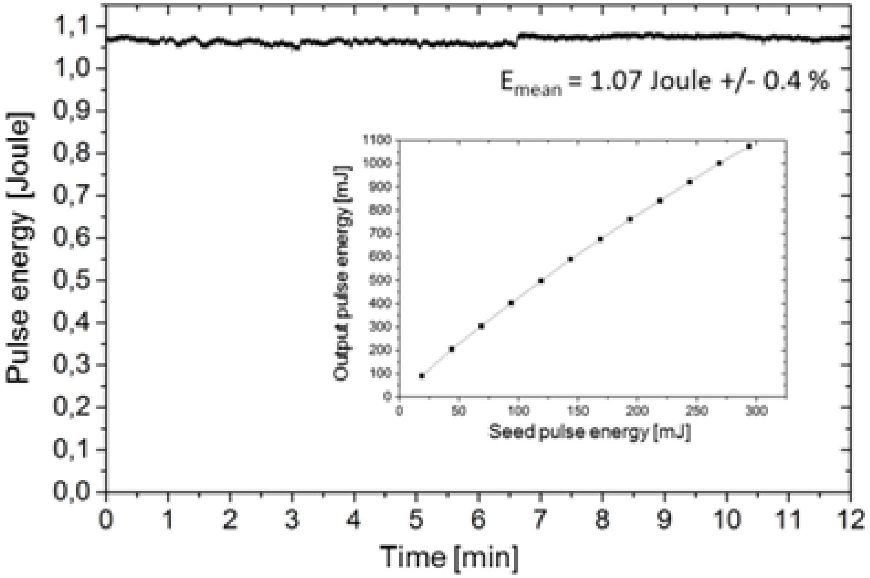




> 3500 hrs operation
> 1.3 e9 shots, no degradation
(100x smaller than EuPRAXIA need)
(Thanks to I. Will, J. Tümmler MBI, for data)

Application 2:
1 J 100 Hz ring amplifier





Challenge 2 for EuPRAXIA: advances in amplifier cooling needed for 100 Hz

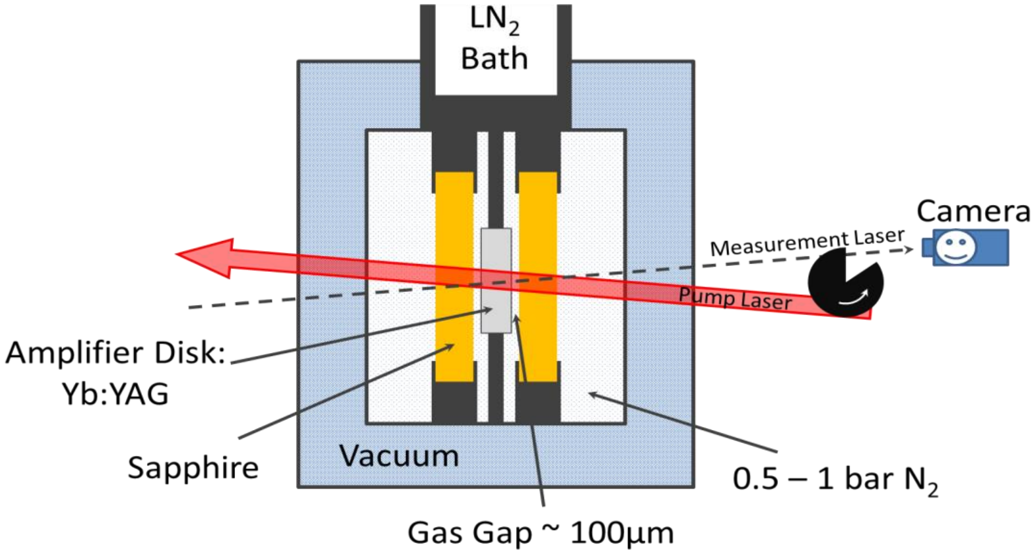
Few studies on 100 Hz pumping! So, trials performed late 2018, FBH + IOQ FSU Jena, Germany

- FBH pump: Operated 0.8 MW/cm^2-sr, 1 ms 100 Hz, 160 W average power, λ_{pump} = 940 nm
- IOQ Amplifier: Static, face cooled cryogenic Yb:YAG (Yb doping with 3 at.-%), no seed laser, so extreme case!

