KALDERA: Laser-Plasma Acceleration

EEAC, Sept. 21st 2022

Andreas Maier

DESY

andreas.maier@desy.de
mls.desy.de
kaldera.desy.de

MLS Group

> Thanks to the team doing the actual work.
> For more details see our website(s)

mls.desy.de
kaldera.desy.de

Lars, Max, Matthias, Manuel, Kaja, Chris, Sören, Timo, Thomas, Eva, AndiW, Paul, Julian, Frida, Tomasz, Abdullah, Juan, Philipp, with Guido, Cora (not on the photo) and more to join soon.

The Case for Active Stabilization

LUX Laser-Plasma Accelerator

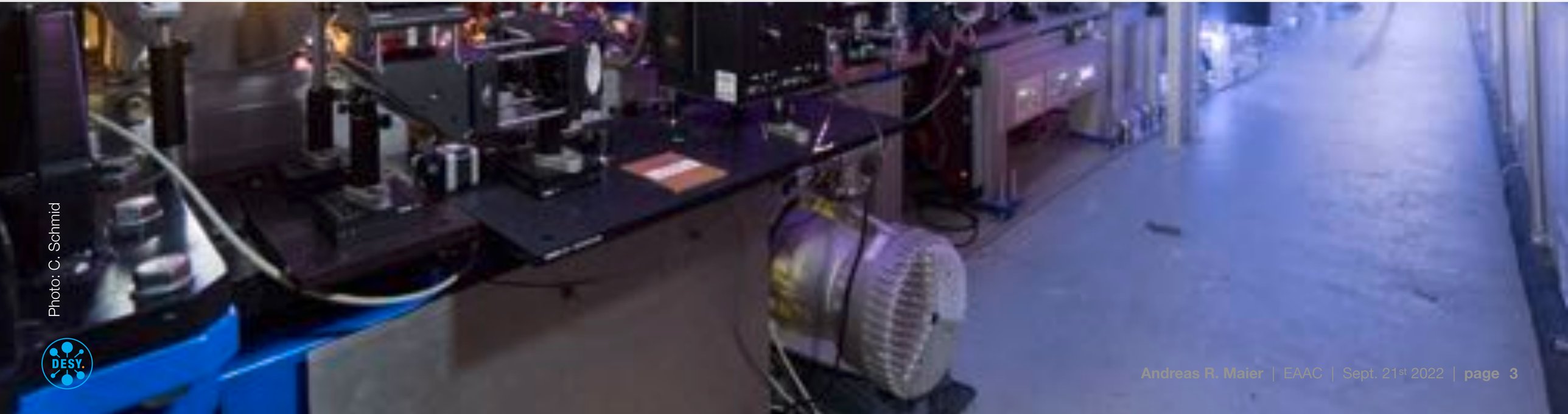
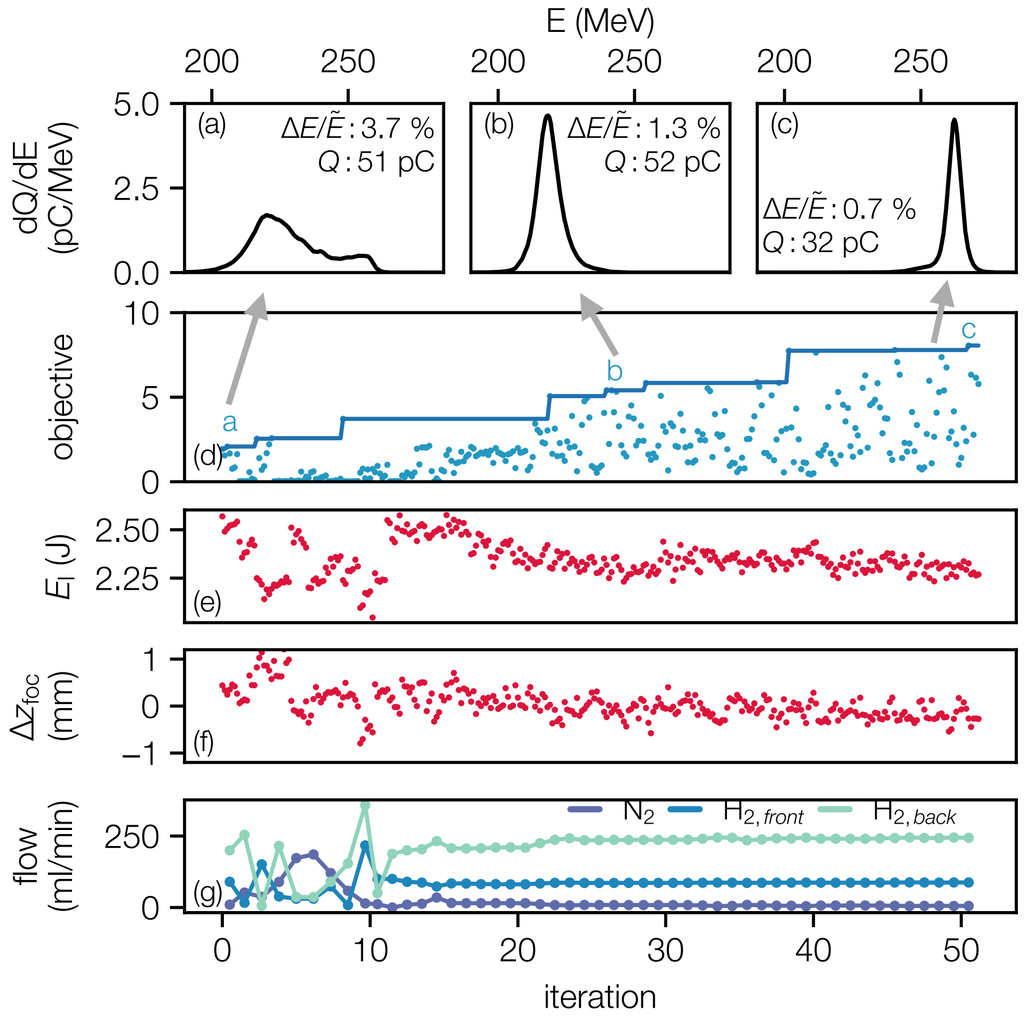


Photo: C. Schmid

Bayesian Optimization of an LPA

In the Experiment

M. Kirchen et al., PRL 126, 174801 (2021)
S. Jalas et al., PRL 126, 104801 (2021)

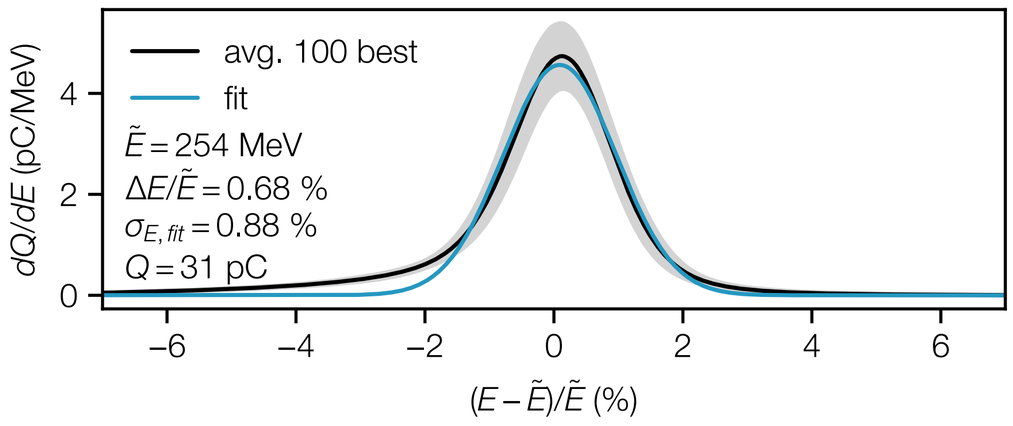


See also Sören's Poster with some very recent results

Random startpoint → sub percent electron beams

No human input

Statistics of 100 best from 2500 shot at optimum



Predictive Modeling of Electron Beam Parameters

Single-Shot Prediction (Experiment)