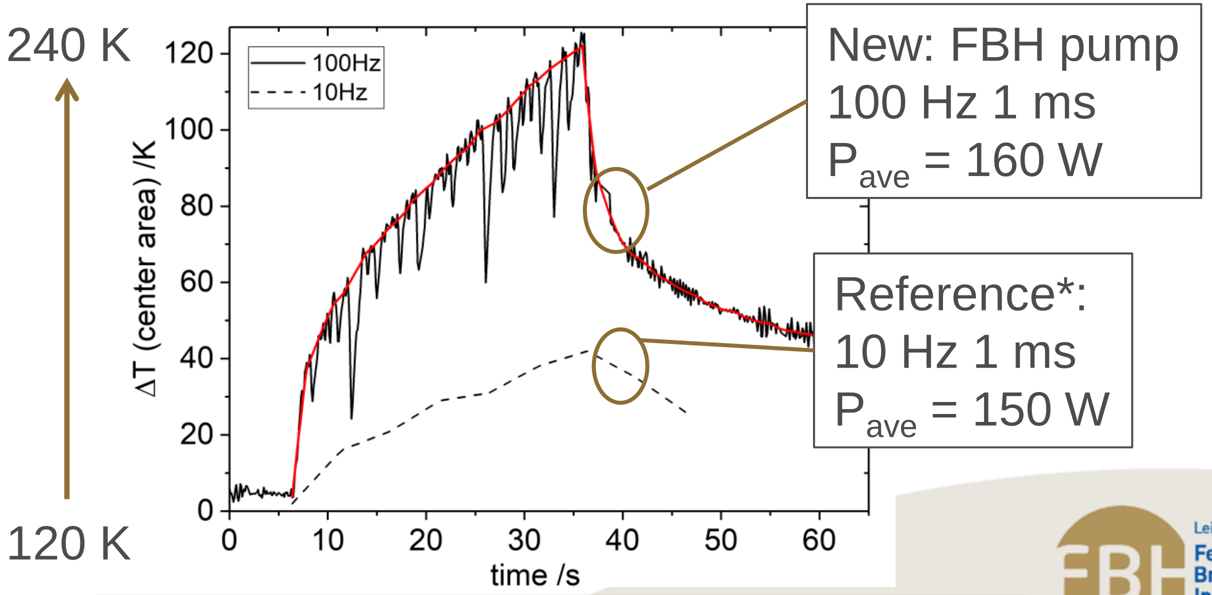
Result: ΔT: 40→120 K, for f: 10 →100 Hz, for same average power!!

- More sophisticated cooling, further analysis needed (submission to EuPRAXIA special issue shortly)

IOQ test head



Test results: 3x ΔT, for f: 10→100Hz



(Thanks to J. Körner and IOQ team, for support)

* J. Körner *et al.* Optics Letters **41**(11), p. 2525 (2016)

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Key challenges for implementation

Diode laser pumps needed for EuPRAXIA do not exist – but generate (all) the photons in the system

Performance window well outside normal specs, exact requirement unclear (really 1600 kW needed?)

Design of amplifier head needs further study – non-linear heating processes, need to be understood

Overheating observed at 100 Hz, best choice of gain media, pump wavelength, cooling scheme unclear

High fabrication costs must be budgeted for; estimate 16 Mio€ purchase just for the pumps!

- ~ 17 €/W: Approx. cost of low-volume prototype pumps (peak power)
  - Valid for FBH (100 Hz 6 kW) and DIPOLE-100 (10 Hz 250 kW) pump units.
- ~ 10 €/W: approx. estimate of pump cost for final system (see graph from Jenoptik below)
  - Feedback LLNL: broadly comparable with current prices for “high volume” QCW pump purchase
- Simple estimate leads to 16 Mio € just for pumps!
  - 1644 kW total estimated pump power
    - Laser 3 (1200 kW) + 2 (360 kW) + 1 (84 kW)
  - Does not include any needed development cost
    - 10% for development means ~ 1…2 Mio €

Time for development, fabrication needed

- Amplifier teams need prototype pumps early

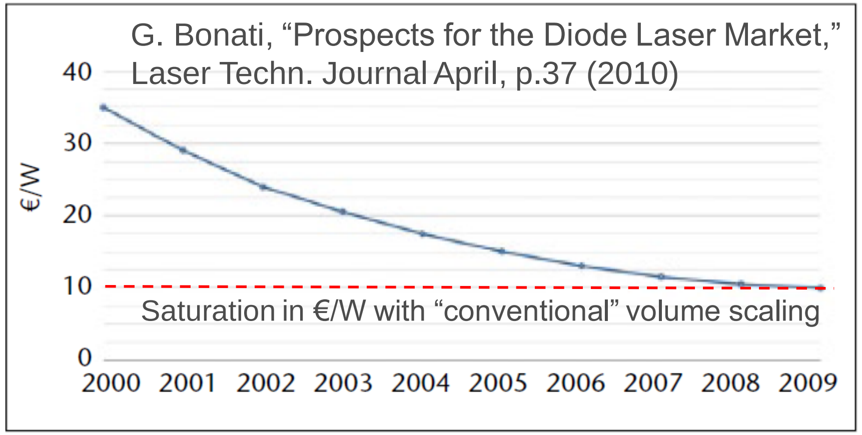

FIGURE 4: The average price per Watt of diode lasers (sold by Jenoptik) is decreasing at an average of 15 %.

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Proposal: Target completing key preparatory tasks in „valley of death“ phase

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	...	2065	2066
Project Phases	Conceptual Design Phase		Technical Design Phase (Jan 2020 – Dec 2025)						Implementation & Construction (Jan 2026 – Dec 2029)				Operation (Jan 2030 – Dec 2065)				Decommissioning (Jan – Dec 2066)
	HORIZON 2020			HORIZON EUROPE													
Funding Land-scape	Application ESFRI Roadmap			Deci-sion			ESFRI Re-view 1				ESFRI Re-view 2						

Horizon 2020 Design Study	"Valley of death" ?	Horizon Europe Preparatory Phase	Horizon Europe / Structural Funds / National Funding
3 Mio. € & in-kind contributions	???	Up to 4 Mio. € (& in-kind contribution)	>200 Mio. € from various sources

EuPRAXIA Pump Development

TDR-phase, ERDF funding?

Includes all technology development plus any transfer to industry

Fabrication phase

Large scale build, qualification

Potential organisation: pump laser cluster

EuPRAXIA
Application beamline facility
CLF, RAL (STFC), UK

EuPRAXIA
Laser & prototyping facility
Plateau de Saclay, Paris, France.

EuPRAXIA
Construction site,
DESY, Hambug, Germany

Prototype pumps

Prototype pumps

Final, qualified pumps

Propose Cluster: 100 Hz pump lasers
Development and construction
Berlin, Germany

FBH + industry

EuPRAXIA
Theory and simulation facility
Instituto Superior Técnico,
Lisbon, Portugal

Support on 100 Hz amplifier?