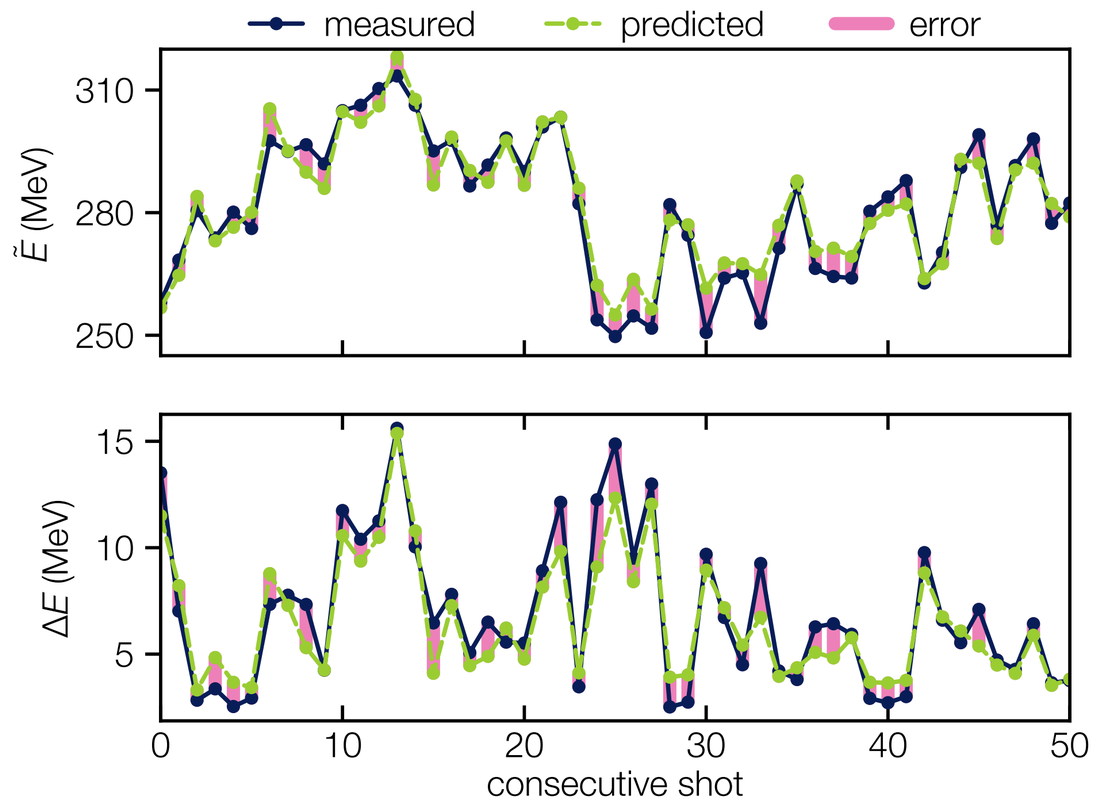
M. Kirchen et al., PRL 126, 174801 (2021)

> We created a predictive model based on machine learning techniques

> Quantifies sources of instability

> Derive requirements on future drive lasers: what energy stability do we really need?

> See Manuel's poster



Next step: Tailored laser w/ active stabilization @ high rep rate → KALDERA

See also Manuel's Poster with some very recent results

KALDERA - 100TW @ kHz LPA Drive Laser

Science Case

Science Case
> Active feedback
> Competitive repetition rate
> Technology demonstrator

Goal:
> 100 TW @ kHz, 3J @ 30 fs laser pulse
> FEL-quality electron beams: sub-percent energy spread, sub-percent energy stability

Initiated by Wim

Fig: SciCom Lab

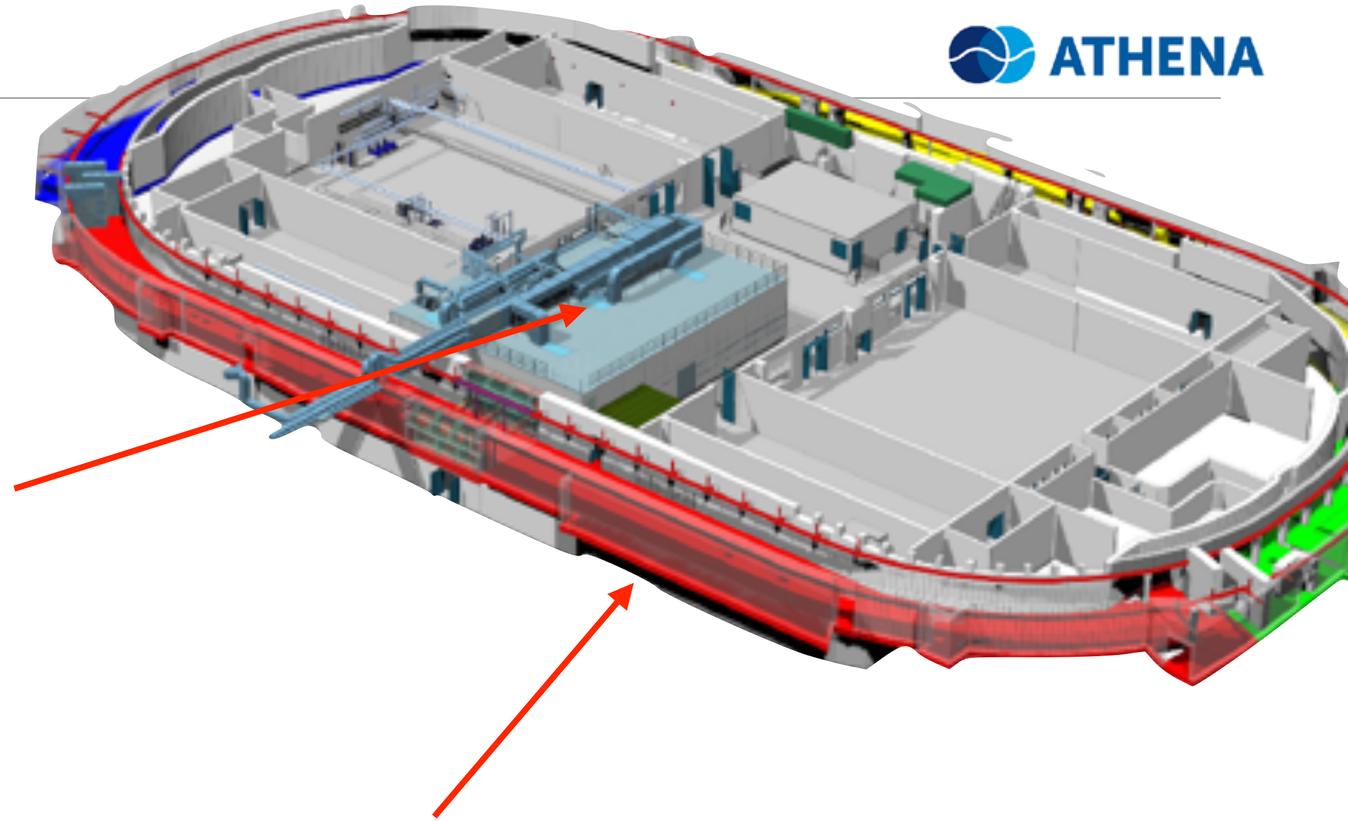
KALDERA Overview

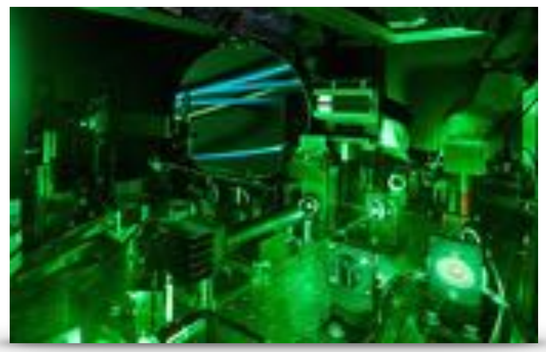
Drive Laser and LPA Electron Beams

ATHENA

New Laser Lab

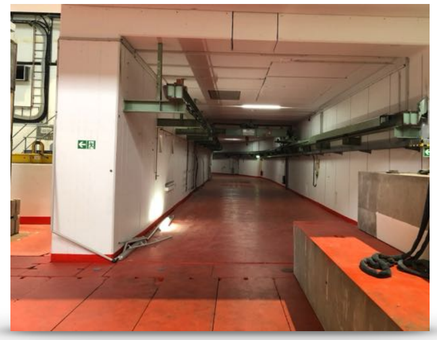
> 400m² ISO5/6 clean room
> 0.1°C stability
> Moving in: October 2022





Laser (under dev.)

> 100 TW @ 1 kHz
> 3J in 30 fs
> Active stabilisation



KALDERA Tunnel

> Generic infrastructure for experiments (many different experiments over time)
> Supports up to 1GeV @ 1kHz

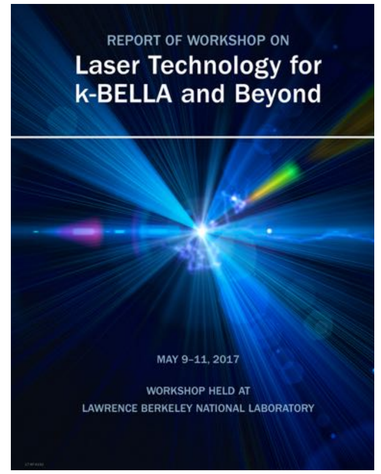
Technology Choice

Goal: Near-Term High-Quality LPA Beams

- Ti:Sapphire
  - well-known laser material
    - poor wall-plug efficiency
    - kHz is probably the limit
    - thermal management will be challenging
  - challenging, but overall lowest risk
  - well-proven LPA driver

- OPCPAs …
- Coherently combined fibres
- Novel laser materials (e.g., Tm:YLF, or Ti:Ga2O3, or…)
  - Our assessment: early-stage development, 5-10 yrs time frame
  - promises +10 kHz
  - high wall-plug efficiency
  - Not a proven LPA driver
- …