Proposed tasks

TDR / prototyping (2019-2023), easily > 1 Mio €

Proposed to include:

- Small scale trials of alternative wavelengths (e.g. 780 nm, 979 nm), but expect 940 nm
  - Efficient, economic delivery of "excess" material from existing programs
- Development of 100 Hz pump head
  - Including margin for technology development and scaling efforts
  - Including build of 100 Hz demonstrators, e.g. full spec Laser 1 pump units (25…40 kW)
  - Including start of material fabrication for system
  - Including necessary qualification (reliability engineering) efforts
- Start 100 Hz pumping trials as early as possible
  - Enable amplifier design to be developed and enhanced
- Implement any needed technology transfer
- Collaboration with industry to define cost, timeline, spec, technology, warranty for full system

Construction (2023-2026), easily 16 Mio €

Proposed to include:

- Build of all pump units for LASERS 1…3 (ca. 1600 kW pump power), targeting at 10 € / W

Rough exemplary timeline

	Fabrication		
Year	Diode	Pump head	Notes
2018			
2019			
2020			Delivery 1: 1x 780 nm 1x 980nm
2021			600 kW Diode laser fab starts
2022			Delivery 2: 25kW 100 Hz
2023			Pump unit fab
2024			Pump unit fab
2025			Delivery 3: 2 x 600kW 100 Hz
2026			

„Valley of Death" Phase!! (2018–2022)

Diode laser fabrication time:
Roughly one wafer process batch per month, spread over 3 years

Use of regional EU funds (for example) to kick-start early TDR phase
Supported by currently available & funded projects

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The FBH and the diode laser pump community in Germany are ideally qualified to support EuPRAXIA

- Long-term, stable industrial-academic partnership to develop and commercialize high intensity pump sources

100 Hz pumps for EuPRAXIA do not exist, either commercially or in research labs

- Closest variant: FBH 100 Hz pumps, but 6 kW prototypes, not 600 kW with warranty

100 Hz pumping leads to challenges in amplifier crystals

- Non-linear overheating, requires further study to enable re-design, implementation of enhanced technology

Path to pump availability proposed, via introduction of EuPRAXIA pump laser cluster

- Early technology development, qualification and prototype testing in „valley of death“ period
  - Goal: seek 1 Mio-€-class funding via ERDF to help make this possible
- Note potential high purchase price of pumps, expected 10€/W leads quickly to 16 Mio€-class pump laser costs
- Plausible, needs confirmation from industry

Thank you for your attention!

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Grainau, 26 Feb 2019

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Appendix: comparison of QCW pumps sources (most recent papers)

	Source	Aperture [cm²]	Solid angle [sr]	Optical Power P_{opt} [W]	Brightness B [MW / cm² / sr]	Repetition rate [Hz]	Pulse width [ms]	Wave length [nm]
Jenoptik 2013	[8], Stack	1.3	0.00120	2200	1.41	10	1	808 / 940
	[8], Module	4.0	0.01065	20000	0.47	10	1	940
	FBH, Stack	**1.1**	**0.00131**	**3600**	**2.57**	**100**	**0.1…100…cw**	**940**
	FBH, Module	**1.1**	**0.00131**	**6000**	**4.29**	**100**	**0.1…100…cw**	**940**
Jenoptik 2016	[5], 8 bars	1.2	0.00120	512	0.36	1.375 / 3	400 / 50	810
	[5], 12 bars	1.3	0.00120	1080	0.68	2	100	810
DILAS 2017	[2]^{con}	1.2	0.00120	4400	3.07	10	1.2	980 (766nm - 1550nm)
	[2]^{in}	1.9	0.00120	1320	0.59	1.375 / 3 / 400	400 / 50 / 0.2	980 (766nm - 1550nm)
	[2], Module	111.6	0.00120	250000	1.86	400	0.2	808
Focuslight 2017	[4], 3 bars	0.2	0.00120	700	2.91	50	0.25	808
	[4], 5 bars	0.4	0.00120	1500	3.11	20	0.25	808
FBH/DILAS 2017 →	[10], 8 bars	1.3	0.00106	260000	3.58	10	1	935
Trumpf 2015	[11], DiPOLE100	62.4	0.00381	250000	1.05	10	1	940
	[12], 25 bars	4.3	0.00094	12000	3.07	10	1	938 (880 - 1000nm)

Table excerpted from paper for EuPRAXIA special issue, submitted shortly