Laser and LPA development run in parallel



KALDERA Overview

Laser Development

Performance Model

Controls

Seed Laser

Lab Infrastructure

Pump Lasers

Amplifier Design

Compressor

MALCOLM

OPCPA Frontend

MALCOLM - KALDERA Seed Laser

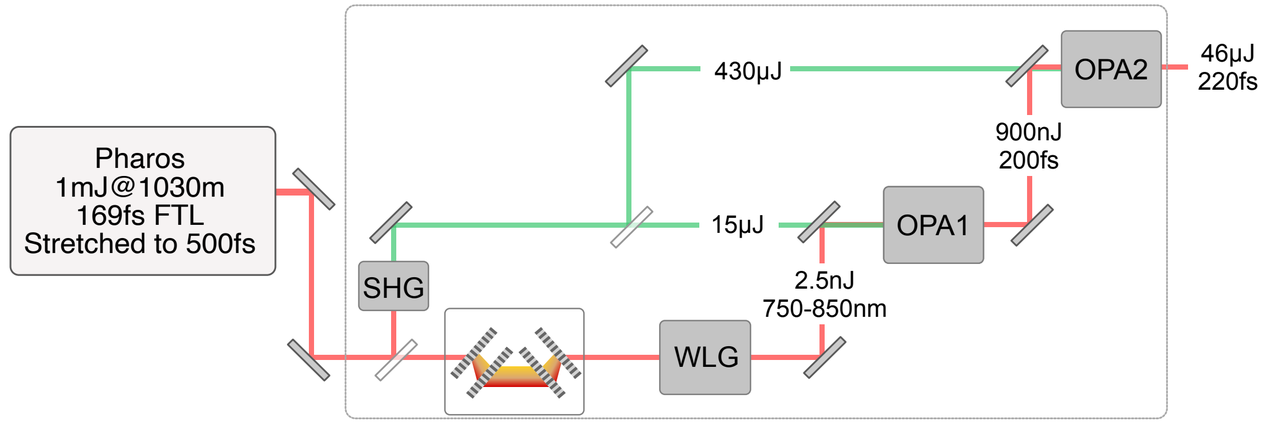
Overview

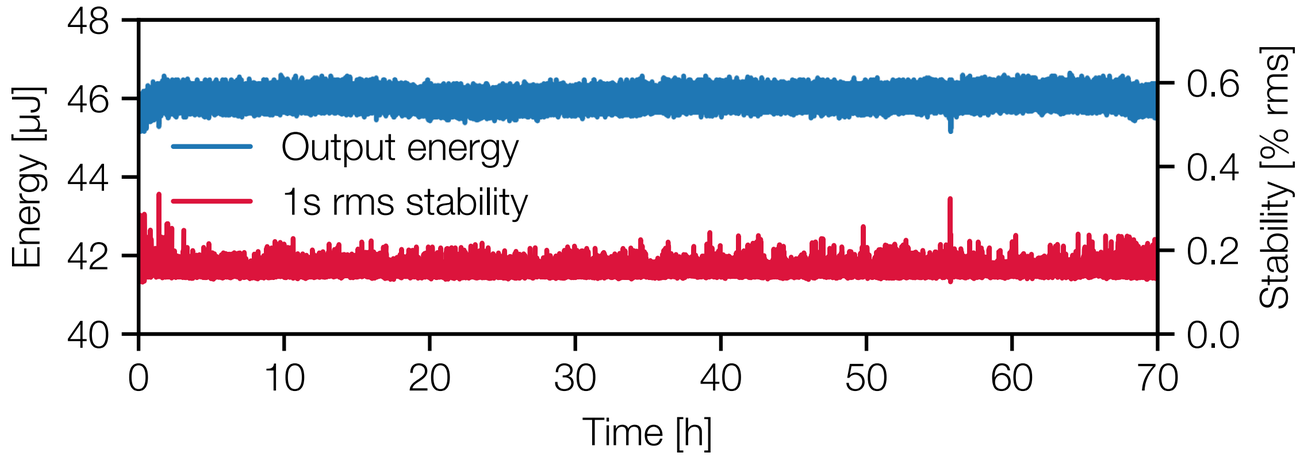
MALCOLM by T. Eichner & T. Hülsenbusch
T. Eichner et al., Opt. Express 30, 3404 (2022)

- > 2-stage white-light seeded collinear OPCPA
- > Monolithic design

specs:

- > 45 µJ @ 1 kHz ✔
- > 800 nm CWL ✔
- > 0.2% rms energy stability ✔
- > < 30 fs FTL ✔
- > 24/7 operation → in progress





Pump Lasers

Technology Options

Pump Lasers

Topcial Workshop at DESY

- 2-day workshop with representatives of both industry and research
- Survey technology options

We require:

- 10+ J green
- excellent energy stability
- At kHz-level rep rate
- 10+ kW average power in the green

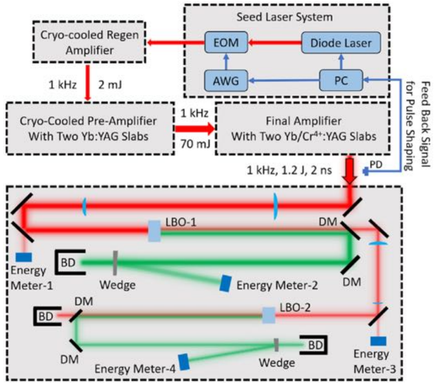
Great progress with Nd:YAG: 100W average power pumps become available.

Pump Lasers

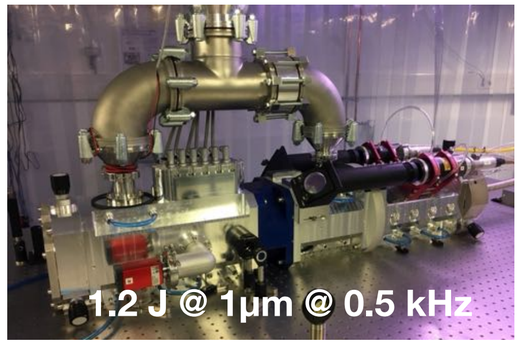
(A Few Selected) Technology Options

Cryo-cooled Yb:YAG thin disk lasers

> Concept by Rocca (CSU) and/or Pergament (DESY)
> Joule class pulses @ kHz demonstrated:
Opt. Lett. 45, 6803 (2020)



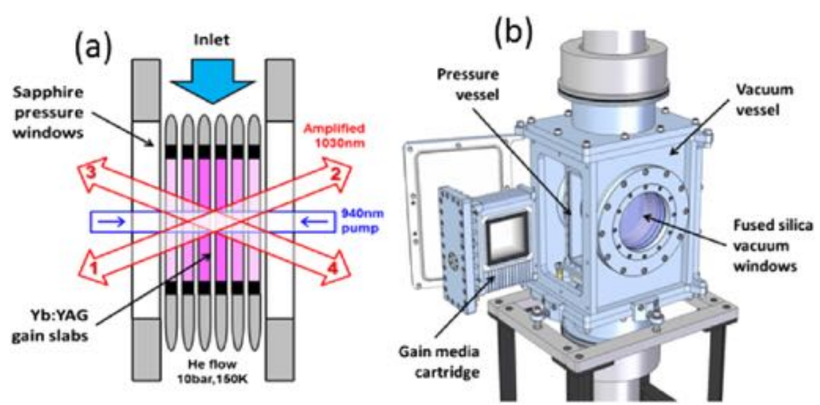
Rocca et al. (CSU)



Pergament et al. (DESY)

Cryo-gas-cooled multi-slabs

> DIPOLE laser, …
> Opt. Lett 41, 2089 (2016)



Pump Lasers

(A Few Selected) Technology Options

Massively Scaled Multi-Core Fibre Lasers

> Expect few-mJ nanosecond pulses per core
> Scalability to few-100 cores per fibre
> Proof of concept experiment (preliminary):
    > 50% conversion IR to green
    > 17 mJ green from a 4x4 core fibre
> C. Aleshire et al. Opt. Lett. 47, 1725 (2022).

4x4 core (2016)

7x7 core (2022)

afs Member of the TRUMPF Group

Fraunhofer IOF

Room-Temperature Thin Disk Laser

> Concept: MOPA architecture based on industry-grade off-the-shelf components
    > Oscillator
    > Thin-disk multipass amplifiers
    > >1J in the green
    > kHz rep rate
    > 0.3% energy stability

TRUMPF

Amplifier Design

For High Average Power

Amplifier Design

For High Average Power

Several concepts out there

> (Multi) Slabs
> Thin/Thick Disks
> Cryo-cooling
> …

Scaling them by factor x100 requires

> a trusted tool chain
> trusted material properties

We’re verifying both, also measuring material properties

Pulse Compressor

Well-known issues at high average power

Pulse Compressor

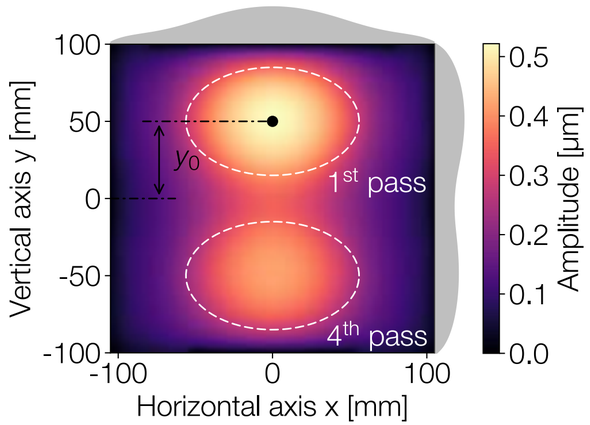
Well-known issues at high average power

T. Eichner et al.

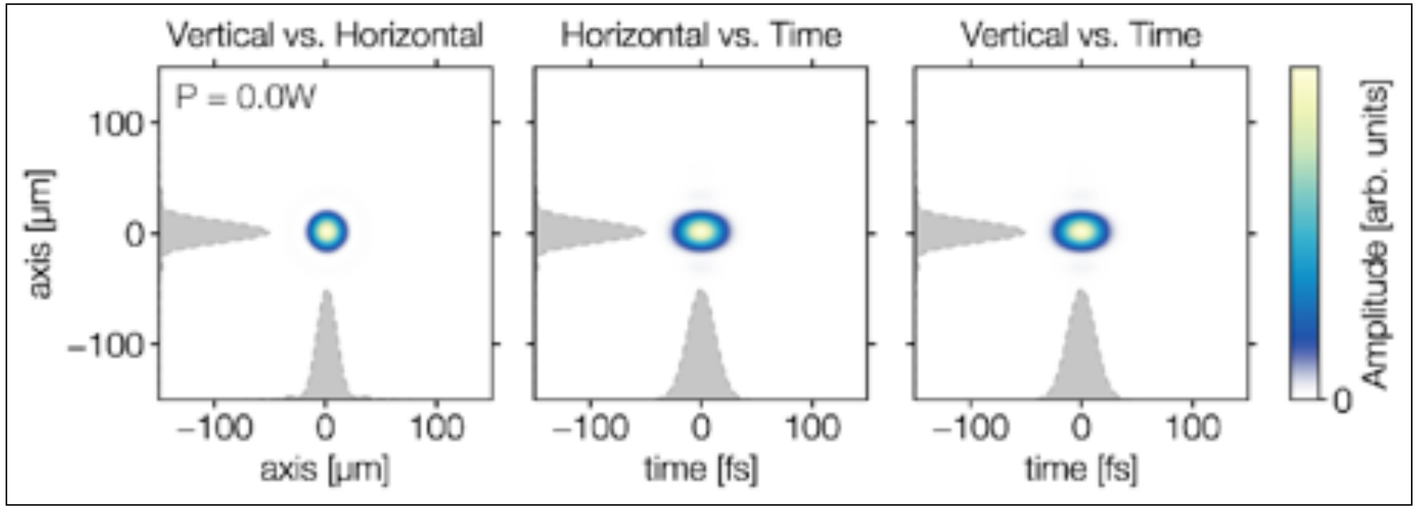
See github.com/VincentLeroux/spatio-temporal-couplings for our code

> Heat-induced substrate deformation causes spatio-temporal couplings

COMSOL Simulation



Simulated degradation of Pulse in Focus



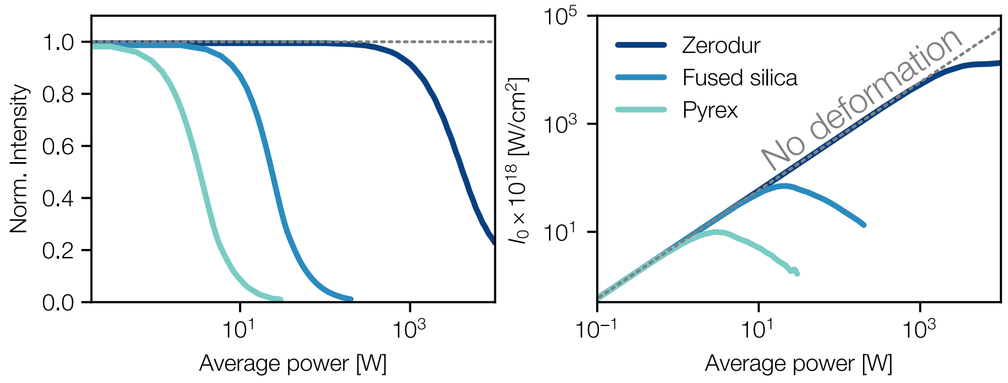
V. Leroux et al., Opt. Express 28, 8257 (2020); V. Leroux et al., Opt. Express 26, 13061 (2018); Li et al., Optics Express (2018); Li et al., Appl. Physics (2017); Opt. Express 24, 30015 (2016)

Compressor

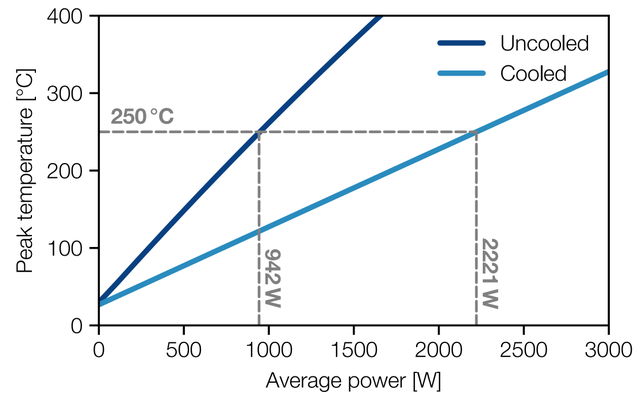
Approaching kW average power

T. Eichner et al.

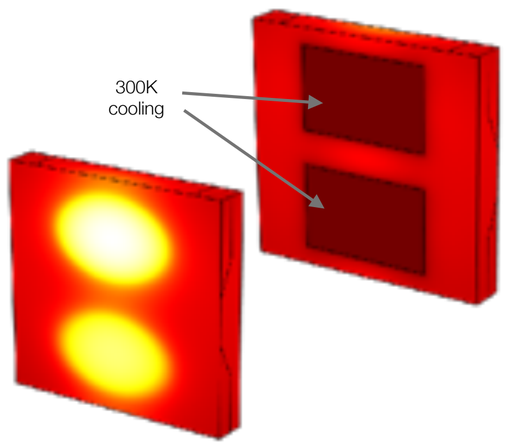
> ULE type substrate helps

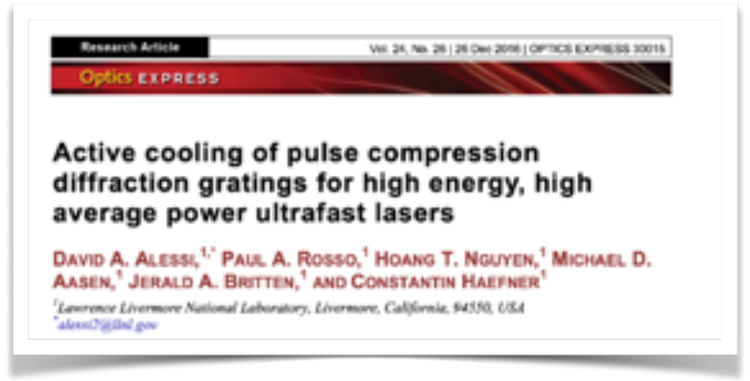


> (Simple) active cooling helps
> But surface temperature increases



> Balance groove integrity, substrate deformation, surface temperature and average power
> 1 kW might be doable with an actively cooled gold grating





Research Article | Vol. 24, No. 26 | 26 Dec 2016 | OPTICS EXPRESS 30015

Optics EXPRESS

Active cooling of pulse compression diffraction gratings for high energy, high average power ultrafast lasers

David A. Alessi,[1,*] Paul A. Rosso,[1] Hoang T. Nguyen,[1] Michael D. Aasen,[1] Jerald A. Britten,[1] and Constantin Haefner[1]

[1]Lawrence Livermore National Laboratory, Livermore, California, 94550, USA
*alessi2@llnl.gov

MLD Based Pulse Compressor

Novel Grating Design

C. Werle et al., in preparation

- MLD gratings can support sub-30-fs bandwidth if operated under Littrow angle
- Extremely low absorption -> no heating problem

- Built on-air test compressor using broadband MLD gratings
- Built matching stretcher

- Stretched and successfully re-compressed sub-30-fs pulses
- Measured up to 90% peak spectral transmission for a 4-MLD grating compressor
- Up to >80% total compressor transmission

- Fully characterized pulses

Out-of-plane geometry

Out-of-Plane Concept:
- *T. Erdogan, PGL Techn Note (2018)*
- *D. Alessi et al., Optics & Laser Tech. 117, 239 (2019)*

Summary

It’s exciting times for LPA

Thanks

Andreas Maier
DESY

andreas.maier@desy.de
mls.desy.de

KALDERA . PLASMABESCHLEUNIGER

kaldera.desy.de

Video: SciCom Lab, S. Jalas, M. Kirchen